ECOMAG-05

HHH-AMT Workshop on Superconducting PulsedMagnets for Accelerators

Frascati (Italy) 26-28 October 2005

Proceedings
Acknowledgement

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June 2005

Dear Colleague,

The past years have seen a growing interest in pulsed superconducting accelerator magnets, ranging from low field, continuously pulsed magnets (typically 2 T peak, 4 T/s, $10^8$ cycles) to medium field, high-duty cycle magnets for storage and booster rings (typically 6 T peak, 1 T/s, $10^6$ cycles) with apertures in the range of 80 to 100 mm. For this reason we wish to address this topic within the frame of the CARE networking activities calling for a:

**HHH-AMT Workshop on Superconducting Pulsed Magnets for Accelerators**

(ECOMAG-05)

that will take place at ENEA - Frascati (Italy) during the week from 26 to 28 October, 2005.

This workshop aims, among others, at giving a technological follow-up to the CARE-HHH-APD Workshop (LHC-LUMI-05, Arcidosso, August 2005), and specifically:

- summarise the requirements from particle physics, accelerator upgrades and other fields (e.g. hadron therapy) to define a set of parameters for the development of pulsed superconducting magnets for accelerators;
- translate the above requirements in specifications for the performance of strand, cable, magnet and auxiliaries (i.e. cryogenics, power supplies, instrumentation, measurement systems);
- define the R&D required to achieve the above specifications and produce a tentative road-map for a procurement and prototyping activity.

The work will be organised in plenary sessions supported by parallel sessions of several working groups that should tackle all aspects of relevance in the design and realisation of pulsed superconducting magnets, ranging from strand and cable $J_c$, AC loss and stability, to magnetic design, magnet protection, heat removal and optimization of iron losses, and extending to issues in connection with the operation of the magnet (power supply control and cryogenics) or the precise measurement of fast changing magnetic fields.

It is our pleasure to invite you to participate to the success of the workshop by contributing to the activities of the working groups and to the discussion in the plenary sessions. Please contact us to obtain more information, confirm your participation and discuss on your contribution.

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HHH-AMT Workshop on Superconducting Pulsed Magnets for Accelerators

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Executive Summary

The workshop ECOMAG was aimed at summarising the requirements from particle physics and planned accelerator upgrades to define a set of agreed parameters for the development of pulsed superconducting magnets for accelerators. The main result of the three days of topical presentations, discussion in Working Groups and summary sessions was to agree on a set of parameters for four magnet classes that respond to the different requirements identified for new pulsed accelerators.

The parameters of the four magnet classes are divided in two sets. The first set, whose parameter range is summarised in Tab. I, covers fast pulsed injectors that have very large number of cycles, considerable radiation dose and very low AC loss requirements. The field and aperture range of these magnets typically overlaps or extends that of normal-conducting magnets. Hence, in practice, these magnets are aimed at providing improved performance with respect to the normal-conducting solution, either in terms of operating cost (reducing resistive losses), magnet size (making use of the high coil current density), or vacuum quality (through cryopumping).

The second set of parameters, whose range is reported in Tab. II, is typical of intermediate energy rings or boosters. In this range of field and aperture the superconducting solution is the only viable technology. The magnet parameters in this second range are thought to be at a challenging but feasible level for what regards AC loss control and heat removal.

A main result of the workshop has been to translate the above requirements in specifications for the performance of strand, cable, magnet and auxiliaries (in particular instrumentation and measurement systems).

Table I – Parameters range for fast pulsed injectors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SIS 100</th>
<th>PS II</th>
</tr>
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<tbody>
<tr>
<td>Peak field</td>
<td>2T</td>
<td>3T</td>
</tr>
<tr>
<td>Good field region H x V [mm]</td>
<td>130x60</td>
<td>130x80</td>
</tr>
<tr>
<td>Field quality</td>
<td>± 6 units</td>
<td>± 4 units</td>
</tr>
<tr>
<td>dB/dT [T/s]</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>Number of cycles (20 years)</td>
<td>200MCycles</td>
<td>60MCycles</td>
</tr>
<tr>
<td>Radiation load [W/m]</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Peak radiation load [W/m]</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>Duration of a cycle [seconds]</td>
<td>2</td>
<td>3.6</td>
</tr>
<tr>
<td>Time of exposure</td>
<td>111 khours</td>
<td>60 khours</td>
</tr>
<tr>
<td>Typical refrigeration power W/m</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Effective duty-cycle</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Magnet length [m]</td>
<td>2.9</td>
<td>4</td>
</tr>
<tr>
<td>Number of dipoles</td>
<td>108</td>
<td>100</td>
</tr>
<tr>
<td>Maximum voltage</td>
<td>1 kV</td>
<td>1 kV</td>
</tr>
</tbody>
</table>
Table II – Parameters range for intermediate energy rings and injector boosters

<table>
<thead>
<tr>
<th></th>
<th>SIS 300</th>
<th>SPS II</th>
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<tr>
<td><strong>Peak field</strong></td>
<td>6</td>
<td>4.5</td>
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<tr>
<td><strong>Good field region H x V [mm]</strong></td>
<td>Φ 80</td>
<td>Φ 80</td>
</tr>
<tr>
<td><strong>Field quality</strong></td>
<td>± 2 units</td>
<td>± 2 units</td>
</tr>
<tr>
<td>dB/dT [T/s]</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Number of cycles (20 years)</strong></td>
<td>1 MCycles</td>
<td>1 MCycle</td>
</tr>
<tr>
<td><strong>Radiation load [W/m]</strong></td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td><strong>Peak radiation load [W/m]</strong></td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td><strong>Duration of a cycle [seconds]</strong></td>
<td>24</td>
<td>12</td>
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<tr>
<td><strong>Time of exposure</strong></td>
<td>6.7 khours</td>
<td></td>
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<tr>
<td><strong>Typical refrigeration power W/m</strong></td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>Effective duty-cycle</strong></td>
<td>0.5</td>
<td>0.4</td>
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<tr>
<td><strong>Magnet length [m]</strong></td>
<td>2.9</td>
<td>6</td>
</tr>
<tr>
<td><strong>Number of dipoles</strong></td>
<td>108</td>
<td>750</td>
</tr>
<tr>
<td><strong>Maximum voltage</strong></td>
<td>1 kV</td>
<td>1 kV</td>
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In particular on the superconducting strand and cable, the experts have identified a series of critical issues that require technological demonstration to show that the above magnets can be built and operated to specification:

- Jc level for wires with small filaments embedded in a resistive matrix and/or resistive barriers;
- Effect of the production route (single vs. double stacking) on the homogeneity of filaments (size and shape), Jc and strand time constant;
- Acceptable level of interstrand resistance, balancing AC loss reduction and stability properties;
- Joints for pulsed operation, ensuring good homogeneity of the current at controlled AC loss;
- Cable insulation schemes compatible with operation at high voltage vs. heat removal in the coil.

It was generally agreed in the discussion of Working Group 1 (Wires and Cables) that a key component to all routes is the strand, for which two specific sets of specifications have been proposed, reported schematically in Tab. III. The first option is strongly advocated for the GSI magnets of the SIS-100 and SIS-300 rings. The second option would be a preferred choice for a superconducting SPS upgrade at CERN. Both strands require industrial R&D, and thus adequate funding from the laboratories.

Table III – Pulsed Strand characteristics

<table>
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<th>GSI</th>
<th>CERN</th>
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<tr>
<td><strong>Strand diameter</strong></td>
<td>0.825 mm</td>
<td>0.65 mm</td>
</tr>
<tr>
<td><strong>Jc (4.2 K, 5 T)</strong></td>
<td>&gt; 2700 A/mm²</td>
<td>&gt; 2000 A/mm²</td>
</tr>
<tr>
<td><strong>Filament diameter</strong></td>
<td>3.5 μm</td>
<td>1 μm</td>
</tr>
<tr>
<td><strong>Number of filaments</strong></td>
<td>150,000</td>
<td></td>
</tr>
<tr>
<td><strong>Matrix/Barriers</strong></td>
<td>CuMn matrix</td>
<td>CuNi barriers</td>
</tr>
<tr>
<td><strong>Losses (0-3-0 T cycle)</strong></td>
<td>&lt; 35 mJ/cm² of NbTi</td>
<td>&lt; 10 mJ/cm² of NbTi</td>
</tr>
</tbody>
</table>
On the side of magnet design, the presentations and discussions focussed on two options for the ranges identified:

- superferric magnets for the 2 T range;
- single and double layer cos-theta magnets for the 4 to 6 T range.

A number of critical issues were identified, namely:

- magnet protection (quench detection method and efficiency) especially in connection with the need for resistive or semi-conducting by-passes, that would affect the ramping behaviour and, possibly, the heat balance of the accelerator (in case of warm by-pass);
- heat transfer from the cable to the cryogenic system, where the mechanism that control the heat transfer are known, but not sufficiently characterised for the technical geometries and operating conditions of interest;
- fatigue behaviour under extremely long lifetimes, with particular attention to structural components, insulation, interconnects and current leads;
- tolerance to the radiation dose

Several magnet design alternatives addressing the above issues were discussed at the workshop, as listed in the summary presentations of the Working Groups 2 (Low Losses Pulsed Magnets) and 3 (Heat Transfer, Quench Protection and Magnetic Measurements). The general consensus is that any of these alternatives could provide a solution, but the specific choice would depend on all aspects of the integrated magnet design. On this topic, a specific accent was put on the need for design methods and codes spanning electromagnetics, quench propagation, and thermohydraulics.

On the issue of heat transfer, the technology allowing to drain the largest power, with up to 100W/m in steady state, is bi-phase force He flow through an hollow conductor, as developed in Dubna. More standard experimental and computational methods need to be agreed upon to generalize the application of these results and to identify efficient alternatives.

Finally, the development of rapidly pulsed magnets for accelerators must be accompanied by a parallel development in the instrumentation and diagnostics. In particular, precision magnetic measurement of ramped fields is a critical issue that is being addressed at several laboratories (BNL, GSI, CERN). The present state-of-the-art allows measurement of field integral to 1 % and field errors to 100 ppm, with a bandwidth of the order of 1 Hz. T developments in the laboratories quoted above aim at pushing these boundaries by one order of magnitude, i.e. field integrals at 0.1 %, field errors at 0.1 units and a bandwidth of 10 Hz.
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<tr>
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</tr>
</tbody>
</table>
## Wednesday 26 October (Brunelli meeting room)

### Morning

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00 - 09:15</td>
<td>Welcome to the participants and Scope of the Workshop</td>
<td>(W. Scandale)</td>
</tr>
<tr>
<td>09:15 - 10:15</td>
<td>Summary from CARE-HHH-APD Workshop Arcidosso</td>
<td>(W. Scandale)</td>
</tr>
<tr>
<td>10:15 - 10:30</td>
<td>Preparation of the Working Groups</td>
<td>(D. Tommasini)</td>
</tr>
</tbody>
</table>

**10:30-11:00**  **Coffee break**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:00 - 12:30</td>
<td>Working Groups (parallel sessions WG1 - WG2 - WG3)</td>
</tr>
</tbody>
</table>

**12:30 – 14:00 lunch**

### Afternoon

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00 - 15:30</td>
<td>Working Groups (parallel sessions WG1 - WG2 - WG3)</td>
</tr>
</tbody>
</table>

**15:30-16:00**  **Coffee break**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:00 - 17:30</td>
<td>Working groups (parallel sessions WG1 - WG2 - WG3)</td>
</tr>
</tbody>
</table>
HHH-AMT Workshop on Superconducting Pulsed Magnets for Accelerators

ECOMAG-05    Frascati (Italy)  26-28  October 2005

**Thursday 27 October (Brunelli meeting room)**

*Morning*

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00 - 09:40</td>
<td>Wires R&amp;D for pulsed superconducting magnets</td>
<td>(D. Leroy)</td>
</tr>
<tr>
<td>09:40 - 10:20</td>
<td>Configurations and properties of low losses superconducting cables</td>
<td>(P. Bruzzone)</td>
</tr>
</tbody>
</table>

**10:20-10:30**  **Coffee break**

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:30 - 11:20</td>
<td>Review of AC applications in superconductivity</td>
<td>(J. Minervini)</td>
</tr>
<tr>
<td>11:20 - 12:00</td>
<td>Review of heat transfer mechanisms in superconducting magnets</td>
<td>(B. Baudouy)</td>
</tr>
</tbody>
</table>

**12:30 – 14:00 lunch**

**Afternoon – Industry session (Chairman: W. Scandale)**

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00 - 14:40</td>
<td>Alstom Experience in production of superconducting wires and magnets</td>
<td>(G. Hoang – Alstom)</td>
</tr>
<tr>
<td>14:40 - 15:00</td>
<td>Superconducting wires and cables production at Outokumpu</td>
<td>(A. Baldini – Outokumpu Italy)</td>
</tr>
<tr>
<td>15:00 - 15:20</td>
<td>Bruker BioSpin activities in superconductor wires and magnets, including low ac loss conductors</td>
<td>(H. Krauth – Bruker)</td>
</tr>
</tbody>
</table>

**15:20-15:40**  **Coffee break**

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:40 - 16:00</td>
<td>Title to be confirmed</td>
<td>(D. Krischel – Accel)</td>
</tr>
<tr>
<td>16:00 - 16:20</td>
<td>Title to be confirmed</td>
<td>(R. Penco – Ansaldo)</td>
</tr>
<tr>
<td>16:20 - 16:40</td>
<td>Magnet Technology at Babcock Noell Nuclear – Recent projects and future perspectives</td>
<td>(W. Walter – BNN)</td>
</tr>
</tbody>
</table>
### Friday 28 October (Brunelli meeting room)

**Morning**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00 - 10:00</td>
<td>WG-1: Wires &amp; Cables</td>
<td>J. Kaugerts</td>
</tr>
</tbody>
</table>

**10:00-10:15** Coffee break

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:15 - 11:15</td>
<td>WG-2: Low losses pulsed magnets</td>
<td>E. Salpietro</td>
</tr>
<tr>
<td>11:15 - 12:30</td>
<td>WG-3: Heat transfer, quench protection and magnetic measurements</td>
<td>A. Siemko</td>
</tr>
</tbody>
</table>

**12:30 – 14:00 lunch**

**Afternoon**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00 - 15:30</td>
<td>Round table</td>
<td>D. Tommasini</td>
</tr>
<tr>
<td>15:30 - 16:00</td>
<td>Closing remarks</td>
<td>L. Bottura</td>
</tr>
</tbody>
</table>
ECOMAG-05
Scope

• Critical review of key topics for pulsed superconducting magnets:
  • low losses wires and cables
  • heat transfer mechanisms
  • magnet configurations
  • quench detection and protection
  • magnetic field measurements

• Define a road map for needed R&D on dipoles 3 T peak - 3 T/s; 6 T peak - 1 T/s

outlook

♦ nominal parameters and timescale for their upgrade
♦ path for the performance upgrade
  ♦ phase 0: the ultimate luminosity
  ♦ phase 1: the IR upgrade
  ♦ phase 3: the injector complex upgrade
♦ concluding remarks
main challenges of LHC

Improvements in LHC respect to previous hadron colliders

- Factor of 1.5 increase in magnetic field
- Factor of 20 increase in luminosity
- Factor of 100 decrease in collimation inefficiency
- Factor of 100 increase in beam stored energy
- Factor of 1000 increase in beam energy density

Special LHC features

- SC dipoles and quadrupoles with two-in-one design
- SC cables operating with 15% margin from critical field
- Superfluid He coolant with tight cryogenic load budget
- e-cloud
- high vacuum without diffused pumping (cryo-pumping)

LHC will use almost all the CERN accelerator complex

The CARE-HHH Network

Mandate

Coordinate and integrate the activities of the accelerator and particle physics communities, in a worldwide context, towards achieving superior High-Energy High-Intensity Hadron-Beam facilities for Europe

- Roadmap for the upgrade of the European accelerator infrastructure (LHC and GSI accelerator complex)
  - luminosity and energy upgrade for the LHC
  - pulsed SC high intensity synchrotrons for the GSI and LHC complex
  - R&D and experimental studies at existing hadron accelerators
  - select and develop technologies providing viable design options
- Coordinate activities and foster future collaborations
- Disseminate information

- HHH coordination: F. Ruggiero (CERN) & W. Scandale (CERN)
  3. Accelerator Physics and Synchrontron Design (APD): F. Ruggiero (CERN) & F. Zimmermann (CERN)
26 October 2005 - ECOMAG 05 W.Scandale, LHC luminosity upgrade - report from LHC-LUMI-05

**time scale of LHC upgrade**

- radiation damage limit: ~700 fb⁻¹

**CARE-HHH time scale of LHC upgrade**

1. Life expectancy of LHC IR quadrupole magnets is estimated to be <10 years due to high radiation doses.
2. The statistical error halving time will exceed 5 years by 2011-2012.
3. Therefore, it is reasonable to plan a machine luminosity upgrade based on new low-β IR magnets before ~2014.

**scenarios for the luminosity upgrade**

- ultimate performance without hardware changes (phase 0)
- maximum performance with only IR changes (phase 1)
- maximum performance with ‘major’ hardware changes (phase 2)

**Nominal LHC performance**

- beam-beam tune spread of 0.01
- $L = 10^{34} \text{cm}^2 \text{s}^{-1}$ in Atlas and CMS
- Halo collisions in ALICE
- Low-luminosity in LHCb

**Phase 0: steps to reach ultimate performance without hardware changes:**

1. Collide beams only in IP1 and IP5 with alternating H-V crossing
2. Increase $N_b$ up to the beam-beam limit
3. Increase the dipole field from 8.33 T to 9 T
   - $E_{\text{max}} = 7.54 \text{TeV}$
4. Halve $z$ with high harmonic RF system
   - $E_{\text{max}} = 7.54 \text{TeV}$
5. Double the no. of bunches $n_b$ (increasing $\beta^*$)
   - $L = 4.6 \times 10^{34} \text{cm}^2 \text{s}^{-1}$

**Phase 1: steps to reach maximum performance with only IR changes:**

1. Modify the SC insertion quadrupoles and/or layout
   - $\beta^* = 0.25 \text{m}$
2. Increase crossing angle $\theta_c$ by $\theta_c = 445 \mu\text{rad}$
3. Increase $N_b$ up to ultimate luminosity
   - $L = 3.3 \times 10^{34} \text{cm}^2 \text{s}^{-1}$
4. Halve $\alpha_z$ with high harmonic RF system
   - $L = 4.6 \times 10^{34} \text{cm}^2 \text{s}^{-1}$
5. Double the no. of bunches $n_b$ (increasing $\beta^*$)
   - $L = 9.2 \times 10^{34} \text{cm}^2 \text{s}^{-1}$

**R&D for phase 1**

- Quadrupole first versus dipole first solutions
  - NbTi versus Nb₃Sn magnets
  - 13 ÷ 15 T dipole with 70 mm coils aperture
  - 300 ÷ 350 Tm⁻¹ quadrupole with 80 to 100 mm coils aperture
  - Structured SC cable (external cable made with HT SC) - McIntyre
  - Dipole D0 embedded in the experiment, reducing the crossing angle and the debris deposition in the triplet - Koutchouk
- RF Crab cavities versus bunches shortening with a 1.2 GHz RF, mitigating luminosity loss induced by large crossing angles
- Local chromaticity correction schemes - Raimondi
- Doublet versus triplet - is it possible to handle flat beams?
- Reduce crossing angle and apply long-range beam-beam compensation with wires close to the beams - Koutchouk

**scenarios for the luminosity upgrade**

- **Phase 0: steps to reach ultimate performance without hardware changes:**
  1. Collide beams only in IP1 and IP5 with alternating H-V crossing
  2. Increase $N_b$ up to the beam-beam limit
  3. Increase the dipole field from 8.33 T to 9 T

- **Phase 1: steps to reach maximum performance with only IR changes:**
  1. Modify the SC insertion quadrupoles and/or layout
  2. Increase crossing angle $\theta_c$ by $\theta_c = 445 \mu\text{rad}$
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**Nominal LHC performance**

- Beam-beam tune spread of 0.01
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- Halo collisions in ALICE
- Low-luminosity in LHCb
luminosity and energy upgrade

Phase 2: steps to reach maximum performance with major hardware changes:

- equip the SPS with SC magnets, upgrade transfer lines to LHC and the injector chain, to inject into the LHC at 1 TeV (super-SPS option)
  - beam luminosity should increase
  - first step in view of an LHC energy upgrade
- for a given mechanic and dynamic apertures at injection, this option can double the beam intensity (at constant beam-beam parameter $\Delta Q_{0b} = N_b / \gamma^2$) increasing the LHC peak luminosity by nearly a factor two, in conjunction with long range beam-beam compensation schemes
- LHC energy swing is reduced by a factor 2, hence the SC transient phenomena should be smaller and the turnaround time to fill LHC should decrease
- interesting alternative: cheap, compact low-field booster rings in the LHC tunnel
- install in LHC new dipoles with a operational field of 15 T considered a reasonable target for 2015 + 2020: beam energy around 12.5 TeV
  - luminosity should increase with beam energy
  - major upgrade in several LHC hardware components

Possible upgrade of the injector chain

- Up to 160 MeV: LINAC 4
- Up to 2.2 GeV (or more): the SPL
- Up to 2.2 GeV (or more): the SPL
- Up to 1 TeV: super-SPS (or a super-BPS)
- Up to 450 GeV: a refurbished SPS
- Up to 60 GeV: a SC super-PS
- Up to 30 GeV: a refurbished PS

Luminosity upgrade should mostly come from:

- shorter turnaround time in filling the LHC
- increased circulating intensity and bunch population

basic assumptions

- PS extraction energy $\geq 25$ GeV
- PS bunch population $2 \times 10^{11}$ within 3.5 $\mu$m emittance, and $4 \times 10^{11}$ within 7 $\mu$m
- PS bunch separation 12.5 ns (or 10 ns, if the impact on RF system should be minimised)
- To evenly spread the energy swing from 25 to 1000 GeV, we need two rings: the first ring should reach 150 GeV and the second 1 TeV
- As a (less efficient) alternative the first ring should reach 60 GeV and the second 1000 GeV

shortening the turnaround time

- injecting in LHC 1 TeV protons reduces the dynamic effects of persistent currents i.e.:
  - persistent current decay during the injection flat bottom
  - snap-back at the beginning of the ramp

  - decrease the turn-around time and hence increases the integrated luminosity

  $$T_{\text{run}} \text{(optimum)} = T_s + \frac{T_{\text{maxwell}}}{\tau_s} e^{\frac{t_s}{\tau_s}}$$

  $$L(t) = L_0 e^{-\frac{t_s}{\tau_s}}$$

  with $\tau_{\text{maxwell}} = 85$ h and $T_s = 106$ h (nom) $\Rightarrow 40$ h (high-L)

  - T turnaround time is a loose concept
  - Its definition vary from lab to lab
  - Operational experience reduces it
  - Hardware upgrade increase it
  - Difficult to quantify the effect of doubling the LHC injection energy $\Rightarrow$ factor of 1.5 to 2 reduction??
Reducing the dynamic effects of persistent current

Decay and snapback in main LHC dipoles vs. Injection current

Integral normalized sextupole in MB3348 during injection (relative to start of injection)

-1 0 1 2 3 4 5 6

-400 -200 0 200 400 600 800 1000 1200 1400 1600

Normalized B3 decay: reduction of a factor 2.6 from 0.45 TeV to 1 TeV injection

Run time and effective luminosity

The optimum run time and effective luminosity are universal functions of $T_{\text{turnaround}}/\tau_L$

$T_{\text{run}}/\tau_L = \frac{T_{\text{run}}}{\tau_L} = \frac{T_{\text{run}}}{\tau_L} \leq 1 - \frac{T_{\text{turnaround}}}{\tau_L} \times \text{ProductLog}[-1, e^{-T_{\text{turnaround}}/\tau_L}]$

$T_{\text{run}}/\tau_L = \frac{T_{\text{run}}}{\tau_L} = \frac{T_{\text{run}}}{\tau_L} \leq 1 - \frac{T_{\text{turnaround}}}{\tau_L} \times \text{ProductLog}[-1, e^{-T_{\text{turnaround}}/\tau_L}]$

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Increasing the circulating intensity

- injecting in LHC more intense proton beams with constant brightness, within the same physical aperture
  - will increase the peak luminosity proportionally to the proton intensity

\[ L = \gamma \Delta Q_{bb}^2 \frac{\pi \varepsilon_n f_{sep}}{r_p^2 \beta^*} \sqrt{1 + \left( \frac{\theta_c \sigma_x}{2 \sigma_y} \right)^2} \]

\[ \frac{d_{sep}}{\sigma} \approx \theta_c \sqrt{\frac{\varepsilon_n}{\gamma \beta^*}} \]

- at the beam-beam limit, peak luminosity $L$ is proportional normalized emittance $\varepsilon_n$ (we propose doubling $N$ and $e_p$, keeping constant $\varepsilon_p/N$).
- an increased injection energy (Super-SPS) allows a larger normalized emittance $\varepsilon_n$ in the same physical aperture, thus more intensity and more luminosity at the beam-beam limit.
- the transverse beam size at 7 TeV would be larger and the relative beam-beam separation correspondingly lower: long range b-b effects have to be compensated.

Why not a 1 TeV ring in the LHC tunnel?

- positive aspects:
  1) no need to upgrade the injection lines TI2 and TI8
  2) relaxed magnets in the injector ring
  3) higher injection energy (if needed we can reach 1.5 TeV)

- drawbacks
  1) unchanged aperture limitation in the transfer lines
  2) by-pass needed for ATLAS and CMS (especially to avoid loss of test beams)
  3) difficult optics for injection extraction with limited space in a dedicated long straight section of LHC tunnel
  4) impedance budget considerably higher due to the small pipe
LHCI - preliminary investigation

- Coolant - supercritical helium (4.2 K, 4 bar, 60 g/s)
- Warm beam pipe vacuum system (ante-chambers required)
- Alternating gradient at 64 m (half dipole length)

Courtesy of Henryk Piekarz

2 in 1 gradient dipole
2 Tesla field (normal operations)
0.1 Tesla (beam injection)
20 mm beam gaps
Energized by 100 kA, single turn
Magnet cross-section area:
26 cm (height) x 24 cm (width)
Small tunnel space & low cost

Coolant – supercritical helium (4.2 K, 4 bar, 60 g/s)
Warm beam pipe vacuum system (ante-chambers required)
Alternating gradient at 64 m (half dipole length)
Magnet cross-section area:
26 cm (height) x 24 cm (width)
Small tunnel space & low cost

pulsed SC magnets for the super-SPS

4÷5 T
1.17–1.50 Ts⁻¹

- a SC dipole for the SPS may produce 70 W/m peak (35 W/m effective => 140 kW for the SPS, equivalent to the cryogenic power of the LHC!)
- a rather arbitrary 'guess' for tolerable beam loss is of about 10¹²px1000GeV/10s = 15 kW
- by dedicated R&D magnet losses should be lowered to 10 W/m peak (5 W/m effective => 20 kW), comparable to 'tolerable' beam loss power

the technological challenge can be modulated:
- B max = 4 T, dB/dt = 1.17 Ts⁻¹ is rather easy, prototypes with close performance already exist, no major R & D required
- B max = 5 T, dB/dt = 1.5 Ts⁻¹ is rather difficult, no prototype exist, a major R & D is requested

pulsed SC magnets for the super-SPS

with the present SPS dipole packing factor, at 1 TeV we need SC dipole with B max = 4.5 T
- to reduce dynamic effects of persistent current, the energy swing should not exceed 10
- the optimal injection energy is of about 100-150 GeV
- a repetition rate of 10 s should halve the LHC filling time

SPS beam size:
- normalized emittance: σ * = 2x3.5 μm (2 factor is related to the higher bunch intensity)
- peak-beta: β max = 100 m (assuming the same focusing structure of the present SPS)
- rms beam size at injection: σ 150 GeV = 2.2 mm σ 1000 GeV = 0.8 mm

SPS aperture
- peak closed orbit: CO max = 5 mm
- dispersive beam size Dx = Δ = 12 mm (assuming D = 4 m, h bucket = 3x10⁻³)
- betatron beam size 6×σ 150 GeV = 12 mm and 6×σ 1000 GeV = 5 mm
- separatrix size for slow extraction 20 mm
- clearance of 6 mm

inner coil aperture 70+100 mm

adding in quadrature the betatron and the dispersive beam size and linearly the closed orbit, the separatrix size, and the clearance one will need a radial aperture of at least 29 mm at injection and 44 mm at top energy.

present SPS supercycle for filling LHC

PS cycle duration: 3.6 s
SPS ramp rate:
78 GeVs/s

LHC
PS
SPS

= 88.924 μS
= 7/27 LHC
= 1/11 SPS
**Tentative PS - SPS interleaved cycle**

**PS cycle duration: 4.5 s**

**SC-PS**
- $B_{\text{MAX}}$: 4 T
- Ramp: 3 T/s

**SC-SPS**
- $B_{\text{MAX}}$: 4.5 T
- Ramp: 1.5 T/s

**SPS**
- $B_{\text{MAX}}$: 2 T
- Ramp: 0.35 T/s

---

**open items**

1. evaluate all consequences of higher intensity operation
2. installation staging in the PS and SPS tunnel → minimal duration of the shutdown
3. lattice design also considering the use the present SPS ring
4. refined estimate of the magnet aperture
5. slow extraction design at 1 TeV within the space available
6. optimal extraction & injection channels (kickers and septa operating on more energetic particles within serious space occupancy constraints)
7. estimate of the expected loss
8. design of SC transfer lines to the LHC
9. optimal design for the SC magnets for the super-SPS: nominal parameters should be proposed and a road map for the requested R & D presented
10. cryogenic system: solution should be investigated for the needs and the installation of cryogenics in the SPS tunnel
11. RF systems: the optimal choice of the RF parameter is not yet available
12. impedance budget: reduce it possibly by an order of magnitude

**foreseeing other uses of the super-SPS for neutrino or flavour physics**

1. scenario to fill the whole super-SPS ring
2. upper value of the circulating intensity
3. optimal cycle duration
4. optimal bunch distance

---

**general considerations**

- A SC-PS at 60 GeV/c would improve the SPS performance - by how much?
- A SC-SPS at 1 TeV/c would also improve the LHC performance - similar reasons

- Difficult quantifying benefit of 1 TeV injector for LHC performance:
  - Dynamic phenomena 2.6 times smaller - certain
  - inject more beam intensity in the same mechanical aperture - very likely
  - turn-around time reduced by a factor 1.5 to 2 - hopefully

- A luminosity gain induced by more beam intensity will increase the long range beam beam effect and affect the required triplet aperture
  - More efficient protection system and collimation - mandatory
  - Beam-beam compensation by external wires - mandatory
  - Larger bore quadrupoles possibly with higher gradient - highly recommended

**Possible alternatives**

- With larger bore higher gradient triplet
  - squeeze $\beta^*$ up to chromaticity correction limit or up to the radiation induced quench limit
  - No detrimental effect for beam-beam neither for protection system nor for collimation

- If denser beams are made available (overcoming the bb limit)
  - Inject and accelerate them, then dilute them just before collisions (anyhow one gain through larger intensity)
  - Need to upgrade the protection system and the collimation
general considerations

- Present bottle-neck of the injector complex
  - The SPS (capture loss, longitudinal stability)
  - The BPS (space charge)

- Best possible improvements
  - The linac (synergy with neutrino-physics needs)
  - The SPS (synergy with neutrino and flavour physics needs – prerequisite for LHC energy upgrade)

however a SC PS turns out to be the best choice for CERN if the PS magnet consolidation program is not a reliable long term solution it is also
  - the right move towards the (high-priority) LHC performance upgrade
  - an opportunity to develop new fast pulsing SC magnets

- The 1TeV SC SPS should remain the strategic objective
- The benefit for LHC should be quantified as much as possible

factorization of the expected luminosity upgrade

- factor of 2.3 on $L_0$ at the ultimate beam intensity ($I = 0.58 \rightarrow 0.86 \, A$)
- factor of 2 (or more ?) on $L_0$ from new low-$\beta$ ($\beta^* = 0.5 \rightarrow 0.25 \, m$)

  $T_{\text{turnaround}} = 10 \, h \rightarrow f \, L \, d \, t = 3 \times \text{nominal} = 200 \, fb^{-1} \, \text{per year}$

- factor of 2 on $L_0$ doubling the number of bunches (may be impossible due to e-cloud) or increasing bunch intensity and bunch length

  $T_{\text{turnaround}} = 10 \, h \rightarrow f \, L \, d \, t = 6 \times \text{nominal} = 400 \, fb^{-1} \, \text{per year}$

A new SPS injecting in LHC at 1 TeV/c would yield

- factor of 1.4 in integrated luminosity for shorter $T_{\text{turnaround}} = 5 \, h$
- factor of 2 on $L_0$ (2 x bunch intensity, 2 x emittance)

$L_0 = 10^{35} \, cm^{-2}s^{-1} \, \text{AND} \, f \, L \, d \, t = 9 \times \text{nominal} = 600 \, fb^{-1} \, \text{per year}$

Concluding remarks

A vigorous R & D programme is required on
- optics, beam control, machine protection, collimation
- high gradient high aperture SC quadrupoles
  - Nb$_3$Sn SC wire and cable
  - radiation-hard design
- RF & crab-cavities
- SC fast ramping magnets

Time-scale required 10-12 years
So START as soon as possible!
WG 01 Superconducting wires and cables
11:00 - 12:30 Jc of low AC loss strands
Juris Kaugerts “Effect of resistive matrices and barriers”
Discussion
14:00 - 15:30 Technological issues
M.Wilson “Effective filament diameter, filament spacing, proximity coupling and bridging, filament distortion”
A. den Ouden “Long term stability for the barriers (abrasion, punching, fatigue)”
Discussion
16:00 - 17:30 Treatments for low losses
Ted Collins “Coupling time constants, strand internal barriers, strand resistive matrix, strand coating, cabling core”
A.Verweij “Optimum interstrand resistance for best balance of stability, current distribution and AC losses”
Discussion

WG 02 Low losses pulsed magnets
11:00 - 12:30 Status of low losses pulsed magnets
Ettore Salpietro
14:00 - 15:30 Definition of reference parameters: proposed specifications and operating parameters for two reference magnets (100 mm aperture, 3T peak 3T/s and 6T peak 1T/s)
16:00 - 17:30 Critical issues and planning:
• proposed conceptual studies to be carried out,
• materials to be qualified,
• radiation resistant insulation,
• fatigue studies,
• computer codes to be developed,
• time schedule for R&D and prototypes

WG 03 Quench protection, Heat Transfer and Magnetic Measurements
11:00 - 12:30 Quench Protection
D. Hagedorn, E. Floch “Protection Of Superconducting Pulsed Magnets For Accelerators” (40 min)
Discussion
14:00 - 15:30 Heat Transfer
R. van Weelden “High Heat Flux Extraction Paths From Magnet Structure”
A. Koosenko “Engineering Heat Transfer Calculations in Pulsed Magnets For Accelerators” (20 min) (ibc)
M. Cali “Stability Margin Calculations In Superconducting Cables” (20 min)
Discussion
16:00 - 17:30 Magnetic Measurements (video conference session)
P. Schnizer “Measuring Fast Pulsed Magnets Using Rotating Coils In Step Mode” (20 min)
A. Jain “Measurements By Means Of Stationary Coils Of The Field Quality In Supercond. Magnets At High Ramp Rates” (20 min)
P. Pugnat “On The Cotton-Mouton Effect & Its Possible Application To Characterize The Magnetic Field Of Acc. Magnets” (20 min)
Discussion
Coupling and ICR in NbTi Rutherford Cables

240. Stabrite coated cables with and without SS cores
   - two core thicknesses
   - four core widths
   - four levels of external compaction
   - several "curing" temperatures

239. Bare-Cu cables with and without SS cores
   - three thickness of core
   - three "curing" temperatures
   - measured under "pressure-release"

Stabrite coated cables with and without cores
   - cores of Titanium, Stainless Steel, Kapton
   - three "curing" temperatures
   - measured under "constant-pressure" and "pressure-release"

226. Stabrite cables with and without SS cores
   - five core widths (including zero width)
   - measured under "constant-pressure" and "pressure-release"

193. Bare-Cu cables with and without SS cores
   - two core thicknesses
   - two "curing" temperatures

184. Subsize cables with variously coated strands
   - strand coatings of Cr, Ni, Ni+Cr, Ni-P

183. Cables with various strand coatings and cores
   - bare-Cu, Ni-plated, stabrite coated strands
   - cores of Titanium, Stainless Steel, Kapton
   - three "curing" temperatures

First experiments -- coatings and cores
For FO and EO fields ramping to $B_m$ at a rate $dB/dt$

$$Q_t = \frac{4}{3} \left( \frac{w}{t} \right) L_p B_m \left[ \frac{N^2}{20 R_{\perp}} + \frac{1}{NR} \right] \left( \frac{dB}{dt} \right)$$

$$Q_s = \left( \frac{t}{w} \right) L_p B_m \left[ \frac{1}{NR} \right] \left( \frac{dB}{dt} \right)$$

Then for general cable-to-cable comparisons it is useful to combine the $R$s into an "effective $R_s$" given by:

$$Q_s = \frac{4}{3} \left( \frac{w}{t} \right) L_p B_m \left[ \frac{N^2}{20 R_{\perp, eff}} \right] \left( \frac{dB}{dt} \right)$$

For application to a sinusoidal field a prefactor $\sqrt{\pi^2/8}$ must be applied. Then the $dB/dt$ must be converted to frequency, $f$, using:

$$\langle dB/dt \rangle_{rms} = \sqrt{\pi^2/8}.4fB_m$$

The above equations thus modified become

$$Q_t = \left( \frac{2\pi^2}{3} \right) \left( \frac{w}{t} \right) L_p B_m^2 \left[ \frac{N^2}{20 R_{\perp}} + \frac{1}{NR} \right] \cdot f$$

$$Q_s = \left( \frac{\pi^2}{2} \right) \left( \frac{t}{w} \right) L_p B_m^2 \left[ \frac{1}{NR} \right] \cdot f$$
The critical frequency

The simultaneous generation and decay of coupling currents gives rise to a maximum in $Q_\parallel(f)$ at a critical frequency $\tau_c = 1/2\pi f_c$ (where $\tau_c$ is the corresponding relaxation time) following the general relationship

$$Q_{e,c} = \frac{\text{const}}{R_\perp} \frac{f}{1 + (f/f_c)^2}$$

This applies to strand eddy currents as well as cable- and cable-stack coupling currents with relaxation times of $\tau_{cab}$ and $\tau_{stack}$, respectively.

Data analysis leading to ICRs

-- The critical frequency route to $R_\perp$

Depending on the type of experiment (ramping or oscillating applied field) the interchange between ramp-rate and frequency is achieved using

$$\langle dB/dt \rangle_{rms} = \gamma (\pi/8).4fB_m$$

or

$$f = (0.23/B_m)(dB/dt)$$

and hence for the "peak" or "critical" values

$$f_{\text{crit.}} = (0.23/B_m)(dB/dt)_{\text{crit.}}$$
The measured critical frequency of the stack of cables, $f_{c,\text{stack}}$, is related to a stack-relaxation time, $\tau_{\text{stack}}$, by the general relationship

$$\tau_{\text{stack}} = \frac{1}{2\pi f_{c,\text{stack}}}$$

The relaxation time of the cable stack, $\tau_{\text{stack}}$, is related to the individual-cable relaxation time by

$$\tau_{\text{stack}} = \frac{(w/t)N_c}{(w/t) + C(N_c - 1)}\tau_{\text{cab}} = E_c\tau_{\text{cab}}$$

where $N_c$ is the number of cables in the stack. And the individual-cable relaxation time is given by

$$\tau_{\text{cab}} = C_s(N^2 - 4N)\frac{2L_c}{R_{\perp}} = \frac{D}{R_{\perp}}$$

hence

$$R_{\perp,fc} = \frac{D}{\tau_{\text{cab}}} = \frac{DE}{\tau_{\text{stack}}} = 2\pi DEf_{c,\text{stack}}$$

--- using which we find in the case of high losses

### Values of $R_{\perp}$ for bare Cu cables determined from $<\text{dB/dt}>_{\text{max}}$

<table>
<thead>
<tr>
<th>Cable name</th>
<th>$T_{\text{cure}}$ °C</th>
<th>Crossover resistance, $\rho_{\perp}$ µΩ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CU250A</td>
<td>250</td>
<td>0.038</td>
</tr>
<tr>
<td>CU250B</td>
<td>250</td>
<td>0.125</td>
</tr>
<tr>
<td>CU-00-250</td>
<td>250</td>
<td>0.70</td>
</tr>
<tr>
<td>CU-00-225</td>
<td>225</td>
<td>1.86</td>
</tr>
<tr>
<td>CU-00-200</td>
<td>200</td>
<td>3.14</td>
</tr>
</tbody>
</table>
Further bare-Cu results
“internal compaction”

Stabrite cable results –
- some comparisons
- effect of “cold pressure”
- effect of core width
Fig. 1. Summary: Normalized calorimetric and magnetic FO losses based on the U/F cycle and the sample length, L. L = L0. Unscored ST170 (×), ST/170 (O), ST170/170 MN (△), and various scored cores ST-S210 magnetic (X), ST-S230 calorimetric (×), and ST-S310 (O).

Fig. 2. Summary: Normalized magnetic EO losses of 170-rated cables based on the U/F cycle and the sample length, L = L0. Unscored ST170 (×), and various scored cores with kapas (ST-KA170 O), dielectric (ST/T170 O), and stainless steel (ST/170 Q). Also shown for comparison is the EO loss of a bare copper cable rated at 170°C (×). Data for ST-KA170, ST/T170, and ST/170 overlap significantly.

Fig. 3. \( R_{eq} \) vs core width.
APPENDIX-I

Stabrite cables
-- tabulation of some representative ICR data

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Cable thickness, $t_c$, mm</th>
<th>Core thickness, $t_r$, mm</th>
<th>Core width, $w_c$, inch (mm)</th>
<th>Present compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-NC</td>
<td>1.887</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ST-SS(75)</td>
<td>1.88</td>
<td>25</td>
<td>3/16(12.7)</td>
<td>--</td>
</tr>
<tr>
<td>ST-SS(50)</td>
<td>1.902</td>
<td>30</td>
<td>3/8(12.7)</td>
<td>--</td>
</tr>
</tbody>
</table>

Series-II: Cables with standard thickness cores (25 mm) and various compactions

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Cable thickness, $t_c$, mm</th>
<th>Core thickness, $t_r$, mm</th>
<th>Core width, $w_c$, inch (mm)</th>
<th>Present compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-SS(3)</td>
<td>1.823</td>
<td>25</td>
<td>3/16(12.7)</td>
<td>3</td>
</tr>
<tr>
<td>ST-SS(6)</td>
<td>1.769</td>
<td>25</td>
<td>3/8(12.7)</td>
<td>6</td>
</tr>
<tr>
<td>ST-SS(9)</td>
<td>1.716</td>
<td>25</td>
<td>1/2(12.7)</td>
<td>0</td>
</tr>
<tr>
<td>ST-SS(11)</td>
<td>1.670</td>
<td>23</td>
<td>3/8(12.7)</td>
<td>11</td>
</tr>
</tbody>
</table>

Series-III: Cables with standard thickness cores (25 mm) of various widths

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Cable thickness, $t_c$, mm</th>
<th>Core thickness, $t_r$, mm</th>
<th>Core width, $w_c$, inch (mm)</th>
<th>Present compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-U</td>
<td>1.948</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ST-SS(1/8)</td>
<td>1.916</td>
<td>25</td>
<td>1/8(6.3)</td>
<td>--</td>
</tr>
<tr>
<td>ST-SS(1/4)</td>
<td>1.917</td>
<td>25</td>
<td>3/16(12.7)</td>
<td>--</td>
</tr>
<tr>
<td>ST-SS(8)</td>
<td>1.921</td>
<td>25</td>
<td>3/8(9.5)</td>
<td>--</td>
</tr>
<tr>
<td>ST-SS(1/2)</td>
<td>1.934</td>
<td>25</td>
<td>1/2(12.7)</td>
<td>--</td>
</tr>
</tbody>
</table>

CERN-Proces cable (uncored)

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Cable thickness, $t_c$, mm</th>
<th>Core thickness, $t_r$, mm</th>
<th>Core width, $w_c$, inch (mm)</th>
<th>Present compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>1.9</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

(0) The stabrite-coated 28-strand cables were 15 mm wide; the cores (SS) were of AISI 316 stainless steel, except ST-NC and ST-U which had no core.

Table 5. Loss-slopes, $dQ/dBdt$ or $dQ/dB$, and effective contact resistances, $R_{eff}, \mu$ohm

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Nom. curing, $t_c$, mm, $T_k$, °C</th>
<th>$Q_e$-slope $^{(a)}$</th>
<th>$Q_e$-slope $^{(a)}$</th>
<th>$Q_e$/$Q_e$ $^{(b)}$</th>
<th>$R_{eff}, \mu$ohm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-NC</td>
<td>170</td>
<td>3.476</td>
<td>0</td>
<td>--</td>
<td>3.5</td>
</tr>
<tr>
<td>ST-NC(200)</td>
<td>200</td>
<td>31.168</td>
<td>70.2</td>
<td>444</td>
<td>0.4</td>
</tr>
<tr>
<td>ST-SS(50)</td>
<td>1.10</td>
<td>61.0</td>
<td>38.13</td>
<td>1.39</td>
<td>197.7</td>
</tr>
<tr>
<td>ST-SS(250)</td>
<td>200</td>
<td>318.8</td>
<td>85.54</td>
<td>3.77</td>
<td>37.8</td>
</tr>
<tr>
<td>ST-SS(500)</td>
<td>170</td>
<td>50.1</td>
<td>20.71</td>
<td>2.42</td>
<td>240.3</td>
</tr>
<tr>
<td>ST-SS(30200)</td>
<td>200</td>
<td>443.4</td>
<td>106.8</td>
<td>4.11</td>
<td>177.7</td>
</tr>
</tbody>
</table>

Table 5. Loss-slopes, $dQ/dBdt$ or $dQ/dB$, and effective contact resistances, $R_{eff}, \mu$ohm

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Nom. curing, $t_c$, mm, $T_k$, °C</th>
<th>$Q_e$-slope $^{(a)}$</th>
<th>$Q_e$-slope $^{(a)}$</th>
<th>$Q_e$/$Q_e$ $^{(b)}$</th>
<th>$R_{eff}, \mu$ohm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-SS(6)/70</td>
<td>170</td>
<td>108.3</td>
<td>107.9</td>
<td>1.00</td>
<td>11.3</td>
</tr>
<tr>
<td>ST-SS(6)/200</td>
<td>200</td>
<td>595</td>
<td>208.1</td>
<td>2.86</td>
<td>20.3</td>
</tr>
<tr>
<td>ST-SS(9)/70</td>
<td>170</td>
<td>265.4</td>
<td>121.0</td>
<td>2.19</td>
<td>45.5</td>
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<tr>
<td>ST-SS(9)/200</td>
<td>700</td>
<td>1.148</td>
<td>777</td>
<td>4.7</td>
<td>10.5</td>
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<tr>
<td>ST-SS(11)/70</td>
<td>170</td>
<td>329.2</td>
<td>93.12</td>
<td>3.54</td>
<td>26.6</td>
</tr>
<tr>
<td>ST-SS(11)/200</td>
<td>200</td>
<td>1.204</td>
<td>303.6</td>
<td>3.97</td>
<td>10.0</td>
</tr>
</tbody>
</table>
### APPENDIX-II

-- visualizing the effect of compaction

---

Footnotes to Table 2

(a) Series-1 and Series-II cables cured for 2 h at T/ under nominal 75 MPa compaction and measured under 0 MPa after PK (magnetic measurements, KEK). Series-III cables were HT (cured) to T/ in 5 h under nominal 80 MPa compaction and measured under nominal 80 MPa after PK (calorimeter measurement, U1T).

(b) Slope of FO-measured $Q_1$ vs d[rad] (10 J/m^2, Series-I and Series-II) or $Q_1$ (10 J/m^2, Series-III as well as CN170 and reference cable). Background hysteresis and strand eddy currents have been subtracted. All values normalized to total volume of cable. Note that $R_{\text{eff}}$ is $0.5$ T and $R_{\text{eff}}$ is $0.4$ T.

(c) $Q_1/Q_0 = Q_1$ slope - slope in the linear regime under consideration.

(d) $R_{\text{eff}}$ values differ from Ref [41] because of a re-analysis with a different baseline.

(e) Reference cable cured at 170°C under no pressure.

(f) The CERN-process cable had initially experienced a "diffusion heat treatment" of 8h/200°C [41].

---

Illustration of the effects of Tuckerman compaction on cables with (a) a thick core, (b) a thin core, and (c) a core. Even a thin core can inhibit the nesting of strands thereby assisting side-by-side compaction.
REFERENCES

ECOMAG-05
Frascati, October 26-28, 2005
Elementary Formulas and Twisting

Critical Frequency and Relaxation Time

\[ f_c = \frac{10^7 \mu}{L \eta} \quad \text{Hz} \]

\[ \tau = \frac{1}{2\pi} \frac{L \eta}{10^7 \mu} \quad \text{s} \]

Thus \( P_c(\mu) \) can be determined in terms of:

1. \( \frac{dP_c}{d\mu} \propto \frac{1}{\mu^2} \)
2. \( f_c \propto \mu \)
3. \( \tau \propto \frac{1}{\mu^2} \)

Example of "Twist Pitch" Dependence
**Effective Matrix Resistivity (Transverse Resistivity)**

Standard formulas

Transverse currents excluded from the filaments (low bulk matrix resistivity and/or high interface resistance)

\[
\rho_{\perp} = \frac{1+\lambda}{1-\lambda} \rho_{\text{bulk}}
\]  

(1)

Transverse currents traverse the filaments (high bulk matrix resistivity and/or low interface resistance)

\[
\rho_{\perp} = \frac{1-\lambda}{1+\lambda} \rho_{\text{bulk}}
\]  

(2)

where \(\lambda\) is the SC fill factor

Including a temperature dependent “interface resistance” as part of the bulk matrix resistivity we have (in Case I, for example)

\[
\rho_{\perp} = \frac{1-\lambda}{1+\lambda} (\rho_{\text{bulk}} + \rho_{\text{int}}(T))
\]

**Field Dependence of \(\rho_{\perp}\)**

The average \(\rho_{\perp}\) is derived from the area of the M-H loop, \(Q_{\perp}\). Its field dependence is derived from the local height of the loop.

\[
\rho_{\perp} = \frac{Q_{\perp}}{H_{\perp}} \cdot \frac{\Delta M_{s}}{H_{\perp}}
\]

where \(\Delta M_{s}\) is the static (+ or -) magnetization height, and assuming that

\[
Q_{\perp} = 2H_{\perp} \Delta M_{s}
\]

we can write for the product of \(\rho_{\perp}\) and the volume, \(V\), of the filamentary region

\[
V_{\text{H}} = \frac{\rho_{\perp} H_{\perp} (\Delta M_{s} \cdot 4 \cdot 10^7)}{\Delta M_{s}}
\]

\(\Delta M_{s}\) is the eddy current component of the moment. In this way we can interpret the field dependence of the eddy current loss in terms of a field dependence of either \(V\) or \(\rho_{\perp}\).
Choice of Interfilamentary Matrix

A pair of similar strands: NTCU with a pure Cu interfilamentary matrix and NTCM with a Cu-0.5%Mn matrix

SAMPLE COIL USED IN TWIST-PITCH STUDIES OF EDDY CURRENT LOSS

CHOICE OF INTERFILAMENTARY MATRIX
--- studies of NTCU and NTCM interfilamentary strands
Filament No. NM5, Filament Dia. 2
Matrix: NTCU = Ca, NTCM = Cu-0.5%Mn

Results of two sets of experiments

Replacing Cu with Cu-0.5%Mn makes little difference to the eddy current loss
Influence of the Outer Cu Shell

Choice of Interfilamentary Matrix

CONCLUSIONS

We have measured the transverse and longitudinal resistivities of superconductive strands with Cu and CuMn matrices.

It was found that at high fields (15 kOe) the $\rho_L$ derived from $\Delta M$ was $2.4 \times 10^7$ for CuMn and $1.9 \times 10^7$ for Cu.

Additionally, we note that the resistivity of CuMn is not very field dependent, while that of Cu is much more so. However, $\rho_L$'s determined from the loss measurements (giving an average or effective $\rho_L$) are similar to those derived from $\Delta M$ at high fields, and nearly the same ratio ($\rho_{L,Cu} = 0.6\rho_{L,CuMn}$). The loss-derived $\rho_L$ are $2.0 \times 10^7$ $\Omega$ cm for Cu and $3.2 \times 10^7$ $\Omega$ cm for CuMn.
Influence of the Central Cu Core

The influence of the outer Cu shell was investigated on small coils of as-received and etched strands. It was found that the presence of the outer shell suppresses the difference between the Cu-matrix and Cu-0.5%Mn effective resistivities.

### Experimental 4.2 K Resistivities

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>( V_{4.2K} ) (m/s)</th>
<th>( V_{Cu} ) (m/s)</th>
<th>( \rho_{Cu} ) (( \mu )Omega cm)</th>
<th>( \rho_{Cu-Mn} ) (( \mu )Omega cm)</th>
<th>( \Delta \rho )</th>
<th>( \rho_{Cu-Mn}^{4.2K} ) (( \mu )Omega cm)</th>
<th>( \rho_{Cu-Mn}^{4.2K} ) (( \mu )Omega cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuU1</td>
<td>4.04</td>
<td>4.28</td>
<td>0.47</td>
<td>0.6</td>
<td>1.0 ± 0.5</td>
<td></td>
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<tr>
<td>CuU2</td>
<td>4.29</td>
<td>4.35</td>
<td>0.22</td>
<td>0.6</td>
<td>1.0 ± 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuU3</td>
<td>4.24</td>
<td>4.28</td>
<td>0.35</td>
<td>0.2</td>
<td>1.0 ± 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuU4</td>
<td>4.29</td>
<td>4.35</td>
<td>0.17</td>
<td>0.6</td>
<td>1.0 ± 0.5</td>
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<tr>
<td>CMU1</td>
<td>4.28</td>
<td>4.60</td>
<td>0.67</td>
<td>2.0</td>
<td>1.0 ± 0.5</td>
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<tr>
<td>CMU2</td>
<td>4.33</td>
<td>4.76</td>
<td>0.013</td>
<td>2.0</td>
<td>1.0 ± 0.5</td>
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<tr>
<td>CMU3</td>
<td>4.28</td>
<td>4.60</td>
<td>0.003</td>
<td>2.0</td>
<td>1.0 ± 0.5</td>
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<td></td>
</tr>
<tr>
<td>CMU4</td>
<td>4.28</td>
<td>4.60</td>
<td>0.003</td>
<td>2.0</td>
<td>1.0 ± 0.5</td>
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<tr>
<td>CuE1</td>
<td>4.08</td>
<td>4.28</td>
<td>9.20</td>
<td>1.3</td>
<td>1.0 ± 0.5</td>
<td></td>
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<tr>
<td>CuE2</td>
<td>4.08</td>
<td>4.28</td>
<td>9.20</td>
<td>1.3</td>
<td>1.0 ± 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM1</td>
<td>4.28</td>
<td>4.28</td>
<td>0.003</td>
<td>2.0</td>
<td>1.0 ± 0.5</td>
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<td></td>
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<tr>
<td>CM2</td>
<td>4.28</td>
<td>4.28</td>
<td>0.003</td>
<td>2.0</td>
<td>1.0 ± 0.5</td>
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<td></td>
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<tr>
<td>CM3</td>
<td>4.28</td>
<td>4.28</td>
<td>0.003</td>
<td>2.0</td>
<td>1.0 ± 0.5</td>
<td></td>
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<tr>
<td>CM4</td>
<td>4.28</td>
<td>4.28</td>
<td>0.003</td>
<td>2.0</td>
<td>1.0 ± 0.5</td>
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</table>

### Strand Specifications

<table>
<thead>
<tr>
<th>Strand Code</th>
<th>NTCU20</th>
<th>NTCM20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand Diameter /10^3μm/</td>
<td>2.287</td>
<td>2.258</td>
</tr>
<tr>
<td>Bundle Diameter /10^3μm/</td>
<td>1.756</td>
<td>1.776</td>
</tr>
<tr>
<td>Piano Wire Number</td>
<td>4995</td>
<td>5650</td>
</tr>
<tr>
<td>Piano Wire Diameter</td>
<td>0.14</td>
<td>0.49</td>
</tr>
<tr>
<td>Matrix Composition</td>
<td>Cu</td>
<td>Cu-0.5%Mn</td>
</tr>
<tr>
<td>Tinning Factor, k</td>
<td>0.963</td>
<td>0.872</td>
</tr>
</tbody>
</table>

**Influence of the Central Cu Core**

- **CMN-21**
  - Cu-0.5%Mn matrix
  - Cu Core

- **NTCM-20**
  - Cu-0.5%Mn matrix
  - No Core
Influence of the Central Core

Strand Types

Table 1: Specification of the Strands

<table>
<thead>
<tr>
<th>Strand Code</th>
<th>Core-Type</th>
<th>No-Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge Beam, $d_e$, 6.35 mm</td>
<td>6.35 g</td>
<td>3.04 g</td>
</tr>
<tr>
<td>Filamentary Beam, $d_f$, 6.35 mm</td>
<td>4.08 g</td>
<td>1.61 g</td>
</tr>
<tr>
<td>Core Beam, $d_c$, 6.35 mm</td>
<td>1.61 g</td>
<td>—</td>
</tr>
<tr>
<td>Filament Number</td>
<td>22,002</td>
<td>9,345</td>
</tr>
<tr>
<td>Filament Beam, $d_i$, 2 μm</td>
<td>3.06</td>
<td>1.902</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Cu</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interlayered Material</td>
<td>Cu</td>
<td>Cu</td>
</tr>
<tr>
<td>Core</td>
<td>Cu</td>
<td>Cu</td>
</tr>
</tbody>
</table>

Fig. 1: Frequency dependence of the normalized eddy-current loss, $Q_{4f}/L^2$, at 4.2 K for the unwound coils: (i) CMN-U, (ii) NCM-U, and (iii) NCU-U.

The enhanced loss associated with CMN21 is attributed to the presence of the unalloyed-Cu core and its role in extending the eddy-current-loop area.
(b) Multistrand Twisted Cables

REFERENCES

K. Kwasnitz and I. Horvath
Cryogenics 22 (1983) p. 9
STAINLESS STEELS

E.W. Collings

Laboratories for Applied Superconductivity and Magnetism

OHIO STATE UNIVERSITY

EDDY CURRENT LOSS AND EFFECTIVE TRANSVERSE MATRIX RESISTIVITY

Compositions and Austenitic (FCC) Stability

Stainless Steel Compositions

<table>
<thead>
<tr>
<th>Grade</th>
<th>UNS No.</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>C (max.)</th>
<th>N</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td>S30400</td>
<td>19</td>
<td>9.5</td>
<td></td>
<td>0.08</td>
<td></td>
<td>austenitic</td>
</tr>
<tr>
<td>304L</td>
<td>S30403</td>
<td>19</td>
<td>10</td>
<td></td>
<td>0.03</td>
<td></td>
<td>austenitic</td>
</tr>
<tr>
<td>316</td>
<td>S31600</td>
<td>17</td>
<td>12</td>
<td>2.5</td>
<td>0.08</td>
<td></td>
<td>austenitic</td>
</tr>
<tr>
<td>316L</td>
<td>S31603</td>
<td>17</td>
<td>12</td>
<td>2.5</td>
<td>0.03</td>
<td></td>
<td>austenitic</td>
</tr>
<tr>
<td>316LN</td>
<td>S31653</td>
<td>17</td>
<td>12</td>
<td>2.5</td>
<td>0.03</td>
<td>0.13</td>
<td>austenitic</td>
</tr>
</tbody>
</table>
STABILITY OF AUSTENITIC STAINLESS STEELS

As austenite stability factor, Δ, is defined by:

\[ \Delta = 2/3(Cr + 1.5Mo - 2Fe) + 0.55N + 385C \]

An austenite temperature (for the onset of martensite transformation in response to 30% strain) is given by:

\[ T_{Au} = 2\Delta \times 10^{-3} \]

Evidence for traces of transformation in rolled 316L 25 μm tape

\[ 2M_s = 0.14 \text{ emu/g} \]

0.03 wt% “Fe”
Magnetic Properties

Relative 0 K Permeabilities of Selected Stainless Steels

<table>
<thead>
<tr>
<th>Alloy Type</th>
<th>Density g/cm³</th>
<th>( \chi \times 10^6 \text{ cm}^3/\text{g} )</th>
<th>( \chi \times 10^4 )</th>
<th>Rel. Perm. ( \mu_r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>316</td>
<td>7.73</td>
<td>140</td>
<td>10.8</td>
<td>1.014</td>
</tr>
<tr>
<td>Nit50</td>
<td>7.50</td>
<td>58</td>
<td>4.35</td>
<td>1.005</td>
</tr>
<tr>
<td>Nit40</td>
<td>7.50</td>
<td>21</td>
<td>1.58</td>
<td>1.002</td>
</tr>
<tr>
<td>Nit33</td>
<td>7.37</td>
<td>16</td>
<td>1.18</td>
<td>1.001_s</td>
</tr>
</tbody>
</table>

Fig. 3 Magnetic susceptibility in the temperature range above 77 K for three representative AISI 300 Series alloys and AWS 330.
The blocking of the SPM moments implies the existence of an energy barrier, \( E \), (or distribution of such barriers) against their being excited by an applied field \( H \), and consequently the replacement of the \( \mu H \) of Equation (2) by \( \mu H - E \). As illustrated schematically in Figures 1b and 1c, this has the effect of shifting the low- and medium-temperature Langevin isothermals to the right. This, in turn, permits the maximum to develop in \( M \) versus \( T \) at a lower temperature, as shown in Figure 1c. Of course, the high-field isothermals are left practically unaffected, and hence, in extreme cases, devoid of magnetization maxima. These effects are illustrated schematically in Figures 1c and 1d. Of course, should the SPM be weak or non-existent any \( M(T) \) maxima would then have to be a property of the matrix alone, and most of the field dependence would disappear.

Two other experimentally observable characteristics of classical micromagnetic alloys at low temperatures can also be explained in terms of the cluster-blocking mechanism. If a classical micromagnet is field-cooled to temperatures below \( T_F / 10 \), the clusters acquire a perpendicularly oriented domain of the strength within the vicinity of \( T_F \). This fixed orientation component is responsible for the unidirectional (as distinct from uniaxial) remanence and a uniform displacement of the low-temperature field-cycling loop. At temperatures in the vicinity of \( T_F \), blocking is partially relaxed, and the clusters exhibit a viscous response to variation of a moderate applied field at constant temperature or variation of temperature at constant applied field. The latter is referred to as thermomagnetic remanence (TMR).

Conclusions

Micromagnetism provides a useful qualitative description of the magnetic behavior of austenitic stainless steels, alloys which occupy a transition region between long-range ferromagnetism and long-range antiferromagnetism (LRAF). Near the ferromagnetic side, large-cluster SPM dominates the magnetic properties in the middle region, micromagnetism exhibiting SPM in an SRAF matrix is evident. Eventually the SPM clustering begins to disappear as LRAF sets in, but a region does seem to exist in which both kinds of property are in evidence.

AWS 330 exhibits all the hallmarks of classical micromagnetism: strong SPM, pronounced \( M(T) \) or \( x(T) \) maxima in low fields, followed by their rapid washing out with increase of the measuring field, unidirectional remanence after field cooling, and thermomagnetic remanence under thermal cycling at constant field. AISI 304N, on the other hand, appears to exhibit nothing more than conventional LRAF.

Finally, AISI 316 seems to occupy a position intermediate between those of the above pair. As evidenced by the magnetic results the alloy is weakly SPM and exhibits a correspondingly weak magnetic remanence after field cooling.
**AISI 316.** This alloy, which supports a low SPM cluster density, exhibits a small but measurable unidirectional remanence during field cycling at 8.0 K after cooling in 0.8 MA m$^{-1}$ (10 kOe) from 187 K to the temperature of measurement (Figure 4a). After zero-field cooling, the hysteresis loop is closed, straight, and passes through the origin. The fourth quarter cycle of the field-cooled loop merges into that line, since by the time that those data were taken (about 1 h from the end of field cool down) the aligned spins had relaxed. Again, the temperature of the experiment was only $\approx T_g/3.5$.

Thermal cycling from 8 to 43 K and back in a field of 0.4 MA m$^{-1}$ (5 kOe) revealed no TMR. Clearly, it requires a much stronger field than this to appreciably align the clusters [evidently more than $\approx 0.8$ MA m$^{-1}$ (10 kOe)].

---

**CONCLUSION**

The 12 austenitic stainless steels examined exhibit superparamagnetism and/or a cusp in the susceptibility temperature dependence to varying degrees. These phenomena may occur either concurrently, as in AISI 316 and AWS 330, or separately, as in AISI 310S (which exhibits superparamagnetism but no cusp) or AISI 304 and the Nitronics (which possess cusps but no superparamagnetism). If the cusp occurs in the presence of superparamagnetism, the height and sharpness of the maximum is field dependent (e.g., AISI 316 and AWS 330) and may also shift to lower temperatures with increasing field (particularly noticeable in AWS 330).

A simple model to explain all the results except the last requires a minor fraction of the alloy to exist as noninteracting ferromagnetic clusters (leading to the superparamagnetism) embedded in a matrix that undergoes a spin-glass transition. But at low temperatures, the clusters must interact with each other and with the matrix, leading to the high-field shift of the maximum to lower temperatures and its eventual disappearance, as in Fig. 5. The situation with regard to the Nitronics is not completely closed. By analogy with the series 300 stainless steels, they are spin glasses. Nevertheless, an interpretation of their properties in terms of metallic antiferromagnetism is not excluded, although several counterarguments have been advanced [4]. The complete lack of superparamagnetism is intriguing and could be the result of the clusters, if they exist, being antiferromagnetic as a consequence of the high manganese levels.
REFERENCES

ECOMAG-05
Frascati, October 26-28, 2005

PROXIMITY EFFECT

E.W. Collings

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OHIO STATE UNIVERSITY

DISCUSSION TOPICS

Basic Issues
- conditions for PE coupling
- normal and magnetic scattering
- mechanism of PE coupling in magnetic fields

Strand Design
- filament spacing
- twist pitch
- influence Nb filament coatings

Materials Selection
- Cu
- Cu-Mn
- Cu-Ni-Mn
- Cu-Si

-- not necessarily in this order
Basic Issues

-- conditions for PE coupling

The problem

Fig. 1: Height of the M(H) hysteresis loop versus nominal filament diameter -- after Ghosh et al. IEEE Trans. Magn. MAG-23, 1724 (1987).

Establishing the conditions for PE coupling

- PE-enhanced filament diam.
- \( k_n^{-1} \)
- PE coupled pair
Basic Issues
-- normal and magnetic scattering
The Proximity Influenced Matrix
-- Normal (Resistive) and Magnetic Scattering

Coupling reduction efficiencies of Ni and Mn

Since Ni has already been identified as a possible proximity-effect suppressant,\textsuperscript{16,17} it is useful to intercompare the efficiencies, in this regard, of Ni and Mn. In order to establish a decay distance of an arbitrarily selected 0.017\(\mu\)m in Cu, 31 at.\% Ni was required, as compared with the above-mentioned 0.9 at.\% for Mn. Thus on an at.\% basis, Ni is 30 times more potent than Mn. Furthermore, taking into account the specific scattering strengths in Cu of Ni (1.1 \times 10^{-12} \text{ cm}/at.\%) and Mn (2.9 \times 10^{-14} \text{ cm}/at.\%), it follows that for a given coupling reduction, the penalty in terms of matrix resistivity increase is a factor of 13 less if Mn is the solute rather than Ni.


Basic Issues
-- mechanism of PE coupling

PE persisting to relatively high fields

![M-H loop for AD40HT-10, bare and clad, 80\% sweep](image)

MECHANISM OF FLUX PINNING IN PE-COUPLED COMPOSITES
SYNERGISTIC PINNING

(a)(b)(c) untwisted

(d) twisted

Asymmetrical PE-coupled M-H loops

Symmetrical and Asymmetrical PE-coupled M-H loops


MECHANISM OF FLUX PINNING IN PE-COUPLED COMPOSITES

Synergistic Pinning: The characteristic "bite" in the M-H loop near the low-field transition from trapping to shielding

Strand Design
-- the Hexagonal Tube Method*
of billet assembly/strand processing


(a) Research type
38,500 fils.
CuMn matrix

(b) SSC-type
7,300 fils.
Cu matrix

List of Research Strands (Note: ASI later changed to AD)

<table>
<thead>
<tr>
<th>Strand Code</th>
<th>Sample Length, cm</th>
<th>Clad Wt., g</th>
<th>Unclad Wt., g</th>
<th>Cu Wt., g</th>
<th>Cu/SC Volume Ratio</th>
<th>SC Wt/cm²</th>
<th>Nbr/ft²</th>
<th>Volcm³</th>
<th>Fil. No.</th>
<th>Fil. Dia, μm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS10HT-35</td>
<td>152.4</td>
<td>12.235</td>
<td>3.629</td>
<td>8.606</td>
<td>1.622</td>
<td>23.809</td>
<td>35.551</td>
<td>38520</td>
<td>3.43</td>
<td></td>
</tr>
<tr>
<td>AS10HT-25</td>
<td>152.4</td>
<td>6.214</td>
<td>1.833</td>
<td>4.381</td>
<td>1.645</td>
<td>12.161</td>
<td>18.159</td>
<td>38520</td>
<td>2.45</td>
<td></td>
</tr>
<tr>
<td>AS10HT-20</td>
<td>152.4</td>
<td>3.755</td>
<td>0.917</td>
<td>2.157</td>
<td>1.644</td>
<td>6.020</td>
<td>8.989</td>
<td>38520</td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td>AS10HT-15</td>
<td>152.4</td>
<td>2.084</td>
<td>0.624</td>
<td>1.460</td>
<td>1.644</td>
<td>4.093</td>
<td>6.112</td>
<td>38520</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>AS10HT-10</td>
<td>177.8</td>
<td>1.133</td>
<td>0.341</td>
<td>0.792</td>
<td>1.617</td>
<td>1.918</td>
<td>2.864</td>
<td>38520</td>
<td>0.97</td>
<td></td>
</tr>
</tbody>
</table>

| AS40HT-35  | 152.4             | 11.718      | 3.652         | 8.066     | 1.513             | 25.966    | 35.785  | 38520  | 3.44    |
| AS40HT-25  | 152.4             | 6.022       | 1.883         | 4.138     | 1.525             | 12.358    | 18.452  | 38520  | 2.47    |
| AS40HT-20  | 152.4             | 3.079       | 0.966         | 2.113     | 1.528             | 6.339     | 9.465   | 38520  | 1.77    |
| AS40HT-15  | 152.4             | 2.078       | 0.653         | 1.425     | 1.535             | 4.295     | 6.413   | 38520  | 1.46    |
| AS40HT-10  | 152.4             | 0.978       | 0.309         | 0.669     | 1.543             | 2.028     | 3.028   | 38520  | 1.00    |
| AS40HT-60  | 106.6             | 4.043       | 1.272         | 2.771     | 1.495             | 11.932    | 18.529  | 7251   | 5.70    |
| AS40HT-45  | 91.44             | 2.204       | 0.697         | 1.507     | 1.492             | 7.622     | 11.836  | 7251   | 4.56    |
| AS40HT-35  | 91.44             | 1.238       | 0.392         | 0.848     | 1.494             | 4.286     | 6.656   | 7251   | 3.42    |
| AS40HT-25  | 91.44             | 0.583       | 0.184         | 0.399     | 1.506             | 2.016     | 3.131   | 7251   | 2.35    |

† In the case of AS10 the "SC" is considered to be Nb46.5Ti plus 7 vol.% Nb
In the case of AS40 the "SC" is considered to be Nb46.5Ti plus 4 vol.% Nb

Details follow ---
The Hexagonal Tube Method

The hexagonal tube method of stacking billets is useful for the manufacture of single (not counting monofilament) extrusion fine filamentary wire. We have fabricated single-stack billets with up to 38,520 filaments, and it may be possible reach 100,000 filaments. \( J_e \) values and \( n \)-values for ASI08HT are among the best of typical SSC wires, and those of ASI40HT compare very well, given the factor of two reduction in \( d_e \). Cabling experiments performed on these wires confirm good mechanical properties, and negligible degradation of electrical properties. Additionally, we find that the hexagonal tube fabrication method is less time-consuming than the comparable double extrusion route, at least for filament numbers greater than 8,000. However, it seems that the filament quality, as measured by area distribution, and the degree of filament roughness, increases with the number of filaments, although the filament quality is better than that typically obtained by double extrusions. The hex cell method allows the fabrication of single-stack billets with large numbers of filaments, useful for low-magnetization- and low-loss applications.
PE onsets for the hexagonal-tube strands compared with those for a pair of all-filamentary strands, (a) NTCM and (b) NTCU.

A pair of similar strands: NTCU with a pure Cu interfilamentary matrix and NTCM with a Cu-0.5%Mn matrix, in them the Nb barrier is absent.

**Strand Design**
- twist pitch (& sample length)

**Twist pitch dependence of PE**

---

Figure 3. $\frac{\Delta M_{s} \Delta M_{m}}{M_{s}}$ for short magnetization samples of: (a) the CuMn matrix strands; AS140HT (30K files C), AS140NHT ( ), and NTCM (5K files A), and (b) the Cu matrix strands; ASI08HT (7K files A) and NTCU (4K files A).
Sample length dependence of PE

Magnetization-based PE critical current density, $J_{cp}$

\[ \Delta M_s \approx \frac{J_{cp} L_p}{5 \pi^2} \]

Strand Design
-- the Nb reaction-barrier issue
Where it began:

Cu-matrix strands produced by SHOWA EWCC using hydrostatic extrusion

<table>
<thead>
<tr>
<th>Filament No., N</th>
<th>Filament Diam., d, μm</th>
<th>Filament Space, s, μm</th>
<th>s/d Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>931</td>
<td>11.34</td>
<td>2.14±0.24</td>
<td>0.19</td>
</tr>
<tr>
<td>6517</td>
<td>3.20</td>
<td>0.54±0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>56791</td>
<td>1.20</td>
<td>0.19±0.09</td>
<td>0.16</td>
</tr>
<tr>
<td>336091</td>
<td>0.54</td>
<td>0.10±0.05</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Materials Selection

--- matrix material summary

hex-cell strands
matrix, Cu
Nb barrier (when present), 4% fil. diam.
fil. diam 2.5 μm
fil. count 560
Onset of PE coupling

<table>
<thead>
<tr>
<th>Matrix composition</th>
<th>$d_0$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>400–700*</td>
</tr>
<tr>
<td>Cu–10% Ni</td>
<td>150–200a</td>
</tr>
<tr>
<td>Cu–30% Ni</td>
<td>125–150b</td>
</tr>
<tr>
<td>Cu–0.5% Mn</td>
<td>95c</td>
</tr>
<tr>
<td>Cu–10% Ni–0.9% Mn</td>
<td>60b</td>
</tr>
<tr>
<td>Cu–30% Ni–0.9% Mn</td>
<td>40–60b</td>
</tr>
<tr>
<td>Cu–2.5% Si</td>
<td>95d</td>
</tr>
<tr>
<td>VAMAS I-series</td>
<td>65b</td>
</tr>
<tr>
<td>VAMAS H-series</td>
<td>150–200c</td>
</tr>
</tbody>
</table>

*Estimated from Figure 4, $\Delta M_{\text{int}}/\Delta M_{\text{bare}}$.

†Estimated from Figure 2, loss versus $d_0$.

‡Estimated from the observance of minute PE in RES strands.

§Estimated from Akita et al.'s loss versus $d_1$21, assuming $d_1/d_0 = 0.19$. 

REFERENCES
Collider vs Fast-Ramped Synchrotron Operation

- For beam colliders, such as RHIC, magnet AC losses were not an important consideration, given low magnet ramp rate (0.042 T/s) and infrequent ramps.
- For fixed target fast-ramping synchrotrons, such as GSI’s SIS 200 at 4 T (and now SIS 300 at 6T) the ramp rate is high (1T/s) and ramps are frequent, so AC loss reduction is an important consideration
Conductor Losses

- Wire losses
  1) Filament hysteresis
  2) Coupling (eddy) current

- Cable losses
  1) Crossover strand resistance $R_c$
  2) Adjacent strand resistance $R_a$

Dipole GSI 001

- A 1m long dipole was built and tested at BNL for the earlier (4T, 1 T/s) SIS 200 synchrotron design, which was updated to the 6 T, 1 T/s present SIS 300.

GSI 001 Dipole Losses/cycle/m with RHIC wire & cable (1 T/s ramp)

<table>
<thead>
<tr>
<th></th>
<th>ramping</th>
<th>mean</th>
<th>loss/</th>
<th>fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>power</td>
<td>power</td>
<td>cycle</td>
<td>of total</td>
</tr>
<tr>
<td>Watts</td>
<td>Watts</td>
<td>Joules</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>trans' se cr'sover</td>
<td>1610.48</td>
<td>3220.6</td>
<td>92.0%</td>
<td></td>
</tr>
<tr>
<td>trans' se adjacent</td>
<td>10.69</td>
<td>21.4</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>parallel adjacent</td>
<td>0.16</td>
<td>0.3</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td>filament coupling</td>
<td>111.94</td>
<td>223.9</td>
<td>6.4%</td>
<td></td>
</tr>
<tr>
<td>hysteresis</td>
<td>15.55</td>
<td>31.1</td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>delta hysteresis</td>
<td>1.34</td>
<td>2.7</td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>total hysteresis</td>
<td>16.89</td>
<td>33.8</td>
<td>1.0%</td>
<td></td>
</tr>
<tr>
<td>total magnet</td>
<td>1750.16</td>
<td>3499.9</td>
<td>100.0%</td>
<td></td>
</tr>
</tbody>
</table>

$R_c = 8 \mu \Omega$ no core
$R_a = 64 \mu \Omega$
13 mm fil. twist pitch

GSI 001 Dipole Losses/cycle/m with RHIC wire & cable (1 T/s ramp)

<table>
<thead>
<tr>
<th></th>
<th>ramping</th>
<th>mean</th>
<th>loss/</th>
<th>fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>power</td>
<td>power</td>
<td>cycle</td>
<td>of total</td>
</tr>
<tr>
<td>Watts</td>
<td>Watts</td>
<td>Joules</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>trans' se cr'sover</td>
<td>1610.48</td>
<td>3220.6</td>
<td>97.7%</td>
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</tr>
<tr>
<td>trans' se adjacent</td>
<td>10.69</td>
<td>21.4</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>parallel adjacent</td>
<td>0.16</td>
<td>0.3</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td>filament coupling</td>
<td>10.60</td>
<td>21.2</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>hysteresis</td>
<td>15.55</td>
<td>31.1</td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>delta hysteresis</td>
<td>1.34</td>
<td>2.7</td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>total hysteresis</td>
<td>16.89</td>
<td>33.8</td>
<td>1.0%</td>
<td></td>
</tr>
<tr>
<td>total magnet</td>
<td>1648.81</td>
<td>3297.3</td>
<td>100.0%</td>
<td></td>
</tr>
</tbody>
</table>
**GSI 001 Dipole Calculated Conductor Loss (as built)**

<table>
<thead>
<tr>
<th>SS core in cable</th>
<th>ramping</th>
<th>mean</th>
<th>loss/ cycle/m</th>
<th>fraction of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra = 62.5 mΩ</td>
<td>Watts</td>
<td>Watts</td>
<td>Joules</td>
<td>%</td>
</tr>
<tr>
<td>Ra = 64 μΩ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fil twist pitch = 4 mm</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Watts</th>
<th>Watts</th>
<th>Joules</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>transv’se cr’sover</td>
<td>0.21</td>
<td>0.4</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>transv’se adjacent</td>
<td>10.89</td>
<td>21.4</td>
<td>27.7%</td>
<td></td>
</tr>
<tr>
<td>parallel adjacent</td>
<td>0.16</td>
<td>0.3</td>
<td>0.4%</td>
<td></td>
</tr>
<tr>
<td>filament coupling</td>
<td>10.60</td>
<td>21.2</td>
<td>27.5%</td>
<td></td>
</tr>
<tr>
<td>hysteresis</td>
<td>15.55</td>
<td>31.1</td>
<td>40.3%</td>
<td></td>
</tr>
<tr>
<td>delta hysteresis</td>
<td>1.34</td>
<td>2.7</td>
<td>3.5%</td>
<td></td>
</tr>
<tr>
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<td>16.89</td>
<td>33.8</td>
<td>43.8%</td>
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<tr>
<td>total magnet</td>
<td>38.54</td>
<td>77.1</td>
<td>100.0%</td>
<td></td>
</tr>
</tbody>
</table>

**SIS 300 Dipole Loss Reduction**

- Previous slide shows that $R_a$, coupling currents and filament hysteresis constitute major loss sources for cored cable conductor.
- Loss reduction:
  1) increase $R_a$
  2) increase matrix resistivity, to reduce coupling currents
  3) decrease filament diameter, to reduce hysteresis loss

---

**Ra Loss Reduction**

- $R_a$ can be increased by heating cable in air.
- $R_a$ increase may reduce current sharing capability of wire and decrease conductor stability. No quantitative data are available, to my knowledge.

**Higher resistance wire matrix**

- Cold working the copper in the wire during it’s production can provide a higher resistivity wire matrix, but cable heat treatment, due to coil curing, or heat treatment to increase $R_a$ will reduce this resistivity again.
- High resistivity barriers (such as CuNi) around filaments or filament regions increase the effective, or transverse, resistivity of the wire.
- A Cu.0.5-0.6% Mn interfilamentary matrix also increases the transverse resistivity and is unaffected by cable curing or heat treatment.
Small filament wire

- Below about 3.5 micrometer filament size, proximity coupling again increases filament hysteresis loss in an all-copper matrix wire
- Use of a CuMn interfilamentary matrix eliminates proximity coupling effects for filament sizes down to around 1 micrometer
- Critical current density is allegedly reduced for CuMn interfilamentary matrix conductors

SSC Cu-0.6%Mn Interfilamentary matrix 2.5 micron filament wire*

- Global matrix ratio: 1.7
- Filament number: 22686
- Filament diameter: 2.63 μm
- Wire twist pitch: 12.5 mm
- Transverse resistivity $\rho_{et} = (4.15 + 1.9B) \times 10^{-10} \, \Omega \cdot m$
- (For RHIC wire $\rho_{et} = (1.24 + 0.9B) \times 10^{-10} \, \Omega \cdot m$)
- Wire diameter: 0.651 mm

* Made for possible use in the SSC High Energy Booster (HEB), using a double stacking production method, and tested for GSI at Twente TU

Possible CuMn Interfilamentary Matrix Wire for SIS 300

IGC has fabricated a 309 mm billet into wire of 2.6 micron filament diameter, with a Cu-0.6%Mn interfilamentary matrix, using a patented single stack approach.

Further parameters are:
- Filament number: 38663
- Matrix to NbTi ratio: 1.5
- Wire diameter: 0.808 mm
- $J_c = 2753 \, A/sqmm$ at 5T, 4.2 K

Such a conductor requires scaling up by a factor of 1.02 in diameter, for application in the SIS 300 dipole.

Calculated value for transverse resistivity $\rho_{et} = 3.4 \times 10^{-10}$

SIS 300 dipole Loss/cycle-m with Cu matrix

<table>
<thead>
<tr>
<th></th>
<th>ramp'g</th>
<th>mean</th>
<th>loss/</th>
<th>fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>power</td>
<td>power</td>
<td>cycle</td>
<td>of total</td>
</tr>
<tr>
<td></td>
<td>Watts</td>
<td>Watts</td>
<td>Joules</td>
<td></td>
</tr>
<tr>
<td>transv'se cros'r</td>
<td>0.36</td>
<td>3.2</td>
<td></td>
<td>3.9%</td>
</tr>
<tr>
<td>transv'se adj'nt</td>
<td>1.21</td>
<td>10.7</td>
<td></td>
<td>13.0%</td>
</tr>
<tr>
<td>parallel adjacent</td>
<td>0.01</td>
<td>0.1</td>
<td></td>
<td>0.1%</td>
</tr>
<tr>
<td>fil'nt coupling</td>
<td>2.48</td>
<td>21.8</td>
<td></td>
<td>26.6%</td>
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<tr>
<td>hysteresis</td>
<td>5.12</td>
<td>45.0</td>
<td></td>
<td>55.0%</td>
</tr>
<tr>
<td>delta hysteresis</td>
<td>0.12</td>
<td>1.0</td>
<td></td>
<td>1.3%</td>
</tr>
<tr>
<td>total hysteresis</td>
<td>5.24</td>
<td>46.1</td>
<td></td>
<td>56.3%</td>
</tr>
<tr>
<td>total magnet</td>
<td>9.30</td>
<td>81.9</td>
<td></td>
<td>100.0%</td>
</tr>
</tbody>
</table>
**SIS 300 Dipole Loss/cycle-m with CuMn interfilamentary Matrix**

<table>
<thead>
<tr>
<th></th>
<th>ramp'g</th>
<th>mean</th>
<th>loss/</th>
<th>fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>power</td>
<td>power</td>
<td>cycle</td>
<td>of total</td>
</tr>
<tr>
<td>Watts</td>
<td>Watts</td>
<td>Joules</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>transv'se cros'Y</td>
<td>0.36</td>
<td>3.2</td>
<td>5.7%</td>
<td></td>
</tr>
<tr>
<td>transv'se adj'nt</td>
<td>1.21</td>
<td>10.7</td>
<td>19.0%</td>
<td></td>
</tr>
<tr>
<td>parallel adjacent</td>
<td>0.01</td>
<td>0.1</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td>fil'nt coupling</td>
<td>1.05</td>
<td>9.3</td>
<td>16.5%</td>
<td></td>
</tr>
<tr>
<td>hysteresis</td>
<td>3.66</td>
<td>32.2</td>
<td>57.3%</td>
<td></td>
</tr>
<tr>
<td>delta hysteresis</td>
<td>0.08</td>
<td>0.7</td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td>total hysteresis</td>
<td>3.74</td>
<td>32.9</td>
<td>58.6%</td>
<td></td>
</tr>
<tr>
<td>total magnet</td>
<td>6.38</td>
<td>56.2</td>
<td>100.0%</td>
<td></td>
</tr>
</tbody>
</table>

- **Rc=20 mΩ SS core in cable**
- **Rc=200 μΩ**
- **5 mm fil. Twist pitch**
- **2.5 μm filaments**

**Loss Reduction with CuMn interfilamentary matrix**

Higher transverse resistivity and smaller filament size give 31% loss reduction over all-cu matrix.

Addition of 10 μm CuNi barrier around filament region reduces filament coupling loss from 9.3 J/cycle-m to 5.7 J/cycle-m, an additional loss reduction of about 6%.

**Tested Wires**

- **double stacked**
- **single stacked**
- **single stacked**
- **double stacked**
- **double stacked**
- **triple extruded, double stacked**

**Wire ID**

- 2A12
- 3N7
- RHIC
- K2 001T4
- G2 001T6
- SSC CuMn

**Filament Distortion Effects**

Wires made with a double stacking process show a greater filament distortion than wires made with a single stacking process, as shown by the difference in magnetization & transport current densities for the preceding wires.

Is this due to increased magnetization due to filament distortion alone, or to a combination of reduced transport current due to filament distortion ("sausaging") plus increased magnetization due to filament shape deformation (ellipsoidal shape)?
Other Interfilamentary Matrix Materials

- Aside from Cu-0.5wt% Mn, Cu-10wt%Ni and Cu-30wt%Ni have been used to reduce eddy current losses in low loss strands.

CuMn versus CuNi Interfilamentary matrix

- Cu-10wt%Ni is about 6 times more resistive than Cu-0.5wt%Mn.
- For stability reasons, avoid making matrix more resistive than needed to reduce AC loss.
- Cu-0.5%Mn is as effective as Cu-10wt%Ni in reducing strand eddy current loss.
- CuNi contains 0.15-1.0 % Mn, so the “active ingredient” for proximity effect suppression appears to be Mn in both cases.

Conclusion

- A Cu-0.5-0.6%Mn interfilamentary matrix wire with fine (2.5 μm or less) filaments, made by a single stacking process appears to give a wire with the lowest loss and highest current density and appears to be the conductor of choice for the SIS 300 dipole, to provide lowest losses with good Jc.
- This should be verified by testing the 0.808 mm SSC wire made by this process. We need to find this wire and test it.
- Afterwards, make two 200 kg billets. First one, with 2.5 micron filament wire. During fabrication of this wire, determine possible Jc degradation with further filament decrease and determine minimum filament twist pitch before Jc decreases. Make second billet with optimum parameters.
Cable $R_a$ & $R_c$

- $R_c > 100$ m$\Omega$ for cables heat treated at 200°C for 4 hours (IHEP tests on cored LHC outer layer cable)
- $R_a \sim 200$-$300$ $\mu$Ω for 8 hour bare cable heat treatment at 200 °C & 30 minute cure cycle of polyimide tape insulated samples at 195 °C & 15-70 MPa (BNL tests). Need more statistics.

**Jc of Low AC Loss Strands**

J. Kaugerts  
GSI  
Oct. 26, 2005  
Frascati, Italy

Strand Losses

- Hysteresis loss depends on critical current density $J_c$ & filament diameter $d_f$
- Eddy current loss depends on transverse matrix resistivity $\rho_{et}$ and filament twist
- pitch $p$

Strand losses

- Hysteresis loss/unit volume of superconductor $U_h = [(4d_f)/3\pi]dB \perp J_c(T,B \perp)$

Eddy current power loss/unit strand volume $P_e = (2\pi \mu_0)(dB \perp /dt)^2$ where $\tau = (\mu_0/2\rho_{et})(p/2\pi)^2$
Filament Twist Pitch

• Rule of thumb is that the minimum filament twist pitch (before $J_c$ degradation) is 8 times the strand diameter.
• Hence, for 0.65 mm strand, this is 5.2 mm
  • (4 mm achieved)
• For 0.825 mm, this is 6.6 mm
  • (5 mm achieved)
Geometry of low loss strand with resistive barriers

SSC Outer Layer Strand
(ASC 1988, p. 1926)

- Starting billet~305 mm dia. cylinder with 284 mm bore, with NbTi, Nb diffusion barriers, Cu-0.5wt%Mn interfilamentary matrix,Cu, formed into hex rods, 1.4 mm flat-to-flat, s/d_f=0.19, matrix/NbTi ratio=1.8:1
- Single stacked, drawn down to 0.65 mm strand
- 22,900 2.5 micron filaments
- J_c=2156 A/mm^2 @5 T, 4.2 K, n=13
- Low J_c value thought to be due to filament degradation from large s/d_f value (0.13-0.17 used before). However, filament cross section and extracted strands don’t show distortion

SSC Outer Layer Strand
(Supercollider 3,1991, p.689)

- Starting billet~309 mm dia. with NbTi, Nb diffusion barriers(4%),Cu-0.6wt%Mn,Cu, matrix/NbTi ratio=1.72
- Double stacked, drawn down to 0.65 mm strand
- 22,686 2.5 micron filaments
- J_c=2720-2760 A/mm^2 @5 T, 4.2 K, n=28
- (A Ghosh measured J_c=2511 A/mm^2 @5T, 4.2 K)
- τ=6 msec (measured, for p=12.7 mm)
- τ=0.6 msec for p=4 mm (calculated)
- ρ_et=4.15*10^-10 Ω·m (measured)

SSC Inner Layer Strand
(Supercollider 4,1992, p. 41)

- Starting billet~309 mm with NbTi, Nb diffusion barriers (2 %), Cu-0.6%Mn,Cu, matrix/NbTi ratio=1.5
- Hexagonal cell single stacked, drawn down to 0.808 mm strand
- 38,663 2.6 micron filaments
- J_c=2753 A/mm^2 @5T, 4.2 K, n=36
- Only small quantities processed to final size, so piece length conclusions can not be made
- τ=1.34 msec (calculated)
- ρ_et=3*10^-10 Ω·m (calculated)
FZK SMES Based Power Modulator Strand  
(Proc. MT-16,2000, p.824)

- Starting elements - NbTi,Cu-10%Ni,Cu, Cu/CuNi/NbTi~1.56/0.68/1, matrix/NbTi ratio=2.24
- Single stacked, drawn down to 0.65mm strand
- 3684 5.9 micron filaments
- \( J_C = 2832 \text{ A/mm}^2 \) at 5T, 4.2 K, \( n=? \)
- \( \tau = 0.073 \text{ msec} \) (measured)
- \( \rho_{et} = 61.3 \times 10^{-10} \Omega \cdot \text{m} \)

RF proposal on the development of low loss NbTi wire for the prototypes of SIS 300 and SIS 100 dipoles

V.I. Pantsyrny, Bochvar Institute (VNIINM), Moscow, RF

- RF interest for wire production
- A possible R&D program aimed to design and produce NbTi wires for magnet prototypes construction
- Previous experience

RF interest for wire production

- In a framework of the preparation for the ITER construction a “new plant” for the production of superconducting materials is established by JSC Concern TVEL under technological guidance of VNIINM with year capacity of 60 t, mainly for the production of ITER relevant superconducting wires.
  The production of superconducting strands will be reestablished in the plant “ChMZ” where the partial fabrication of NbTi wires took place earlier.

- Main facilities is already installed (7200 tf hydraulic extruder, ALD produced electron beam furnace, drawing and twisting machines, etc) procurement of other equipment is in process.

- Pilot batches of composite rods for Nb3Sn and NbTi strands have been fabricated (in cooperation due to lack of some equipment)
- Other types of superconducting wires are planned to be produced (for MRI, SMES et al)

NbTi composite rods extruded from 250mm billets
R&D program aimed to provide wire for 3 magnet prototypes construction

Goals for SIS 300: (after J. Kaugerts, Protvino, June 20, 2005)

✓ filament diameter 2.5 micron  (wire diameter 0.825 mm)
✓ critical current density 2700 A/mm² (5 T, 4.2 K); 2130 A/mm² (6 T, 4.2 K)
✓ Matrix/ Sc Ratio     1.4-1.5
✓ twist pitch   5 mm
✓ losses minimization
✓ cost minimization

Goals for SIS 100 wire should be formulated in terms of wire and filament
diameter and twist pitch.
Field ramp is much faster for SIS 100 (4T/s against 1T/s)
The best option for producer is unified target requirements from both
groups of magnet people.

Objectives:
The evaluation of two main approaches (single stacking or
double stacking) for a fabrication of low loss wire

1. Single stacking - cell stacking of round rods. This stacking
   process seems to be rather sophisticated (in case of
   extremely large amount of filaments), however best
   properties could be expected for the wire.

1. Double stacking – the new layout has to be developed on the
   base of the experience on the development of both
   accelerators and AC wires. In case the wire performance is
   acceptable this approach seems to be most promising for
   mass production.

Scope of work:
1. Design of final wires and billets layouts.
2. Selection of resistive matrix materials.
3. Procurement of initial materials (Cu, resistive copper alloys, Ti, Nb).
4. Preparation of NbTi alloy of high purity and high homogeneity.
5. Characterization of initial materials.
7. Semi-items fabrication and characterization
8. Billets assembly
9. Composite rods extrusion
10. Samples fabrication. Heat treatment and twisting optimization.
11. Samples qualification including transport critical current measurement, Jc
   and "n" estimations, magnetization measurements, hysteresis loops will
   be provided.
12. Analysis and technology adjustment
13. Wire fabrication in amounts required to build one prototype of SIS 300
   and two prototypes of SIS 100. (Preliminary estimated amounts are 35 km
   of 0.825 mm wire for SIS 300 and 4+4 km) of wire (final diameter is TBD
   for SIS 100).
14. Analysis of the results and Final report

Previous experience
Single stacking approach has been proven at Bochvar Institute with small sized
billets and Cu-5wt%Ni matrix. Some results are available on the performance of
recently fabricated 0.65 and 1.0 mm wires having filament diameter of 3.5 and 6
micron.


The improvements of layout and technology revealed to be necessary and possible.
ITER relevant strand layouts

Different approaches were applied for these wires fabrication

EXPERIMENTAL STRANDS for ITER (Bochvar)

TABLE presents the results on hysteresis losses for model strands in Cu-Ni matrix (#4 and 5) in comparison with that for ITER PF strand with Cu matrix (#1, #2 and 3). The losses for the model samples with 6 and 3.5 μm filaments were higher than expected (#4, #5), but no signs of “proximity effect” were revealed.

For the strands with a Cu matrix and a spacing >1 μm, the losses depend on filament diameter and varied in the range of 250 to 177 kJ/m³ (per NbTi volume) at field amplitude ± 3 T. When the spacing becomes <1 μm proportionality is broken and the hysteresis losses sharply increase (up to 344 kJ/m³ for the sample with 5.2 μm filaments).

<table>
<thead>
<tr>
<th>#</th>
<th>Wire diam., mm</th>
<th>Dff, μm</th>
<th>Cu/non-Cu ratio (PF)</th>
<th>Matrix</th>
<th>μm</th>
<th>Hysteresis losses wire/NbTi, kJ/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1T</td>
</tr>
<tr>
<td>1</td>
<td>0.73</td>
<td>9.8</td>
<td>1.4 (0.42)</td>
<td>Cu</td>
<td>1.5</td>
<td>54/126</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>6.7</td>
<td>1.4 (0.42)</td>
<td>Cu</td>
<td>1</td>
<td>42/100</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>5.2</td>
<td>2.8 (0.26)</td>
<td>Cu</td>
<td>0.79</td>
<td>54/208</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>6.0</td>
<td>1.8 (0.36)</td>
<td>Cu-5Ni</td>
<td>0.86</td>
<td>51/141</td>
</tr>
<tr>
<td>5</td>
<td>0.65</td>
<td>3.5</td>
<td>1.8 (0.36)</td>
<td>Cu-5Ni</td>
<td>0.5</td>
<td>32/89</td>
</tr>
</tbody>
</table>
10374 superconducting filaments 6 $\mu$m in dia., each of them is surrounded by Nb barrier and matrix from commercial resistive alloy (Cu-5 wt.%Ni), which resistivity is more than twice higher than resistivity of pure Cu. Filament spacing is 0.77 $\mu$m, Nb barrier/NbTi = 8.4%, Cu/non Cu = 1.8.

SEM micrograph of a fragment of 0.65 mm strand cross section (the marker corresponds to 6 $\mu$m).

26-28 October 2005

ECOMAG-05, Fraskati

Arjan Verweij

CERN, AT-MAS/SC

ECOMAG, Oct 2005

Optimum contact surface for best balance between loss, stability and current distribution.

... requires knowledge of tire material/design, car design, weather and road conditions.

Optimum contact resistance for best balance between loss, stability, and current distribution.

... requires knowledge of strand material/design, magnet design, cooling and operating conditions.

Note:

- Typically order of 10000 contact resistances per meter cable.
- Usually $R_c$ (and $R_a$) denotes an average value expected for a certain cable length.
- In some publications $R_c$ and $R_a$ are defined per cable transposition pitch and not per contact.
- For low dB/dt magnets $R_a$ is often disregarded.
**Type of currents**

**Transport current**
- Non-uniform distribution is due to variations in strand inductances (not relevant for Ruth. cables) and joint resistances.
- Diffusion speed of non-uniformity depends on Ra and Rc, but amplitude is independent of Ra and Rc.

**Inter-Strand Coupling Currents (ISCC's)**
- Amplitude linear to dB/dt and inversely proportional to Ra and Rc.

**Boundary Induced Coupling Currents (BICC's)**
- Due to variations in dB/dt along the cable length.
- St. st. amplitude linear to dB/dt and linear to parallel connection of ALL contact resistances in a cable, including those in the joints (even if they are located outside the magnetic field).
- Diffusion speed increases with decreasing cable length and increasing Ra and Rc.

**The joints**

To have a uniform distribution of the transport current AND to reduce the BICCs to non-significant values, one should make the joint to the current leads as "strand-by-strand type" with non-zero longitudinal resistance

**Inter-strand Coupling Loss**

Loss due to Inter-Strand Coupling Currents is well-known:

\[
P = L_p w^2 (0.17/R_a + 0.008 N_s^2/R_c) \left(\frac{dV}{dt}\right)^2 \quad [W/m \text{ of cable}]
\]

Note the very strong dependence on the cable size.
Stability

Better electrical contact → Better possibility for current transfer → Higher stability

Stability against what type of disturbances?

<table>
<thead>
<tr>
<th>Short (&lt;100 µs)</th>
<th>Long (ms to s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local (mm)</td>
<td>- local strand movement</td>
</tr>
<tr>
<td>Global (cm to m)</td>
<td>- cable movement</td>
</tr>
<tr>
<td></td>
<td>- non-uniform current distribution</td>
</tr>
</tbody>
</table>

Quench energy for short local heat release

Adiabatic case

\[ Q = \frac{1}{2} k \int_{t}^{t+T} I(t) I(t+T) \, dt \]

With transient cooling to open bath of He I:

\[ 200(T_{b} - T_{cab}) \]

Trans. He, 10 mOhm, f=1, K=500
Trans. He, 10 mOhm, f=1, K=10
Trans. He, 10 mOhm, f=0.5, K=500
Trans. He, 10 mOhm, f=0.5, K=10
Trans. He, 10 mOhm, f=0.5, K=10
Approach for Ra-Rc-stability ‘arrangement’

1. Define operating conditions and maximum allowed loss.
2. Assume one or more strand / cable / magnet designs.
3. Set minimum values for Ra and Rc so that the Inter-strand Coupling Loss is about 10% of maximum allowed loss.
4. Reduce the BICCs to <10% of the transport current by careful design of the joints.
5. Make the MQE vs I/Ic curve with these Ra and Rc values, and check as well the Quench Energy Margin (QEM) for other type of disturbances.
6. Try to get the operating point in the "multi-strand stability" region, by reducing Iop/Ic, improving matrix thermal and electrical conductivity, increasing He contents, ....

Concluding remarks (1/5)

For a given magnet/cable/strand design, the inter-strand resistance can hardly be optimised. One can just define the minimum value in order to keep the inter-strand coupling loss at an acceptable level.

The inter-strand resistance should therefore be an integral part of the magnet design, cable design, and strand design.

In this case one can try to get the operating point in the "multi-strand stability" region, by changing Iop/Ic, matrix thermal and electrical conductivity, He contents, strand surface, cable insulation etc.

However, the type of expected disturbances should be known in order to optimize the design for best stability.

Concluding remarks (2/5)

In principle a cable with high inter-strand resistance is not less stable than a coil wound of a single strand, if:
- the distribution of the transport current is uniform,
- the strands have no local defects,
- ISCC << I$_C$,
- BICCs << I$_C$.

Soldered splices/joints in high field areas should be avoided. Therefore:
- 2-layer design with grading not possible,
- 2-layer design with the same cable seems favorable to reduce the losses and reduce the BICCs. However, good cooling channels to the outer layer should be present.

The joint to the current leads should be carefully designed, preferably as a 'multi-strand joint' with additional longitudinal resistance.
Concluding remarks (3/5)

For loss optimisation one can tolerate a lower Ra (typically Ra=Rc/10).

However, I don't think that separate tuning of Ra and Rc will lead to significantly better stability for pulsed magnets.

The need of a core is therefore doubtful. This volume could possibly be used more efficiently for additional strand stabiliser, an interturn heat drain, or reduction of I/Ic.

A locally very small Ra or Rc will not have a significant effect on the loss and the BICC, so a punch-through in a resistive core is not as dramatic as a punch-through in a car tire.

Concluding remarks (4/5)

Ra and Rc do not seem the most critical parameters for stability. Even in existing magnets with 'low' Ra and Rc, there are often areas with high contact resistance (e.g. coil ends). And these magnets work!!

Good electrical and thermal conductivity of the matrix is much more important than low Ra and Rc. Therefore, strands with a good conducting outer ring (that does not generate eddy current loss) would be a great advantage.

Poor cooling conditions:
- Good thermal contact between the strands is more important than good electrical contact.

Transient He cooling to open bath:
- The MQE of a cable with high Ra and Rc is as good as the one with low Ra and Rc.
- Good thermal contact between the strands is less important since the He takes over this role.

Concluding remarks (5/5)

Three important R&D topics:

1. Is it possible to increase the electrical contact while keeping a good inter-strand thermal contact (since there is no direct correlation between the two)?

2. How to change the strand surface in order to improve the heat transfer to helium?

3. Experiments of MQE and QEM of cables with high contact resistance (as compared to cables with low contact resistance). In the pipeline at CERN.

Fine Filaments etc

Martin Wilson (Consultant to GSI)  data by Andries den Ouden and Arup Ghosh

Plan

- Why bother?
  - ac losses
  - field quality

- What are the problems?
  - filament distortion
  - proximity coupling
  - Jc
  - cost and feasibility

- Our results
- What to do
**Why bother - losses**

Calculated loss per cycle in the SIS300 dipole (ramping 1.6T to 6.0T at 1T/s)

<table>
<thead>
<tr>
<th>filament dia</th>
<th>2.5μm</th>
<th>3.5μm</th>
<th>6.0μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>loss per cycle (Joules)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>transverse crossover</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>transverse adjacent</td>
<td>21.3</td>
<td>21.3</td>
<td>21.3</td>
</tr>
<tr>
<td>parallel adjacent</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>filament coupling</td>
<td>15.2</td>
<td>15.2</td>
<td>15.2</td>
</tr>
<tr>
<td>hysteresis</td>
<td>33.5</td>
<td>46.9</td>
<td>80.4</td>
</tr>
<tr>
<td>delta hysteresis</td>
<td>0.7</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>total hysteresis</td>
<td>34.2</td>
<td>47.9</td>
<td>82.2</td>
</tr>
<tr>
<td>total magnet</td>
<td>74.2J</td>
<td>87.9J</td>
<td>122.1J</td>
</tr>
</tbody>
</table>

Data: $R_c = 20\text{mΩ}$  $R_u = 100\mu\text{Ω}$  cable twist pitch $p_c = 74\text{mm}$
wire dia = 0.85mm  wire twist pitch $p_w = 6\text{mm}$
matrix transverse resistivity $\rho_{tr} = (4.1 + 1.9B) \times 10^{-10}\text{Ωm}$

**Why bother - field shape**

Field error terms in Dip001 computed by Vector Fields using OPERA units of 10^{-4}Bo at 25mm radius

Data:

- Dipole
  - by stress: $-0.017$  $-0.174$  $-0.456$
  - filament coupling: $-0.000$  $0.000$  $-0.001$
  - cable transverse field: $-0.002$  $0.007$  $0.015$
  - cable parallel field: $-0.026$  $-0.013$  $-0.003$
  - all: $-0.20$  $-0.25$  $-0.21$

- Sextupole
  - by stress: $-0.77$  $-2.45$  $-0.28$
  - filament coupling: $-1.40$  $-0.493$  $0.079$
  - cable transverse field: $-0.03$  $0.319$  $0.091$
  - cable parallel field: $-0.002$  $-0.013$  $-0.003$
  - all: $-0.015$  $-2.46$  $-0.229$

- Decapole
  - by stress: $-0.575$  $-2.240$  $-0.034$
  - filament coupling: $0.238$  $0.092$  $0.006$
  - cable transverse field: $-0.087$  $-0.044$  $-0.012$
  - cable parallel field: $0.004$  $0.002$  $0.000$
  - all: $-0.434$  $-0.194$  $-0.038$

**Our work on filament distortion**

- **Filament distortion:** magnetization and hence ac losses and field distortion is $J_c d$, where $d$ is the filament dimension transverse to the field. For the same area, distorted filaments always have a bigger magnetization than round
- **Proximity Coupling:** when the thickness of matrix between the filaments gets ~< 1/3 μm Cooper pairs can tunnel across the matrix, thereby increasing the magnetization. In extreme cases the benefits of finer filaments can be lost completely. Strongest at low fields
- **$J_c$:** some indication of reduced $J_c$.
  - but old wires or small production, so perhaps not optimized
- **Cost:** it’s a lot of filaments!
  for $d_f = 3\mu\text{m}$, $d_m = 0.855\text{mm}$ mat = 1.6  $N = 31000$
with single stage packing and a billet dia of 300mm, the rod dia is only 1mm

**The Problems**

- Filament distortion: magnetization and hence ac losses and field distortion is $J_c d$, where $d$ is the filament dimension transverse to the field. For the same area, distorted filaments always have a bigger magnetization than round
- Proximity Coupling: when the thickness of matrix between the filaments gets ~< 1/3 μm Cooper pairs can tunnel across the matrix, thereby increasing the magnetization. In extreme cases the benefits of finer filaments can be lost completely. Strongest at low fields
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  - but old wires or small production, so perhaps not optimized
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with single stage packing and a billet dia of 300mm, the rod dia is only 1mm
Our work on filament distortion

Second batch of samples tested

<table>
<thead>
<tr>
<th>manufacturer</th>
<th>EAS EAS</th>
<th>IGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>code</td>
<td>K2001T4</td>
<td>G2001T6</td>
</tr>
<tr>
<td>stack</td>
<td>double</td>
<td>double</td>
</tr>
<tr>
<td>wire dia</td>
<td>0.665mm</td>
<td>0.845mm</td>
</tr>
<tr>
<td>filament dia</td>
<td>3.4μm</td>
<td>4.25μm</td>
</tr>
<tr>
<td>filament number</td>
<td>12300</td>
<td>12300</td>
</tr>
<tr>
<td>matrix : ratio</td>
<td>2.21:1</td>
<td>2.21:1</td>
</tr>
<tr>
<td>Nb barrier: filament ratio</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>twist pitch</td>
<td>6mm</td>
<td>4mm etched</td>
</tr>
</tbody>
</table>

Our work on filament distortion

Methodology

• measure magnetization at various sweep rates
• at defined fields, take the mean of \( M \) in each of 4 quadrants (removes magnetometer unbalance and reversible magnetization of NbTi)
• extrapolate \( M \) to zero sweep rate
• calculate \( J_{cm} \) from magnetization using

\[
J_{cm} = \frac{2}{5\pi} \frac{B}{\mu_0} \int \left( \frac{b^2-a^2}{3} \right) \frac{2a}{\pi(b-a)^2} dB
\]

• correct transport current \( J_{ct} \) for self field; I use the mean self field
• fit \( J_{cm}(B) \) and \( J_{ct}(B) \); I use a modified Kim Anderson fit; constrain both curves to be the same shape
• calculate the ratio \( \tau = J_{cm}/J_{ct} \)

Our work on filament distortion

Results

<table>
<thead>
<tr>
<th>wire</th>
<th>2A212</th>
<th>3N7</th>
<th>RHIC</th>
<th>K2 001T4</th>
<th>G2001T6</th>
<th>B944-02-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>ratio ( J_{cm}/J_{ct} )</td>
<td>1.40</td>
<td>0.94</td>
<td>0.92</td>
<td>1.15</td>
<td>1.10</td>
<td>1.23</td>
</tr>
<tr>
<td>ratio relative to RHIC</td>
<td>1.52</td>
<td>1.02</td>
<td>1.00</td>
<td>1.25</td>
<td>1.20</td>
<td>1.34</td>
</tr>
<tr>
<td>filament dia</td>
<td>3.4μm</td>
<td>3.4μm</td>
<td>5.71μm</td>
<td>3.4μm</td>
<td>4.25μm</td>
<td>~2.5μm</td>
</tr>
<tr>
<td>effective filament dia (rel to RHIC)</td>
<td>5.2μm</td>
<td>3.5μm</td>
<td>5.71μm</td>
<td>4.25μm</td>
<td>5.1μm</td>
<td>3.35μm</td>
</tr>
</tbody>
</table>

Digression: how can the ratio \( J_{cm}/J_{ct} \) be <1?

• with sausaged filaments, you might expect that \( J_{cm} \) is governed by the narrowest cross section and that \( J_{ct} \) fills up the rest
• this would cause the ratio \( (J_{cm}/J_{ct}) \) to be always >1
• I suggest that the answer lies in flux flow resistance
• we normally measure transport current at a sensitivity of \( \rho = 10^{-14}\Omega m \)
• at this resistivity and with the self inductance of a single filament, the time constant for decay of the magnetization currents is ~ 350μs
• for a 10 sec decay time, the resistivity must be \( \rho = 4 \times 10^{-14}\Omega m \)
• if the empirical rule \( \rho = \rho_e (JJ_e)^n \) applies down to low resistivity and \( n = 40 \), the required resistivity will be reached when \( J_{cm} = 70\% J_s \)
• so the RHIC value of \( (J_{cm}/J_{ct}) = 92\% \) seems quite reasonable
Our work on proximity

- wire 2A212 at different twist pitches and etched
- filament dia = 3.4μm
- interfilament spacing ~0.5μm
- etched magnetization doesn't agree with others at high field; magnetometer or sample volume error? - scale it!
- proximity magnetization decreases with twist pitch, but not pro rata

Critical current density

Summary of our measurements

<table>
<thead>
<tr>
<th>wire</th>
<th>2A212</th>
<th>3N7</th>
<th>91-O-080122-A-05 (RHIC)</th>
<th>K2 001 T4</th>
<th>G2001T6</th>
<th>B944-02-20 (SSC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jc A/mm² at 5T 4.2K</td>
<td>2558</td>
<td>2922</td>
<td>3029</td>
<td>2759</td>
<td>2773</td>
<td>2397</td>
</tr>
</tbody>
</table>

- again single stack looks the best
- finer filaments seem to bring lower Jc

What to do?

- with pure Cu matrix, there's no point in going below 3.5μm filaments because of proximity coupling - means 23600 filaments for SIS300
- Cu-0.5wt%Mn is attractive because of reduced proximity and higher matrix resistivity
- with Cu-0.5wt%Mn, can contemplate 2.5μm filaments - means 46200 filaments for SIS300
- worry about Jc with CuMn but IGC claimed equivalent of 2790A/mm² at 5T and 4.2K
- single stack seems the best for filament distortion and Jc
- conventional single stack limited by the diameter of rods which can be stacked in the extrusion can without twist. For a 300mm extrusion billet, 1.5:1 ratio:
  - 13000 filaments ⇒ 2.09mm rods
  - 23600 filaments ⇒ 1.55mm rods
  - 46200 filaments ⇒ 1.11mm rods
- we are pushing single stack beyond it's limit, must find an alternative
- most promising approach seems to be 'hexagonal cell' single stack
Hexagonal cell single stack

- round (or hexagonal?) rods stacked in hexagonal containers
- hot isostatically pressed to reduce voidage
- very little apparent filament distortion

HC Kanitii, P Valaris, B & Zeitlin
'A novel approach to make fine filament superconductors', Supercollider 4, pp41

A 3 T superferric magnet

A. Portone (magnetic design)
VNIKP and NIIEFA (cable prototype)
L. Bottura (summary)

Field homogeneity (x)

5 units over ±20 mm

Pole shaping, coil shaping and shimming required
Field homogeneity (y)

- 2 units over ±15 mm
- 3 units
- 5 mm

Winding pack

- Optimal aspect ratio (W/H) of 0.75 minimizes the size of the winding pack and field errors
- 20 x 6 kA turns in each pole
- 6 kA cable at average 50 A/mm² engineering current density

Cable

- Relatively low Jc required
  - Internally cooled cable (for heat removal and heat transfer)
  - Outer cable insulation (allows use of standard system)
- lop = 6 kA
dl/dt = 12 kA/s
-dB/dt tests in preparation

Conclusions

- A 3 T, 3T/s magnet could be realised using an iron-dominated design
- Magnetic field quality (few 10⁻⁴) and aperture (100 mm) requirements seem possible with some optimisation
- This design allows to use internally cooled cables, whose advantage is:
  - Standard insulation system (vacuum impregnated), or other radiation resistant scheme
  - Controlled heat removal through forced flow
  - Improved heat transfer from strands to helium
FAIR Magnets
(a short overview)

G. Moritz,
GSI Darmstadt

Magnet locations in the FAIR facility

SIS 100
SIS 300
Super
FRS
CR
HESR
HEBT
RESR
NESR

SIS100

dipole (2T, 4T/s)
iron-dominated,
cold iron, 3m, straight

1 m

quadrapole (33.4 T/m)

SIS300

dipole (6T, 1T/s), 3 m, straight
cos theta, two-layer coil

1 m

quadrapole (90T/m, 15T/ms)
Collector Ring (CR) with sc dipoles (blue) and resistive multipoles (red)

- DC mode
- Warm bore
- Dipoles in series

Superferric dipole of CR and Super-FRS

- Warm bore diameter of 38 cm, 1 m
- Cold iron, iron-dominated
- High pole-tip field (≈ 2.4 T)
- Quadrupole triplet + separated sextupoles
- Octupole correction coils are embedded

Superferric Multiplets for the Super-FRS

- 1.6 T, DC, large aperture, 2.1 m iron-dominated, warm iron

High Energy Storage Ring (HESR)

- All magnets in the arcs are superconducting magnets

by courtesy of R. Tölle, FZ Jülich
**HESR cosθ-magnets**

- Dipole, 3.6 T, low ramp rate
- cosθ-magnet, one-layer coil

**HEBT / Conclusions**

- SIS100 dipoles and quadrupoles
- SIS300 dipoles and quadrupoles
- CR dipoles

**Conclusions**

- A relatively large zoo of different superconducting magnets:

**Radiation Resistant Dipole Magnets**

- Design and cost estimate for radiation resistant dipole magnets by BINP, Russia

**Unit costs:** 1200 k€

**Parameter:**

- $B = 1.6$ T
- $I = 600$ A
- $J = 1.5$ A/mm²
- $P = 50$ kW
- $\Delta B / B = 2 \times 10^{-4}$
- $\Delta R = \pm 20$ cm

**Weights (12.5 m, 11°):**

- Fe: 72 t
- Cu: 9.5 t
Fast - Pulsed Superconducting Accelerator Magnets R&D

G. Moritz, GSI Darmstadt, ECOMAG 5
October 26 – 28 2005

Outline

• Introduction to the planned facility 'FAIR'
• Main R&D topics
• Fast-pulsed superconducting magnets for the synchrotrons of FAIR
• Related R&D activities
• Conclusions

Key parameters synchrotrons

Gain Factors of FAIR

- Primary beam intensity: factor 100 – 1000
- Secondary beam intensities for radioactive nuclei: up to factor 10,000
- Beam energy: Factor 15

<table>
<thead>
<tr>
<th>Ring</th>
<th>Bending power (Tm)</th>
<th>Circumference (m)</th>
<th>Reference energy</th>
<th>Operation modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS 100</td>
<td>100</td>
<td>1080</td>
<td>1.5 GeV/u U²⁸⁻</td>
<td>acceleration mode: continuous triangular cycle with 1 sec injection time, cycle length 1 - 2 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>29 GeV protons</td>
<td></td>
</tr>
<tr>
<td>SIS 300</td>
<td>300</td>
<td>1080</td>
<td>34 GeV/u U⁹²⁻</td>
<td>acceleration mode: continuous triangular cycle with 50% duty cycle, cycle length: 18 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 GeV/u U²⁸⁻</td>
<td>stretch mode: DC operated</td>
</tr>
</tbody>
</table>

International Facility for Beams of Ions and Antiprotons (FAIR)

SIS100 (Synchrotron 100 Tm):
- “work horse”
- accelerates heavy ions/protons
- fast extraction to SIS 300 or RIB/Antiproton targets

SIS300 (Synchrotron 300 Tm):
- stretcher ring
- accelerates heavy ions to high energies
- slow extraction

SuperFRS (Fragment Separator):
- analyses and separates secondary beams

CR/RESR (Collector Ring complex):
- collects secondary beams
- stochastic precooling of ions and antiprotons
- accumulation of antiprotons

NESR (New Experimental Storage Ring):
- electron cooling and storage of ions
- in-beam experiments with RIB

HESR (High Energy Storage Ring):
- experiments with antiprotons
Magnets for the synchrotrons

<table>
<thead>
<tr>
<th>SIS100</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Magnets</td>
<td>Useable Aperture (mm)</td>
<td>Eff. Magnet Length (m)</td>
<td>Max. Field / Max. Gradient</td>
<td>Max. Ramprate</td>
</tr>
<tr>
<td>Dipoles</td>
<td>108</td>
<td>130 x 60 (gap height: 65)</td>
<td>2.9</td>
<td>2 T</td>
</tr>
<tr>
<td>Quadrupoles</td>
<td>168</td>
<td>135 x 65 (pole radius: 50)</td>
<td>1.1</td>
<td>35 T/m</td>
</tr>
<tr>
<td>SIS 300</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dipoles</td>
<td>108</td>
<td>86 (circular) (coil inner radius: 100mm)</td>
<td>2.9</td>
<td>6 T</td>
</tr>
<tr>
<td>Quadrupoles</td>
<td>168</td>
<td>86 (circular) (coil inner radius: 100mm)</td>
<td>1.0</td>
<td>90 T/m</td>
</tr>
</tbody>
</table>

Main R&D Topics for fast-pulsed magnets

- Minimization of eddy current and persistent current effects
  - affect field quality
    - correction system?
  - produce large steady-state AC-losses
    - appropriate magnet cooling system

Cryogenic system
- heat load is dominated by AC-losses in the magnet
  - SIS 100: 12 KW magnet/beam pipe; 1 KW beam loss
  - SIS 300: 6 KW magnet/beam pipe; 1 KW beam loss
- heat load varies with cycles

Mechanical structure / lifetime of the magnets
- SIS100: 200 millions cycles within 20 years
  - material fatigue, crack propagation

Cryogenic stability
- conservative stability margins

Main R&D Topics for fast-pulsed magnets (continued)

- Quench protection of the individual magnets
  - high charging voltage
    - stack of diodes or 'warm bypass'
  - Iron selection
    - search for the best compromise between high saturation flux density and low coercive force / high specific resistivity
      (I. Bogdanov, EPAC 04 WEPKF061)
- Radiation deposition due to primary beam loss affects (in the high intensity synchrotrons)
  - heat load of the cryogenic system
  - lifetime of components (coil insulation, diodes)
  - quench stability
    (E. Mustafin, EPAC TUPLT112)

R&D policy

- look for existing magnets with similar parameters
- establish collaborations
- start R&D for dipoles, transferring results to quadrupoles...
- build model magnets with existing material and toolings
  => saves time and money
- build full length prototypes
Collaborations 2004

**SIS 100:** window-frame magnet
- JINR (RU) 2/2000
- BNL (US) 1/2000
- INFN (IT) 1/2001
- Serpukhov (RU) 1/2002
- Twente University (NL)
- Jena University (D)
- LLNL (US)
- CEA (F)
- CERN (CH)
- EAS (D)
- BNL (D)
- Accel (D)

**Large Aperture Magnets** (Storage Rings, SFRS, R3B)
- NSCL/MSU (US) 1/2002
- CEA (F)
- FAIR China Group
- BINP (RU)
- Toshiba

**Scientific Coordination Magnet and Cryogenic Design Magnet Test Facility GSI**

**Consulting**
- CERN (CH) 8/2002
- FZ Karlsruhe (D)
- DESY (D)
- M.N. Wilson (GB)
- B. Hassenzahl (US)

**Quench Protection**
- CERN (CH)
- Dynex (GB)

Superconducting Magnets for SIS 100

**R&D goals**
- Improvement of DC-field quality
- 2D / 3D calculations
- Guarantee of long term mechanical stability
  (≥ 2×10⁸ cycles)
  - concern: coil restraint in the gap, fatigue of the conductor
  - Reduction of eddy / persistent current effects
  (field, losses)

**Nuclotron Dipole**
- Collaboration: JINR (Dubna)
- Iron Dominated (window frame type) superferric design
- Maximum magnetic field: 2 T
- Ramp rate: 4 T/s
- Hollow-tube superconducting cable, indirectly cooled
- Two-phase helium cooling

Nuclotron Dipole – AC Losses

<table>
<thead>
<tr>
<th>AC heat load to Helium (4K)</th>
<th>Nuclotron-Dipole (1.4 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (W/m)</td>
<td>38</td>
</tr>
<tr>
<td>Yoke (W/m)</td>
<td>29</td>
</tr>
<tr>
<td>Coil (W/m)</td>
<td>9</td>
</tr>
</tbody>
</table>

- **Coil (30%)**:
  - main contribution: wire magnetization (74%)
  => reduction of filament size to 3.5 mm
- **Yoke (70%)**:
  - magnetization losses in the central core
  - eddy current losses
    - in the endparts due to longitudinal field components B_z
    - in structural elements of the central core

AC Losses along Magnet axis z

- Temperature rise in the end part!

- OPERA-3D calculations of the integral magnetic flux \( \Phi (z) \)
AC loss calculations: yoke

Vectors of the longitudinal induction $B_z(t)$ in the yoke

Isosurfaces of eddy losses density in yoke ($t=0.36$ s), W/m$^3$

Isosurfaces of eddy losses density in yoke ($t=0.52$ s), W/m$^3$

AC loss calculations: yoke

Vectors of eddy current density in yoke at triangular current cycle

Hysteresis losses in the yoke

AC loss calculations: brackets, end plates

Vectors of eddy current density in brackets at triangular current cycle

Hysteresis loss in the brackets and end plates

AC loss calculations: beam pipe

Vectors of eddy current density in the beam pipe
AC loss calculations: beam pipe

Nuclotron R&D: loss reduction

AC heat load to Helium (4K) triangular cycle: 0-2T, 4 T/s, 1 Hz

Nuclotron-type Dipole – AC Losses

<table>
<thead>
<tr>
<th></th>
<th>Nuclotron-Dipole (1.4 m)</th>
<th>planned prototype (2.6 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (W/m)</td>
<td>42</td>
<td>22</td>
</tr>
<tr>
<td>Yoke (W/m)</td>
<td>29</td>
<td>11</td>
</tr>
<tr>
<td>Coil (W/m)</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Beam pipe (W/m)</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
How does the prototype magnet look like?

- **Yoke (cold iron)**
  - Laminations (homogenisation slits, neg. shimming)
  - glued endblocks with
    - slits (eddy current reduction)
  - Rogowski end profile
  - stainless steel endplate
  - stainless steel structure
- **Coil**
  - standard Nuclotron cable / low loss wire
  - 2 layer, 16 turns
  - reduced bedstead (eddy current reduction)
  - rigid coil structure (G11)
  - coil ends restrained

SIS 100 Dipole - Alternatives

- **Nuclotron Superferric Window-frame Dipole**
  - (cold iron, cold bore, cryogenic pumping)
- **Superferric H-type design**
  - (warm iron, warm bore)

Max. Field: 2 T
Max. Ramp Rate: 4 T/s
Field quality: ±6x10^-4
Aperture: 110x55mm²

Study at BINP, Russia

Resistive
Comparison sc and nc 100 Tm dipole

<table>
<thead>
<tr>
<th>COSTS (M)</th>
<th>sc</th>
<th>nc</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRODUCTION</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>OPERATING</td>
<td>8</td>
<td>45</td>
</tr>
<tr>
<td>TOTAL</td>
<td>44</td>
<td>82</td>
</tr>
</tbody>
</table>

based on:
- 248 dipoles (SIS 100 and beamlines)
- 20 years of operation, 6500 h/y
- Present status of the R&D
- Aperture (55 mm x 110 mm)
- Operation cycles mix
- Present electricity costs

includes costs for
- Power supplies, quench detection and protection
- Cryogenic system
- Tests and operation crew

→ saves 17,000 t CO₂ / year

Superconducting Accelerator Magnets: SIS 200 / 300

- RHIC dipole
- Collaboration with BNL
- Coil dominated: cost
- Maximum field: 3.5 T ⇒ 4 T
- Ramp rate: 70 mT/s ⇒ 1 T/s !!!
- Supercond. Rutherford cable
- One-phase helium cooling

R&D Goals for RHIC type dipole

- Reduce the effects due to the high ramp rate:
  - Lower loss in wire, cable and iron
  - Better AC field quality
- Improve the cooling of the Rutherford cable:
  - Open Kapton insulation with laser cut holes
- Use collars to ensure long-term mechanical stability

Dipole Parameters

RHIC dipole

- Superconducting wire:
  - NbTi-Cu (1:2.25)
  - Filament diameter 6 μm
  - Twist pitch 13 mm
  - No coating
- Rutherford cable:
  - No core

RHIC type dipole GSI 001

- Superconducting wire:
  - NbTi-Cu (1:2.25)
  - Filament diameter 6 μm
  - Twist pitch 4 mm
  - Stabrite coating
- Rutherford cable:
  - 2 x 25μm stainless steel core

Coil
- Phenolic spacer
- Cu wedges

Yoke
- \( H_o = 145 \text{ A/m} \)
- 6.35 mm laminations

- Coil
  - Stainless steel collar (G11 keys)
  - G11 wedges

Yoke
- \( H_o = 33 \text{ A/m}, 3.5\% \text{ Silicon} \)
- 0.5 mm laminations, glued
**RAMP RATE TESTS GSI001 (vertical bath)**

- 4 quenches to short sample limit
- continuous 2T/s operation up to short sample limit
- 3 cycles 4 T/s up to 4T

Thermal time constant ~ 1 min.

by P. Wanderer

---

**Quench current Ramp Rate Limitation (RRL)**

- continuous cycling to reach thermal equilibrium
- type 'A' behavior: quench current reduced by AC-conductor heating
- type 'B' behavior: quench current reduced due to unequal current distribution between strands - unwanted!

Calculation: cable loss $\rightarrow$ heat conduction / transfer to helium $\rightarrow \Delta T$ of superconductor $\rightarrow$ reduced quench current!

Conclusion: type 'A', but small degradation only in the region of interest due to moderate AC-heating and good cooling; small Ra allows current redistribution.

---

**cryogenic losses**

- 0-4 T, 1 T/s, triangular cycle: 8.8 W, 7.3 W/m

Loss contributions:
- hysteresis loss (not dependent on ramp rate): iron and sc filaments
- eddy current loss (dependent on ramp rate): sc filament coupling and interstrand coupling

Results:
- good agreement for hysteresis loss (intercept, dB/dt=0)
- discrepancies for eddy current loss (slope), especially at high fields > 3 Tesla
  - measured values larger than calculated by theory $\rightarrow$ unexpected contribution by ????

---

**Calculated and measured losses of GSI001**

by M.N. Wilson

Hysteresis part (intercept) (including iron and transport current contribution)

Parameters used for calculation:

- $\rho_{Fe}(B) = 1.24 \times 10^{-10} + 0.9 \times 10^{-10} \text{ B}$
- $\rho_{m}$ in $\Omega m$ and B in Tesla.

<table>
<thead>
<tr>
<th>Loss contribution</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel loss ($R_a$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Transverse adjacent loss ($R_{ad}$)</td>
<td>12.0</td>
</tr>
<tr>
<td>Eddy current loss (Cu-matrix)</td>
<td>11.9</td>
</tr>
<tr>
<td>Filament coupling loss ($R_{cu}$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Hysteresis loss ($d_{ai} = 6 \mu m$)</td>
<td>69.7</td>
</tr>
</tbody>
</table>

Eddy current part (slope)
Eddy current losses in dewar and cryostat (soft iron)

unexpected measured power loss and OPERA-calculation with a magnetic dewar

- 23.9% stainless steel shell of cold mass
- 6.8% stainless steel helium containment
- 69.3% iron vacuum vessel

Conclusion:
Good understanding of cryogenic losses!!

2D Field Quality - DC and AC

- Measurements (DC and 2-4 T/s)
  - BNL developed stationary harmonic coil system (16 coils)
- Codes
  - ROXIE
  - VF Opera 2D
- Newly implemented in both codes:
  - Superconductor hysteresis
  - Interfilament coupling (including magnetoresistance)
  - (tentatively: interstrand coupling (3 contributions, only one relevant))

2D Field Quality: b3 at 2 T/s

- Magnet was built to demonstrate the feasibility of fast-pulsing, using existing components
- Not optimized for DC field quality (large geometrical sextupole, increasing at higher fields due to iron saturation)
- Please note: The very good agreement between measurement and calculation by ROXIE!
**2D Field Quality: $B_5/b_5$**

decapole $B_5/b_5$ (half difference between up and down)

- in Tesla @ 25 mm radius
- $10^{-4}$ units @ 25 mm radius

- measured DC
- Roxie DC
- Opera DC
- measured 2T/s
- Roxie 2T/s
- Opera 2T/s

**Conclusions:**

- magnet looks suitable for the use in a synchrotron
- quench behavior is dominated by Joule heating
- cryogenic losses are tolerable
- "AC" field quality is predictable and acceptable

**Further work:**

- horizontal test of the magnet, with one-phase helium cooling in the new

---

**SIS 300 - Dipole**


**Main results:**

- cooling: one phase Helium 4.4 K
- temperature margin: 1.0 K
- option: lowering Helium-temperature
- collared coil supported by iron shell (taking part of the load)
- strand: diameter: 0.825 mm filament: 3.5μm
- Rutherford-cable: 36 strands with core (LHC outer layer)
- quench protection: needs heater, 20 magnets per PS / dump resistor

**UNK Dipole**

- 2 layer cosθ design
- 80mm bore ⇒ 100 mm
- 5.11 T ⇒ 6 T
- 0.11 T/s ⇒ 1 T/s

---

**SIS 300 Dipole: coil cross section**

First winding tests with cored cable (LHC outer, partially keystoned):

- favor radially oriented cable
- suggest for the ends not more than 10 turns per block in the inner layer

---

**Summary of test results GSI 001**

Purpose of this work was to investigate the influence of persistent and coupling currents on

- quench behavior
- cryogenic losses
- field quality

of the fast-pulsed cosθ dipole GSI 001.

**Conclusions:**

- magnet looks suitable for the use in a synchrotron
- quench behavior is dominated by Joule heating
- cryogenic losses are tolerable
- "AC" field quality is predictable and acceptable

Acknowledgement: thanks to
Juris Kaugerts, GSI,
John Escallier, George Ganetis, Animesh Kumar Jain, Andrew Marone,
Joseph F. Muratore, Richard Thomas, Peter Wanderer, BNL,
Bernhard Auchmann, Riccardo de Maria, Stephan Russenschuck, CERN
Martin Wilson, Consultant, Oxford

---

**SIS 300 Dipole: coil cross section**

First winding tests with cored cable (LHC outer, partially keystoned):

- favor radially oriented cable
- suggest for the ends not more than 10 turns per block in the inner layer

---

**SIS 300 Dipole: coil cross section**

First winding tests with cored cable (LHC outer, partially keystoned):

- favor radially oriented cable
- suggest for the ends not more than 10 turns per block in the inner layer
**SIS 300 dipole – cold mass cross section**

1–coil, 2–wedges, 3–key, 4–collars, 5–iron yoke, 5–slot, 6–iron yoke, 7–stainless steel shell, 8–hole for II-phase helium.

**Further work SIS 300 magnets**

- **SIS 300 dipole (IHEP / CERN / GSI)**
  - final 2D / 3D coil design
  - winding of model coil
  - mechanical design (collar / yoke) (fatigue!)
  - technical design (drawings)
  - construction and testing of model dipoles
  - radiation test of cold diodes

- **SIS 300 quadrupole (CEA Saclay / GSI)**
  - parameters, work packages and milestones defined

**Small filament size wire R&D**

Motivation: 60 -70% of the coil AC-losses caused by wire magnetization

- filament size reduction
- but limit due to ‘proximity coupling’

\[ d_{eff} \geq 3.5 \mu m \text{ for Copper matrix} \]

Preliminary tests:

- single stack 3N7
- double stack 2A212

\[ d_{eff} = 3.5 \mu m, \text{ but problems with stacking of 12000 monocores (1.5 mm wide)} \]

\[ d_{eff} = 4.8 \mu m \text{ due to filament distortion (near the copper)} \]

**Small filament size wire R&D (continued)**

- Modified double stack method:
  - 6 x 2050 filaments
  - 0.65 mm wire diameter
  - 1.80 : 1 Cu / NbTi ratio
  - 4 mm twist pitch
  - \( j_c = 2759 \text{ A} / \text{mm}^2 @ 5T, 4K \)
  - 3.3 micron NbTi filaments (nominal)
  - Full size billet (120kg) is ready for wire production

- Cu-Mn-matrix (2.5 micron NbTi filaments) wire is under investigation!
Cable R&D (Rutherford)

Rutherford cored cable R&D

- RHIC-type cable
  - different cores (stainless steel, titanium, Cu-Ni, brass, Kapton)
  - different mandrels (hollow, slotted)
  - measurement of $J_c$, $R_a$, $R_c$, AC-losses
    details in A. Ghosh, WAMS-workshop, Archamps, 2004
- LHC outer cable
  - same program as above

Cable R&D (Nuclotron-type)

High current cable (LHE, GSI)

EU INTAS 03-54-4964 : improved N- CICC

by Bottura, Wilson
by P. Bruzzone
by V. Keylin
realisation by VNIIPK

Summary

- Fast-pulsed sc magnets are foreseen for the synchrotrons of FAIR
- R&D to develop these magnets is under way.
- First dipole models have been built and tested.
- R&D will continue on quadrupoles and full size magnets.

Acknowledgements

I am greatly indebted to all members of the collaborations, to our consultants and to the members of the GSI magnet group for their dedicated work.

Technology Task TW5-TMSC-RESIN

Qualification and optimization of resin systems for the TF coils of ITER

Handout

Atomic Institute of the Austrian Universities, Vienna, Austria

October 25, 2005
RADEFF/RESIN - Results

- Unacceptably low mechanical strength of the ITER TFMC insulation systems (ANSALDO, ALSTOM) after exposure to the ITER design fluence of 1x10^{22} m^{-2} (E > 0.1 MeV)

- Expensive cyanate ester (CE) resins offer higher radiation resistance

- A 40/60 CE/epoxy blend shows high radiation resistance (mechanical strength improved by ~20%, ITER criteria fulfilled)

- Advantages of pure CE ester compared to CE/epoxy blend?

- Optimal (lowest) percentage of CE in blends for cost reduction?

- Availability of radiation harder epoxy resins for cost reduction?

Insulation Systems

<table>
<thead>
<tr>
<th></th>
<th>T1a</th>
<th>T1b</th>
<th>T1c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Cyanate Ester</td>
<td>Cyanate Ester</td>
<td>Cyanate Ester</td>
</tr>
<tr>
<td>Resin</td>
<td>ArCy-L10</td>
<td>ArCy-L10</td>
<td>ArCy-L10</td>
</tr>
<tr>
<td>Hardener</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Additives</td>
<td>Mn Acetylacetonate in Nonylphenol</td>
<td>Mn Acetylacetonate in Nonylphenol</td>
<td>Mn Acetylacetonate in Nonylphenol</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>R-glass / Kapton</td>
<td>R-glass / Kapton</td>
<td>R-glass</td>
</tr>
<tr>
<td>Curing Temp.</td>
<td>4 h @ 140°C / 5 h @ 210°C</td>
<td>4 h @ 100°C / 5 h @ 160°C</td>
<td>4 h @ 100°C / 5 h @ 160°C</td>
</tr>
</tbody>
</table>

Vacuum pressure impregnation

Fabrication:
Marti-Supratec Corporation, Wallisellen, Switzerland

Glass fiber / Kapton tapes wrapped half overlapped around steel plate

Anisotropic material properties

Tests carried out parallel (0° direction) and perpendicular (90° direction) to the winding direction

Insulation systems with Kapton
1 glass fiber layer + 7 glass fiber / Kapton layers

Dimensions:
R-glass fiber tape: 0.24 mm x 40 mm
Kapton H foil: 0.04 mm x 36 mm
Resulting sample thickness: ~ 4 mm

Insulation systems without Kapton
8 glass fiber layers
Test procedures

All tests @ 77 K

Static and dynamic tensile tests

Short-beam-shear (SBS) test with span to thickness ratio of 4:1 and 5:1

Neutron irradiation in TRIGA reactor (Vienna) to a fast neutron fluence of $1 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$)

Test specimens

SBS

Tensile

Results

Ultimate tensile strength (UTS) in 0° direction

Results

Ultimate tensile strength (UTS) in 90° direction

Results

Interlaminar shear strength (ILSS) in 0° direction
Results

Interlaminar shear strength (ILSS) in 90° direction

Swelling and weight loss

Summary

- No significant degradation of the mechanical strength (static and dynamic) was observed for the pure CE systems at the ITER design fluence of 1x10^{22} m^{-2}.

- The previously tested 40/60 CE/epoxy blend (RADEFF) showed the same radiation hardness as the pure CE system and demonstrated improved mechanical integrity at the ITER design level.

- All commercial epoxy based systems show reduced mechanical integrity at the ITER design level and can be excluded, except the “Oritherm” system, which shows the best radiation resistance. It will be used as baseline material for comparison with the innovative CE/epoxy blends.

Catalyst

- At present all the CE/epoxy blends are fabricated with a Mn-based catalyst (low activation in the Triga reactor). A Co-based catalyst offers more stability but shows higher activation by the thermal neutrons in the Triga reactor (expensive health physics, handling and disposal of radioactive materials). Qualification work of the Co-based catalyst for the CE/epoxy blends is currently under way by Huntsman.

- Both the Mn and the Co-based catalysts are registered as PIC materials (Pre Information Control) in Switzerland, the EU countries and Japan. An application form to the Swiss government has to be provided by Huntsman to export both materials, e.g. to Japan or other EU countries after agreement of the respective governments.
Outlook

• Assess the optimal (lowest) percentage of CE in the CE/epoxy blend for high mechanical material performance and radiation response up to the ITER design fluence level and beyond ($2 \times 10^{22}$ m$^{-2}$), but low fabrication costs.

• First screenings on a 70/30 epoxy/CE blend did not show any change in the radiation response compared to the 60/40 system. This blend and a further 80/20 epoxy/CE system with lowest percentage of CE will be investigated in detail.

• Assess the influence of various epoxies (PY306 and the radiation harder Orilight) on the mechanical integrity of the CE/epoxy blends.

• Characterization of a filler material at $5 \times 10^{21}$ m$^{-2}$.

• Fundamental investigations in load/strain-controlled tension fatigue.

Outline

- Capabilities
- EFDA dipole design
- Ongoing projects

Capabilities (I)

- Design of superconducting magnets:
  - 2-D and 3-D magnetic analysis:
    - Roxie
    - Ansys
  - 2-D and 3-D mechanical analysis:
    - Ansys
  - Quench propagation simulation for fully impregnated magnets: code based on a finite difference method.
- Design of HF electromagnetic devices: HFSS
Capabilities (II)

- Fabrication of prototypes:
  - Winding machines:
    - Double pancake coils up to 2 m long.
    - Conventional machine: small flat coils and solenoids.

Capabilities (III)

- Fabrication of prototypes:
  - Machine to glue a ribbon of wires.
  - Design and fabrication of vacuum impregnation moulds.

Capabilities (IV)

- Testing of superconducting magnets up to 400 mm long and 250 mm diameter (liquid helium). Maximum current 1600 A.
- A new cryostat for magnets up to 600 mm long and 350 mm diameter will be installed during next year.

EFDA dipole magnetic design
EFDA dipole mechanical design

(courtesy J. Lucas)

Ongoing projects (I)

- Testing of a combined superconducting magnet for TESLA 500.
- Design and fabrication of a superferric magnet for XFEL.
- Design and fabrication of different devices for CTF3.

Ongoing projects (II)

- Working group on magnet design in the framework of NED.
- Design and fabrication of a HTS conduction-cooled solenoid.
- Characterization and testing of a 200 kW switched reluctance machine

A combined function magnet for the J-PARC neutrino Beam Line with a Fast Ramp Test

A. Yamamoto
For the J-PARC Neutrino Beam Line Group
To be presented at ECOMAG workshop
2005-10-26~28
JPARC project and neutrino beam line

A next generation long baseline neutrino oscillation experiment is planned to study fundamental nature of neutrinos.

@Tokai village

Neutrino Beam Line

To SK

FD

• Superconducting magnet system is adopted

System Overview

• 28 SCFM
  - Dipole 2.6 T
  - Quad 18.6 T/m
  - Length 3.3 m
  - 2 in 1 Cryostat
• 13 interconnects
  - 6 beam monitor
  - 3 correctors
  - 4 quench valves

Magnet Design

• Op. Current: 7345 A
• Op. Margin: 72%
• Inductance: 14.3 mH
• Stored Energy: 386 kJ
• SC Cable: NbTi/Cu for LHC Dipole Outer-L

Cost saving has been strongly requested.

Reduce:
- Development time
- No. of Magnets in the beam line
  (40 → 28)

SCFM

Supercconducting Combined Function Magnet

Combined Field

F : Q-grad
B dipole

B+D

FODO

F + D

B

B + F

SCFM

Dipole

Quadrupole

OR

Concept of Combined Function Magnet

Dipole

Quadrupole

Combined Field

F: Q-grad
B dipole

Coil ID.: 173.4mm
Mech. Length: 3630 mm @RT
Tmax: < 5.0K
(Supercritical Helium)
Dipole Field: 2.59 T
Quad. Field: 18.6 T/m
Peak Field on the cable: 4.7 T
Magnet Design

- Left-right asymmetry
- Single layer coil
- Plastic Spacer

Fabrication of Prototype Magnet

Coil Winding

Yoking Interfaced with Plastic Collar to Coil

Magnet Complete
Cool-down and Excitation Test at 4.2

Installation into vertical cryostat

$I_{op} = 7345 \text{ A} @ 50\text{ GeV} \text{ (and } I_{max} = 7,700\text{ A)}$ reached with no quench.

**Excitation Test Results**

- The max. Exc. reached 7.7 kA with No Training Quench
- Fast Ramp Test: $1000\text{ A/s} (0.7\text{ T/sec}) \text{ (also no quench)}$

**Load line & Field Quality**

Operation Conditions at 50 GeV
- Peak field in the coil: 4.6 T
- Load Line Ratio: 72 % @ 5 K
- Higher Order Component: $< 10^{-3} @ R = 50 \text{ mm}$

**Comparison ~1st & 2nd & Comp.**

3D Field Quality (Ref=50 mm)

- Integral field strength @ ref. radius of 5 cm
### Construction Schedule

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat w/ 2-SCFMs</td>
<td>1 (proto)</td>
<td>7</td>
<td>7</td>
<td>1 &amp; Install</td>
</tr>
<tr>
<td>Transfer Tube</td>
<td></td>
<td></td>
<td></td>
<td>Install</td>
</tr>
<tr>
<td>Refriger.</td>
<td></td>
<td></td>
<td></td>
<td>Install</td>
</tr>
<tr>
<td>PS</td>
<td></td>
<td></td>
<td></td>
<td>Install</td>
</tr>
<tr>
<td>Corrector Magnet</td>
<td></td>
<td></td>
<td></td>
<td>Install</td>
</tr>
<tr>
<td>Quench Detector</td>
<td></td>
<td></td>
<td></td>
<td>Install</td>
</tr>
</tbody>
</table>

### Summary

- Superconducting combined function magnets for J-PARC Beam Line successfully developed and tested at KEK,
- The magnet reach the Bmax of 4.7 T without training and a fast ramp rate of 0.7 T/s to reach the Bmax, as well,
- Magnet production started and the beam line to be commission in March, 2009

### Mechanical Short-section Model Study
**FAST-RAMPED FAST CYCLING SUPPERCONDUCTING MAGNETS: DUBNA EXPERIENCE AND RECENT RESULTS**

Alexander KOVALENKO
Joint Institute for Nuclear Research, Laboratory of High Energies (141980, Dubna, Russia)

ECOMAG'05
Fraskatti, Italy, October 26-28, 2005

---

I consider it as the topic for the future work program within the frames of ECOMAG activity, because the comparison of different magnet design approach will be necessary.

---

**2 T, 4 T/s, 1 Hz superferric magnets were designed and constructed at LHE JINR (Dubna) in 1978-79,**

**JINR/GSI collaboration on improvements of the magnets parameters in accordance with the SIS100 specification - from 2000**

The optimization of all parameters was made to obtain the following operating performances at $f = 1$ Hz pulse repetition rate:

- Quench current higher than 7500 A
- AC power losses per NbTi volume $q = 68$ mJ/cm$^3$ per cycle.

**THE NUCLotron-TYPE DIPOLE**

2 T, 4 T/s, 1 Hz: Two-phase He flow, hollow NbTi composite cable, yoke at 4.5 K
**FAST-RAMPED SUPERCONDUCTING CABLES**

**KEYSTONED NbTi WIRE**

**HOLLOW SC CABLE made from keystoned wires**

**SINGLE-LAYER COIL DIPOLE**

**DESIGN AND TEST OF A HOLLOW SUPERCONDUCTING CABLE BASED ON KEYSTONED NbTi COMPOSITE WIRES, presented at ASC 2004, October 2004, Jacksonville, USA**

**4 T, 3-4 T/s Cos(\theta) style dipole**

**Characteristics**

<table>
<thead>
<tr>
<th>Nuclotron Keystoned Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling channel diameter</td>
</tr>
<tr>
<td>Cu-Ni tube diameter</td>
</tr>
<tr>
<td>Number of strands</td>
</tr>
<tr>
<td>Twist pitch of strands</td>
</tr>
<tr>
<td>Ni-Cr wire diameter</td>
</tr>
<tr>
<td>Ni-Cr wire binding pitch</td>
</tr>
<tr>
<td>Cable diameter with insulation</td>
</tr>
<tr>
<td>Current density in the winding</td>
</tr>
</tbody>
</table>

**Graph:**

- B (T) vs. Current (A)
- B3/B1 vs. Current (A)
- Main field and sectupole lines
### Table 1: Comparison of Hollow cables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KWAT1</th>
<th>KWAT2</th>
<th>KWAT3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable diameter with insulation, mm</td>
<td>7.34</td>
<td>8.92</td>
<td>8.92</td>
</tr>
<tr>
<td>Cooling channel diameter, mm</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Strands cross-section area, mm²</td>
<td>4.26</td>
<td>16.8</td>
<td>24.2</td>
</tr>
<tr>
<td>NbTi cross-section area, mm²</td>
<td>4.26</td>
<td>16.8</td>
<td>24.2</td>
</tr>
<tr>
<td>Percentage of NbTi in coil cross-section, %</td>
<td>10.1</td>
<td>28.9</td>
<td>30.4</td>
</tr>
<tr>
<td>Critical current density @ 4.5 T and 4.5 K, A/mm²</td>
<td>2,070</td>
<td>2,960</td>
<td>2,960</td>
</tr>
<tr>
<td>Operating current at T = 4.5 K, kA</td>
<td>207</td>
<td>304</td>
<td>464</td>
</tr>
<tr>
<td>Structured current density at T = 4.5 K, A/mm²</td>
<td>225</td>
<td>304</td>
<td>464</td>
</tr>
<tr>
<td>Number of the strands</td>
<td>15 (keystone)</td>
<td>40 (keystone)</td>
<td>40 (keystone)</td>
</tr>
<tr>
<td>Critical current at 4.5 K, kA</td>
<td>17.4 @ 2 T</td>
<td>49.6 @ 4.5 K</td>
<td>64.6 @ 4.5 K</td>
</tr>
<tr>
<td>Critical to operating current ratio</td>
<td>1.45</td>
<td>1.24</td>
<td>1.61</td>
</tr>
</tbody>
</table>

**SI3100 AT GSI: THE MAGNETS COOLING SCHEME**

Dependent on the supercycle, the heat released in a dipole coil and yoke varies between 6.08 (cycle 3b) and 25.0 W (cycle 2c). On the other hand, the heat release in a quadrupole lens varies between 3.17 and 10.39 W.

The mass flow rate through the dipoles on one hand and the modules on the other hand is given by the geometry of the cooling channel and by the pressure difference between supply and return line. By adjusting the pressure difference the mass flow can be influenced. Calculations have shown that for the maximum load (cycle 2c) a pressure difference of 0.29 bar is required, whereas for minimum load (cycle 3b) a pressure difference of 0.2 bar is sufficient.
**New design: (KWIT)**

Keystoned Wires Inside a Tube

- FAST-RAMPED SUPERCONDUCTING CABLES

The wires fix themselves (arc principle) and form a cooling channel with small hydraulic resistance. The direct contact of two-phase helium flow with the wires provides the highest cryogenic stability any time interval.


**Progress in the Design of a Superconducting Synchrotron Dipole Magnet with Pulse Repetition Rate up to 20 Hz**

The works on the design of a superconducting synchrotron magnets with a pulse repetition rate up to 20 Hz are continued at the Laboratory of High Energies of JINR. Modification of the magnet from the 4K yoke option to the 50K one was made. The new test was performed in July 2005.

Fig. 2. View of the 50K yoke dipole with a single-layer coil in the cryostat

A cold iron (T = 4.5 K) window-frame Nuclotron dipole with a single-layer coil made from the new high current hollow NbTi composite cable was constructed and tested first time about a year ago. The new high current hollow NbTi composite cable was used with an average current of 45 kA. The coil is separated from the yoke by a gap of 1 mm. Epoxy impregnated glass fiber is used to secure the coil from the yoke. The septum of the beam can be adjusted and moved to the yoke window with special adjustable G10 pins and plates. General view of the magnet in the cryostat is shown in Fig. 2.

Fig. 1. Schematic cross section of the 50K yoke dipole

**MODIFICATION OF THE DIPOLE**

Cross section of the new dipole version is presented in Fig. 1. Similar to that was made earlier for manufacturing the model dipoles 80KDP2 and 80KDP3 [2] the magnet coil at T = 4.5 K was separated from the yoke with a gap of 1 mm. Epoxy impregnated glass fiber is used to secure the coil from the yoke. The septum of the beam can be adjusted and moved to the yoke window with special adjustable G10 pins and plates.

**TEST OF THE MAGNET**

The magnet was tested at different conditions, nevertheless, limited by the power supply parameters. The measured AC losses (in W) are presented in the Table. The coil and the yoke are cooled with four two-phase cold helium lines and plates. Operating parameters of the magnetic field are shown in the Table.

**Progress in the Design of a Superconducting Synchrotron Dipole Magnet with Pulse Repetition Rate up to 20 Hz**

The magnet was tested at different currents, nevertheless, limited by the power supply parameters. The measured AC losses (in W) are presented in the Table. The coil and the yoke are cooled with four two-phase cold helium lines and plates. Operating parameters of the magnetic field are shown in the Table.
Measuring fast pulsed magnets using rotating coils in step mode

Pierre Schnizer

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ecomag@Frascati 26 - 28 October 2005

Outline

1 Motivation
2 Approaches
   - Introduction
   - Comparison of Methods
   - Aliasing
   - Methods summary
3 Choosing the Method
4 Implementation
   - Coil Probe Requirements
   - Devices
5 Conclusion

Motivation

- Magnetic measurement needed
  - R&D phase
    - Magnet qualification
    - Computer model quality
    - Aid design decisions
  - Production phase
    - Quality control
    - "Equality" of magnets
    - Data for machine startup

Required Information

- Steady state (injection, extraction, stretcher mode)
  - Field
    - Strength
    - Angle
    - Homogeneity
  - Axis
- Ramp
  - Field
    - Strength
    - Angle
    - Homogeneity
  - Axis
Measurement: Ramp vs Steady State

\[ \Phi = \sum_{n=1}^{N} C_n e^{i\omega t} \]  
(1)

\[ \Phi = \text{flux} \]
\[ C_n = B_n + i\omega n \text{th multipole} \]
\[ \omega = \text{angular velocity of the coil probe} \]

\[ \frac{d\Phi}{dt} = \sum_{n=1}^{N} \left( nC_n e^{i\omega t} + nC_n e^{i\omega t} \right) \]  
(2)

Flux change given by two effects
- area of the probe
- field of the magnet

Approaches Overview

- All harmonics at once (A. Jain)
- Ramp by ramp (N. L. Smirnov, A. Kovalenko)
- Rotating coil during ramp (L. Bottura, A. Jain; ...)
- Special devices for one multipole
  - in detail discussion follows

All harmonics at once

\[ \frac{d\Phi}{dt} = \sum_{n=1}^{N} C_n \frac{d}{dt} e^{i\omega t} \]  
(3)

Ramp by Ramp

\[ \frac{d\Phi}{dt} = \sum_{n=1}^{N} C_n \frac{d}{dt} e^{i\omega t} \]  
(4)

Analysis
- gather data from different coils for one \( t \) — all multiples
- flux — scale — multiples

Advantages
- coil manufacturing, maximum order limited (practical 6), individual calibration
- same probe as for DC; compensation possible

Drawbacks
- reproducibility of power supply + magnet
Rotation during ramp

\[
\frac{d\Phi}{dt} = \sum_{n=1}^N \left[ d_n C_n d t e^{i n \omega t} \right] + n \omega C_n e^{i n \omega t}
\]  (5)

Analysis:
- Calculate harmonics from steady-state 
- Compare to measured \( \Phi \)
- Readjust harmonics to fit measured flux

Advantages:
- Allows to use DC equipment for slow ramps

Disadvantages:
- Only applicable if \( \omega \ll \frac{d_n}{C_n} d t \)

---

One harmonic at a time

special devices for one harmonic (J. DiMarco, L. Bottura)
- Morgan coils
- Hall probe arrays

Advantages:
- Signal corresponds to harmonic strength

Disadvantages:
- One for each harmonic, hall probe array manufacturing, calibration

---

Excurs: Aliasing

different approaches for multipole measurement

- Rotating coil = harmonic analysis
- Rotating coil = fit of wanted harmonics
- Morgan coils, hall probe arrays

Analysis:
- Sampling of the probe
- Nyquist’s frequency
- Not analysis

---

Direct versus Step versus Rotating

<table>
<thead>
<tr>
<th>Method</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>All at once</td>
<td>Complicated to manufacture, aliasing, limited Nyquist frequency, stability of the power supply, magnet for “slow” ramp rates, complicated analysis</td>
</tr>
<tr>
<td>Ramp by ramp measurement</td>
<td>Use of existing equipment</td>
<td></td>
</tr>
<tr>
<td>Rotating</td>
<td>Use of existing equipment</td>
<td>Only for “slow” ramp rates, limited Nyquist frequency, complicated analysis</td>
</tr>
<tr>
<td>Special devices</td>
<td>Direct multiple measurement</td>
<td>Difficult to manufacture, needs a lot of probes</td>
</tr>
</tbody>
</table>

---
Choosing the method: Ramp by Ramp

Considerations:
- ramp rates are high → 17/s → 47/s
- minimise necessary equipment
- power supply reproducibility
- reproducibility from ramp to ramp necessary for machine operation
- can be measured using stationary coil
- current reading and flux reading on the same galvanic trigger line
- triggered by time
- current trigger possible with "of the shelf electronics"

Pierre Schnizer
Measuring pulsed magnets

Successful implementation
Nikolay Smirnov for UNK (Protvino)
Alexander Kovlenko for Nuclotron (Dubna)
Motivation

Approaches

Choosing the Method

Implementation

Conclusion

Coil Probe Requirements

Devices

Anticryostat

- two fibre glass tubes (eddy currents)
- separate vacuum (safety)
- moveable by motors (rectangular apertures)

Pierre Schnizer
Measuring pulsed magnets

Conclusion

- different approaches to pulsed measurement were shown
- ramp to ramp measurement was selected
- reuse of equipment for DC measurements
- allows compensation coil to be used
- magnet needs repeatability for accelerator operation
- stability of the power supply limits main field measurement not harmonics
- static coil can reduce the requirement

Pierre Schnizer
Measuring pulsed magnets
Outline

• Introduction:
  – The Cotton-Mouton Effect (CME)
• A novel measurement method of the CME:
  – Motivations
  – Principle
  – Optimization & effects of the imperfections of the optical elements
• CME Measurements for air inside a LHC dipole
• Toward a measurement of the integrated transfer function & field angle of dipoles, quadrupoles,…
• Conclusions

Introduction
The Cotton-Mouton Effect (CME)

• Discovered in 1905
  Faraday’s law, – 1831
  Faraday’s effect, 1845
• CME: Production of birefringence by a transverse $B$
  i.e. Voigt configuration

\[ \beta = \frac{2\pi(n_i - n_e)l}{\lambda} = -2\pi l B^2 \]

• The dephasing $\beta$ between the 2 polarization eigen modes of the laser beam propagating over $l$ in the medium submitted to the transverse $B$ is

CME: Magnetic analog of the Kerr effect

\[ M \left(10^4/Tm\right) \quad 10^{-3} \quad 30 \quad \text{Plasma} \]
\[ (\text{density}) \]
CME: A novel measurement method

Motivations

* CME of the vacuum?

Δn = few 10^-22 in 9.5 T

Technical challenge since its prediction in 1936 by Euler & Heisenberg from earlier QED development...

Required high transverse field over a long length

⇒ LHC dipoles are ideal

+ optical cavity

+ optimized measurement method

Can be used to characterize accelerator magnets

CME: A novel measurement method Principle

Jones’ Matrices formalism

\[ M_{	ext{CM}} = \begin{pmatrix} \exp(-i\pi/n) & 0 \\ 0 & \exp(i\pi/n) \end{pmatrix} \]

\[ R_M = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \]

\[ M_{\text{MW}} = \begin{pmatrix} \exp(-i\beta/2) & 0 \\ 0 & \exp(i\beta/2) \end{pmatrix} \]

Effects of imperfections

Parameter s

<table>
<thead>
<tr>
<th>Description</th>
<th>Typical values (in rad) for classical components</th>
<th>Typical values (in rad) for optimised components</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta )</td>
<td>( 2 \pi \times 5 \times 10^{-4} )</td>
<td>( 2 \pi \times 10^{-6} )</td>
</tr>
<tr>
<td>( \phi )</td>
<td>( 2 \pi \times 5 \times 10^{-4} )</td>
<td>( 2 \pi \times 10^{-6} )</td>
</tr>
<tr>
<td>( \delta_{\lambda} )</td>
<td>( 3.10^{-4} )</td>
<td>( 10^{-5} )</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>( 3.10^{-4} )</td>
<td>( 10^{-5} )</td>
</tr>
</tbody>
</table>

\[ E_{\text{in}} = R_{\chi} \cdot M_{\lambda} \cdot R_{x_{\text{qwave}}+\delta_{\lambda}} \cdot R_{y_{\text{qwave}}+\delta_{\lambda}} \cdot M_{\text{CM}} \cdot R_{\gamma_{\text{misalign}}+\delta_{\gamma}} \cdot M_{k/2+\kappa_{\text{misalign}}} \cdot R_{\beta_{\text{misalign}}} \cdot E_{\text{in}} \]

CME: A novel measurement method Optimization (1/3)

Modeling the imperfections

CME: A novel measurement method Optimization (2/3)

A Taylor expansion up to the 4th order in \( \epsilon, \delta, \delta_{\lambda}, \) and \( \delta_{\chi}, \) and to the 2nd order in \( \beta, \) has been made analytically using Mathematica.

\[ P_{\text{wpt}} = P_{\text{wpt}}^{\text{classical}} + \frac{1}{2} \pi^2 \beta^2 + 2 \pi \beta \delta_{\lambda} + \frac{1}{2} \pi \delta_{\chi} \delta_{\lambda} \]

For classical components

\[ \beta = 2 \times 10^{-7} \]

\[ P_{\text{wpt}}^{\text{classical}} = 2 \times 10^{-6} \]

\[ P_{\text{wpt}}^{\text{optimized}} = 2 \times 10^{-11} \]

\[ P_{\text{wpt}}^{\text{optimized}} = 2 \times 10^{-14} \]

\[ P_{\text{wpt}}^{\text{optimized}} = 2 \times 10^{-17} \]
CME: A novel measurement method

**Optimization (3/3)**

<table>
<thead>
<tr>
<th>Proposed experimental method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expression of</strong> $\beta$</td>
</tr>
<tr>
<td><strong>Required conditions</strong></td>
</tr>
<tr>
<td><strong>Loss of validity</strong></td>
</tr>
</tbody>
</table>

From Noise limitation, $\beta_{\text{min}} = 10^{-8}$ rd \(\sqrt{f}\)

---

**Improvements**

- 1/f Noise limitation
  - 1/ Laser with low RIN
  - 2/ Modulation of the signal should be with $f >$ few kHz

- 1st step: rotating $\lambda/2$ wave plate $\Rightarrow$ modulation expected up to $\sim 20$ kHz

- 2nd step: electro-optic modulator $\Rightarrow$ modulation expected up to the MHz range

---

**CME Measurements for air**

Experimental

1st trial with a really “crazy” rotating system (motor + belt) … $\lambda = 1550$ nm
CME Measurements for air

Results

From the slope,

$$\beta = \frac{2\pi(n_1 - n_2)}{\lambda} = -2\pi M B^2$$

and \( l = 2 \times 14.3 \) m

$$M_{\text{air}} = 1.12 \pm 0.02 \times 10^{-6} \text{ rad T}^{-2} \text{ m}^{-1}$$

To be compared to the value from the literature:

$$M_{\text{air}} = 1.13 \times 10^{-6} \text{ rad T}^{-2} \text{ m}^{-1}$$

Toward the Field Characterisation of Accelerator Magnets

For B angle, measurement of the phase of the \( P_{\text{qil}} \)

To obtain \( \beta \) and \( l \), 3 optical measurements are necessary with precise measurements of the mirror position along the magnet axis

Conclusions

- The R&D has just started, and
  - The use of CME combine with mirror position measurements seems very promising to determine
    - B dl
    - B Angle
    - Quadrupole axis, TF…
  - With respect to the stretched wire technique, we can say that we use a "wire of light"

- This new measurement method
  - Requires small developments before to be put in practice,
  - Is particularly suitable for pulsed magnets or/and with small apertures,
  - Will be surely competitive (not only for high field), complementary & can provide fully independent results to track systematic errors coming from other systems.

More information

Introduction

- String - 2

Two - volume model - Description

Schematic two – volume model

Assumptions of two – volume model

- the volumes $V_a$ and $V_b$ are separated by a fully adiabatic virtual piston;
- conduction heat transfer, through the helium and/or via the magnet structure, during the very fast compression phase is negligible

Input parameters:
- $x$ – fraction of confined helium volume relative to total helium volume
- $\Delta T$ – the temperature rise in the confined helium during process
Two-volume model – Applicability

Modified $x_s$ – fraction used for calculations of peak pressure in String 2:

$$x_s = \frac{x \cdot N}{N + M}$$

where:
- $x_s$ – denotes the fraction of confined helium for the string of magnets,
- $N$ – number of magnets quenched,
- $M$ – number of magnets in superconducting state.

Application of two-volume model to the string of magnets, $N = 3$,

$$x = 2\% \Delta T = 20 K$$

Peak pressure as a function of a number of simultaneously quenched magnets in String 2.

### Advantage
The small number of input parameters $x$, $\Delta T$

### Disadvantage
- Single magnet quench measurement is necessary to fix these modelisation parameters for each type of magnet.
- The model is predictive and can be applied to analyze different cases of accelerator magnet resistive transition thermohydraulics.
- The lack of a criterion allowing to judge on the moment of the transition from the isentropic to the isochoric process.

Two-volume model – +s and -s

### Detailed two-volume model

Heat transfer through the magnet structure;

Heat transfer via adiabatic piston $\Rightarrow$ Quasi – adiabatic piston $\approx 12$ W/m

To calculate the $Q_{BFin}$ we need the magnet structure.

Detailed two-volume model – He - geometry simplification

LHC mail dipole cross section with the selected control – volume of helium.

Geometrical specification of slice:
- Inner radius: 40 mm
- Outer radius: 100 mm
- Thickness: 100 mm
- Amount of helium per meter: 2.15 kg/m
Calculations of „piston” displacement and temperature of confined helium

Pressure evolution after simultaneous resistive transition of 6 magnets composing STRING 2 (measured)

Temperature evolution in confined helium (calculated) and virtual piston displacement (calculated)

Modeling of non stationary temperature field in the collar

The equation describing the unsteady heat transfer in solid elements – general case

\[ \rho c_p(T) \frac{dT}{dt} = \text{div}(\lambda(T) \nabla(T)) \]

The specific heat and thermal conductivity of steel

Specific heat (J/K kg)

50 100 150 200 250 300

0

100

200

300

400

500

The geometry simplification of solid

Detailed two - volume model - Geometry simplification of solid

Axisymmetric

Modeling of non stationary temperature field in the collar

Scheme of the collar fin and boundary conditions in axisymmetric geometry

Input data:
1. Geometry of fin
2. Material properties of steel (density, specific heat and thermal conductivity)
3. Evolution of the coil temperature
4. Boundary conditions from two-volume model
5. Heat transfer coefficients
Modeling of non stationary temperature field in the collar - Evolution of the coil temperature

The evolution of average coil temperature can be calculated from the formula and be based on the assumption of adiabatic dissipation of the magnetic energy in the coil immediately after a resistive transition.

\[
dT = \frac{\delta_{\text{el}} - \delta_{\text{rot}}}{C_p(T, B)} \cdot \frac{I^2(T, B)}{A} \cdot f(T) + \frac{\delta_{\text{rot}}}{C_p(T, B)} \cdot \frac{I^2(T, B)}{A} \cdot f(T - \tau)
\]

dt

Average coil temperature evolution

Non stationary temperature field in the fin

Evolution of the temperature in the fin

Animation of evolution of temperature in the fin

Energy transfer from the magnet structure to the helium

A close analysis of the phase diagram indicates the deviation from isentropic process before the peak pressure is reached. Although the temperature change seems to be negligible, a corresponding heat flux is significant due to the increase in the helium heat capacity when approaching the lambda line – compare figure.

Phase diagram of the bulk helium evolution after simultaneous resistive transition of 6 magnets composing STRING 2 (average values of temperature and pressure)
Energy transfer from the magnet structure to the helium

The evolution of helium temperature (CFX)

Conclusions

1. An original two-volume model provided, in spite of its simplicity and limited physics description, results in good agreement with experiment and can be used as input for modelling of events of strings composed of identical magnets. The main shortcoming of the model is the lack of a criterion allowing to judge on the moment of the transition from the isentropic to the isochoric process.

2. We propose the equalization of the energy transfer modes (work versus heat transfer) a criterion allowing to judge on the moment of the transition from the isentropic to the isochoric process. We have shown that the heat transferred to helium can be calculated with a simplified geometry finite element model.

Future prospect

1. Improving the numerical calculations in CFX code for real substance
2. Taking into consideration interaction between the helium (fluid) and the magnet structure
3. Comparing numerical results with the data got from the test of individual magnet, String 1 and String 2.
High heat flux extraction paths from magnet structure

A brief, generic, qualitative view of heat transfer paths, from coil until cold source, followed by quantitative values as deduced from LHC dipole quenches will be given. The need for quantitative knowledge of heat exchange coefficients in specific configurations will be addressed. A description of a dedicated test cryostats constructed and presently under construction at WUT will be given.

CLASSIFICATION OF HEAT EXTRACTION PATHS (1/4)

CLASSIFICATION OF HEAT EXTRACTION PATHS (2/4)

CLASSIFICATION OF HEAT EXTRACTION PATHS (3/4)

From Cable to Helium directly will be treated by B. Badouy (CEA Saclay)

High heat flux case, Cable to Helium directly and indirectly will be exemplified by LHC dipole quench analysis
High heat flux case, Cable to Helium directly and indirectly will be exemplified by LHC dipole quench analysis.

![Graph showing heat flux to helium over time.](image)

**Figure 11.** Heat flux to the cold mass helium after a 13.1 kA quench during the discharge phase of the prototype string (measured).

**Quench summary**

- For \( t < 0.6 \)s compression work if power exceeds He conduction limits (independent of HeII/pressurized or pool boiling, or supercritical)
- For \( t > 0.6 \) s conduction heat transfer through structure (cable, insulation, collars, yoke -> helium)
- (collar plus yoke)“fin” surfaces to be optimized for He contact on one side, coil on the other.
- Fin spacing adequate (convection minimum)
- Test cryostat under construction

**Summary of work in progress**

- Measurement facility from Cable to Helium directly at CEA Saclay (cryostat provided by WUT)
- Measurement facility for heat transfer coefficients in general at WUT (Cern WUT collaboration)
- Thermal modeling of cross section (as evolution of quench work) Ansys plus CFX at WUT (Cern WUT collaboration)
Introduction

The protection of pulsed superconducting magnets may have to satisfy different requirements compared to the protection of slowly ramped superconducting magnets (quasi dc-magnets).

Especially the following components of a protection system are concerned:
- protection heaters (are they required or not)
- high current by-pass (is it required or not)
- quench detection system
- powering and energy extraction

The choice and dimensioning of these components depend on the ramp rate as shown in the following for the SIS Magnets for FAIR and for the LHC magnets for comparison.

The high inductive voltage contributions during pulsing will be a challenge especially for the quench detection.

SIS - and LHC Main Magnet Characteristics, Ramp- and Discharge Characteristics

<table>
<thead>
<tr>
<th>Magnet Type</th>
<th>I [A]</th>
<th>dI/dt [A/s]</th>
<th>L [mH]</th>
<th>V [V]</th>
<th>( \tau ) [s]</th>
<th>No. of dump coils</th>
<th>T_{res} [K]</th>
<th>V_{max} to ground [V]</th>
<th>Heaters</th>
<th>Current By-p</th>
<th>By-p _</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS 100 Dipole</td>
<td>6660</td>
<td>14063</td>
<td>2</td>
<td>28.1</td>
<td>0.25</td>
<td>6</td>
<td>&lt;350</td>
<td>&lt;500</td>
<td>NO</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>2T, 4T/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIS 100 Quads</td>
<td>5600</td>
<td>11804</td>
<td>1.02</td>
<td>12</td>
<td>0.25</td>
<td>1</td>
<td>&lt;300</td>
<td>&lt;500</td>
<td>NO</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>SIS 300 Dipole</td>
<td>6300</td>
<td>1050</td>
<td>36</td>
<td>37.8</td>
<td>4.8</td>
<td>6</td>
<td>&lt;300</td>
<td>&lt;500</td>
<td>YES</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>6T, 17T/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>SIS 300 Quads</td>
<td>7830</td>
<td>1305</td>
<td>4.4</td>
<td>5.7</td>
<td>4.8</td>
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<td>&lt;300</td>
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<td>LHC Dipole</td>
<td>1185</td>
<td>10</td>
<td>99</td>
<td>1</td>
<td>99</td>
<td>2 per octant</td>
<td>&lt;300</td>
<td>&lt;500</td>
<td>YES</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>LHC Quadr.</td>
<td>1187</td>
<td>10</td>
<td>5.6/ apert</td>
<td>0.06/ apert</td>
<td>45</td>
<td>1 per circuit</td>
<td>&lt;300</td>
<td>&lt;500</td>
<td>YES</td>
<td>YES</td>
<td></td>
</tr>
</tbody>
</table>
**Quench heaters**

Quench heaters for the protection of superconducting accelerator magnets must be envisaged if the quench load exceeds the quench capacity of the cable for a given maximum allowable temperature $T_{\text{max}}$ in the coil:

$$\int_0^{T_{\text{max}}} \left( I^2 dt + I_o^2 \cdot \Delta t_{\text{delay}} \leq A_{\text{Cu}} \cdot A_{\text{Sc}} \cdot \int_0^{T_{\text{max}}} \left( \frac{C_{\text{pav}}}{\rho_{\text{Cu}}} \right) \cdot dT \right)$$

In case the current decay is dominated by the external dump resistor ($R_{\text{magnet}} \ll R_{\text{dump}}$) like for the SIS 100 magnets then the equation above becomes:

$$\frac{I_o^2}{\tau/2} + I_o^2 \cdot \Delta t_{\text{delay}} \leq A_{\text{Cu}} \cdot A_{\text{Sc}} \cdot \int_0^{T_{\text{max}}} \left( \frac{C_{\text{pav}}}{\rho_{\text{Cu}}} \right) \cdot dT$$

For the SIS 100 superconducting magnets heaters are not required

---

**By-pass with cold diodes**

Essential items:
- self protected magnet with heaters
- stored energy of one quenching magnet only will be dissipated
- safe de-excitation of the still superconducting magnets

**Diode Stack for SIS-300 Dipoles**

For DC application one diode would be enough

Use of LHC diodes
- $V_{\text{turn-on}} = 5.5\, \text{V}$
- $V_{\text{dipole max}} = 37.8\, \text{V}$
- so use of 8 diodes
- $V_{\text{stack turn-on}} = 44\, \text{V}$

For DC application one diode would be enough
Electrical characteristics of various diodes measured at cryogenic and ambient temperatures

<table>
<thead>
<tr>
<th>Electrical parameter</th>
<th>Typical</th>
<th>Epitaxial</th>
<th>EU-PEC</th>
<th>EU-PEC</th>
<th>DYNEX</th>
<th>WE ST CODE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Initial)</td>
<td>diffused,</td>
<td>diffused,</td>
<td>diffused,</td>
<td>diffused,</td>
<td>diffused,</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>GaAs,</td>
<td>GaAs,</td>
<td>GaAs,</td>
<td>GaAs,</td>
<td>GaAs,</td>
</tr>
<tr>
<td></td>
<td>$T_a$ [K]</td>
<td>spec. develop.</td>
<td>spec. develop.</td>
<td>spec. develop.</td>
<td>spec. develop.</td>
<td>spec. develop.</td>
</tr>
<tr>
<td>Turn-On Voltage</td>
<td>4.2</td>
<td>1.2 - 1.3</td>
<td>125 - 165</td>
<td>64 - 88</td>
<td>70 - 80</td>
<td>5.7 - 9.7</td>
</tr>
<tr>
<td>$V_{to}$ [V]</td>
<td>1.8</td>
<td>1.3 - 1.7</td>
<td>155 - 172</td>
<td>69 - 94</td>
<td>86 - 84</td>
<td>6.0 - 11.9</td>
</tr>
<tr>
<td>Forward Voltage</td>
<td>500</td>
<td>1.2</td>
<td>1.4</td>
<td>108</td>
<td>12</td>
<td>0.96</td>
</tr>
<tr>
<td>$V_f$ [V]</td>
<td>4.2</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>at $I_f = 15kA$</td>
<td>1.0</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Maximum Reverse Voltage</td>
<td>500</td>
<td>-100</td>
<td>&gt; 720</td>
<td>&gt; 428</td>
<td>&gt; 1100</td>
<td>&gt; 550</td>
</tr>
<tr>
<td>$V_{r}$ [V]</td>
<td>4.2</td>
<td>-150</td>
<td>&gt; 500</td>
<td>&gt; 315</td>
<td>&gt; 1100</td>
<td>&gt; 480</td>
</tr>
<tr>
<td>$V_{max}$ [V]</td>
<td>1.0</td>
<td>-100</td>
<td>&gt; 170</td>
<td>&gt; 151</td>
<td>&gt; 640</td>
<td>&gt; 475</td>
</tr>
<tr>
<td>Dynamic Resistance</td>
<td>500</td>
<td>-15</td>
<td>-35</td>
<td>-16</td>
<td>-21</td>
<td>12</td>
</tr>
<tr>
<td>All $\mu m$ [μm]</td>
<td>4.2</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

$*$ not measurable ** not measured

Reverse Blocking Voltage $V_r$, Turn-On Voltage $V_{to}$, and Radiation Tolerance versus n-base width of LHC-Diodes

Simplified circuit for a protection unit of four heater protected dipoles in series with a thyristor at ambient temperature and safety leads as warm by-pass

- On all four magnets the heaters must be fired
- Uniform quenching of all magnets assumed

Simplified circuit for a protection unit of four heater protected dipoles with 4 thyristors at ambient temperature, safety leads and voltage compensation leads as warm by-pass

Voltage compensation leads will prevent magnets from high voltage peaks due to non-uniform quenching of the magnets
Principle electrical scheme for a purely passive by-pass (crow bar) using a thyristor and a unijunction transistor.

The turn-on voltage can be adjusted by the potentiometer \( P \) to any value between a few Volts up to about 100 Volts.

Advantages and Disadvantages of a Warm By-Pass

1. Advantages of the warm by-pass:
   1.1 No radiation sensitive elements in the cryostat, by-pass thyristors can be located in low radiation areas and can easily be replaced in case of problems.
   1.2 When using a passive element for the by-pass like a crow bar, the turn on voltage can easily be adjusted if necessary

2. Disadvantages of the warm by-pass:
   2.1 Quench Stoppers and safety leads are required for each protection unit of 4 magnets. Both are technically difficult, space consuming, and will impose an additional heat load on the cryogenic system (up to about 1 W/lead).
   2.2 In case of a quench in one magnet all other three magnets of the protection unit must be driven normal by heaters dumping the energy of about 2.7 MJ into the helium compared to about 1 MJ of a cold by-pass with 8 diodes when one magnet quenches only.
   2.3 Monitoring equipment for temperature and voltages on safety leads are required.
   2.4 Helium gas recuperation equipment with remote controlled regulation valve for fast cool-down after quench is required.
   2.5 Maintenance of the safety leads and He-gas recuperation system.
   2.6 Non-uniform cold masses and cryostats for magnets.

Conclusions on the by-pass

The **warm by-pass** with thyristors is a more complex system, but it consists of classical components with well-known behaviour and can be installed in low radiation areas. The complexity can affect the reliability during operation and maintenance is required.

The **cold diode by-pass** is less complex and may operate more reliable as long as the radiation load is not too high. Normally no maintenance is required.

A replacement of damaged cold diodes on the other hand is very time consuming and expensive.

Magnet quench detection

Pulsed magnet \( \Rightarrow \) inductive voltages \( \Rightarrow \) Use of one Bridge per magnet

The bridge principle is:

\[
V_1 = \frac{(V_A - V_B) + (V_B - V_C)}{2}
\]

if \( R_1 = R_2 \) for high accuracy resistors : \( \Delta R/R \approx \pm 0.05\% \)

Bridge error:

\[
\Delta (2V_1) = \Delta R/R * (V_A - V_C)
\]

Quench detection threshold \( V_{th} \) chosen at 0.2 V so that \( T_{max} \) magnet < 350 K

- SIS magnets will use : LHC bridges with \( V_{th} = 0.2 \) V (instead of 0.1 V for LHC magnets)

<table>
<thead>
<tr>
<th>SIS100 dipole</th>
<th>SIS100 Quadrupole</th>
<th>SIS300 dipole</th>
<th>SIS300 Quadrupole</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.1</td>
<td>12.0</td>
<td>37.8</td>
<td>5.7</td>
</tr>
<tr>
<td>14</td>
<td>6</td>
<td>19</td>
<td>3</td>
</tr>
</tbody>
</table>

\( R_1 \) and \( R_2 \) must be dimensioned to withstand the maximum magnet voltage and to limit the current in the detection leads (200V, \( R_1 = R_2 = 20 \) k\( \Omega \) for LHC) in case of a short.
Bus bar configurations

Quench simulations in bus bars give the influence of $V_{th}$ on $T_{max}$

<table>
<thead>
<tr>
<th>Bus bar</th>
<th>$V_{th}$ (V)</th>
<th>$T_{max}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS100</td>
<td>0.2</td>
<td>&lt; 350</td>
</tr>
<tr>
<td>SIS300</td>
<td>0.5</td>
<td>&lt; 250</td>
</tr>
</tbody>
</table>

Choice made after simulations

SIS100 bus bar inductance

$$L = \frac{\mu_0}{\pi} \cdot \ell \cdot \ln\left(\frac{2 \cdot W}{D_1} - 1\right)$$

For $\ell = 1083$ m, $D_1 = 6$ mm and $W = 16$ mm

$L = 0.64$ mH or $0.3 \mu$H per meter of single bus bar

SIS100 bus bar inductance

Quench detection in bus bars

Case of a simple bus bar routing
Quench detection on one SIS magnet string

**Quench detection equipment:**
- LHC-Type bridges for magnets and bus bars
- LHC-Type quench detection units for current leads
- May be a voltage comparator (has to be developed) for the 2 bus bars in a long cryogenic link (40 to 60 m)

Current dumping SIS100 dipole ring

Current dump with $\tau = 0.25 \text{ s}$ (equivalent to $-8\text{ T/s}$)
- $R_{\text{dump,total}} = 0.862 \Omega$
- Distributed along 6 resistors so that:
  - $R_{\text{dump}} \times 6300 \text{ A} < 1 \text{ kV}$
  - $V_{\text{coil to ground}} < 500 \text{ V}$
  - $T_{\text{max dipole}} < 350 \text{ K}$

Current dumping SIS300 dipole ring

Current dump with $\tau = 4.8 \text{ s}$ (equivalent to $-1\text{ T/s}$)
- $R_{\text{dump,total}} = 0.810 \Omega$
- Distributed along 6 resistors so that:
  - $R_{\text{dump}} \times 6300 \text{ A} < 1 \text{ kV}$
  - $V_{\text{coil to ground}} < 500 \text{ V}$

Conclusions for SIS-magnets

All the detection electronics for the SIS100 and 300 rings will be located in radiation protected areas with cabling distances up to 220 m.

- Above 3 kA there is the need to:
  - use a cold by-pass for each magnet
  - or a warm by-pass across 4 magnets
  - use quench heaters

Differences between DC and pulsed magnet strings

<table>
<thead>
<tr>
<th></th>
<th>DC magnet strings</th>
<th>Pulsed magnet strings</th>
</tr>
</thead>
<tbody>
<tr>
<td>If cold diodes</td>
<td>1 diode</td>
<td>stack of several diodes</td>
</tr>
<tr>
<td>Quench detection on magnets</td>
<td>Bridge</td>
<td>Bridge</td>
</tr>
<tr>
<td>Bus bars</td>
<td>General detection scheme like the LHC one with digital detectors</td>
<td>Use of several bridges</td>
</tr>
</tbody>
</table>

What must be investigated: attenuation and extra noise due to long cabling distances.

In order to avoid unwanted electromagnetic coupling effects between bus bars and detection leads it is essential that the routing of detection wires will be carried out in such a way that the electromagnetic coupling is reduced to a minimum (twisted wires).
GENERAL CONCLUSIONS

- Pulsed superconducting magnets allow high energy extraction rates without initiating a quench in the still superconducting magnets. Protection heaters and a current by-pass may not be required.
- The higher inductive voltage contributions across magnets and bus bars and electro-magnetic coupling effects during pulsing are a challenge for the quench detection systems. Multiple bridge-type detectors may be required or even specially developed comparators.
- High voltages to ground during energy extraction can be avoided by subdivision. More dump resistors, current breakers, and current leads would be needed.

SIS100 magnets

**SIS100 magnets**

<table>
<thead>
<tr>
<th></th>
<th>Dipole (2 T, 4T/s)</th>
<th>Quadrupole (8 turns per pole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable</td>
<td>31 strands around CuNi tube</td>
<td></td>
</tr>
<tr>
<td>Strand diameter</td>
<td>0.5 mm</td>
<td></td>
</tr>
<tr>
<td>( \beta_{\text{max}} = A_C/A_{\text{NbTi}} )</td>
<td>1.38</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SIS100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I ) (A)</td>
<td>6680</td>
</tr>
<tr>
<td>( \frac{dl}{dt} ) (A/s)</td>
<td>14063</td>
</tr>
<tr>
<td>( L_{1\text{magnet}} ) (mH)</td>
<td>2</td>
</tr>
<tr>
<td>( V_{1\text{magnet_max}} ) (V)</td>
<td>28.1</td>
</tr>
</tbody>
</table>

SIS300 magnets

**SIS300 magnets**

<table>
<thead>
<tr>
<th></th>
<th>Dipole 6 T, 1 T/s</th>
<th>Quadrupole</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS300 cable</td>
<td>36 strands + 316LN core</td>
<td></td>
</tr>
<tr>
<td>Strand diameter</td>
<td>0.825 mm</td>
<td></td>
</tr>
<tr>
<td>Matrix</td>
<td>CuMn0.33Fe</td>
<td></td>
</tr>
<tr>
<td>Shell</td>
<td>Cu</td>
<td></td>
</tr>
<tr>
<td>( \beta = (A_C + A_{\text{Mn}}) / A_{\text{NbTi}} )</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Filament diameter</td>
<td>2.5 ( \mu ) m</td>
<td></td>
</tr>
<tr>
<td>Sainless Steel core</td>
<td>0.025*13 mm2 in 316LN</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SIS300</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I ) (A)</td>
<td>6300</td>
</tr>
<tr>
<td>( \frac{dl}{dt} ) (A/s)</td>
<td>1050</td>
</tr>
<tr>
<td>( L_{1\text{magnet}} ) (mH)</td>
<td>36</td>
</tr>
<tr>
<td>( V_{1\text{magnet_max}} ) (V)</td>
<td>37.8</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>7830</td>
</tr>
<tr>
<td>( \frac{dl}{dt} ) (A/s)</td>
<td>1305</td>
</tr>
<tr>
<td>( L_{1\text{magnet}} ) (mH)</td>
<td>4.39</td>
</tr>
<tr>
<td>( V_{1\text{magnet_max}} ) (V)</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Measurements of the Field Quality in Magnets at High Ramp Rates Using Stationary Coils

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*Brookhaven National Laboratory*

Upton, New York 11973-5000, USA

HHH-AMT Workshop On Superconducting Pulsed Magnets For Accelerators ECOMAG-05, Frascati, Italy, October 26-28, 2005
Introduction

• In many instances, it is necessary to measure the field quality (harmonics) under dynamic conditions, e.g. to study:
  – Time decay and snap back of harmonics ("Fast" measurements; negligible field variation)
  – Eddy current effects during ramping or under AC operation. (Rapid field variations)

• This paper describes a technique developed at BNL for the measurement of field harmonics at very high ramp rates (> 1 T/s).

• Results of measurements in a superconducting dipole at ramp rates of up to 4 T/s are presented.

BNL Projects Needing High Ramp Rates

• Dipoles for the FAIR project at GSI:
  – 4 Tesla superconducting dipoles ramped at 1 T/s.
  – More than an order of magnitude faster than typical storage ring applications.
  – A prototype has been built and tested up to 4 T/s.

• Dipoles for a Biomedical Project:
  – Dipole field up to 0.4 T in a 4 T solenoid
  – Field to track motion of an unsedated rat’s head (frequencies up to several Hz)
  – Effective ramp rate in excess of 10 T/s
  – A prototype will be tested soon for field quality.

“Fast” Measurements with Rotating Coils

• Rotating coils are the only well established means of measuring field harmonics in accelerator magnets. (Typical rotation period ~ several seconds)

• One could rotate a harmonic coil as fast as practical to improve time resolution. ⇒ ~ 1 s resolution. (OK for time decay and snapback studies)

• Specific harmonics (e.g. sextupole) have been measured at faster rates with dedicated harmonic coils rotated at several Hz.

• Rotating coils are ideally suited only for DC fields, even with improved time resolution.

Other Techniques for “Fast” Measurements

• One could use non-rotating probes to overcome the time resolution problem.

• Without a rotating probe, one needs a multiple probe system to get harmonic information.

• A system of 3 Hall probes, for example, can measure the sextupole component. Similarly, NMR arrays have been built with many probes.

• Intercalibration of individual probes and non-linear behavior are some of the problems that must be addressed in using these techniques.
Measurements of “Fast Changing” Fields

- The analysis of rotating coil data can be improved to account for some variation of the field during one rotation.
  - Used successfully for studying eddy current effects in superconducting magnets at ramp rates of < 0.1 T/s.
  - Difficult to analyze the data at faster ramp rates.

- A non-rotating, multi-probe system provides an instantaneous measurement of the field harmonics.

- In principle, a multi-probe system could be used for measuring field harmonics in magnets at very high ramp rates.

BNL System of Non-rotating coils

- Uses a set of 16 tangential pickup coils covering the full azimuthal range.

- Voltage signal is induced in each of the coils under ramping conditions, with the probe held stationary.

- Analysis of the angular distribution of the voltages at any instant provides instantaneous harmonics.

- Time resolution is limited only by the abilities of the data acquisition system (100 μs in the present system based on 16-bit ADCs).

- Use of pickup coils allows easy, stable, calibration.

- No non-linearities or dynamic range problems with pickup coils.

- The probe can also be rotated to measure DC fields.

BNL Harmonic Coil Array

- 16 Printed Circuit coils, 10 layers
- 6 turns/layer
- 300 mm long
- 0.1 mm lines with 0.1 mm gaps

Matching coils selected from a production batch

Radius = 26.8 mm (GSI) 35.7 mm (Bi M d)

Signal Handling

- The system should be versatile, with capabilities for measurements over a wide range of $dB/dt$ (several orders of magnitude).

- Signal fed to programmable gain amplifiers (1 to ~100X). The output goes to 16-bit ADCs.

- Voltage offsets and gain variations are potential problems that need to be addressed during measurements and data analysis.

- Entire amplifier/ADC system is mounted inside a temperature controlled enclosure.
Prototype Dipole Collared Coil for GSI

Many unique design features for high ramp rate compatibility.

Measurement Details
• Cycle from 0.1 kA to 7 kA (3.2 T), and back, to set history (carried out 3 times).
• 0.6 s dwell at 0.1 kA.
• Quadratic acceleration to intended ramp rate (3.3 to 8.8 kA/s, or 1.5 to 4 T/s)
• Constant ramp rate region, followed by a quadratic deceleration to flat top at 7 kA.
• 0.1 s dwell at 7 kA, followed by a symmetric ramp down to 0.1 kA.
• Entire sequence repeated 4 times in a row.

Basic Formalism

\[ V_i(t) = \sum_{n=1}^{\infty} \frac{2N_iL_iR_{ref}}{n} \left( \frac{R_i}{R_{ref}} \right)^n \sin \left( \frac{n\Delta_i}{2} \right) \cos(n\theta_i) \]

Obtained by fitting Use rotating mode just prior to ramp

Voltage Offsets \(\Rightarrow\) Drift in harmonics!

Drift in Harmonics: Offset Correction

\[ B_n(t) = B_n(0) + \int B_n(t) dt \]
\[ A_n(t) = A_n(0) + \int A_n(t) dt \]

Slope of line gives offset in \(B_n\) or \(A_n\)
**Reproducibility: 4 Cycles of One Run**

- Sextupole Terms (units at 25 mm):
  - Normal; Up
  - Normal; Dn
  - Skew; Up
  - Skew; Dn

- Decapole Terms (units at 25 mm):
  - Normal; Up
  - Normal; Dn
  - Skew; Up
  - Skew; Dn

**Sextupole: Ramp Rate Dependence**

- DC
- 1.5 T/s
- 2 T/s
- 3 T/s
- 4 T/s

**Sextupole Hysteresis Vs. Ramp Rate**

- Sextupole Hysteresis (T): DC, 1.5 T/s, 2 T/s, 3 T/s, 4 T/s
Sextupole Hysteresis Vs. Ramp Rate

\[ y = 1.2x + 3.3 \]

Decapole Hysteresis Vs. Ramp Rate

\[ y = 0.25x + 0.39 \]

14-pole Hysteresis Vs. Ramp Rate

\[ y = 0.04x + 0.22 \]

Skew Dipole Hysteresis Vs. Ramp Rate

\[ y = 9.75x^2 + 10.75x + 20.29 \]

\[ y = 7.18x - 10.49 \]
**Stationary Coils: Problems & Solutions**

- **Sensitivity at lower ramp rates (< 1 T/s):**
  - Use more turns; easy to do!
  - Use the probe in rotating mode; needs analysis.

- **Spurious harmonics due to calibration errors:**
  - Calibration error = angular dependence = harmonics.
  - Only *relative* calibration must be very precise.
  - Much better done with rotating mode in DC field.
  - Complicates construction of the probe.
  - Requires reference multipole fields (dipole, quad,..)
  - Effect needs further study (analytic or simulations)
  - Potentially the most severe limiting factor!

- **Aliasing due to limited number of coils:**
  - Need many more coils; possible with radial coils.
  - Increases complexity and cost of the system.
  - Combine data from multiple ramps with the probe rotated slightly between ramps; cheaper solution, should work when ramps can be reproduced very well.

- **Unbucked Signal:**
  - Bucking is *not essential*, unlike rotating coils.
  - However, must resolve harmonics in the presence of the main field signal.
  - Use coil systems insensitive to the main field.

**Summary**

- A system for measurement of harmonics at very high ramp rates has been developed.
- The system provides measurement of all harmonics simultaneously, up to 14-pole.
- Problem of offset correction is circumvented by using data from several cycles in the same run.
- Good reproducibility at the level of ~ 1 unit is demonstrated for main field of ~ 1 Tesla.
- There is scope for many improvements for better accuracy; some will be tried soon.

**Wire R&D for pulsed superconducting magnets**

- **Introduction**
- A view of past experience and existing accelerators or projects
- Source of losses and losses in SIS 300 as a base
- Magnetization and proximity effects
- Double stack and deformation
- Losses due to inter-filament coupling currents for a base-design strand for 1T/s ramp strand
- Comments for strand R&D and strand coating
- Conclusions
Wire R&D for pulsed superconducting magnets

INTRODUCTION

A lot of studies have been performed for the understanding of the superconducting wire and cables in pulsed mode:

- **GESS collaboration** (IEKP, RAHL, CEA) in 1972 for 5 T/s dipoles: Fabricated models in the range 4.5-5 T with rise time of 3-5 - 15 s for a machine cycle of 10 s. Filament size of 5 to 12 μm. Use of Cu-Ni at RAHL and development of very sophisticated strands. Goal of 5-10 W/m for dynamic losses in magnets.

- **AC applications** for generators and motors; Large number of filaments (900,000 × 0.12 μm in 0.2 mm wire with Cu-Ni) in low fields.

- **Fusion Programs**: LCT coils, TORE supra, NET’s projects, ITER.

- **GSI project (SIS 300)**: 6 T at 1 T/s in a magnet bore of 100 mm.

### Review of accelerator machines

<table>
<thead>
<tr>
<th>Machine</th>
<th>Field (T)</th>
<th>Rise time (T/s)</th>
<th>Dynamic range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>4.4</td>
<td>0.2</td>
<td>6</td>
</tr>
<tr>
<td>HERA</td>
<td>4.7</td>
<td>0.004</td>
<td>20</td>
</tr>
<tr>
<td>RHIC</td>
<td>3.5</td>
<td>0.042</td>
<td>11</td>
</tr>
<tr>
<td>LHC</td>
<td>8.3</td>
<td>0.007</td>
<td>17</td>
</tr>
<tr>
<td>SIS 200</td>
<td>4</td>
<td>4</td>
<td>Model built</td>
</tr>
<tr>
<td>SIS 300</td>
<td>6</td>
<td>1</td>
<td>Injection at 1.6 T</td>
</tr>
<tr>
<td>XXX</td>
<td>3.4</td>
<td>3.3-4</td>
<td>20-25</td>
</tr>
</tbody>
</table>

Remarks

- The limits with the present SC technology in wires for an increase in the ramp rate? Where are the main problems? Are they feasible? Cost?

- A typical cycle: (W. Scandale)

  - Ramp up: 0.9-1 s Plateau: 0.9 s Ramp down: 0.9-1 s Dead time: 0.9 s

  B max=3.4 T

- The cooling scheme at 4.2-5 K and He in cable are essential. At ramp-up, the losses lead to an increase in temperature (ΔT=0.8 K) of the cable fixing the temperature of the critical current characteristics. It is of good experience to have lop/ic≈0.6.

  During the plateau, the coils are cooled down to accept the losses due the ramp down. At the end of the dead time, the temperature of the cable must be at the same temperature as initially. (Same magnetization currents...).

- A low injection field (or high B dynamic range) leads to magnetization problems since there exists proximity effects between the Nb-Ti filaments.
Wire R&D for pulsed superconducting magnets
Source of losses

- In wires: Hysteresis losses in the filaments: diameter of the filaments, deformation of the filaments, proximity coupling
  - Inter-filament coupling losses through matrix: matrix resistivity, inter-filament spacing.
- In cables:
  - In B perpendicular: Rc, Ra, cable width
  - In B parallel: Ra
- Related problems: stability, protection, fatigue
- Remarks: 1. There exists magnet design aspects which reduce the effect of Rc and combination of various filament size to reduce the sextupole.
  2. The dominant loss origin is hysteresis (55% in SIS 300) (J. Kaugerts)

---

Losses distribution (extrapolation from J. Kaugerts-GSI)

<table>
<thead>
<tr>
<th>Loss Type</th>
<th>Loss/cycle (J)</th>
<th>Ramp Power (W)</th>
<th>Ramp Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu matrix</td>
<td>3.5 μm fil</td>
<td>3.2 (11%)</td>
<td>0.36</td>
</tr>
<tr>
<td>Cu-Ni/Cu</td>
<td>2.5 μm fil</td>
<td>3.2 (6.4)</td>
<td>1.6 (1.3)</td>
</tr>
<tr>
<td>Cu-Ni/Cu</td>
<td>1μm fil</td>
<td>10.7 (38%)</td>
<td>1.21</td>
</tr>
<tr>
<td>SIS 300</td>
<td>t= 4 s</td>
<td>10.7 (0.11)</td>
<td>5.4 (0.65)</td>
</tr>
<tr>
<td>B perp.</td>
<td>(Rc=20μΩ)</td>
<td>0.1 (0.11)</td>
<td>0.01</td>
</tr>
<tr>
<td>B paral.</td>
<td>(Ra=200μΩ)</td>
<td>0.1 (0.11)</td>
<td>0.05</td>
</tr>
<tr>
<td>ISCC</td>
<td>20.8 (26%)</td>
<td>0.1 (17%)</td>
<td>1.11</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>46.1 (56%)</td>
<td>0.1 (17%)</td>
<td>1.5</td>
</tr>
<tr>
<td>Total /m</td>
<td>80.8</td>
<td>0.1 (17%)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

---

Filament Hysteresis Losses: influence of the matrix showing proximity effects by Cu etching on LHC wire. Complex region in 0-0.3T

- They are dominant: W = f(M dBa) [W = J/cycle, m³]
- \( \Delta M = (4/3)a \lambda J_d(B_d) d_f \) when \( B_d > B_s = (1/a) \mu J_d d_f \) and the magnetic fluxes reach the center of the filament.
  - (for \( d_f = 2.5 \mu m, B_s = 50 \mu T \text{ if } J_d = 5 \times 10^{10} \text{ Am}^{-2} \) )
  - (for \( d_f = 1 \mu m, B_s = 18 \mu T \text{ if } J_d = 4.5 \times 10^{10} \text{ Am}^{-2} \) )
  - Binj should be larger than Bs
- \( W_t = (4/3) \lambda J_d J_b \ln [(B_s+B_c)(B_s+B_c)] \)
  for a cycle between \( B_s \text{ and } B_c \), with the Kim-Anderson relation \( J_d(B) = J_d(B_s)/(B_s+B_c) \)
  (N.B. M. Wilson has added 2 constants \( A_1 \text{ and } A_2 \) in the Kim’s law)
  With a transport current, M has to be increased by \([1+ (I_t/I_c)^2]\)
- \( J_d \) at 5 T varies with the filament size and the twist pitch. Cascade of HT have to be adapted to the small filament size.
  With a LHC 01 strand, \( J_d = 0.28 \times 10^{10} \text{ Am}^{-2} \) in a 0.45 mm strand, twist pitch of 4mm, 2.95 μm filament in a Cu matrix have been produced. Confirmation of A. Ghosh, results.
Excess of Magnetization due to filament proximity effect  
Effects to be studied for a low injection field

- $\Delta M = \Delta M_f + \Delta M_p + \Delta M_i = (\text{losses in filaments} + \text{losses in matrix per proximity} + \text{losses due to filament irregularities})$

- When the spacing between filaments becomes small, the losses increase. This increase in magnetization is caused by the fact that the matrix becomes a weak superconductor due to inter-filamentary coupling currents. This effect is noticeable when the inter-filamentary spacing is $\leq \xi_m$ (effective coherence length of the matrix).

- The excess magnetization is proportional to the twist pitch $l_p$ of the strand as shown by Jr.Carr.

$$M_p = \frac{2}{\pi^2} \mu_0 \lambda_p \lambda_m J_{cf} (Ba) l_p \left[1 + \frac{D}{2} \frac{l_p}{D}\right]$$

$\lambda_p, \lambda_m$ are volume fraction of multifilamentary region in strand and of weak sc matrix in multifilamentary zone

$$M_p = \frac{2}{\pi^2} \mu_0 \lambda_p \lambda_m J_{cf} (Ba) l_p$$ for the usual case $l_p \gg D$

- Measuring $dM_p/dl_p$ will give the properties of $J_{cf} (Ba)$.

Magnetization due to proximity effect between filaments

- $J_{cf} (Ba)$ has been measured to be $0.002xJ_{cf} (2.4x10^7 \text{ Am}^{-2})$ at 0.3 T for a spacing of 0.39 $\mu$m and $d=2.13$ $\mu$m ($s/d=0.183$) in a Cu matrix

- $\xi_m$ for Cu can vary a lot between clean limit (0.34 $\mu$m) and dirty limit due to hardening

- $\xi_m \sim (1/\rho) T^{0.5}$

- When $\rho$ increases, $\xi_m$ decreases. Impurities must be added for electron scattering. Cu-Mn introduces magnetic scattering (E.Collings).($\rho = 3.4 \times 10^{-6} \Omega m$ for Cu-Ni30 and 1.8 $10^{-6} \Omega m$ for Cu-Mn0.5)

- The inter-filament spacing (s) should be at least 5 $\xi_m(0.15 \mu m)$ for Cu-Ni as a base

- From the measurements of $J_{cf} (Ba)$ in strands with various spacing, the $\xi_m$ could be estimated.

- $\Delta M_i$ results from irregularities depending on the fabrication process and an insufficient support between neighboring filaments. $s/d$ should be inferior to 0.2

Magnetization due to proximity effect between filaments  

<table>
<thead>
<tr>
<th>Cu-Ni 30</th>
<th>$d=0.095 \mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dM_p/dl_p$</td>
<td>(mT/mm)</td>
</tr>
<tr>
<td>$J_{cf}(Ba)$</td>
<td>$[10^7 \text{ Am}^{-2}]$</td>
</tr>
<tr>
<td>$\xi_m$ at 4.2 K</td>
<td>$[\mu$m]</td>
</tr>
<tr>
<td>Cu-Ni 30</td>
<td>0.11 at 0.05 T</td>
</tr>
<tr>
<td></td>
<td>0.05 at 0.3 T</td>
</tr>
<tr>
<td></td>
<td>$\Delta M(0)=0.3 \text{ mT at}$</td>
</tr>
<tr>
<td></td>
<td>0.3 T</td>
</tr>
<tr>
<td>Cu-Ni 10</td>
<td>0.75 at 0.05 T</td>
</tr>
<tr>
<td></td>
<td>0.28 at 0.3 T</td>
</tr>
<tr>
<td></td>
<td>$\Delta M(0)=5 \text{ mT at}$</td>
</tr>
<tr>
<td></td>
<td>0.3 T</td>
</tr>
<tr>
<td>Cu-Mn 0.5</td>
<td>0.8 at 0.05 T</td>
</tr>
<tr>
<td></td>
<td>0.5 at 0.3 T</td>
</tr>
<tr>
<td></td>
<td>$\xi_m$ at 4.2 K</td>
</tr>
<tr>
<td></td>
<td>$[\mu$m]</td>
</tr>
</tbody>
</table>

- Cu-Ni30 gives less M increase than Cu-N10

- For the same spacing, Cu-Ni is better than Cu-Mn

Magnetization with Cu-Ni30 (5 $\mu$m fil.)

- FZK 96-80 Cu90Ni10

- $\xi_m$ at 4.2 K

- $d=1.03 \mu$m

- Cu-Ni 30

- $s/d=0.13$

- $d=0.095 \mu$m

- Cu-Ni 10

- $s/d=0.21$

- $d=0.305 \mu$m

- Cu-Ni 30

- $s/d=0.15$

- $d=0.359 \mu$m

- Cu-Ni 10

- $s/d=0.25$

- $d=0.305 \mu$m

- Cu-Ni 10

- $s/d=0.13$

- $d=0.359 \mu$m

- Cu-Ni 10

- $s/d=0.7$

- $d=0.095 \mu$m

- Cu-Ni 10

- $s/d=0.13$

- $d=0.305 \mu$m

- Cu-Ni 10

- $s/d=0.13$

- $d=0.305 \mu$m

- Cu-Ni 10

- $s/d=0.13$

- $d=0.305 \mu$m

- Cu-Ni 10

- $s/d=0.13$

- $d=0.305 \mu$m

- Cu-Ni 10

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- Cu-Ni 10

- $s/d=0.13$

- $d=0.305 \mu$m

- Cu-Ni 10

- $s/d=0.13$

- $d=0.305 \mu$m

- Cu-Ni 10

- $s/d=0.13$
Wire R&D for pulsed superconducting magnets

Single and Double stack

In single stack, up to 15000 fil
For a larger number, needs of double stack

Single stack
6600 filaments in superhex (OKAS)-LHC
38000 fil made for SSC

For LHC, 55 billets on 6050 have been rejected for magnetization reasons.

Filament deformation
- filament deformation depends on matrix material and spacing between filaments and spacing between bundles.

Superhex (6 μm)
Double stack (5 μm)

Inter-filament coupling currents (IFCC)

Cross-section of a single stack 02 strand for a) non deformed, b) deformed, c) heavily deformed filaments.

Cross-section of a double-stack 01 strand with heavily deformed filaments - M = 35 mT at 0.5 T, 1.9 K

Zone 1: current flows through Cu and CuNi barriers, $\tau_1$ ~ 0.02 ms
Zone 2: $\tau_f = \tau_{f1} + \tau_{f2}$
$\tau_{f1}$ inside bundles (0.05 ms)
$\tau_{f2}$ between bundles (0.06 ms ?)
Zone CuNi barrier: $\tau_2$ ~ 0.06 ms
Zone outer shell: $\tau_3$ ~ 0.03 ms
Eddy currents (Foucault) in central and outer Cu: 0.05 ms
Total $\tau = 0.27$ ms
Cu will be selected to have a RRR not larger than 100
Losses have to be measured in adequate equipment.
Cu amount for quench protection (1200 Amm⁻²)
Wire R&D for pulsed superconducting magnets

- The strand into consideration has 150,000 filaments of 1 µm and a diameter of 0.65 mm. The twist pitch is 4 mm. What is the critical current?

- Even with 1 µm filaments, the hysteresis losses are predominant and represent 4 times the ISCC losses. The ISCC time constant can be higher if stability requires it. The hysteresis losses could be reduced by using 0.85 µm filament diameter (200,000 filaments) and reducing the Bmax.

- The Nb barriers around filaments are increased. What are the values of the (pe) at the interface Nb/CuNi and Cu-Ni/Cu?

Comments - Coating

- Strand Coating or core in cable?

  A high resistive coating like Cr on strand diameter of 0.65 mm could be envisaged instead of a core. Rc≈10 mΩ and Ra≈20 mΩ would decrease the losses by 27%.

- Is the redistribution of current between the strand still active? The time constant linked to a perturbation in the cable (dB/dzdt,..) is reduced. What is the strand current at the end of the ramp?

- I op/Ic =0.6. Is it acceptable for cable stability?

Conclusions (1/3)

- Estimations and calculations are necessary but measurements are better. Equipments to measure a strand time constant of 0.5 ms are needed.

- To develop strands with a large number (>150,000) of ~1 µm Nb-Ti filaments, the R&D program should investigate in double stacking:
  - Jc vs filament diameter and twist pitch with new cascade of HT
  - Filament deformation (Magnetization) and loss time constants with various spacing of Cu-Ni and Cu and various twist pitch. Cu/Sc≈1.4.
  - Proximity effect (important for Binj~150 mT)
  - MQE measurements
Conclusions (2/3)

• Cables consisting of strands with resistive coating (Rc~20 mΩ) should be tested from losses and stability aspects.

• For machines at 1 T/s and Bmax=6T (GSI 300), the proposed strand specification seems adequate.

• For machines at 4 T/s and high dynamic range, the strand and cable fabrication is challenging, specially with a low injection field. There is a need of a R&D program based on the present “state of the art” after the progresses made in the last 20 years.

Conclusions (2/3)

• Trends for such a strand specification could be:

  - Strand diameter: 0.65 mm
  - Filament size: ≤ 1 μm
  - Number of filaments: > 150'000
  - Twist pitch: 4 mm
  - Mixed Cu/Cu-Ni30 matrix
  - Resistive coating: 1 μm Cr or other material

R&D Remark

• Loop of actions—work in synergy based on pragmatic approach

  - Machine requirements
  - Cable & magnet design
  - Specs +Magnet Construction + Tests
  - Corrective actions on specs & design

Directions for bewildered conductor designers

Configurations and properties of low losses superconducting cables
The role of conductor designer

The endangered species *peritus delineandi optimorum ductorum* is not adequately protected, his natural enemies being the fierce magnet designers and the elusive strand specialists.

Squeezed between the magnet designer, who is generally his boss, and the strand / material suppliers, who are safely out of reach in the industry, the conductor designer has sometimes to solve problems without solutions and is made responsible for whatever failure of the project.

The conductor designer should actually be involved in the project since the definition of the magnet conceptual design. The feedback between conductor and coil design must be active and start early.

If the conductor designer is involved in the project when all crucial decisions are already taken, he may not be able to find an adequate solution.

The pulsed field conductor triangle

It is impossible to have excellent results for the three vertexes of the triangle: low ac loss -> low heat removal -> bad current distribution good current distribution -> high ac loss -> heat removal problem

Current density

Why pulsed conductors do not like high current density

- High current density \( J_{op} / J_c > 0.8 \) requires that the current distribution is well balanced among the current carrying elements (strands / filaments).
- In case of non-uniform joint resistance or non-symmetric transposition, the current must be able to re-distribute locally without initiating a quench: the transverse resistance among current carrying elements must be low.
- High coupling loss and high power generation arise from low transverse resistance.

Either a large \( \Delta T \) is allowed for large heat removal or large cross section is allowed for the coolant. In both cases the engineering current density is depressed.
Heat removal

Depending on the duty cycle and "strategy" of the project, the heat removal may be limited either by the cryo-plant capacity (average load) or by the local coolant inventory / heat transfer coefficient (peak load).

- The most effective solution for large heat removal, is bath cooling and helium transparent winding: it guarantees constant temperature up to high removal rate.
- Force flow cooling is restricted by the balance of the average power to be removed and residence time of coolant in the coil: the operating temperature increases with generated power.

However, bath cooling and transparent winding are questionable in case of high mechanical stress (conductor movement) and/or high electric voltage (Paschen discharge).

AC Losses - Hysteresis

Hysteresis Loss: unavoidable!, but... As the loss is roughly proportional to filament diameter, the plain solution is to aim for ~0.1 μm filaments

$\text{Nb}_3\text{Sn}$ filaments as thin as 1/10 μm have excellent quality (high uniformity of the chemical composition). However, $\text{Nb}_3\text{Sn}$ filaments must be spaced to avoid bridging during the heat treatment. Adequate spacing (s/d > 0.5 at initial assembly) must also account for irregular deformation and A15 growth. As the matrix is accounted in the non-copper cross section, the well known results for $\text{Nb}_3\text{Sn}$ is

Low hysteresis loss = generous separation = Low current density

In $\text{NbTi}$ filaments down to 2-3 μm are achievable with $J_c$ marginally decreasing compared to standard 6 μm. Adequate spacing must be grant to avoid the field dependent proximity effect. Spacing, s, is here an absolute measure. For Cu-matrix, s ≥ 0.6 μm. Using matrix with impurities (magnetic CuMn0.5 or non-magnetic CuNi10), s can be reduced to less than 0.2 μm.

$\text{NbTi}$ filaments below ~10 μm require Nb barrier (~8%) for co-processing. This gives a non-negligible contribution to hysteresis loss below 0.5 T.

AC Losses - Coupling Currents Loss - Interfilament

Inter-filament coupling loss is proportional to $\frac{F^2}{ρ}$

Loss reduction can be achieved either by:

- Short twist pitch or
- High resistivity matrix

Short twist pitches, down to 6 times the strand diameter are achievable without large penalty on $J_c$ (less than 3%).

High resistivity matrix is expensive. The benefits in coupling loss compared to copper are of the order of 10-50. However it depresses the current density, as the copper cross section must be kept for stability/protection. The use of mixed matrix is not justified, unless in combination with very small filament spacing (double use of high resistivity matrix).
AC Losses - Coupling Currents Loss - Interfilament

Optimization of inter-filament loss is an issue only at very high field rate, $\Delta B \cdot f$, for example at 50 Hz application. In pulsed accelerators, it is not a major issue.

E.G. (GSI): A 0.5 mm NbTi strand, Cu:non-Cu = 1.4, $L_x = 3$ mm, filament 3 $\mu$m
Operating conditions 0-2-0, 1 Hz (4 T/s)

Hyst. Loss $\approx 14$ mW/cm$^3$ of NbTi composite
Inter-filament Loss (at 1 ms) $= 12$ mW/cm$^3$ of NbTi composite

Reduction of inter-filament coupling loss may stop when it achieves the same level as hysteresis loss

Very low hysteresis loss (thin, non-coupled filaments) and very low interfilament loss can be achieved with a high resistivity matrix

Example of pulsed field conductors

DPC-U, JAERI 1989

• CICC of 486 NbTi formvar insulated, $\phi = 1.1$ mm, mixed matrix strands, fil. diameter 10 $\mu$m
• Design: 7 T, 7 T/s, 30 kA
• Coupling time constant 0.32 ms

Excellent pulsed performance was achieved, but the coil quenched 1 s after full current due to unbalanced current distribution: the current can only re-distribute at the joints, but the diffusion time from weak spot to the joint is much too long compared to the quench propagation

Example of pulsed field conductors

Polo, Fzk 1994

• Two separate channels, stagnant supercritical and forced flow 2-phase
• 78 NbTi strands, $\phi = 1.25$ mm, mixed matrix, fil. $\phi = 10$ $\mu$m
• Design: 1.63 T, up to 500 T/s, 15 kA, 23 kV
• Coupling time constant 0.2 ms

Excellent transient field performance and low ac loss, but only 70% of $I_c$ achieved in dc, likely due to current unbalance

Beside cost considerations, the design is not applicable to high current density projects and high duty cycle operation
Roadmap for key decisions about pulsed field conductors

1. **Superconductor or normal conductor?**
   - Key input: $B_{\text{max}}$ and duty cycle
   - Project funding: prefer low investment cost or low operation cost

2. **Material: NbTi, Nb$_3$Sn, HTS?**
   - Key input: $B_{\text{max}}$
   - Parameters affected by the choice: material cost, $\Delta T$, coil technology/cost

3. **Cooling: bath or forced flow (supercritical or 2-phases)**
   - Key input: range of stored energy
   - Strong impact on: heat removal, eng. current density, insulation, support
   - Some impact on: operating temperature, conductor size, cryo-plant

General recommendation for pulsed field conductors-1

**AC Losses / Current Distribution / Heat removal**

The best pulsed field conductor is a small conductor, possibly a monolith, where the best compromise between low coupling loss/heat removal and balanced current distribution can be achieved.

**Operating Margin**

For pulsed conductors, temperature margin is essential, rather than margin on load curve.

**Hysteresis Loss**

Very low hysteresis loss is possible, but may be very expensive. Try to use what is available on the market ($= 3\mu m$)

General recommendation for pulsed field conductors-2

**Inter-filament coupling loss**

Mixed matrix can drastically cut the inter-filament loss, but is expensive the current density. Tight pitches are much cheaper.

**Inter-strand/subcable coupling loss**

This is likely the largest source of loss. Reducing the loss by high transverse resistance risks jeopardizing the current re-distribution.

**Mechanical**

The number of cycles to life time is crucial. Carefully watch moving parts (e.g. cabled conductors and transparent windings).

Review of AC Applications in Superconductivity

Joseph V. Minervini

ECOMAG-05 Workshop
ENEAG, Frascati (IT)
26-28 October, 2005
Summary of major AC applications

- Superconducting Magnetic Energy Storage (SMES)
  - 1970’s - ~1990’s
- Pulsed magnets for fusion
  - 1970’s - present
- Pulsed magnets for high energy and nuclear physics
- Special applications
  - Test facility magnets for conductors
    - Stability and ac losses
    - Typically for fusion conductors
  - Adiabatic demagnetization Refrigeration (ADR)
  - Other, e.g. electromagnetic launch, rail guns, etc.

SMES Magnets

- Initial goal was load leveling (diurnal storage)
  - Very large coils,
    - Huge stored energy - GJ’s - TJ’s (~5000MWh)
  - Mostly NbTi
    - Complex cables of SC, Cu, CuNi, Al and/or SS
- Goal was later changed to power system stabilization
  - Real and reactive power transfer, voltage sag
- Early magnets pool-cooled magnets
  - He I or He II
- Later magnets use CICC with forced-flow supercritical He
- $B_{peak} \sim 4-7$T
SMES Magnets (continued)

- Load leveling required relatively slow charge/discharge
  - No real examples of operating systems, just test coils
- System stabilization requires ripple AC current on large DC bias current at relatively high voltage or power insertion/extraction over short time span
  - Both require AC-DC-AC power conversion interface to load or power system
- Some examples:
  - BPA-LANL 30 MJ
  - Double SMES System for Korea Electric Power System
  - CAPS/FSU SMES 100 MJ
  - Toshiba 100 kWh SMES Model Coil

Bonneville Power Administration-LANL SMES

- Installed on grid in Tacoma, WA 1982-83
- Main problems were related to the helium refrigerator
- Over 1200 hours of operation
- Peak Stored Energy = 30 MJ
- Peak current = 5.4 kA
- Peak Coil voltage = 5 kV
- Peak Field = 2.85 T
- Maximum power ~11 MW

Bonneville Power Administration-LANL SMES

- Real and reactive power injected into grid at frequencies of 0.1 Hz to 1.2 Hz
- Cumulative testing time ~120 hours
  - ~10^6 total cycles

Double SMES System for Korea Electric Power System

- 2 Superconducting Solenoids
- NbTi strand (from UNK) and SS wire cabled around a rectangular Cu core (RRR ~30)
- DC-AC-DC converter to transfer stored energy between the coils at 2s ramp time
- Each coil stores 0.5 MJ at 1.55 kA
- System designed/built at Kurchatov Institute
- \( B_{\text{max}} \approx 3.7 \) T
**Fusion Magnet Applications**

- Pulsed magnets for Poloidal Field (PF) coils in tokamaks
  - Plasma initiation
  - Plasma ohmic heating and inductive current drive
  - Plasma shaping and control
- Geometry - ring coils and long solenoids
- High current (10 - 60 kA)
- High voltage (5 - 25 kV)
- Bipolar flux swings
  - Pulse duration over 10’s to 1000 seconds
  - Repetition- minutes or much more between pulses
- Early prototypes 1970's - 1980's
  - NbTi multistage composite cables in pool-boiling LHe
  - Example ANL Split Pair Test Facility magnet
- Since ~ 1990 CICC NbTi or Nb3Sn
  - Many examples

**ANL 3.3 MJ Pulsed Superconducting Coil**

- Achieved 6 T/s to 6 T with repetitive triangular pulses 5 s apart.
- NbTi and copper composite cable
  - Stabrite coated
- Insulated steel cable core
- Partial solder filling

**ETL Pulsed Magnets for Fusion**

- Development of pulsed magnet technology for a tokamak ohmic heating coil (circa 1985)
- Energy transfer between a 3MJ and a 4MJ coil.
- Achieved 0-6.6T-0 in 3 s (~4.4 T/s)

**Al stabilized NbTi cable**
CICC for Pulsed Fusion Magnets

- First Pulsed Coils in CICC - DPC Program
  - JAERI/DPC-U1-U2, NbTi
  - JAERI/DPC-EX, Nb₃Sn, React and Wind, Rutherford Cable
  - US-DPC, Nb₃Sn, Wind and React
- CICC is now used for all coils (pulsed and DC) for all superconducting fusion devices being built
  - Wendelstein 7-X (Germany)
  - EAST (China)
  - KSTAR (Korea)
  - SST-1 (India)
  - LHD-PF Coils (Japan) - in operation since 1998
  - ITER
- Other Pulsed CICC Test Coils
  - POLO (Germany)
  - ENEA 12T (Italy)
  - ITER CSMC
  - ITER CS Insert

Demo Poloidal Coil, DPC

- Three Coil Systems to demonstrate pulse magnet technology for fusion poloidal field coil applications
  - DPC-U (JAERI, Japan)
    - NbTi CICC split coil pair
    - Highly unstable due to formvar insulation of wires
  - DPC-EX (JAERI, Japan)
    - Nb₃Sn Rutherford cable-in-conduit, React-and-Wind
  - US-DPC (MIT, US)
    - Nb₃Sn, dual jacket CICC, Wind-and-React
    - Peak design field in series mode 7T-10 T depending on insert coil
    - Design goal of up to 10 T/s pulse rate

US-DPC

- 225 Cr plated Nb₃Sn strands, low RRR. Square cable-in-conduit with double channel at the four corners.
- Wind & React method, with insulation applied after the heat treatment
- 3 double pancakes. One double pancake has a heater wire in the center and lower void fraction (33% instead of 38%)
- Peak field 5.7 T @ 30 kA in single coil operation, 8 T @ 25.9 kA in series with DPC-U1/U2 (limited by quench of U1 coil).
**Ramp rate Limitation - Single Coil tests**

- **Figure 14**: Current vs. Time curve for single coil, trapezoidal waveform, ramp-rate time > 1.2 s. Don't forget the joints!

**Ramp Rate Limitation - Series Coil tests**

- **Figure 16**: Current vs. Time curves for series coil, trapezoidal waveform.
- **Figure 17**: Measured field vs. Time curve for series coil, trapezoidal waveform.
- **Figure 18**: Comparison of measured field vs. Time curves for non-quenched and quenched series coil, trapezoidal waveform.

---

**Table 4.1 - Best performance in single coil tests for trapezoidal pulse runs ramped to fields from 3.8 T to 6.0 T (5 s flat top without quench).**

<table>
<thead>
<tr>
<th>run no.</th>
<th>ramp rate</th>
<th>field</th>
<th>current</th>
<th>$I_2$ noncooper</th>
</tr>
</thead>
<tbody>
<tr>
<td>139</td>
<td>19 T/s</td>
<td>3.8 T</td>
<td>20 kA</td>
<td>400 A/mm²</td>
</tr>
<tr>
<td>128</td>
<td>4.3 T/s</td>
<td>4.3 T</td>
<td>23 kA</td>
<td>460 A/mm²</td>
</tr>
<tr>
<td>122</td>
<td>2.7 T/s</td>
<td>4.7 T</td>
<td>25 kA</td>
<td>500 A/mm²</td>
</tr>
<tr>
<td>124</td>
<td>0.71 T/s</td>
<td>5.7 T</td>
<td>30 kA</td>
<td>600 A/mm²</td>
</tr>
<tr>
<td>134</td>
<td>0.35 T/s</td>
<td>6.0 T</td>
<td>32 kA</td>
<td>640 A/mm²</td>
</tr>
</tbody>
</table>

**Table 4.2 - Best performance in series coil tests.**

<table>
<thead>
<tr>
<th>run no.</th>
<th>charging waveform</th>
<th>ramp rate</th>
<th>field</th>
<th>current</th>
<th>$I_2$ noncooper</th>
</tr>
</thead>
<tbody>
<tr>
<td>265</td>
<td>trapezoidal</td>
<td>0.5 s</td>
<td>6.4 T</td>
<td>21 kA</td>
<td>420 A/mm²</td>
</tr>
<tr>
<td>271</td>
<td>round-edge trapezoidal</td>
<td>3.0 s</td>
<td>2.3 T (avg)</td>
<td>22 kA</td>
<td>440 A/mm²</td>
</tr>
<tr>
<td>277</td>
<td>rippled trapezoidal</td>
<td>0.5 s</td>
<td>6.8 T</td>
<td>22 kA</td>
<td>440 A/mm²</td>
</tr>
</tbody>
</table>
DPC-EX

- 2 Nb$_3$Sn double pancakes (1.3m dia.) inserted between background U1-U2 coils.
- React and wind, Cr plated strands
- Achieved 18 kA, 7.1 T at 14 T/s

POLO (FzK)

A demonstration coil for high voltage and fast field ramp rate

- Designed for 15 kA, 2 T, 16.3 kV
- Tested up to 25 kA, 3.6 T
- A midpoint electrical connection allows a very high field transient in a half coil by fast discharge of the other half coil
- Max current on slow charge ~70% of $I_c$
- However, could be fast pulsed at up to 100's of T/s!

POLO (FzK)

Low Loss Conductor for Fast ramp Rate

- NbTi strand $\phi = 1.25$ mm, Cu/CuNi mixed matrix, $\sigma_{\text{eff}} = 10$ $\mu$m, $t < 0.2$ ms
- Subcables wrapped by CuNi strip (half coil) or prepreg tape with 70% coverage
- CICC dual channel, stagnant supercritical He @ 4 bar in the outer ring, two-phase forced flow 4.5 K, 1.2 bar 2 g/s in the central pipe of kapton insulated Copper

Large Helical Device (LHD)
National Institute for Fusion Science
Toki, JAPAN

- LHD has been used for extensive plasma experiments since 1998 with 8 months operation period in each year.
- Seven cycles of experimental campaigns have been performed in four years.
**LHD Poloidal Field Coils**

- NbTi strands, $\varnothing = 0.76$ and 0.89 mm. Bare strand surface
- Cable of 486 strands 3x3x3x6, 38% void fraction, $t = 300$ ms
- $I_c/I_{op} = 3$ is used as a design criterion. The temperature margin ranges from 1.2 to 1.6 K
- Prepreg turn insulation.
- The OV coil, diameter of 11.5 m, wound on the LHD site
- Operational since 1998
- Relatively slow ramp rates. Long time constant circulating currents observed.

**ITER CS and PF Coil System**

- PF3 and PF4 have 24 meter diameter
- Poloidal Field Coils use NbTi CICC
- Central Solenoid uses Nb$_3$Sn CICC

**Overall Magnet System Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of TF coils</td>
<td>18</td>
</tr>
<tr>
<td>Magnetic energy in TF coils (GJ)</td>
<td>$\sim 41$</td>
</tr>
<tr>
<td>Maximum field in TF coils (T)</td>
<td>11.8</td>
</tr>
<tr>
<td>Centering force per TF coil (MN)</td>
<td>403</td>
</tr>
<tr>
<td>Vertical force per half TF coil (MN)</td>
<td>205</td>
</tr>
<tr>
<td>TF electrical discharge time constant (s)</td>
<td>11</td>
</tr>
<tr>
<td>CS peak field (T)</td>
<td>13.0</td>
</tr>
<tr>
<td>Total weight of magnet system (t)</td>
<td>$\sim 9,000$</td>
</tr>
</tbody>
</table>

**Central Solenoid Operation**

Typical Central Solenoid pulse cycle for a long plasma burn cycle

Present ITER CS has 6-module segmentation with separate power supplies.
The document describes the composition and specifications of a coil system used in a scientific facility. The system is composed of three modules:

- **CS Insert Coil (JA)**
- **US Inner Coil Module**
- **JA Outer Coil Module**

The schematic assembly shows these modules connected in a specific configuration. The coils are surrounded by an Incoloy Alloy 908 jacket and feature a cable consisting of 1080 strands. The superconductor is Nb₃Sn, with a chrome-plated surface, and the CICC is 50 mm x 50 mm. Each strand is 0.81 mm in diameter, with a sub-element bundle containing superconducting filaments approximately 3 μm in diameter.

The coils are assembled in the Vacuum Vessel of the model coil test facility at JAERI, Naka, Japan. Key features include:

- The magnet stores 640 MJ at 13 Tesla peak field.
- It charges fastest in about 6.5 seconds, reaching 2 T/s in the CS Insert Coil.

The figure also shows the scale of each ITER CS Module compared to the complete CS Model Coil, highlighting the size and complexity of the system.
Three Inserts

- CS Insert (JA)
- TF Insert (RF)
- NbAl Insert (JA)

CSMC and CSIC - DC Properties

- No training – reached operating point from first trial
- $I_c$ and $T_{cs}$ were less than expected
  - Particularly after cycling
- All CICC showed N-value lower than in original strands

CSMC Pulse Testing

- 0.6 T/s symmetric, trapezoidal ramp to 13T field in the CS insert.

Charging the CS Insert to 13 T by a ramp rate of 1.2 T/s
Technology & Engineering Division

Ramp Rate Limitation Observations

- All ITER simulations shots passed with no quench for both CSMC and CS Insert
- CSI does not show instabilities until 1.2-2 T/s, only trivial heat load due to losses
- CSMC showed some deviation from full stability above 0.6 T/s
- Both results give very comfortable level of safety for ITER operation and confidence that ramp rate will not be a limitation
- Similar conductors, but quite different results

★ Note: had to use elevated helium inlet temperature to induce ramp instability

AC losses

Coupling loss time- deduced from selected dumps

<table>
<thead>
<tr>
<th>Conductor 1 A</th>
<th>Coupling loss time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25% dump</td>
<td>100</td>
</tr>
<tr>
<td>50% dump 4/17 (2nd 50% dump)</td>
<td>150</td>
</tr>
<tr>
<td>25% dump 4/17 (1st 25% dump)</td>
<td>200</td>
</tr>
<tr>
<td>25% dump 4/17 (1st 25% dump)</td>
<td>250</td>
</tr>
<tr>
<td>10% dump 4/17 (1st 10% dump)</td>
<td>300</td>
</tr>
<tr>
<td>5% dump 4/17 (1st 5% dump)</td>
<td>350</td>
</tr>
</tbody>
</table>

Note: had to use elevated helium inlet temperature to induce ramp instability
Stability of CS Insert Coil

Reduction of CSMC Coupling Losses With Cycles

History of $T_{cs}$ Evolution in the CS Insert

SAMSUNG SSTF for KSTAR
- Main Coil for Samsung Superconductor Test Facility (SSTF)
  - Split solenoid pair
  - Central Field = ±8 T at 22.6 kA
  - Max Field at Coil = ±9.75 T at 22.65 kA
  - Central Field Ramp Rate up to ±3 T/s
  - Conductor is Nb$_3$Sn CICC (same as KSTAR CS)
  - Designed by Kurchatov Institute (Russia)
EAST Tokamak
Institute of Plasma Physics
Chinese Academy of Sciences, Hefei, P.R. China

- All Magnets are superconducting using NbTi CICC with SS Jacket
- Operating temperature is 3.8 K
- TF Prototype coil has been successfully tested to 16.3 kA at 5.8 T
- CS model coil has been successfully tested in a plasma initiation cycle - 15.2 kA @ 3.34 T
- Fast discharge at 4.4 T/s for 0.7 T

Under Construction - Finish Machine Assembly in 2005

Conductor design and R&D

<table>
<thead>
<tr>
<th>TF</th>
<th>CS and PF 7-10</th>
<th>FF 11-14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>20.4 x 20.4</td>
<td>20.4 x 20.4</td>
</tr>
<tr>
<td>Number of SC strands</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Coating</td>
<td>Sn alloy</td>
<td>Ni</td>
</tr>
<tr>
<td>Cu / non-Cu</td>
<td>4.91</td>
<td>4.91</td>
</tr>
<tr>
<td>Void fraction</td>
<td>0.34</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Total weight of NbTi strands: 20 tons

ASIPP
Aspects of AC Coil Design

- All use multistrand cables of small wires to reduce AC losses
  - High current to limit inductive operating voltage
  - Allow helium penetration for good stability
  - Sometimes introduce special wire surface coatings or resistive components to lower AC losses
    - Puts uniform current distribution and good transverse heat conduction in competition with lower AC losses
- Must consider **high cyclic fatigue** on conductor and coil components
  - Mechanical integrity
  - Electrical insulation
  - AC properties
- Quench detection gets harder
  - Compensation of relatively large inductive voltages required
- Pool-Boiling requires good winding pack ventilation
- CICC requires good forced flow for SS heat removal
  - For long lengths must consider transit time in winding and heat accumulation for multiple pulses

Heat Capacity Data

- A. Helium (10 atm)
- B. Helium (1 atm)
- C. GE varnish
- D. Stainless steel
- E. Nb-Ti
- F. Epoxy
- G. Silver
- H. Copper
- I. Aluminum

Helium Heat Transfer Coefficient Data

Based on data from Luca Bottura (CERN, Geneva)

Helium Heat Transfer Data—Nucleate & Film Boiling

Based on data from Luca Bottura (CERN, Geneva)
**Power Density Equation—CICC**

\[ C_c(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ k_c(T) \frac{\partial T}{\partial x} \right] + \rho_c(T) \frac{f_p P_{cd}}{A_g} q(T) \]

\[ C_f(T) \frac{\partial T_f}{\partial t} = \frac{f_p P_{cd}}{A_f} h_f (T - T_f) \]

\[ h_f = 0.0259 \frac{k_w}{D_{wy}} Re^{0.8} Pr^{0.4} \left( \frac{T_f}{T} \right)^{0.716} \]

---

**Conclusions**

- There are many examples of pulsed magnets which have been built which successfully achieved performance goals desired by the LHC and GSI accelerator programs
  - (and some which did not)
- Includes both pool-cooled and CICC designs and NbTi and Nb₃Sn
- Accelerator goals could be achievable with proper engineering
- Only two magnets have been operated extensively for many cycles
  - BPA SMES magnet (~ 10⁶ cycles)
  - ITER CSIC (10⁴ cycles)
- No experience for many-year operation

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**Review of heat transfer mechanisms in superconducting magnets**

Bertrand Baudouy
CEA Saclay
DSM/Dapnia/SACM/LCSE

HHH-AMT Workshop on Superconducting Pulsed Magnets for Accelerators
ECOMAG-05 Frascati (Italy) October 27 2005
Outline

- Different heat transfer modes to cool magnets
  - Introduction
  - Pool boiling, Static He II, Forced flow single phase, Forced flow two-phase
  - Comparison
- Heat transfer in the electrical insulation and coil: Rutherford Cable type
  - Phenomenology
  - Past Results
  - Some ideas
- Current and Possible R&D programs (NED)
  - The method
  - The experimental apparatus
  - The Tests

Introduction – Temperature margin

- Heat transfer from the conductor to the cold source define the temperature margin
- Electrical insulation is the largest thermal barrier against cooling
- Electrical insulation can be
  - Non-existent
  - Monolith
  - For LHC magnet
    - $T_{\text{conductor}} = 1.9 \text{ K}$ or $T_{\text{conductor}} = 4 \text{ K}$
    - [Burnod 1994]
- Previous works focused on the thermal paths (He II)
  - Creating paths between the conductors by wrapping configurations and minimizing the glue…
  - No complete work on the solid material (holes, conductive insert or porosity)
  - No complete work with He I or ShE

Introduction – Cooling modes

- Cooling mode and thermodynamical state
  - Working temperature and stability margin (superconducting properties), Refrigeration power, Mechanical constraint (space), Size and cost
  - Immersion in a stagnant liquid
    - Saturated and sub-cooled He I, Saturated or pressurized He II
  - Forced flow cooling (internal or external to the cable)
    - Sub-cooled Helium, Supercritical, Superfluid, two-phase
  - Two types of magnet for heat transfer point of view
    - "Dry coil" magnet: Helium in contact with the insulation or structure only
      - Conduction (cable + insulation + structure) and surface heat transfer
    - "Wet coil" magnet: Helium in contact with the insulation and the cable
      - Helium Heat transfer and conduction (cables + insulation) and Surface heat transfer
  - With heat exchanger or not
- Best solution for thermal stability: helium in contact with the cable?
  - Entropy reserve in the cable, better heat transfer coefficient
  - Quench issue: $\Delta p$ within the insulation?

Pool boiling @ Atm pressure

- Characteristics
  - High heat transfer coefficient in nucleate boiling
  - Easy design
  - Heat transfer by natural convection and easily influenced by gas
  - Major (dis)advantage is $T = 4.2 \text{ K}$
  - Non uniform cooling due to vapor formation
- Heat transfer
  - 3 Regimes: Natural convection, Nucleate boiling, Film boiling
  - Highest heat transfer in nucleate boiling, no film of gas on surface
    - $q_{\text{max}} = 10^4 \text{ W/m}^2$ for $\Delta T = 1 \text{ K}$
  - Solutions to enhance heat transfer rates and thermal stability
    - Natural convection Channels or thermosiphon to eliminate stagnant vapor zone and enhancement of heat transfer [Jones 1978]
- Typical heat loads 1 W/m and magnet length of 20 m [Van Weelderen 2004]
**Saturated He I forced flow**

- Characteristics
  - Isothermal fluid over the cooling circuit (4.2 K)
  - High heat transfer coefficient
  - Save space and weight compared to pool boiling
  - Smaller helium content in the system
  - Two-phase flow but (p/p_c=7 at 4.2 K)

- Heat transfer
  - Good heat transfer up to x=98 % [Mahé 1991] et [Neuvéglise 1995]
  - \( q_{max} = 10^4 \text{ W/m}^2 \) for a SS tube of Ø10 mm \( m=610^{-5} \text{ kg/s} \) and \( \Delta T=1 \text{ K} \) [Mahé 1991] (titre initial de O).

**Static pressurized He II**

- Characteristics
  - Lower operating T (higher performance of superconductor)
  - Improved local heat transfer
  - High heat conductivity (reduced vapor generation)
  - Bath cooled magnet and also CICC (45T Magnet @ NHMFL)
  - Double bath technique or with HX

- Heat transfer
  - \( k=10^5 \text{ W/m.K} \) for \( \Delta T=0.3 \text{ K} \), over it is He I (k=0.02 W/m.K)
  - Dimension of cooling channel between cable and HX
  - \( q_{max}=10 \text{ kW/m}^2 \) for \( L=1 \text{ m} \) and \( \Delta T=0.35 \text{ K} \) (15 kW/m² for He II sat)
  - Interface thermal resistance between solid and He II (Kapitza resistance)
    - \( \text{Cu} R_T=3 \times 10^{-5} \text{ K.m/K} \) and Kapton \( R_T=1 \times 10^{-7} \text{ K.m/K} \)

- Performances:
  - For LHC main magnets 1 W/m and for high heat loads (inner triplets 15 W/m)
  - If Requires attention to conduction paths then extendable to 50 W/m [Van Weelderen 2004]

**Forced flow He II**

- Characteristics
  - Same advantages of Static pressurized He II
  - Applied when He II static cooling is not sufficient
  - Internally cooled magnets
  - Needs specific pumps, HX, more complicated cooling scheme

- Heat transfer
  - Kapitza resistance not a function of velocity [Kamer 1988]
  - Classical Frictional \( \Delta p \) up to \( Re=10^7 \) [Fuzier 2001]
  - Transition velocity for advection effect (1m/s for \( \Delta T=0.1 \text{ K} \) @ 1.8 K) [Van Sciver 1998]
  - Negative JT coefficient (0.2 m/s for 100 m)
    - CICC : \( D_h=0.5 \text{ mm}, \Delta p=75 \text{ kPa} \) (150 mK)
    - Smooth tube : \( D_h=10 \text{ mm}, \Delta p=1 \text{ kPa} \) (5 mK)
  - Pumps add heat loads on the system
  - Parallel hydraulic channel may help

- Not applied for accelerator magnets [Van Weelderen 2004]

**Forced flow supercritical helium**

- Characteristics
  - Comparable heat transfer coefficient to pool boiling
  - Single phase flow (no vapor formation)
  - Adjustable heat transfer with mass flow (temperature optimization)
  - Can be « plugged » to refrigeration plant and use of cooling from 300 K
  - Internally cooled conductor, For CICC, better electrical insulation

- Heat transfer
  - Classical heat transfer \( Nu \) [Giarratono 1971], \( q=10^4 \text{ W/m}^2 \) for \( \Delta T=1 \text{ K} \)
  - JT coefficient positive or negative
  - Pressures are \( P=3-8 \text{ bar}, \Delta T=1-2 \text{ mbar per magnet} \)
  - \( T=4.4 \text{ K}, \Delta T=50-150 \text{ mK per magnet} \)

- Performances [Van Weelderen 2004]:
  - Typical heat loads are \( =2 \text{ W per magnet (RHIC)} \)
  - 6 W per magnet (cross flow in SSC)
Comparison of cooling modes

- Pool boiling (~1 W/m)
  - Liquid-vapour phases, vertical liquid heat conduction paths and ullage space necessary

- Forced convection of superfluid helium (~1 W/m)
  - Single phase, circulation pump needed, no accelerator implementation yet

- Forced convection of supercritical helium (~1-10 W/m)
  - Easy to implement for low heat loads, Single phase Mass flows of O(W/0.1 kg/s), High heat load possible at the expense of T-margin and high ΔP, Cross-flow construction needed for high heat loads

- Static pressurized He II (~1-10 W/m)
  - With a two-phase flow of saturated helium II (bayonet heat exchanger) heat loads of O(10W/m), High conductivity avoids "dead spots", Concept certainly extendable to heat loads of about 50W/m

Evolution of insulation

- Historical insulation : 2 wrappings
  - First wrapping in polyimide with 50% overlap
  - Second wrapping in epoxy resin-impregnated fiberglass with gap

- The LHC insulation work : 2 wrappings
  - First wrapping in polyimide with 50% overlap
  - Second wrapping in polyimide with polyimide glue with gap

- Current LHC Insulation : 3 wrappings [Meuris 1999] [Kimura 1998]
  - First 2 wrappings with no overlap
  - Last wrapping with a gap
  - Apical R₉, Kapitza and κ @ 2 K

  Just tested at Saclay

- Innovative insulation for Nb₃Sn magnet
  - Fiberglass tape + Ceramic precursor
  - Smaller Porosity (d=0.1 μm, ε?, th=400 μm)
  - κ= 10⁻² W/K.m (κₑ₅₉₀=10⁻² W/K.m) @ 2 K

  Courtesy of F. Rondeaux (CEA)

Heat transfer in superconducting coil

- Heat transfer in a coil
- Insulations
- Phenomenology
- Past results
- Insulation for GSI
- "Comparison"
- Some ideas

Heat Transfer : Phenomenology

[Meuris 1999]
**Results : The different configurations**

- Epoxy Resin or glue on both side of the layer fills up the helium path
- Dry fiber thermally decouples the conductors
- Very small paths for He for polyimide insulations with gaps due to overlapping

**Results : The insulation is participating**

- Study on conventional insulations
  - d~10 μm, channel length ~ mm
  - He II in + conduction + Kapitza

For Large $\Delta T$, He II HT < Conduction HT

**Results : Conclusions**

- GSI001 : a conductive insulation
  - Inner layer : Polyimide 25 μm thick with adhesive on one side (50 % overlap)
  - Outer layer : Polyimide 24 μm thick with adhesive on both side (50 % overlap)
- UNK magnets PF insulation : A classic
  - Inner layer : Polyimide 20 μm thick with twist pitch of 5 mm
  - Outer layer : Prepreg fiber glass 100 μm thick with 1mm gap
- UNK magnets PP insulation : An all Polyimide Insulation
  - Inner layer : Polyimide 20 μm thick with twist pitch of 5 mm
  - Outer layer : Polyimide 40 μm thick with adhesive on both side, 1 mm gap
- UNK magnets PFM insulation : A classic improved for He II
  - Inner layer : Polyimide 20 μm thick with twist pitch of 5 mm
  - Outer layer : Prepreg fiber glass 100 μm thick with 5 mm gap
Comparison

Test in boiling He I

Heat transfer in He I and He II

Small face with holes

Artificial permeability with 6 holes of $\Phi$ 200 $\mu$ [Baudouy 1996]
Holes reduce permeability and $R_m$ of small face and of the insulation

Small $\Delta T$, heat transfer through the holes
High $\Delta T$, heat transfer through holes and conduction

Ideas for insulation in non He II

Work needed on the material itself
Thermal conductivity of Kapton, Apical, Peek?
Can it be enhanced?
Other insulation system?

Increase heat transfer between the cable layer
Porous second layer like for NED or dry fiber glass
Has to be tested in He I or SHe

Increase the Heat transfer through the small face
No epoxy resin and minimum amount of polyimide glue
Large overlap gap for second layer
Optimized overlap for the second layer

Direct contact between helium and the conductor is good
has to be tested in He I or SHe

Increase the helium in the cable
Central core in porous material?
NED R&D program : Method

1D transverse HT through the small face

1D longitudinal HT (and transverse!) through the large face

Stack = Drum + Conduit

Stack experiment
1D transverse HT (Drum set-up)
1D longitudinal HT (Conduit experiment)

NED R&D program : Experimental apparatus

Stack of five insulated conductors under mechanical constraint
Conductor = CuNi Strands Ø 0.8 mm (w=11 mm x t=1.5 mm)

Drum experiment for 1D steady-state measurement

NED R&D program : The tests

Two types of insulation are considered
- glass fiber tape, vacuum-impregnated with epoxy resin
- "innovative" insulation (glass fiber tape + ceramic)

At least four cooling schemes can be envisioned
- pool boiling He I at 4.2 K and 1 atm
- superfluid helium at 1 atm
- He I at 4.35 to 4.5 K and 1.2 to 1.7 atm
- Static supercritical helium?

References

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- M. N. Wilson, Superconducting Magnets, Clarendon Press, 1986
- H. Kamer, Proceedings of ICEC 12, p. 299-304, 1988
- Fuzier, Cryogenics 41, p. 453-458, 2001
- Van Sciver, Cryogenics, 38, p. 503-512, 1998
- [Giarratono 1971]

Courtesy of F. Rondeaux (CEA)
Phase diagram of helium

Temperature (K)

Pressure (10^5 Pa)

Solide

He II (liquide)

He I (liquide)

Gaz

T=1.76
p=2.97

T=2.163
p=1

T=2.172
p=0.05

T=4.2
p=1

He II

He I

Solide

Gaz

Heat transfer curves

Heat transfer curves

Rₙ Kapton

He II, 1 m

Forced He II

He I,
Ø10 mm
m=610⁻³ kgs⁻¹

ALSTOM

Power Turbo-Systems

Experience in production of Superconducting Wires and Magnets

Hoang Gia Ky
C. Kohler
F. Beaudet
A. Bourquard

ALSTOM

Power Turbo-Systems

- Turnkey plants
- Steam turbines, generators
- Gas turbines
- Superconductivity

Power Turbo-Systems

ECOMAS 05
October 2005

ALSTOM

Experience in production of Superconducting Wires and Magnets

Hoang Gia Ky
C. Kohler
F. Beaudet
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Past in magnet business

- Very long past experience in magnets:
  - BEBC 34 years ago at CERN
  - Start of development of cryo machines and Cryo-turbo 300MW 40 years ago
  - MRI Magnets: more than 500 magnets manufactured at Belfort. ALSTOM co-developer of Family of magnets with IGC
  - Fusion: Tore Supra model, Polo & TFMC
  - Magnets for HEP with CEA: first world superconducting dipole ALEC, 126 Quadruples for HERA.
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Fusion development programs

- Polo coil for European fusion program

ITER Toroidal Field Model Coil (TFMC)

- ALSTOM participated in one of the seven major focused R&D Projects to demonstrate the feasibility of key technologies of ITER (International Thermonuclear Experimental Reactor).
- Each Project included development and verification of industrial level manufacturing techniques.

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Magnets

Alec: 1er dipole with CEA

Quadrupole HERA - DESY
Magnets for 50 Hz applications

Leader in 50/60 Hz machines with AC low loss wires

Past in wire business

Historic

- Development and manufacturing of 50/60 Hz Wires and Cables
- Half Tore supra conductor 20 years ago
- Participation to SSC Vendor Qualification Program

Historic

- Development and manufacturing of 50/60 Hz Wires and Cables
- Half Tore supra conductor 20 years ago
- Participation to SSC VQP
Wire diameters: 0.12 to 0.3 mm
Filament diameter: 0.3 to 1.3 μm
Filamentary area matrix: CuNi/Cu or CuNi
Twist pitch about 8 times of strand diameter

First generation of Low Loss Wires for 50/60 Hz applications (1982)

Historic

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– Half Tore supra conductor 20 years ago
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Tore supra Conductor

Historic

– Development and manufacturing of 50/60 Hz Wires and Cables
– Half Tore supra conductor 20 years ago
– Participation to SSC Vendor Qualification Program
Best manufacturer of the SSC VQP!

Manufacture of 15 tones of Outer Wires to optimize Strand performances and Process

Today and tomorrow

Table 1. Percent of Phase II completion, percent yield and coefficient of variation of multifilament bulrs for inner and outer wire manufacturers.

<table>
<thead>
<tr>
<th>VENDOR</th>
<th>% Complete</th>
<th>% YIELD</th>
<th>CV %</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTER</td>
<td>100</td>
<td>85.3</td>
<td>2.3</td>
</tr>
<tr>
<td>AISA</td>
<td>100</td>
<td>79.2</td>
<td>3.2</td>
</tr>
<tr>
<td>UST</td>
<td>100</td>
<td>85.1</td>
<td>2.6</td>
</tr>
<tr>
<td>ERC</td>
<td>30</td>
<td>81.3</td>
<td>0.4</td>
</tr>
<tr>
<td>HET</td>
<td>6</td>
<td>92.1</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Project need:
1234 fifteen meter long dipole magnets: ALSTOM among the 3 suppliers delivers 1/3 of total dipoles.
1200 tons of cables: ALSTOM awarded half the quantities vs. The other half to 4 suppliers world-wide for the dipoles
Magnet Manufacturing means

- Large manufacturing facility (6000m²) totally devoted to magnet manufacturing part of one of France's largest industrial sites.
- Includes state-of-the-art equipment: clean room with a controlled air environment, large presses, welding & control equipment...

Clean room
for LHC dipole assemblies

MSA Design Capacity
Industrial means

- Large manufacturing facility (>7500m²) totally devoted to wire manufacturing part of one of France's largest industrial site.
- Includes rule of art equipment: powerful draw-bench, bull-blocks, slip less machines, EB welding,... in a controlled air environment.
- All equipment is new or has been specially upgraded for large scale production of fine filament wires.
Wire Manufacturing Means

Manufacturing means:
- In house Cabling Machine
- Mastering of Cabling process (up to 40 strand rutherford cable)

MSA’s Markets

- Wire for all Superconducting Magnets:
  - Magnetic resonance base products (MRI,NMR)
  - High energy physics (accelerators, colliders, synchrotrons...)
  - Fusion research
  - Laboratory magnets
  - New emerging applications (SMES, magnetic separation...)
  - AC applications

CERN LHC cable shares

IGC and LMI are now Outokumpu
LHC Dipole inner layer Cable

Filament \( \Phi \): 7 \( \pm \) 0.1 \( \mu \)m
Strand \( \Phi \): 1.065 \( \pm \) 0.0025 mm
Coating: SnAg
Inter-strand res.: 20 \( \pm \) 5 \( \mu \)\( \Omega \)
Nb of strands: 28
Cable width: 15.10 \( \pm \) 0.02 mm
Keystone angle: 1.25 \( \pm \) 0.05°
Mid-thick.: 1.530 \( \pm \) 0.006 mm
\( I_c \) at 1.9K, 10 T: >13750 A
Tot. length: 2370 km
Tot. mass: 474 tons

ALSTOM part = 5/8 total quantity

LHC Dipole outer layer Cable

Filament \( \Phi \): 6 \( \pm \) 0.1 \( \mu \)m
Strand \( \Phi \): 0.825 \( \pm \) 0.0025 mm
Coating: SnAg
Inter-strand res.: 40 \( \pm \) 5 \( \mu \)\( \Omega \)
Nb of strands: 36
Cable width: 15.10 \( \pm \) 0.02 mm
Keystone angle: 0.90 \( \pm \) 0.05°
Mid-thick.: 1.480 \( \pm \) 0.006 mm
\( I_c \) at 1.9K, 9 T: >12960 A
Tot. length: 4080 + 520 km
Tot. mass: 653 + 83 tons

Part of ALSTOM = 3/8 of Total Quantity

CERN Golden Hadron Award 2004

LHC suppliers win Golden Hadron awards

LHC but also..
Wire for MRI magnets

Copper matrix **round or rectangular** section
Outer insulated diameter:
From 0.4 to 2 mm typical
24 to 100 NbTi filaments

Alternatively wire in copper channel are used for MRI magnets

ALSTOM supply wires to MRI magnet manufacturers representing more than 70% of worldwide production.

Wire for NMR magnets

Copper matrix round or rectangular wire.
ALSTOM standard product
54 filaments with Cu/Sc ratio 1.35.
Insulated diameter from 0.438 to 1.3mm

Insulated dimensions for rectangular wire
- 1.05 x 0.77mm
- 1.25 x 0.80mm
- 1.65 x 1.05mm
- 1.96 x 1.26mm
- ...

Enamelled rectangular wires

ALSTOM has developed and manufactured a large range of enamelled rectangular wires with RRR value higher than 100.

Manufacture of **2000 km** of Superconducting enamelled rectangular wires for the **LHC corrector magnet coils**.

Internal Tin wire
Wire for SMES
- Process: Single stacking
- Matrix: Copper
- Number of filaments: 5712
- Nominal Cu/CuNi/Sc ratio: 5/1/1

Customers: ASINEL (Spain)
  KERI (South Korea)
  IGC (USA)

Cu matrix NbTi Wire 19200 filaments by Hex-cell single stack
- Process: Single stacking (hex cell)
- Matrix: Copper
- Number of filaments: 19200
- Nominal CuSc ratio: 1.7

Cored cables
- 36 strands cable
  - Strand diameter: 0.825mm
  - Insert: Stainless steel 304 annealed 25 μm thickness
- 24 strands cable
  - Strand diameter: 0.648mm
  - Insert: Austenitic Stainless steel 2.54 x 4.66 mm

Composite NbTi superconductor
- CEBAF HMS Dipole
  - Copper width: 13.96mm
  - Copper thickness: 3.98mm
  - Number of SC strand: 6
  - Strand diameter: 0.8mm
  - Critical current: 5500 A at 4.2k and 2T
- CEBAF
  - Copper width: 14.65 mm
  - Copper thickness: 1.97 mm
  - Number of SC strand: 20
Development and Manufacture of Low Loss Superconductors at MSA

Two families of AC low loss Conductors

- Ultra fine NbTi Filament for 50/60 Hz applications
  - ALSTOM was the pioneer in the development of low A.C. loss NbTi superconducting wires and cables with sub-micron filaments.
  - This advent has led to the possibility of using superconductors in many AC 50/60 Hz applications

- Fine NbTi Filament for Fusion Magnets
  - Five micron Filament, Low loss Wires
  - critical current densities optimized for magnetic field up to 8 Tesla, 4.2K
  - low thermal gradient across the strand section for 1.8 K uses

Basic Conceptual Design for AC low losses

- Reduce Hysteresis losses
- Reduce filament diameter
- Optimize Inter-filament Spacing
- High Resistivity Matrix
- Small Twist Pitch
- High Resistivity Barrier

Technological Challenges

- Design Parameters
  - Reduce Filament Diameter
  - Reduce Filament Spacing
  - Reduce Twist Pitch
  - CuNi less ductile than pure Cu

- IMPACTS
  - Jc degradations
  - Wire Breaks (piece length / yield problem)
  - Increase of hysteresis and Coupling Losses by Proximity Effects
First generation of Low Loss Wires for 50/60 Hz applications (1982)

- Wire diameters: 0.12 to 0.3 mm
- Filament diameter: 0.3 to 1.3 μm
- Filamentary area matrix: CuNi/Cu or CuNi
- Twist pitch about 8 times of strand diameter

Long lengths of wires have been obtained

Wires Characteristics

<table>
<thead>
<tr>
<th>Type of wire</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand diameter (mm)</td>
<td>0.3</td>
<td>0.12</td>
<td>0.3</td>
</tr>
<tr>
<td># filaments</td>
<td>13068</td>
<td>14496</td>
<td>254100</td>
</tr>
<tr>
<td>Filament diameter (μm)</td>
<td>1.33</td>
<td>0.55</td>
<td>0.3</td>
</tr>
<tr>
<td>Filamentary area matrix</td>
<td>Cu+CuNi</td>
<td>CuNi</td>
<td>CuNi</td>
</tr>
<tr>
<td>Jc @ 5T 4.2 K (A/mm²)</td>
<td>1950</td>
<td>1570</td>
<td>1030</td>
</tr>
</tbody>
</table>

Jc @ 4.2K of 0.14 micron filament Wires

Critical current densities of ultra fine filament wires

![Graph of critical current densities vs. magnetic field](image)
Influence of twist pitch on Jc degradations

Twist pitch length dependence of the critical currents $I_c$ at 4.2 K, 5 Tesla

Special process has been developed to reduce Twist Pitch down to 5 times the wire diameter with low Jc degradations

Second Generation of 50/60Hz Conductors

Conductor C = (6+1) Strands

<table>
<thead>
<tr>
<th>Strand diameter (mm)</th>
<th>L</th>
<th>T</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>377982</td>
<td>597102</td>
<td>920304</td>
</tr>
<tr>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>1.0 T</td>
<td>1.25</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Cu:CuNi:NbTi MF</td>
<td>0:4.3:1.0</td>
<td>CuNi 70-30</td>
<td>CuNi 70-30</td>
</tr>
<tr>
<td>Inner Core</td>
<td>CuNi 70-30</td>
<td>Cu-CuNi</td>
<td>Cu-CuNi</td>
</tr>
</tbody>
</table>

50 Hz Losses in the Wires versus filament diameters

$P^* = P / Jc (B_{max})$

AC losses of 50 /60Hz wires
Proximity effects on Hysteresis losses

Wire for Fusion Magnets: 40 kA cable (NET)
Structure: ((NbTi, CuNi1)m CuNi2, Cu2)n Cu3
m=499  n=78

<table>
<thead>
<tr>
<th>Wire diameter</th>
<th>1.9 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td># filaments</td>
<td>38922</td>
</tr>
<tr>
<td>Filament diameter</td>
<td>5.2 µm</td>
</tr>
<tr>
<td>NbTi / Cu / CuNi</td>
<td>29% / 43% / 28%</td>
</tr>
<tr>
<td>Twist pitch</td>
<td>19 mm</td>
</tr>
</tbody>
</table>

Characteristics of wire for Fusion 40 kA cable (NET)

<table>
<thead>
<tr>
<th>Filament diameter</th>
<th>5.2 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of CuNi around filament</td>
<td>0.45 µm</td>
</tr>
<tr>
<td>Thickness of CuNi around bundle</td>
<td>11 µm</td>
</tr>
<tr>
<td>Thickness of Cu around bundle</td>
<td>7 µm</td>
</tr>
<tr>
<td>Thickness of Cu outer shell</td>
<td>75 µm</td>
</tr>
</tbody>
</table>

NET 40kA Wire Coupling & Eddy Losses

<table>
<thead>
<tr>
<th></th>
<th>Time constant (ms)</th>
<th>Resistivity (Ω m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central zone</td>
<td>0.018</td>
<td>0.17 10^{-7}</td>
</tr>
<tr>
<td>Filament zone inside bundles</td>
<td>0.043</td>
<td>0.54 10^{-7}</td>
</tr>
<tr>
<td>Filament zone between bundles</td>
<td>0.656</td>
<td>0.8 10^{-9}</td>
</tr>
<tr>
<td>Copper shell</td>
<td>0.59</td>
<td>3.4 10^{-7}</td>
</tr>
<tr>
<td>Copper Nickel Shell</td>
<td>0.212</td>
<td>1.33 10^{-10}</td>
</tr>
<tr>
<td>Eddy current</td>
<td>0.526</td>
<td>1.33 10^{-10}</td>
</tr>
</tbody>
</table>

For copper RRR=100, B=11 T, overall time constant $\theta = 1.0$ ms

Loss $P = 2 \times dB/dt \times \theta / \mu_0$ (Duchateau/Turck/Ciazynski CEA)
**NET Wire Current Densities at 4.2K**

![Graph showing evolution of Jc with applied field](image)

**Critical Currents @ Superfluid Helium temperature**

<table>
<thead>
<tr>
<th>B(T)</th>
<th>Jc (A/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2500</td>
</tr>
<tr>
<td>4</td>
<td>2300</td>
</tr>
<tr>
<td>5</td>
<td>2000</td>
</tr>
<tr>
<td>6</td>
<td>1800</td>
</tr>
<tr>
<td>7</td>
<td>1600</td>
</tr>
<tr>
<td>8</td>
<td>1400</td>
</tr>
<tr>
<td>9</td>
<td>1200</td>
</tr>
<tr>
<td>10</td>
<td>1000</td>
</tr>
<tr>
<td>11</td>
<td>800</td>
</tr>
</tbody>
</table>

**Fusion Magnet: Wires with internal CuNi barrier**

- Process: Single stacking
- Matrix: Copper
- Number of filaments: about 8900 of 6 micron filaments
- Nominal CuSc ratio: 1.7
- CuNi Barrier around filamentary area

**Role of CuNi Internal Barrier:** reduce couplings between Strands

**Measured Losses: Influence of CuNi barrier positions**

<table>
<thead>
<tr>
<th></th>
<th>Strand # 1</th>
<th>Strand # 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Cu+CuNi)/NbTi</td>
<td>1.52</td>
<td>1.23</td>
</tr>
<tr>
<td>Cooper outer sheet thickness</td>
<td>22 µm</td>
<td>0</td>
</tr>
<tr>
<td>Hysteresis Losses</td>
<td>107 mJ / cm³ non Cu</td>
<td>128 mJ / cm³ non Cu</td>
</tr>
<tr>
<td>Coupling loss time constant</td>
<td>4.8 ms</td>
<td>7.0 ms</td>
</tr>
<tr>
<td>Coupling loss time constant of 3x3x4 CICC Cable</td>
<td>32 ms</td>
<td>12 ms</td>
</tr>
</tbody>
</table>

Cable sample tested in the Sultan test facility

Wire with internal CuNi barrier  Full size Cable 3x3x3x4

Comparison between Ni cladded Wire and CuNi barrier Wire

Concluding Remarks (1/2)

- Today Alstom MSA is the superconductor manufacturer which has the largest experience in Single Stacking Process:
  - 15 tons of SSC outer wire (4182 of 5 µm filaments)
  - 600 tons of LHC outer and inner Wires (6400 to 8892 of 6/7 µm filaments)

- Concerning Low Loss wires, thanks to the use of appropriate design, we are able to produce wires with ultra fine filament usable for 50/60 Hz applications

Concluding Remarks (2/2)

ALSTOM is very interested in participating to Pulsed Magnet Projects.
We are ready to contribute by our experience to both Development and Production Phase in the two areas:
- Wires and Cables
- Magnets
Thanks for your attention

www.alstom.com

Content

• Brief description of Outokumpu Copper Group
• Description of the SC Business Line
• SC wires production
• SC cables production
• Low losses wires

Outokumpu Copper – Strong presence around the world

• Annual net sales € 1.7 billion
• Employs some 6 400 people
• Production close to customers in Europe, the Americas and Asia
Superconductors in Outokumpu Copper Organization

Outokumpu Advanced Superconductors Inc. (OKAS Inc.)

Outokumpu Superconductors (OCSI)

Fornaci di Barga (LU) Mill

Superconductor Manufacturing in Pori

Subcontractings:
- NbTi, Nb
- Machining
- HIP/CIP
- EB Welding
- Hydrostatic extr.
- Insulation
- Cabling
History and present

- The 3 plants entered the field of superconductors between 1971 (Waterbury) and 1983 (Pori) and have since that manufactured a variety of metallic superconducting wires and cables in NbTi and Nb3Sn
- Range of wires comprises
  - Number of filaments up to 46000
  - Cu/non Cu ratio from 0.5 to 14
  - Piece lengths up to 300 kg
  - Critical current density up to 3300 A/mm² @ 5T, 4.2 K (NbTi) and 2700 A/mm² @ 12 T, 4.2 k (Nb3Sn)
- The production plants have modern equipment and sophisticated process technologies and are qualified according to the international standard ISO 9001:2000

Some highlights from Outokumpu activities

- 26 Km of flat Nb/Ti cable supplied to the National Institute for Nuclear Physics of Milan and wound in the Cyclotron currently used at the University of Catania for the therapy of eye tumours (Adrontherapy).
- 500 Km of Ni/Ti “Rutherford” cable used for winding 50% of the dipoles installed in the proton ring of HERA at DESY (Hamburg).
- 3000 Kg of Nb3Sn superconducting strand Ø 0.81 mm for the NET/ITER programme.
- 5000 Kg of Nb3Sn superconducting strand Ø 0.78 mm for the KSTAR programme.
- 1000 m of superconducting cable in Nb3Sn for the T.F.M.C (Toroidal Field Model Coil) for the NET/ITER nuclear fusion programme.
- 40 Km of Nb/Ti superconducting cable for the ATLAS detector and 50 Km of Nb/Ti superconducting cable for the CMS detector of CERN.
- 2.200 Km of Nb/Ti superconducting outer cable for the magnetic dipoles of the LHC project of CERN of Geneva.
- 60 Km of Nb/Ti superconducting cable for W7-X project for nuclear fusion, currently being supplied.

Outokumpu’s role in superconductors business

- Number 1 manufacturer
- Three facilities; Pori (Finland), Waterbury (USA) and Fornaci di Barga (Italy)
- Capacity and capability to manufacture high volumes
- In-house high purity Copper and advanced technology
- more than 30 years experience
- Major source of superconductors for MRI and NMR applications
- Main supplier for e.g. commercial SMES application and Crystal Grower application plus Maglev and Nuclear Fusion projects

SC wires and cables

- 1000 m of superconducting cable in Nb3Sn for the T.F.M.C (Toroidal Field Model Coil) for the NET/ITER nuclear fusion programme.
- 40 Km of Nb/Ti superconducting cable for the ATLAS detector and 50 Km of Nb/Ti superconducting cable for the CMS detector of CERN.
- 2.200 Km of Nb/Ti superconducting outer cable for the magnetic dipoles of the LHC project of CERN of Geneva.
- 60 Km of Nb/Ti superconducting cable for W7-X project for nuclear fusion, currently being supplied.
**NbTi wire for MRI systems**

**Nb$_3$Sn wire for ITER**

- 26 bundles distributed barrier
- 37 bundles distributed barrier
- 85 bundles distributed barrier

**HEP SC cables**

- LHC dipole Outer Cable
- ATLAS cable

**Thermonuclear Fusion SC cables**

- TFMC cable
- W7-X cable
Low losses wires

- Cu$_{90}$Ni$_{10}$ resistive matrix
- CuMn resistive matrix

Final characteristics of SMES Cu$_{90}$Ni$_{10}$ cable

<table>
<thead>
<tr>
<th>Type</th>
<th>Rutherford</th>
<th>Extracted strand 1</th>
<th>Extracted strand 2</th>
<th>SC strand before cabling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical current measurements (A/cm$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hysteresis losses (J/cm$^3$)</td>
<td>138</td>
<td>65</td>
<td>65</td>
<td>378</td>
</tr>
<tr>
<td>SC strand before cabling</td>
<td>0.012</td>
<td>0.047</td>
<td>0.072</td>
<td>0.113</td>
</tr>
<tr>
<td>RRR measurements</td>
<td>70</td>
<td>70</td>
<td>77</td>
<td>82</td>
</tr>
</tbody>
</table>

Critical current measurements: $I_c$ (A), $J_c$ (A/mm$^2$), $n$

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<tr>
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<th>Rutherford</th>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hysteresis losses (J/cm$^3$)</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>475</td>
</tr>
<tr>
<td>SC strand before cabling</td>
<td>0.011</td>
<td>0.047</td>
<td>0.072</td>
<td>0.113</td>
</tr>
<tr>
<td>RRR measurements</td>
<td>70</td>
<td>70</td>
<td>77</td>
<td>82</td>
</tr>
</tbody>
</table>

SMES wire - CuMn matrix

OK3900
- CuMn matrix in filament area
- Cu/CuMn/Sc=1.5:0.5:1
- Number of filaments: 3858
- Wire diameter (mm): 0.575
- Filament diameter (μm): 5.3
- Matrix/Sc: 2.0
- Twist pitch (mm): 11
- RRR: >140
- $I@ST, 4.2\,K$ (A): >260

OK2930
- CuMn matrix in filament area
- Cu/CuMn/Sc=2:1:1
- Number of filaments: 2928
- Wire diameter (mm): 0.93
- Filament diameter (μm): 8.6
- Matrix/Sc: 3.0
- Twist pitch (mm): 11.5
- RRR: >150
- $I@ST, 4.2\,K$ (A): >475
Concluding with low losses wires ...

- A large experience was acquired in the past years in resistive matrix SC wires, mainly for SMES applications.
- Some activities in the field of resistive matrix NbTi SC wires with fine filaments (below 3 \( \mu \text{m} \)) are currently under development to investigate the workability of the composite materials.
- In order to remain number 1 manufacturer of SC wires and cables, Outokumpu Superconductors BL is clearly interested in the development of new industrial products.
- Late addition...

Late addition ...

- Bruzzone was complaining his position of conductor's designer as being the last wheel in the magnetic system construction.... He was not right

The actual last wheel are conductor's manufacturers

Outline of the Talk

1. Operational Divisions
2. Capabilities
3. Recent Projects
4. Lessons Learned
5. SIS100 Magnets for FAIR
6. Conclusion
Operational Divisions

Magnet Technology

- Magnets and Components for Thermonuclear Fusion and Accelerators, Individual Magnet Developments
- Fabrication and Assembly of Normal and Super-conducting Magnets and Magnet Systems
- Individual Developments e.g. of Solenoid Systems
- Mechanical Structures for Nuclear and Magnet Technology
- Design and FE-calculations
- Feasibility and Fabrication Studies
- Management of Large Scale Projects for Nuclear Industry and Research Institutes
- Special-purpose Tools for Fabrication of Magnets
- Cryostats and Vacuum Vessels
- Manipulator Systems for Magnets

Nuclear Technology

Nuclear Service

Environment Technology

Our Capabilities

- Studies
  - FE-Calculations
  - Models, Prototypes & Product Development
  - Individual Solutions & Systems
- Series Production
- Project Management & Engineering
- Remote Handling & Specialized Tools

Product

Introduction to the Project: Dipole Cold Masses LHC

- Customer: CERN
- Fabrication of 416 dipole magnets
- 15 m long, 27 t
- Main components and part of tooling supplied by CERN
- Planned output: 3.5 magnets per week
LHC Dipole Fabrication

Collared Coil production at Würzburg
Approx. 4.500 m² production area

Cold mass production at Zeitz
Approx. 4.500 m² production area

LHC Dipole Fabrication - History and Outlook
• 1990: 10 m Prototype Cold Masses
• 1995: 10 m All Kapton Collared Coil
• 1997: Tooling Extension 15 m
• 1999: Two 15 m Prototype Collared Coils
• 1999: 30 Cold Masses
• 2002: 386 Cold Masses
• 2005: Collared Coil production finished
end of Cold Mass production November 2005
approx. 7 month ahead of contract schedule

Introduction to Non Planar Coils for W7-X
• Customer: Max-Planck-Institute for Plasma Physics
• Fabrication of 50 non-planar coils within consortium Wendelstein (ASG & BNN)
• 3,5 m diameter, 7 t
• Procurement of all components within scope of consortium Wendelstein
• Planned output: 2 magnets per month

W7-X Manufacture at Zeitz
W7-X Manufacture – History and Commitment

- 1998 – 1999: Test of DEMO coil in TOSKA facility at FZ-Karlsruhe
- 1998: Award of series contract

- End of 2005: Stable production rate of 2 magnet/month
- Target: April 2007 delivery of last magnet

Examples: Recent Projects

- 10 trim-coils for W7-X
- Toroidal support structure for RFX
- Automatic driven boogies for LHC
- AGAN: ITER TFMC

Lessons learned during past projects

- Fix essential requirements early (interfaces, design, specification and acceptance criteria) otherwise there is the danger of disturbance or interruption of production
- Establish a suitable and reasonable quality assurance Performing the right tests at the right time
- Establish a sophisticated maintenance concept for tooling
- Execute expediting for components consequently
- Industry has to be prepared for series production

SIS100 Magnets for FAIR

Task in EU 6th Framework Programm Project:
Consortium Leader: GSI
Partners: JINR, Accel, Babcock Noell Nuclear

Developments with respect to an series production:
- Insulation System
- Structural Elements
- Winding Scheme
Cable Insulation System

Nuclotron cable: 1) 2-phase He, 2) CuNi tube
3) sc. Wire, 4) NiCr wire 5) Kapton tape,
6) glassfiber tape (wet wound)

Nuclotron cable has limited storing time.
2 alternative insulation concepts:

- Prepreg Insulation
- All-Kapton Insulation

Structural Elements

Improvements of
• Mechanical properties of winding pack
• Positioning of cable

Suggestion: structural elements (G11)

Winding Scheme

Nuclotron Winding Scheme:
Layer-jump at coil-head makes structural elements complicated.

Alternative Winding Scheme

Simple shape for structural elements seems possible:
Conclusion

Past projects showed:
Close co-operation between the partners guarantees the best results.

Superconducting pulsed magnets are an interesting option for upgrades and future machines.

Generally:
We met the challenges in the past and are looking for the next.

Thank You!

- Consider conductors for following dipole magnet designs
  - 3 T, 3 T/s (CERN)
  - 5T, 1.5 T/s (CERN)
  - 6T, 1T/s (GSI)

- CERN requirement for future desired upgrade of PS and/or SPS
- GSI requirement is for present construction of FAIR facility

- CERN (LeRoy) proposes 0.65 mm wire with 150,000 1 micron filaments, Cu Ni barriers, perhaps $I_{op}/I_c = 0.6$
- GSI has immediate need & proposes less ambitious steps to achieve a low loss conductor.
• Present GSI wire design~0.825 mm with 3.5 micron filaments (4.3 micron available now) & all-copper matrix
• Future goal: 0.825 mm wire with 2.5 micron filaments, resistive interfilamentary matrix, to reduce hysteresis and coupling current losses by about 30%, without major R&D

What do we know?
• Jc of wires with smaller filaments is smaller (Alstom presentation)
• Wires with resistive matrices are unstable and as the wire diameter increases, Jc deceases (Brucker presentation)
• Hence, don’t make filaments too small or the matrix too resistive.
• CuMn interfilamentary matrix wires can have a good Jc (Outokumpu presentation)

Possible Wires for fast Ramping
2.5μm filaments in 0.8mm wire means ~40000 filaments

Hex single stack
• use hexagonal copper cans to keep the filaments in a ‘tidy’ array
• enables the single extrusion of up to 40000 filaments (300mm billet) or 30000 filaments (250mm billet)
• single extrusion produces less filament distortion
• copper or CuMn hex’s

Double stack
• extrude bundles of ~200 filaments
• stack ~200 bundles and re-extrude
• significant distortion of filaments
• copper between the bundles

Factors in making the choice

Hex single stack
• good filament shape
• low proximity coupling
• good Jc?

Con
• limit on filament diameter, N=30000 or 40000 depending on billet size?
• dynamic stability – or can we make small bundles and thicker hex’s?
• patent situation

Double stack
• no limit on filament diameter
• low proximity coupling
• good dynamic stability if bundle size <50-100μm

Con
• filament distortion, so must make filaments ~75% of nominal size, eg for 2.5μm effective need 1.8μm actual
• Jc?

For both types: CuMn jacket round each filament (to suppress proximity coupling) produces enough matrix crossing resistance for 1T/s, but extra barriers (CuNi?) will be needed for 4T/s

For both types: need CuMn around the filaments to suppress proximity coupling
R&D for Cable

1. How big can Ra be?
   - more computing of MQE with parameters directly related to the cables required by CERN and GSI – low Ra and high Ra (with and without core)
   - measure MQE for cored GSI001 cable with high Rc and low Ra
   - measure MQE for similar uncored cable with high Rc and high Ra

2. Joints and their effect on current partition
   - measure current partition between strands on cable samples (low Ra and high Ra with and without core) with different joints
   - investigate fast ramping performance of magnets with different types of joint

3. Insulation and cooling
   - measure heat transfer for GSI001 cable with cooling holes in boiling & supercritical helium
   - measure similar cable with no cooling holes in boiling & supercritical helium
   - measure SIS300 cable in boiling & supercritical helium

A combined function magnet
for the J-PARC neutrino Beam Line with a Fast Ramp Test

A. Yamamoto
For the J-PARC Neutrino Beam Line Group
To be presented at ECOMAG workshop
2005-10-26~28
Yoking Interfaced with Plastic Collar to Coil

Excitation Test Results

- The max. Exc. reached 7.7 kA with No Training Quench
- Fast Ramp Test – 1000 A/s (0.7 T/sec) (also no quench)

Summary

- Superconducting combined function magnets for J-PARC Beam Line successfully developed and tested at KEK,
- The magnet reach the Bmax of 4.7 T without training and a fast ramp rate of 0.7 T/s to reach the Bmax, as well,
- Magnet production started and the beam line to be commission in March, 2009

CIEMAT capabilities
CIEMAT capabilities

EFDA dipole magnetic design

EFDA dipole mechanical design

CIEMAT Ongoing projects (I)

- Testing of a combined superconducting magnet for TESLA 500.
- Design and fabrication of a superferric magnet for XFEL.
- Design and fabrication of different devices for CTF3.

(courtesy J. Lucas)
Main R&D Topics for fast-pulsed magnets

Minimization of eddy current and persistent current effects
- affect field quality
  correction system?
- produce large steady-state AC-losses
  appropriate magnet cooling system

Cryogenic system
- heat load is dominated by AC-losses in the magnet
  - SIS 100: 12 KW magnet/ beam pipe; 1 KW beam loss
  - SIS 300: 6 KW magnet/ beam pipe; 1 KW beam loss
- heat load varies with cycles

Mechanical structure / lifetime of the magnets
- SIS100: 200 millions cycles within 20 years
  - material fatigue, crack propagation

Cryogenic stability
- conservative stability margins

Main R&D Topics for fast-pulsed magnets (continued)

- Quench protection of the individual magnets
  - high charging voltage
    - stack of diodes or ‘warm bypass’
- Iron selection
  - search for the best compromise between
    high saturation flux density and low coercive force / high specific resistivity
    (I. Bogdanov, EPAC 04 WEPKF061)
- Radiation deposition due to primary beam loss affects (in the high intensity synchrotrons)
  - heat load of the cryogenic system
  - lifetime of components (coil insulation, diodes)
  - quench stability
    (E. Mustafin, EPAC TUPLT112)
Superconducting Magnets for SIS 100

R&D goals
- Improvement of DC-field quality
  - 2D / 3D calculations
- Guarantee of long term mechanical stability
  (≥ 2x10^6 cycles)
  - concern: coil restraint in the gap, fatigue of the conductor
- Reduction of eddy / persistent current effects
  (field, losses)

Nuclotron Dipole
- Collaboration: JINR (Dubna)
- Iron Dominated (window frame type) superferric design
- Maximum magnetic field: 2 T
- Ramp rate: 4 T/s
- Hollow-tube superconducting cable, indirectly cooled
- Two-phase helium cooling

Nuclotron Dipole - Alternatives
- Resistive
- Nuclotron Superferric Window-frame Dipole
  (cold iron, cold bore, cryogenic pumping)
- Superferric H-type design
  (warm iron, warm bore)
  Study at BINP, Russia

Nuclotron R&D: loss reduction
- Heat release in test dipoles
  - simplified FEM models for:
    - standard yoke
    - with SMP block
    - alternative end plate
  - horizontal cuts

AC Losses along Magnet axis z
- Temperature rise in the end part!

SIS 100 Dipole - Alternatives
- OPERA-3D calculations of the integral magnetic flux Φ(z)
**RHIC dipole**

Superconducting wire:
- NbTi-Cu (1:2.25)
- filament diameter 6 µm
- twist pitch 13 mm
- no coating

Rutherford cable
- no core

Coil
- phenolic spacer
- Cu wedges

Yoke
- \( H_c = 145 \) A/m
- 6.35 mm laminations

**RHIC type dipole GSI 001**

Superconducting wire:
- NbTi-Cu (1:2.25)
- filament diameter 6 µm
- twist pitch 4 mm
- Stabrite coating

Rutherford cable
- 2 x 25 µm stainless steel core

Coil
- stainless steel collar (G11 keys)
- G11 wedges

Yoke
- \( H_c = 33 \) A/m, 3.5% Silicon
- 0.5 mm laminations, glued

---

**RAMP RATE TESTS GSI001 (vertical bath)**

- 4 quenches to short sample limit
- continuous 2T/s operation up to short sample limit
- 3 cycles 4 T/s up to 4T

Thermal time constant ~ 1 min.

---

**SIS 300 - Dipole**


- cooling: one phase Helium 4.4 K
- temperature margin: 1.0 K
- option: lowering Helium-temperature
- collared coil supported by iron shell (taking part of the load)
- strand: diameter: 0.825 mm
- filament size: 3.5 µm
- Rutherford-cable: 36 strands with core (LHC outer layer)
- quench protection: needs heater, 20 magnets per PS / dump resistor

---

**cryogenic losses**

0-4 T, 1 T/s, triangular cycle: 8.8 W, 7.3 W/m

Loss contributions:
- hysteresis loss (not dependent on ramp rate): iron and sc filaments
- eddy current loss (dependent on ramp rate): sc filament coupling and interstrand coupling

Results:
- good agreement for hysteresis loss (intercept, dB/dt=0)
- discrepancies for eddy current loss (slope), especially at high fields > 3 Tesla
- measured values larger than calculated by theory
- unexpected contribution by ????
**Small filament size wire R&D**

**Motivation:** 60-70% of the coil AC-losses caused by wire magnetization

- filament size reduction
- but limit due to 'proximity coupling' $d_{fil} \geq 3.5\mu m$ for Copper matrix

**Preliminary tests:**
- $d_{eff} = 3.5\mu m$, but problems with stacking of 12000 monocores (1.5 mm wide)
- $d_{eff} = 4.8\mu m$ due to filament distortion (near the copper)

**Cable R&D (Nuclotron-type)**

**High current cable (LHE, GSI)**

**EU INTAS 03-54-4964 : improved N-CICC**

by Bottura, Wilson

by P. Bruzzone

by V. Keylin

realisation by VNIKIP

**Summary**

- Fast-pulsed sc magnets are foreseen for the synchrotrons of FAIR
- R&D to develop these magnets is under way.
- First dipole models have been built and tested.
- R&D will continue on quadrupoles and full size magnets.

**ACKNOWLEDGEMENTS**

I am greatly indebted to all members of the collaborations, to our consultants and to the members of the GSI magnet group for their dedicated work.
EOMAG-05
WG-2 : definition of critical parameters / 1

<table>
<thead>
<tr>
<th></th>
<th>SIS 100</th>
<th>PS II</th>
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</thead>
<tbody>
<tr>
<td>Peak field</td>
<td>2T</td>
<td>3T</td>
</tr>
<tr>
<td>Good field region H x V [mm]</td>
<td>130x60</td>
<td>130x80</td>
</tr>
<tr>
<td>Field quality</td>
<td>± 6 units</td>
<td>± 4 units</td>
</tr>
<tr>
<td>dB/dT [T/s]</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>Number of cycles (20 years)</td>
<td>200MCycles</td>
<td>60MCycles</td>
</tr>
<tr>
<td>Radiation load [W/m]</td>
<td>1</td>
<td>10</td>
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<tr>
<td>Peak radiation load [W/m]</td>
<td>3</td>
<td>30</td>
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<tr>
<td>Duration of a cycle [seconds]</td>
<td>2</td>
<td>3.6</td>
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<tr>
<td>Time of exposure</td>
<td>111 khours</td>
<td>60 khours</td>
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<tr>
<td>Typical refrigeration power W/m</td>
<td>10</td>
<td>20</td>
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<tr>
<td>Effective duty-cycle</td>
<td>0.5</td>
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<tr>
<td>Magnet length [m]</td>
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<td>4</td>
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<tr>
<td>Number of dipoles</td>
<td>108</td>
<td>100</td>
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<tr>
<td>Maximum voltage</td>
<td>1 kV</td>
<td>1 kV</td>
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</table>

EOMAG-05
WG-2 : definition of critical parameters / 2

<table>
<thead>
<tr>
<th></th>
<th>SIS 300</th>
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<tbody>
<tr>
<td>Peak field</td>
<td>6</td>
<td>4.5</td>
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<tr>
<td>Good field region H x V [mm]</td>
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<td>80</td>
</tr>
<tr>
<td>Field quality</td>
<td>± 2 units</td>
<td>± 2 units</td>
</tr>
<tr>
<td>dB/dT [T/s]</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Number of cycles (20 years)</td>
<td>1 MCycles</td>
<td>1 MCycles</td>
</tr>
<tr>
<td>Radiation load [W/m]</td>
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<tr>
<td>Peak radiation load [W/m]</td>
<td>3</td>
<td>30</td>
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<tr>
<td>Duration of a cycle [seconds]</td>
<td>24</td>
<td>12</td>
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<tr>
<td>Time of exposure</td>
<td>6.7 khours</td>
<td>7 khours</td>
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<tr>
<td>Typical refrigeration power W/m</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Effective duty-cycle</td>
<td>0.5</td>
<td>0.4</td>
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<tr>
<td>Magnet length [m]</td>
<td>2.9</td>
<td>6</td>
</tr>
<tr>
<td>Number of dipoles</td>
<td>108</td>
<td>750</td>
</tr>
<tr>
<td>Maximum voltage</td>
<td>1 kV</td>
<td>1 kV</td>
</tr>
</tbody>
</table>

EOMAG-05
WG-2 : conceptual design team

It is proposed the above critical parameters for the 4 design ranges are explored by 4 conceptual design teams animated by:

G. Moritz for SIS 100
D. Tommasini for PS II
P. Fabbricatore for SIS 300
Glyn Kirby for SPS II

The main aim of these teams shall be the identification of alternatives and of specific issues to be addressed for the respective design range.

EOMAG-05
WG-2 : critical issues

- Radiation dose on insulation (Ettore)
- Computer codes: electromagnetic codes AC&DC are OK (Bernhard & Fernando)
  - Quench propagation? (WG-03)
  - Thermohydraulic codes & models (WG-03)
- Long bent or short not bent? (WG conceptual teams)
- Choice of operating temperature (WG conceptual teams)
- Rules/tests for fatigue limits at low temperature, radiation environment (WG conceptual teams to identify specific issues relevant to their design range)
- Feasibility schedule for first model magnets
  - SIS 100: two years
  - PS II: three years
  - SIS 300: three years
  - SPS II: three years
ECOMAG-05
WG-2: Additional issues

• Flat-top for machine commissioning and operating cycle

ECOMAG-05
WG-2: conclusions

• the objective of the conceptual design teams is to clearly state the rational for design choices, identify critical issues, make plan for R&D including time schedule: to provide information for managerial decisions.

• continuous flow of information between working teams is the key for success

• next spring is a good time for a workshop

ECOMAG-05
Working group 3

Conclusion Session

WG 03A Magnet protection
WG 03B Heat transfer
WG 03C Magnetic measurements

ECOMAG-05
Working group 3A

Main topics for WG03A

• Magnet protection and quench detection in pulsed superconducting magnets

• In which aspects magnet protection has to be treated differently from quasi-DC magnets?
The protection of pulsed superconducting magnets may have to satisfy different requirements compared to the protection of slowly ramped superconducting magnets (quasi dc-magnets).

Especially the following components of a protection system are concerned:
- protection heaters (are they required or not)
- high current by-pass (is it required or not)
- quench detection system
- powering and energy extraction

The choice and dimensioning of these components depend on the ramp rate as shown in the following for the SIS Magnets for FAIR and for the LHC magnets for comparison.

The high inductive voltage contributions during pulsing will be a challenge especially for the quench detection.
For DC application one diode would be enough.

Use of LHC diodes

\[ V_{\text{turn-on}} = 4.2K \approx 5.5 \text{ V} \]

\[ V_{\text{dipole max}} = 37.8 \text{ V} \]

so use of 8 diodes

\[ V_{\text{stack turn-on}} = 44 \text{ V} \]

Note: The voltage drop across the by-pass should be as small as possible as it will drive a residual current through the magnet after a quench until the current dumping process has finished.

The warm by-pass with thyristors is a more complex system, but it consists of classical components with well-known behaviour and can be installed in low radiation areas. The complexity can affect the reliability during operation and maintenance is required.

The cold diode by-pass is less complex and may operate more reliable as long as the radiation load is not too high. Normally no maintenance is required. A replacement of damaged cold diodes on the other hand is very time consuming and expensive.
Working group 3A

**GENERAL CONCLUSIONS**

- Pulsed superconducting magnets allow high energy extraction rates without initiating a quench in the still superconducting magnets. Protection heaters and a current by-pass may not be required.

- The higher inductive voltage contributions across magnets and bus bars and electro-magnetic coupling effects during pulsing are a challenge for the quench detection systems. Multiple bridge-type detectors may be required or even specially developed comparators.

- High voltages to ground during energy extraction can be avoided by subdivision. More dump resistors, current breakers, and current leads would be needed.

---

Working group 3A

**Critical issues. Call for R&D.**

- Individual magnet quench detection and individual magnet protection as well as design of the magnet protection system must be included already in early stage of the magnet development (integrated design approach).
  - Critical parameters:
    - Inductance (keep as low as possible),
    - Quench velocity (depends on cable and magnet design, call for R&D).

- Radiation tolerance of bypass diodes is an issue. Material limitation:
  - 3 kGray in case of LHC diodes,
  - 30-50 kGray in case of epitaxial diodes.

- Possible way to go (K-H. Mess): development of fast superconducting bypass switch (2-5 year time schedule).

- Basic “quench” computer codes, like QUABER, exist but are not integrated with other magnet design codes.

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ECOMAG-05

**Working group 3B**

**Topics for WG3B**

- Cryogenics and heat transfer
- Review of available heat transfer experiments
- Thermal modeling of cross section
- Heat transfer between cable and surrounding helium

---

ECOMAG-05

**Working group 3B**

**WG 03B Heat Transfer 14:00 - 15:30**

- R. van Weelderen “High Heat Flux Extraction Paths From Magnet Structure” (20 min)
- A. Kovalenko “Engineering Heat Transfer Calculations In Pulsed Magnets For Accelerators” (20 min) (tbc)
- M. Calvi “Stability Margin Calculations In Superconducting Cables” (20 min)

Discussion
Heat extraction paths

- For a 10m long magnet, 100 W/m heat load, with the proposed temperature budget:
  - When conduction cooled via the ends an axial cross section of about 500 cm² need to be included in the magnet design. Significantly less if intermediate connections to a bayonet HX could be provided.
  - Conduction channels from the coil to the axial conduction of about 15 mm diameter, for 0.5 m radial vent spacing need to be included in the magnet design. About 8.5 mm for 0.2 m spacing.

Dubna experience and recent results.

- **FAST-RAMPED SUPERCONDUCTING CABLES**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Number</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer jacket</td>
<td>mm</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Copper - Nickel-Copper</td>
<td>mm</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Inner winding (NiCr wire)</td>
<td>mm</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Twist pitch of strands (NiCr wire)</td>
<td>mm</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Cable diameter with insulation</td>
<td>mm</td>
<td>7</td>
<td>7.34</td>
</tr>
<tr>
<td>Current density in the winding</td>
<td>A/mm²</td>
<td></td>
<td>122.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>219.1</td>
</tr>
</tbody>
</table>

**HOLLOW SC CABLE made from keystoned wires**

**SINGLE - LAYER COIL DIPOLE**

**4 T, 3-4 T/s Cos(θ)-style dipole**
**Working group 3B**

Dubna experience and recent results. Design variants of the hollow conductor

The wires fix themselves (arc principle) and form a cooling channel with small hydraulic resistance. The direct contact of two-phase helium flow with the wires provides the highest cryogenic stability any time interval.


**Working group 3B**

THEA, SPQR Codes. Transient Losses.

Stability margin calculation in 1D model

Steady State Losses

A heat transfer in the main magnets. Arrows indicate the path of the heat through magnet coil.
**Working group 3B**

**Steady State Losses. Network Model.**

Network model of the main magnet coil

**Conclusions**

- Several different approaches and schemes to extract the heat generated in pulsed superconducting magnets (with ramp rates of the order of 6 T/s) were discussed.

- The most mature and best performing technique of heat extraction from magnet coil seems to be at present the hollow conductor cooled with the two phase forced flow of He, which is under continuous development in Dubna. Results obtained within this project should serve as a reference for all variant design and approaches:
  - the two phase He forced flow through the hollow conductor allows extraction of 100W/m

- R&D and specific experimental tests need to be carried out to establish a standard approach to compute heat transfer in pulsed magnet cross sections.

- Relevant experiments and simulations, which are undergoing at Saclay, CERN and WUT in Wroclaw need to be intensified in view of the requirements of the pulsed superconducting magnets.

**ECOMAG-05 Working group 3C**

**Topics for WG3C**

- Fast magnetic measurements
- Accuracy and rates achievable with short term development (< 2 years)
- with more development (< 5 years)
WG 03C Magnetic Measurements 16:00 - 17:30
(video conference session)

P. Schnizer “Measuring Fast Pulsed Magnets Using Rotating Coils In Step Mode”
A. Jain “Measurements By Means Of Stationary Coils Of The Field Quality In Supercond. Magnets At High Ramp Rates”
B. L. Bottura “Tools for Fast Magnetic Measurements

Discussion

<table>
<thead>
<tr>
<th></th>
<th>pros</th>
<th>cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct</td>
<td>all at once</td>
<td>complicated to manufacture, aliasing, limited N</td>
</tr>
<tr>
<td>ramp</td>
<td>by ramp</td>
<td>stability of the power supply, magnet</td>
</tr>
<tr>
<td>rotating</td>
<td>reuse of existing equipment</td>
<td>only for “slow” ramp rates, complicated analysis</td>
</tr>
<tr>
<td>special devices</td>
<td>direct multipole measurement</td>
<td>difficult to manufacture needs a lot of probes</td>
</tr>
</tbody>
</table>

Discussion in detail follows.
Fast rotating coils - summary

- Present systems
  - absolute accuracy 3 units @ 17 mm
  - short term repeatability 0.03 units @ 17 mm
  - bandwidth 0.05 … 0.5 Hz
- On-going development at CERN to achieve
  - the same accuracy and repeatability
  - bandwidth 1 … 10 Hz
- R&D on
  - fast, continuous rotation (dampers, slip rings, …)
  - electronics (digital integrators)
  - algorithm (corkscrewed harmonic analysis)

16 Printed Circuit coils, 10 layers
6 turns/layer
300 mm long
0.1 mm lines with
0.1 mm gaps
Matching coils selected from a production batch
Radius =
26.8 mm (GSI)
35.7 mm (BioMed)
A Novel MM method.
Magnetooptical Cotton-Mouton effect.

From the slope,
\[ \beta = \frac{2\pi(n_i - n_0)}{\lambda} = -2\pi M B^2 \]
and \( l = 2 \times 14.3 \) m

To be compared to the value from the literature:
\[ M_{\text{exp}} = 1.12 \pm 0.02 \times 10^{-6} \text{ rad T}^{-2} \text{ m}^{-1} \]

Feasibility and reference accuracy parameters (harmonics - 0.5 unit; main field integral abs. - 100 units) of this technique were demonstrated within Nuclotron and UNK.

Other techniques based on pick-up coils:
- "Stationary coils", developed at BNL, started to produces first results but there is scope for many improvements for better accuracy. System requires further development,
- "Fast rotating coils", under development at CERN, require development effort (<2 years) and prove of accuracy/performance.

A novel, promising magneto-optical technique, based on Cotton-Mouton effect, particularly suitable for pulsed magnets, was presented by P. Pugnat. Further R&D is needed to explore and to demonstrate full capacity of this technique.

Conclusions

- Several different approaches to magnetic field quality measurements in pulsed superconducting magnets (with ramp rates of the order of 2 T/s) were discussed.
- Taking into account what is available in the different laboratories, the most mature project seems to be the "ramp to ramp" (or "step rotation") technique, which is under development in GSI.
- Other techniques based on pick-up coils:
  - "Stationary coils", developed at BNL, started to produces first results but there is scope for many improvements for better accuracy. System requires further development,
  - "Fast rotating coils", under development at CERN, require development effort (<2 years) and prove of accuracy/performance.

A novel, promising magneto-optical technique, based on Cotton-Mouton effect, particularly suitable for pulsed magnets, was presented by P. Pugnat. Further R&D is needed to explore and to demonstrate full capacity of this technique.
I would like to acknowledge all participants of WG3 and in particular all speakers for professional, high quality presentations.

WG3 was a forum of discussion to advance the art and science of simulations, modeling, experiments and measurements in support of superconducting magnet design programs.

Scope covered three very different aspects of superconducting magnet systems. To review and to discuss within 90 min each of three disciplines, appeared to be the most critical issue and challenge.
Summary of three days

- Aims of the workshop
- A digression on various triangles
- Achieved objectives and identified R&D
- Networking results

Aims

- Summarise the requirements from particle physics and accelerator upgrades to define a set of parameters for the development of pulsed superconducting magnets for accelerators.
- Verify where we stand with our present design and manufacturing capability.
- Translate the above requirements in specifications for the performance of strand, cable, magnet and auxiliaries (i.e. cryogenics, power supplies, instrumentation, protection, measurement systems).
- Define the R&D required to achieve the above specifications and produce a tentative road-map for a procurement and prototyping activity.

The tri-lemma of PERITVS DELINEANDI OPT. DVCTORVM

Achieve a balanced design meeting performance specifications

The magic triangle of pulsed cables

How can we remove the magic?

If you pray hard enough
And you really believe it
It will, eventually, work…
One more triangle…

annoying
management

Cost and user’s support matter!

users' requirement
designers and builders expertise

Do we know what we want? A qualified YES

Results - 1

- Four magnet families have been identified
  - FAIR
  - Upgrade of the CERN injector chain (PS & SPS)
- Ball-park parameters discussed
- Some brainstorming on the main design options
- Detailed discussion of the most advanced and challenging design (SIS-300)

Parameters selection - WG2

- Low field, high repetition rate
  - SIS-100: 2 T, 4 T/s, +/- 6 units, 130x60 mm, $2 \times 10^8$ cycles, 10 W/m
  - PS-upgrade: 3 T, 3T/s, +/- 4 units, 130x80 mm, $6 \times 10^7$ cycles, 20 W/m
- Medium field, moderate repetition rate
  - SPS-upgrade: 4.5 T, 1.5 T/s, 80 mm, +/- 2 units, $10^6$ cycles, 10 W/m
  - SIS-300: 6 T, 1 T/s, 80 mm, +/- 2 units, $10^6$ cycles, 10 W/m

Can we build these magnets? YES

Results - 2

- All magnet families have difficulties and challenges
  - Conductor margin, losses, heat removal (all) in Pierluigi’s triangle
  - Field quality in ramped conditions (all)
  - Large dynamic range (PS-upgrade)
  - Radiation (1…10 MGy), fatigue, joints
  - …
- All factors can be addressed and seem to be in reach of present technology, possibly need optimized industrial process
Strand design - WG1

- **Existing strand(s)**
  - D = 0.5 ... 0.8 mm
  - Jc > 2500 ... 3300 A/mm²
  - Dfil < 3.5 ... 5 μm (Qh (0-3-0 T, 4.2 K) = 25 mJ/cc)
- **Low Loss Strand I**
  - D = 0.8 mm
  - Jc > 2700 A/mm²
  - Dfil < 2.5 μm (Qh (0-3-0 T, 4.2 K) = 15 mJ/cc)
  - Copper/Matrix/NbTi = ?/?/1
  - RRR = ?
- **Low Loss Strand II**
  - D = ?
  - Jc > 2000 A/mm²
  - Dfil < 1 μm (Qh (+/- 3 T, 4.2 K) = 3.5 mJ/cc)
  - Copper/Matrix/NbTi = ?/?/1
  - RRR = ?

Comments

- Good magnets rely on a good superconducting strand, but fail because of poor electrical insulation (call the house electrician) and leak tightness (call the house plumber)
  - Obviously, any strand R&D has to start first (to keep the peritus delineandi optimorum ductorum happy ?!?)
  - Many warnings on the several, critical aspects to be considered in the initial design process
    - Radiation dose (classical insulation scheme ?), fatigue (long life and availability issues), field quality (large dynamic range), joints (AC performance), protection, measurement (fast field changes), economics of the whole choice (ISR tunnel at CERN), …

On the strand

- Present strand technology is sufficient for the demands of FAIR
- The requirements for an efficient upgrade of the CERN injector chain demand further reduction of AC loss (factor 3...5)
  - Industrialize the baseline strand for SIS-300 through the production of several billets to achieve consistent and continuous performance
  - Set clear targets for improved performance of FAIR magnets and economic CERN injector upgrade and assist manufacturers in this development

On the cable

- Open issues remain on basic understanding of collective thermal and electromagnetic behaviors
  - Heat transfer experiments (as proposed)
  - Stability experiments and simulations (as proposed)
    - What is the optimum resistance ?
  - Perform AC loss measurements (program ?)
On the magnets
- We did not discuss prototypes, but responsibles were identified for the four magnet families (WG-2)
  - Examine magnet concepts
  - Question the conductor selection
  - Identify main R&D issues (see presentation of ES)
  - Quantify work (prototypes, how many, by when ?)

The final answer will only come from a magnet test: we do need prototypes!

Networking
- This is a CARE (Coordinated Accelerator Research in Europe) workshop
- Review/Spread/Discuss information on pulsed magnets (AC magnets)
  - ≈ 70 participants from HEP labs, fusion labs, industry
- Industry involved from the start of the brainstorming
- General interest in the community of clients and producers

Follow-up
- We (organizers) will collect and distribute the material discussed (www and/or CD, 2 weeks)
  - Contributors/presenters please send write-ups if available!
- Design coordinators to maintain momentum on the identified issues
- Reconvene in 6…8 months to verify progress
  - WAMDO, April 3-7 2006, CERN (Archamps)

Thank you!
- To the WG chairmen (tough job)
- To the local organizers, and especially to A. Della Corte, U. Gambardella, C. Melorio

• To the participants for the time, effort and stimulating discussion