FRIB Nb_3Sn ECR ion source magnet: Schedule, Cost, and Progress monthly report

Tengming Shen for the Supercon team
Lawrence Berkeley National Laboratory
Oct 2024 report

2024/10/07

- FRIB: Yoonhyuck Choi, Junwei Guo, Xiaoji Du, Dalu Zhang, Ting Xu, Guillaume Machicoane, Tomofumi Maruta, Jie Wei
- LBNL: Tengming Shen, Ye Yang, Philip Mallon, Ray Hafalia, Lianrong Xi, Mariusz Juchno, Paolo Ferracin, Soren Prestemon

The Indico site where the meeting slides can be downloaded: https://conferences.lbl.gov/event/1873/

Access key: FRIB

Past meetings slides are available at https://conferences.lbl.gov/category/109/

Progress since our last meeting (2024/09/09)

- Prototype coil fabrication.
  - Coil winding in progress. ~48% done.

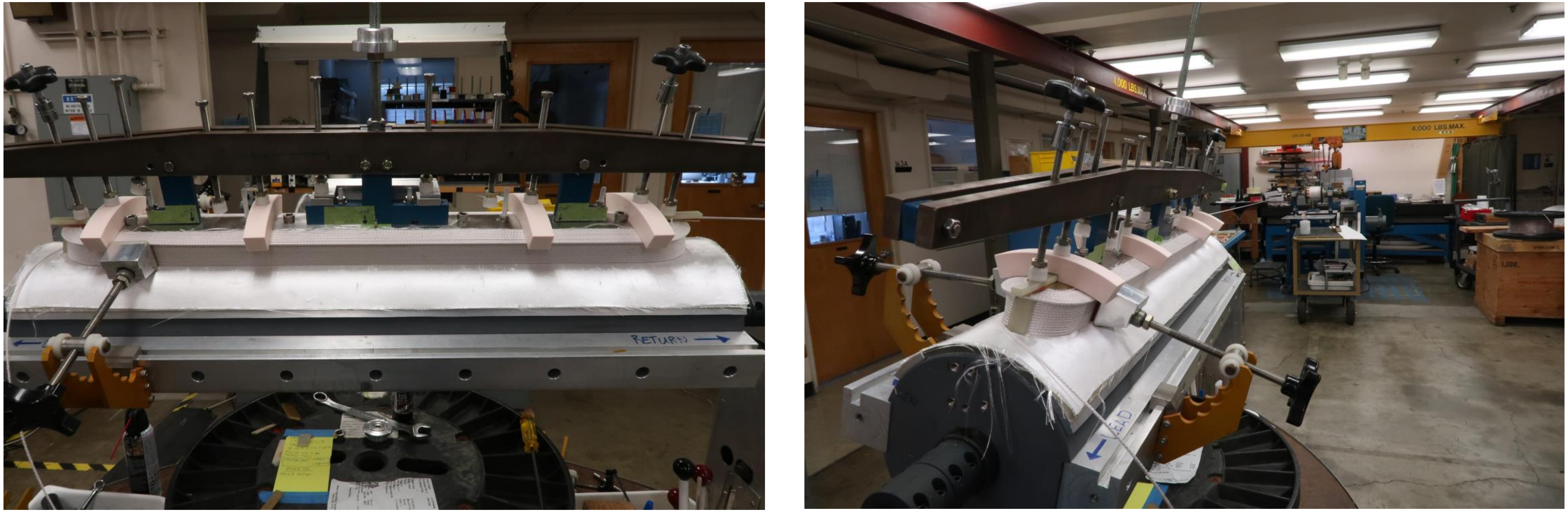
- Impregnation of the practice coil done and checked.

- Prototype coil cold test: Mirror magnet structure model review, prepared for fabrication. Mirror magnet assembly plan reviewed. Mirror magnet test preparation ongoing.

- ASC2024 manuscript submitted.

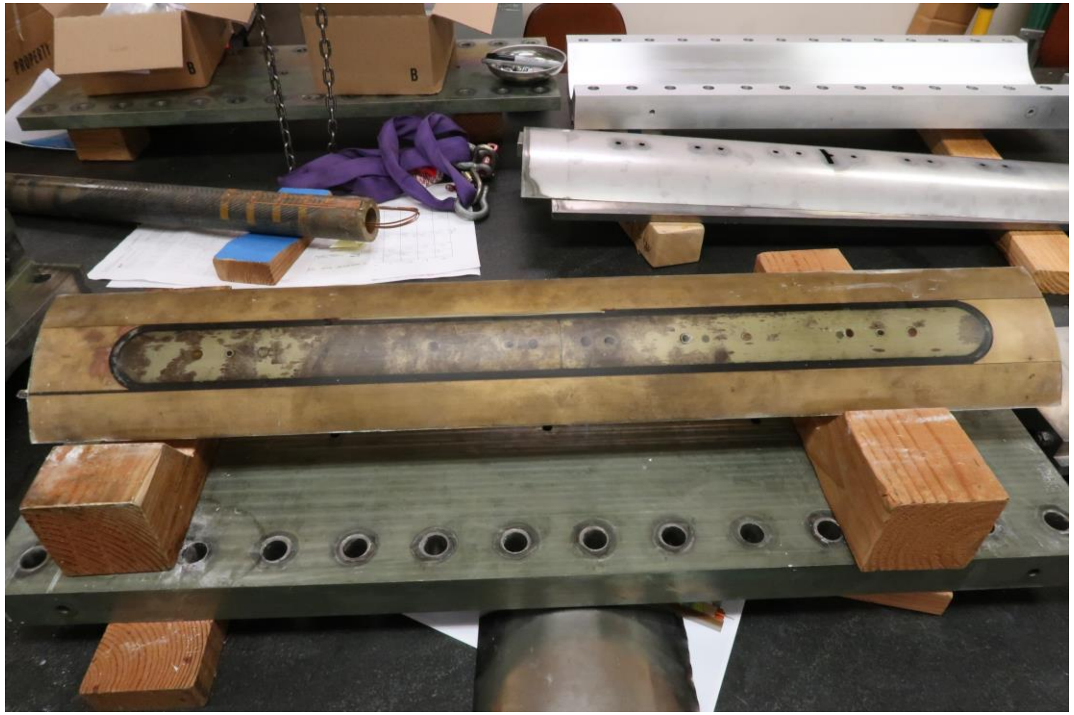
Progress since our last meeting (2024/09/09)

Prototype coil winding – 12 layers wound. 168 turns (~48%)



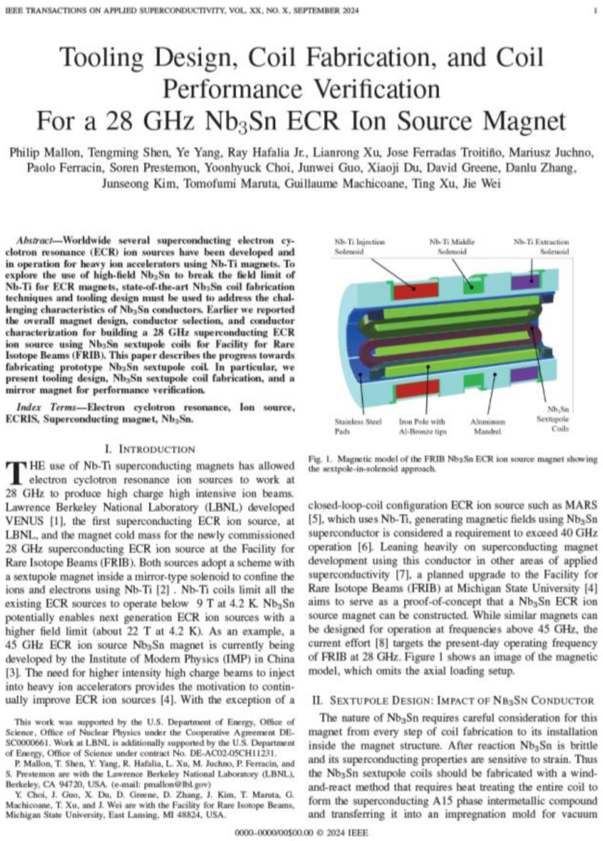
Progress since our last meeting (2024/09/09)

Practice coil impregnated and out of mold
lessons learned and improvements identified.



Progress since our last meeting (2024/09/09)

ASC2024 paper submitted.



Tooling Design, Coil Fabrication, and Coil Performance Verification For a 28 GHz Nb_3Sn ECR Ion Source Magnet

Philip Mallon, Tengming Shen, Ye Yang, Ray Hafalia Jr., Lianrong Xu, Jose Ferradas Troitiño, Mariusz Juchno, Paolo Ferracin, Soren Prestemon, Yoonhyuck Choi, Junwei Guo, Xiaoji Du, David Greene, Danlu Zhang, Junseong Kim, Tomofumi Maruta, Guillaume Machicoane, Ting Xu, Jie Wei

***Abstract*—Worldwide several superconducting electron cyclotron resonance (ECR) ion sources have been developed and in operation for heavy ion accelerators using Nb-Ti magnets. To explore the use of high-field Nb_3Sn to break the field limit of Nb-Ti for ECR magnets, state-of-the-art Nb_3Sn coil fabrication techniques and tooling design must be used to address the challenging characteristics of Nb_3Sn conductors. Earlier we reported the overall magnet design, conductor selection, and conductor characterization for building a 28 GHz superconducting ECR ion source using Nb_3Sn sextupole coils for Facility for Rare Isotope Beams (FRIB). This paper describes the progress towards fabricating prototype Nb_3Sn sextupole coil. In particular, we present tooling design, Nb_3Sn sextupole coil fabrication, and a mirror magnet for performance verification.**

***Index Terms*—Electron cyclotron resonance, Ion source, ECRIS, Superconducting magnet, Nb_3Sn.**

Fig. 1. Magnetic model of the FRIB Nb_3Sn ECR ion source magnet showing the sextpole-in-solenoid approach.

I. INTRODUCTION

THE use of Nb-Ti superconducting magnets has allowed electron cyclotron resonance ion sources to work at 28 GHz to produce high charge high intensive ion beams. Lawrence Berkeley National Laboratory (LBNL) developed VENUS [1], the first superconducting ECR ion source, at LBNL, and the magnet cold mass for the newly commissioned 28 GHz superconducting ECR ion source at the Facility for Rare Isotope Beams (FRIB). Both sources adopt a scheme with a sextupole magnet inside a mirror-type solenoid to confine the ions and electrons using Nb-Ti [2] . Nb-Ti coils limit all the existing ECR sources to operate below 9 T at 4.2 K. Nb_3Sn potentially enables next generation ECR ion sources with a higher field limit (about 22 T at 4.2 K). As an example, a 45 GHz ECR ion source Nb_3Sn magnet is currently being developed by the Institute of Modern Physics (IMP) in China [3]. The need for higher intensity high charge beams to inject into heavy ion accelerators provides the motivation to continually improve ECR ion sources [4]. With the exception of a closed-loop-coil configuration ECR ion source such as MARS [5], which uses Nb-Ti, generating magnetic fields using Nb_3Sn superconductor is considered a requirement to exceed 40 GHz operation [6]. Leaning heavily on superconducting magnet development using this conductor in other areas of applied superconductivity [7], a planned upgrade to the Facility for Rare Isotope Beams (FRIB) at Michigan State University [4] aims to serve as a proof-of-concept that a Nb_3Sn ECR ion source magnet can be constructed. While similar magnets can be designed for operation at frequencies above 45 GHz, the current effort [8] targets the present-day operating frequency of FRIB at 28 GHz. Figure 1 shows an image of the magnetic model, which omits the axial loading setup.

II. SEXTUPOLE DESIGN: IMPACT OF NB_3SN CONDUCTOR

The nature of Nb_3Sn requires careful consideration for this magnet from every step of coil fabrication to its installation inside the magnet structure. After reaction Nb_3Sn is brittle and its superconducting properties are sensitive to strain. Thus the Nb_3Sn sextupole coils should be fabricated with a wind-and-react method that requires heat treating the entire coil to form the superconducting A15 phase intermetallic compound and transferring it into an impregnation mold for vacuum

This work was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under the Cooperative Agreement DE-SC0000661. Work at LBNL is additionally supported by the U.S. Department of Energy, Office of Science under contract No. DE-AC02-05CH11231.

P. Mallon, T. Shen, Y. Yang, R. Hafalia, L. Xu, M. Juchno, P. Ferracin, and S. Prestemon are with the Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA 94720, USA. (e-mail: pmallon@lbl.gov)

Y. Choi, J. Guo, X. Du, D. Greene, D. Zhang, J. Kim, T. Maruta, G. Machicoane, T. Xu, and J. Wei are with the Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA.

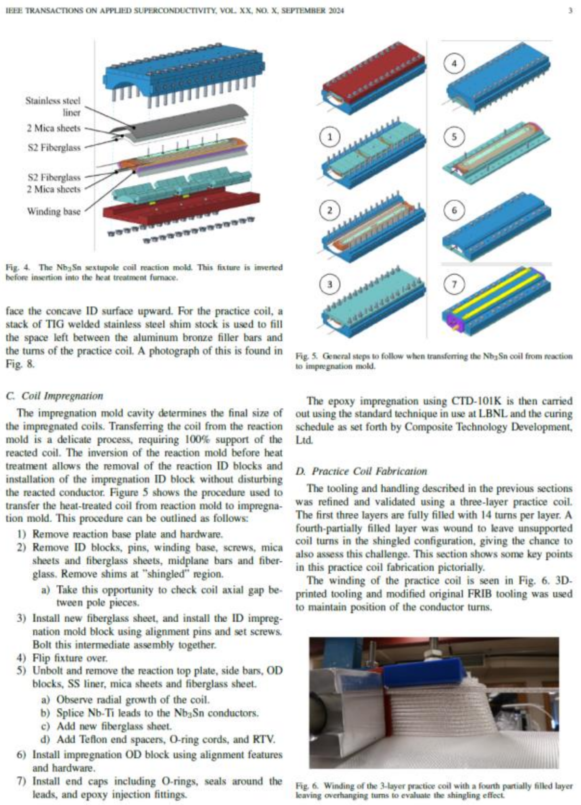


Fig. 4. The Nb_3Sn sextupole coil reaction mold. This fixture is inverted before insertion into the heat treatment furnace.

face the concave ID surface upward. For the practice coil, a stack of TIG welded stainless steel shim stock is used to fill the space left between the aluminum bronze filler bars and the turns of the practice coil. A photograph of this is found in Fig. 8.

C. Coil Impregnation

The impregnation mold cavity determines the final size of the impregnated coils. Transferring the coil from the reaction mold is a delicate process, requiring 100% support of the reacted coil. The inversion of the reaction mold before heat treatment allows the removal of the reaction ID blocks and installation of the impregnation ID block without disturbing the reacted conductor. Figure 5 shows the procedure used to transfer the heat-treated coil from reaction mold to impregnation mold. This procedure can be outlined as follows:

1) Remove reaction base plate and hardware.
2) Remove ID blocks, pins, winding base, screws, mica sheets and fiberglass sheets, midplane bars and fiberglass. Remove shims at "shingled" region.
    a) Take this opportunity to check coil axial gap between pole pieces.
3) Install new fiberglass sheet, and install the ID impregnation mold block using alignment pins and set screws. Bolt this intermediate assembly together.
4) Flip fixture over.
5) Unbolt and remove the reaction top plate, side bars, OD blocks, SS liner, mica sheets and fiberglass sheet.
    a) Observe radial growth of the coil.
    b) Splice Nb-Ti leads to the Nb_3Sn conductors.
    c) Add new fiberglass sheet.
    d) Add Teflon end spacers, O-ring cords, and RTV.
6) Install impregnation OD block using alignment features and hardware.
7) Install end caps including O-rings, seals around the leads, and epoxy injection fittings.

Fig. 5. General steps to follow when transferring the Nb_3Sn coil from reaction to impregnation mold.

The epoxy impregnation using CTD-101K is then carried out using the standard technique in use at LBNL and the curing schedule as set forth by Composite Technology Development, Ltd.

D. Practice Coil Fabrication

The tooling and handling described in the previous sections was refined and validated using a three-layer practice coil. The first three layers are fully filled with 14 turns per layer. A fourth-partially filled layer was wound to leave unsupported coil turns in the shingled configuration, giving the chance to also assess this challenge. This section shows some key points in this practice coil fabrication pictorially.

The winding of the practice coil is seen in Fig. 6. 3D-printed tooling and modified original FRIB tooling was used to maintain position of the conductor turns.

Fig. 6. Winding of the 3-layer practice coil with a fourth partially filled layer leaving overhanging turns to evaluate the shingling effect.

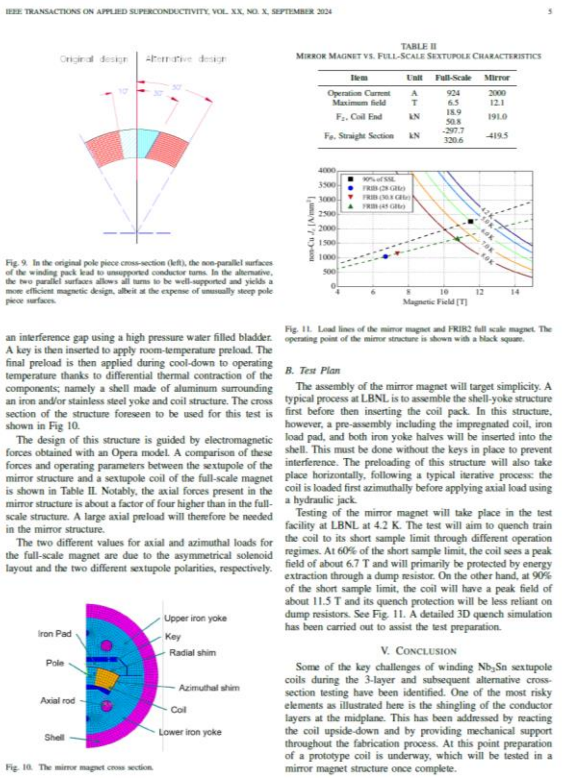


Fig. 9. In the original pole piece cross-section (left), the non-parallel surfaces of the winding pack lead to unsupported conductor turns. In the alternative, the two parallel surfaces allows all turns to be well-supported and yields a more efficient magnetic design, albeit at the expense of unusually steep pole piece surfaces.

an interference gap using a high pressure water filled bladder. A key is then inserted to apply room-temperature preload. The final preload is then applied during cool-down to operating temperature thanks to differential thermal contraction of the components; namely a shell made of aluminum surrounding an iron and/or stainless steel yoke and coil structure. The cross section of the structure foreseen to be used for this test is shown in Fig 10.

The design of this structure is guided by electromagnetic forces obtained with an Opera model. A comparison of these forces and operating parameters between the sextupole of the mirror structure and a sextupole coil of the full-scale magnet is shown in Table II. Notably, the axial forces present in the mirror structure is about a factor of four higher than in the full-scale structure. A large axial preload will therefore be needed in the mirror structure.

The two different values for axial and azimuthal loads for the full-scale magnet are due to the asymmetrical solenoid layout and the two different sextupole polarities, respectively.

Fig. 10. The mirror magnet cross section.

TABLE II
MIRROR MAGNET VS. FULL-SCALE SEXTUPOLE CHARACTERISTICS

Item	Unit	Full-Scale	Mirror
Operation Current	A	924	2000
Maximum field	T	6.5	12.1
F_z, Coil End	kN	18.9 50.8	191.0
F_θ, Straight Section	kN	-297.7 320.6	-419.5

Fig. 11. Load lines of the mirror magnet and FRIB2 full scale magnet. The operating point of the mirror structure is shown with a black square.

B. Test Plan

The assembly of the mirror magnet will target simplicity. A typical process at LBNL is to assemble the shell-yoke structure first before then inserting the coil pack. In this structure, however, a pre-assembly including the impregnated coil, iron load pad, and both iron yoke halves will be inserted into the shell. This must be done without the keys in place to prevent interference. The preloading of this structure will also take place horizontally, following a typical iterative process: the coil is loaded first azimuthally before applying axial load using a hydraulic jack.

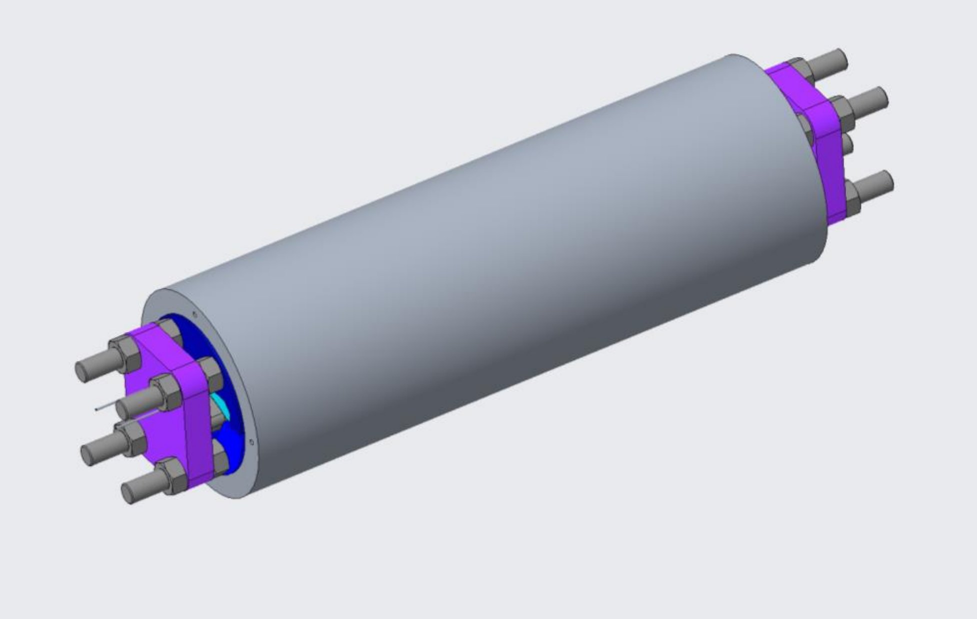
Testing of the mirror magnet will take place in the test facility at LBNL at 4.2 K. The test will aim to quench train the coil to its short sample limit through different operation regimes. At 60% of the short sample limit, the coil sees a peak field of about 6.7 T and will primarily be protected by energy extraction through a dump resistor. On the other hand, at 90% of the short sample limit, the coil will have a peak field of about 11.5 T and its quench protection will be less reliant on dump resistors. See Fig. 11. A detailed 3D quench simulation has been carried out to assist the test preparation.

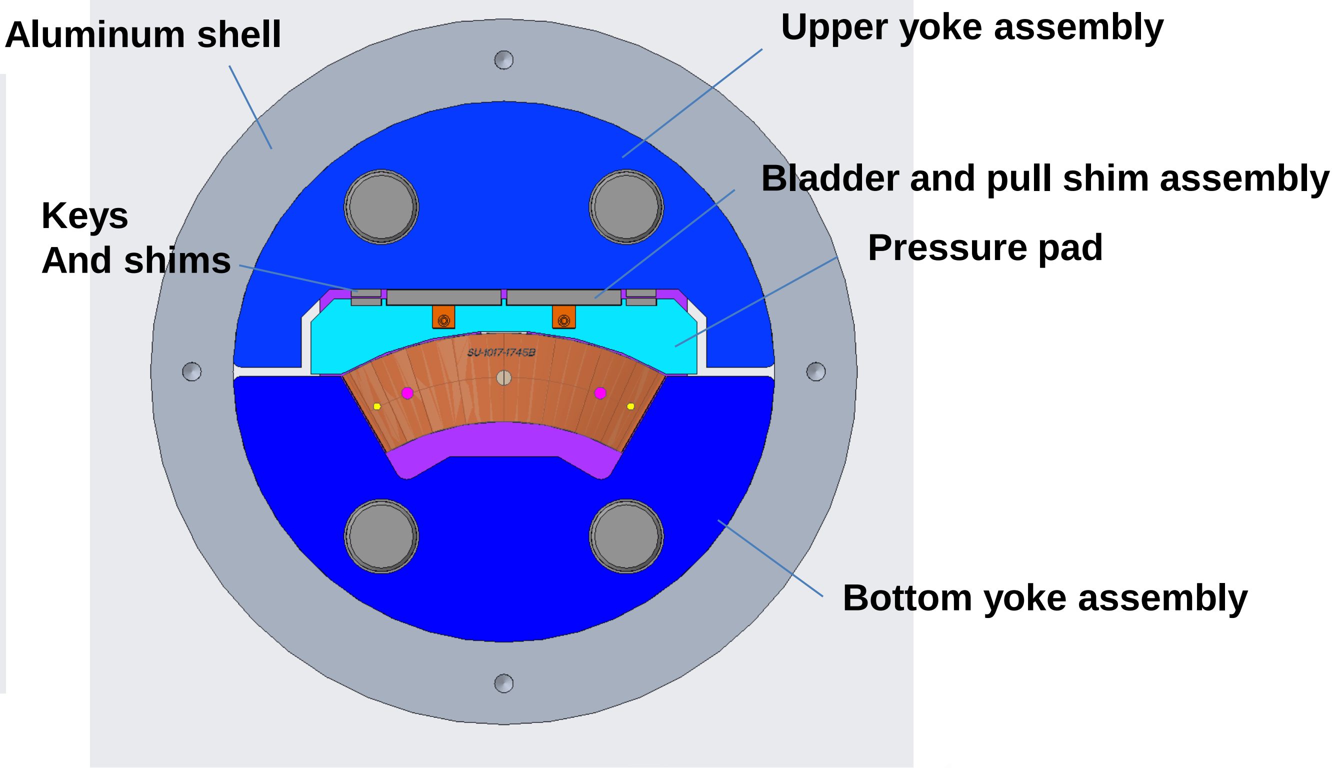
V. CONCLUSION

Some of the key challenges of winding Nb_3Sn sextupole coils during the 3-layer and subsequent alternative cross-section testing have been identified. One of the most risky elements as illustrated here is the shingling of the conductor layers at the midplane. This has been addressed by reacting the coil upside-down and by providing mechanical support throughout the fabrication process. At this point preparation of a prototype coil is underway, which will be tested in a mirror magnet structure once complete.

Progress since our last meeting (2024/09/09)

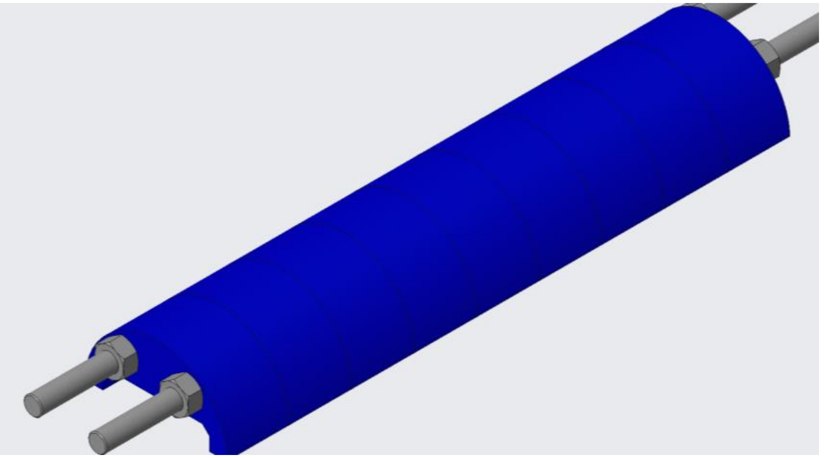
- Mirror magnet design and assembly plan reviews. Preliminary assembly plan in place.
- CAD model revisions mostly done. Production drawings being prepared.
- Test preparations: 1) Power circuit – selection of dump resistor values (quench simulation - Ye); 2) Instrumentation plan – hall sensor and SGs (Ye, Philip); 3) Mechanical mounting coil to test header (Ray).



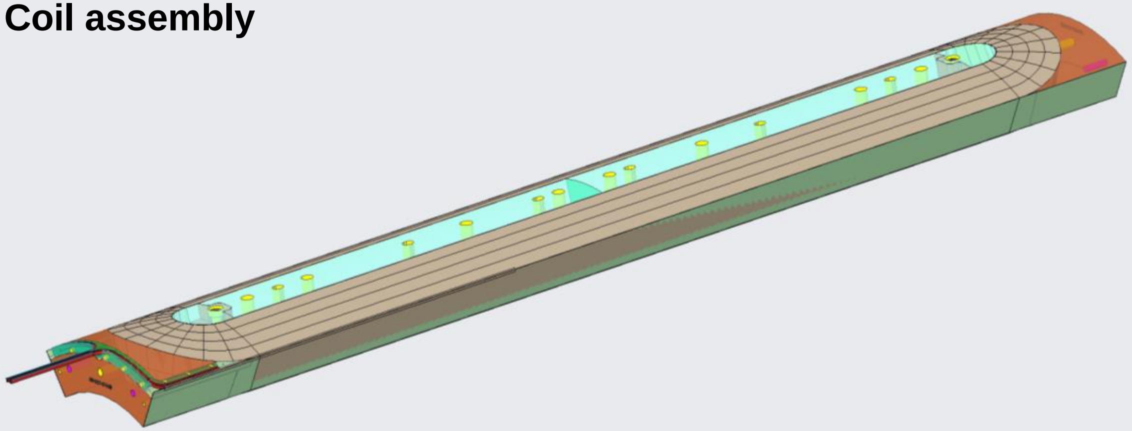


Mirror magnet structure

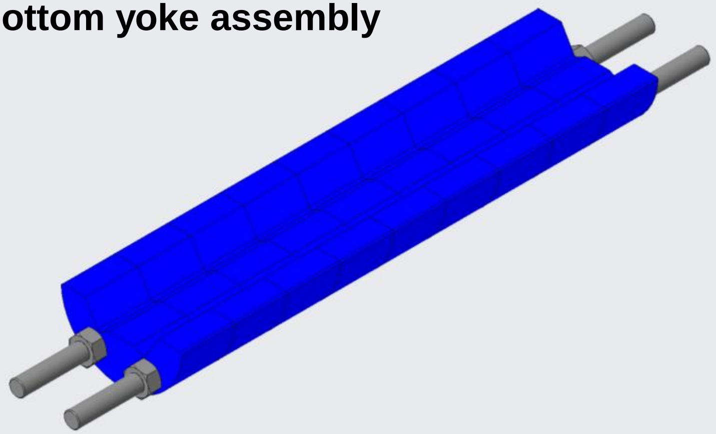
Upper yoke assembly

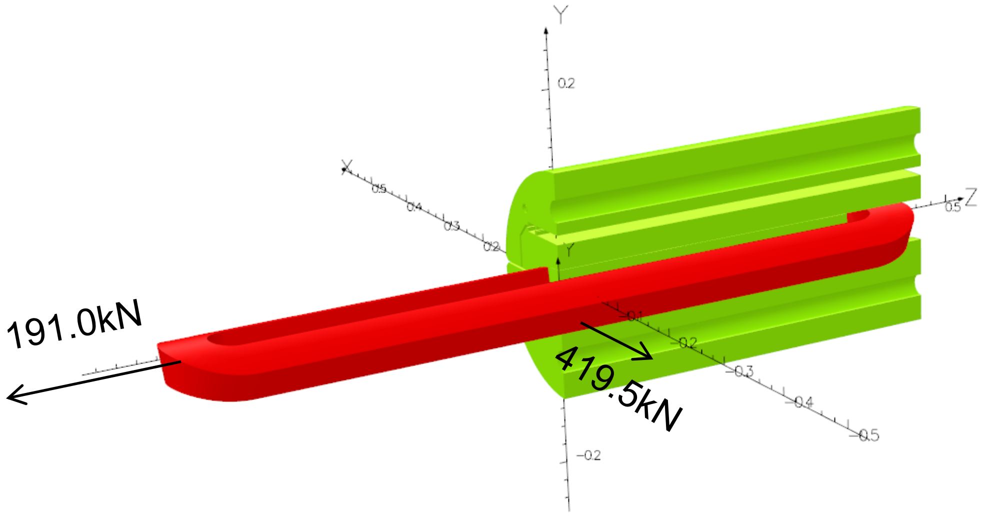


Coil assembly



Bottom yoke assembly





Planning

- **Oct – winding completed. Reaction started.**
- **Nov – Reaction and coil transfer for impregnation.**
- **Dec 15 – Coil impregnated and out of mold.**
- **Jan/Feb/March 2024 – Assembly and test.**

- **Project needs a non-cost extension.**