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## **High Temperature Superconducting Magnet Control Actuators for the NGST**

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## **Executive Summary**

In this program, the use of high temperature superconducting monoliths for drivers for actuators was investigated. The properties of commercially available bulk YBCO and BSCCO monoliths were measured, and compared with those obtained in laboratory samples. The monoliths were charged, and the capability of holding field was determined.

It was found that the properties of commercially available YBCO monoliths was substantially lower than that of laboratory samples that had been carefully manufactured. The reason is that the material is not single crystal, as advertised by the commercial vendors. Carefully manufactured, single crystal disks can be manufactured, but are not commercially available. For BSCCO, on the other hand, multigrain commercially available material is all that is commercially available, and its performance agrees with reported properties.

Two charging schemes were investigated: saturation pumping and flux pumping. A simple driver consisting of a capacitor, a switch, a load-matching transformer and driven by triggers from a computer system was built. The computer system also provided the data acquisition necessary for the system. It was found that even though the superconductor was truly persistent, there were transients. The transients lasted varying amounts, and as long as 12 hours, and the amount of the transient was ~10 % of the field. The transient time-constant as well as the fraction of the field variation during a transient, have a large distribution of values, lasting in some cases from a few minutes to 24 hours. At this point, the nature of the transient is not well understood.

A total of 19 actuators, with different geometries and materials, were tested.

It is concluded that because of the transients, the best application of this type of magnets is for controlling actuators that do not require very sensitive setting, such as on-off actuators, or gross-motion actuators.

## **Abstract**

The use of monolithic high temperature superconductors in solenoidal configurations for use as actuators is analyzed in this report. The properties of monolithic high temperature superconductors are documented. Monolithic tubes, disks and rods of different cross section and sizes can presently be obtained from several commercial vendors. In this report, design issues solenoidal magnets using single crystal or highly textured YBCO monoliths are addressed, as well as multigrain BSCCO 2212. The properties of these materials operating at elevated temperatures ( $> 10$  K) are summarized. High field, cryo-stable, highly complex solenoidal magnets can be manufactured in the proposed manner. The charging schemes for the disks, based upon induction, are also addressed.

## I. Introduction

High temperature superconducting (HTS) materials are ceramic and brittle in nature. The development of long lengths of wires or tapes suitable for winding magnets has limited the application of high-temperature superconductors. The same solutions associated with high performance A-15 superconductors (such as  $\text{Nb}_3\text{Sn}$ ) are being pursued in the fabrication of HTS wires. Presently, the wires and tapes have small superconductor fraction, with a large decrease of the “engineering” current density. The non-superconducting fraction is a requirement of the fabrication process, rather than driven by design considerations. In addition, joints between wires/tapes are also difficult to prepare.

On the other hand, bulk HTS materials have been manufactured in large sizes. These materials are either single crystal or multiple crystals, with currents flowing across the grains. In particular, BSCCO 2212 and YBCO-123 have shown excellent characteristics at low to intermediate temperatures and high fields. YCBO has impressive performance even at high temperatures.

BSCCO 2212 shows good intergrain current transfer even though the intragrain current density is substantially smaller than that for the YBCO materials. The BSCCO bulk material is being fabricated for applications as current leads in superconducting magnets and for current interrupters [Bock, Elschner, Herrman, Albrecht]. The YBCO material has also been used for current leads for both SMES [Neimann] and for superconducting magnets [Hull], and is being manufactured as levitators [Ohyama]. The most impressive performance of YBCO at 77 K has been obtained by the group in Texas [Ren, Chen, Weinstein]. In addition, YBCO flat disks have been manufactured by Boeing [Blohowiak], and are available from commercial vendors [Aventis (Frankfurt), Superconducting Components (Illinois), among others].

In the past, solenoidal and dipole-type magnets from high temperature superconducting BSCCO 2212 tubes were tested by the MIT group. The BSCCO bulk material tested was manufactured in the shape of hollow cylinders. YBCO disks have also been tested. The superconducting material is near single crystal in the case of YBCO, while it is textured in the case of BSCCO 2212.

Since the bulk HTS materials do not have leads, they are referred as monoliths. The superconducting monoliths are charged by induction, using externally applied magnetic fields. In the past, the MIT team has tested solenoids with a self generated 3 T, and inserts producing a net 21 T in a 20 T background field. In addition, a 1.2 T self-generated dipole magnet, and a 5 T dipole in a 4 T background have been successfully tested

The behavior of the high  $T_c$  magnets differs from that of typical A-15 superconductors. At low ramp rates (rate of variation of an externally applied field) and at critical conditions, the magnetic field can be made to flow in the superconductor without quenching. At high ramp rates and low temperatures, the magnets experience quench-

like phenomena, but recover before all the current has disappeared. At the higher temperatures, the magnets do not experience quench-like phenomena at the fastest ramp rates that we have tested.

In this report, the issues of designing solenoidal magnets for use as actuators using YBCO disks and BSSCO tubes are discussed. The design options are investigated, exploring the design space. The methods of charging the monoliths are described. Finally, the conclusion summarizes the work and describes applications where monolithic, high temperature superconducting magnets may offer attractive options for the design of actuators.

## II. Superconducting Properties

### A. YBCO properties.

The properties of YBCO 123 have been determined by several teams. The most impressive results have been obtained by the teams in Texas [Sawh] and in Japan [Ohyama].

Measurements of YBCO-123 properties at several temperature as a function the magnetic field are shown in Figure 1 [Maley]. These results were obtained for highly textured tapes, and show the difference in the behavior of these highly anisotropic superconductors to fields that are applied either perpendicular or parallel to the main plane in the crystal.

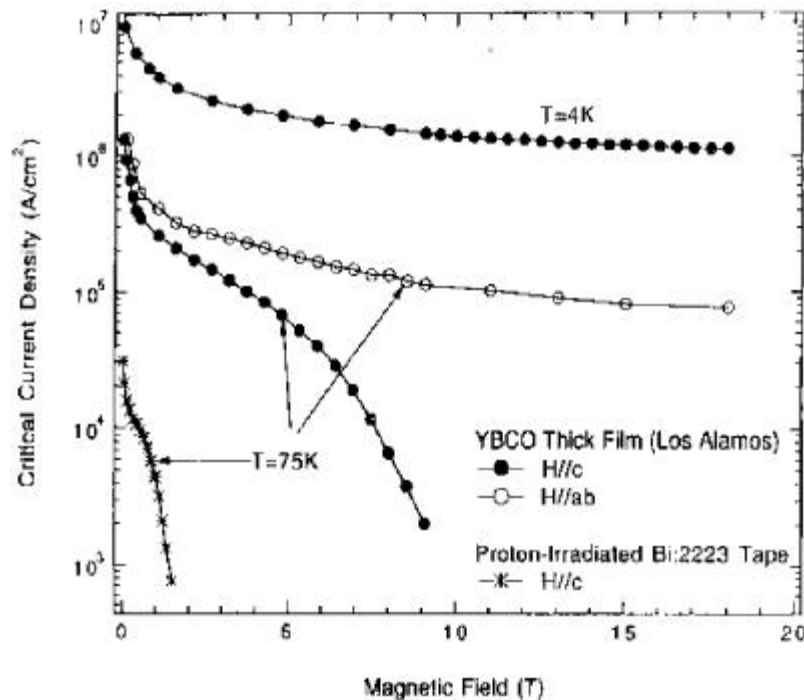


Figure 1. Critical current density for YBCO-123 as a function of field, for several temperatures and for different orientation of the field with respect to the crystal.

We will assume properties obtained by the group in Texas [Sawh] using monolithic disks. In those studies, the field on the surface of a 30 mm diameter disk, 10 mm thick, was on the order of 10 T at 55 K. Assuming that the current density is not a strong function of the field, it is possible to calculate the critical current density in the superconductor at this temperature. Figure 2 shows the contours of constant magnetic field and the flux lines for a sample of the size used in the experiments. With a peak field at the surface of the superconducting monolith of 10 T, the current density in the superconductor, at field and at 50 K, is  $1.67 \cdot 10^9 \text{ A/m}^2$ . The peak magnetic field, which occurs inside of the superconductor, is on the order of 16 T.

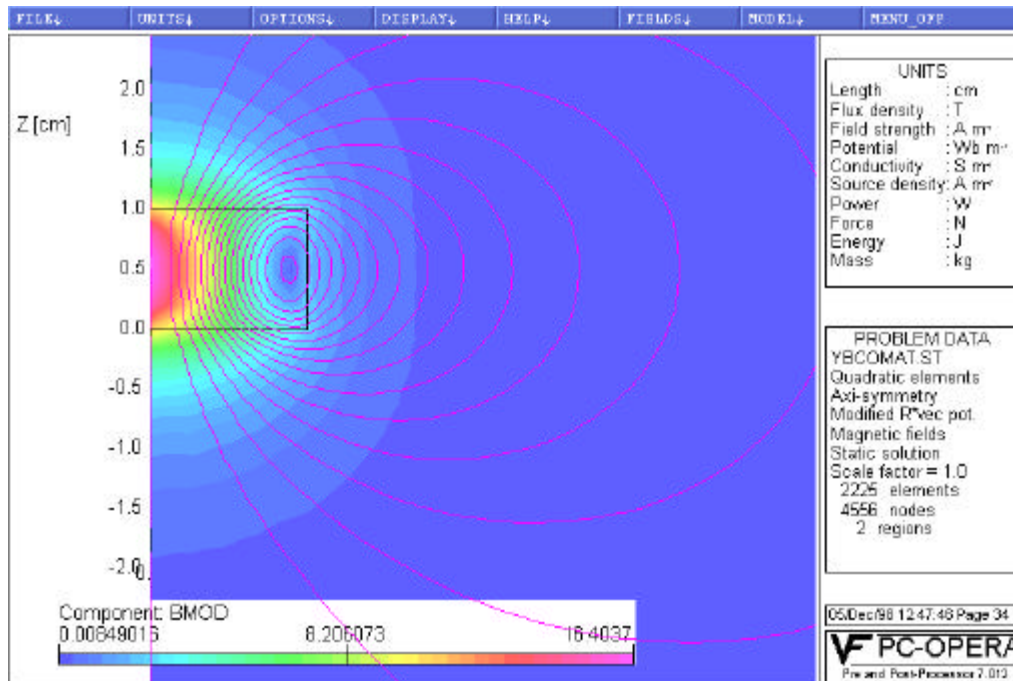


Figure 2. Contours of constant magnetic field and flux lines for a YBCO sample, assuming a uniform current density of  $1.67 \cdot 10^9 \text{ A/m}^2$ .

It should be noted that this performance is comparable to the non-copper current density of  $\text{Nb}_3\text{Sn}$  superconductor, at 4 K and 10 T. Indeed, once the structure and stabilizer/quench protection is included in the  $\text{Nb}_3\text{Sn}$  designs, the average current density is substantially lower than that for YBCO at elevated temperatures.

Some of the difficulties of using low temperature superconductors are solved by the use of high temperature superconductors at higher temperature. The problems of flux jumping and coupling losses that at low temperatures require the fabrication of filamentary superconductors, can avoided by operating HTS materials at the higher temperatures. However, manufacturing issues of the tapes/wires, as well as their use in winding magnets, may require that HTS wires be fabricated using filamentary superconductors or thin films on tapes.

The properties of YBCO disks, purchased from Superconducting Components, Inc, (<http://www.superconductivecomp.com/index.html>) were measured. 10 disks were purchased, in order to determine variation from one disk to the next. The disks were purchased it two different times, in order to test different batches.

A picture of the disk is shown in Figures 3 (a) and (b). The disks are 25 mm (1 in) in diameter, and about 12 mm long (1/2 in).

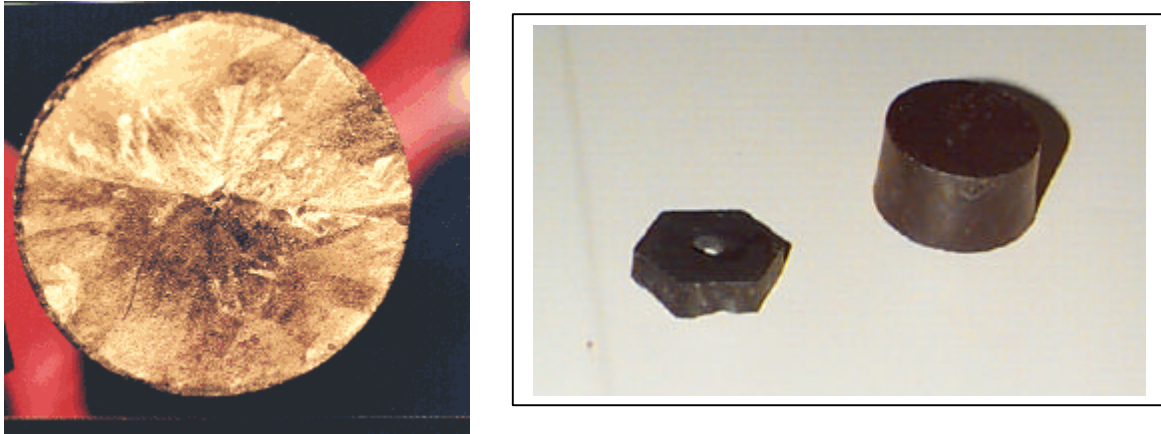


Figure 3. (a) Picture of a 1 in disk, made of near-single crystal YBCO by the method of melt-texturing, grown from a seed; (b) smaller sample, with a hole through the axis, next to a full size YBCO disk.

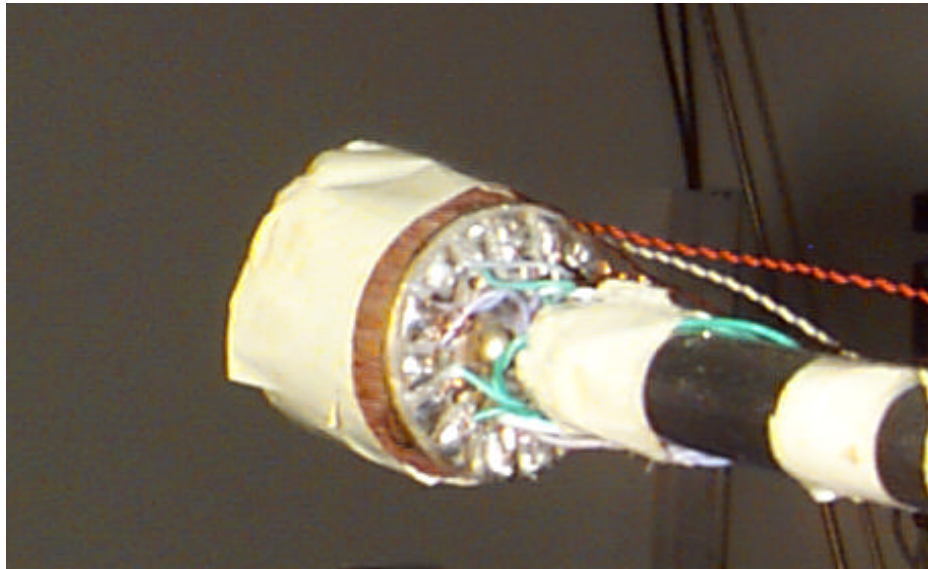


Figure 4. Picture of the probe used to determine characteristics of YBCO samples. The sample has a temperature and a Hall probe sensors.

The disks were mounted on a probe, and tested in a constant temperature cryostat. A picture of the probe is shown in Figure 4. The temperature was measured using a Cernox resistor model CX-1070-SD, obtained from Lake Shore Cryotronics, Inc.

(<http://www.lakeshore.com/>). The calibration was obtained from 3.5 K to 55 K, and it was extrapolated for temperatures higher than 55 K.

The Hall probe used in the measurements was obtained from the Lebedev Physics Institute in Moscow, Ru. It was carefully calibrated in Moscow, and was recalibrated at MIT using a carefully built magnetic field coil and a Keithly current amp-meter.

The characteristics of different disks were different. Figure 5 shows the characteristics of the critical self field (where it is on the superconducting/normal boundary at the given field, current density and temperature) for one of the disks. The behavior indicates multiple grains on the disk.

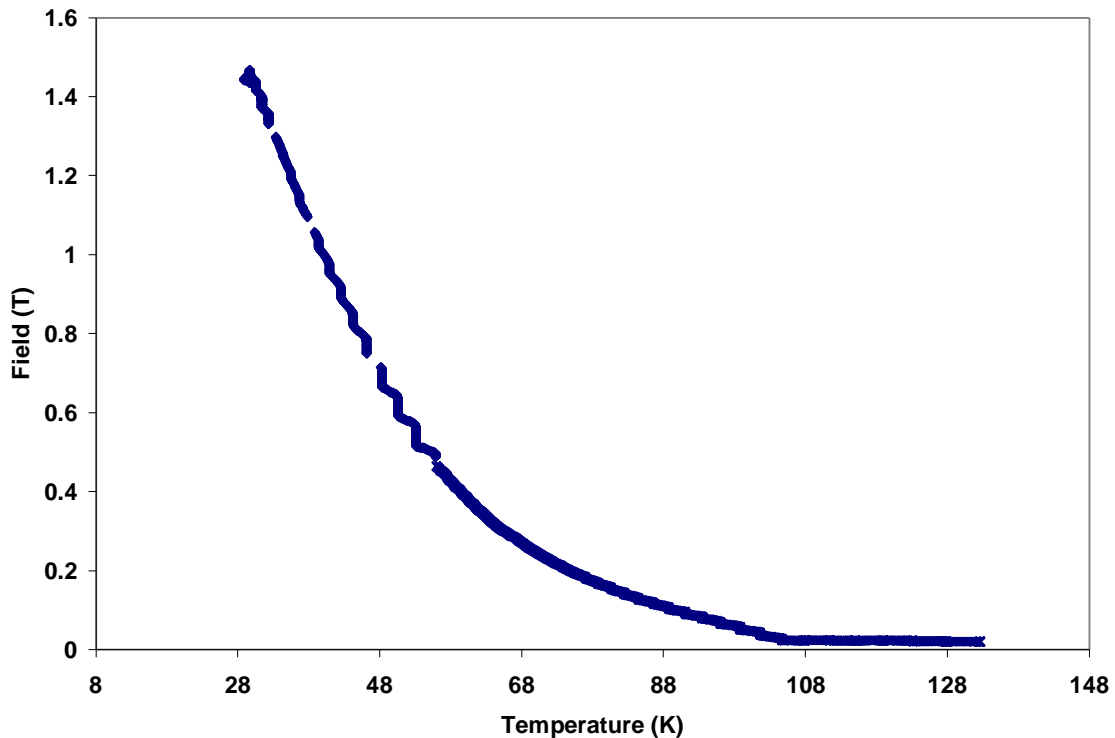


Figure 5. Critical self field for YBCO samples as a function of temperature.

This presence of multiple grains was verified by moving the Hall probe, at liquid nitrogen temperature, on the surface of the disk. The measurements indicated that the magnetic field structure on the surface of the disk had off-axis peaks, and indeed the maximum field was near the edge, indicating that the largest crystal occurred at the edge of the disk.

## B. BSCCO properties.

The BSCCO material that was tested in the program was obtained from Hoechst in Frankfurt, now Aventis Superconductors (<http://www.aventis.de/en/index.htm>). This material has much lower critical current densities than single crystal YBCO, but it is



easier to manufacture. Some of the samples (actuators) that were tested in this program are shown in Figures 6 and 7, with the copper winding/windings in place around the superconductor.

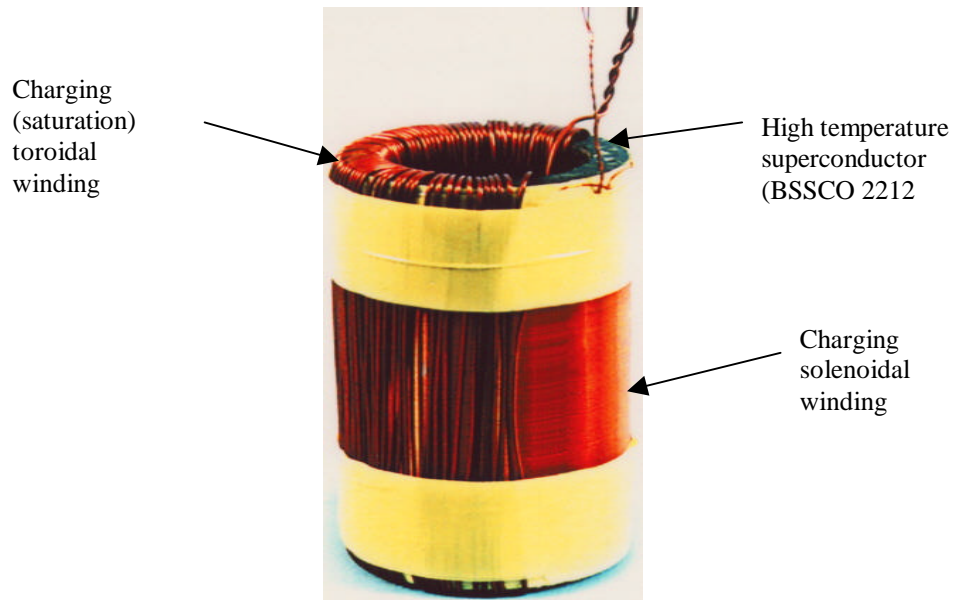


Figure 6. Picture of a BSSCO 22121 tube that is ready for testing.

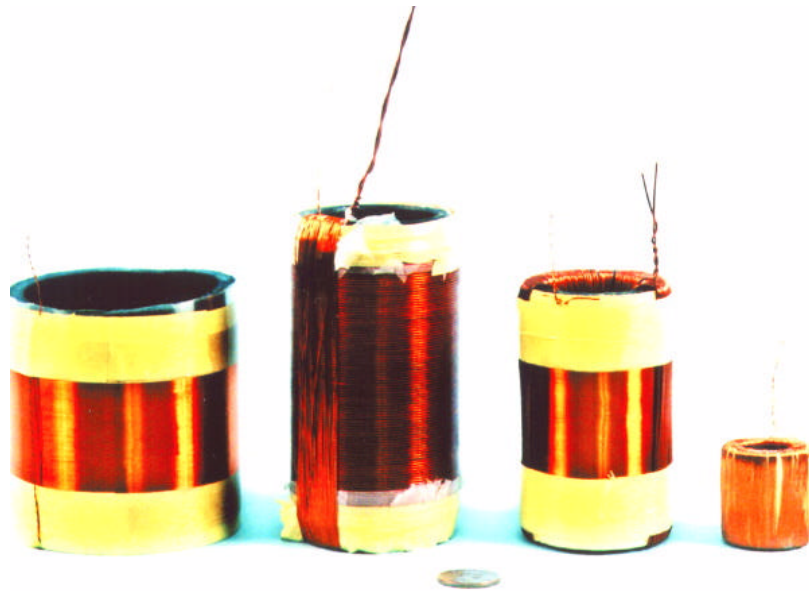


Figure 7. Several High-Tc tubes made from bulk material. The tubes are wound with charging coils. The other tubes are BSSCO-2212. A penny is shown for scale.

The properties of the BSSCO were measured as a function of temperature. They are shown in Figure 8. The sample was charged to about 0.7 T at 4K, limited by the magnet used in the experiments. Since it was known that the field at the actuator operating

temperatures, 20-50K, was lower than this, the measurements provide the required information. In previous tests, it was determined that the critical self field at 4 K for these BSCCO tubes employed in the program was about 1.3 T.

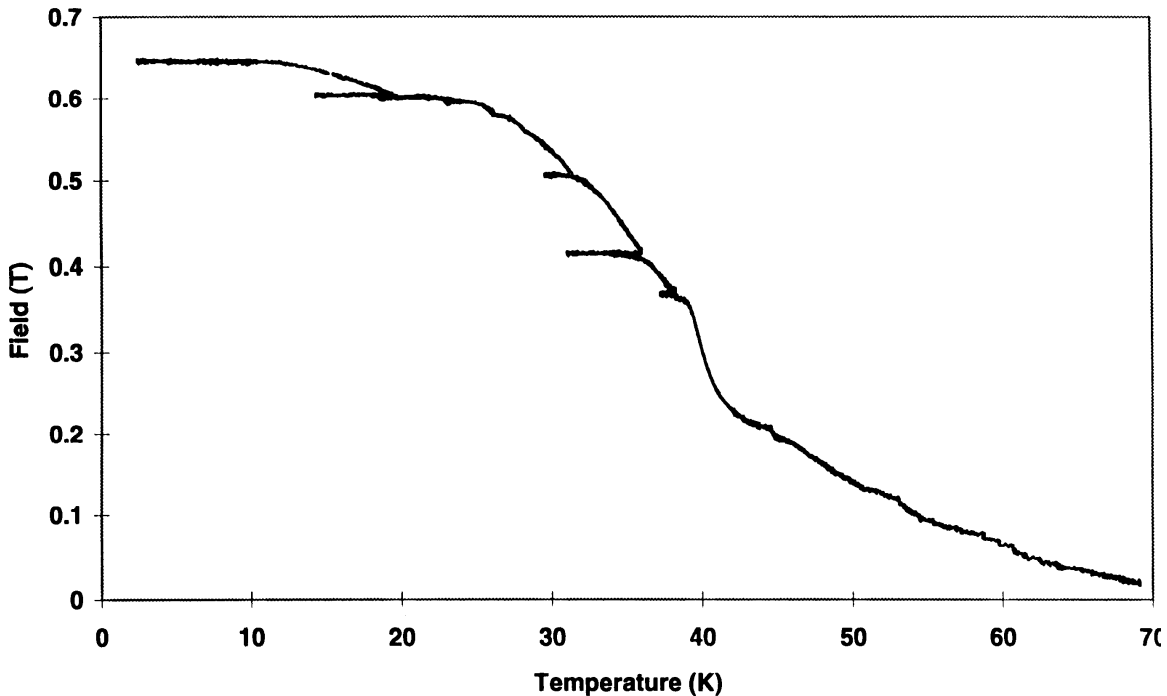


Figure 8 Properties of a BSCCO 2212 tube 25 mm OD, 15 mm ID, 25 mm long, as a function of temperature.

The superconducting tube was allowed to warm up slowly, using a temperature controlled cryostat. In this manner, the temperature of the magnet could be increased, decreased or held constant at will. Figure 8 shows cases when the temperature was held constant or slightly decreased, in order to determine whether indeed the superconductor was operating persistently. This was done at 20K, 30K, 35K, 40K and 45K. Any decay in the field would have been observed. Since none was observed during the duration of the experiment (on the order of 12 hours per hold-period), then the superconducting is not decaying, or at least decaying fast enough for NGST applications. **Using the noise as the maximum decay, it was determined that the decaying rate was longer than 40 years.**

### III. Actuators With High Temperature Superconducting Monoliths..

Two schemes of utilizing high temperature monoliths for actuators were investigated in the program. The first one utilizes magnetostriction. In this case, the magnetic field is used to induce strain in magnetostrictive material. The second manner utilizes direct magnetic interaction between the actuator and a magnetic membrane.

Figure 9 shows a schematic diagram of a scheme to make an actuator magnet using bulk HTS. Three concepts are shown depending on the distribution of the superconducting and the charging coil. In this case, only the case of flux charging is drawn. For saturation

charging, a second toroidal coil would be needed. The actuator is surrounded by a magnetic material in order to shield the magnetic field and therefore reduce cross talk between adjacent actuators.

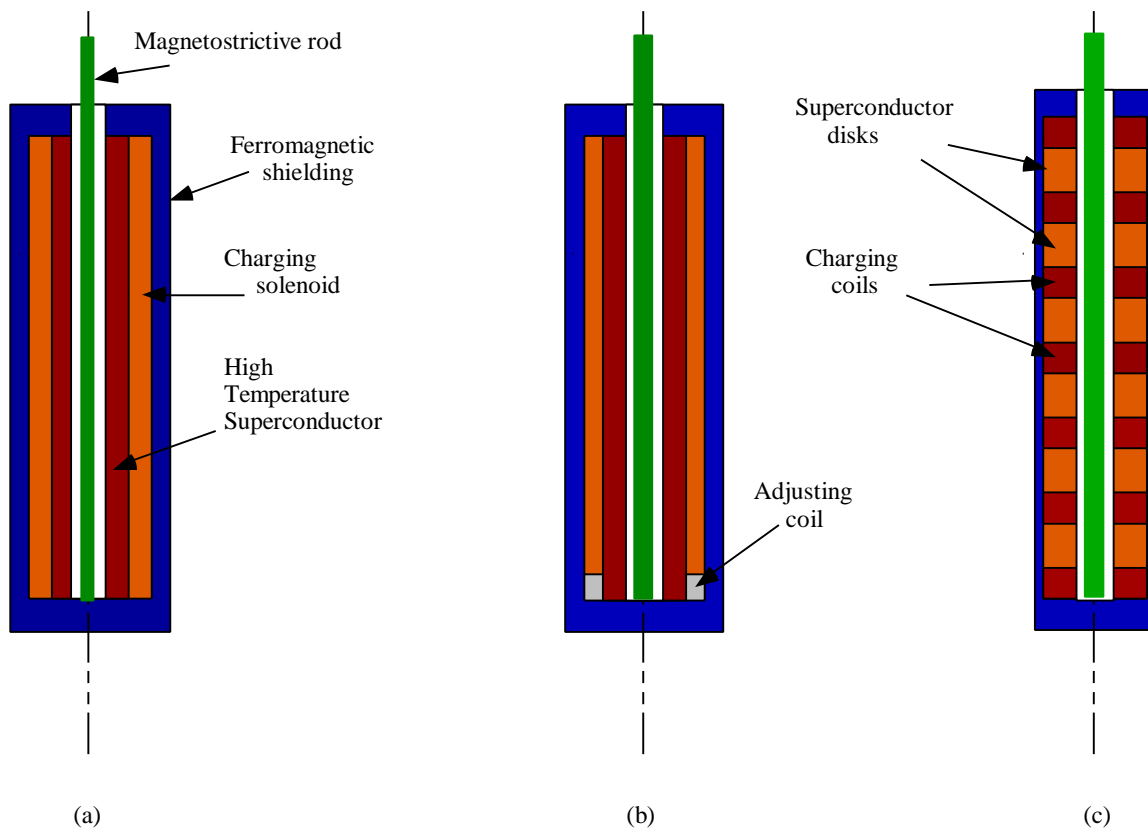


Figure 9. Three types of magnetostrictive actuators, with different allocation of superconductor and charging coil.

An alternative approach consists of using the superconductor to attract a magnetic element. This case is shown in Figure 10. The magnetic element could either have large hysteresis or small hysteresis, but in both cases the material has a large magnetic permeability. In the case of a magnet element with hysteresis, it is possible to induce both attraction and repulsion loads. Both cases have been analyzed in this program. The first case was analyzed in the report: *High Tc Monoliths for Force Actuators*, by L. Bromberg, M. Sidorov and R. Torti. The second case was analyzed in the report *High Tc Monoliths for Force Actuators: Calculations with permanent magnets*, by L. Bromberg, M. Sidorov and R. Torti.

The size of the commercially available monoliths has increased with time. Inexpensive commercial monoliths of 25 mm are available from several vendors, and 100 mm wafers are manufactured at research laboratories [Ohyama]. The size limitation of the monoliths limits the maximum size of the actuator. For BSCCO, good material can be purchased commercially, as shown in Table 1.

Table 1  
 BSSCO 2212 material available from Aventis (formerly Hoechst)

ID (mm)	OD (mm)	length (mm)	
5.5	10	80	20 available in stock
5.5	13	100	in stock
3	7.9	40	standard size can be used relatively quickly for tests

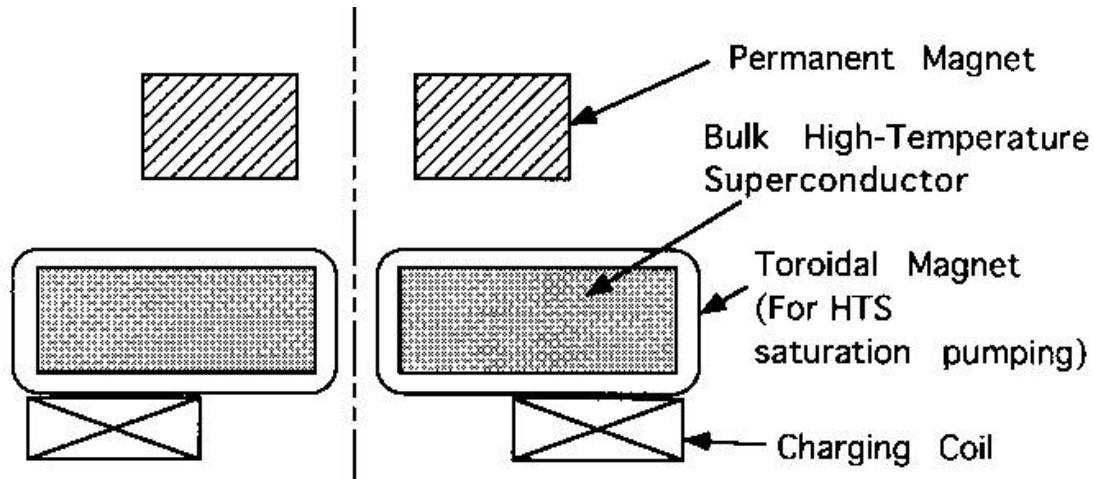


Figure 10. Schematic drawing of a permanent-magnet/High temperature superconductor system in which a HTS YBCO disc or radius  $R_d$  and a thickness  $d$  interacts with a permanent magnet placed  $d$  above the superconductor.

Some of the tubes that they have available in stock have silver contacts that make them less useful. The tubes are also rather expensive, they are charging \$3000 for 4 tubes to our specifications (3 mm ID, 8 mm OD, 40 mm long).

There are two advantages to using bulk HTS materials for making magnets as opposed to using wires. The first advantage is the much higher current densities that can be produced using the HTS superconducting magnets. The typical HTS wires/tapes have an engineering current density substantially smaller than the superconductor, due to the presence of the silver or other substrate required to give the superconductor a high texture. A second advantage is that the HTS magnet is persistent, while HTS tapes can not be because of the unavailability of HTS joints technology.

#### IV. Charging/discharging of the superconductor.

##### A. Charging Mechanism

Inducting charging of superconducting monoliths (bulk material) has been attempted even with low temperature superconductors. The technique of flux trapping was used by a Stanford University group in the 1970's to study the persistent magnetic field trapped in low-Tc superconductors [Rabinovich]. Recently, flux trapping has been studied YBCO

at high and low temperatures, and for BSCCO at high temperature. The most impressive performance of flux trapping with YBCO at 77 K has been obtained by the group in Texas [Ren, Chen, Weinstein]. High fields, as high as 10 T at 50 K, can be produced with YBCO single crystal disk about 25 mm in diameter and 10 mm thick.

The charging mechanism used in the past consists of applying a magnetic field when the material is not superconducting, the decreasing the temperature until the material is superconducting, and then removing the externally applied field [Ren, Chen, Weinstein]. This manner of charging, known as field freezing, is not convenient, as the sample needs to be cooled quickly, resulting in large thermal stresses. Cracks can develop during the cooling period. In addition, it is necessary to increase the temperature of the superconductor in order to alter the magnetic field. Finally, since the cooling is relatively slow, the external magnet field needs to be applied for long times (many seconds), complicating the design of the charging coils.

For the present magnets, a different manner of charging will be used. The basic principle consists in bringing the superconductor to its critical state at near-constant temperature by applying additional fields/currents. Once in the critical state, magnetic flux can freely move in-and-out of the superconductor (flux pumping), with some dissipation (resulting in small increases in temperature due to the large thermal capacity at the temperatures of interest (20-50 K). The HTS material at these temperatures does not experience quenching, and little evidence of flux jumping has been observed.

The superconductor can be driven critical with the charging coil itself (flux pumping), or by a second set of coils that induce large enough currents in the superconductor that the critical state is reached at lower fields (saturation pumping). For the case of saturation pumping, the saturation coil is made from a toroidal winding around the superconductor. An attractive feature of this charging mechanism is that fast pulsed coils can be used, simplifying the design of the charging coils.

It is important to match the superconductor to the application, because of the need to raise it to its critical state. YBCO material has very high critical current density and fields at the temperatures of interest (20-40 K), and is difficult to machine (self fields on the order of 10 T for 10-20 mm diameter disks). BSSCO-2212 material on the other hand, is easy to machine but has lower critical current  $\sim 10^8$  A/m<sup>2</sup>. For the present application, YBCO bulk material is superior.

## **B. Charging Circuit**

Figure 11 shows a simple schematic of the electrical circuit. A power supply is used to charge a capacitor, which is discharged through the charging coil. A matching transformer is used between the capacitor and the charging coil to match the impedances. The superconductor is represented as an inductor in series with a variable resistor. The variable resistor limits the current flowing in the superconductor to below or equal to critical current (the value of the resistor varies automatically). The variable resistor has zero resistance when the superconductor is away from critical.

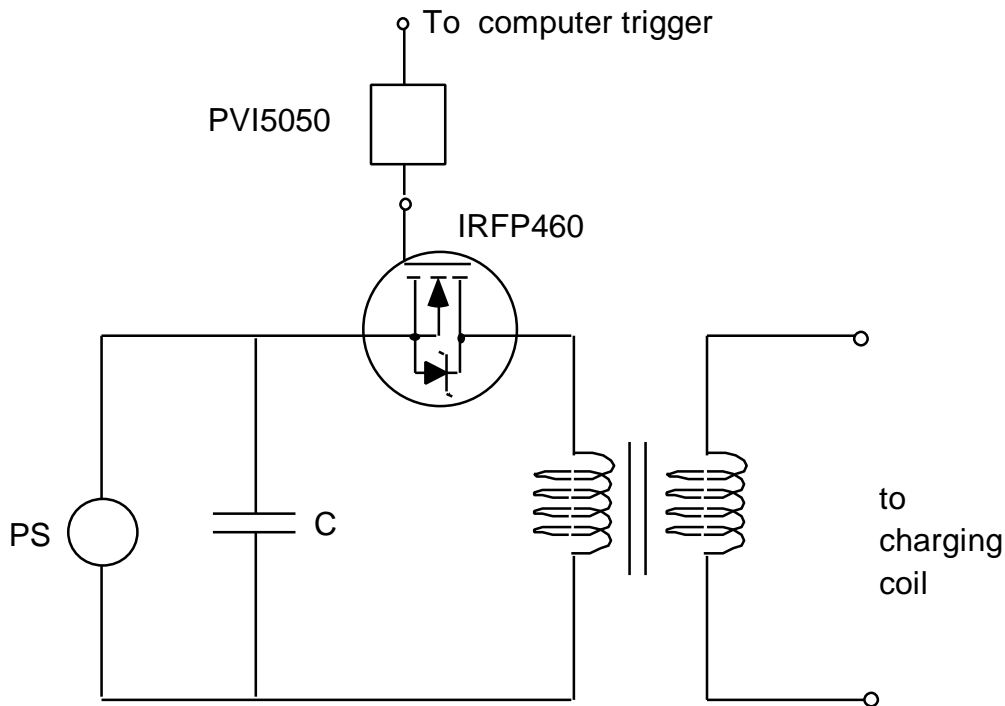
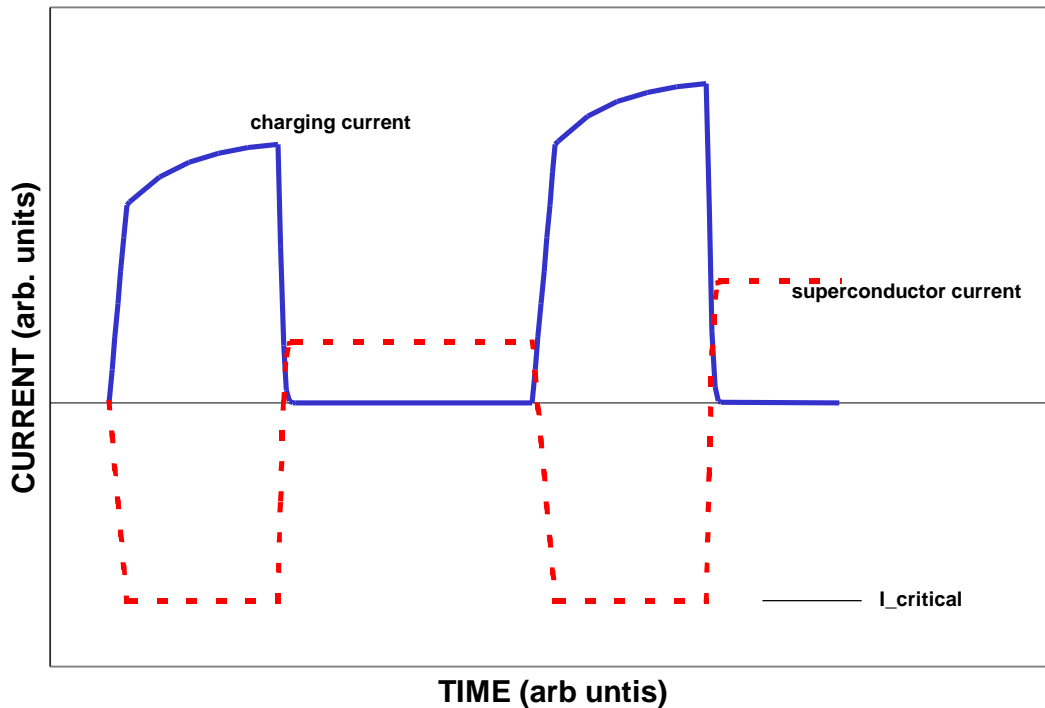


Figure 11. Schematic supply used for flux pumping. For saturation pumping, two of these power supplies, triggered by different pulses from the computer, were used.

It is assumed that the charging coil and the high-T<sub>c</sub> tube have good coupling coefficient. The currents in the charging coil and the induced current in the high-T<sub>c</sub> monoliths are shown in Figure 12. As the switch is closed, since the coils are well coupled, the circuit looks like a short circuit, and the current raises rapidly. Increases in current in the charging coil are balanced by opposite changes in current in the superconductor (and therefore the net inductance of the system is near zero). As the high-T<sub>c</sub> superconductor reaches critical conditions, the current in the superconductor remains steady at critical, and the load suddenly looks inductive, slowing down the rate of rise of the current. The circuit looks like a coupled capacitor-inductor system, with an LC time constant. After the charging circuit current reaches the maximum current and the current starts decaying, the superconductor is moved away from the critical condition, and suddenly the inductive load disappears and the circuit becomes a short circuit, with zero voltage but large current. With no driving voltage, the current in the charging coil decreases very fast, without oscillations. The final result is that the energy in the capacitor, minus the energy dissipated in the charging and superconducting coils, is transferred to the inductor.

The process can be repeated until the right current in the superconductor is reached, as long as it is below the critical current. The discharging process is the opposite, with the capacitor charged in the reverse direction.

The switch can be a semiconductor switch, realized with a high power MOSFET (Harris Semiconductor, IRFP460; <http://www.semi.harris.com/> ). The MOSFET is fired by a Photovoltaic Isolator (International Rectifier, PVI5050; <http://www.irf.com/> ). The photovoltaic isolator is for the protection of the computer, but also results in better triggering of the MOSFET. It is also necessary to match the impedance of the load by using a transformer between the power supply and the charging coil. The matching



transformer was hand-wound, using a ferrite toroid.

Figure 12. Current waveforms in charging and superconducting coils

## V. Charging results.

In this section, the results of flux and saturation pumping are described.

### A. Flux pumping.

The case of flux pumping is shown in Figure 13. As indicated in the figure, the field is first increased and then decreased. The time in the Figure is not continuous, and after recording a change, the data acquisition system stops recording data. Since there are small transients, these are reflected in the fact that the Hall probe signal has discontinuities. These discontinuities have been marked in the figure. The interval between the pulsing is about 30 seconds long, needed to recharge the power supply, i.e., the capacitor. Therefore there are substantial changes in the signal within 30 seconds of the pulse.

The red lines (solenoid) indicate the current through the charging solenoid. The current traces extend beyond the region of the graph. There are two traces since the current first rises rapidly, then decreases equally rapidly. There seems to be a delay in the signal of the Hall probe, due to frequency response limitation of the Hall probe amplifier.

The data in Figure 13 was taken using the 25 mm OD, 15 mm ID 25 mm long BSCCO sample, operating at 77 K. Similar results are obtained at lower temperature, but then the transients take longer.

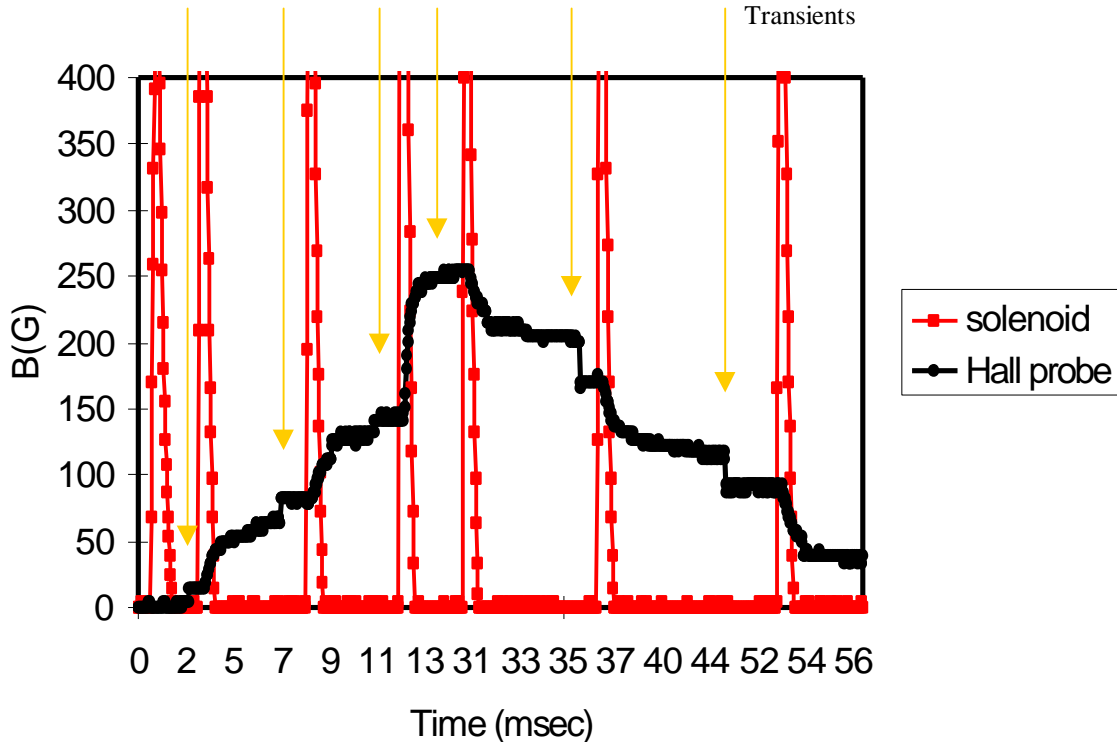


Figure 13. Charging and discharging of BSCCO 2212 tube, 25 mm OD and 15 mm ID, 25 mm long, Yellow arrows indicate the discontinuities due to stopping and restarting the data acquisition system.

The behavior is similar at the lower temperatures. Figure 14 shows the current density of a 25 mm OD, 15 mm ID, 25 mm long. The measurements were taken at 20 K, with much lower ramping rates (on the order of 10 ms). The ramping rate was changed by changing the capacitor in the power supply shown in Figure 10.

The transients in this case are long. In the case in Figure 14, the transients are as long as 30 hours. The transients at the lower temperatures are not understood, since in some cases they last substantially shorter. The process responsible for the variation of the decay times was not understood by the end of the program.



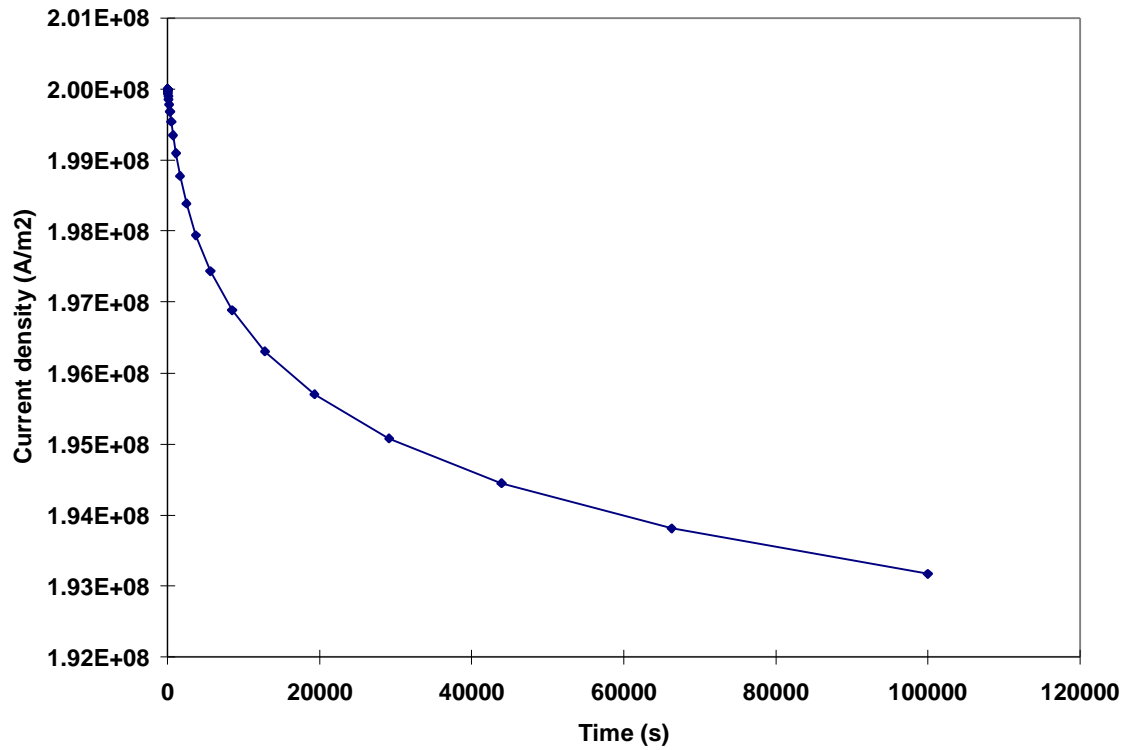


Figure 14. Value of current density (linearly proportional to magnetic field) as a function of time. 20 K, self field of about 1.2 T.

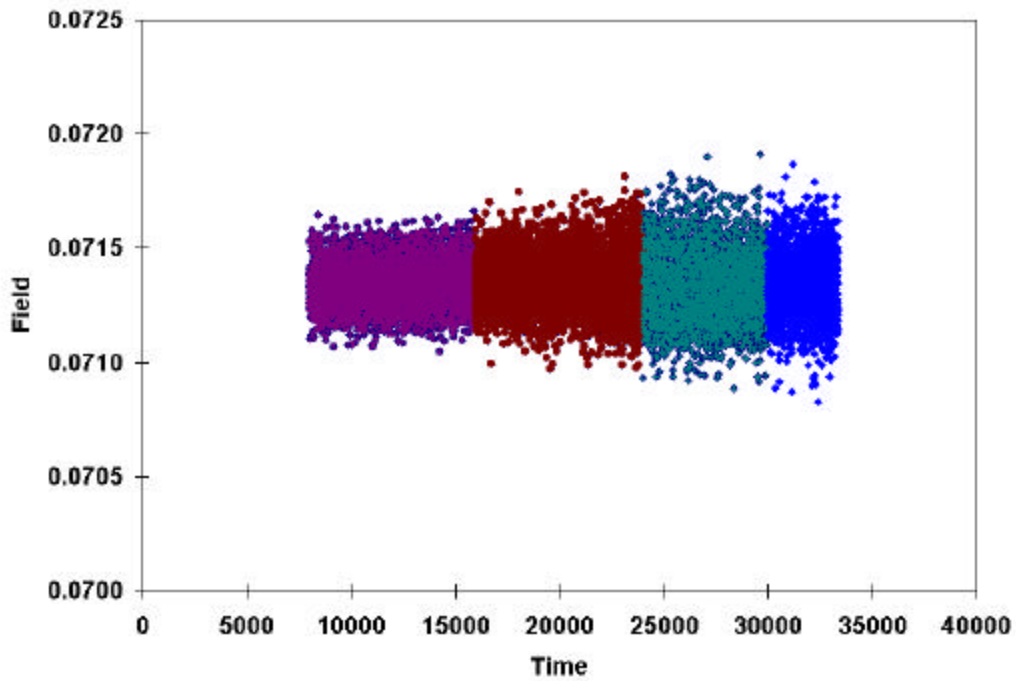


Figure 15. Field in T as a function of time, after transients have died away. 70 K.

However, it should be stressed that after the transient, the field is persistent. This was indicating while discussing Figure 15 above, when the temperature was held fixed until the transient disappeared. This is illustrated with a case at 70 K with the 25 mm OD, 15 mm ID, 75 mm tube. After the decay occurring in the first few hours, the field ceased to decrease. There is noise associated with the amplifier and the Hall probe, and pick up, but it is small. It should be noted that after 10 hours, there has been no significant drop of field.

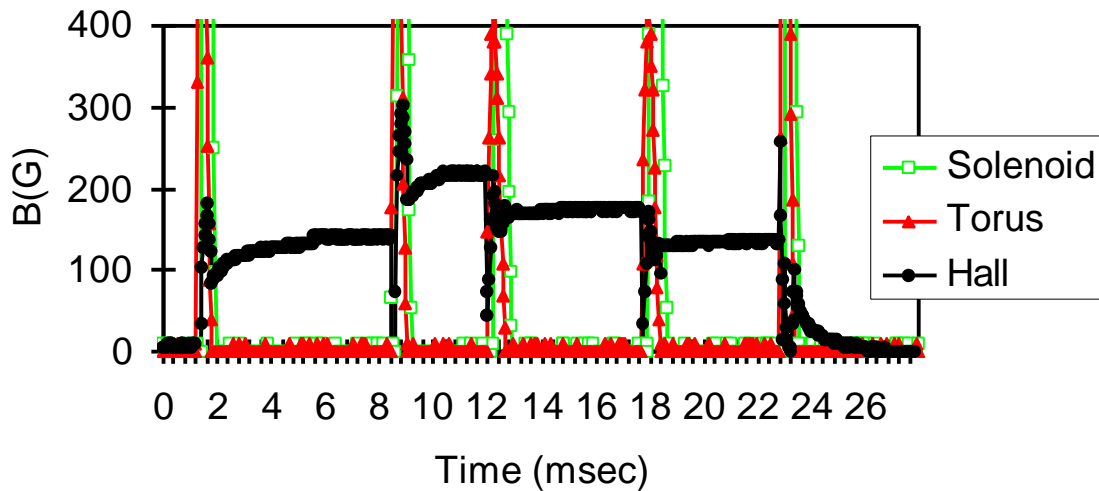


Figure 16. Charging and discharging of monolithic superconductor as a function of time, for the case of saturation pumping. Note that the transients are substantially smaller in this case, and that there are no longer time constant transients.

### B. Saturation pumping.

In saturation pumping, a second magnetic field is energized in order to drive the superconductor into the critical state. At that point, the superconductor loses all its flux pinning, and it is possible to drive flux in and out of the superconductor. The geometry chosen to drive the superconductor normal was a toroidal winding around the superconductor, as shown in the figures above. In addition, as shown in the figure 9-c the superconductor has been cut in slices (in the form of thin washers), in order to decrease the value of the toroidal field at which the superconductor becomes normal.

Once the toroidal field is energized, currents flowing in the poloidal direction are generated. These current prevent the penetration of the toroidal field inside the superconducting washers. The value of field required to drive critical currents in the superconductor scales inversely proportional to the thickness of the superconductor washer. It should be noted that in this case, the superconductor is at the normal state because of the large current, as opposed to in the case of saturation pumping, when it occurs because the field is high enough to drive the superconductor into the critical state.

Figure 16 shows the value of the trapped magnetic field in the case of saturation pumping. Also shown are the currents for both the toroidal field (saturation field) and solenoid. The toroidal field is generated first, to drive the superconductor normal. Then the solenoidal field is energized, to charge the magnet. Then the toroidal field is decreased, and finally the solenoidal field is decreased. Note that the duration and magnitude of the transient is much reduced compared to flux pumping. In order to study this, Figure 17 shows the results of Figure 17 in an expanded time ordinate.

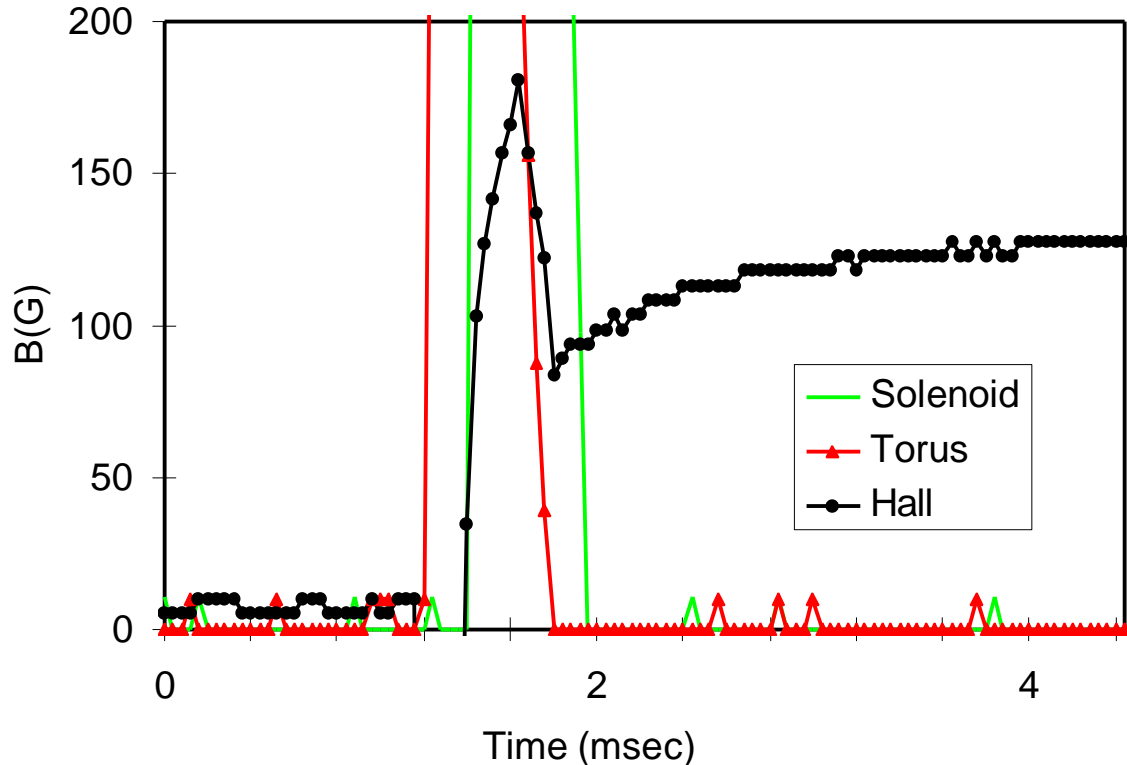


Figure 17. Currents in toroidal and solenoidal windings, and Hall probe (field) as a function of time. 77K. 25 mm OD, 15 mm ID, and 25 mm long magnet.

The short time behavior of the field and currents are shown in Figure 17. It is not known whether the effect of the transient is real, or whether it is due to the finite frequency response of the hall probe/amplifier system.

In Figure 16, however, it is clear that the transients are substantially smaller after the third and fourth pulses. It is not clear why this is the case, or how they differ from the first two pulses or the last one.

### C. Measurements along the solenoid.

For use with a magnetostrictive actuator, it is important to know the stability and characteristics of the field along the axial direction. The field and the long term stability

of the field have been measured as a function of the distance along the axis and as a function of time. The Hall probe was mounted on a moving apparatus that was connected mechanically to a potentiometer, so that the resistance of the potentiometer could be used to measure distance along the axis. The tests were carried out at 77 K, with a 25 mm OD, 15 mm ID and 25 mm long sample. After charging and waiting for the transients to die down (a few minutes), the field along the axis was recorded. The field profile is shown in Figure 18 at several times, starting 9 minutes after charging to 200 minutes after charging. The field profiles do not change, although there are slight variations of the field magnitude.

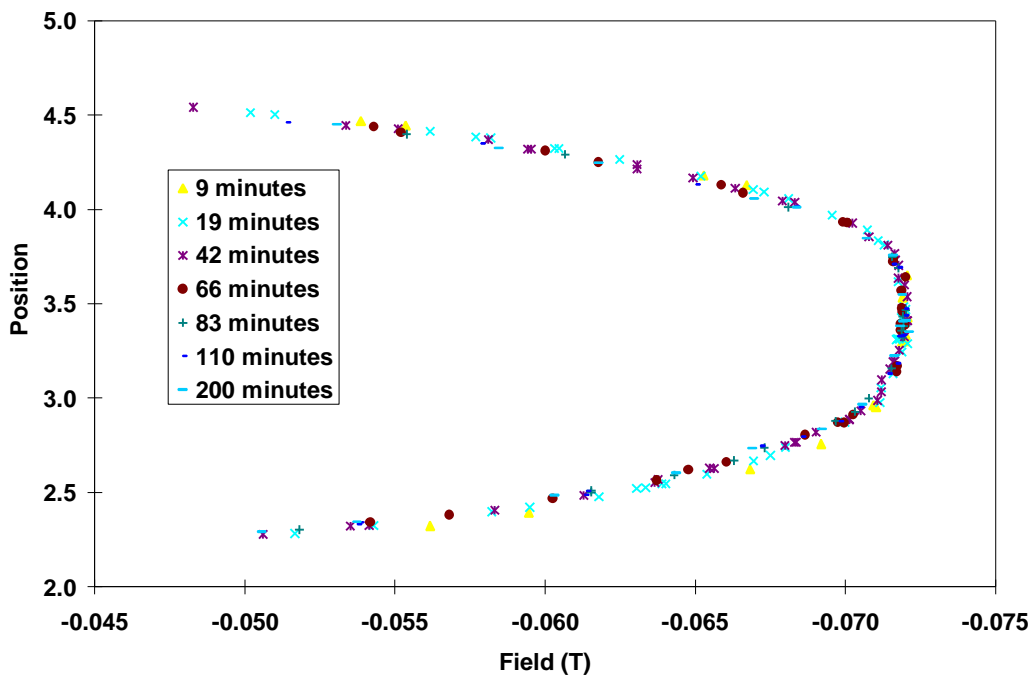


Figure 18. Profile measurements at 70 K (pumped LN<sub>2</sub>). 25 mm OD, 15 mm ID, 25 mm tall BSCCO 2212 tube. 70K measurement.

## VI. Force measurements

The forces between the superconducting monolith and magnetic material were measured. The forces were measured using a calibrated load cell, Model MLP-10, from Transducer Techniques, Inc (<http://www.ttloadcells.com/product1.html>). The load cell model can be used in either compression (repulsion forces) or tension (attractive forces). The maximum recommended load is 45 N (10 lbs), and has a linearity of better than 0.07%.

Figure 19 shows the setup. The micrometer screw is used to vary the distance between the magnetic membrane and the superconducting element. The superconducting element

is shown at the bottom of the container. Only experiments at liquid nitrogen temperature were carried out. In these experiments, the superconductor was cooled by pouring liquid nitrogen in the styrofoam container shown in Figure 19.

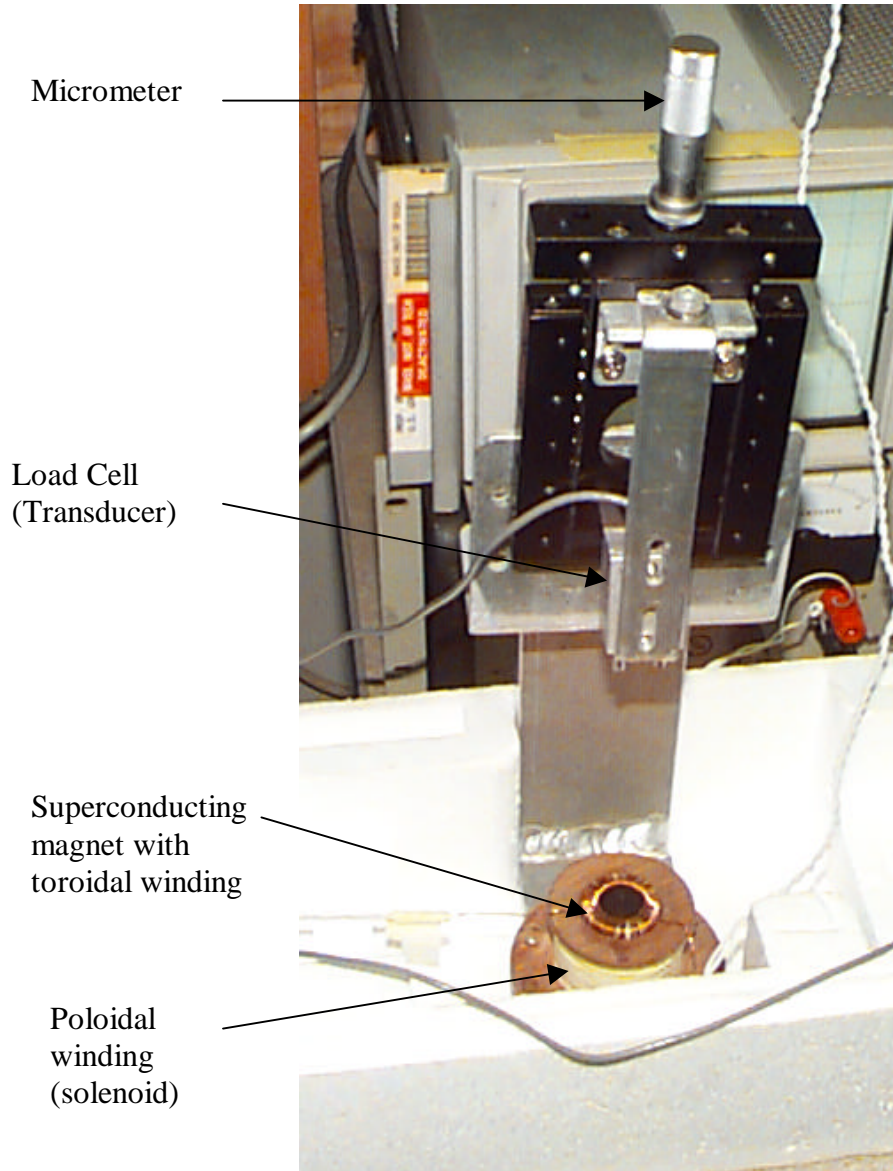


Figure 19. Picture of setup to measure forces with superconducting actuator.

The resulting force when a 25 mm diameter, 12 mm thick YBCO sample was used with a 1 mm thick Ni membrane is shown in Figure 20. The distance between the superconductor and the membrane was estimated to be 1 mm, by using the micrometer screw.

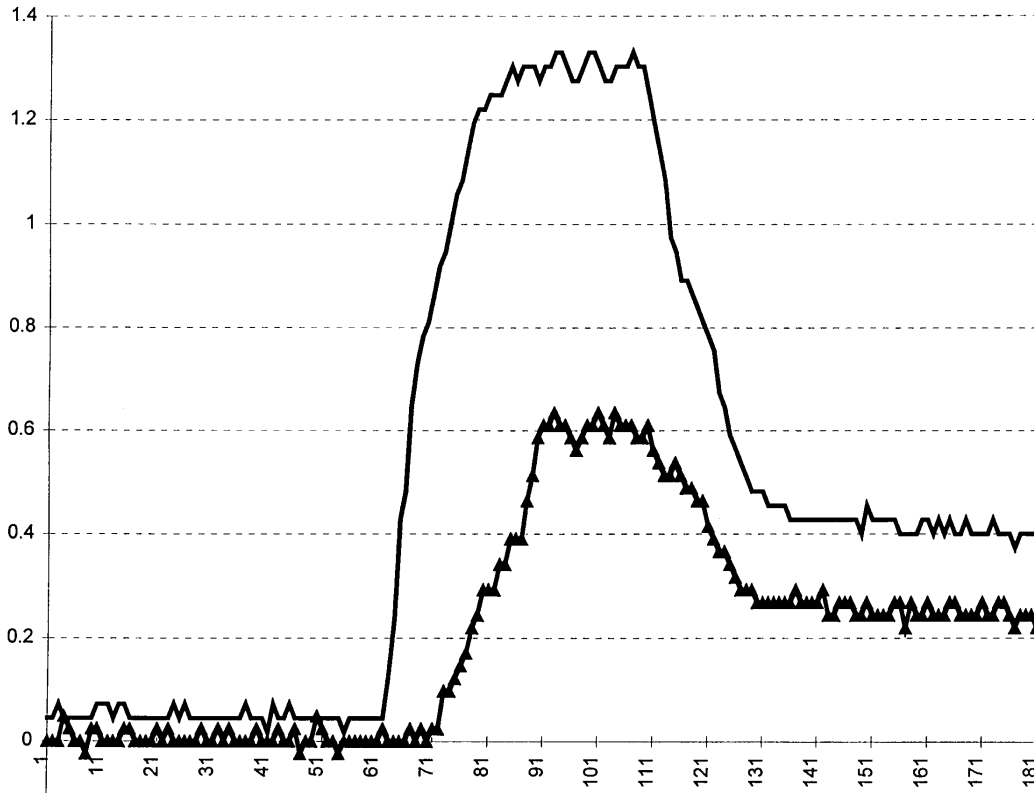


Figure 20. Field (kG) and force (N) in superconducting actuator. 77 K. 25 mm YBCO sample, 12 mm long, interacting with 1 mm thick Ni membrane. The ordinate is time, in seconds.

## VII. Conclusion

The possibility of using high temperature superconductors as elements in control actuators has been described. There are several advantages for this type of manufacturing. First, the average current density in the superconductor is substantially higher than for low-T<sub>c</sub> superconductors or equivalent current density in permanent magnets, resulting in higher field gradients and forces. The maximum field is higher than possible with LTS or permanent magnets.. The monoliths can be presently acquired from several vendors, who are selling them mainly as levitators. These monoliths are nearly single crystal.

It has been demonstrated that the HTS bulk material does not experience flux jumping or quenching at temperatures higher than 10 K. Therefore, there is no need for stabilizer or quench protection. Instead of flux jumping or quenching, the superconductor goes through a flux-flow period, excluding the field until it reaches critical conditions.

We empirically understand the process for charging the monoliths. It is possible to charge them to their locally critical state without quenching. For applications where it is

important to maximize the use of the superconductor (i.e., with high average current densities), this mode of charging is particularly relevant.

The proposed technique opens the possibility of manufacturing actuators with HTS materials in the near term. It may provide a method of manufacturing actuators even in the long term, by avoiding the need of bending HTS wires or tapes to small dimensions.

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