Large, High-Field Magnet Projects at the NHMFL

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(Invited Paper)

***Abstract*—The National High Magnetic Field Laboratory has developed and operated large, high-field dc and pulsed magnets for research in condensed matter physics. We are now developing three resistive/superconducting hybrid magnets with fields ranging from 25 to 45 T, and are developing concepts for hybrid magnets up to 60 T as well human-head MRI magnets up to 20 T and repetitively pulsed magnets to reach 60 T every 30 sec.**

***Index Terms*—Hybrid magnets, RPMF, ultra-high field magnetic resonance imaging (MRI), 60 T.**

I. INTRODUCTION

THE National High magnetic field Laboratory (NHMFL) has been developing large, high-field magnets for $>$ 20 years and presently is the home of the 45 T resistive/superconducting hybrid magnet which is not only the world's highest-field dc magnet, but the largest Nb_3Sn CICC magnet in routine operation [1]. We also developed and operate a 100 T, 25 ms, 170 MJ multi-shot magnet as well as a 60 T, 100 ms, 90 MJ magnet [2]. Presently the NHMFL is involved in three hybrid magnet projects, one each for the Helmholtz Zentrum Berlin (HZB) [3], the NHMFL [4], and Radboud University in Nijmegen, The Netherlands [5].

In addition, the NHMFL is developing a conceptual design of Magnetic Resonance Imaging (MRI) magnets suitable for human-head MRI at 20 T as well as a next-generation hybrid magnet providing 60 T dc. Furthermore, a novel combination of superconducting, dc resistive, and pulsed resistive magnets is being considered to enable more time to be available for science than is presently possible with traditional pulsed magnets while requiring relatively modest capital investment.

II. STATUS OF SERIES-CONNECTED HYBRID FOR FSU

A. Program Overview

While fifteen hybrid magnets have been previously built by labs in the USA, UK, Russia, Japan, France, and China [6], all used separate power supplies for the resistive insert and the superconducting outsert. In such a configuration, if the inner resistive magnet trips off, it induces additional current to flow in the outer superconducting magnet which results in higher field on the outsert during than during normal operations as well as higher temperature due to ac losses. Consequently, all hybrids built to date except the NHMFL's 45 T hybrid will quench if the insert trips off. In developing the 45 T, it was felt that the time required to re-cool after a quench ($>$ 1 day) would be an inconvenience for visiting users of the magnet and the system should be designed to be stable even if the power supply for the inner magnet trips off. Consequently, Cable-In-Conduit Conductor (CICC) technology was chosen and the magnet was designed to operate through this transient condition without quenching. This approach was successful, but it results in a superconducting coil that is larger and more expensive than would be required if the magnet did not need to operate through this transient.

For the new generation of hybrid magnets, a novel approach is taken where the resistive and superconducting coils are connected electrically in series. In this Series-Connected Hybrid (SCH) configuration, if the power supply trips off, both magnets are discharged with a time-constant of $\sim$10 seconds due to resistance of the resistive magnet and inductance of the superconducting one. By again using CICC technology, it is possible for the superconducting coil to be sufficiently stable that it does not quench and heating during this fast discharge is much less than that associated with a quench ($\sim$2 s time constant). The resulting magnet can then be more compact than a traditional system using two separate power supplies and still return to service quickly after a trip of the insert power supply [7].

B. The NHMFL SCH

Presently, two magnets are in construction using this technology, one for the Helmholtz Zentrum Berlin and one for the NHMFL. The final design of the NHMFL magnet is shown in Fig. 1.

The superconducting coil consists of three grades of Nb_3Sn CICC. The conductor has been fabricated, wound into a coil, joints have been made, reaction and impregnation completed. Presently the helium supply lines and the structural supports are being installed. We expect the cold-mass to be complete in early 2015.

The coil employs some novel or unusual features. There are five pieces of conductor in the coil, requiring four joints. Unusually, the joints are located at the outer diameter of the coil to minimize the background field and are parallel to the axis of the coil (and fringe field) to facilitate testing. The

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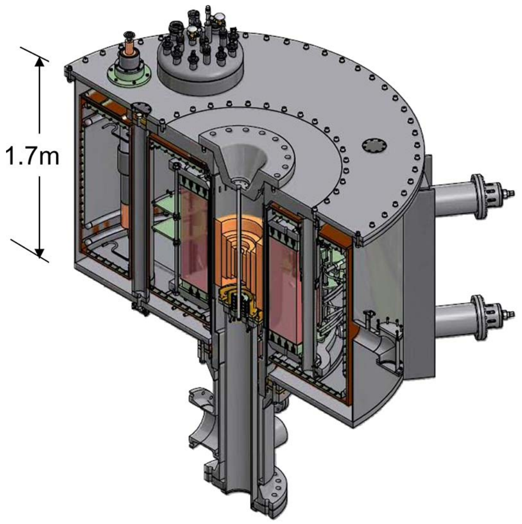

Fig. 1. Vertical section of SCH for the NHMFL Four inner resistive coils, one outer superconducting coil are visible. The 20-kA current-leads are located to the left, beside the helium and nitrogen services. Power and cooling water for the resistive insert enter through the hydrant at the bottom.

coil includes "lead-anchors" to minimize stress concentrations where the conductors enter and exit the coil at the inner and outer diameter. At internal joints, there are "splice-ties" that provide structural connection between the outgoing and incoming CICCs, again reducing stress concentrations. During the winding process, impedance spectra were taken at the completion of each layer to check for electrical shorts between turns. This approach is more sensitive than dc resistance or impulse measurements [8].

The cryostat includes an unusual feature of steel columns passing through the vacuum space to support the two endplates in compression. This requires much less material than would be required for thicker endplates or reinforcement ribs. Fabrication, pressure-testing, and leak-testing of the cryostat has been completed and it is en route from Italy to Florida. When it arrives at the NHMFL it will undergo cold testing prior to installation of the coil in 2015.

The 20 kA current-leads are being developed in-house and use Bi2223 tape and a heat exchanger made of a jelly-roll of pierced copper sheet. Unusually, they will operate in a background field of 0.4T and are cooled with LN_2 rather than GHe. A full-scale mock-up of a lead including all components and features except for copper strips replacing the Bi2223 has been fabricated to practice the various fabrication steps. Fabrication of the real leads has started. When complete, the leads will be shipped to the High Field Magnet Lab at Radboud University in Nijmegen, The Netherlands for testing to full current [9]. They are expected to return to the NHMFL in early 2015 to be installed in the magnet.

The resistive insert design has been completed. It consists of four nested Florida-Bitter coils labelled A, B, C, and D from the inside out. The magnet is intended to attain 1 ppm homogeneity and stability over a 1 cm diameter spherical volume. The homogeneity will be accomplished by introducing a gap at the mid-plane of the B coil as well as reduced current density at the mid-plane of the A coil. The unshimmed magnet will have a bore of 54 mm and the homogeneity is expected to be ~50 ppm. Ferromagnetic and resistive shims will be provided by Oxford NMR. Stability will be provided by a combination of feedback from a pick-up coil to correct short-term ripple and an NMR lock to correct long-term drift [10]. Table I presents coil parameters for the resistive insert.

TABLE I
DESIGN PARAMETERS OF RESISTIVE INSERT FOR NHMFL SCH

	Units	A	B	C	D
Inner Radius	mm	27	71.5	112.1	161.8
Outer radius	mm	68.5	109.2	158.8	230.0
Height	mm	361	499	558	569
Mass	kg	27	88	186	408
Self field	T	10.0	4.2	4.1	4.7
Central field	T	36.0	25.8	21.3	17.1
stress	MPa	650	390	350	300
Power	MW	4.4	2.4	2.5	4.3
Curr. Dens.	A/mm^2	475	158	113	94
Pow. Dens.	W/mm^3	6.13	0.51	0.24	0.17
Press. Drop	bar	25	25	25	25
Effect. Temp.	°C	75	78	46	47
Space Factor		0.73	0.85	0.89	0.91
Material		CuAg	CuZr	Cu	Cu
# turns 1		22.1	1.0	64.0	106.2
# turns 2		74.0	2.0	11.9	7.9
# turns 3		13.9	64.0	6.0	5.8
# turns 4		5.9	7.9	0	0
# turns 5		0	6.0	0	0
Turn thick. 1	mm	2.27	6.13	5.11	4.08
Turn thick. 2	mm	2.23	9.19	10.97	8.25
Turn thick. 3	mm	4.98	5.13	15.00	11.94
Turn thick. 4	mm	14.3	9.71	0	0
Turn thick. 5	mm	0	14.37	0	0

III. 20 T MRI MAGNET

The US National Academies commissioned a "MagSci" committee to write a report on the needs for high-field magnets in the US. The MagSci report became available in 2013 and it concludes that 1) a 20 T MRI system would have resolution of 50 ıgrave;m, 2) time to acquire equivalent signal-to-noise data will be reduced by a factor of 8 from that at 7 T and of 33 from that at 3 T, 3) changes in spectral dispersion and relaxation times will allow investigations of metabolites that cannot be observed by any other methods, and 4) imaging of nuclei such as 13C, 15N, 17O, 23Na, 31P, 37Cl, 39K would become possible [11]. Consequently, the report recommends performing a design study of 20 T magnets suitable for human head MRI.

Fig. 2 shows the field and warm-bore of MRI magnets available worldwide today. (The bore available to the patient is smaller due to installation of gradient and rf systems.) The highest-field system is a 21.1 T (900 MHz), 10.5 cm bore system at the NHMFL that is used for rat-brain imaging. There are a few systems with bores of ~20 cm with fields between 16 T and 18 T that are used for cats. The University of Florida has a system providing 11.1 T in 40 cm bore. There are human-head-MRI systems with bores of ~68 cm. The one with highest field that is operational provides 9.4 T (400 MHz) in Minneapolis while the National Institutes of Health has an 11.7 T (500 MHz) system that is expected to return to operations soon. Human whole-body systems have bores of ~88 cm. Again, 9.4 T is

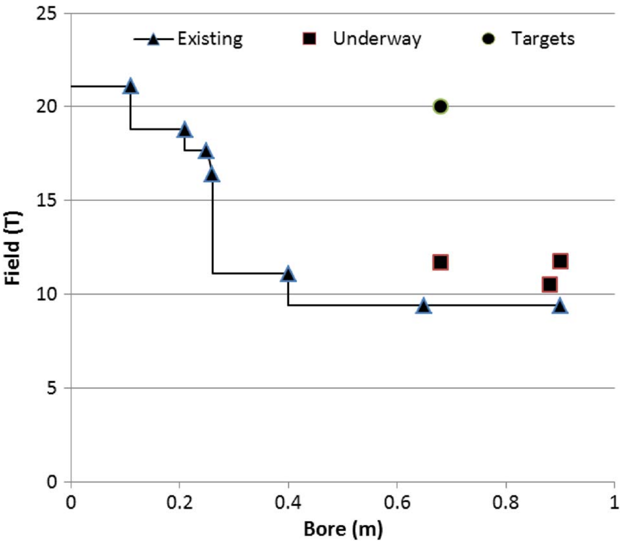

Fig. 2. MRI magnet field vs bore. Triangles indicate operational magnets. Squares indicate magnets that are underway but not yet operational. Circles indicate the target values of 14 T and 30 T appropriate for human-head MRI.

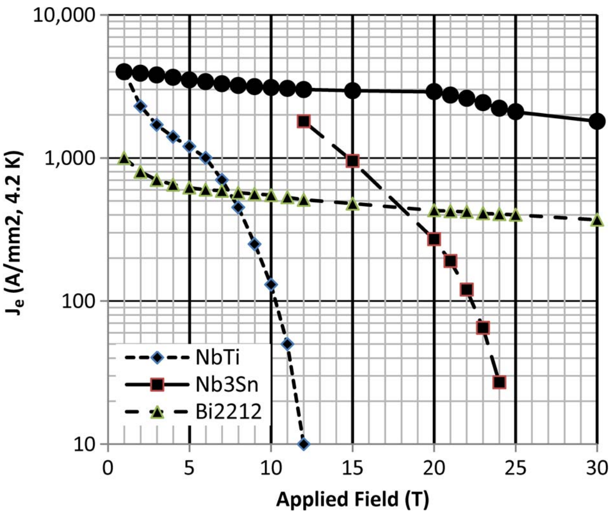

Fig. 3. Current densities of various conductors as a function of field.

operational in both Tuebingen and Juelich, Germany and the Iseult magnet being developed by CEA-Saclay is expected to provide 11.75 T (500 MHz) in a 90 cm bore [12]. For more information on MRI magnets, see [13], [14].

All of the magnets with bores greater than 30 cm use NbTi technology. Developing a 20 T MRI system will require developing Nb_3Sn coils with a field of 16 T or more and a bore of 70 cm or more. In addition, given the fact that at 20 T and 4.2 K, the High-Temperature Superconductors (HTS) have current-densities higher than Nb_3Sn (Fig. 3) suggests that a 20 T MRI magnet might employ these materials to produce a more compact system. We have performed preliminary design studies for 20 T magnets both with and without HTS materials. Of course, the calculations based on HTS conductors are somewhat speculative, but they suggest the magnet with HTS conductors would be a bit more compact and might justify developing this technology.

TABLE II
COMPARISON OF PROPOSED 20 T HEAD-ONLY MAGNET WITH OTHER LARGE MRI SYSTEMS

	Unit	Juelich	Iseult	Proposed
Central Field	T	9.4	11.75	20
Magnet Warm Bore	Cm	90	90	68
Stored Energy	MJ	190	338	~500
Current Density	A/mm^2		26.4	~30
Conductor Mass	Ton	<57	65	~40
Coil Length	m	3	3.9	~2.7
Coil Outer Diameter	m	~2	4.3	~2

Interestingly, most of the MRI magnets presently in service employ copper in the dual role of stabilizer and reinforcement. The strength at 4.2 K of austenitic steel is approximately three times that of copper, hence its use in CICC coils. We believe that the use of steel reinforcement is essential in a 20 T MRI magnet to keep the size manageable.

The conductor in MRI magnets is also typically a single strand of superconductor with persistent joints. Iseult is taking the unusual approach of using a 10-strand cable in a double-pancake construction. This results in 150 double-pancakes and joints. Each joint contains 10 strands. Consequently, if the magnet were to be persistent, it would require 1500 persistent joints. The Iseult project has elected not to use persistent joints and to install an ultra-stabilized power-supply instead. This means the leads will not be retractable and dedicated helium refrigerator will be needed. This approach also allows them to use an external dump resistor to discharge the magnet, which simplifies protection [12].

If a 20 T MRI magnet were to include HTS materials, then it would not include persistent joints and it would be easier to incorporate steel reinforcement into the windings if cables were employed. Cables also facilitate a ventilated winding or CICC construction which would increase stability and reduce the probability of the magnet quenching with a patient inside.

Table II presents preliminary design parameters for a 20 T head-MRI system as well as those for the largest MRI system presently in operation, a 9.4 T whole-body system at Julich [15], [16], and the 11.75 T Iseult whole-body magnet presently under construction. It is important to note that the Juelich magnet uses an iron shield to reduce the fringe-field whicle the Iseult magnet uses a pair of active shield coils. The proposed 20 T magnet does not include shield coils, hence would use iron. We see that the 20 T magnet is projected to have less conductor mass and smaller size than the 11.7 T Iseult. This is due to three important differences: 1) smaller bore and length (head vs. whole-body), 2) steel reinforcement instead of copper, 3) the higher current-density of Nb_3Sn wire a 14 T, 4.2 K vs NbTi at 12 T, 2.0 K, 4) no active shield. In addition, if HTS cables develop fast enough, they might be incorporated in the magnet design and reduce the size further.

Of course, simply having a large-bore, high-homogeneity magnet does not necessarily mean one can perform human MRI. There are various safety and feasibility concerns associated with such an endeavor ranging from the impact of field, field-gradient, and field-transients on the human body as well as challenges associated with rf-penetration and heating as discussed in [17]. Consequently, the first step is to demonstrate feasibility and safety while developing a more detailed magnet design and a proposal has been submitted to begin this. Another important point to mention is that by operating at a higher field, one can image elements other than hydrogen. Potassium, chloride, sodium, and various other elements can be imaged at 14 T, all at much lower frequencies than hydrogen, this solving some of the heating challenges.

IV. 60 T HYBRID

In 2005 the Committee on Opportunities at High Magnetic Fields (COHMAG) which had been appointed by the US National Academies issued its final report calling for the development of a 60 T hybrid magnet for use in studying condensed mater and materials physics ranging from quantum magnets to semi-metals. This challenge has since been re-issued by the more recent MagSci committee in 2013.

In considering a 60 T dc magnet, the first question to address is should the magnet be all superconducting or should it be a resistive-superconducting hybrid? Presently, the NHMFL is developing an all-superconducting 32 T magnet that uses YBCO tape from SuperPower for the inner coils. The average current-density in these coils is < 200 A/mm^2 [18]. In contrast, 30 T resistive magnets typically operate at > 600 A/mm^2 in at the inner diameter [19]. Consequently, when we perform design optimization using today's technology along with some extrapolation for larger coils, we consistently find that hybrid magnets result in more compact systems than all-superconducting designs do. The more compact magnet should be dramatically less expensive to fabricate and the savings would be more than adequate to cover the cost of the electric bill associated with the resistive inner coils of the hybrid, assuming a 20-year lifetime of the magnet [7].

Given the size of the 60 T hybrid, we would want to use cables for the superconducting section to facilitate protection with an external dump-resistor. Assumptions can be made of the performance of cables made of various HTS materials and we can develop preliminary conceptual designs of a 60 T hybrid magnet [8]. Given the large size and high field of these solenoids, the HTS cables are expected to require additional reinforcement. Hence we refer to these conductors as HTS CICCs.

The second question is, can the magnet be built using the well-developed LTS CICC and Florida-Bitter technologies being employed in hybrids today and not waiting for the development of HTS technology on a very large scale? We do not see a way to do it with today's technology. Without HTS, the resistive part of the magnet would need to be much larger than is possible with today's technology. New resistive magnet technology would need to be developed. Given the potential of HTS cables for high-energy physics (HEP) and other applications, as well as the power savings they would afford, it seems prudent to plan on using HTS cables in the 60 T hybrid. Fig. 4 shows a vertical section of this preliminary design. While the magnet is significantly larger than any hybrid either existing or under development, it is not as large as various fusion or HEP detector magnets.

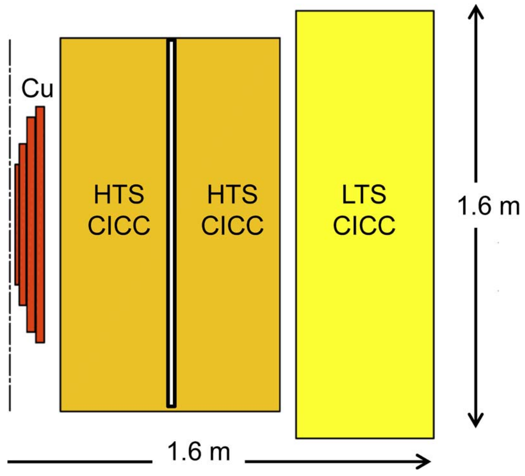

Fig. 4. Preliminary design of 60 T hybrid magnet.

We intend to protect the magnet via external dump-resistor(s). In the past, we have used a single dump-resistor for the three coils of the 45 T hybrid and the single coil of the SCH magnets. For the 60 T hybrid, if we want to operate the HTS and LTS coils in electrically in series and discharge voltage below 10 kV, the current might need to be as much as 80 kA (depends on some uncertainty in performance of HTS coils). However, winding an 80 kA conductor on the relatively small diameter of the inner HTS coil ($\sim$36 cm) will not be straightforward. There are at least 2 other options. The first would be to have different coils in the outsert operating on different power supplies at different current-levels: lower current for the inner coils and higher current for the outer ones. The other option is to build the entire magnet at lower current (< 20 kA) and have leads coming out at several point through the circuit with dump resistors. This second option is essentially the same as that used by accelerators which might have 1 GJ in a circuit but modest current enabled via a separate dump-resistor for each dipole.

V. DEVELOPMENT OF HTS CABLES FOR 20 T MRI AND 60 T HYBRID

Obviously, the performance of large magnets constructed from HTS CICCs is not well-understood at this point. To refine the design, we need to develop real HTS CICCs and test them in a realistic operating condition to determine their actual performance and then update the designs of both the 20 T MRI magnet and the 60 T hybrid magnet using this data.

The NHMFL presently has three facilities that are suitable for testing HTS CICCs and a fourth that could be made rather easily. The first of these is a split 12.5 T superconducting magnet built in the early 1990's by Oxford Instruments. It has a 150-mm bore and has been used to characterize Nb_3Sn CICCs for use in the 45 T hybrid and the SCH magnets. Conductors are made into hairpin specimens and installed in the split with the field perpendicular to the CICCs. The temperature of the CICCs can be controlled separately from that of the background magnet between 4 K and 20 K. Up to 20 kA of current can be provided to the CICC being tested and tension up to 250 kN (25 metric tons) can be applied as well.

TABLE III
PARAMETERS OF VARIOUS CICC TEST FACILITIES AT THE NHMFL

	Units	12 T	17 T	Hybrid	Hybrid**
Background Field	T	12.5	17	11.4	24
Configuration		split	solenoid	solenoid	solenoid
Cold Bore	cm	15	16	23* 50**	20**
Applied Tension	kN	250	self	self	self

*Presently available, ** Potential upgrade

TABLE IV
TEST CAPABILITIES OF NHMFL FACILITIES AND OPERATING PARAMETERS OF HTS SECTIONS OF 20 T MRI AND 60 T HYBRID

	Units	Testing Completed		Magnet Requirements		
		2014	~2017	20 T MRI	60 T outer	60 T inner
Field	T	~15	24	20	~25	~43
Current	kA	~10	20	<10	~20	~10
Tension	kN	0	250	<80	~95	~160
Stored Energy	MJ	0	~4	~25	~100	~450
Transients		None	?	N/A	?	?
Homogeneity		None	?	?	N/A	N/A

The second facility is a 17 T resistive solenoid with a room-temperature bore of 195 mm. An insert cryostat is available with a sample-space of 165 mm. An HTS CICC can be wound into a turn or two and energized. This facility has the advantage of going to higher field than the split magnet as well as being able to subject a longer piece of conductor to high-field due to the capacity to coil the conductor. It is also possible to get tension in the conductor due to Lorentz forces.

The third facility is the 45 T. The resistive coils can be removed easily leaving a bore of ∼600 mm with a background field of 11.4 T on the axis. A cryostat is available that allows coils up to ∼230 mm diameter can be installed. However, it would be relatively straight-forward to procure and install a cryostat that would allow coils up to ∼500 mm diameter to be tested. While this would operate at lower field than the 17 T magnet, the larger space allows a real coil including real manufacturing techniques and joints to be tested.

Finally, it is possible to remove the inner resistive coils only from the 45 T hybrid leaving a background field of 24 T in a 230 mm room-temperature bore. A new cryostat could be installed to allow ∼200 mm for testing. This would allow testing at a uniquely high field. Table III provides parameters of the facilities.

Table IV shows the present state of conductors and coils that have been tested worldwide as well as what could be attained using the test-facilities described above and the operating parameters of the proposed HTS coils for a 60 T hybrid. We see that using the various facilities at the NHMFL, we could qualify conductors for use in the 20 T MRI as well as the outer HTS section of the proposed 60 T hybrid.

A. Pulsed Magnet

Given the size, cost and amount of technology development required to meet the challenge of a 60 T hybrid, re-considering the challenge seems relevant. Why develop a 60 T hybrid? There are already 60 T pulsed magnets in operation at various facilities worldwide. The NHMFL operates magnets with ∼25 ms pulses that can reach 65 T once every 40 minutes. We also operate a magnet with a 100 ms flat-top that reaches 60 T once every 120 minutes. There are two possible reasons to use a dc magnet instead of a pulsed magnet: 1) the need for pulses longer than 100 ms and 2) the need for more time at field per day. If the need is time at field, then it would be possible to build a pulsed magnet that reaches 60 T for ∼25 ms with 30 seconds between pulses instead of 30 minutes using technology we demonstrated previously in a repetitively pulsed magnet for neutron scattering [20].

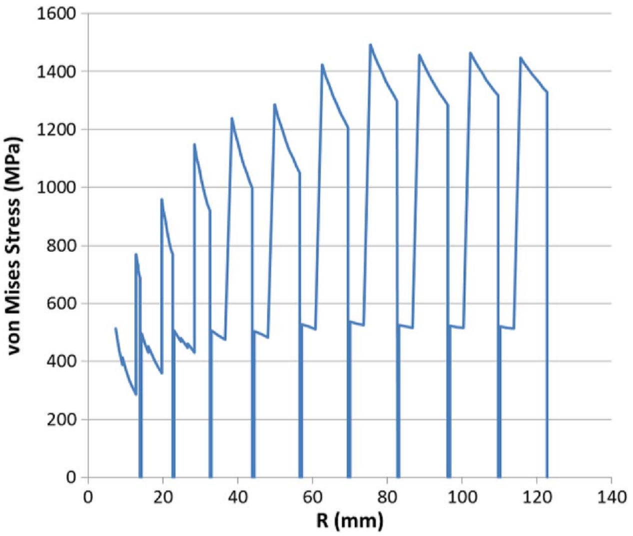

Fig. 5. Distribution of hoop-stress in 40 T pulsed magnet operating in a 23 T dc background.

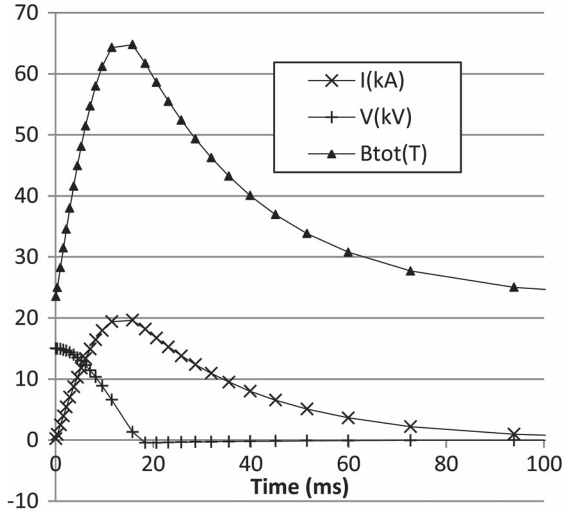

Fig. 6. Voltage, current and field vs. time for the 40 T pulsed coil operating in a 23 T background.

To accomplish this, we would remove the inner three resistive coils from the 45 T hybrid. This would provide a 24 T background field in a 248 mm wet bore. Cylinders of copper-alloy would be machined into variable-pitch helices and reinforced with zylon and glass fiber. They would be nested together leaving space for cooling water at the inner diameter of each. Fig. 5 shows the stress in the pulsed coils and reinforcement at peak field while Fig. 6 shows the current and field vs. time.

Because there is cooling-water on each layer of conductor, the conduction path is much shorter than a standard pulsed magnet and the repetition-rate will be limited by the rate at which one draws power from the grid to re-charge the capacitor bank, rather than the time it takes to re-cool the magnet.

VI. CONCLUSION

The NHMFL continues to develop concepts for large, high-field magnet systems that show potential for application in condensed-matter physics, chemistry, biology and medicine. HTS materials will play a major role in our future developments and we have unique facilities that enable characterization of materials and components needed for magnet systems.

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The 20 T MRI proposal was initiated by T. Budinger along with L. Frydman and J. Long.

Software developed by Y. Eyssa was used to design the repetitively pulsed magnet. Doan Nguyen and C. Swenson engaged in fruitful discussions.

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