BERKELEY LAB
Bringing Science Solutions to the World

U.S. DEPARTMENT OF ENERGY
Office of Science

Test Facility Dipole

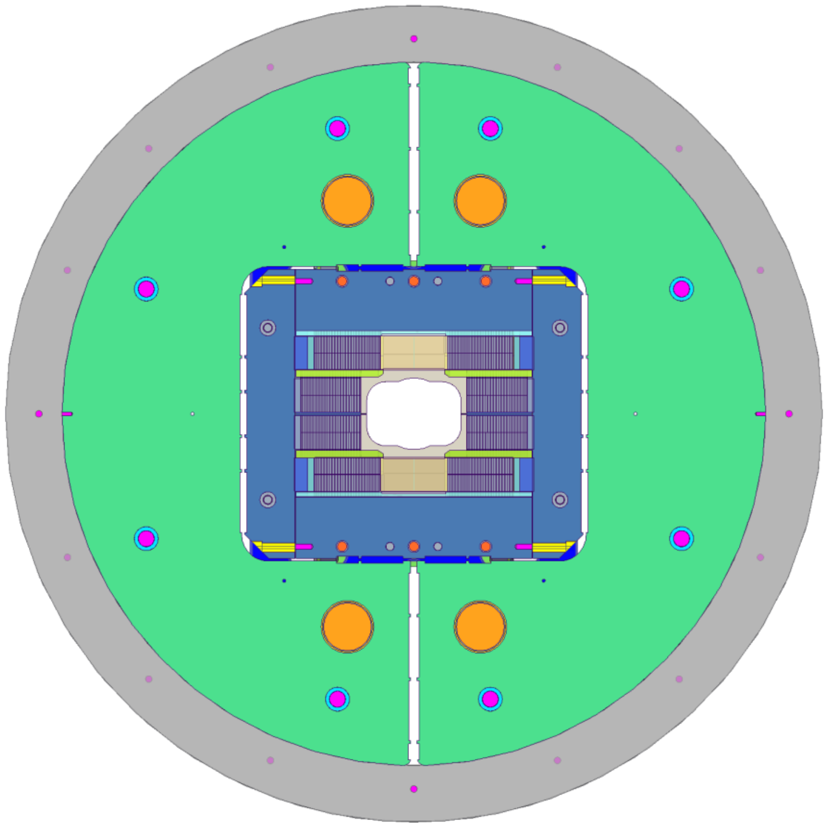
D. Arbelaez, J. L. Rudeiros Fernández, P. Ferracin, R. Hafalia, P. Hayes, E. Lee, R. Lee, P. Mallon, M. Naus, I. Pong, S. Prestemon, G. Sabbi, G. Vallone

HFVMTF Cable Test Facility: First Workshop on User Interfaces

Outline

- Test facility dipole design parameters
- Technical background
- Coil and structure design
- Fabrication and assembly infrastructure
- Summary

Design Parameters

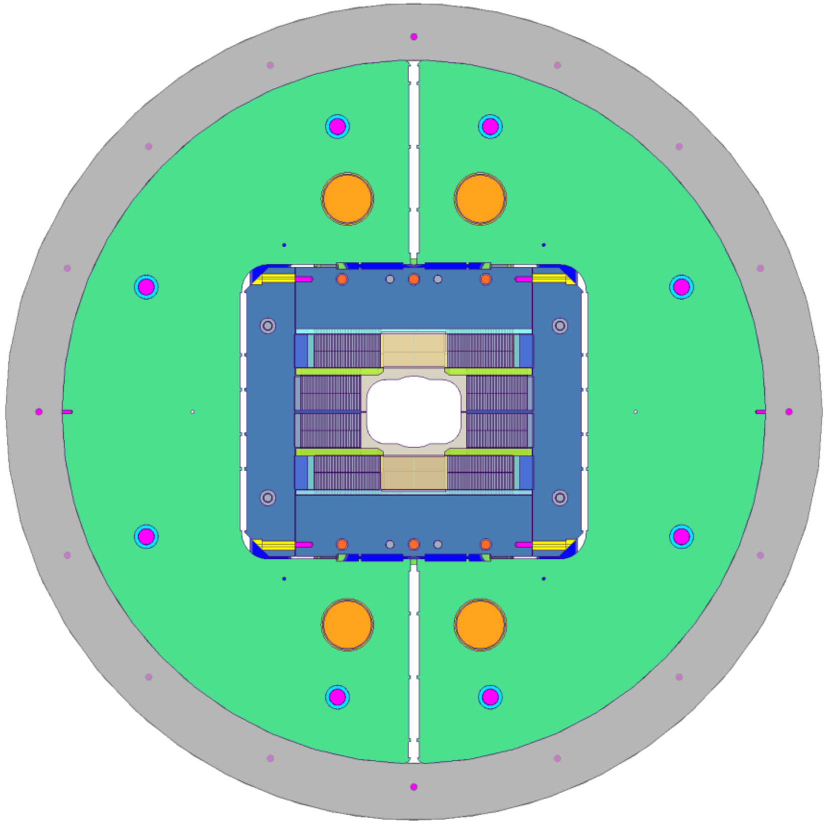


Cable test facility magnet for testing inserts and cables in a high dipole filed.

Joint effort between the offices of *Fusion Energy Sciences* and *High Energy Physics* (US Department of Energy)

- **Target field:**
  - Operation target: **15 T at 1.9 K**
  - *Design target*: 16 T with 15% margin at 1.9 K
- **Clear bore size:**
  - 144 mm x 94 mm rectangular aperture with superimposed 106 mm diameter.
- **Nb_3Sn coils layout:**
  - Block coil design with flare ends and rectangular bore.
  - *Coil 1: 40 turns/layer, Coil 2: 44 turns/layer. (Non-graded coils).*
- **Mechanical design:**
  - Aluminum shell-based structure using key-and-bladder technology, with axial pre-load.

Design Parameters



Cable test facility magnet for testing inserts and cables in a high dipole filed.

Joint effort between the offices of *Fusion Energy Sciences* and *High Energy Physics* (US Department of Energy)

- **Uniform field length:** straight section (within 1% variation) > 750 mm
- **Wire specification:** RRP 162/169, 1.1 mm diameter
- **Cable specifications:**

Parameter	Unit	Value
Strand diameter	mm	1.1
No. strands		44
Cable width (bare, before reaction)	mm	26.20
Cable thickness (bare, before reaction)	mm	1.91
Cable width (bare, post-reaction)	mm	26.46
Cable thickness (bare, post-reaction)	mm	1.99
Insulation thickness	mm	0.185
Cable width (insulated)	mm	26.81
Cable thickness (insulated)	mm	2.34
Inter-layer insulation	mm	0.4

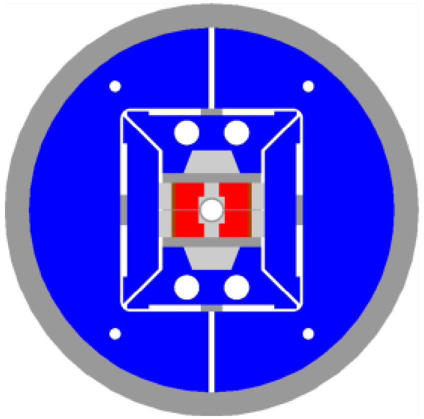
Technical Background

- The Test Facility Dipole design is based on studies and development of large aperture, high field dipoles over the past 15+ years:
  1. LARP studies of HL-LHC "Dipole First" IR *(LBNL/FNAL/BNL, 2003-04)*
  2. EFTA Dipole (EDIPO) Design Study *(EFDA/CEA/CRPP/FZK/LBNL, 2004-06)*
  3. LD1 magnet design *(2009-12)* at LBNL
  4. FRESCA2 magnet development *(CERN/CEA/EuCARD, 2010-2018)*
  5. HEPdipo design study (CERN/PSI/F4E/LBNL, 2017+)
- We are taking full advantage of these efforts and experience to accelerate the TFD development and decrease risk in a broad range of areas, in particular:
  - Winding layout and parameters (LARP, EFDA, LD1/HD, FRESCA2, HEPdipo)
  - Coil tooling, parts, and fabrication process (FRESCA2, LD/HD)
  - Magnetic, mechanical, protection models and analysis (FRESCA2, HEPdipo)
- However, while building on this experience we are also optimizing the design to reflect the specific TFD requirements, in particular the higher field target

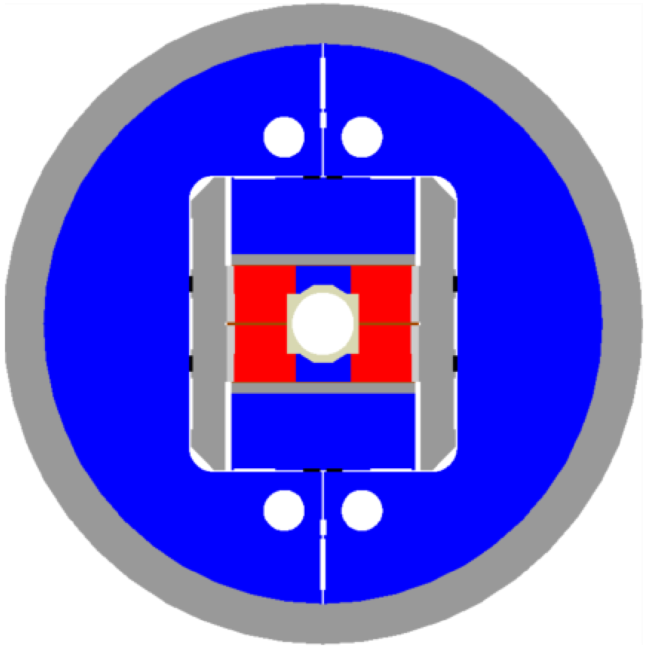
Comparison of “traditional” *block-type magnets*

“traditional”
Cosθ

HD2

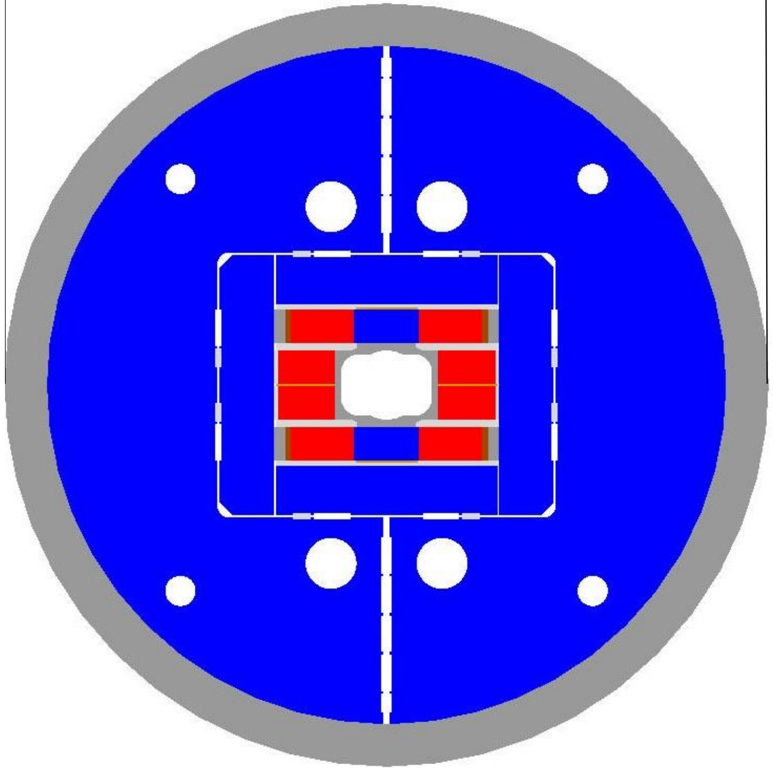


FRESCA2



1300 mm

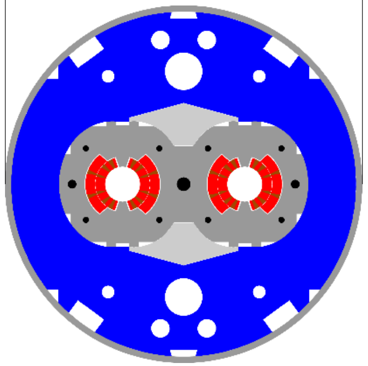
TFD



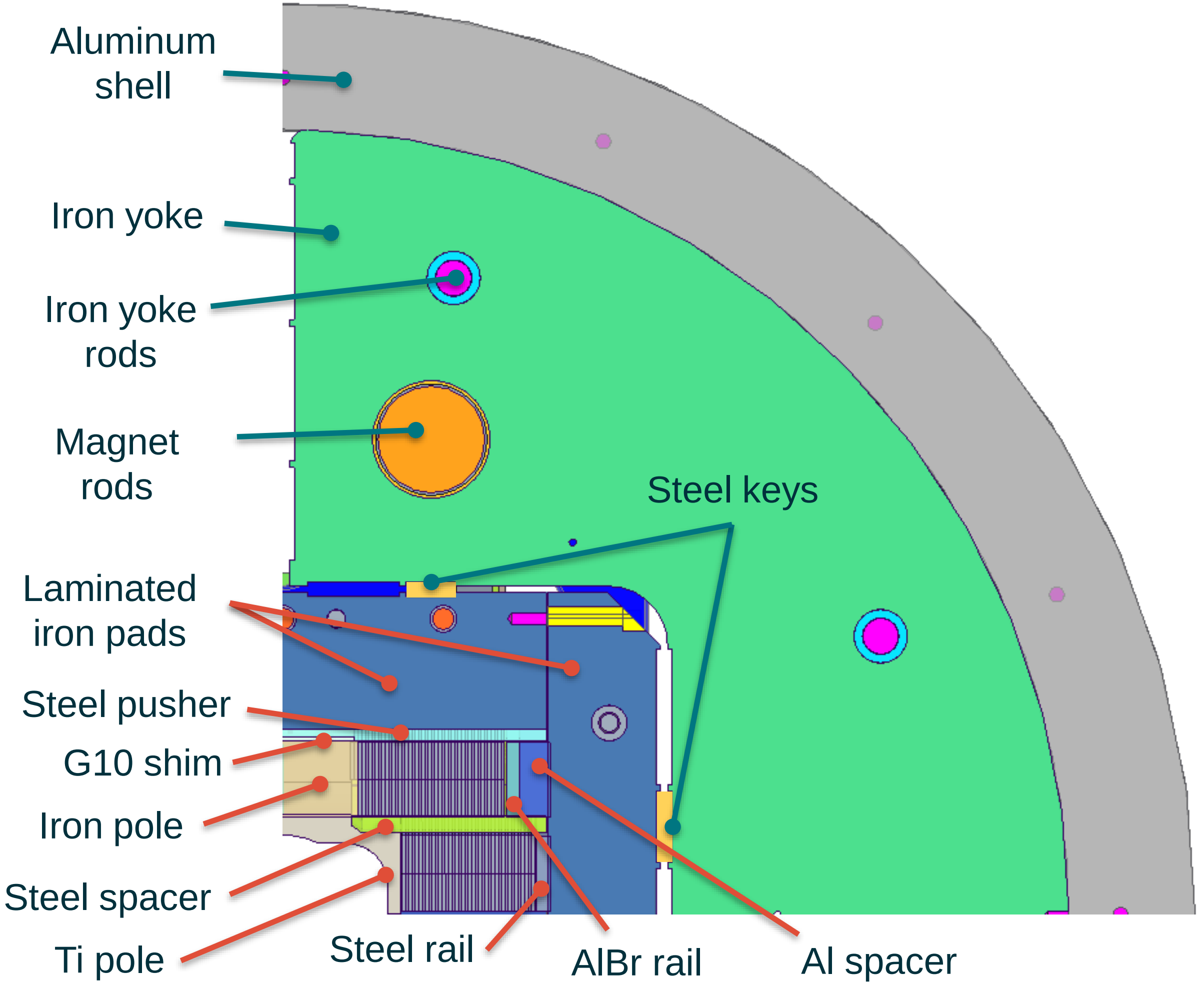
18050 kg

LHC dipole

570 mm



Magnet Cross-Section and Main Design Features



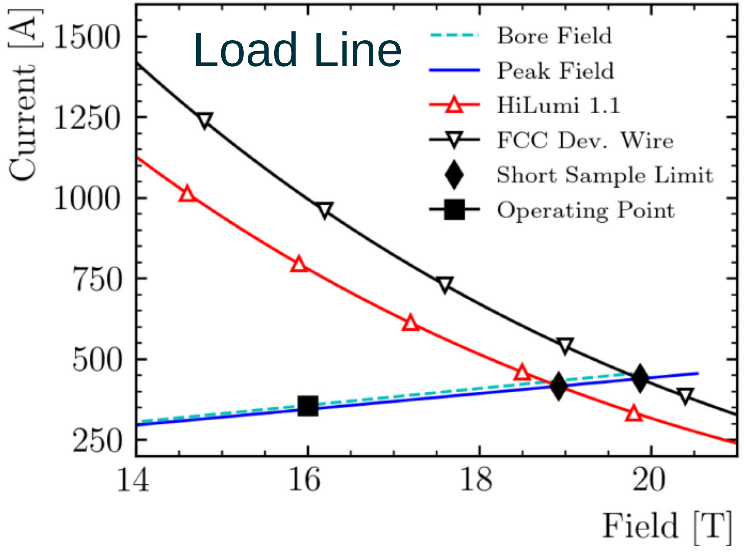
- The preloading at room temperature through the bladders placed between the iron yokes reduce the peak stress within the coil.
- The inclusion of a G10 shim reduces the overall stress in the pole and within the pole to coil interface.
- The location of the keys is based on the reduction of the peak tension stress at the pole to coil interface.
- A series of smartshims will be place within the midplane of the magnet, coil 1 to coil 2 interface and coil 2 to vertical iron pad in order to guarantee perfect contact geometry.

Two Dimensional Optimization (Magnetic)

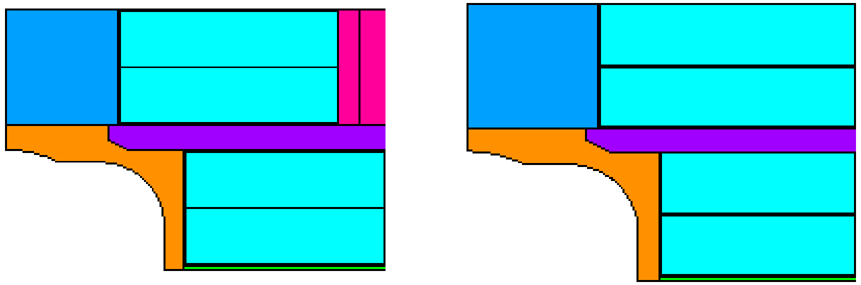
- Coil size and position chosen to minimize load line margin while maintaining reasonable field quality
- Load line margin at 1.9 K
  - Approximately 81% at 16 T
  - Approximately 76% at 15 T
- Field uniformity is approximately 0.2% at 50 mm radius

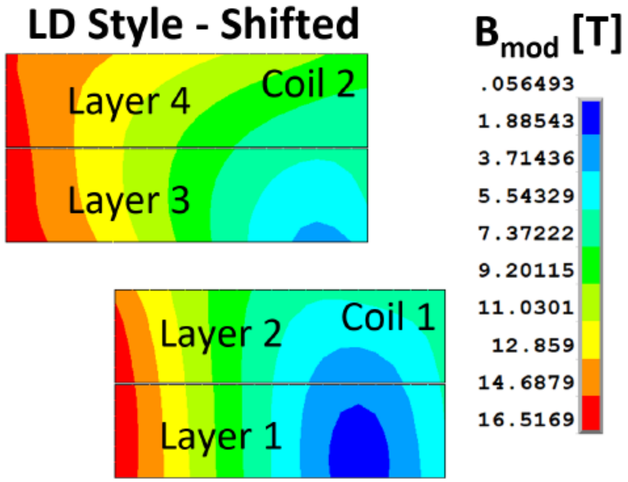
TABLE III
ALTERNATIVE LAYOUT RESULTS

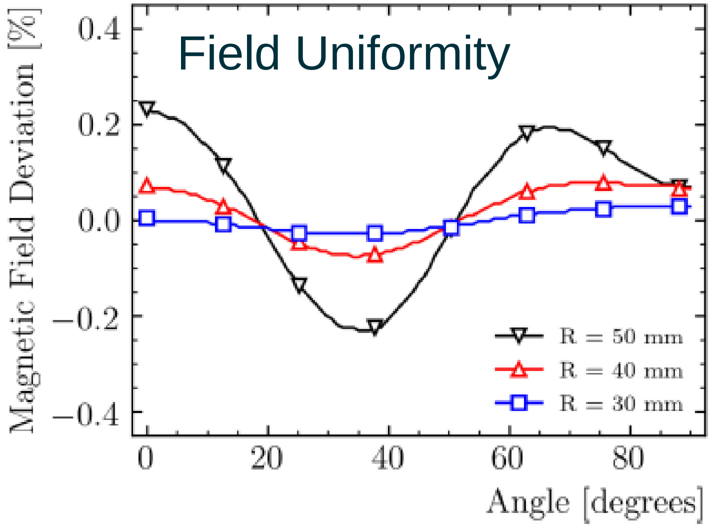
Parameter	Shifted
Operating Current	15.6 kA
Short Sample Current	19.2 kA
Load Line Margin	81.2%
Max Field (coil 1)	16.5 T
Max Field (coil 2)	16.1 T
Stored Energy (per quadrant)	1.8 MJ/m
Total Fx (coil 1)	6.3 MN/m
Total Fy (coil 1)	-2.7 MN/m
Total Fx (coil 2)	10.0 MN/m
Total Fy (coil 2)	-6.9 MN/m



Coil Layouts Considered in 2D Design





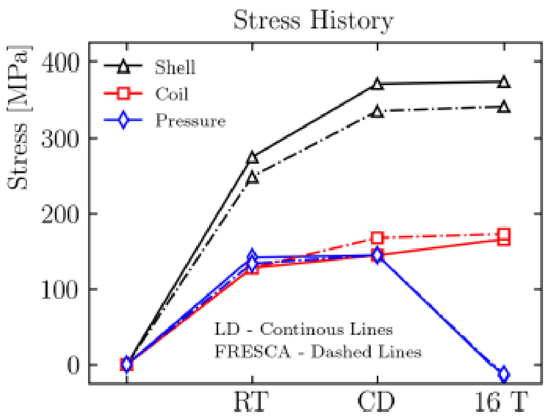


G. Vallone et al.,*IEEE Trans Appl Supercond*, Vol 31 No. 59500406

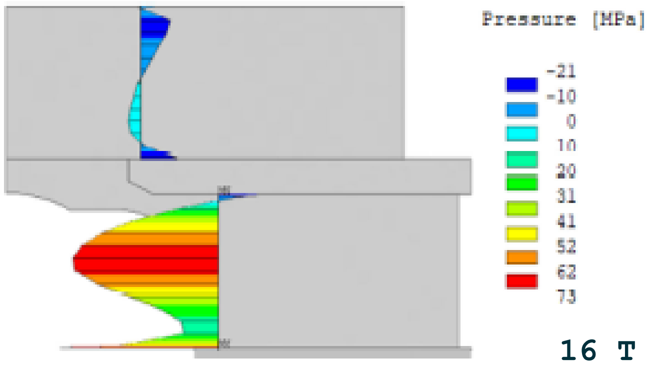
Two Dimensional Optimization (Mechanical)

- Spacer is introduced between the coils to minimize bending stress on the coils
- Key positions are optimized to minimize von Mises stress and tension at contact interfaces
- Maximum von Mises stress on the coils
  - RT Loading: 126 MPa
  - Cooldown: 145 MPa
  - Powering: 166 MPa
- Ensure sufficient safety margin is present for other structure materials (i.e. pole, yoke, shell) taking into account fracture toughness where appropriate

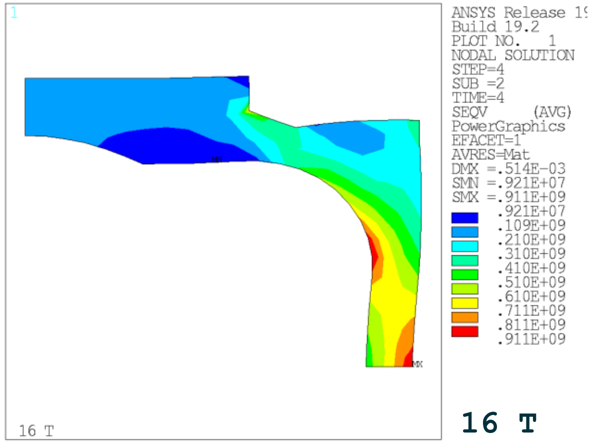
Stress History



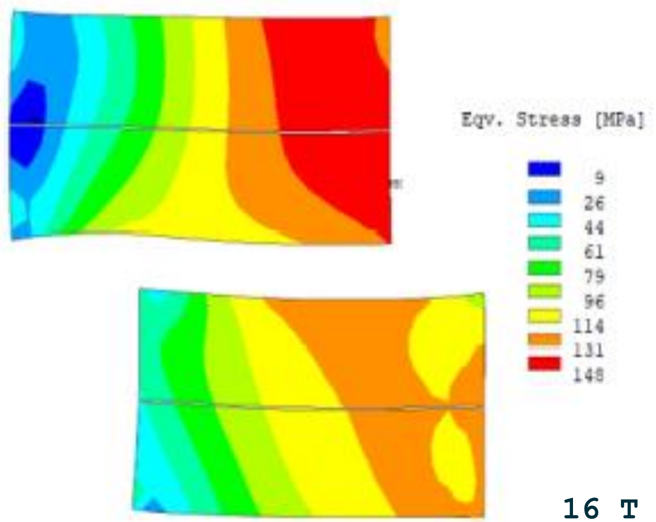
Contact Pressure



Pole Stress

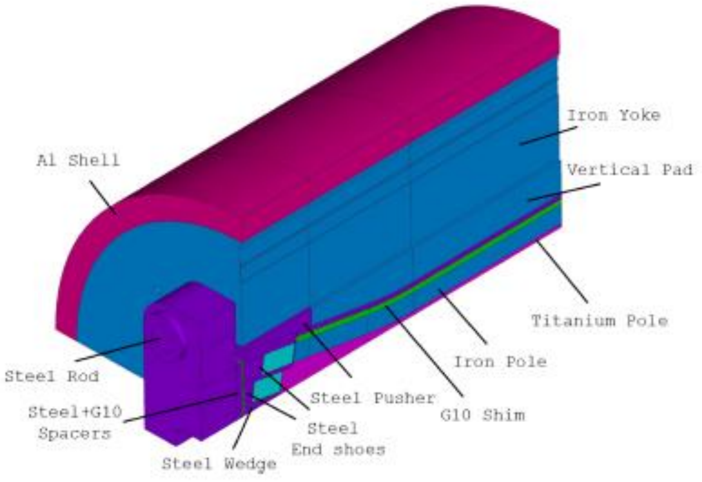


Von Mises Stress



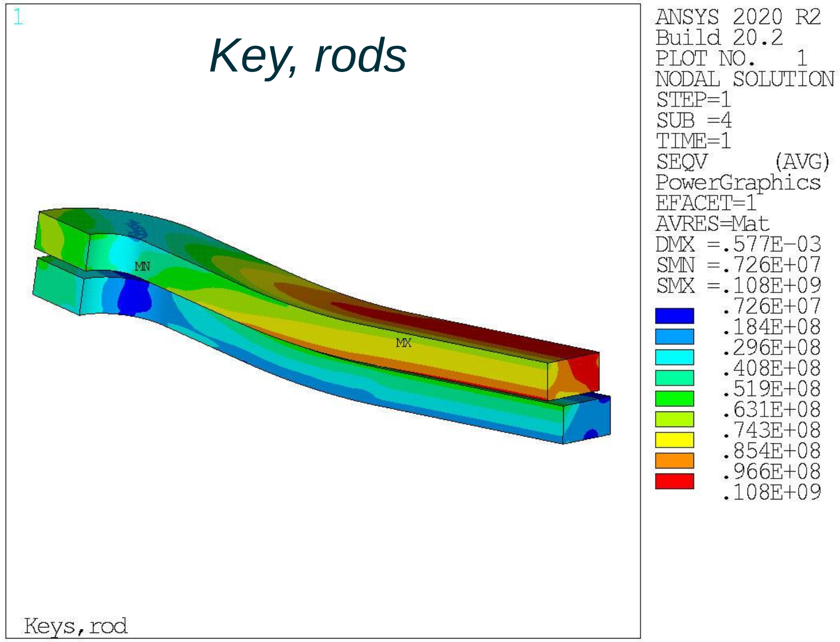
G. Vallone et al.,*IEEE Trans Appl Supercond*, Vol 31 No. 59500406

Three Dimensional Mechanical Analysis

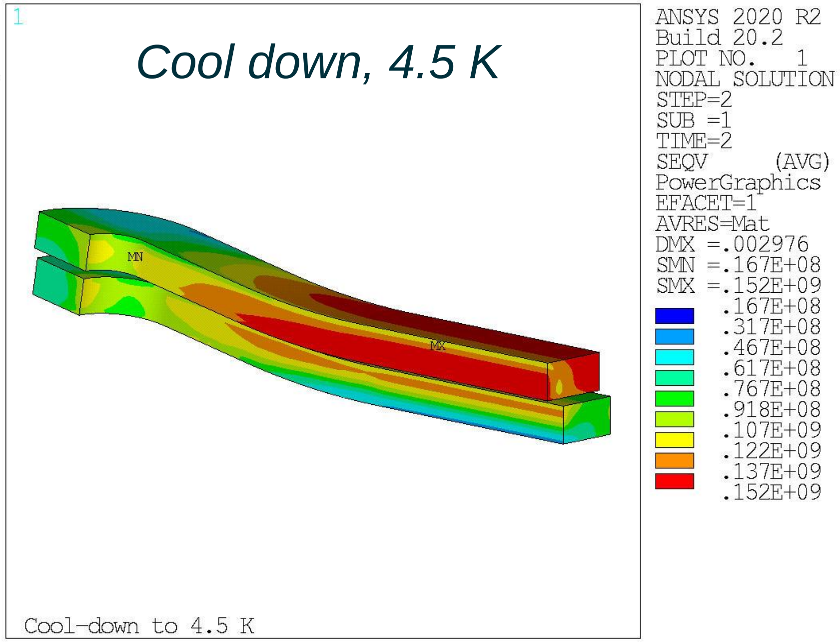


3D design has been optimized – produces similar peak stress as for 2D cross-section

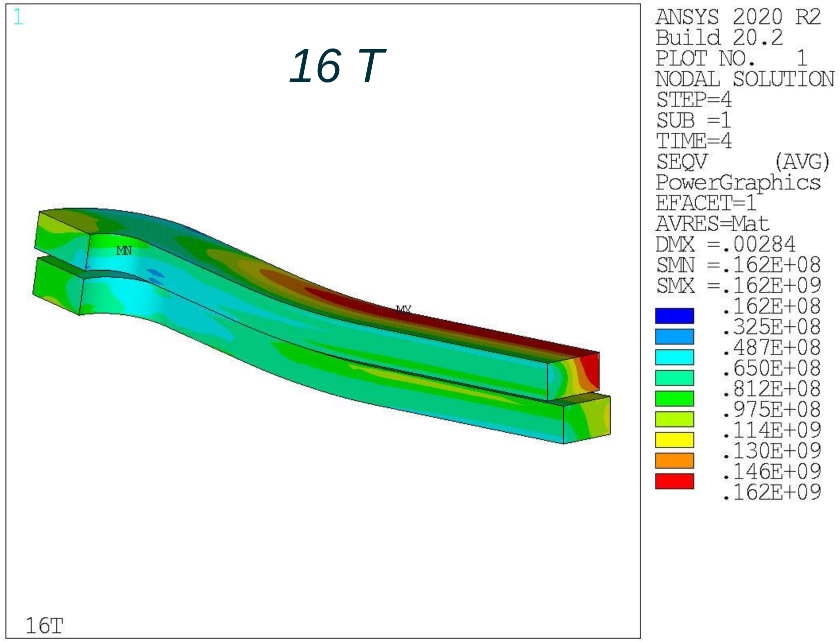
Current design – Mechanical results (with full prestress for 16 T)



Peak stress below **110 MPa** at room temperature



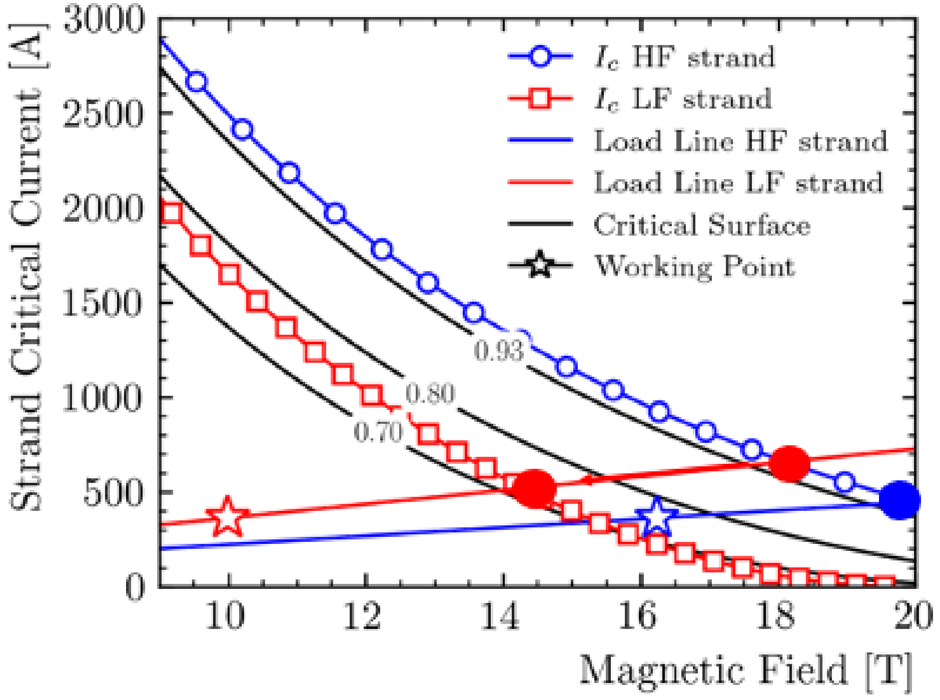
152 MPa on the high field region after cooldown

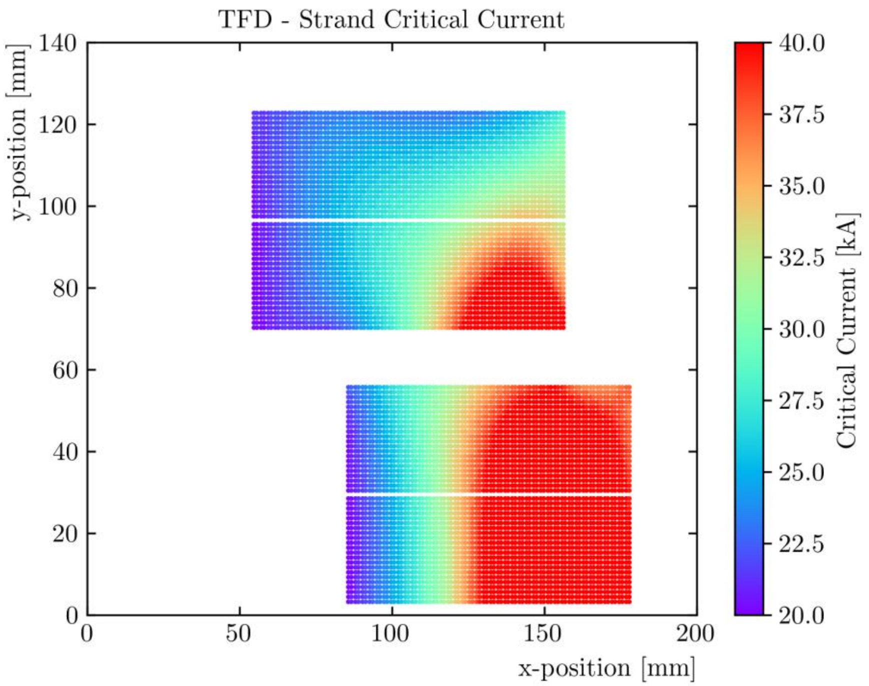


162 MPa in the low region at 16 T

Advanced Modeling Including Strain Dependence on Critical Current

Load line margin with strain dependence



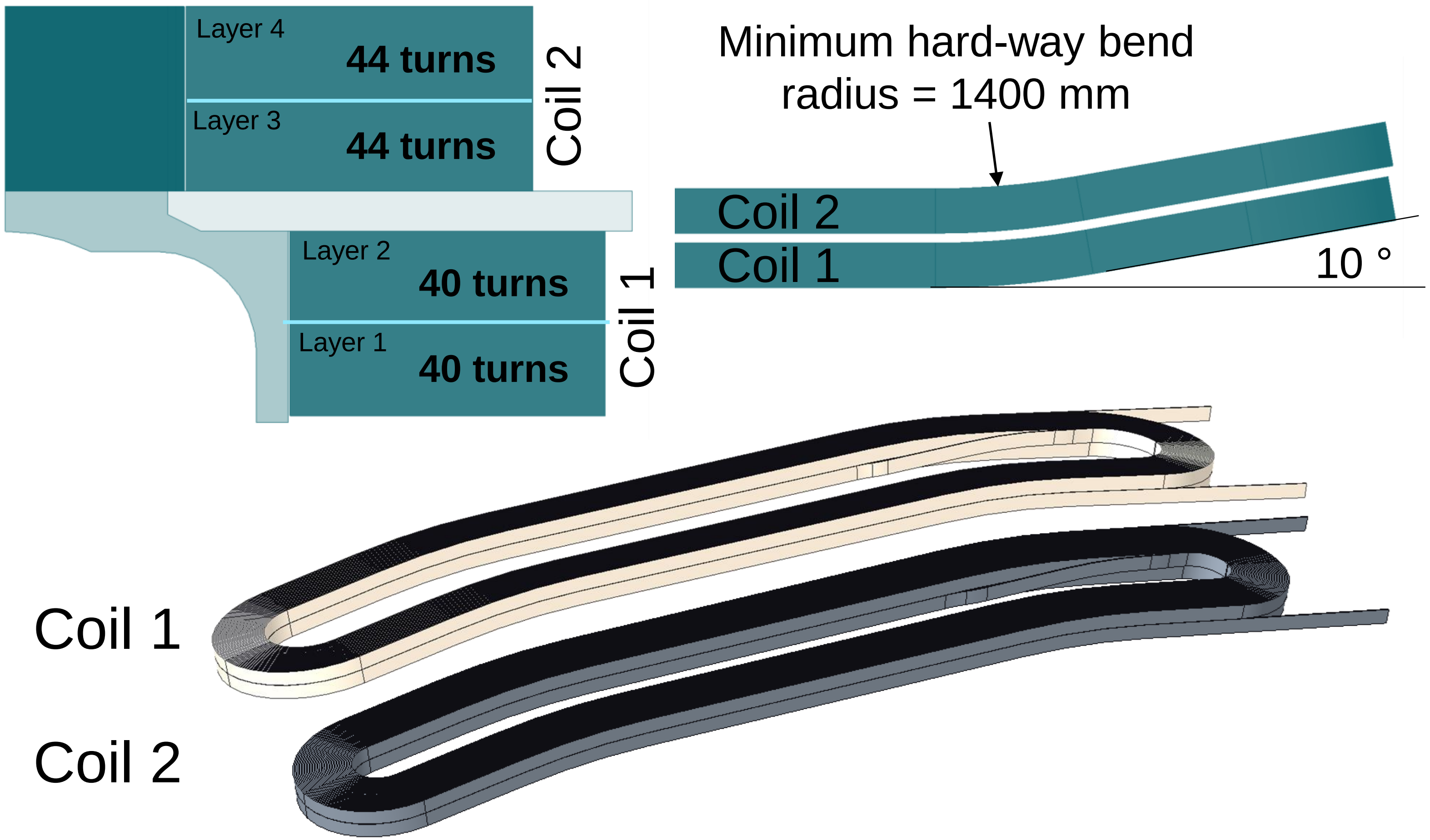


- The **short sample limit** for each strand, as a function of **field** and **strain** is computed:
  - Detailed 'strand' model of the magnet (2D)
  - Critical surface parametrization from strand measurements

- 80% in the **high field** / low stress region
- 57% in the **low field** / high stress region

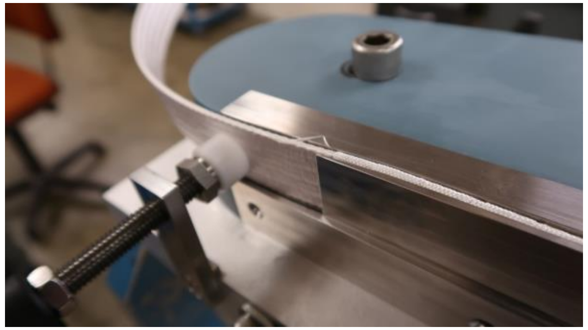
Computation of the Strain Induced Critical Current Reduction in the 16 T Nb3Sn Test Facility Dipole by G. Vallone, Presented at ASC22

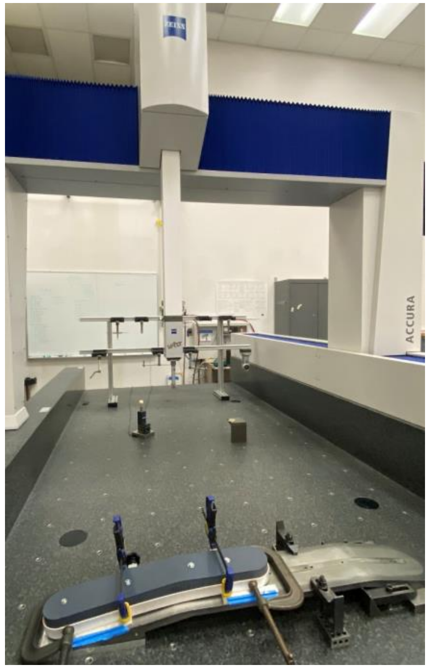
Development of the Nb_3Sn coils (Coil Design)



- A **fully parametric** 3D CAD model of each coil has been implemented in CREO parametric and is being used as the reference driving the rest of the parts of the magnet.
- The current version of the parametric models ensure the requirement of region of field uniformity of 750 mm.

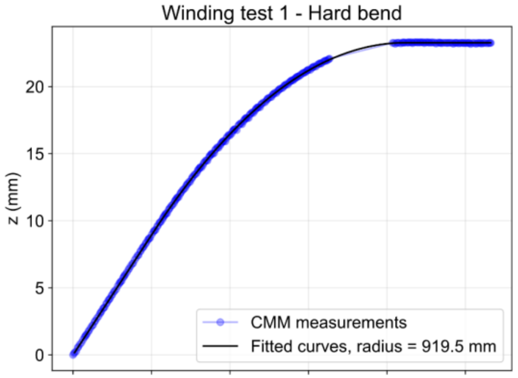
Development of the Nb_3Sn coils (Winding Tests)

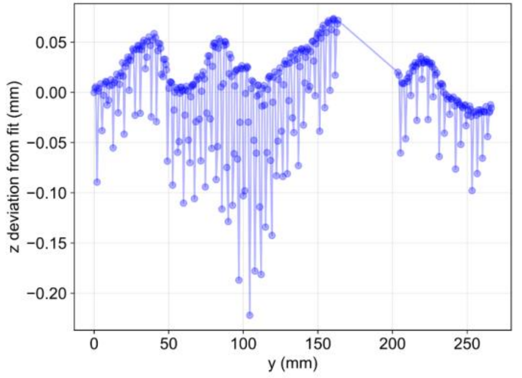




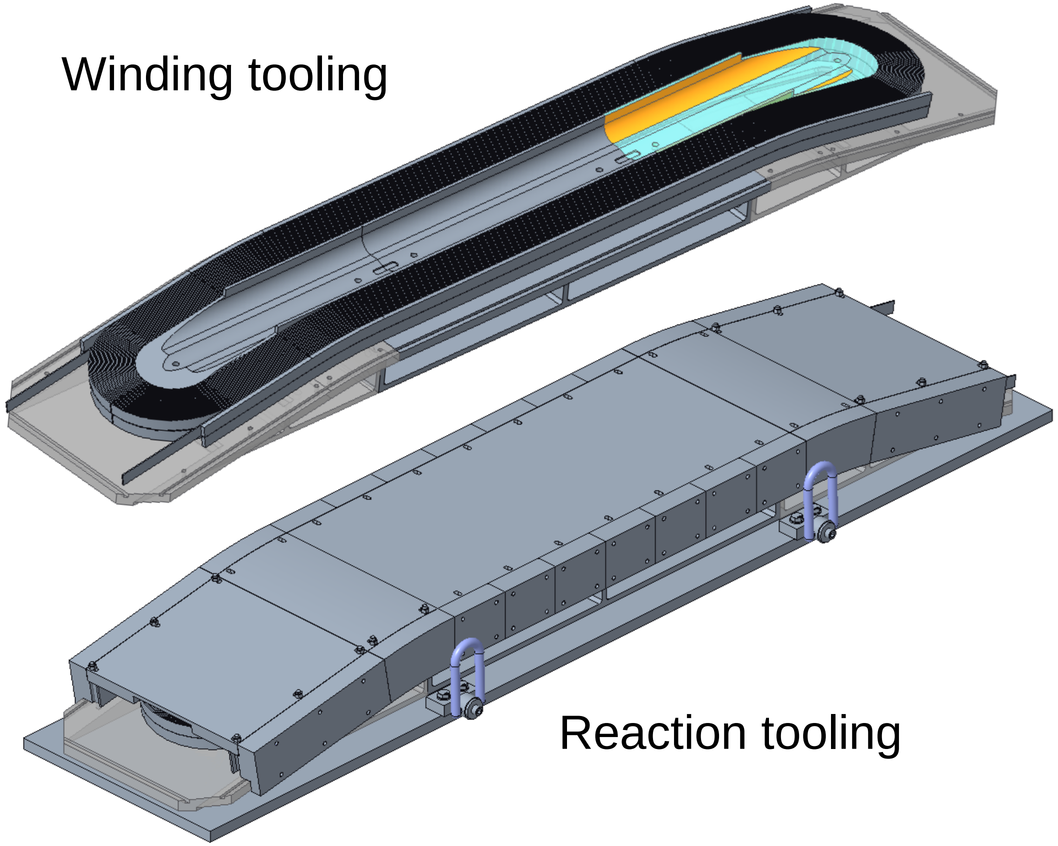
- Winding tests were performed with the prototype cable
- 3D printed components were used where possible to expedite testing
- CMM measurement were performed to determine cable position and used to define coil hard bend radius
- Test of layer jump design was performed

Winding Test CMM Measurements



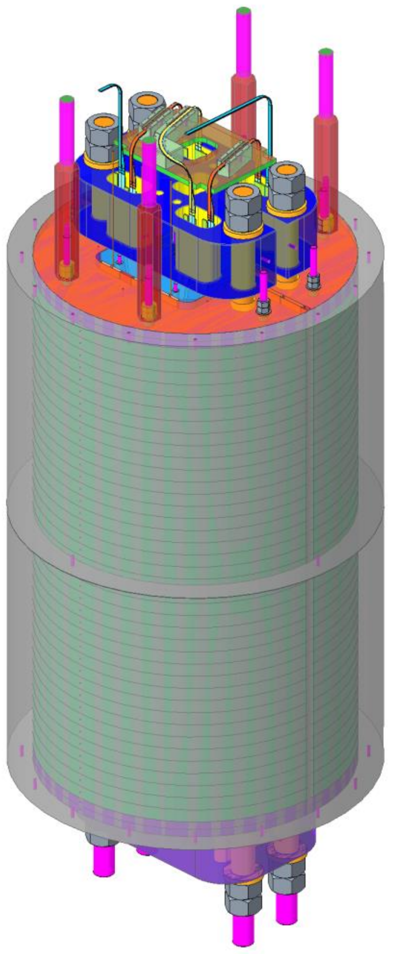


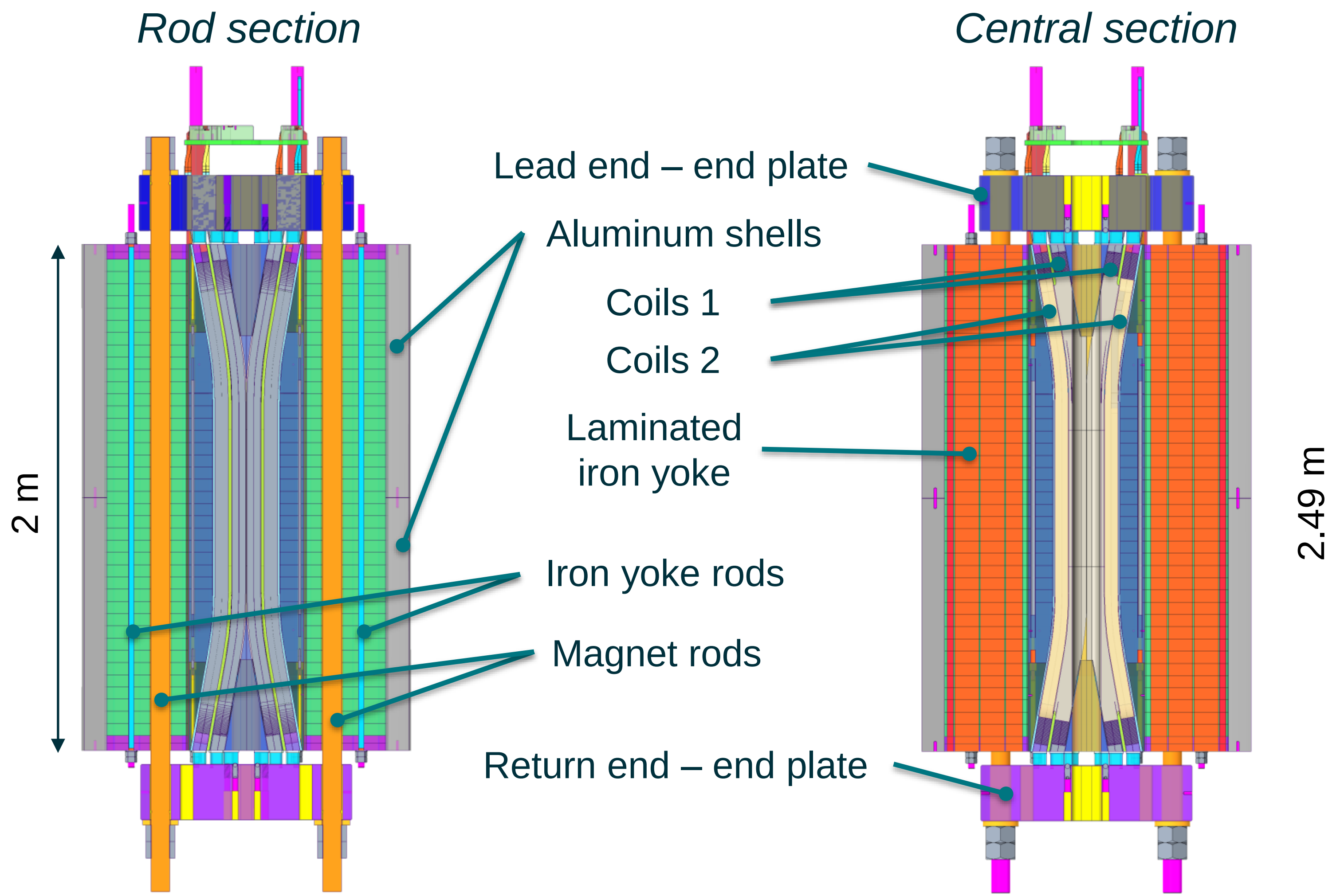
Development of the Nb_3Sn coils (Coil Winding and Reaction)



- The design of the **winding tooling** for Coil 1 is currently being finalized, incorporating the design feedback from the winding and layer jump tests.
- The **reaction tooling** for Coil 1 is being developed along with the winding + reaction + impregnation manufacturing sequence.
- The global insulation scheme for winding, reaction, and magnet assembly has been developed following the constraints for insulation, manufacturing of the coils, and magnet assembly.
- Winding and reaction tooling for Coil 2 are currently being designed in parallel.

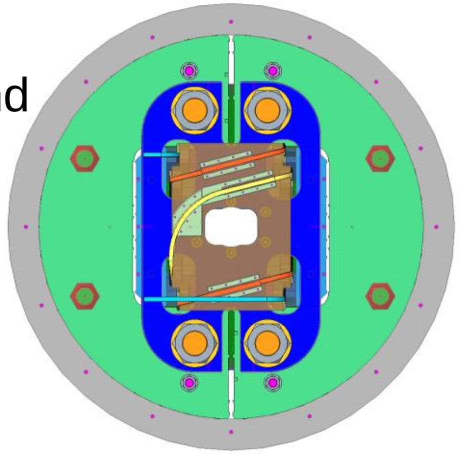
Magnet Structure Overview

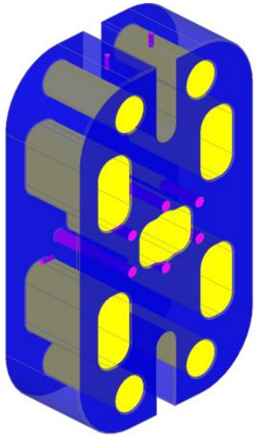


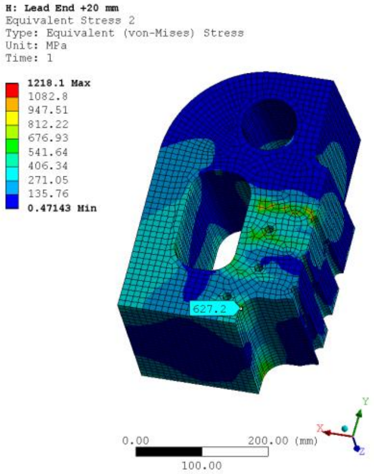


End Plates

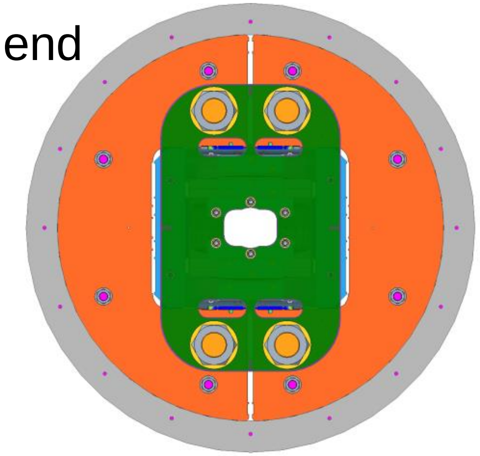
Lead end

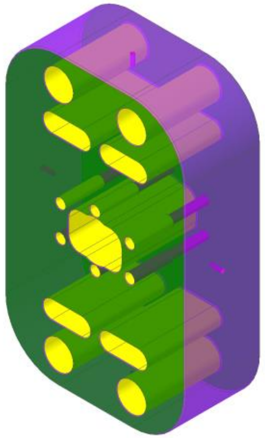


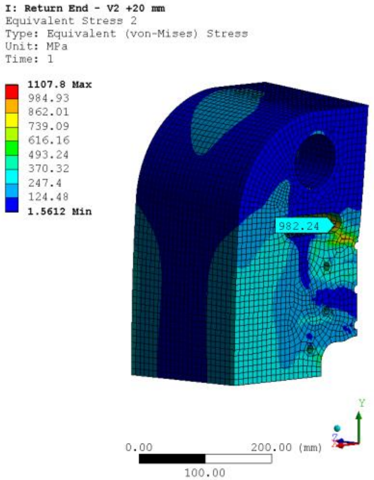




Return end







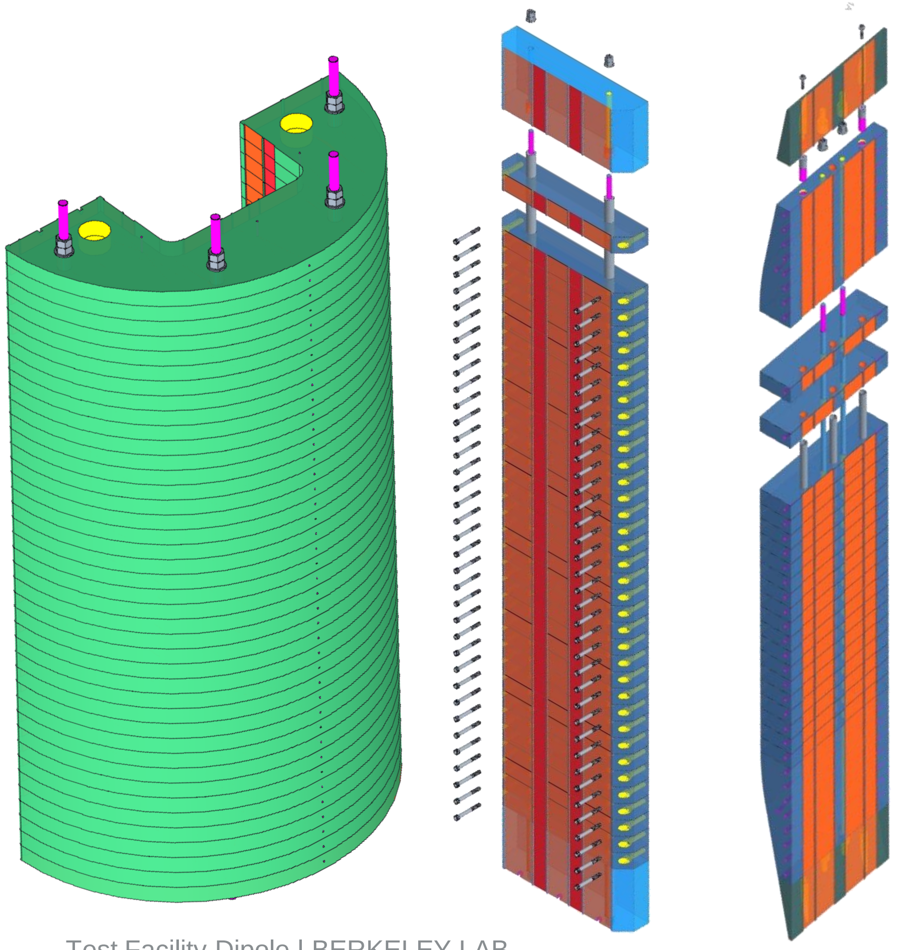
- The geometry of the **end plates** geometry has been created based on the FE analysis, and to comply with the following constraints:
  - Allow for the leads to pass through the end plate towards the splice box.
  - Allow for clear access to the aperture of the magnet.
  - Allow for clear access to all bladders and keys locations during the assembly operations.

Step	Fz (MN)
Loading	9.05
Cold	10.62
15 T	10.89
16 T	10.92

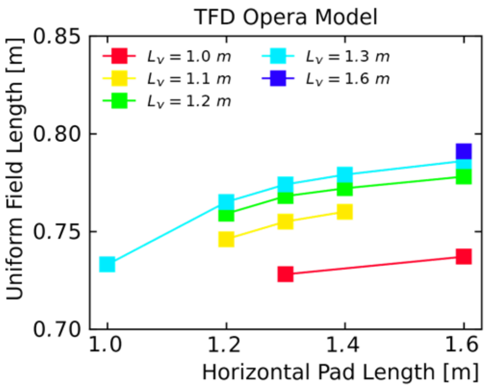
Yoke and Loading Pads

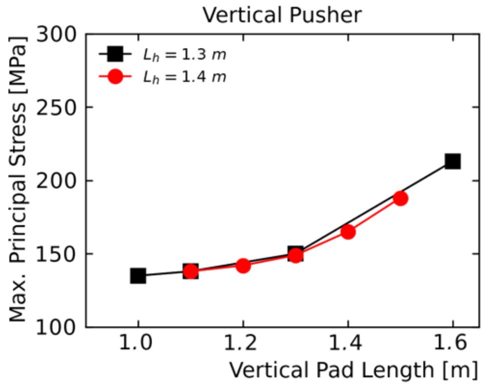
Laminated structures

Iron yoke Vertical pad Horizontal pad



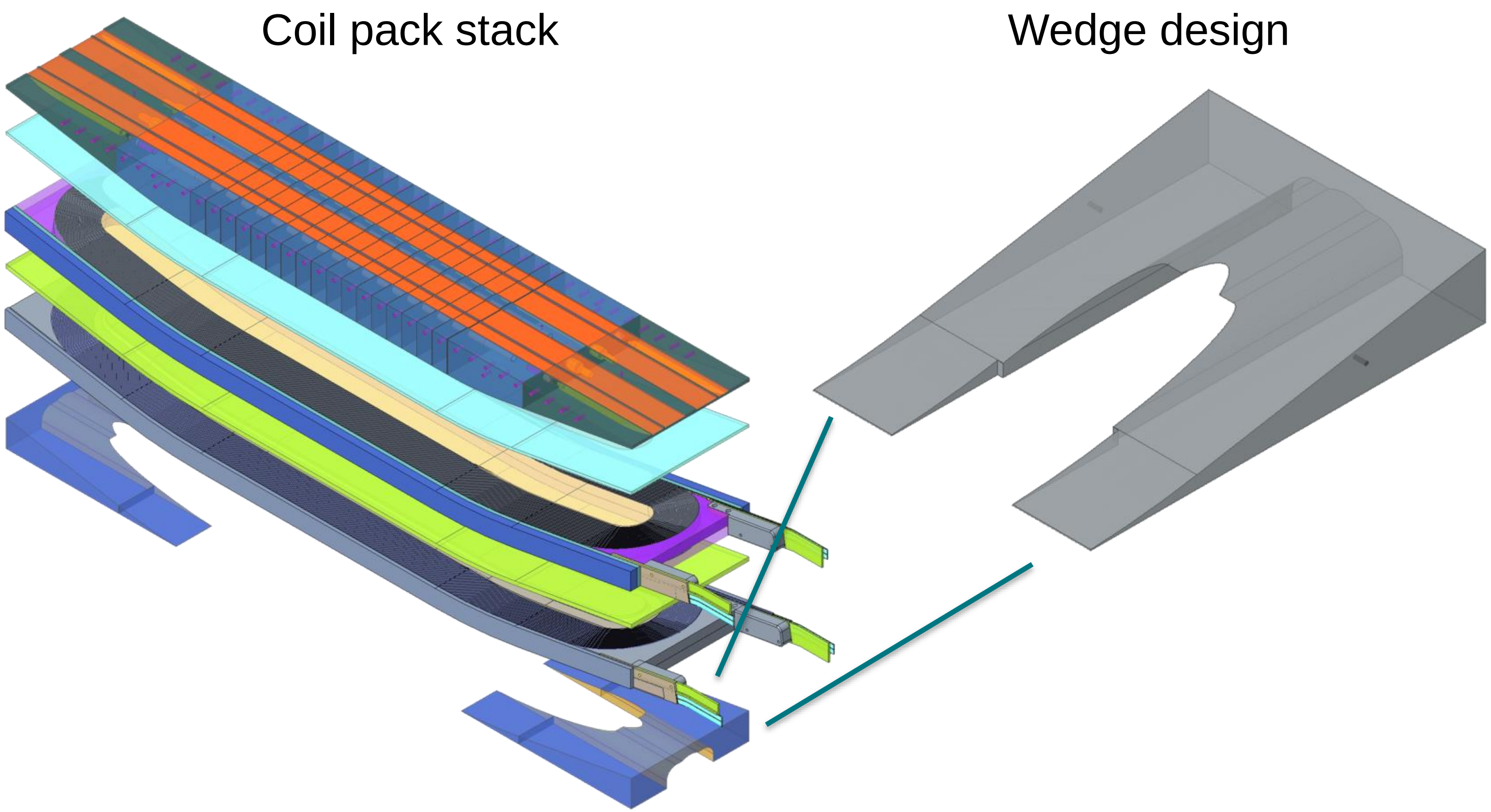
Iron Length Optimization





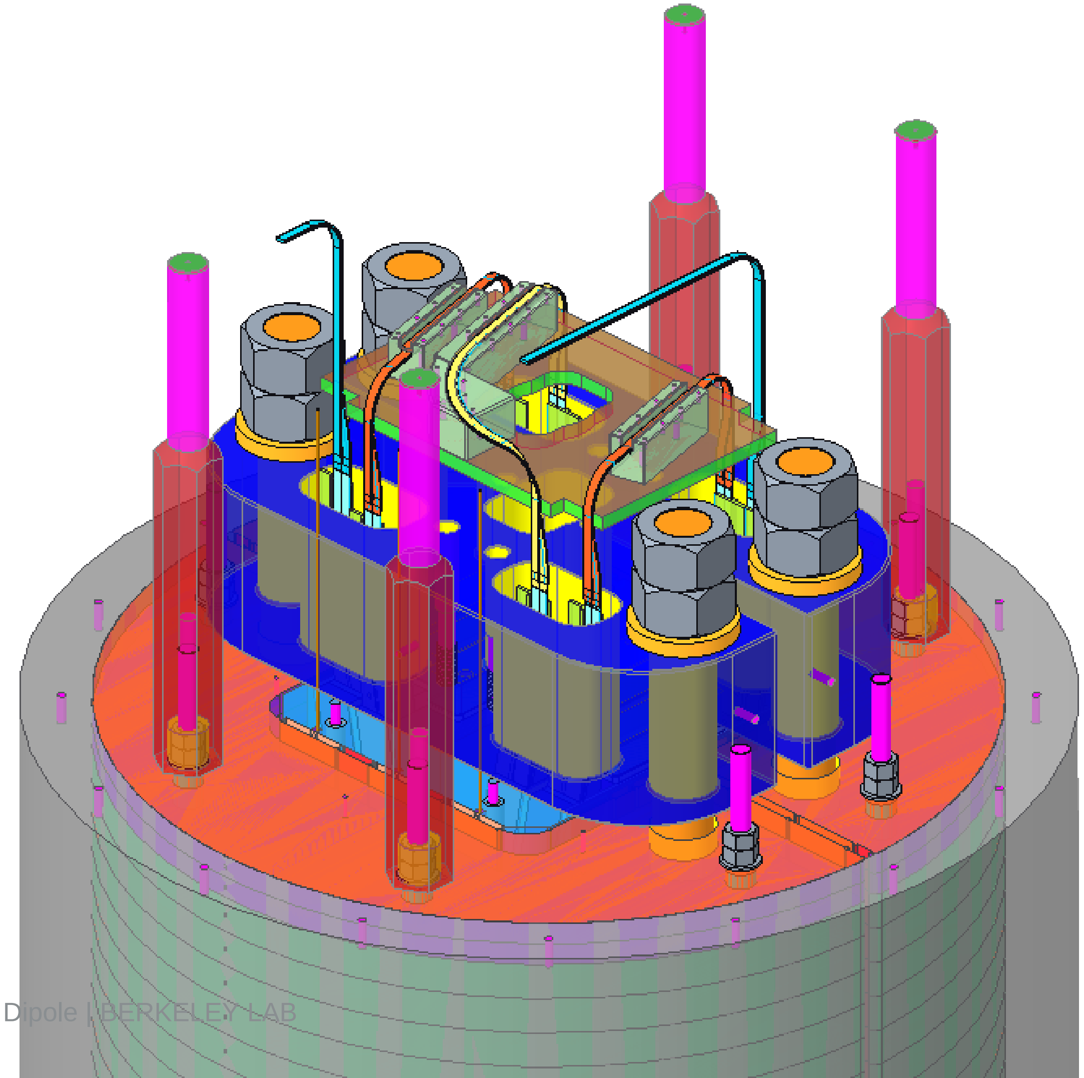
- The **yoke** structure has been adapted to laminations manufactured with ARMCO grade 4 plate stock of ~50 mm. The current design includes the optimized location and size of keys and bladders.
- The vertical and horizontal **pads** are now constructed as a laminated structure based on ARMCO grade 4.
- The structure of the pads has been optimized to facilitate the manufacturing and assembly of the parts and to allow for the transition to stainless steel segments towards the ends of the magnet.

Wedge Design and Implementation



- The wedge has been re-designed to incorporate the modifications from the FE analysis to reduce the stress in the conductor.
- Wedge analysis performed under different contact geometry conditions and bonding assumptions
- The wedge will be impregnated along with coil 1 but will be mold released following the analysis recommendations.

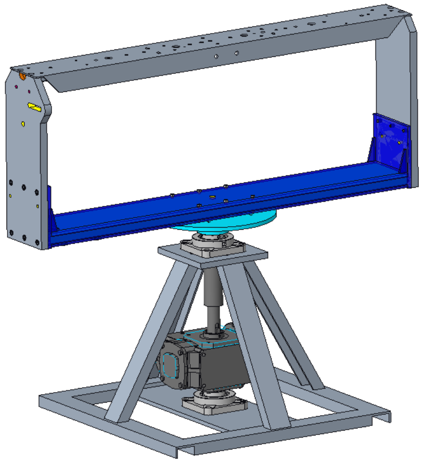
Splicing and Connection Box

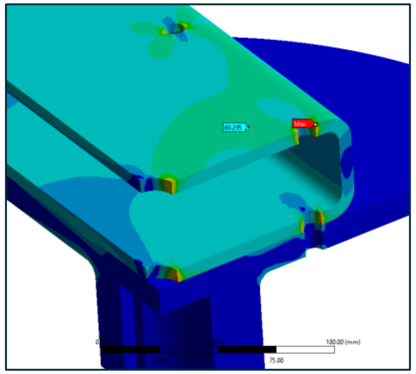


- The splicing method, operation sequence and integration within the end shoe structure is currently being developed for coil 1 and 2.
- Each Nb_3Sn lead will spliced to two NbTi cable that will be then further spliced in the connection box sitting above the end plate.

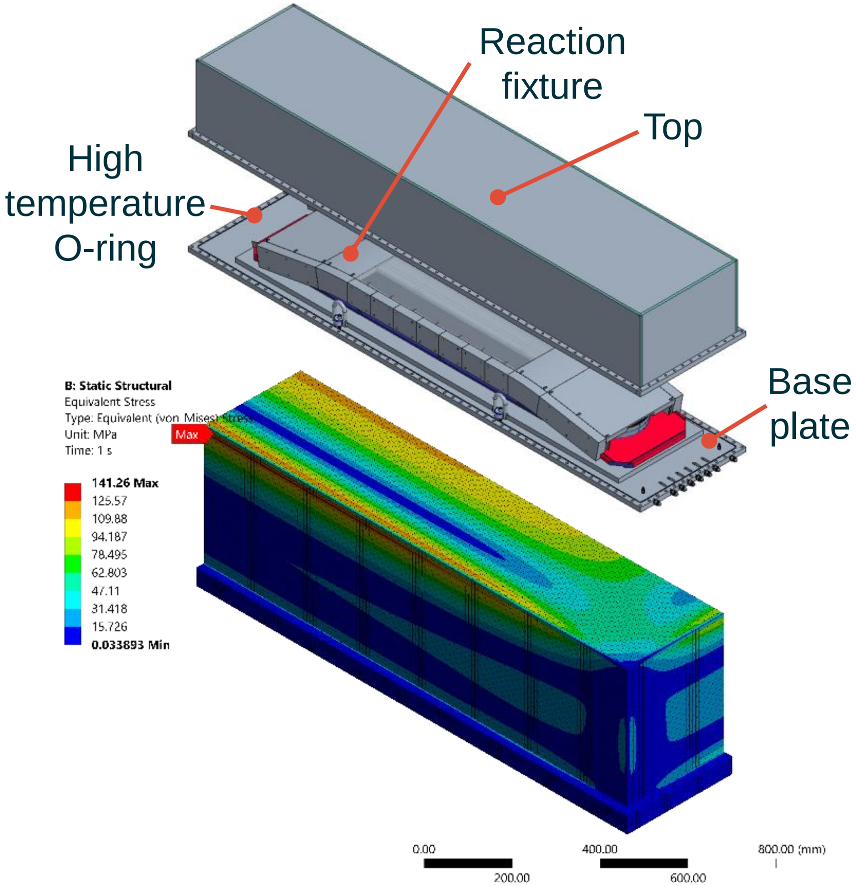
Development of infrastructure (Winding and Reaction)

Winding table





Reaction retort

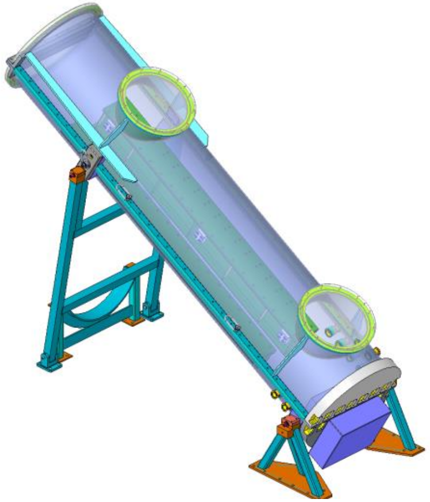


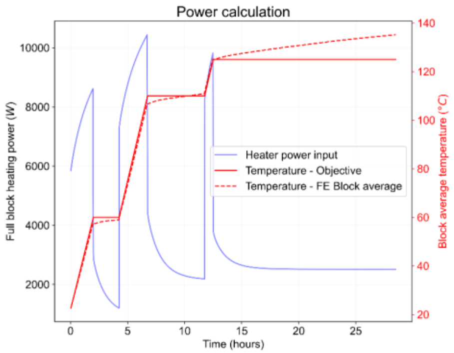
- Following the FE analysis performed, the main **winding table** selected for the project has been updated with new components to allow for the weight of the coil to be supported.
- The **retort** design relies on a high-temperature O-ring, and the top structure has been selected in order to simplify the sequence of operations for inserting and extracting the reaction fixture.

Development of infrastructure (Reaction and Impregnation)

Reaction furnace

Impregnation chamber





- Extensive work has been carried out regarding the instrumentation of the furnace and powering connections, following the relocation to the new location at Berkeley lab.
- The power requirements for a new heating system for the impregnation chamber have been assessed based on a transient FE thermal model assuming CTD-101K as the epoxy system.
- The power supply, control system, and instrumentation are being developed for three heating zones along the coil.

Conclusions and next steps

- The coil models and detailed engineering drawings of components are being finalized. The start of the procurement required for coil 1 winding, i.e. coil components and tooling, is expected for the beginning of 2023.
- The first prototype coil (coil 1) is expected to be fabricated by mid 2023.
- Preliminary drawings for many of the components for the magnet support structure have been generated.
- Extensive work is still ongoing with regards to design of several coil components, magnet support structure, and associated tooling.
- The preparation of the infrastructure and manufacturing processes is in progress.

Thanks!