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*Research on Magnet Replicas
and the Very Incomplete Meissner Effect*

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from
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This work (1-19) was undertaken in order to develop permanent magnets composed of high temperature superconductor (HTS). Such magnets are now generally referred to as trapped field magnets (TFM). The particular HTS which most of the work was done on was $\text{YBa}_2\text{Cu}_3\text{O}_7$ (Y123), the composition of which was varied as a result of the research. This will be described below.

At the outset of the work our major goal was to increase the magnitude of field trapped. It would also be useful to reduce the rate of loss of trapped field, called creep, and to strengthen the materials.

At the outset of this work the materials could be categorized by any one of the numbers, given in column one of Table 1⁽¹⁹⁾. The first number gives the maximum field, $B_{t,\text{max}}$, which could be trapped in one "grain," or quasi-crystal of the HTS. This, and all other numbers given in Table 1 depend on the critical current density, J_c , which the grain can support, and the diameter, d , of the grain (or quasi-crystal) in the a,b crystal plane. The trapped field is closely given by

$$B_{\text{trap,max}} \propto J_c f(d) \quad \text{Eq. 1}$$

where $f(d)$ is a monotonically increasing function of d .^(16,7)

The second number given is $B_{t,\text{max}}$ after irradiation by protons⁽¹⁸⁾, to increase the maximum current, J_c . The third number is the maximum field achieved in a fabrication of several tiles. Later numbers give $B_{t,\text{max}}$ at temperatures below 77K.

During the course of this project a variety of approaches were taken to improve $B_{t,\text{max}}$.

	<u>Maximum Trapped Field (Gauss)</u>	
	<u>At Start of DOE Study</u>	<u>At end of DOE Study</u>
Single grain not irradiated	500 G	4,400 G
Single grain irradiated	1,500 G	12,500 G
Mini-magnet	4,380 G	23,000 G
Mini-magnet at T=65K	8,587 G	53,000 G
Mini-magnet at T=55K	--	70,000 G

All data shown is at 77K, unless otherwise specified.

From Table 1 we see that $B_{t,max}$ has been increased from circa 8600 Gauss to 70,000 Gauss during the course of this study, and that field for comparable conditions (e.g., single grain irradiated) has been improved by a factor of 8.⁽⁵⁾

Prior to this work, the record permanent magnet field was 23,000 Gauss, achieved at Stanford in 1976 by Rabinowitz, et al,⁽²⁰⁾ at 4.3 K. We broke that record by achieving 40,000 at 65K, in 1992 ⁽⁶⁾, and then broke our own record by achieving 70,000 Gauss at 55K in 1993.⁽⁵⁾

The stated goal of our original proposal was to achieve over 10,000 Gauss. The reason for this benchmark is that most magnets in use in the world are electromagnets operating at 10-15,000 G. As one exceeds trapped fields of 10,000-15,000 G with TFMs, the reasons to use the new TFMs in applications become more and more compelling. With 70,000 Gauss now available in TFMs, application to products becomes highly probable. Prototyping for applications is now in progress on:

- motors⁽²¹⁾ (Emerson & Reliance)
- generator⁽¹⁾ (Emerson)
- levitating bearings (ISTEC and TCSUH)
- flywheels (ISTEC and TCSUH)
- spacecraft bumper (IBPD-UH)
- MHD boat (Ship & Ocean Foundation, Tokyo)

The improvement in $B_{t,max}$ was accomplished by a variety of techniques. The study of some of these is still in progress, and will eventually increase the field even further. In this class the most notable example is the U/n method, described below.

Excess Y: Varying $YBa_2Cu_3O_7$ by using 20-100% excess Y makes the samples more uniform by dispersing large clumps of the non-superconducting phase Y_2BaCuO_5 (Y211).⁽¹³⁾ The uniformity results in larger grains (which increases d) and acts as pinning centers (which increases J_c). Both effects increase $B_{t,max}$.

Chemical and T gradients: Such gradients allow an increase in grain size, by matching the growth front of the crystal to the solidification temperature.⁽¹⁵⁾

Precision Temperature Processing: Melt-texturing of large grains requires a high degree of temperature control. Our temperature control at 1100° C improved from a 40 degree error to a 1 degree error during the course of these studies.

Seeding: We use $\text{SmBa}_2\text{Cu}_3\text{O}_7$ (Sm123) as a seed crystal to control the location and orientation of the Y123 crystal growth⁽³⁾. This produces an increase of grain size by a factor of two.

Heavy Ion Bombardment: We developed a method of distributing U^{235} in Y123.^(3,5) Subsequent bombardment by thermal neutrons (n°) then fissions the U^{235} . This method uniformly exposes large samples of Y123 to bombardment by fission fragments. Unirradiated Y123 (with excess Y) has $J_c \sim 8\text{-}12,000\text{A}/\text{cm}^2$. Proton or He bombardment increases this to $40,000\text{ A}/\text{cm}^2$. The U^{235}/n° process increases J_c to $85,000\text{G}$. Based upon Eq. 1, we expect that mini-magnets (fabrications) of grains made by the U/n method will achieve fields of $50,000\text{ Gauss}$ at 77K . However, time has not yet permitted us to perform this prototyping.

Platinum: The addition of 1% Pt by weight has been used to control the size and shape of large, undesirable deposits of non-superconducting Y_2BaCuO_5 (Y211).⁽⁴⁾

Reduction of Operating Temperature: A study was done using unirradiated Y123, and a very simple law of temperature dependence was found.⁽¹⁰⁾ This was followed by a study of irradiated materials in which the same law was found to hold.⁽⁶⁾ The law indicates that achievable field at 20K , if cracking of tiles or quenching of field does not cause an earlier limit, is at least $180,000\text{ Gauss}$.

Summary: A wide variety of temperature and processing changes, and high energy irradiation has very substantially increased $B_{t,\text{max}}$. This plus variation of the HTS mix to $\text{Y}_{1.7}\text{Ba}_2\text{Cu}_3\text{O}_7\text{Pt}_{0.01}\text{U}_{25\text{ppm}}^{235}$, has increased trapped field by a factor of 8, and promises an additional factor of 2. The original goal of the work, to produce $10,000\text{ Gauss}$ of trapped field, has already been exceeded by a factor of 7.

A variety of applications including motors, generators, levitating bearings, flywheels, magnetic bumpers and MHD propulsion are in progress at various labs and industries.

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