

FAST TRACK ACTIVELY SHIELDED NB3SN IR QUADRUPOLE R&D *

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Abstract

eRHIC is a hadron, ep and eA , collider for 30-140 GeV CM with a luminosity range of 10^{32} to 10^{34} $\text{cm}^{-2}\text{sec}^{-1}$. The hadron Interact Region (IR) quadrupoles have large apertures with high gradients and correspondingly large coil B-fields. The nearby e-beam from large external fields [1]. For the most critical IR quadrupole we presently adopt an actively shielded design, motivated by the successful ILC QD0 R&D [2], but now based upon an Nb₃Sn coil inside a NbTi coil of opposite polarity that is used to cancel the external field. In order to demonstrate the feasibility of our design concept with minimal expenditure and in a short time, we reuse a Nb₃Sn coil from the US LARP program and combine it with a new BNL produced Direct Wound NbTi coil in a new mechanical structure [3-4]. We denote this newly funded approach “Fast Track Active Shielding R&D.”

DESIGN CONSIDERATIONS

The US LARP program was a multi-year, multiple laboratory R&D program to develop large aperture, high gradient Nb₃Sn quadrupoles for the LHC. Reusing an existing LARP HQ coil represents substantial savings in time and effort compared to fabricating all new coils. Figure 1 shows the 3D coil configuration for a Direct Wind active shield coil located outside an HQ Nb₃Sn main coil along with the equivalent location where the electron beam would pass by the coil structure. While the external field from the active shield cancels the external field coming from the main coil, the active shield also reduces the net gradient inside the common main coil aperture (by about 7% for the geometry shown in Fig. 1). Still when the coils are operated to achieve a 133 T/m net gradient, the inner main coil sees a 9.3 T peak field; this high field is the reason we use Nb₃Sn for the inner coil.

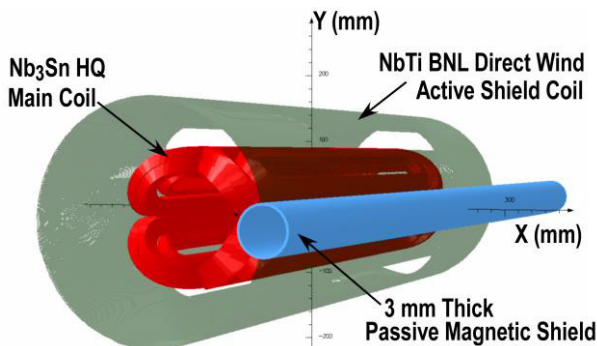


Figure 1: Fast Track R&D quadrupole with a Direct Wind active quadrupole shield coil a Nb₃Sn main coil shown in 3D view.

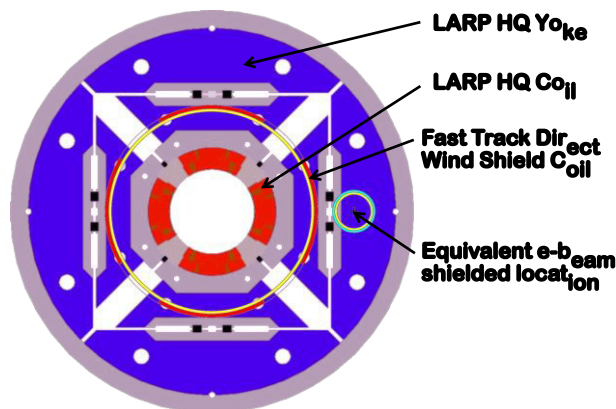


Figure 2: Comparison of LARP HQ mechanical structure with dimensions of new Direct Wind shield coil and equivalent eRHIC e-beam offset position.

In Fig. 2 we compare the LARP HQ magnet structure with the size of the shield coil and equivalent shielded position for the eRHIC e-beam by overlaying the two cross sections. It is obvious that we must design a much more compact mechanical structure to accommodate the shield coil since the shield falls well inside the HQ yoke structure. Fortunately the actively shielded geometry does not need a magnetic yoke and in fact providing any magnetically active material between the two coil structures is undesirable. The active shield effectively channels all the external flux to go between the main and shield coils and in operation this flux would saturate any magnetic material. In fact a magnetic yoke only complicates the design by altering the field harmonics at low field and would also spoil the perfect linear tracking between the two coils.

The new compact mechanical structure is shown in Fig. 3. Space that would have been taken up by yoke material is now given over to a circular, high-tensile strength, full-circular aluminum collar. This outer collar contacts an inner stainless steel collar around the HQ coil in order to provide coil prestress. The collars are mechanically loaded by inflating bladders in the slots shown to

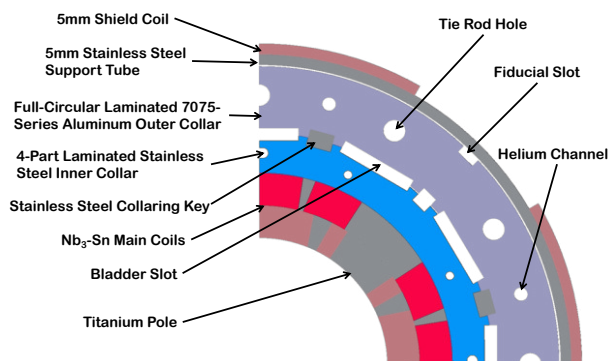


Figure 3: Design information for new compact mechanical structure with aluminum outer collar providing prestress to LARP HQ Nb₃Sn main coil.

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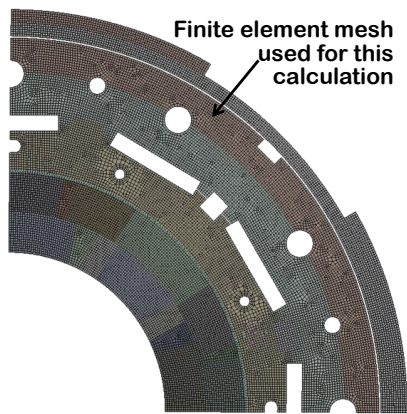


Figure 4: Finite element mesh used for ANSYS and MAXWELL calculations.

allow insertion of keys to lock the structure in place after the bladders are deflated. Note the NbTi Direct Wind shield coil is wound on a concentric support tube and receives its own prestress via tensioned s-glass fiber wrap layers during its fabrication.

FINITE ELEMENT CALCULATIONS

LARP experience has taught us that in order to ensure good performance much care has to be taken in designing the mechanical structure that provides coil prestress. Nb₃Sn is a brittle material that can easily be damaged if the local mechanical stress is too high. On the other hand coils with insufficient prestress permit excessive conductor motion leading to early quenches and poor training. Thus it is important to ensure via computer simulations that the coil receives an appropriate amount of prestress during each critical stage:

- ✓ bladder inflation at room temperature,
- ✓ collar keying at room temperature,
- ✓ after cooldown to liquid helium temperature,
- ✓ and when the coils are powered.

The above cases were analyzed using the ANSYS and MAXWELL finite element codes using the finite element mesh shown in Fig.4.

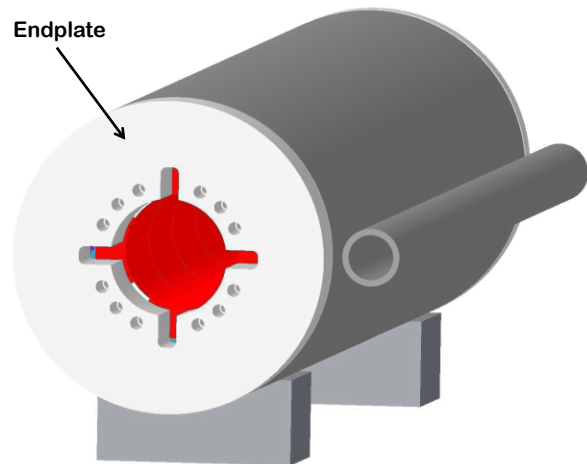


Figure 6: Fast Track 3d mechanical assembly view.

The results of these calculations are summarized in Fig. 5. In Fig. 5 we see that when the bladders are inflated, the inner Von Mises coil stress at the midplane goes to 87 MPa. Then it drops to 19 MPa after the keys are inserted and the bladders are deflated. Upon cool down the aluminum outer collar shrinks more than the Nb₃Sn coil and stainless steel collar giving a maximum stress on the inner coil of 57 MPa. When the coils are finally energized to a net 133 T/m operating gradient, inner coil stress at the mid-plane increases to 114 MPa. This is comfortably below the maximum permissible coil stress of 200 MPa.

Also when the magnet is energized, the coil force at the pole does not go negative. With a minimum stress of 18 MPa, the Nb₃Sn coil does not loose contact with the pole spacer (i.e. circumvent coil movement that could lead to a quench). Thus in spite of taking up less radial space, the new 2D mechanical structure provides an appropriate level of support to the coil; there is sufficient prestress without risking damage to the HQ coil.

Longitudinal prestress is applied to the HQ coil from the endplates shown in the 3D view in Fig. 6. The end plates are welded to an outer support tube that also provides lateral stiffness to the magnet structure.

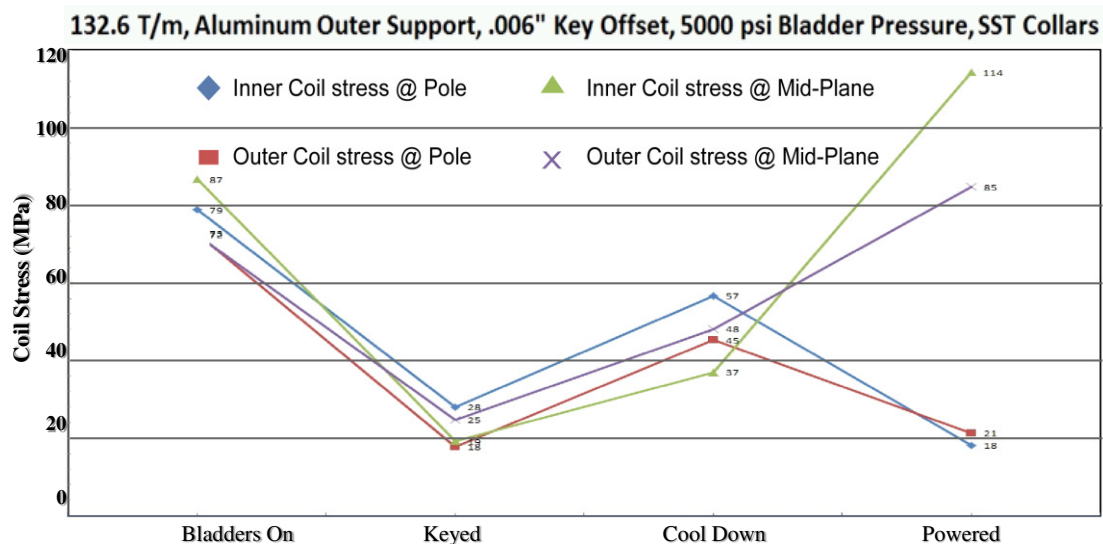


Figure 5: Coil stress results from finite element modeling of the Fast Track R&D structure.

Table 1: Fast Track R&D Test Magnet Parameter

Main Operating Gradient, G_{main}	143 T/m
Shield Operating Gradient, G_{shield}	-10 T/m
Net Operating Gradient, G_{net}	133 T/m
Main Aperture Radius, R_{apt}	60 mm
Main Peak Field, B_{main}	9.3 T
Shield Peak Field, B_{shield}	3.1 T
Total Stored Energy, U_{tot}	466 kJ
Main Operating Current, I_{main}	13.6 kA
Shield Operating Current, I_{shield}	705 A
Main Coil Inductance, L_1	5.6 mH
Shield Coil inductance, L_2	192 mH
Mutual Coil Inductance, L_{12}	5.2 mH
Inductance Coupling Coefficient, K	16%
$K = L_{12} / \sqrt{L_1 \times L_2}$	

R&D TEST CONSIDERATIONS

Calculated electrical parameters for the Fast Track R&D magnet are summarized in Table 1 and the load lines for the main Nb₃Sn main and NbTi shield coils are shown in Fig. 6. Note because there is no magnetic yoke the relationship between gradient and current is linear for both coils. Thus it is sufficient to scale both currents by the same factor to ensure external field cancellation at a different field gradient. Also since the available space for mechanical support structure is more limited in the Fast Track actively shielded magnet, we keep to operating currents lower than the approximately 16 kA (90% short sample) plateau achieved during LARP HQ testing [5]. Above 16 kA the HQ magnet experienced many training quenches and there was no significant quench current change over the temperature range of 1.9 to 4K. The conclusion was made that these quenches were from mechanical limitations and not simply conductor performance.

Since this actively shielded magnet utilizes two independent power supplies, it is to be expected that quench protection will be more complicated. Fortunately, as shown in Table 1, the main and shield coils are not

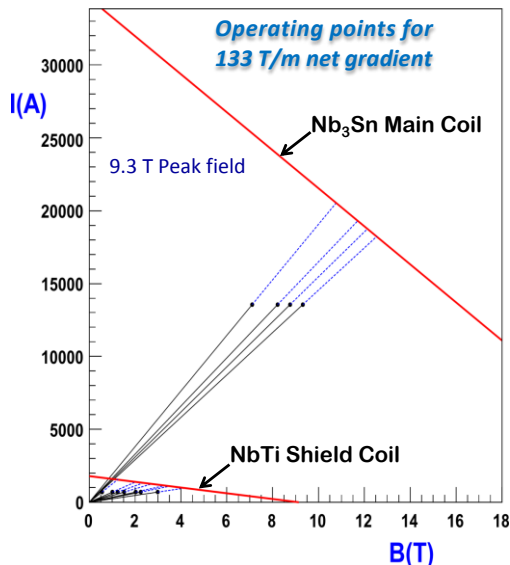


Figure 6: Load line diagram for main and shield coils.

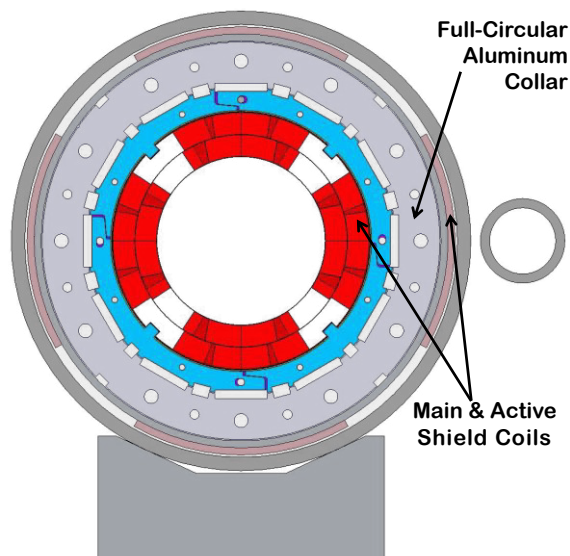


Figure 7: Cross section of the Fast Track mechanical assembly showing circular aluminum collar between the main and shield coils.

strongly magnetically coupled, with an inductance coupling coefficient of only 16%. In addition we expect that given the thick aluminum collar located between the main and shield coils, as shown in Fig. 7, there should be significant energy deposited in the collar structure due to eddy current heating during a quench. This energy deposition can speed up the quench and therefore reduce the energy deposited in superconductor. We plan to simulate quenches in this coil geometry to inform our configuration of the quench detection and protection circuitry.

Before assembling the HQ coils in the new structure we will do a mockup test with a short mechanical structure by reusing sections of strain gauge instrumented Nb₃Sn coils from a previous test bed. In this way we can ensure that the new compact mechanical structure will function as predicted. Once the LARP HQ magnet is disassembled and the Direct Wind shield coil is wound we will assemble and test the Fast Track magnet at 4.2K in a vertical dewar. We anticipate finishing this test during in time to retire the risk associated with using a Nb₃Sn actively shielded magnet and inform the eRHIC IR design before the eRHIC CD0 milestone.

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