Magnetic shielding of the TESLA TTF superconducting cavities

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Abstract

In order to reach their nominal performance level, the superconducting cavities of TESLA TTF must be cooled in a magnetic field smaller than ca 20 mGauss. This corresponds to a field 20 to 40 times smaller than the ambient magnetic field in the hall of TESLA TTF. 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. Why should we shield Tesla cavities and what is the required shielding level ?

In principle, a perfect superconductor cooled in an ambient, static magnetic field smaller than its critical field Hc1, should expel the magnetic flux from its volume. However, it has been demonstrated that in the case of a niobium superconducting cavity cooled in an ambient field smaller than c.a 3 Gauss, 100% of the magnetic flux was trapped in the cavity walls (ref. 1). The pinning of the flux lines is thought to be due to the lattice imperfections in the niobium sheet, or to its surface oxidation. This trapping of flux gives rise to an RF dissipation, which can be represented by a local residual surface resistance: $R_S \simeq R_n \frac{H}{H_{c2}} sin\alpha$, where R_n is the normal state surface resistance of niobium, H the ambient magnetic field during cooldown and α the angle between the field and the surface. When applied to the case of a TESLA cavity (Nb of RRR 300, at a frequency of 1.3 GHz), this corresponds to an average surface resistance of 0.35 nΩ/mGauss, in good agreement with experimental results. In order to get the Q value of 5.10^9 specified for the TESLA TTF cavities, it is desirable to have a residual surface resistance due to trapped flux smaller than 25 nΩ. This corresponds to a remanent field of 70 mGauss or less. This prescription may not seem very stringent, but if one wants to improve slightly the Q-value above this design value, it will be necessary to improve drastically the shielding. For example, in order to get a Q value of 10^{10}, the residual surface resistance due to trapped flux must be smaller than 3 nΩ, corresponding to a remanent field of 10 mGauss. This level of field is the one achieved in well shielded vertical test cryostats. This standard value may be difficult to achieve in an actual accelerator environment. For this reason, we propose (with some arbitrariness) a more modest and reasonable objective for the remanent field around TESLA TTF, namely: B=20 mGauss.

2. The ambient magnetic field

At the latitude of Hamburg, the earth magnetic field has a magnitude of 400 mGauss. Its horizontal component (250 mGauss, oriented North-South) is roughly equal in magnitude to the vertical component. The experimental hall of TESLA TTF has been used in the past for testing magnets, and has kept a remanent magnetization, mainly from the floor. Measurements at the floor level indicate field levels as high as 2 000 mGauss. Fortunately, the field from the floor is short ranged, and decreases to a typical value of 50 mGauss at the cavity level. This component varies from place to place in magnitude and in orientation along the linac (fig. 1). The possibility of degaussing the floor is being examined by the Saclay group.

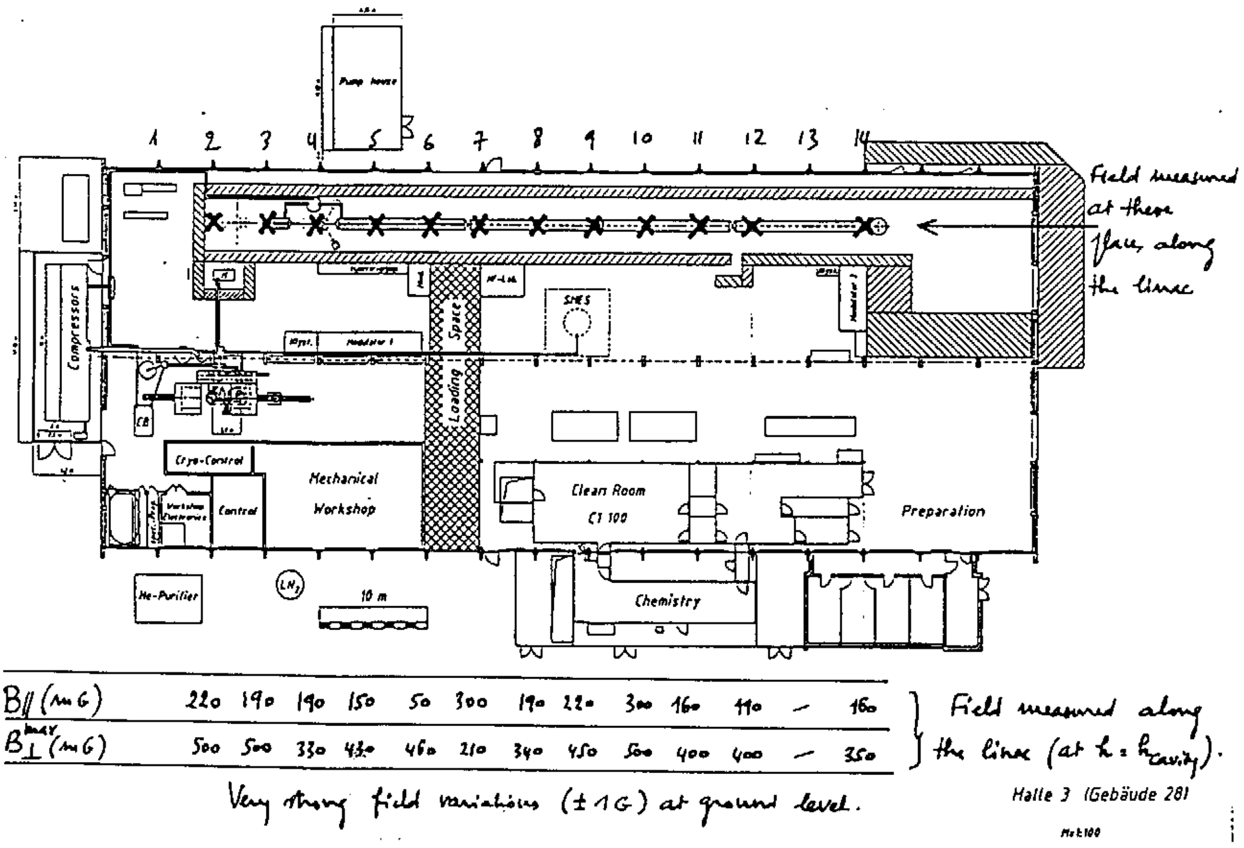


Figure 1 Map of the magnetic filed in the hall of TESLA TTF.

3. How to shield TESLA cavities ?

Two possibilities will be examined in turn: passive shields, and active cancellation of the ambient field by coils.

3.1 Passive shields. By passive we mean layers of a material with a high magnetic permeability, which concentrate the field lines in their volume, thus producing an attenuation of the field in the vicinity of the cavity. The attenuation depends on the value of the permeability

μ. Values as high as 50 000 are reported in the literature or even in catalogs for commercially available material such as Mumetal, Conetic or Cryoperm. However, the permeability of most materials decreases strongly with temperature (ref. 2), with the exception of Cryoperm (fig. 2). On the other hand, to be effective, passive shields must lie reasonably close to the cavity. This

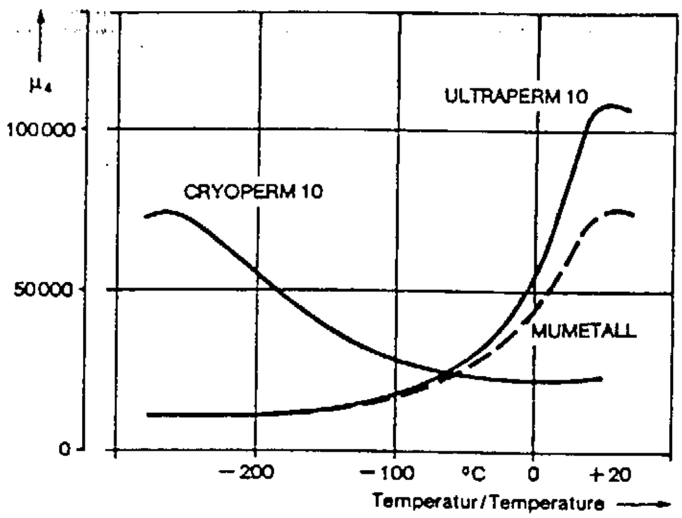


Figure 2 Permeability of some magnetic materials as a function of temperature (from VAC catalogue)..

implies that the shield will be cooled at cryogenic temperatures. Measurements of μ were made at room temperature (RT) and at 4 K on cylinders of Mumetal and Cryoperm (Table 1).

	Mumetal	Cryoperm
RT	54700	10200
4K	7500	13300

Table 1. Permeability μ_1 measured on test cylinders (from M. Bork, VAC, private communication)

The μ—degradation predicted between RT and 4 K appeared indeed on Mumetal, but the expected opposite behaviour for Cryoperm was hardly observed. Altogether, it should be noted that these magnetic materials are very delicate to handle: proper annealings are required to obtain high permeabilities; moreover, shocks or strains (either thermal or plastic) can reduce μ drastically. Finally, we consider that the choice material for the passive shielding of TESLA TTF cavities is still Cryoperm, but that a realistic value for its permeability is only μ = 12000. Specialists from the company VAC confirmed this view.

3.1.1 Shielding factors for one single cylinder

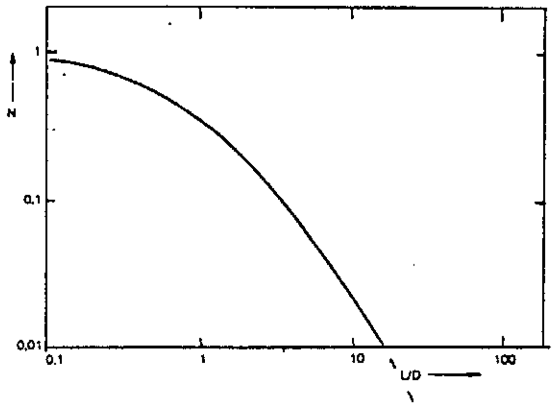
The shielding factors of a passive shield can be defined as the ratio of the field before and after installation of the shield. Analytical formulae exist for the shielding factors at the center of single cylinders placed parallel or perpendicular to the field (ref. 3). These are:

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

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

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

In these equations, D is the diameter of the cylinder, L its length, d the wall thickness and N its demagnetizing coefficient, shown in fig. 3.



long cylinder:
→ $N \sim \frac{D^2}{2L^2}$
id. ellipsoids
- 2

Figure 3 The demagnetizing coefficient of a cylinder vs its Length/Diameter ratio.

Orders of magnitude can readily be obtained from the above equations for *single* tubes of dimensions fitting those of TESLA cavities. For example, for a tube of dimensions L=1300 mm, D=250 mm, d=1 mm, and a permeability of μ=12000, $S_{\perp} = 50$ and $S_{\parallel} = 12$. The former value may be acceptable, but the latter is not sufficient for TESLA TTF purposes.

It can already be seen at this stage that the longitudinal component of the field will be much more difficult to shield than the transverse one.

For very elongated tubes, the demagnetizing coefficient N goes to zero like $(D/L)^2$. These tubes will shield the transverse component of the field, but not the longitudinal one. Almost by definition, linear accelerato.'s are very elongated structures, and we shall see that this will cause severe difficulties for a proper shielding of the TESLA TTF cavities with purely passive magnetic shields.

3.1.2 Role of end caps

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. 4). Calculations with a numerical code (ref. 4) confirm this point, and 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). The field enhancement is then stronger, but extends on a smaller distance, thus permitting an improved shielding of the cavity end cells.

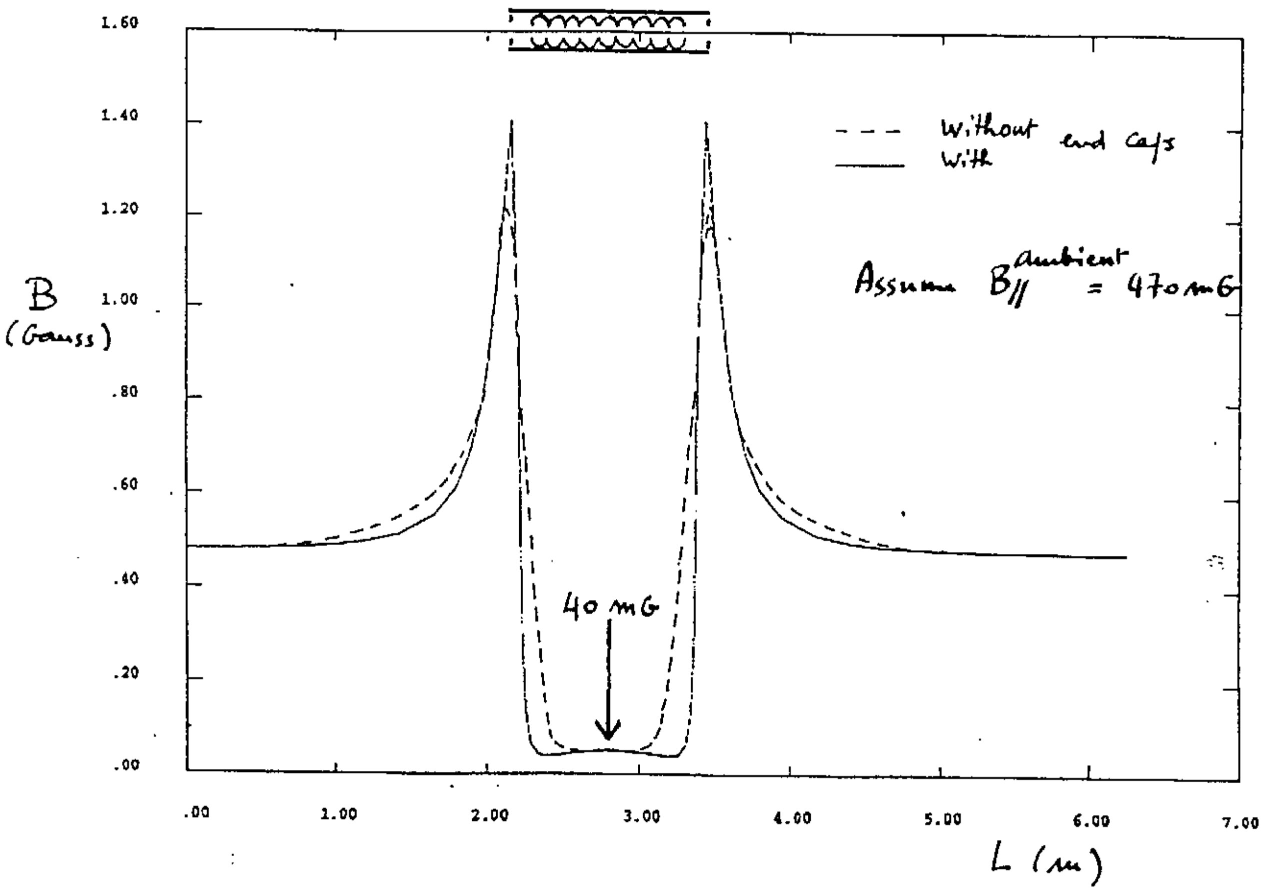


Figure 4 Distribution of $B_{\|}$ along the axis of a cylindrical shield: a) without end cap; b) with end cap. Calculation with the finite element code BACCHUS (ref 4) , assuming a tube of dimensions: L=1300 mm, D=250 mm, d=1 mm, with a permeability μ=12000.

3.1.3 Shielding factor of a string of cylinders

It should be noted that a given cavity surrounded by its passive shield cannot be considered as magnetically isolated from its neighbours. If the string of cavities of TESLA TTF is to be shielded by a string of tubes, each tube will modify the field seen by other tubes. 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. Also, fringe fields are to be expected at the ends of the tubes. These complications can hardly be handled analytically, and this motivated the use of a numerical code (BACCHUS, ref. 4) to describe the field geometry.

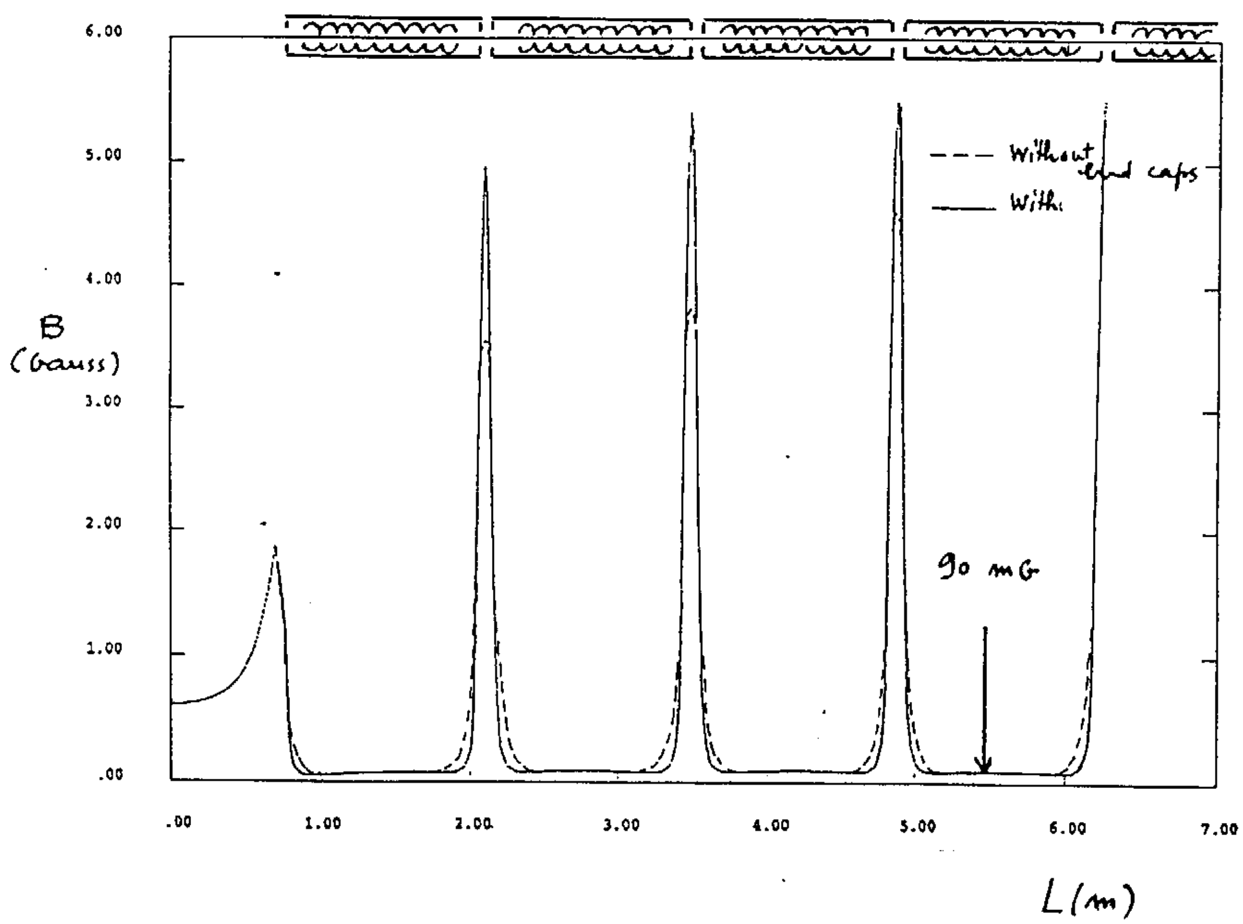


Figure 5 Distribution of $B_{\parallel}$ along the axis of a string of cylindrical shields of same dimensions and characteristics as in fig. 4: a) without end cap; b) with end cap.

The field profile for a string of tubes corresponding to the TESLA geometry (one magnetic cylinder around the Helium vessel of each cavity) is shown in fig. 5. It can be seen there that the shielding is much poorer in the case of a string as it is for a single tube. Even by using large thicknesses, by optimizing the spacing between tubes and by adding end caps, it is probably very difficult to achieve a shielding level better than 50 mGauss at the end cells of TESLA cavities with a single layered string of magnetic cylinders. Therefore, this solution cannot be recommended in the practical case of TESLA.

3.1.4 Plausible schemes using purely passive shields

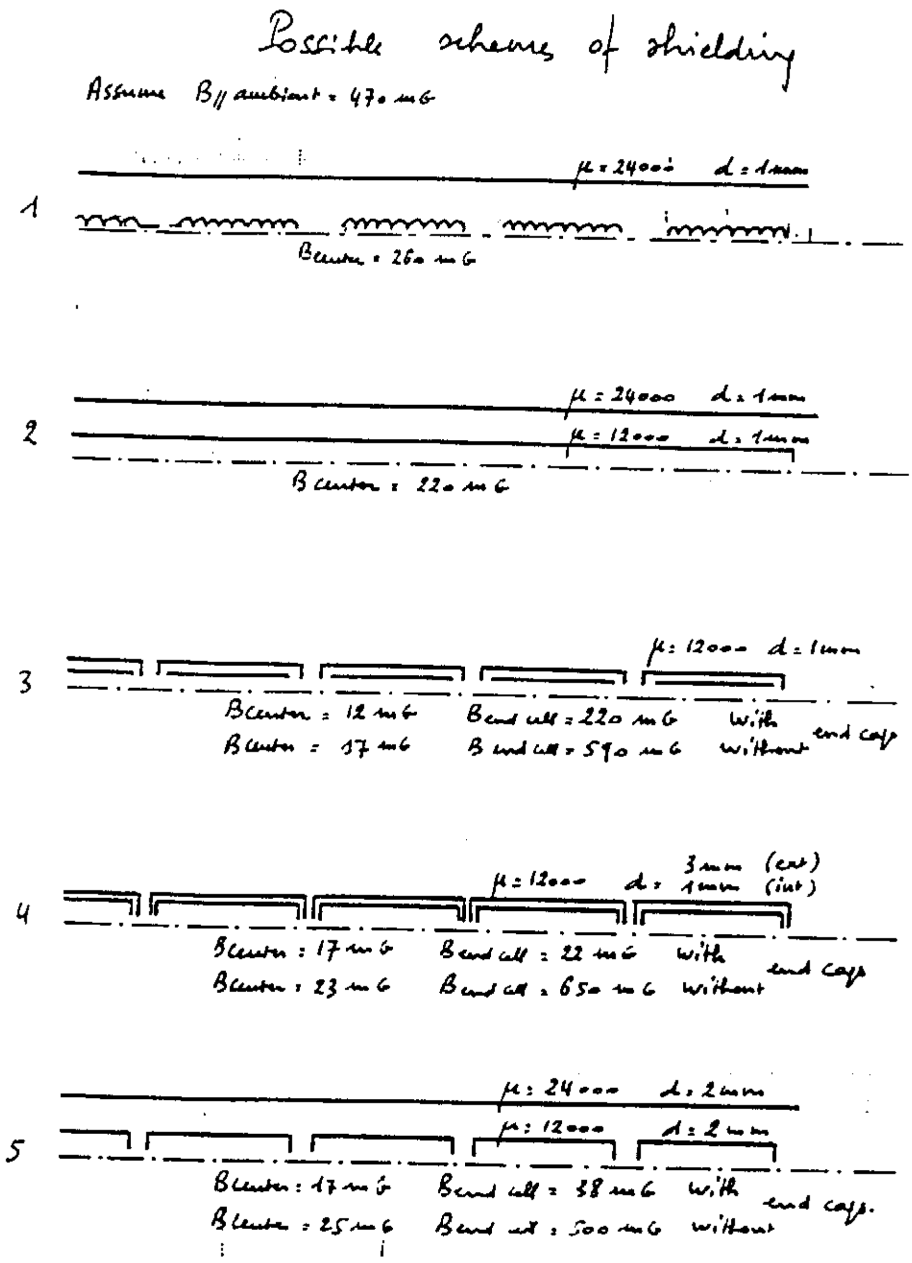


Figure 6 Several possible schemes for the shielding of TESLA TTF cavities. The field profile for scheme 5 is shown in fig. 7.

Various concepts of passive shielding with two layers of magnetic material, either inside or outside the helium vessel, were considered (fig. 6). Results from BACCHUS on the best geometry fitting the one for a TESLA TTF cryomodule are shown on fig. 7. Here, the considered geometry was a string of passive shields consisting of two layers of magnetic material, one outside the Helium vessel, one outside the vacuum vessel. With this double shield and realistic values for μ and for the shield thickness, it is not very difficult to reach acceptable field levels at the center of the shield. The difficult part is to shield the cavity end cells. This is already true for an isolated cavity, and is even more so if one takes into account the deleterious effect of neighbouring tubes.

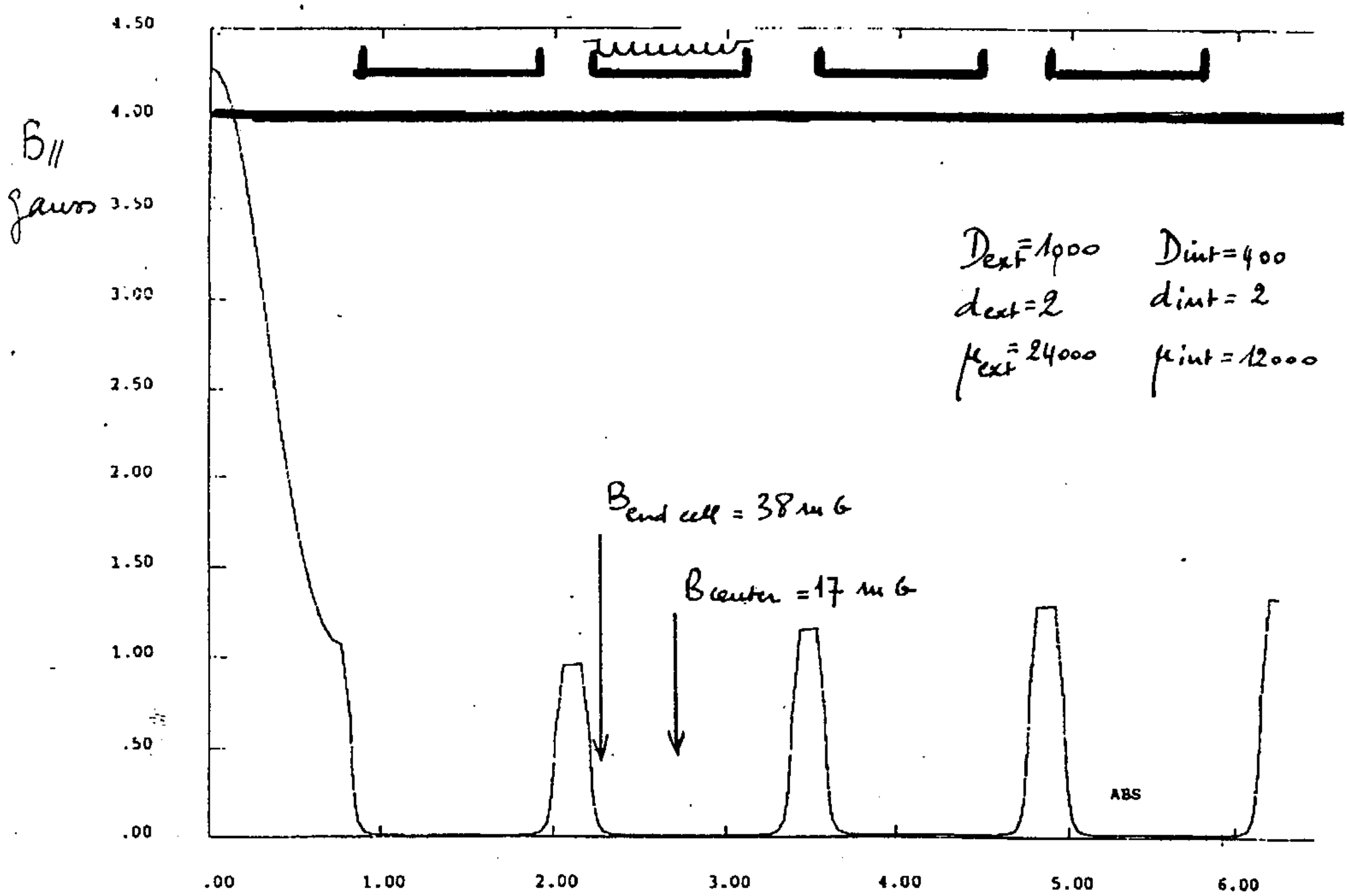


Figure 7 Field profile along the axis of a TESLA TTF cryomodule shielded by two layers of passive shields, as calculated with BACCHUS.

To conclude, it is possible — but rather difficult — to obtain on a TESLA TTF cryomodule the required shielding of the longitudinal component of the field by means of purely passive shields. Large shield thicknesses, and probably two layers of shielding are necessary. The shield could be a string of tubes containing the string of cavities. 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. End caps can cure the problem to some extent, but they complicate the design and increase the cost of the shields.

4. Active devices

The principle of active devices is to cancel the ambient magnetic field by coils. The advantages of this option lie in its simplicity, and cheapness. Cancellation of the longitudinal component of the field, so difficult with passive shields, can readily be achieved with a very simple solenoid or a string of Helmholtz coils.

A few drawbacks remain, however: The current circulating in the coils is constant in time, so that the cancellation of the time dependent components of the ambient magnetic field is not secured by active devices. Does the ambient field contain high frequency components? The usual gaussmeters cannot answer this question. In the following, these components will be postulated to be small as compared with the static earth field. Another drawback of coils is that the magnetic environment of the accelerator may change during its history, for instance due to the installation of new magnetic material in the tunnel, close to the cavities. If this change goes unnoticed, the current in the coils will become inadequate for a proper protection of the cavities. In principle, the current in the coils needs to be set only during cooldown of the cavity, since flux trapping occurs only at the superconducting transition. However, during a quench, a macroscopic portion of the cavity becomes normalconducting, and is re-cooled down to the superconducting state immediately afterwards. At the transition, the cavity is again liable to trap flux, and this means that the shields must be operating at this time. This is not automatically secured with active shields.

5. The recommended solution for TESLA: a mixed scheme

In view of the respective qualities of passive shields and active devices, it is very tempting to combine advantages of both, by cancelling the average longitudinal component of the field by a coil, and by taking care of $B_\perp$ and of the fluctuations of $B_\parallel$ by a light passive shield (fig. 8).

In order to qualify completely the above described concept, a 1/4 scale model of a TESLA TTF cryomodule was built at Saclay (fig. 9). 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 $(\mu d)_{Model} \simeq scale * (\mu d)_{Tesla}$.

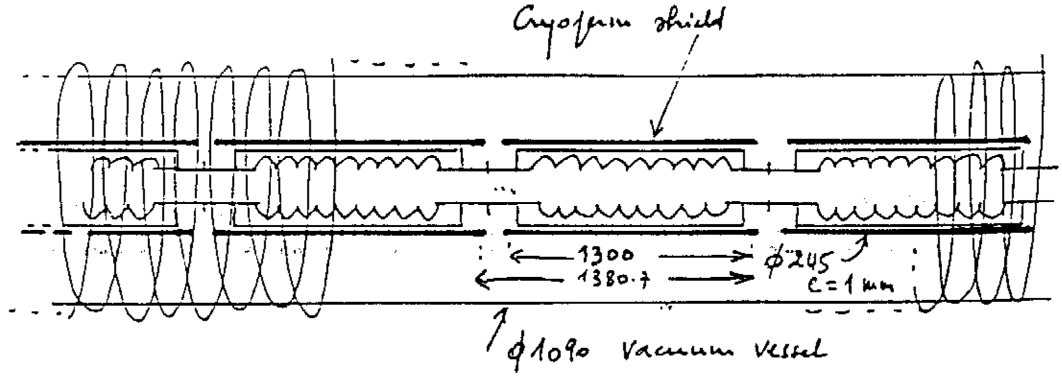


Figure 8 Principle of a mixed shielding scheme, applied to a TESLA TTF cryomodule.

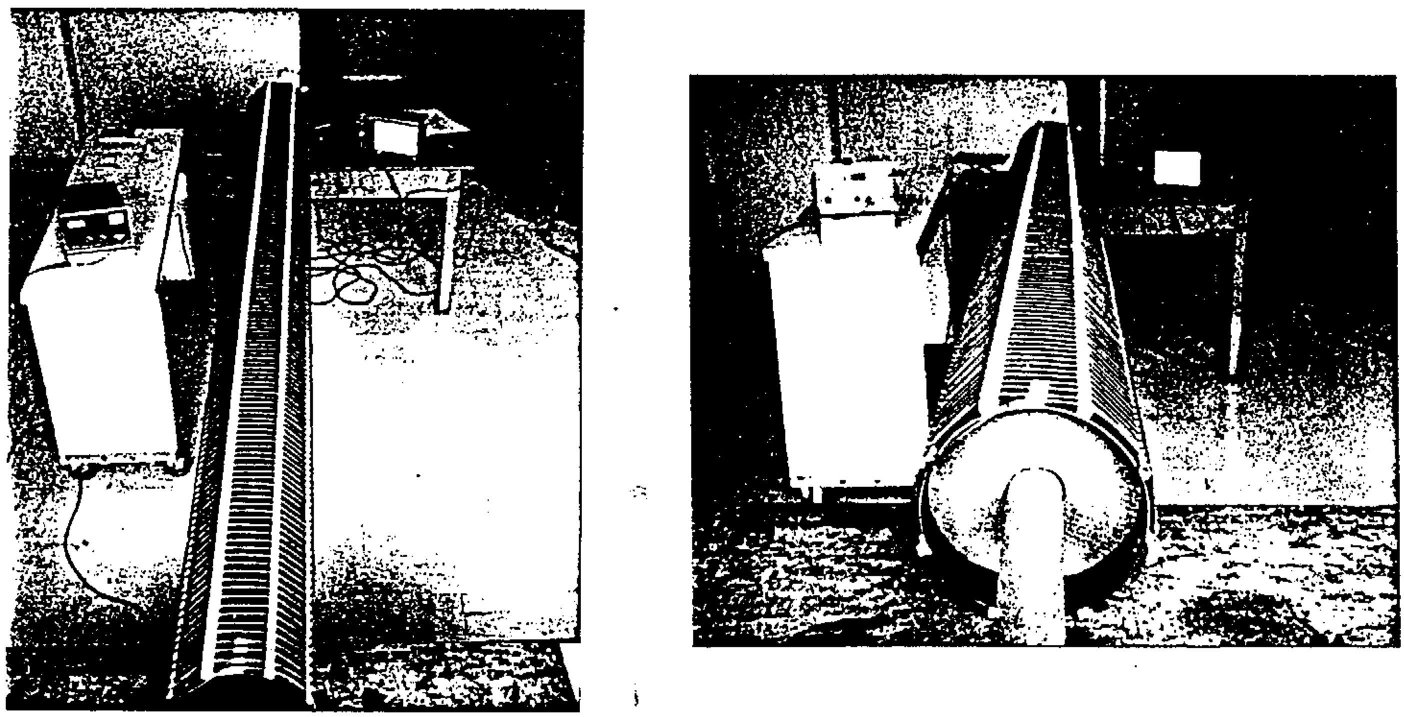


Figure 9 Scale 1/4 model of the TESLA TTF shielding scheme.

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 optimization of the shield geometry and careful degaussing of the "vacuum vessel" is shown in fig. 10 and Table 2. 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.

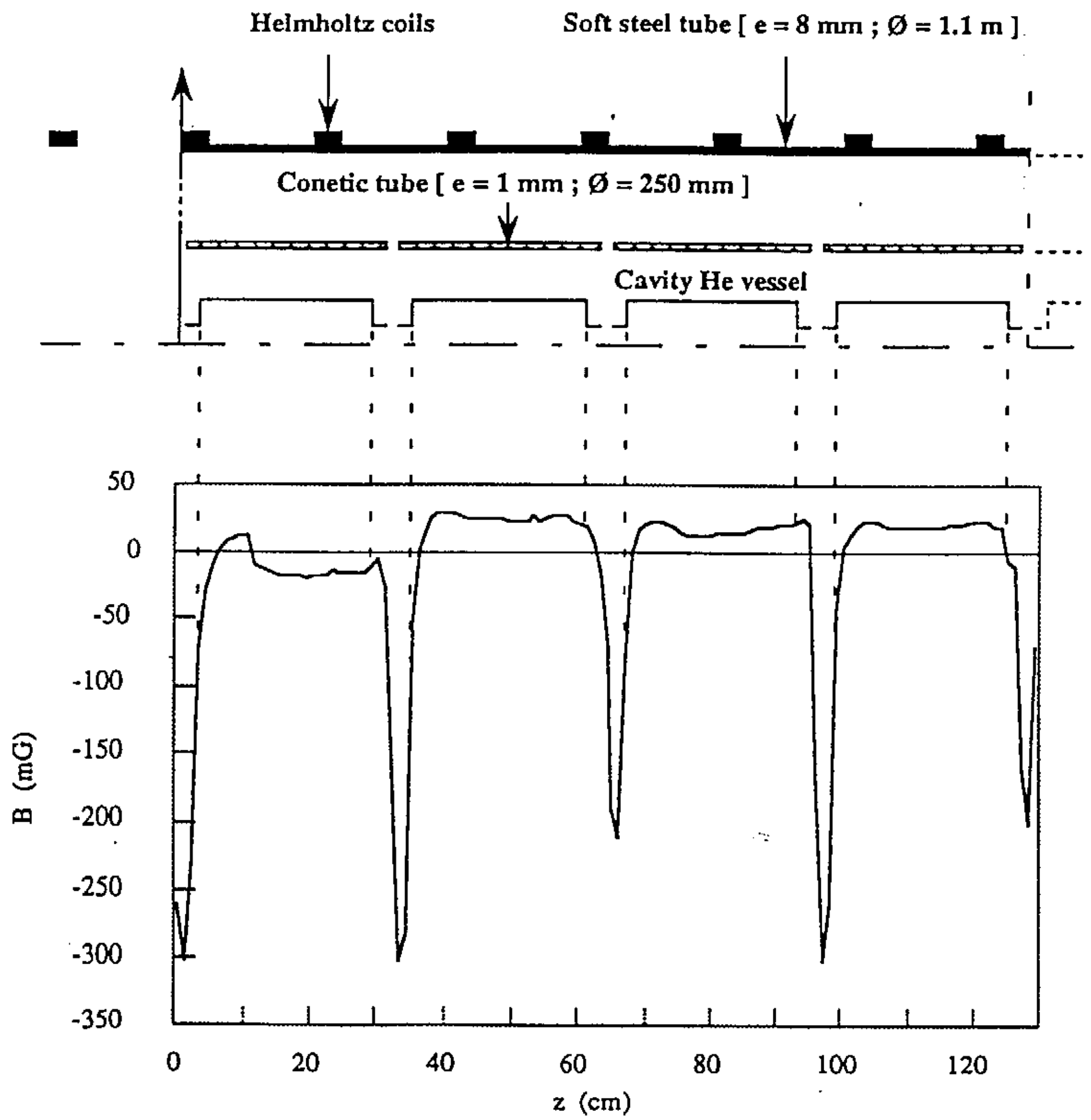


Figure 10 The field profile measured along the axis of the scale 1/4 model of a TESLA TTF cryomodule.

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

Table 2 Field level measured on the scale 1/4 model of a TESLA TTF cryomodule.

The 1/4 scale model enabled us to recommend the following design for the TESLA TTF shielding scheme:

5.1 The Cryoperm tube

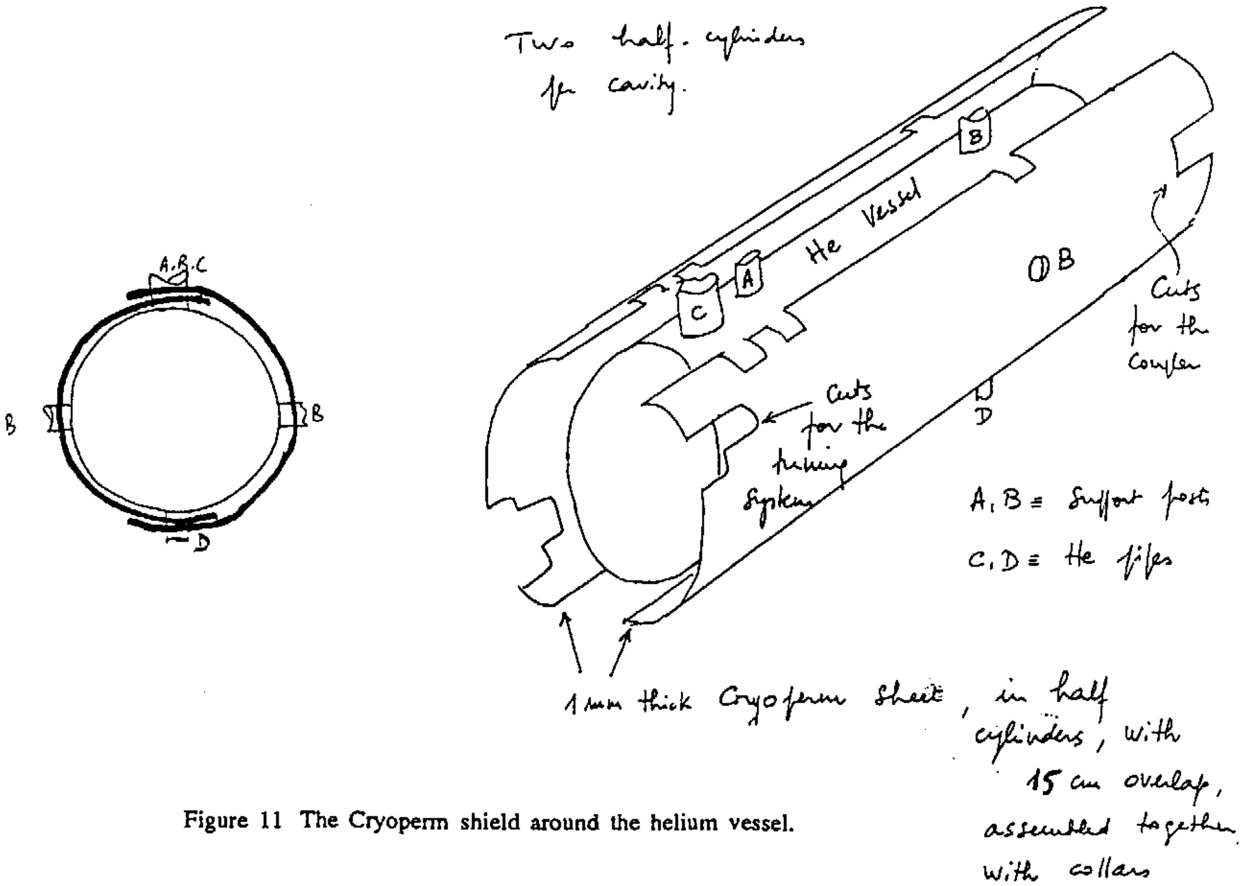


Figure 11 The Cryoperm shield around the helium vessel.

The passive shield should be of small diameter to minimize the range of fringe fields. For this reason we recommend the use of a single tube around the helium vessel. The thickness of the tube wall should be of 1 mm, to give a transverse shielding factor of 50. To avoid the complication brought by end caps, the tube should extend rather far away on each side of the cavity. As mentioned above, the exact length of the Cryoperm cylinder is a compromise between the average quality of the longitudinal shielding, and the local quality of the longitudinal shielding at the end of the tubes, due to fringe fields. This length has been optimized on the scale

1/4 model. The criterion retained here was to minimize $B_{||}$ at the level of the cavity end cells. The optimal shield length was found to be 1300 mm (full scale). Given the spacing between cavities, this corresponds to a gap between shields of 80.7 mm. Some cuts will be necessary at the tube ends to allow room for the coupling lines and cold tuning system. Being cold, the shield should be made of Cryoperm. Its assembly will probably take place at a late stage (after the clean room stage, in order to minimize the number of operations in the clean room, and the complexity of the parts handled there). For an easy assembly, this shield should be made in two overlapping halves (fig. 11). The assembly of the halves should avoid welding, because local heating would destroy the magnetic properties of the tube. For the same reason, bending of the sheet should be prohibited during the assembly, as well as any other mechanical stress. We recommend to re-anneal the half cylinders *after* forming to shape.

5.2 Design of the coils

The average current necessary to cancel $B_{||}$ is 25 to 50 Amp. turns/m. Due to chimneys and lateral ports, the active device cannot be a regularly wound solenoïd. A plausible solution might be to use a string of Helmholtz coils instead of a solenoid. The modularity of the coils, and their mechanical independence with respect to the vacuum vessel would be another advantage of this solution. What is the allowable spacing between coils compatible with an homogeneous cancellation of the field? The effect of the winding irregularities has been investigated at Saclay. On the TESLA TTF cryomodule, the diameter of the lateral ports in the vacuum vessel is 60 cm. This corresponds to a minimal spacing ratio S/D of 0.6 for the coils, where S is the spacing of the coils, and D their diameter. Such a geometry was tried on the scale 1/4 model and yielded results very similar to the ones obtained with a uniformly wound solenoid. Of course, inhomogeneities grow when the coil spacing increases, but we found that acceptable results, identical to the ones reported in Table 2, were still obtained with a spacing ratio of 1.1, corresponding to a coil spacing of 1.2 m on the TESLA TTF cryomodule. We are thus led to recommend a spacing between 0.6 and 1.2 m for the Helmholtz coils of the TESLA TTF shielding scheme.

5.3 Magnetic properties of the vacuum vessel

The TESLA TTF vacuum vessel is made of steel, and will not be neutral from the magnetic point of view. The vacuum vessel may help to shield the cavity, playing the role of a (poorly controlled) passive shield. However, its ratio $\mu d/D$ will be of the order of 2 to 3, ie small as compared to the $\mu d/D$=50 of the Cryoperm shield. The efficiency of the vacuum vessel as a shield will thus be rather limited.

But the role of the vacuum vessel may also be a harmful one: as seen on the scale 1/4 model, it will have a remanent magnetization, due to its metallurgical, thermal and magnetic history. This magnetization, especially probable at the welds, risks to perturb the field distribution in the tube. Fortunately, it was demonstrated on the scale 1/4 model that the vacuum vessel can be demagnetized with the coils of the active device. The degaussing procedure consisted of DC pulses of alternating sign and decreasing intensity (fig. 12). Note that the current capability of the coils required by the degaussing procedure (300 Amp. turn/m during a few seconds) differs from the one needed for the cancellation of the earth field (25 to 50 Amp. turn/m, DC). This should be taken into account in the final engineering of the coils.

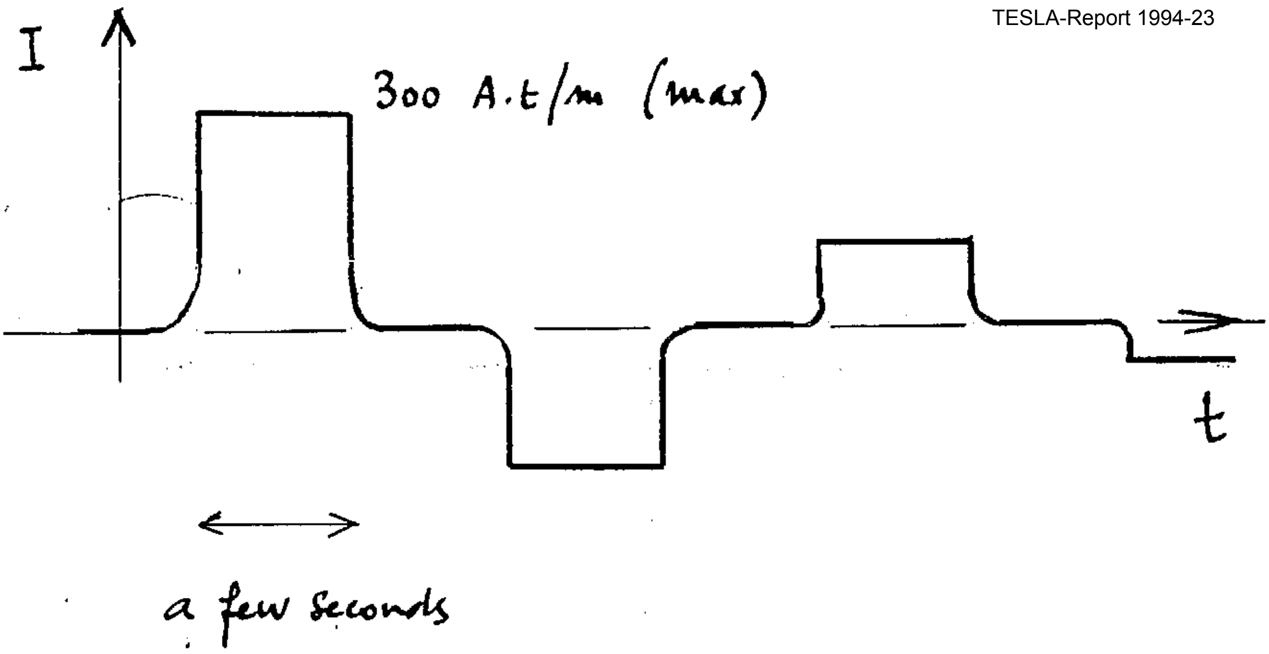


Figure 12 Time dependence of the current in the coils, during demagnetization of the cryomodule vacuum vessel.

6. Conclusion

The shielding of TESLA TTF cavities turned out to be more difficult than expected, due to the intrinsic geometry of linear accelerators. We realized during completion of this work that it is much easier to shield a single cavity than a string of such objects. Apparently, this difficulty had been largely 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 even accelerating gradients.

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