Magnetic shielding of superconducting cavities

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Abstract

In order to reach their nominal performance level, most superconducting cavities must be cooled in a magnetic field smaller than 20–30 mGauss. This corresponds to a field 20 times smaller than the ambient magnetic field in a typical accelerator tunnel. To achieve this shielding level, the use of a mixed scheme, combining a Cryoperm tube around the cavity helium vessel, and a string of Helmholtz coils around the cryomodule vacuum vessel, is recommended.

1. INTRODUCTION

When cooled in an ambient, static magnetic field, superconductors usually trap some flux [1]. In the case of superconducting cavities, this causes undesirable RF dissipation, which must be minimized by a proper magnetic shielding of the cavities. The residual surface resistance caused by flux trapping (for a type II superconductor like Niobium, with a Ginzburg-Landau parameter κ of order unity, and for small trapped flux $B \ll B_{c2}$) is given by:

$$R_s = R_n \frac{B}{B_{c2}}$$

where R_n is the normal-state resistance of the superconductor. In some accelerator applications, like TESLA or ELFE, cavities with low surface resistance are required. The order of magnitude for the tolerable surface resistance due to trapped flux is a few nano Ohms. It is then deduced from the above equation that the level of the residual magnetic field must be brought below 20 mG on the inner cavity surface.

2. PASSIVE MAGNETIC SHIELDINGS

The main contribution to the ambient magnetic field is in general the earth magnetic field, whose magnitude is about 400 mG. The required shielding factor $S = \frac{B_{without}}{B_{with\ shield}}$ must thus lie around 20. A priori, this shielding level may be achievable by means of a simple passive tube of magnetic material around the cavity. For such a tube, analytical formulae exist, giving the shielding factors $S_{\parallel}$ and $S_{\perp}$ for the longitudinal and perpendicular components of the field [2]:

$$S_{\perp} \simeq \frac{\mu.d}{D} + 1$$

$$S_{\parallel} \simeq \frac{4N(S_{\perp} - 1)}{1 + D/2L} \text{ closed cylinder}$$

$$S_{\parallel} \simeq 4NS_{\perp} \text{ open cylinder}$$

In these equations, μ is the permeability of the tube, D is the tube diameter, diameter, L its length, d the wall thickness and N its demagnetizing coefficient. Application of these equations to the realistic case of a TESLA-type cavity (L=1300 mm, D=250 mm, d=1 mm) show that $S_{\parallel}$=12 and $S_{\perp}$=50 if μ=12000. These values seem to be almost satisfactory. Unfortunately, this too optimistic conclusion must be revised for three reasons:

1) Being close to the superconducting cavity, the magnetic tube will necessarily be cold. Most magnetic materials lose in permeability when their temperature decreases [3]. The only commercially available exception to this trend seems to be Cryoperm. This material, like all other high permeability alloys, is rather delicate to handle. Proper annealings are required to obtain high permeabilities; shocks or strains (either thermal or plastic) can reduce μ drastically.

Altogether, the best choice for a close shielding of superconducting cavities will still be Cryoperm, but measurements made on tube samples show that a realistic value for its permeability at 4 K is only $\mu \simeq 12000$.

2)The above equations neglect end effects. Fringe fields are to be expected at the ends of the tube. Elementary considerations on the conservation of $\int B_{\|} dl$ along the cylinder axis indicate that the longitudinal component of the field is depleted in the tube, and is enhanced at the ends of the tube. This enhancement extends over a diameter inside the tube (fig. 1). Calculations with the numerical code BACCHUS [4] indicate that it is possible to reduce the effective diameter of the tube, and thus the range of the fringe fields by adding annular shaped pieces at the end of the tube(s). Unfortunately, this gain in range is more or less compensated by an enhancement of the longitudinal component of the field at the tube ends.

3) In most cases, superconducting cavities are used in closely packed strings. For this reason, a given cavity surrounded by its passive shield cannot be considered as magnetically isolated from its neighbours. The situation of the string is in fact close to the case of a continuous tube of the same total length and diameter. Since the aspect ratio of this "global tube" is very long, the corresponding longitudinal shielding factor will probably be rather poor, necessarily less good than the one evaluated for one single cylinder shielding an isolated cavity.

For these three reasons, it is possible-but rather difficult-to obtain the required level of shielding of the longitudinal component of the field by means of purely passive shields. Calculations made with the finite element code BACCHUS indicate that the gap between tubes is a crucial parameter: if it is too small, the overall shielding factor of the string becomes small because the geometry of the shield becomes close to the shape of a very elongated cylinder with very small demagnetizing coefficient; if the gap is too large, the shielding tubes are not much longer than the cavities, and the fringe fields at the end of the tubes hamper a proper shielding of the cavity end cells.

3. ACTIVE CANCELLATION OF THE FIELD, AND MIXED SCHEMES

In view of these difficulties, it is very tempting to cancel the ambient magnetic field by using active devices, ie coils. The advantages of this option lie in its simplicity and cheapness. Furthermore, the counter-field produced by the coils can be used to degauss any magnetic material in the cavity surrounding, eg the vacuum vessel or any passive shield. Cancellation of the longitudinal component of the field, so difficult with passive shields, can readily be achieved with a very simple solenoid or string of Helmholtz coils. The perpendicular component of the field are less of a problem, and can be reduced by a purely passive shield.

This "mixed" scheme has been tested in the special case of a TESLA TTF cryomodule, by means of a 1/4 scale model. The vacuum vessel was simulated by a 2 mm thick steel tube. The passive shield was simulated by tubes of Conetic of adequate length and diameter. The permeability of the Conetic was roughly 30000, and the thickness of the tube was d=0.1 mm, chosen so that $(\mu d)_{Model} \simeq scale * (\mu d)_{Tesla}$.The model was oriented North-South, in an ambient magnetic field similar to the one of the TESLA TTF hall. The distribution of the three components of the magnetic field in the model was measured by means of a Förster probe. The field distribution obtained after careful degaussing of the "vacuum vessel" is shown in fig. 1 and Table 1.

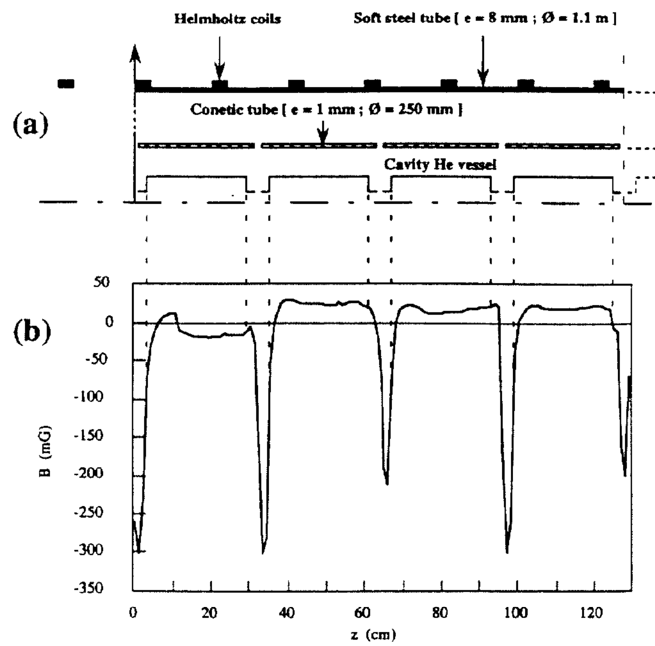

Figure 1. a) A mixed scheme for TESLA TTF cryomodule, b) Field profile measured along the z-axis on a scale 1/4 model

	Cavity center	Cavity end cell
$B_{\parallel}$ (mG)	0±25	0±35
$B_{\perp}$ (mG)	10±8	15±5

Table 1. Field level measured on the scale 1/4 model of a TESLA TTF cryomodule.

The level of field achieved in the model is quite satisfactory, thus giving much hope that similar results will be obtained with the full scale cryomodule.

4. CONCLUSION

We realized during completion of this work that it is much easier to shield a single cavity than a string of such objects. It is possible that this difficulty had gone unnoticed in the past. We feel, however, that a proper shielding of the superconducting cavities is an indispensable prerequisite to the obtention of high cavity Q-values, and accelerating gradients.

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5. REFERENCES

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2. A. Mager J. Appl. Phys. 39 (1968) 1914
3. D. L. Martin and R.L. Snowdon Rev. Sci. Inst. 46 (1975) 523
4. The finite element code BACCHUS was developed by CISI engineering for the study of charged particle beams in static electromagnetic fields.