CEA EXPERIENCE AND EFFORT TO LIMIT MAGNETIC FLUX TRAPPING IN SUPERCONDUCTING CAVITIES

Juliette Plouin[#], Nicolas Bazin, Patrice Charon, Guillaume Devanz,
Hervé Dzitko, Philippe Hardy, Fabien Leseigneur, Jérôme Neyret, Olivier Piquet
CEA-Saclay, Gif-sur-Yvette, France

Abstract

Protecting superconducting cavities from the surrounding static magnetic field is considered as a key point to reach very good cavity performances. This can be achieved by both limiting the causes of magnetic flux around the cavity in the cryomodule, and enclosing cavities and/or cryomodules into magnetic shields. We will present the effort made at CEA into this direction: shield design, shield material characterization, at room and cryogenic temperature, and search and attenuation of the magnetic background present in the cryomodule during the cavities superconducting transition. This last point will be especially studied for the IFMIF project where the cryomodule houses the focusing magnets.

INTRODUCTION

In low beta cryomodules with high intensity beams it is generally necessary to have solenoids close to superconducting cavities. When the cryomodule contains more than one or two cavities, the solenoids are usually inside the module, which adds a level of complexity to the cryomodule design considerations [1], because the static magnetic field can degrade the cavities performance. The static field close to a cavity must be lower than the critical field (tens of mT) when it is in the superconducting state. It has to be lower than some µT during the superconducting transition to avoid a significant increase of the surface resistance.

Then it is mandatory to prevent magnetic pollution generated by these solenoids, even when they are switched off.

Moreover the cavities must be protected from the earth magnetic field (~50 µT).

MAGNETIC SHIELD OF THE IFMIF CRYOMODULE

The IFMIF cryomodule contains all the equipment to transport and accelerate a 125 mA deuteron beam from an input energy of 5 MeV up to 9 MeV. It consists of a horizontal cryostat of about 6 m long, 3 m high and 2 m wide, which includes 8 superconducting HWRs (Half Wave Resonators) for beam acceleration working at 175 MHz and at 4.5 K, 8 power couplers to provide RF power to cavities, and 8 Solenoid packages as focusing elements [2].

A warm magnetic shield is installed on the inner walls of the vacuum vessel to protect the cavity from the earth

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juliette.plouin@cea.fr

magnetic field. Calculations have shown that with 2 mm thickness and with standard mumetal, the static magnetic field should stay lower than 2 µT inside the cryomodule, which is the design target for the HWR.

Several views (inside, outside the cryomodule, exploded) of this magnetic shield are shown in Figure 1.

The many apertures of the cryomodule are critical for the shielding, and overlap of mumetal sheets are mandatory. The tendering phase of this magnetic shield has started.
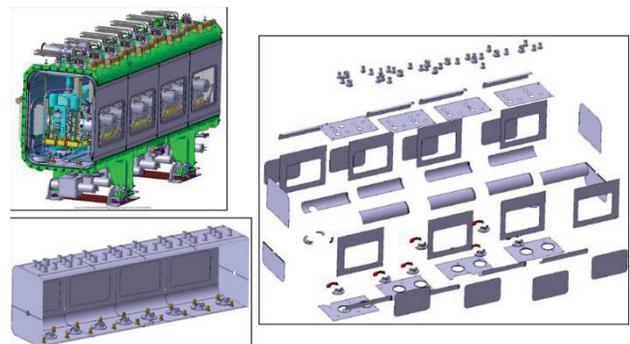
Figure 1: Magnetic shield of the IFMIF cryomodule.

MAGNETIZATION OF CRYOMODULE ELEMENTS

Due to space charge associated to the high intensity beam, a short, but strong, superconducting focusing magnet package is necessary between cavities. During the cryomodule operation, the solenoids will only be switched on once the cavities are in superconducting state. Each magnet package contains one inner solenoid, which can reach 7 T, four steerers, and one outer solenoid connected in series with the inner one with current established in opposite sense, in order to work as an active shielding. The fringe field at the cavity flange is then limited to 20 mT [3]. Figure 2 shows the magnetic field pattern generated by the solenoid package at several places in the cryomodule. Our concern is that some cryomodule components could be magnetized by this fringe field, and be a source of remnant field once the solenoid is switched off. We have focused our attention in particular on the needles bearings, the invar rod, and the magnetic shield itself.

Moreover the supporting frame was initially planned to be made of stainless steel 316L C-beams which are welded together. The large number of welding rims with potentially higher permeability than expected represented

a risk. Thus the frame will finally be made of welded titanium I-beams which are totally non-magnetic.
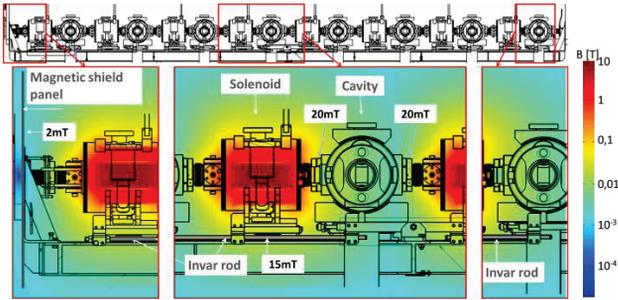
Figure 2: Static magnetic field pattern generated by the solenoid package in the cryomodule.

Needle Bearings

Cavity and solenoids supported by rolling systems similar to XFEL using needle bearings. One can see in Figure 3 that the needle bearings are close to the area of the cavities where the RF magnetic field is the highest.
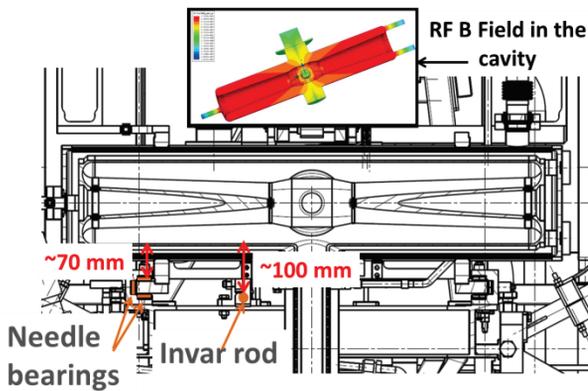
Figure 3: Position of the needle bearings and the invar rod in the cryomodule.

We observed that the bearings off the shell we had planned to use (Figure 4) were naturally magnetized [4]. We proceeded to magnetic measurements to estimate this magnetization. The magnetic field is measured with a Förster probe at several distances from the bearings. Measurements are performed inside a Cryoperm box (HIPPI magnetic shield), supported on a cardboard box instead of a table to avoid possible magnetic fields in the structure. The results are shown in Table 1 for 8 samples. The magnetic field reaches up to 400 µT at contact, and is still much higher than the 2 µT allowed on the cavity at 10 mm from the bearings. Sample 7 was dismounted and the field was measured at direct contact to each needle, reaching up to 1 mT (see Table 2).

To discard any magnetization of these elements we developed homemade bearings with brass cage and ceramic needle (Figure 5). Then these elements cannot anymore be a source of remnant magnetization.

Table 1: B Field at Different Distances from the Needle Bearing

Sample number	Average value at 10 mm (µT)	Average value at 4 mm (µT)	Average value at contact (µT)
1	5	10	25
2	25	72	220
3	60	50	140
4	42	100	215
5	34	80	135
6	5	19	39
7	42	105	440
8	16	70	235

Table 2: B Field at Contact with the Needles of Sample 7

Needle from sample 7	Field amp. at contact (µT)
1	750
2	1000
3	260
4	1000
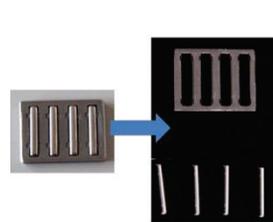
Figure 4: Off the shelf needle bearings.
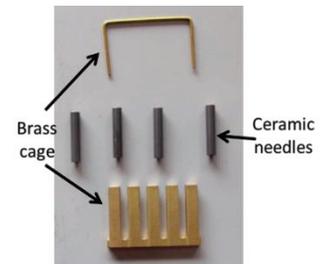
Figure 5: Home-made needle bearing.

Invar Rod Magnetization

In order to take into account the thermal shrinking of the cold mass, the cavity and solenoid will be fixed on a common specific mechanical support composed of a titanium frame to support the cold mass and of invar reference rods, to control the position along the beam axis with some sliding attachments to manage the differential thermal deformation between the frame and the invar rod. Two long invar rods will be placed in the cryomodule, each measuring half the size of the structure and the discontinuity between these two rods can be seen in Figure 2. These rods are situated at 100 mm from the cavity surface (Figure 3).

The invar material, well known for its very low thermal shrinkage at cold temperature, is also ferromagnetic, and can be magnetized. We made some tests with two invar rods (1 short, 1 long), with diameter 12 mm, like in the cryomodule, and with respective length 50 mm and 500 mm.

The rods were magnetized using a board magnet (which can be seen in Figure 11) which generates a 100 mT field quite uniformly on its surface.

The short rod was magnetized in both axial and transverse direction. For the axial magnetization, while one section was placed on the magnet, the field at the other section was 25 mT, thus the whole rod is magnetized, even if non-uniformly. After each magnetization the B field is measured in different directions indicated in Figure 6.
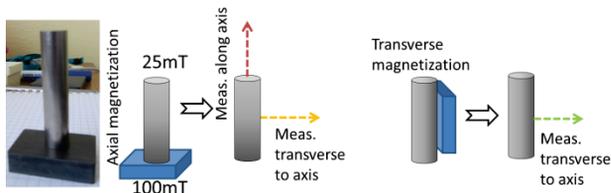
Figure 6: Magnetization of the short invar rod with a magnet.

The results presented in Figure 7 show that the field is still higher than 2 µT at 100 mm from the rod, which corresponds to the minimal distance invar/cavity in the cryomodule (see Figure 3).
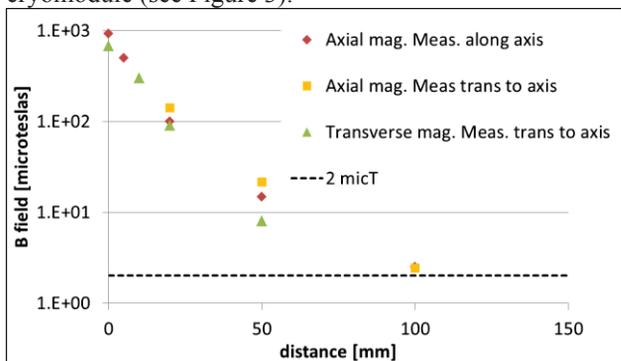
Figure 7: B field at different distances from the magnetized short invar rod.
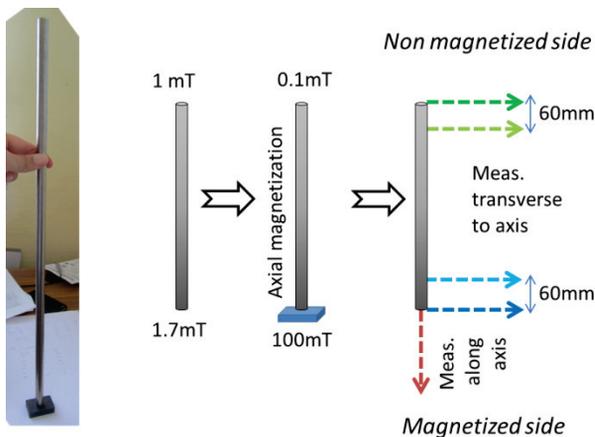
Figure 8: Magnetization of the long invar rod with a magnet.

The long rod was magnetized in the axial direction, and while one section was placed on the magnet, the field at the other section was 0.1 mT, even less that without the magnet; thus the rod is only locally magnetized. The B field is measured in different directions indicated in Figure 8. The results presented in Figure 9 show that the field is higher than 2 µT even at 100 mm from the non-magnetized side. It is even 10 times higher at the same distance from the magnetized side. One can also notice on the graph that the field is higher in the plane containing the rod end section than in a plane situated at 60 mm. Figure 2 shows that two rod extremities are situated close to a cavity (at 100 mm, see also Figure 3). It appears that this could cause the presence of a field higher than 2 µT close to the cavity, and lead to a surface resistance degradation.
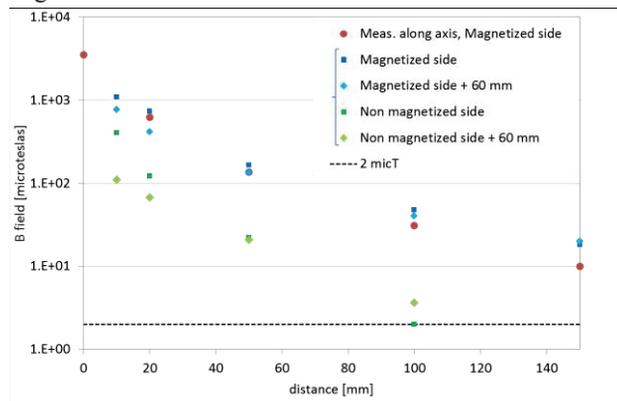
Figure 9: B field at different distances from the magnetized long invar rod.

We envisage different solutions to avoid the presence of this remnant field near the cavity. A local magnetic shield could be installed around these two invar rod extremities. An extra piece of invar could also be fixed to each extremity to deviate the magnetic flux from the cavities. Moreover, a procedure of demagnetization of the cryomodule, using the solenoids, in order to cancel all remnant static fields which could be present, in particular due to the invar rod.

In this perspective we proceeded to a demagnetization test on the short invar rod.

Invar Rod Demagnetization
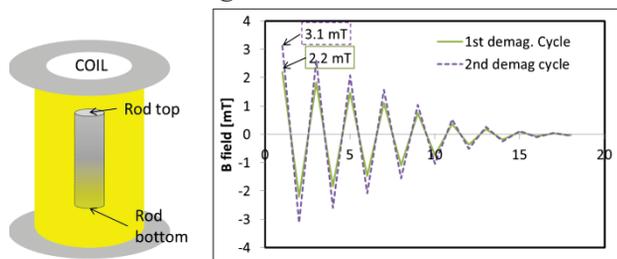
Figure 10: Demagnetization of the short invar rod placed in the centre of a coil.

The short rod was placed inside a home-made coil (see Figure 10) and subjected to a sequence defined in Table 3. The demagnetization cycles are represented in Figure 10. The abscissa represents the cycle's steps; the time constant was at least 2 s per mT.

The field was measured at top and bottom of the rod (Figure 10). The results in Table 3 show that our demagnetization sequence lowers the remnant field, but is not strong enough to properly demagnetize the rod. We were limited by the current delivered by the supply connected to the coil, and we should carry out further tests with another supply.

Table 3: Magnetization/Demagnetization Cycles

Seq. #	Description	B at rod top [mT]	B at rod bottom [mT]
1	Initial	0.53	0.22
2	Magnetization +2.2 mT	0.57	0.3
3	1st demagnetization cycle	0.28	0.18
4	Magnetization -3.1 mT	0	0.2
5	Magnetization +3.1 mT	0.53	0.31
6	2nd demagnetization cycle	0.26	0.16

More demagnetization tests should also be performed with the coil described in section "SATHORI TESTS".

Mumetal Magnetic Shield

We also worried about the possible magnetization of the mumetal shield, which will be exposed up to 2 mT (see Figure 2).

We proceeded to the magnetization of a 1 mm thick ring made of Cryophy (Cryophy and mumetal have the same saturation field) (Figure 11). The applied field, given by the board magnet, is 100 mT (>>2 mT).

We observed that the remnant field at contact was the same before and after magnetization, lower than 2 μT, and for two different ring samples. In conclusion, the mumetal shield should not be magnetized by the solenoid. Our results are consistent with FRIB similar measurements [5].
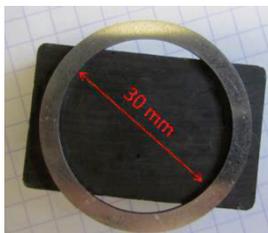
Figure 11: Cryophy ring sample on the board magnet.

SATHORI TESTS

A special horizontal test cryostat, called SATHORI ("SAtellite de Tests HOrizontal des Résonateurs IFMIF"), is under development at CEA-Saclay, in the SRF test area, and will be connected to the existing CRYHOLAB (Figure 12) [6]. This cryostat is dedicated to the IFMIF HWR performance check, fully equipped with its power coupler and cold tuning system. It will be protected from earth magnetic field by a mumetal magnetic shield with 2 mm thickness like the IFMIF shield.
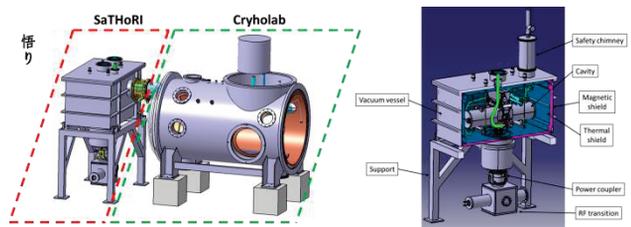
Figure 12: The SATHORI test cryostat.

Among others, it is planned to study how the presence of magnetic field from solenoid could degrade the cavity RF performances. To this intend special holes are made on the large panels of the magnetic shield to allow the penetration of the field generated by a coil placed outside the cryostat. The positioning of this coil is shown in Figure 13, left, and a schematic view of the shield with hole and coil is shown in Figure 13, right. The holes can be closed by special mumetal doors to constitute a closed shield during tests without coil.
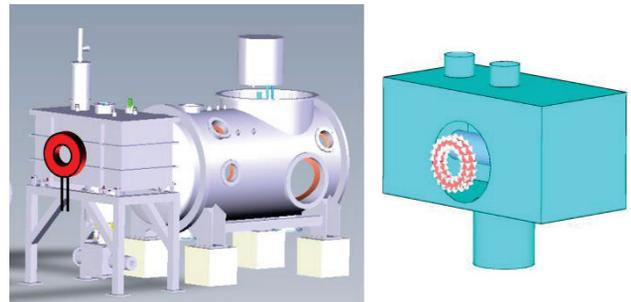
Figure 13: Positioning of a test coil in SATHORI (left). Schematic view of the magnetic shield with hole and with coil (right).

The tests foreseen with the coil are summarized hereafter:

- Cavity is in superconducting state, the coil is switched on and the current increased. The RF performances of the cavity are measured (Q-E curves) and the influence of the surrounding magnetic field is observed.
- Cavity is in superconducting state, the coil is switched on and the current increased. The cavity is forced to quench and recover. The influence of the magnetic field level on the cavity performances after recovering is studied.
- Cryogenic and RF are off. The cryostat with all elements inside is magnetized by the coil. Remnant field is measured inside the cryostat. Then a demagnetization procedure is realized. Remnant field is measured once again to check its remaining level.

The coil we plan to use for these tests is made of 144 turns and can work with 125 A. The field pattern of this coil, positioned at the outside wall of the cryostat is shown in Figure 14, in a horizontal plane crossing the cavity. The magnetic shield has been taken into account in the simulation, and the cavity has been considered either as vacuum (top) either as in Meissner state with $\mu_r \approx 0$ (bottom).
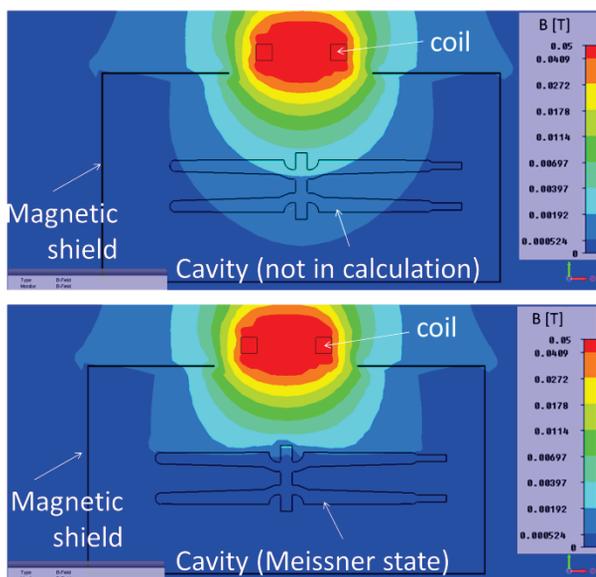
Figure 14: B field pattern given by the 144 turns, 125 A coil with magnetic shield and cavity. Cavity is in vacuum (top) or in Meissner state (bottom).

CONCLUSION

The magnetic environment of the cavities in the IFMIF cryomodule is considered in order to avoid any decrease of the superconducting cavities performance. The material of some elements (frame, needle bearings) has been changed to avoid magnetization. Solutions are under development to limit the remnant field from invar rods. A demagnetization procedure of the cryomodule is under study. Finally, the influence of the magnetic field from solenoid on the cavity performance will be observed in the SATHORI test stand.

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