We are studying the trapped magnetic field, $B_t$, in high-temperature superconductors (HTSC). At IUCF we study the improvement of $B_t$ achieved by radiation-induced pinning centers. We have studied radiation-induced pinning centers using $^1\text{H}^+$, $^3\text{He}^{++}$ and $^4\text{He}^{++}$ bombardment at IUCF, and using thermal neutrons at the Texas A&M reactor in the reaction $n^0\text{U}^{235}+\text{f}\rightarrow\text{f}^+\text{f}'$.

We define $R$ to be the ratio of the trapped field before irradiation to the trapped field after irradiation. For high-energy charged-particle bombardment we find:

$$R = 1 + \Delta R_{max}(1 - e^{-F/F_0})$$

where $F_0 \approx 6 \times 10^{15} \text{ p}^+ / \text{cm}^2$ or $2.1 \times 10^{15} \text{ He}^{++} / \text{cm}^2$. Fig. 1 shows the trapped field in a tile of HTSC before and after $p^+$ bombardment. Fig. 2 is an example of Eq. 1 applied to a $^3\text{He}^{++}$ run done at IUCF.

The trapped field is given by:

$$B_{t,max} \propto J_c f(d)$$

where $J_c$ is the critical current, $d$ is the diameter of a current-carrying grain (quasi-crystal), and $f(d)$ is a monotonically increasing function of $d$. $J_c$ increases with the number and quality of pinning centers, and also increases with decreasing temperature. During the past year, we did a systematic study of how $J_c$ depends on temperature. Using this and the expression for $B_{t,max}$, we found a simple phenomenological law valid in the region $20 \leq T \leq 65 \text{ K}$:

$$B(T_2) = B(T_1) \left[ \frac{93 - T_1}{93 - T_2} \right]^2$$

We had previously studied $B_t$ at 77 °K and, by pumping on the liquid nitrogen, at 65 °K. We found:

$$B_t(65 \text{ °K}) = 2.6B_t(77 \text{ °K})$$

Thus a magnet made of the processed materials will trap eighteen times as much field at 20 °K as at 77 °K.

We used a set of 8 tiles which had been bombarded at IUCF to construct a mini-magnet. The tiles were composed of $Y_{1.4}\text{Ba}_2\text{Cu}_3\text{O}_7$, and were a mixture of $^1\text{H}^+$ and $^3\text{He}^{++}$ bombardment products. This magnet set a record for field trapped at 77 °K, $B_t = 1.52 \text{ T}$ (Ref. 2). The results are shown in Fig. 3.
Figure 1. Mapping of magnetic field vs. position on a tile of HTSC, before and after irradiation with $^1\text{H}^+$ at 200 MeV at IUCF.

Figure 2. Plot of $R$ vs. fluence for $^4\text{He}^{++}$ bombardment. The data were taken at IUCF.
Figure 9. Trapped field at 77 °K and 65 °K. At each point the warm mini-magnet is placed in the activation field, $B_A$. After cooling, the magnet traps a field $B_t$.

During the past year we obtained and refurbished a low-$T_c$ superconducting activation magnet capable of 10.7 T fields. We are also building, but have not yet commissioned, a cryostat to achieve constant $T$ in the range $10 \leq T \leq 77$ °K. In lieu of the cryostat, we again pumped on the liquid nitrogen to obtain 65 °K. Using the high-field activation magnet, we achieved a stable trapped field of $\sim 4$ T (Ref. 3, see also Fig. 3) on the 8 tile magnet processed at IUCF.

The previous record for a permanent field for any bulk material at any temperature was set at Stanford University in 1976, and was 2.3 T at 4.3 °K. This 17-year-old record has now been surpassed.

We continue work to increase $J_c$, and increase $d$. To date, both have been doubled compared to the materials in the record magnet. However, even the old materials have excellent potential. The expression for the maximum trapped field indicates that the record magnet (4 T at 65 °K) will trap $\sim 27$ T at 20 °K. Before reaching this field, we expect the tiles to crack under $B^2$ pressure. We will study this cracking in the near future, and methods to prevent it.