An ongoing study to test a YBCO HTS magnet at fields approaching 40 T

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ABSTRACT

YBCO appears to be the best available HTS material for the needed very high field solenoids for a muon collider's final ionization cooling. Two nested YBCO coils will be built, that should generate 10 and 12 T respectively, at 4 degrees Kelvin, and over 20 Tesla together. It is planned to test them later in a 19 Tesla resistive coil at the NHMFL. The current status of construction and a measurement of the coil's stainless steel 'insulation' is described. Quench protection is discussed.

a) Introduction

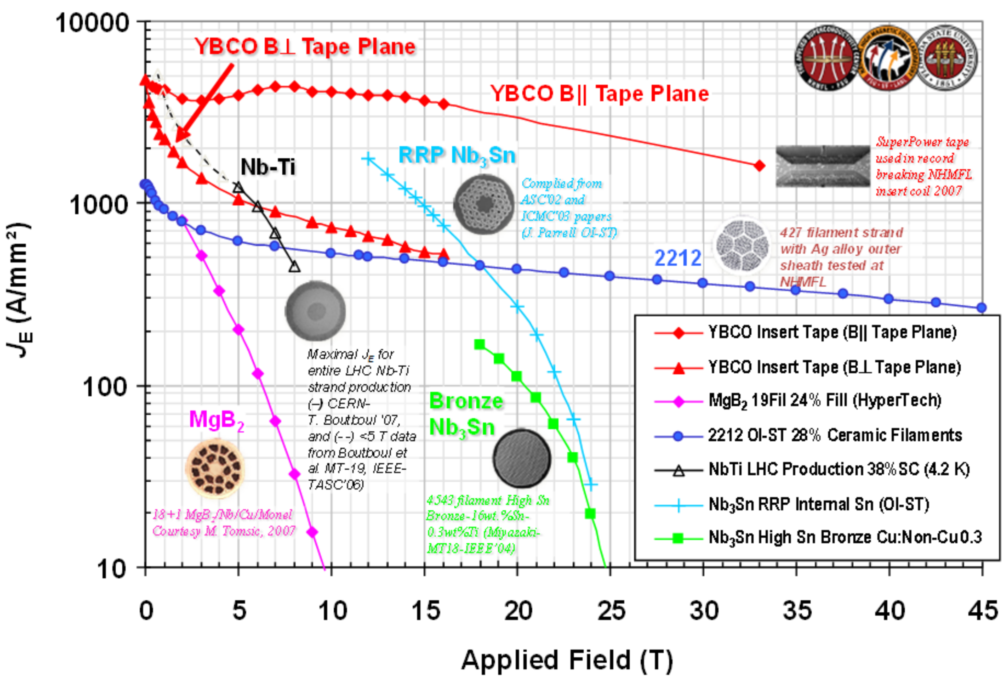

Figure 1: Engineering current density of YBCO, demonstrating its potential superiority over Bi-2212.

A Complete Scheme of Ionization Cooling for a Muon Collider [ref. 1] uses, for the last stages, ionization cooling in liquid hydrogen pipes in 50 T solenoids. A 45 T solenoid [ref.2] using superconducting coils on the outside and resistive magnets inside, operates at the National High Magnetic Field Laboratory (NHMFL) demonstrating that the forces at such high fields are not untenable, but its power consumption (~25 MW) would not be acceptable in the multiple magnets needed for the muon collider. A design of an all superconducting, using High Temperature Superconductor (HTS), 50 T solenoids have been published [ref. 3], yet the highest field demonstrated in an HTS coil, inserted in a resistive magnet, is only 33.8 T [ref. 4]. Here we discuss an ongoing program that could test HTS coils at fields approaching 40 T.

This is effort is a collaboration between Particles Beams Lasers (PBL) and the Magnet Division at Brookhaven National Lab. The current work is funded by two SBIR grants: the first [ref. 5] is building an HTS solenoid with 10 cm bore, that should generate approximately 10 T at 4 deg K; the second [ref. 6] will build a smaller solenoid that fits inside the first. On its own it should generate approximately 12 T. The second grant also covers bringing both coils to the National High Magnetic Field Lab (NHMFL) where they can be tested in a 19 T resistive solenoid. Together, they could generate a central field approaching 40 T.

b) Consideration of YBCO conductor

YBCO has a very high J_c at high fields, although this advantage is somewhat reduced in practice by three factors.

1) The J_e is greatly reduced due to the substrate and buffer layers that must be incorporated into a practical conductor.
2) YBCO J_c values are highly anisotropic.
3) In contrast to Nb_3Sn and Bi-2212 that are available as round wires, YBCO is available only as a high aspect ratio tape, and is more challenging to use in a practical coil.

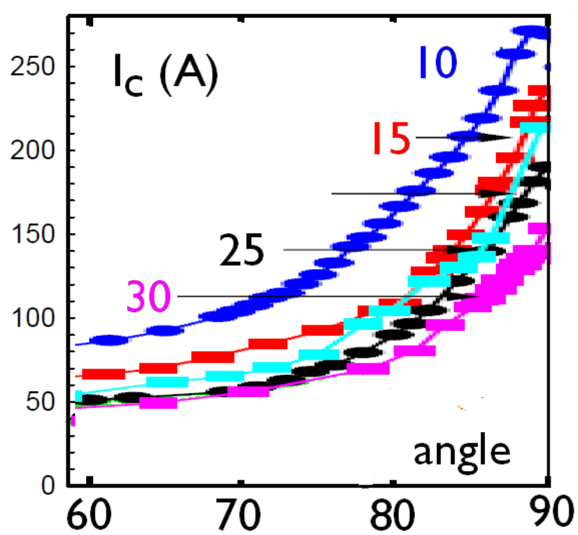

Figure 2: Current density vs. angle of YBCO tape and the field direction. The colors and numbers refer to the applied field strength in Tesla. The angle is that between the field direction and the normal to the flat faces of the tape.

Nevertheless, Figure 1 reveals that YBCO has a current density much superior to Bi-2212 provided that the field orientation is sufficiently favorable so that the appropriate curve is more like that for a parallel field rather than a perpendicular one. Figure 2 shows the currents in a sample vs the angle for differing magnetic fields [ref. 7].

Figure 3 shows the field angles in a 50 T solenoid design. The maximum field angle is about 8° for the innermost coil, 12° for the second coil, and 17° for the third coil. The current densities at these angles are significantly reduced but they remain above those for BSCCO, and these reductions apply only to pancakes near the end of the magnet.

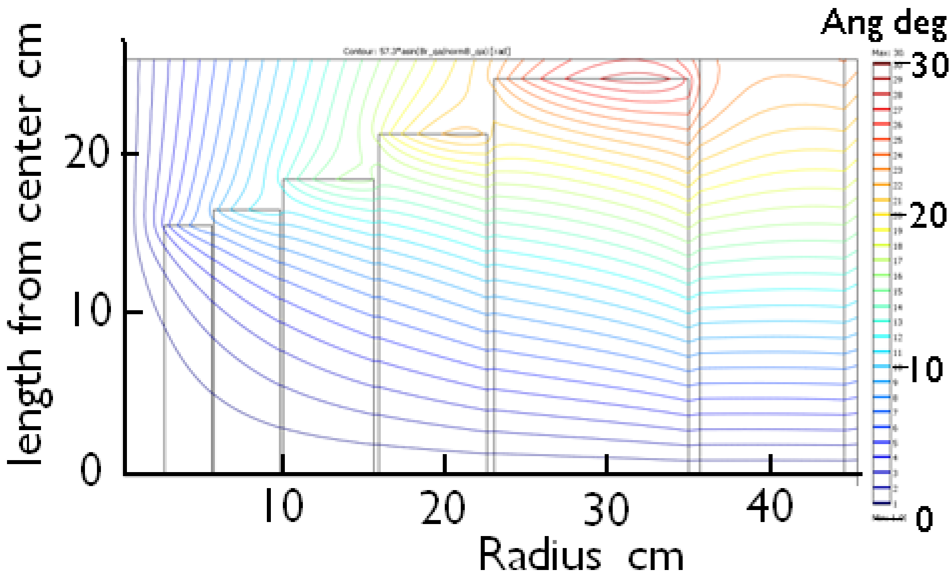

Figure 3: Contours of field orientation in 50-T all-superconducting magnet, demonstrating that the field orientation in the innermost coils may be sufficiently favorable for YBCO. The angle is that between the field and the flat surface of the tape.

c) Ongoing Work

The first phase II will build an outer YBCO coil, and the second phase II will build the insert. Their parameters are given in table 1.

Table 1: Dimensions of two YBCO coils and NHMFL resistive magnet

	Length mm	Inside diam. mm	Outer diam. mm	Field T
NHMFL Resistive 1	595	233	1010	19
YBCO 1	128	100	165	10
YBCO 2	64	25	95	12

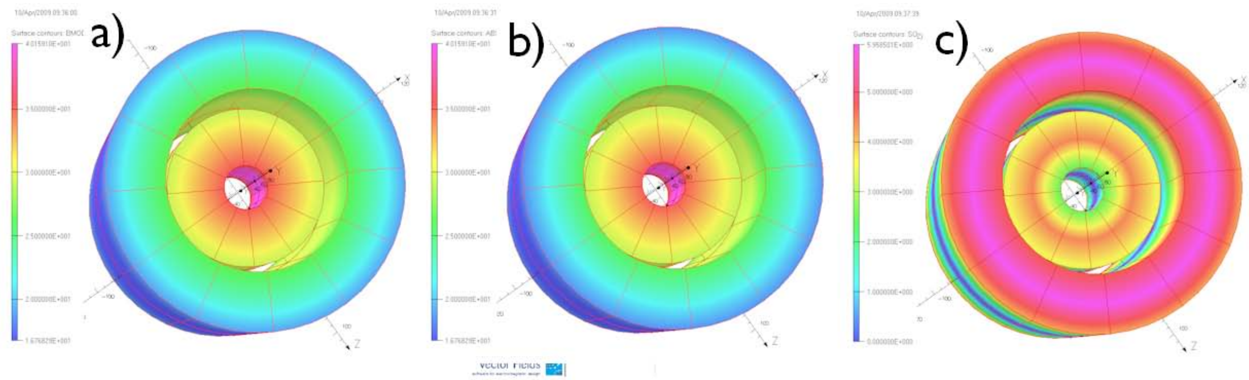

Figure 4: magnetic fields coded by color for the combined 100 mm outer YBCO coils and 25 mm diameter insert YBCO coils; a) of the absolute field magnitudes, b) of the fields in the axial direction (field parallel to the surface of YBCO tape), and c) in the radial direction (field perpendicular to the surface of the tape). Current carrying capacity of the YBCO tape depends on the magnitude and the direction of the field.

Each coil is fully self supported (no transfer of radial hoop stress from inner to outer). The construction and testing of YBCO is to learn from the exercise. A real magnet might use Bi2212 for the magnet ends where the field angles are larger, and YBCO for the inner coils where the field is more parallel.

BNL will build and individually test, at liquid nitrogen temperature, 14 YBCO double pancakes with 25 mm ID, 95 mm OD. BNL will then build an outer support containing hoop stresses (either wire wrap, or a clamp), and then test all pancakes together giving up to 12 T field. Figure 6 shows the geometry for testing the pancakes of the YBCO insert coil in a vertical dewar at BNL.

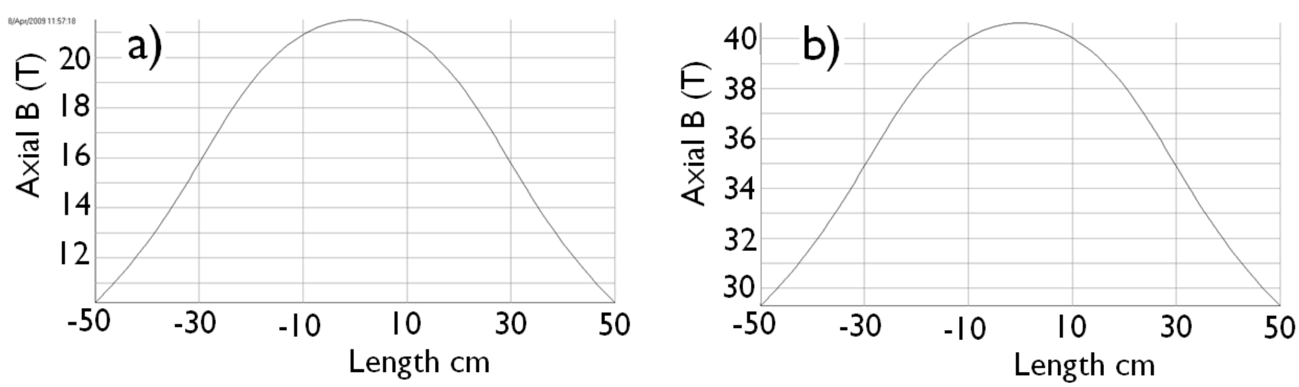

Figure 5: a) Optimistic axial field for combination of YBCO insert and YBCO outsert operating at 4 K; b) Optimistic axial field for combination of YBCO insert and YBCO outsert operating at 4 K; assembled in the NHMFL 19 T resistive magnet.

PBL will design and build a quench protection system for the following combined systems.

BNL will then assemble the YBCO 95 mm OD 12 T coil inside the 10 TYBCO coil with ID 10 cm and OD 165 mm

Figure 4 shows, by colors, fields for the 12 T YBCO coil inside the 10 T one. BNL will then test both combined coil combinations at 4 K, at which temperature they should generate field approaching 22 T. They will also be tested at higher temperatures and lower fields. Figure 5a shows the expected axial fields for the case with YBCO coils as both insert and outsert.

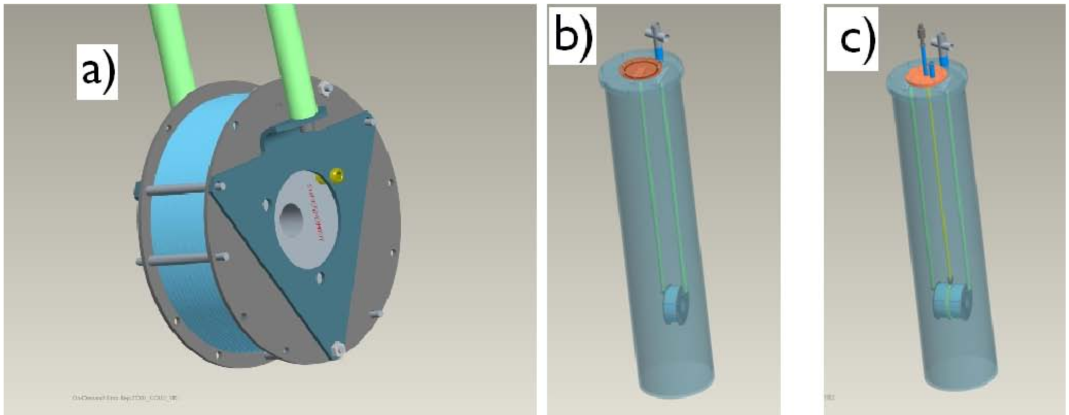

Figure 6: a) 14 pancake coils to be built and tested in FY 2010. b) on left shows a solenoid with 14 pancake coils to be built and tested inside the cryostat in FY09 and (c) on right shows 28 pancake coils (a 14-pancake coil on either side of a test sample) in FY10 as a part of the current SBIR Phase II .

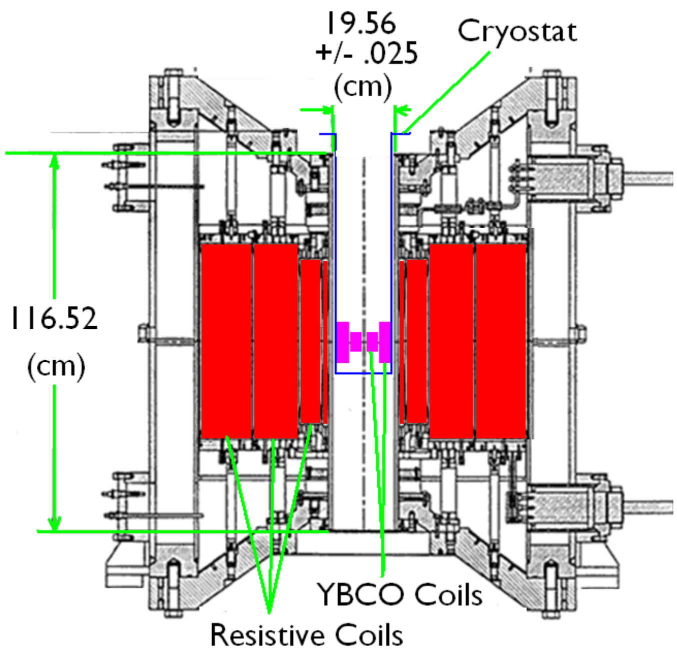

Figure 7: Cross section of the NHMFL 19 T resistive magnet with the 12T and 10T YBCO coils in their cryostat, inside the magnet.

PBL will also design a quench protection system for the following test.

BNL, together with PBL, will test one or both of the new coils (YBCO and Bi 2212), together with the YBCO 10 T outsert coil inside the background field of from a 19 T Bitter coil at the NHMFL. In this test, the field on the axis should approach 40 T. Figure 5 b) shows an optimistic plot of the axial

magnetic fields with the 12 T YBCO insert, 10 T YBCO outsert, and 19 T NHMFL resistive magnet. With the 4T Bi 2212 insert, 10 T YBCO outsert and 19 T NHMFL resistive magnet, fields of approaching 33 T should be obtained at 4 K.
Figure 7 shows a cross section of the 19 T resistive magnet with the YBCO coils in their cryostat, inside the magnet.

These tests will provide essential and valuable experience in operating such high field multiple coil designs that are needed prior to designing and testing 50 T coils. Since the design and construction of an all-superconducting 19 T solenoid would be fairly straightforward, then, if 40 T is achieved in this test, the practicality of an all-superconducting 40 T solenoid would be established. And if 40 T is not achieved, then valuable information on the real technical challenges of such a system will have been gained.

d) Expected performance including angle effects

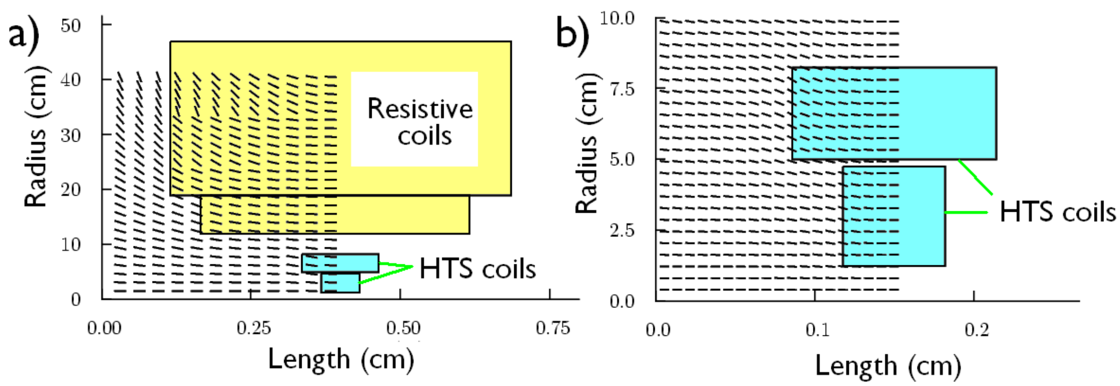

Figure 8: Field directions with 12 T YBCO insert and 10 T YBCO outsert inside the 19 T resistive magnet; a) shows all coils; b) shows detailed fields around the YBCO coils.

Figure 8 shows the field directions with both YBCO and the resistive magnet powered. It is seen that the field directions at the ends of the outer YBCO magnet are at small angles (≤18 deg) to the axis, but even such small angles will significantly reduce the current carried.

In order to predict the performance of these YBCO magnets, we derive formulae to describe the expected tape performance based on measured values. We start with measured [ref. 8] currents at 10 T, in the favored direction, divided by the coil cross section including insulation which gives the predicted engineering current density at 10 T to be:

$$j(10) = \frac{720}{(4.4+0.13)(0.145+.025)} = 935A/mm^2$$

Note that this value is much lower than the record value (4000 A/mm2) plotted by the NHMFL and shown in figure 1. For the field dependence we use data from NHMFL[ref.7], plotted in figure 9. Together we obtain an approximate formula for our assumed engineering current density vs. field and angle:

$$j = 1140\,(1 - 0.018\,B)\,\exp -(0.057 - .0001(B-20)^2)\,\theta \quad (\mathrm{A/mm^2})$$

Where B is in Tesla, theta is in degrees between field direction and flat face of the tape, and j is in amps per square mm.

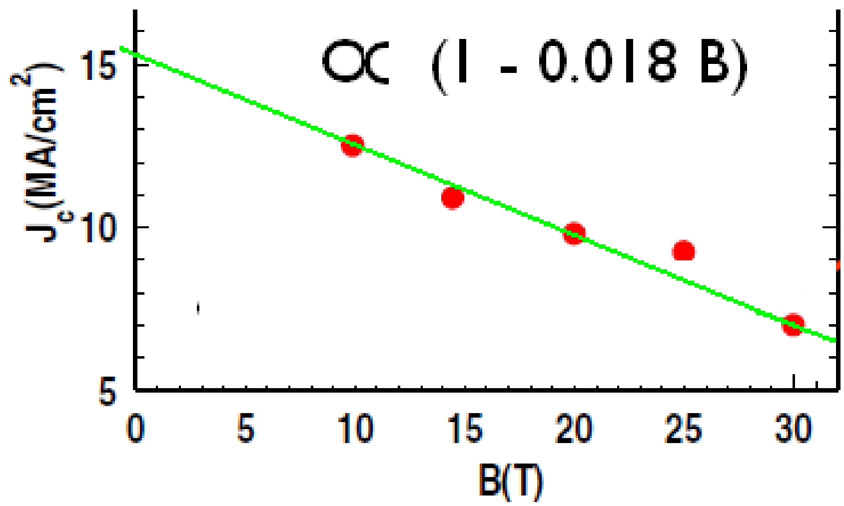

Figure 9: assumed field dependence of engineering current density vs field in the favorable direction.

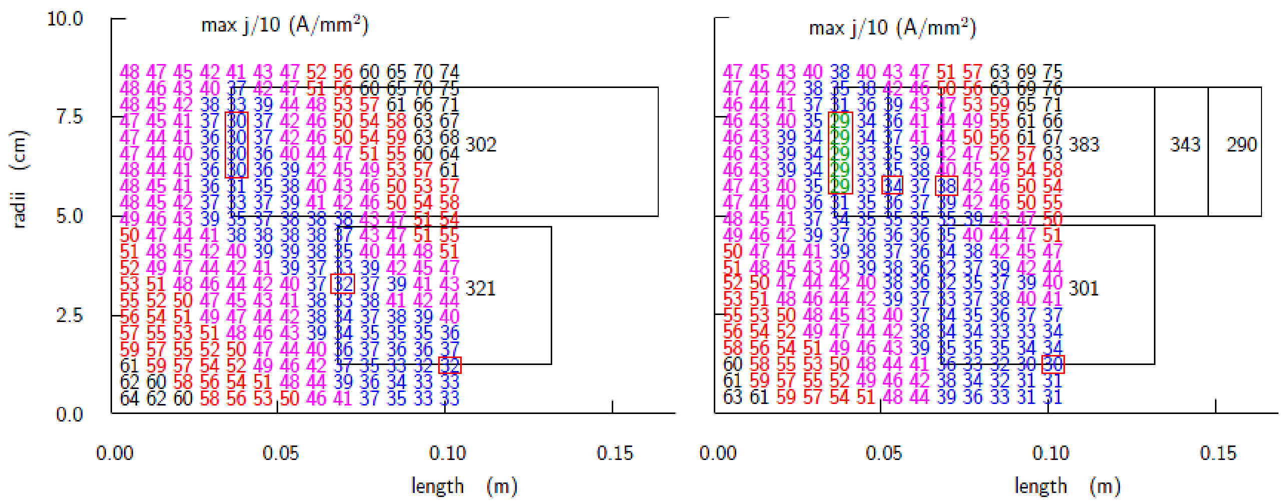

Figure 10: calculated maximum current densities vs location in the proposed YBCO magnets operating in the field of the NHMFL 19 T resistive coils. a) on the left, with all pancakes in each coils powered to the same current given by the maximum assumed current at the worst location; b) on the right, with the outer coil power with three different current densities given by the maximum assumed current at the worst location of that region.

Using this, we calculate the maximum current densities in the two coils operating in the 19 T resistive magnet. These local current densities are printed in figure 10a. The maximum central field in this case is 38.9 T.

But separate power supplies can be used to allow the end pancakes to run at lower currents than those in the center. An example of this is illustrated in figure 10b. Here, three different current densities are used, with those densities in each region limited by the worst location in that region. In this example the maximum central field is 39.9 T. Powering each pancake separately, would give a further gain.

A detailed design will only be completed after the angular dependence of the chosen YBCO material is known. We have used the phrase “approaching 40 T” and other values, understanding that the angular dependence and other characteristics may limit the achieved fields. This is an experimental program – not a final design.

e) Current status

The Superconducting Magnet Division at the Brookhaven National Laboratory (BNL) has constructed thirteen coils with 100 mm i.d. All of these coils have been tested in liquid nitrogen. These coils are part of the 10 T HTS outer solenoid. Conductor for the insert solenoid has been delivered.

A quench protection system is being developed on other HTS projects which will also be used in this program and is discussed below.

Fig. 11: Ten HTS pancake coils (see left) made with YBCO from SuperPower for the 20 T solenoid now under construction at BNL. The picture on the right shows a double-pancake coil being prepared for intermediate test.

f) Measurements of coil and stainless insulation resistance at room temperature

To determine the room temperature resistance of the coils and stainless steel insulation, the resistance of one half pancake was measured as a function of frequency. This resistance will be that due to two resistances in parallel: a) that radially through the stainless insulation, independent of frequency, and b) that through the coil windings plus an impedance term proportional to frequency:

$$R(f) = \frac{1}{\frac{1}{R_{ss}} + \frac{1}{R_{Cu} + Lf}}$$

The data fit this realtionship with R(ss)=39.5 ohm and R(Cu)=11.1 ohm.

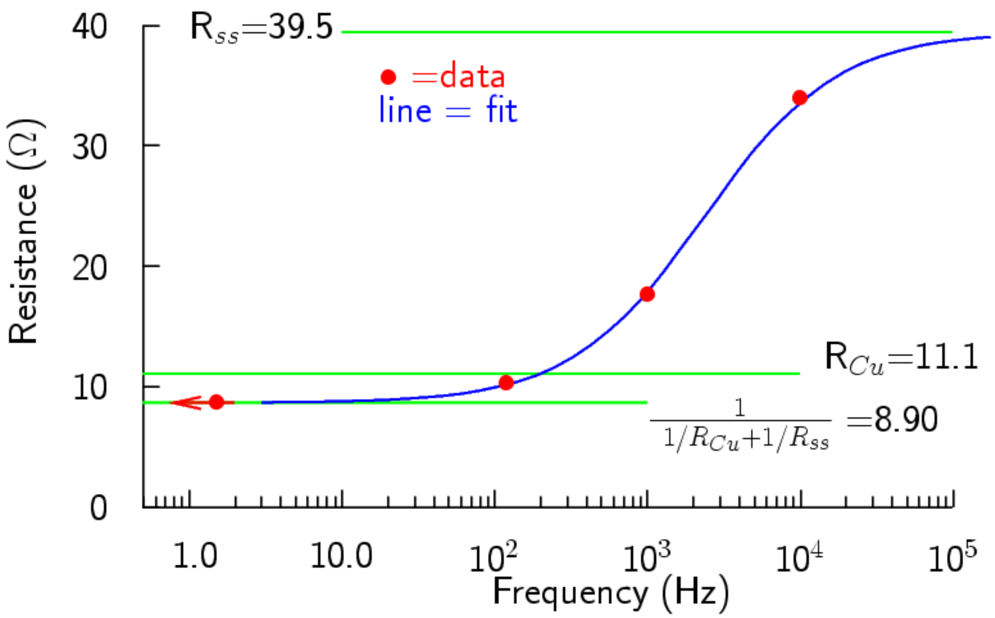

Figure 12: Room temperature resistance of one half pancake as a function of frequency.

g) Quench protection

Maximum allowable discharge time to avoid overheating: A superconducting magnet must be able to survive a quench. To avoid thermal strains that endanger brittle superconductors, magnet designers recommend limiting the hot-spot conductor temperature to ~200 K. The hot-spot temperature of an adiabatic normal zone, with negligible cooling by either conduction or cryogen, depends on a parameter $Z \equiv \int j^2(t)\,dt$, where the integral is from zero to infinity and j(t) is the current density in the matrix metal, also known as "stabilizer" or "bypass conductor"—typically copper—that carries the current whenever the superconductor is above its transition temperature. The maximum permissible value of Z depends on the ratio of heat capacity to electrical resistivity of the matrix metal, integrated from the initial to the final temperature—in our case, 4 K to 200 K. If one employs copper with a residual resistivity ratio, including the effect of magnetoresistance, of 50, then one must limit Z to ~10.6×10^{16} $A^2\ m^{-4}$ s. [9].

The design current density for the above YBCO magnets is 350 A/mm^2, or 3.5×10^8 A/m^2. If the current density in the copper is twice this, or 7×10^8 A/m^2, an adiabatic normal zone will reach 200 K in approximately $t_{200K} = (10.6 \times 10^{16}) / (7 \times 10^8)^2 = 0.2$ seconds. If one employs a resistor R to discharge the magnet exponentially as $j(t) = j_0 \exp(-t/\tau)$, with time constant $\tau = L/R$, where L is the inductance of the system, then $Z = ½\, j_0^2\, \tau$. Solving for τ as a function of Z gives $\tau = 2\, Z / j_0^2$. One needs to discharge the magnet with a time constant of no more than 2 x $10.6\text{x}10^{16}$ / $(7\text{x}10^{8})^2$ = 0.4 seconds.

Discharge voltage: The magnetic energy, U, in a magnet depends on its inductance, L, and current, I, as $U = ½ L I^2$; solving for inductance gives $L = 2 U / I^2$. The discharge voltage, V(t), is L dI/dt. For a current that decays exponentially, the maximum voltage, occurring at t = 0, is $V_0 = L I_0/\tau = 2 U / (I_0 \tau)$, where I_0 is the initial magnet current, ~350 A if the current density is 350 A/mm^2 and each turn has a cross section of ~1 mm^2.

The outer magnet, when energized alone, stores 45 kJ. Therefore its peak discharge voltage is V_0 = 2 x $45\text{x}10^3$ / (350 x 0.4) = 300 volts, and required external resistance.2.1 ohms. The inner magnet (of Figs. 5-9), if operated alone, would store 7.4 kJ and have a peak discharge voltage of 2 x $7.4\text{x}10^3$ / (350 x 0.4) = 100 volts, and external resistance 0.7 ohms. These external resistances are very small compared with that trough the stainless steel insulation: 28 x 11.1=310 ohms for the outer coil and about a third of this for the shorter inner coil, meaning that only a very small part of the stored energy is returned to the coil by currents passing through the insulation.

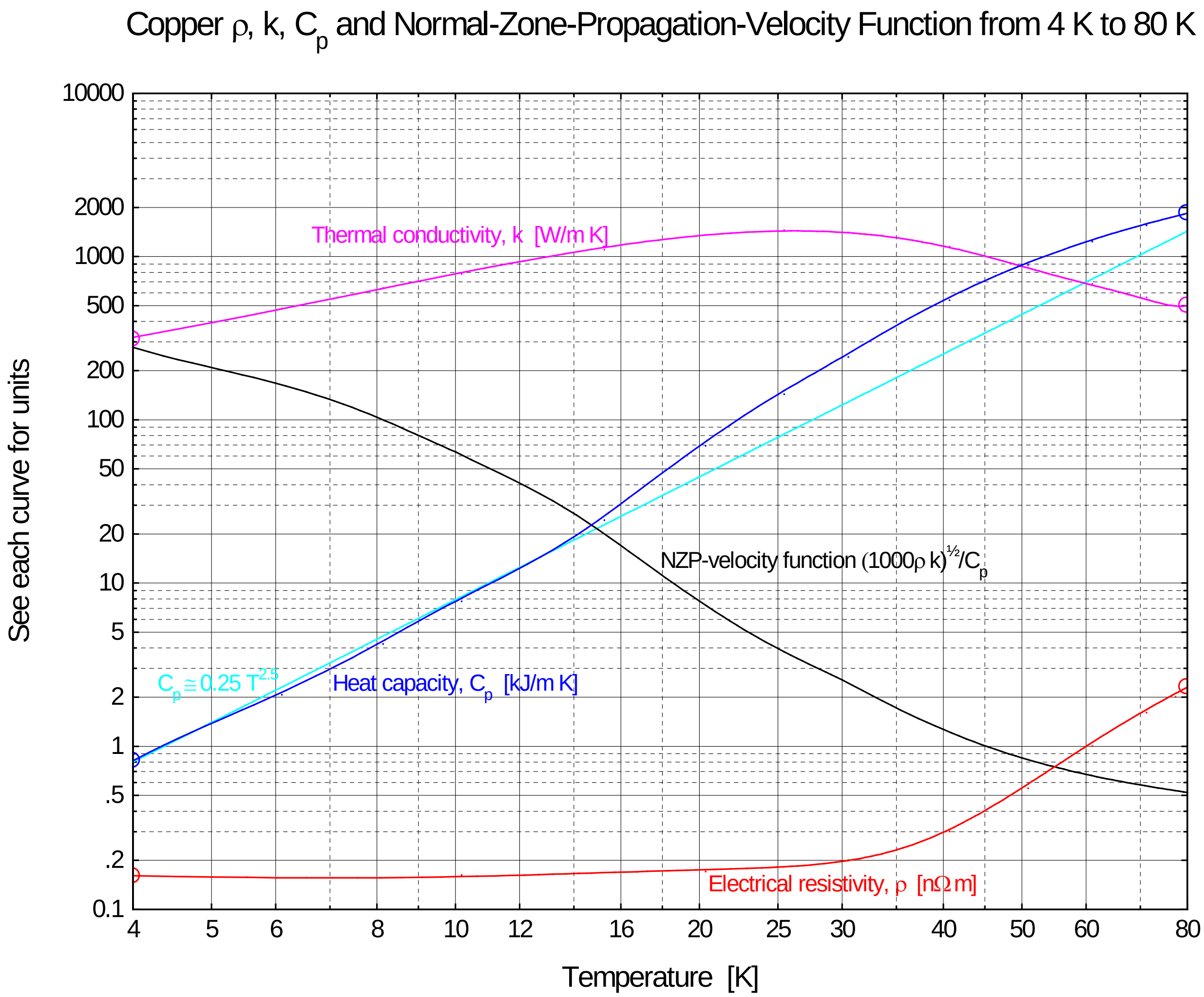

Fig. 13: Electrical resistivity ρ, thermal conductivity k, heat capacity C_p and normal zone propagation velocity function for copper-stabilized superconductors.

Together the magnets store 70 kJ. The peak discharge voltage for the two magnets in series is 2 x 70×10^3 / (350 x 0.43) = 930 volts, requiring an external resistance of 6.9 ohms. This resistance is still much less than that (310+100=410 ohms) through the stainless steel insulation, so, again, most of the energy is dissipated in the external resistor. With both coils in series, the 930 volts is enough to call for precautions against voltage breakdown, but, in practice, the inner coils, and smaller subsections of the outer coil would be powered separately, thus greatly lowering the voltages.

Normal zone propagation (NZP) velocity: To protect a magnet by dumping its energy into an external resistor, one must be able to detect normal zones quickly, to give time to switch in the resistor and discharge the magnet before its hot spot temperature exceeds ~200 K. For the above magnets, the upper limit on detection time is only tens of milliseconds. To facilitate detection, one would like the normal zone to spread rapidly, to grow sufficiently to have enough resistance (and therefore resistive voltage) to be unmistakable despite the background of inductive voltage. High-temperature superconductors at or near liquid-nitrogen temperature are notorious for the slowness of their normal-zone propagation—only millimeters per second. However, theory suggests that the normal-zone propagation velocity should be much faster at the temperature of liquid helium.

The normal zone propagation velocity U_l predicted for a composite superconductor depends on the current density j in the stabilizer, usually copper, and on its electrical resistivity ρ, thermal conductivity k and heat capacity C_p averaged over the temperature range from the magnet operating temperature T_{op} to the transition temperature T_t of the superconductor [10]: $U_l \approx. [j / C_p] [\rho k / (T_t - T_{op})]^{1/2}$.

Figure 13 plots the parameters ρ, k and C_p for copper from 4 K to 80 K, and also the "NZP velocity function" $(C_p)^{-1} [1{,}000 \rho k]^{1/2}$. Evaluated at $T = T_{op}$ the NZP velocity function increases by a factor of ~500 from 4.2 K to 77 K. For greater accuracy, one should evaluate the function at the mean temperature $T_m \equiv \frac{1}{2} (T_{op} + T_t)$ or even at $T = T_t$, because evaluation at the upper end of the temperature range more accurately represents the average value of the function. Evaluated at $T = T_m$, with $T_t = T_{op} + 10$ K, the 4.2 K/77 K NZP velocity ratio is ~150. Evaluated at $T = T_t .= T_{op} + 10$ K, the ratio is ~50. Experiments on high temperature superconductors suggest that this function overestimates the improvement in NZP velocity realized by lowering the magnet temperature, but the combination of very high current density and low temperature should improve the NZP from millimeters per second to centimeters per second or even tens of centimeters per second.

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