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SUPERCONDUCTING PLATES AS MAGNETIC SHIELDS*

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Abstract

The effectiveness of magnetic shielding between superconducting niobium tin plates has been studied. Shielding factors, field profiles and gradients have been established for transverse magnetic fields up to 19.5 kG. In addition, it has been found that starting with a "frozen-in" field of -19.5 kG between the plates, it is possible to return the magnetic field to +19.5 kG suitable for particle acceleration, leaving -13.3 kG between the plates to establish reverse orbit curvature. It is the purpose of this writing to set forth the details of these endeavors for possible application to future accelerator extraction systems.

Introduction

Recent studies[1] of the shielding properties of Nb_3Sn plates have established shielding factors, the effect of plate thickness, flux jump effects and their control, and a model that can be used to calculate shielding factors and field distributions. The plates, rectangular in shape, 3.0 x 2.5 x 0.3 cm thick, were prepared by isostatically pressing and sintering a stoichiometric mixture of Nb and Sn powders.

Shielding Fields

For experimental investigations, the applied field B_1 in Fig. 1 was supplied by a 14.6 cm diameter circular magnet with an 8.36 cm gap. The field B_2 between the plates was measured by either a bismuth wire (2 mm long x 0.217 mm diam) or a Hall probe (Siemens SV210T).

If the applied field B_1 is changed so rapidly that flux jumps are produced, then the resulting solid line hysteresis curve is unpredictable. The discontinuities of this curve are created by flux jumps which degrade the shielding capabilities of the plates. Such effects can be avoided if the rate of change of B_1 is restricted to a value below the critical rate of increase that is denoted by $(dB_1/dt)_c$ in Fig. 2. For plates of 0.318 cm thickness, this value is 20 G/sec for a B_1 field of 19.5 kG. If this rate constant is not exceeded, then smooth repeatable hysteresis curves are obtained.

Fig. 3 illustrates a family of field profiles obtained along an axis centrally located between the plates and parallel to the 2.5 cm dimension. These data are presented in terms of the absolute shielding produced by the super currents. Each profile relates to a specific point on the hysteresis curve of Fig. 1. Profiles 1, 2, 3, 4 and 4A are free of flux jump effects and illustrate the changes that occur for various levels of applied field. A flux jump distorts the distribution as shown by 5. If B_1 is increased, this profile will change to that of 6 and 7. Symmetry can not be restored until the plates are raised above their critical temperature T_c to remove all "frozen-in" flux.

The current penetration and current density deduced from model calculations is 0.6 cm and 1.3×10^5 A/cm^2 for the 4A profile.

An extension of the magnetic shielding capabilities of the plates has been obtained by inducing field differences as large as 32.8 kG between B_1 (+19.5 kG) and B_2 (-13.3 kG). Plates of 0.635 cm thickness were required to support the induced current. This reversed field was established by first cooling the plates through the critical temperature T_c with B_1 being -19.5 kG. B_1 was then decreased through zero and then raised to +19.5 kG, leaving -13.3 kG between the plates for reversed orbit curvature. Fig. 4, points "a" through "e", illustrate the "freezing-in" procedure. Corresponding field profiles are given by Fig. 5.

Possible Application

Now that the superconducting plate capabilities have been partially established, the question arises as to the possibility of accelerator application. In view of the large shielding factor provided by the plates, it seems justifiable to explore their use in a beam extraction system. For such an application, the following requirements must be satisfied. In referring to Fig. 6 to establish the parameters, one has B_1 the accelerating guide field, b the amplitude of the field bump created by the plates, Δ the transition region, B_2 the field between the plates and "a" the width of the resulting field well.

If we consider increasing orbit radius to be in the direction of increasing R, then the first consideration is that the motion of the circulating beam remain stable prior to entering the transition region Δ. Because of the nonlinear guide field and the crossing of the $\nu_R = 1$ resonance for $\nu_R < 1$ extraction, the first harmonic component of the overshoot "b" may induce

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unacceptable radial oscillations. To the first approximation, the overshoot amplitude can be related to the calculated allowable first harmonic component δ by the relation $b = \pi\delta R/L \ B_1$ where R is the radius of extraction, L is the length of the plates and B_1 is the guide field. For stability and extraction in the region of $\nu_R < 1$, δ is calculated to be $\leq 2.5 \times 10^{-4}$ for the proposed HIVEC and b is about 0.01 B_1 for L and R being 12.7 (4° azimuthal length) and 190.5 cm, respectively. If $\nu_R > 1$, then the maximum allowable δ is calculated to be $\leq 5 \times 10^{-4}$ and b is about 0.02 B_1. Since parameters will vary for different accelerators, these values are set forth only to illustrate the required constraint of b.

The profile 4A of Fig. 3, gives a "b" value of about 0.080 B_1 which is too great by a factor of 8. To determine the feasibility of reducing this overshoot, a section of Vanadium Permendur was positioned to the external side of the plates. Fig. 7 illustrates the position of this flux shunt and the overshoot is improved by a factor of 2. It is to be noted that these data were obtained with a field of 6 kG and for higher applied fields, the volume of iron will have to be increased to minimize saturation effects. Further reduction of b can be achieved by a split pair of distributed coils, located next to the plates, but above and below the region of overshoot. High current density requirements (5 to 10,000 A/cm^2) for these coils and the existence of a closed circuit refrigeration system for the plates would make the use of superconducting wire very attractive.

For good extraction efficiency, the transition region Δ should be small as compared to the turns separation at the entrance to the deflector system. It is estimated that if $\Delta \leq 0.12$ cm and the turns separation is 0.25 cm, then the extraction efficiency will be about 50%. Experimental data indicates that Δ is about 1 cm or 8 fold too great. This is a serious deficiency and more work is required to decrease the width of this transition.

It is estimated that the width "a" of the well should be $\geq$ 2.5 cm, assuming a 0.6 cm incoherent radial amplitude and a 300 keV energy spread. Since the shielding factor is about 90%, allowable nonuniformity of field over this distance could be as great as 10%. This of course is dependent upon the emittance characteristics of the beam that can be excepted by the external beam transport system. This condition has been somewhat approximated by the tests where iron was used as a flux shunt. Introducing C-shaped iron as a shunt may well extend this width to 2.5 cm.

Conclusions

A significant reduction in field can be developed with superconducting plates acting as shields.

It appears that the limited gradient thus far attained is a serious drawback to the use of the plates as a first stage deflector. Additional effort is required to improve this deficiency.

If a second stage deflector is constructed, where the beam splitting is already achieved, the gradient requirement can be relaxed. For the parameters given, the width of the gradient field could be about 0.5 cm which is close to the existing measurements.

References

[1] R. Benaroya and H. P. Mogensen, J. Appl. Phys. 37, 2162 (1966).

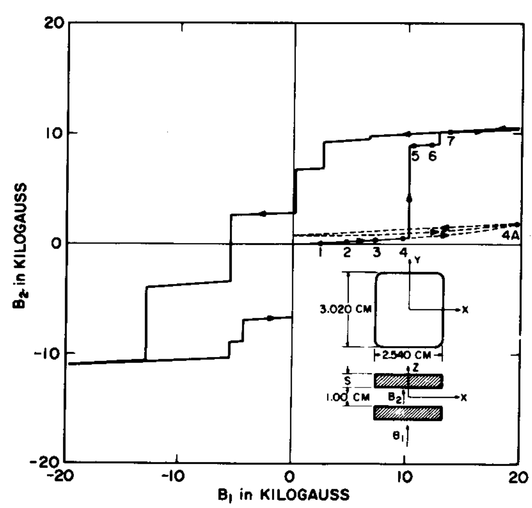

Fig. 1. Magnetization of a pair of s = 0.318 cm thick Nb_3Sn plates. B_1 is the external magnetic field applied perpendicular to the plates and B_2 is the magnetic field measured petween the plates at the coordinates (0,0,0). Dashed curve, without flux jumps was achieved by keeping dB /dt < 0.020 kG/sec whereas no rate control was applied to B_1 for the solid curve.

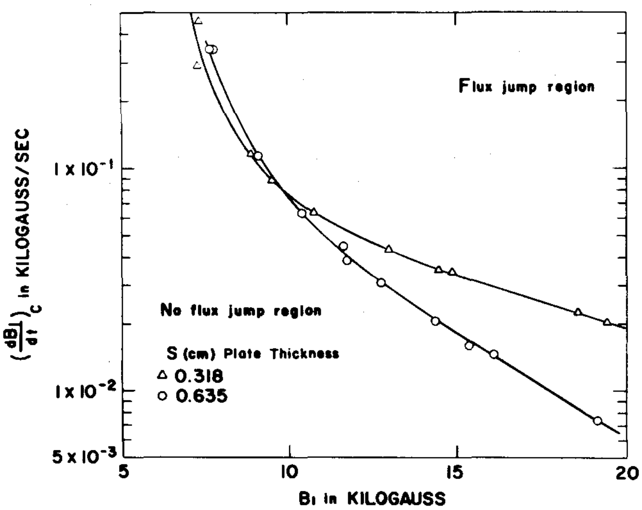

Fig. 2. Relationship between the applied field B_1 and its critical rate of increase $(dB_1/dt)_c$, below which flux jumps do not occur for pairs of two plate thicknesses.

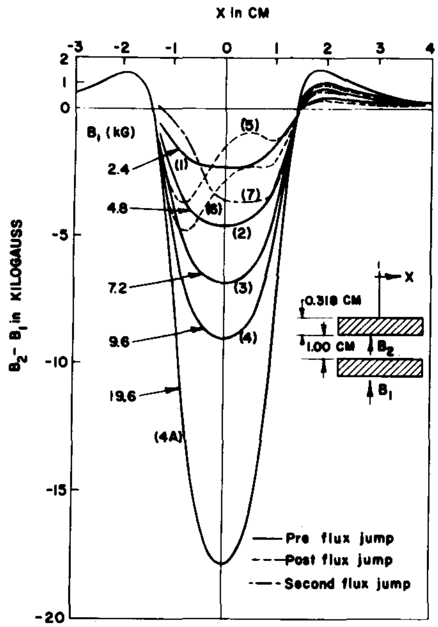

Fig. 3. Curves (1)-(7) represent induced superconductor field profiles along the x axis corresponding to points 1-7, respectively, in Fig. 1.

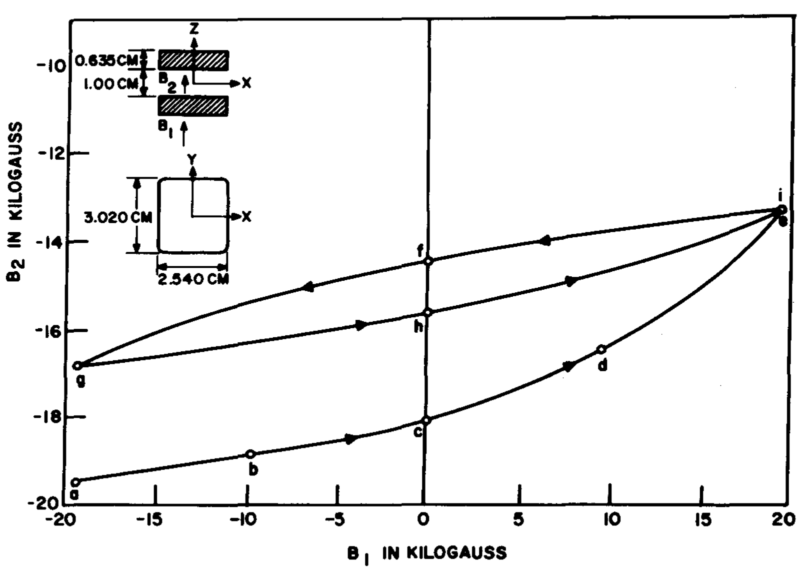

Fig. 4. Hysteresis loop at coordinates (0,0,0) between two Nb_3Sn plates when cooled through T_c in the presence of a -19. 5 kG field.

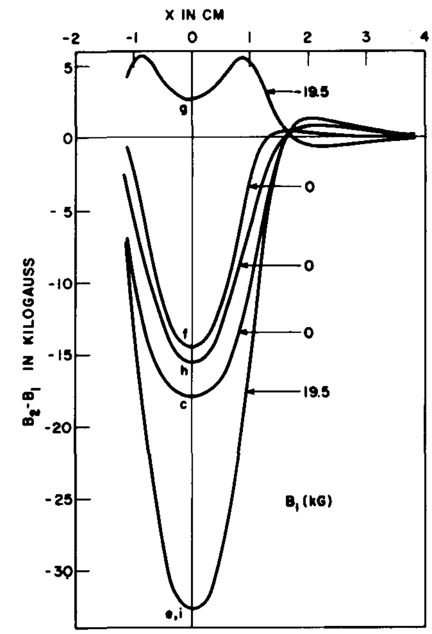

Fig. 5. Induced superconductor field profiles along the x axis corresponding to points c, e-i in Fig. 4.

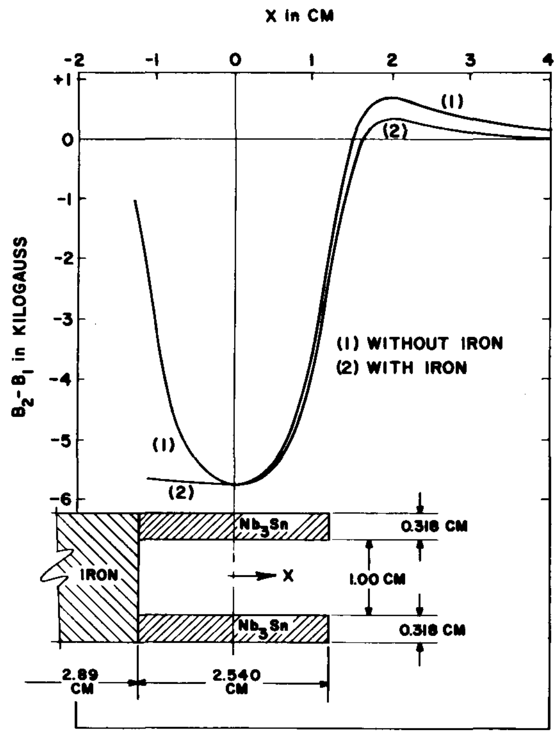

Fig. 7. The use of Vanadium Permendur iron as shown in sketch and its effect on the B_2-B_1 profile along the x axis is shown in curve (2). Curve (1) was obtained without the use of iron. B_1 in both cases is 5.98 kG and the thickness of each set of plates is 0.318 cm. The use of iron reduces the field overshoot and increases the field well.

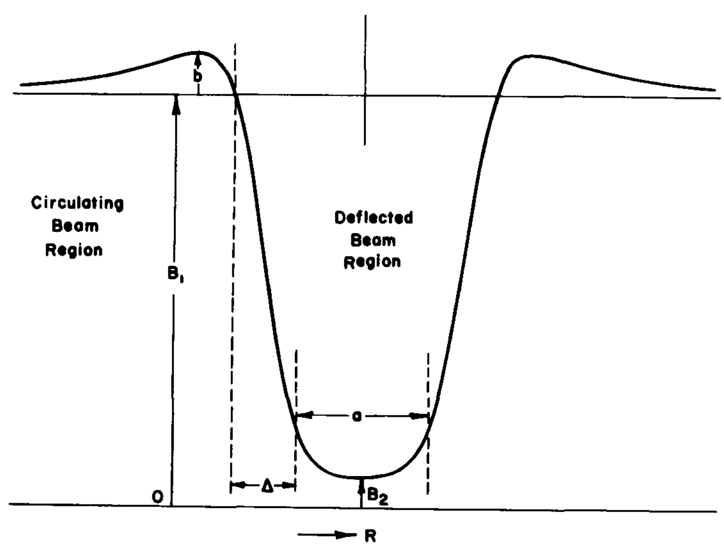

Fig. 6. A typical field distribution between the plates illustrating the field bump b, the transition region Δ and the field well a.

DISCUSSION

TENG: Have you tried only parallel plates?

BENAROYA: Yes.

KELLY: Does this material stand up under radiation fields as high as you see in a cyclotron?

BENAROYA: Our present program of irradiating these materials should soon provide some answer to this. The niobium-zirconium has been irradiated to a certain extent; in some cases it shows improvement, in other cases deterioration. I don't think any work has been done with niobium-tin plates.

HUDSON; Have you considered the current sheet at 90° to the sheet you have, as we use iron in the ORIC, to get very abrupt radial compensation in the field in that direction.

BENAROYA: We have done no work in that.

HUDSON; If you do, you could cut the transition space down to a very small value, in your case.

BENAROYA: Right.

