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FAST SUPERCONDUCTING KICKER MAGNET

Final Technical Report

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DISCLAIMER

I. INTRODUCTION

Fast kicker magnets are needed in accelerators to deflect the beam out of the storage ring and into experimental targets and beam dumps.

The work reported here is on a new type of fast kicker magnet. The basic idea is to transport the beam along the axis of a tube made of Type I superconductor. An ordinary magnet is used to create a field, B_o perpendicular to the axis of the tube. If $B_o<B_c$, where B_c is the critical field of the superconductor, the tube remains in the superconducting condition. Due to the Meissner effect, the tube shields the beam (on the axis of the tube) from B_o. Thus the beam is in a zero field region.

In order to apply a kicker field to the beam, B_o is increased such that $B_o>B_c$. The tube of superconductor then goes normal. The field which had been shielded from the beam can now penetrate to the beam. This concept is applicable as a fast magnetic switch. DOE has been granted a patent on this device, which was disclosed to DOE by N.K. Mahale and D. Goren while they were at SSC.

In accelerators such as the Fermilab Booster, the train of bunches does not have a large gap to accommodate the large rise time of conventional extraction kickers. As a consequence, several bunches are lost during extraction with conventional kickers. In addition, some of these bunches are steered into the septum, resulting in serious damage and radioactivity.

We aim to make the switching time of the new magnet as short as we can. (We estimate 1-10ns may be feasible.)

One desires the field, B_o, close to the value of B_c, but slightly below it. An additional coil will raise the field by ΔB_o, such that the total field seen by the superconductor switches from $B_o<B_c<B_o + \Delta B_o$.

The kicker's magnetic field at the beam, with the kicker field acting on the beam, will thus be about $B_o + \Delta B_o$.

The rise time of this field is limited by the rise time of the added field, ΔB_o, and by the effect of any inductive materials present. The movement of flux into the region of the beam results in a magnetic flux change in the region, resulting in induced EMF, and therefore bucking fields. This results in an inductive rise time for the field within the tube.

Thus, in order to decrease the rise time, as little metal as possible should be present. The superconductor tube should also be as thin as feasible. We estimate that a kick of over 1000 Gauss can be achieved if thin Niobium film and a suitably fast coil are used.

We report below feasibility studies on this new form of kicker magnet.

II. Equipment Built, and Tests Run.

A. Cryostat and Transducers

In order to perform tests, we first designed a non-metallic cryostat, the lower half of which is entirely made of G-10. This was produced by Cryo Industries of America. A metallic cryostat would have inductive effects which would slow the magnetic field rise time, and the eddy currents would affect other experimental results. An existing 2 Tesla electromagnet in our lab was used. This has pole faces 6.5 inches apart. This does not allow us, though desirable, a nitrogen jacket in the cryostat. A vacuum space between inner and outer G-10 cylinder is the only barrier to heat transfer. The inside diameter is 3 inches and outside diameter is 5.75 inches. The test specimen hangs from the cryostat top plate (bulkhead) via G-10 rods.

For magnetic field measurements we installed both a hall probe, and a loop-probe. We also installed a temperature probe. A series of resistors was constructed to measure the liquid He level. The loop probe produces a 6.5mV response per Tesla/second field change. The experimentally observed response time of the loop probe is of the order of a fraction of a microsecond. The probes are supported on a G-10 rod which passes through the bulk head.

B. Magnetic Field Variation

The major component of the applied field, B_o, is provided by the 2 Tesla variable laboratory magnet. A fast, low field, tickler coil was planned to drive the superconductor normal. At the outset of the studies, funds did not exist for the tickler coil construction or its associated electronic pulser. As a result, we used the main magnet itself to raise the field at different rates. As a consequence these rates are relatively slow. This stage of work allowed us to measure the parameters needed to design the final tickler coil. The rate of increase of field was controlled through a voltage input to the control circuit of the magnet from LabView. The ramping of the magnet and data acquisition were synchronized through an Apple Quadra computer with the LabView software. The Hall probe has large noise, while noise in the loop probe is much lower. To filter the noise out we averaged several readings. For the hall probe we averaged 50 readings, while for the loop probe we averaged over five data points. For the loop probe we have a data point every 10ms. Thus this early test is slow.

C. The Superconducting Tube

We had initially proposed to study Niobium (Nd) tubes of various thicknesses and diameters eventually using thin films of Nb. In the interim, however, we concluded that it would be better to switch to Lead (Pb). The material chosen must exhibit the basic effect, have a sharp value of B_c, and allow us to study rise time and dependence on thickness of the film and diameter and shape of the tube. We proposed to investigate Niobium tubes of various thickness, rather than pipes coated with thin films of Niobium, in order to more rapidly achieve a proof-of-principle, and to keep down the cost and variability of the special thin film coated beam pipes.

In order to develop clean signals from the working of this switch we observed the response of the probe to the ramping of the magnet at (a) liquid helium temperature and (b) at liquid nitrogen temperature. The experiment in liquid nitrogen measures the ramping of the magnet because the beam pipe is normal. In liquid helium, however, the beam tube sample is below T_c. Hence, for low fields, the applied field is shielded, and the field inside the beam pipe is negligible. When the applied field exceeds the critical field, B penetrates, and the loop response shows a spike. This clearly shows the quenching of the superconductor. The width of the spike gives the rise time.

Fig. 1 shows the data for a Pb tube of 90 mill thickness. The curve without a spike was taken in liquid nitrogen, and the curve with the spike was taken in liquid helium. It is seen in the data of Fig. 1 that initially the field rise is shielded. Then, at about $t \approx 0.2$ sec., the field penetrates as shown by the leading edge of the spike. After the spike we see the two curves merge which shows that the Pb has become normal and the field inside the beam tube at liquid helium temperature follows the same magnet ramping as it does at liquid nitrogen temperature.

Comparison between Nd and Pb

Fig. 2 shows data for a Niobium tube, with the magnet being ramped at the same rate as for the Pb tube discussed above (Fig. 1). The Lead we use is 99.95% pure. However, the purity of the Nb is not known. First we note that the field penetration is at much higher rate in Nb, as shown by the difference in pulse size compared to Pb. Unfortunately, however, there are several spikes, indicating that the transition field of the Nb tube, to its non-superconducting state, is not uniform. In addition we see that the curves do not merge for a long time. This we believe is due to two reasons. First, the Nb material is not pure and therefore the difference between the two

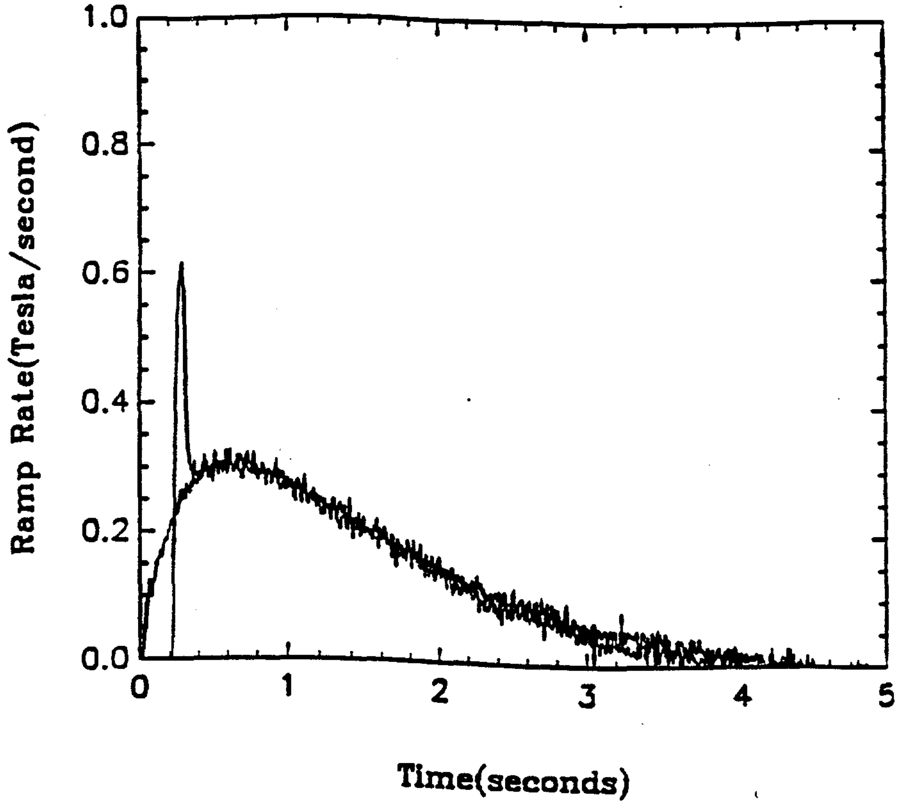

Figure 1: **Comparison of Pb at** 4.2°*K* **and at** 77°*K*.

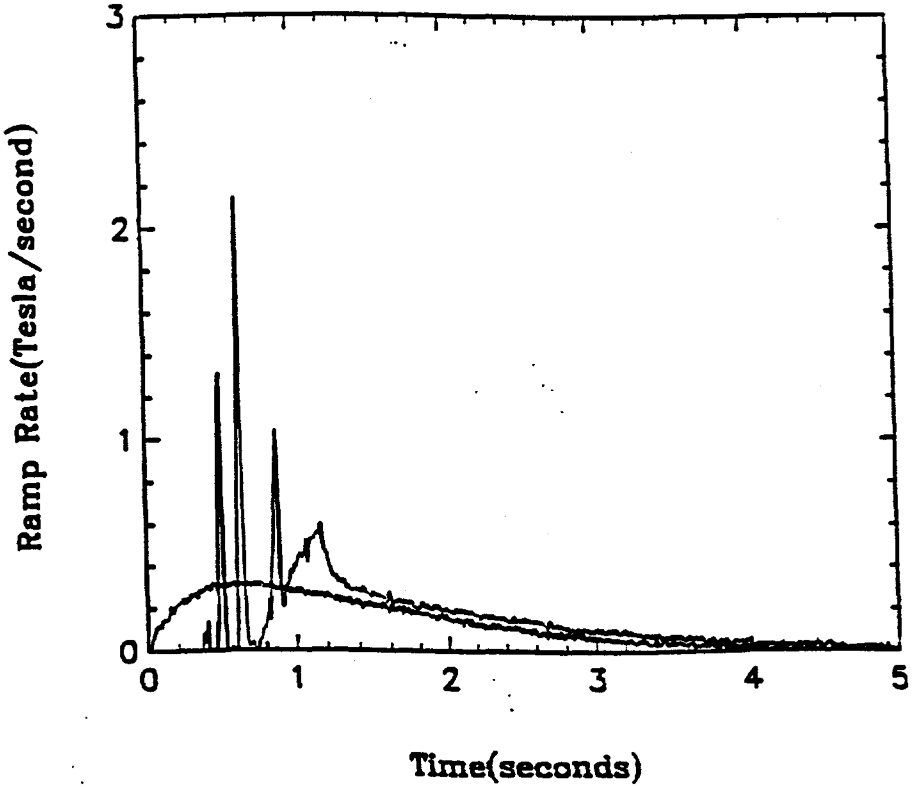

Figure 2: **Comparison of Nb at** 4.2°*K* **and at** 77°*K*.

critical fields is rather large. Several spikes indicate that *the Niobium specimen lacks uniformity in material.* The material is probably stressed and indicates the need to be stress annealed. However, also notice the better side: *dBdt* is much higher, and if a uniform Niobium tube could be made the three spikes would combine into one, and a large signal would result.

There is at present no adequate theoretical understanding of sudden penetration of field. We expect that if the several Nb spikes can be made to coincide by purifying and annealing the Nb the rise time will be further shortened. However, this would require added equipment expenditure for thin film Nb tubes and the funds were not available. This is one of the reasons we chose to experiment with Pb.

A second reason to chose Pb was that it remains a Type I superconductor when a sheet is wrapped around the tube. Thus, with one thickness of Pb foil we can wrap varying numbers of turns, and hence varying thicknesses of Pb around the beam tube without purchasing several separate beam pipes.

D. Effect of Ramping Rate of Magnet

Fig. 3 is for a 90 mill Lead tube, with 99.95% purity. Here we show the response of the loop probe at different magnet ramp rates. For clarity we only have plotted the quenching curves. The curves are for four different peak ramp rates of about 0.1, 0.2, 0.3 and 0.4 Tesla per sec. It is seen that, as the field is more rapidly increased, there is an increase in the heights of the spikes and reduction in the width. This data shows that the rise time we observe in this configuration is not the inherent penetration time, but is the time to raise the field from H_{c1} to H_{c2}. This indicates that the secondary, or tickler coil is needed to raise the field in a matter of nanoseconds. We used this experiment (Fig. 3) to define the parameters of the needed secondary coil, plus the cost of the high power fast pulsed electronics.

E. Comparison of Two Tube Thicknesses

Fig. 4 shows the results for a 10 mill lead foil wrapped around a G-10 tube. The ramping rate of the applied magnetic field is the same as that for Fig. 1. Though the pulse width seems to be different, the width at the base is the same. This shows that the ramp rate of the magnet is a dominant factor. Within the accuracy of measurement the two curves are not significantly different. With the difference in the thickness involved in Figs. 1 and 4 (a factor of 9), we should expect a large difference in the rise time if inductive limitation was occurring due to the tube. Instead, the rise time is essentially governed by the time required to raise the field from H_{c1} to H_{c2}.

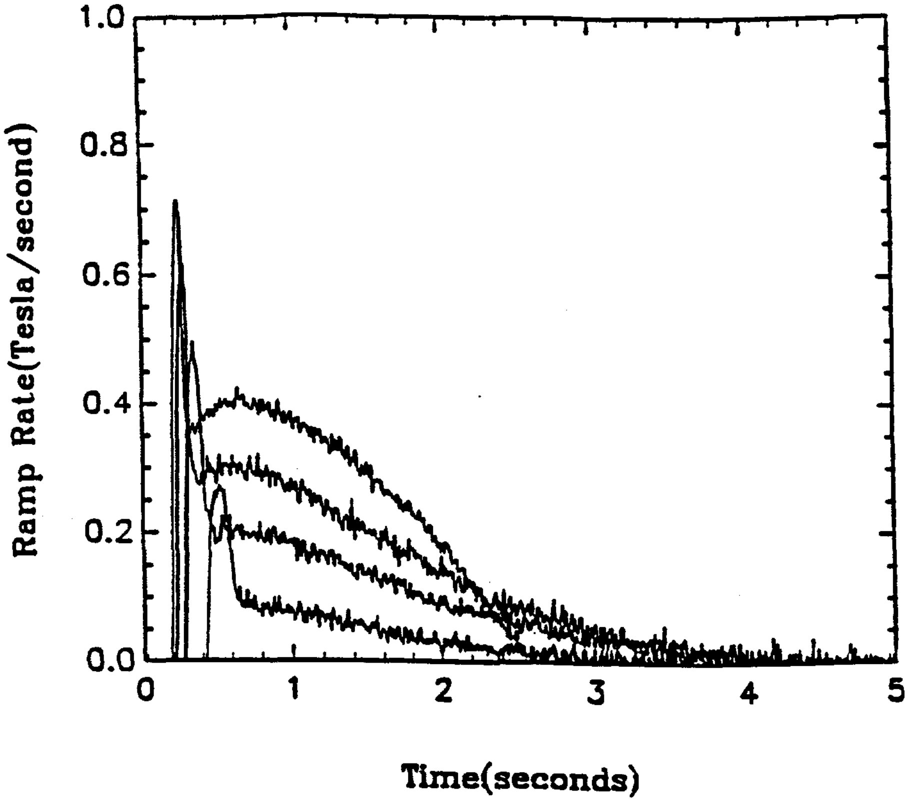

Figure 3 Effect of Ramp Rates on the Field Penetration

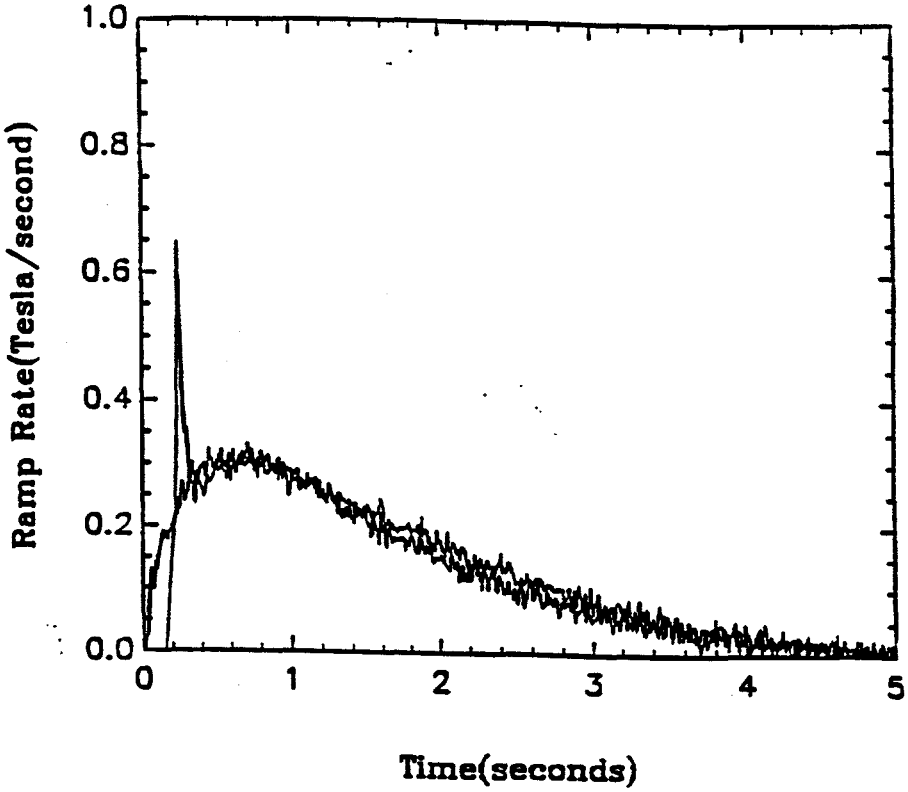

Figure 4 Field Penetration with a 10 mill shield

F. Trapped Field Reversal

Any work hardening, bruising, etc., in a Type 1 superconductor, crates regions which have been converted to Type 2. This is an added reason why lead was chosen over Nb for the early work. It is less subject to work hardening. As a consequence of work hardening of the Nb tube, when the external field is reduced there remains some trapped field. This can be expelled by heating the superconducting material between switching cycles. Another way to recycle the kicker is to jump from the trapped field in the opposite direction. Fig. 5(a) shows a schematic diagram of the trapped dipole field. If we apply the external field in the opposite direction, once the material becomes normal, we will get the field as shown in Fig. 5(b). To investigate this behavior we applied a field opposite to the trapped field after the external field had been reduced to zero (corresponding to the experiment for Fig. 1). Fig. 6 shows the results of this experiment. The penetration spike is larger than in Fig. 1. This suggests the possibility of recycling the kicker magnet in this manner. The quality of the trapped field needs to be good. Higher multipoles of the field should be insignificant or should be correctable. Also, we see some penetration before the big spike. However, purer material could improve this significantly. If this mechanism is usable, it would approximately double the kick obtainable from Type 1 superconductor.

G. Heat Generation

During quenching we expect some heat generation. This heat should evaporate some liquid helium, and if the heat generated is significant, we should see a puff of helium gas coming out of the vent. In all the experiments no release of He gas was observed. Apparently there is more field energy in the field configuration when the field is shielded. But the shielded state is at least a metastable state and is a local minimum of thermodynamic free energy. The superconducting state consists of Cooper pairs and there is binding energy associated with pairing of electrons. Field penetration requires that some of the Cooper pairs be broken. This gives rise to a minimum in the free energy. It appears that most of the excess field energy in the shielded configuration is spent in breaking the Cooper pairs. It is well known that, though the phase transition near T_c is second order, away from the critical point transition through magnetic field involves latent heat.

H. Argon Oven

It is evident in Fig. 2 that the Nb tube is not uniform. Although most initial tests were done with Pb, we planned to later use annealed Nb thin films. Hence a programmable oven was designed and built which was capable of annealing Nb in an Argon atmosphere.

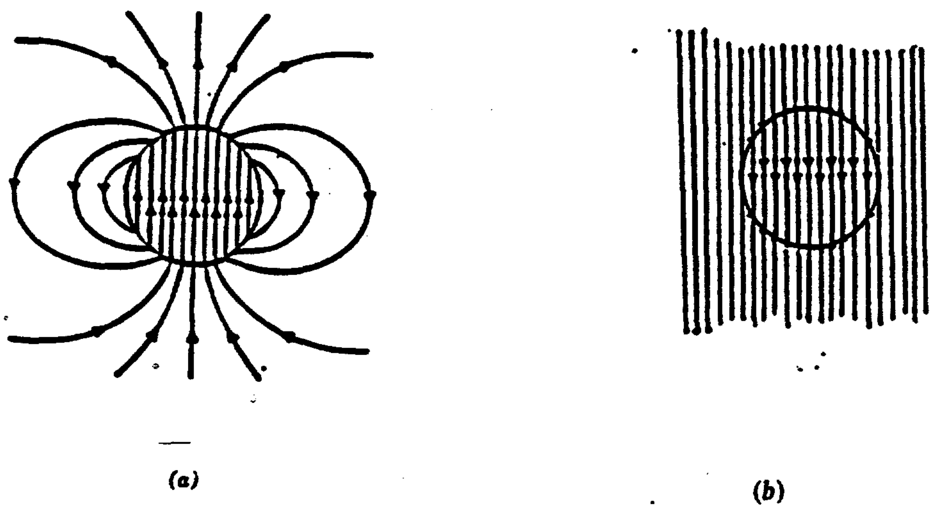

Figure 5 Trapped Field Reversal Kicker Principle

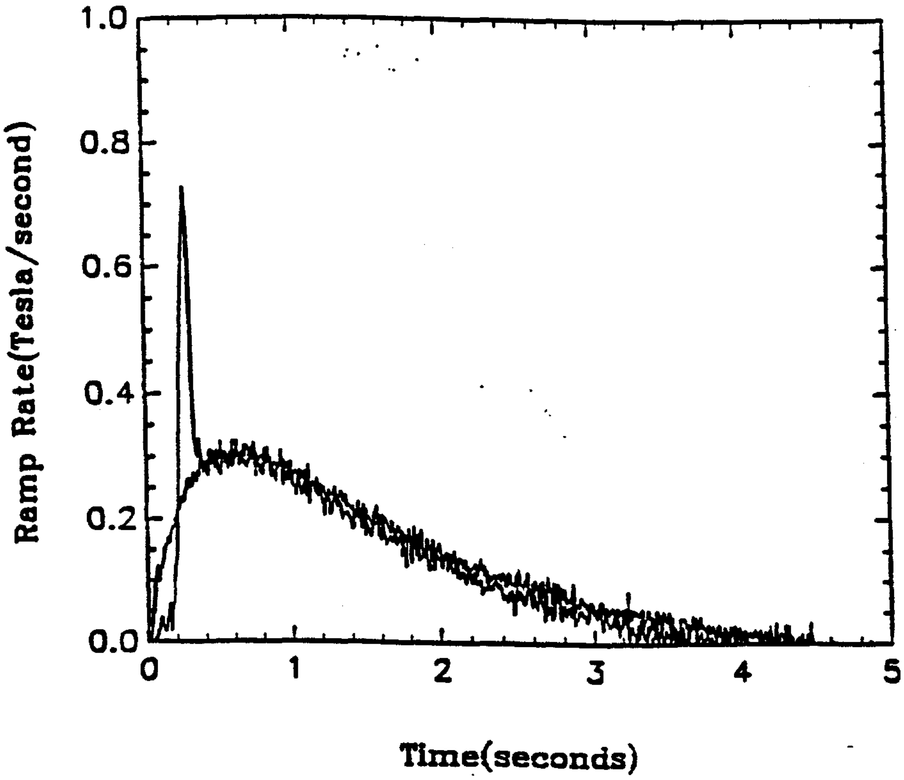

Figure 6 Field Penetration with reverse trapped field

Summary

We built a G-10 cryostat, a programmable oven for annealing Nb in Ar, and associated measuring devices. Design of the "ticker" coil was done after its parameters were set by experiment. A pulsing circuit was then designed. While we desire ultimately to explore the 1-10ns region, the cost of the required pulser, for this time range, made its construction prohibitive at the present time. A 1ms coil and pulser allow for a feasibility check, at reasonable cost, of the much more expensive 1-10ns coil. We therefore built a pair of Helmholtz coils with a rise time of about 1ms which can provide about 200 gauss field, and started testing with these secondary coils. The cost of this coil was very small. If we operate the field of the primary magnet at about 200-250 gauss, and kick in an additional field using the 1ms Helmholtz Coil, this is adequate to drive the material normal. Using this system, we were able to reduce the upper limit on the rise time measurement by a factor of about 100. At this point, using the thick superconducting Pb sheets described above, it is likely that we will be able to measure and learn about the inherent rise time. If the field is raised beyond critical field suddenly, we will learn how long the field takes to penetrate a given thickness of superconductor. We do not yet have experimental evidence on scaling. If, however, we assume the scaling similar to a normal conductor, the rise time scales as the square of the thickness. The present limit of 0.1 sec rise time for 90 mil Pb tube indicates that a 10 nanosecond rise time will require film thickness of about .8 microns. The time delay caused by the Lead tube of thickness of 10 mil, at room temperature, is a fraction of millisecond. We should observe this rise time with our millisecond pulse, and thus provide experimental evidence on scaling. In our original proposal we estimated required thickness of about 8 microns for Nb. Thus the above argument indicates that we are a factor of ten off, and we still have room to improve (a) purity and uniformity of the material, (b) shape of the tube, and (c) the material itself.