Resistive Magnet Upgrades: BETTER TECHNOLOGY = HIGHER FIELDS, GREATER DURABILITY

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Design work to upgrade various resistive magnet facilities at the NHMFL is now underway. There are three major upgrade design projects that will eventually impact the magnets in cells 5, 7, 8, 9, and 12. All of these projects involve using the technology developed for the 33 T resistive magnet and the Hybrid insert and applying it to the existing (obsolete) facility magnets. In so doing, field increases up to 7 T should be attained. In addition, reliability and user friendliness of some facilities should increase.

When designing and comparing magnet systems, one needs to consider what is meant by "efficiency." For resistive magnets, the field, *B*, is proportional to the current, *I*, and the power, *P*, is roughly proportional to the square of the field ($I \sim B,\ P \sim I^2R,\ \Rightarrow P \sim B^2$). In addition, for magnets consuming the same amount of power, those with larger bores provide lower fields. One can show then that a simple measure of the "efficiency," *E* of a resistive magnet is given by:

$$E = B(a_1/P)^{1/2}\ [1],$$

where, a_1 = inner radius.

50 mm Bore (Cell 5)

Upgrading the 25 T, 50 mm bore high field magnet in cell 5 to 32 T is being undertaken first due to the need to provide spare coils for this aging magnet. This 7 T increase is attained by a global re-optimization that includes three main features: (1) changing from a 3-coil design to a 4-coil design, (2) introducing axial current density grading, (3) re-sizing the coils based upon the previous two features. Figure 1 presents a vertical section through the existing 25 T magnet and the newly designed 32 T magnet.

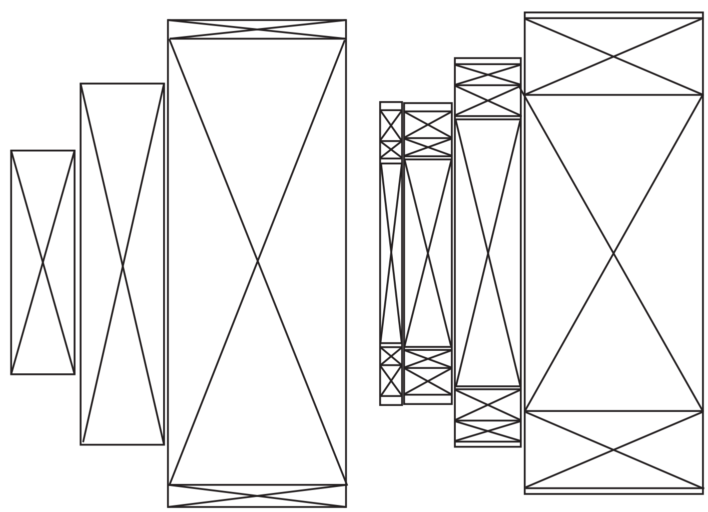

Figure 1. Vertical section of old (left) and new (right) 50 mm bore high field magnets.

One sees that the old system used three coils labeled *A*, *B*, and *C* from the inside out. Coils *A* and *B* have uniform current density along their lengths. Coil *C* has one turn at each end with reduced current density. In the new design, we utilize four coils labeled A_1, A_2, *B*, and *C* from the inside out, similar to the existing 33 T magnets in cells 9 and 12. By introducing an additional coil, one has more degrees of freedom for the optimization process which means we can obtain a practical solution closer to the "theoretical" limit of efficiency.

In addition, the new coils include substantial current density grading with coils A_1, A_2, and B utilizing three symmetric zones of grading and C using much larger reduced current density zones at the ends than presently. In the existing magnet, the end turns of the B coil consume the same amount of power as do the mid-plane turns. The end turns, however, are further from field center and do not contribute as much to the field on-sample as do the mid-plane turns. Thus, the end turns are not as efficient as the mid-plane ones as defined above. By introducing axial current density grading, the end turns run at lower current density and consume less power than the mid-plane turns, thereby bringing their efficiencies more in line with the mid-plane.

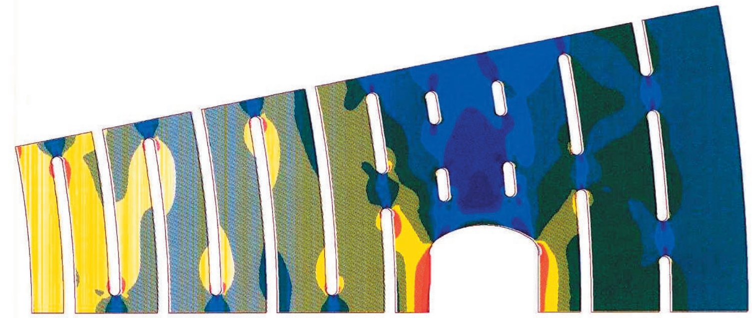

Figure 2. Mid-plane temperature of the new A2 coil.

Figure 3. Mid-plane stress of the new A2 coil.

Finally, given four coils and the possibility of axial current density grading, we re-optimize the whole system resulting in the design shown in the right side of Figure 1. Table I compares parameters and efficiencies of the old and new designs. We see that the outer diameter of the new A coil is larger than that of the old one. What has happened is that power has been shifted from the ends of the B and C coils to the mid-plane of the outer part of the A coil. It is important to recall that a system is more than simply a collection of parts bolted together. If one studies Table I, one might conclude that the A_1 and A_2 coils are less efficient than the old A coil and that the new B coil is less efficient than the old B coil. However, if one computes the efficiency of the new A_1 and A_2 coils together and compares that to the old A coil, one sees an improvement of 5.91 vs. 5.31 $T/MW^{1/2}$. In addition, the new B coil has a larger inner radius than the old one. If we correct their efficiencies by the square root of the inner radii, we see they are similar. Ultimately, the critical parameter is the total system efficiency. Figures 2 and 3 present temperature and stress distributions, respectively in the new A_2 coils as computed by Iain Dixon using ANSYS.

Coil design of this new system is complete and a design review was held June 11, 2003. Detailed mechanical design is underway and purchasing of materials is starting to occur.

TABLE I: Comparison of old and new 50 mm bore magnets.

Coil	a_1 (mm)	B (T)	P (MW)	$B/P^{1/2}$ ($T/MW^{1/2}$)
EXISTING DESIGN				
A	28	10.0	3.54	5.31
B	77	10.1	6.21	4.05
C	152	7.6	6.14	3.07
TOTAL		**27.7**	**15.9**	**6.95**
NEW DESIGN				
A_1	28	7.07	2.63	4.36
A_2	49	9.66	5.36	4.17
B	93	8.00	5.31	3.47
C	152	7.55	5.64	3.18
TOTAL		**32.3**	**18.9**	**7.42**

32 mm Bore (Cells 8, 9, 12)

The second upgrade project is to re-design the 32 mm bore high field magnets and increase the field available to users from 33 T to 35 T. This will be accomplished by using the same *B* and *C* coils as in the new 50 mm bore magnet and installing new A_1 and A_2 coils for the 32 mm bore system as shown in Figure 4. Eventually these new magnets will be installed in cells 8, 9, and 12 as the existing coils wear out.

Again, we can compare efficiency of the new design to the old as shown in Table II. We see that the overall system efficiency of the new magnet is only slightly better than that of the old magnet. The new magnet, however, is designed to provide 2 T more field at the same stress level as the older, lower field magnet. Thus, while the new design principles do not impact the overall "efficiency", they do allow for higher field with the same (or better) lifetime and reliability.

The 32 mm bore upgrade is presently still in the coil design phase which should be completed in September 2003. The numbers presented in Table II are preliminary. The detailed mechanical design phase will then initiate based upon availability of personnel.

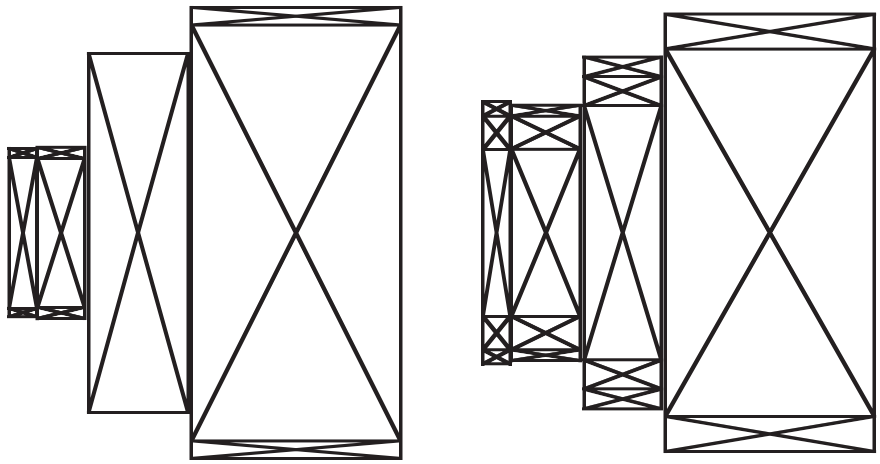

Figure 4. Vertical sections of old (left) and new (right) 32 mm bore high field magnets.

TABLE II Comparison of old and new 32 mm bore magnets.

Coil	a_1 (mm)	*B* (T)	*P* (MW)	$B/P^{1/2}$ (T/MW$^{1/2}$)
EXISTING DESIGN				
A_1	19	7.57	1.88	5.52
A_2	40	8.90	4.12	4.38
B	77	9.17	5.25	4.00
C	152	7.41	5.70	3.10
TOTAL		**33.1**	**17.0**	**8.03**
NEW DESIGN				
A_1	19	7.91	2.47	5.03
A_2	40	11.63	5.42	5.00
B	93	8.15	5.58	3.45
C	152	7.68	5.85	3.18
TOTAL		**35.4**	**19.3**	**8.06**

50 ppm (Cell 7)

Presently, cell 7 provides 24.5 T in a 32 mm bore with inhomogeneity of roughly 50 ppm over a 10 mm DSV for periods up to one hour. For extended periods of time the field is restricted to 23.2 T due to power supply limitations. We intend to upgrade cell 7 to a new coil design based heavily upon one of the designs presented above. There is some advantage to having both cell 5 and 7 configured with 50 mm bore high field magnets. One could then install inserts into either of them to provide high homogeneity, modulation, gradient, etc. However, the current densities in the insert necessary to achieve high homogeneity in the overall system would be quite high which would require developing new coil technology. In addition, the resulting system would be very sensitive to imperfections. Slight coil mis-alignments and manufacturing tolerances could result in unacceptably large in-homogeneities.[2] Hence it appears, at this point, that the new magnet for cell 7 will be a modification of the new 32 mm bore magnet as shown in Figure 5. The field available should be above 29 T for 8 hour shifts.

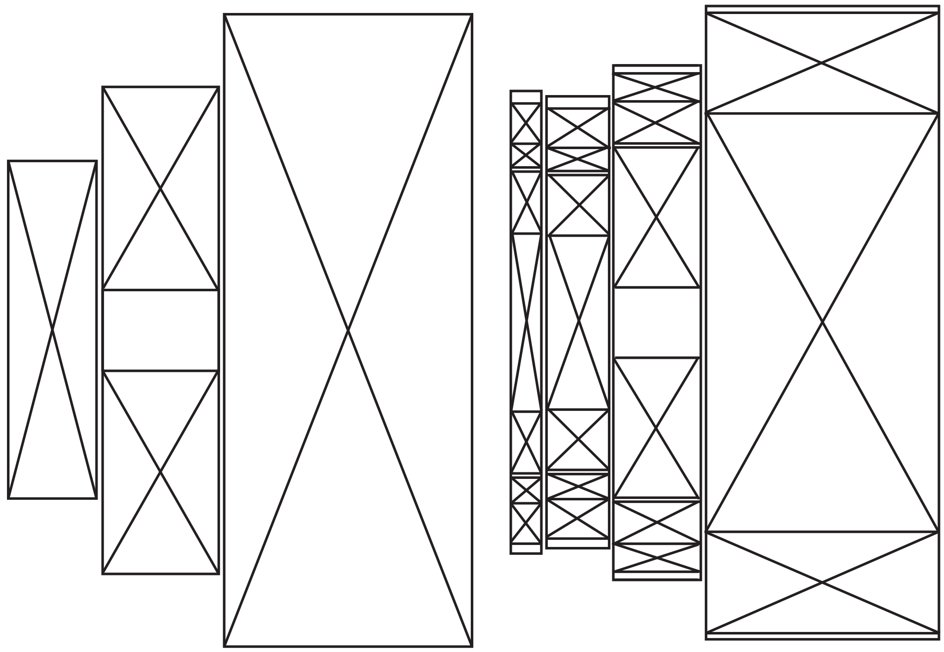

Figure 5. Vertical sections of old (left) and new (right) 50 ppm magnets.

TABLE III Preliminary inhomogeneity of new 50 ppm magnet [B(z)-B0/B0*1e6].

z (mm)	A_1 (ppm)	A_2 (ppm)	*B*	*C*	Total
0	0.0	0.0	0.0	0.0	0.0
2	-0.5	-0.7	10.4	-9.4	-0.2
4	-1.4	-2.3	42.1	-37.2	1.3
6	-2.6	-5.9	94.4	-83.4	2.5
8	-3.8	-13.3	166.7	-148.1	1.5
10	-4.3	-26.8	258.2	-231.4	-4.2

In the existing 50 ppm magnet, the *A* and *C* coils are standard high field coils where the field drops off as one moves away from the mid-plane along the axis of symmetry. We call this negative field curvature. The *B* coil has a gap at the mid-plane which gives it positive curvature. The sum of the fields of the three coils is roughly zero field curvature over a 10 mm DSV.

For the new magnet, a different approach is taken. Again the *C* coil is the same high field coil with negative field curvature as the two designs above. The *B* coil again has the split to provide positive curvature. The A_1 and A_2 coils, however, employ slightly lower current density at the mid-plane zone than at the next outboard zone. Thus, their fields are essentially flat. Field inhomogeneities of these preliminary coil designs are presented in Table III assuming no imperfections or mis-alignments. If one used the high field A_1 and A_2 coils of the 32 m bore magnet, one could not introduce enough positive curvature into the *B* coil to compensate the overall system. Hence, the "flat" design of the A_1 and A_2 coils.

Design of this magnet is in a preliminary stage. When then 32 mm bore coil design is complete, we will proceed with design of this new system. It is important to note that the final magnet will have substantially higher in-homogeneity due to manufacturing tolerances than indicated in Table II. The final in-homogeneity is expected to be comparable with that presently in cell 7 or what was attained in Keck prior to ferroshimming, i.e., about 50 ppm over a 10 mm DSV.

Future Systems

The user community has repeatedly requested a transverse field magnet and high gradient insert coils. Design of these systems should begin in coming months as personnel become available.

[1] D.B. Montgomery & R.J. Weggel, *Solenoid Magnet Design: The Magnetic & Mechanical Aspects of Resistive and Superconducting Systems*, John Wiley & Sons, 1969.

[2] M.D. Bird and Z. Gan, "Low Resolution NMR Magnets in the 23 to 35 T Range at the NHMFL," *IEEE Trans. On Appl. Supercond.,* vol. 12, no. 1, March 2002, pp 447-451.