MAGNETIC SHIELDING: OUR EXPERIENCE WITH VARIOUS SHIELDING MATERIALS

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Abstract

Magnetic properties of various shielding materials for superconducting RF cavities were examined by measuring their permeability at room and at cryogenic temperatures, and comparing them against each other. It was found that the catalog performance of such materials was not always reproduced in the measurements. Some degradation was observed which depended on how the materials were handled. The results of investigation into possible causes for the performance degradation of the shielding materials at cryogenic temperature will be presented, along with permeability measurement results for various shielding materials at different temperatures. The dependence of shielding effectiveness on the permeability is calculated using the measured permeability applied to a simple cylindrical shell model. It was found that a single thickness of the higher permeability material provided better shielding than a double thickness of the lower permeability material.

INTRODUCTION

Magnetic shielding is a key technology for superconducting RF cavities. The tolerance of the ambient magnetic field depends on factors such as the operating RF frequency, acceleration gradient and operation mode (pulse or CW), but it can be as small as a few mG. Some high-Ni-content alloys, such as Cryperm 10 or Cryophy, which are claimed to maintain high permeability at cryogenic temperatures such as where superconducting RF cavities are operated, are commercially available at present and are used for magnetic shielding of superconducting cavities. The permeability of various materials, their temperature dependences, and the effects of the heat-treatment and mechanical strain have been reported in the past [1,2] and a brief summary of relevant measurements are given in the following sections.

PERMEABILITY AT ROOM AND LIQUID HELIUM TEMPERATURES

Permeability was measured using ring samples. Each ring sample was cut from a sheet of the material and heat treated prior to the measurements. Two sets of coils were wound around the ring, a primary for magnetizing the material, and a secondary coil for picking up the signal, which is proportional to the magnetic field inside the material. The ring sample was degaussed before each measurement. The permeability at liquid helium (LHe) temperature was measured by soaking the ring sample in liquid helium in a dewar. The results are shown in Fig. 1 and Fig. 2 for the room temperature measurement and the LHe temperature measurement, respectively. "Tokin R"

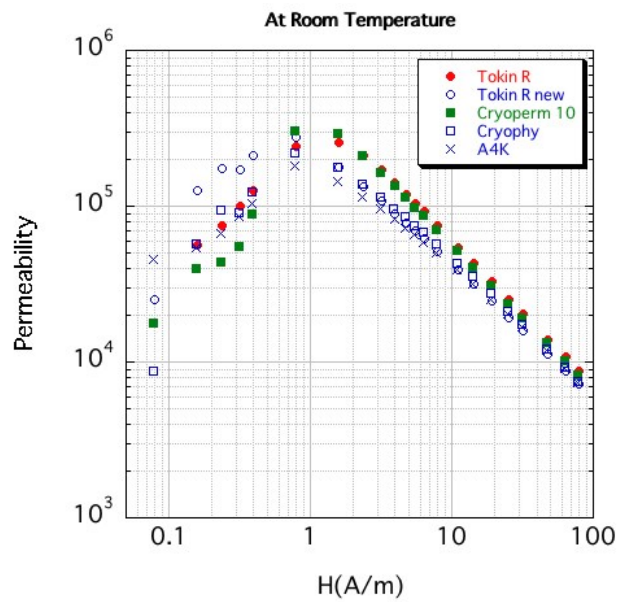

Figure 1: Permeability measured at room temperature. Solid circles, open circles, solid squares, open squares and crosses indicate "Tokin R", "Tokin R new", Cryoperm 10, Cryophy and A4K, respectively.

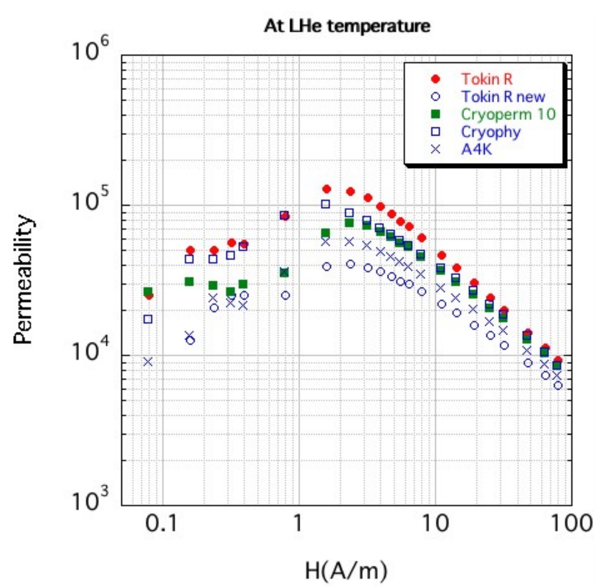

Figure 2: Permeability measured at LHe temperature. Solid circles, open circles, solid squares, open squares and crosses indicate "Tokin R", "Tokin R new", Cryoperm 10, Cryophy and A4K, respectively.

and “Tokin R new” were supplied by NEC/TOKIN (Japan). Cryoperm 10 was given by TESLA, and cut and annealed by TOKIN. Cryophy was provided after annealing by ArcelorMittal, France. A4K was provided after annealing by Amuneal, U.S.A. “Tokin R,” which is not available now, shows the highest permeability at LHe temperature, though “Tokin R new” does not. It is not known why TOKIN can not produce material of the same quality. Cryophy gives the second best permeability at LHe temperature.

DEPENDENCE ON HEAT TREATMENT

The permeability dependence on the heat treatment conditions i.e., the cooling rate and the maximum temperature, was examined.

Cooling Rate

Three patterns, with different cooling rates as shown in Fig.3, were tested first. The first heat treatment pattern is the standard pattern used by the manufacturer for annealing the standard permalloy products for commercial use. The samples are cooled more rapidly, ~30 % faster, in the second pattern. In the third pattern, the supplier’s recommended rate is used. The maximum oven temperature for all three heat treatment patterns is 1100°C. Fig. 4 shows the maximum permeability of the samples from the three groups, measured at room temperature and at liquid nitrogen temperature (77K).

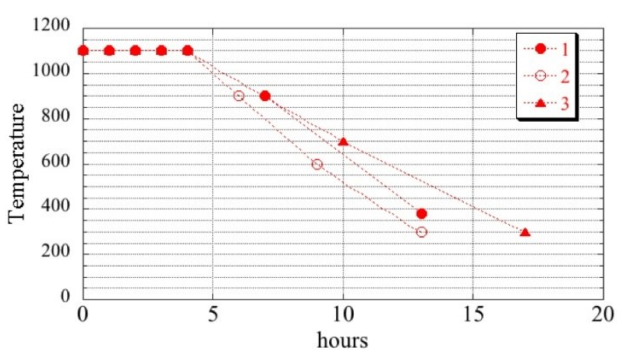

Figure 3: Three different heat treatment patterns tested.

Maximum Temperature

Permeability dependence on the maximum annealing temperature was examined for Cryophy samples annealed at two different temperatures, 1170°C and 1100°C. The maximum temperature of 1170°C is recommended by the supplier. This was carried out using a small oven dedicated to experimental use. The 1100°C annealing was carried out in a large oven for commercial use at a manufacturer. The maximum annealing temperature in a pure and dry hydrogen environment could not exceed 1100°C due to safety restrictions at the manufacturer. The other parameters such as the hold time and the cooling rate were controlled to be the same for both annealing temperatures. At room temperature, the difference between the two groups is small, if any, while

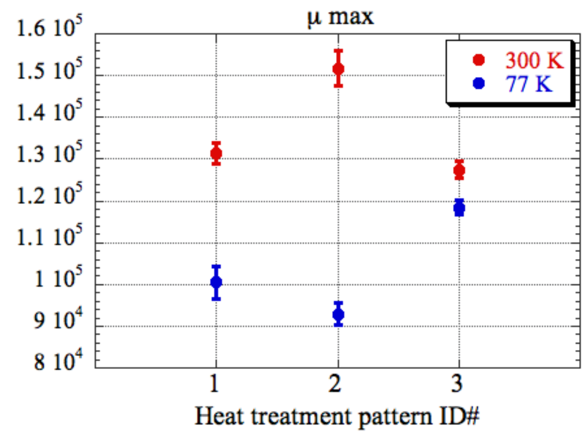

Figure 4: Maximum permeability for the different heat treatment patterns #1, #2 and #3 at room temperature (solid red circles) and at liquid nitrogen temperature (solid blue circles).

the difference is visible at LHe temperature as shown in Fig. 5. A difference of 70°C resulted in almost a factor of two in the maximum permeability.

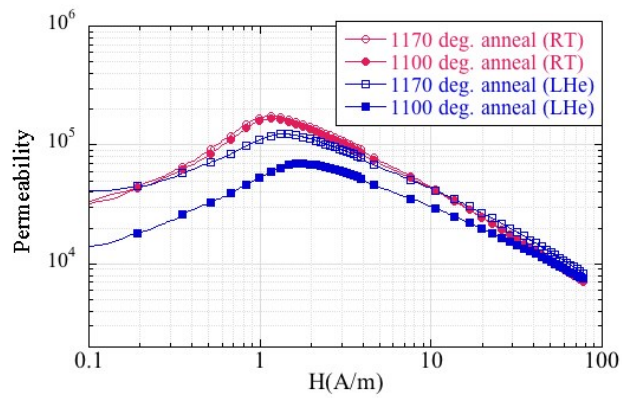

Figure 5: Permeability measured at room (circles) and LHe (squares) temperature. The solid and open symbols correspond to the sample annealed at 1170°C and 1100°C, respectively.

EFFECT OF MECHANICAL STRAIN

Next the effect of mechanical strain on the shielding performance was evaluated. The ring samples were deformed using a pressing machine, shown in Fig. 6. The degree of strain is characterized by the parameter ε, defined as:

$$\varepsilon = \Delta t / R \qquad (1)$$

where Δt and R are the thickness of the sample and the radius of the curvature of the template blocks. Two types of template blocks are made to obtain ε = 0.5 % and 3 % as given by Eq. (1). When a sample of a thickness of 1 mm is deformed by using a block template of R = 197.7 mm, for example, ε = 0.5% is obtained. The permeability is measured for ε = 0% (no stress added), 0.5% and 3%

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for two types of materials, “P” and “R,” at room temperature. The results are summarized in Fig. 7. Significant degradation in permeability is observed in both samples “P” and “R” when they are deformed. With $\varepsilon = 5\%$, the maximum permeability becomes an order of magnitude smaller compared to the case where no mechanical stress is added. This should be taken into account when designing and assembling a magnetic shield.

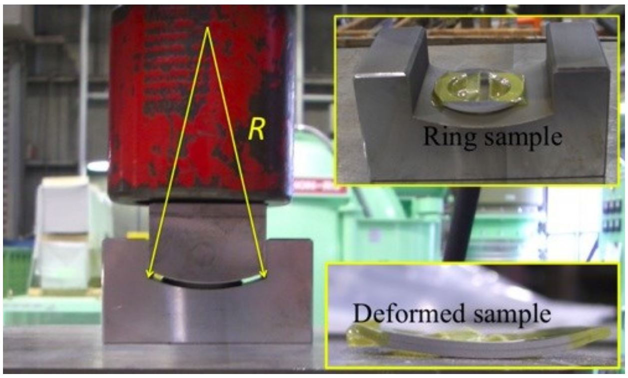

Figure 6: The setup for bending the ring samples is shown. Template blocks with different R are used to achieve different deformations of the sample rings.

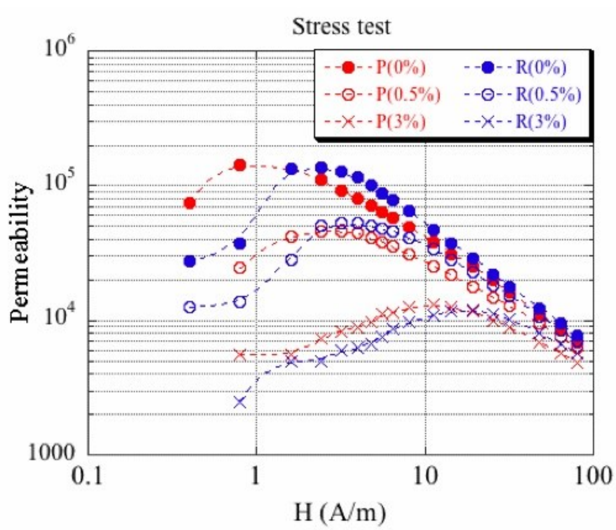

Figure 7: Permeability for $\varepsilon = 0\%$ (solid circles), 0.3% (open circles) and 5% (crosses) for two samples “P” (red) and “R”(blue) measured at room temperature.

SHIELDING EFFECTIVENESS

Using the permeability data obtained at LHe temperature, simulation was carried out using a simple cylinder shell model with a radius of 110 mm and a length of 1000 mm. The thickness was varied from 1 mm to 2.5 mm. The ambient magnetic field was set to 0.5 G, which is of the same order at that of the earth’s magnetic field, the direction being the axis of the cylinder. The calculation results are summarized in Fig. 8 and Fig. 9 for various materials. The magnetic field at the center of the cylinder is plotted as a function of the thickness of the cylinder shell. Figure 8 indicates that 1 mm-thick iron is almost transparent in this case. The standard shielding material, Permally PC, blocks the magnetic field much better than iron, though about 3 times worse than the other materials for cryogenic use. It was found that a single thickness of Cryophy annealed at 1170°C provided much better shielding than a double thickness of the lower permeability material such as Permalloy PC.

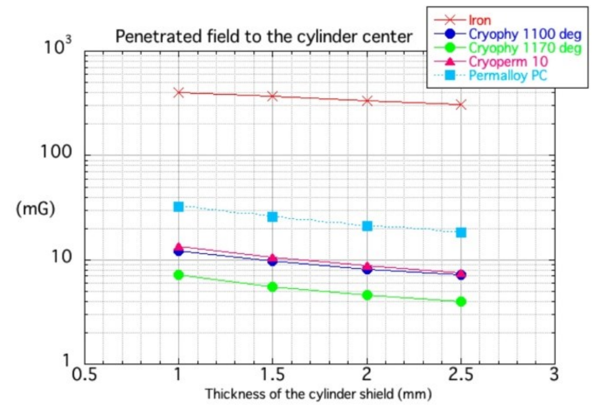

Figure 8: Magnetic field at the center of the cylinder for various materials plotted against the thickness of the cylinder shell. Crosses, blue circles, green circles, triangles and squares correspond to iron, Cryophy annealed at 1100 °C, Cryophy annealed at 1170 °C, Cryoperm 10 and Permalloy PC, respectively.

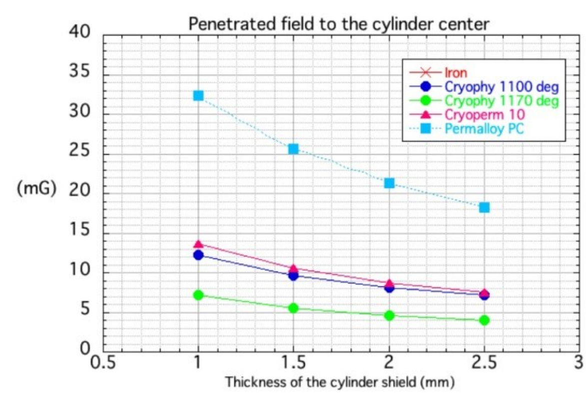

Figure 9: Magnetic field at the center of the cylinder for various materials for cryogenic use plotted against the thickness of the cylinder shell. Crosses, blue circles, green circles, triangles and squares correspond to iron, Cryophy annealed at 1100°C, Cryophy annealed at 1170°C, Cryoperm 10 and Permalloy PC, respectively.

THE CASE OF COMPACT ERL MAIN LINAC CAVITIES

From the measurements described above, Cryophy was chosen for the magnetic shield for the cERL [3] main linac superconducting RF cavities. The magnetic shield is a square shape. The square shape was chosen in order to simplify the alignment, and also to avoid unwanted mechanical stress during the assembly. Each part of the magnetic shield was cut out from a sheet of a thickness of 1.5 mm. Each part was then annealed in an oven, with the maximum temperature being 1100°C due to safety restrictions at the manufacturer, as described earlier. A simulation was carried out to confirm that the 1100°C annealing is sufficient as indicated in Fig. 10. Figure 11 shows the result of the high power test [4] carried out in December 2012. The Q_0-value exceeded the design value of 10^{10}, which indicates that the magnetic shield kept the ambient magnetic field to a level of 10 mG at cryogenic temperature. This agrees well with the simulation results.

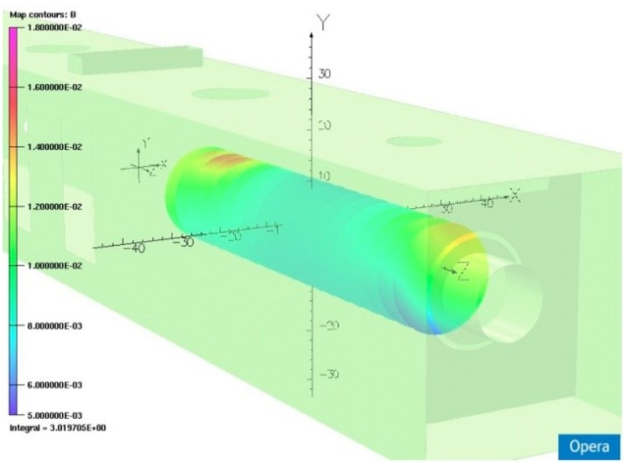

Figure 10: Simulation results. Contour map of the magnetic field is shown along the beam direction. The color scale on the left corresponds to the magnetic field inside the cavities, with 18 mG being the maximum.

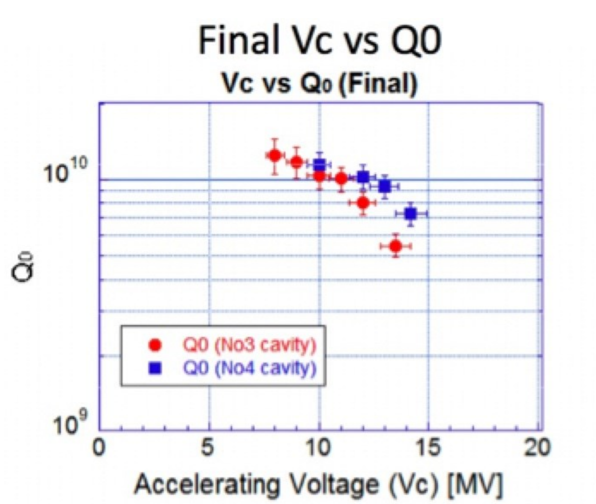

Figure 11: High power test of the cERL 9-cell cavity system. The Q_0-value exceeded the design value of 10^{10} at low accelerating voltage.

SUMMARY

Permeabilities of various materials used for magnetic shielding were measured at room temperature and LHe temperature, and compared against each other. Among the samples measured, Cryophy gave the highest permeability at LHe temperature.

Attention should be paid not only to the material, but also to the annealing and assembling processes, as these can degrade the performance of the shield. As for the cost of the material, Cryophy is more expensive than the other standard materials, such as Permalloy PC.

Shielding effectiveness was calculated for increased thickness of the shield, to investigate the possibility of using less expensive material, but in greater quantity, to compensate for the lower permeability. The results indicate that choosing a material with higher permeability is better than adding more lower-grade material. These factors should be taken into account when choosing the material, with a clear understanding of the required tolerance on the ambient magnetic field.

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