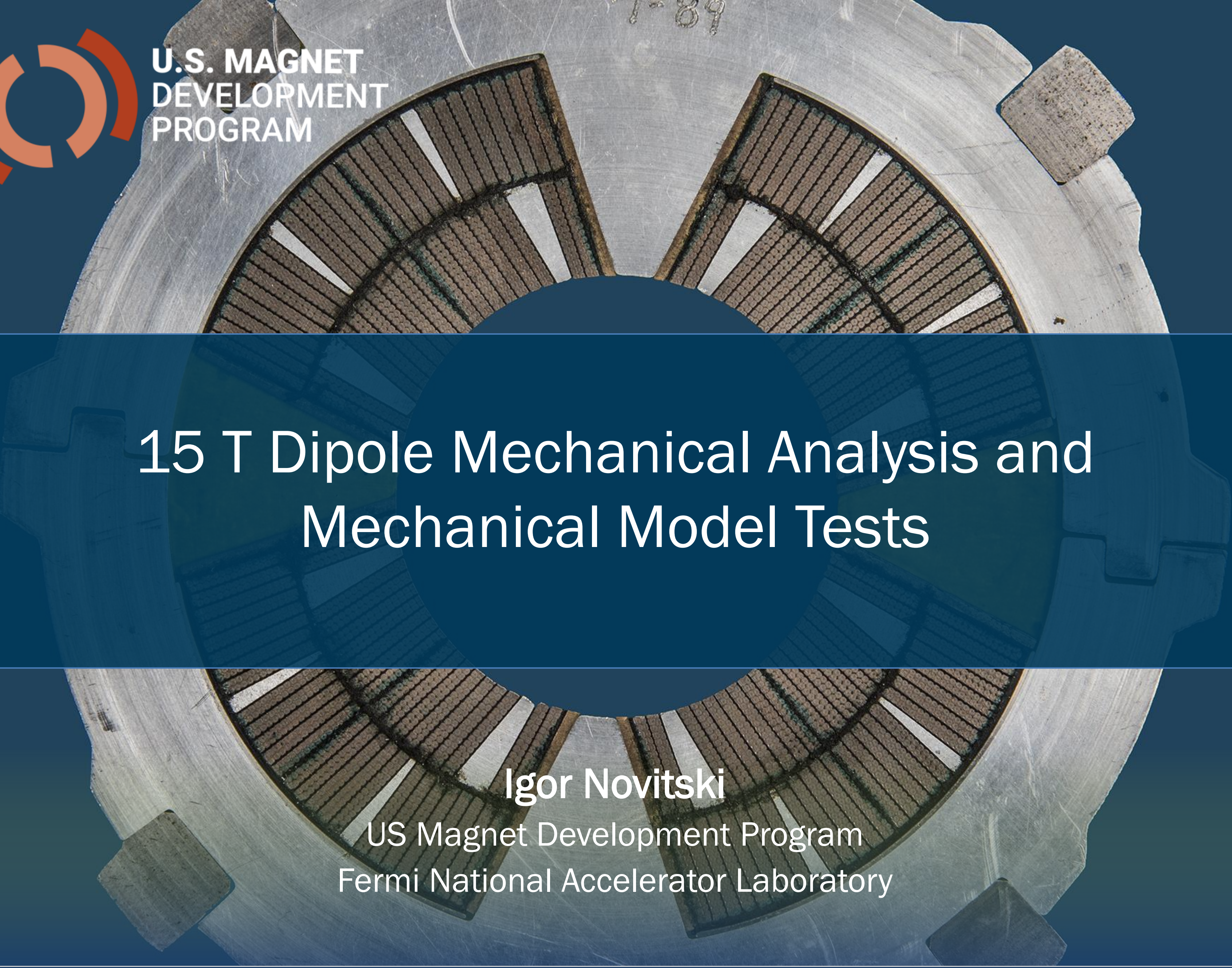
U.S. MAGNET DEVELOPMENT PROGRAM



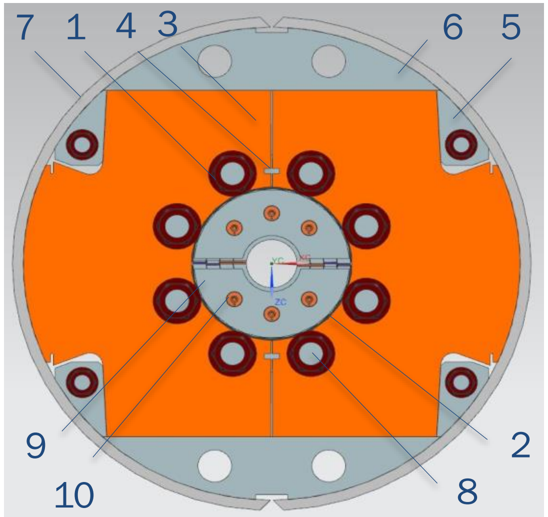
15 T Dipole Mechanical Analysis and Mechanical Model Tests

Igor Novitski
US Magnet Development Program
Fermi National Accelerator Laboratory

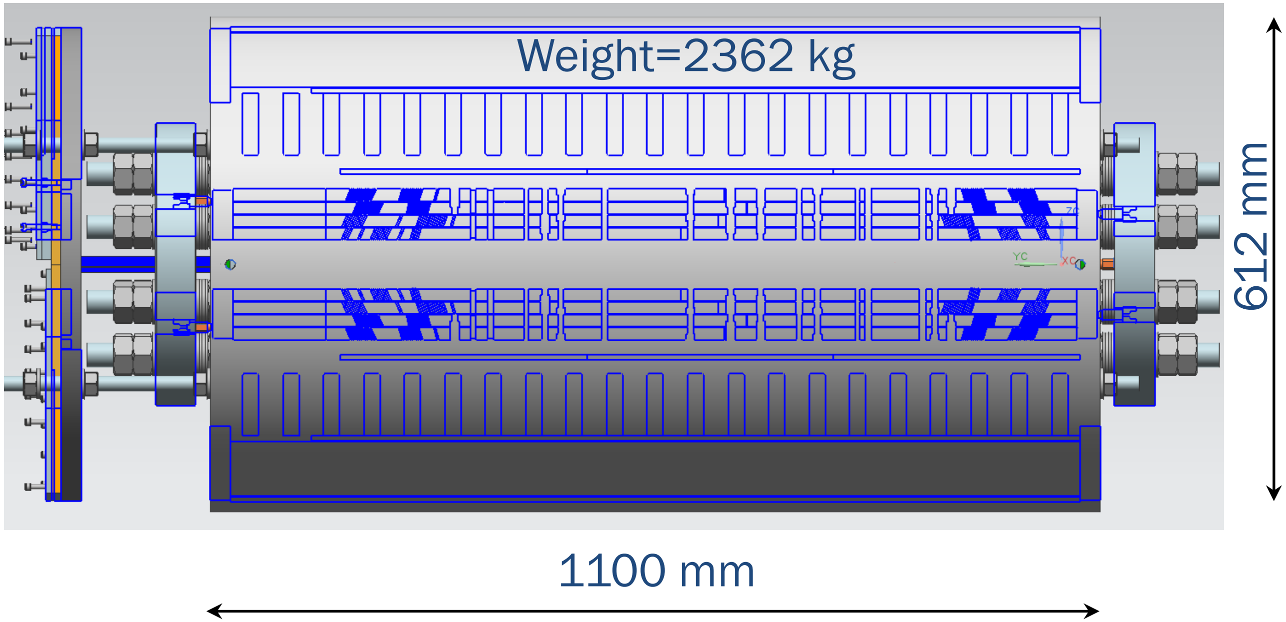
Outline

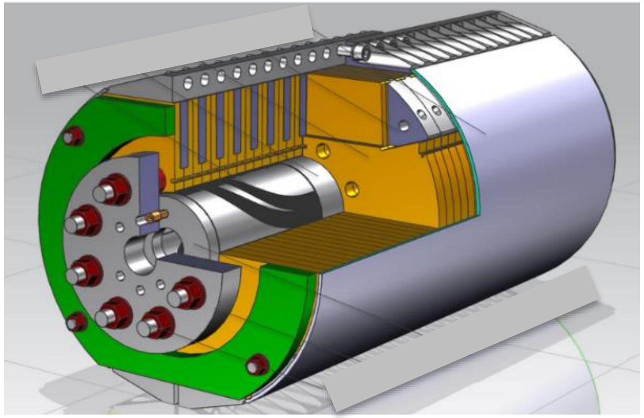
- Magnet Design
- Assembly Procedures
- Mechanical Models
- Summary

15T Dipole Magnet



1 – 4-layer Nb_3Sn coil
2 –coil-yoke stainless steel spacer
3 – iron yoke laminations
4 – alignment key
5 – aluminum I-clamp
6 – iron filler
7 – stainless steel welded skin
8 – stainless steel axial rod
9 – stainless steel pusher plate
10 – bullet





Magnet Assembly

Magnet FEA

- FNAL 2D
- FEAC 2D + Sensitivity Study

FEA Parameters	MP L1/2	MP L3/4	Coil-Yoke Radial	Yoke-Skin Radial	Yoke-Yoke Gap	Yoke-Clamp Interference	Skin Weld
FNAL	0	0	0	0.3	0.275-0.375	0.3	0.4
FEAC	0	0.06	0.025	0.6	0.36-0.42	0.4	0.4

Results verification with real structure

Material Test

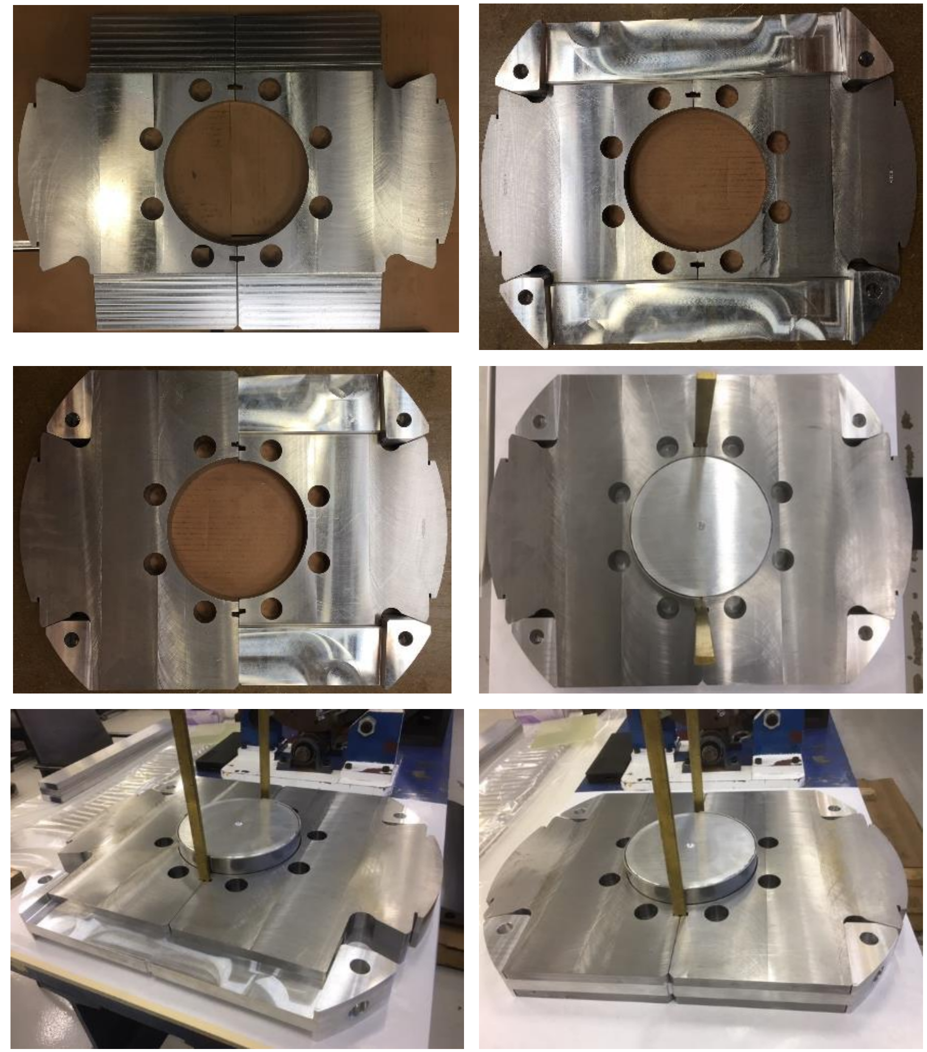
Magnet Assembly Plan and Procedure

Short Mechanical Model

2 in-long Model for Cold Test

- 3D FEA results validation
- Material cold test
- Stress and displacements vs radial interference
- Instrumentation

The short model consists of four laminations, two clamps and AL cylinder



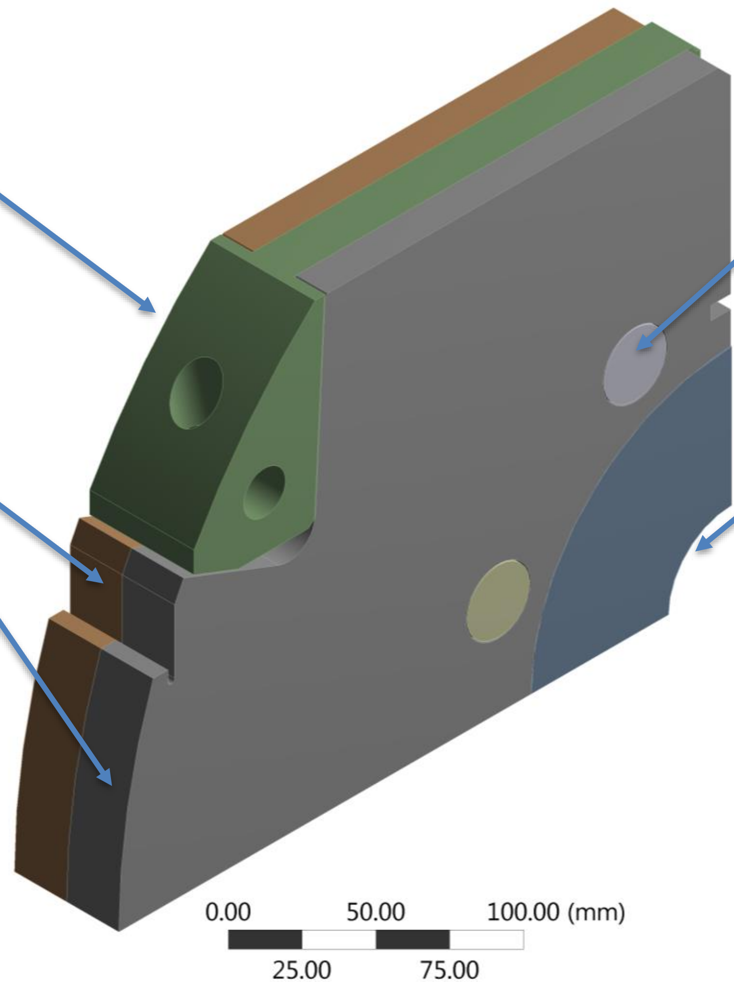
3D FEA Model

Clamp

7075-T6
Yield: 503 MPa
UTS: 572 MPa

Laminations

Steel 1020HR
Yield: 250 MPa
UTS: 460 MPa

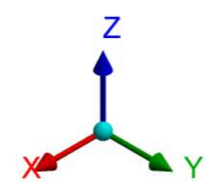


Rods

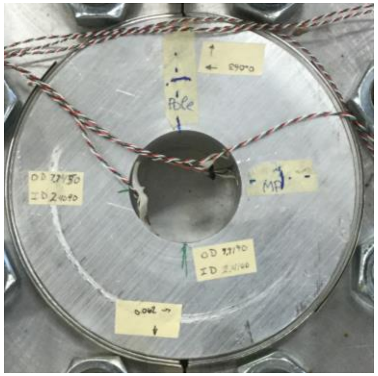
316 Stainless
Yield: 415 MPa
UTS: 620 MPa

Cylinder

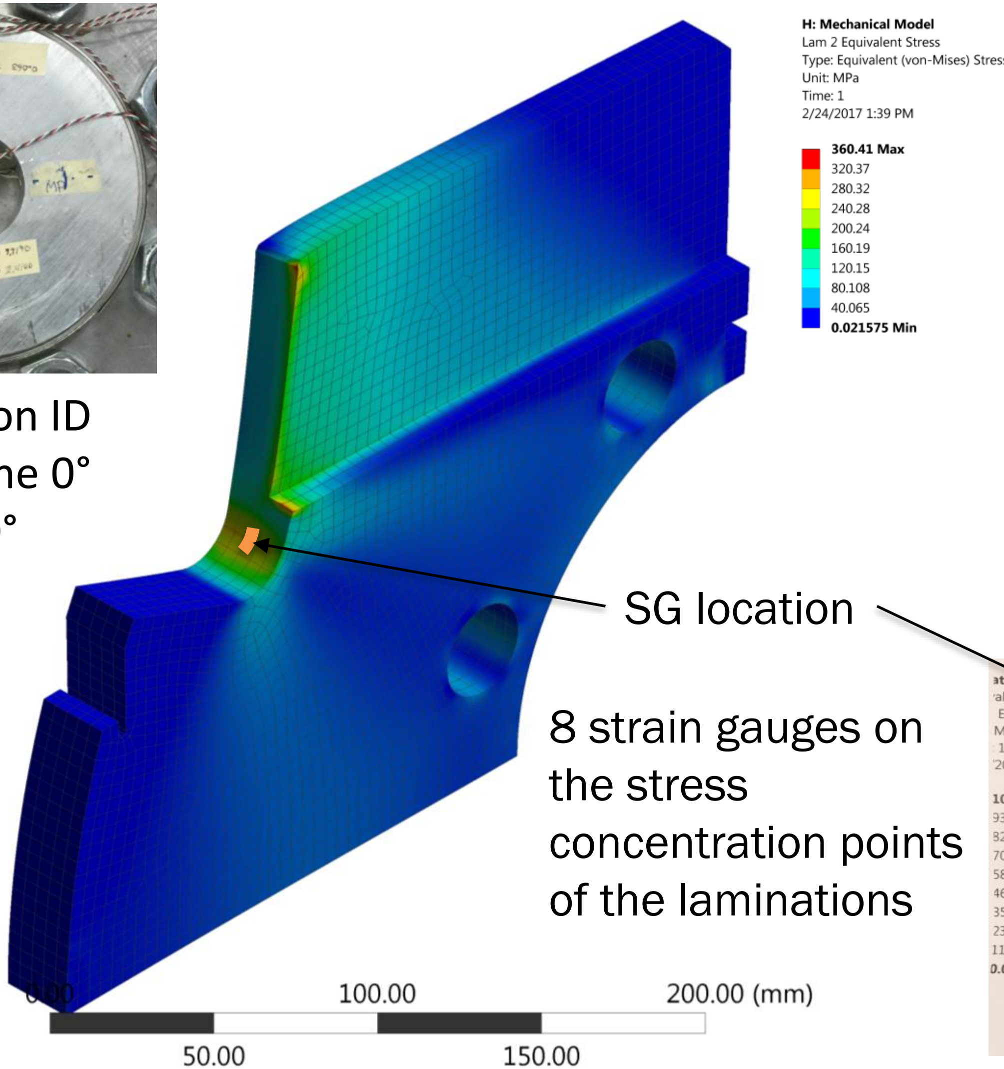
6061-T6
Yield: 276 MPa
UTS: 310 MPa



Instrumentations

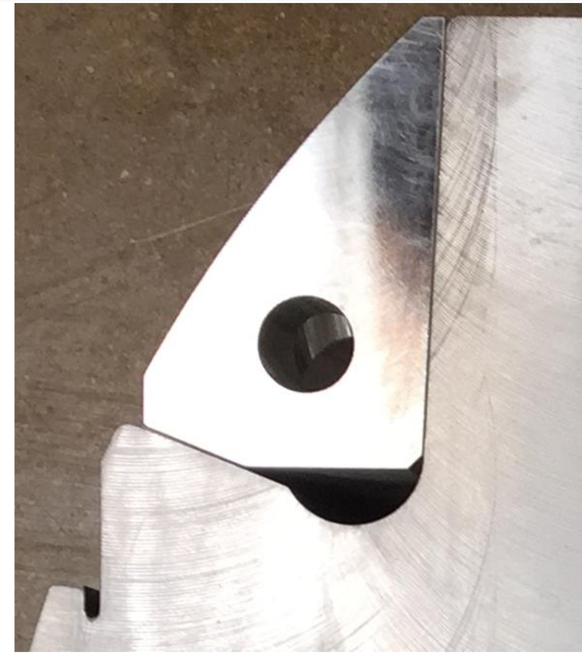


2 gauges on ID
at midplane 0°
at pole 90°

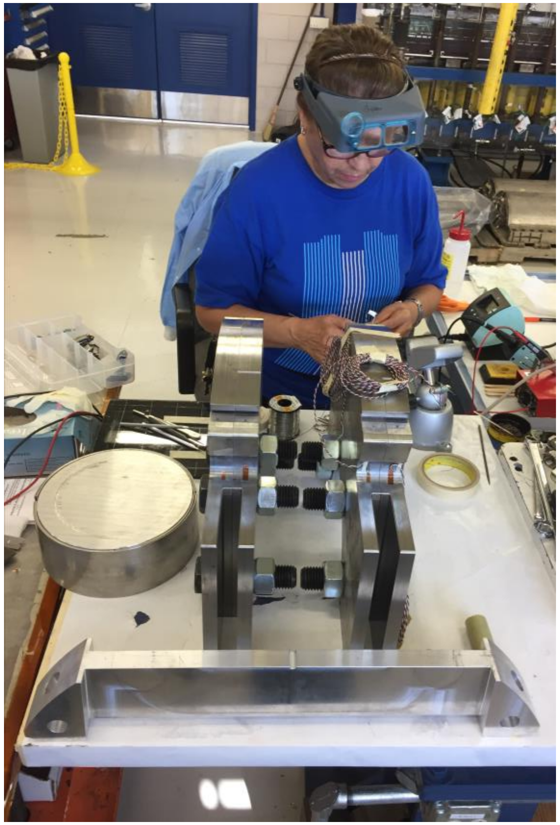


SG location

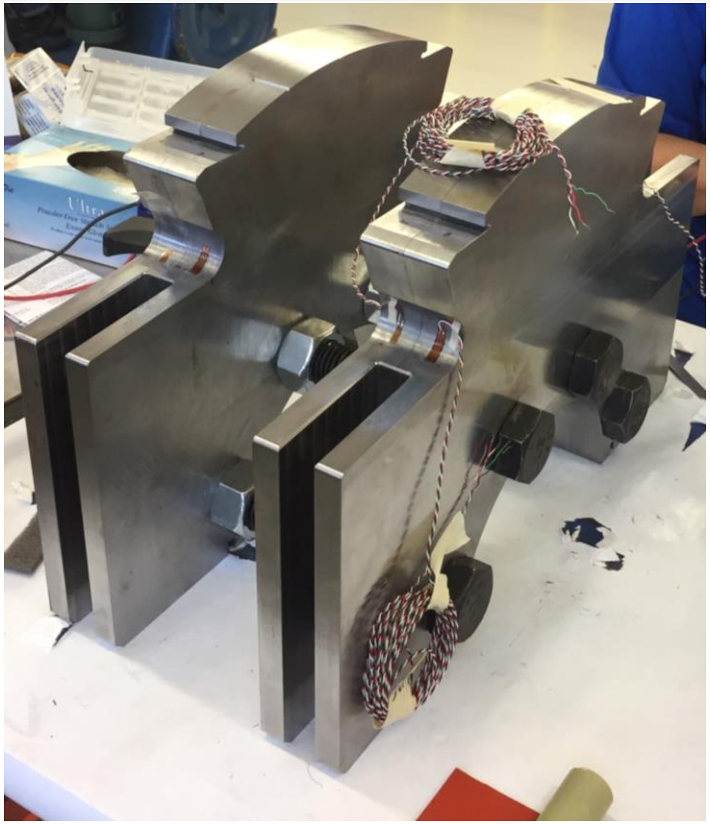
8 strain gauges on the stress concentration points of the laminations



SG Placement

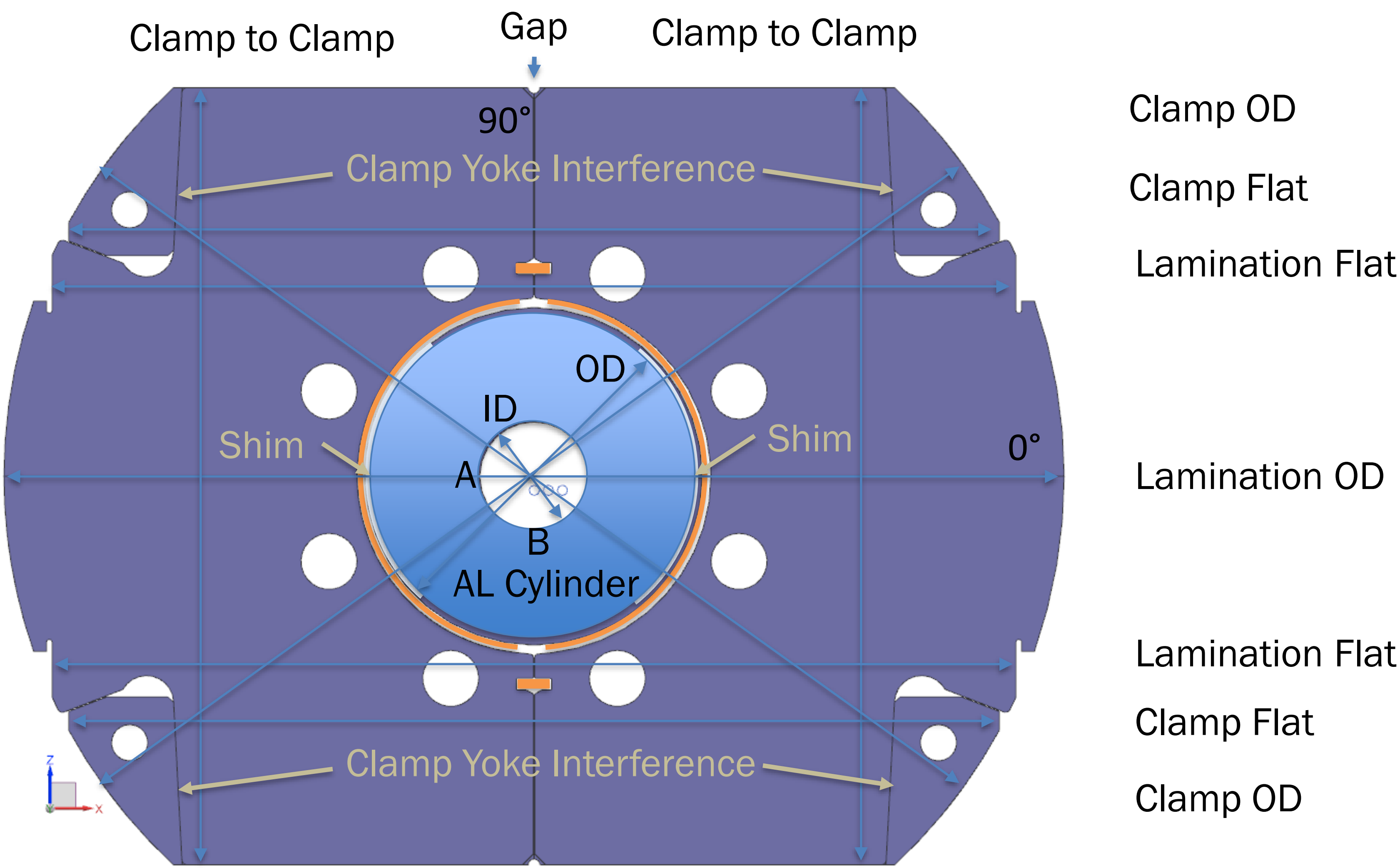


WK-05-062ED-350W
WK-13-125AD-350W
WK-09-250BG-350W

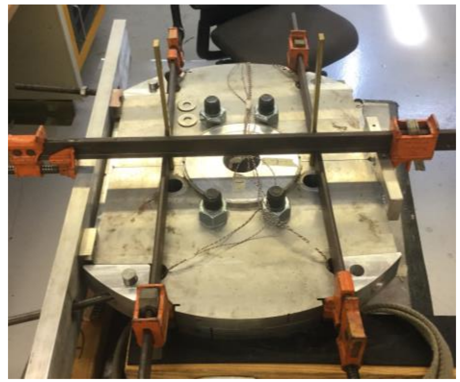


Out of the eight lamination strain gauges, four were 125, three were 250, and one was 60. With one exception, the lamination gauges were series 9. The dummy coil had two series 13, 250 length gauges. The 60 mil gauge was a series 5.

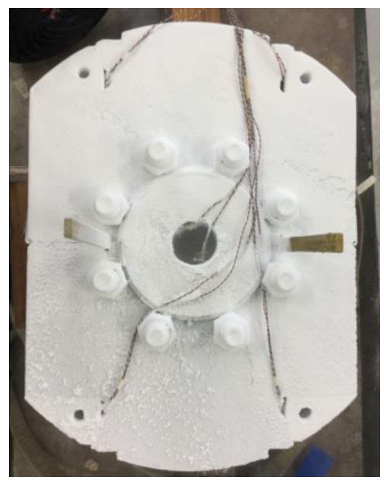
Model Parameters



First Cold Test

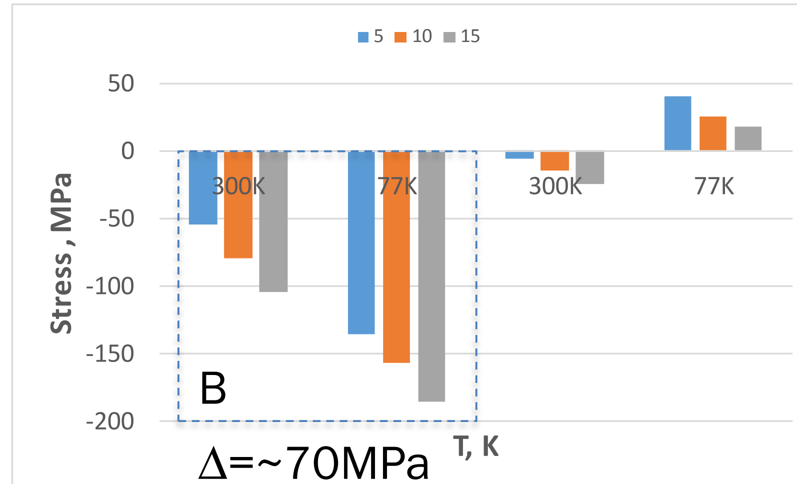


- Model placed in an LN2 bath in “free” and under four shimming configurations
- Total 10 TCs
- Old SG reading cart
- Physical measurements

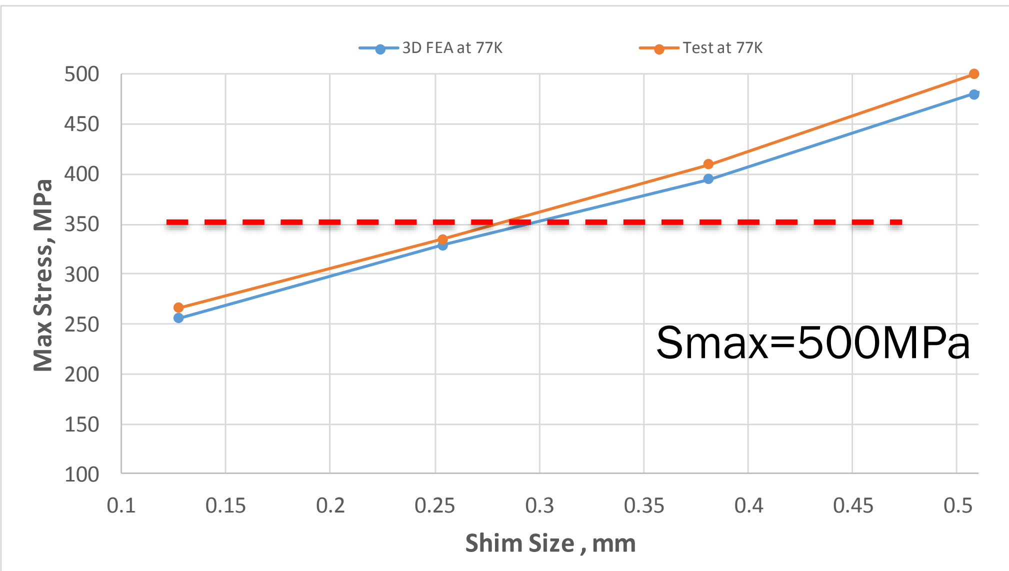


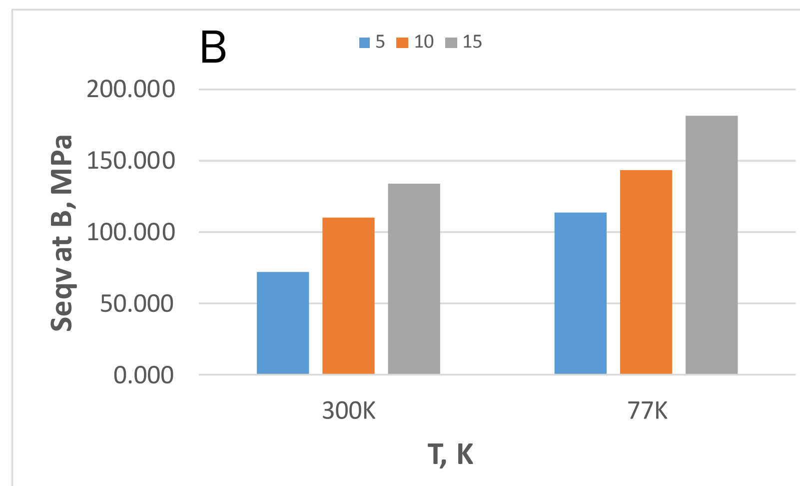
MM Iron Lamination and Cylinder

Cylinder Test



Iron Lamination

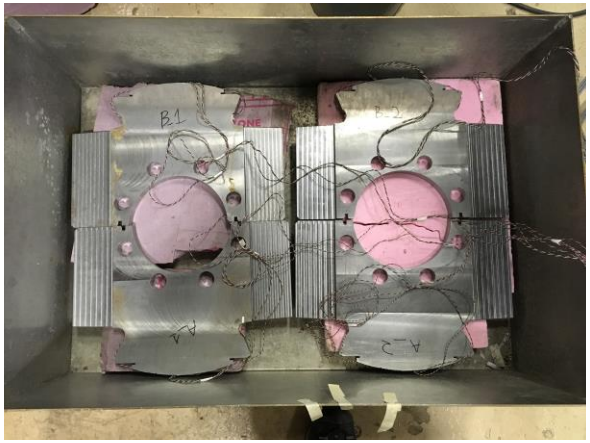




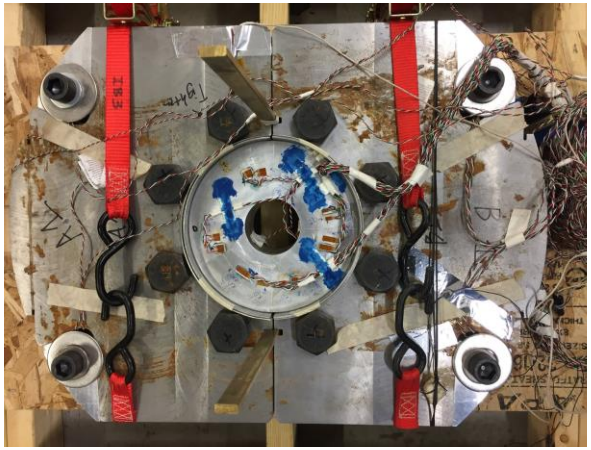
Cylinder FEA

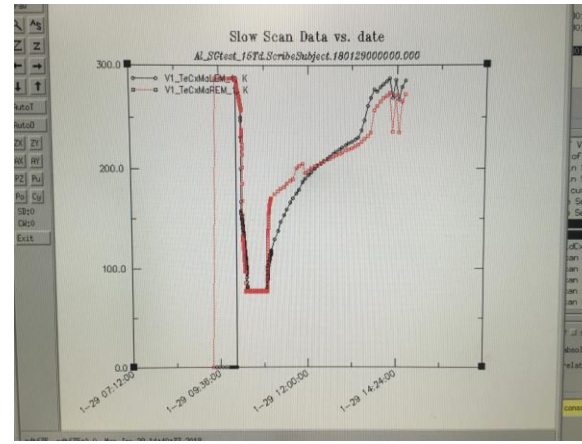
Second Cold Test

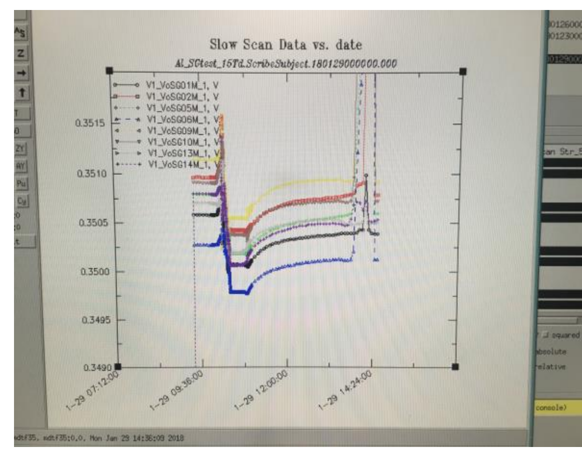
- Model placed in an LN2 bath in "free" and with one max shimming configuration
- New SG on Iron Lams
- SG added on AL Cylinder
- 2 Thermal Gauges added
- Total 4 TCs
- Physical measurements
- VMTF DAS reading



VMTF DA System

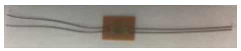


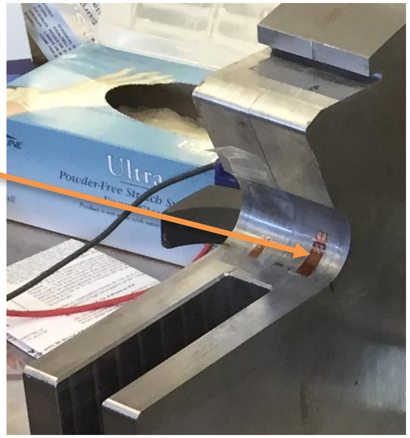


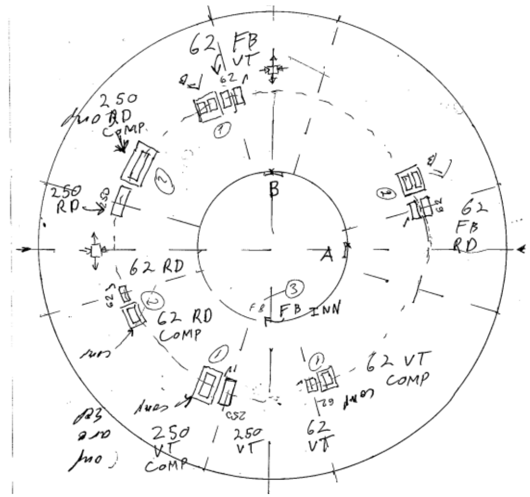


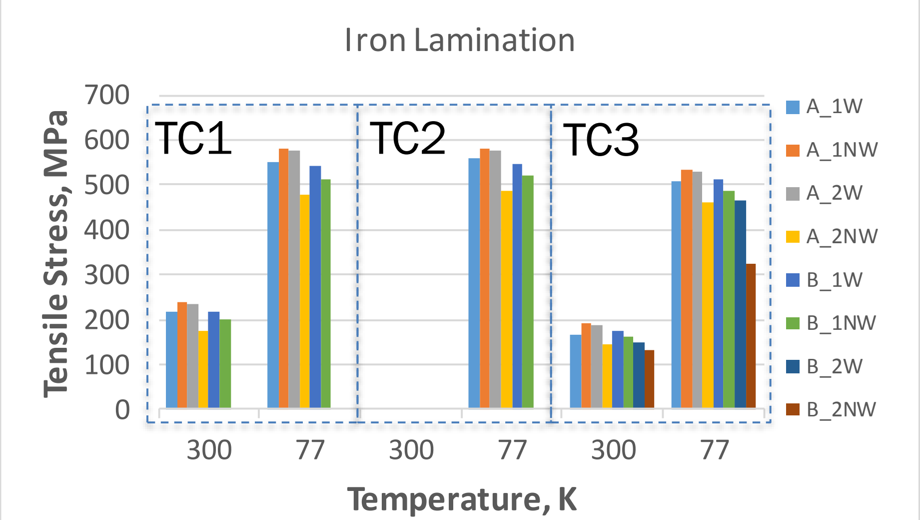
MM Iron Lamination and Cylinder

WK-06-062ED-350

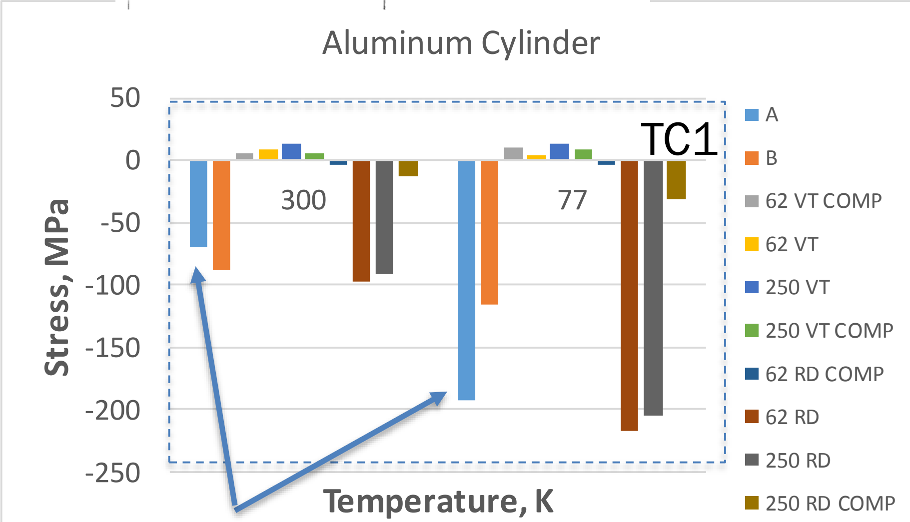








Smax~580MPa



Δ=~110MPa

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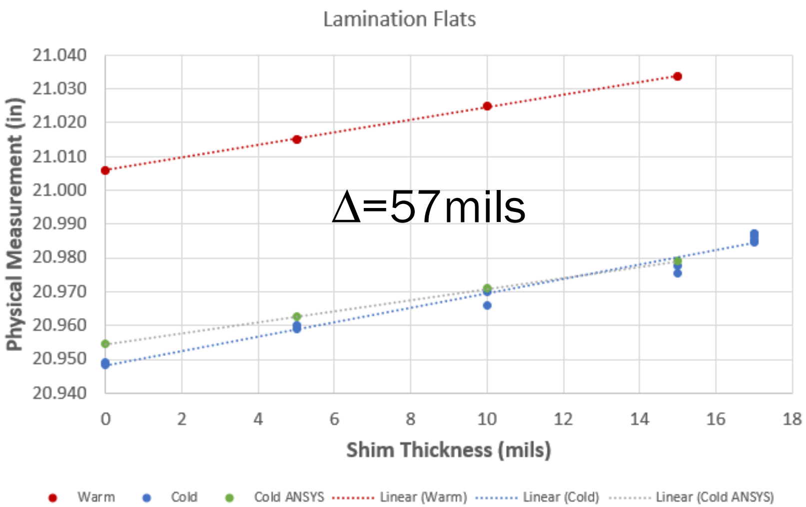
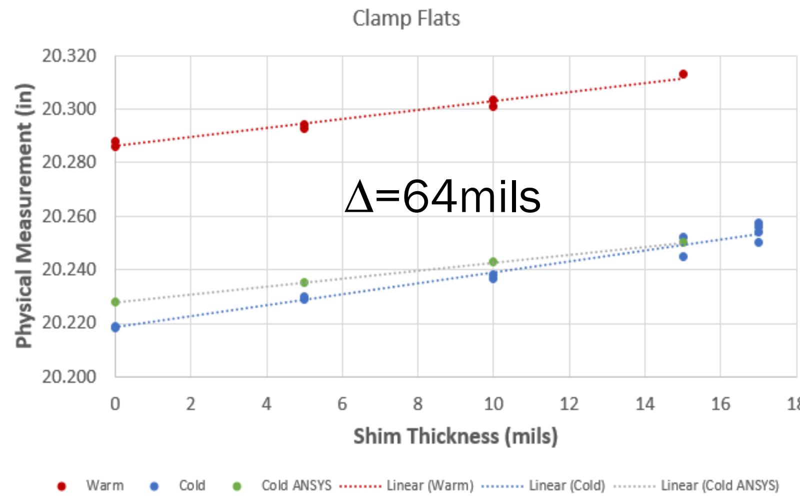
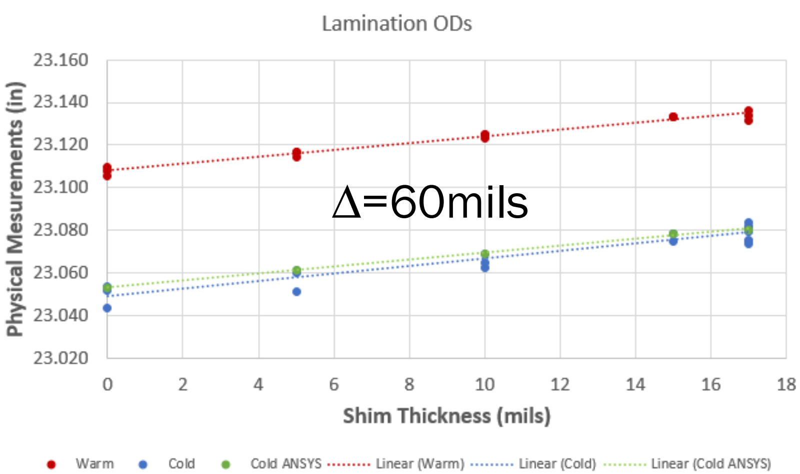
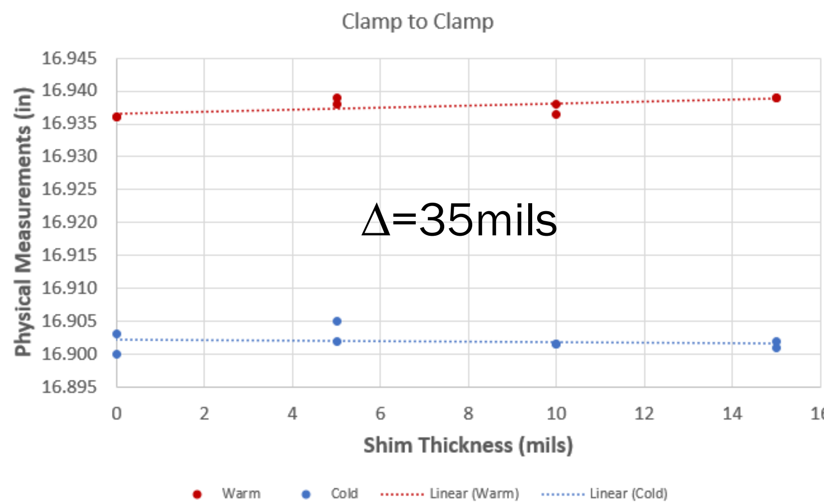
MM Size Measurements

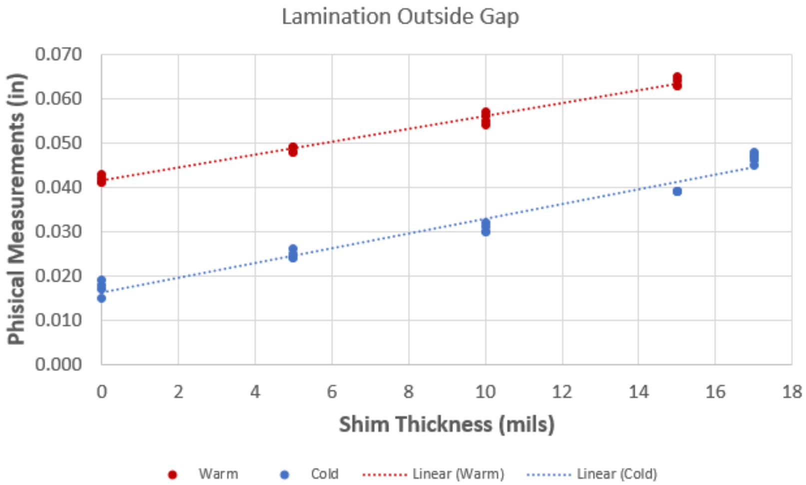




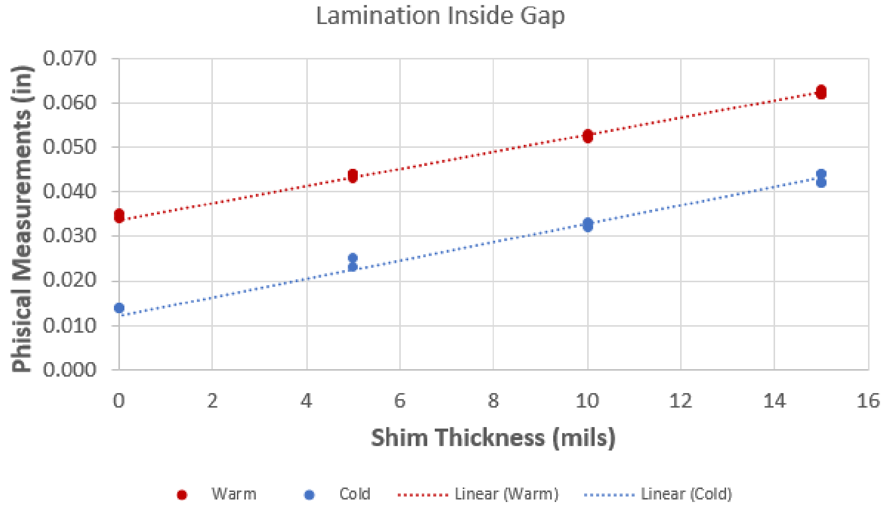




MM Size Measurements



Δ=23mils



Δ=0.019mils

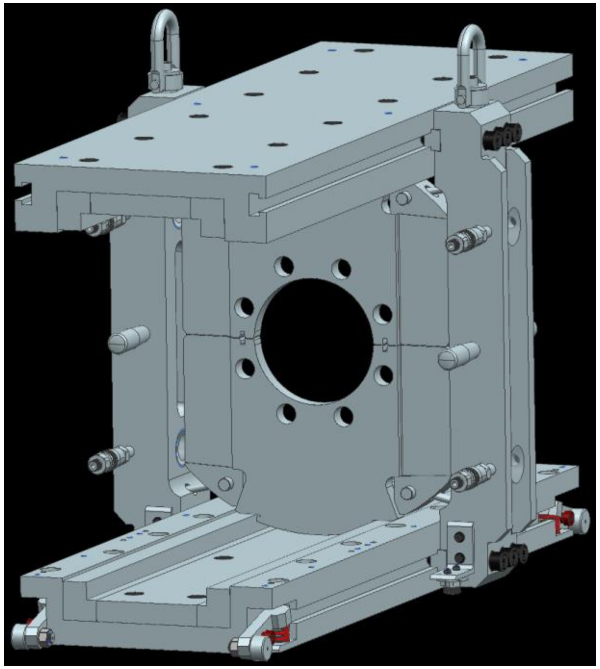
Short Mechanical Model Status

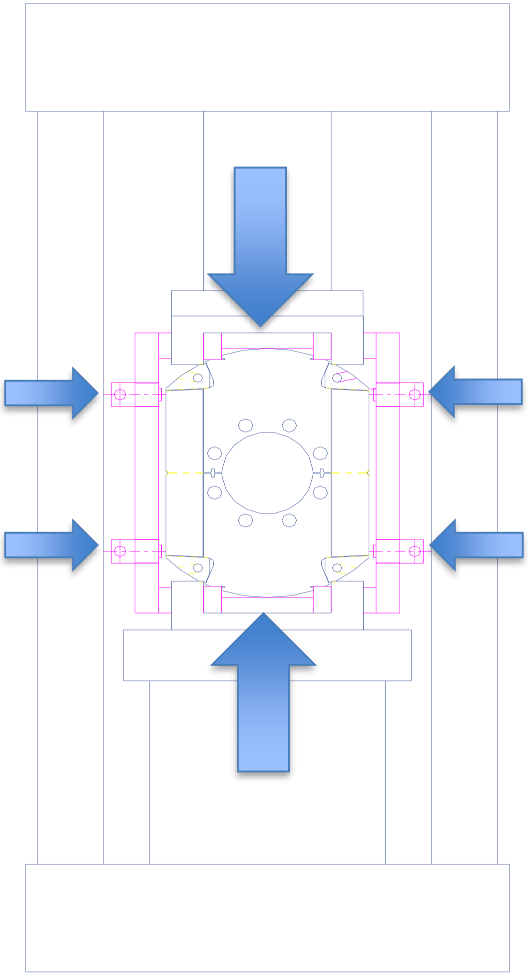
- Material Cold Test *
- Instrumentation *
- Stress and Displacements *
  vs Radial Shim
- FEA Data Verification in progress

Mechanical Model for Technology Test

Iron Yoke Clamping - key assembly step

- Structure
- Tooling
- Procedure
- Instrumentation
- FEA Data Verification
  (Shim Plan)





Dummy Coils

Al Cylinders

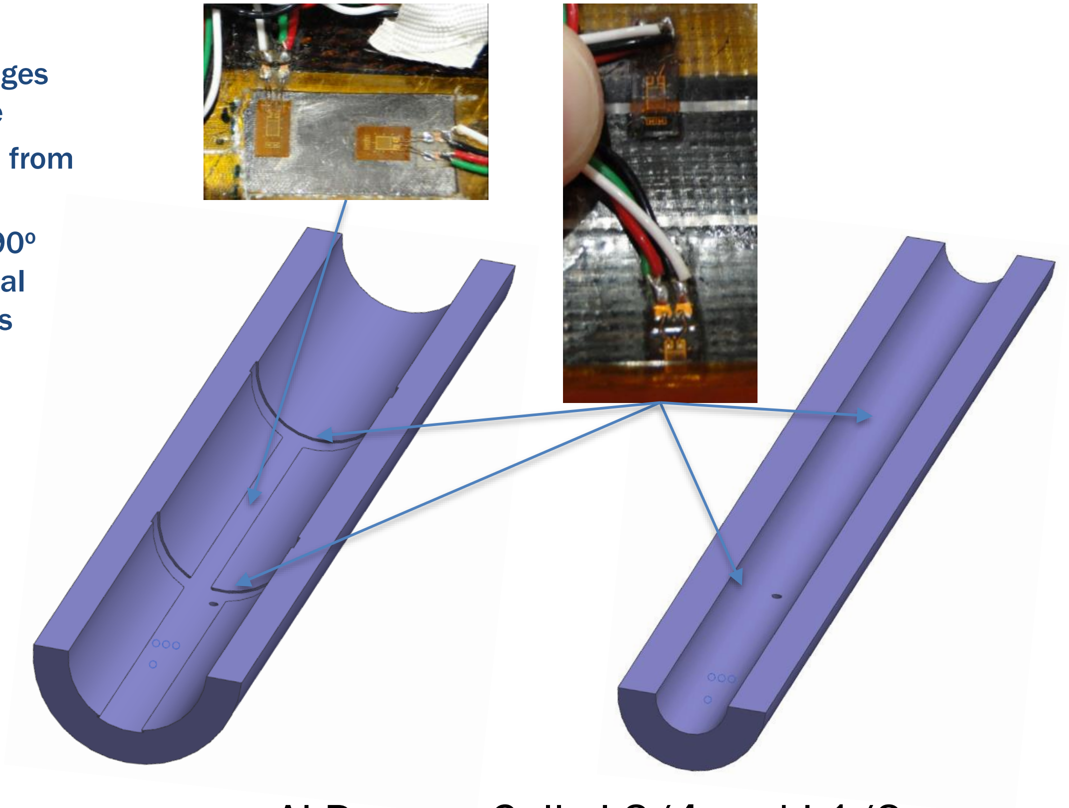
Two gauges per bore

~50mm from one end

0º and 90º azimuthal locations

The first dummy coil configuration has all coils represented by 3 aluminum cylinders

The second configuration uses four half cylinders, two for layers 1 and 2 and two for layers 3 and 4

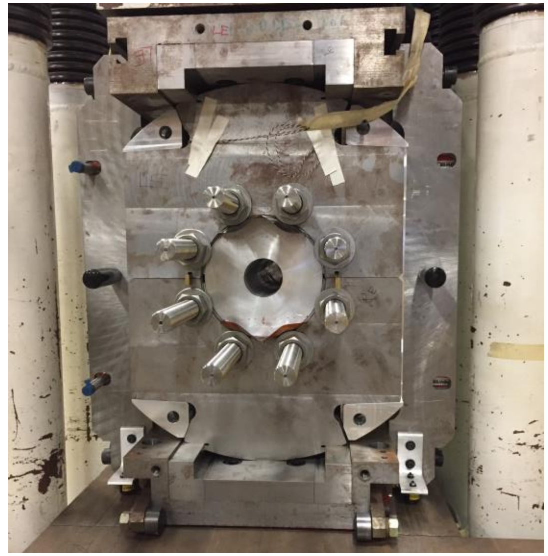


Al Dummy Coils L3/4 and L1/2

- Two channels ~320mm from each end
- Six gauges per channel
- Five azimuthal, one longitudinal

- Same locations axially
- Four gauges per location
- Three azimuthal, one longitudinal

Full-Scale Mechanical Model



The 43-inch long model is a full-scale magnet structure, which consists of all the laminations, clamps and rods.

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Full-Scale Mechanical Model Status

• Structure	*
• Tooling	*
• Procedure	in progress
• Instrumentation	in progress
• FEA Data Verification	in progress
• Assembly Shim Plan	in progress

Summary

- 15T 2D mechanical structure have been analysed by two independent experts.
- Mechanical design provides the required coil prestress and restricts turn radial, azimuthal and longitudinal motion for the operating current range up to 15T.
- Small Mechanical Model have been tested at 300K and 77K for 2D-3D FEA verification and material tests.
- Work with full-scale Mechanical Model have been started to finalize the clamping assembly step and magnet shim plan.

Back Up Slides

MT 25
25th International Conference
on Magnet Technology

FEA Model and Mechanical Analysis of the Nb3Sn 15 T Dipole Demonstrator

ID:MT25-Wed-Af-Po3.01-03

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Abstract

Nb3Sn magnets with a nominal operation field of 15-16 T are being considered for the LHC energy upgrade (HE-LHC) and a post-LHC Future Circular Collider (FCC). To demonstrate the feasibility of 15 T accelerator quality dipole magnets, the US Magnet Development Program (MDP) is developing a single-aperture 15 T Nb3Sn dipole demonstrator based on a 4-layer graded cos-theta coil with 60 mm aperture and cold iron yoke. The main design challenges for 15 T accelerator magnets include large Lorentz forces at this field level. To counteract them, an innovative mechanical structure based on a vertically split iron yoke, locked by large aluminum IC-clamps and supported by a thick stainless steel skin, has been developed at Fermilab. To study the performance of the structure a parametric multi-physics FEA model has been setup. This paper describes the numerical model as well as the results of a sensitivity analysis of the effect of geometrical tolerances and assembly parameters.

Mechanical Structure

The main features of the 15 T design are illustrated in *Figure 1*.

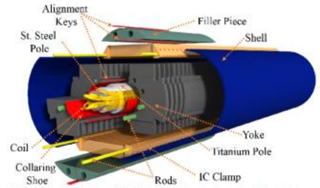

Figure 1. Exploded view of the 15 T Dipole showing the main design features

The coil consists of 4 layers. The two innermost layers (layer 1 & 2) are separated by three wedges, while the two outermost layers (layer 3 & 4) do not use wedges. Titanium poles are impregnated with the layer 1 & 2 of the coil, while layer 3 & 4 is impregnated with St. Steel poles (*Figure 2*). Aluminum IC-clamps interleave with the iron yoke laminations at their top and bottom sectors, thus reducing the iron filling factor in these areas to ~60% (*Figure 2*).

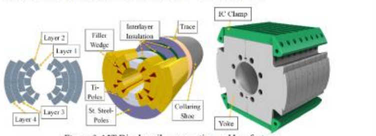

Figure 2. 15T Dipole coil cross section and key features

2D Model

Magnetic Analysis

The electromagnetic model is analyzed in MAXWELL & PITHIA [5] to compare results between the Finite Element (FEM) and the Boundary Element Method (BEM). The magnetic field at 15T is shown in *Figure 3* and the Lorentz forces are shown in Table 1.

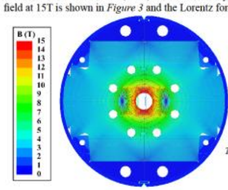

Figure 3. Magnetic field at 15 T

B_0 (T)	Pithia	Maxwell		
	I (kA)	I (kA)	Fx (MN)	Fy (MN)
15	10.32	10.35	6.35	-3.65
16	11.09	11.13	7.17	-4.21
17	11.86	11.92	8.05	-4.82

Table 1. Lorentz Forces and comparison between Maxwell and PITHIA

Structural Analysis

A structural analysis was implimented in order to determine the structural integrity of the magnet. Four loadsteps (LS) were considered in the FEM (*Figure 4*)

LS1:Shell welding @ RT → LS2: Cooldown @ 4.2 K → LS3:Powering @ 15 T → LS4:Powering @ 16 T

Figure 4. Loadsteps

The Von-Mises Coil Stress (MPa) evolution for the four load steps is shown in *Figure 5*. The stress gradients are smooth and very symmetric and the peak stress remains below 200 MPa up to 16 T. The difference in radial deformation of the midplane between two sequential load-steps of layer 1, 2, 3 and 4 is presented in *Figure 6*.

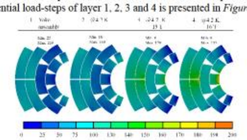

Figure 5. Von-Mises Coil Stress (MPa) evolution

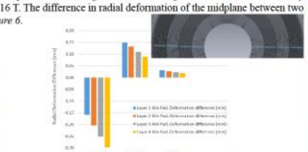

Figure 6. Difference in radial deformation of the midplane between two sequential load-steps

Design Space & Sensitivity Analysis

The sensitivity analysis is conducted by utilizing the DoE method (Design of Experiments) which determines sampling points used to construct a response surface.

Figure 7 presents the Local Sensitivity Chart regarding Coil Von Mises Stress for the Shimming configuration used to produce the final results. The effect of the variation of shim dimensions was under investigation. *Figure 8* presents the effect of the variation of the coil's material properties, namely the Young's Modulus and the Coefficient of Thermal Expansion.

Eleven input parameters (*Table 2*) were chosen for this study, corresponding to 206 sampling points with the CCD (Central Composite Design) algorithm.

The produced response surface is a full 2nd-order polynomial. The tolerances cover a wide range, leading to a response surface that covers a large design space. *Figure 9* presents the response surface of the Coil's max. equivalent stress (MPa) in correlation with the radial coefficient of thermal expansion, a_r (mm/m) and the azimuthal module of Elasticity, E_θ (GPa).

Figure 7. Effect of the variation of shim dimensions on Coil Von Mises Stress

Figure 8. Effect of the variation of the coil's material properties on Coil Von Mises Stress

Parameter	Nominal Value	Range	Coil-VonMises @293K (119 MPa)		Coil-VonMises @4.2K (153 MPa)		Coil-VonMises @15T (170 MPa)		Coil-VonMises @16T (193 MPa)	
			Range [MPa]	$\Delta\sigma_{max}$ [MPa]	Range [MPa]	$\Delta\sigma_{max}$ [MPa]	Range [MPa]	$\Delta\sigma_{max}$ [MPa]	Range [MPa]	$\Delta\sigma_{max}$ [MPa]
Weld shrinkage	0.4 mm	0-0.06	117-120	3	152-154	2	170-171	1	192-194	2
MP Inner (1)	0	0-0.09	109-119	17	153-179	26	170-218	48	193-241	48
MP Outer (2)	0.06 mm	0-0.06	102-145	43	151-162	11	170-196	26	192-205	13
Yoke – Yoke (3)	0.36 mm	0.5-0.65	103-120	17	128-178	50	167-177	10	189-199	10
Yoke - Shell (4)	0.6 mm	0.35-0.45	118-120	2	152-154	2	170-171	1	192-194	2
Yoke - IC Clamp (5)	0.4 mm	0.31-0.41	113-123	10	152-155	3	170-171	1	191-195	4
Collaring Shoe - Yoke (6)	0.025 mm	0.35-0.45	119-138	19	143-178	35	170-180	10	183-205	22
E_r	44GPa @ RT 55GPa @ 4.2K	20-60 GPa 25-77 GPa	118-124	6	153-154	1	170-187	17	188-214	26
E_θ	44GPa @ RT 44GPa @ 4.2K	20-60 GPa 20-60 GPa	100-141	41	17-177	80	136-199	63	157-226	69
α_r	2.6 mm/m	2-3 mm/m	119-119	0	126-126	90	168-213	45	193-234	41
a_θ	3.5 mm/m	3-4 mm/m	119-119	0	143-163	20	164-177	13	190-198	8

Table 2

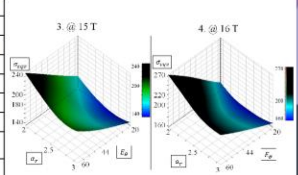

Figure 7. Response surface of the Coil's max. equivalent stress in correlation with ar and Eθ

Conclusions

The sensitivity analysis regarding the impact of the variation of shim dimensions on Coil Von Mises Stress showed that:

- During LS1 (assembly) the outer midplane shim and the Coil-Yoke shim have the largest impact on the coil stress. The mid-plane shim exerts pressure on the coil in the azimuthal direction and the coil-yoke one in the radial direction. The thicker the shims are, the more pressure is exerted on the coil, hence the positive correlation. The coil is deformed elliptically along the vertical axis as a result of this shimming. For the tapered shim at the yoke-yoke interface there is a limit imposed on the thickness due to the specification that the Yoke gap shall remain open at room temperature. A thick shim reduces the coil stress but will close the gap.
- During LS2 (cooldown) the yoke-yoke shim and the Coil-Yoke shim have the largest impact on the coil stress. The location of maximum equivalent stress changes from the third layer to the first. The impact of the outer mid-plane shim is diminished and the inner mid-plane shim is more impactful on the coil stress, again with a positive correlation. The coil-yoke shim continues to be important. The shim with the highest impact on coil stress is the tapered Yoke shim. At cold, the yoke gap closes and the yoke becomes a rigid envelop for the coil.
- During LS3 & LS4 (powering) the inner midplane shim becomes the more impactful one, as max stress continues to appear on the first layer of the coil. The coil-yoke shim now has a negative impact on coil stress. As the coil is deformed by the Lorentz forces, being ovalized along the horizontal axis, the coil-yoke shim counteracts this, pushing the coil towards the vertical axis, limiting the deformation and stress. The outer mid-plane shim's impact is positive at 15T, as an area of high stresses appears in the third layer. At 16 T the high stresses are removed from that area and the outer mid-plane shim's impact is decreased. The tapered Yoke shim still has a negative correlation with Coil stress, although it is reduced. This is explained because the gap is closed and the yoke's rigidity remains stable.
- The Yoke-Clamp and Yoke-Shell shims, as well as the displacement simulating the welding have much lower sensitivities than the rest of the shims in the range of variation that was imposed on them.
- During LS3 & LS4 (powering) the coil's Coil Von Mises Stress remains below 200 MPa.
- During LS1 (assembly) the yoke gap remains open while in LS2, LS3 and LS4 it is closed.

The sensitivity analysis regarding the impact of the variation of the coil's material properties on Coil Von Mises Stress showed that:

- During LS1 (assembly) E_θ has the largest impact on coil stress, as thermal expansion is not taking place yet. As the structure is shimmed, the coil is ovalized along the vertical axis. Because of this ovalization and the pressure exerted by the outer mid-plane shim on the coil in the azimuthal direction, variations of E_θ are much more important than those of E_r.
- During LS2 (cooldown) the effect of the coefficients of thermal expansion becomes apparent. The coil shrinks, mainly along the radial direction. This can be observed by the high impact of ar, which has the largest sensitivity in this load step. As ar increases the coil contracts more and the pressure exerted upon it from the rest of the structure lessens. This causes a decrease in coil stress. At the same time, E_θ maintains a decreased but still high impact on coil stress as the ovalization of the coil lessens and it becomes more circular.
- During LS3 & LS4 (powering) the sensitivity of a_r remains relevant since the structure remains at a cryogenic temperature but decreases as the Lorentz forces increase. The main input remains E_θ as the magnetic forces change the ovalization of the coil, deforming it along the horizontal axis. This deformation is connected with the steady increase of the sensitivity of E_r throughout powering. The majority of the magnetic forces act along the horizontal axis. The radial orientation of the coil is more along the X axis, less along the vertical plane. So as the magnetic forces become stronger, the radial value of E becomes more relevant.

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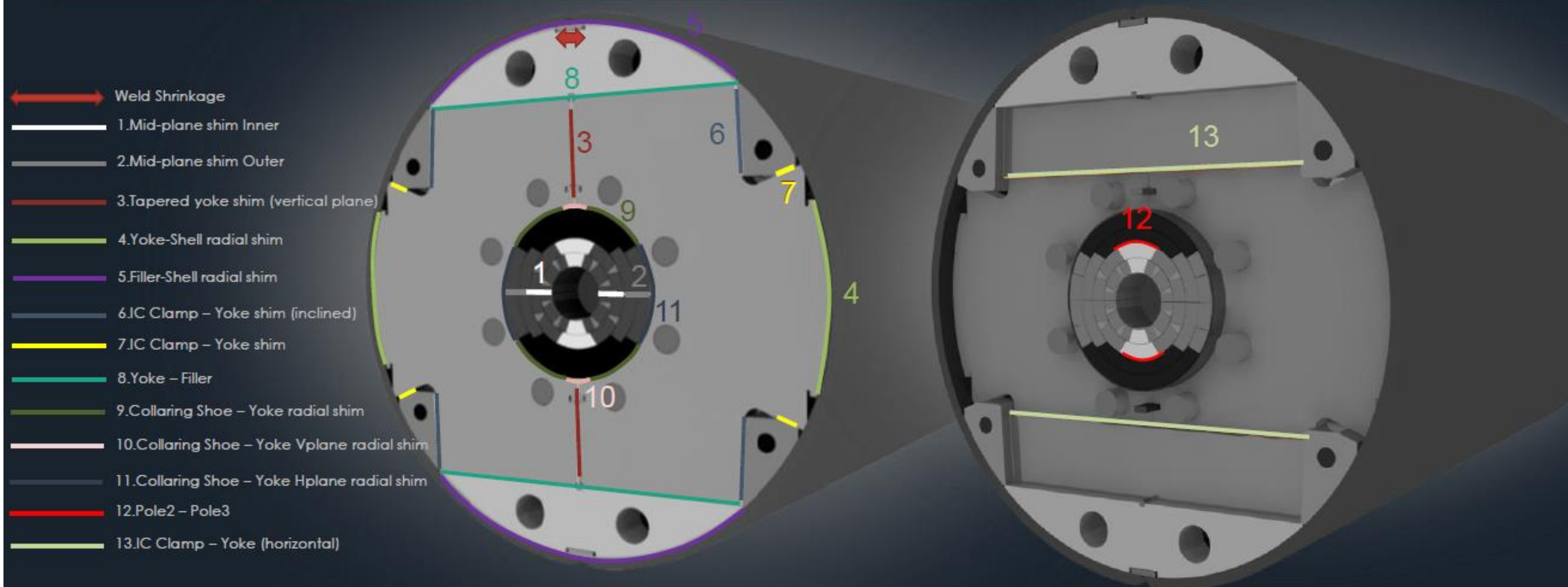
Shimming Locations

13 shims are used to tune the distribution and magnitude of the generated stresses and deformations. The thickness of those shims and the combination between their effects, is tested and evaluated.



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Sensitivity Data

Parameter	Nominal Value	Range	Coil-VonMises @293K (119 MPa)		Coil-VonMises @4.2K (153 MPa)		Coil-VonMises @15T (170 MPa)		Coil-VonMises @16T (193 MPa)	
			Range [MPa]	$\Delta\sigma_{max}$ [MPa]	Range [MPa]	$\Delta\sigma_{max}$ [MPa]	Range [MPa]	$\Delta\sigma_{max}$ [MPa]	Range [MPa]	$\Delta\sigma_{max}$ [MPa]
Weld shrinkage	0.4 mm	0-0.06	117-120	3	152-154	2	170-171	1	192-194	2
MP Inner (1)	0	0-0.09	109-119	17	153-179	26	170-218	48	193-241	48
MP Outer (2)	0.06 mm	0-0.06	102-145	43	151-162	11	170-196	26	192-205	13
Yoke – Yoke (3)	0.36 mm	0.5-0.65	103-120	17	128-178	50	167-177	10	189-199	10
Yoke - Shell (4)	0.6 mm	0.35-0.45	118-120	2	152-154	2	170-171	1	192-194	2
Yoke - IC Clamp (5)	0.4 mm	0.31-0.41	113-123	10	152-155	3	170-171	1	191-195	4
Collaring Shoe - Yoke (6)	0.025 mm	0.35-0.45	119-138	19	143-178	35	170-180	10	183-205	22
E_r	44GPa @ RT 55GPa @ 4.2K	20-60 GPa 25-77 GPa	118-124	6	153-154	1	170-187	17	188-214	26
E_θ	44GPa @ RT 44GPa @ 4.2K	20-60 GPa 20-60 GPa	100-141	41	17-177	80	136-199	63	157-226	69
α_r	2.6 mm/m	2-3 mm/m	119-119	0	126-126	90	168-213	45	193-234	41
a_θ	3.5 mm/m	3-4 mm/m	119-119	0	143-163	20	164-177	13	190-198	8