STUDIES OF RADIATION-INDUCED PINNING CENTERS AND PERSISTENT MAGNETIC FIELD BASED ON $Y_1Ba_2Cu_3O_7$ SUPERCONDUCTOR MATERIALS

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Background

The research of our group is aimed at producing materials which will retain large magnetic fields, supported by supercurrent, with as slow a field loss (creep) as possible. The starting material used is the high temperature superconductor $Y_1Ba_2Cu_3O_7$ (Y123). We introduce faults by various techniques, and these faults trap (pin) the fields.

Prior to running at IUCF, we had produced materials which, in single "tiles," $1 \times 1 \times 0.2$ cm^3, trapped 1500 G, and we had fabricated a mini-magnet $1 \times 1 \times 1$ cm^3 which trapped 4,380 G. Both results were at 77 °K. The material was Y123, which had been bombarded by protons at the Harvard cyclotron.

Following the Harvard experiment we produced, by chemical methods, more uniformly textured material via the addition of excess Y, resulting in $Y_1 + x\ Ba_2Cu_3O_7$, where $0 \leq x \leq 0.8$. This material trapped 1500 G in a single tile without bombardment.

p^+ *Bombardment at IUCF*

Our first experiment at IUCF exposed this new material to 200 MeV p^+. The object was to learn if the Y additive had emulated the effect of the protons, in which case no further improvements would result from bombardment, or if proton bombardment would further improve the new material. The IUCF proton bombardment again increased the trapped field, by the same factor as the Harvard bombardment. This meant that whatever the effect of the excess Y was, it was independent of and multiplicative with the effect of proton bombardment.

Both the Harvard and IUCF results for the trapped field, B_T, are reasonably well described by

$$\Delta B_T/B_T \;=\; 2.7\,(1 - e^{-f/f_0})$$

where ΔB_T is the increase in trapped field, f is the fluence of protons, and $f_0 \approx 6 \times 10^{15}$ protons/cm^2. (Even at this large fluence, the material is improved rather than degraded by bombardment, because of the pinning effect of the faults.)

Using the IUCF p^+ bombarded materials, we obtained a single tile trapped field of 6,418 G. We also constructed a mini-magnet $1 \times 1 \times 1.2$ cm^3, which trapped 14,200 G, and one $1 \times 1 \times 1$ cm^3 which trapped 12,000 G. Figure 1 shows the activation curve of the 12,000 G mini-magnet.

The 14,200 G value stands as a world record permanent magnet field, as determined by reports in the current year.[1,2]

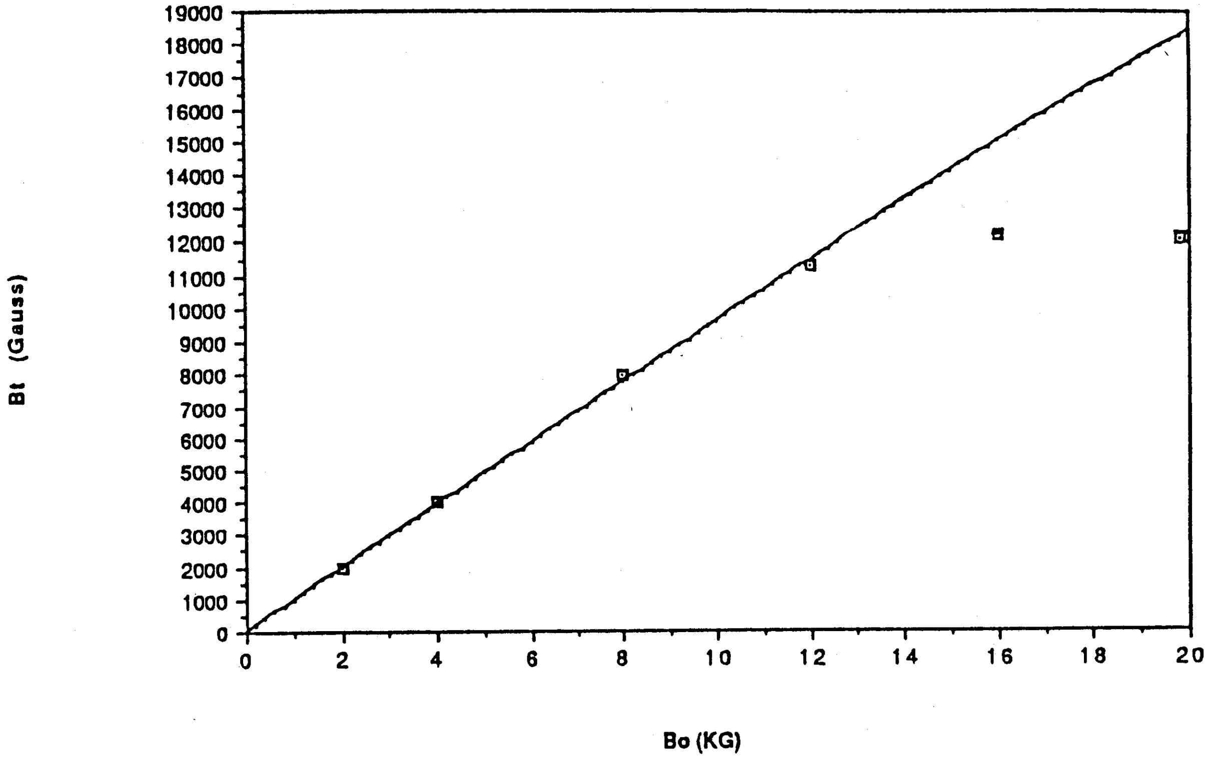

Figure 1. Activation data for mini-magnet $1 \times 1 \times 1$ cm^3. Each point is taken by cooling the material in a pre-existing activation field of the value shown, and then turning off the activation field. (This is the so-called "Field Cooling Method.")

Model of Currents

In order to explain the results, we developed a model of the super-currents which flow in the tiles to maintain the trapped fields. We tried a naive model, using a constant surface current J_S, such as used by Ampere to describe the field of permanent ferromagnets. In addition, we used a constant volume current, J_V, unlike that suggested by Kim,[3] but like that suggested by Bean.[4] Surprisingly this model works excellently, with no modifications. Figure 2 shows the fit of this model to an IUCF produced tile. (The model, with J_S alone, provides excellent fits to SmCo permanent magnets, as expected.)

The insights provided by the model were helpful in guiding further development of the materials. The proton bombardment increases the total critical current, J_C. The Y additive increases the size of the single grains (quasi-crystals) in the tile. The trapped field, B_T, is given by

$$B_T = J_C \times f(d)$$

where d is the grain diameter, and $f(d)$ is a complicated function of d given by the model.

With this understanding, we set up two parallel research and development efforts to increase J_C (a goal of many research groups) and increase d (a goal of very few research groups). At the present time, we have increased d to 2 cm. Using 2 cm tiles, and considering an IUCF experiment planned for August 1992, the model predicts that we will be able to produce a mini-magnet trapping 25,000 G.

The model also enables us to estimate reasonable lower limits of B_T which should be achievable at 77 °K. We expect to reach 30,000 G (3 T) by the end of 1992 and 5 T eventually. These fields, and the value of 14,200 G already achieved, compare to typical SmCo fields of 3000 G. We further note that increases in B_T of about an order of magnitude are achieved by running these magnets at lower temperatures (See Fig. 3).

$^3He^{++}$ *Bombardment*

A second IUCF run during the past year was done using $^3He^{++}$. Conventional wisdom was that the results should look very much like the p^+ data. The basis of this argument is the widely held assumption that for light bombarding particles, only nuclear collisions result in centers which pin the field.

Instead we were surprised to find that a far lower particle fluence of ^3He was needed to match the p^+ results. The ^3He results are shown in Fig. 4. The results are reasonably well described by

$$\Delta B_T/B_T = 2.9\,(1 - e^{-f/f_0})$$

with $f_0 = 2.1 \times 10^{15}/\mathrm{cm}^2$. The f_0 found for ^3He is thus about 1/3 the value found for protons.

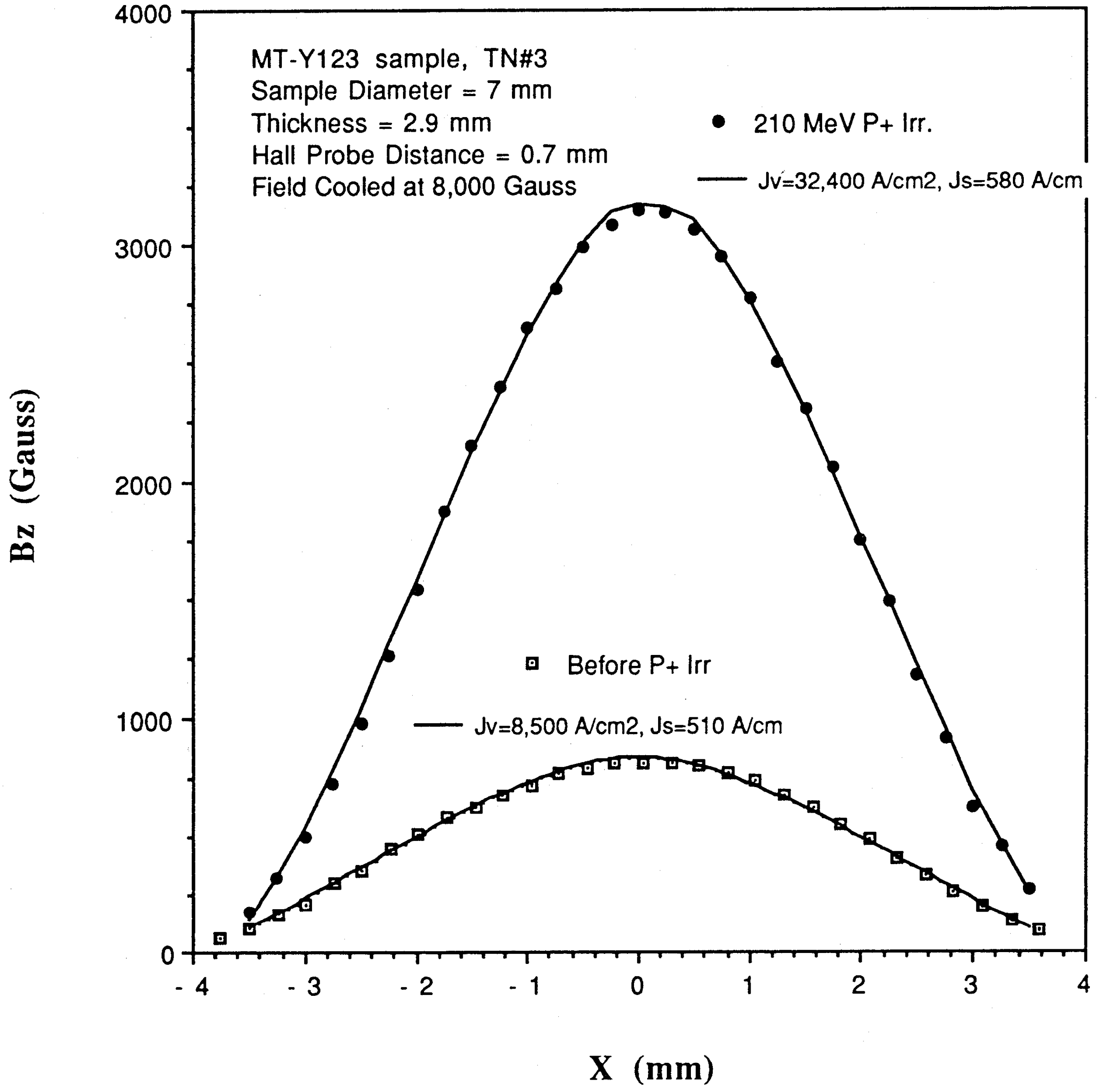

Figure 2. Trapped field vs. traverse coordinate on a single tile, before and after p^+ bombardment. The solid line is the theory described in the text (with two adjustable parameters).

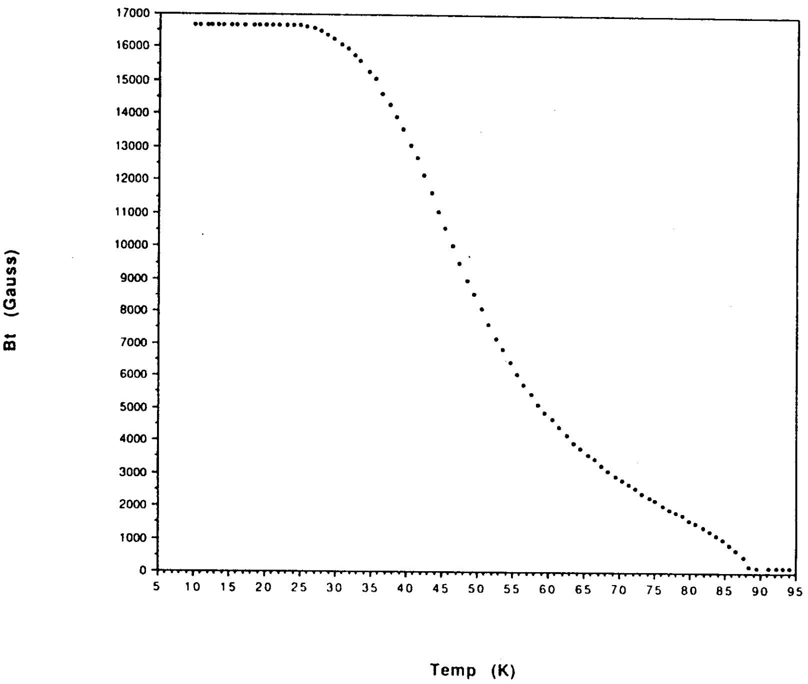

Figure 3. Improvement, R, in field trapping vs. fluence. $B_{\mathrm{T}}(f)/B_{\mathrm{T}}(0)$ for various f are shown. Several separate tiles are used, and two points are taken on each tile. Scatter is due to presently uncontrolled variables.

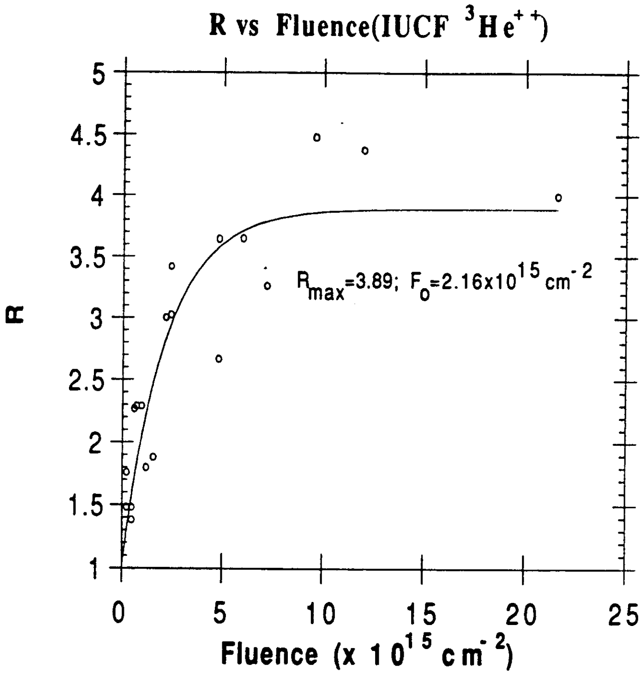

Figure 4. Maximum trappable field vs. temperature. Data is for a single tile, prior to irradiation.

Clearly, even for light ions, dE/dx (which was an order of magnitude higher on the He run) plays a role. Our present model is that $^3He^{++}$ has local upward fluctuations in dE/dx, which form a "string of beads" of damaged material, and these act as good pinning centers.

Current Work and Future Runs

We are currently using both temperature gradients and chemical gradients in our laboratories to grow larger grains.

We are currently performing split beam runs on ^3He and ^4He at IUCF to determine whether ambient temperature during bombardment effects results. Data will be taken at temperatures of 77 °K, 20 °C, and 200 °C. The ^4He run will also obtain further data on dE/dx effects.

We will also perform a high fluence proton run in August, to produce about 20 tiles. With these we can study the limits which self (trapped) field impose on J_C. We also plan to fabricate a small dipole beam-bending magnet with these tiles.

We are also currently using Y(211) grains, in sub-micron size, to emulate p^+ pinning centers in order to produce tiles free of radioactivity.

We are also currently seeding tiles with ^{235}U and using thermal neutrons to produce very high dE/dx fission tracks, such as those produced by Civale *et al.*[5] using Sn ions (but Sn ions are of low penetrating ability). The early ^{235}U results are very encouraging.

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2. R. Weinstein, I. Chen, and V. Obot, Materials, Characterization, and Applications for High T_C Superconducting Permanent Magnets, Proceedings of the Third World Conference on Superconductivity, Munich (World Scientific Press, 1992).
3. Y.B. Kim, *et al.*, Phys. Rev. **129**, 528 (1963).
4. C.P. Bean, Phys. Rev. Lett. **8**, 250 (1962).
5. L. Civale, *et al.*, Vortex Confinement by Columnar Defects in Y123 Crystals, Phys. Rev. Lett. **67**, 648 (1991).