Technical Design Report for the CBM

Superconducting Dipole Magnet

The CBM Collaboration

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Summary

This document describes the technical design of the superconducting dipole magnet for the Compressed Baryonic Matter (CBM) experiment at FAIR. The magnet houses the Silicon Tracking System (STS), and provides a magnetic field integral of 1 Tm which is needed to obtain a momentum resolution of $\Delta p/p = 1\%$ for track reconstruction at FAIR beam energies.

The magnet gap has a height of 140 cm and a width of 250 cm in order to accommodate the STS with a polar angle acceptance of $\pm 25^\circ$ and a horizontal acceptance of $\pm 30^\circ$. The magnet is of the H-type with a warm iron yoke/pole and cylindrical superconducting coils in two separate cryostats like the SAMURAI magnet at RIKEN. The potted coil has 1749 turns. The wire – similar to the CMS wire – has Nb-Ti filaments embedded in a copper matrix, and is soldered in a copper stabilizer with a total Cu/SC ratio of about 13 in the conductor. The operating current and the maximal magnetic field in the coils are 686 A and 3.25 T, respectively. The coil case made of stainless steel contains 20 l of liquid helium for one coil. The vertical force in the coils is about 250 tons. The cold mass is suspended from the room temperature vacuum vessel by six suspension links. Six cylindrical support struts compensate the vertical forces. The energy stored in the magnet is about 5 MJ. The magnet will be self-protecting. However, in order to limit the temperature rise to 100 K in case of a quench, the energy will be dumped in an external resistor. The technical design precedes the tender and the procurement of the magnet, and, hence, is subject of possible modifications during this process.
1. Introduction

1.1 Exploring the phase diagram of nuclear matter

Substantial experimental and theoretical efforts worldwide are devoted to explore the phase diagram of strongly interacting matter which is governed by Quantum ChromoDynamics (QCD). At top RHIC and LHC energies, the QCD phase diagram is studied at very high temperatures and very low net baryon densities. These conditions presumably existed in the early universe about a microsecond after the big bang. For larger net baryon densities and lower temperatures, it is expected that the QCD phase diagram exhibits a rich structure such as a critical point, a first order phase transition between hadronic and partonic or quarkyonic matter, and the chiral phase transition. The experimental discovery of these prominent landmarks of the QCD phase diagram would be a major breakthrough in our understanding of the properties of nuclear matter. Figure 1 illustrates the possible phases of nuclear matter and their boundaries in a diagram of temperature versus the baryon chemical potential.

![Phase Diagram](image)

*Figure 1. Sketch of the phase diagram for strongly-interacting matter (taken from [1]).*

The high-density region of the QCD phase diagram can be experimentally explored in nucleus-nucleus collisions where high net-baryon densities are created. As shown in Figure 2 - which depicts results of transport code calculations for central Au+Au collisions [2] - very high densities can be produced already at beam energies above 5 A GeV which are delivered by the SIS100/300 accelerators of FAIR.

Several experimental programs have been devoted to the exploration of the QCD phase diagram at large baryon-chemical potentials. The STAR collaboration at RHIC scanned the beam energies...
in order to search for the QCD critical endpoint. However, due to a rapid decrease of luminosity with decreasing beam energy at RHIC, the data obtained by the STAR experiment at a collision energy of $\sqrt{s} = 7$ GeV (corresponding to 30 A GeV on fixed target) suffer strongly from statistics [3]. The measurements with the upgraded NA49 detector (NA61) at the CERN-SPS are also limited in luminosity due to the use of a Time-Projection Chamber [4]. In contrast, the Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt is designed for high-rate precision measurements of multidimensional observables including particles with very low production cross sections, and will benefit from the high-intensity heavy-ion beams provided by the FAIR accelerators.

![Figure 2](image.png)

*Figure 2. Baryon density as function of elapsed time for central Au+Au collisions at different energies as calculated with the HSD transport code [2].*

### 1.2 CBM physics cases and observables

The CBM research program is focused on the following physics cases:

**The equation-of-state of matter at neutron star densities**

In the laboratory, the highest net-baryon densities can be produced in nucleus-nucleus collisions at FAIR energies. The relevant measurements are:

- The excitation function of the collective flow of hadrons which is driven by the pressure created in the early fireball (SIS100/300).
- The excitation functions of multi-strange hyperons in Au+Au and C+C collisions at energies from 2 to 11 A GeV (SIS100). At subthreshold energies, $\Xi$ and $\Omega$ hyperons are produced in sequential collisions involving kaons and $\Lambda$'s, and, therefore, are sensitive to the density in the fireball.
**Modifications of hadron properties in dense baryonic matter**

The restoration of chiral symmetry in dense baryonic matter will modify the properties of hadrons. The relevant measurements are:

- The in-medium mass distribution of vector mesons decaying in lepton pairs in heavy-ion collisions at different energies (2 – 45 A GeV), and for different collision systems. Leptons are penetrating probes carrying the information out of the dense fireball (SIS100/300).
- Yields and transverse mass distributions of charmed mesons in heavy-ion collisions as function of energy (SIS100/300).

**Phase transitions from hadronic matter to quarkyonic or partonic matter at high net-baryon densities**

Already at SIS100 energies densities of up to 7 times saturation density are reached in central collisions between heavy-ions. Under these conditions the nucleons overlap, and theories predict a transition to a mixed phase of baryons and quarks. A discontinuity or sudden variation in the excitation functions of sensitive observables would be indicative of a transition. The relevant measurements are:

- The excitation function of yields, spectra, and collective flow of strange particles in heavy-ion collisions from 6-45 A GeV (SIS100/300).
- The excitation function of yields, spectra, and collective flow of charmed particles in heavy-ion collisions from 6-45 A GeV (SIS100/300).
- The excitation function of yields and spectra of lepton pairs in heavy-ion collisions from 6-45 A GeV (SIS100/300).
- Event-by-event fluctuations of conserved quantities like strangeness, baryons, and net-charge in heavy-ion collisions with high precision as function of beam energy from 6 - 45 A GeV (SIS100/300).

**Hypernuclei, strange dibaryons and massive strange objects**

Theoretical models predict that single and double hypernuclei, strange dibaryons and heavy multi-strange short-lived objects are produced via coalescence in heavy-ion collisions with the maximum yield in the region of SIS100 energies. The planned measurements include:

- The decay chains of single and double hypernuclei in heavy ion collisions at SIS100 energies.
- Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects. If these multi-strange particles decay into charged hadrons including hyperons they can be identified via their decay products.

**Charm production mechanisms, charm propagation, and in-medium properties of charmed particles in (dense) nuclear matter**

The relevant measurements are:

- Cross sections and momentum spectra of open charm (D-mesons) in proton-nucleus collisions at SIS100/300 energies. In-medium properties of D mesons can
be derived from the transparency ratio $T_A = \sigma_{pA \to DX} / (A \sigma_{pN \to DX})$ measured for target nuclei of different sizes.

- Cross sections, momentum spectra, and collective flow of open charm (D-mesons) in nucleus-nucleus collisions at SIS300 energies.
- Cross sections, momentum spectra, and collective flow of charmonium ($J/\psi$) in proton-nucleus and nucleus-nucleus collisions at SIS100/300.

As discussed above, a substantial part of the CBM physics cases can be addressed already with beams from the SIS100 synchrotron. The intended measurements at SIS100 including the results of simulations and count rate estimates are described in the CBM Report 2012-01 [5]. A general review of the physics of compressed baryonic matter, the theoretical concepts, the available experimental results, and predictions for relevant observables in future heavy-ion collision experiments can be found the CBM Physics Book [6].

Most of the diagnostic probes of dense matter like lepton pairs, multi-strange hyperons and charm will be measured for the first time with the CBM experiment in the FAIR energy range. Therefore, the CBM experiment has a unique discovery potential both at SIS100 and SIS300 energies.

1.3 The future Facility for Antiproton and Ion Research (FAIR)

The future international Facility for Antiproton and Ion Research (FAIR) in Darmstadt will provide unique research opportunities in the fields of nuclear, hadron, atomic and plasma physics [7]. The CBM research will start with primary beams from the SIS100 synchrotron (protons up to 29 GeV, gold up to 11 A GeV, nuclei with $Z/A = 0.5$ up to 14 A GeV), and will be continued with beams from the SIS300 synchrotron (protons up to 90 GeV, gold up to 35 A GeV, nuclei with $Z/A = 0.5$ up to 45 A GeV). The layout of FAIR is presented in Figure 3.

![Figure 3. Layout of the future Facility for Antiproton and Ion Research (FAIR).](image-url)
1.4 The Compressed Baryonic Matter (CBM) experiment

The CBM experimental strategy is to perform systematic measurements of particles produced in nuclear collisions (i.e. yields, phase-space distributions, correlations and fluctuations) with unprecedented precision and statistics. These measurements will be performed in nucleus-nucleus, proton-nucleus, and proton-proton collisions at different beam energies. The identification of multi-strange hyperons, hypernuclei, particles with charm quarks and vector mesons decaying into lepton pairs requires efficient background suppression and very high interaction rates. In order to select events containing those rare observables, the tracks of each collision have to be reconstructed and filtered online with respect to physical signatures. This concept represents a paradigm shift for data taking in high-energy physics experiments: CBM will run without hierarchical trigger system. Self-triggered read-out electronics, a high-speed data processing and acquisition system, fast algorithms, and, last but not least, radiation hard detectors are indispensable prerequisites for a successful operation of the experiment. Figure 4 and Figure 5 depict the CBM experimental setup with electron detectors and the muon detection system, respectively.

The CBM experiment comprises the following components

Dipole magnet

The H-type magnet will be superconducting in order to reduce the operation costs. It has a large aperture of ± 25 ° polar angle, and provides a field integral of 1 Tm.

Micro-Vertex Detector (MVD)

The determination of the decay vertices of open charm particles (cτ = 123 μm/c for D⁰ mesons and cτ = 314 μm/c for D± mesons) requires detectors with excellent position resolution and a very low material budget in order to reduce multiple scattering. These requirements are met by Monolithic Active Pixel Sensors (MAPS). The pixel size will be between 18x18 μm² and 20x40 μm². A position resolution of σ = 3.5 - 6.0 μm can be achieved depending on the pixel size. The goal of the detector development is to construct vacuum compatible MAPS detector stations with a total thickness of about 300 – 500 μm silicon equivalent for sensors and support structures, depending on the size of the stations. The MVD consists of 3 MAPS layers located 5, 10, and 15 cm downstream the target in the vacuum. A 4th MAPS station might be located at 20 cm behind the target. This detector arrangement permits to determine the secondary decay vertex of a D-meson with a resolution of about (50-100) μm along the beam axis.

Silicon Tracking System (STS)

The task of the STS is to provide track reconstruction and momentum determination of charged particles. The multiplicity of charged particles is about 700 per event within the detector acceptance. The STS consists of up to 8 tracking layers of silicon detectors. They are located downstream of the target at distances between 30 cm and 100 cm inside the magnetic dipole field. The required momentum resolution is of the order of Δp/p = 1 %. This performance can only be achieved with an ultra-low material budget of the stations, imposing particular restrictions on the location of power-dissipating front-end electronics in the fiducial volume. The concept of the STS tracking is based on silicon microstrip sensors mounted onto lightweight mechanical support ladders. The sensors will be read out through multi-line micro-cables with fast electronics at the periphery of the stations where cooling lines and other infrastructure can be placed. The micro-strip sensors will be double-sided with a stereo angle of 7.5°, a strip pitch
of 60 μm, strip lengths between 20 and 60 mm, and a thickness of 300 μm of silicon. The micro-cables will be built from sandwiched polyimide-Aluminum layers of several 10 μm thickness.

**Ring Imaging Cherenkov (RICH) detector**

The RICH detector is designed to provide identification of electrons and suppression of pions in the momentum range below 8-10 GeV/c. This will be achieved using a gaseous RICH detector built in a standard projective geometry with focusing mirror elements and a photodetector. CO2 with a pion threshold for Cherenkov radiation of 4.65 GeV/c will be used as radiator gas. The detector will be positioned behind the dipole magnet about 1.6 m downstream of the target. It will consist of a 1.7 m long gas radiator (overall length approximately 2 m) and two arrays of mirrors and photodetector planes. The mirror plane is split horizontally into two arrays of spherical glass mirrors, each (4x1.5) m². The 72 mirror tiles have 3 m radius of curvature, 6 mm thickness and a reflective AL+MgF² coating. Rings will be projected onto two photodetector planes of (2x0.6) m² each being located behind the CBM dipole magnet and shielded by the magnet yokes. The design of the photodetector plane is based on MAPMTs (e.g. H8500 from Hamamatsu) in order to provide high granularity, high geometrical efficiency, high detection efficiency of photons also in the near UV region and a reliable operation. In-beam tests with a RICH prototype being real dimension in its length could show that 22 photons are measured per electron ring. On the order of 100 rings are seen in central Au+Au collisions at 25 A GeV beam energy due to the large material budget in front of the RICH detector. Still, due to the high granularity (approx. 55000 channels) and high number of photons per ring, a pion suppression on the order of 500 is expected to be achieved according to simulations.

**The Muon Chamber system (MUCH)**

The experimental challenge for muon measurements in heavy-ion collisions at FAIR energies is to identify low-momentum muons in an environment of high particle densities. The CBM concept is to track the particles through a hadron absorber system, and to perform a momentum-dependent muon identification. This concept is realized by segmenting the hadron absorber in several layers, and placing triplets of tracking detector planes in the gaps between the absorber layers. The absorber/detector system is placed downstream of the Silicon Tracking System (STS) which determines the particle momentum. In order to reduce meson decays into muons the absorber/detector system has to be as compact as possible. The actual design of the muon detector system consists of 6 hadron absorber layers (iron plates of thickness 20 cm, 20 cm, 20 cm, 30 cm, 35 cm, 100 cm) and 18 gaseous tracking chambers located in triplets behind each iron slab. The definition of a muon depends on its momentum which varies with the mass of the vector mesons and with beam energy. The challenge for the muon chambers and for the track reconstruction algorithms is the very high particle density of up to 0.5 hits/cm² per event in the first detector layers after 20 cm of iron. For a reaction rate of 10 MHz this hit density translates into a hit rate of 5 MHz/cm². Prototype chambers based on GEM technology were operated successfully at rates of about 3 MHz/cm² with pion beams. In total, the muon chambers cover an active area of about 70 m² subdivided into about half a million channels. The low particle multiplicities behind the muon absorber favors the implementation of a trigger on muon pairs. The trigger concept is based on the measurement of short track segments in the last tracking station triplet, and extrapolation of these tracks to the target. After selection of tracks with good vertices the event rate can be reduced already by a factor of about 600 for J/ψ measurements in minimum bias Au+Au collisions. For J/ψ measurements at SIS100 a MUCH start version with 3 chamber triplets is sufficient.
**Transition Radiation Detector (TRD)**

Three Transition Radiation Detector stations each consisting of 3 detector layers will serve for particle tracking and for the identification of electrons and positrons with $p > 1.5$ GeV/c ($\gamma > 1000$). The detector stations are located at approximately 5 m, 7.2 m and 9.5 m downstream the target, the total active detector area amounts to about 600 m². For example, at small forward angles and at a distance of 5 m from the target, we expect particle rates on the order of 100 kHz/cm² for 10 MHz minimum bias Au+Au collisions at 25 AGeV. In a central collision, particle densities of about 0.05/cm² are reached. In order to keep the occupancy below 5% the minimum size of a single cell should be about 1 cm². The TRD detector readout will be realized in rectangular pads giving a resolution of 300-500 μm across and 3-30 mm along the pad. Every second TR layer is rotated by 90°. Prototype gas detectors based on MWPC and GEM technology have been built and tested with particle rates of up to 400 kHz/cm² without deterioration of their performance. The pion suppression factor obtained with 9 TRD layers is estimated to be well above 100 at an electron efficiency of 90%. For measurements at SIS100 only one station with 3 detector layers will be used as an intermediate tracker between the STS and the TOF wall.

**Timing Multi-gap Resistive Plate Chambers (MRPC)**

An array of Resistive Plate Chambers will be used for hadron identification via TOF measurements. The TOF wall covers an active area of about 120 m² and is located about 6 m downstream of the target for measurements at SIS100, and at 10 m at SIS300. The required time resolution is of the order of 80 ps. For 10 MHz minimum bias Au+Au collisions the innermost part of the detector has to work at rates up to 20 kHz/cm². Prototype MRPCs built with low-resistivity glass have been tested with a time resolution of $\sigma = 40-60$ ps at 20 kHz/cm². At small deflection angles the pad size is about 5 cm² corresponding to an occupancy of below 5% for central Au+Au collisions at 25 AGeV.

**The Electromagnetic CALorimeter (ECAL)**

A "shashlik" type calorimeter as installed in the HERA-B, PHENIX and LHCb experiments will be used to measure direct photons and neutral mesons ($\pi^0, \eta$) decaying into photons. The ECAL will be composed of modules which consist of 140 layers of 1mm lead and 1mm scintillator, with cell sizes of $3 \times 3$ cm², $6 \times 6$ cm², and $12 \times 12$ cm². The shashlik modules can be arranged either as a wall or in a tower geometry with variable distance from the target.

**Projectile Spectator Detector (PSD)**

The PSD will be used to determine the collision centrality and the orientation of the reaction plane. A precise characterization of the event class is of crucial importance for the analysis of event-by-event observables. The study of collective flow requires a well-defined reaction plane which has to be determined by a method not involving particles participating in the collision. The detector is designed to measure the number of non-interacting nucleons from a projectile nucleus in nucleus-nucleus collisions. The PSD is a full compensating modular lead-scintillator calorimeter which provides very good and uniform energy resolution. The calorimeter comprises 44 individual modules, each consisting of 60 lead/scintillator layers with a surface of $20 \times 20$ cm². The scintillation light is read out via wavelength shifting (WLS) fibers by Multi-Avalanche Photo-Diodes (MAPD) with an active area of $3 \times 3$ mm² and a pixel density of $10^4$/mm².
Online event selection and data acquisition

High statistics measurements of particles with very small production cross sections require high reaction rates. The CBM detectors, the online event selection systems, and the data acquisition will be designed for event rates of 10 MHz, corresponding to a beam intensity of $10^9$ ions/s and a 1% interaction target, for example. Assuming an archiving rate of 1 GByte/s and an event volume of about 10 kByte for minimum bias Au+Au collisions, an event rate of 100 kHz can be accepted by the data acquisition. Therefore, measurements with event rates of 10 MHz require online event selection algorithms (and hardware) which reject the background events (which contain no signal) by a factor of 100 or more. The event selection system will be based on a fast on-line event reconstruction running on a high-performance computer farm equipped with many-core CPUs and graphics cards (GSI GreenIT cube). Track reconstruction, which is the most time consuming combinatorial stage of the event reconstruction, will be based on parallel track finding and fitting algorithms, implementing the Cellular Automaton and Kalman Filter methods. For open charm production the trigger will be based on an online search for secondary vertices which requires high speed tracking and event reconstruction in the STS and MVD. The highest suppression factor has to be achieved for J/$\psi$ mesons where a high-energetic pair of electrons or muons is required in the TRD or in the MuCh. For low-mass electron pairs no online selection is possible due to the large number of rings/event in the RICH caused by the material budget of the STS. In the case of low-mass muon pairs some background rejection might be feasible.

Figure 4. The CBM experimental facility with the electron detectors RICH and TRD.
Figure 5. The CBM experimental facility with the muon detection system.
2. Engineering Considerations

2.1 Required parameters of the CBM dipole magnet

The CBM superconducting dipole magnet is a central part of the detector system. The target station and the Silicon Tracking System are placed in the magnet gap. The magnet has to provide the vertical magnetic field with a bending power of 1 Tm on the length 1m from the target. Next to the magnet there is the RICH detector placed in 1.6 m from the target. The following list contains the required parameters of the dipole magnet:

**Geometry**
- Opening angle: ±25° vertically, ± 30° horizontally from the target
- Free aperture: 1.4 m vertically x 1.8 m horizontally, no conical geometry!
- Distance target- magnet core end: 1m (STS detector must fit in)
- Total length: 1.5 m
- Space upstream of the magnet: <1 m

**Field**
- Field integral within STS detector (along straight lines): 1 Tm -> max. Field ≥ 1 T, depending on the magnet length
- Field integral variation over the whole opening angle along straight lines: ≤ 20% (± 10%)
- Fringe field downstream < reasonable value of the order of 50 to 100 Gauss at a distance of 1.6 m from the target (RICH only)

**Operating conditions**
- Operates at both polarities
- 100% duty cycle, 3 months/year, 20 years
- No real time restriction on the ramp: 1 hour up ramp
- Radiation damage (<10MG for organics): no problem
- Radiation Energy deposit in the cryosystem: max. 1 W

**Assembly**
- Field clamps dismountable for MUCH
- Assembly in situ
- Weight restriction: crane 30 tons (including lifting jacks)
- Maximum floor load: 100 tons/m²
- beam height over the floor: 5.8 m

**Alignment**
- Position accuracy: ± 0.2 mm
- Orientation accuracy: ± 0.5 mrad

2.2 General Concepts

The CBM superconducting dipole magnet has a large magnetic gap of 1.4 m with a relatively short length of 1 m and an average value of the magnetic field on this length of 1 T. This magnetic field requires a total current in the magnet coils of about 1-2 MA*turns. In this case, the Lorentz
forces in the coils reach up several hundred tons and the conductor stays in the high magnetic field region. These parameters are very important while designing superconducting coils. So, an H-type magnet with tapered poles and flat cylindrical coils was chosen to reduce the influence of these negative factors. Cylindrical coils are easy to produce and the forces in the plane of the winding do not change the coil shape. The request for a free horizontal space of about 1.8 m for the STS detector requires a separate cryostat for each coil. The Nb-Ti superconductor of the coils is wound on a stainless steel bobbin and is directly cooled by liquid helium (LHe).

The shape and sizes of the magnet yoke have been chosen to take most of the return magnetic flux. So, the upper and lower horizontal balks have a width of 2 m. The cryostats are attached to these wide balks and the huge vertical electromagnetic forces are transferred from the coils to the yoke. The horizontal and vertical balks have large cross sections.

The corresponding 3D model was prepared for electromagnetic analysis. The dimensions of this model are presented in Figure 6.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{model.png}
\caption{Sketch of the model for electromagnetic analysis.}
\end{figure}

\subsection{2.3 Electromagnetic analysis}

The 3D magnetic analysis for the dipole magnet was performed using the ANSYS program \cite{8} and the code Opera 3D \cite{9}. The B-H curve of steel 1010 used for the iron yoke and the poles in
the EM analysis is shown in Figure 7. The coil in the electromagnetic analysis used default copper material properties and the surrounding air was modeled as vacuum. The total magnetic flux density is shown in Figure 8 and magnetic field and forces in coil and iron are shown in Figure 9 – Figure 15. The analysis results are presented in Table 1.

Table 1. The analysis results for the dipole magnet performed by means of program ANSYS and code Opera 3D.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total current per coil</td>
<td>1.2</td>
<td>MA*turns</td>
</tr>
<tr>
<td>Maximum magnetic field in the coil</td>
<td>3.25</td>
<td>T</td>
</tr>
<tr>
<td>Vertical force in the coil</td>
<td>254</td>
<td>tons</td>
</tr>
<tr>
<td>Tangential forces in the coil</td>
<td>56</td>
<td>tons</td>
</tr>
<tr>
<td>Vertical force in the pole</td>
<td>-279</td>
<td>tons</td>
</tr>
<tr>
<td>Stored energy</td>
<td>5.15</td>
<td>MJ</td>
</tr>
</tbody>
</table>

Figure 7. B–H curve for the yoke (steel 1010).
Figure 8. Total magnetic flux density

Figure 9. Magnetic field in the coil.
Figure 10. The field integral is 0.9979 Tm. The current is 1.2 MA. The current density is 48A/mm$^2$. The origin is in the magnet center, the target at z=-0.5m.

Figure 11. Magnet’s field distribution along the beam.
The fringe field has been studied in detail. There are two possible problems: the sensitivity of the multi-anode photomultipliers of the RICH photo-detector to the magnetic field, and the magnetic field in the volume of the RICH radiator gas. In order to reduce the fringe field in the photo detector region, field clamps have been implemented. The remaining fringe field is in the order of several mT (see Figure 12), it can be further reduced by an additional iron box surrounding the photo detector.

The field in the entrance of the volume of the RICH radiator gas is in the order of several 10 mT. According to simulations this field does only little affect the trajectories of the electrons, and, hence, the quality of the Cherenkov rings. A possible way to further reduce the effect of the fringe field would be to shift the RICH downstream by 20 cm.

Figure 12. Magnetic field distribution in the y−z-plane at x=0. The three boxes correspond to possible positions of the RICH photodetector.
Figure 13. The magnet saturation.

Figure 14. $|B|$ field distribution in the coils.
2.4 Yoke design

The magnetic flux generated by the two SC coils is shaped and guided by the iron yoke. It produces the vertical magnetic field in the gap between the pole faces. The yoke consists of two conical poles, two identical horizontal parts and two identical vertical parts to close the flux return. Each horizontal part is split in two beams due to weight reason. The maximum weight of each part should not exceed the crane limit of 30 tons. The total weight of the yoke is about 140 tons. The vertical parts have two channels for coil services. All parts are made of standard rolled low-carbon steel (SAE 1010). The vertical and horizontal parts will be assembled out of plates of 80 to 160 mm thickness welded together with subsequent machining. Four removable field clamps should be installed on the yoke when the RICH detector is placed next to the magnet. The 1400 mm gap does not include a pole bump (shim). Due to the high saturation of the pole a shim will not help much. Besides, the integral homogeneity of the present design fulfills the specification. Figure 16 shows a perspective view of the yoke only and Table 2 gives the main parameters of the yoke parts. A vertical force of 279.4 tons will separate the pole from the horizontal yoke beams at nominal current. Four threaded studs with diameter of 76 mm will keep the pole in place.

Table 2. The main parameters of the yoke parts.

<table>
<thead>
<tr>
<th>Part name</th>
<th>Material</th>
<th>Dimensions M</th>
<th>Weight tons</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole</td>
<td>SAE 1010</td>
<td>D1.2x0.5</td>
<td>3.14</td>
<td>2</td>
</tr>
<tr>
<td>Horizontal beam</td>
<td>SAE 1010</td>
<td>0.65x1x4.64</td>
<td>20.5</td>
<td>4</td>
</tr>
<tr>
<td>Vertical balk</td>
<td>SAE 1010</td>
<td>1.14x2x2.5</td>
<td>24.5</td>
<td>2</td>
</tr>
<tr>
<td>Field clamp</td>
<td>SAE 1010</td>
<td>0.19x0.6x2.7</td>
<td>1.85</td>
<td>4</td>
</tr>
</tbody>
</table>
2.5 Engineering design of the superconducting coils

The engineering magnet design in this report is finalized by the selection of the superconducting conductor, the structure and the fabrication technology.

The coil has a ring-shaped configuration, the Nb-Ti core wire is embedded in a rectangular copper stabilizer with a total Cu/SC ratio of about 9.1. The cryostat provides the necessary vacuum and the cryogenic environment for the operation of CBM dipole coils. Coils will be surrounded by liquid helium in the coil case and a thermal radiation shield is inserted between the cryostat and the coil case. The coil case and the thermal shield are suspended by a support system.

2.5.1 Conductor

The chosen conductor consists of a superconducting strand (designed for the CMS solenoid [10]) and a copper stabilizer (size 2.02 mm x 3.25 mm). Figure 17 presents the scheme of a “wire in channel” conductor.

Due to the very high overall current density of 58 A/mm² the overall size of the coils is reduced compared to resistive coil.

The main parameters of the conductor are listed in Table 3.
Figure 17. Conductor cross section: \( df \) = filament diameter, \( ds \) = strand diameter, \( R_1, R_2 \) = corners roundings, \( wsta \) and \( hsta \) are dimensions of the stabilizer.

Table 3. Parameters of the conductor.

<table>
<thead>
<tr>
<th>CONDUCTOR PARAMETER</th>
<th>CMS STRAND+CU STABILIZER</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ds ) (mm)</td>
<td>1.28±0.005</td>
</tr>
<tr>
<td>Cu/NbTi</td>
<td>1.1±0.1</td>
</tr>
<tr>
<td>df: filament diameter (µm)</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>filament twist pitch (mm)</td>
<td>45</td>
</tr>
<tr>
<td>RRR_strand</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>( Jc(4.2K,5T))min (A/mm²)</td>
<td>3000</td>
</tr>
<tr>
<td>( Ic(4.5K,Bm))min (A)</td>
<td>2358</td>
</tr>
<tr>
<td>hsta (mm)</td>
<td>2.02</td>
</tr>
<tr>
<td>wsta (mm)</td>
<td>3.25</td>
</tr>
<tr>
<td>R1 (mm)</td>
<td>0.45</td>
</tr>
<tr>
<td>R2 (mm)</td>
<td>0.25</td>
</tr>
</tbody>
</table>

A similar conductor (produced by OST) was used for the Super-FRS dipole prototype manufactured and tested by a Chinese consortium. The strand is soldered to the copper-channel [11].

No problems with the contact resistance between the core and the stabilizer were reported by the Chinese colleagues. High contact resistance may

- increase the propagation velocity that leads to a flattened temperature profile (which is good).
- slow the radial current transfer from the core to the stabilizer, typically of the order of milliseconds. In the CBM dipole (without dump resistor) the current is dumped in 40 s. A few millisecond for the current to transfer from the core to the stabilizer has therefore little influence.
- slightly increase the hotspot temperature (maybe a few degrees).
2.5.2 Coil design

The coil design is based on the design of the FAIR Super-FRS dipole [12]. The coil has 1749 turns. There are 53 layers with 33 turns per layer. The cross section of the coil is presented in Figure 18. Corresponding dimensions and coil parameters are listed in Table 4. The conductor insulation consist of 2x 0.05 mm polyimide tape and 2 x 0.1 mm glassfiber material (tape or braid), in total 0.3 mm. In Figure 19 the magnet inductances Lw and Ld are shown. The load line of the magnet is plotted in Figure 20.

![Cross section of the coil winding](image)

*Figure 18. Cross section of the coil winding: wa and wr are the insulated coil dimensions, wil, wc and wg are thicknesses of the inter-layer, conductor and ground insulation respectively.*

![Inductances Lw and Ld of the dipole magnet](image)

*Figure 19. Inductances Lw and Ld of the dipole magnet [13,14,15].*
Table 4. Parameters of the cable and the coil.

<table>
<thead>
<tr>
<th>CABLE OR COIL PARAMETER</th>
<th>CMS WIRE+CU STABILIZER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acore (mm²)</td>
<td>1.287</td>
</tr>
<tr>
<td>ANbTi (mm²)</td>
<td>0.613</td>
</tr>
<tr>
<td>ACu_core (mm²)</td>
<td>0.674</td>
</tr>
<tr>
<td>ACu_stabilizer (mm²)</td>
<td>4.902</td>
</tr>
<tr>
<td>ACu_total (mm²)</td>
<td>5.575</td>
</tr>
<tr>
<td>ACu_total/ANbTi</td>
<td>9.1</td>
</tr>
<tr>
<td>(B_m): maximum field in the coil (T)</td>
<td>3.25</td>
</tr>
<tr>
<td>Jc(4.2K,5T) (A/mm²)</td>
<td>3000</td>
</tr>
<tr>
<td>wc: conductor insulation thickness (mm)</td>
<td>0.3</td>
</tr>
<tr>
<td>wil: interlayer insulation (mm)</td>
<td>0.3</td>
</tr>
<tr>
<td>wg: ground insulation thickness (mm)</td>
<td>2</td>
</tr>
<tr>
<td>(\text{n}^\circ) of layers</td>
<td>53</td>
</tr>
<tr>
<td>(\text{n}^\circ) of turns per layer</td>
<td>33</td>
</tr>
<tr>
<td>(\text{n}^\circ) of turns per pole</td>
<td>1749</td>
</tr>
<tr>
<td>(w_r) (mm)</td>
<td>158.8</td>
</tr>
<tr>
<td>(w_a) (mm)</td>
<td>131.1</td>
</tr>
<tr>
<td>(J_{\text{eng}}=I_n/(ACu+ANbTi+A_{\text{ins}})) (A/mm²)</td>
<td>57.7</td>
</tr>
<tr>
<td>(I_n) (A)</td>
<td>686</td>
</tr>
<tr>
<td>(I_n/I_{\text{loadm}}) (%)</td>
<td>0.29</td>
</tr>
<tr>
<td>(J_{\text{NbTi}}) (A/mm²)</td>
<td>1120</td>
</tr>
<tr>
<td>Tcs (K)</td>
<td>6.84</td>
</tr>
<tr>
<td>Tcs-4.5 (K)</td>
<td>2.34</td>
</tr>
<tr>
<td>E/Vol_pole (MJ/m³)</td>
<td>50</td>
</tr>
<tr>
<td>Tav (K)</td>
<td>90</td>
</tr>
<tr>
<td>(\rho_{\text{Cu}}(B=0,Tav)) (ohm.m)</td>
<td>3.02E-09</td>
</tr>
<tr>
<td>R_pole(Tav) (ohm)</td>
<td>4.73</td>
</tr>
<tr>
<td>Vqm_estimated= 0.403*R_pole(Tav)*I_n (V)</td>
<td>1307</td>
</tr>
<tr>
<td>wire length per pole (km)</td>
<td>8.745</td>
</tr>
</tbody>
</table>
2.5.3 Coil winding

The basic structure of the coil consists of the layer type helical winding on a stainless steel bobbin of 1373 mm ID x 1820 mm OD x 236 mm. The bobbin is afterwards welded shut to become a helium can. The inner walls of the SS bobbin are covered with 3 sets of spacers made of G-10 Glass Epoxy laminate placed with 4º pitches. Two sets of the spacers are glued on the aluminum shims and one set is glued directly on the bobbin. The space between the spacers is used for the liquid helium circulation. Over the spacers there is a tray made from thin G-10 Glass Epoxy laminate and covered by few layers of fiber glass fabric with epoxy resin with total thickness of 2 mm. The coil is wound inside this tray. The cable has two layers of insulation with total thickness of 0.26~0.31 mm. The first layer is wrapped with 50 micron thick Kapton tape with a 50% overlap for electrical insulation purposes. The second layer is wrapped with 100 micron thick fiberglass epoxy prepreg tape with a 50% overlap. The cable cross section is shown on Figure 21. The turns are circular and have a helical pass about 80-100 mm to the next turn. Due the same winding pattern only one turn one turn from 1749 turns shall be lost. Figure 22 shows winding pattern of the first two layers. Each layer is insulated with three layers of 0.1mm fiber glass fabric with epoxy resin. Since the coils and conductor experience radial and axial forces of a high magnitude, the winding is required to be done at high tension of 20kg and gaps between turns are needed to be filled with epoxy resin to restrict movement of the conductor. This impregnation should be done with a brush. The last layer should be wrapped with 23 layers of 0.1mm fiber glass fabric with epoxy resin.

Figure 23 shows cross section of the coil case after winding.
Figure 21. Cross section of the SC cable.

Figure 22. The first two layers.

Figure 23. Cross section of the coil case.
2.5.4 Coil case

The coil case is designed considering two main functions: one is to protect the windings against magnetic forces during operation, and the other is to use the case as a container for liquid helium (LHe) to cool the winding. The volume of the LHe in the case is about 20 liters for one coil, including the LHe stored in the current leads box. The case is welded of stainless steel 316LN [17]. The minimal thickness of the case is 20 mm. Table 5 shows the steel mechanical properties. Its magnetic permeability is about 1.01 ~ 1.02. Figure 24 shows the cross section and top view of the coil. The cross section has the height of 230 mm and the width of 230 mm. The coil occupies only a part of the internal space of the case. The rest space is filled with two aluminum circular shims (AW6061 or AW3003) and four sets of the spacers made of NEMA G10. Two sets of the spacers are glued on the shims, one set is glued on the bobbin and the last set is placed between the coil and the outer wall of the coil case. In addition, the shim provides good thermal conduction that allows to distribute the heat load caused by friction if the coil moves or cracks under the Lorentz forces [18]. The large cross section is necessary to have a very rigid structure. The case should transmit huge vertical forces from the coil to the supports.

The case is supported by six main cylindrical supports and six tie rods. To reduce the heat flux to the helium system, the outer surface of the casing will be wrapped with 20 layers of a multi-layer insulation.

*Table 5. Mechanical properties of stainless steel 316LN.*

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Tensile strength</th>
<th>Yield strength</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \sigma_b ) (MPa)</td>
<td>( \sigma_{0.2} ) (MPa)</td>
<td>( \delta ) (%)</td>
</tr>
<tr>
<td>300 K</td>
<td>≥650</td>
<td>≥350</td>
<td>≥35</td>
</tr>
<tr>
<td>4 K</td>
<td>≥1500</td>
<td>≥1000</td>
<td>≥35</td>
</tr>
</tbody>
</table>

*Figure 24. Top view and the cross section of the coil.*
2.5.5 Thermal shield

The thermal shield must have good thermal conductivity, good rigidity to weight ratio, and it should be easy to fabricate and assemble. The thermal shield consists of two main pieces: the top shield and the cover. The shield has a radial cut for an electrical break. All pieces are made of copper sheets each 2mm thick. The forced-flow cryogen for cooling the thermal shield is cold helium gas to intercept thermal radiation from the cryostat. The cooling pipes are made of a copper tube 1mm thick having a rectangular shape with an outer dimension of 20 mm × 8 mm. To reduce the heat flux to the helium system, the outer surface of the thermal shield will be wrapped with insulation of 20 layers. The thermal shield is fixed to the main cylindrical supports. Figure 25 shows the top view of the thermal shield.

![Figure 25. Top view of the thermal shield.](image)

2.5.6 Suspension

The cold mass is suspended from the room temperature (RT) vacuum vessel using 6 support struts and 6 tie rods. These support struts are described as “warm-to-cold” because the warm end is free nested into the socket of the RT vacuum vessel and the cold end is free nested into the socket of the coil case. The suspension during the working cycle has two types of loading. When the magnet is switched off only the weight of the cold mass is applied to the suspension.
In this case the vertical force is about 2000 kg. When the magnet is switched on, the vertical component of the Lorenz forces should be added to the weight of the cold mass. The maximum vertical force in this case is 254 tons. The lateral forces should not exceed a few hundred kilograms due to symmetry of the magnet. The calculated lateral force in the coil with the displacement of 3mm from the nominal position is equal to 458kg. The displacement of the coil will not exceed 1-1.5 mm due to manufacturing tolerances. So the lateral force will not exceed...
230kg. The support struts are typically compressed. Only the green parts require pre-compression while manufacturing the CBM dipole magnet. The tie rods will provide this pre-compression. The support struts have a nominal compression force of 42 tons. The tie rods are tensed with the force of 500 kg. Figure 26 shows the suspension of the coil case on the flange of the vacuum vessel.

The support strut consists of four composite tubes nested coaxially in each other and connected in series by three stainless steel tubes with Z-shaped cross section. The composite tubes are a polar wound tube with glass fibers and epoxy resin. The axial winding angle is ± 15º. Few layers have the winding angle of 90º to fix the main layers. The glass fiber composite has small thermal conductivity at low temperature. The Z-shape tubes are made of the SAE 304 stainless steel. Five layers of MLI are inserted in each gap between the tubes. The middle tube is connected with the thermo shield at the temperature of 80 K. Figure 27 shows the cross section of the support strut. The tie rods are used to sustain the cold mass and preload the support struts. The tie rods, which are attached on one side to the vacuum vessel and on the other side to the coil case, are subjected to a thermal gradient from 4.5 K till room temperature. Titanium alloy Ti 5Al 2.5Sn [19] has been chosen as tie rod material for its low thermal conductivity and high mechanical strength. The tie rods have spherical hinges on both sides. The hinge attached to the vacuum vessel is fixed with a key. The hinge on the other side has a thread for adjusting. On 1/3 of the length from the vacuum vessel it has a shoulder for a thermo bridge. Figure 28 shows the tie rod with the hinges.

![Figure 28. Tie rod.](image)

### 2.5.7 Vacuum vessel

The vacuum vessel seals the vacuum around the cold mass to allow the cooling system to reach the desired cryogenic temperature. The vacuum vessel consists of a support ring, a shell and a weldolet. The rest parts are made of stainless steel SAE 304. The thickness of the shell is 15-20 mm. The support ring is 48mm thick. All parts of the vacuum vessel will be assembled by welding. Figure 29 shows the vacuum vessel.
2.6 The quench analysis for the CBM dipole magnet

2.6.1 Requirements to the quench protection

The CBM dipole magnet has very large dimensions and will store about 5.15 MJ at its nominal current. Adequate magnet protection means minimizing of the peak coil temperature and of the resistive-inductive voltage imbalances, which can generate large voltages to the ground. The operating current and maximal magnetic field in the coil are 686 A and 3.25 T, respectively. The total number of turns in the coil is equal to 1749. The data used in all quench calculations performed in this document is presented in Table 6. This data was derived from section 2.5 (Engineering design of the superconducting coils, see Table 3 and Table 4.)

<table>
<thead>
<tr>
<th>In (A)</th>
<th>686</th>
</tr>
</thead>
<tbody>
<tr>
<td># of turns</td>
<td>1749</td>
</tr>
<tr>
<td>ACu (mm²) - one conductor</td>
<td>5.575785</td>
</tr>
<tr>
<td>ANbTi (mm²) - one conductor</td>
<td>0.612760</td>
</tr>
<tr>
<td>Ains (mm²) - one conductor</td>
<td>5.707108</td>
</tr>
<tr>
<td>Acond = ACu + ANbTi + Ains (mm²)</td>
<td>11.895653</td>
</tr>
<tr>
<td>Bm (T)</td>
<td>3.25</td>
</tr>
<tr>
<td>Average turn length (m)</td>
<td>5</td>
</tr>
<tr>
<td>Emagnet (MJ)</td>
<td>5.15</td>
</tr>
<tr>
<td>Ld(I) (H)</td>
<td>see fig. 19</td>
</tr>
<tr>
<td>B(I) (T)</td>
<td>see fig. 20</td>
</tr>
</tbody>
</table>
The dipole magnet will be self-protecting. It means that the hot-spot temperature and the voltages (turn-to-turn, coil-to-ground, layer-to-layer), induced by a quench, do not damage the magnet insulation.

In order to avoid vaporization of helium, an external dump resistor will be used. In that case significant part of the magnet energy will be dump in the external resistor (placed at 300 K) instead of heating up the helium.

2.6.2 Quench calculations

There were three types of quench calculations performed for the CBM dipole magnet:

- "First approximation"
- Instantaneous quench
- 3D calculations using GSI [20] and CIEMAT [21] quench program (with and without a dump resistor).

2.6.2.1 "First approximation"

This simplified calculation can be used for self-protecting magnets. It gives the order of magnitude of the coil average temperature $T_{av}$ and the maximum quench voltage $V_{qm}$.

The coil volume is equal to:

$$Vol = A_{cond} \cdot 1749 \cdot 5 = 0.104 \text{ m}^3.$$  
(5 m is the average turn length)

The energy density in the coil is equal to:

$$E = \frac{5.15 \cdot 10^6}{Vol} = 49.51 \text{ MJ/m}^3.$$  

The $T_{av}$ can be derived out of following equation:

$$\frac{E}{Vol} = \int_{4.5K}^{T_{av}} C_v(T) \cdot dT.$$  

In this case it is 90 K.

Having the $T_{av}$ one can estimate the $V_{qm}$ using an empiric formulation [15]:

$$V_{qm} = 0.403 \cdot R_{pole}(T_{av}) \cdot I_n,$$

where $I_n$ is the nominal current and $R_{pole}(T_{av})=\rho_{Cu}(T_{av}) \cdot 1749 \cdot 5/A_{Cu}$.

In this case $R_{pole}(T_{av})=4.7 \text{ Ω}$ and $V_{qm}=1307 \text{ V}$.

2.6.2.2 Instantaneous quench

The instantaneous quench means that the whole coil is heated up instantaneously above the critical temperature. There is no heat propagation within the coil. The calculation is performed for a short-circuit magnet.

The assumption of the instantaneous and homogeneous quench makes the quench calculation easy and gives a good estimation of the maximum quench voltage ($V_{qm}$). It also gives the average temperature ($T_{av}$) at the end of the quench which will be lower than the real hotspot temperature in the coil. Our calculations assume that one coil has one uniform temperature ($T_{av}$).

At the start of the quench $T_{av}$ is equal to 10 K and $B_{av} = B_{max}(I_n)/2$, where $I_n$ is the nominal current.

For a short-circuit magnet the electrical equation is [15]:

$$V_{qm} = R_{pole}(T_{av}) \cdot I_n.$$
\[ L_d(I) \cdot \frac{dI}{dt} + R_q(T_{av}) \cdot I = 0 \]
\[ R_q(T_{av}) = r l(T_{av}) \cdot n_{pp} \cdot \nu_{1\text{turn}}, \quad \text{Eq. 1} \]
\[ \Rightarrow dI = - \frac{R_q(T_{av}) \cdot I}{L_d(I)} \cdot dt \]

where \( n_{pp} \) is the number of turns per pole and \( l_{1\text{turn}} \) is the average turn length, \( L_d \) is the differential inductance [21]. For a conductor having Cu and NbTi, the linear resistance \( r l \) (given in Ohm/m) is given as follows:
\[ r l_{av} = \left[ \frac{1}{r l_{\text{Cu}}(RRR,B_{av},T_{av})} + \frac{1}{r l_{\text{NbTi}}(T_{av})} \right]^{-1} = \left[ \frac{A_{\text{Cu}}}{\rho_{\text{Cu}}(RRR,B_{av},T_{av})} + \frac{A_{\text{NbTi}}}{\rho_{\text{NbTi}}(T_{av})} \right]^{-1}, \quad \text{Eq. 2} \]

where \( r l_{\text{Cu}} \) is the resistivity and \( A \cdot \) the cross section of one material in the conductor.

The heat equation is written for one pole and gives the following temperature increase:
\[ R_q(T_{av}) \cdot I^2 \cdot dt = V o l \cdot C_{p_{av}}(T_{av}) \cdot dT_{av} = A_{\text{coil}} \cdot \nu_{1\text{turn}} \cdot C_{p_{av}}(T_{av}) \cdot dT_{av} \]
\[ \Rightarrow dT_{av} = \frac{R_q(T_{av}) \cdot I^2}{A_{\text{coil}} \cdot \nu_{1\text{turn}} \cdot C_{p_{av}}(T_{av})} \cdot dt, \quad \text{Eq. 3} \]

where \( A_{\text{coil}} \) is the coil cross section (made of \( n_{pp} \) insulated conductors and the ground insulation) and \( C_{p_{av}} \) is the average specific heat (in J/(m\(^2\)K)) of the pole.

The average specific heat of one pole is given by the following formula:
\[ C_{p_{av}}(T) = \left[ A_{\text{Cu}} \cdot C_{p_{Cu}}(T) + A_{\text{NbTi}} \cdot C_{p_{NbTi}}(T) + A_{\text{ins}} \cdot C_{p_{ins}}(T) \right] \left[ A_{\text{Cu}} + A_{\text{NbTi}} + A_{\text{ins}} \right]^{-1}, \quad \text{Eq. 4} \]

where \( A \) is the cross section of the corresponding material and “ins” stands for insulation.

The calculation takes also into account the inductance function \( L_d(I) \) depicted in Figure 19 and the \( B_{\text{max}}(I) \) function depicted in Figure 20.

Figure 30 and Figure 31 show instantaneous quench calculation results [14, 15, 16]. The average temperature is about of 90 K. The resistance of quenched pole is equal to 4.7 Ohm and the maximum quench voltage is equal to 1230 V.

![Figure 30. Instantaneous quench calculation of the CBM dipole - the magnet current and the average coil temperature.](image-url)
2.6.2.3 3D quench calculations (GSI and CIEMAT quench programs)

The 3D GSI quench program is described in [20]. Figure 32 and Figure 33 show the results of 3D quench calculations [15,16] when no dump resistor was used. The calculation is performed for the uniform field map distribution in the coil using the maximal values $B_m(I)$ (see Figure 20). It takes also into account the inductance function $L_d(I)$ depicted in Figure 19. The detection threshold was set to 0.6 V. The validation time equals to 10 msect and the time to open the switches is 40 msect. The current decay lasts 20.5 s (10% In). The maximum hot-spot temperature equals to 124 K. The maximum quench voltage equals to 1240 V and the quench resistance ($t=$infinite) equals to 4.7 Ohm. 100 % of 5.15 MJ is deposited in the magnet at the cold side.

**Figure 31.** Instantaneous quench calculation of the CBM dipole - the quench voltage and the quench resistance.

**Figure 32.** 3D quench calculation of the CBM dipole - the magnet current, hot-spot temperature and the average coil temperature.
The detailed description of the 3D CIEMAT quench program is presented in [21]. The quench calculation assuming adiabatic conditions has been performed solving the heat balance equation by means of the finite difference method [21]. An analog electrical circuit models the quench propagation. Each wire is subdivided longitudinally in a number of parts which are the node of the analog circuit.

The calculation is also carried out using \( L_d(I) \) dependences (see Figure 19) and the field map distribution in the coil taken from Figure 9 [23]. The results of the 3D calculations [14, 24] when no dump resistor was used is also presented in Figure 32 and Figure 33. The current decay lasts 40.0 s (1% In). The maximum hot-spot temperature equals to 160 K. The maximum quench voltage equals to 1242 V and the quench resistance (t=infinite) equals to 4.8 Ohm. The difference between the results calculated with the GSI and CIEMAT models is related to the different field map distribution in the coil, and also to different material data bases used in those programs.

Figure 34 and Figure 35 compare the quench calculation results between the GSI and CIEMAT computations with a dump resistor of 2.1 Ohm. The detection threshold was set to 0.6 V. The validation time equals to 10 msec, and the time to open the switches is 40 msec.

**Figure 33.** 3D quench calculation of the CBM dipole – the quench voltage and the quench resistance.

**Figure 34.** 3D quench calculation of the CBM dipole – magnet current, magnet voltage and the maximum (hot spot) coil temperature.
Figure 35. 3D quench calculation of the CBM dipole - the quench voltage and the quench resistance.

The current decay lasts 21.9 s (10% In). Both of these models predict a maximum hot-spot temperature on the level of 70 K. The maximum quench voltage equals to 249 (190) V, and the quench resistance (t=infinite) equals to 1.04 (0.9) Ohm for GSI and CIEMAT computations, respectively. Approximately 85% of 5.15 MJ are dissipated in the external dump resistor. The maximum voltage across the magnet occurs when the dump resistor turns on. It is equal to V_magnet_max=1441 V.

2.6.3 Quench detection and protection schemes

Figure 36 shows the magnet, the power supply (PS) scheme, the simplified PS control unit scheme, the dump resistor (for quench protection) and the quench detection system. Each magnet pole has a separate cryostat. The current is brought from the room temperature to the magnet (4.5 K) by current leads (CL). There are 4 current leads (two per one pole). The quench detection system consists of:

- 4 voltage detectors (CLD1) used for current leads
- 1 classical bridge detector (BRD) used for the magnet
- Voltage threshold in the power supply unit (safety trigger).

Grounding resistors define the ground. The dump resistor $R_d$ is connected in parallel to the magnet (always on). The maximum magnet voltage needed to ramp up the magnet (see Figure 37) is estimated to be <7 V. Thus the estimated maximum PS voltage should not exceed 12 V (value depends on the distance between the PS and the magnet). There will be a power loss in the “always on” $R_d$ (2.1 Ω) of around 60 W. It is negligible loss in comparison to the power of the magnet. Nevertheless “always on” $R_d$ is a very reasonable solution.

During the normal operation the DC-circuit breaker is closed. When a quench occurs a quench trigger is given by detection system. After the quench trigger, the DC-circuit breaker disconnects the PS and the magnet current is dumped via the dump resistor. Using $R_d=2.1$ Ω around 88% out of the magnet energy (5.15 mj) will dissipated in the $R_d$ at the room temperature.
The bridge detection (BRD) system is unable to detect a symmetrical quench (i.e. both poles quench at the same time). In that case, the quench trigger is given by the power supply. The maximum magnet ramping voltage is given by

\[ V = L_d \left( \frac{dI}{dt} \right) = 6.2 \text{ V} \]

with \( L_d(I=0)=32.3 \text{ H} \) and an assumed ramp rate of 0.19 A/s (magnet is charged to its nominal energy in 1 h – just an example).

This corresponds to a triangular cycle depicted in Figure 37. Such triangle cycles can be used to erase the magnetic history of the magnet. The magnet can be also ramped with a constant voltage.

If the power supply is designed for a maximum voltage of 15 V, a certain threshold will be set (for example 13 V). When a power supply voltage exceeds this threshold, a quench trigger will be given.

Figure 38 shows the typical quench detection time sequence. Table 7 presents the quench detection time sequence.
Figure 37. Example of magnet ramping up and down at constant $dI/dt = 0.19$ A/s. $I_n=686$ A, $t_r=1$ h.

Figure 38. Quench detection time sequence.
### Table 7. Quench detection time sequence (definitions).

<table>
<thead>
<tr>
<th>DEFINITION</th>
<th>EXAMPLES OF VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t = 0 )</td>
<td>quench or thermal run-away start</td>
</tr>
<tr>
<td>( V_{\text{in}} )</td>
<td>voltage threshold 600 mV for one SIS100 Chr. Sext</td>
</tr>
<tr>
<td>( t_{\text{rt}} )</td>
<td>time to reach ( V_{\text{in}} ) without filter ( \geq 6 ) ms for one SIS100 Chr. Sext</td>
</tr>
<tr>
<td>( t_{\text{rf}} )</td>
<td>time to reach ( V_{\text{in}} ) with filter ( t_{\text{rf}} &lt; t_{\text{rt}} + 10 ) ms for all magnets except chr. Sext.(+5 ms)</td>
</tr>
<tr>
<td>( t_{\text{v}} )</td>
<td>validation time 10 ms for all magnets except chr. Sext.(5 ms). 100 ms for a resistive current lead.</td>
</tr>
<tr>
<td>( t_{o} )</td>
<td>time between the release of the “quench” trigger and start of the dumping 1 ms for SIS100 dipoles and quadrupoles</td>
</tr>
<tr>
<td>( t_{\text{Rd}} )</td>
<td>time between quench or thermal run-away start and start of current dumping ( V_{\text{q}} ) non filtered: ( t_{\text{Rd}} = t_{\text{rt}} + t_{\text{v}} + t_{o} ) ( V_{\text{q}} ) filtered: ( t_{\text{Rd}} = t_{\text{rf}} + t_{o} )</td>
</tr>
</tbody>
</table>

### 2.6.4 Summary and conclusions

A potted coil (1749 turns) with a nominal current of \( I_{\text{n}} = 686 \) A is proposed for the CBM dipole. To make the designed magnet self-protecting a “wire in channel” conductor has been chosen. The conductor consists of a superconducting strand with a diameter of 1.28 mm and a copper stabilizer. The strand used in the CMS solenoid [10] is planned to be used in the CBM dipole. A self-protecting design requires a high copper to superconductor ratio (9.1). A standard size of 3.25 mm x 2.02 mm is planned to be used. Hopefully the conductor manufacturer will be capable to manufacture a conductor length of 8.9 km. Superconducting joints in the coil are strongly undesired. Table 8 presents required stabilizer and strand masses.

### Table 8. Cable dimensions.

<table>
<thead>
<tr>
<th></th>
<th>X-section</th>
<th>Density (kg/m3)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>length: 8.9 km</td>
<td></td>
</tr>
<tr>
<td>ANbTi (mm2)</td>
<td>0.613</td>
<td>6029</td>
<td>33</td>
</tr>
<tr>
<td>ACucore (mm2)</td>
<td>0.674</td>
<td>8920</td>
<td>54</td>
</tr>
<tr>
<td>ACu_stabilizer (mm2)</td>
<td>4.902</td>
<td>8920</td>
<td>389</td>
</tr>
<tr>
<td>ACu_total (mm2)</td>
<td>5.576</td>
<td>8920</td>
<td>443</td>
</tr>
<tr>
<td>Ainsulation (mm2)</td>
<td>5.707</td>
<td>1930</td>
<td>98</td>
</tr>
<tr>
<td>Acore (mm2)</td>
<td>1.287</td>
<td>-</td>
<td>86</td>
</tr>
<tr>
<td>Atotal (mm2)</td>
<td>11.896</td>
<td>-</td>
<td>574</td>
</tr>
</tbody>
</table>

\( \text{ACu_total/ANbTi}=9.1 \)

With a CMS wire in a \( \text{Cu} \) stabilizer \( (Jc(4.2K,5T) = 3000 \) A/mm2), the temperature margin (at 4.5 K) is 2.3 K. It decreases only by 0.1 K in case of a current safety margin of 10%. The current margin along the load line is 52% \( (I_{\text{n}}/I_{\text{loadm}} = 0.52) \).
Quench calculations showed that the magnet is self-protecting (against both temperature and voltages: coil-to-ground and coil-to-coil).

The 3D GSI (CIEMAT) quench calculation performed for a magnet without a dump resistor gives an average pole temperature of 89 K, a hotspot temperature $T_m$ of 124 (160) K, and a maximum quench voltage of 1240 (1242) V. In this case, all the magnet energy (5.15 MJ) is dissipated in the magnet.

When using an external dump resistor of 2.1 Ohm, 83% (86% for CIEMAT) of the 5.15 MJ can be dissipated in the resistor. In that case, the average pole temperature, the hotspot temperature and the maximum quench voltage are equal to 48 K, 67(69) K and 249(190) V for GSI (CIEMAT) computations, respectively. The maximum voltage across the magnet occurs when the dump resistor turns on. It is equal to $V_{magnet\_max}=1441$ V and the magnet insulation needs to withstand it. The summary of the quench calculations is given in Table 9.

The additional literature for the quench calculations can be found in Refs. [20-22].

Table 9. Quench calculation summary.

<table>
<thead>
<tr>
<th>Rd (Ohm)</th>
<th>$T_{average_max}$ (K)</th>
<th>$T_{max}$ (K)</th>
<th>$R_{qm}$ (Ohm)</th>
<th>$V_{qm}$ (V)</th>
<th>ERd/Emag (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First estimation $V_{qm}=0.403*R_{pole}\cdot(T_{av})\cdot\ln\frac{90}{4.7}$</td>
<td>0</td>
<td>90</td>
<td>-</td>
<td>4.7</td>
<td>1307</td>
</tr>
<tr>
<td>Instantaneous quench</td>
<td>0</td>
<td>90</td>
<td>-</td>
<td>4.8</td>
<td>1320</td>
</tr>
<tr>
<td>3D quench calculation_GSI</td>
<td>0</td>
<td>89</td>
<td>124</td>
<td>4.7</td>
<td>1240</td>
</tr>
<tr>
<td>3D quench calculation_CIEMAT</td>
<td>0</td>
<td>160</td>
<td>4.8</td>
<td>1242</td>
<td>0</td>
</tr>
<tr>
<td>3D quench calculation_GSI</td>
<td>2.1</td>
<td>48</td>
<td>67</td>
<td>1.04</td>
<td>249</td>
</tr>
<tr>
<td>3D quench calculation_CIEMAT</td>
<td>2.1</td>
<td>69</td>
<td>0.9</td>
<td>190</td>
<td>86</td>
</tr>
</tbody>
</table>
3. Heat Loads

The operation of the superconducting magnet requires both liquid helium (4.5 K) and cold helium gas (80 K) for cooldown and refrigeration of the thermal shields. Similar systems have been used successfully throughout the SAMURAI magnet [24, 25]. A summary of the cryogenic loads per coil is given in Table 10 and Table 11. The total heat loads for the magnet including the feedbox and the transfer lines between are 22.6 W at 4.5 K and 91 W at 80 K and 0.15 g/s liquefaction at 4.5 K. The coils will be equipped with a full set of instrumentation sensors for monitoring, control, and diagnostic purposes. Instrumentation includes temperature sensors for the cold mass, shield cryogenic flow monitoring, and strain gauges in the coil supports. Voltage taps will monitor the electrical resistance of the conductor joints and the leads and provide the quench detection voltages. An inductive spot heater will be installed to provoke a quench.

Table 10. Heat loads at 4.5 K per coil.

<table>
<thead>
<tr>
<th>Item Parameter</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Mass</td>
<td>1800 kg</td>
</tr>
<tr>
<td>Total Surface Area</td>
<td>6.2 m²</td>
</tr>
<tr>
<td>Radiation Heat Flux (Design)</td>
<td>0.07 W/m²</td>
</tr>
<tr>
<td>Radiation Heat Load (Design)</td>
<td>0.44 W</td>
</tr>
<tr>
<td>Cable Joints</td>
<td>max 2 W</td>
</tr>
<tr>
<td>Support Struts Load</td>
<td>2.8 W</td>
</tr>
<tr>
<td>Tie Rods Load</td>
<td>0.1 W</td>
</tr>
<tr>
<td>Gas Connection Load</td>
<td>1 W</td>
</tr>
<tr>
<td>Feed Box Load</td>
<td>5 W</td>
</tr>
<tr>
<td><strong>Total 4.5K</strong></td>
<td><strong>11.3 W</strong></td>
</tr>
<tr>
<td>Liquefaction 4.5 K for current leads [g/s]</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 11. Heat loads at 80 K per coil.

<table>
<thead>
<tr>
<th>Item Parameter</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield Mass</td>
<td>130 kg</td>
</tr>
<tr>
<td>Total Surface Area</td>
<td>8.2 m²</td>
</tr>
<tr>
<td>Radiation Heat Flux (Design)</td>
<td>1.3 W/m²</td>
</tr>
<tr>
<td>Radiation Heat Load (Design)</td>
<td>10.7 W</td>
</tr>
<tr>
<td>Support Struts Load</td>
<td>20 W</td>
</tr>
<tr>
<td>Tie Rods Load</td>
<td>1.8 W</td>
</tr>
<tr>
<td>Feed Box Load</td>
<td>10 W</td>
</tr>
<tr>
<td>Gas Connection Load</td>
<td>2 W</td>
</tr>
<tr>
<td>Diagnostic Wires</td>
<td>1 W</td>
</tr>
<tr>
<td><strong>Total 80K</strong></td>
<td><strong>45.5 W</strong></td>
</tr>
</tbody>
</table>
4. Cryogenics

4.1 Cryogenic supply

According to the ongoing plan of the FAIR cryogenic distribution, it is foreseen that the cryogenic supply for CBM dipole will be provided via a dedicated cryogenic transfer line from the Distribution Box 2 (DB2) which is located in the Super-FRS target hall as shown in Figure 39. DB2 is supplied from the cryoplant CRYO1 through the cryogenic transfer line inside the Super-FRS tunnel.

Figure 39. FAIR cryogenic distribution for CBM cave together with the building plan.

Figure 40 shows the flow scheme for DB2 and the cryogenic transfer line to the CBM cave, the cryogenic feedbox including its warm helium gas management and the CBM upper and lower coil cryostats. The interface between the FAIR cryogenic distribution system and the cryogenics for CBM dipole is preliminarily defined by the grey lines in the diagram.
Figure 40. Flow scheme of the FAIR cryogenic distribution for the CBM cave and the cryogenics for the CBM dipole.

Figure 41. Flow scheme for the cryogenic feedbox of the CBM dipole.

Figure 41 shows the flow scheme of the cryogenic feedbox. During cooldown the cooling flow firstly cools the two shields of the coils and afterwards the two cold masses in series. In such a way the temperature gradient over the shield structures and over the cold masses of the two coils could be conveniently adjusted, especially during the cooldown phase from 300 K to 100 K. During normal operation the two separate liquid helium baths for the upper and lower coils are to be re-filled with liquid helium independently by two JT valves. If one of the two coils quenches, the quench gas will be collected through the warm multi-purpose line via the control valve in the feedbox or through the quench relief valves on the coil cryostats as shown in Figure 42.
4.2 Cooldown

One single coil of the CBM dipole has a perimeter of 5 meters. The conductor of the coil consists of NbTi, Cu and insulation material as G-10 CR, whose integral volumes and weights have been listed in the Table 4. Using specific heat data of these materials - as published by the National Institute of Standard and Technology NIST, USA, - one can calculate the required cooldown energy for the individual materials and for the overall coil structure. Table 12 shows that the single coil of the CBM dipole weighs about 762 kg and at least 67.7 MJ are needed to cool the coil from 300 K to its operating temperature around 4 K.

<table>
<thead>
<tr>
<th>Vol_pole</th>
<th>Volume [m³]</th>
<th>Ratio</th>
<th>Weight [kg]</th>
<th>Cooldown energy from 4 K to 300 K [MJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol_NbTi</td>
<td>0.0054</td>
<td>4.3%</td>
<td>35</td>
<td>3.3</td>
</tr>
<tr>
<td>Vol_Cu</td>
<td>0.0713</td>
<td>56.8%</td>
<td>639</td>
<td>51.5</td>
</tr>
<tr>
<td>Vol_ins (G-10 CR)</td>
<td>0.0488</td>
<td>38.9%</td>
<td>88</td>
<td>13.0</td>
</tr>
</tbody>
</table>

The total cold mass of the CBM dipole comprises 2 coils and their stainless steel coil casings including their current leads boxes with a total weight of about 2000 kg. Therefore the CBM dipole has a total of about 3.5 tons cold mass, which is more or less half of the cold mass of the SAMURAI superconducting dipole [27] and needs at least 320.3 MJ cooldown energy from room temperature down to its operation temperature around 4 K.
Table 13. Cold mass weight and the overall cooldown energy.

<table>
<thead>
<tr>
<th>Cold mass</th>
<th>Weight [kgs]</th>
<th>cooldown energy from 300 K to 4 K [MJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 coils</td>
<td>1524</td>
<td>135,5</td>
</tr>
<tr>
<td>2 Stainless steel coil casings</td>
<td>2000</td>
<td>184,8</td>
</tr>
<tr>
<td>Cold mass total weight</td>
<td>3524</td>
<td>320,3</td>
</tr>
</tbody>
</table>

For the epoxy-impregnated superconducting coil which is proposed to be used for the CBM coil winding, studies at CERN and other laboratories [28] show that epoxy resin becomes brittle at lower temperature and the so-called epoxy failures may occur, which means micro-cracking and micro-fractures occur during cooldown. The reason is that the epoxy has a higher thermal contraction than the composite superconductor (to which it is glued) and the resin is in tension after cool-down. Therefore the appropriate cooldown rate of the overall coil structure is one of the important parameters to limit the epoxy failures as much as possible. The experience at CERN and in other institutes is that one should keep the cooldown rate of the epoxy-impregnated coil structure below 1.0 K / hour during the cooldown from 300 K to 100 K. The fact is that the thermal contractions of almost all the engineering materials used in the coil structure are finished when the cooldown temperature reaches 100 K. Therefore thermal stress issues don’t limit the cooldown rate below 80 K.

Because the specific heat of different composites in the conductor varies with the temperature, the cooldown is arranged into 4 phases, which are from 300 K to 200 K as phase No. 1, from 200 K to 100 K as phase No. 2, from 100 K to 10 K as phase No. 3 and the final cooldown from 10 K to 4.5 K including the liquid helium filling as phase No. 4. For the cooldown phase No. 1 and No. 2, only the cooling power at 80 K is required. During these first two phases cold helium gas at 50 K is needed to mix with 300 K warm helium in order to keep the maximum temperature difference between the warmest point in the cold mass and the coldest helium temperature at the inlet always smaller than 40 to 50 K. This is also one of the important parameters which keeps the thermal gradient stress in the coil structure below allowed values. For the cooldown phase No. 3 and No. 4, not only the cooling power at 4.5 K, but also at 80 K is required because the heat load due to the radiation from 300 K to the cold mass below 100 K needs to be taken away by the shield cooling flow at 80 K. The nominal load for the thermal shield is the minimal requirement. High refrigeration power is required in order to speed up the cooldown below 80 K (phase 3). As an alternative, one can use the enthalpy difference of the supercritical helium between 5 K and 50 K as a more effective solution [29]. The cooldown phase No. 4 covers the final cooldown from 10 K to 4.5 K and the liquid helium filling into the coil casing including the required liquid helium volume in the current leads boxes.

Table 14. Required cooling power at 80 K and 4.5 K during different cooldown phases with specified cooldown rates.
The total cooldown time of all the 4 phases takes about 11 days: 8 days for phase 1 and 2 (1 K/hr rate), 2 days for phase 3 (2 K/hr rate) and final cooldown and liquid helium filling takes about one day. Figure 43 shows the required cooling power to cooldown the CBM dipole correspondingly. The FAIR cryogenic distribution system should fulfil all those requirements.

![Figure 43](image)

**Figure 43.** Required cooling power for the cooldown of the CBM dipole to 4.5 K and for the filling of the coil casings with liquid helium.

### 4.3 Normal operation

The superconducting upper and lower coils of the CBM dipole are cooled in two separate helium baths at 4.5 K. Table 15 contains the operating parameters and the total static loads at 4.5 K and 80 K of the CBM dipole (both coils). The liquid helium level in the helium vessel inside the current leads box is kept constant by filling the liquid helium from top via the refilling line which is connected to a Joule-Thomson valve in the feedbox. The evaporated helium gas returns at 1.3 bar via the return line which is connected to the feedbox of the FAIR distribution system.

**Table 15.** Operation parameters and static heat loads at 4.5 K and 80.0 K

<table>
<thead>
<tr>
<th>Coil Temperature [K]</th>
<th>4.5</th>
<th>4.5 K Liquefaction [g/s] current leads</th>
<th>Shield Temperature [K]</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat load [W]</td>
<td>22.6</td>
<td>Inlet pressure [bar]</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>Operation pressure [bar]</td>
<td>1.3</td>
<td>Outlet pressure [bar]</td>
<td>17.0</td>
<td></td>
</tr>
<tr>
<td>Liquid helium after JT [g/s]</td>
<td>1.2</td>
<td>Mass flow rate at 50 K [g/s]</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Supercritical helium before JT [g/s]</td>
<td>1.4</td>
<td>With design factor of 1.5</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td></td>
<td>0.23</td>
<td>1.9</td>
</tr>
</tbody>
</table>
The shield cooling starts at 18.0 bars and 50 K at the inlet of the shield circuit and ends at the outlet at 17.0 bars and 80 K. With the design factor of 1.5, the mass flow rates for the CBM dipole normal operation are specified as 2.1 g/s at 5 K and 3 bars, 1.9 g/s at 50 K and 18.0 bars, respectively. The FAIR cryogenic distribution system should fulfill these requirements.

4.4 Helium pressure rise during a quench

After the detection of a quench, the quench protection system will normally trigger actions in order to dump most of the stored energy in an external dump resistor. However, here we have to assume the worst-case-scenario, that in case of failure of the protection system- all stored energy will be deposited into the cold mass of the magnet. In such an “emergency” the ‘self-protected’ magnet will not be damaged, but the coils will be heated up and the helium will evaporate. The helium pressure in the coil casings will surge and the helium warm up. This pressure rise may trigger the pressure relief system.

As one of the worst case scenarios, the quench without dump resistor has been simulated in order to investigate the helium pressure rise behavior when the total stored energy of the magnet is deposited in one coil. The results predict that the current decay after the quench initiation takes about 45 s. The total stored energy of the deposition in the coil is around 5.0 MJ when the CBM dipole is charged to its operation current of 686 A. Therefore the average power of energy deposition is about 110 kW over 45 s.

The helium pressure surges to about 13 bars within 45 s. The pressure rising speed averages out to about 0.25 bar /s with its peak speed of 1.0 bar /s in the first few seconds after the quench starts. The maximum calculated coil temperature reaches 94 K under adiabatic conditions. Taken the heat transfer between the coil and helium into account, the calculation predicts an average

![Figure 44. Helium pressure and temperature in one CBM coil casing during quench without dump resistor and pressure release valve remaining closed.](image)
coil temperature of 70 K. The helium gas temperature finally reaches also 70 K. In the calculation is assumed that there is 20 liters liquid helium at 1.2 bars in the coil casing and the current leads box in one single coil cryostat, in total 40l LHe in the magnet. In addition 10 liters helium gas volume is above the liquid helium volume in the current lead box.

4.5 Quench recovery

After the current decayed to zero, the quench recovery can start. But, even with the proper operation of the pressure relief system, the helium pressure in the coil casing may be still too high. Besides, one must be aware that the gas temperature of 70 K is too high to send it back to the refrigerator through the 4 K circuits of the FAIR distribution system. Therefore it is foreseen that the quench gas collection line for warm helium recovery will be used further for the pressure reduction during the quench recovery. To prevent the quench gas collection line from icing, vacuum shield for this line is necessary.

Table 16. Required cooling power at 4.5 K during quench recovery (after the full stored energy was deposited in the single coil during a quench).

<table>
<thead>
<tr>
<th>Quench recovery steps</th>
<th>Average temperature of quenched coil [K]</th>
<th>Cooldown energy for recovery [MJ]</th>
<th>Cooling power needed at 4.5 K during recovery [W]</th>
<th>Cooling power needed at 4.5 K during recovery [W]</th>
<th>Quench recovery time [days]</th>
<th>cooldown rate during recovery [K/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSF 1</td>
<td>Stage 30-12</td>
<td>7.9</td>
<td>91</td>
<td>119</td>
<td>4.7</td>
<td>2.4</td>
</tr>
<tr>
<td>CSF 2</td>
<td>Final cooldown from 18 K to 4.5 K</td>
<td>3.3</td>
<td>91</td>
<td>119</td>
<td>4.7</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Static heat loss at 4.5 K (W)</td>
<td>38.8</td>
<td>4.5 K cooling power needed during quench recovery [W]</td>
<td>4.7</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Evaporation (static heat loss) [kJ]</td>
<td>2.3</td>
<td>mass flow rate before Fil during filling [g/s]</td>
<td>5.3</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Current leads number x</td>
<td>16</td>
<td>net liquid flow rate filling [g/s]</td>
<td>5.3</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Current [A]</td>
<td>680</td>
<td>Liquid helium after Fil [g]</td>
<td>5.3</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Current leads cooling flow at zero current [g/s]</td>
<td>0.05</td>
<td>Total recovery time [days]</td>
<td>1.2</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

After the helium pressure in the coil cryostat decreased to about 3 bars, which is the supply pressure at 4.5 K circuit in the feedbox, the cooldown of the quenched coil structure from about 70 K to 4.5 K can be started. Such cooldown processes are quite similar to the cooldown phase No 3 and No. 4. One of the major differences could be that the starting temperature of the quench recovery is 70 K instead of 100 K. In addition only one quenched coil may need to be recovered because the two coils are located in separate cryostats. In the calculation one assumes that the forced current decay would not quench the second coil due to AC losses (no “quench back”). Table 5 contains the operation parameters and required cooling power for the quench recovery of a single coil. The total recovery time takes 1.2 days with a cooling power of about 120 W at 4.5 K. In fact, the FAIR cryogenic distribution system can deliver high refrigeration power. As an alternative, it is foreseen that - by using the enthalpy difference of the supercritical helium from 5 K to 50 K - one can have a more effective solution to reach a shorter quench recovery time.

4.6 Safety design for helium vessel

For the helium system, a primary and secondary system of relief devices are required. The rupture disk (the secondary system) is sized for fire or loss of vacuum to air, and the primary relief should handle any other “operational emergency” condition, including quenching [30]. As more in details, relief systems are sized to protect the cryogenic system in the event of loss of insulating vacuum to helium, loss of insulating vacuum to air, fire, quenching, and simultaneous quenching and loss of insulating vacuum to air. This final event generally requires the greatest venting capability [31]. One has to foresee that a large heat flux may be imposed on the surface of
the helium vessel when loss of insulating vacuum to air occurs. The imposed heat flux could be as high as 6.0 kW/m² which is a measured value given in one of the important reference papers [32]. For one single coil of CBM dipole with about 6 m² outer surface of the cold mass 36 kW heat power will be deposited. By taking the average power of 110 kW of energy deposit on a single coil during a quench (calculation above), one must foresee that up to 150 kW (~ 110 kW + 36 kW) could be imposed in one coil casing during simultaneous quenching and loss of insulating vacuum to air. This is the basic requirement for the sizing of the rupture disk as the secondary system of safety device for CBM cave together with the building plan.
5. Safety considerations

For operating the magnet an approval by the local authorities e.g. TÜV is necessary. This approval incorporates the proof of the design, the construction as well as final tests. The extent of this approval is given in the pressure vessel directive [33] and differs according to the classification of the vessel.

A preliminary analysis of the design according to the classification within the pressure vessel directive was performed. The statements of this analysis are for information only and without responsibility. A final analysis is to be done in close collaboration with the authorities. It is mandatory to involve the authorities already in the early design stage to avoid problems.

The basis for the classification of a pressure vessel is the product of the maximum pressure and the volume.

The volume of the device was estimated to be 40 litres.

For the specification of the maximum pressure two contrary criteria have to be taken into account:

1. A high design pressure makes the cross section of safety valves smaller and eases their integration. In addition a high design pressure can avoid helium blow off in case of a quench.
2. A design with a small pressure could lead to a simpler design and classification into a lower category.

At first the high pressure limit is investigated.

In chapter 4 the maximum pressure was calculated for the case that all stored energy is dumped into the magnet. In that case all helium is evaporated. The average heat load in this case is 110 kW. A maximum pressure of ~13 bar is reached.

For comparison the breakage of the insulation vacuum is checked. Then the heat load is determined by the room temperature of the cryostat vessel. The specific heat load in that case was determined to be 6 kW/m² [34]. The surface of the cold mass is ~6 m². Therefore the total heat load is 36 kW, much smaller than in the case of a quench.

Therefore, the maximum pressure of the quench scenario (13 bar) is taken for the following estimations.

The product of pressure and volume is under these conditions 520 bar·l. This is well above the limit for a category I device (200 bar·l) and below the limit of category III device (1000 bar·l).

Trying to avoid a category II device would lead to a design pressure well below 5 bar. This is very close to the operating pressure of 3.5 bar and would lead to the above described problems with the safety valve design. Therefore this is not an option.

This preliminary analysis classifies the pressure vessel as a category II device. It is proposed to assume a design pressure of 20 bar for the pressure vessel. This is the same pressure as it is used for the sc-magnets in the Super-FRS.

Based on this proposal assumptions for the primary and secondary system of relief devices can be made (compare chapter 6). The primary safety relief valve would be set to 14 bar, which is equal 70% of design pressure [35]. The rupture disc (secondary system of relief devices) would be set to the design pressure of 20 bar.
6. Structural Analysis

The program package ANSYS is used for the structural analysis.

6.1 Cryostat

Figure 45 shows the results of the vacuum vessel calculation. The maximum deformation is 0.06 mm and the maximum stress is 26 MPa. The safety factor is about 5. The material of the vacuum vessel is stainless steel SAE 304 with the allowable stress ~140 MPa.

![Vacuum vessel](image)

Load external pressure

Max deformation 0.06 mm

Max stress 26 MPa

Safety factor ~5

*Figure 45. Deformation of the vacuum vessel.*
6.2 Cold mass

The following pictures show results of calculations of the deformation of the cold mass due to a pressure of 20 bar in case a quench. The case is welded of stainless steel 316LN. The minimal thickness of the case is 20 mm. The case cross section is 230 mm (height) times 230 mm (width). This preliminary analysis classifies the pressure vessel as a category II device. A design pressure of 20 bar is assumed for the pressure vessel. The maximum deformation about is 0.04 mm. The maximum stress about is 70 MPa. The allowable stress for welding of the 316LN steel at RT is ~300 MPa.

Figure 46. The maximum deformation of the cold mass is about 0.04 mm.

Figure 47. The maximum stress is about 70 MPa.
Figure 48. The maximum deformation is about 0,04 mm.

6.3 **Deformation of the cold mass due to the Lorentz forces**

The following pictures illustrate the deformation of the cold mass due to the Lorentz force acting in the vertical direction. The top flange of the case is mounted on 6 support structures. The maximum deformation of the case is about 0,14mm. The maximum stress in the case is about 100MPa. The allowable stress is 650MPa at 4K.

Figure 49. Vertical Lorentz forces on the cold mass.
Figure 50. The maximum stress is about 100MPa.

Figure 51. The maximum deformation is about 0.14 mm.
7. Assembly sequence

The following sequence of figures illustrates the design of the major parts of the magnet and shows the sequence of their assembly.

Note that only the parts related to the cold mass, cryostat and the support structure are considered in this sequence. Since the design at this stage is conceptual, many details, such as electrical and hydraulic connections, are shown schematically. Everything related to the design of the radiation shield and multi-layer heat insulation (MLI) is omitted. These details are usually developed during later stages of the design effort.

1. Preparation of the bobbin for winding the SC cable:
   - Install two aluminum shims
   - gluing of three sets of the fiber glass laminate spacers (3 x 90pcs) with the pitch of 4° on each inner surface of the bobbin
   - installation of the tray
   - installation of few layer of the ground insulation

   [Figure 52. Bobbin before winding.]

2. Winding of the SC cable on the bobbin:
   - fix the SC cable end (length 900 mm)
   - wind the first layer (33 turns) of the SC cable on the bobbin (cable tension of 20 kg)
   - impregnate the layer with a brush
   - wrap three layers of fiber glass fabric with epoxy resin

   The last three operations should be repeated 53 times.
   - wrap additional 20 layers of fiber glass fabric with epoxy resin
   - fix the second end of the SC cable (length 900 mm)
   - fix both ends together with the separating isolators
   - gluing the last set of the fiber glass laminate spacers (90pcs) with the pitch of 4° on outer surface of the coil

3. Welding of the outer wall:
   - fix the outlet tube and two wall halves on the bobbin with clamps
   - weld the parts together
   - test the weld seams
4. Installation of the support struts:
   - install six supports on the top surface of the coil case
   - connect the support terminals to the 80 K helium line
   - glue the thermocouples and the strain gauges on the coil case
   - cover the coil case with the blankets of superinsulation (20 layers)

5. Installation of the top part of the thermal shield:
   - install the thermal shield top
   - install the blankets of superinsulation (20 layers)
6. Installation of the support ring of the vacuum vessel:
   - install the support ring
   - install six tie rods and adjust them (pretension 500 kg)
   - install the thermal shield cover
   - install the last blanket of superinsulation (20 layers) on the thermal shield

Figure 55. Installation of the top part of the thermal shield.

Figure 56. Installation of the support ring of the vacuum vessel.
7. Welding of the vacuum vessel:
   - weld the outlet tube and the shell to the support ring
   - test the weld seams

8. Connection of the coil cryostat with the control box for the top end:
   - place the control box near the vacuum vessel
   - join the coil ends to the current buses of the control box
Figure 58. Solder joint of superconducting cable.

- isolate the SC cable
- connect all helium lines of the control box to the coil cryostat
- connect all diagnostic wires
- install the thermal shield parts
- weld the vacuum vessels of the coil cryostat and the control box through the sleeve
- test the weld seams
9. Assembly of the dipole magnet
   - install the magnet support structure
   - mount two bottom horizontal beams on it
   - install the bottom pole on the place and fix it with the four threaded studs
   - install the bottom coil cryostat
- install two vertical parts of the return yoke
- install the temporary support frame on the bottom pole
- place the top pole on the temporary support frame
- place the top coil cryostat on the temporary support frame
- mount two top horizontal beams on the top of the vertical parts
- fix the pole and the top coil cryostat on them
- connect the cryogenic lines and the current buses to the control boxes
- install the field clamps on the yoke

The CBM superconducting dipole magnet is ready for operation.
8. Survey and Alignment

8.1 General Considerations

The fundamental task of survey and alignment in the context of the construction of accelerators is the precise physical and geometrical positioning of machine elements, especially dipoles, quadrupoles, beam diagnostic devices, collimators etc. according to an exactly specified nominal position – the lattice – and the required alignment tolerances. Additional part of the scope of work is the metrological support to the physics experiments like providing geodetic infrastructure in the experimental areas, aid on installation and precise spatial measurement of physics detectors.

A precise alignment is not only needed for first installation; also a regular control of the actual position of the accelerator components and detectors and the preservation of the nominal values over a long period is essential for an undisturbed operation of a machine or an experiment.

Accelerator components like magnets et al need to be positioned globally and relatively within tolerances in a range of some tenth of millimeters, and shall remain in their shape and position for a long time. To meet these demands it is essential to be able to rely on mechanical conditions and it requires high precise measurement tools for the accurate survey and alignment of the components in the tunnel and caves.

Outer references of different types are needed which represent precisely the mechanical or magnetic axis respectively magnetic field vector. These references come predominantly from the manufacturer and must be several times more accurate than the final alignment tolerances.

Moving a magnet to its ideal position requires adjustment systems with a resolution substantially exceeding the final alignment tolerances.

A support structure for a magnet or a group of components must not simply serve as a spacer between floor and beam line but have to provide stability.

These points lead to the fact, that beside an accurate construction of a magnet several particularities concerning survey and alignment requirements need to be taken into account.

8.2 Basic survey and alignment steps (installation phase)

Accelerator components need to be aligned to very tight tolerances. In order to perform these tasks, following basic survey and alignment steps are essential:

- Definition of appropriate coordinate systems
- Design, lay-out and installation of a primary network on the surface for the orientation of the connected machines (existing and planned) and increasing the accuracy of the tunnel network
- Network densification by transferring the primary net into the single machine buildings and experiment caves. These networks are the basis for the mark out of the ideal positions of the supports and accelerator components (accuracy ± 1-2 mm) and the pre-alignment.
- Precise three-dimensional reference network measurements including component positions for each individual machine or experimental setups (accuracy ± 0.1 mm)
- Relative alignment of neighbouring magnets, beam diagnostic devices and other components that have to be positioned to tight tolerances
- Precise three-dimensional measurement for quality control in order to detect failings in initial alignment or meanwhile occurred deformation

Independent of the methods that will be used to align any component, it has to be clear, that every component, which requires alignment, needs to be fiducialized before installing them into the beamline.

To be able to perform any exact alignment at all, a general alignment ability of a component needs to be given: all beam guiding magnets and detectors that are sensitive to positional behaviour need to be mechanically designed and manufactured in a way, so that precise, accurate and reproducible survey and alignment can be guaranteed.

8.3 Description of basic principles

8.3.1 Fiducialization

Fiducialization is a term for relating the magnetic respectively mechanical axis of a component to some kind of reference marks – the fiducials – that can be seen or touched by instruments. These fiducials are used for positioning the accelerator components within the tunnel. Fiducialization is a two-step-process. Firstly the axis has to be determined; secondly the position of this axis has to be related to the external fiducials [36]. The results of any fiducialization should be 3D-coordinates x, y, z of the fiducials with respect to the magnetic axis and the field vector. This allows an explicit description of the six degrees of freedom – that is position and orientation in space – for every component.

8.3.2 Considerations on total error budget

Undoubtedly the process of fiducialization has to be at least as accurate as the positioning of the component to their nominal coordinates; actually much more accurate than that, due to the different sources of errors, which form the total error of a final magnet position within the tunnel [37].

Possible sources of error:

- Manufacturing
- Determination of the axis / "magnetic measurements"
- Relating axis to fiducials / "geometric measurements"
- Deformation of cryostat / deformation of correlated fiducials
- Displacement magnet versus cryostat due to transport
- Residuals after least square network adjustment
- Uncertainty of measurements during alignment procedure
- Movement of the floor (long / short term)
- etc.

⇒ Total error of final magnet position within the tunnel, which can be expressed as

\[ s^2 = s_1^2 + s_2^2 + s_3^2 + s_4^2 + ... \]

This quadratic sum of all individual errors has to be taken into account when reflecting on positional tolerances, which are usually several times the r.m.s. again. Note that assumed errors of 0.1 (0.15 / 0.2 / ...) mm for all above mentioned error sources (which does not reflect the truth in either case) yield to a total error of 0.3 (0.4 / 0.6 / ...) mm.

The knowledge of a total error budget can help to derivate or re-evaluate reasonable tolerances.
8.3.3 Instrumentation / Measuring devices

State-of-the-art Laser Tracker, which is a mobile three-dimensional coordinate measurement machine, precision Total Stations and precise digital levels, will be the preferred instruments to fulfil the tasks of surveying and alignment in the majority of cases – both in initial installation phases and in regular periods of realignment.

The Laser Tracker is a dynamic measurement system which consists of a laser interferometer and a device for an absolute distance measurement, motor driven rotating mirrors with angle encoders to follow a corner cube reflector to the desired spot. The tracker gives 3D coordinates of a target in space with single point accuracy of ~27 µm (2sigma) at a distance of 2 m (~50µm @ 10m / ~110µm @30m). Due to its multiple use this kind of instrument will attend the entire project duration: from quality checks on components to test measurements at the magnet test facility, from fiducialization via reference network measurements within the tunnel to the alignment of magnets, detectors and other experiment installations.

Figure 60. Type of a Laser Tracker (left) and an Industrial Total Station (right).

Figure 61. General design floor nest (left) and floor nest in-ground (right).

Again, the predetermination of measuring technology guides to the design of reference points in the cave floor and walls just like on the magnets and other components, which have to be aligned to very tight tolerances (fiducial points). For global alignment tasks no permanent instrument monuments (like pillars) will be installed within any tunnel. Each reference point will be shaped in a way, that removable targets with a diameter of 1,5 inch can be inserted with highest repeatability (e.g. ball mounted retroreflectors, etc. – see Figure 62).
Figure 62. Wall nest with 1,5” corner cube reflector (left) and Design drawing wall nests and component fiducials.

8.3.4 Survey networks

Simulation

The design of a survey network, represented by reference points within the CBM cave and the connecting beamline in front, is a major task, which results in scheduling the most suitable number and position of the points and the quantity and kind of observations. The required network accuracy of currently expected ±0,1mm in the CBM area has to be achieved. Detailed simulation calculations yields to a prediction of global and relative uncertainties of all reference points including fiducial points on magnets etc. Up to now no simulation was calculated for this subsystem.

Free stationing

The actual survey and alignment plan relies on Laser Tracker combined with levelling, and in some cases combined with Total Station. Laser Tracker uses free stationing technique for orientation. Free stationing technique has no need for fixed instrument monuments. The measurement system can be set up very flexible, only visual contact to evenly spread points on the wall and floor is required. However, the number of necessary points – compared to a centred instrument setup – has to be higher; it has to be paid careful attention to the configuration of reference marks. This makes clear, that a robust, consolidated floor and side walls – at least during survey and alignment period - is imperative.

The principles of installing a three-dimensional net and the determination of the net parameters with the help of Laser Trackers are state of the art; they correspond to the proceeding of the international community in accelerator alignment.

8.3.5 Alignment – positioning of components

The precise, fast and correct online-alignment of machinery in three dimensions within the tunnel and cave depends on the network configuration and quality as well as on suitable mechanics respectively the adjustment ability of a component at all.

With the knowledge of the position of the pre-aligned magnets et al with respect to the reference network points, adequate correction values can be calculated due to the comparison of actual coordinates with ideals. An online-alignment (absolute control of component movement) can be carried out by using a Laser Tracker.
8.4 Requirements on the mechanical design and manufacturing of the CBM magnet

The following requirements [38] are valid for an accelerator component which needs to be positioned in space with a precision better than 1mm. The given 1mm is a rule of thumb and is meant to be a limit in order to classify accelerator components into elements, which need to get a fine alignment, performed using laser tracker systems et al, or simply a "rough alignment", done with a plummet and a level w.r.t. a marked line on the floor.

8.4.1 Yoke mechanical structure / alignment references

The center of a magnet field is defined by the position of the yoke laminations. Locating the magnet, and therefore the position of the field, is initially reached by precise mechanical references given on the yoke. For fiducialisation purposes the outer side of the lamination can get a groove with a depth of 10mm +0.1/-0.0mm and a width of 20mm +0.02/-0.0mm, which represents accurately the ideal beam path on the upper and lower yoke. If not possible, at least three fit drilled holes in the yoke surfaces, representing precisely the intersection point of the path tangents and their direction, and some reference planes, well defined relative to the pole surface respectively the magnet mid plane (±0.02 mm), are required. Machining of the completed yoke may be necessary for achieving the required tolerances.

In case of the splitted yoke and bolted assembly of the CBM magnet, each single yoke part needs to get additional individual reference planes and 4 fit drill-holes of 10H7, even if dowel pins are used between mating parts. The geometry of these drill-holes relative to the gap center is to be given from the manufacturer in a unique coordinate system. The position of the yoke parts among each other shall be checked after reassembling at GSI by a Laser Tracker. Reproducibility of position of upper and lower yoke among each other after disassembling and reassembling must be guaranteed to 0.2 mm.

Figure 63. Iron yoke of CBM magnet with suggested references for fiducialisation (also to be placed on the far side).
In assembled condition the magnets reference planes, fit drill-holes and groove – especially at the vertical endplates – have to be reachable and visible by optical measurement tools. They have to be protected against corrosion, but not varnished.

Above described reference holes, grooves and planes will be used for fiducialisation purposes. They are usually not suitable for alignment purposes due to problems with line of sights, but describe the relation to the non-touchable object (the beam) that needs to be aligned. As a convention they should be named as 'references', while the term 'fiducials' should be applied to the marks which will be used directly for alignment within the cave.

### 8.4.2 Fiducials

Magnets et al which need to be aligned to tight tolerances have to be equipped with fixed reference marks – the fiducials – which can be seen or touched by instruments and which are used for precise alignment within the tunnel and cave. The fiducials consist of a fiducial socket respectively fiducial target seat and a removable target (usually a 1.5” sphere with reflector), which is only inserted during measurement and part of the survey and alignment equipment. The position of these fiducials onto the magnet needs to be chosen concerning the final place of the magnet within the tunnel and thus concerning the possible position of the measurement instrument applied to align the magnet.

Concerning the superferric CBM magnet the fiducial sockets are located directly on the yoke. The relation between magnetic/geometric axis, field vector respectively dedicated references on the yoke and fiducials needs to be precisely determined during fiducialisation measurements. Once measured the fiducials must not change their position.

The fiducials should describe the changes in position and orientation of the entire component at the best. The number and configuration of the fiducials at one single component must be chosen so that an explicit description of the 6 degrees of freedom – that is position and orientation in space – of any component is possible accurately.

At least four fiducials per unit, which has to be aligned, should be designed with following minimum requirements

- suitable for dedicated measurement equipment
- stable with respect to the magnet axis
- stable among each other within a range of ± 0.01 mm
- all fiducials of one unit must be visible from one single instrument station
- excellent configuration on the magnet, as far from each other as possible but in a good relation to the adjustment feet position
- shall be equipped with protection caps to prevent mechanical damage

### 8.4.3 Mechanical support and adjustment system

Each component to be aligned need to get supports and adjustment systems that must provide stability and a fineness of motion substantially exceeding the final alignment tolerances. These supports and alignment feet are the interface that allows mechanical mounting of components and their subsequent alignment to a nominal position in three-dimensional space as a fine motion system to enable the surveyor to move the component to its ideal location within the required tolerance.

### 8.4.4 Manual adjustment systems

All beam components need to be moved and fixed at accurate locations by adjustment mechanisms. These systems – in their final position - should include the following design features:
• Adequate alignment precision: for precise adjustability the system’s resolution should be ten times the required alignment tolerance.
• An over-constraint system induces stress into the support and/or component, resulting in a deformation of the component. Thus no more than three adjustment feet must be utilized. If absolutely not avoidable a further support can be applied which must not be used in 3D but only in vertical direction in order to avoid sag.
• Orthogonal motion: The component must be capable to be positioned in x, y, z direction independently, and to be corrected for rotation errors (roll) of the magnetic field. There should be no cross coupling between the axes for the adjustment motions.
• The positions of the adjustment fixtures should be selected according to the principle of the Bessel points. They must be chosen as close as possible to the object to be aligned – which is in fact the invisible magnetic axis - in order to reduce lever arm effects.
• Stability: the support should provide a stiff base when locked down where incidental contact will not cause movement of the magnet. It should also not deform the component during adjustment.
• As installation space is usually limited components must often be placed very close together. Thus a small footprint is preferable.
• Vibrational stiffness: typical ground motion frequencies should not be amplified by the support system.
• For rough alignment purposes and due to expected setting movements of the ground an adjustable range in horizontal and vertical direction of ±20 mm is to be provided.
• Maximum loads on alignment feet: to be customized according to arising overall weight of magnet, cryostat etc.
• Space is to be kept free around the alignment feet, to have free access to them for operation.

8.4.5 Support structure
Accurate supporting and stable positioning of the magnets and detectors is essential for the machine and experiment alignment. Vertical sag of the total magnet in itself has to be minimized by stiffening the yoke or – in case of unavoidable separated yoke parts – by an appropriated support structure.
In some cases it might be reasonable to group a number of single components into one unit (e.g. one girder) which will be aligned in one step.
High flexural stiffness of the supports is therefore a basic mechanical requirement in order to guarantee that magnets or a group of components are stable under variation of external forces. The support structures need to be customized according to their final place and function.
9. Tests after assembly of the magnet

This part gives a rough overview over the recommended measurements during the first operation of the magnet:

- Determine the field direction / polarity
- Check the powering and quench detection and protection scheme
- Measure the coil resistance at 300 K
- Test the spot heater
- Control the cooldown by measuring the magnet resistance
- Determine the cryogenic losses at 0 A and test the spot heater again
- Measure the cryogenic losses at nominal current
- Magnet ramping (0A -> nominal current -> 0A)
- Single ramp up to 1.2 * nominal current
- Quench tests at nominal current with / without dump resistor acc. Table 17
- Quench tests at 1.2 * nominal current with / without dump resistor acc. Table 17
- HV to ground test at cold.
- Control warm up by measuring the magnet resistance

Table 17. Test sequence for the magnet.

<table>
<thead>
<tr>
<th>Test sequence</th>
<th>I/I_{nom}</th>
<th>R_d/R_{dnom}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>1.2</td>
<td>0</td>
</tr>
</tbody>
</table>

Details can be found in [39]
10. Magnetic measurements

Preparation
The magnet parts (girder, yoke parts and pole, cold mass, cryogenic components, leads etc.) and the power converter with the parts of the protection scheme will be delivered to the CBM cave at FAIR. The magnet will be assembled in situ as described in Chapter 7, section 9. No inserts will be installed in the magnet gap at this time. Afterwards the magnet will be aligned as described in chapter 8. The magnet has to be tested cryogenically and electrically (refer to chapter 9) before the magnetic measurements.

Specification of the measurement parameter
The dipole is a warm iron dipole of the H-type with a superconducting coil. The large gap is easily accessible. The dipole is a DC magnet and will operate only at the nominal current.

Load line
The load line for either $B_{mod}$ or $B_y$ in the magnet center, highly non-linear due to iron saturation, has to be measured at 10 different currents (at least) up to 10% above the nominal current.
Accuracy: 0.1%

Field map
All three components will be measured. The field region of interest is shown in Figure 12. We distinguish 2 different areas
- Area inside the opening angles
- Area downstream fringe field

The field data close to the coil allow to determine the high field point in the coil.
The map is requested only at the nominal field level of 1.1 T. However the non-linear behavior of $\int B dl$ along the beam axis (z-axis) is desired.
The required accuracy relative to the peak field in the main region of the STS detector is 0.1%.
The required field accuracy in the fringe field is 0.2 mT.
We will define a standard cycle and repeat it three times before each measurement.
The precision of the data (refer to Figure 64) should be determined by repeating the measurement at some points several times.

![Figure 64. Definition of accuracy and precision.](image-url)
Sensors

Figure 65 shows for different sensors the achievable accuracy as a function of the field.

![Figure 65. Accuracy of magnetic measurement sensors as a function field (Courtesy of K. Henrichsen, L. Bottura).]

Obviously, NMR and DC-Hall probes are well suited for the planned measurements. The loadline in the magnet center should be measured with an NMR. For the field map we will use DC hallprobes.

Conclusions for the concept

A field map is required in large volumes. This requires point measurement with Hall probes (absolute field value). Detailed information about Hall sensors can be found in [40].

- 3D measurements (all 3 components Bx, By, Bz) require a careful calibration of the 3D Hall probe
  - Position of the 3 sensors
  - Orientation of the 3 sensors
  - Non-linearity of the 3 sensors including planar Hall effect etc.
  - Temperature dependence of the Hall voltage
- The large measurement volumes with the many nodes lead to a long measurement time. Therefore one requests
  - A careful monitoring of all parameters as Hall sensor temperature, Hall sensor current, room temperature, etc.
  - An overlapping of the mapping regions
  - The measurements have to be done ‘On the fly’, which reduces measurement time and avoids mechanical vibrations.
GSI bench

At GSI, Darmstadt a bench was built in 1985 for the magnetic measurement of an electron cooler device. It is based on air cushions and has all 6 degrees of freedom, the rotations u and w can be done manually [41]. Figure 66 shows the bench and a typical application.

![GSI bench](image)

Figure 66. GSI bench for the magnetic measurement and a typical application.

<table>
<thead>
<tr>
<th></th>
<th>CBM request</th>
<th>GSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (x,y,z)</td>
<td>2 x 1.4 x 2.5 m</td>
<td>0.98 x 0.95 x 2.700 m</td>
</tr>
<tr>
<td># axis total</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td># air cushion axis</td>
<td>2-3</td>
<td>3</td>
</tr>
<tr>
<td># rotations(u,v,w)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Position accuracy</td>
<td>± 25 µm</td>
<td>± 10 µm</td>
</tr>
<tr>
<td>Orientation accuracy</td>
<td>± 1 mrad ( u and v)</td>
<td>± 1 mrad</td>
</tr>
</tbody>
</table>
The GSI bench was built for an application with an orientation accuracy of 1 mrad. In the error budget the biggest contribution comes not from the mechanical properties of the bench, but from the motor control leading to oscillations of the long probe arm.
The necessary measurement range requires several positions of the mapping device. A careful survey and alignment procedure is planned (refer to chapter 8). The position and orientation of the mapping system will be determined in this context. The sensor position will checked the same way, its orientation will be determined by autocollimation.

3D Hallprobe and its calibration
Typically the 3 Hall sensors are mounted orthogonally on a probe holder. They should be aligned in the direction of the main measurement axis at a distance of the typical step width of data taking 'on the fly'(Figure 67) That avoids possible interpolation errors. All three sensors are powered in series, the temperature of each sensor is measured as close as possible to the sensor.

![Figure 67. Sketch of 3D Hall probe (courtesy of F. Bergsma).](image)

Figure 68 and Figure 69 show the GSI 3D Hall probe with a mirror, which defines the coordinate system of the 3D probe. The center of the mirror defines also the origin of the coordinate system. The rotation around the longitudinal axis is still a free parameter.

![Figure 68. GSI 3D Hall probe with front mirror.](image)
Details of the calibration procedure can be found in [42]. However with the required accuracy of 0.1% such a complicated procedure as described in [43] seems not to be necessary.
<table>
<thead>
<tr>
<th>Nr.</th>
<th>Vorgang/Name</th>
<th>Dauer</th>
<th>Anfang</th>
<th>Fertigstellung</th>
<th>Vorgänger</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Projektablauf</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Start</td>
<td>5 Tage</td>
<td>W 01.01.14</td>
<td>M 01.01.14</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Festung</td>
<td>10 Tage</td>
<td>W 02.01.14</td>
<td>D 02.01.14</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Engineering Design</td>
<td>200 Tage</td>
<td>W 03.01.14</td>
<td>D 03.11.14</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Design approval</td>
<td>10 Tage</td>
<td>W 04.11.14</td>
<td>D 04.11.14</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Purchase</td>
<td>500 Tage</td>
<td>W 05.01.14</td>
<td>D 05.11.14</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Installation (preparation, building, decision</td>
<td>100 Tage</td>
<td>W 06.01.14</td>
<td>D 06.11.14</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>steel</td>
<td>7 Tage</td>
<td>W 07.01.14</td>
<td>D 07.01.14</td>
<td>73</td>
</tr>
<tr>
<td>9</td>
<td>steel steel</td>
<td>8 Tage</td>
<td>W 08.01.14</td>
<td>D 08.01.14</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>gap</td>
<td>9 Tage</td>
<td>W 09.01.14</td>
<td>D 09.01.14</td>
<td>73</td>
</tr>
<tr>
<td>11</td>
<td>insulated conductor</td>
<td>12 Tage</td>
<td>W 10.01.14</td>
<td>D 10.01.14</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>insulated lead</td>
<td>12 Tage</td>
<td>W 11.01.14</td>
<td>D 11.01.14</td>
<td>73</td>
</tr>
<tr>
<td>13</td>
<td>winding machine</td>
<td>10 Tage</td>
<td>W 12.01.14</td>
<td>D 12.01.14</td>
<td>73</td>
</tr>
<tr>
<td>14</td>
<td>winding machine</td>
<td>10 Tage</td>
<td>W 13.01.14</td>
<td>D 13.01.14</td>
<td>73</td>
</tr>
<tr>
<td>15</td>
<td>Production</td>
<td>500 Tage</td>
<td>W 14.01.14</td>
<td>D 14.11.14</td>
<td>73</td>
</tr>
<tr>
<td>16</td>
<td>Production</td>
<td>200 Tage</td>
<td>W 15.01.14</td>
<td>D 15.11.14</td>
<td>73</td>
</tr>
<tr>
<td>17</td>
<td>horizontal beam</td>
<td>12 Tage</td>
<td>W 16.01.14</td>
<td>D 16.01.14</td>
<td>73</td>
</tr>
<tr>
<td>18</td>
<td>vertical beam</td>
<td>12 Tage</td>
<td>W 17.01.14</td>
<td>D 17.01.14</td>
<td>73</td>
</tr>
<tr>
<td>19</td>
<td>flat clamp</td>
<td>12 Tage</td>
<td>W 18.01.14</td>
<td>D 18.01.14</td>
<td>73</td>
</tr>
<tr>
<td>20</td>
<td>tool</td>
<td>500 Tage</td>
<td>W 19.01.14</td>
<td>D 19.11.14</td>
<td>73</td>
</tr>
<tr>
<td>21</td>
<td>welding (no. 1)</td>
<td>12 Tage</td>
<td>W 20.01.14</td>
<td>D 20.01.14</td>
<td>73</td>
</tr>
<tr>
<td>22</td>
<td>welding, ins.</td>
<td>12 Tage</td>
<td>W 21.01.14</td>
<td>D 21.01.14</td>
<td>73</td>
</tr>
<tr>
<td>23</td>
<td>thermal shield</td>
<td>40 Tage</td>
<td>W 22.01.14</td>
<td>D 22.01.14</td>
<td>73</td>
</tr>
<tr>
<td>24</td>
<td>vacuum vessel</td>
<td>40 Tage</td>
<td>W 23.01.14</td>
<td>D 23.01.14</td>
<td>73</td>
</tr>
<tr>
<td>25</td>
<td>stand and base</td>
<td>12 Tage</td>
<td>W 24.01.14</td>
<td>D 24.01.14</td>
<td>73</td>
</tr>
<tr>
<td>26</td>
<td>stand</td>
<td>12 Tage</td>
<td>W 25.01.14</td>
<td>D 25.01.14</td>
<td>73</td>
</tr>
<tr>
<td>27</td>
<td>floor</td>
<td>12 Tage</td>
<td>W 26.01.14</td>
<td>D 26.01.14</td>
<td>73</td>
</tr>
<tr>
<td>28</td>
<td>Assembly at manufacturer</td>
<td>16 Tage</td>
<td>W 27.01.14</td>
<td>D 27.01.14</td>
<td>73</td>
</tr>
<tr>
<td>29</td>
<td>cold plates</td>
<td>40 Tage</td>
<td>W 28.01.14</td>
<td>D 28.01.14</td>
<td>73</td>
</tr>
<tr>
<td>30</td>
<td>cold plates</td>
<td>40 Tage</td>
<td>W 29.01.14</td>
<td>D 29.01.14</td>
<td>73</td>
</tr>
<tr>
<td>31</td>
<td>cold plates (cold-steel, stainless)</td>
<td>100 Tage</td>
<td>W 30.01.14</td>
<td>D 30.01.14</td>
<td>73</td>
</tr>
<tr>
<td>32</td>
<td>.Evaluate (Quality Assurance Test)</td>
<td>12 Tage</td>
<td>W 31.01.14</td>
<td>D 31.01.14</td>
<td>73</td>
</tr>
<tr>
<td>33</td>
<td>plate preparation</td>
<td>40 Tage</td>
<td>W 32.01.14</td>
<td>D 32.01.14</td>
<td>73</td>
</tr>
<tr>
<td>34</td>
<td>plate test</td>
<td>40 Tage</td>
<td>W 33.01.14</td>
<td>D 33.01.14</td>
<td>73</td>
</tr>
<tr>
<td>35</td>
<td>end assembly</td>
<td>40 Tage</td>
<td>W 34.01.14</td>
<td>D 34.01.14</td>
<td>73</td>
</tr>
<tr>
<td>36</td>
<td>Shipping</td>
<td>40 Tage</td>
<td>W 35.01.14</td>
<td>D 35.01.14</td>
<td>73</td>
</tr>
<tr>
<td>37</td>
<td>Assembly in cart</td>
<td>50 Tage</td>
<td>W 36.01.14</td>
<td>D 36.01.14</td>
<td>73</td>
</tr>
<tr>
<td>38</td>
<td>magnetic, incl. field clamp</td>
<td>30 Tage</td>
<td>W 37.01.14</td>
<td>D 37.01.14</td>
<td>73</td>
</tr>
<tr>
<td>39</td>
<td>power connector</td>
<td>20 Tage</td>
<td>W 38.01.14</td>
<td>D 38.01.14</td>
<td>73</td>
</tr>
<tr>
<td>40</td>
<td>magnetic connector</td>
<td>30 Tage</td>
<td>W 39.01.14</td>
<td>D 39.01.14</td>
<td>73</td>
</tr>
<tr>
<td>41</td>
<td>testing (Quality Assurance Test)</td>
<td>120 Tage</td>
<td>W 40.01.14</td>
<td>D 40.01.14</td>
<td>73</td>
</tr>
<tr>
<td>42</td>
<td>test (note: chapter 2 TSG)</td>
<td>80 Tage</td>
<td>W 41.01.14</td>
<td>D 41.01.14</td>
<td>73</td>
</tr>
<tr>
<td>43</td>
<td>alignment (incl. Mapping device)</td>
<td>50 Tage</td>
<td>W 42.01.14</td>
<td>D 42.01.14</td>
<td>73</td>
</tr>
<tr>
<td>44</td>
<td>magnetic measurement</td>
<td>50 Tage</td>
<td>W 43.01.14</td>
<td>D 43.01.14</td>
<td>73</td>
</tr>
</tbody>
</table>

11. Timeline
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