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Development of a cryogen-free test cryostat for a superconducting CCT short magnet

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Abstract. In the framework of the ISOLDE Superconducting Recoil Separator (ISRS) project, a short and straight CCT magnet demonstrator (MAGDEM) has been designed comprising a dipole and a quadrupole. The final ISRS spectrometer is intended to consist of 10 units of this CCT magnet arranged in a ring configuration. Additionally, this type of magnet could potentially be used for proton therapy gantry systems. A cryogen-free test cryostat has been developed for the MAGDEM, considering the space constraints related to the installation of the spectrometer at ISOLDE. The magnet will be conduction cooled using cryocoolers to be independent of any liquid Helium supply. To speed up the cool-down time, a liquid nitrogen pre-cooling system has been included. This work mainly focuses on the design of the cryostat, encompassing descriptions of the different components, an optimization study of the current leads, and an analysis of the cool-down time. A prototype of the MAGDEM and its cryostat will be built and tested at Huelva University in the forthcoming years, funded by Spain's Recovery and Resilience Plan.

Instroduction

The "ISOLDE Superconducting Recoil Separator" (ISRS) project aims at developing a new high-resolution recoil separator for the HIE-ISOLDE facility at CERN [10], which is a particle accelerator that can accelerate over 1000 isotopes of 70 elements to energies up to 10 MeV [2]. The ISRS separator was designed to fit into the available space at ISOLDE, and it will consist of a compact 3 m diameter storage ring made of superconducting magnets. A first conceptual design was given in [11], in which four 90° bends are made by Canted Cosine Theta (CCT) superconducting curved magnets detailed in [7], named FUSILLO. More recently, a second conceptual design of the ISRS separator is under development at the University of Huelva (Spain), in which the ring is composed of 10 straight superconducting short CCT magnets called MAGDEM. Each magnet will bend the beam by 36°, forming the ring in figure 1.

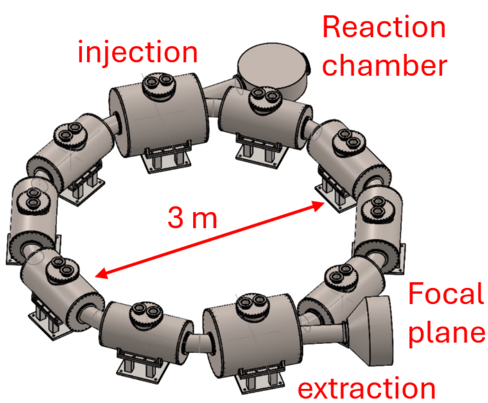

Fig. 1: Conceptual design of the ISRS ring composed of 10 MAGDEM

The MAGDEM will be made of Nb-Ti wires, which require to be cooled below 9K to be superconducting. Due to the difficulties of using liquid Helium at 4K as a cryogenic fluid in ISOLDE, it was decided to cool the MAGDEM in a dry cryostat using cryocoolers. This type of cryostat has already been successfully used for other types of superconducting magnets, such as in [3] or in [4]. In this article, the design of the MAGDEM cryostat is detailed. The specificity of the cryostat lies in its design to be as compact as possible to accommodate the space constraints at ISOLDE.

1 Solenoid design

The MAGDEM was designed to bend the various accelerated particles by 36° [8]. It was designed with a rather short length of 580 mm, while maintaining a relatively large 200 mm beam aperture. It is composed of 4 layers of wiring, with the 2 inner layers forming a dipole and the 2 outer layers forming a quadrupole. The different layers of the MAGDEM are shown in the figure 2. In each layer, the superconducting strands are assembled in ropes and positioned in channels as represented in the figure 3. The characteristics of the MAGDEM are listed in the table 1.

In each layer, the channels are made in an aluminum alloy block called former. These formers support the axial Lorentz forces created by the magnet. In order to deal with the radial Lorentz forces, an additional aluminum support cylinder surrounding the MAGDEM was designed with the minimum possible mass.

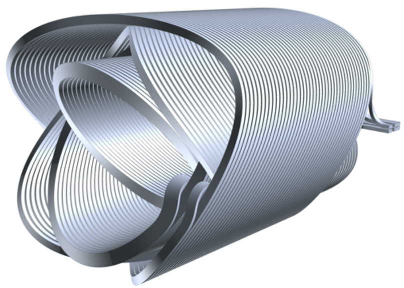

Fig. 2: 3D view of the 4 MAGDEM layers

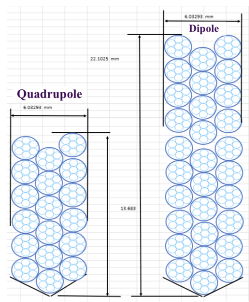

Fig. 3: Assembly of the superconducting strands in the channels

Table 1: Specifications of MAGDEM

Specifications	**Dipole**	**Quadrupole**
Nominal current	91.6 A	112.8 A
Integrated field	0.751 T.m	0.246 T.m
Inductance	25.6 H	
Stored energy	142 kJ	
Inner radius (m)	115 mm	171 mm
Outer radius (m)	166 mm	203 mm
Number of layers	2	
Number of turns per layer	43	
Number of ropes per layer	30	18
Number of strands per rope	7	
Number of strands	210	126
Strand diameter	0.5 mm conductor + 0.125 mm insulation	
Strand conductor	Copper stabilized Nb Ti	
Copper / Nb Ti ratio	2 : 1	
Mass of conductor	27 kg	23 kg
Rope length	2.5 km	2.1 km
Strand length	17.5 km	14.7 km

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2 Cryostat design

2.1 General description

Two versions of the cryostat were designed: one with a single cryocooler positioned at the top of the magnet, and another with two cryocoolers positioned at both the top and bottom of the magnet. In the end, the single cryocooler version shown in the figure 4 was selected for the future construction.

A two stage G-M cryocooler with the cooling capacity of 1.5 W at 4.2 K on the second stage and approximately 40 W at 40 K on the first stage is mounted on the cryostat. The first stage of the cryostat cools the thermal shield, while thermalizing the current leads and the tie beams at 40 K - 50 K. Then the second stage extracts the MAGDEM heat and cools the current leads to approximately 4 K. The G-M cryocooler performances should not be altered by the MAGDEM magnetic field, as the peak field on the cryocooler is below 0.6 T [9].

The vacuum vessel of the cryostat is made of Stainless Steel, and it is made of two parts. The first part is the horizontal cylinder housing the magnet, with a length of 775 mm and a diameter of 900 mm. The second part contains the cryocooler head and the current leads, with a height of 400 mm and a diameter of 500 mm. During operation, the pressure inside the vacuum vessel is pumped below 1e-6 mbar to suppress convection heat transfer.

The thermal shield is made of 2 mm thick copper for facilitating the heat extraction by conduction to the cryocooler first stage. To reduce the radiative heat flux coming from the room temperature vacuum vessel, the horizontal part of the thermal shield will be gold-plated using an electrolytic bath. The remaining of the thermal shield surface will be covered with 30 layers of Multi-Layer-Insulation (MLI). The use of gold cover saves space compared to MLI.

The internal components are maintained in position by 8 tie beams made of Ti-6Al-4V alloy. These tie beams support the weight of the components ($\simeq$ 400 kg), as well as the Lorentz forces and the forces induced by thermal contractions. The Lorentz force could reach 20 kN in the axial direction if two MAGDEM units are positioned 0.5 m apart. To accommodate this, the tie beams are positioned with an angle relative to the radial direction. Spring washers are added at the warm ends of the tie beams to compensate the thermal contraction forces.

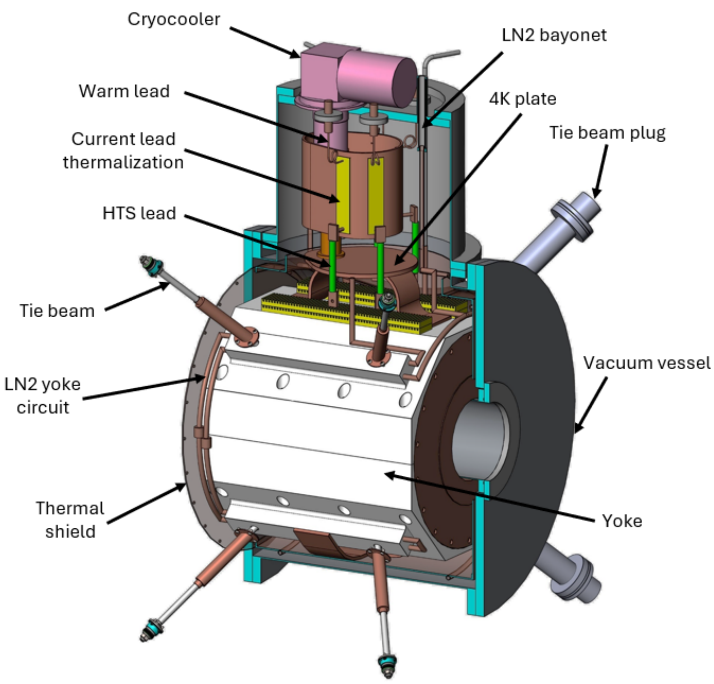

Fig. 4: 3D model of the MAGDEM cryostat

In order to minimize the thermal loads on the magnet, the 4 current leads are composed of 2 stages. The warm stage connects the 300 K vacuum vessel to the first stage of the cryocoolers at $\simeq$50 K. The HTS stage connects the first stage of the cryocooler to its second stage at $\simeq$4 K. The warm leads are copper wires of diameter 3 mm and length 23 cm. These optimal dimensions were determined by solving a 1D model with conduction and Joule effect for different length and diameter, and taking the dimensions associated to the lowest heat load of 5.3 W, similarly to [1]. When the current is off, the pure conduction heat load is equal to 3.2 W. The HTS leads is made of a High Temperature Superconductor material, which become superconducting below approximately 80 K, eliminating the Joule effect heat load. The HTS leads considered are the CBS-0150-174 from the supplier HTS-110, which are optimized for 150 A and have an associated heat load of 65 mW between 64K and 4K. The current leads are thermalized along a 200 mm^2 cross-section and 190 mm long copper conductor which is in thermal contact with the thermal shield. This part is electrically insulated.

LN2 pre-cooling piping is implemented to accelerate the cool-down phase of the MAGDEM cryostat. The LN2 will be injected through a bayonet to reduce the thermal losses. Inside the cryostat, the LN2 piping is divided into two circuits : one for cooling the thermal shield and the other for cooling the MAGDEM. The control valves at the exit allow regulating the cool-down speed of each circuit. An electric heater is implemented close to the exit to avoid vapor condensation on the vacuum vessel.

3 Thermal study of the cryostat

3.1 Static heat loads

The static heat loads which were estimated based on the cryostat design are given in the table 2. The heat load at 4.2 K is equal to 0.52 W, it is a rather low value due to the low current requirements which reduces the heat loads of the current lead and the wire joints. The heat load at 50K is equal to 48.2 W.

Component	On 50K (W)	On 4.2K (W)
Supports	12.1	0.36
Current leads	24.0	0.13
Radiation heat flux	12.1	0.01
Wire joints	-	0.02
Total heat loads	48.2	0.52

Table 2: Result of the thermal study of the MAGDEM cryostat

3.2 Cool time down simulations

A python program was written based on the work of [4] to estimate the cryostat cool-down time. The idea is to compute the temperature variations at distinct locations in the cryostat by solving the simplified heat equation :

$$\sum_k [m_k C_{p,k}(T_i)] \frac{dT_i}{dt} = Q_{\text{cond}} + Q_{\text{rad}} + Q_{\text{contact}} + Q_{\text{cryocooler}} \tag{1}$$

where i indicates the component and k the materials. The different components whose temperature are resolved and the various thermal resistance considered in the model are represented on the figure 5, and the masses and materials of the components used in the model are given in the table 6.

As the materials properties vary significantly at low temperatures, interpolation functions based on the CryoData libraries are used in the program for the thermal conductivity λ and the heat capacity C_p. The conduction heat flux in a material k is given by :

$$Q_{\text{cond},i\to j} = \frac{S_k}{L_k} \int_{T_i}^{T_j} \lambda_k(T)\, dT \tag{2}$$

where S_k the surface of conduction and L_k the length of conduction. The radiative heat flux is given by :

$$Q_{\text{rad},i\to j} = \sigma F_e S_j (T_j^4 - T_i^4) \tag{3}$$

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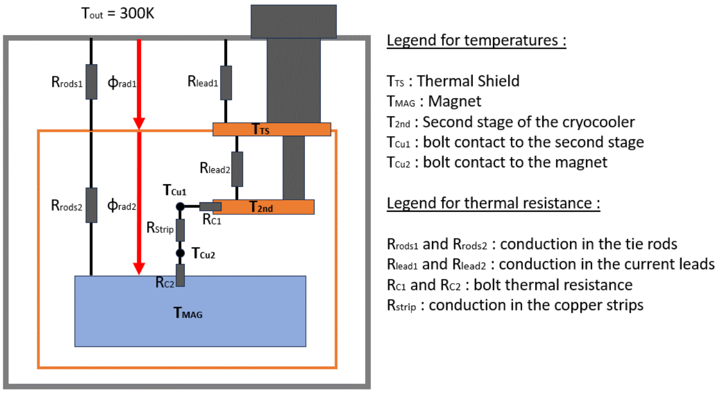

Fig. 5: Diagram of the modelled cryostat

Component	Material	Mass
Thermal shield	Cu	50 kg
Magnet and yoke	Cu NbTi Al	40 13 kg 275
2nd stage copper plate	Cu	10 kg
Copper strips (4 units)	Cu	0.2×4 kg

Fig. 6: Component's mass and materials

where $\sigma = 5.67\,10^{8}$ W.m^{-2}.K^{-4} is the Stefan-Boltzmann constant, F_e the emissivity factor, and S_j the surface of j. Finally, the heat transfers across the bolts contacts are computed using :

$$Q_{\text{contact},i\to j} = \int_{T_i}^{T_j} C_{\text{contact}}(T)\,dT \tag{4}$$

where $C_{\text{contact}}(T)$ is the contact conductance. Some solid-solid joint conductance values can be found in [5]. The heat flux $Q_{cryocooler}$ is computed according to the capacity map of a `PT415` from Cryomech which delivers 1.5W at 4.2K given in [6]. A python function was written to approximate this capacity map.

The cool-down estimations are given for 1 and 2 cryocoolers on the 7 and 8, for starting temperatures of 100 K and 293 K respectively. The estimation starting at 100 K assumes that the cryostat has been pre-cooled with LN2. The cryostat should take approximately 46 hours to cool-down from 100 K to 4 K with one cryocooler, and about 35 hours with two cryocoolers. If the cooling starts at 300 K, the cryostat should take approximately 185 hours to cool-down with one cryocooler, and about 119 hours with two cryocoolers.

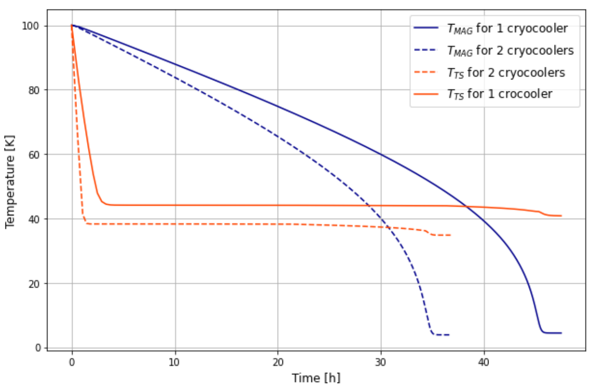

Fig. 7: cool-down simulation starting at 100 K

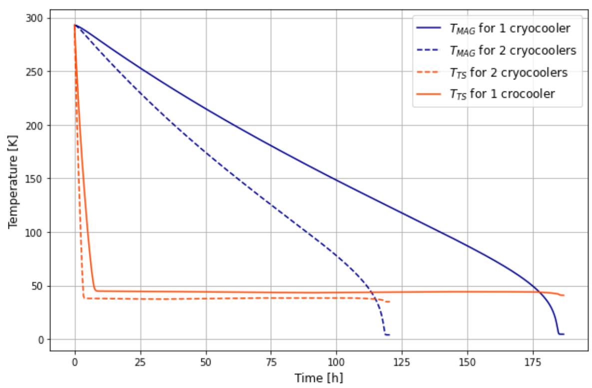

Fig. 8: cool-down simulation starting at 293 K

After a quench, the average temperature T_q of the MAGDEM can be estimated using the stored magnetic energy $E_{mag} = 142$ kJ, with the relation :

$$E_{mag} = m_{Al}\int_4^{T_q} Cp_{Al}\,\mathrm{d}T + m_{Cu}\int_4^{T_q} Cp_{Cu}\,\mathrm{d}T + m_{NbTi}\int_4^{T_q} Cp_{NbTi}\,\mathrm{d}T \tag{5}$$

Solving this equation gives $T_q \simeq 35$ K. Thus, after a quench, it should take approximately 4 hours to cool-down the MAGDEM with one cryocooler, and 2.5 hours with 2 cryocoolers.

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4 Concluding remarks

A dry test cryostat was designed within the framework of the ISRS collaboration, for cooling down a CCT superconducting magnet called MAGDEM to approximately 4 K. The cryostat was design to be as short as possible, and it was optimized for having the lowest heat loads. The cool-down study performed has shown that the cryostat with a single cryocooler should take about 46 h to cool-down after a LN2 pre-cooling. The MAGDEM prototype and its cryostat will be built and tested at Huelva University in the forthcoming years.

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