Collaboration meeting on DS 11T Dipole grounds
FNAL, Sep. 21-23, 2015

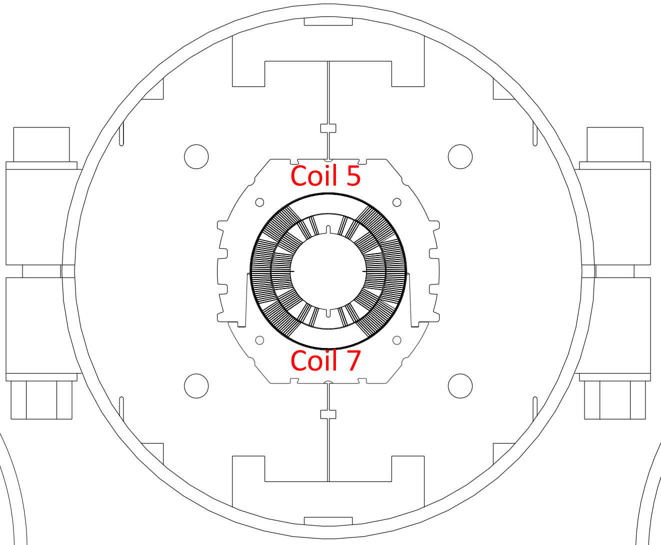
Model Magnets Assembly at FNAL

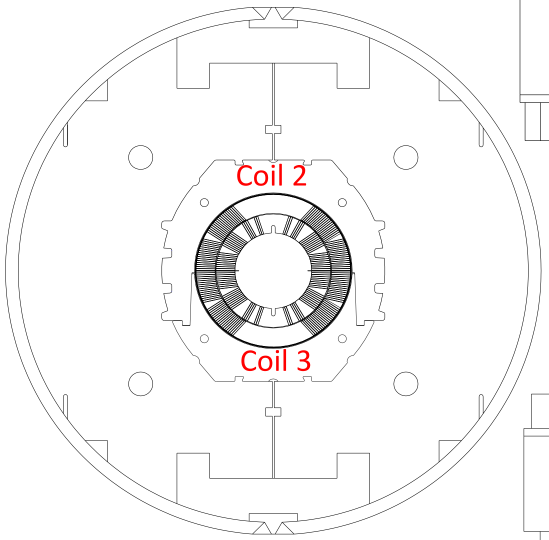
Igor Novitski

September 21, 2015

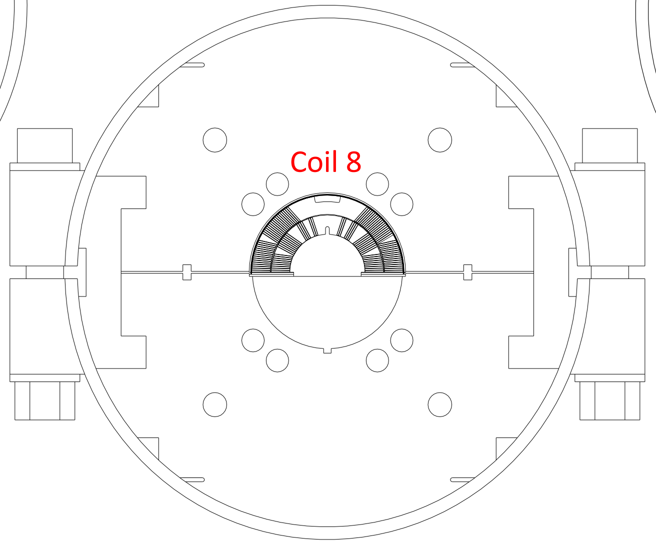
Model Magnets

MBHSP02

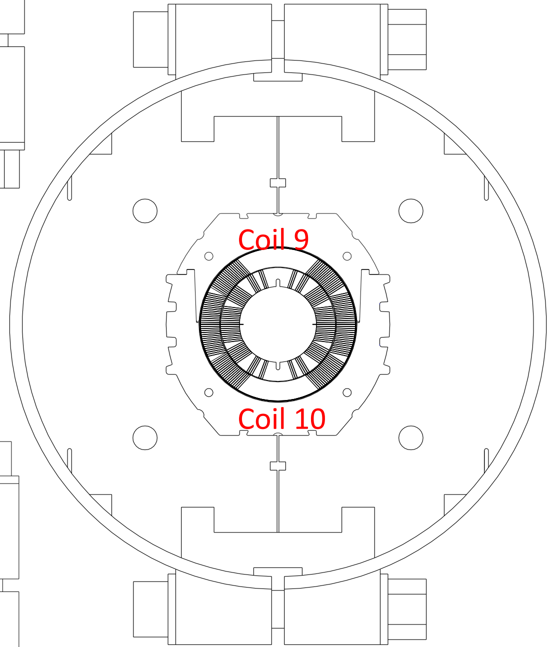




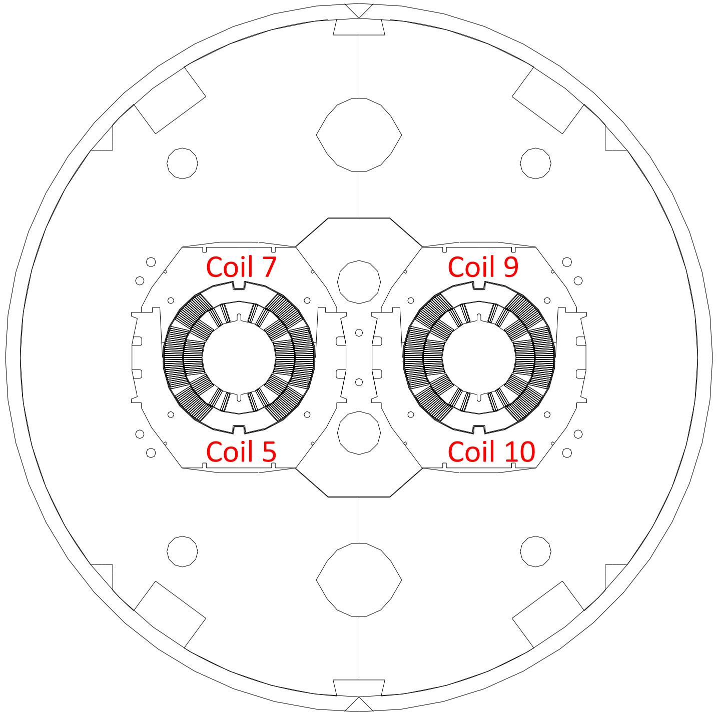
MBHSP01



MBHSM01



MBHSP03



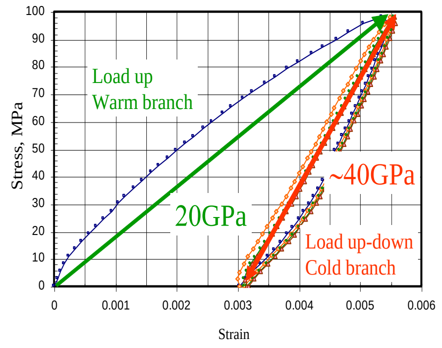
MBHDP01

Mechanical Models

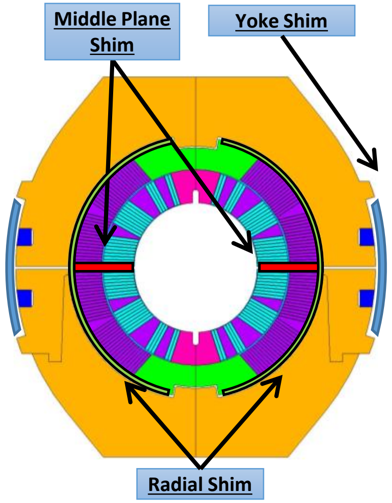
- Define "warm" magnet shim sizes
- Check parts and tooling
- Finalize collaring and yoke clamping procedures

"Study of Mechanical Models of a Single-Aperture 11 T Nb3Sn Dipole" presented at ASC 2012 (Portland, USA)

Coil Shims

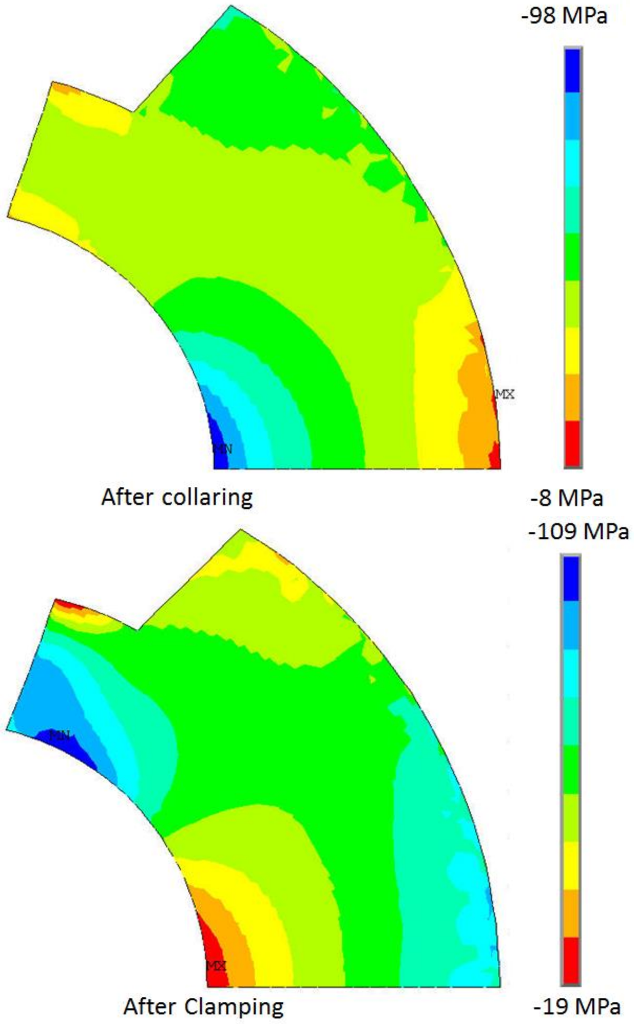


- FEA simplifies coil properties by using the cold elastic modulus
- Coil warm and cold properties are different
- Coil has an anisotropy in the azimuthal and radial directions
- Warm magnet shims are different from calculated ones and need to be optimized with real parts to achieve the desired warm coil pre-stress.



FEA RESULTS OF THE DIPOLE MECHANICAL STRUCTURE

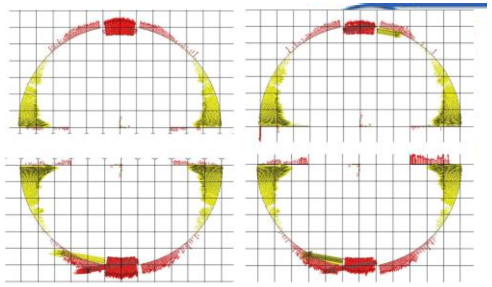
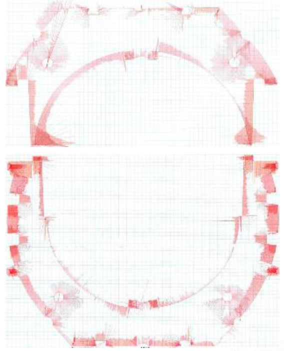
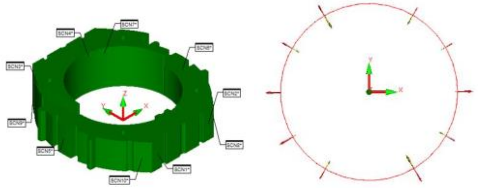
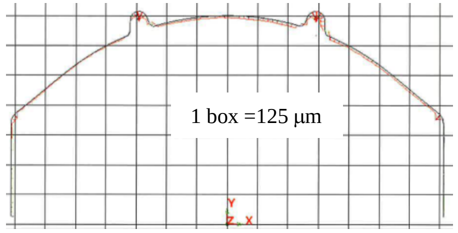
Position in coil	Azimuthal Coil Stress, MPa		
	Collared coil	Clamped yoke	Cold mass
Inner pole	-44	-60	-120
Outer pole	-64	-55	-87
Inner midplane	-97	-58	-79
Outer midplane	-51	-55	-108

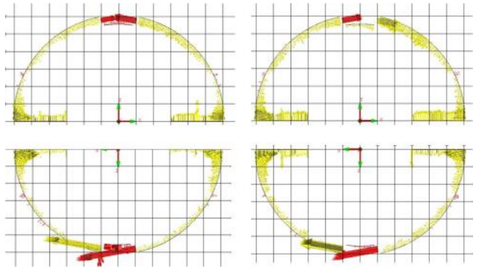


Azimuthal stress distribution in Nb_3Sn coil after collaring (top) and clamping (bottom).

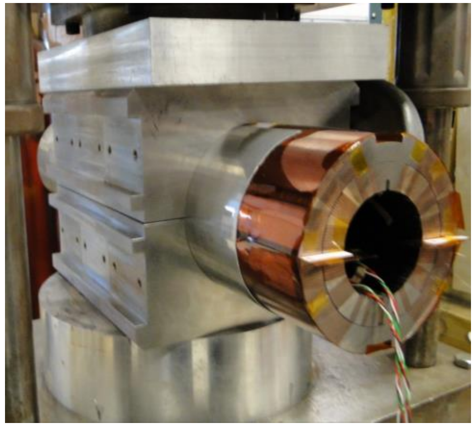
Coil Cavity Size Control

- The coil outer diameter (OD) and midplane were measured in the coil free state using a coordinate measuring machine.
- A collar lamination profile after laser cutting performed on the optical table
- The deviations of the collar inner surface from the design value are < 50 µm
- The inner diameter of the assembled and keyed collar packs was also measured with a micrometer
- Based on the coil and collar pack sizes the coil-collar interface was shimmed to compensate for collar fabrication errors.
- The accuracy of wire-cut 25 mm thick yoke laminations is within ± 25µm on all working surfaces.
- Coils become smaller radially and azimuthally by 50-100µm after been used in the MMs.

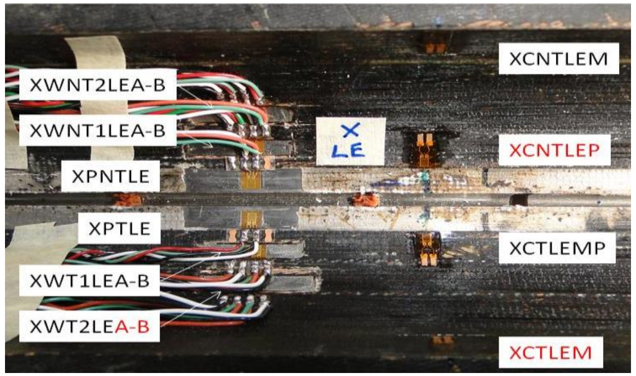





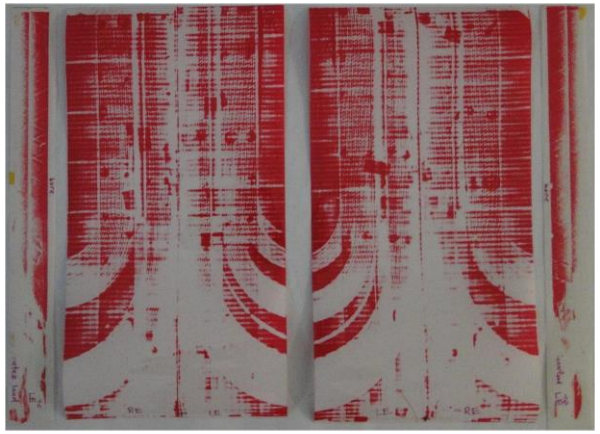


Mechanical Models



- 2 m long Nb_3Sn practice coil was cut into six pieces
- Resistive strain gauges glued on the coil inner surface, on the stainless steel wedges and on the titanium poles
- Fuji film measures stress gradients
- Six collared models were built with different shimming (0-0.12mm)
- One collared model was clamped twice
- Magnet shim plan was finalized





MBHSP01 2m Long Magnet

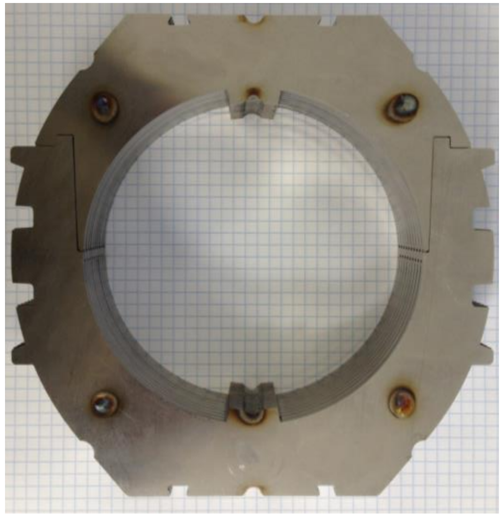
- RRP 108/127 conductor
- No Core
- Original ends
- Laser cut collars
- Collaring after MM
- Shims after MM
- Welded skin
- Welded end plates

"Development and Test of a Single-Aperture 11 T Nb3Sn Demonstrator Dipole for LHC Upgrades" presented at ASC 2012 (Portland, USA)

Collar Pack

Use 0.127 mm shim between laminations.
Welded longitudinally along the pole
and on the O.D. above the pole.
Have 2 pins each welded at the ends.

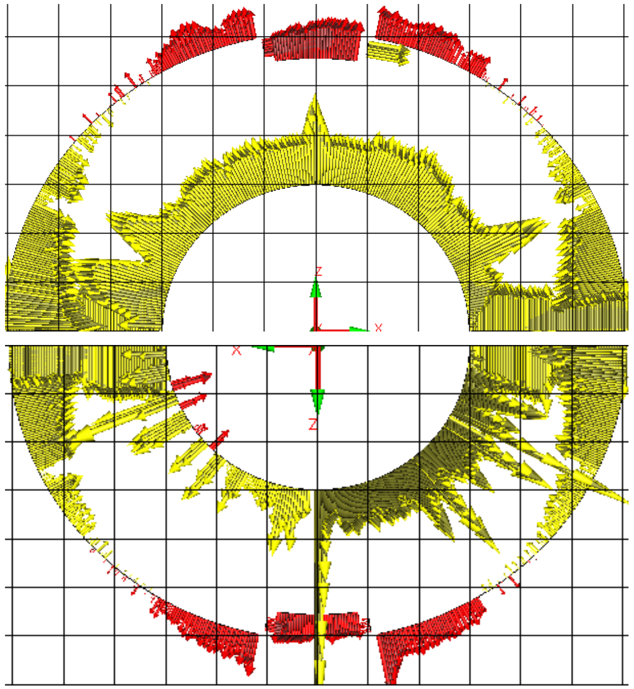
Parameter	Value
Collar material	Nirosta high-Manganese SS
Collar width, mm	17.75
Lamination thickness, mm	1.5
Collar pack length, mm	38



Size Control

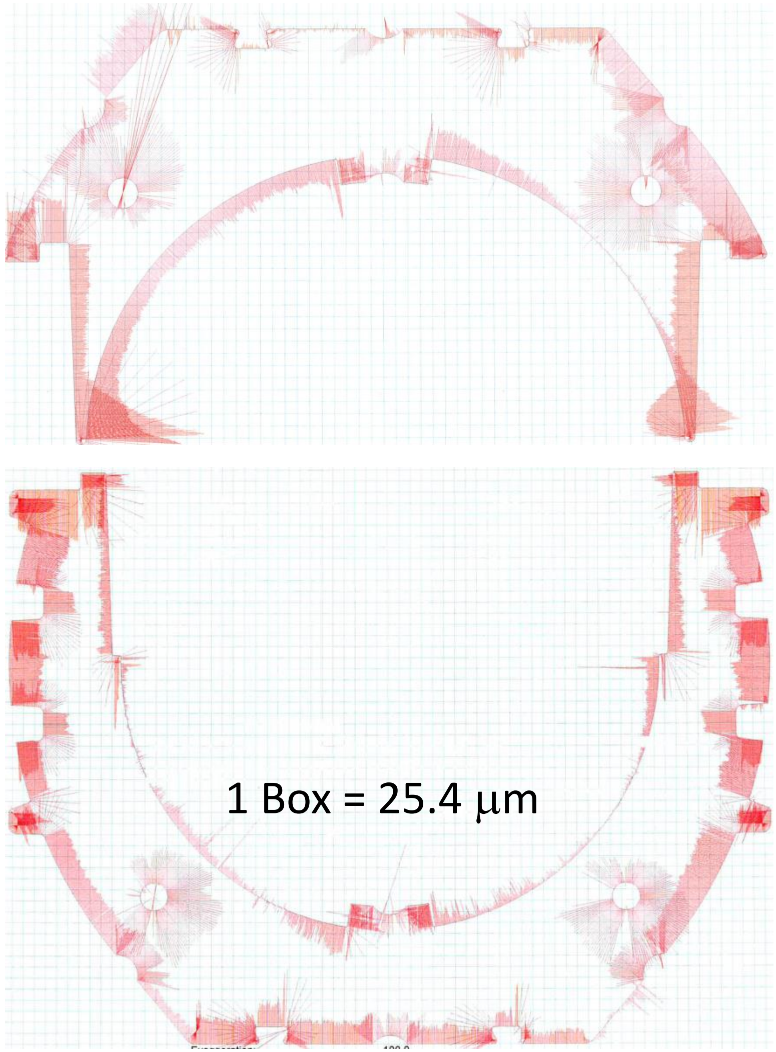
MBHSP01

MBH02
445 mm from RE

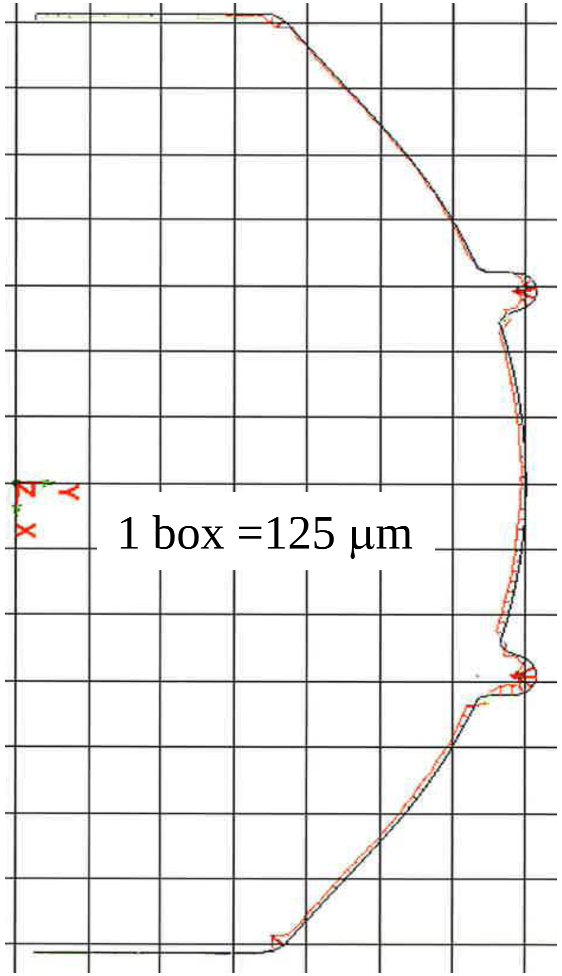


MBH03
435 mm from RE

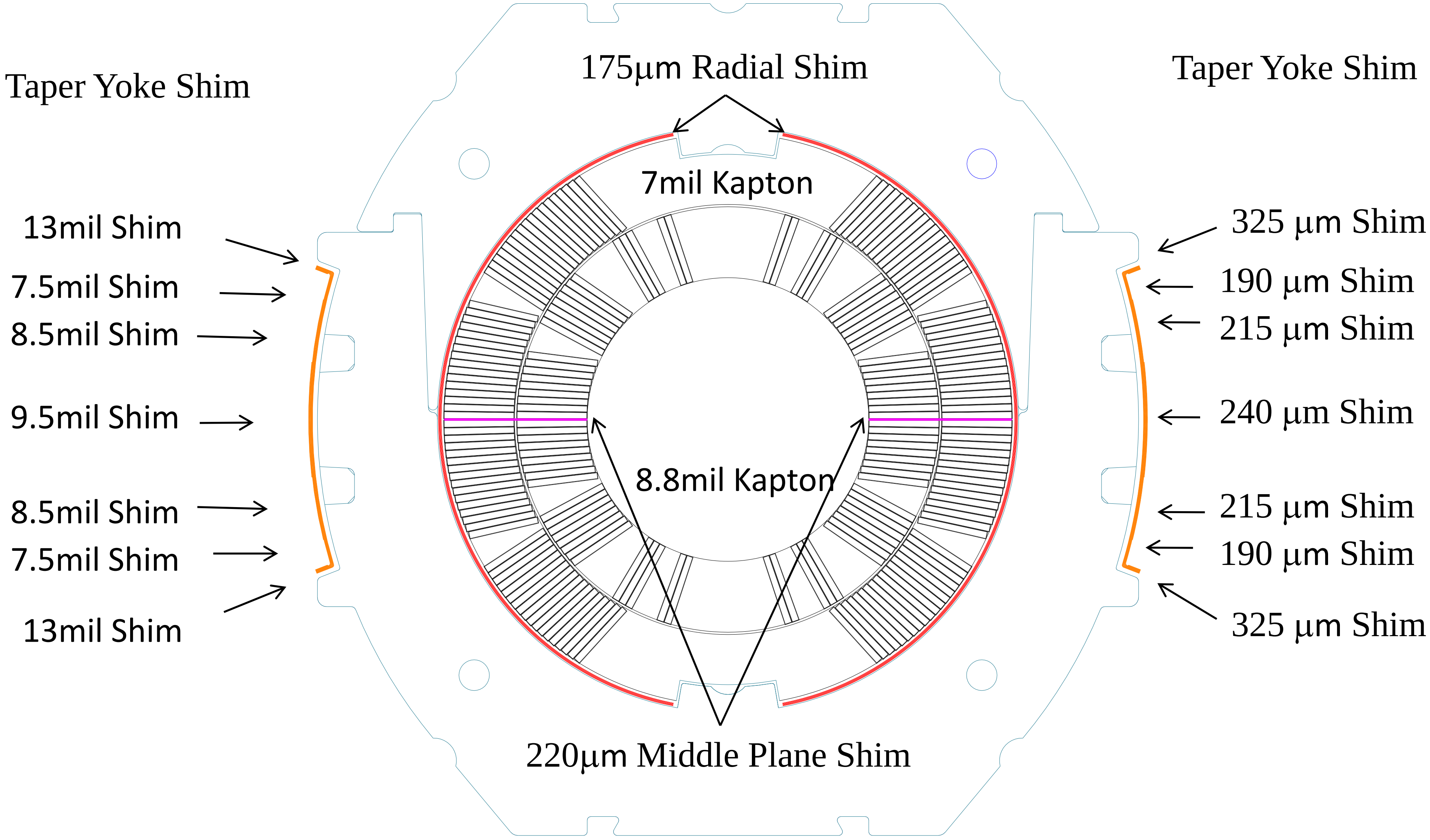
Laser Cut Collar lams



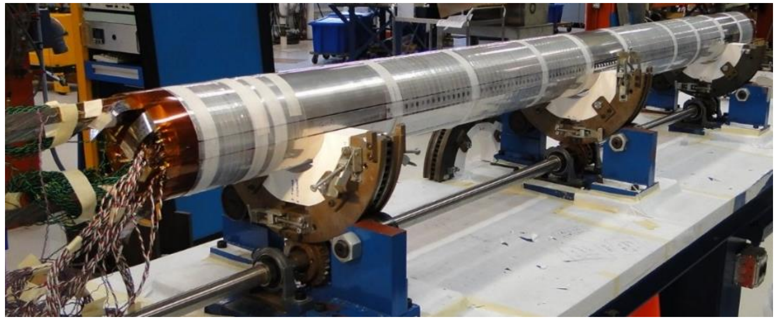
Wire EDM Iron lams



MBHSP01 Shim Plan



Coils assembly



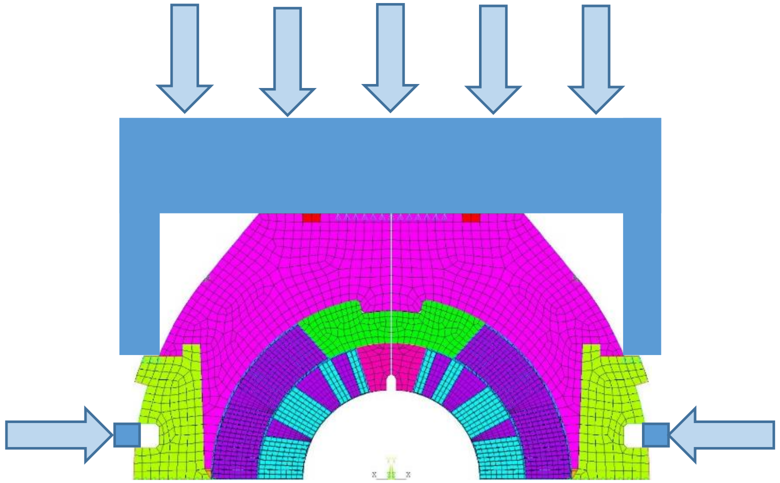
- A layer of 0.112mm (4.4mil) thick pre-preg Kapton ironed to the coil
- The two coils, surrounded by ground insulation (5x0.127mm Kapton) and 0.5mm protection shoes

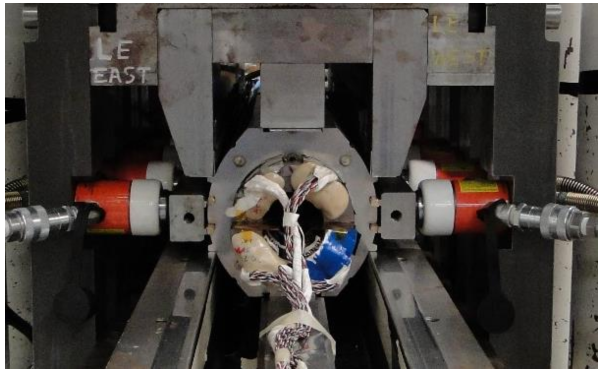
- Coil assembly process developed with mechanical model
- Upper and lower collar packs are shifted to interlock all collar packs together

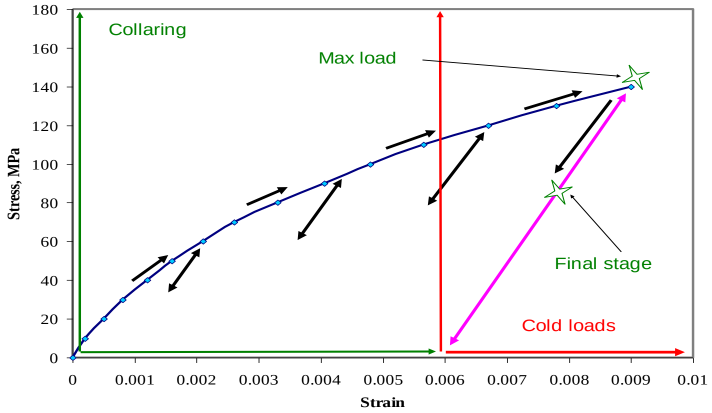
Collaring

- Press gradually increase vertical pressure on a contact tooling to open collar keyways.
- Tapered keys are hydraulically pressed into the collars
- Press released with coil spring-back

Parameter	Value
Protection shoe thickness, mm	0.5
Protection shoe material	304
Collar material	316LN
Collar width, mm	17.75
Lamination thickness, mm	1.5
Collar pack length, mm	38
Number of keys	4
Key height, mm	6
Key thickness, mm	5
Key material	Bronze

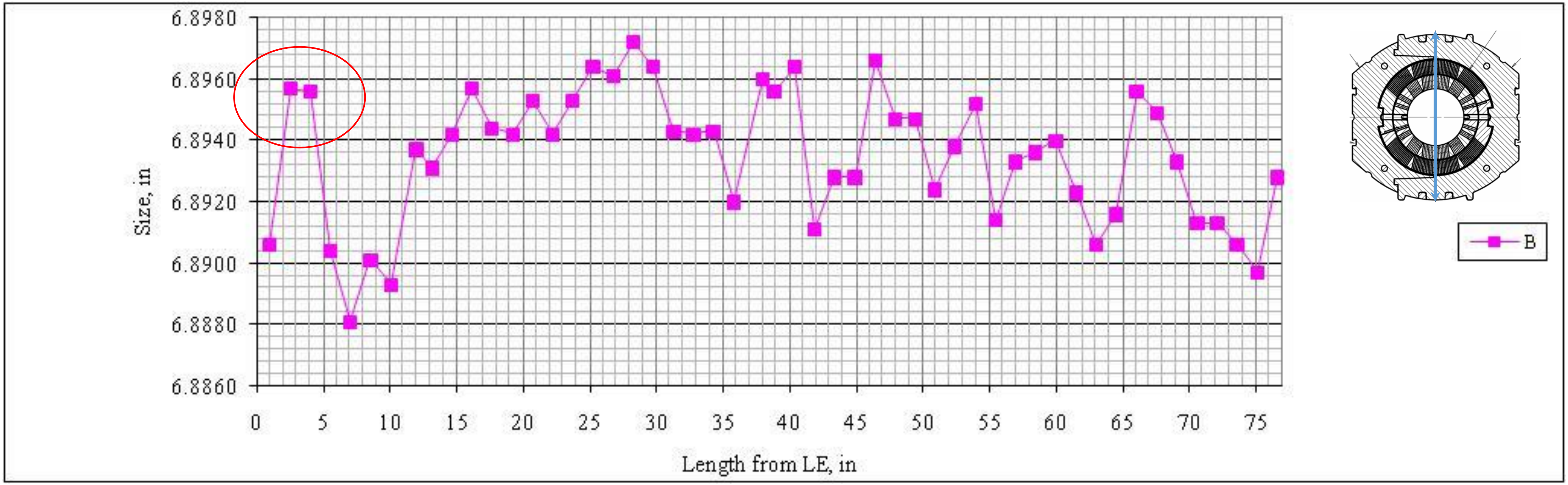




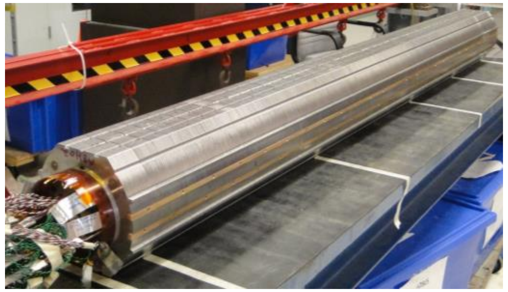


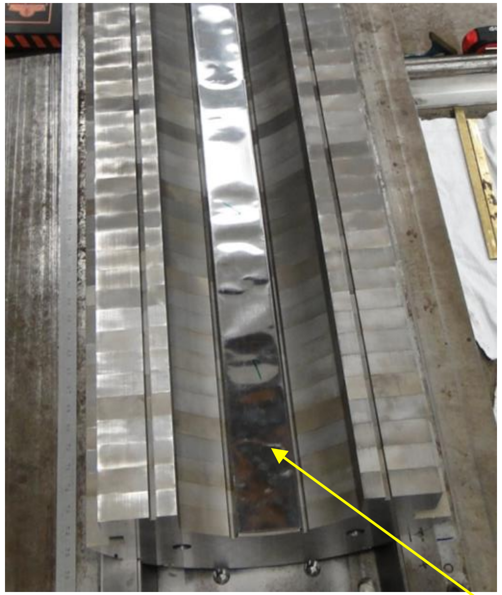
Collared Coil Mechanical Measurements

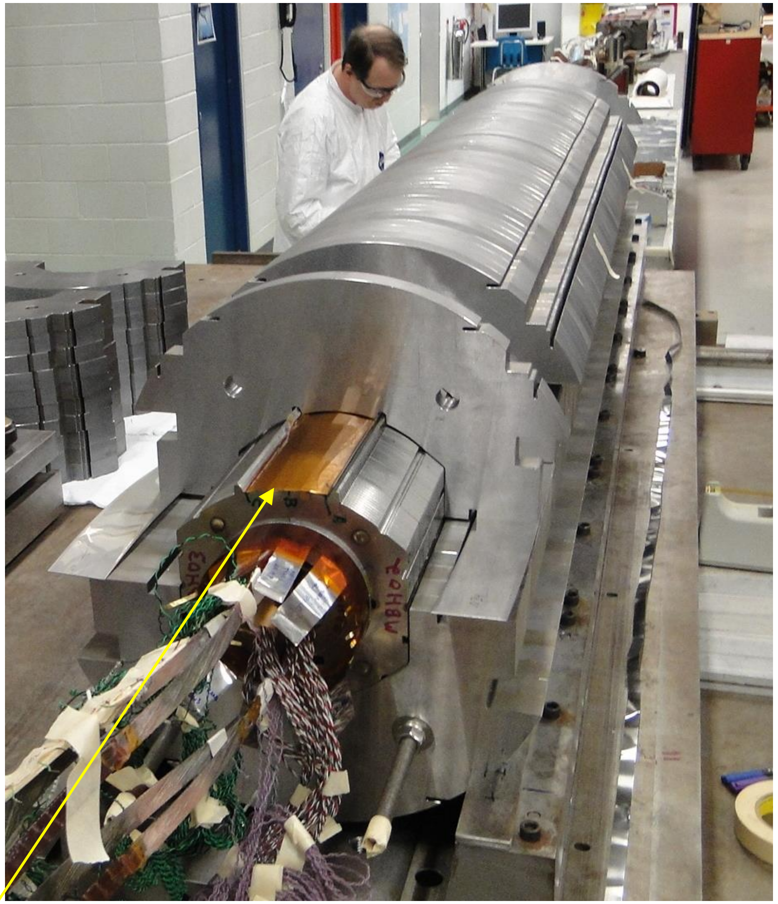
Splice block size even
with magnet SS

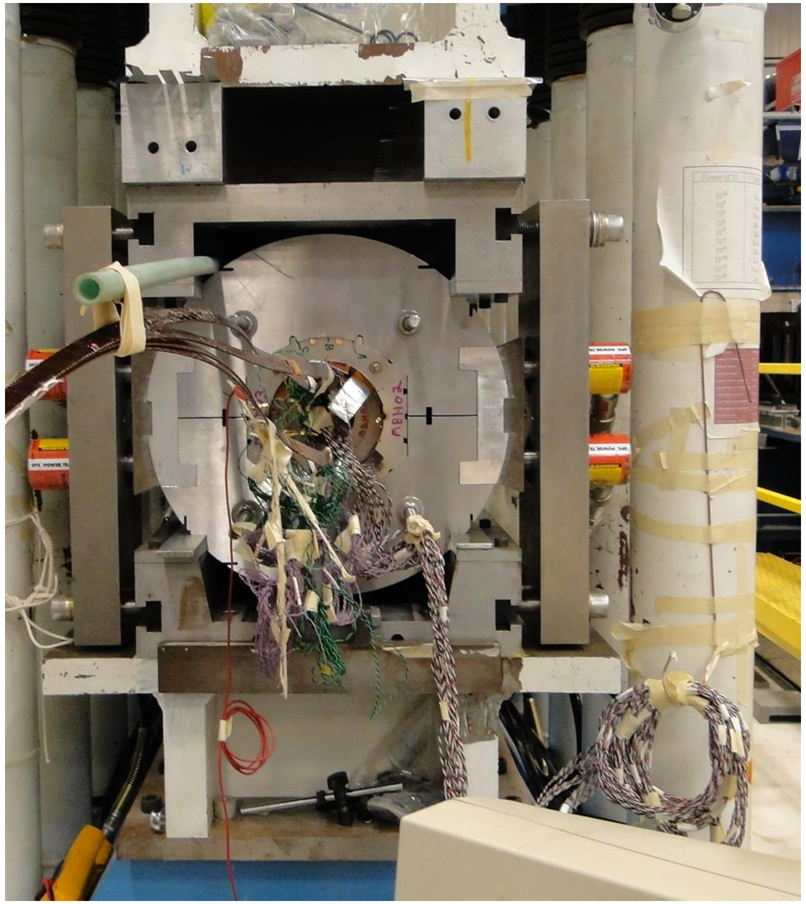


Yoking and Clamping



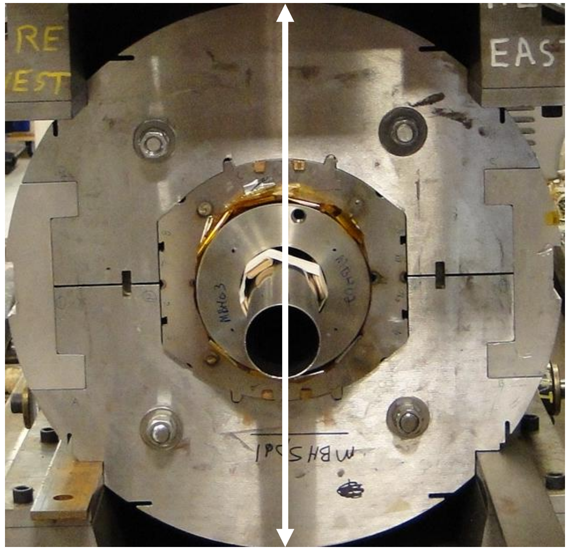


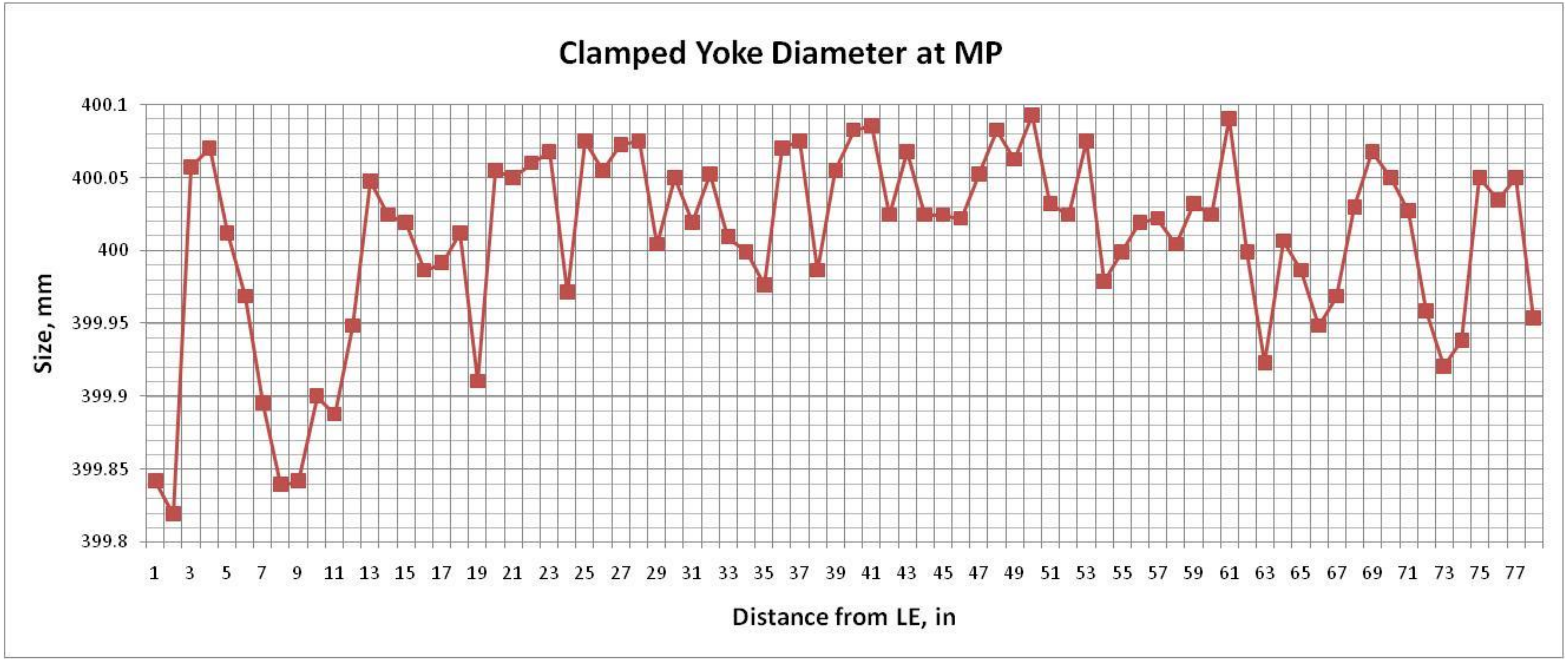




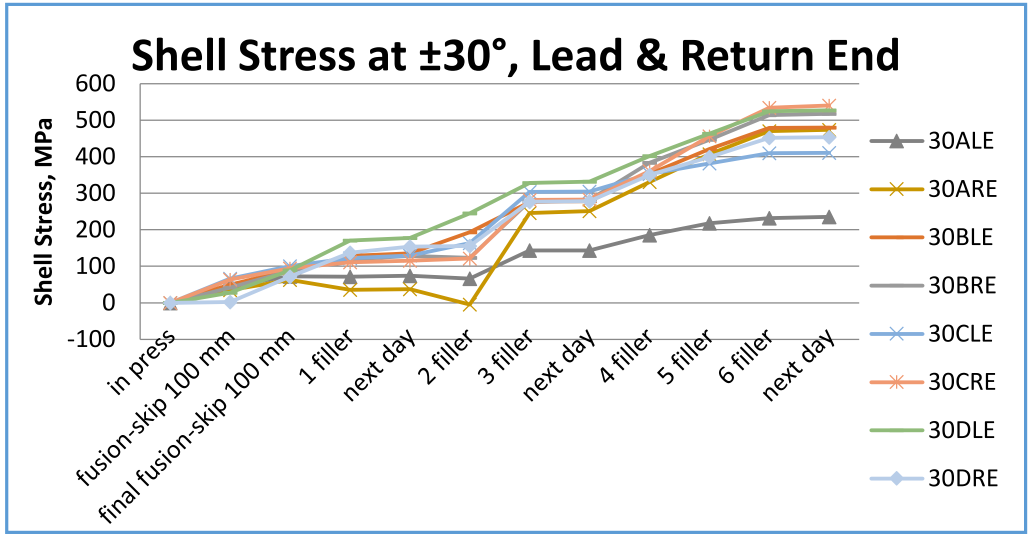
Collar-Yoke Shim

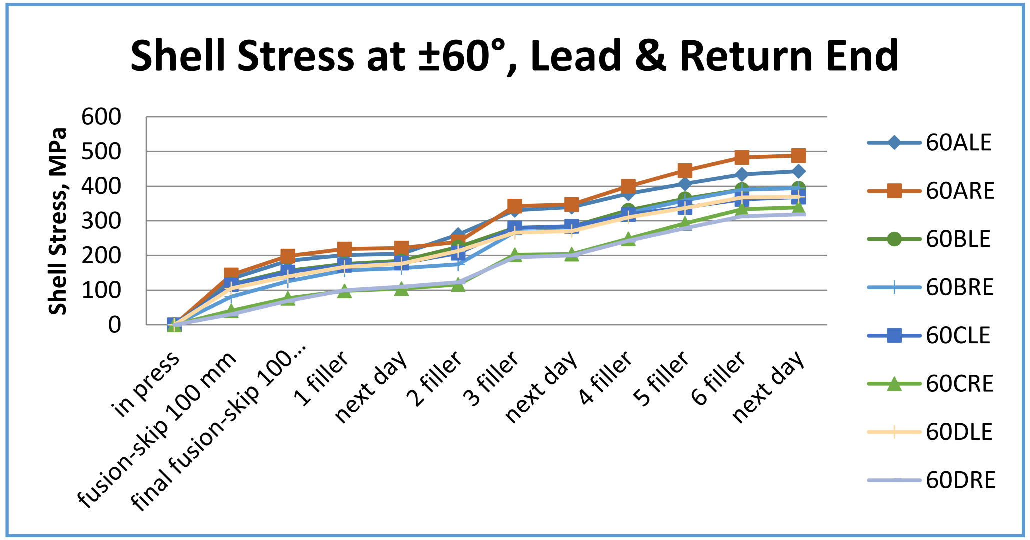
Clamped Iron Mechanical Measurements

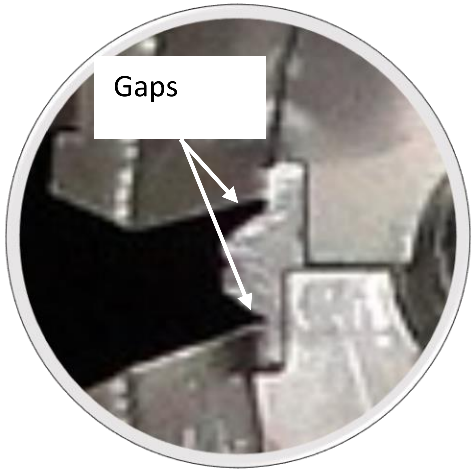




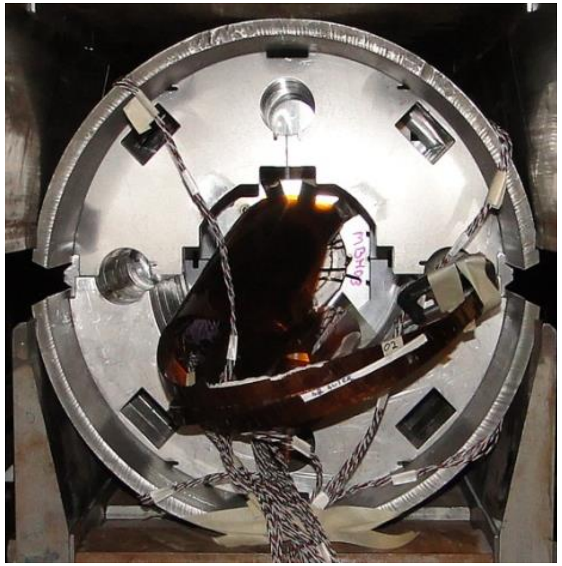
Skin Welding



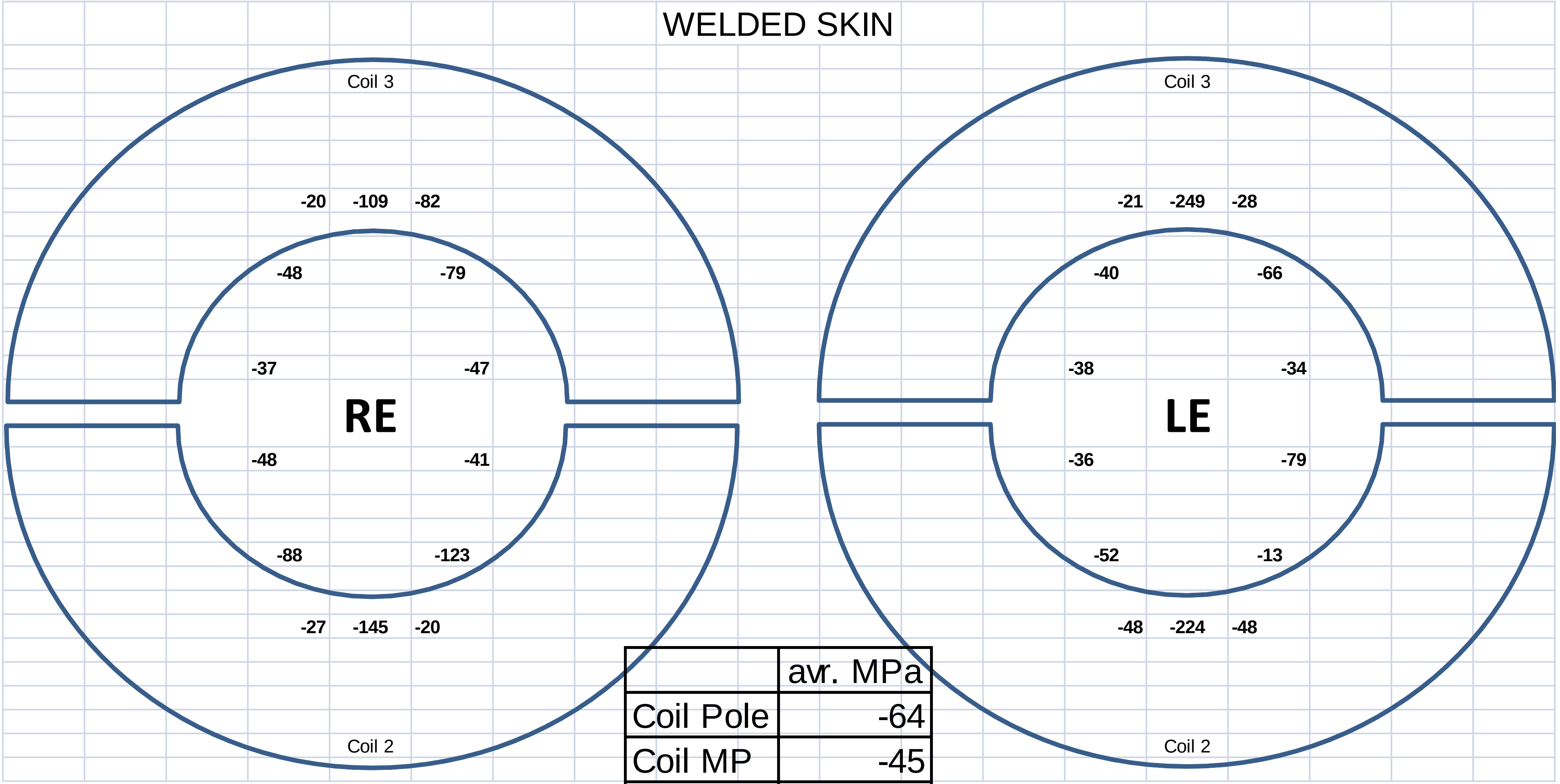




Actual gap ~3 mm (design=0.7mm)

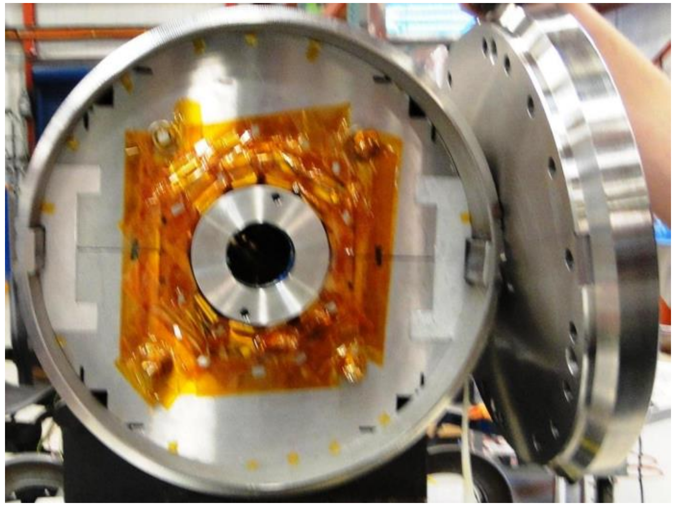


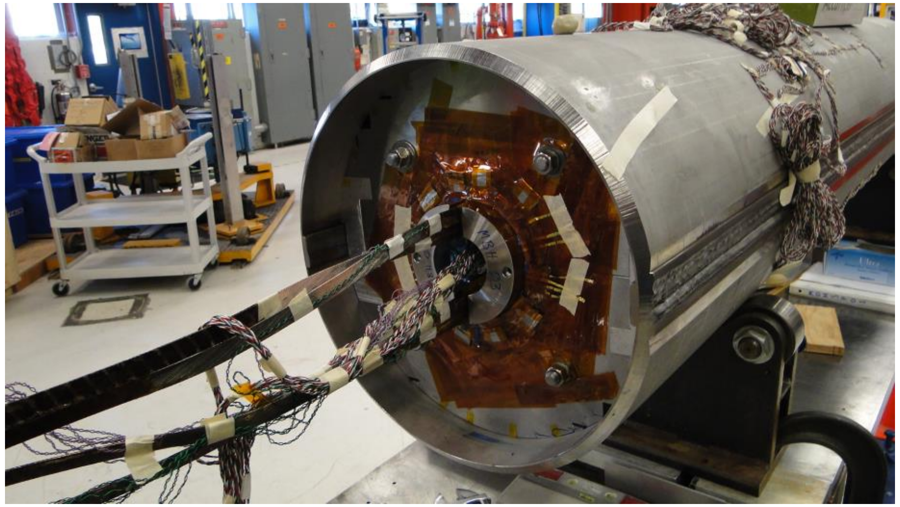
MBHSP01 SG Data

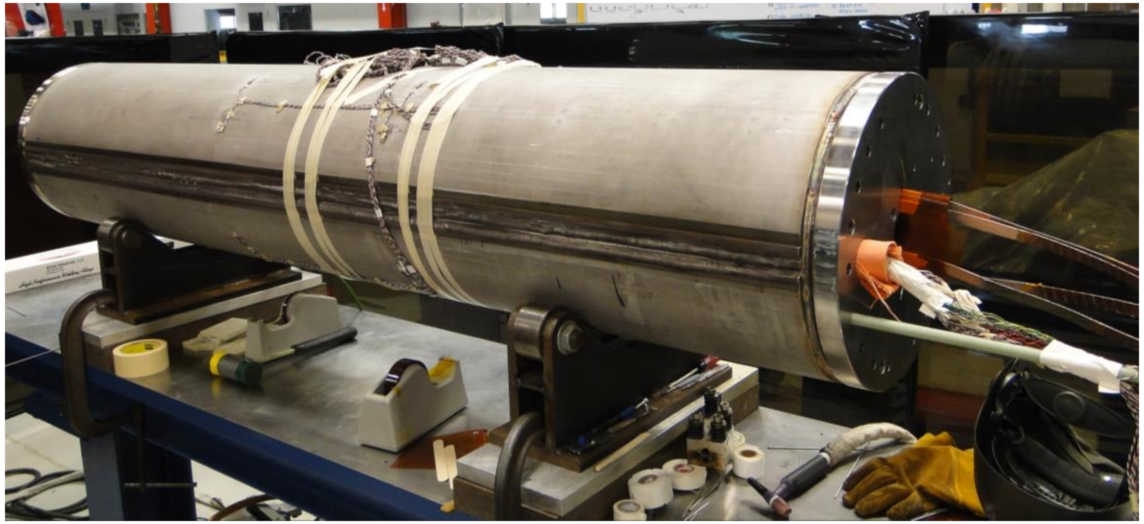


	avr. MPa
Coil Pole	-64
Coil MP	-45
Ti Pole	-37
LE Pole	-237
RE Pole	-127

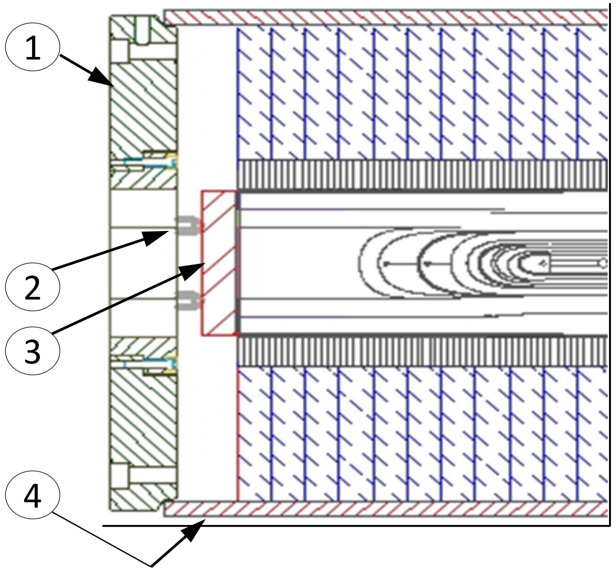
Skin Cutting and End Plate Welding





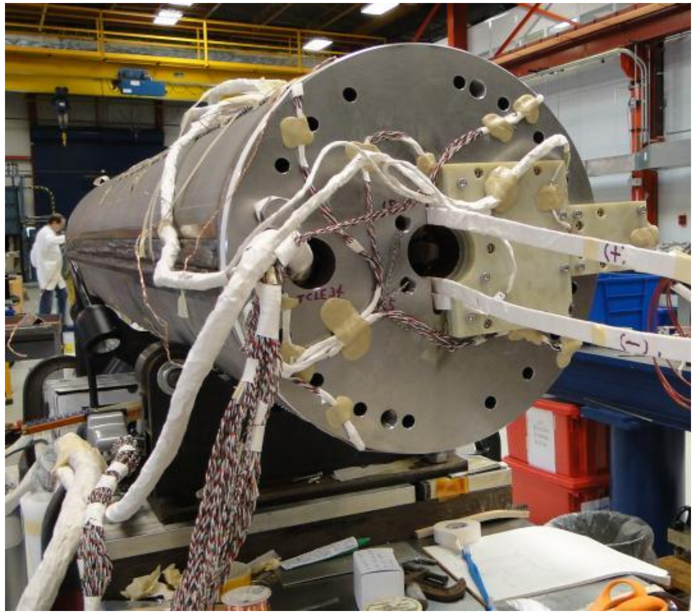


End Design



Return end cross section: 1 – end plate; 2 – strain gauge bullets; 3 – bullet pressure plate; 4 – skin

Parameter	Value
Yoke lam thickness, mm	25
Yoke material	Hot rolled steel SAE 1045
Clamp material	Al 7075-T6
Skin material	304L
Skin thickness, mm	12.7
End plate material	304L
End plate thickness, mm	50
Bullets load, kN per end	17.6

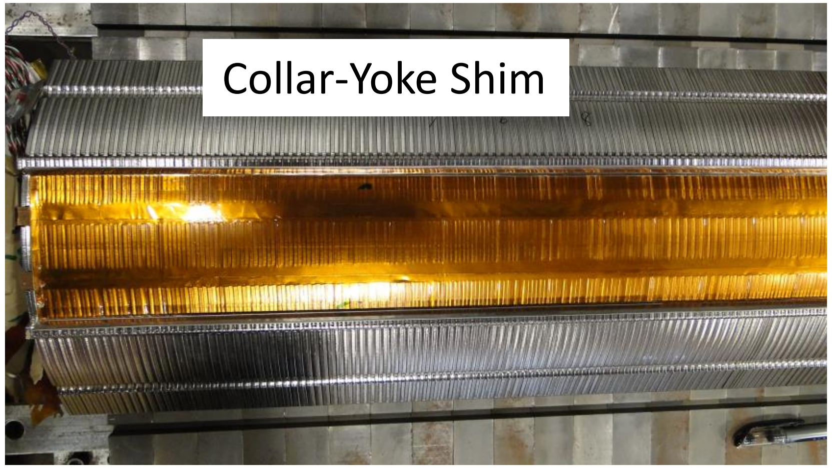


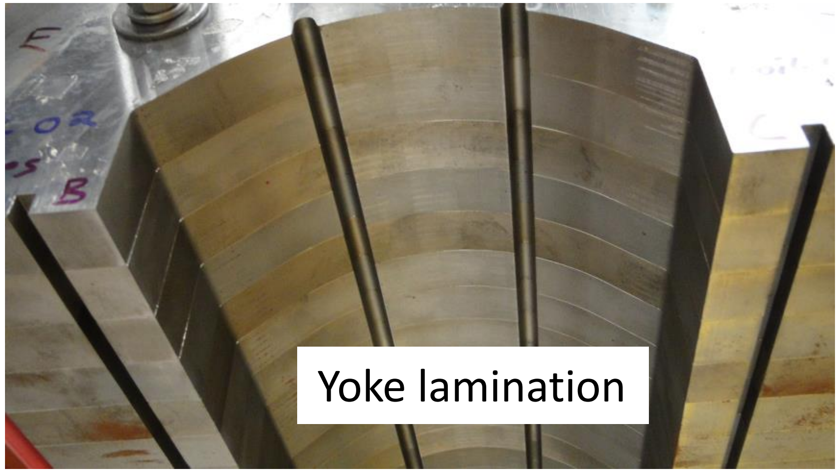
NbTi leads splicing
Instrumentation wiring and connectors soldering
Final electrical and hi-pot test

MBHSP01 Test Results

Magnet reached 10.4 T or 78 % of SSL at 1.9 K showing limited quench performance. Most quenches at low ramp rates, all holding quenches and quenches at intermediate temperatures initiated in the mid-plane block of the outer coil layer. Only few training quenches occurred in the high field area at the very beginning of test at 4.5 K and 1.9 K. Quench location, ramp rate and temperature dependence studies, and additional tests point out on the problems with coil outer-layer lead in both coils. Possible conductor damage in the mid-plane area during fabrication could cause the observed degradation.

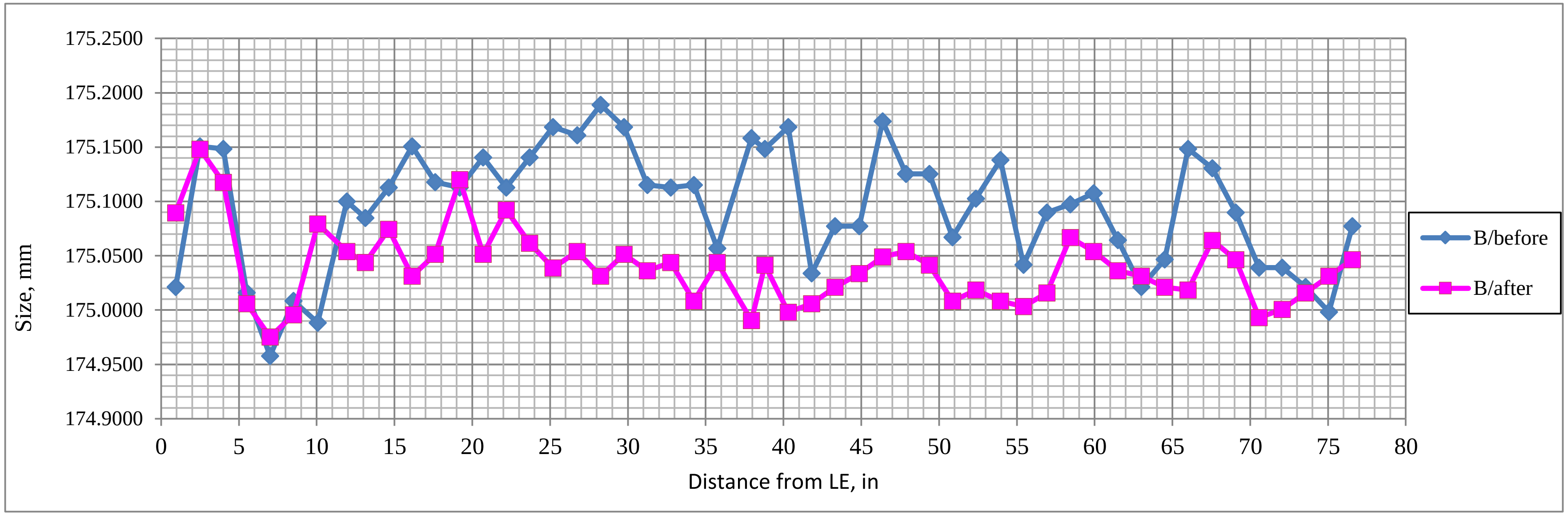
Magnet Autopsy

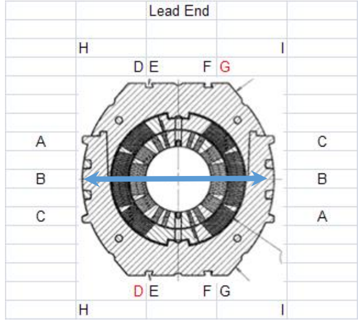




LE Marks on the Collar-Yoke Interface – high pressure at the magnet LE

Collared Coil Size "B"

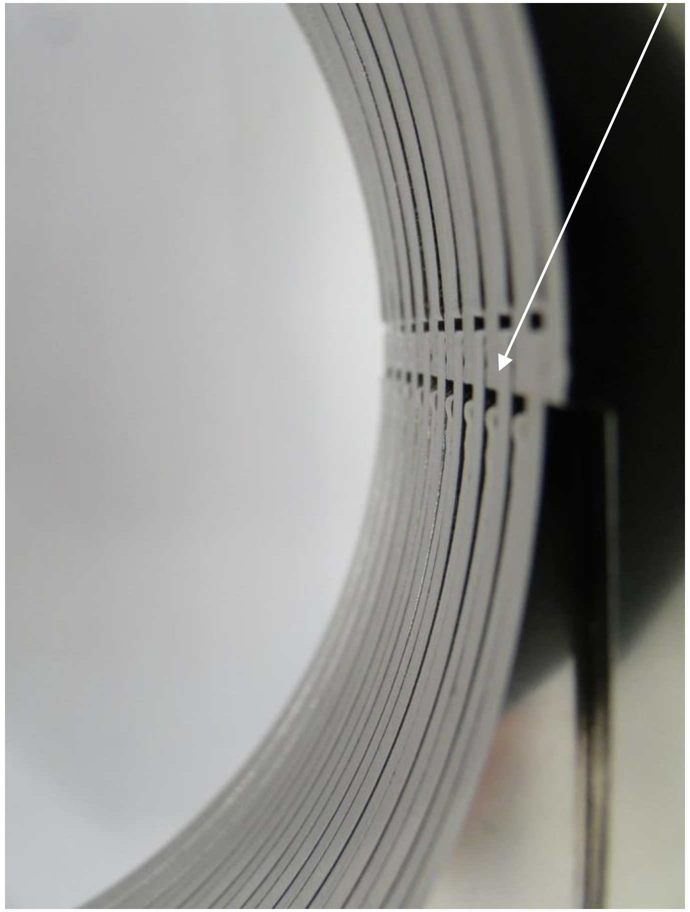


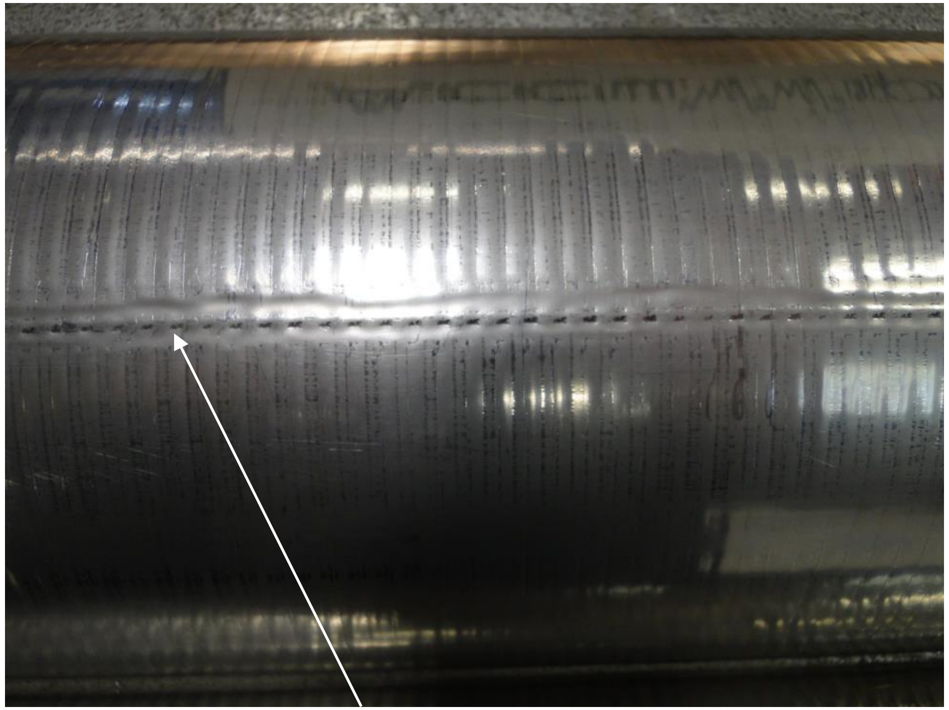


175.1126
175.0376
0.075

Marks on the Protection Shoe

LC Collar Pack Inner Surface at Middle Plane





Imprint on the GI and Protection shoe

Recommendation

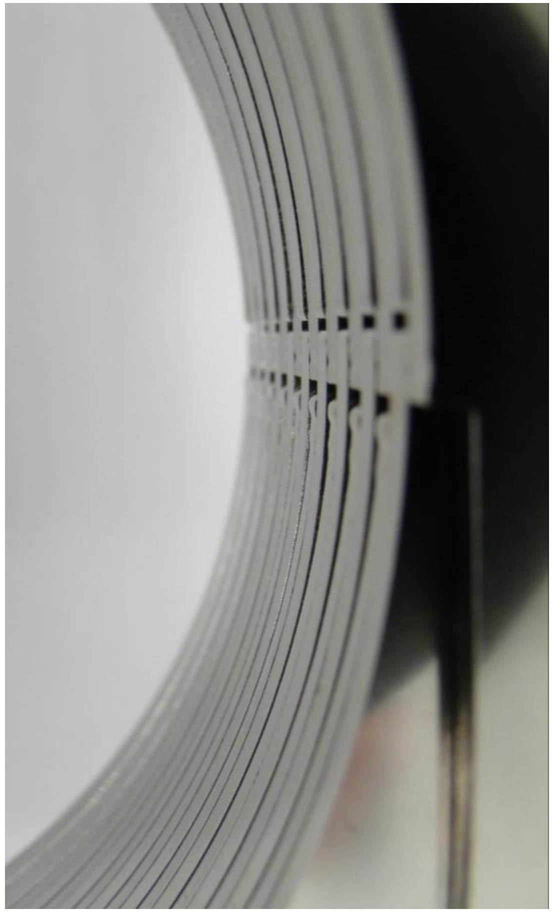
- Reduce skin load at the LE => reduce cold splice stress by ~40MPa
- Change material for LE saddle and splice block cylinder from SS to AlBr => better match coil radial motion
- Reduce radial yoke-collar shim at MP area
- Bigger Collar ID
- Thicker Retainer
- Stamped Collars
- Bolted Skin

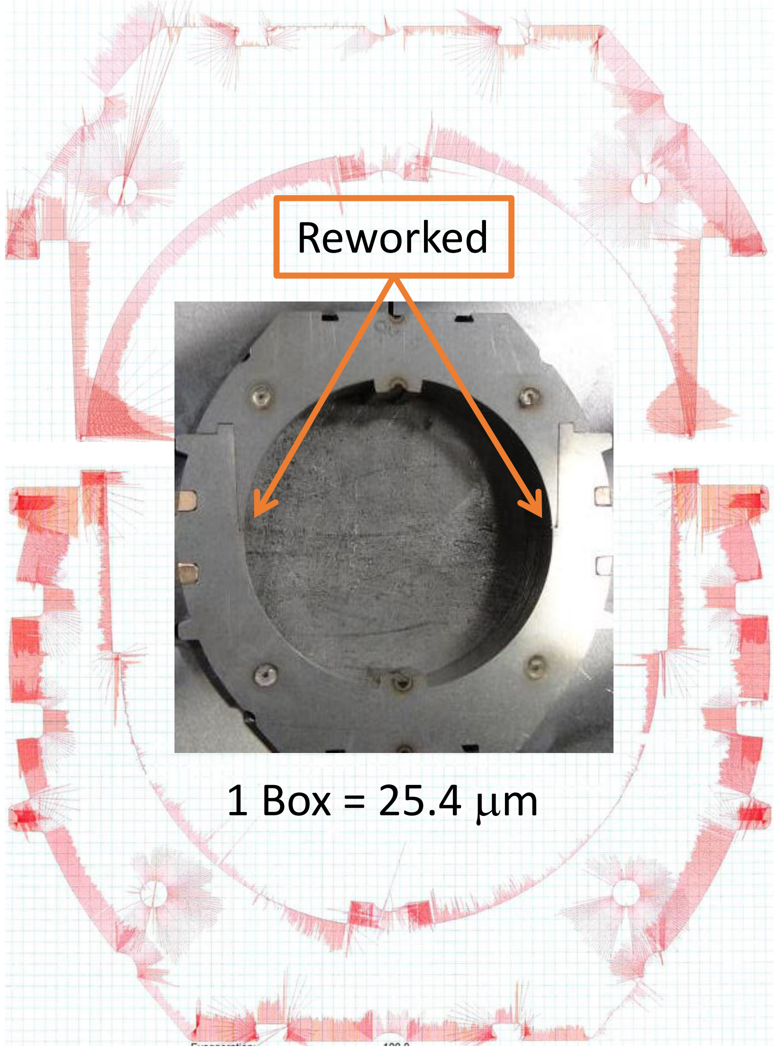
MBHSP02

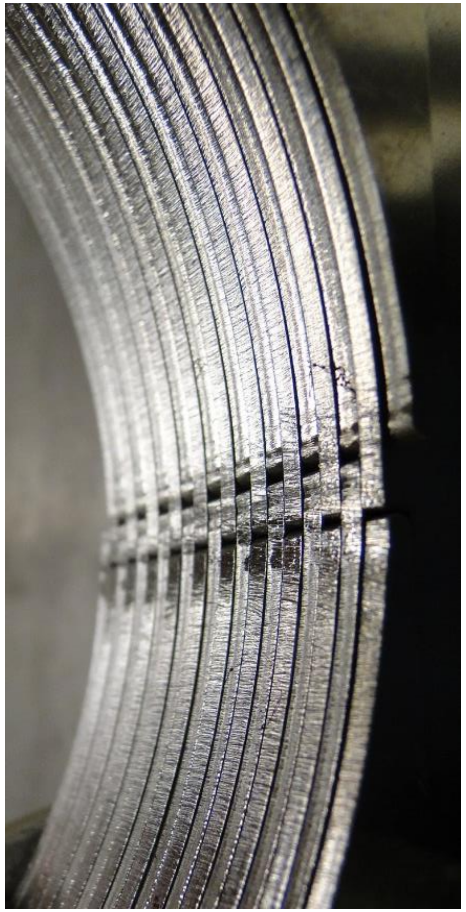
- RRP 150/169 conductor
- Core cable
- Modified ends
- Laser cut lams and modified collar packs
- Two Collaring Iterations
- Thicker radial shim
- Smaller bending shim
- Horizontally bolted skin
- Bolted end plates

“FABRICATION AND TEST OF A 1 M LONG SINGLE-APERTURE 11 T NB3SN DIPOLE FOR LHC UPGRADES ” presented at IPAC 2014 (Dresden, Germany)

Reworked Collar Packs







Reworked Collar Packs for MBHSP02

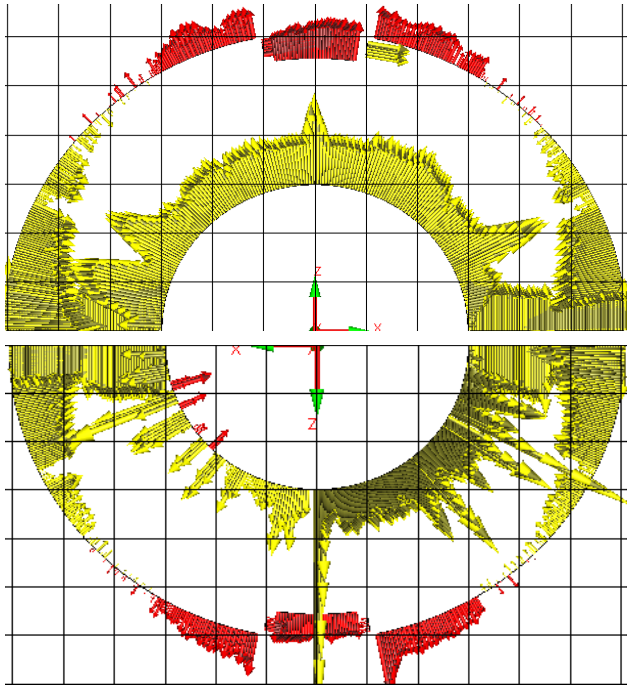
Coil Sizes

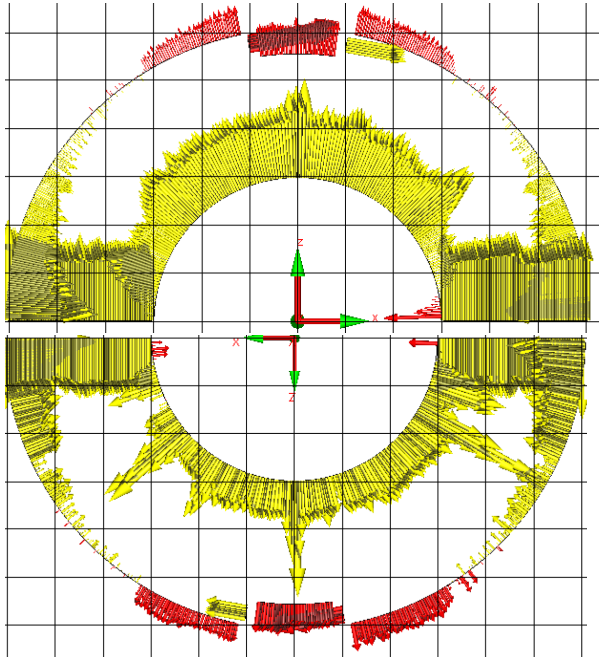
MBHSP01

MBHSP02

MBH02
445 mm from RE

MBH05
479 mm from RE

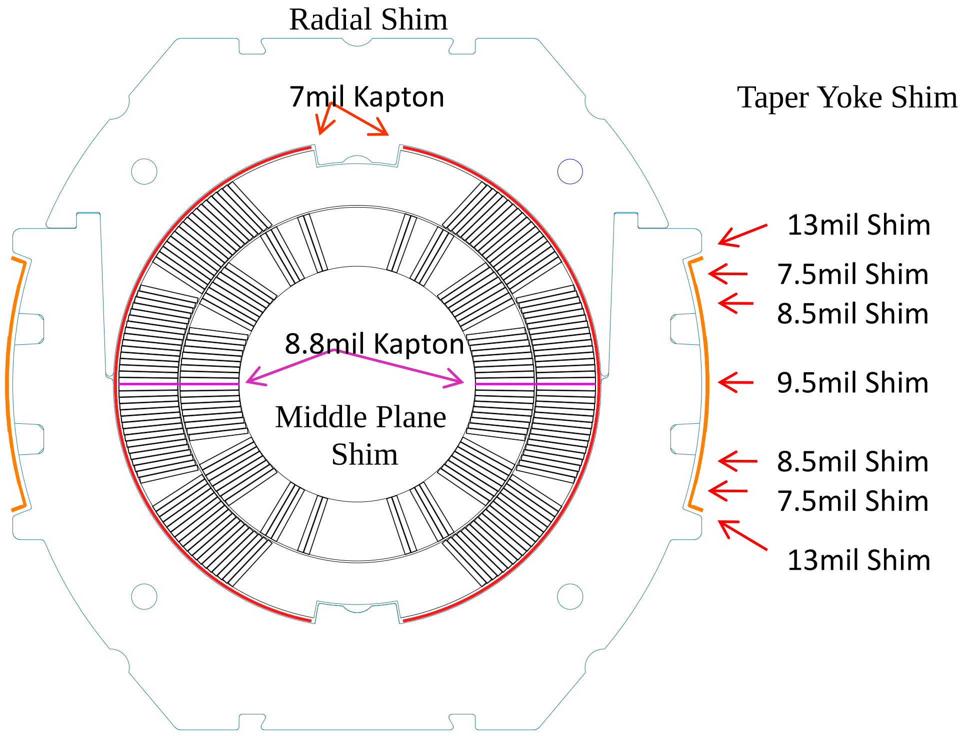


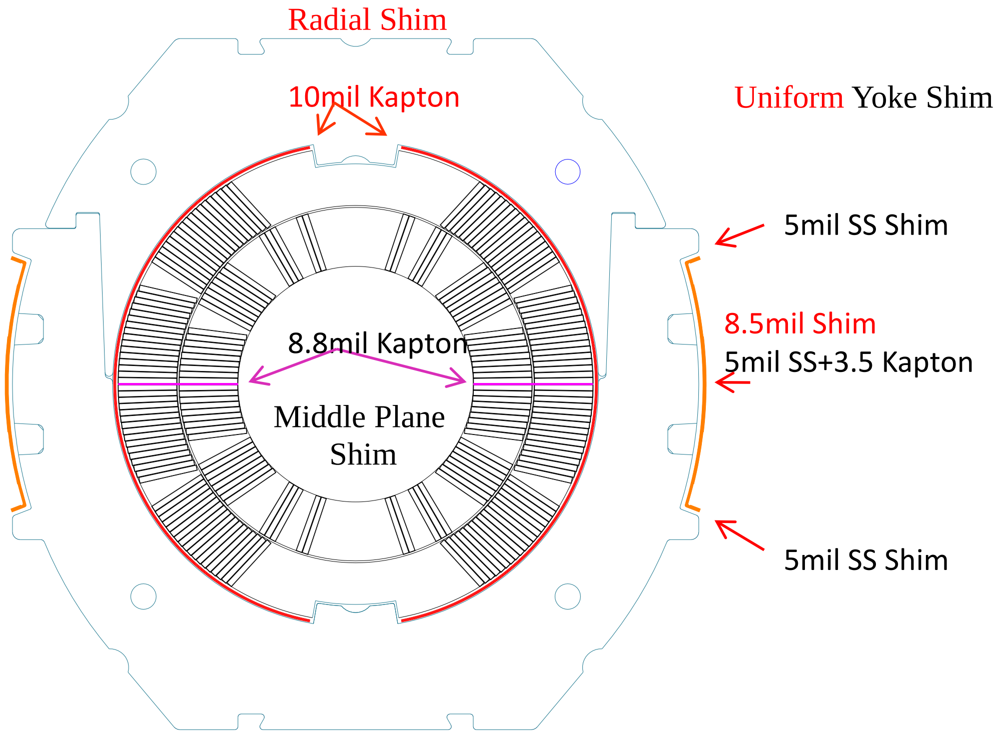


MBH03
435 mm from RE

MBH07
467 mm from RE

MBHSP01 and MBHSP02 Shimming





MBHSP02 Test Results

MBHSP02 demonstrated better performance than MBHSP01 and reached 11.7 T or 97.5% of its design field at 1.9 K

Still significant quench current degradation observed

Both magnets showed so called “holding quenches”, when magnet is quenching at a fixed current after holding it for a certain time (resistive conductor)

MBHSM01

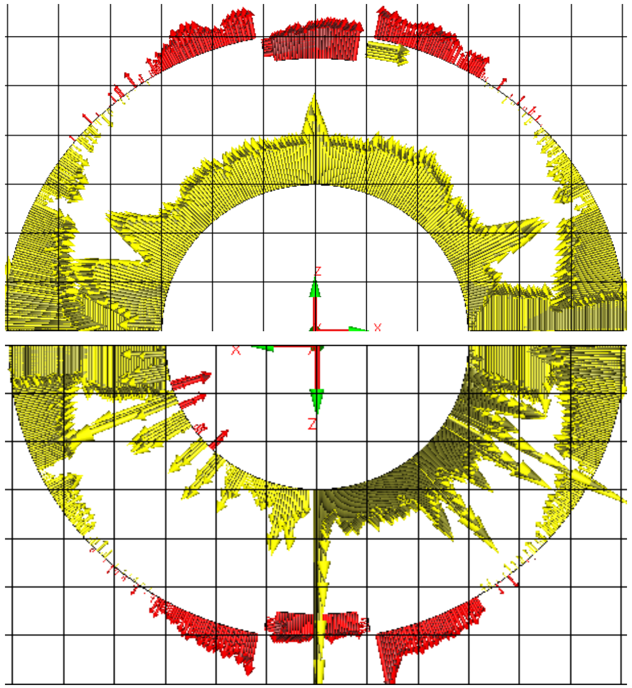
- RRP 109/127 conductor w core
- Ordinal end parts
- New coil sizing
- Mirror structure
- No collars
- Reduced coil prestress and bending
- Horizontally bolted skin
- Bolted end plates

"TESTING OF A SINGLE 11 T Nb3Sn DIPOLE COIL USING A DIPOLE MIRROR STRUCTURE" presented at IPAC 2014 (Dresden, Germany)

Coil Sizes

MBHSP01

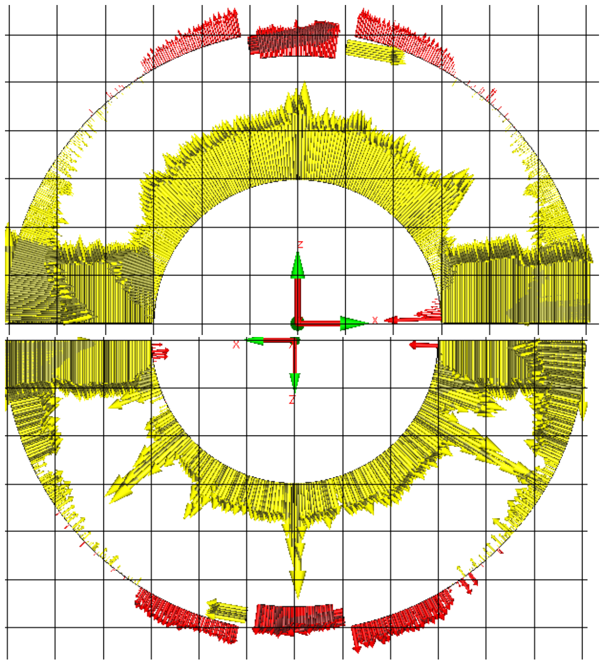
MBH02
445 mm from RE



MBH03
435 mm from RE

MBHSP02

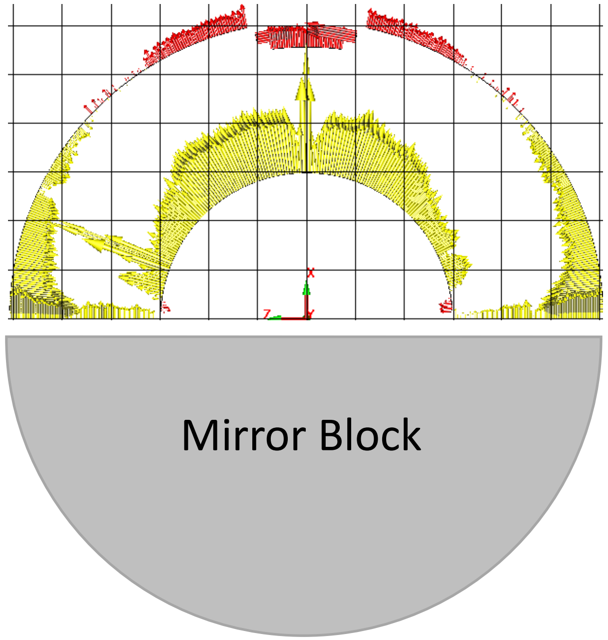
MBH05
479 mm from RE



MBH07
467 mm from RE

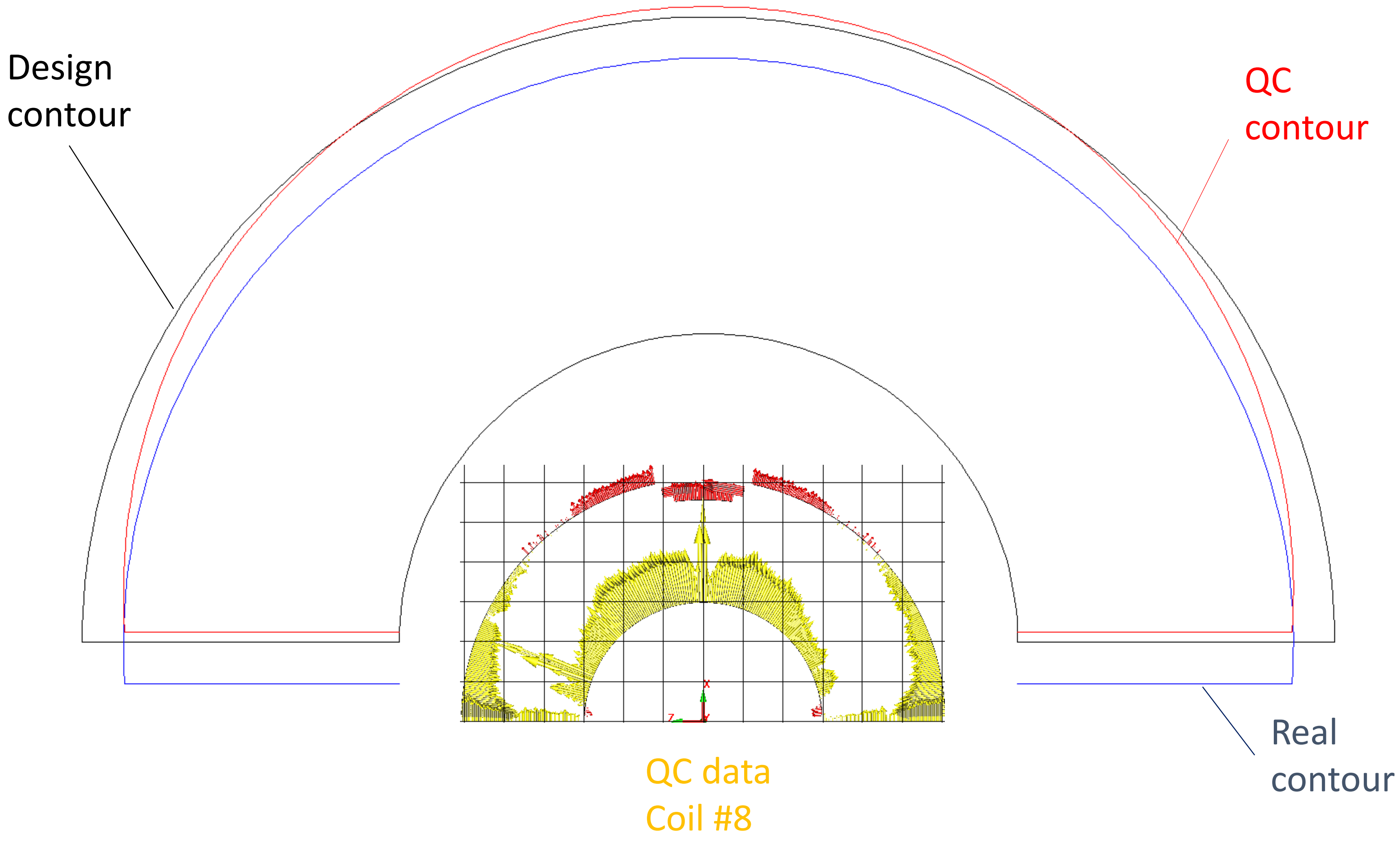
MBHSM01

MBH08
447 mm from RE



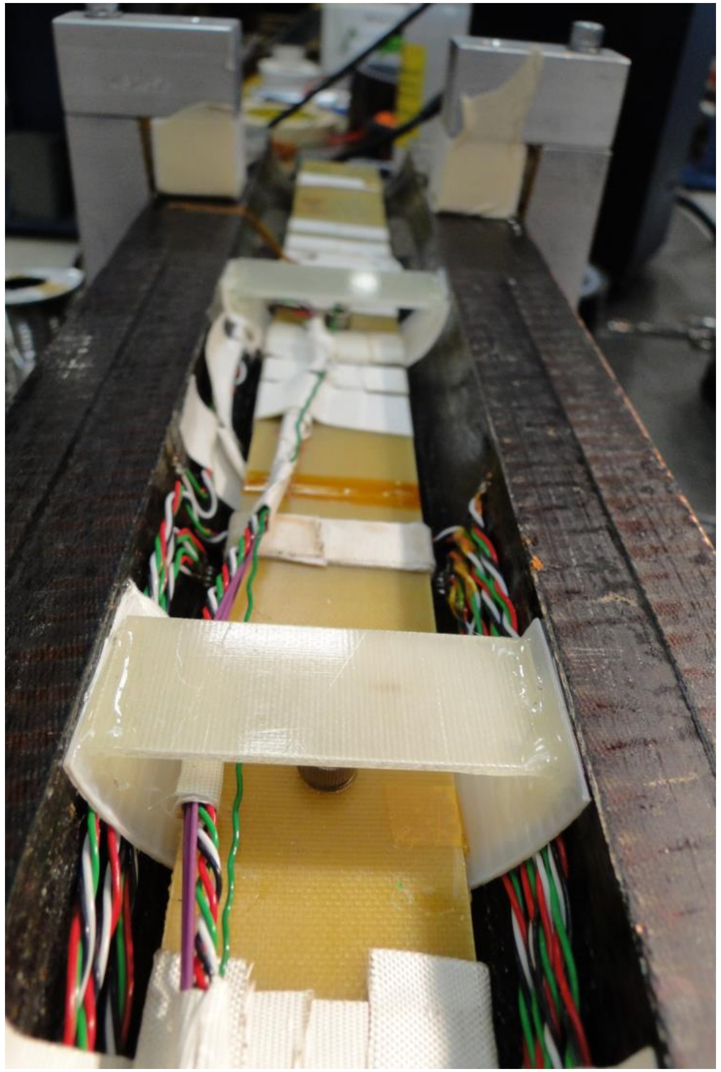
(1 box = 101.6 μm)

Coil Sizes

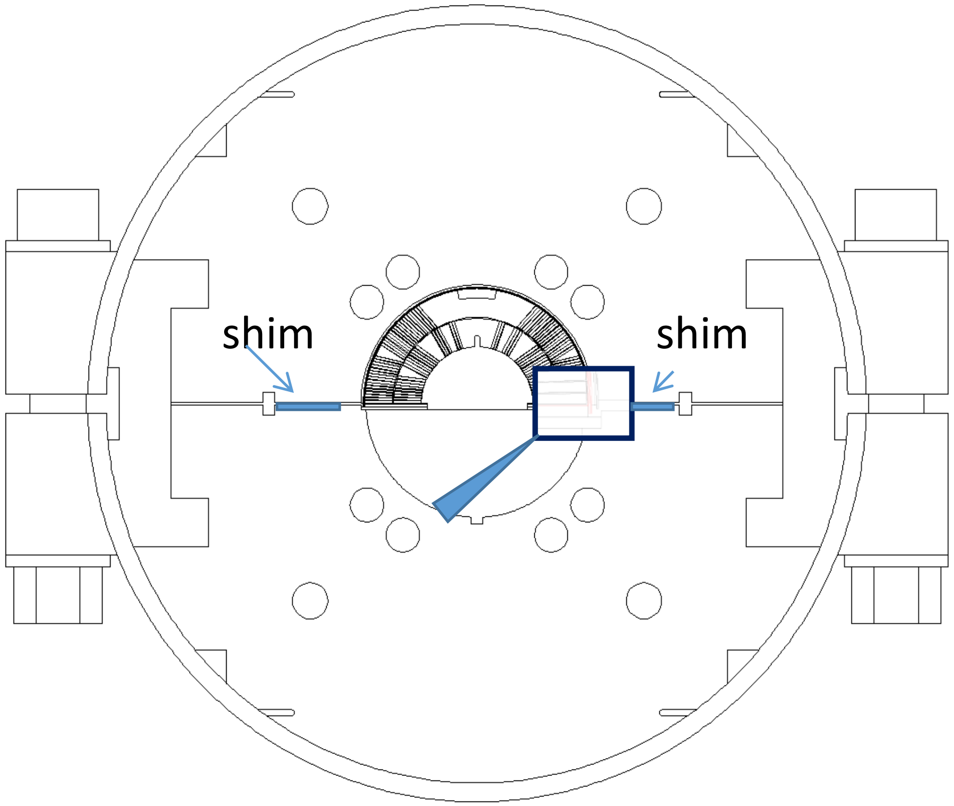


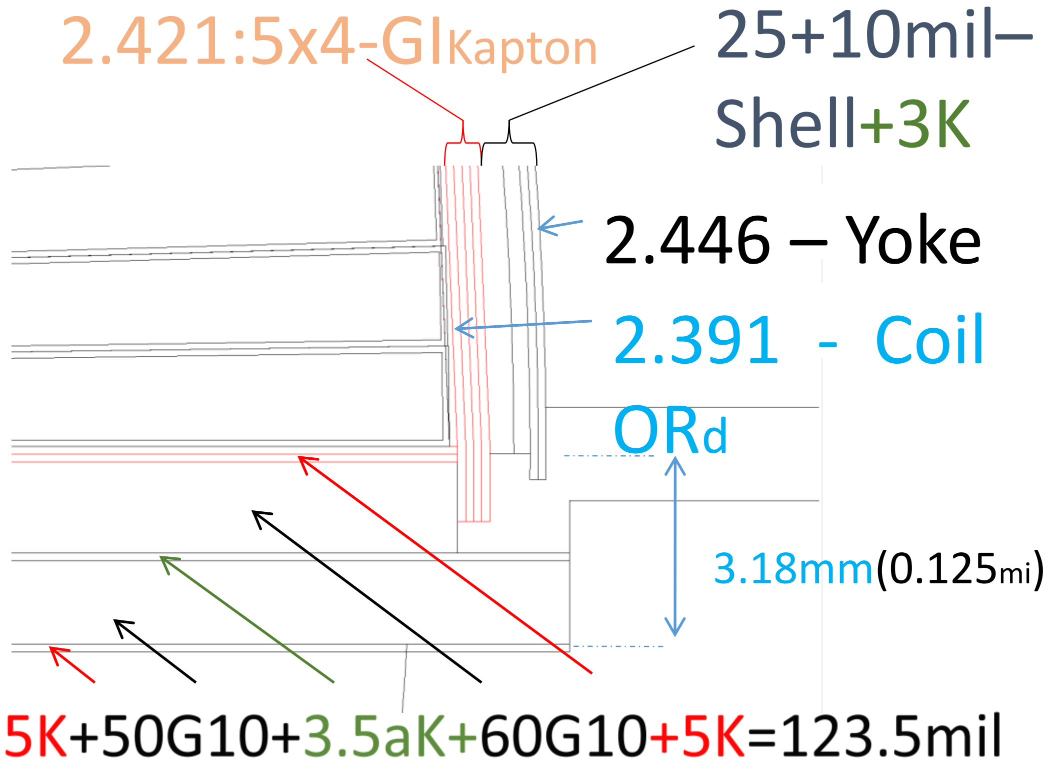
Coil #8 by 4mil smaller on OR and by 3mil bigger at MP wrt design
Coil #2 by 5mil smaller on OR and by 1mil bigger at MP wrt design

Coil #8 Instrumentation



MBHSM01 Shimming





MBHSM01 Test Results

MBHSM01 reached ~ 13 kA or (92-100)% of SSL at 4.5 K, and 14.1 kA or 89-97 % of SSL at 1.9 K

The stainless steel core, successfully implemented in this model, significantly reduced the magnet ramp rate sensitivity at the high current ramp rates

The magnet exhibited stable performance, no spontaneous quenches observed when "holding" 12 kA at 4.5 K and 13 kA at 1.9 K for ~ 25 minutes

MBHSP03

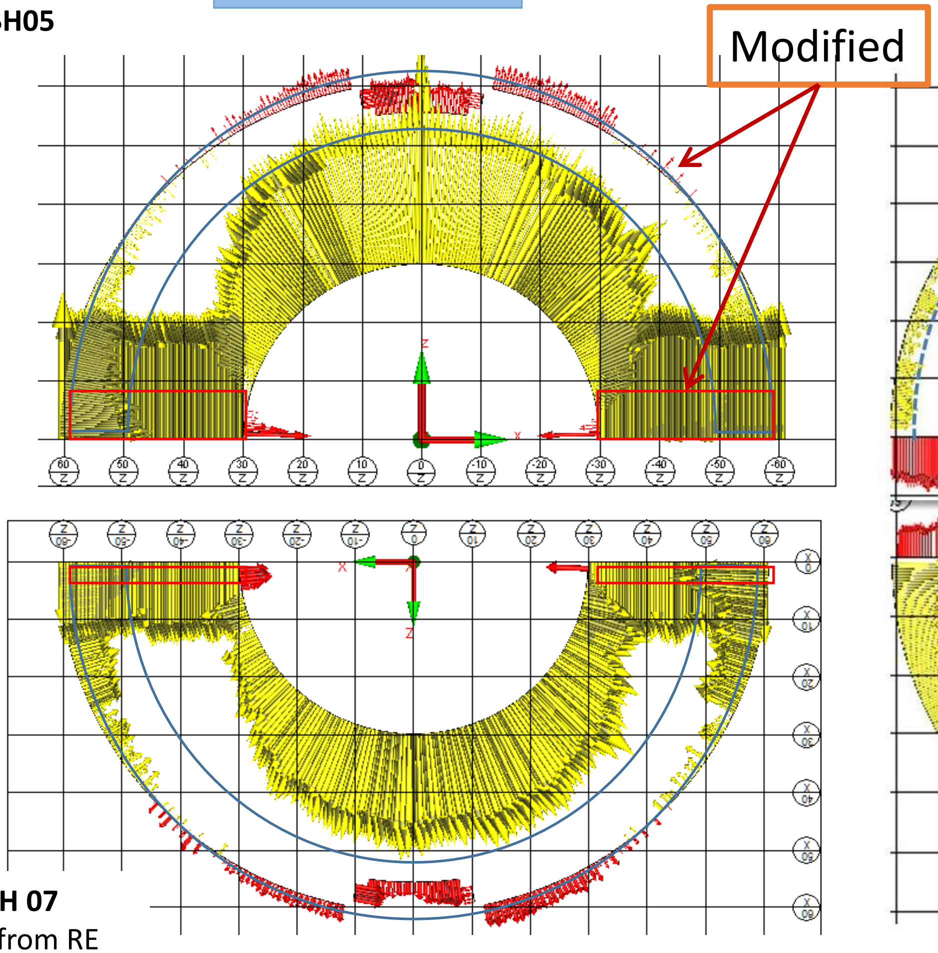
- RRP 108/127 conductor w core
- Modified ends
- New coil sizing
- New stamped collar with larger ID
- Thicker shoe
- Conservative coil prestress
- Mirror as target
- Less bending
- Vertically bolted skin
- Bolted end plates

"STATUS OF 11 T 2-IN-1 Nb3Sn DIPOLE DEVELOPMENT FOR LHC" presented at IPAC 2014 (Dresden, Germany)

Coil Sizes

MBHSP02

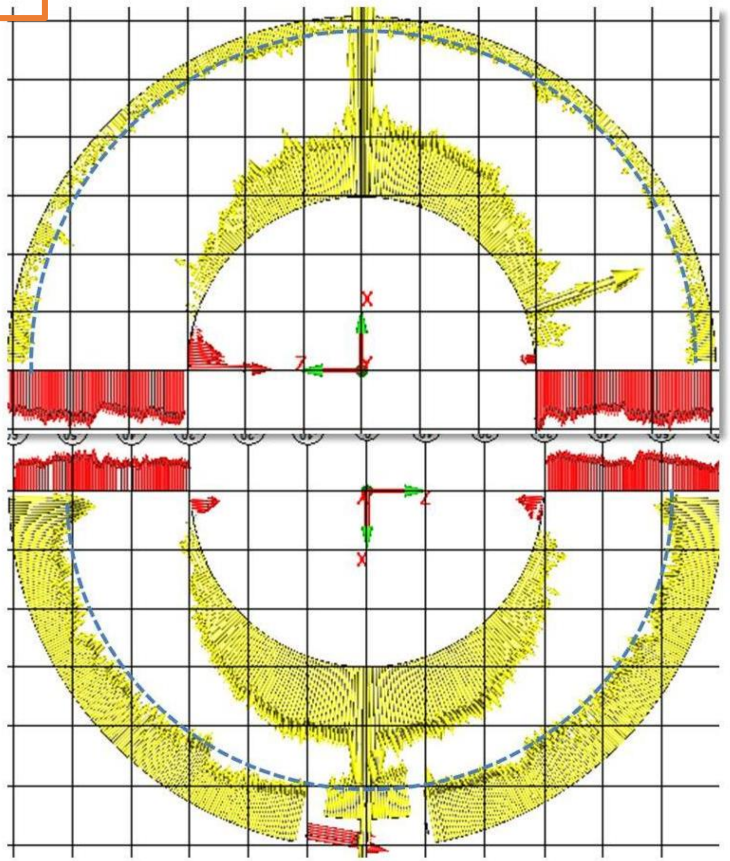
MBH05



MBH 07
262 mm from RE

MBHSP03

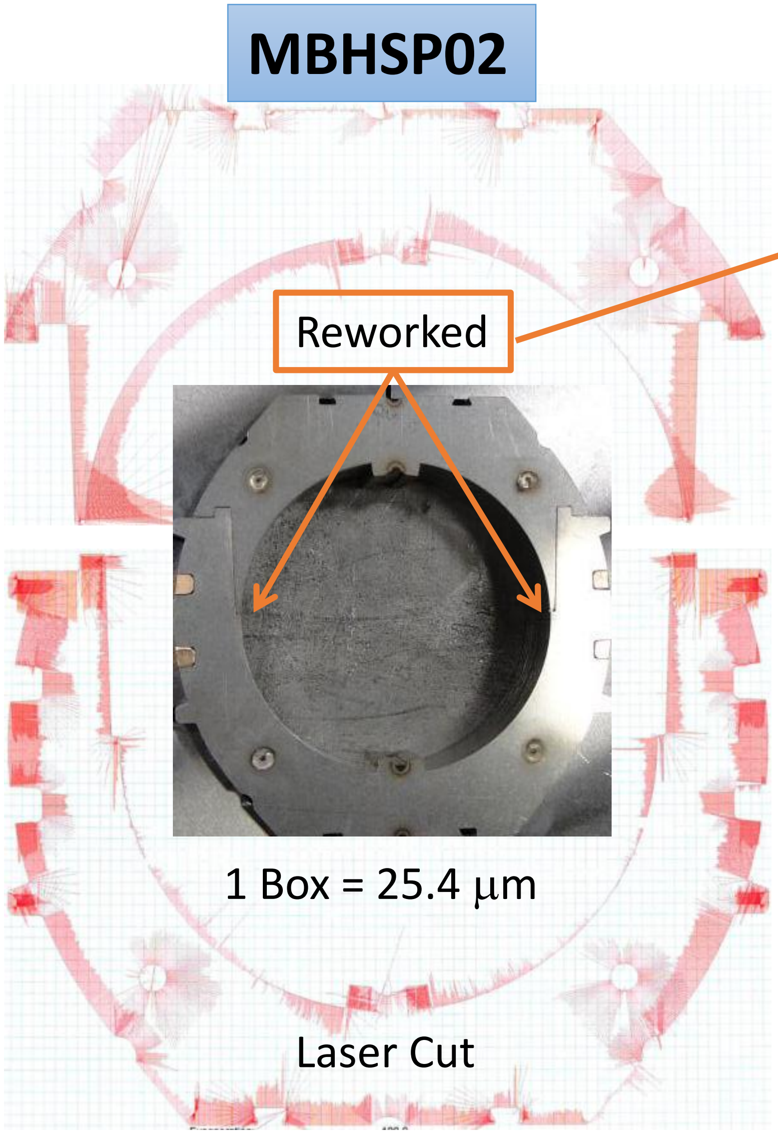
MBH10

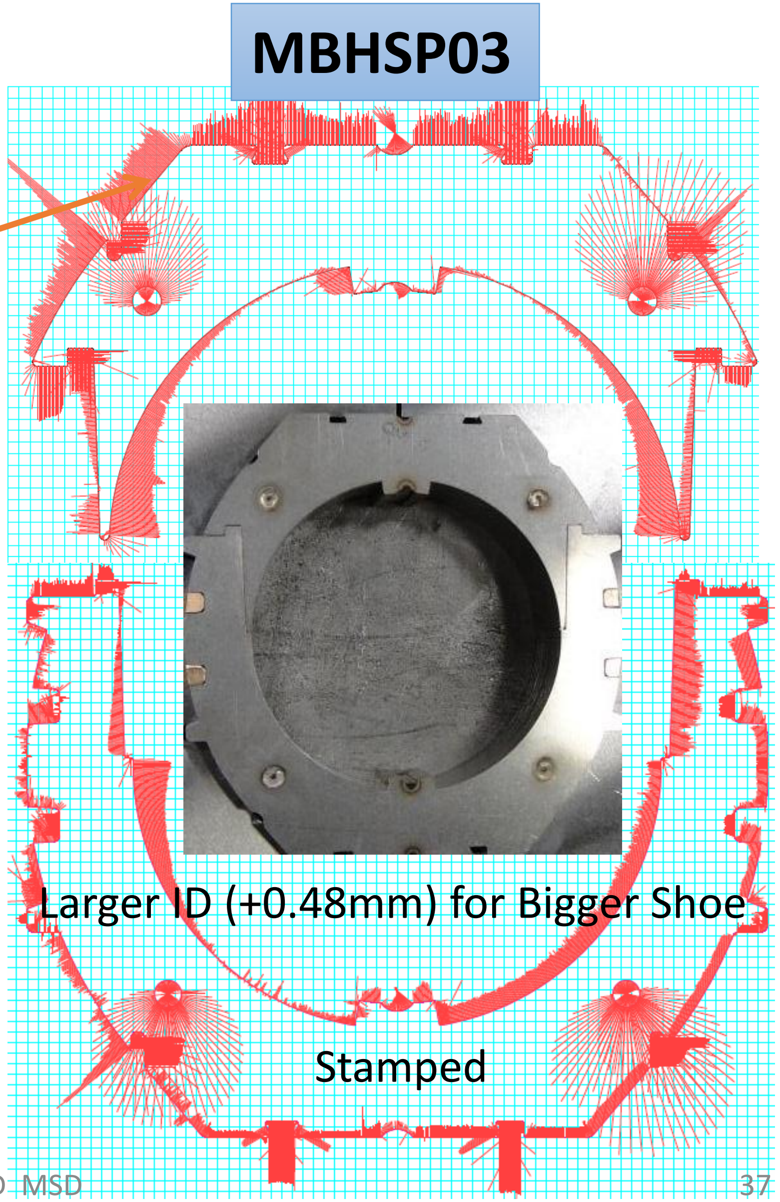


MBH09

Coil Bigger at MP

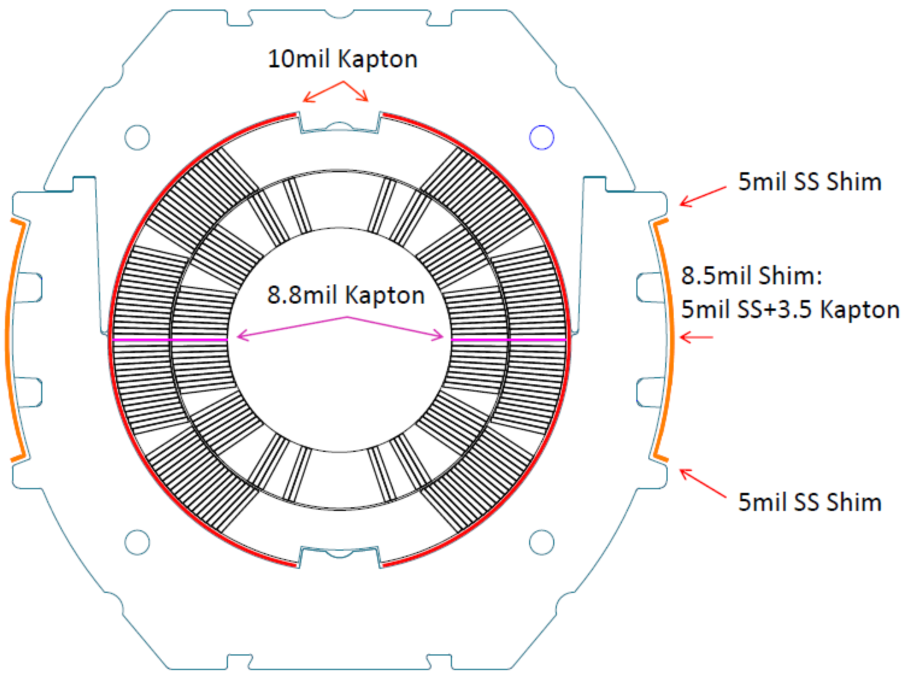
Collar Packs





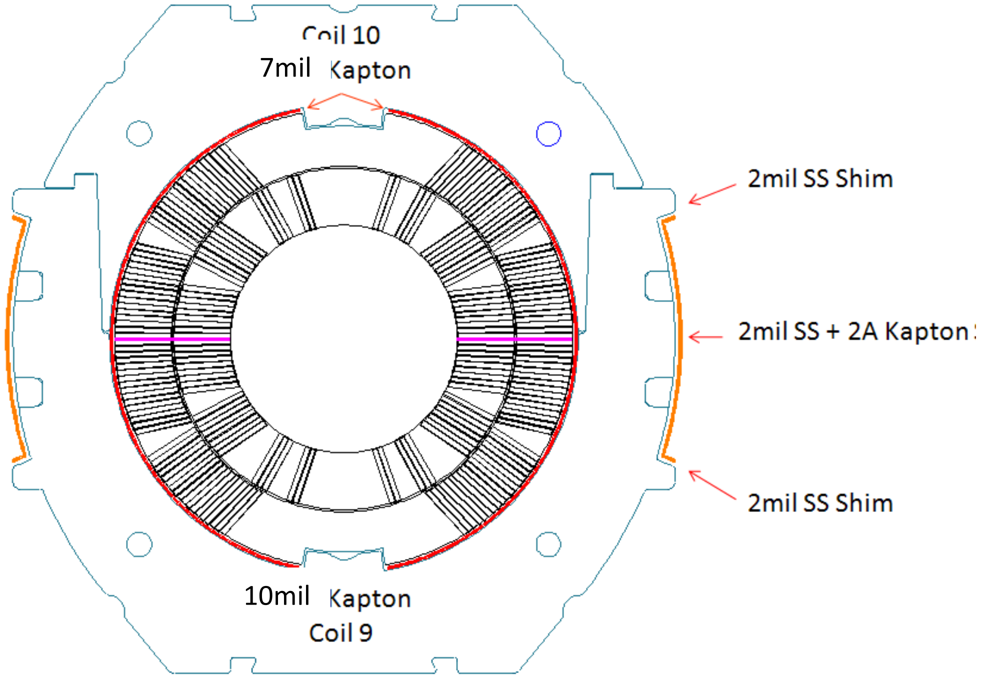
Shim Plans

MBHSP02



17mil Shoe
10mil Radial Shim
8.8mil MP Shim

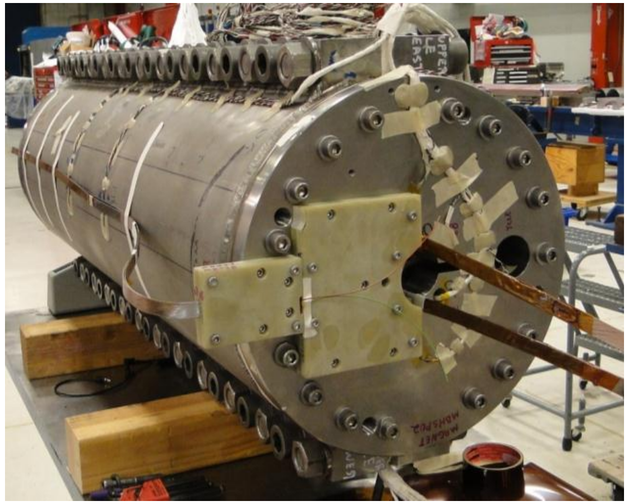
MBHSP03

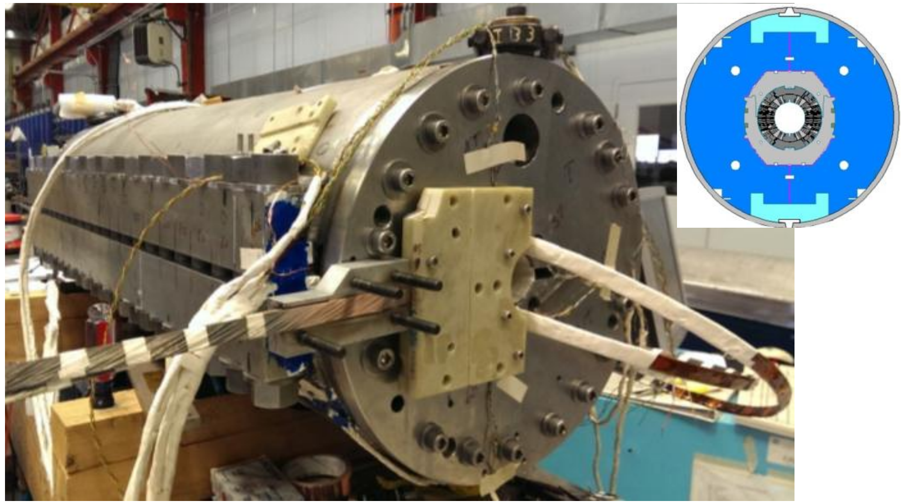


32mil Shoe
7 and 10 mil Radial Shim
0 MP Shim

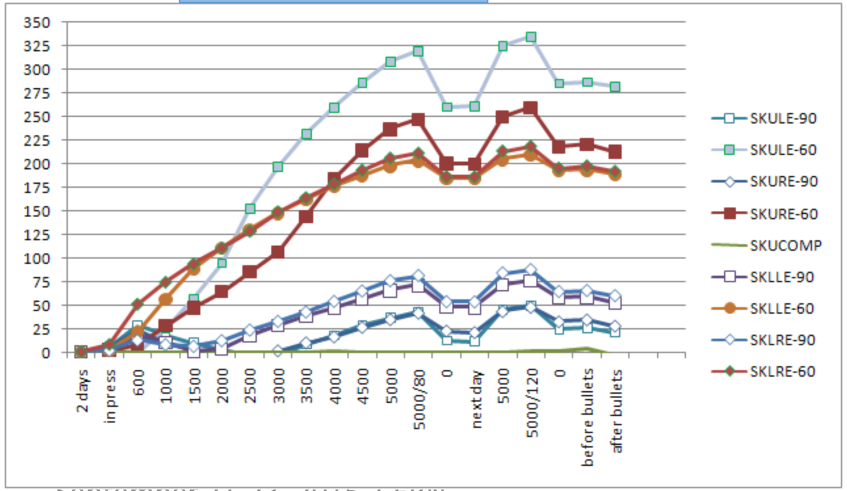
Magnet Assembly

Rotated 90°

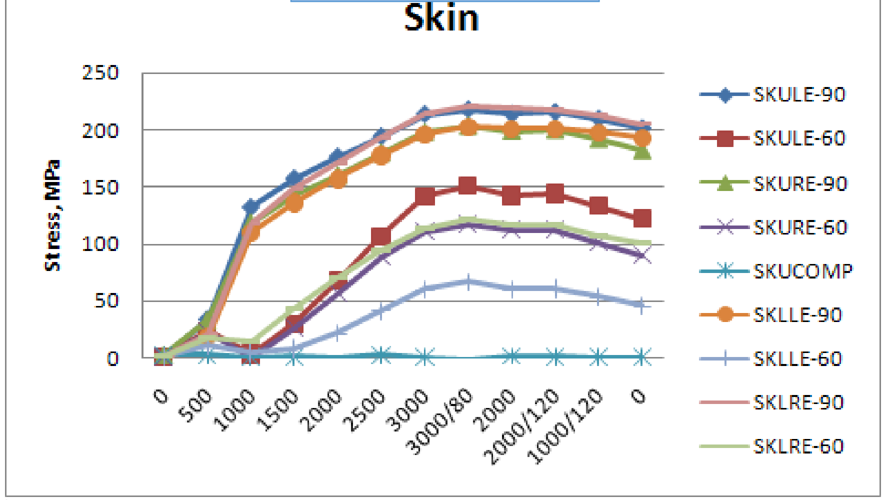




MBHSP02



MBHSP03



MBHSP03 Test Results

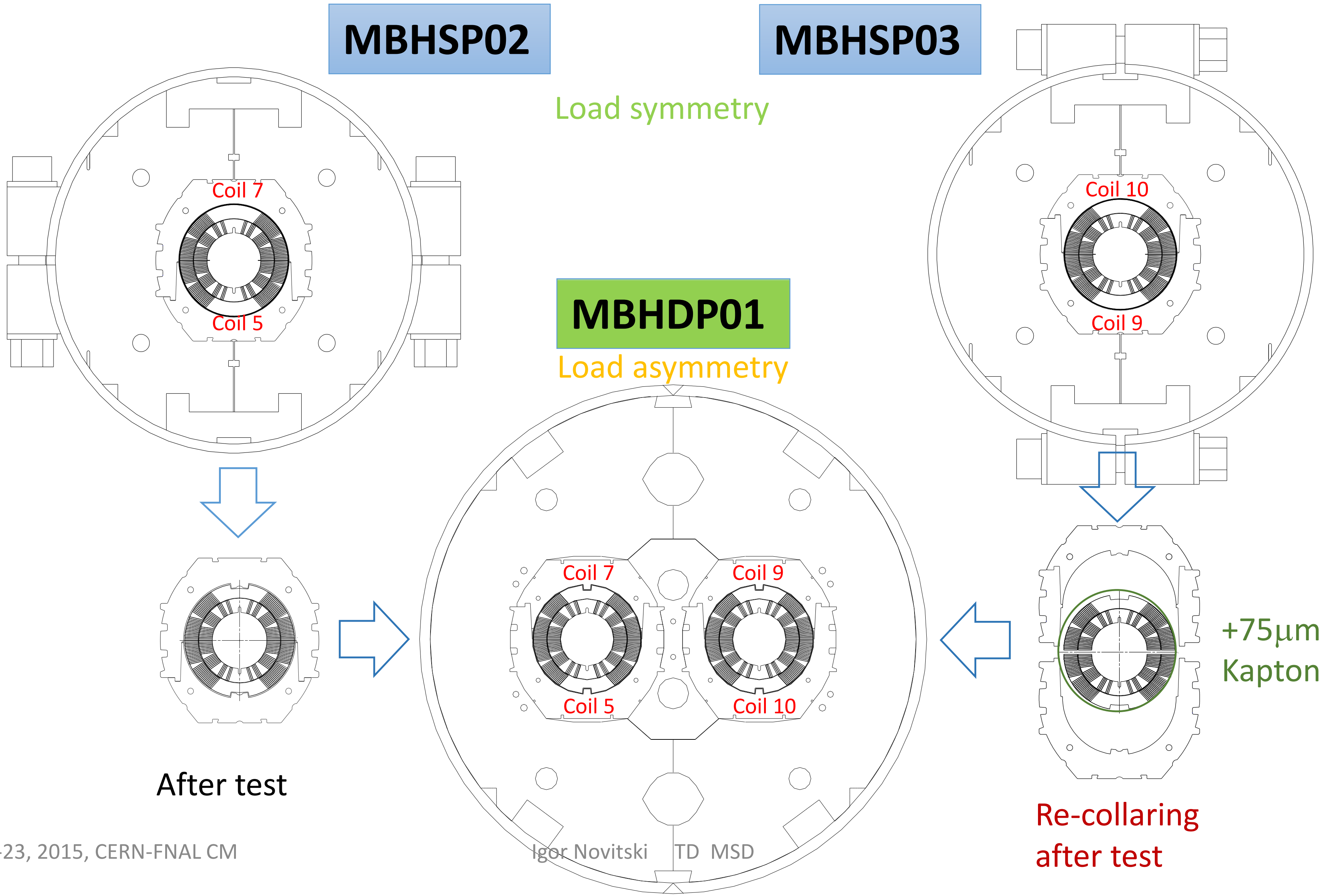
- MBHSP03 was trained to 11.2 T or 93.3% of the magnet design field.
- All the training quenches at 1.9 K occurred in the inner-layer high-field blocks.
- Quench current fluctuations, seen at the field level of 11 T, are likely due to epoxy cracking between the inner-layer pole blocks and coil pole turns caused by the conservative coil pre-stress in this model.
- To avoid possible conductor degradation the magnet training was interrupted.

MBHDP01

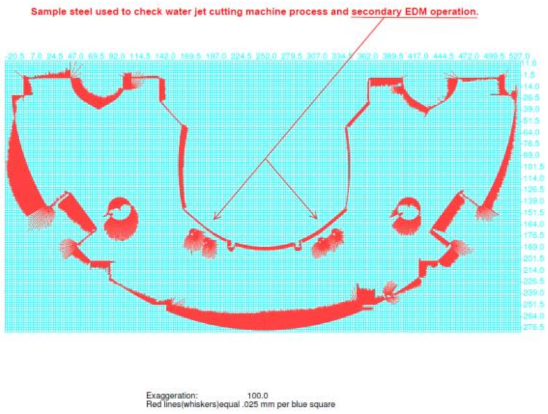
- First Nb3Sn twin aperture dipole magnet
- Tested collared blocks
- Symmetry of collar-yoke shimming
- Welded skin
- Welded end plates

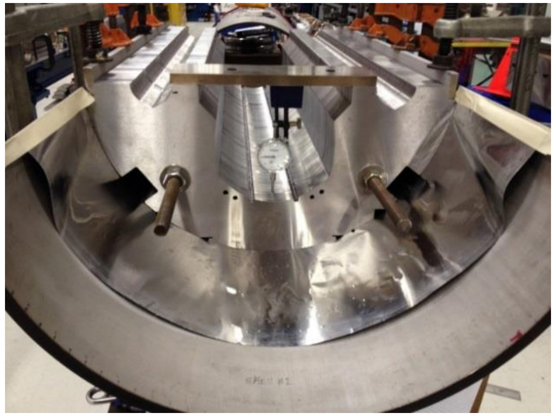
"STATUS OF 11 T 2-IN-1 Nb3Sn DIPOLE DEVELOPMENT FOR LHC" presented at IPAC 2014 (Dresden, Germany)
"11 T Twin-Aperture Nb_3Sn Dipole Development for LHC Upgrades" presented at ASC 2014 (Charlotte, USA)

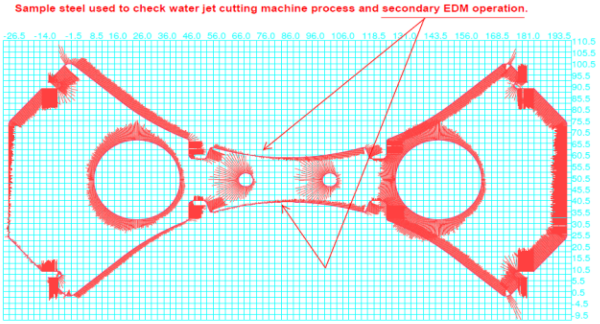
Twin-aperture Dipole: Coil History

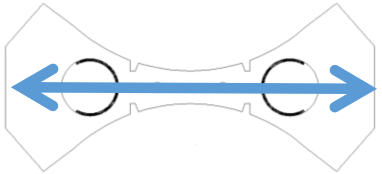


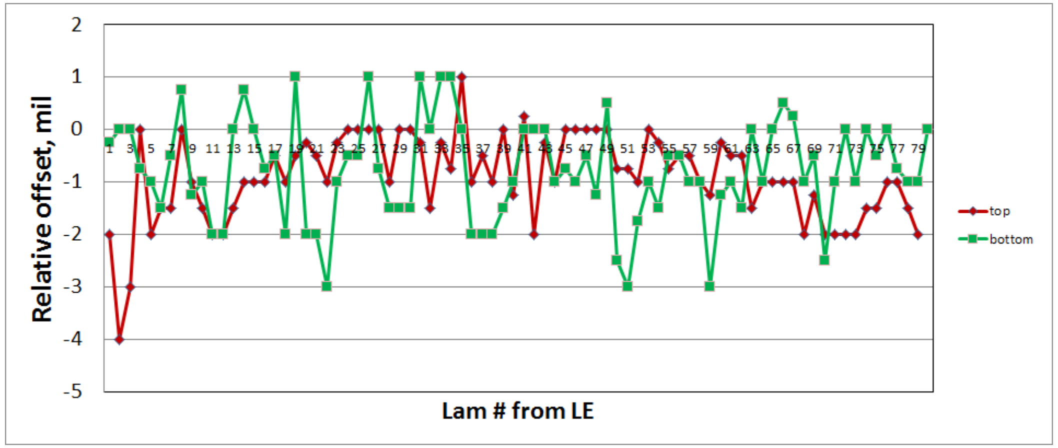
Iron Geometry

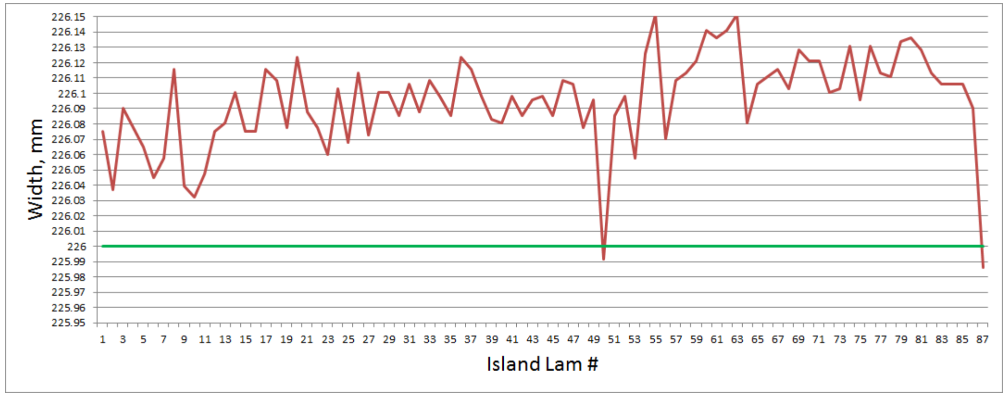




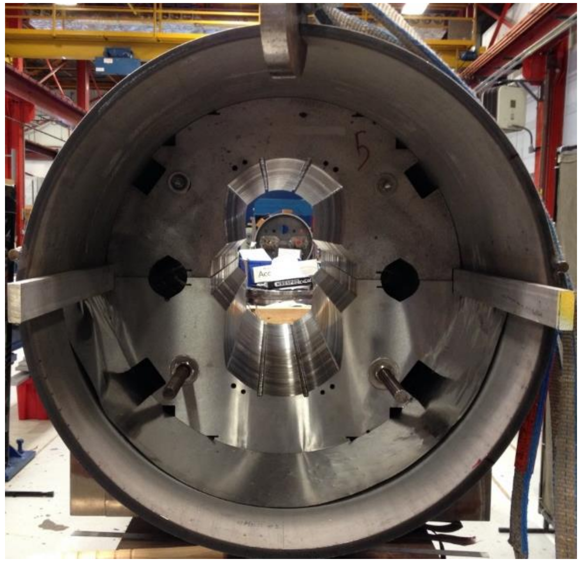


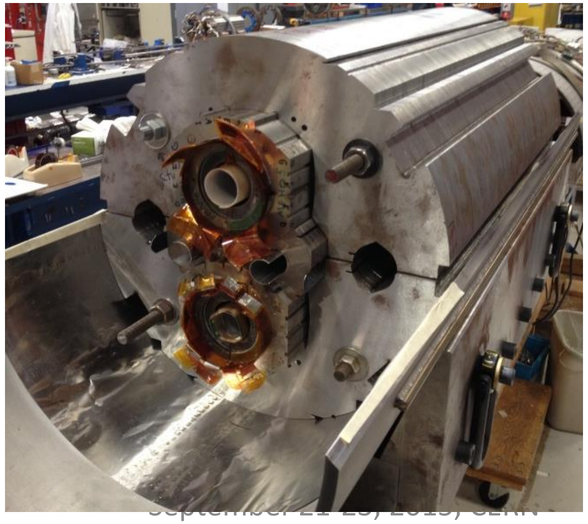


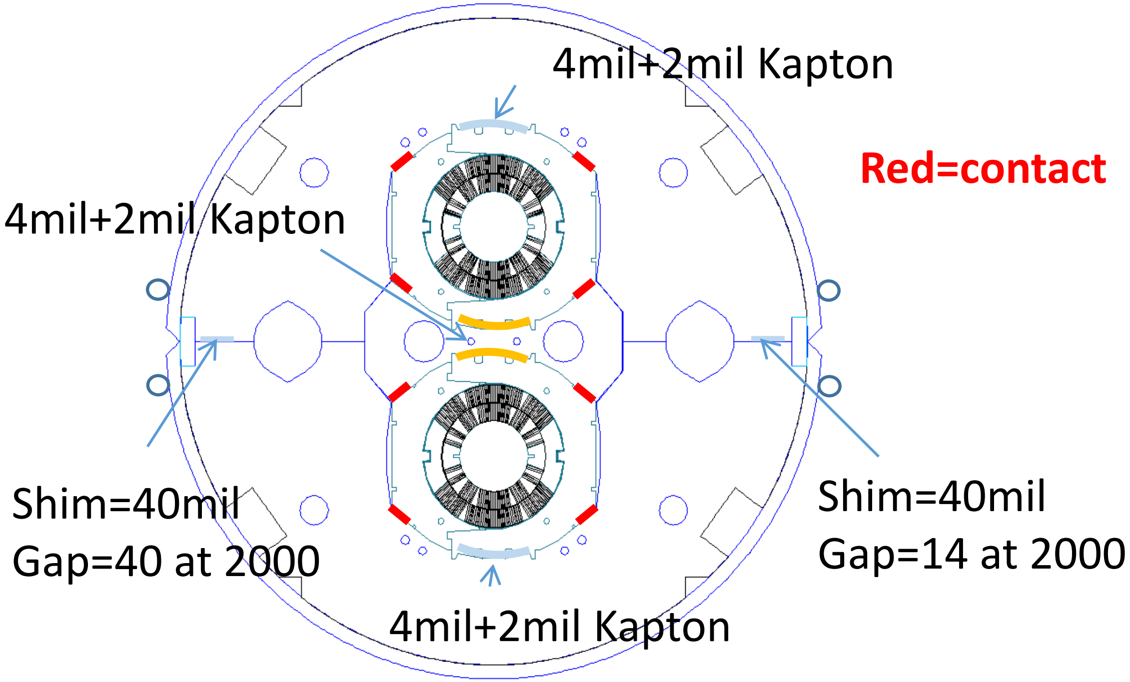


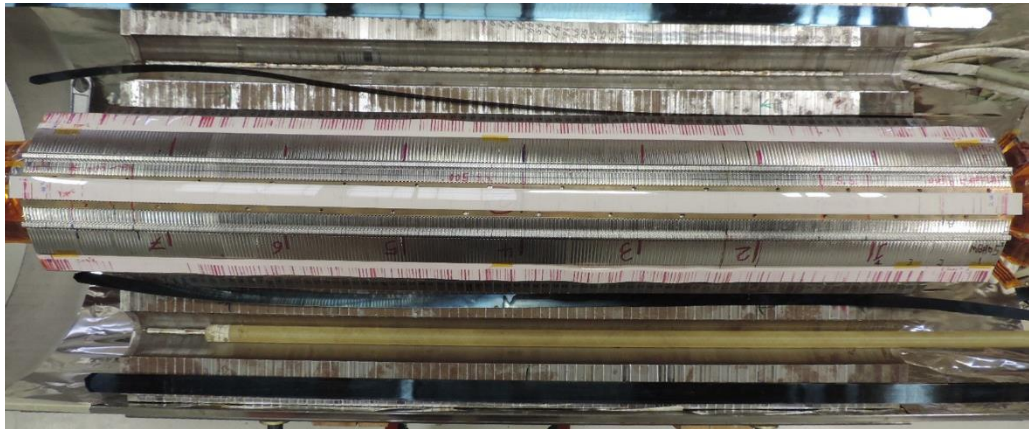


Geometry Check

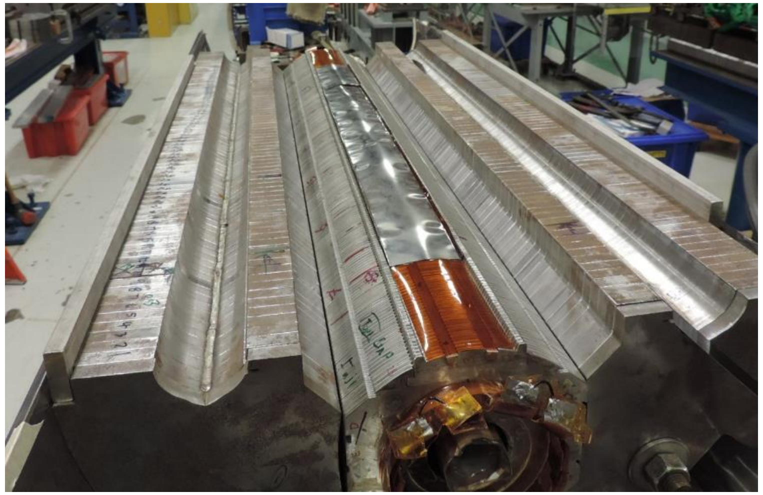


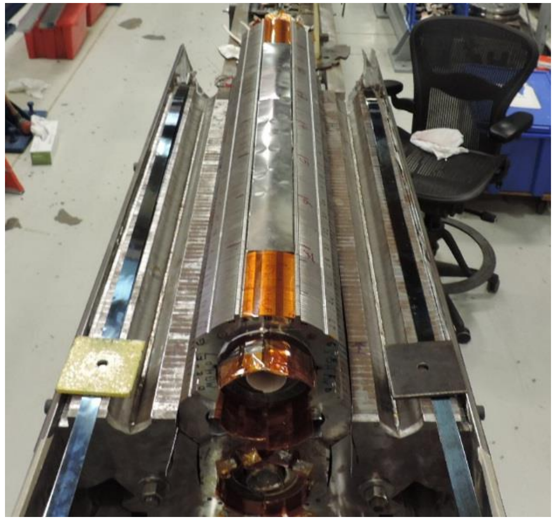


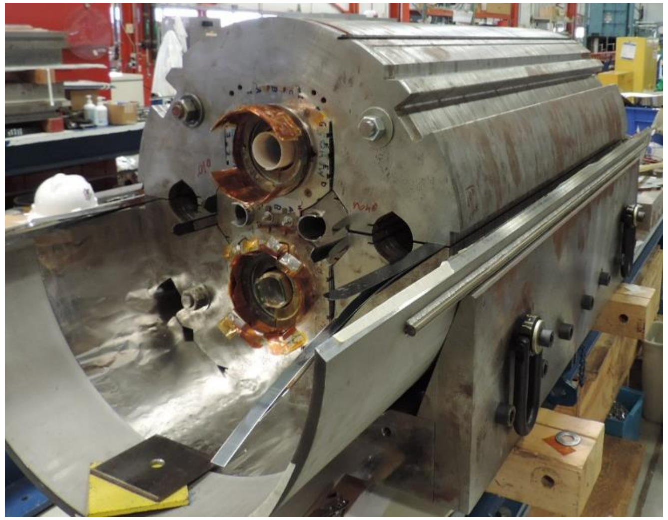


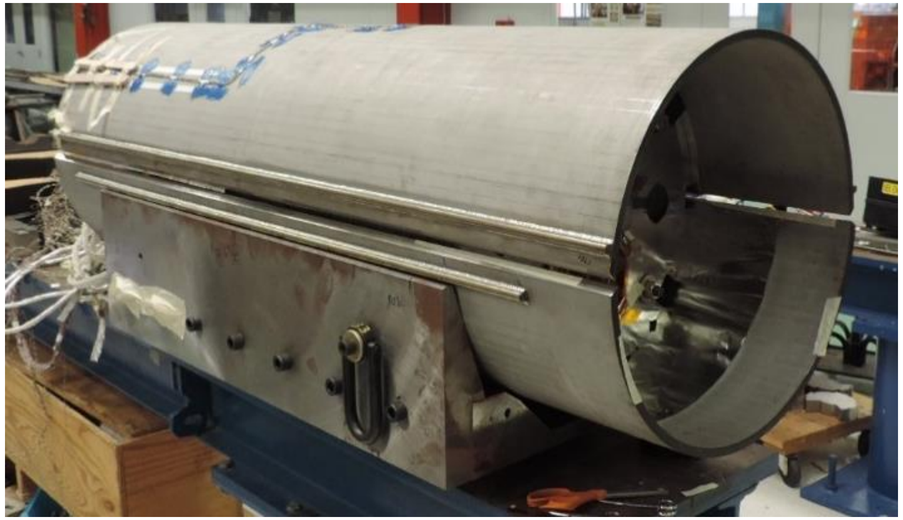


Magnet Yoking and Skinning



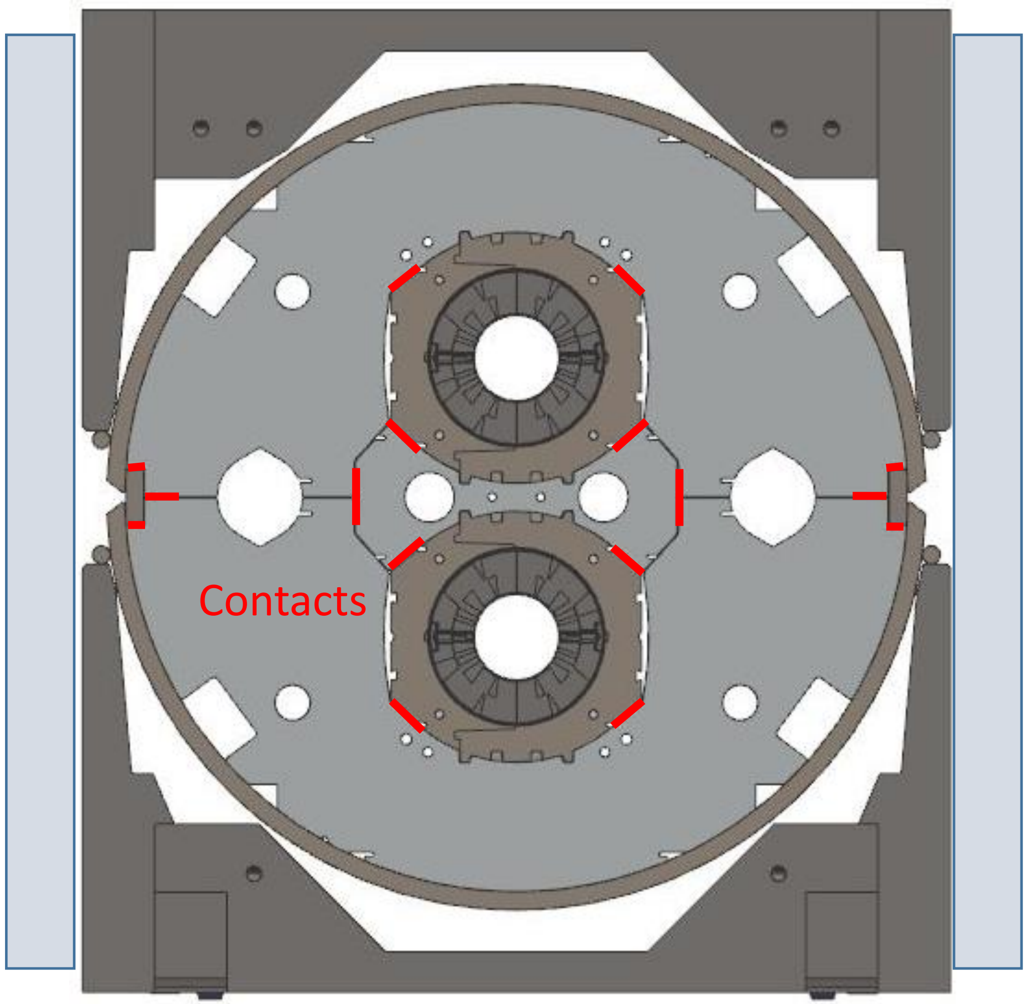




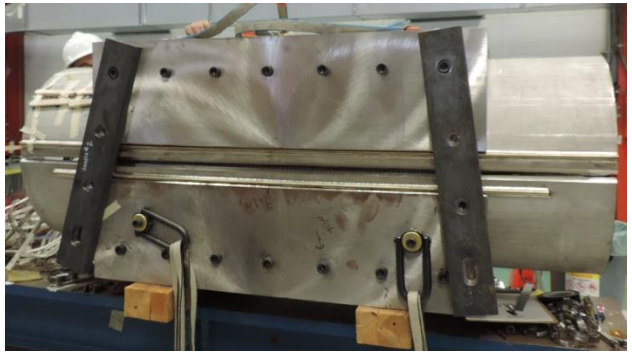


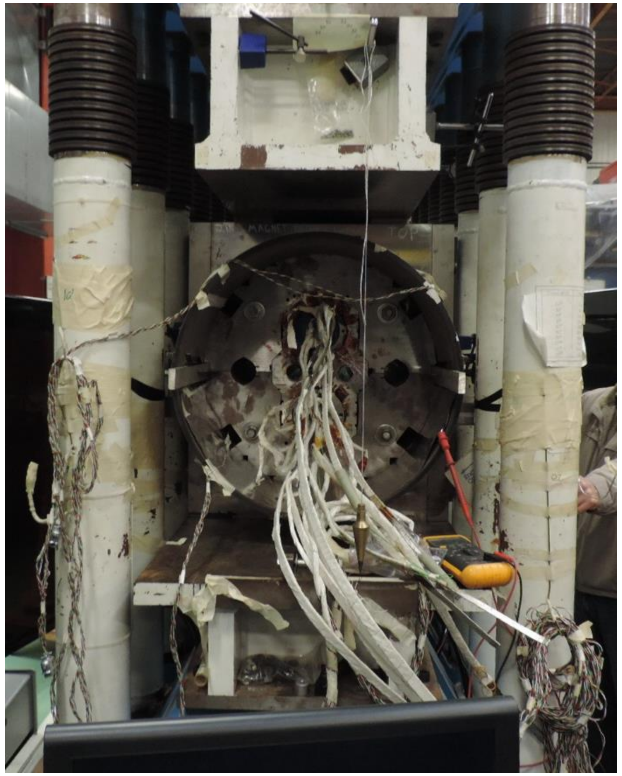
Skin Welding

Main pressure =1500psi

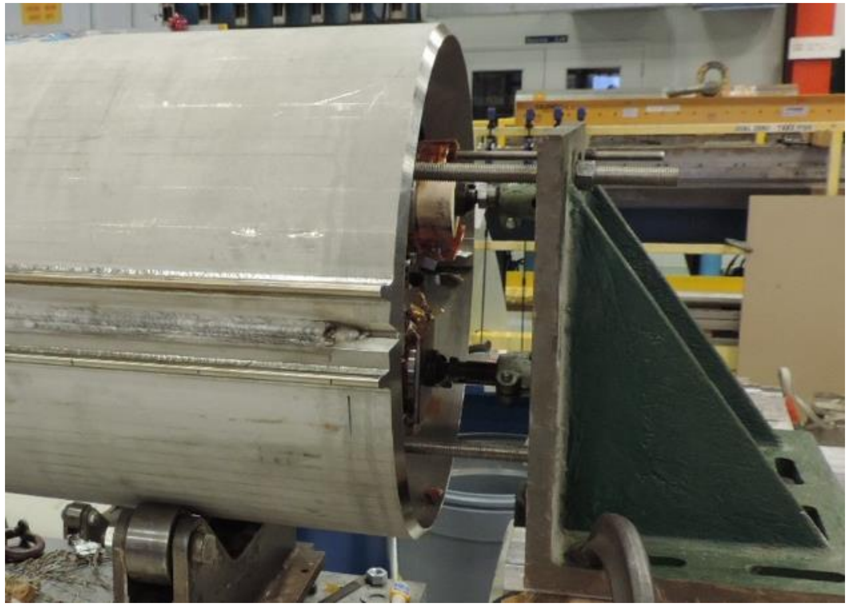


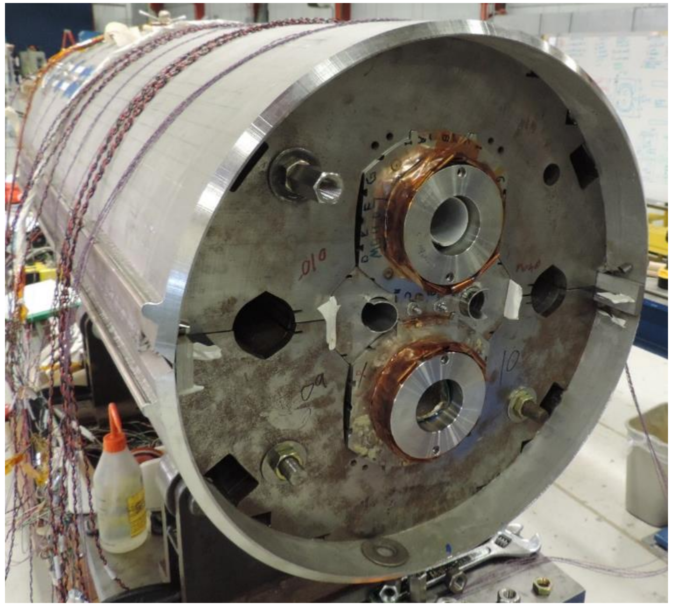
Side bars added for stability

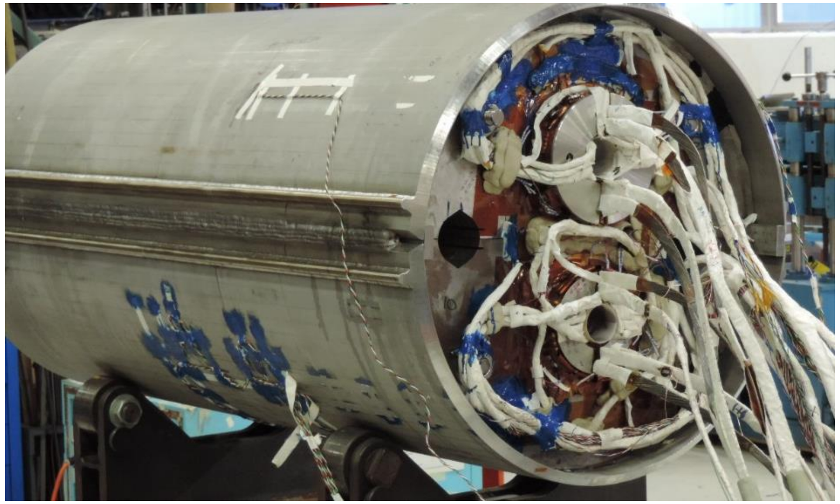


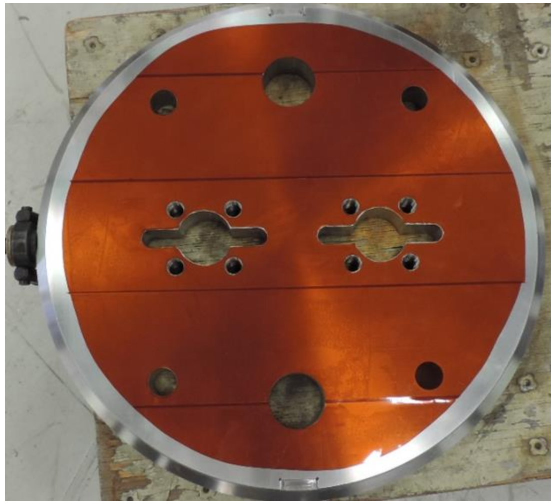


End Plates

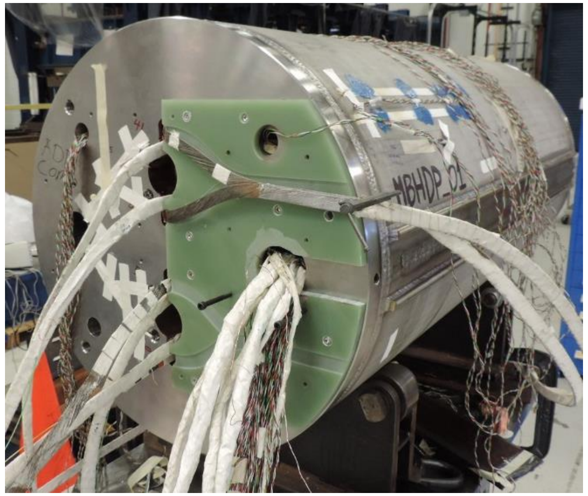


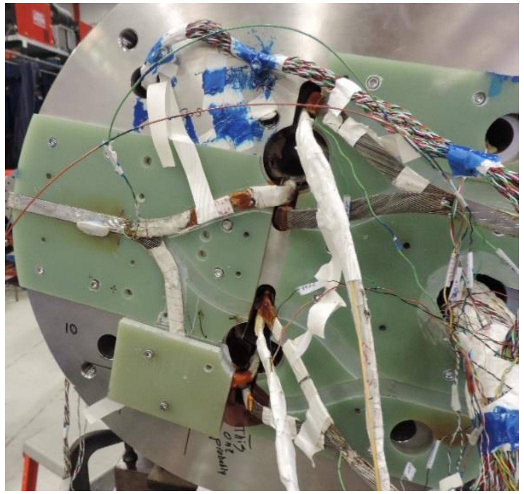


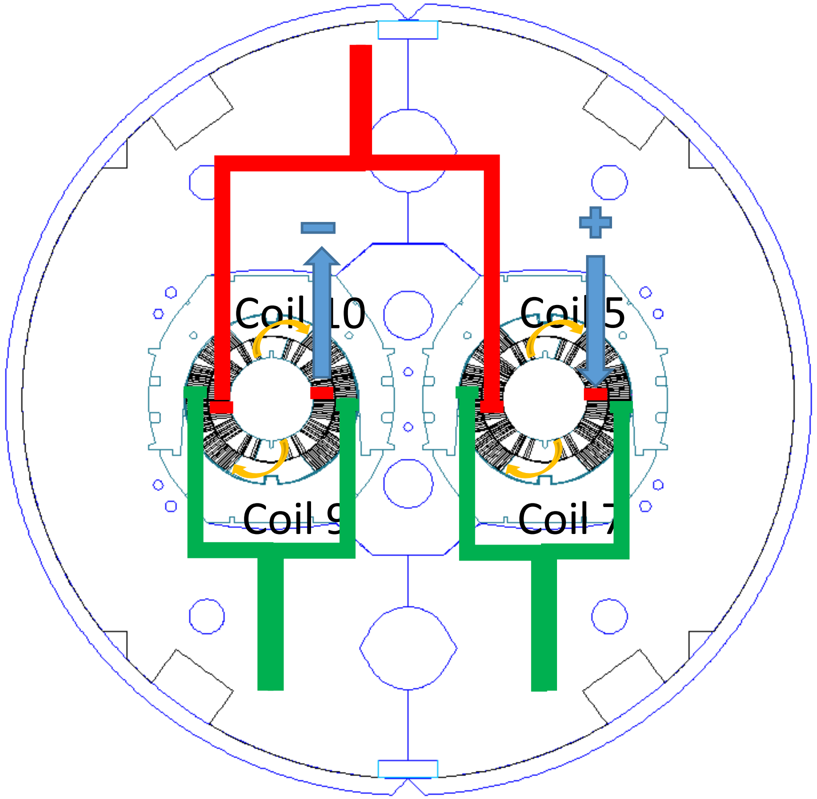




Leads Connection







MBHDP01 Test Results

The magnet reached a bore field of 11.5 T at 1.9 K, which is 97% of its design field, which is less than 1% lower than the maximum bore field obtained in the single-aperture models.
The magnet demonstrated similar quench performance which was limited by large conductor degradation in the collared coil used in MBHSP02. No additional coil degradation was introduced during re-assembly of one of the collared coils and twin-aperture dipole assembly process.
Magnetic measurements in one of the two apertures will be performed in the next test run.

"QUENCH PERFORMANCE OF THE FIRST TWIN-APERTURE 11 T DIPOLE FOR LHC UPGRADES" presented at IPAC2015,(Richmond, USA)

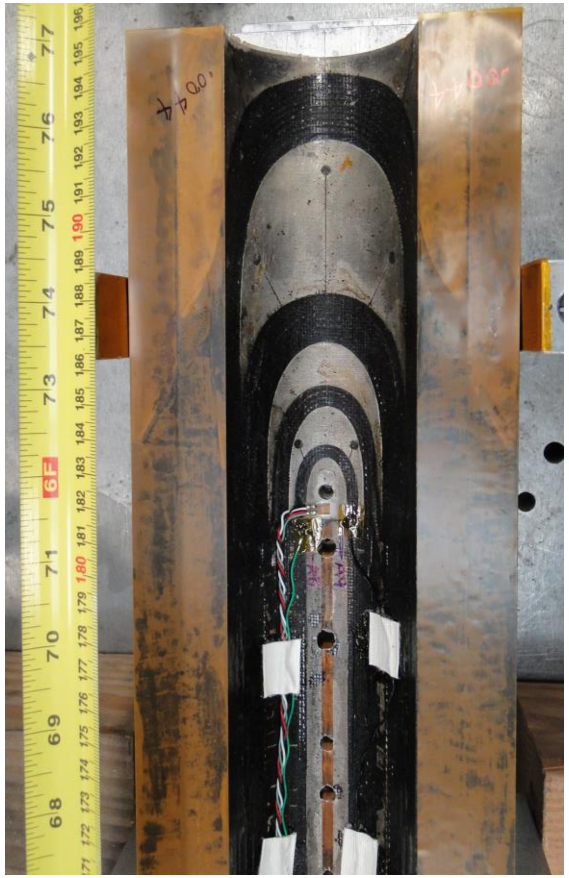
FABRICATION	MBHSP01	MBHSP02	MBHSM01	MBHSP03	MBHDP01
Coil used	MBH02 & 03 (2m long)	MBH05 & 07 (1m long)	MBH08 (1m long)	MBH09 & 10 (1m long)	MBHSP02 & MBHSP03(1m long)
Cable					
Strands	RRP 108/127	RRP 150/169	RRP 108/127	RRP 108/127	RRP108/127 (#2), RRP150/169 (#3)
Core width/ thickness, mm	no	SS 12/0.025	SS 12/0.025	SS 12/0.025	SS 12/0.025
Cable insulation thickness, in	E-Glass 0.005	E-Glass 0.005	E-Glass 0.005	E-Glass 0.005	E-Glass 0.005
Insulation orerlap, %	44.5	44.5	44.5	44.5	44.5
Witness Ic, A at 4.2K/1.9K 12T	413/423 583/597				
Coil Winding & Curing					
winding tension	1st-20, 35	1st-20, 35	1st-20, 35	1st-20, 35	1st-20, 35
End parts		Shortened leg length & saddle midplane reducing gap between current block and L2 coil spacer	Coil 8 (no slits)	Shortened leg length of end parts. Coil 9 (no slits), Coil 10 (no slits)	
Curing shim in/out, mm	1.0/1.0	1.0/1.5	0.8/1.3	0.8/1.3	
Curing pressure/temp	MBH02 & 03 (2m long)	MBH05 & 07 (1m long)	MBH08 (1m long)	MBH09 & 10 (1m long)	MBHSP02 & MBHSP03(1m long)
Coil Reaction					
HT cycle	72 h at 210C, 48 h at 400C, 48 h at 640C	72 h at 210C, 50 h at 400C, 50 h at 633C(#2), 640(#3)	72 h at 212C, 48 h at 402C, 48 h at 642C	72 h at 212C, 48 h at 402C, 48 h at 649C	
Mandrel shim, mm	0	0	0.2	0.2	
Form block shim, mm	0	0	0.2	0.2	
Coil Impregnation					
Mandrel shim	0	0	0.2	0.2	
Form block shim	0	0	0.2	0.2	
Mold relized OR shim, mm	0	Kapton/	0.254 mylar	0.2	
Coil CMM Data					
Midplane size, mm	-0.025 & -0.025	-0.050 & -0.050	+0.100	+0.100 & +0.125	
Radial size, mm	-0.100 & -0.100	-0.100 & -0.100	-0.100	-0.100 & -0.050	
Collared Coil Assembly					
Coil shim at midplane, mm	0.223	0.223	0	0	0
Coil shim radial, mm	0.178	0.25 w/ tapered ends	0.075	0.25 (#9)/0.178 (#10)	0.25 (#9)/0.178 (#10)+0.075/0.075
Quench heater thickness	0.025 mm S.S.	0.025 mm S.S.	0.025 mm S.S.	0.025 mm S.S.	0.025 mm S.S.
Quench heater to coil ins. Kapton	0.250 mm/0.125 mm	0.125 mm	0.125 mm	0.125 mm	0.125 mm
Coil retainer thickness, mm	0.5	0.5	2 layer; 0.89	2 layer; 0.813	2 layer; 0.813
Collars	laser cut	laser cut, reworked at midplane	No collars	stamped, larger ID	Colladed #2 & recollared #3
Pressure main/side, psi	6000/8000	6000/8000		4000/10000	5000/10000 (#3)
Clamped Yoke Assembly					
Iron split orientation	vertical	vertical	horizontal	vertical	vertical
Collar-Yoke shim plan, mm	Graded: 0.24 MP --> 0.216 --> 0.19	0.216 w/ tapered ends	0 mm	0.114 mm	0.127 mm
Pressure main/side, psi	4000/4000	4000/5000	4000/4000	3000/4000	
Final Assembly					
Shell split orientation	vertical	horizontal	horizontal	vertical	vertical
Shell type	welded, auto	bolt on	bolt on	bolt on	welded by hand
Pressure main, psi	1000 in weld press	5000	5000	3000	2000
Skin stress az. (90/60), MPa	(30/60): 290/310	50/200	370/160	200/100	180/140
Coil stress az. (MP/Pole), MPa	-42/-62	-57/-60	-80/-26	-55/-25	-70/-50, -85/-30
Bullet load LE/RE, lbs	4x1000/4x1000	4x1000/4x950	2x1000/2x950	4x1000/4x1000	8x1100/8x1000
Lead length, mm	1000 & 500	1000 & 1000	1000 & 1000	1000 & 1000	1000 & 1000
Fabrication Time					
	9/16/11-5/22/12 (8+ months)	7/25/12-2/4/13 (6+ months)	3/8/13-11/1/13 (7+ months)	3/8/13-4/10/14 (1+ yr)* *Includes mirror magnet assy & test	8/20/14-1/15/15 assy

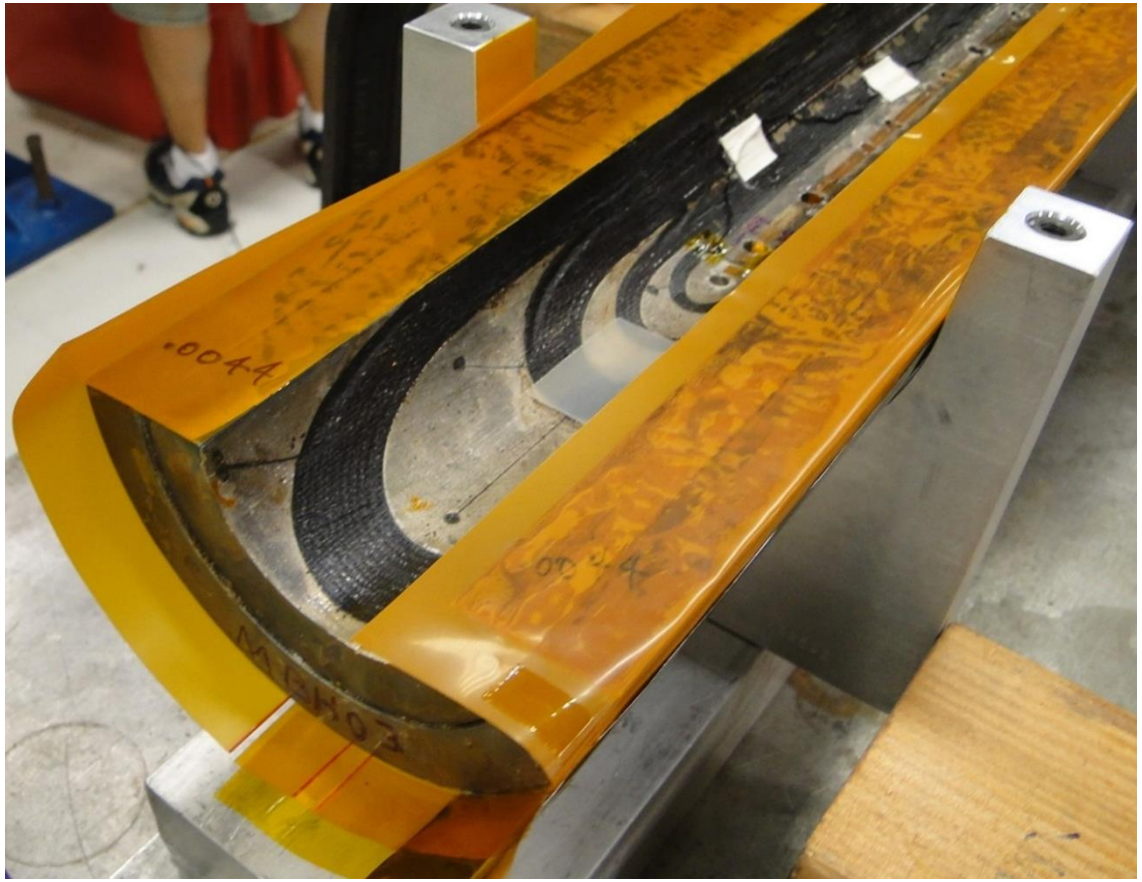
Back Up Slides

MBHSP01

Coil Ground Insulation

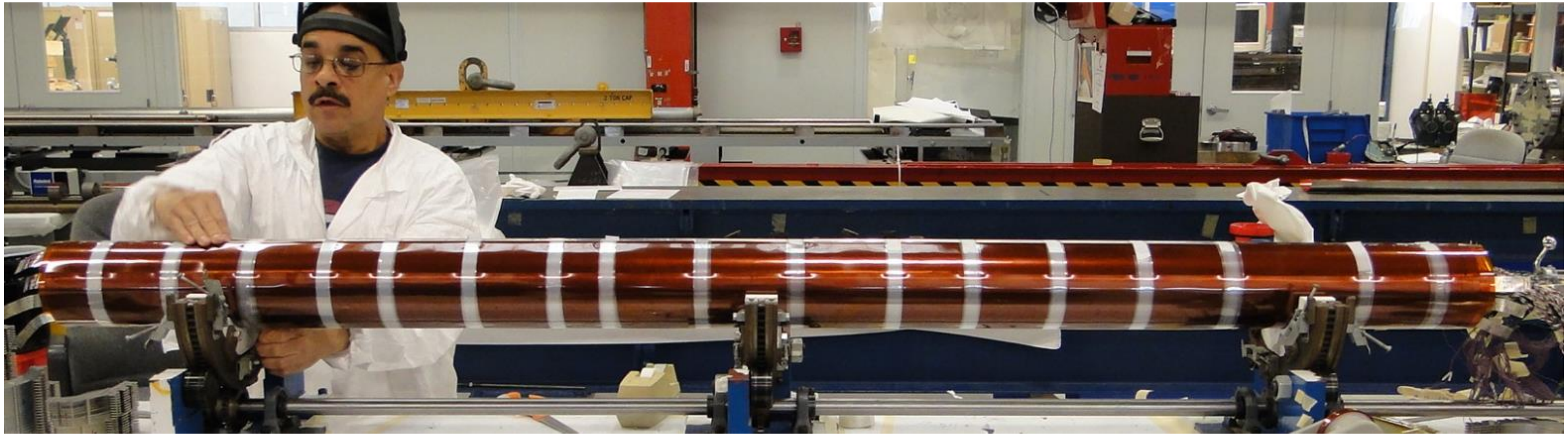
112um(4.4mil) thick pre-preg Kapton ironed to the coil





Coil placement on the rotation station

Ground Insulation Final Wrap



FEA Result

4K

300K

Coil Straight section

-329 ← -132

197

dR in mic at coil MP OR before and after CD

Splice with SS cylinder

-264 ← -80

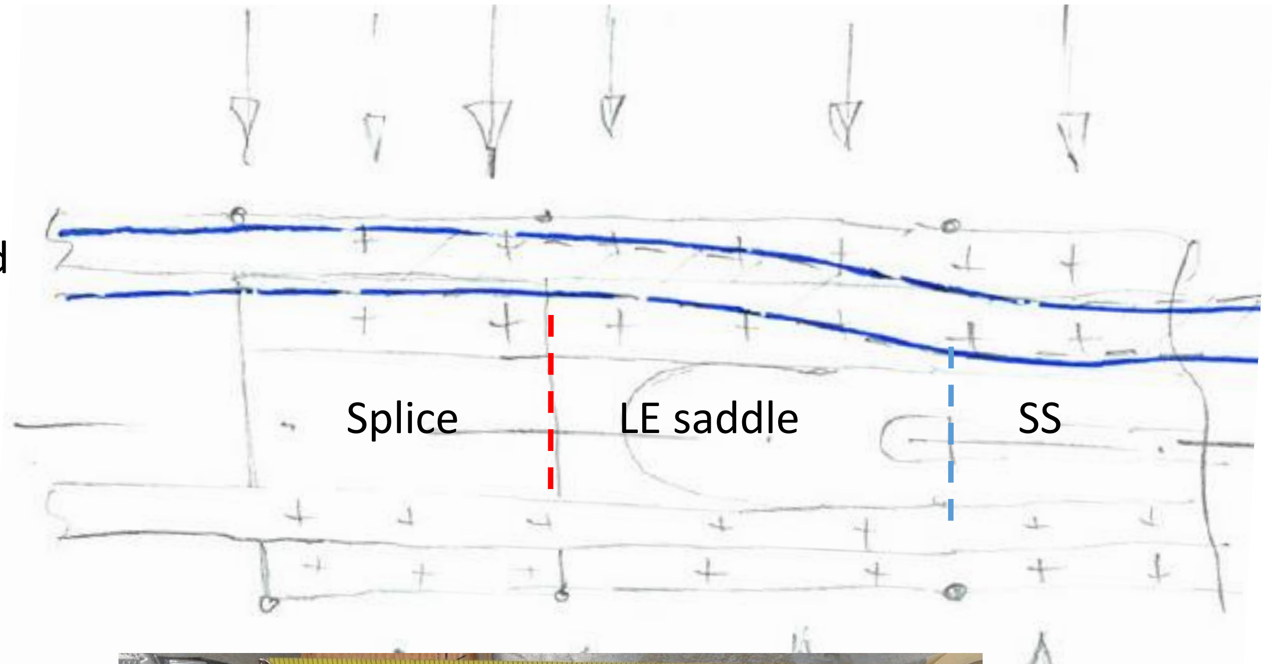
184

Splice with AlBr cylinder

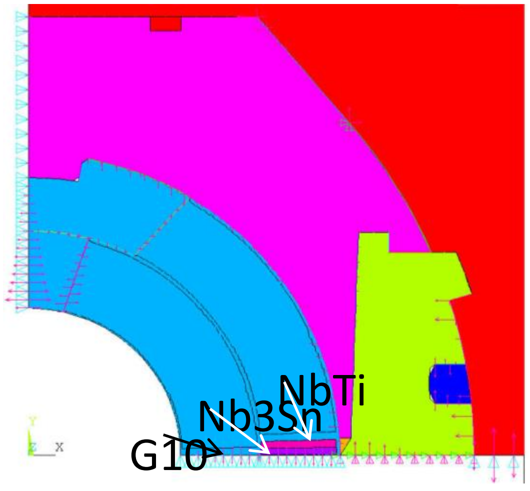
-315 ← -102

213

Radial Load at the Magnet Lead End



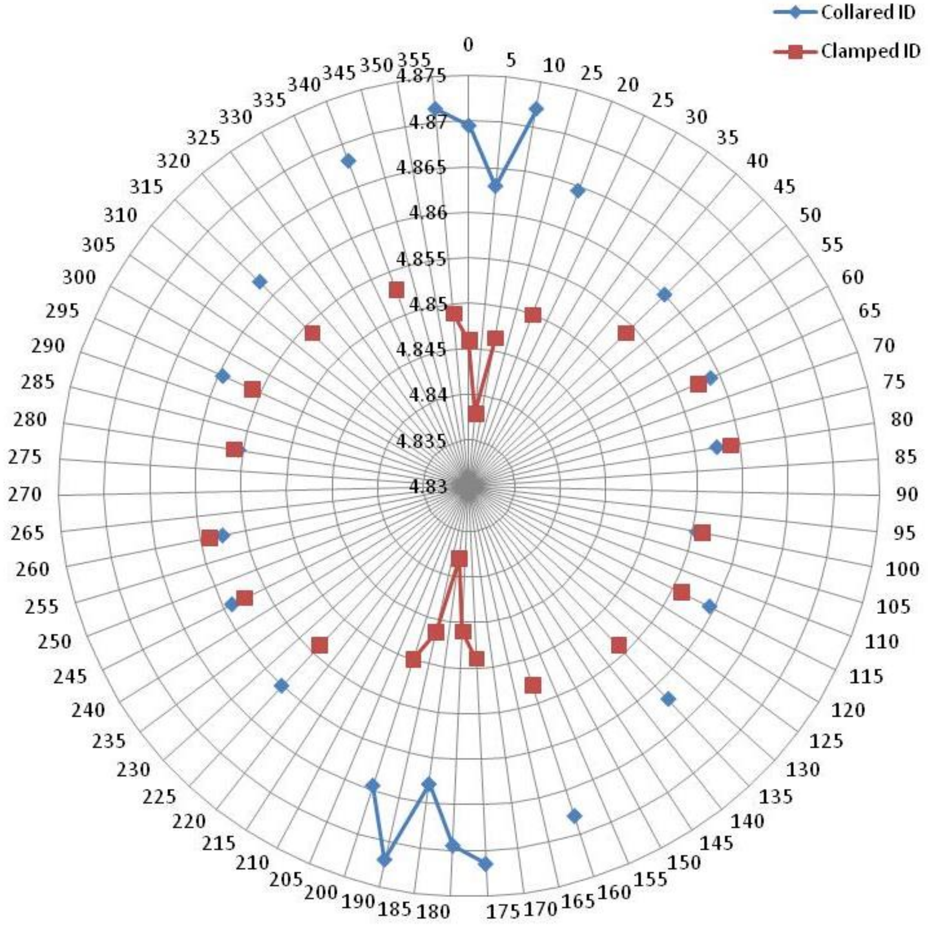
FEA Model of the
Magnet Splice Block

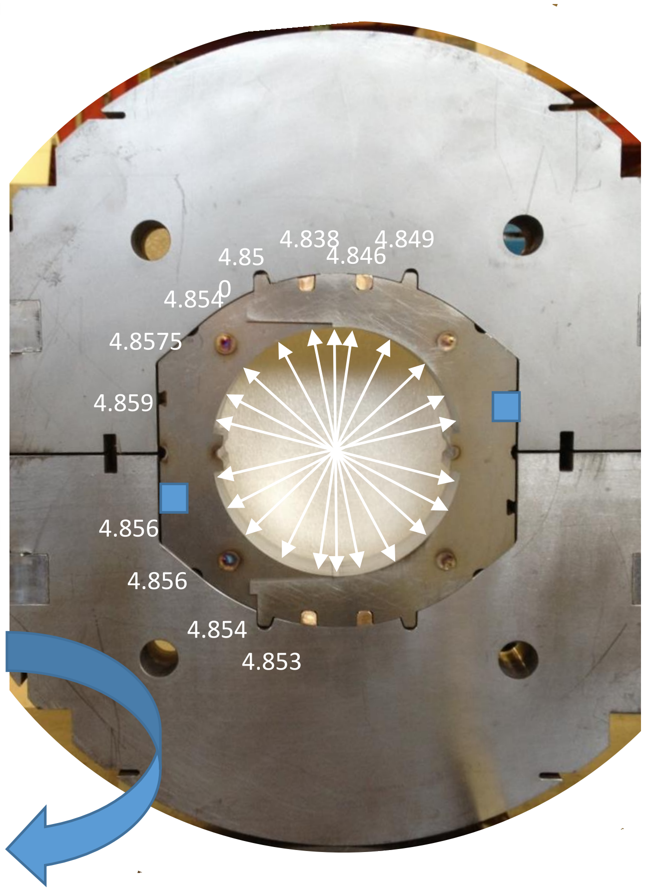


MBHSP02

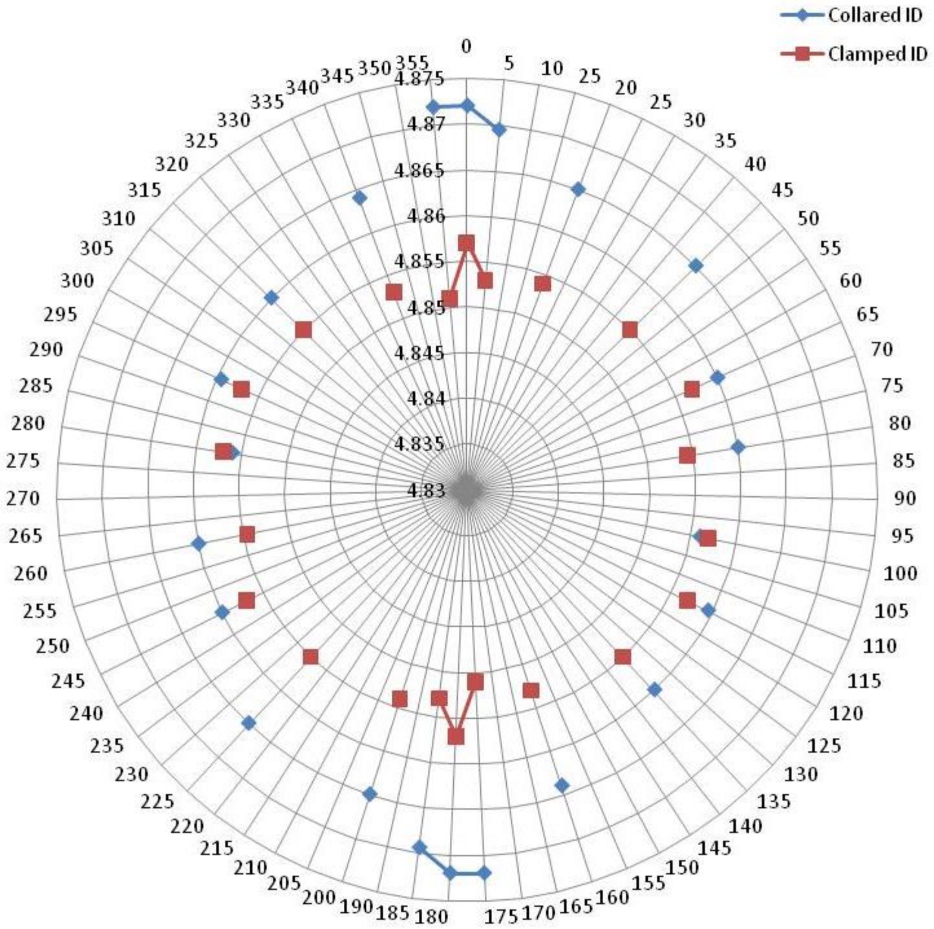
Reworked Collar Packs

Unused Pack

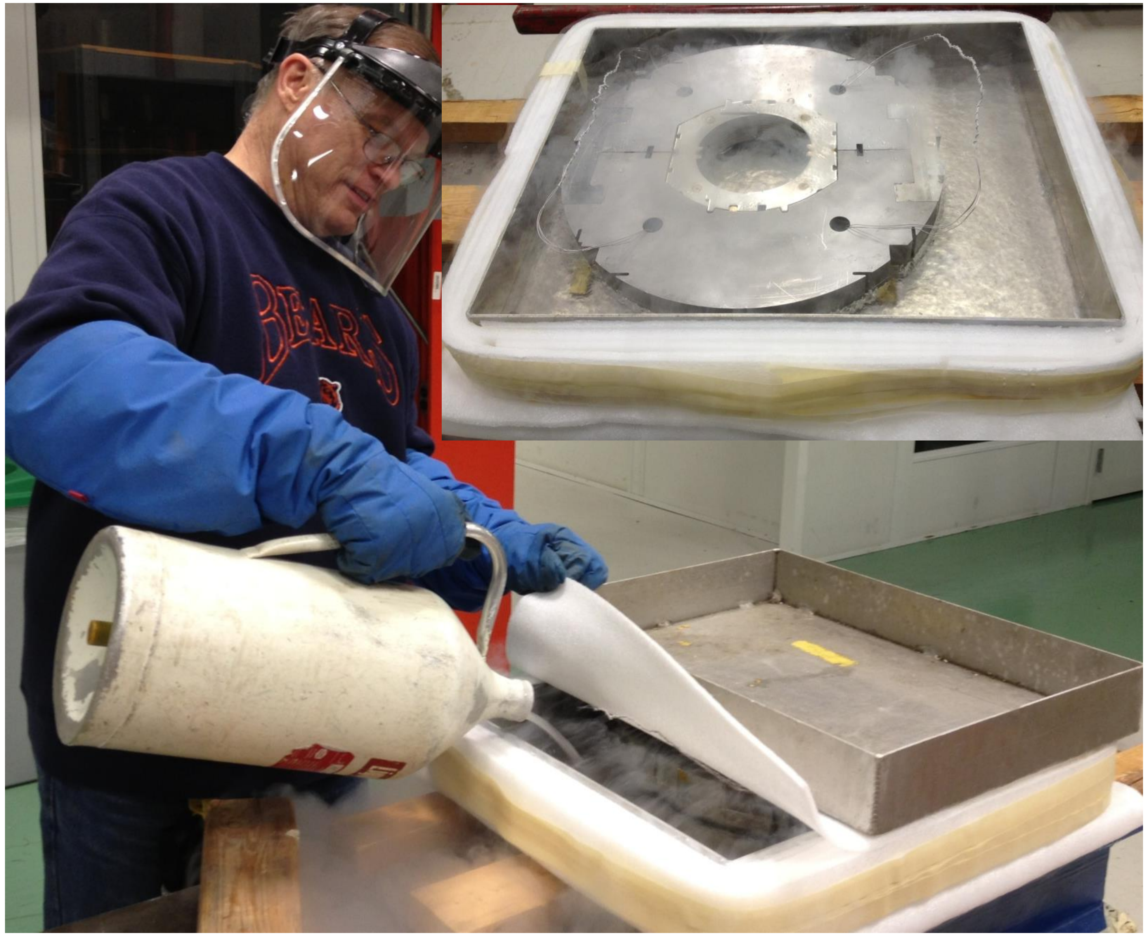


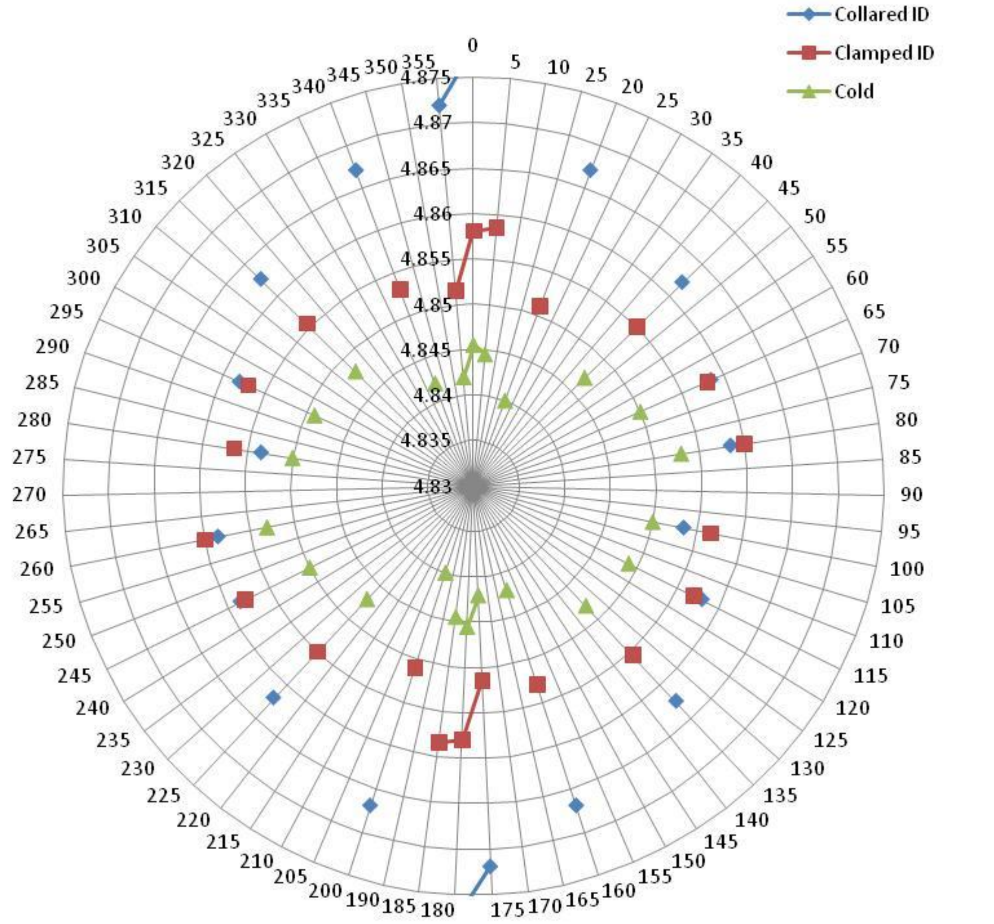


Used and Modified Pack #12



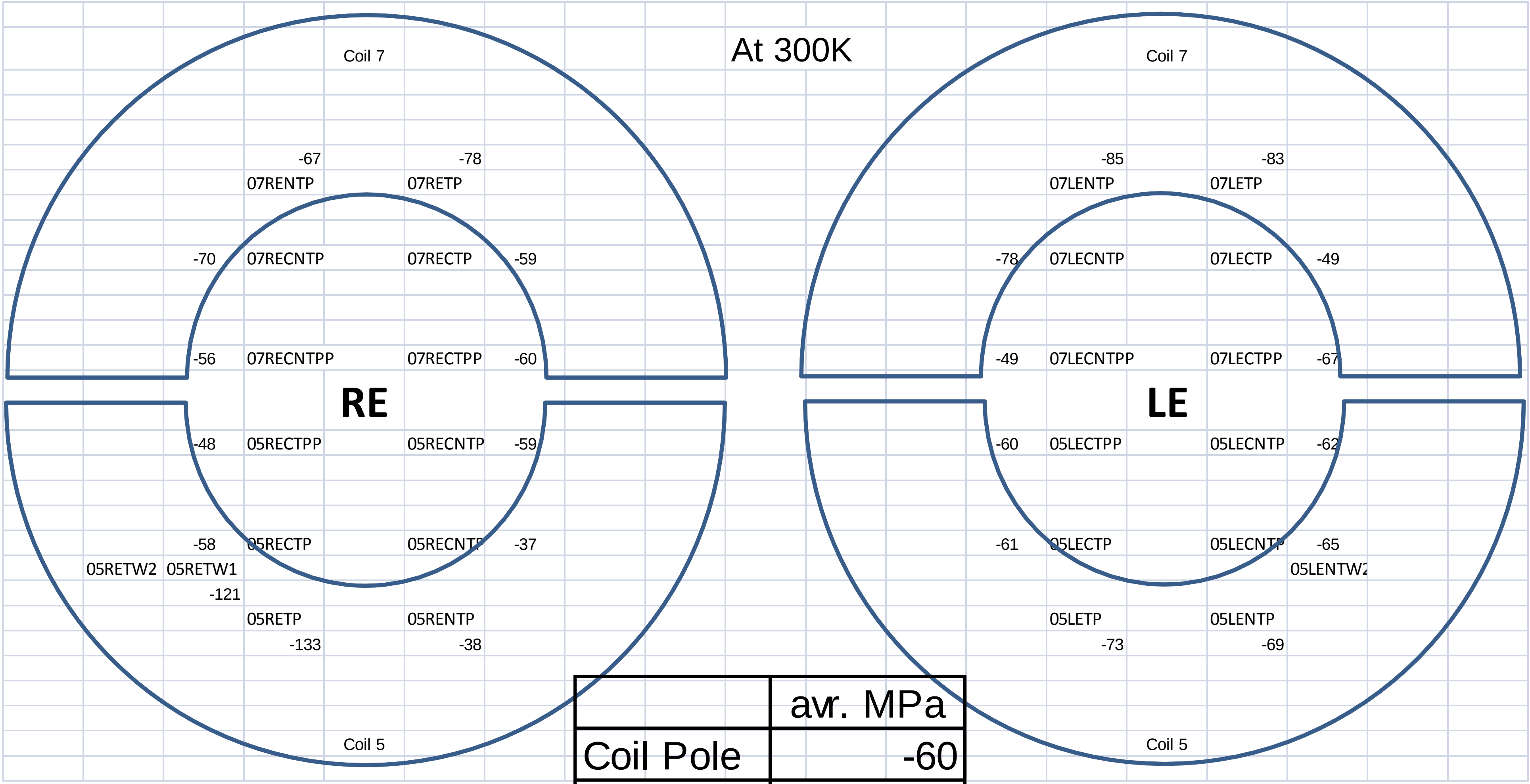
Reworked Collar Packs





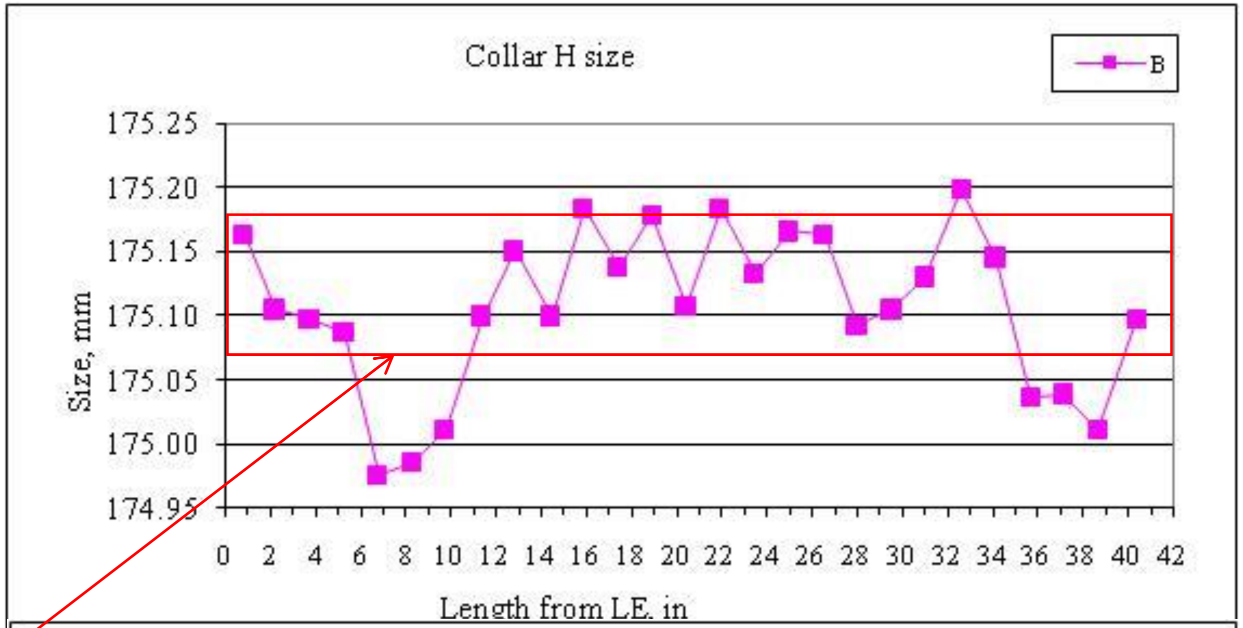
Used and Modified Pack #21

MBHSP02 SG Data

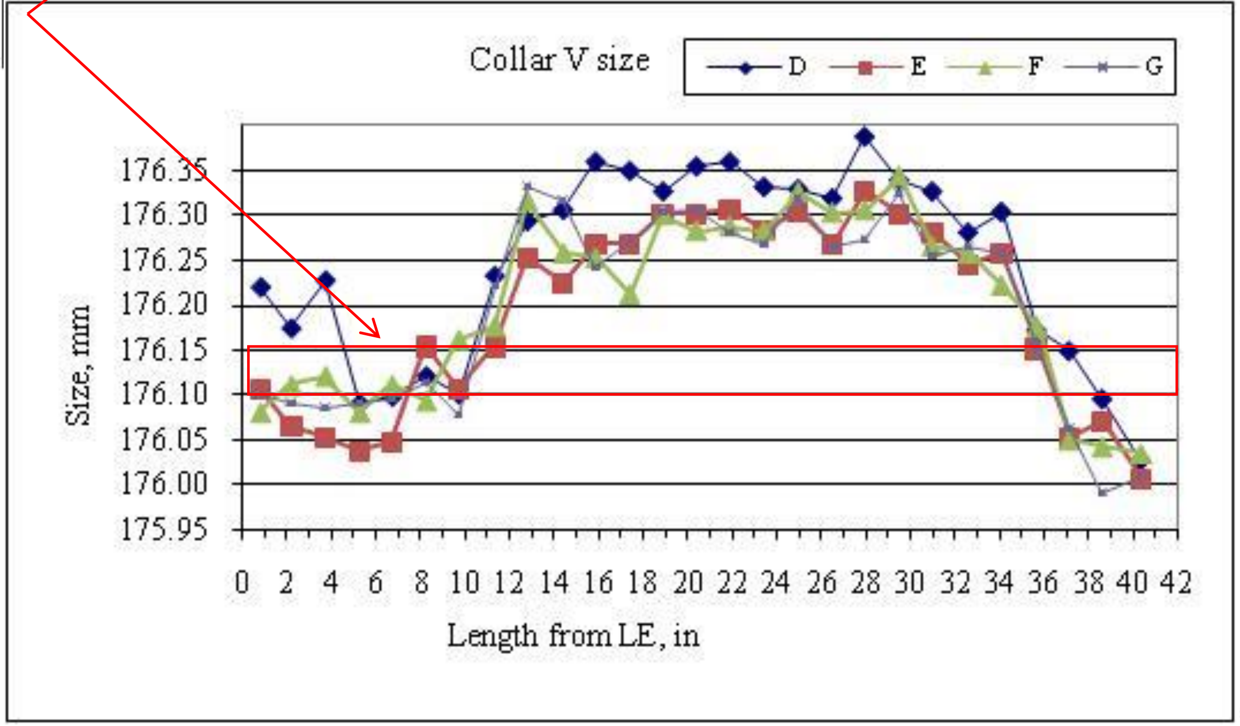


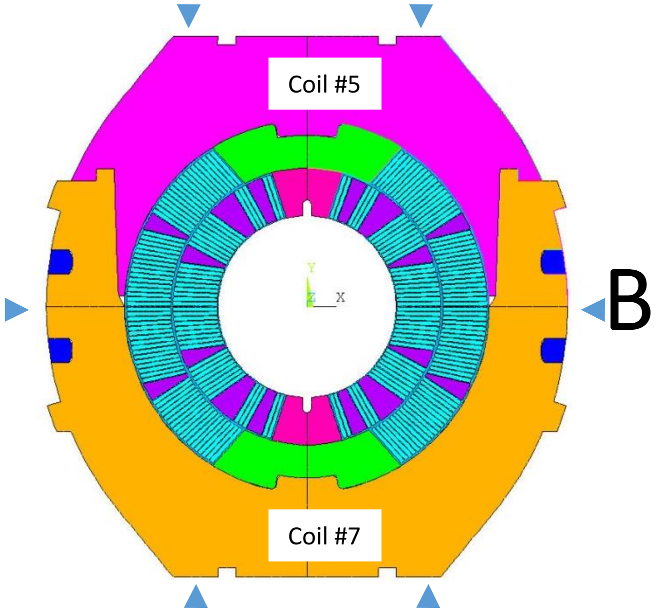
	avr. MPa
Coil Pole	-60
Coil MP	-57
Ti Pole	-78
Wedge	-121

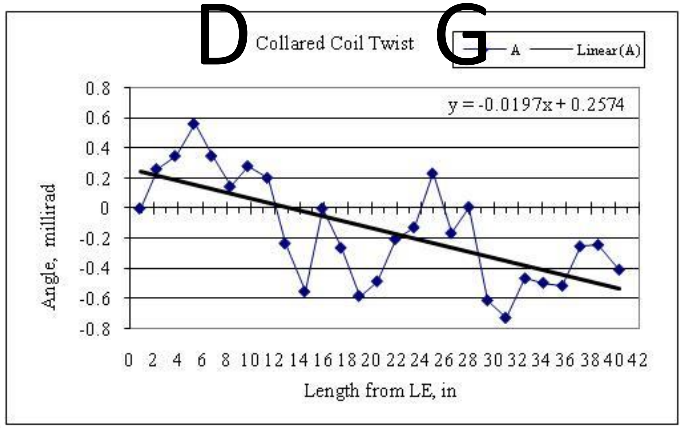
MBHSP02 Collared Coil Size



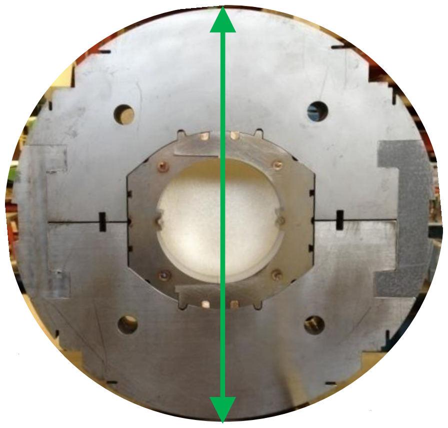
MBHSP01

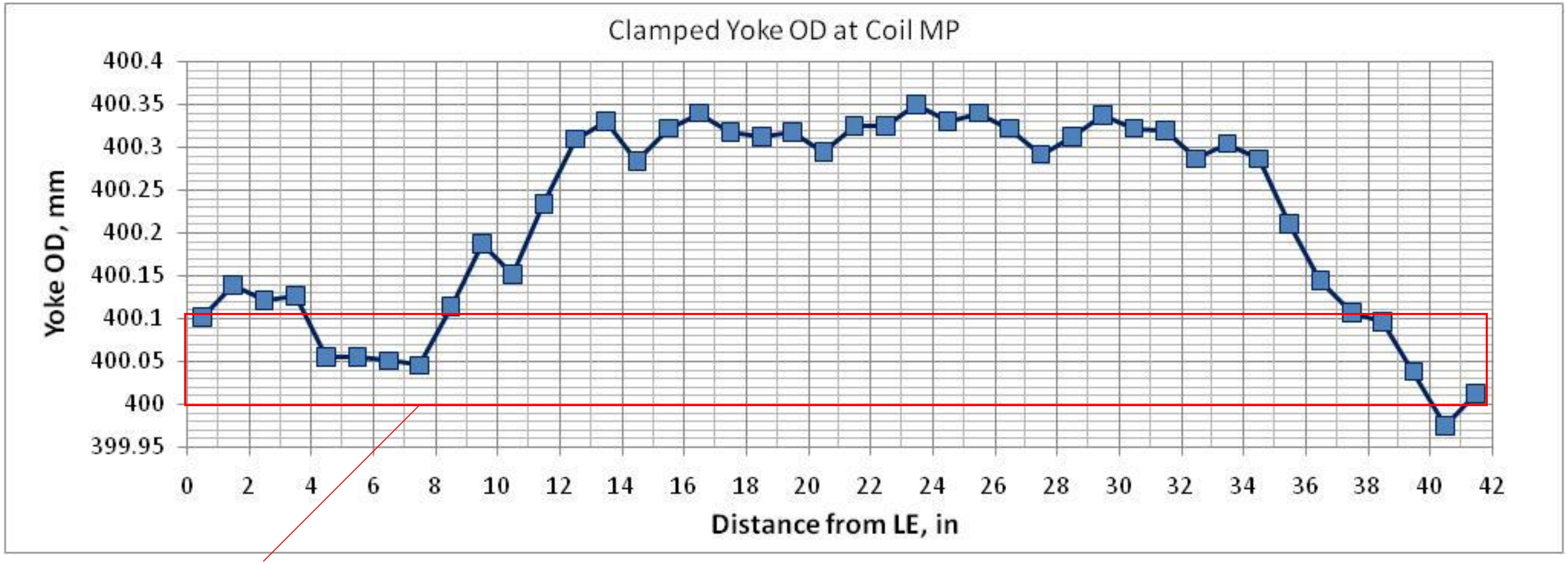






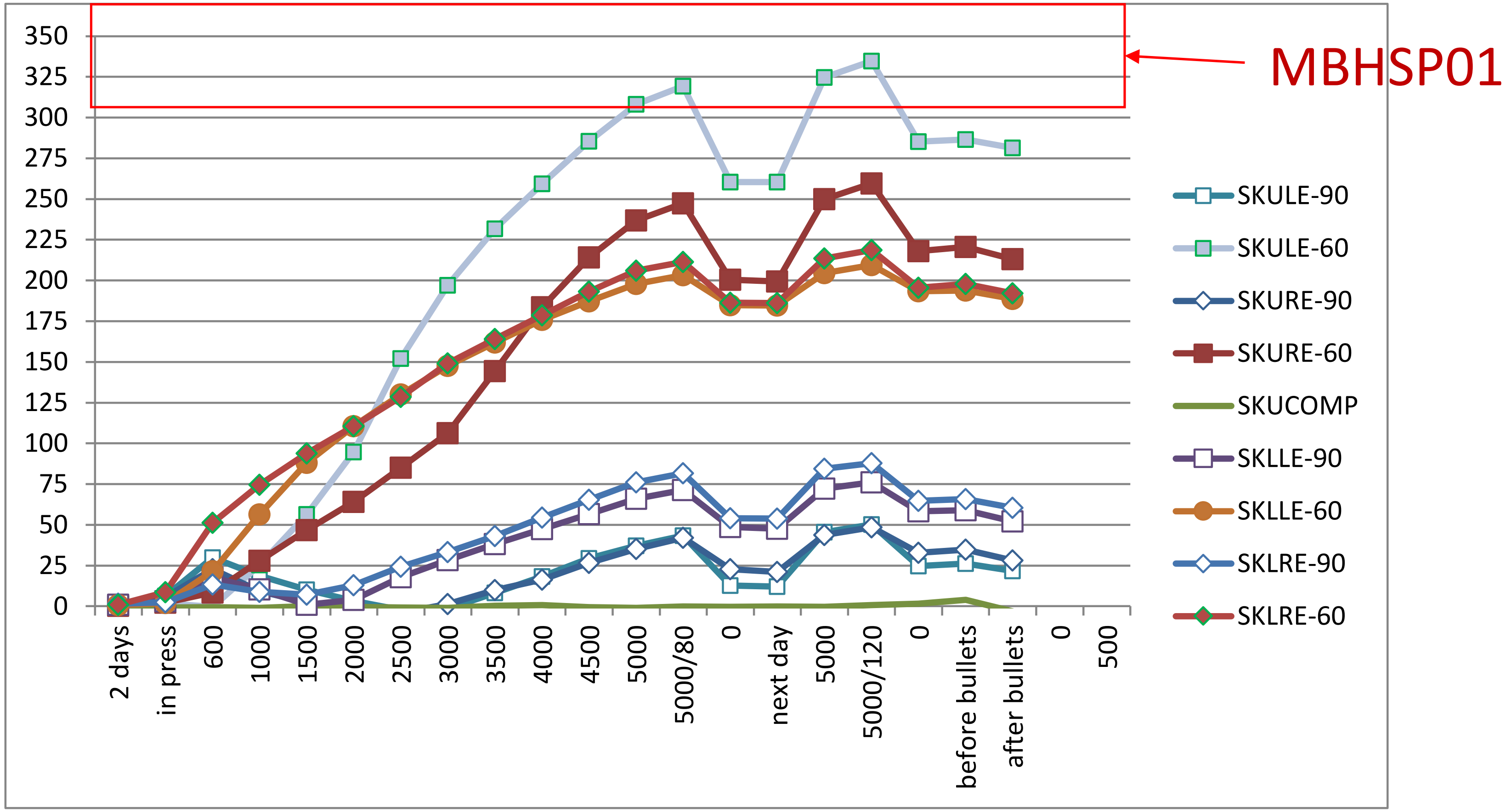
Clamped Iron Mechanical Measurements





MBHSP01 after test

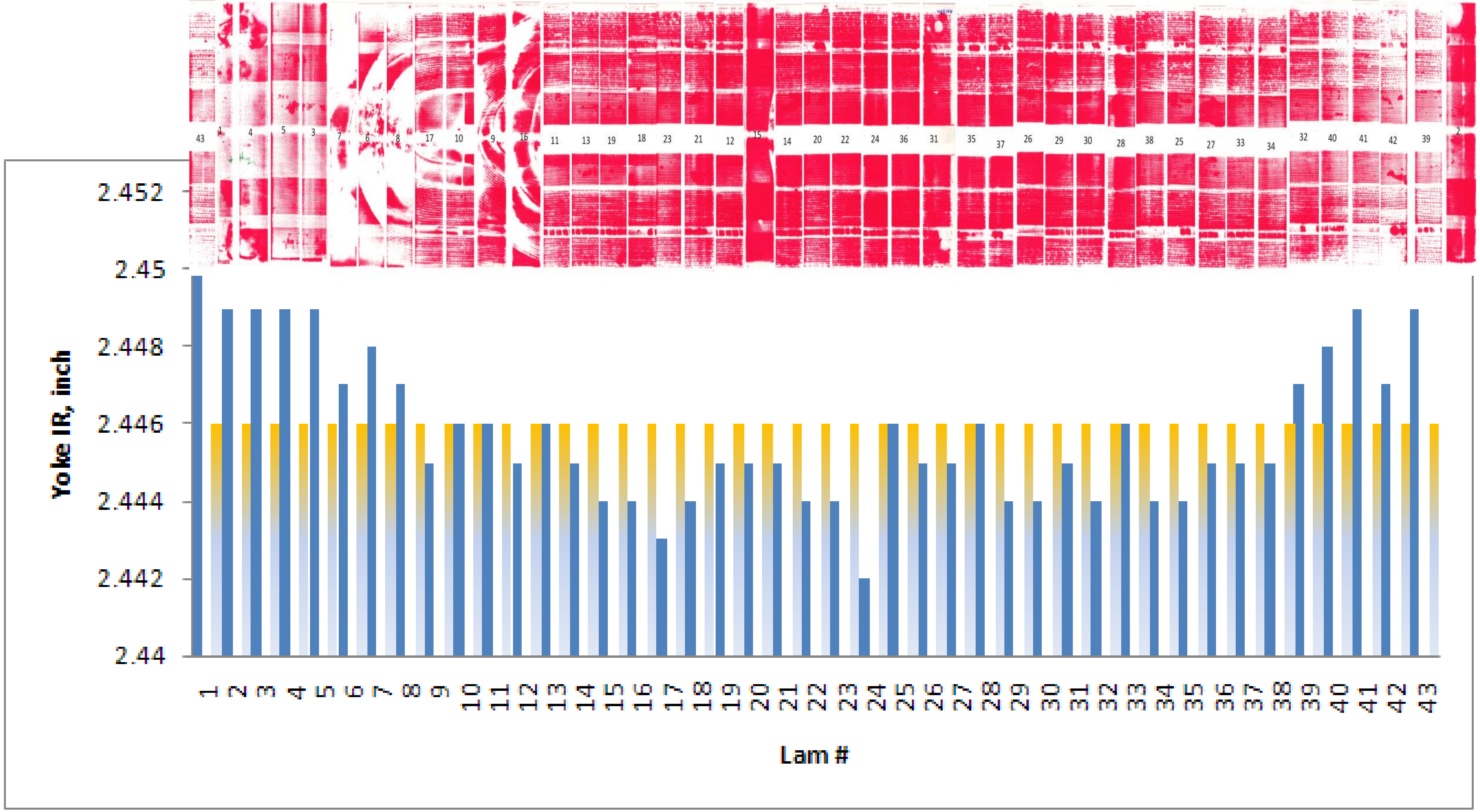
Skin Stress

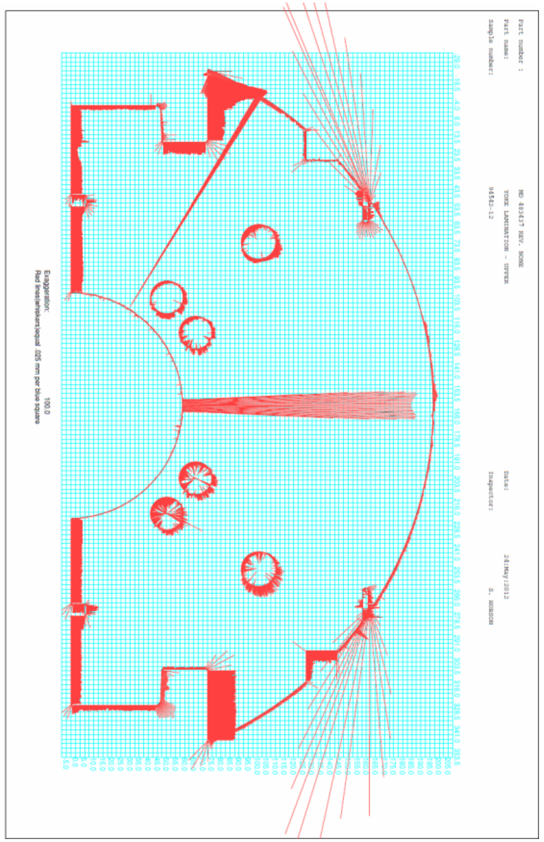


MBHSP01
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
2 days
in press
600
1000
1500
2000
2500
3000
3500
4000
4500
5000
5000/80
0
next day
5000
5000/120
0
before bullets
after bullets
0
500
SKULE-90
SKULE-60
SKURE-90
SKURE-60
SKUCOMP
SKLLE-90
SKLLE-60
SKLRE-90
SKLRE-60

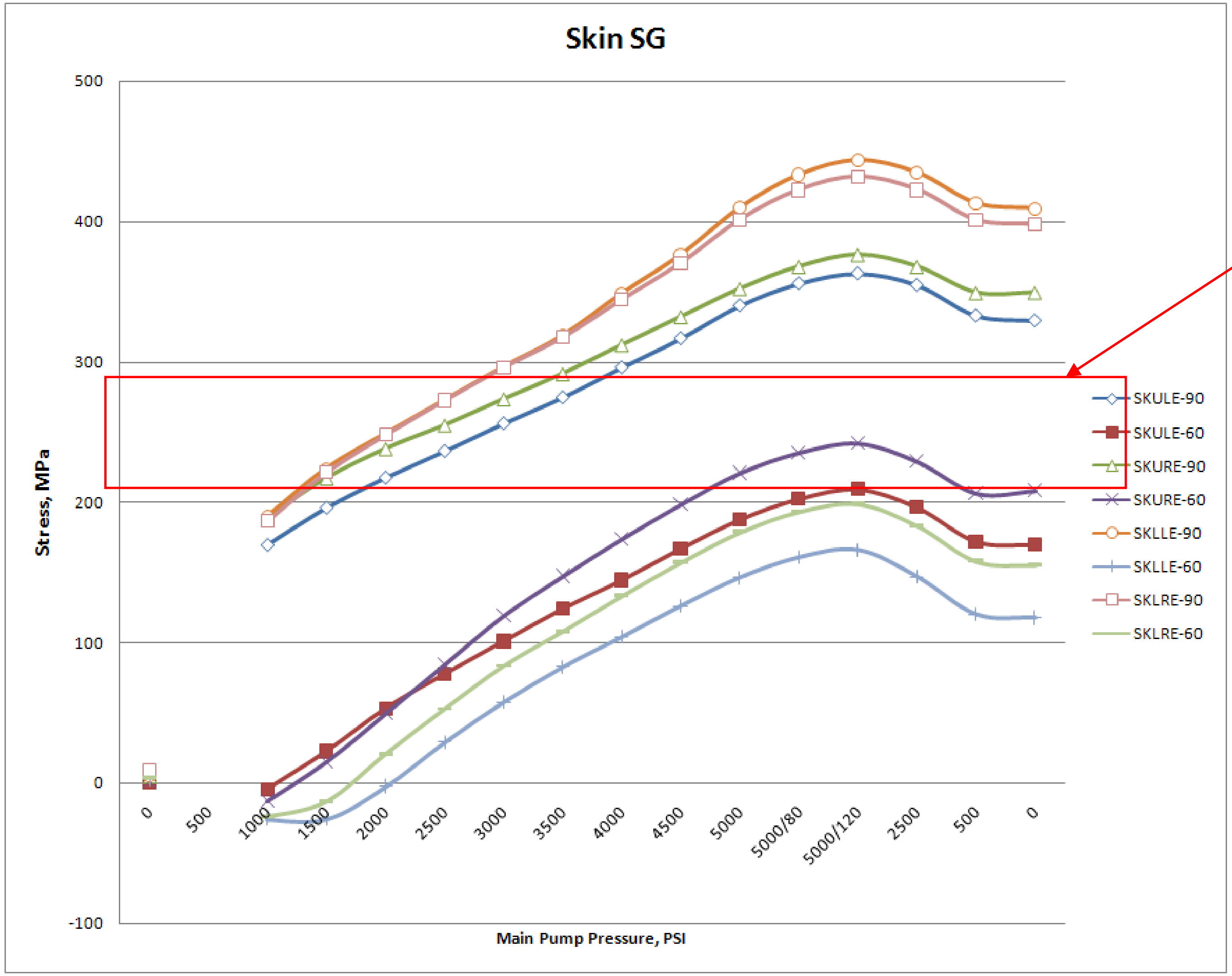
MBHSM01

Iron Laminations



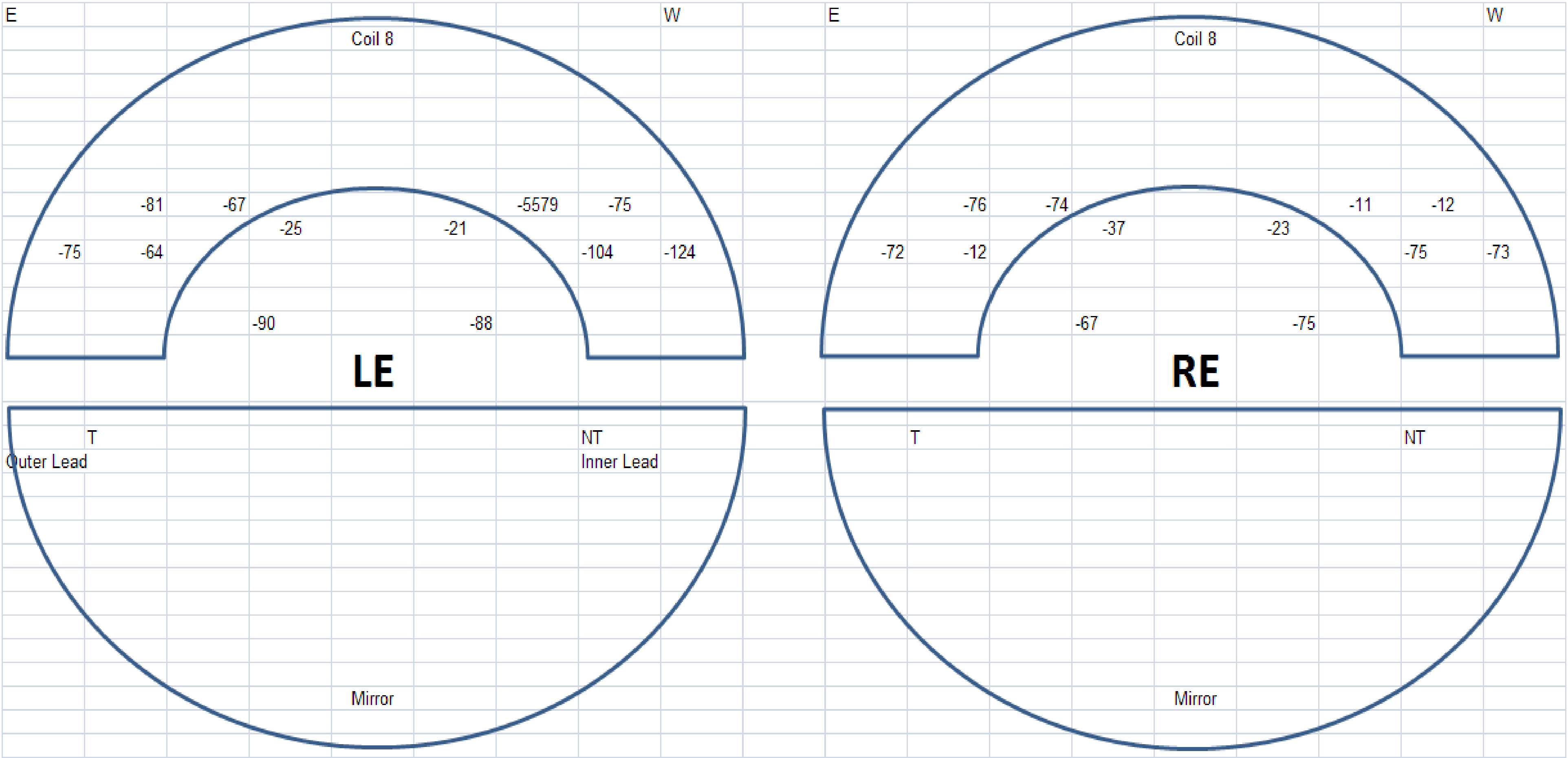


Skin Stress



MBHSP02

MBHSM01 SG Data after Skin Bolting

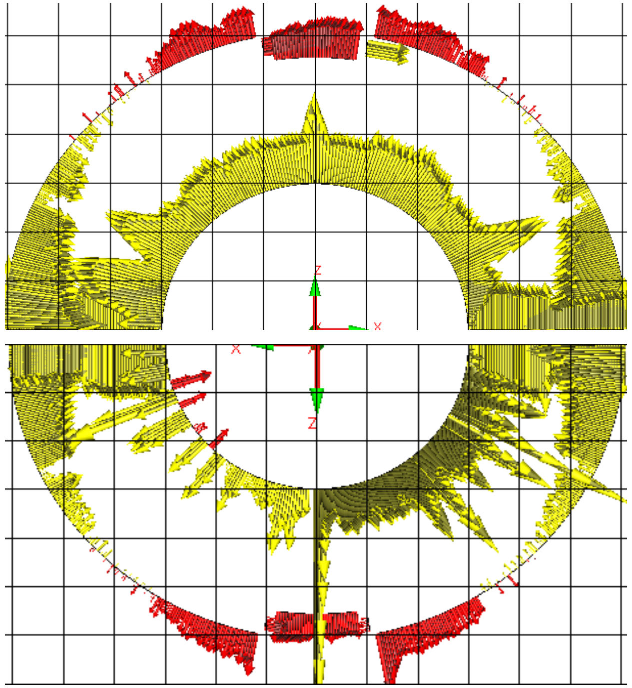


MBHSP03

Coil Sizes

MBHSP01

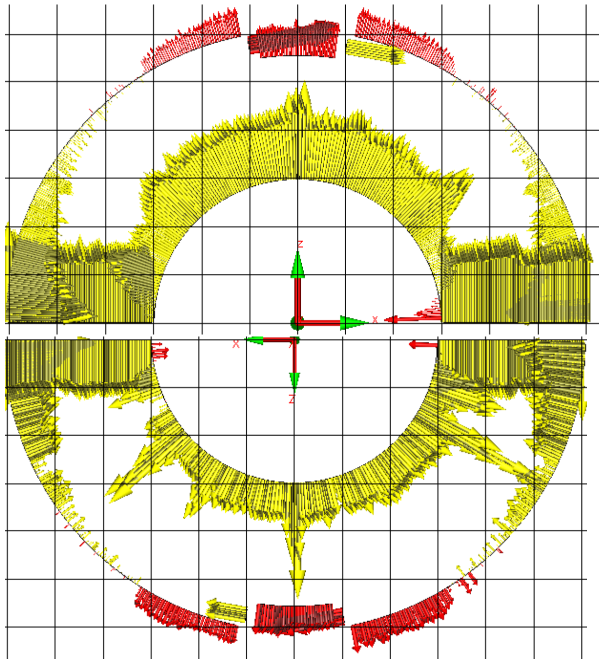
MBH02
445 mm from RE



MBH03
435 mm from RE

MBHSP02

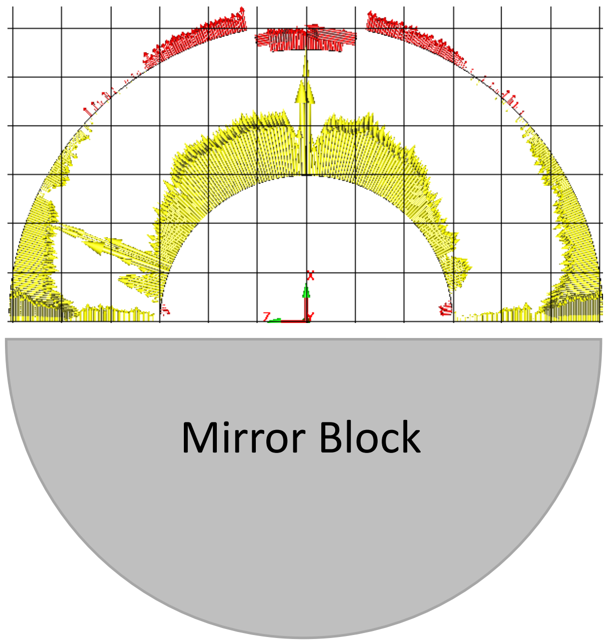
MBH05
479 mm from RE



MBH07
467 mm from RE

MBHSM01

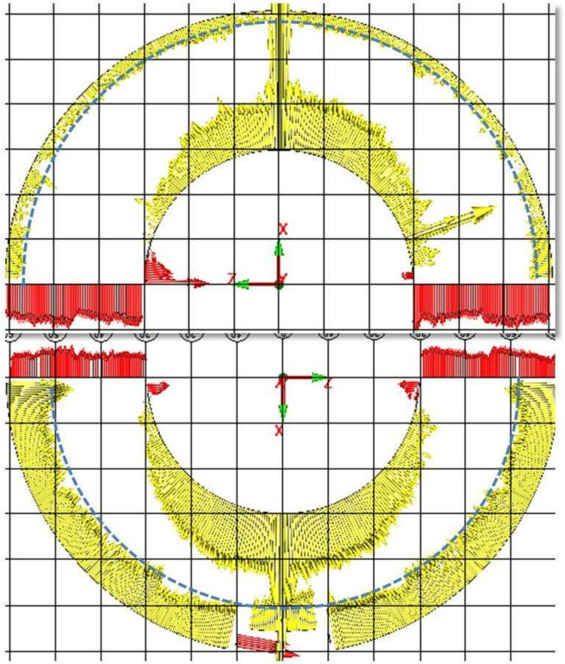
MBH08
447 mm from RE



(1 box = 101.6 μm)

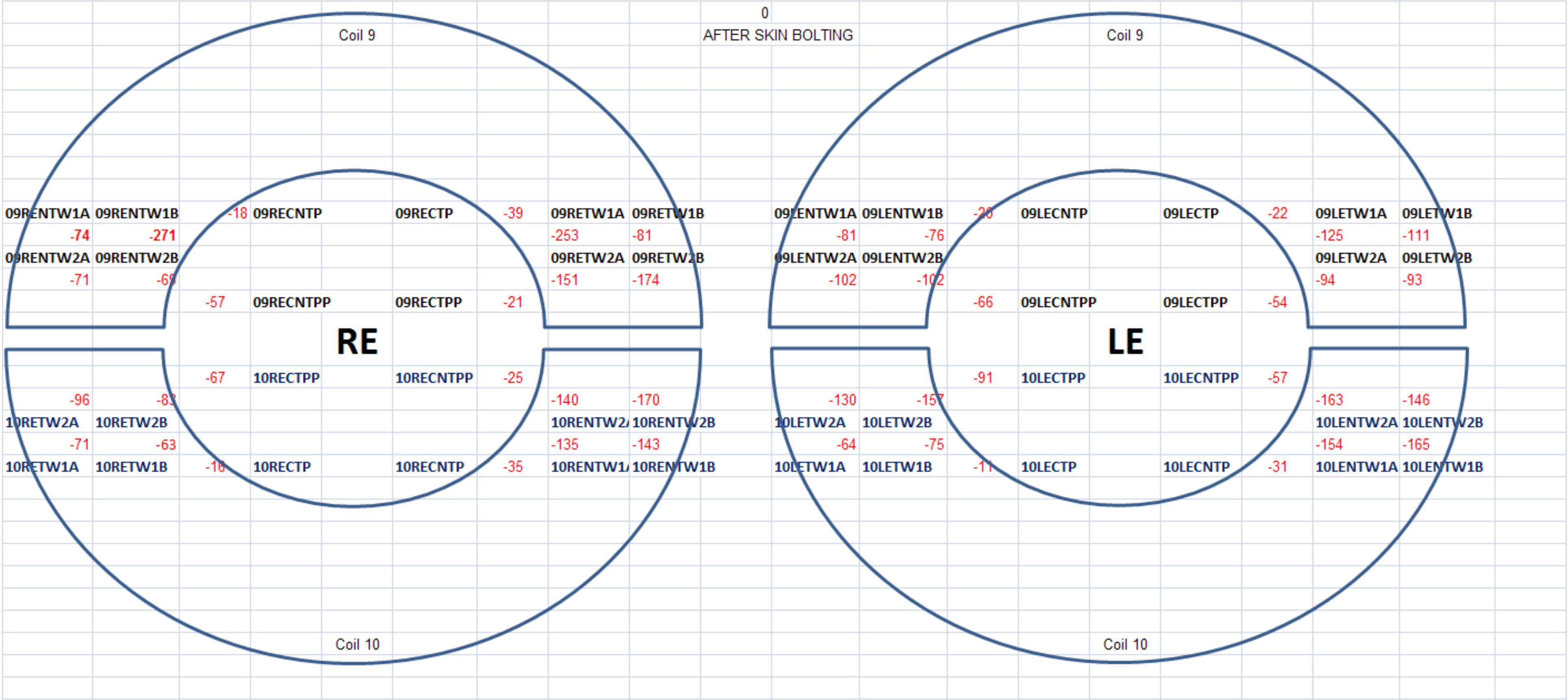
MBHSP03

MBH10



MBH09

After Skin Bolting



Total	avr. MPa
Coil Pole	-24
Coil MP	-55
Wedge 1	-121
Wedge 2	-121

Coil 9	avr. MPa
Coil Pole	-25
Coil MP	-50
Wedge 1	-134
Wedge 2	-107

Coil 10	avr. MPa
Coil Pole	-23
Coil MP	-60
Wedge 1	-109
Wedge 2	-136

Left	avr. MPa
Coil Pole	-16
Coil MP	-70
Wedge 1	-97
Wedge 2	-101

Right	avr. MPa
Coil Pole	-32
Coil MP	-39
Wedge 1	-146
Wedge 2	-141

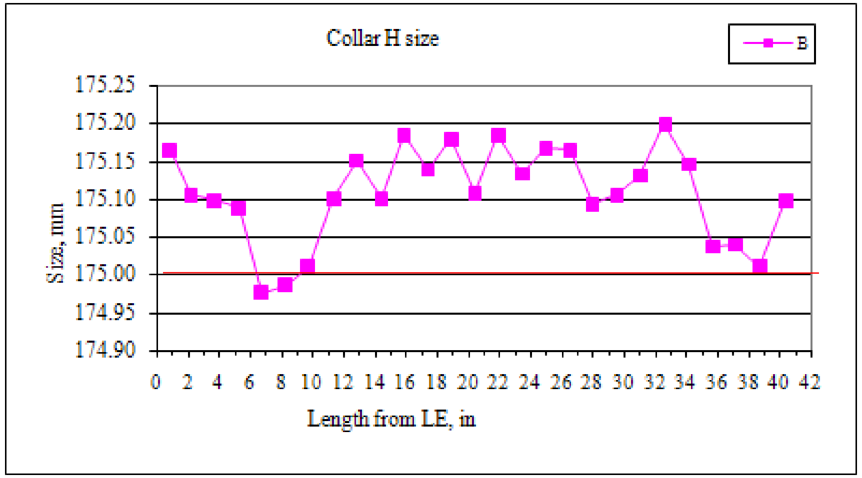
\	avr. MPa
Coil Pole	-26
Coil MP	-51
Wedge 1	-137
Wedge 2	-120

/	avr. MPa
Coil Pole	-22
Coil MP	-58
Wedge 1	-105
Wedge 2	-122

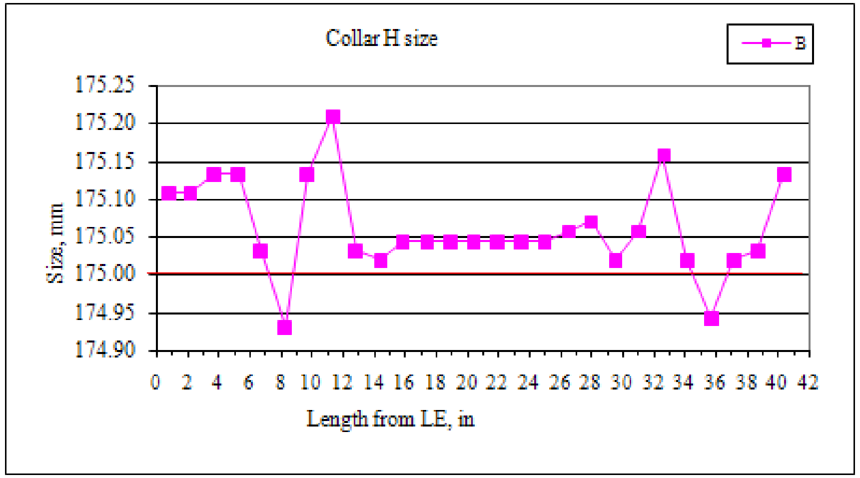
OD after Collaring

MBHSP02

MBHSP03

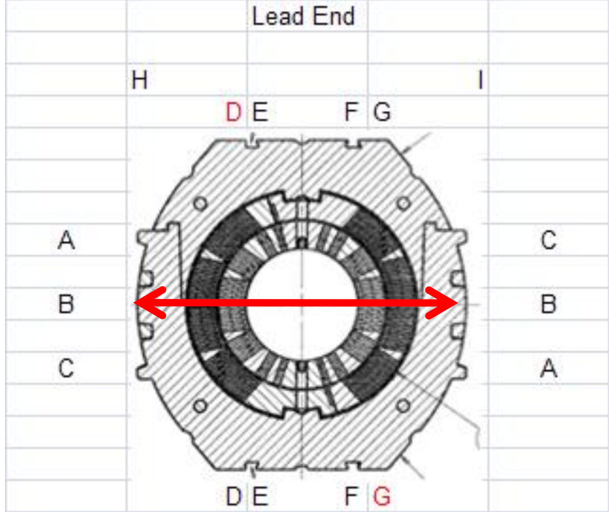


Design



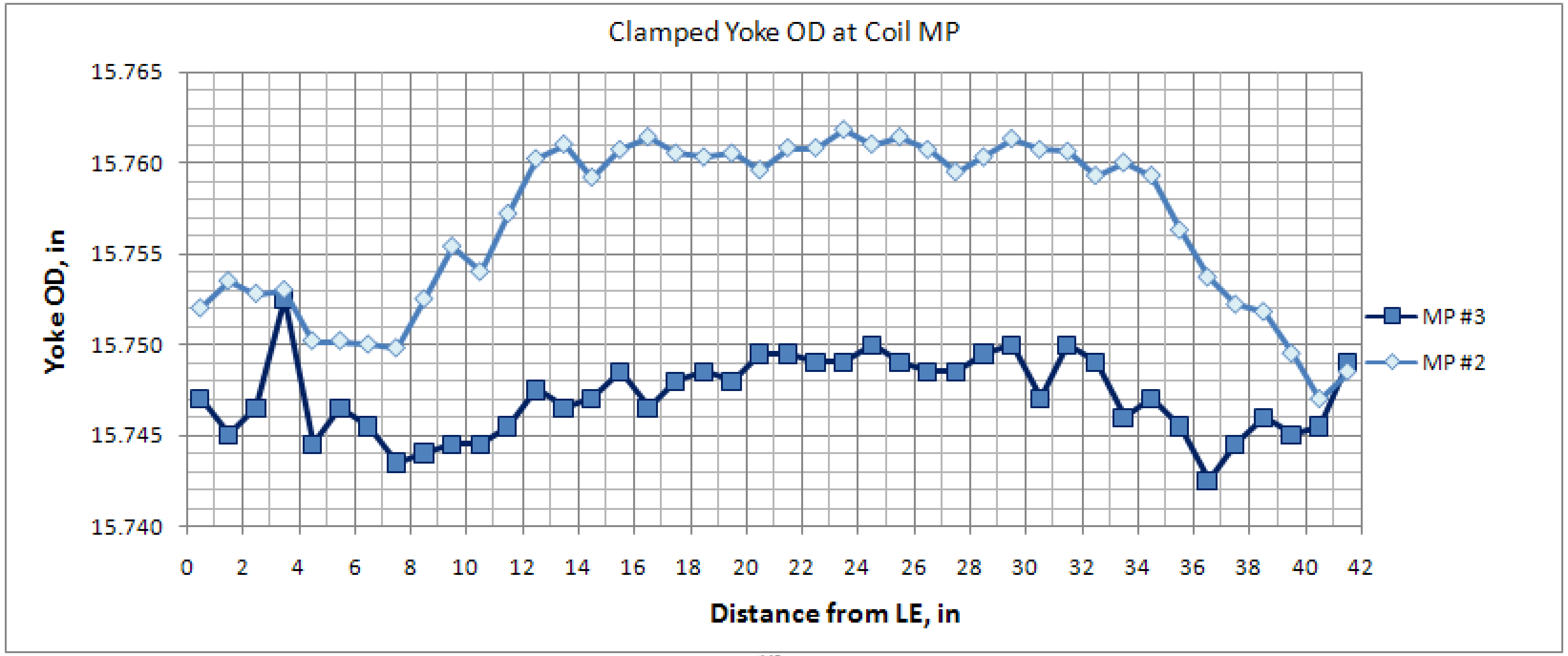
Collared twice
with radial shim increase
by 3mil=75um

Main pressure 6000psi
Key pressure 8000psi



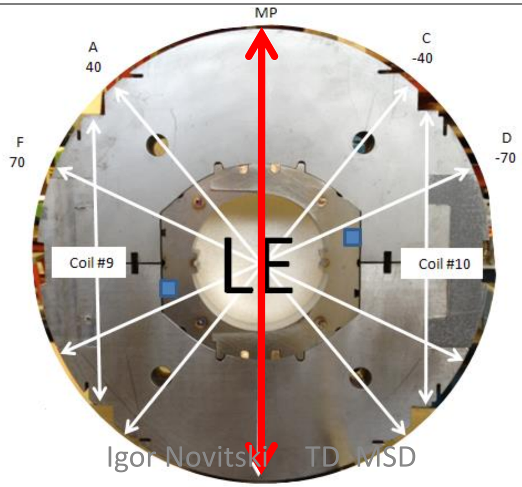
Main pressure 4000psi
Key pressure 10000psi

After Yoke Clamping



MBHSP02

Main pressure 2500psi
Key pressure 3500psi

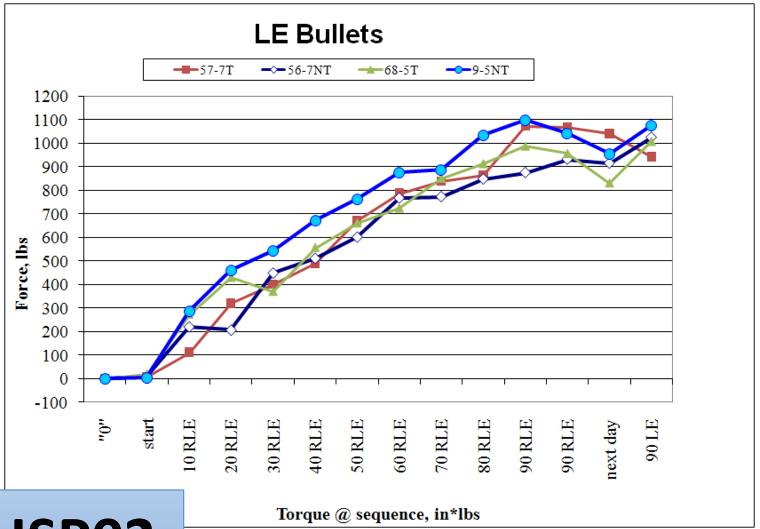


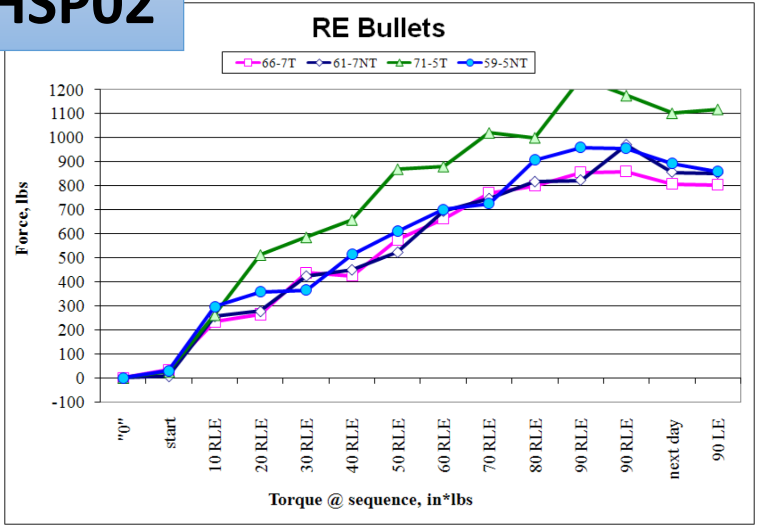
MBHSP03

Main pressure 3000psi
Key pressure 3500psi

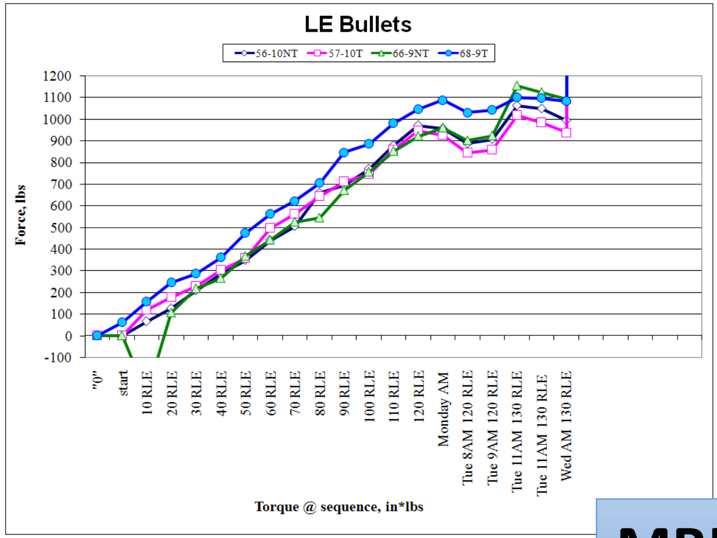
Bullets

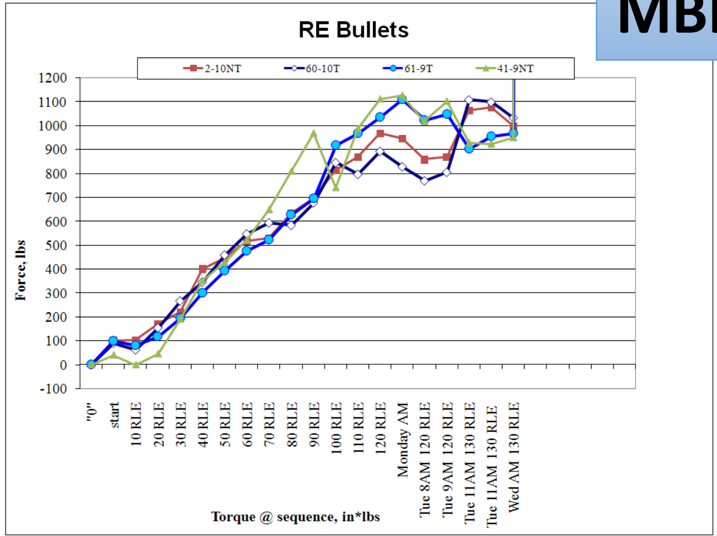
MBHSP02





MBHSP03

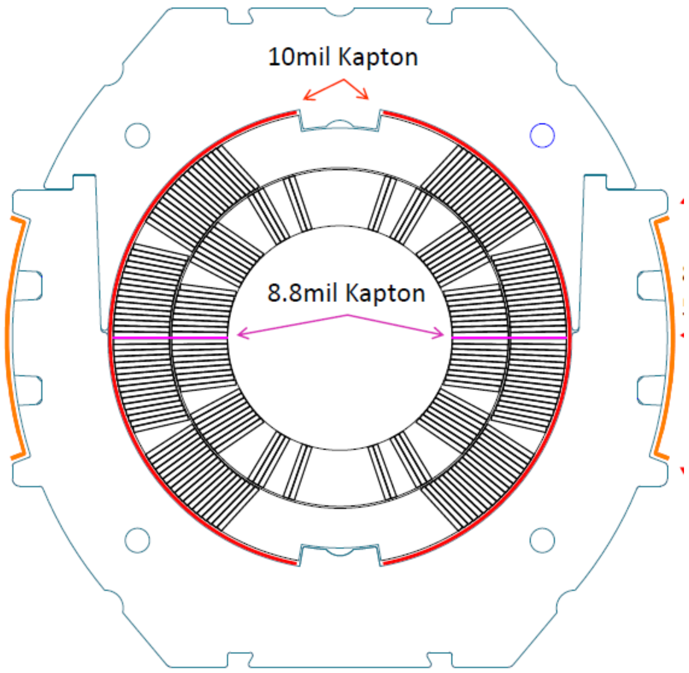




MBHDP01

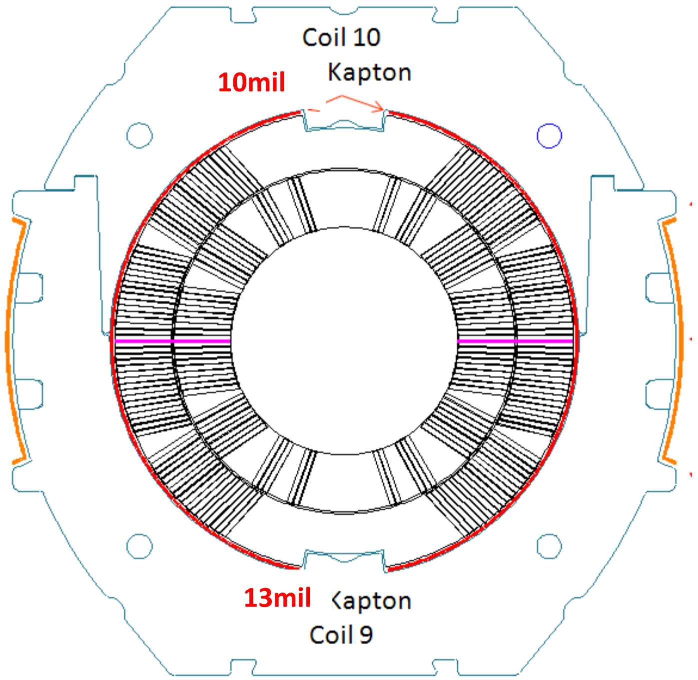
Collared Coil Shims

MBHSP02



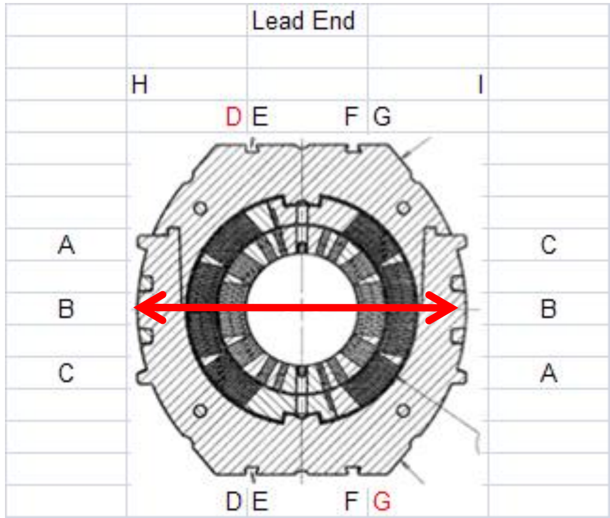
17mil Shoe
10mil Radial Shim
8.8mil MP Shim

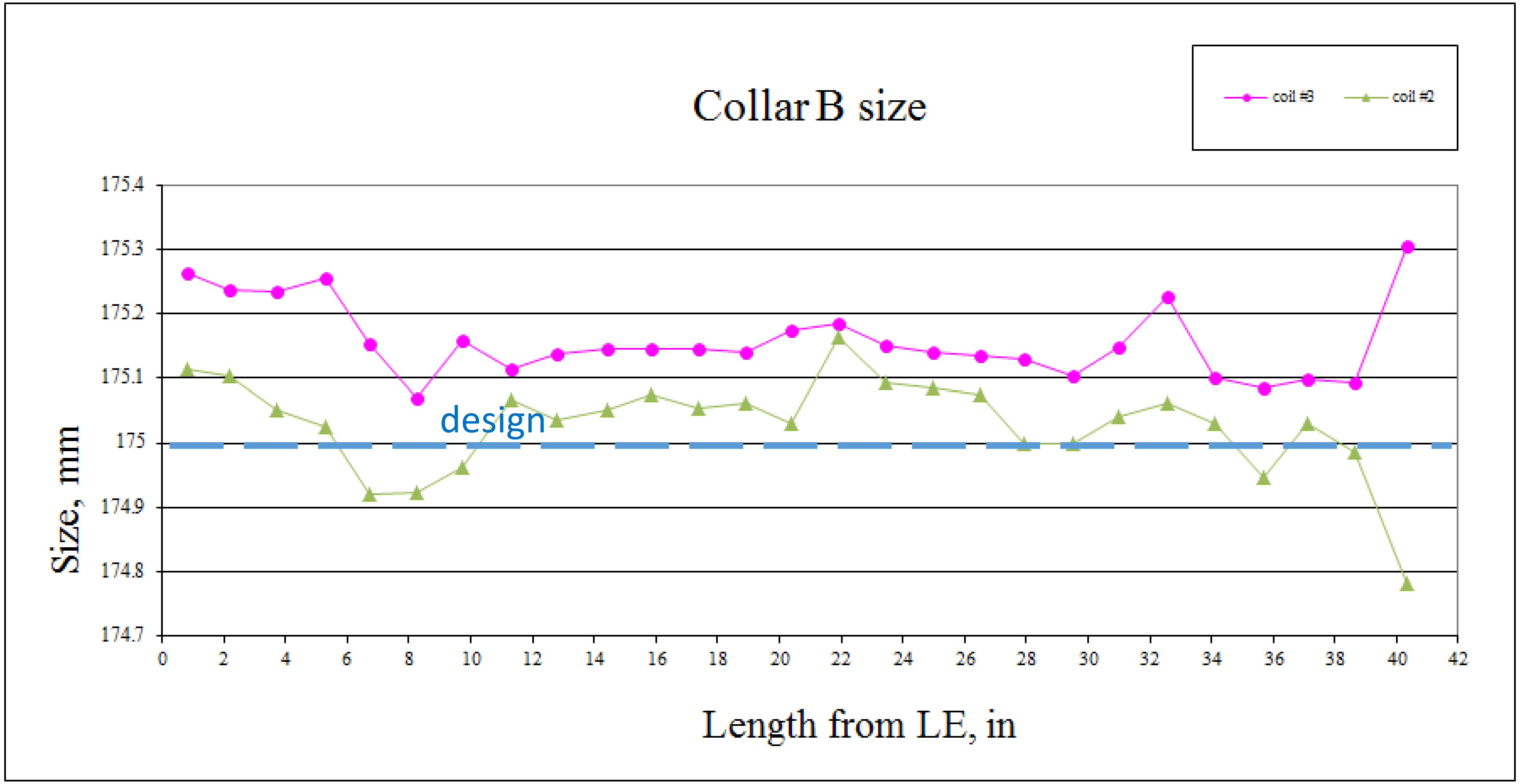
MBHSP03a



32mil Shoe
10 and 13 mil Radial Shim
0 MP Shim

Collared Coil Geometry

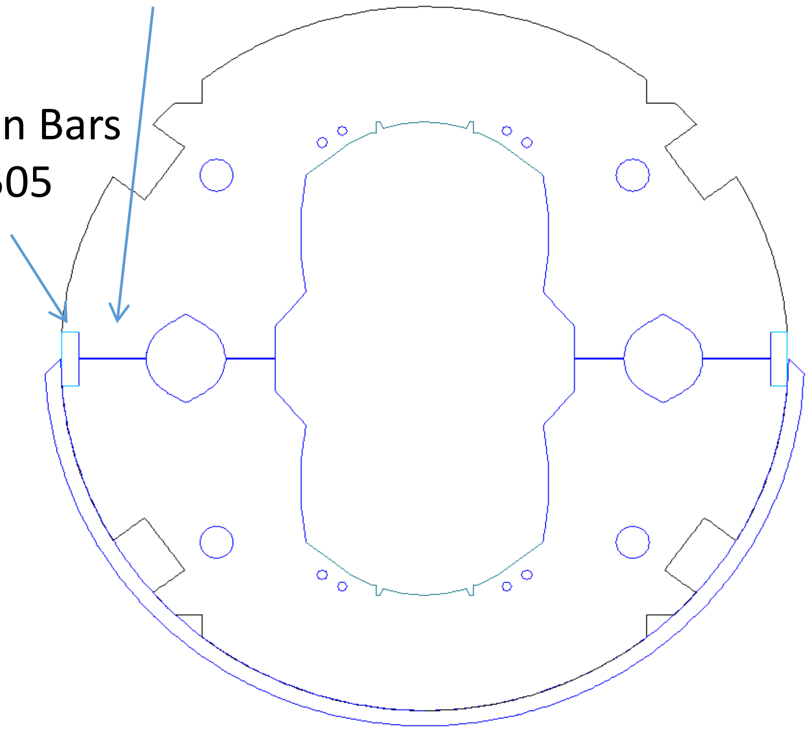


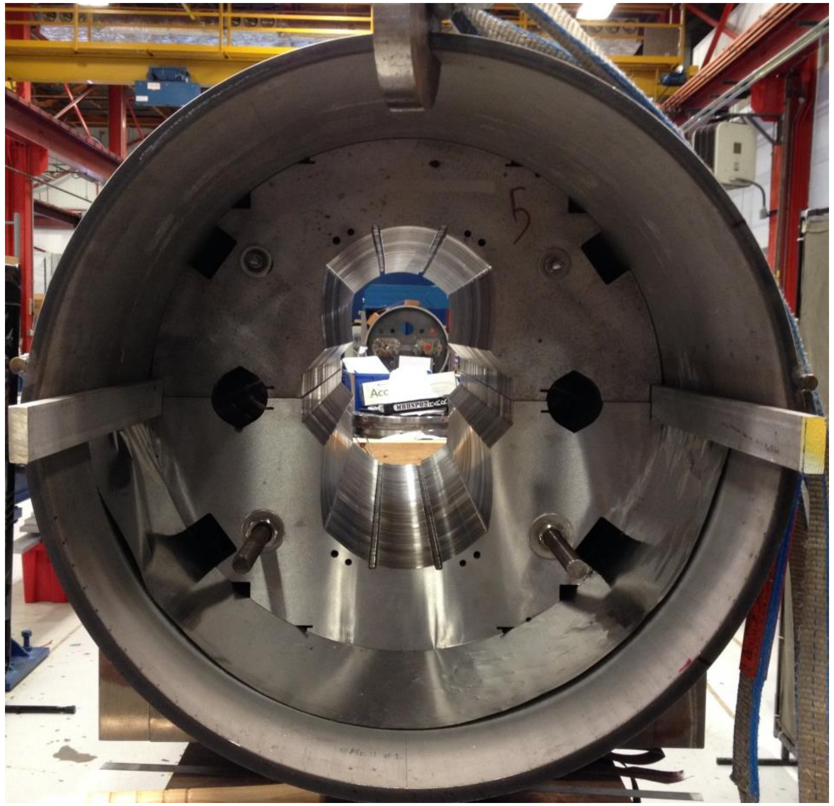


Iron Geometry Check

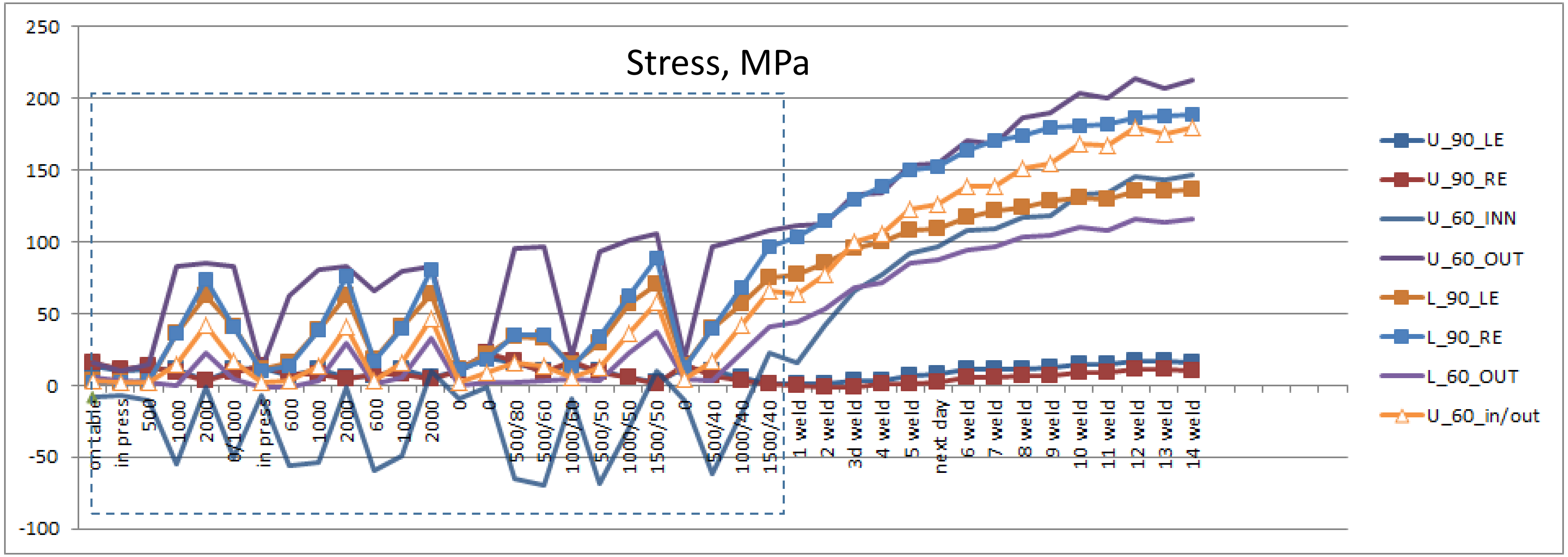
Measured gap 10-15mils (design~40 mils)
At the ends ~0, locally at ss ~20
Witness marks on opposite sides

"0" gap on Bars
1.503-1.505





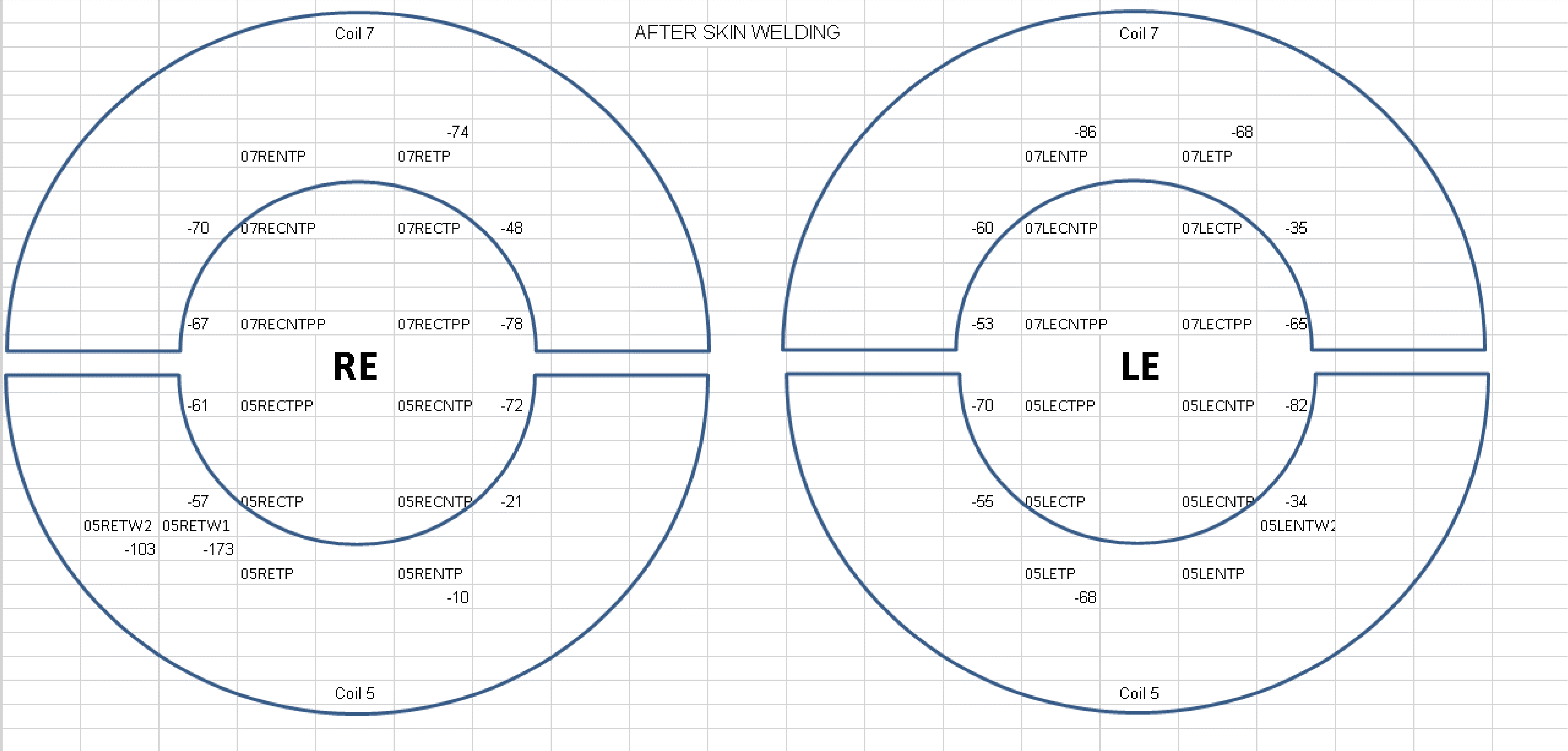
Skin SG Readings



Massaging

Welding

MBHDP01 SG Data



Total

	avr. MPa
Coil Pole	-48
Coil MP	-69

Coil 7

	avr. MPa
Coil Pole	-53
Coil MP	-66

Coil 5

	avr. MPa
Coil Pole	-42
Coil MP	-71

Left

	avr. MPa
Coil Pole	-61
Coil MP	-63

Right

	avr. MPa
Coil Pole	-34
Coil MP	-74

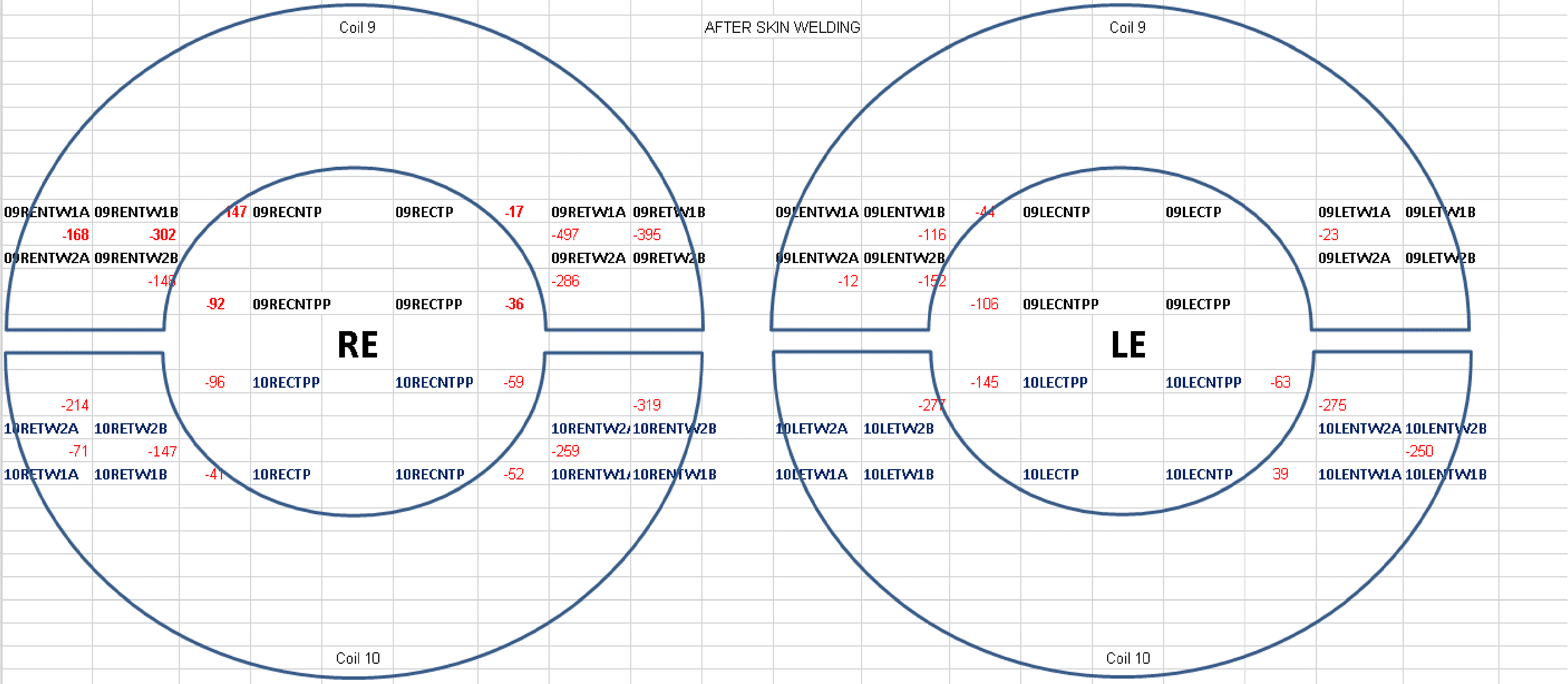
****

	avr. MPa
Coil Pole	-46
Coil MP	-68

/

	avr. MPa
Coil Pole	-49
Coil MP	-69

MBHDP01 SG Data



Total

	avr. MPa
Coil Pole	5
Coil MP	-85
Wedge 1	-223
Wedge 2	-211

Coil 9

	avr. MPa
Coil Pole	28
Coil MP	-78
Wedge 1	-250
Wedge 2	-150

Coil 10

	avr. MPa
Coil Pole	-18
Coil MP	-90
Wedge 1	-182
Wedge 2	-271

Left

	avr. MPa
Coil Pole	20
Coil MP	-110
Wedge 1	-161
Wedge 2	-161

Right

	avr. MPa
Coil Pole	-10
Coil MP	-52
Wedge 1	-285
Wedge 2	-293

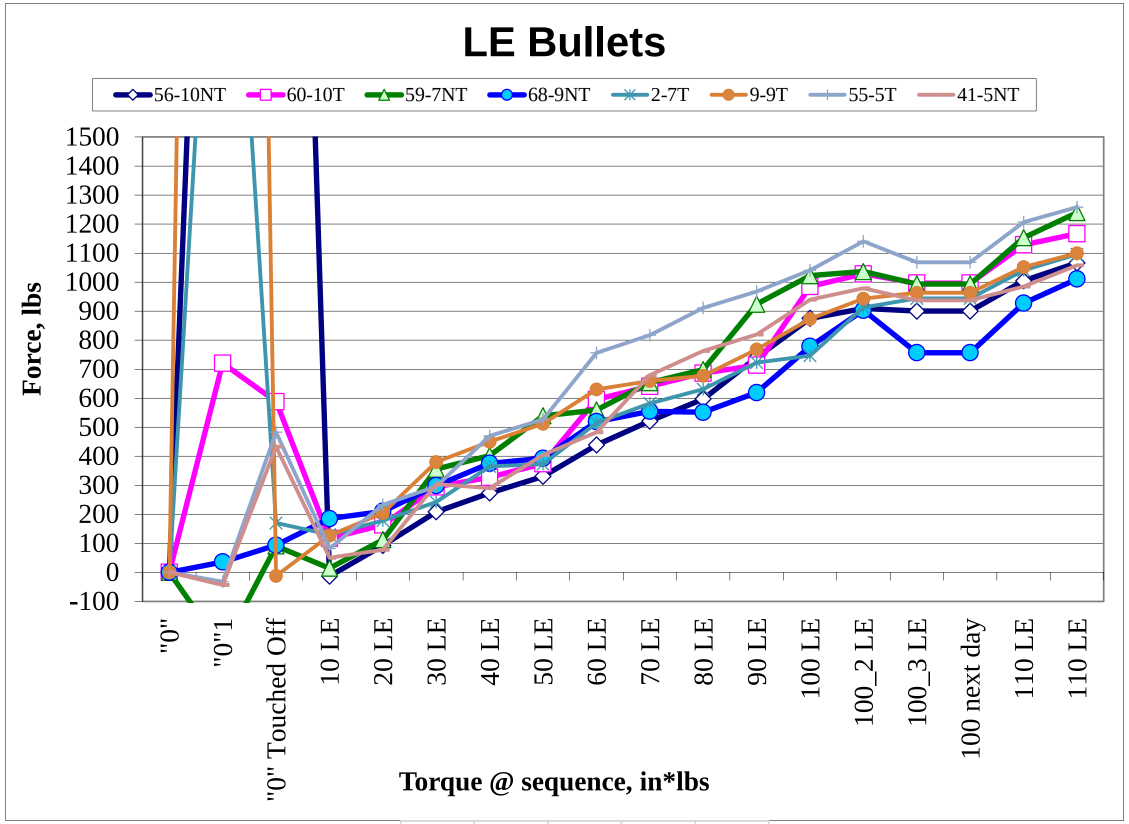
****

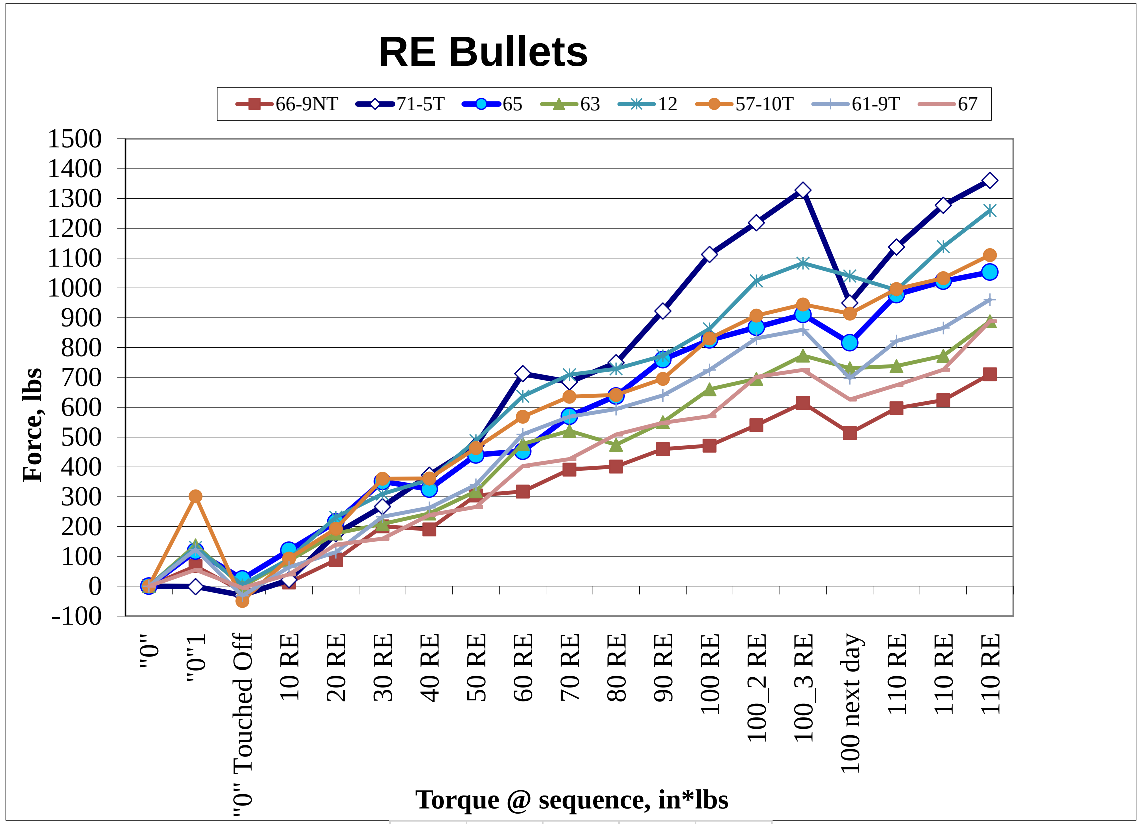
	avr. MPa
Coil Pole	22
Coil MP	-80
Wedge 1	-219
Wedge 2	-181

/

	avr. MPa
Coil Pole	-29
Coil MP	-92
Wedge 1	-226
Wedge 2	-259

Bullets Loading





		LE		
	NT		T	
	Bullet#68		Bullet#60	
COIL 09				COIL 10
	Bullet#09		Bullet#56	
	T	C??-comp	NT	
	NT		T	
	Bullet#59		Bullet#55	
COIL 07				COIL 05
	Bullet#02		Bullet#41	
	T		NT	

		RE		
	T		NT	
	Bullet#67		Bullet#57	
COIL 10				COIL 09
	Bullet#61		Bullet#12	
	NT	C??-comp	T	
	T		NT	
	Bullet#65		Bullet#71	
COIL 05				COIL 07
	Bullet#63		Bullet#66	
	NT		T	