Conceptual Design for a next generation Resistive Large Bore Magnet at the NHMFL

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INTRODUCTION

The National High Magnetic Field Laboratory (NHMFL) has successfully operated its 20 Tesla 195 mm large bore magnet for over 20 years. Eventually, as there was a certain slowdown in demand for that magnet at the time, it had been decommissioned in 2016 and its two outer coils have been re-used for parts in a higher energy density configuration to facilitate the fast construction of the world record 41.5 Tesla, 32 mm bore NHMFL resistive magnet. With no resistive large bore magnet providing fields in the 20 Telsa range available for the last two years, the demand or desire for such a facility has been steadily rising at the NHMFL. Again, cost and schedule for the construction of such a magnet are critical very aspects under consideration. One elegant solution to keep these factors most manageable is to not design a new stand-alone magnet but to design one or a set of insert coils that is interchangeable with a smaller bore existing magnet at the NHMFL. Different alternative configurations for such a large bore resistive insert including two different existing NHMFL magnets to serve as the outsert as well as different usable bore sizes have been considered on a preliminary level of detail for comparison only. Eventually, a more detailed conceptual design has been developed for a chosen magnet system. In this poster, the authors present a summary of the different alternative considerations as well as an introduction to the conceptual design of a next generation 195 mm Large Bore Magnet capable to produce well above 20 Tesla.

***Terms*—High field magnets, resistive magnets, water cooled magnets.**

ALTERNATIVE LARGE BORE CONFIGURATIONS BASED ON PRELIMINARY INSERT DESIGNS COMPATIBLE WITH EXISTING NHMFL MAGNETS

I) NHMFL Magnet Installations that could serve as platforms for LB inserts

Two existing magnet installations including the 45 T Hybrid as well as the 41.5 T all resistive magnet with a 1.0 m outer diameter are most suitable compared to the smaller 600 mm outer diameter resistive magnets (ruled out early on).

Large Bore (LB) Magnet configurations corresponding to a cold bore ranging from 100 mm to 200 mm in diameter have been considered in this study.

Cold Bore vs. Resmag ID vs. Warm Bore

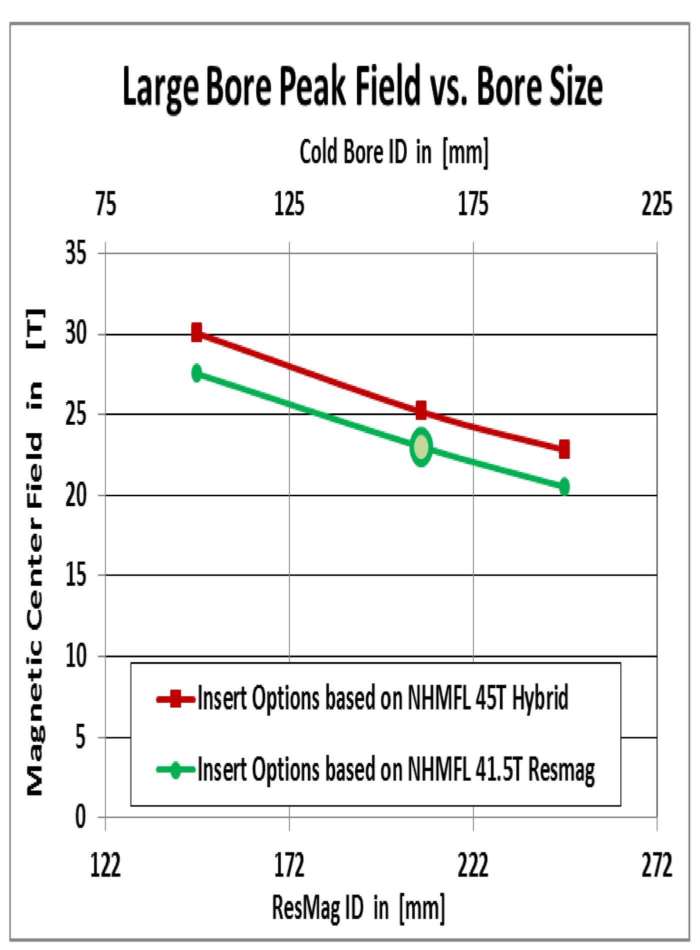
Resmag warm bore ID	**134**	**195**	**234**
cold bore	100	161	200
resmag coils ID	147	208	247

NHMFL 45T HYBRID MAGNET MODIFICATIONS WITH DIFFERENT BORE INSERT COILS

Field [T]	30.1	25.3	23.5
Power [MW]	22.3	16.8	15.9
Coil Configuration	A=CuAg ($$$) (new cooling holes) +10mm return bus bar B=CuBe (same cooling holes) C=Cu (same cooling holes)	A=CuBe (new cooling holes) B=Cu (same cooling holes)	A=CuBe (same cooling holes) B=Cu (same cooling holes)

NHMFL 41.5T RESISTIVE MAGNET MODIFICATIONS WITH DIFFERENT BORE INSERT COILS

Field [T]	27.6	23.0	21.0
Power [MW]	33.5	32.9	29.9
Coil Configuration	A=CuAg ($$$) (new cooling holes) B=CuBe (new cooling holes) C&D=Cu unchanged coils same as 41.5T D&E	A=CuBe (new cooling holes) B&C=Cu unchanged coils same as 41.5T D&E	A=CuBe (new cooling holes) B&C=Cu unchanged coils same as 41.5T D&E



II) Comparisons

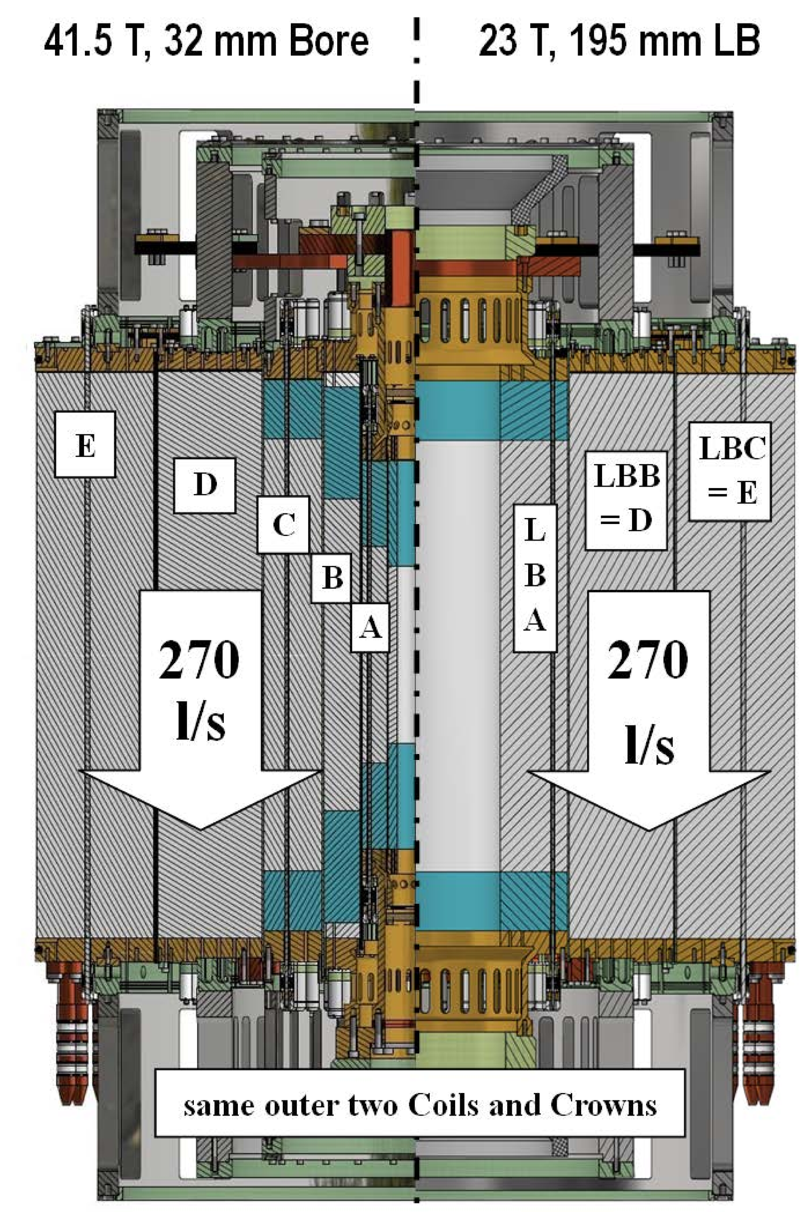
- The highest fields can always be achieved while consuming less power with insert designs employing the 45T Hybrid vs. the NHMFL 41.5T all resistive magnet
- A LB configuration with a 134mm Resmag warm bore can deliver ~5 Tesla more field than the typical 195mm option. However, such designs would require the usage of expensive CuAg sheet metal as materials for the A-coil
- Manufacturing of only one single new 195mm bore A-Coil can deliver 23T if inserted into the two outer (unchanged) coils of the existing NHMFL 41.5T magnet
- 23.5T can be generated by only removing coils from the 45T Hybrid

SYSTEMATIC FEA-AIDED DESIGN OF A NEW 23 T ALL RESISTIVE 195 MM LARGE BORE MAGNET COMPATIBLE WITH THE EXISTING NHMFL 41.5 T MAGNET INSTALLATION

I) Summary of General Design Parameters

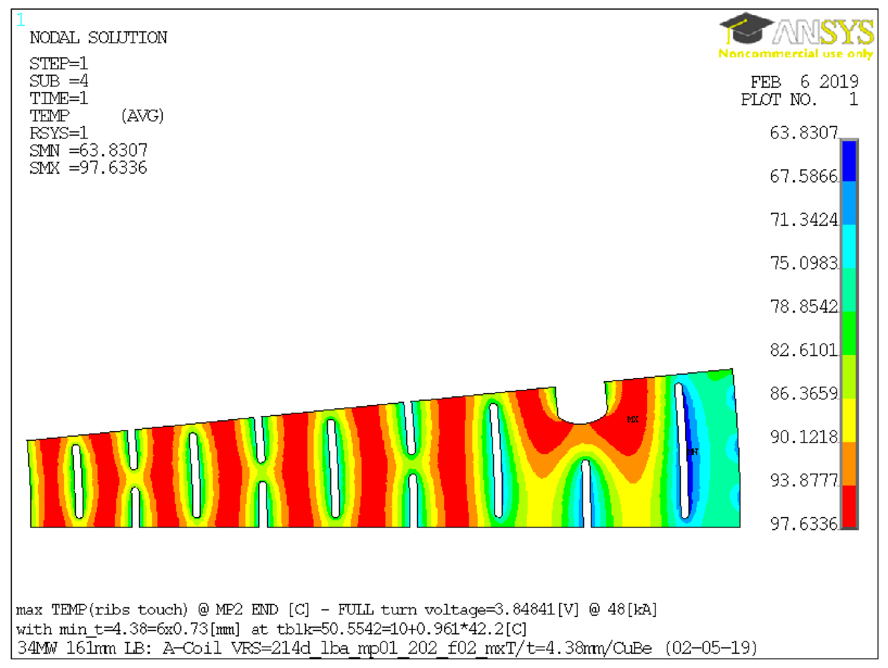
The NHMFL developed a LB insert coil optimized to maximize the magnetic field generated using up to 33.5 MW of total electric power when it is installed in series to the two outer coils of the existing 41.5 T magnet. The new insert coil (LBA) utilizes the strongest sheet metal available to the NHMFL in that larger size of 400 mm x 400 mm. The high strength CuBe alloy with a design stress limit of 550 MPa is chosen for the high current density winding and typical high strength Cu for its end sections. The end turn disks of this inner most nested coil (LBA) are fabricated using the drops of its mating outer coil (starting from the 0.75 mm thick LBB-Coil disks. The ratio of midplane disks (MP) versus Endturn (ET) disks used in each coil is quantified in the table below and illustrated via different shading in the figure. The total required minimum cooling flow for this magnet was kept the same as in the 41.5 T version and it is set to 270 l/s.

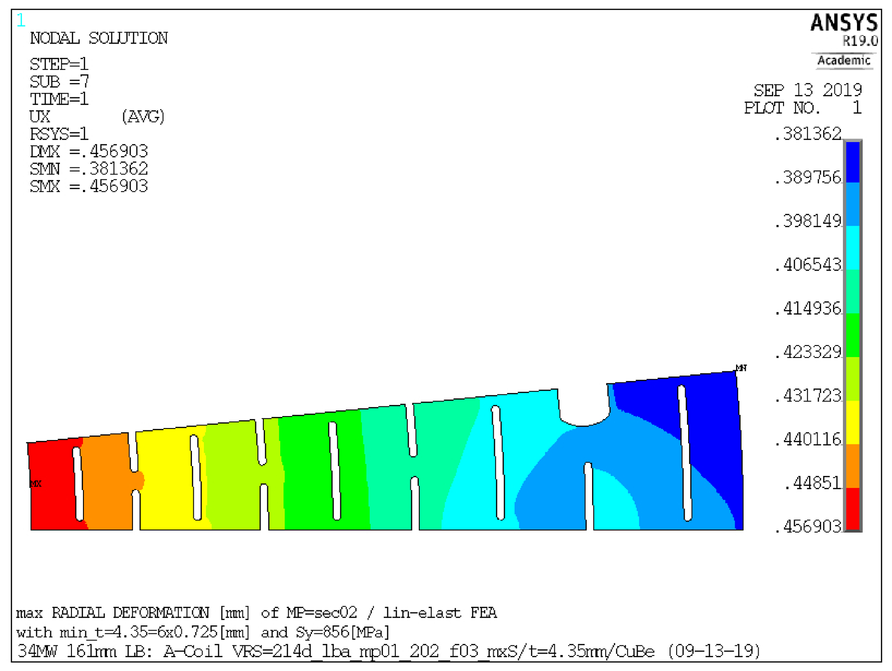
Coil Number	LB-A	LB-B	LB-C
Inner radius [mm]	107.6	200.0	343.0
build [mm]	89.4	140.0	157.0
Outer radius [mm]	197.0	340.0	500.0
MP winding height [mm]	562	731	730
ET winding height (with blinds) [mm]	149	0	0
total winding height (with blinds) [mm]	710.0	730.8	730.5
# of tierods	31	32	32
MP Material	CuBe	Cu	Cu
MP-thickness w/o plating [mm]	0.73	0.75	0.94
ET Material	Cu	Cu	Cu
ET-thickness w/o plating [m]	0.75	0.75	0.94
Self Field [T]	11.27	8.33	3.47
Current [kA]	48.0	48.0	48.0
Voltage [V]	386.7	224.0	88.9
power	18.56	10.75	4.27
min space factor	0.857	0.904	0.966
MP cooling hole width	0.98	2.10	2.10
ave MP water velocity [m/s]	14.2	13.7	14.4
effective cooling flow [l/s]	110.8	89.8	38.7
water temperature rise [deg]	40.0	28.6	26.4
max disk temperature [C]	97.8	93.1	76.6
ave J(a1) [A/mm^2]	193	127	48
max ave Stress [Mpa]	535	300	50
Stress Limit [Mpa]	550	315	200
Coil Winding Mass [kg]	516.1	1511.1	2824.1
Coil Winding Mass [lbs]	1135	3324	6213

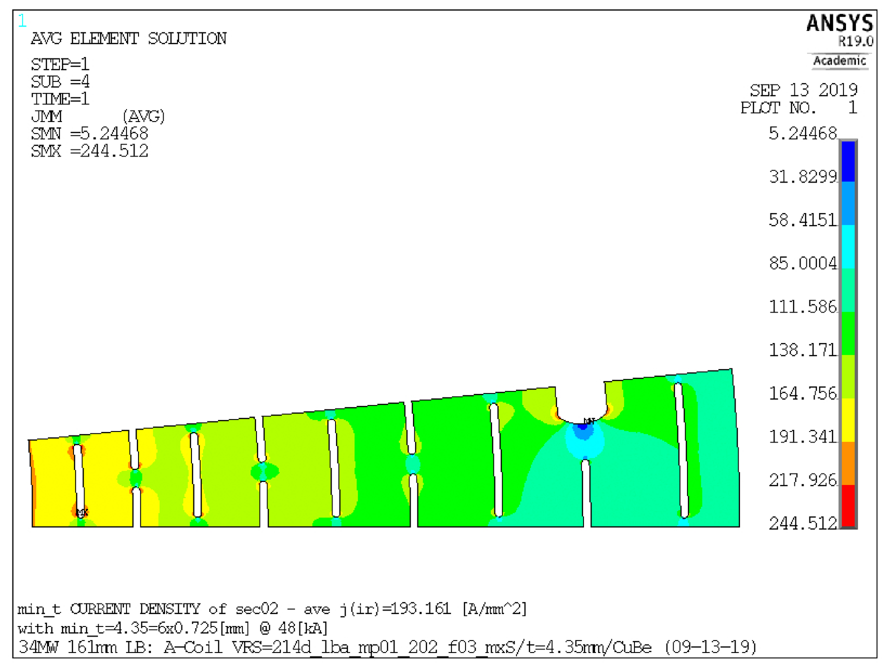


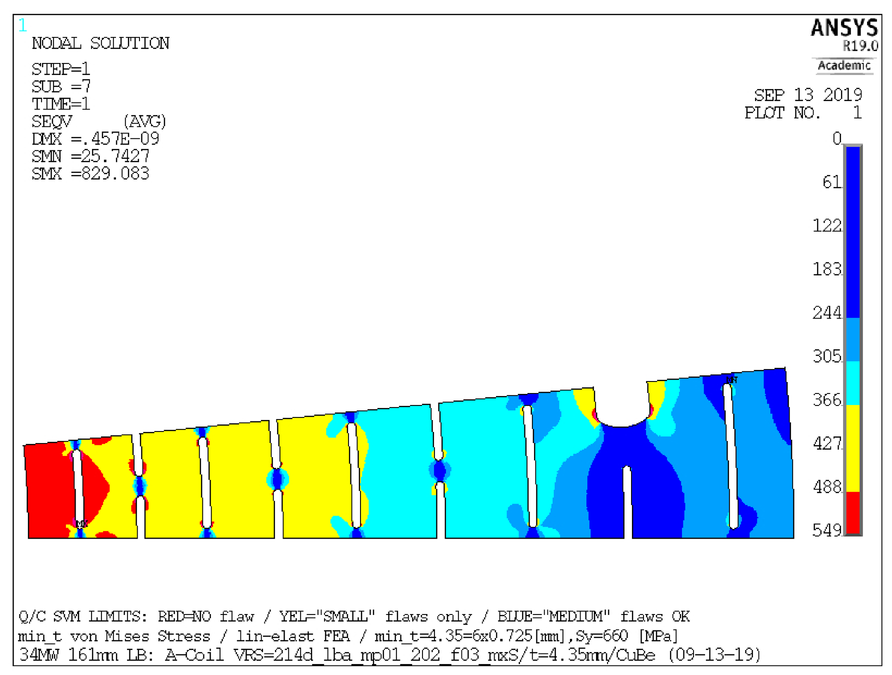
II) Detailed Disk Design – Midplane Disks

Iterative FEA was utilized to design disk geometries of new LBA-coil have. Cooling holes have been optimized to achieve relatively uniform temperature distributions across each individual plate with peak temperatures not to exceed 100 C based on conservative thermal boundary conditions with flows based on a friction coefficient of 0.05 and 25 bars design pressure drop.

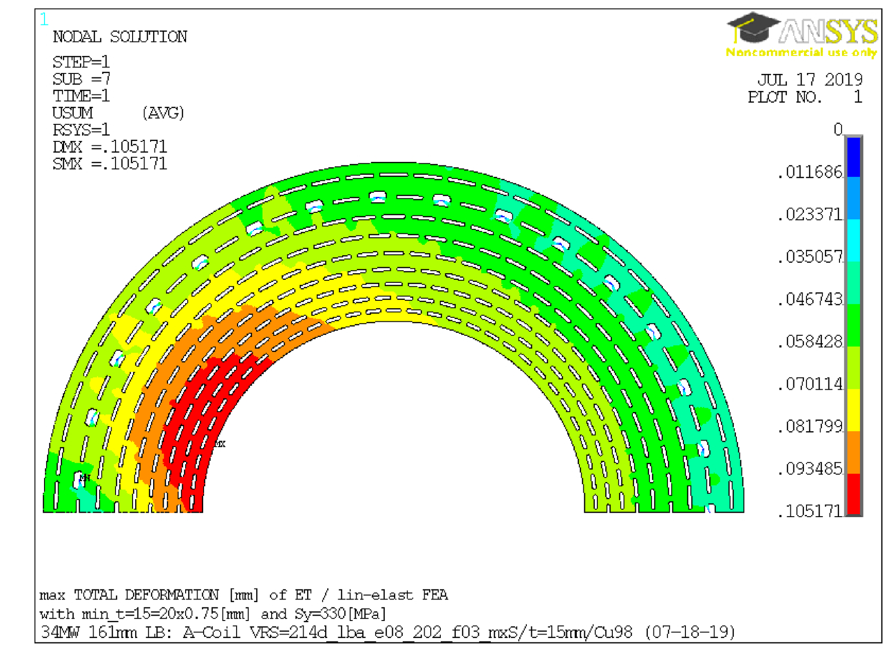


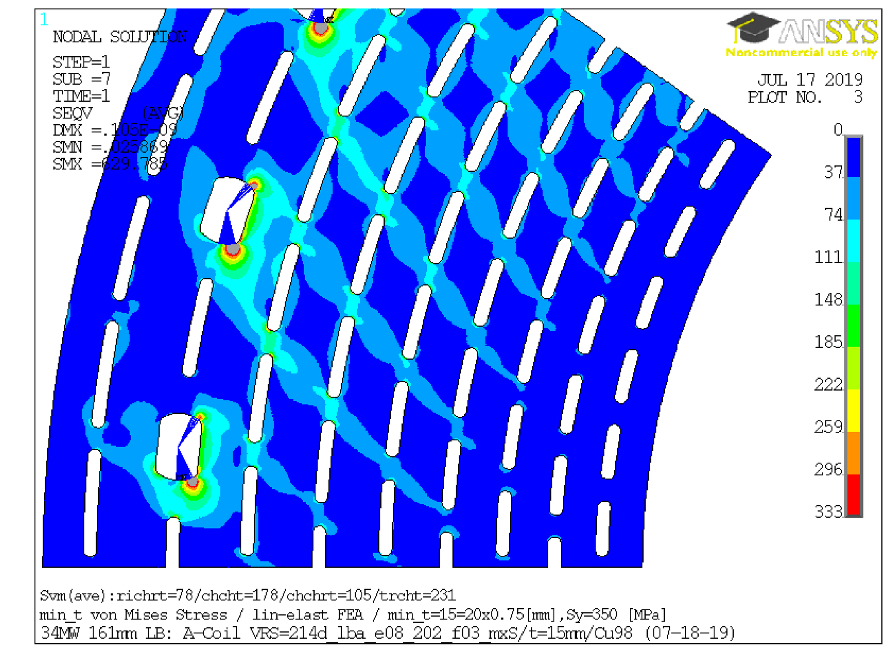






III) Endturn Disk FEA with dedicated boundary Conditions





Large magnetic clamping forces are generated in each winding pack. These forces are gradually accumulated turn by turn starting with zero from the coil ends and reaching maxi-mum clamping compression at the mid-plane, where these are actually helping to hold each turn made out of individual discrete disks tightly together.

These operational clam-ping forces are not pre-sent at the coil ends, where the winding is only supported by so called pre-stressed "tierods".

A dedicated structural FEA with boundary conditions accounting for the dis-crete support by the edges of the tie-rods has been performed for all the end turns.

IV) Summary of 23 T Large Bore Coil Stacking and Disk Design Parameters

Coil	LBA	LBB	LBC
# of Tie Rods	31	32	32
# of Cooling Rings	9	12	5
MP Channel Width [mm]	0.98	2.10	2.10
ET Channel Width [mm]	1.08	-	-
Turn Thickness #1 [mm]	4.69	4.19	10.14
Turn Thickness #2 [mm]	5.28	6.07	15.06
Turn Thickness #3 [mm]	10.14	8.21	20.12
Turn Thickness #4 [mm]	15.77	9.97	
Turn Thickness #5 [mm]		12.24	
# of Turns zone #1	100	50	50
# of Turns zone #2	6	6	6
# of Turns zone #3	6	30	4
# of Turns zone #4	6	4	
# of Turns zone #5		15	
Peak J Density [A/mm^2]	193	127	48
Peak Temperature [°C]	98	93	77
FEA Disk Deform [mm]	0.46	0.44	0.01
FEA Disk Stress [MPa]	535	300	50

CONCLUSION

The NHMFL has finished a study comparing the feasibility and performance versus cost and efforts for the design and construction of its next generation Large Bore magnet. Designing a new 195 mm bore insert for its 41.5 T, 32 mm bore all resistive magnet with the option to compliment that hardware later to a stand-alone magnet system has been determined to present the most cost and time effective solution for the NHMFL.

Next, a design for such a magnet generating 23 T with a power consumption below 33.5 MW has been developed in detail. Fabrication of the proposed insert is estimated to be achievable within one calendar year. However, a pack-age of detailed engineering drawings would still have to be developed first and any further earnest activities are not planned to start until hardware funds can be allocated.

ACKNOWLEDGMENT

This work was supported by the National Science Foundation through NSF Cooperative Grant No. DMR-1644779 and the State of Florida.