Conceptual Design for a Next Generation Resistive Large Bore Magnet at the NHMFL

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Abstract—**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 resistive magnet. Without any 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 our laboratory. Again, cost and schedule for the construction of such a magnet are very critical 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 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 paper, 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.**

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

I. Introduction

In THE past, the NHMFL has traditionally always been offering all-resistive standard solenoid high field magnets in three bore sizes to its user program with accessible warm bore diameters of 32 mm, 50 mm [1] and 195 mm [2]. Until 2017, all of those magnets were designed and operated at an electric power level of up to 20 MW each. Currently, our facility is upgrading its four power supplies from a current of 20 kA to 24 kA at 700 Volts each. This will enable us to operate two large resistive magnets each consuming up to 34 MW of power in parallel. The first magnet upgrade utilizing this full power capacity is the 32 mm bore 41.5 T magnet installed in cell 6 of our DC facility and operational since August 2017 [3]. Also upgrading the 50 mm bore as well as the 195 mm large bore magnets in following years was always the plan of logical progression. The demand and preference for installing a next generation large bore magnet at our laboratory next has particularly increased in the most recent years, because the original 20 Tesla wide bore 20 MW magnet installation had been decommissioned in 2016 after over 20 years of service. Offering high magnetic fields for a variety of bore sizes including a 200 mm bore is also a standard in other world leading magnet laboratories [4] and [5].

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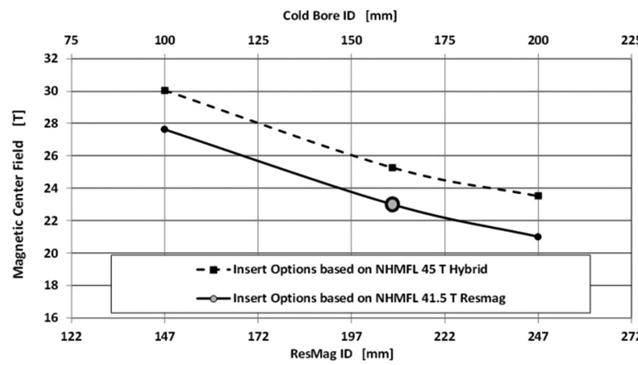

Fig. 1. Results of a feasibility study comparing achievable peak fields for a new Large Bore magnet based on preliminary level insert designs for two existing magnet installations available at the NHMFL each developed for a range of different bores.

II. Preliminary Design and Feasibility Study

As the steadily rising capital cost as well as the schedule for the construction of a new Large Bore magnet growing in size and in power are becoming ever more constraining aspects most cost and time saving solutions has to be given the highest preference. To keep these factors most manageable, the option to design a completely new stand-alone magnet has been pushed back in favor of the design of a single coil or a compact set of insert coils, that is compatible and can be interchanged with selected smaller bore coils of a magnet installation that is already existent at the NHMFL.

Two existing magnet installations including the 45 T Hybrid [6] 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. Results regarding the achievable peak field are summarized in Fig. 1. The insert designs compatible with the 41.5 T were all developed for a power level of ~33 MW. All the results shown including the ones for the 45 T.

Hybrid inserts are applicable for designs that keep the outer coils unchanged and compatible with the existing installations.

In conclusion, any LB insert operated in the 45 T Hybrid magnet system has the advantage of delivering the highest available fields at a lower power consumption (same benefits as reported in [6]). However, only building a LB insert for the 41.5 T magnet at first, does not exclude the option to install an additional 1.0 meter housing later, which increases the accessibility of such a new LB magnet as needed in the future. Such a magnet configuration would also be convenient as it allows to share the inventory of spare coils for the outer two coils with the existing 32 mm bore installation and it will also most likely be kept compatible with future 50 mm bore versions.

Also keeping the bore size of such a new LB magnet at 195 mm represents the most cost saving configuration as it allows to even keep using the same covers for the resistive magnet housing. The following chapters are presenting a detailed coils design for such a chosen magnet configuration designed to generate 23 T in a 195 mm bore consuming 33.5 MW.

III. General Coil Design

A. Global Design Consideration

Our study allowed the conclusion that for a ∼33 MW, 195 mm bore magnet the maximum field is most efficiently obtained with a three coil configuration.

It has also been verified that re-stacking the outer two coils to increase their power density is hardly possible without also changing the cooling hole patterns of those coils. The potential field gain for re-designing those coils from scratch is estimated to be less than 0.5 T which is outweighed by the substantial cost and time savings by sharing the same coils and related hardware.

B. Summary of General Coil Design Parameters

The NHMFL developed an LB insert coil that is optimized to maximize the magnetic field for a total power consumption of up to 33.5 MW when it is installed in series with the two outer coils of the existing 41.5 T magnet. The new insert coil (LBA) utilizes the strongest sheet metal commercially available for purchase in that larger size of 400 mm × 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 Table I and illustrated via different shading in Fig. 2. 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. It may be pointed out, this value is very conservative, because certain water running through the radial assembly gaps in between the coils was not counted towards the effective flow actively cooling the coils. The tabulated power and voltage values summing up to 33.5 MW and 699 V represent theoretical worst-case upper limits that are not expected to be fully reached during normal operation.

TABLE I
General 23 T LB Coil Design Parameters

Coil	LBA	LBB	LBC
Inner Radius [mm]	107.6	200	343
Outer Radius [mm]	197	340	500
MP Winding Height [mm]	561	731	731
ET Winding Height [mm]	149	0	0
Total Coil Height [mm]	710	731	731
Current [kA]	48.0	48.0	48.0
Voltage [V]	386.7	222.0	88.9
Power [MW]	18.56	10.63	4.22
effective cooling flow [l/s]	110.8	89.8	38.7
Coil Self Field [T]	11.25	8.30	3.45
MP=Midplane Material	CuBe	Cu	Cu
MP Disk Thickness [mm]	0.73	0.75	0.94
ET=Endturn Material	Cu	N/A	N/A
ET Disk Thickness [mm]	0.75	N/A	N/A
Coil Weight [kg]	615	1610	2925

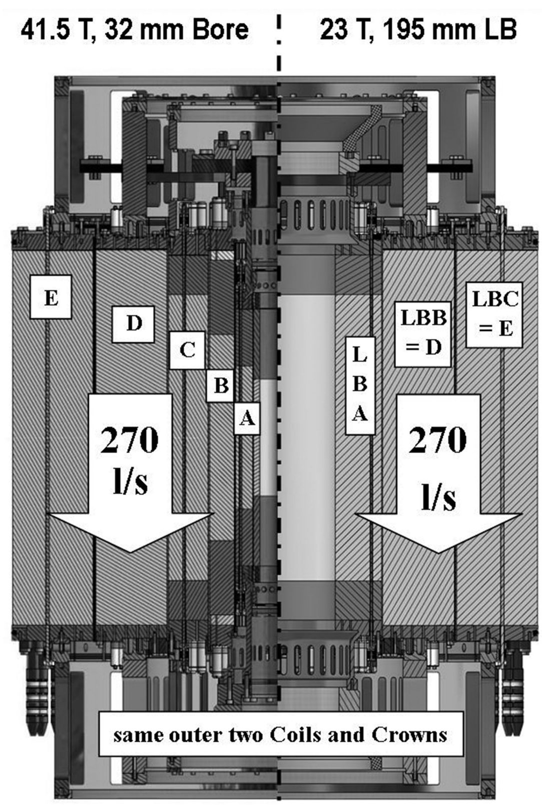

Fig. 2. Comparison of the cross sectional views of the existing 6-coil 41.5 T NHMFL 32 mm bore resistive magnet shown side-by-side next to the new design 3-coil 23 T 195 mm LB magnet. Electric current enters the magnet on the top of the innermost A-Coil and exits on the bottom of the outmost E-coil. Operational loads and fault loads are supported through four insulated metal structures (named support "crowns") on each coil end.

IV. Detailed Disk Design and Coil Stacking Plans

All disk geometries of the new LBA-coil have been iteratively optimized via FEA to provide a relatively uniform temperature distribution across each individual plate with peak temperatures below 100 °C in any part of the winding. The outer coils

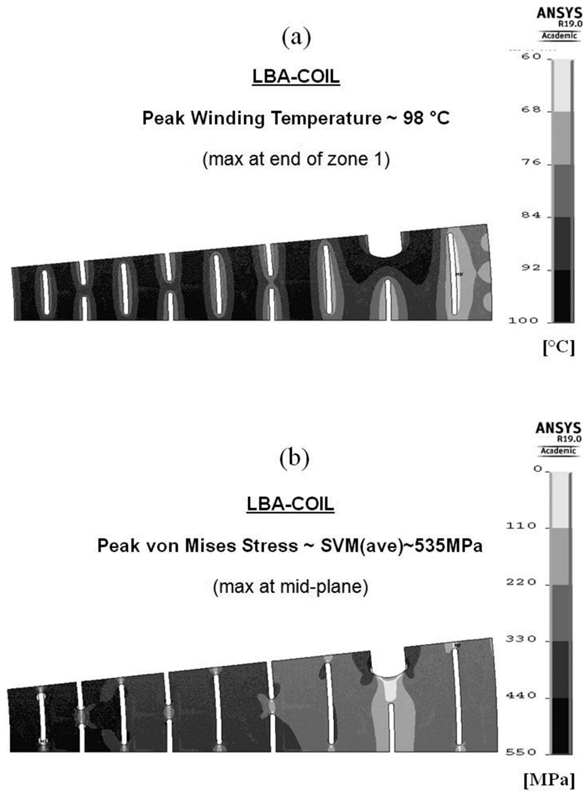

Fig. 3. Results of coupled thermal-electric and subsequent structural FEA evaluating the proposed LBA-Coil. (a) Winding temperature distribution with peak at end of zone 1. (b) Peak stress distribution at mid-plane.

LBB and LBC are unchanged in their design from the 41.5 T magnet installation and the same thermal conditions are being assumed, only the stress calculations needed to be repeated and updated for the slightly different magnetic field distributions and corresponding Lorentz-forces. All evaluations for peak winding temperatures (as shown in Fig. 3(a) for the LBA-Coil) are based on conservative thermal boundary conditions with flows based on a friction coefficient of 0.05 and 25 bars design pressure drop. Calculations for the expected power consumption were based on even more conservative thermal conditions. That strategy typically contributed to a 5% voltage margin (as recorded during actual testing of several existing magnet installations). This margin is intended to be used as a reserve for future coil deviations (when the coils age) as well as to allow small adjustments possibly needed for fully reaching the 23 T design field.

Extensive axial current density grading including up to five individual zones (as listed in Table II) was employed for ease of power management [8] as well as to accommodate smooth transitions all the way up to double or triple thick endturns. Systematic parametric FEA was used to confirm, that all winding sections satisfy the structural design criteria of von Mises stresses, integrated along any path of conductor webbing in each disk, not to exceed 550 MPa for the CuBe sections of the LBA-Coils (as shown in Fig. 3(b)) and 350 MPa for all other winding portions using disks made out of Cu.

TABLE II
DETAILED 23 T LB 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	N/A	N/A
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

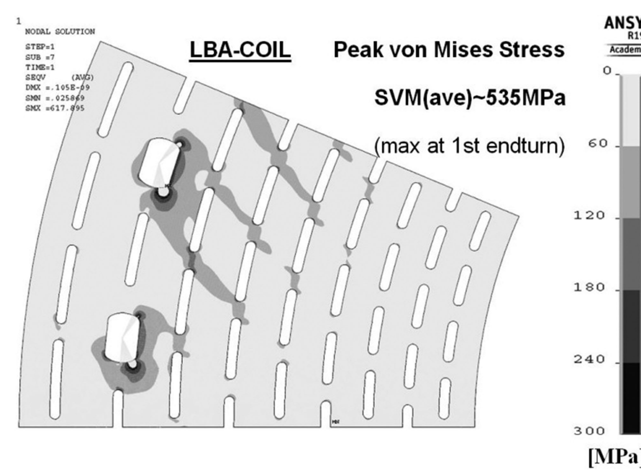

Fig. 4. Structural FEA results evaluating the Peak stress distribution in the end turns of the proposed LBA-Coil. The selected region illustrates the stress concentrations around the most critical tie-rods near the slit of the disk.

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 maximum clamping compression at the mid-plane, where these actually improve the rigidity of each turn constraining the slip-sliding of the individual discrete disks. These operational clamping forces are absent at the coil ends, where the winding is only supported by so called pre-stressed "tie-rods". A dedicated structural FEA with boundary conditions accounting for the discrete support by the edges of the tie-rods has been performed for all the end turns, (stress results shown in Fig. 4).

V. HYDRAULIC DESIGN

As previously described in [2], during the design of the 41.5 T magnet, a hydraulic model was developed in Microsoft Excel calculating the water flow and corresponding water velocities in each of the various parallel flow channels as a function of an applied total water pressure drop. That same model has now been extended to alternatively include the new LBA coil instead of the 41.5 T A/B-Coils. Next, this hydraulic model has been used to iteratively design the cooling-hole pattern of the new LBA-coil. The required cooling water flow for proper heat removal for the 18.56 MW LBA coil is 111 l/s. A cooling hole configuration including nine staggered rings of elongated cooling channels all with a width of 0.98 mm for the midplane disks and 1.08 mm wide for the endturn disks has been designed and evaluated to accomplish that correct cooling water flow at the same operational water pressure drop as the 41.5 T configuration does. Therefore, the A/B-Coil of the 41.5 T magnet and the LBA-Coil of the new 23 T Large Bore magnet are from hydraulic aspects interchangeable. Both coil configurations allow supplying the same amount of cooling water to the magnet (total flow: 270 l/s) while also keeping the cooling conditions of the outer two coils the same.

The cooling channel widths of the new LBA were also optimized to tune the water velocities to around 15 m/s in the high current density portion of the windings to achieve effective cooling conditions. That approach is considered to be conservative leaving a decent margin towards the limit of 20 m/s (where cavitation could start becoming an issue). The water velocities in the sections comprised of end turn disks (149 mm total high) is estimated to be below 10 m/s due to the increased cooling channel width in these disks. Because of the hydraulic diameters being different in these sections installed in series the water velocities and corresponding cooling conditions of the coil are dependent on the final disk stacking plan. Therefore, these water velocities were also systematically updated while the coil stacking plan had been derived and the cooling hole geometries kept being adapted as they were used to define the boundary conditions for all the iterative thermal-electric disk FEA described in chapter IV above.

As before for the 41.5 T hydraulic design, this comprehensive hydraulic model also helped quantifying and minimizing the water bypassing the winding along the assembly gaps with minimal cooling benefit. Fairly high friction factors of 0.05 were applied to account for the water quantities effectively cooling the coil windings conservatively.

VI. Verification of the Structural Integrity of the Housing and Other Components Supporting the Coils

Complex FEA including a full 3D model of the housing was developed in 2017 and used to confirm compliance of the housing with the ASME Boiler and Pressure Vessel Code. A wide range of load conditions from normal operation to likely faults as well as unlikely severe faults of the 41.5 T magnet had been considered. For instance, the failure of any resistive coil shorting one complete half of the winding (in either direction from the midplane) causes substantial axial forces which are considered fault forces. Axial forces and torques due to unintended coil misalignments (of 1.5 mm) plus 28 bar water pressure drop are considered normal operating conditions.

All the net loads reacting on the housing were recomputed for the proposed new LB 23 T magnet coils and compared to similar load cases for the 41.5 T magnet. Of those, the following cases, which include the water pressure, represent the most critical scenarios:

- normal operation, net force F = 2.15 MN (96%)
- likely fault (LBA-Coil failure), net F = 5.55 MN (98%)
- max fault up (LBB-Coil failure), net F = 5.75 MN (89%)
- max fault down (LBB-Coil failure), net F = 4.97 MN (89%)

The percentages listed above represent the 23 T versus 41.5 T load ratios (all being safe and lower than 100%). Thus, the design of the housing including the covers can be safely used in both bore configurations. As the summary also shows, for this magnet design, the total net loads reacted by the housing differ less than 4 percent between a rather likely fault of an A-Coil and the theoretical maximum fault load due to a less likely B-Coil failure. The same systematic evaluation also considering elastic plastic buckling was conducted for all the critical structural load path components (see "crowns" in Fig. 2). That analysis is still outstanding for the new LBA-Coil support crowns and may require small adjustments of their geometries before the whole system design can be completed in earnest.

VII. 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 appears to be the most cost and time effective solution for our facility. 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 package 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.

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