12th FAIR Machine Advisory Committee: SIS18 and SIS100 RF

Contents

• Overview on SIS18 and SIS100 RF systems
• Status of individual RF projects/work packages
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  • SIS100 Bunch Compressor System
  • SIS100 Barrier Bucket System
  • SIS100 Longitudinal Feedback System
  • SIS18 h=2 System
  • Interfaces & Low-Level RF (LLRF)
• Results of recent machine development experiments

All results presented here are based on the work of the colleagues of the GSI Ring RF department PBRF, several other departments, and collaboration partners
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#### Synchrotron RF Systems

<table>
<thead>
<tr>
<th>Ring</th>
<th>RF System</th>
<th>Frequency Range [MHz]</th>
<th>Voltage per Cavity [kV]</th>
<th>Duty Cycle</th>
<th>Length</th>
<th>Qty</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS18 Upgrade</td>
<td>Ferrite cavities, h=4 Accel. h=2</td>
<td>0.85 ... 5.5</td>
<td>16</td>
<td>100%</td>
<td>3.0 m</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Bunch Compression</td>
<td>0.43 ... 2.8</td>
<td>13.3</td>
<td>100%</td>
<td>1.3 m</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8/1.2</td>
<td>40</td>
<td>0.05%</td>
<td>1.2 m</td>
<td>1</td>
</tr>
<tr>
<td>SIS100 2.8.4</td>
<td>Accel. h=10 (Ferrite) Bunch Compression</td>
<td>1.1 ... 3.2</td>
<td>20</td>
<td>100%</td>
<td>3.0 m</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Barrier Bucket</td>
<td>0.310/0.560 broadband</td>
<td>40</td>
<td>0.3%</td>
<td>1.2 m</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Long. Feedback</td>
<td>broadband</td>
<td>15</td>
<td>15%</td>
<td>1.1 m</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(12)</td>
<td>100%</td>
<td>100%</td>
<td>1.1 m</td>
<td>2</td>
</tr>
</tbody>
</table>
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Status of Individual RF Projects
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SIS100 Acceleration System (2.8.4.1)
(FAIR Procurement)
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**SIS100 Acceleration**

*Project Leader: Dr. H. G. König   Deputy: Dr. U. Laier*

**Tasks:**
- Main RF system of the SIS100
- Acceleration (h=10)

**Main Parameters** (one of 14 RF units):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>$1.1 &lt; f \leq 3.2$</td>
</tr>
<tr>
<td>Gap voltage (kV)</td>
<td>0.03 to 20</td>
</tr>
<tr>
<td>Harmonic distortion of gap voltage</td>
<td>$\leq -26$ dB</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>c.w.</td>
</tr>
<tr>
<td>Maximum beam impedance at 0.5 kV ($\Omega$)</td>
<td>3000</td>
</tr>
<tr>
<td>Maximum beam impedance at 20 kV ($\Omega$)</td>
<td>2000</td>
</tr>
<tr>
<td>Maximum RF power delivered to the beam (kW)</td>
<td>30</td>
</tr>
<tr>
<td>Aperture of the beam pipe, circular diameter (mm)</td>
<td>150 (CF160)</td>
</tr>
<tr>
<td>Installation length, flange to flange (m)</td>
<td>3.0</td>
</tr>
<tr>
<td>Available installation height (m)</td>
<td>2.1</td>
</tr>
<tr>
<td>Height of beam axis (m)</td>
<td>1.4</td>
</tr>
<tr>
<td>In situ heating of the cavity beam pipe (°C)</td>
<td>300</td>
</tr>
</tbody>
</table>
SIS100 Accelerating System

- Modified SIS18 ferrite cavity
- Reproduction of FXC8C12m ferrite ring cores desired
- One tetrode RS2054
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General Status – SIS100 Acceleration

Project Leader: Dr. H. G. König    Deputy: Dr. U. Laier

“Done”

• Specification (released) based on modification of SIS18 ferrite cavity
• First call for tenders failed (costs too high)
• Negotiations with different potential suppliers took place
• Second call for tenders now completed
• Letter of intent (LoI) submitted to main contractor
  (includes cavity, power amplifier and supply unit with PLC
  – LLRF will be provided by PBRF dept.)

“Still Outstanding”

• Contract with main contractor still to be signed
• Agreement with ferrite supplier on ring core specification
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SIS100 Bunch Compressor System (2.8.4.3)
(German Inkind Contribution)
General Status – SIS100 Bunch Compression

**Task:** Bunch compression \((h=2)\) by 90° rotation of bunches in phase space

**Main Parameters** (one of 9 RF units):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>(0.310 \leq f \leq 0.560)</td>
</tr>
<tr>
<td>Gap voltage (kV)</td>
<td>1 to 40</td>
</tr>
<tr>
<td>Maximum beam impedance at 40 kV ((\Omega))</td>
<td>1000</td>
</tr>
<tr>
<td>Minimum bunch pulse width (ns)</td>
<td>30</td>
</tr>
<tr>
<td>Maximum bunch current (A)</td>
<td>150</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>(3 \times 10^{-3})</td>
</tr>
<tr>
<td>Maximum RF pulse duration ((\mu s))</td>
<td>3000</td>
</tr>
<tr>
<td>Maximum repetition rate (Hz)</td>
<td>1</td>
</tr>
<tr>
<td>Aperture of the beam pipe, circular diameter (mm)</td>
<td>150 (CF160)</td>
</tr>
<tr>
<td>Installation length, flange to flange (m)</td>
<td>1.2</td>
</tr>
<tr>
<td>Height of beam axis (m)</td>
<td>1.4</td>
</tr>
<tr>
<td>Available installation height (m)</td>
<td>2.1</td>
</tr>
<tr>
<td>In situ heating of the cavity beam pipe (°C)</td>
<td>300</td>
</tr>
</tbody>
</table>

Source: CDR Aurion GmbH
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General Status – SIS100 Bunch Compression

Project Leader: Dr. H. G. König  Deputy: PD Dr. P. Hülsmann

“Done”

• Call for tenders completed
• Contract with main supplier signed (cavity, amplitude control loop, power amplifier – supply unit and further LLRF to be delivered by GSI/PBREF)
• CDR available
• Specification of supply unit available

“Still Outstanding”

• Approval of CDR under preparation
• Preparation of call for tenders for supply units
SIS100 Barrier Bucket System (2.8.4.4)
(German Inkind Contribution)
General Status – SIS100 Barrier Bucket

**Task:** Pre-compression by moving single-sine wave barriers

**Main Parameters** (one of two RF units):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-sine duration (ns)</td>
<td>555</td>
</tr>
<tr>
<td>Max. barrier voltage (kV)</td>
<td>15</td>
</tr>
<tr>
<td>Duty cycle (barrier/total)</td>
<td>15% / 3%</td>
</tr>
<tr>
<td>Aperture of the beam pipe, circular diameter (mm)</td>
<td>150 (CF160)</td>
</tr>
<tr>
<td>Installation length, flange to flange (m)</td>
<td>1.1</td>
</tr>
<tr>
<td>Height of beam axis (m)</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**Note:** Pre-distortion of RF signals is needed to generate single sine waves.
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General Status – SIS100 Barrier Bucket

Project Leader: M. Frey
Deputy: A. Klaus

“Done”

• Results of different barrier bucket machine experiments available (G. Schreiber)
• Specification exists
• Results from R&D projects available (e.g. Helmholtz ARD)
• Recent calculations of heat flow lead to higher cooling requirements, official change request under preparation

“Still Outstanding”

• Revised specification
• Call for tenders
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R&D Results for Barrier Bucket System

Signal Generation

- Firmware with TDC allows shifting of single-sine pulses without significant steps (PhD work E. Bayer completed)
- Studies on small-signal generation started (see below)
- R&D project started for handling nonlinear cavity system behavior (large-signal)
SIS100 Longitudinal Feedback System (2.8.4.5)

(German Inkind Contribution)
General Status – SIS100 Longitudinal Feedback

Project Leader: R. Balß  
Deputy: Prof. Dr. H. Klingbeil

Task:  
• Damping of coherent longitudinal bunch oscillations  
• At least dipole and quadrupole mode

“Done”

• Results of different machine experiments available  
• Specification exists (preliminary)  
• Results on LLRF/feedback loop available from research project  
  (BMBF Verbundforschung @ TU Darmstadt)

“Still Outstanding”

• Specification of cavity closely related to SIS100 Barrier Bucket cavity  
• Approval of specifications  
• Call for tenders
Beam Experiment Longitudinal Feedback

Responsible: K. Groß  
(18.10.2014)

- One ferrite cavity produced feedback voltage, whereas the other cavity created the normal bucket (equivalent to future SIS100 operation)
- Bunch-by-bunch demultiplexing and multiplexing
- Bandwidth of ferrite cavity not sufficient for bunch-by-bunch operation
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SIS18 h=2 System (2.14.11.1)
(SIS18 Upgrade)
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SIS18 h=2 System

Project Leaders (system responsibility/technical responsibility): PD Dr. P. Hülsmann, R. Balß

**Task:** Dual-harmonic operation in combination with old ferrite cavities

**Main Parameters** (one of 3 RF units):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>0.43 to 2.8</td>
</tr>
<tr>
<td>Gap voltage (kV)</td>
<td>13.3</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>CW</td>
</tr>
<tr>
<td>Aperture of the beam pipe, circular diameter (mm)</td>
<td>150 (CF160)</td>
</tr>
<tr>
<td>Installation length, flange to flange (m)</td>
<td>1.34</td>
</tr>
<tr>
<td>Maximum power consumption (kW)</td>
<td>600</td>
</tr>
<tr>
<td>Cooling water for power amplifier</td>
<td>300 l/min</td>
</tr>
<tr>
<td>Cooling oil for cavity</td>
<td>36 m³/h=600 l/min</td>
</tr>
</tbody>
</table>


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SIS18 h=2 System

Project Leaders (system responsibility/technical responsibility): PD Dr. P. Hülsmann, R. Balß

- Cavity (designed by P. Hülsmann) - opened
- Oil cooling system for cavity
- Pressure tank with MA ring cores (FT3M) - opened
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SIS18 h=2 System

Project Leaders (system responsibility/technical responsibility): PD Dr. P. Hülsmann, R. Balß

LLRF System for SIS18 h=2 Cavity

Platform for power distribution, power supply unit & oil cooling
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Supply Unit for SIS18 h=2 System

Project Leaders (system responsibility/technical responsibility): PD Dr. P. Hülsmann, R. Balß

Supply Unit for SIS18 h=2 System (OCEM Energy Technology)
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SIS18 h=2 System

Project Leaders (system responsibility/technical responsibility): PD Dr. P. Hülsmann, R. Balß

SIS18 h=2 cavity with tetrode power amplifier on top (photography: G. Otto, GSI)
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SIS18 h=2 System – first beam experiment

Project Leaders (system responsibility/technical responsibility): PD Dr. P. Hülsmann, R. Balß

Water fall plot of dual harmonic operation (B. Zipfel) – FAIR@GSI Newsletter, May 2014
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SIS18 h=2 System

Project Leaders (system responsibility/technical responsibility): PD Dr. P. Hülsmann, R. Bals

“Done”

• Commissioning of first unit completed (with beam: 05.03.2014)
• Results of first machine experiments available
• All components for second and third unit delivered

“Still Outstanding”

• Assembly and installation of 2nd and 3rd unit
Interfaces & Low-Level RF (LLRF)
Control Aspects, LLRF Requirements

- CW systems (e.g. accelerating systems) vs. pulsed systems (e.g. bunch compressor)
- Cavities with "high" Q factor (e.g. accelerating systems, Q=5...10) vs. broadband cavities (e.g. barrier bucket, Q<1) → different response times
- Fundamental RF frequencies: 300 kHz...5.4 MHz (exception: NESR high harmonics, CRYRING 10 kHz), partly with higher harmonics, fast ramping
- Mutual synchronization of cavities required, also multi-harmonic (requirement ±3°, note: 1° phase deviation @ 5.4 MHz ↔ about 500 ps)
- Mutual synchronization of synchrotrons (e.g. for bunch-to-bucket transfers)
- Several RF supply areas in SIS100
- Longitudinal beam stabilization (beam phase control, longitudinal feedback), especially for high beam intensities
- Complex RF manipulations (barrier bucket, dual harmonic acceleration, bunch merging, etc.)
General Status – Interfaces & LLRF

Project Leader LLRF: Dr. K.-P. Ningel
Project Leader Gap Periphery: Dr. H. G. König

“Done”

• New digital LLRF architecture fully established
• Results of different machine experiments available
• Specifications exist
• Several procurement steps/call for tenders (depending on component)

“Still Outstanding”

• Many different components with different status (some ready for series production, others in design phase)
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Modular Driver Amplifier

- modular solution, developed by commercial company in close collaboration with PBRF dept.
- 500W per module
- 300 kHz...6 MHz
- flat phase response: max. 0.6° for Δf=10 kHz (even much less for upper frequency range)
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IF Preprocessing for DSP System

Frequency Generator
(21.4 MHz IF, 28.533 MHz Clock)
(A. Klaus, H. Klingbeil, K.-P. Ningel)

Mixer Module
(21.4 MHz IF, 250kHz bandwidth)
(A. Klaus, H. Klingbeil, K.-P. Ningel)

Controller (e.g. for AGC)
(H. Klingbeil, M. Kumm, S. Schäfer, C. Thielmann)
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IF Preprocessing for DSP System: Offset LO and AGC Modules

Digital Offset-LO
(M. Kumm)

Fast AGC
(S. Sanjari)
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DSP System and DSP Interface Board DIB

DSP System (Sundance Ltd)
- 2 x TMS320C6713
- XILINX FPGAs
- 2 ADC+2 DAC channels
- Diamond RTOS (3L Ltd)

(H. Klingbeil, GSI RF software)

Call for tenders for new DSP system under preparation

Optical DSP Interface Board (oDIB)
(S. Schäfer)
Fiber-Optical Hub (FOH) and Ramp Converter

**Fiber-Optical Hub (FOH)**
Multiplexing of ramp data (ODL) and control telegrams (OTR) via DSP Link (electrical) (S. Schäfer)

**Ramp Converter**
Conversion of electrical ramps into ODL ramps and vice versa (C. Thielmann)
Amplitude and Resonant Frequency Control

**Resonant Frequency Controller**
(H. G. König, T. Wöber)

**Amplitude Detector**
(A. Klaus, U. Niedermayer, S. Schäfer)

**Amplitude Modulator**
(A. Klaus, H. G. König, J. Mohr, T. Wöber)
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New Generic Digital Controller

GDC
(A. Klaus, S. Schäfer)

- Already works in the new SIS18 h=2 cavity system, first beam acceleration took place on March 5th, 2014
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Distribution Amplifier (Predecessor of Switch Matrix)

- 4 RF channels, 2 fixed outputs each
- 4 x 2 switched outputs
- remote control via FIB/OTR (T. Wollmann) or Ethernet
- DC...30 MHz (3dB bandwidth), 13 dBm max
  (H. Klingbeil, M. Kumm, J. Mohr, K.-P. Ningel)

Digital Amplitude and Phase Detector

- also used in spark-over detection
  (S. Schäfer)
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Calibration

Calibration Electronics Module CEL
(S. Schäfer, A. Klaus)

- Output depends on digital frequency ramp (e.g. for phase correction) and, optionally (e.g. for amplitude correction), also on analog input voltage
- Software packages for automatic calibration (*B. Zipfel, D. Lens*)
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**FAIR RF Maintenance & Diagnostics System**

- Remote firmware update, e.g. via JTAG
- Remote data acquisition & analysis
Two optical fiber channels (2x in, 2x out), typically 1 x Optical Token Ring (OTR) + 1 x Optical Direct Link (ODL)

- FIB is used for example as
  - Central Control System Interface (CCS-FIB)
  - Motherboard for DDS
- FIB II: Altera Cyclone EP1C6Q240C8

New version FIB III under development: Altera ARRIA II GX
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RF Signal Generation: DDS

**DDS module** of the ring RF dept. consists of
- FPGA interface board (FIB) as motherboard and
- DDS piggyback as FPGA adapter board (FAB)  
(M. Kumm, P. Moritz, C. Thielmann, H. Walter)
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## RF Signal Generation: DDS

**Responsible: C. Thielmann**

- **Features:**
  - All DDS units inside the same crate are strictly synchronous – independent of their harmonic number, $\pm 1^\circ$ reached
  - Calibration/phase correction (D. Lens, S. Schäfer) currently external, in future inside FPGA on DDS module
  - External ODL ramps for phase or frequency correction in closed-loop control operation
  - OTR configuration

- **Next steps:**
  - Porting functionality to new SCU/FESA control system (first operation: CRYRING)
  - New FIB3 mother board
  - Change of clock frequency from 25 MHz to 200 MHz
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Bunch Phase Timing System (BuTiS)

• Different RF supply areas in SIS100
• RF signals of variable frequency should not be distributed since delay compensation is difficult (fast ramping!)
• Better: Distribution of fixed-frequency reference clock signals → Idea of BuTiS (P. Moritz)
• Synchronized clock signals for DDS modules will guarantee coherence between different rooms/areas
• Synchronous activation of ramp data has to be ensured in addition → Resynchronization, cooperation with White Rabbit

Extracted from preliminary FAIR drawing
BuTiS
(P. Moritz, M. Bousonville, B. Zipfel)

Clock Signal Distribution
- Target stability: 100ps/km
- Optical fiber
- Transport delay compensation based on measurement of optical delay

Resynchronization
Information from central control system (e.g. ramp interpolation points)

Clock Signal Distribution Diagram:
- Clock 1 (100 kHz)
- Clock 2 (200 MHz)
- BuTiS Decoder
- Local Device (e.g. DDS)
- Command
- Availability of data
- Activation of data
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BuTiS
(P. Moritz, M. Bousonville, B. Zipfel)

BuTiS Center

BuTiS Receiver
(WORK Microwave, Holzkirchen)

Switch Matrix
- Call for tenders completed
- FoS expected in 12/2014
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Machine Development Experiments in SIS18
Bunch Merging Experiment 30./31.03.2012

- $^{238}\text{U}^{73+}$
- $h=4\rightarrow2\rightarrow1$
- $6\text{kV}/3\text{kV}/1.5\ \text{kV}$
- $400\ \text{MeV/u}$
- $1\cdot10^9$
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Bunch Merging Experiment 30./31.03.2012

- 238U73+
- h=4→2→1
- All ramps provided by central control system (old one), therefore de- and rebunching on flattop was easier to implement (will of course never be used in standard operation)
Bunch Merging Experiment 30./31.03.2012

Contributors: Hartel, Kaufmann, Klingbeil, Laier, Lens, Mondry, Moritz, Ningel, Reeg, Reimann, Riehl, Schäfer, Schütt, Spiller, Thielmann, Winnefeld, Zipfel
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Bunch Merging Experiment 30./31.03.2012

Calibration Curves that were used:
Bunch Merging & Compression Experiment 18.09.2014

- $^{124}\text{Xe}^{48+}$
- Merging $h=4 \rightarrow 2 \rightarrow 1$ and subsequent bunch compression at 300 MeV/u with SIS18 bunch compressor
- All ramps and switching commands provided by new LSA data generation
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Bunch Merging & Compression Experiment 18.09.2014

- Unfortunately, the SIS18 bunch compressor was not fully operational
- Therefore, the compression ratio could not be maximized
- However, it was possible to verify the LLRF control

FCT beam signal
Thank you!