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Magnetic Analysis of LARP HQ Mirror Model

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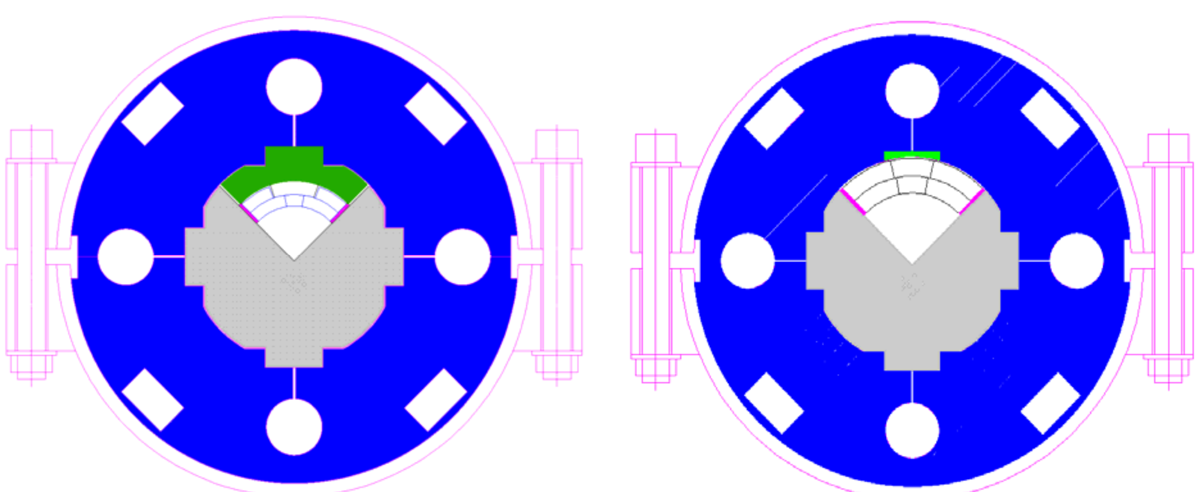
Introduction

Test results of Nb3Sn model magnets show that the coil design, conductor and structural materials, and coil fabrication procedures are critical to their performance. The optimization of Nb_3Sn coil designs and technologies requires fabrication and testing of series of coils. A possibility to do it efficiently is to test coils in magnetic mirror configurations [1, 2]. This approach allows testing individual coils at field, current and force levels similar to that of real magnet, thus reducing the turnaround time of coil fabrication and evaluation, as well as material and labor costs. Mirror configurations are also instrumental for the technology scale-up [3, 4]. This approach was successfully used in the Fermilab HFM program to study and optimize 43.5 mm dipole and 90-mm quadrupole Nb3Sn coils.

This note analyses the possibility of using the developed quadrupole magnetic mirror structure for testing of 120-mm Nb3Sn quadrupole coils used in LARP high gradient quadrupole (HQ) [5].

Magnetic design and analysis

The quadrupole mirror cross-section with 90-mm TQ coil is shown in Fig. 1 (left). It consists of iron mirror blocks and iron spacers, surrounding the coil. This sub-assembly is installed in the standard TQ iron yoke and pre-compressed by a bolted skin. It was found that the larger 120-mm HQ coil could be accommodated in the same mirror structure by removing the iron spacer placed between the coil and iron yoke, and making the inner surface of corresponding iron yoke round. All other magnetic components are the same as in the TQ mirror. The quadrupole mirror with 120-mm HQ coils is show in Fig. 1 (right).



Fugure 1. Quadrupole mirror cross-section with 90-mm TQ (left) and 120-mm HQ (right) coils supported by bolted skin.

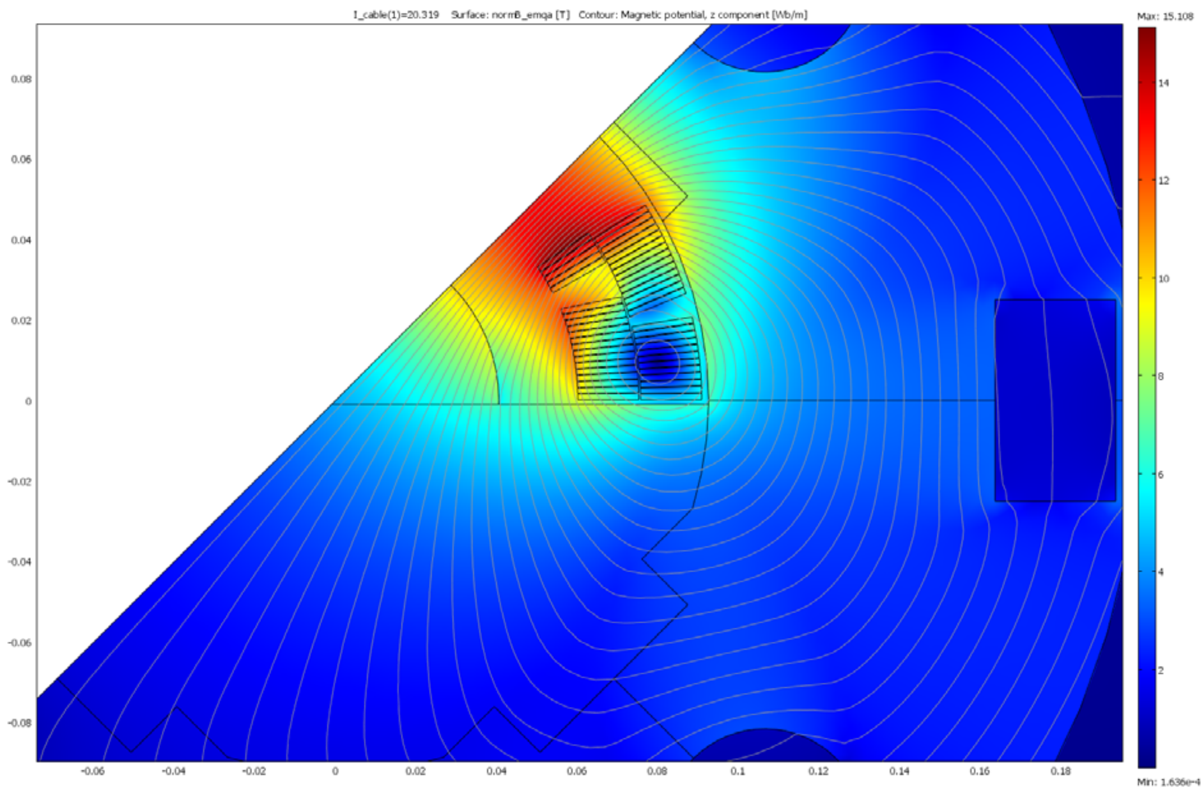


Figure 2. HQ mirror cross-section with flux density distribution at 20.319 kA.

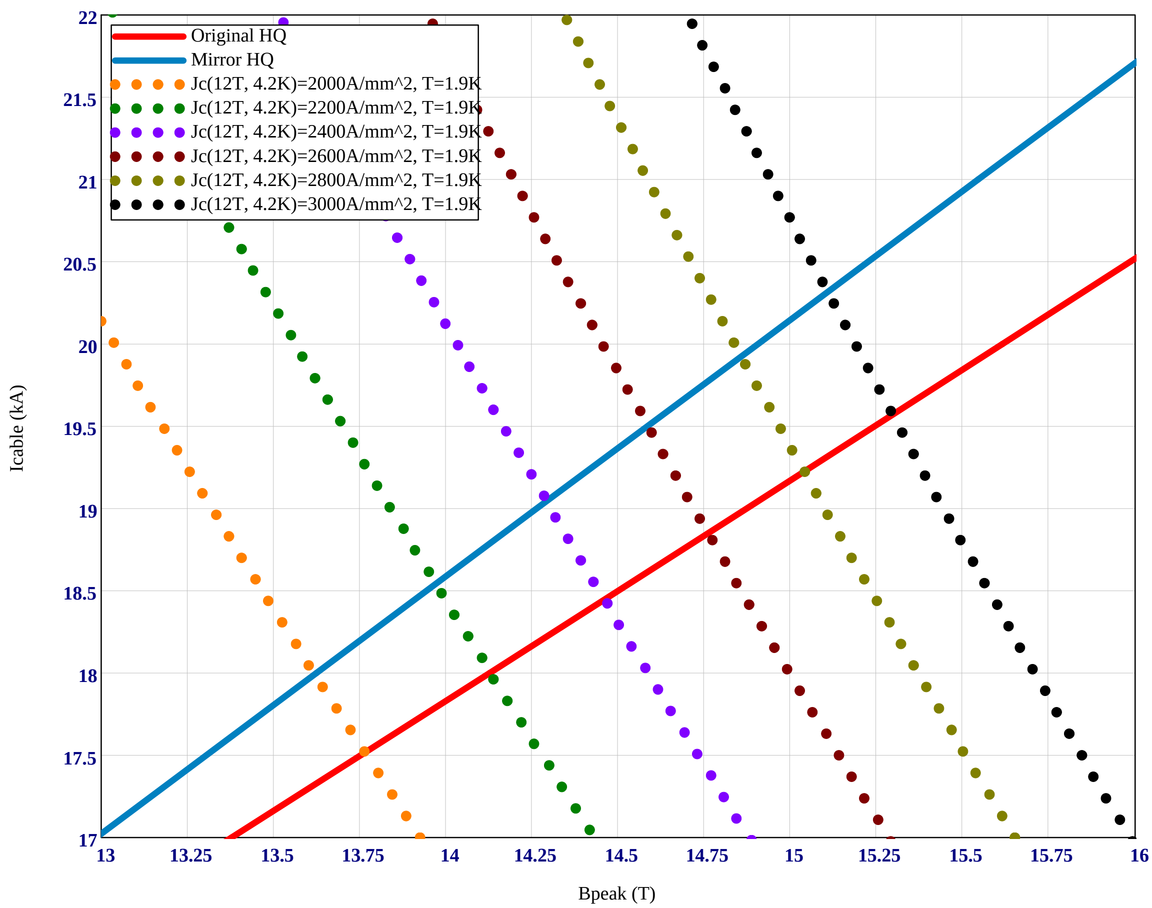


Figure 3. Load lines and critical current curves.

Fig. 2 shows the cross-section of HQ coil in the mirror structure with the magnetic flux plot. HQ cable and coil parameters are summarized in Table.1. The HQ mirror load line is shown in Fig. 3 together with the load line of the original HQ magnet and different critical current curves. Note that the presented load lines correspond to the peak field point located in the magnet straight section. The peak field point may move to the coil end depending on the coil and iron end design that is a subject of separate analysis.

Table 1. HQ cable and coil parameters.

Parameter	Unit	Value
Bare cable width	mm	15.150
Bare cable mid-thickness	mm	1.437
Cable keystone angle	deg	0.750
Cable insulation thickness	mm	0.100
Turns per quadrant IL/OL	-	20/26
Minimum pole width	mm	23.82

Table 2 shows the comparison of the HQ mirror and HQ quadrupole model parameters. Because of the iron proximity, the HQ coil can reach practically the same peak field as the original magnet, albeit at a slightly higher current. The inductance and stored energy of the HQ mirror are ~1/4 or the full magnet values due to the proportionally smaller number of coils.

Table 2. Comparison of HQ mirror and magnet parameters.

Parameter	**Unit**	**Design**	
		HQ mirror	**HQ v8**
Midplane shim per octant	mm	0.140+	0.140
Yoke OR	mm	200	260
Quench* gradient @ 1.9K	T/m	n/a	219.78
Quench* peak field @ 1.9K	T	15.11	15.29
Quench* current @ 1.9K	kA	20.32	19.57
Inductance @ quench*	mH/m	1.68	7.71
Stored energy @ quench*	MJ/m	0.347	1.48

* J_c(12T, 4.2K) = 3000A/mm^2, $K_{cu/nonCu}$ = 0.87

Mechanical design and analysis

Lorentz forces in the HQ mirror and quadrupole model at quench current are summarized in Table 3. The horizontal Lorentz force in the mirror is nearly the same as in the quadrupole magnet, while the vertical force is ~30 % lower. The azimuthal Lorentz force per the inner coil layer is nearly zero due to strong saturation of the magnetic mirror in the vicinity of the coil midplane, while the azimuthal force per the outer layer retains ~55 % of the original magnet value.

Table 3. Lorentz forces in HQ mirror and quadrupole models at quench current.

Parameter		Unit	Design	
			HQ mirror	HQ v8
Octant forces @ quench	F_x total	MN/m	3.33	3.38
	F_y total	MN/m	-3.41	-5.03
	F_θ IL/OL	MN/m	0.13/1.76	2.63/3.15

Stress distribution diagrams in the HQ coil in a mirror configuration calculated using ANSYS model at room temperature (left) and after cooling down (right) are shown in Fig. 4. Stress distribution diagrams at operation temperature 4.5 K and the current in the coil of 17.0 kA (left) and 19.5 kA (right) are shown in Fig. 5. One can see that the maximum coil stress after assembly ~130 MPa allows keeping the coil under compression up to its ultimate short sample limit ~20 kA. Due to the larger azimuthal length the outer layer is unloaded earlier than the inner layer. The maximum stress in the coil of ~160 MPa is reached after cooling down in the inner layer next to wedges.

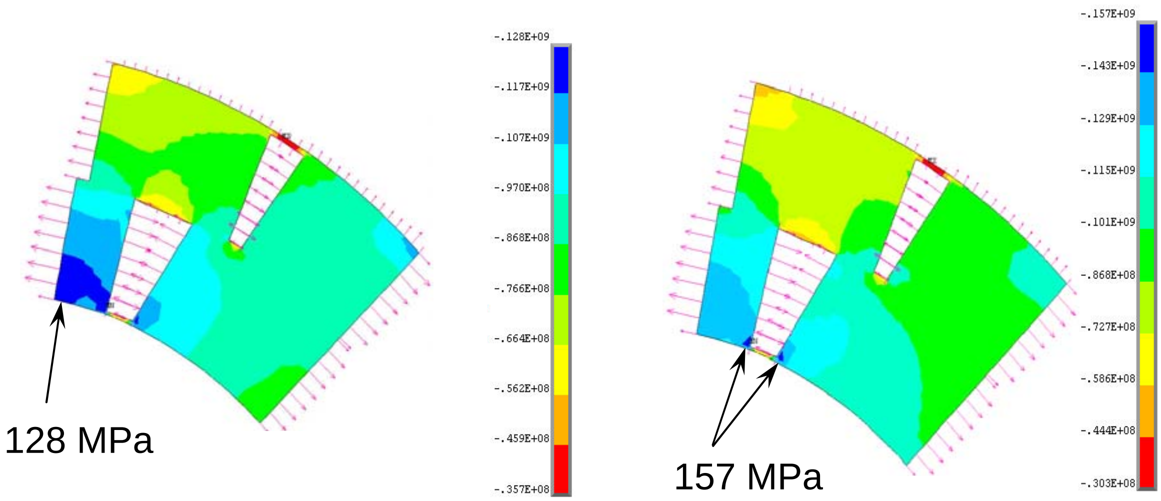


Figure 4. Stress distribution in the HQ coil in mirror configuration at 300 and 4.5 K.

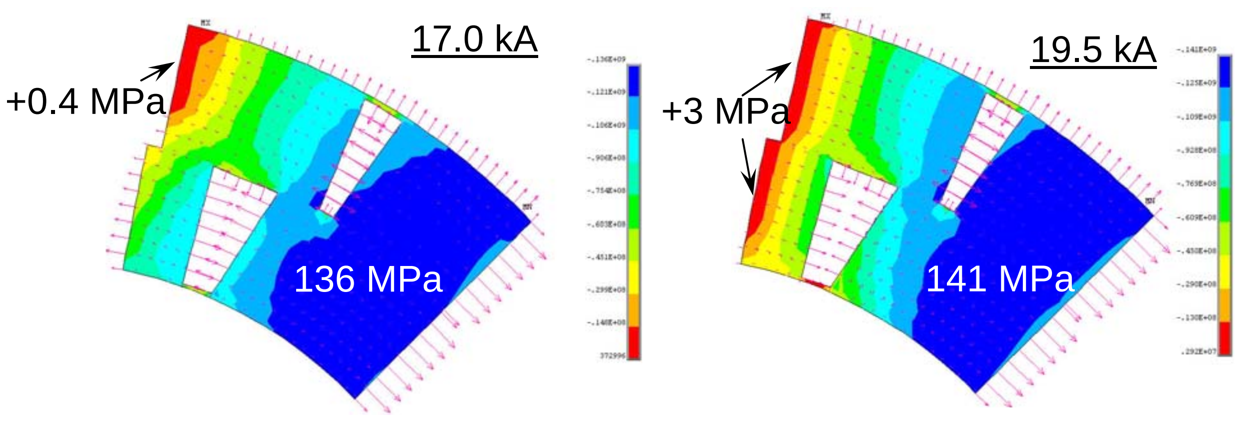


Figure 5. Load lines and critical current curves.

Conclusion

A preliminary magnetic and mechanical analysis of the HQ mirror magnet has been performed. It was found that the HQ coil placed in the TQ mirror structure would perform close to the original HQ magnet design in terms of the peak magnetic field and current. There is a significant redistribution of azimuthal Lorentz forces between the two coil layers, although the force level is relatively low compared to the full HQ magnet. The room temperature prestres of 130 MPa allows preserving the coil compression up to currents of 20 kA. The maximum mechanical stresses in the coil are below 160 MPa at all conditions.

References:

1. V.V. Kashikhin, A.V. Zlobin, "Magnetic Design of Mirror Magnets Based on Fermilab's Nb_3Sn Cos-theta Coils", *Fermilab Technical Note* TD-02-045, 02/12/02.
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