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– Annex to SLS-2 Conceptual Design Report –

Abstract

Due to the complexity of the 6T bend magnet it was decided to dedicate it a separate document. This document is the complete version of the conceptual design of the 6T superbend magnet. It describes the physical and technical concepts and presents the main parameters used for the design of the 6 T superconducting dipole magnet for SLS 2.0. A baseline version of the design concept is contained in the main (parent) document.

1 General Informations

As opposed to undulators or wigglers, bending magnets (normal or superconducting) are insertion devices that are an integral part of the machine lattice. The consequence is that a light source will not produce synchrotron radiation if any one of its bend magnets is not in operation. This is the reason why, especially in case of superconducting bends (superbend), the cryogenic refrigeration must be extremely reliable. The superbend dipole of the Advance Light Source (ALS) at LBNL is one of the first example of this type of device [1]. The choice of the optimal cryogenic refrigeration system for a complex machine is dictated by the total number of low temperature devices and by the distance between them. In the SLS 2.0, the three superconducting bend dipoles are the only devices that operate at cryogenic temperatures. There are no other devices (excepting the superconducting 3rd-harmonic cavity ¹) which operate at temperatures in the 4 K range. With only three superconducting devices the distance between superbends is large and the losses in the transfer line (0.5-1 W/m) make the use of a central refrigerator less efficient. Based on the analysis in [1], the least expensive cooling system for SLS 2.0 superbends is to use individual 4 K cryo-coolers on each superconducting magnet. These cryo-coolers have the advantage of delivering refrigeration power not only at 4.2 K but also at 50 to 60 K which can be used to cool the radiation shield and the current leads. The reliability and operability can be increased if the cryo-coolers are backed-up by a liquid helium and a liquid nitrogen bath.

1.1 Purpose

This section describes the physical and technical concepts and parameters used for the baseline design of the 6 T superconducting dipole magnet for SLS 2.0.

1.2 Design and Manufacturing

The present design was performed with the help of COMSOL for the magnetic and stress calculations and ANSYS for the thermal calculations. The design includes:

1. Magnetic design
2. Thermal calculations
3. Mechanical design

1.3 Prototype Manufacturing

The final detailed design, including the vacuum vessel will be part of a contract for manufacturing the prototype magnet and will be agreed with the Contractor. The Contractor has to follow the solutions presented in this design, however it is also free to suggest alternative solution. The contractor proposals must be agreed with PSI before implementation.

1.4 Units

SI units are used throughout this chapter. Exceptions are: 1) Pressure is measured in bar absolute. i.e. $\text{bar} \equiv \text{bar(a)}$ Overpressure (when necessary) is indicated as bar(g) . For vacuum $\text{mbar} = 100 \text{ Pa}$ is used. 2) Volume is measured in liters (L).

¹issue not yet decided

2 Dipole Specification

2.1 Introduction

The draft design of the new lattice for SLS 2.0 requires the replacement of the existing 12 triple-bend achromats by 12 seven-bend achromats containing longitudinal gradient bends (LGB) and ant-bends (AB). The LGBs will minimize the emittance by compensating the growth of the betatron amplitude dispersion. To extend the photon range of the SLS 2.0 up to 80-100 keV, LGBs with a field strength of 5-6 T with hyperbolic longitudinal field shape will be installed in three cells. The magnet should have a small bore to accommodate the 20 mm diameter copper beam-pipe with an anti-chamber. The high field specified can be obtained only with superconducting wires. The winding pack is made of two pairs of race-track shaped superconducting coils wound with Nb₃Sn and NbTi. The magnet, including the Iron yoke will be cooled by a two-stage cryocooler.

2.2 Magnet localization and Position

Total number of magnets	3 (up to 12)
Magnet central axis above the floor	1400 mm
Magnet pitch and roll	nominally level with respect to gravity

2.3 Available Space

The available space along the beam (axial direction) is limited to 500 mm.

2.4 Field Requirements

Nominal maximum operating field	6 T
Nominal maximum operating current	500 A
Nominal operating field integral	0.611 Tm
Nominal operating current margin	25 % below quench current
Conductor critical current at 4.2 K	big coil (725 A @ 5 T), small coil (810 A @ 12 T)
Nominal multipole content at R=3 cm	$B_n/B_1 \leq 10^{-3}$

3 Design Parameters

3.1 Diameter of the beam-line vacuum chamber

The vacuum chamber of the beam line has a diameter of OD24 × ID20.

3.2 Magnet Iron Yoke

Magnet yoke material is ARMCO steel or equivalent according to the chemical composition shown in Table 1. The steel with the above chemical composition can be purchased from SCANA Steel (www.scana.no).

Table 1: Recommended chemical composition for yoke material

	C	Si	Mn	P	S	Cr	Ni	Cu	Al
Min.	-	-	0.20	-	-	-	-	-	0.02
Max.	0.02	0.14	0.35	0.025	0.01	0.20	0.30	0.25	0.06

3.3 Coil Parameters

	Small Coil (central)	Big Coil (outer)
Conductor	Nb ₃ Sn	NbTi
Copper/non-Copper ratio	~ 1	~ 2.8
Number of filaments	51	2200
Matrix RRR	50	70
Conductor size (bare)	Ø0.8 mm	Ø1.25 mm
Conductor size (insulated)	Ø0.93 mm	Ø1.35 mm
Conductor insulation	S-glass	Formvar
Engineering critical current	810 A (@ 12 T, 4.2 K)	752 A (@ 5 T, 4.2 K)
Number of turns (one coil)	1480	220
Conductor length (one coil)	652 m	200 m

3.4 Coils Position Tolerances wrt Magnet Center

Direction	Tolerance
Vertical	± 0.200 mm
Horizontal (transversal)	± 0.200 mm
Longitudinal	± 0.200 mm

3.5 Liquid Helium Vessel

Material	316L
Volume	40 L
Max. pressure	20 bar
Test pressure	16 bar
Pressure relief valve setting	1.5 bar

3.6 Liquid Nitrogen Vessel

Material	Aluminium
Volume	20 L
Max. pressure	20 bar
Test pressure	16 bar
Pressure Relief valve setting	1.5 bar

3.7 Cryocoolers

There are two commercially available types of cryocoolers (cold-head) with a cooling power at the second stage of 1.5 W at 4.2 K: the Sumitomo RDK-415D model and the PT415 model from Cryomech

. The Sumitomo RDK-415D is a Gifford-MacMahon displacer type cryocooler. It is the most reliable of all models and is intensively used in re-condensing units all over the world. It has a relative high level of vibration as compared to the alternative cooler, the pulse-tube type. A Sumitomo 1.5 W pulse-tube, model SRP-182B2 will be available probably by the end of 2016. An alternative pulse-tube cryocooler with 1.5 W cooling power at 4.2 K is the PT415 model from Cryomech, with a very low level of vibration. A comparative view of the main parameters of the Sumitomo cryocoolers is presented in Table 2. The two cryocoolers are shown in Fig. 1.

Table 2: Main Cryocooler Paramaters

Cryocooler model	RDK-415D	SRP-182B2
1 st stage cooling power	45 W @ 50 K	TBD
2 nd stage cooling power	1.5 W @ 4.2 K	1.5 W @ 4.2 K
Compressor model	CSA-71A, CAN-61C/D,F50L/H,F70L/H	TBD
Power	6.5-9.2 kW @ 50 Hz	TBD
Maintenance interval	10'000 hours	20'000 hours



Figure 1: Sumitomo RDK-415D (left) and SRP-182B2 (right) cryocoolers

3.8 Vacuum Vesel

Material	Stainless Steel
Length along beam line	500 mm
Gap for the vacuum chamber	26 mm
Test pressure	Vacuum
Relief valve setting	0.5 bar(g)

3.9 Quench Protection

Detection voltage	150 mV
Detection and Validation time	100 ms

3.10 HTS Current Leads

Number	2 (one pair)
Manufacturer	HTS-110 Ltd. ²
Operating current @ 64 K	500 A
Diameter	14.3 mm
Length	305 mm
Distance between attachment holes	290 mm

3.11 Normal Conducting Current Leads

Number	2
Lead diameter	8.75 mm
Optimum length	495 mm
Lead material	Copper RRR 90

3.12 Instrumentation

Number of temperature sensors	16
Type	CERNOX ³
Liquid Helium level sensor	1 (Model 1700 ⁴)
Liquid Nitrogen level sensor	1 (Model 1700 ⁴)

3.13 Power Supply

Operation	unipolar
AC input	220 V, 3 phase, 50 Hz
Operating current, max.	500 A
Voltage	10 V
Current stability	10 ppm

4 Design Description

The magnet has a C-type cold iron core driven by four superconducting racetrack coils (two on each side). The magnet assembly is installed in a cryostat that can be inserted around the SLS2.0 storage ring vacuum chamber and then be centered on the beam orbit. The cryostat includes, in addition to the magnet, the coil HTSC leads, a helium vessel, a liquid nitrogen vessel, a 50 K thermal shield, a cold mass support system, a cryocooler, a quench protection system including an external dump resistor and/or eventually cold quench diodes and a pair of conduction-cooled normal conducting current leads with vacuum feedthroughs which are housed within the cryostat vacuum vessel as well as an external

²Gracefield Research Center, New Zealand, <http://www.hts-110.com/current-leads/>

³Lake Shore Cryotronics Inc., <http://www.lakeshore.com>

⁴American Magnetics AMI, <http://www.americanmagnetics.com/1700.php>

support system. The schematic view is shown in the Fig.2. The requirements to each element/system will be detailed later.

4.1 Thermal Design

The following considerations were taken into account in developing the thermal design for the 6 T superconducting bend-dipole for SLS2.0:

1. The maximum temperature of the magnet windings should not exceed 4.5 K.
2. The total heat load at 4 K should be less than 1 W.
3. Liquid helium and nitrogen should be used to cool the magnet in case of a cryocooler failure.
4. The magnet autonomy (operating time without cryocooler and external liquid cryogenic supply) will be dictated by the capacity of the liquid helium and nitrogen vessels which in their turn depend on the available vertical space in the storage ring tunnel. It should not be lower than 8 hours. For longer autonomy without mechanical cooling external supply of liquid nitrogen and helium must be provided.
5. The cooling should be provided by only one cryocooler due to the restricted space. If possible a low vibrational model of the pulse tube type should be used. Otherwise a pure Gifford-McMahon (GM) could be used with special measures to damp the typical vibrations.
6. The cooling must be very reliable because the magnet is an integral part of the SLS storage ring.
7. Magnet cooling must not be affected by power shutdowns.
8. The cooldown of the magnet is performed with external LN supply between 300 K and 80 K and in the temperature range 80 K-4 K by the cryocooler and/or external liquid helium transfer from a Dewar.

The superconducting coils are indirectly cooled by conduction from the iron yoke. The yoke is cooled by conduction from a liquid helium vessel placed on the top of the yoke. The helium in this vessel is re-condensed by a condenser placed at the top of the vessel, cooled from the second stage of a GM refrigerator. The small cryocooler provides at its first stage the refrigeration to cool the shield (at 50 K) along with delivering refrigeration to a liquid nitrogen (LN_2) vessel. The cryocooler is also used to cool a pair of conventional, normal conducting current leads operating between room temperature and the first stage and a pair of high temperature superconducting (HTSC) current leads between the first and the second stage. Finally, the whole assembly is supported on a 3-part cylindrical post placed below the iron yoke (see Fig. 25). The static heat leaks calculated for all components of the magnet are shown in Tables 3 and 4.

The estimates of the stage temperatures, T_1 and T_2 were made assuming the load curves of the Sumitomo RDK-415D cryocooler. The total heat load on the first stage of the cryocooler is 55 W and this corresponds to an operating temperature of the first stage of 67 K. At this temperature the nitrogen in the LN_2 vessel is close to the triple point (63.15 K, 125.2 mbar) and has a saturation pressure of 243 mbar i.e. the LN_2 vessel is under vacuum. For the second stage, the total heat load is 0.91 W and this corresponds, in correlation with the heat loads on the first stage, to an operating temperature of 3.8 K. At this temperature, the liquid helium in the helium vessel has a saturation

⁵Sumitomo private communication

⁶LBNL fit over 300 samples of HTS current leads from American Superconductor [2]

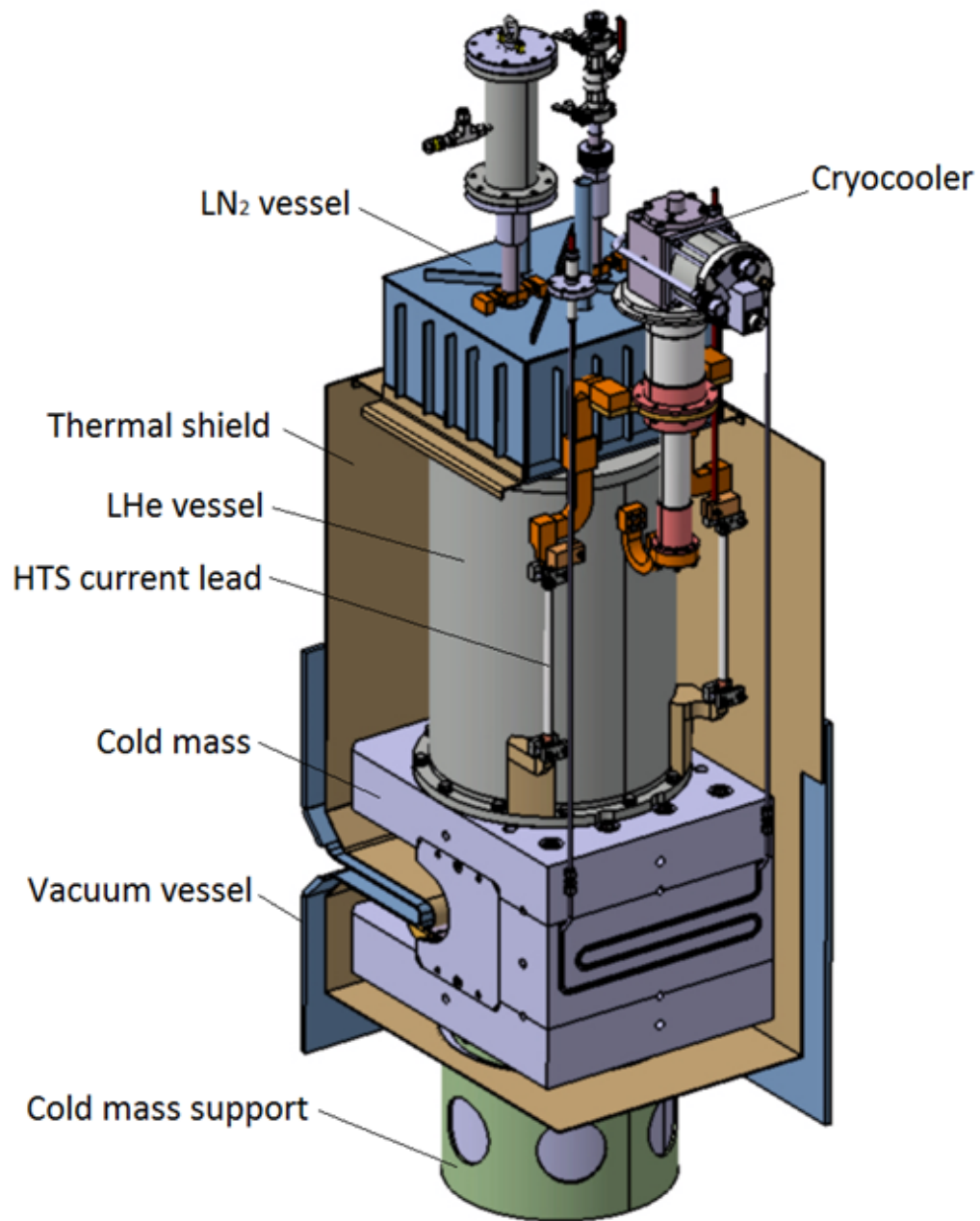


Figure 2: General view of the 6 T superconducting longitudinal gradient bend magnet

Table 3: Magnet Static Heat Loads at the 1st Stage

Heat load source	$\dot{Q}$ W	d_i mm	w mm	L mm
One SS tube for LHe filling	0.452	Ø18	0.5	209
One SS tube for He venting	0.647	Ø26	0.5	256
Two SS tubes for LN ₂ filling	1.276	Ø25	0.5	204
Two SS tubes for LN ₂ pre-cooling	0.68	Ø4	1	150
Two current leads, 500A	46.3	Ø8.75	-	495
MLI LN ₂ vessel	0.365	20 layers	0.79 W/m ²	300 K-77 K
Shield MLI	2.138	20 layers	0.79 W/m ²	300 K-77 K
G10 magnet support post	2.183	Ø340	-	280
Sensor wires	0.241	16 × 4 Cu wires	Ø0.25 mm	1500
Total	54.28	→ T ₁ =67 K		
Conduction down the first stage	11.2 ⁵	if cryocooler is OFF		
Total if cryocooler is OFF	65.5			
LN₂ boil-off	1.4	L/hr		

pressure of 657 mbar. At this pressure, the liquid helium density is 132 kg/m³, higher than the density of liquid helium at 4.2 K, 125 kg/m³. This effect will produce a lowering of the liquid level in the vessel by about 2 L. A more detailed investigation of the temperature distribution on the components attached to the first stage of the cryocooler has been performed using an ANSYS steady-state thermal analysis. We were mainly interested in the temperature distribution (gradients) over the LN₂ vessel surface. The components attached to the first stage are: two normal conducting current leads loaded with 500 A, LN₂ vessel with two stainless steel tubes for filling and venting, two stainless steel tubes thermally anchored on the top of the LN₂ vessel and penetrating the LN vessel, for filling and venting the liquid helium vessel and two copper straps connecting the bottom of the LN₂ vessel with the first stage clamp and the bottom clamps of the normal conducting current leads. Appropriate boundary conditions were applied: top of all tubes and current leads at room temperature, bottom of helium tubes at 4 K, MLI heat load (0.79 W/m²) corresponding to 20 layers of COLCAT 2 NW superinsulation⁷, and 4.5 W (1.5 W on the three sides of the LN₂ vessel) as heat load from the 50 K shield (from a separate calculation). The first stage cryocooler clamp was fixed at 50 K and the reaction (heat load) was calculated. Two materials were tested for the LN₂ vessel, stainless steel and aluminum alloy. The result for stainless steel was disappointing due to the large thermal gradients on the LN₂ vessel, and will not be shown here. For an aluminum alloy LN₂ vessel the result was positive and the temperature distribution on all components is shown in Fig. 3. The thermal gradients on the LN₂ vessel are presented in Fig. 4

4.2 Magnet Autonomy

The autonomy time is strongly dependent on the accuracy of the values for the heat leak of cryocooler when it is OFF. Based on the data from Sumitomo (see Table 3, 4) the autonomy times for the LN₂ and LHe vessels are: 14 hr and 17 hr respectively. Estimation at ALS gives much higher values for the thermal conduction down the first and second stage of the stopped cryocooler: 50 W and 1.96 W. With these values the autonomy times are reduced to 9 hr and 10 hr respectively. Taking into account that at the moment when the cryocooler is off, the two vessels may not be completely full and considering other sources of error we believe that a general autonomy of 8 hr is guaranteed.

⁷Austria Aerospace GmbH, Stachegasse 16, A-1120 Vienna, www.space.at

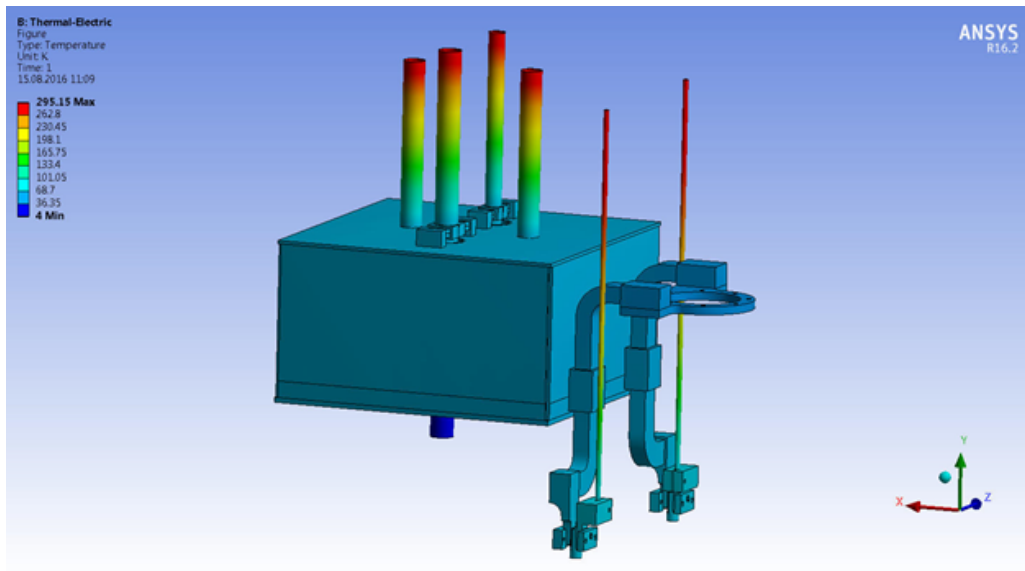


Figure 3: Temperature distribution over the parts connected to the LN₂ vessel and the first stage of the cryocooler.

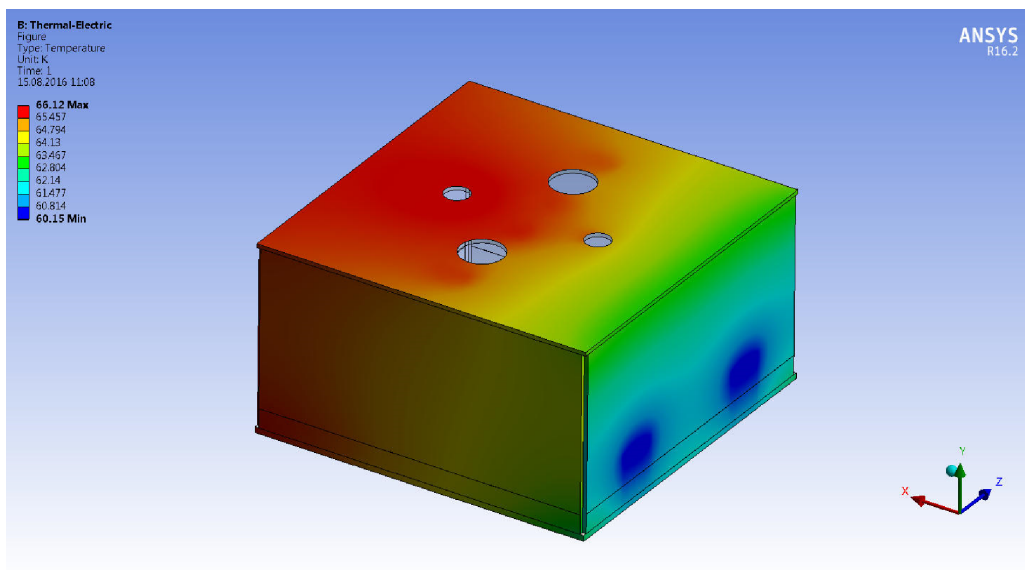


Figure 4: Temperature distribution on the LN₂ vessel

Table 4: Magnet Static Heat Loads at the 2nd Stage

Heat load source	$\dot{Q}$ W	d_i mm	w mm	L mm
One SS tube for LHe filling	0.023	Ø18	0.5	209
One SS tube for He venting	0.034	Ø26	0.5	256
Two SS tubes for LN ₂ pre-cooling	0.009	Ø4	1	150
Two HTS current leads, 500A	0.414 ⁶			495
MLI LHe vessel	0.019	10 layers	0.024 W/m ²	77 K-4 K
MLI Iron yoke	0.098	10 layers	0.024 W/m ²	77 K-4 K
G10 magnet support post	0.179	Ø340	-	280
LHe level sensor, G10 part	0.005	Ø6.35	-	910
Sensor wires	0.125	16 × 4 Cu wires	Ø0.25 mm	1500
Total	0.906	→ T ₂ =3.8 K		
Conduction down the second stage	0.76 ⁵	if cryocooler is OFF		
Total if cryocooler is OFF	1.666			
LHe boil-off	2.3	L/hr		

4.3 Current Leads

Two types of current leads are used in this magnet: a) Normal conducting (NC) between 300 K and 50 K-80 K and b) High temperature superconducting (HTSC) in the temperature range 50 K-4 K. Because the magnet will be powered all the time, the NC current leads must be made from high purity OFHC copper with RRR=90 or better. For RRR=90, I=500 A and a length of 495 mm, resulting from the mechanical design, the diameter of the optimum current lead d_{opt} =8.75 mm was calculated. The heat leak at 50 K is 46.3 W per pair and, as can be seen from Table 3, is the largest contribution to the heat load on the first stage of the cryocooler. This value is what decides if the magnet can be cooled by one or by two cryocoolers. Two types of HTSC current leads were considered:

1. The American Superconductor Corporation (ASC, Devens, MA, USA) current leads
2. The HTS-110 (Gracefield Research Centre, New Zealand) current leads

The American Superconductor Corporation (ASC) current leads are made from BSCCO silver tape encapsulated in a G10 rod. The HTS-110 current leads are made from a composite conductor. The composite conductor consists of HTS filaments in a low thermal conductivity matrix, providing a very high current density and low heat leak through the small cross-section. The heat load at 4 K from a pair of ASC type HTSC current leads at 500 A is 414 mW. A pair of HTSC current leads from HTS-110 under the same conditions has a load of 130 mW as shown in Fig.5. In addition to this main load, there will be always a small additional heat load contribution at the cold end due to the short path through the copper end tab and through the joint to the LTS cable of the coils. The heat load due to the copper path is in the range 4-5 mW per lead. The heat load due to the joint depends on the quality of the joint but generally, assuming an indium-bismuth solder or an indium shim, this contribution should not be more than about 10 mW per lead. So in total the expected heat load at the cold end of the HTS-110 current lead could be approximately 130+2*5+2*10=160 mW per pair at 500 A. Despite this result, in Table4 we still keep the ASC value (414 mW) in order to get a conservative calculation (higher temperature at the top of the lead) but strongly recommend using the HTS-110 current lead.

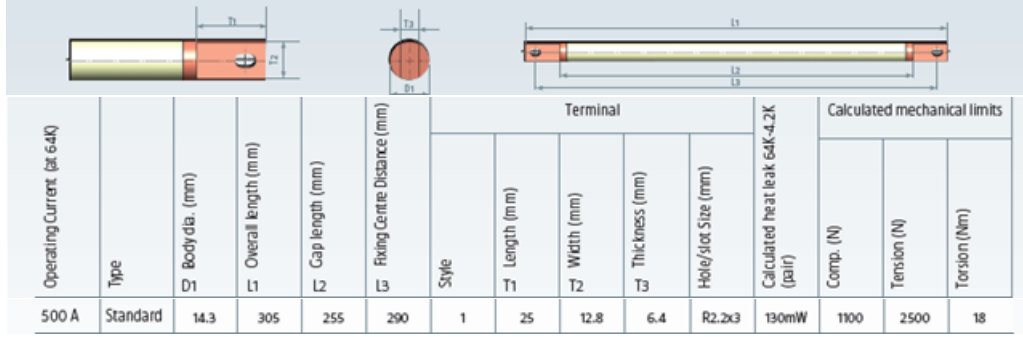


Figure 5: Typical dimensions and properties of the HTS-110, CRYOSAVER™ high temperature superconducting current leads

The designed warm end operating temperature of the HTS-110 is 64 K. A lower warm end temperature will reduce the total heat leak down the leads. Depending on external field the leads can be operated at a slightly higher warm-end temperature, 67 K in our case. For the 500 A leads at zero external field it should be safe to operate the leads at a heat-sink temperature of up to 70 K (assuming the leads are mounted with sapphire washers). Lead performance depends on warm end operating temperature, field magnitude and field orientation. Note that the plane of the HTS tape is in the same plane as the flat faces of the lead end-tabs, so in the following section the *perpendicular* field is the field component orientated perpendicular to the lead end-tab faces and the *parallel* field is oriented anywhere in the plane of the lead end-tab faces. As a rough guide the following thresholds are defined by the manufacturer:

1. Warm end at ~ 64 K. No more than 40 mT of perpendicular field along the top 1/4 of the length of the lead. The parallel field component can be as high as 400 mT at the same position. If the lead is operated at a higher temperature the field would have to be substantially smaller.
2. Cold end at ~ 20 K. No more than 3 T of perpendicular field at the bottom 1/4 of the lead. The parallel field component can be as high as 10 T.
3. For fields outside these range, or if the higher field extends further than 1/4 of the way up the lead the manufacturer (HTS-110) can offer a custom lead.

A 1000 A lead operated at 500 A could be run at a much higher temperature. The limit for a 1000 A lead (at 500 A) would be approximately 80 K. The heat leak for a pair of 1000 A leads with warm end temperature at 80 K would be in the range 300 mW. Depending on the required warm end temperature, operating current and warm-end magnetic fields, it may be better to order custom leads specific to our requirements. For example, HTS-110 provided 600 A leads (64 K-4.2 K), and 500 A leads (70 K-4.2 K) by adding extra HTS paths to the existing 500 A leads. These have a slightly lower heat leak than 1000 A leads and can be less expensive. Unlike an optimized resistive lead (in which the heat leak doubles when carrying full operating current compared with carrying zero current) the heat leak down a HTS lead is approximately constant. The only difference when the current is dropped to 0 A is that there is no longer the injection voltage heat leak (the approximately 10-15 mW per lead due to resistance in the cold end copper and the solder joint to the cable). So the 160 mW load described earlier would drop to 130 mW.

4.4 Magnet Cooldown and Warm-Up

The cooldown time of the magnet was calculated using an ANSYS transient thermal simulation. The cool down was separated in two stages. In the first stage, liquid nitrogen (LN_2) is circulated in the heat exchanger located on the rear side of the iron yoke and the magnet is cooled from room temperature to 80 K. An effective heat transfer coefficient of $h=1000 \text{ W/m}^2\text{K}$ and a reference temperature of $T_{ref}=80 \text{ K}$ were assumed in the calculation. The temperature dependence of the heat capacity and thermal conduction for the iron in the yoke was taken into account. The resulting cooldown time is 10 hr. In the second stage, liquid helium is transferred in the helium vessel on the top of the yoke and the cooling down from 80 K is continued until the lowest temperature of 4.5 K has been reached. The convective cooling parameters were in this case $h=2000 \text{ W/m}^2\text{K}$ and $T_{ref}=4.5 \text{ K}$. The specific heat of iron is very small in this temperature range and this result in a very short time of only 670 s. All in one, and considering that not all components of the magnet have been included in the calculation (shield, cryocooler, LN_2 vessel and different copper straps) our estimation for the total cooldown time to 4.5 K is $\sim 12 \text{ hr}$. The warm-up scenario assumes empty liquid helium and liquid nitrogen vessels, stopping the cryocooler and activating two 300 W electrical heaters placed on the left and right side of the iron yoke. Neglecting other sources of heat going into the magnet, the warm up to 300 K takes around 15 hr. If LN_2 and LHe vessels are not empty the warm-up time will be longer.

4.5 Fault Modes

The magnet is prepared to withstand the following fault conditions:

1. A compressor failure. The compressor can be replaced quickly since the compressor can be disconnected from cryocooler while the cryocooler is still cold. A spare compressor must be available.
2. The cryocooler failure is rare (MTBF ≥ 8000 hours) and the cryogen cooling (LN_2 and LHe) will keep the magnet operating until the next closest accelerator shut-down.
3. An electrical power failure will stop the compressor and the cryocooler. The magnet is kept cold by LN_2 and LHe stored in the magnet. After the electrical power is restored, the cryocooler can be restarted.
4. A magnet quench will stop the magnet and heat it up to some level. Probably the LN_2 and LHe reserve will be exhausted. The cryocooler operation is not affected. The magnet can be re-cooled using either only the cryocooler (longer cool down but no human intervention) or the cryocooler and external liquid cryogen (shorter cooldown, human intervention is needed).
5. A quench of one of the current leads. It is also a rare event as the cryocooler stop. The magnet must be quickly discharged to protect the lead and it can quench. Case (4) applies and the magnet must be repowered.

5 Magnetic Design

5.1 Design Requirements

The magnetic system consists of two outer solenoidal coils to provide the desired field integral along the beam path and two inner racetrack coils to produce the desired B-field peak. The magnetic design has been performed using OPERA 3D TM(see Fig.6) according to the following requirements: a) Necessity

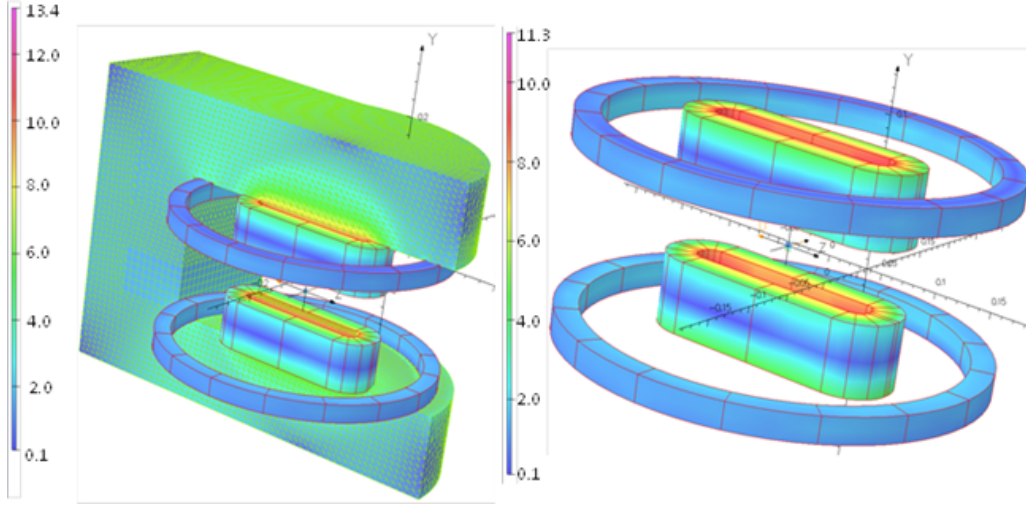


Figure 6: Magnetic field distribution in the coils and in the iron yoke (left). Magnetic field distribution in the superconducting coils (right). The peak field is calculated in the portion of the yoke located in the bore of the inner coils.

to evacuate the synchrotron radiation, b) Allow maximum magnet length in the longitudinal direction, c) B-field profile full width half maximum (FWHM): 40-70 mm, d) B-field peak: ≤ 6 T, e) B-field integral (along the beam path): 0.61 Tm.

The first requirement determines the vertical aperture of the magnet. A preliminary design of the lattice, a Multi Bend Achromat with 7 bending magnets in each of the 12 arcs, has an emittance of 137 pm-rad, an rms energy spread of 0.105% and it would radiate a power of 232 kW at a beam current of 400 mA. Furthermore it is necessary to guarantee a high reliability for the whole light source. A solution with a warm bore with an external diameter of the vacuum chamber of 24 mm was selected. The thermal insulation between the vacuum chamber and the magnet cold mass, along with the mechanical clearances and tolerances to assemble all the components, require a vertical distance between the two inner coils of 53 mm. Moreover the vacuum chamber has to host a radiation fan that protrudes out of the cylindrical vacuum chamber for about 50 mm (in the beam bending plane). To guarantee a sufficiently wide horizontal aperture to host the whole vacuum chamber a C-shape geometry was selected, which makes easier the assembly of the magnet with the vacuum chamber and the cryostat. Only a C-shaped cryostat allows the magnet to be retracted from the vacuum chamber without opening it. The maximum longitudinal magnet length is instead dictated by the position of the adjacent magnets in the accelerator. In our case those magnets are normal conducting and the available space is 500 mm. Considering the room to host the cryostat and the connections between room and cryogenic temperature, a longitudinal space of 400 mm remains available for the LGB. This dimension determines the diameter of the outer coils used to guarantee the required field integral. The most challenging aspect concerns the production of a 6 T field with a very narrow peak profile. The required B-field profile is produced employing four coaxial superconducting coil as shown in Fig.6. The outermost coils are solenoids whereas the innermost ones are racetrack coils. The first ones are used to guarantee the desired field integral along the beam path, while the peak in the B-field profile is provided by the innermost coils. The outermost coils are arranged in a configuration similar to the one used by the ALS superbend[3]. The magnetic geometry is such that the innermost part of the inner coils experiences a peak field of 11.3 T (1.8 times higher than the field in the good field region). This peak field at the conductor location limits the choice of superconducting material, as it will be explained later. The average field in the inner coils is 6 T and 10% of the winding pack experiences a field above 10 T. For the outer coils the average field is 0.8 T and only 3.6% of the winding pack

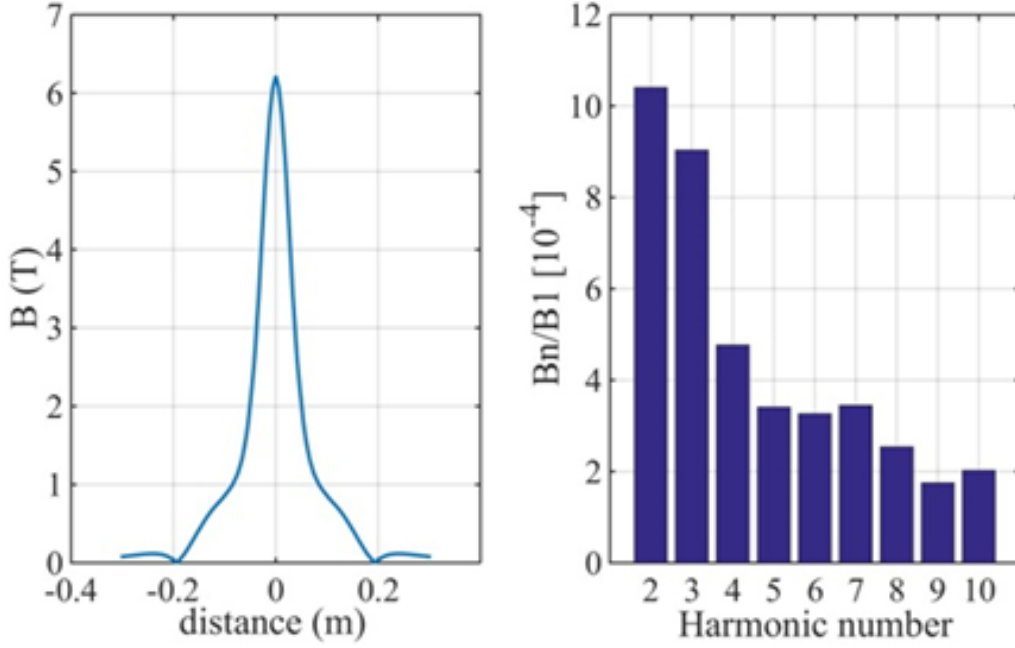


Figure 7: At the left- B-field profile along the beam path calculated on the magnet axis. At the right- harmonics normalized to the fundamental calculated in the good field region.

experiences a field above 2 T with a peak of 2.8 T. Thanks to the C-shape ARMCO yoke it was possible to reduce both the coil current and the magnet stray field for the same peak field in the GFR. A maximum field of 13.4 T is calculated in the portion of the yoke located in the bore of the inner coils.

5.2 Multipoles

The B-field profile is shown in Fig.7 (left) along the beam path and in Fig.8 in 3D.

The field quality has been calculated on a rectangular GFR of 6 mm $\times$ 8 mm. The harmonics were calculated on the circumference inscribed in this rectangle (3mm reference radius). Field errors are given in unit of 10^{-4} relative to the dipole field strength at the reference radius. The highest harmonic is the quadrupole component (harmonic number 2 in Fig.9) which is below 11 units. The corresponding homogeneity is around 22 units. In Fig.9, the integrated harmonics are calculated along the beam path over a distance of ± 200 mm from the center of the magnet. A transverse shift with respect to the beam path of 3 mm was also considered to analyze possible issues due to beam misalignment.

5.3 Stray Field

To produce a peak field of 6 T with a narrow profile, the maximum B-field at the conductor location is 11.3 T (see Fig.6). The ARMCO yoke allows concentrating the flux lines reducing the needed current in the coils and the stray field. The peak field in the yoke is 13.4 T (see Fig.6 and Fig.10). Fig.10 shows the peak field location in the yoke as well as the fully saturated regions, i.e. the region where the B-field is higher than 2.1 T.

The cooling system will rely on one cryocooler. The operation of cryocooler is limited by magnetic field. For a GM cryocooler, a 10% power reduction has to be expected if the B-field is over 1.5 T

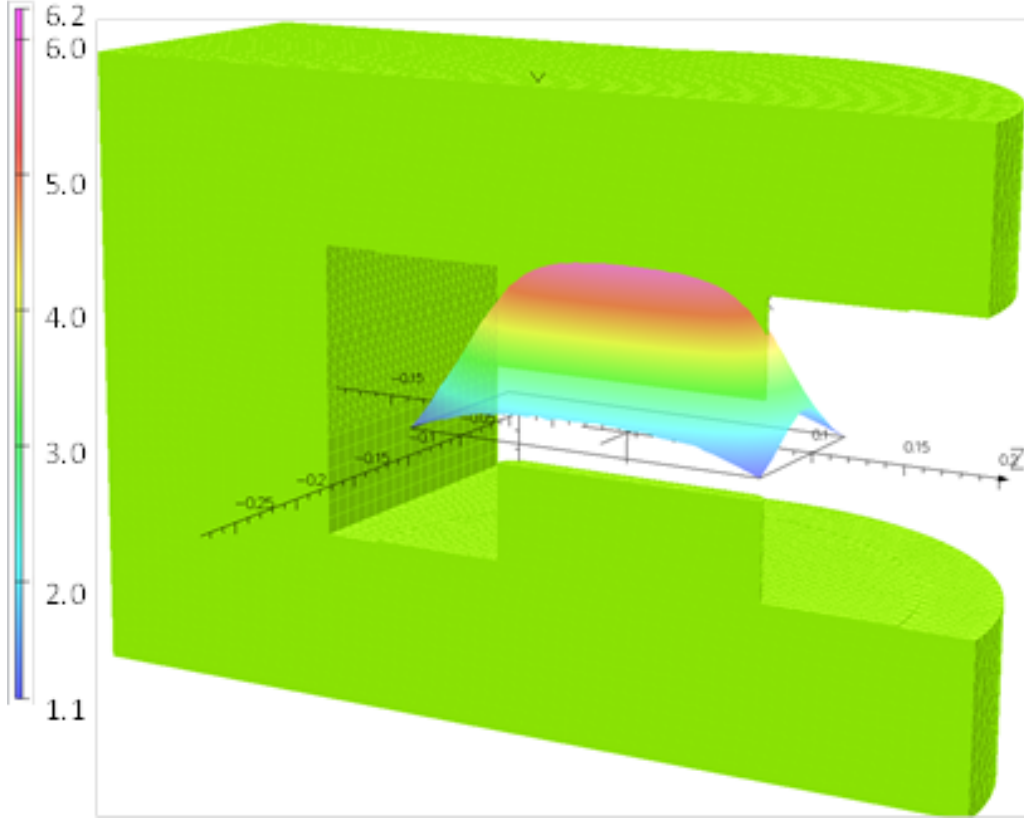


Figure 8: 3D view of the B-field in the magnet aperture.

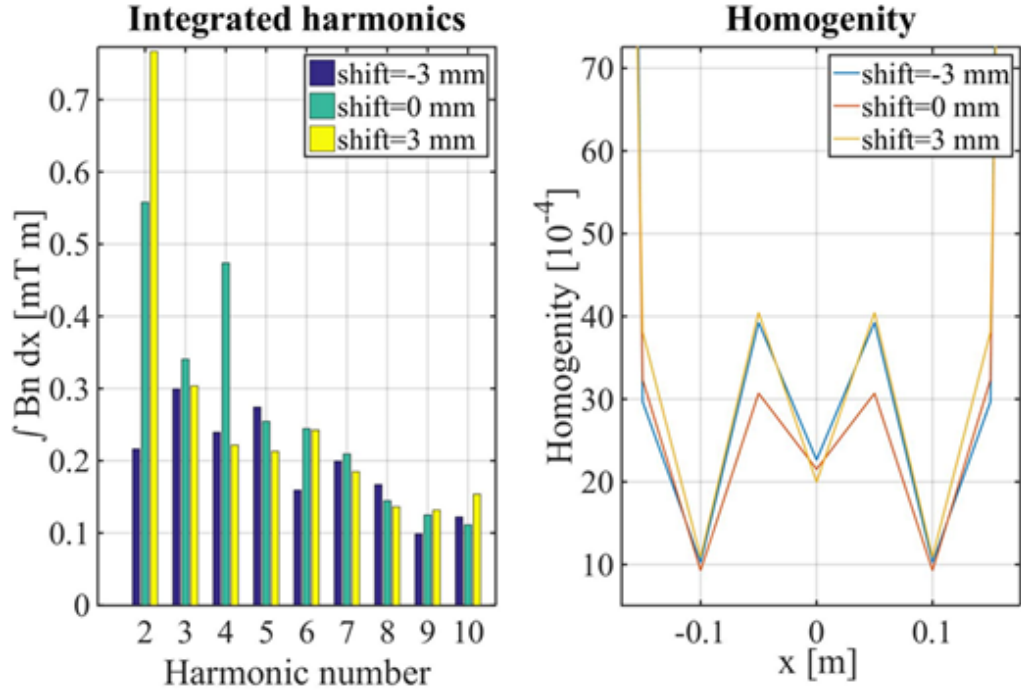


Figure 9: At the left - integrated harmonics calculated along the magnetic axis and along two parallel axes shifted of ± 3 mm with respect to the magnetic axis. At the right homogeneity, calculated at different locations along the beam path on the magnetic axis and on two parallel axes shifted by ± 3 mm.

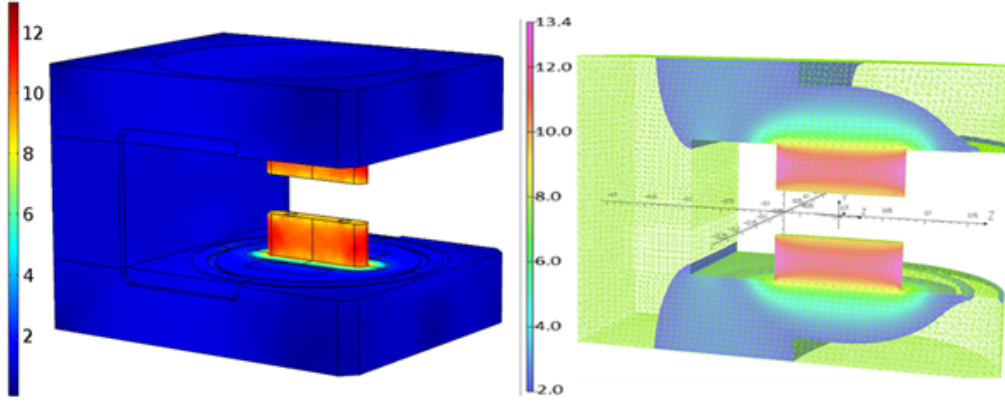


Figure 10: At the left- B-field in the ARMCO yoke. At the right- yoke saturated region ($B \geq 2.1$ T).

at the regenerator. For the step motor and the displacer the field has to be below 50-80 mT. Fig.11 shows that the stray field at the cryocooler location is below 20 mT and therefore it does not need any further shielding. Other magnet components very sensitive to stray field are the current leads. In this design all the coils are powered in series. The location of the current leads in the field of the magnet is depicted in Fig.11. For the thermal calculation we considered high temperature superconducting current leads at 500A which would provide a heat input as large as 160 mW. The warm end should not work with a perpendicular B field exceeding 40 mT, whereas the cold end could sit in a region up to 3 T. The calculations show that the iron yoke is thick enough to properly shield the current leads.

5.4 Load Line and Operating Margin

The four coils will be connected in series to reduce the number of current leads and consequently the heat input. The outer coils will be wound using NbTi strands with the highest B-field at the conductor around 2.8 T. For the inner coil we necessarily need high critical current density Nb₃Sn strands as the peak field is 11.3 T. Furthermore increasing the current density in the inner coils allows decreasing the FWHM of the B-field profile. The RRP strand developed for LARP [4] should be a very good candidate for the inner coils providing sufficient current density and mechanical strength. As the magnet will be operated in DC mode, AC losses are not an issue. All the coils will be wound using single strands. The nominal operating current will be 401 A, as shown in Fig.12. Considering the B-field and the temperature experienced by the conductors, the inner coils will operate at about 75-80% of the quench current, whereas the outer coils will work below 50% of the quench current.

To estimate the coils temperature during operation, the winding pack was modeled as a homogenous material characterized by a diagonal thermal conductivity tensor. Along the current direction the conductivity is considered to be that of copper weighted according to the copper surface area with respect to the total one. In the transverse direction the conductivity of the epoxy resin was instead considered as the magnet will be impregnated. Fig.13 shows the temperature distribution in the winding pack.

In the simulation, the liquid helium bath was considered at 4.2 K. The magnet is insulated with 20 MLI foils between the thermal shield connected to the first stage of the cryocooler (60-70 K) and the room temperature environment and with 10 MLI foils between the cold mass and the thermal shield. The first interface is characterized by a heat load of 0.79 W/m² and the second one by 0.024 W/m². The magnet is supported by two coaxial G10 pipes assembled with a stainless steel link in between. Thanks to this structure (see Fig.25) it is possible to minimize the heat input to the magnet. The outer coils are in good thermal contact to the yoke and to the CuBe mechanical support and should

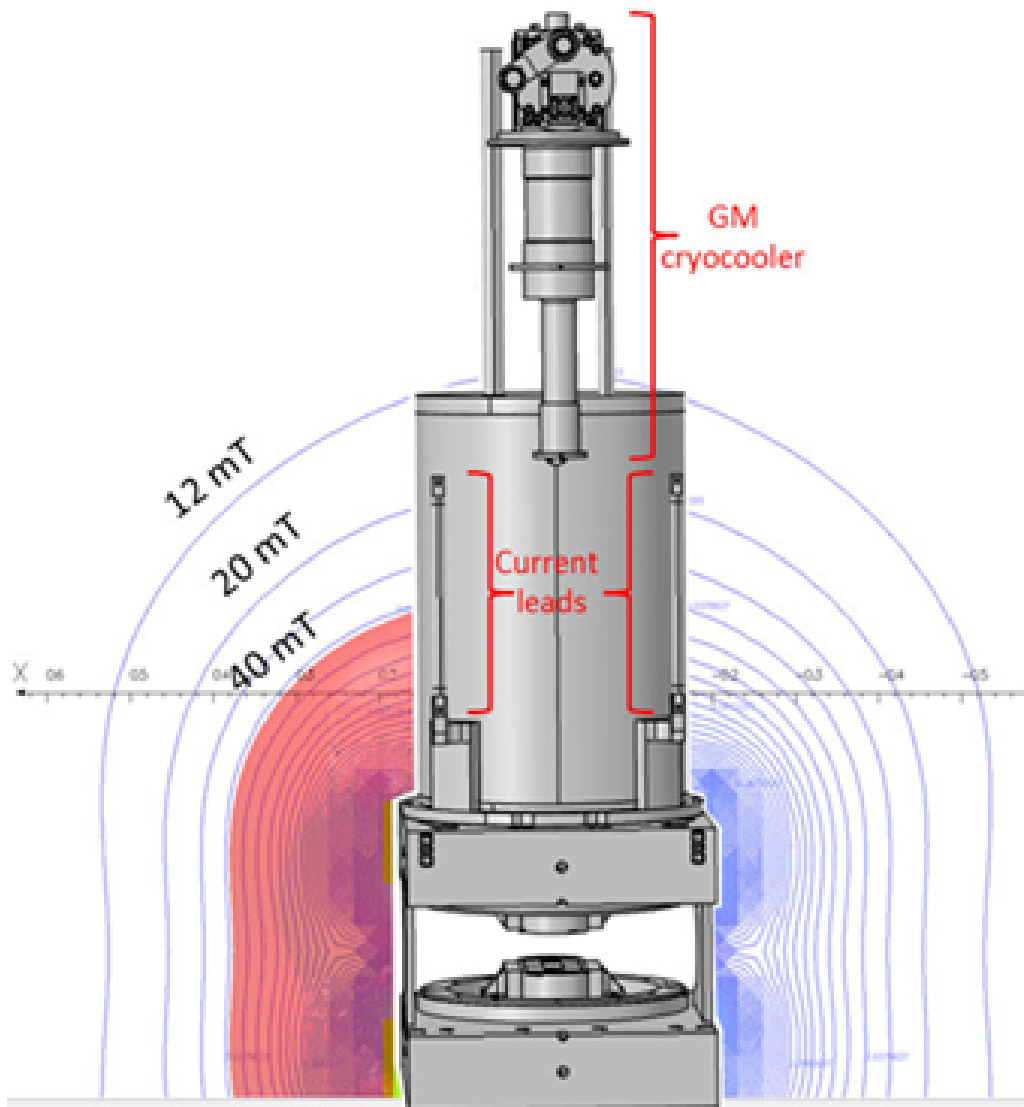


Figure 11: Magnet and B-field lines. The cryocooler sits in a field region below 20 mT. It does not need further shielding.

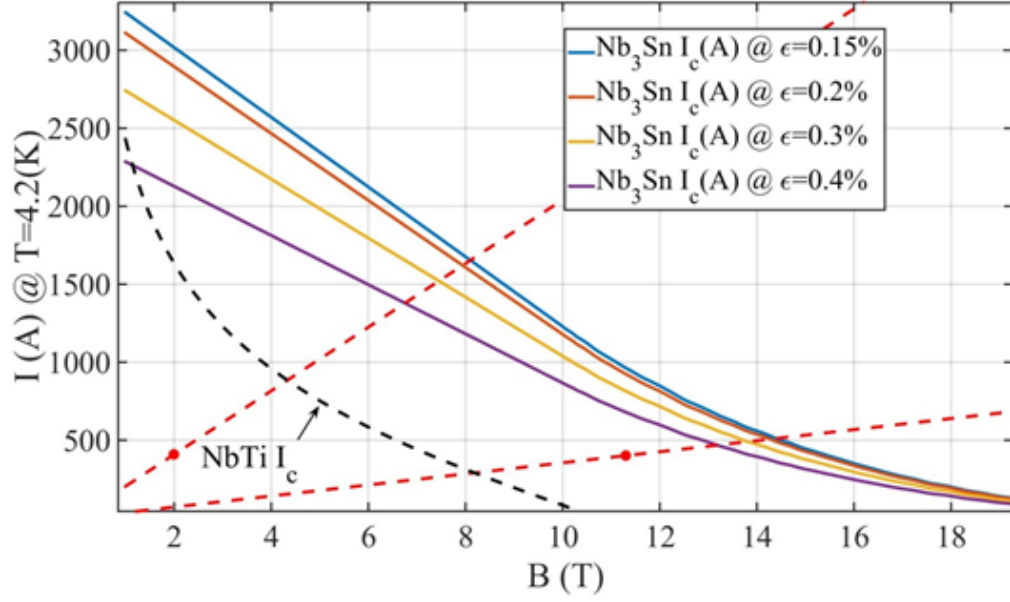


Figure 12: Magnet load line and critical current of the Nb₃Sn and NbTi strands. For the Nb₃Sn, the critical current has been plotted at four different intrinsic strain levels.

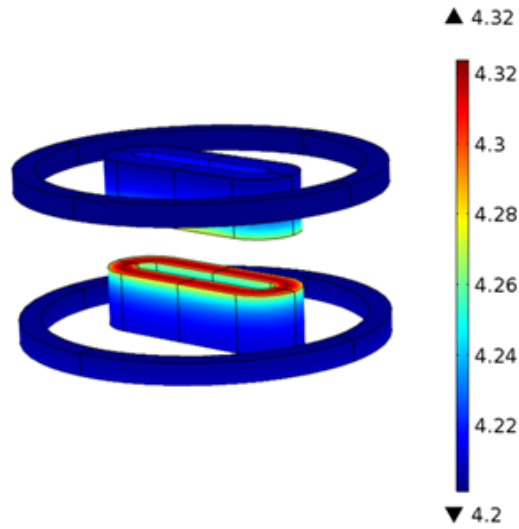


Figure 13: Temperature distribution in the winding pack calculated considering a helium bath at 4.2 K.

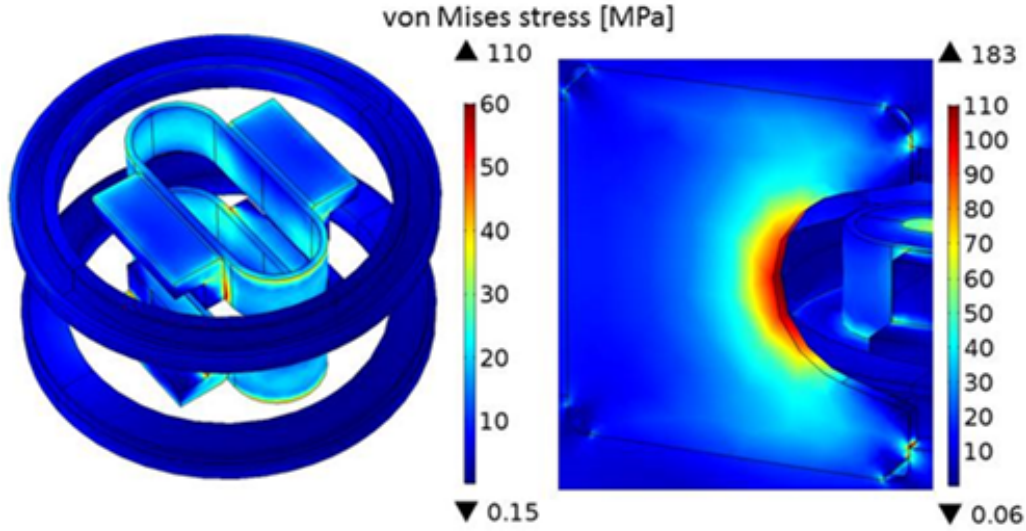


Figure 14: Von Mises stress in the CuBe coils support structure due to the Lorentz forces (left). von Mises stress in the yoke reinforcements (right).

remain at 4.2 K. The inner coils will experience a peak temperature slightly higher (4.3 K) but in any case sufficiently low to guarantee a current margin around 20%.

5.5 Mechanical Support Structure

For both the inner and the outer coils we use beryllium copper (C17200, C17300) structural rings to sustain the coils against the Lorentz forces. For the inner coils the rings are sustained by two additional stainless steel 316LN supports to counteract the radial Lorentz forces. The left panel of Fig.14 shows the von Mises stress distribution in the CuBe rings due to the Lorentz forces. The highest calculated stress is well below the yield stress of the material at operating temperature. An annealed and aged C17000 Beryllium Copper with aging temperature around 460 K, is characterized by a yield strength of 260 MPa at 77 K. From a structural mechanical point of view, other critical parts of the magnet are the stainless steel (316LN) reinforcement ribs located on both sides of the ARMCO yoke (see ?). They have to intercept the vertical Lorentz forces and guarantee sufficient rigidity to the whole assembly. In Fig.14, right panel, the corresponding von Mises stress distribution is shown. At 4.2 K the yield strength for the 316LN is around 750 MPa.

5.6 Quench Protection

The quench detection system relies on an external dump resistor, see Fig.15, solid line. The choice of the dump resistor value was done considering both the peak voltage and the hot spot temperature in case of quench. Fig.16 summarizes the results of the quench calculations as a function of τ_{dump} , the time constant of the exponential current dump. $\tau_{dump}=0.4$ s was selected as trade-off between a maximum voltage below 1 kV and a peak temperature below 140 K. The corresponding R_{dump} value is 2.4 Ohm. The resistance of the developing normal zone was neglected as the circuit resistance is dominated by the dump resistor. Keeping the magnet temperature below 140 K will avoid too high thermal stresses and material damage. An alternative with parallel cold diodes (dash line in Fig.15) will also be investigated and compared with the proposed dump resistor solution. During a current discharge each magnet would be bypassed by its parallel diode that acts as a shunt.

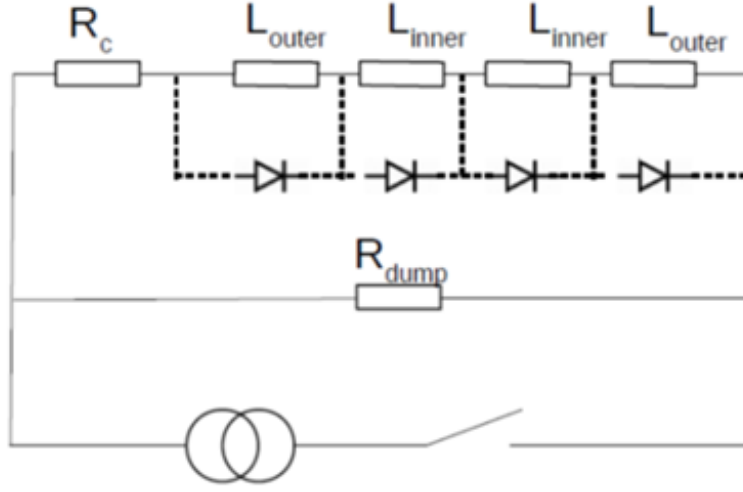


Figure 15: Quench protection circuit. Dump resistor-solid line, Cold diodes-dashed-line

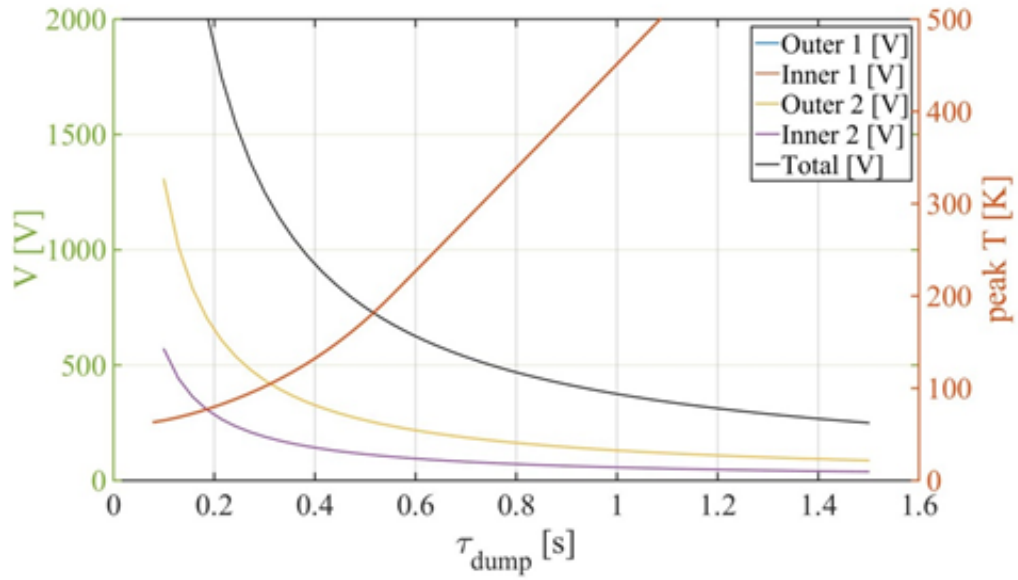


Figure 16: Voltages and peak temperature in the four coils for different time constants of the exponential dump.

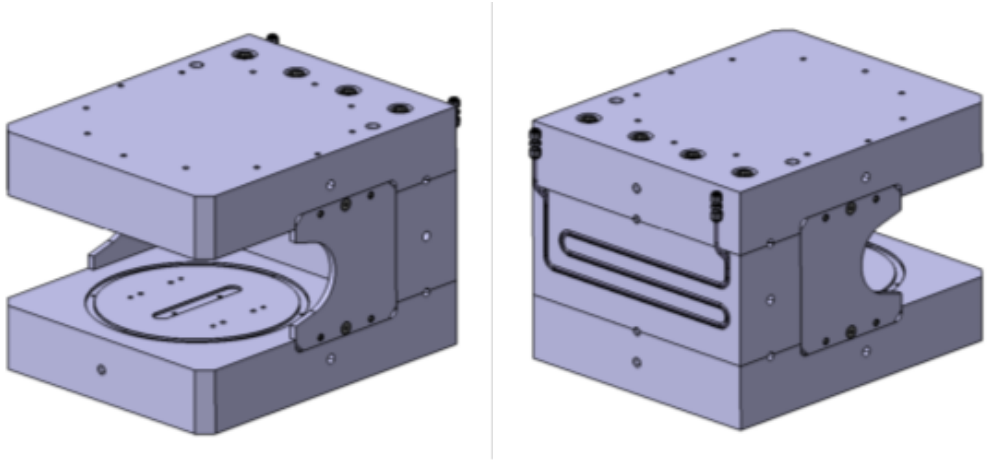


Figure 17: Magnet yoke

6 Mechanical Design

6.1 The Yoke

The magnet has a C-type iron yoke such that the magnet can be installed around the SLS 2.0 storage ring vacuum chamber see Fig.17.

The yoke consists of two horizontal (top and bottom) plates, each of 500x400x95 mm and a vertical plate of 400x165x120 mm. Two reinforcement ribs, made of 316LN stainless steel, are put into a recess on each plate and screwed into it to form a rigid structure. The overall dimensions and the weight of the yoke are as below:

1. Provided gap between two coils 53 mm
2. Length of the yoke along the beam 400 mm
3. Height of the yoke 355 mm
4. Width of the yoke 500 mm
5. Weight of the yoke 360 kg

The yoke fabrication starts with the machining of top and bottom plates into requested dimension with flatness and parallelism of two major surfaces within 0.050 mm. Two grooves are created on each plate to accommodate and to centre racetrack coils. A special assembly tool has to be fabricated and used to centre the circular big grooves on the top and bottom plates. Using this tool, the three pieces of the yoke are put together. When top and bottom plates are centered, the bolts (four on each side) are tightened and then the holes (6 in total) for the dowel pins must be machined to fix the position of the top and bottom plate one about another one. The yoke can now be dis-assembled to mount the coil. Twelve M10 holes are provided on the top plate to fix the liquid helium vessel. To speed up the cool down time the yoke will be additionally cooled using LN_2 circulating in the ID4/OD6 stainless steel pipe brazed into the vertical wall of the yoke (see Fig.17).

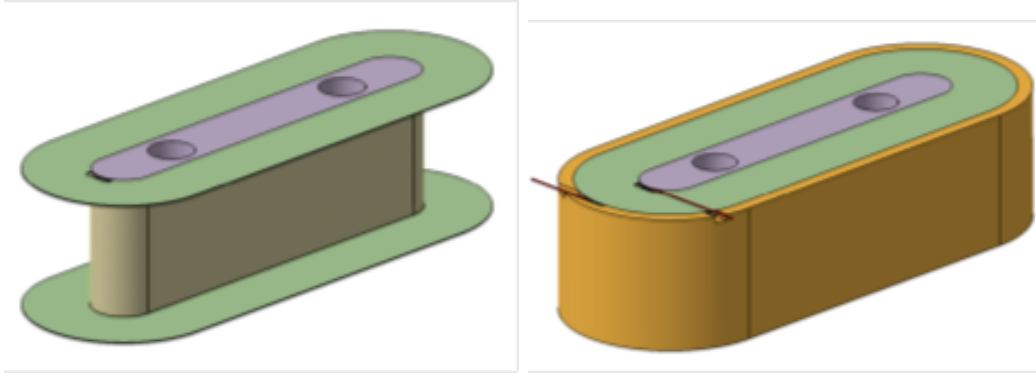


Figure 18: The small coil

7 Magnet Coils

7.1 The Small Coils

For the small coils Nb_3Sn superconducting wire will be used due to a field at the conductor up to 12 T. The small coil is wound on the ARMCO core using the special designed winding tool to form the coil of the requested height of 55mm (conductor only). The cross-section of the finished coil is expected to be 25x55 mm. The core has two holes for M8 screw used to fix the coil to the yoke. The core is 3 mm longer as the body of the coil in order to be inserted into the groove on the magnet yoke for a good centering. Before the winding starts, the ARMCO core is insulated using the fiberglass tape 0.15 - 0.25 mm thick half overlapped. Two G10 insulating sheets of 0.5 mm thick are placed on both extremities of the winding tool. Conductor resistance is monitored to insure that the conductor is not overstressed that can result the decreasing of the critical current density. After the coils are wound, they have to be heat treated to form Nb_3Sn . After the heat treatment is completed, the outer surface of the coils is insulated with 0.15 - 0.25 mm thick fiberglass, half overlapped. Before impregnation the leads of the Nb_3Sn coils are spliced to flexible NbTi cables. Because of the high magnetic forces, the beryllium copper (C17200 & C17300) structural ring must be placed around each coil. After the coil winding has been completed, the inside dimensions of the ring are determined from the outer dimensions of a coil. The ring is machined so that a 0.5 mm gap is provided all the way around the coil when it is inserted into the ring. After the coil is inserted into the ring the 0.5 mm gap is filled with fiberglass and impregnated with epoxy resin. After the coil impregnation, the insulation resistance against the ARMCO core and beryllium copper ring must be controlled applying a voltage of 1 kV. The ARMCO core insulated with fiberglass together with the G10 sheets and the finished small coil are shown in the Fig.18.

7.2 The Big Coils

For the big coils, NbTi superconducting wire is used as this part will remain at lower magnetic field. The conductor is easy to wind and does not require a thermal treatment. The big coil is wound on the 316L stainless steel structural mandrel using the special designed winding tool to form the coil of the requested height of 20 mm (conductor only). The cross-section of the finished coil is expected to be 20x20 mm. The mandrel has six holes for M6 screw to be used to fix the coil to the yoke. Before the winding starts, the mandrel is insulated using the fiberglass tape 0.15 - 0.25 mm thick half overlapped. Two G10 insulating sheets of 0.5 mm thick are placed to the mandrel flange and to the opposite extremity on the winding tool. Conductor resistance is monitored to insure that the conductor is not overstressed that can result the decreasing of the critical current density. After

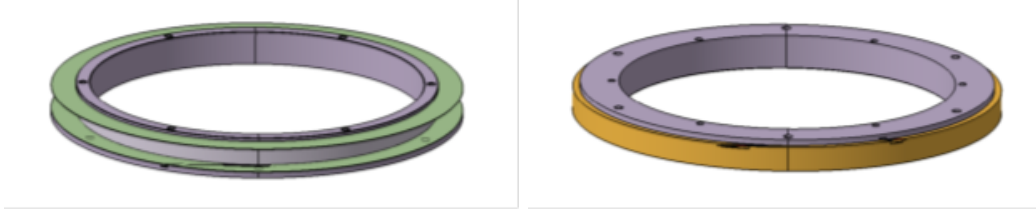


Figure 19: The big coil

winding is completed, the outer surface of a coil is insulated with 0.15 - 0.25mm thick fiberglass half overlapped. Because of the high magnetic forces, the beryllium copper (C17200 & C17300) structural ring must be placed around a coil. After the coil winding has been completed, the inside dimensions of the ring are determined from the outer dimensions of a coil. The ring is machined so that a 0.5 mm gap is provided all the way around the coil when it is inserted into the ring. After the coil is inserted into the ring the gap 0.5 mm is filled with fiberglass and impregnated with epoxy system. After the coil impregnation, the insulation resistance against the mandrel and beryllium copper ring must be controlled applying a voltage of 1 kV. The mandrel insulated with fiberglass together with G10 sheets and finished coil are shown in the Fig.19.

7.3 The Current Leads

The Superbend magnet uses two types of current leads: Normal conducting (Copper, high RRR) conduction cooled current leads from room temperature to 50 K and High Temperature Superconductor (HTS) current leads from 50 K to 4.2 K. The copper, conduction cooled current lead is a combination of a standard type vacuum feedthrough with a round copper bar of Φ 8.75 mm (L=495 mm, I=500 A and RRR=90). The bottom of the normal conducting current lead is clamped by a custom clamp to the top of the HTS current lead. Both are thermally anchored to the liquid nitrogen vessel by a flexible copper strap. The copper strap is electrical insulated from the current lead by two layers of KAPTON, each of 0.1 mm thick. A second clamp, having a G10 stick that prevents the sliding of the clamp to avoid an eventual electrical short cut, clamps the three pieces (the first clamp, the HTS current lead and the strap) together. The design of this connection is shown in the Fig.20. A rigid copper bridge thermally anchors the bottom part of the HTS current lead to the bottom of the liquid helium vessel such that, in case of a cold-head failure, the magnet will be kept cooled until all liquid is evaporated. The design of this bottom clamp is shown in Fig.21.

7.4 Liquid Helium Vessel

Liquid Helium (LHe) is required to maintain the coils in the superconducting state when the cold-head fails. The estimated autonomy with 40 L of LHe is 8-10 hours. The proposed design has an internal re-condensing unit above the bath of LHe. The sketch of the LHe vessel with some dimensions is shown in the Fig.22. When the cold head is in operation, the LHe in the vessel is cooled to about 3.5 K with a corresponding vapour pressure of around 466 mbar. Because the liquid helium bath is below atmospheric pressure, all valves and fittings that communicate with the LHe vessel must be leak tight to prevent the air from being pumped into the vessel. An air leak could pose a potential hazard since a plug could form that could prevent the vessel from venting in the case of the a pressure build up caused by heating due to cold head failure, magnet quench, HTS current lead quench or loss of insulating and consequent vaporization of the LHe bath.

When the cold-head fails, the temperature and pressure of the LHe will rise to 4.3 K and 1.08 bar

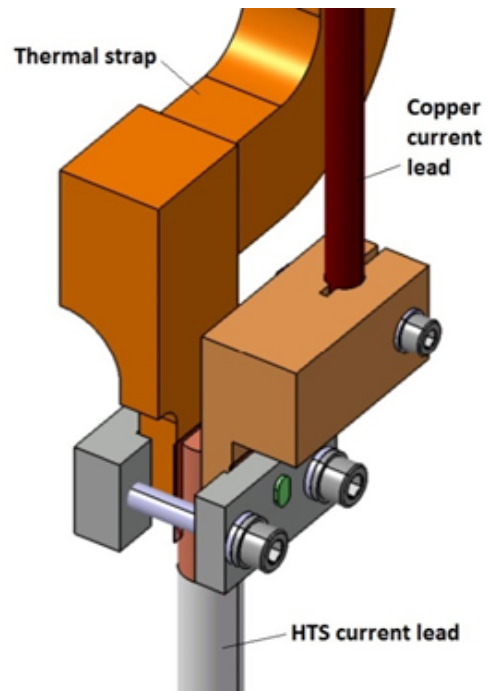


Figure 20: HTS current lead connection at the 50 K side

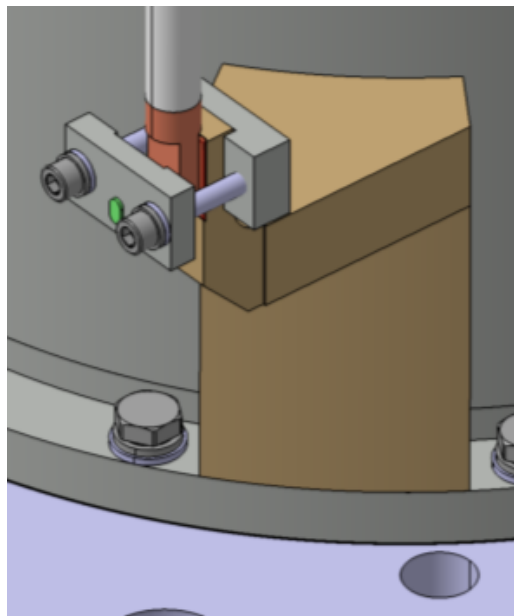


Figure 21: HTS current lead connection at the 4.2 K side



Figure 22: LHe vessel

accordingly and the refrigeration will be provided by the liquid helium heat of vaporization. The LHe vessel can be replenished as required using an external transfer line. Two scenarios are possible:

1. either open the roof of the storage ring or use the penetration in the concrete radiation shielding to replenish LHe from an external Dewar.
2. or replenish the LHe from pre-installed transfer lines.

A superconducting type LHe level sensor will be used to monitor the liquid level. The LHe vessel is made of 316L steel and is designed to meet the requirements of the EN 13445. The maximal allowed pressure is 20 bar. The room temperature test pressure is 20 barg. The LHe vessel is tightened to the top of the iron yoke. To improve the thermal transfer the indium washer of 0.1-0.2 mm thick is applied between the vessel and yoke. The LHe vessel has two stainless steel tubular penetrations that allow the filling, venting and level sensor installation. The penetrations are thermally anchored to the LN₂ vessel by mean of the flexible straps in order to minimize the heat input from the room temperature to the LHe vessel. An external manifold is installed on the venting tube provided with a security valve and a rupture disk. The rupture disc setting is 10 barg. To reduce the heat flux due to the thermal radiation, the cylindrical surface of the LHe vessel is covered with a minimum of 10 layers of Multilayer Insulation (MLI).

7.5 Liquid Nitrogen Vessel

Liquid nitrogen is required to intercept the heat due to the radiation and conduction from room temperature as well as to continue the operation in the case of the cold-head failure (see Fig.23). The estimated autonomy with 20 L of LN₂ is 8-10 hours.

When the cold-head is in operation, the LN₂ in the vessel is cooled to about 50 K and frozen to ice (solid nitrogen) with a corresponding vapor pressure of around 7 mbar. Therefore, all valves and

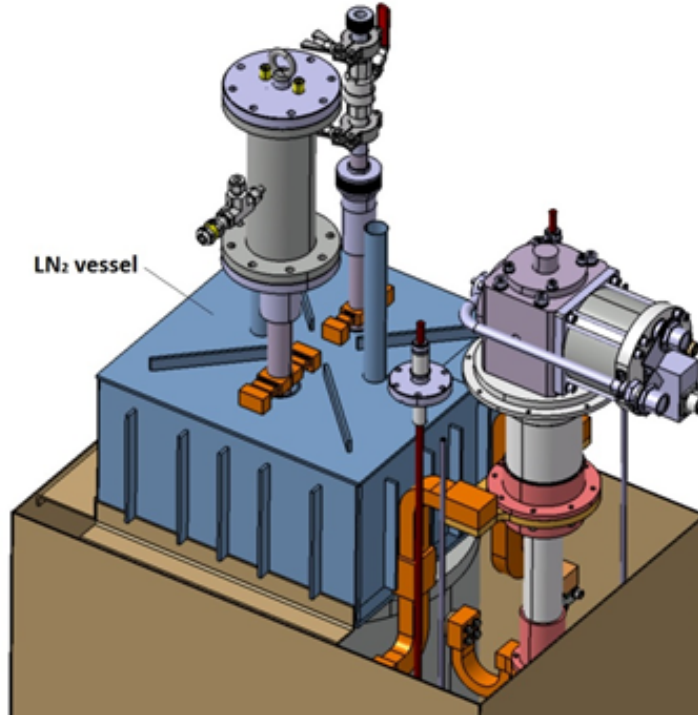


Figure 23: LN₂ vessel

fittings must be leak tight to prevent air from being pumped into the vessel. An air leak could pose a potential hazard since an ice plug could form that could prevent the vessel from venting in the case of a pressure build up caused by heating due to cold-head failure, magnet quench, HTS current lead quench or loss of thermal insulation and consequent vaporization of the LN₂ bath. When the cold head fails, the increased heat load will cause the solid nitrogen to melt, the temperature and pressure in the LN₂ vessel will rise to 78 K and 1.07 bar respectively and the refrigeration will be provided by the evaporation LN₂ so the liquid must be replenished after several hours. Two scenarios are possible:

1. either open the roof of the storage ring or use the penetration in the concrete shielding to refill LN₂ from an external dewar.
2. or refill LN₂ using the pre-installed transfer lines.

A capacitance type LN₂ level sensor will be used to monitor the LN₂ level. The LN₂ vessel is made out of Aluminium alloy, type 6061, and designed to meet the requirements of the EN 13445. The maximal allowed pressure is 20 bar. The room temperature test pressure is 20 barg with the rupture disc setting of 10 barg. Similar to the LHe vessel, the LN₂ vessel has also a stainless steel tubular penetrations and a manifold that allow the filling, venting and level sensor installation. An aluminium to stainless-steel transition pipe allows the penetrations to be welded to the aluminium vessel.

7.6 Thermal shield 50 K

The iron yoke together with the LHe vessel are surrounded by a 50 K thermal shield made out of 2 mm thick CU-OFHC copper sheets. From the back side the wall of the thermal shield has to be removable to allow the access for the cold head installation/removing (see Fig.24)

The shield is thermally connected on three sides to the bottom of the LN₂ vessel. It will allow to cool down the shield when the cold head is out of operation. To minimize the heat load from thermal

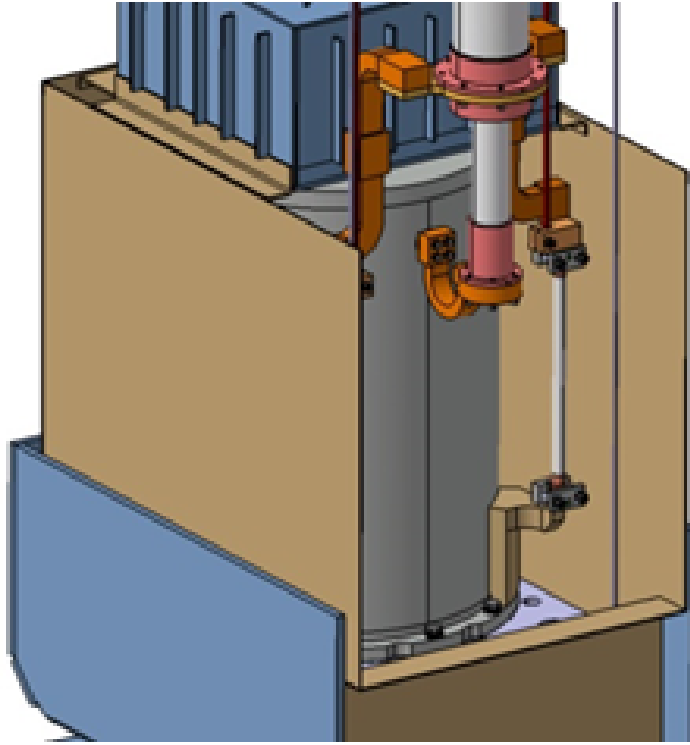


Figure 24: Thermal shield 50 K

radiation to the thermal shield, the outer surface of the thermal shield has to be covered with a minimum 10 layers of MLI.

7.7 Cold Mass Support

The cold mass is supported by a cylindrical support made out of two G10 pipes (5 mm thick wall) and a stainless steel link in between. The principle of this support is shown in the Fig.25. The support has a ring that will be tightened to the bottom of the cold mass and will center the inner G10 pipe. The inner G10 pipe is sitting in the 316L stainless steel link that is connected to the 50 K thermal shield at the place where the 316L steel link sits on the outer G10 pipe. The outer G10 pipe will be centered inside the vacuum vessel on the support plate. Inside the support, a thermal shield with minimum 10 layers of MLI is attached to the 316L steel link. A minimum gap of 2 mm is provided between all cylindrical parts. The space between the coils and the C-opening of the vacuum vessel for the beam-line vacuum chamber is very critical. The cold mass with its support has to have alignment possibilities in order to insert properly the cold mass in the C-opening of the vacuum vessel, including the 50 K thermal shield. The available space and tolerances are shown in Fig.25.

7.8 Heat transfer at material interface

At all screwed connections where a good heat transfer is required, indium washers of 0.1-0.2 mm thick must be used between the two surfaces. Where a good thermal transfer but a bad electrical contact is needed (current leads) sapphire or polymer washers can be used.

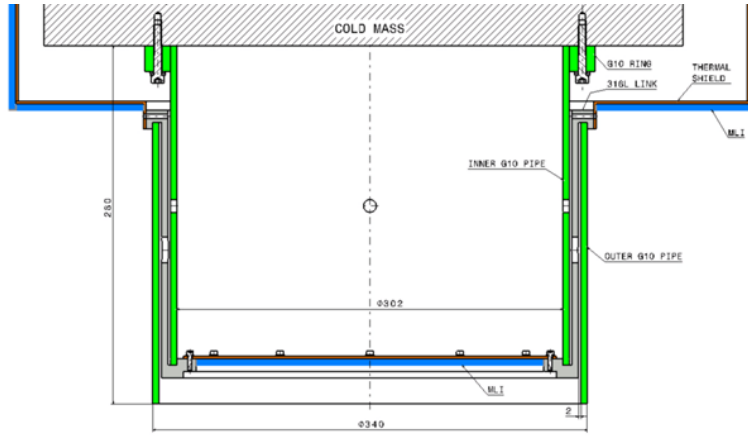


Figure 25: Cold mass support cross section

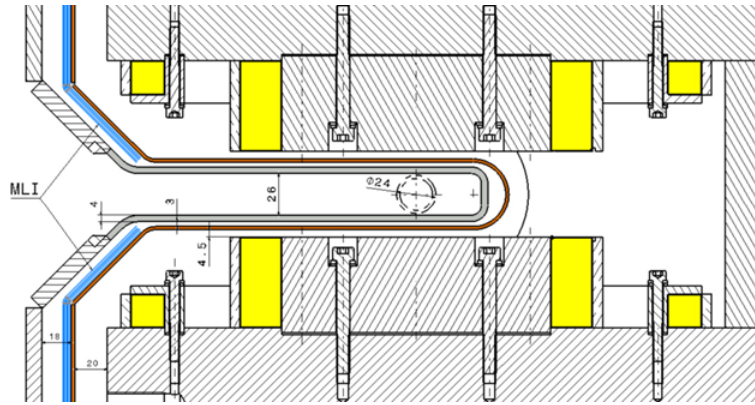


Figure 26: Room budget in the magnet centre

8 Instrumentation

8.1 Temperature sensors

CERNOX type temperature sensors are used to control the magnet temperature. The temperature sensors are installed at least at 12 locations of each Superbend Magnet:

1. T1 cold head first stage
2. T2 cold head second stage
3. T3 HTS current lead top
4. T4 HTS current lead bottom
5. T5 lower coil small
6. T6 low coil big
7. T7 upper coil small
8. T8 upper coil big
9. T9 top yoke

10. T10 bottom yoke
11. T11 yoke LN cooling inlet
12. T12 yoke LN cooling outlet

The list of the sensors can be extended if other sensors are required.

8.2 Level sensors

A superconducting type LHe level sensor will be used to monitor the liquid helium level. A capacitance type LHe level sensor will be used to monitor the liquid nitrogen level. The level sensor feedthroughs must be provided with the rapid exchange option or a second (spare) level sensor must be installed. A Model 1700⁸ liquid level instrument is used to monitor simultaneously the liquid helium and liquid nitrogen levels.

8.3 Vacuum vessel

The cold mass together with the 50 K thermal shield is to be located inside of the vacuum vessel. The vacuum vessel will be made out of 316L steel and must conform to the requirements of the EN 13445. At least the following interface points have to be provided:

No.	Description	Qty
1	Crane lifting points	4
2	Fiducial posts	4
3	Rear access port for cold-head installation	1
4	Cold-head port	1
5	LHe transfer port	1
6	LHe ventilation and instrumentation port	1
7	LN2 transfer port	1
8	LN2 ventilation and instrumentation port	1
9	Current feedthroughs	2
10	Electrical feedthroughs for different sensors	1
11	Vacuum pumping port	1
12	Vacuum safety valve	1

Additional ports may be requested. The location and size of each port will be determined during the detail design by the manufacturer. The total length of the vacuum vessel in the beam direction **must not exceed 500 mm** in the region ± 300 mm from the beam in the vertical direction.

8.4 External vacuum vessel support

The external support has to provide the following alignment possibilities:

The interface points with the floor or girder TBD.

⁸American Magnetics, www.americanmagnetics.com

Alignment	Range	Accuracy
Longitudinal (along beam)	5 mm	0.050 mm
Radial (horizontal)	5 mm	0.050 mm
Vertical	5 mm	0.050 mm
Pitch	4 mrad	0.1 mrad
Roll	4 mrad	0.1 mrad
Yaw	4 mrad	0.1 mrad

9 Beam-Line Tunnel Ceiling Modifications

The installation of the SLS2.0 Superbend Magnet in the SLS 2.0 ring will request some modification of the roof (ceiling) of the concrete radiation shielding due to the following reasons:

1. Operation: The total height of the unit is over the 1000 mm from the beam and interferes with the main ceiling plate of the shielding. The main plate can be replaced by another one that will be put 400 mm higher (as already made on some points of the actual SLS) but still will probably request some modification as the total height of the magnet is not yet fixed.
2. Maintenance: If the cold head needs to be removed (maintenance, failure, etc.) some additional space will be necessary. Due to this reason, the modification of the ceiling plates is mandatory.
3. LHe and LN₂ replenishment: If the replenishment of the LHe and LN₂ is made using the transfer lines, the penetrations must be provided in the ceiling plates.

The modification are shown in Fig.27.

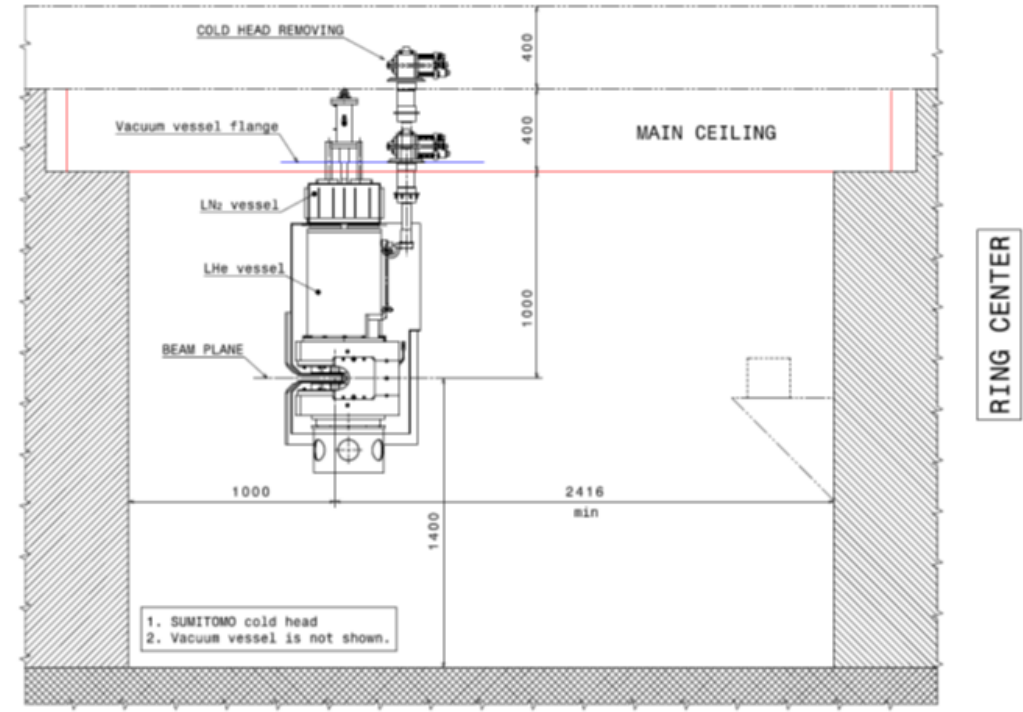


Figure 27: Ceiling modification in the beam-line tunnel

10 Cost Estimation

A rough estimation of the costs for the prototype manufacturing is shown in Table 5.

Table 5: Estimation of Prototype Cost

1	Cold head including compressor, cables, gas pipes and tools	1 set	CHF 45'000
2	Superconducting wire	~ 10 kg	CHF 7'500
3	Pair of HTS current leads	1	CHF 4300
4	ARMCO steel for Iron yoke	~ 400 kg	CHF 1'500
5	Stainless steel for the vacuum vessel	~ 900 kg	CHF 9'000
6	Copper for the 50 K thermal shield	~ 50 kg	CHF 750
7	Stainless steel pile for LHe vessel	~ 20 kg	CHF 200
8	Stainless steel pipe for LN ₂ vessel	~ 25 kg	CHF 250
9	Design (engineering and technical drawings)	1	CHF 20'000
10	Manufacturing	1	CHF 3000'000
11	Project management	1	CHF 10'000
12	Magnet Power supply	1	CHF 4'900
TOTAL			CHF 403'400
With contingency 20%			CHF 484'080

11 Authors contribution

A.Anghel conceived the cryogenic design and performed the thermal calculation. C.Calzolaio worked out the magnetic design and performed the magnetic field calculation and superconductor specification. S.Sidorov carried out the mechanical design and managed the writing of the first draft of the report with contribution from A.Anghel and C.Calzolaio. S.Sanfilippo coordinated the project. All authors commented on the manuscript.

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