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Multipole Magnets Using Monolithic High Temperature Superconductor Materials:
I Quadrupoles

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Abstract

The use of monolithic high temperature superconductors in multipole configurations is analyzed in this paper. The properties of monolithic high temperature superconductors have been well documented, and monolithic tubes, disks and rods of different cross section and sizes can presently be obtained from several commercial vendors. In this paper, design issues of quadrupole magnets using single crystal or highly textured YBCO monoliths are addressed. The excellent properties of YBCO operating at elevated temperatures (> 10 K) are also summarized. High field, cryo-stable, highly complex multipole 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 Nb_3Sn) 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/MRAT 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/MRAT 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 Tc 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 paper, the issues of designing quadrupole magnets using YBCO disks are discussed. The design options are investigated, exploring the design space. Special attention is given to exploring the resulting magnetic field geometry, including the gradients and undesirable harmonics. The methods of charging the monoliths are briefly reviewed. Finally, the conclusion summarizes the work and describes applications were monolithic, high temperature superconducting magnets may offer attractive options for the design of high field quadrupoles.

II. 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.

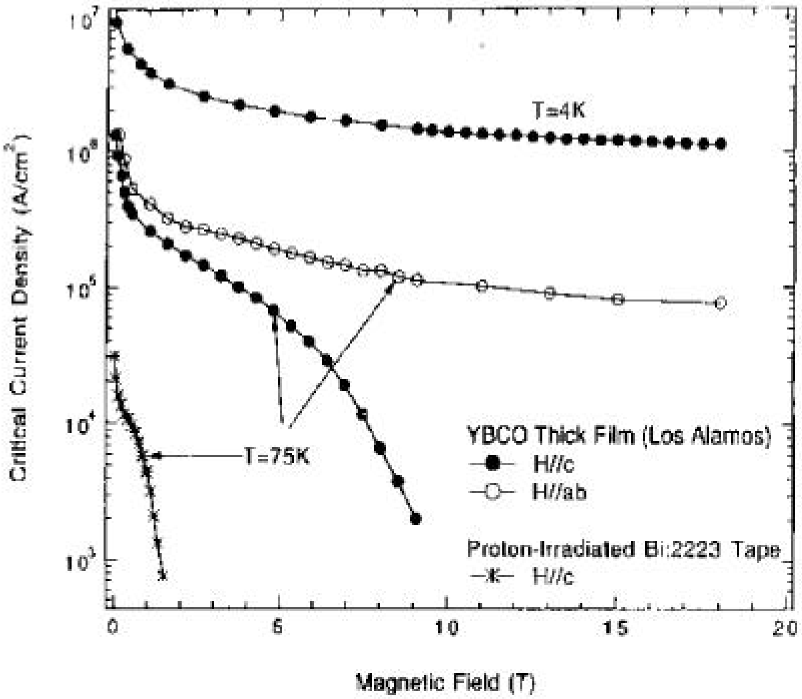
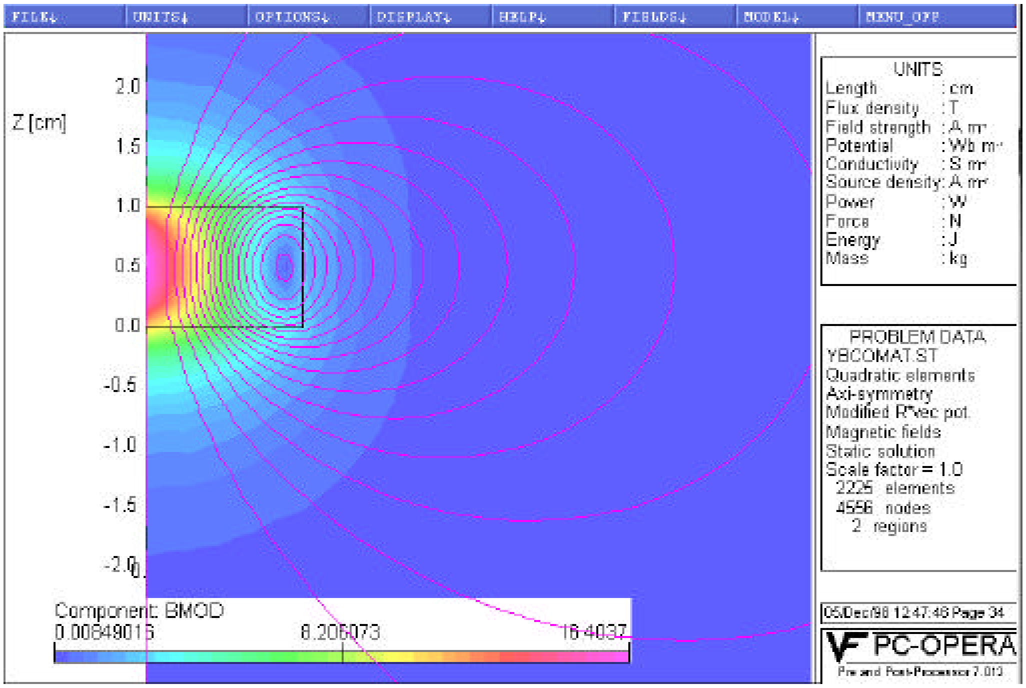


Figure 1. Critical current density for YBCO-123 as a function of field, for several temperatures and for different orientation of the field with respect to the crystal.

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 10^9 A/m^2. The peak magnetic field, which occurs inside of the superconductor, is on the order of 16 T.



UNITS
Length : cm
Flux density : T
Field strength : A m
Potential : Wb m
Conductivity : S m
Source density: A m
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
YBCOMAT.ST
Quadratic elements
Axi-symmetry
Modified R*vec pot.
Magnetic fields
Static solution
Scale factor = 1.0
2225 elements
4556 nodes
2 regions

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

It should be noted that this performance is comparable to the non-copper current density of Nb_3Sn superconductor, at 4 K and 10 T. Indeed, once the structure and stabilizer/quench protection is included in the Nb_3Sn 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.

An alternative approach, investigated in this report, is to use monolithic HTS. In the next section, the possibilities of using bulk HTS in quadrupole magnets are explored.

III. Quadrupole magnet design using HTS monoliths.

Figure 3 shows a schematic diagram of a scheme to make a quadrupole magnet using bulk HTS. The design is similar to that using permanent magnets.

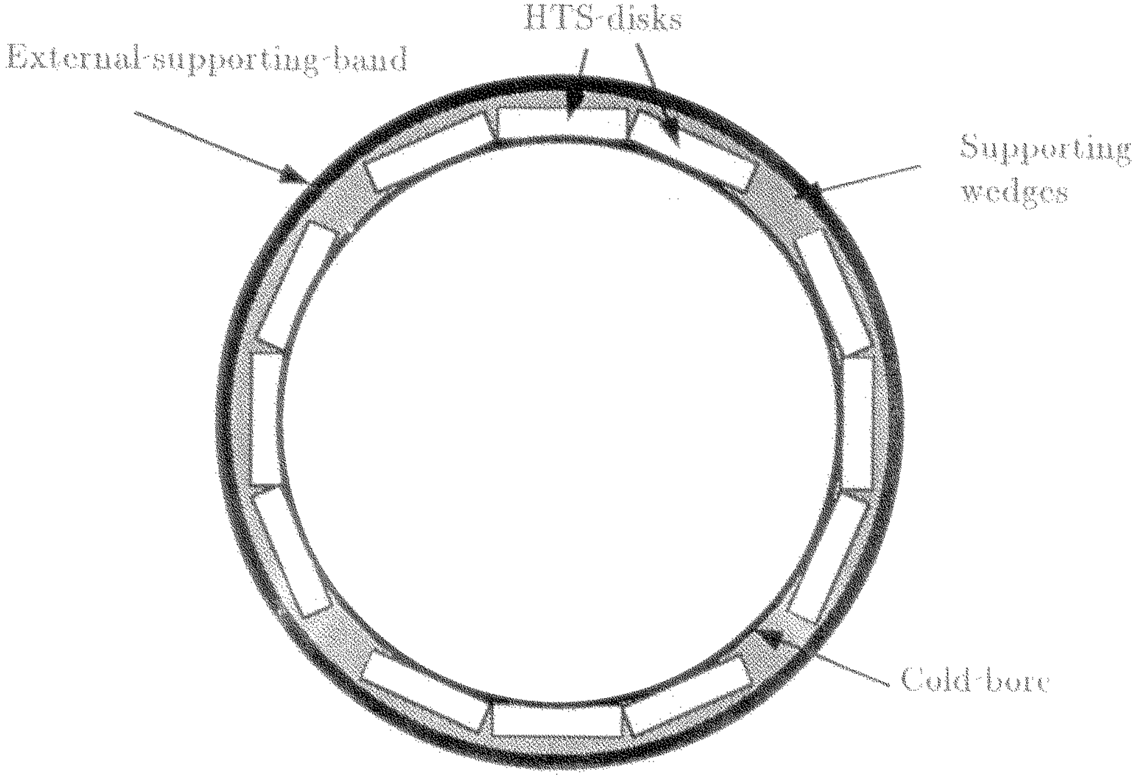


Figure 3. Schematic diagram of quadrupole magnet using HTS monoliths.

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 quadrupole magnet.

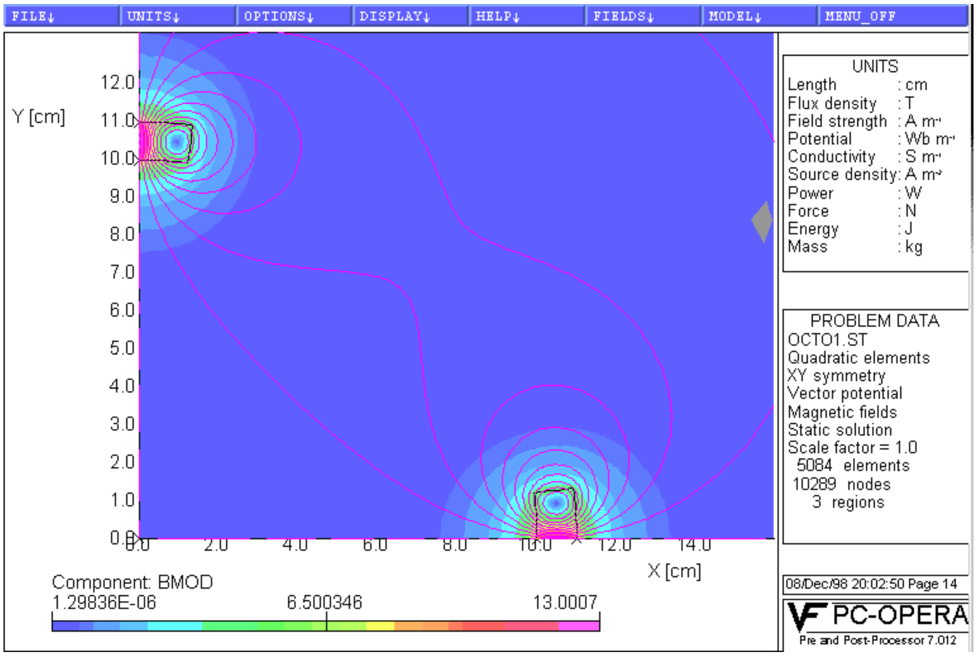
The localized, non-uniform magnetic fields in multipoles result in forces that are unusual. The forces are similar to those that appear when permanent magnets are used for manufacturing the multipole magnet. A useful analogy is to assume that the HTS materials behave as permanent magnets with a very low Curie temperature (the critical temperature of the superconductor). From symmetry, it can be concluded that the forces on the superconducting disks are radially directed (no net torque). Additionally, the forces result in tension loads in the superconducting material, which are large but have been shown that can be supported by the HTS material itself, without the use of external support. This may not be the case when several of these disks are stacked upon each other. The radially inward forces can be supported by placing wedges in-between the magnets, as shown in Figure 3.

There are three advantages to using HTS materials for making multiple magnets as opposed to using permanent magnets. The first advantage is the much higher current densities that can be produced using the HTS superconducting magnets. The effective magnetization in typical permanent magnets can alternatively be described as current loops with an equivalent current density of only about 10^8 A/m^2 even for the best permanent magnet materials, vs. the much higher current density (more than an order of magnitude larger) for the HTS materials. A second advantage is that the maximum field in permanent magnets is limited to about 1 T, vs. the much higher fields in the HTS materials. A final advantage is that the multipole can be assembled at room temperature (with the pieces not charged), and then charged after assembly, while multipoles with permanent magnets need to be assembled with special tools to handle the large loads.

IV. Parametric analysis of quadrupole magnets.

In this section, a parametric analysis for the design of quadrupole magnets is performed. It is assumed that the required bore of the magnet is 10 cm radius (cold bore), with magnets located on the 10 cm radius surface.

Several cases have been analyzed. The number of elements that are placed next to each other to make a pole, n_p, has been varied between 1 and 5 (n_p= 3 in Figure 3). The number of elements that are stacked upon each other, (n_r), has been varied from 1 to 2 (n_r = 1 in Figure 3). To make a quadrupole, the magnets on opposite sides of the quadrupole have the same polarity facing the axis.



UNITS
Length : cm
Flux density : T
Field strength : A m^{-1}
Potential : Wb m^{-1}
Conductivity : S m^{-1}
Source density: A m^{-2}
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
OCTO1.ST
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 1.0
5084 elements
10289 nodes
3 regions

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Component: BMOD
1.29836E-06 6.500346 13.0007

Figure 4. Contours of constant magnetic field and flux lines for a quadrupole configuration, assuming 1.67 10^9 A/m^2 current density.

The case with a single disk at each pole of the quadrupole (n_p=1, n_r-1) is shown in Figure 4. Due to symmetry, only one quadrant needs to be shown. It has been assumed that the current density is the same as in the case of the single disk. Also, it has been assumed that the problem is independent of the z-coordinate, coming out of the paper. This implies that instead of disks, the superconducting material is manufactured in the shape of square rods (parallelepipids).

If the field is exclusively quadrupole-like, the field components are given by $B_x \sim r \cos \theta$ and $B_y \sim r \sin \theta$, where θ is the poloidal angle and r is the radius. The x-y system can be defined (by rotation) in order to satisfy the relation for B_x and B_y. Therefore the value of mod B ($|B| = (B_x^2+B_y^2)^{1/2}$) scales linearly with radius, independent of angle. A method of comparing performance of superconducting quadrupoles is to calculate the value of the coefficient A, where $A = |B|/r$.

The coefficient A has been calculated as a function of the number of disks that are placed at each pole (n_p), and as a function of the number of the number of the thickness of the disks placed at the poles (n_r). The results of these calculations are shown in Figure 5.

As can be expected the scaling is less than linear with either the number of the disks stacked along each other, since the disks away from the center of the pole are less effective in generating the field than the one placed at the center of the pole. Similarly, the disks that are stacked on top of the ones placed at a radius of 10 cm are farther away (at 11 cm) and therefore are less effective. A fit to the field coefficient indicates a scaling approximately given by $A \sim t^{0.93}$ where t is the thickness of the disk stack. It should be pointed out that the peak field of the doubly stacked superconductors is higher than 18 T, and is hard to induce.

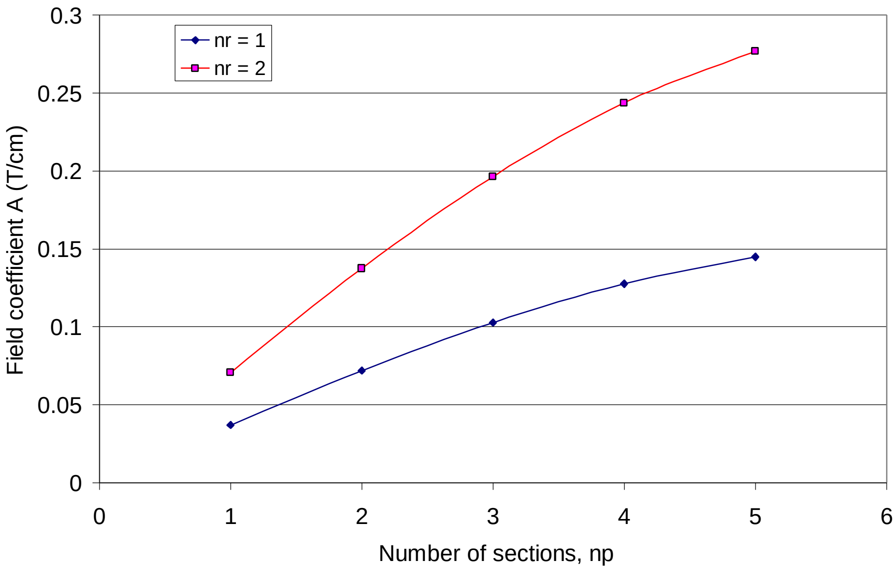
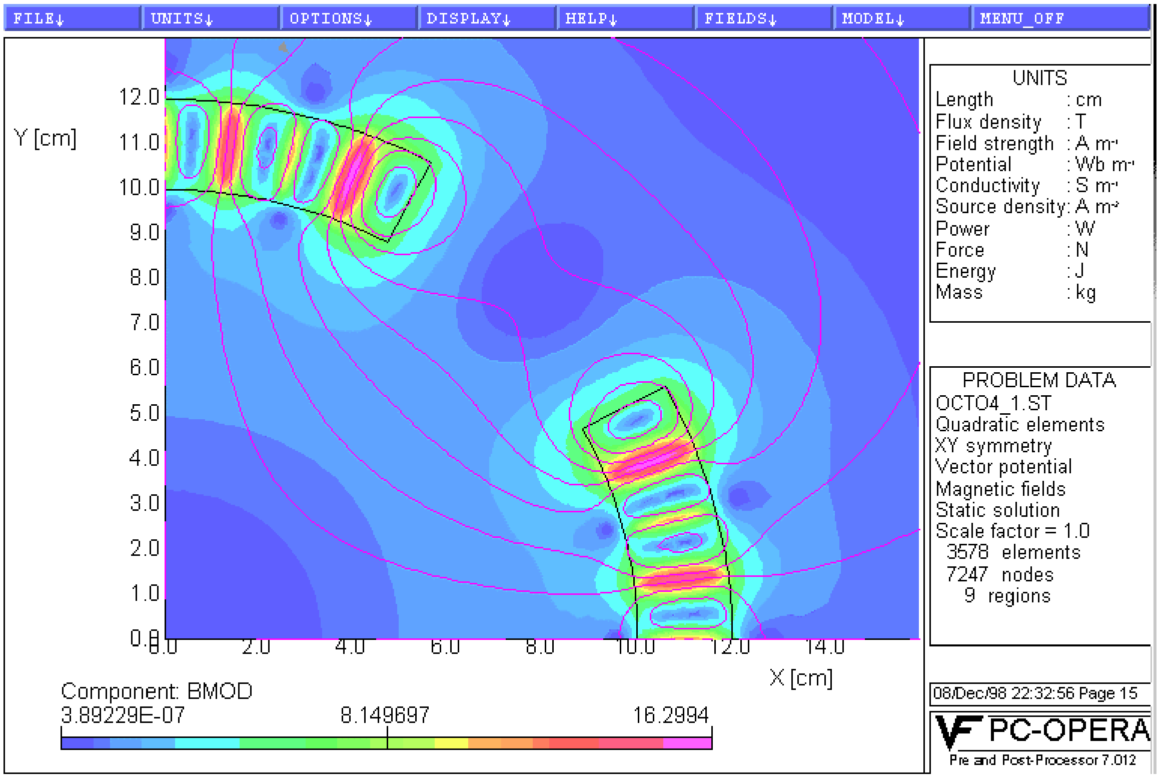


Figure 5. Field coefficient as a function of the number of disks placed next to each other and as a function of the number of disks stacked on top of each other.

The magnetic field distribution in the case of the double stacked disks is shown in Figure 6 for the case $n_r = 2$, $n_p = 4$.



UNITS
Length : cm
Flux density : T
Field strength : A m⁻¹
Potential : Wb m⁻¹
Conductivity : S m⁻¹
Source density: A m⁻²
Power : W
Force : N
Energy : J
Mass : kg

PROBLEM DATA
OCTO4_1.ST
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 1.0
3578 elements
7247 nodes
9 regions

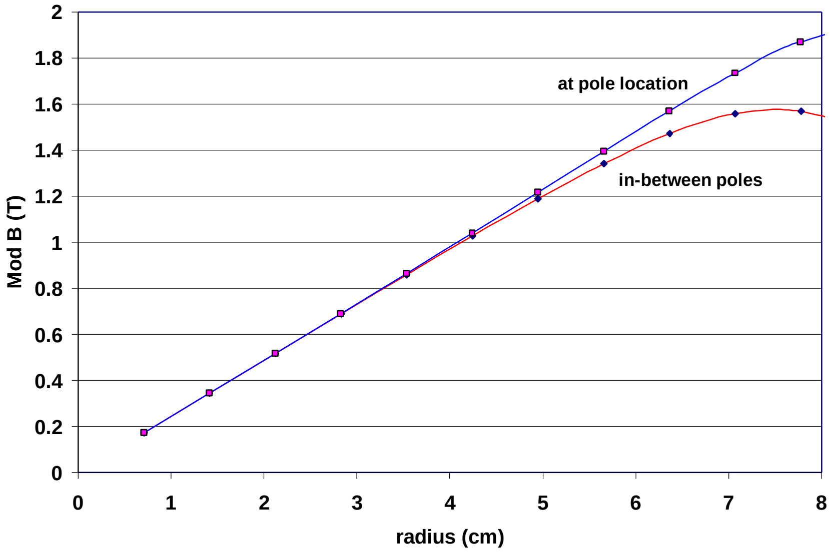
Figure 6. Case of 4 sets of doubly stacked disks at each pole. The peak field is around 16 T.

V. Field purity.

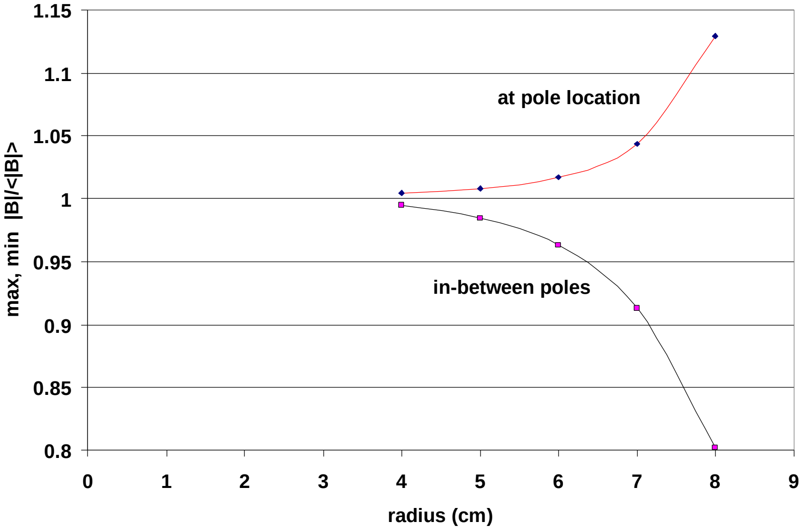
In this section, the field purity of the quadrupole magnets made of monolithic superconductors is investigated.

As mentioned before, the field scales as |B| ~ r, where r is the radius. However, since there are other harmonics generated by the disks, the field does not behave linearly with r. Figure 7a shows |B| as a function of r. The magnetic field is shown at two poloidal locations: at the midline of the pole as well as midway between poles. The field scales linearly to about 6 cm, where substantial deviations from linear are observed. It is possible to improve the performance by either shaping the rods (parallelepipids) or by placing them differently in the poloidal direction. We have not attempted to optimize the design as much as to explore the main characteristics of this type of magnet design.

In order to investigate the behavior of the field as a function of the azimuthal angle, the ratio of |B| to <|B|>, the poloidal average of |B| at a fixed radius, was calculated as a function of radius. As discussed above, for a pure quadrupole $|B| \sim (B_x^2 + B_y^2)^{1/2}$ is independent of θ. The measure by which |B| is not independent of θ can be used as a measure of non-quadrupole behavior. Figure 7b shows the maximum and minimum value of |B|/<|B|> for θ between 0 and $\pi/2$, as a function of radius. For small values of the radius, the deviation from quadrupole is small, less than about 0.5% for r ~ 4 cm. It scales strongly with the radius. For the case in Figure 7b, the error scale as ε~ $(1+r^5)$.



(a)



(b)

Figure 7. (a) Radial dependence of |B| underneath and in-between poles. (b) Radial variation of max{|B|/<|B|> and min(|B|/<|B|>) as a function of poloidal angle.

Finally, Figure 8 shows the behavior of |B|/<|B|> as a function of the poloidal angle θ at a fixed radius, for several values of the radius. It is obvious that there are higher order harmonics generated, and the their contribution increases with increasing radius.

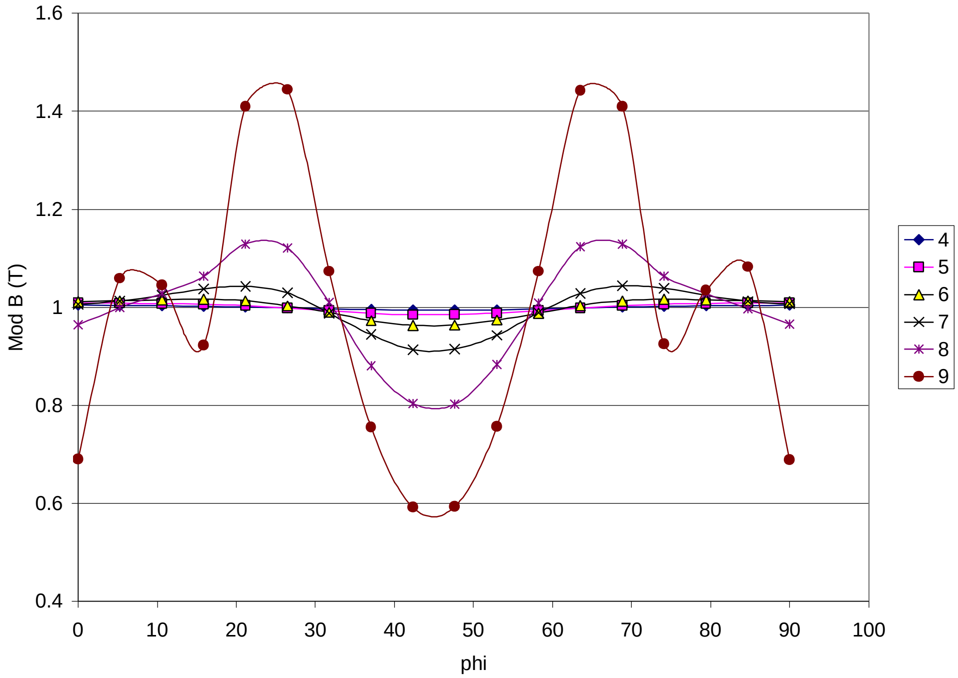


Figure 8. Poloidal variation of |B| for several radii.

VI. 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 ~ 10^8 A/m^2. For the present application, YBCO bulk material is superior.

B. Charging Circuit

Figure 9 shows a simple schematic of the electrical circuit. A power supply is used to charge a capacitor, which is discharged through the charging coil L1. The superconductor is represented as an inductor L2 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.

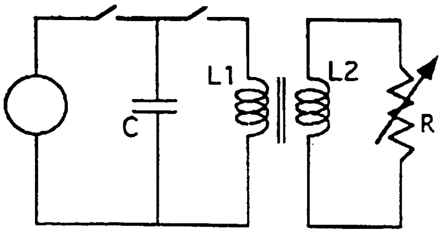


Figure 9. Schematic diagram of power supply

It is assumed that the charging coil and the high-Tc tube have good coupling coefficient. The currents in the charging coil and the induced current in the high-Tc monoliths are shown in Figure 10. 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. As the high-Tc 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 either a fast IGBT or a high power MOSFET. It is also necessary to match the impedance of the load by using a transformer between the power supply and the charging coil.

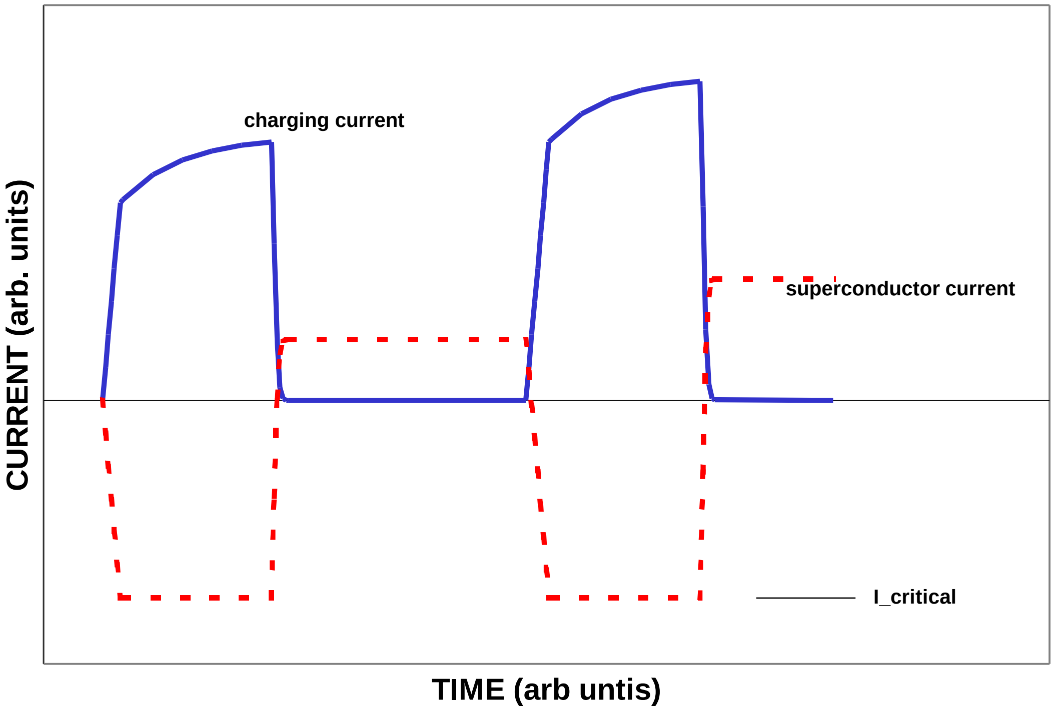


Figure 10. Current waveforms in charging and superconducting coils

VII. Conclusion

The possibility of using high temperature superconductors as elements generating multipole fields 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-Tc superconductors or equivalent current density in permanent magnets, resulting in higher field gradients. The maximum field is higher than possible with LTS or permanent magnets. The system can be assembled prior to magnetization, something that can not be done when using 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.

Because of the size availability of these disks, for large quadrupole radii it may not be cost effective to manufacture the multipoles using YBCO monoliths. If the size of the magnet increases substantially beyond that used in this paper, the attractiveness of the use of monolithic high temperature superconducting elements decreases substantially. This can be explained as follows: the monoliths placed next to each other in a pole (when $n_p>1$) have currents flowing in opposite directions in adjacent section of adjacent monoliths. To zeroth order, these currents cancel, leaving only the currents in the outer section of the outermost monoliths (on both sides) of each pole. Therefore, as n_p, the number of monoliths that are placed next to each other increases, the average effective current density decreases (inversely proportional to the number of monoliths). Thus, if the radius of the magnet is large compared to the size of the monoliths, the effective current density decreases and the use of monoliths becomes less attractive.

The above discussion is relevant for long quadrupoles, or when many quadrupoles are needed, as in long beam lines. For short quadrupoles, the advantage of using high temperatures, with many monolithic magnets, may still be

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. These magnets could find uses in accelerator physics (if the field errors can be controlled), in Electron-Cyclotron Resonance Ion Sources (ECRIS), or in other general physics applications where high current density and high field is needed in compact systems.

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

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