SUPERCONDUCTING SHIELDS FOR MAGNETIC FLUX EXCLUSION AND FIELD SHAPING*

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Abstract

Superconducting shields provide a means of obtaining arbitrarily reduced magnetic fields over considerable volumes for use in diverse applications. Various shielding techniques for high and low flux densities are surveyed and some recent results discussed. In particular, the flux shielding properties of laminates of Nb_3Sn have been studied in fields up to 2.5 T. Measurements are presented on the shielding efficiency of the laminate as a function of the number of lamellae, the properties of overlap regions, and the methods of construction. The practical application of these devices is illustrated.

Introduction

The purpose of this report is twofold: The first is to present a representative cross section of past work on shielding of magnetic fields with superconductors for various applications. We find that this work falls naturally into two groups, characterized by the magnitude of the flux density to be excluded. Thus, on the one hand, we have shielding of apparatus against fields of the order of a microtesla, methods which usually make use of the Meissner effect and which in the ultimate low-field region exploit the quantization of flux. On the other hand, we are concerned with superconducting shields in which the screening currents are of a magnitude characteristic of the high-field Type II alloy superconductors. It is this latter type of magnetic shielding, the study and application of which to practical problems form the second part of this article. We have found, moreover, that it appears to be possible to combine both sets of properties of superconductors to obtain large regions of truly zero magnetic field.

Review of Shielding Techniques

Magnetic shielding with superconductors is, of course, an old concept; however, the approach to shielding tended to be largely empirical. The literature is full of references to lead or tin foil screens surrounding particular experiments to reduce stray magnetic fields, but little attention seems to have been devoted to a systematic examination of the conditions required to do so efficiently. The Space Age changed this. Magnetometers for space application have to be tested and calibrated in low ambient fields, typically of the order of 10^{-8} tesla or less. Such flux densities are achievable with conventional shielded rooms but further reduction in the field can only be effected by exploiting the intrinsic properti.s of superconductors. Thus, Hildebrandt[1] describes a fairly typical combination of a μ-metal shielded room and a dewar containing superconducting lead shells which make use of the Meissner effect to achieve a final static magnetic field of less than 2×10^{-10} tesla. Unfortunately this technique is limited by the fact that a perfect Meissner effect is extremely difficult to achieve in practice. Although most superconducting metals will exclude a large fraction of the applied field as they undergo a superconducting transition, some flux will invariably remain trapped in the metal. These regions of flux remain pinned in the superconductor either by non-superconducting impurities or by specific states of the lattice of the superconductor. In a sense, it is the perfect conductivity of the material which makes complete elimination of the trapped flux so difficult. Of course, the number of pinning sites can be reduced considerably by using very pure, strain-free materials, but the shields then become very difficult to make and rather delicate to handle.

The next step is to perform the shielding process in increments: effectively to reduce the external field by some other means before the shield is made superconducting, so that the Meissner effect will have to remove a correspondingly reduced amount of flux from the material. An interesting realization of this stepwise process has been described by Vant-Hull and Mercereau.[2] Many superconductors, and tin in particular, show a spectacular drop in the electrical resistivity just before the metal becomes superconducting. The magnetic shield in the form of a tin cylinder is rotated rapidly while being cooled through the transition region. An ambient magnetic field will induce eddy currents in the metal which will tend to shield the region inside the cylinder from the non-axial components of the field. As the cylinder is cooled through the transition region, an almost perfect Meissner effect will be achieved because the effective resistivity of the metal decreases rapidly which in turn enhances the eddy current flux exclusion by several orders of magnitude before any region of the shield is able to trap flux. The authors were able to achieve an ultimate trapped field somewhat less than 10^{-10} tesla.

Before leaving the subject of very low fields, we mention one method which uses the phenomenon of flux quantization, whereby in principle the field can be reduced to zero. Suppose a folded superconducting container is cooled in a magnetic field; it will exclude some flux and it will trap the remainder. If the container is now unfolded, the flux density inside is reduced and hence the field is lowered. Another folded container inserted into the first and cooled slowly will repeat the flux expulsion process and, on being unfolded, similarly reduce the field still further. Thus, given enough steps, it is possible to reduce the field far enough until less than half a quantized flux unit remains. If the conditions are then right, a current is induced in the inner folded container which exactly cancels this flux and produces the lowest quantized state inside, i.e., there remains zero flux inside the container. Brown[3] has constructed such a flux "vacuum pump" and has achieved remanent magnetic fields less than 10^{-10} tesla in two stages. Variants of these and other exotic devices are described in some detail in a review by Hamilton.[4]

The shielding of magnetic fields in excess of about 250 millitesla required virtually that a new technology

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*Work supported by the U.S. Atomic Energy Commission

of superconductors be developed. We find the first reference outlining the possible use of the then newly discovered superconducting compound of niobium and tin[5] for magnetic shielding in an early paper by Autler,[6] who, in the same article, made some rather remarkable predictions concerning the use of this material. The macroscopic theory of magnetization of hard superconductors due to Bean,[7,8] and Anderson[9] and the experimental work of Kim et al.[10,11] underscored the usefulness of Type II superconductors for such applications as magnetic field shielding and magnetic field stabilization. Thus Dunlap et al.[12] described the operation of a simple tubular field stabilizer constructed very much along the lines first suggested by Autler[6] and elaborated on by Foner,[13] while Hempstead et al.[14] investigated the inductive behavior of a closed system of superconductors. This study encompassed not only flux shielding and flux trapping but also discussed some flux concentration schemes to achieve various degrees of intensification in field strength, including flux pumping.

It may seem rather surprising that after such an auspicious a beginning of a new technology, applications should lag behind. However, we must not forget that the production of these high-field superconducting alloys in a form useful for shielding purposes and in any quantity was far from simple. Benaroya and Mogensen,[15] who undertook a study of the shielding properties of Nb_3Sn with a view of making superconducting plate shields for a deflector system for a high-intensity variable-energy cyclotron, give a good insight into the fabrication techniques of the day. It was not a process that every laboratory would undertake lightly. Incidentally, these authors were among the first to study the shielding properties of a hard superconductor for practical reasons. They were followed by others: Minet et al.[16] developed a simple analog model for use in field shaping problems involving superconductors, Haid et al.[17] explored the feasibility of making superconducting flux shields by a process of plasma deposition of mixed niobium and tin powders. A little later, Kawabe et al.[18] studied the magnetic shielding by superconducting Nb-40 Zr-10 Ti hollow cylinders.

About this time, an unexpected sector of the industry began to show a keen interest in the shielding characteristics of superconductors: the manufacturers of electron microscopes. As Echarri and Spadoni[19] commented in their review article, here at last was a possibility of constructing highly corrected electron lenses of short focal length. The work of Dietrich et al.[20] is a good example of the degree of shielding sophistication achievable.

While electron microscopy provided the incentive for the study of small compact shielding systems, it was high-energy physics that demanded further development. The idea of a field-free beam channel leading to a typical particle detector, be it a bubble chamber or a spectrometer system, has always claimed more than its share of the particle physicist's attention. Firth et al.[21] and Schmeissner and Haebel[22] at CERN described some preliminary work on field-free beam paths using superconducting flux shields. This was followed almost simultaneously by a proposal for an experiment at the Stanford Linear Accelerator Center, requiring a 4-m long and 1.3-cm average inside diameter flux exclusion tube.[23]

A shielding tube for that experiment was constructed and the experiment was successfully concluded earlier this year.[24] We understand at the time of writing that the CERN flux shield, which uses niobium titanium for the shielding elements, has also passed its acceptance tests.

Cylindrical Flux Shields

In this description of the SLAC work on superconducting flux excluders, we should like to briefly mention some of the steps in our development program and we should like to comment on certain gray areas which would benefit from further study.

Our early work was based on the assumption that well-cooled, oriented, niobium-titanium foil is essential to any large-scale construction, as at the time we could not visualize a method of construction other than an assembly of spirally-wound sheets. Experiments not directly concerned with magnetic shielding, however, very soon convinced us that motion of the foils under magnetic forces, rather than inadequate cooling, prevented us from reaching the theoretically desirable screening current density in the superconductor. Niobium-titanium is, in metallurgical terms, a singularly uncooperative alloy. This fact, more than anything else, convinced us that the solution to our shielding problem was very closely coupled to our choice of superconductor. However, before giving up niobium-titanium completely, we undertook a series of tests of flux shields made for us by the Linde Division of Union Carbide Corporation,[17] with disappointing results.

We were thus effectively reduced to experimentation with Nb_3Sn tape. As a construction based on 5-cm wide spirally-wrapped modules was quite obviously totally unsuitable for any kind of design involving long shielded lengths, we proceeded to develop the concept of combining two long semi-cylindrical shells into an equally long cylinder.

We found in our tests that no matter how carefully the superconductor was interleaved with copper and processed into a shielding tube, the shielding behavior would tend to be erratic and the samples would often exhibit mechanical damage on completion of the measurements. Furthermore, as we mentioned before, while the quality of the cooling did not seem to affect the performance of the shield, the rate at which the external field was applied did. We therefore coated our material with a variety of metallic bonding agents, including Wood's alloy and various types of soft solder and soldered a number of tapes together in an effort to eliminate all relative motion of the superconductors. Figure 1 is typical of the improvement that this treatment produced. Figure 2 illustrates the characteristic shielding curve of a short sample tube after we had developed the fabrication technique.[25] The smoothness of the penetration of the applied field into the shielding tube and the degree of reversibility attained proved to be a very sensitive diagnostic of the mechanical condition of the sample. For example, inadequate bonding or an excessive reheating cycle resulted in a discontinuous flux penetration pattern. Into a "good" sample, the flux would penetrate smoothly and no flux jumps would be observed.

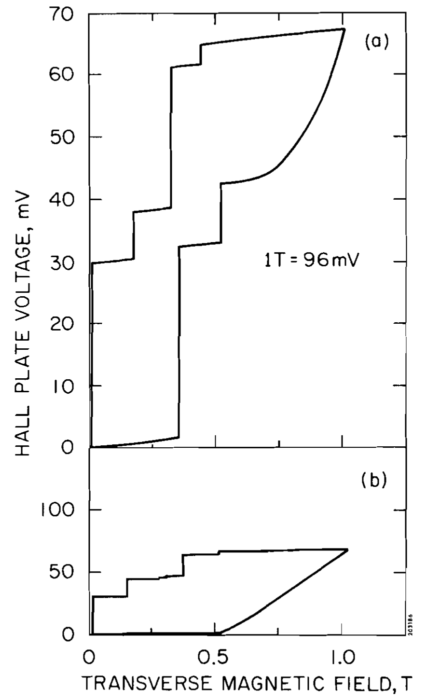

Fig. 1. Flux penetration behavior of a Nb_3Sn flux shield with (a) layers mechanically clamped; (b) layers bonded by soldering.

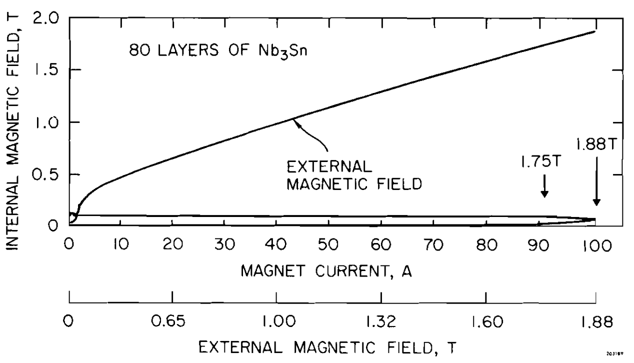

Fig. 2. Flux penetration into a bonded shielding tube.

The results of the measurements are summarized in Fig. 3. It is a plot of the external field at which flux penetration begins, as a function of the number of layers of superconductor in the same tube. The points reflect the measurements of numerous shielding tubes having various lengths, diameters, and differing in the amount of superconducting ribbon used.[26] The regularity of this graph is striking, particularly when one takes into account that a considerable fraction of the superconductor is always in the metastable critical state. This state as we know from other evidence, is unstable, and small disturbances in the applied field or in the temperature will tend to produce local flux instabilities which may drive that region into the normal state. As flux penetration is a regenerative process, we would expect a disturbance to propagate through the tube and tend to drive it into the normal state. Our experimental evidence contradicts this: No matter how large the disturbance, no matter how small the amount of copper "stabilizer," as long as the mechanical integrity of the tube remained unimpaired, the shield continued to exclude the same amount of flux. As Fig. 3 shows, the measurements made under very different conditions are reproducible to a remarkable degree, even to the point that our line passes very close to the point where Firth et al.[21] in their tests observed smooth flux penetration.

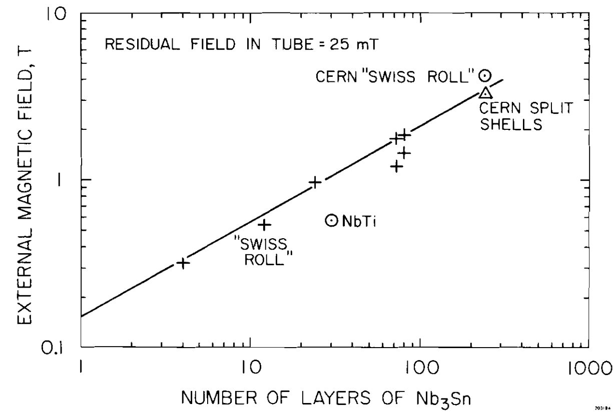

Fig. 3. Flux shielding characteristics of Nb_3Sn tubes of various thicknesses.

For reasons connected with the experiment, the diameter of the flux shield was required to change along the beam direction. We therefore examined the shielding effect of overlapping superconductors. Figure 4 typifies our findings: As long as the overlap length between two concentric shielding tubes exceeds the diameter of the larger tube, its shielding characteristics are maintained without a discontinuity across the overlap, provided, of course, the shielding capacity of the smaller or inner tube is not exceeded.

Figure 5 indicates the scale of the final apparatus: The pole pieces of the magnet are 1.5 m in diameter and the shielding tube and its associated cryostat is over 7 m long. The actual construction of the shield is illustrated in Fig. 6: The superconducting semi-cylindrical shells are soldered to the copper-plated stainless steel support tube, and the entire bonded assembly is further clamped with a number of brass and stainless steel clamps, two of which are shown.

The flux shield behaved as predicted by the test program. The system has now been thermally-cycled between ambient and liquid helium temperatures some sixteen times, and has remained cold for periods of up to two weeks. No deterioration in performance has been observed. On several occasions, partial flux penetration took place as a result of malfunctioning of the magnet and its associated power supplies. These events had no detectable effect on the shielding performance. We have concluded that the field penetration

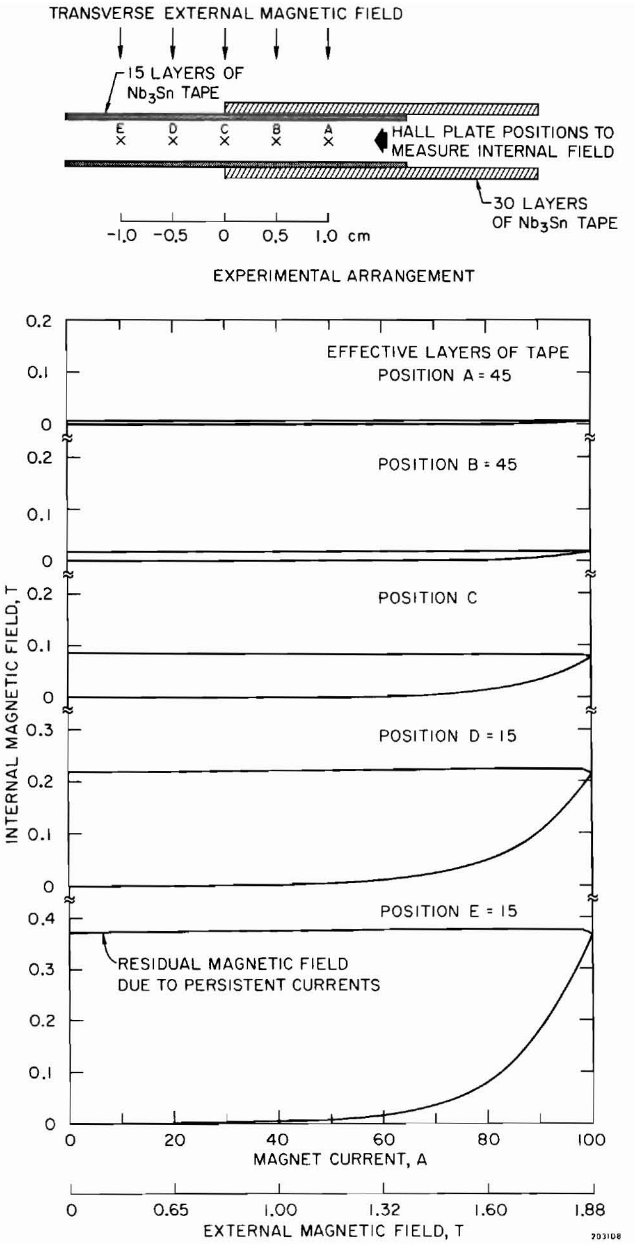

Fig. 4. Flux shielding characteristics of overlap regions.

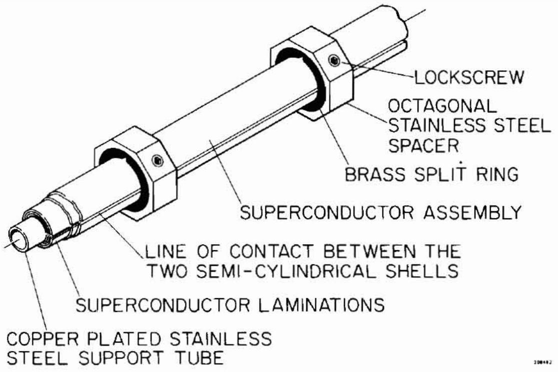

Fig. 6. Detail of the construction of the flux exclusion tube.

was the result of abrupt motion of the shielding tube within the cryostat in spite of the massive supports, rather than being due to changes in the external flux.

On one occasion, we have used the incident electron beam to map the residual magnetic field inside the tube at various external flux densities.

As Fig. 7 shows, at 1.5 T, the field penetration, of the order of 10^{-2} T, is sufficient to deflect the beam almost totally into the walls of the shielding tube. Here the position of the beam is given as a function of the shunt voltage in the two beam-steering magnets, 19D5.1 (south) and 19D5.2 (down). The area contained by the solid and dashed contours is proportional to the usable fraction of the beam. Clearly, at 1.5 T, very little remains for the experimenter!

Because the shielding tube does not quite clear the fringe field of the magnet, the beam arrives at the entrance beam window bent slightly down. We have calculated that the two transverse (to the beam direction) components of the magnetic field are 6.4 and 10.4 mT, respectively, when the external impressed field is 1 T.

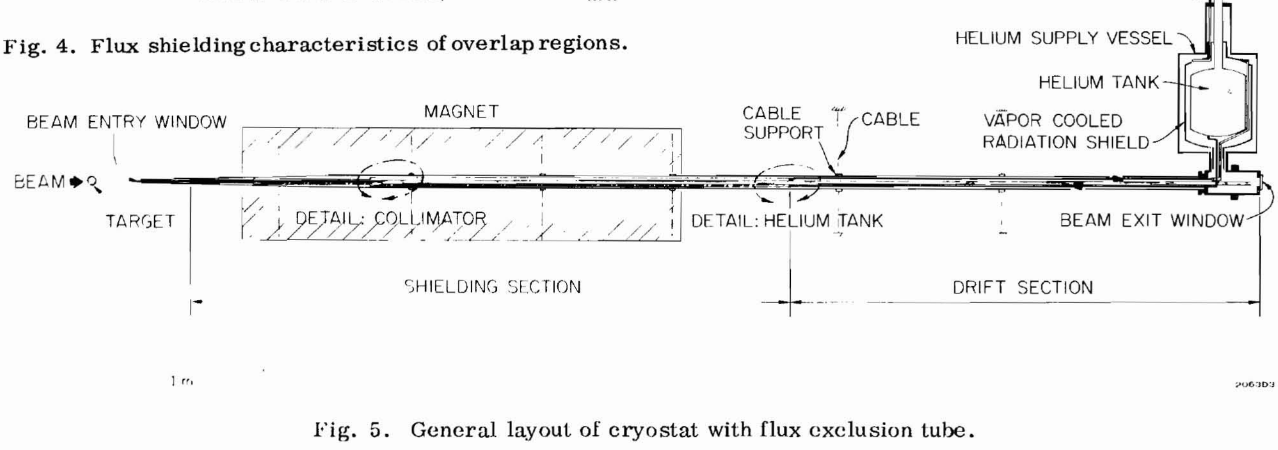

Fig. 5. General layout of cryostat with flux exclusion tube.

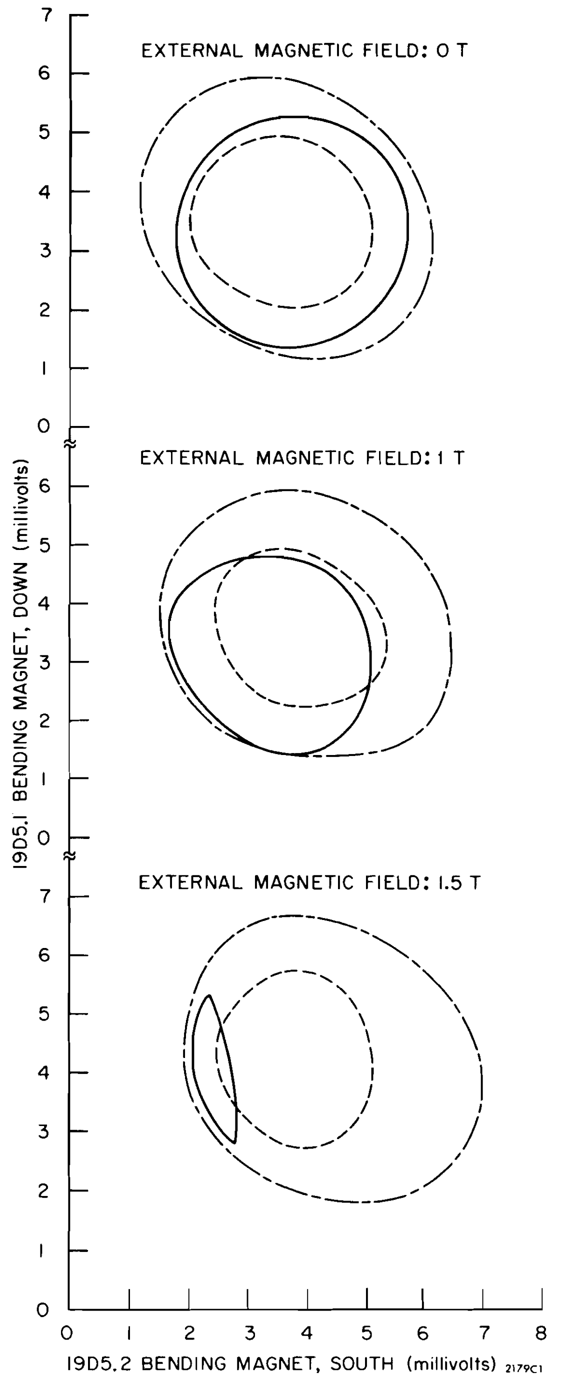

Fig. 7. Deflection of the beam by the remanent magnetic field in the shielding tube.

Solid line: Effective beam profile at exit of shielding tube.

Chain line: Effective beam profile at entrance to shielding tube.

Dashed line: Defines effective beam aperture limits determined by counting rate.

Further Work

The flux penetration into the tube is a very intriguing phenomenon: We have analyzed the field distributions in and around the tube and we have found that the major contributions to the trapped field arise from the multipole distributions in the superconductor induced by the external field.[27] We have further concluded that when the slit separating the two half-shells exceeds the penetration depth of the superconductor, the field generated by the screening currents is negligible and the external field penetrates the slit. On the other hand, when the shell separation is less than the penetration depth, the external field is prevented from entering into the interior of the tube. Thus, to eliminate the internal field entirely, even in the presence of the unavoidable misalignments, we could add inner shells whose slits were rotated 90° with respect to the outside slits. This would certainly reduce the field leakage but it would not completely eliminate the inductive effects of the screening currents. As the remanent internal fields can be reduced to 200 mT or less, this suggests making use of the Meissner effect as described earlier. Work is now in progress to study these alternatives; in particular, we are interested in mapping the internal fields to determine the order of multipolarity and to examine the process of flux penetration.

References

1. A. F. Hildebrandt, Rev. Phys. Appliquée 5, 49 (1970).
2. L. L. Vant-Hull and J. E. Mercereau, Rev. Sci. Instr. 34, 1238 (1963).
3. R. E. Brown, Rev. Sci. Instr. 39, 549 (1968).
4. W. O. Hamilton, Rev. Sci. Appliquée 5, 41 (1970).
5. J. E. Kunzler, E. Buehler, F. S. L. Hsu, and J. H. Wernick, Phys. Rev. Letters 6, 89 (1961).
6. S. H. Autler, Proc. Int. Conf. on High Magnetic Fields, MIT, 1961 (MIT Press and John Wiley & Sons, Inc., New York) p. 324.
7. C. P. Bean, Phys. Rev. Letters 8, 250 (1962).
8. C. P. Bean and M. V. Doyle, J. Appl. Phys. 33, 3334 (1962).
9. P. W. Anderson, Phys. Rev. Letters 9, 309 (1962).
10. Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. Letters 9, 306 (1962).
11. Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. 129, 528 (1963).
12. R. D. Dunlap, C. F. Hempstead, and Y. B. Kim, J. Appl. Phys. 34, 3147 (1963).
13. S. Foner, Rev. Sci. Instr. 34, 293 (1963).
14. C. F. Hempstead, Y. B. Kim, and A. R. Strnad, J. Appl. Phys. 34, 3226 (1963).

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

16. R. Minet, H. A. Combet, J. Y. LeTraon, and J. Schmouker, IEEE Trans. Magnetics MAG-3, 271 (1967).

17. D. A. Haid, C. A. Houck, and C. R. McKinsey, Tech. Report AFAPL-TR-67-155 (1968), Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio.

18. U. Kawabe, T. Doi, and M. Kudo, J. Appl. Phys. 40, 10 (1969).

19. A. Echarri and M. Spadoni, Cryogenics 11, 274 (1971).

20. I. Dietrich, R. G. Maier, R. Weyl, and H. Zerbst, Third Int. Cryogenic Engineering Conf., Berlin, 1970 (Heywood-Temple Industrial Publications Ltd., London), p. 422.

21. M. Firth, L. Krempasky, and F. Schmeisser, CERN TC-LTL Report (1969).

22. F. Schmeissner and E. U. Haebel, Int. Conf. on Instrumentation for High Energy Physics, Dubna, 1970, USSR, p. 161.

23. B. Dieterle, W. Lakin, F. Martin, E. Petraske, M. L. Perl, J. Tenenbaum, and W. T. Toner, SLAC Proposal No. 65 (1970).

24. F. Martin, S. J. St. Lorant, and W. T. Toner, SLAC-PUB-1040 (1972). To be published in Nucl. Instr. and Methods.

25. A. C. Newton, F. Martin, S. J. St. Lorant, and W. T. Toner, SLAC-PUB-1102 (1972). Submitted to Rev. Sci. Instr.

26. Nb_3Sn ribbon, supplied in 5-cm width by Kawecki Berylco Industries, P.O. Box 1462, Reading, Pa., U. S. distributors for Thomson-CSF, 51 Boulevard de la Republique, 78, Chatou, France.

27. F. Martin and S. J. St. Lorant, SLAC-PUB-1104 (1972). to be published in J. Appl. Phys.