ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB089

CHARACTERISATION OF MAGNETIC SHIELDING MATERIAL FOR HL-LHC CRAB CAVITIES*

K. Eiler†, A. Parrella[1,2], P. Arpaia[2], M. Buzio, O. Capatina, S.A.E. Langeslag,
CERN, Geneva, Switzerland
N.J. Templeton, STFC Daresbury Laboratory, Warrington, UK
[1]also at University of Lisbon, Portugal
[2]also at University of Naples Federico II, Italy

Abstract

In order to guarantee optimum performance, the crab cavities for the high-luminosity upgrade of CERN's LHC need to be shielded from external magnetic fields. Consequently, they will be enclosed by two layers of magnetic shielding, of which the inner is immersed in superfluid helium at 2 K. A Ni-based high-permeability material with a tailored composition and a designated heat treatment is applied. Its magnetic properties at cryogenic temperatures are however not yet fully assessed. Especially the effect of deformation on magnetic properties has not been thoroughly investigated, however strain effects may have severe consequences.
A magnetic measurement set-up has been developed, and the magnetic permeability at room temperature and at cryogenic temperatures is evaluated, showing that the maximum relative permeability at 4 K exceeds the design criteria of 100 000. Measurements of the magnetic permeability after introduction of uniaxial plastic deformation between 0% and 3% are conducted by means of an Epstein frame. Results show that deformation induces significant decrease of the magnetic performance, underlining that particular care must be taken during all stages of handling and operation.

INTRODUCTION

The High Luminosity upgrade of the LHC at CERN includes the installation of bulk niobium crab cavities, which are SRF cavities intended to tilt proton bunches for compensation of their crossing angle at the interaction points. The prototypes of the crab cavities will be tested with a proton beam in the Super Proton Synchrotron (SPS) at CERN in 2018 [1]. As for other bulk niobium cavities, magnetic shields are used to cancel the initial magnetic field on the cavities' radio frequency (RF) surfaces to guarantee optimum performance and a high quality factor. Cryophy, a high Ni-content alloy, has a very high maximum relative permeability, and is used as the inner of two layers of passive magnetic shielding, immersed in liquid helium. Its composition and heat treatment are designed to achieve maximum permeability at 2 K.
The magnetic layer operating at cryogenic temperature, hence the cold magnetic shield, is designed to be assembled from various parts and bolted, to avoid any plastic deformation that adversely affects its magnetic permeability. However, not least due to the low shield thickness of 1 µm, there is a certain risk of introducing plastic deformation. The effects of such a deformation are not entirely understood and little literature exists on this topic, but it is evident that mechanical strain already at low deformation can have a serious impact on the magnetic properties [2].
The magnetic shields have been designed to obtain no more than 1 µT of initial magnetic field on the cavity surface with an external field of 200 µT [3]. Therefore, the requirement for the cold magnetic shield is a relative magnetic permeability of more than 100 000 at liquid helium temperature [4].

EXPERIMENTAL

Cryophy is a ferromagnetic material developed to reach maximum magnetic permeability at cryogenic temperature. Its composition and heat treatment are adjusted to this purpose.
The following sets of samples were made for the tests conducted at CERN:

- 15 sample rings for direct current (DC) measurements of the magnetic permeability at room temperature (RT) as well as cryogenic temperatures (77 K and 4 K) with inner and outer diameters of 76 mm and 114 mm, respectively
- 32 rectangular samples (320 mm by 40 mm) for alternating current (AC) measurements of the magnetic permeability in an Epstein frame to assess the influence of unidirectional mechanical strain

The samples, as well as all parts of the magnetic shields for the SPS test, have been annealed by the supplier, Magnetic Shields Ltd, in their final geometry in order to avoid loss of magnetic permeability during cutting. The parts for the magnetic shield are bolted together during assembly of the shield around the cavity, so that no major plastic deformation is introduced.
To be as close as possible to the actual conditions of the application, the sample thickness of 1 mm is the thickness of the magnetic shield prototypes.

* Research supported by the High Luminosity LHC project
† konrad.eiler@cern.ch

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB089

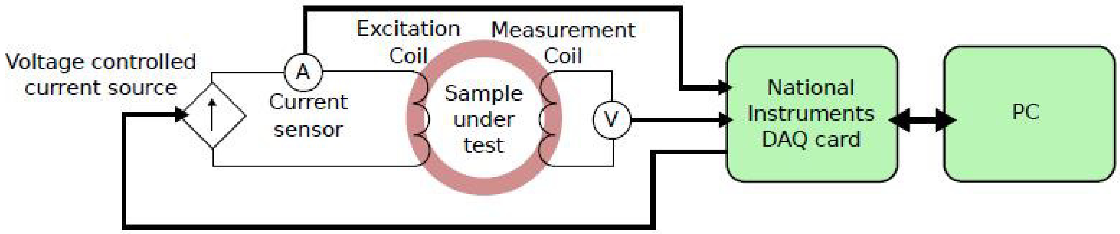

Figure 1: Architecture of the measurement system.

Ring Measurements

In the ring measurement, the magnetic properties of the material are measured in a DC field according to IEC 60404-4. After an initial demagnetisation, an excitation current is introduced via the excitation coil to magnetise the sample consisting of five layers of sample rings. The current induced in the pick-up coil (a toroidal sensing coil with 14 turns) is measured (Fig. 1).
From the voltage in the pick-up coil, the magnetic flux Φ in the sample and the relative magnetic permeability μ_r are derived.
For the measurements at cryogenic temperatures, the set-up is introduced into a cryostat and filled with either liquid nitrogen for measurements at 77 K, or liquid helium for measuring at 4 K (cf. Fig. 2).

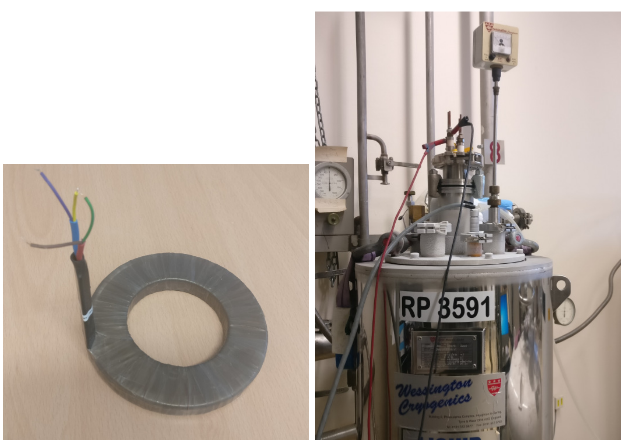

Figure 2: Left: Cryophy sample with excitation and measurement coils; right: cryogenic dewar with sample inside.

Straining of Samples

On four different sets of samples, strain states of 0.5%, 1%, 2%, and 3% were introduced. This was done on a UTS tensile machine using an extensometer with a gauge length of 50 mm to measure the strain. The strain was induced along the length of the samples (uniaxial strain). The cross-head displacement speed during straining was 5 mm/min.
The material which had been clamped by the grips, as well as the outer edges of the samples, were cut off after the straining to avoid areas of inhomogeneous strain. Elastic spring-back of the samples is neglected.

Epstein Frame Measurements

The Epstein frame measurement is a method to determine the uniaxial magnetic properties of a material, as defined in IEC 60404-2. The set-up at CERN requires eight samples for each measurement, which are assembled into a quadratic frame (cf. Fig. 3).

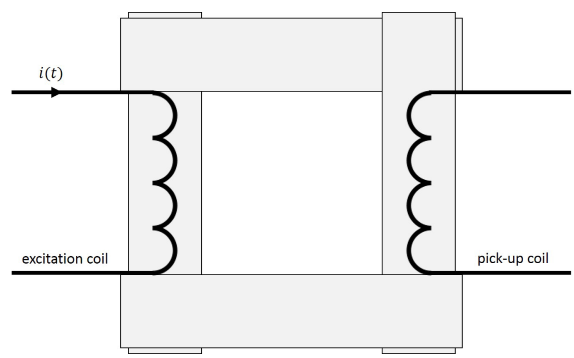

Figure 3: Sketch of the Epstein frame measurement set-up.

As for the ring measurement, a primary coil is used to magnetise the sample. In this case, this is done via an alternating current in the coil. The alternating magnetisation of the sample induces a current in the pick-up coil of a secondary circuit. Both coils have 700 windings in accordance with the standard.
The secondary current is used to determine the magnetic polarisation J in the sample, from which the magnetic flux density B is calculated [5].

$$J = \mu_0 M = B - \mu_0 H$$

where μ_0 is the permeability of free space, M the magnetisation of the sample, and H is the magnetic field strength.
During the measurements of the strained samples, the magnetic field was oriented in the direction of the strain. For reference, a set of unstrained samples was measured as well.
All samples were measured at different frequencies (of the AC), which were 0.5 Hz, 5 Hz, and 50 Hz.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB089

RESULTS

Ring Measurements

The curves for all temperatures show a high slope at first, and then go into saturation. It is observed that the saturation induction is reached much earlier at RT, but at a lower value. At 4 K, the highest magnetisation is reached.

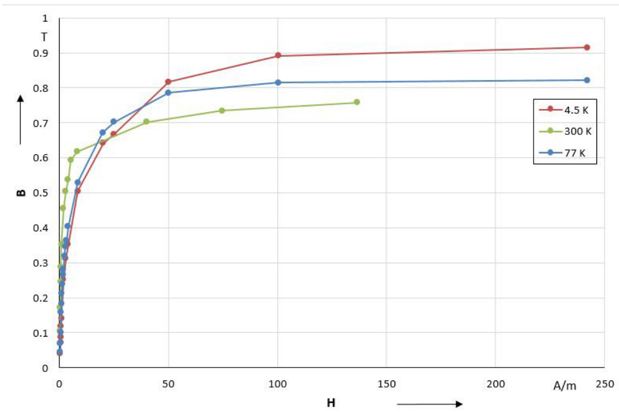

Figure 4: Initial magnetisation curves for varying temperatures.

The magnetic permeability decreases with decreasing temperature at lower magnetic fields Fig. 5.

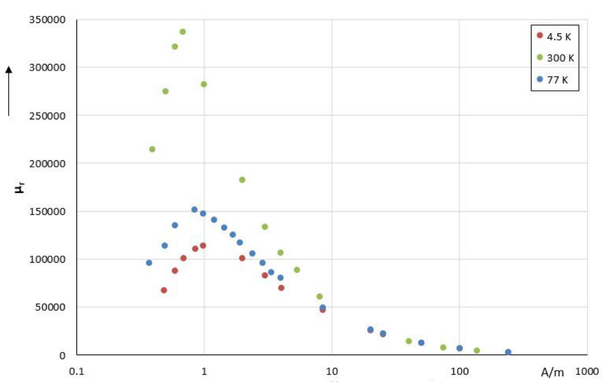

Figure 5: Relative magnetic permeability for varying temperatures.

In addition, ility shifts to slighty higher field strength at cryogenic temperatures. The peak permeability at all temperatures exceeds 100 000 (Table 1).

Straining of Samples

After straining the samples to the desired plastic strain, a continuous increase in surface roughness was observed (Fig. 6). A visual inspection suggests that the roughness increases with increasing strain.

Table 1: Peak magnetic permeability for varying temperatures

Temperature [K]	Peak permeability
4	114 000
77	151 000
300	337 000

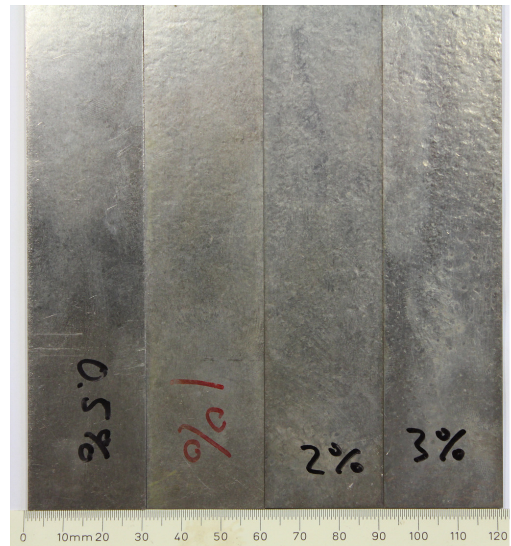

Figure 6: Surface state of strained samples in comparison. From left to right: 0.5%, 1%, 2%, and 3%.

Epstein Frame Measurements

For the measurements done at 0.5 Hz, a strong dependence of the magnetic permeability on mechanical strain is observed. The higher the strain, the higher the loss of permeability. Furthermore, the position of the peak of permeability moves towards higher field strength with increasing strain (Fig. 7).

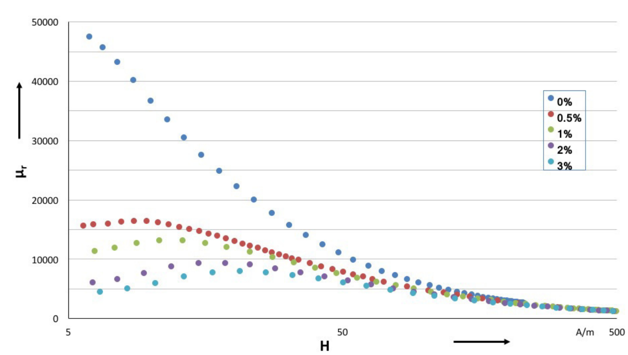

Figure 7: Magnetic permeability of Cryophy for varying strain states.

The peak permeability of the unstrained samples is not observed, however, measurements at lower fields are not feasible with the existent set-up since the response produced by the magnetisation of the material is very high at low

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB089

excitation currents, and the input current is not adjustable with sufficient precision.

For higher frequencies, a lower magnetic permeability is observed on the unstrained material. However, the curves for all frequencies become congruent above approx. 50 A/m (Fig. 8).

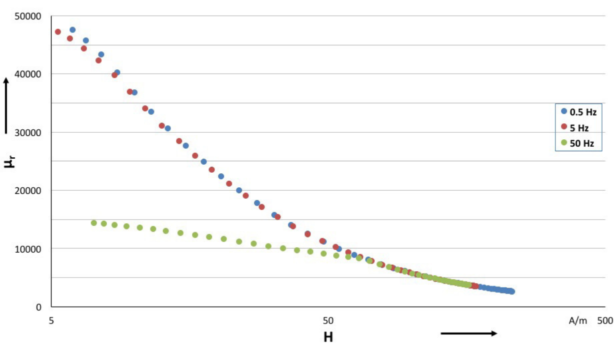

Figure 8: Magnetic permeability of Cryophy for varying frequencies.

The measurements on strained materials show a similar effect, with congruent curves above approximately 50 A/m (Fig. 9).

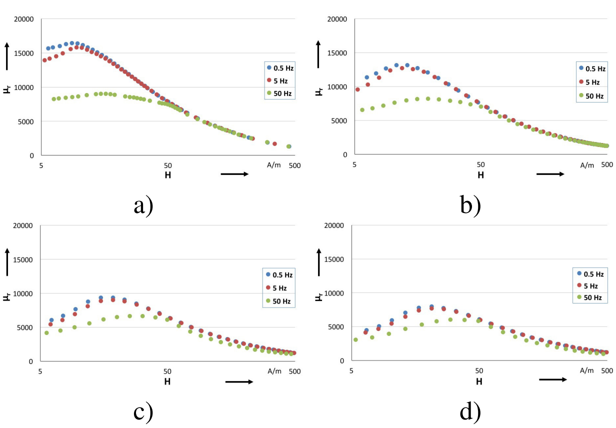

Figure 9: Magnetic permeability of strained Cryophy for varying frequencies, a) 0.5%; b) 1%; c) 2%; d) 3%.

DISCUSSION

The DC measurements at different temperatures reveal the temperature dependence of the magnetic permeability. The peak permeability at 4 K is about one third of the peak permeability at RT, yet the design requirement of μ_r = 100 000 was reached.

The plastic deformation has a negative effect on the magnetic permeability of Cryophy at low magnetic fields, and would therefore lead to a peak permeability inferior to 100 000 at 4 K. This underlines that plastic deformation of the magnetic shields must be absolutely minimised.

Based on the estimation that the magnetic field at the position of the crab cavities would be 160 A/m [6], the field which reaches the cold magnetic shield was initially estimated at 8 A/m. However, measurements of the magnetic flux at LSS6, the foreseen position of the crab cavities in the SPS, have shown that the magnetic field during operation of the main dipole and quadrupole magnets is around 50 A/m (60 µT) and on the order of magnitude of the earth's magnetic field [7]. The field which reaches the cold magnetic shield (i.e. after penetrating the warm magnetic shield) would therefore be significantly lower.

An alternating magnetic field at the crab cavities is not expected. In the SPS, the main origins of an external magnetic field, apart from the earth's magnetic field, are the main magnet busbars of the accelerator's dipoles and quadrupoles. The dipole busbars are working with a pulsed DC which is ramped up to its top current in 3 s, held constant for 0.5 s or 6 s, and ramped down to their minimum current in 2 s [7].

The magnetic field in the SPS can therefore be seen as a ramped DC field, so that the negative effect of AC fields is not relevant for the application.

CONCLUSION

The measurements show that the design requirement for material of the cold magnetic shield for the crab cavity prototypes was met, exceeding μ_r = 100 000. The material can be readily employed as the cold shielding material, however, even low amounts of plastic deformation significantly decrease the magnetic permeability, so that particular care must be taken to avoid degradation by absolutely minimising plastic deformation after annealing.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Magnetic Shields Ltd for their cooperation and the provision of the annealed samples. Prof. A. Liccardo and Prof. P.M. Ramos for stimulating discussions. R.B. Mercadillo, T. Koettig and S. Prunet for the technical support to the cryogenic permeability measurements. V. Pricop for the support to the Epstein frame measurements.

REFERENCES

[1] C. Zanoni *et al.*, "The crab cavities cryomodule for SPS test," in *Proc. IPAC'17*. Copenhagen, Denmark, 2017, pp. 1082–1084.

[2] M. Masuzawa, A. Terashima, and K. Tsuchiya, "Magnetic properties of shielding materials for superconducting cavities," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, 2012.

[3] N. Templeton *et al.*, "Design of the thermal and magnetic shielding for the LHC high luminosity crab-cavity upgrade," in *Proc. SRF'15*. Whistler, BC, Canada, 2015, pp. 852–856.

[4] L. Alberty *et al.*, "Engineering specification: dressed bulk niobium radio frequency crab cavities," CERN,

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOPB089

Geneva, Switzerland, 2016. [Online]. Available: https://edms.cern.ch/document/1389669

[5] V. Pricop, E. Helerea, and G. Scutaru, "A procedure for measurement of magnetic characteristics in quasistatic regime," *Pollack Periodica*, vol. 10, no. 3, pp. 31–42, 2015.

[6] J. Bauche and A. Macpherson, "Estimate of the ambient magnetic field in the SPS crab cavity location," CERN, Geneva, Switzerland, 2014. [Online]. Available: https://edms.cern.ch/document/1377806

[7] J. Bauche, private email correspondance, Oct. 2016.