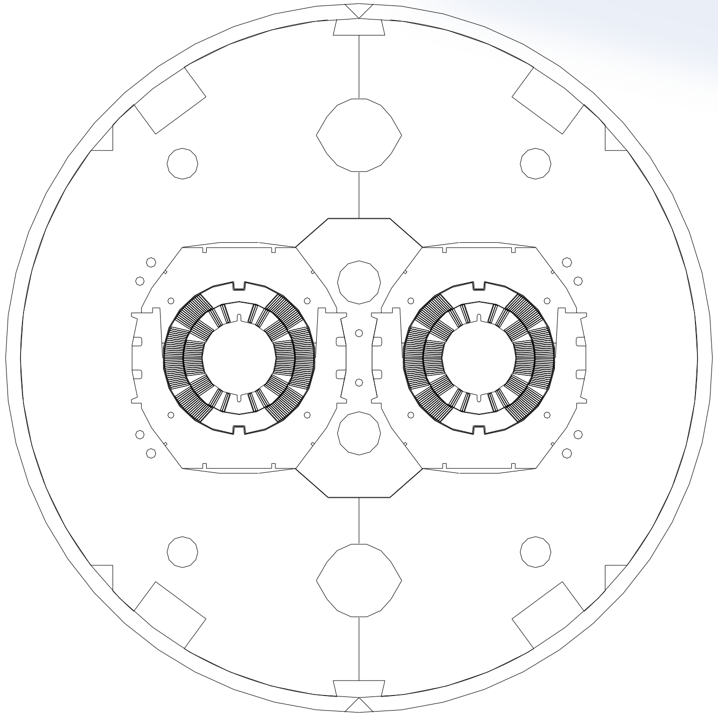
Collaboration meeting on DS 11T Dipole grounds
FNAL, Sep. 21-23, 2015

11T Dipole Mechanical structure and analysis at Fermilab

Igor Novitski
September 21, 2015

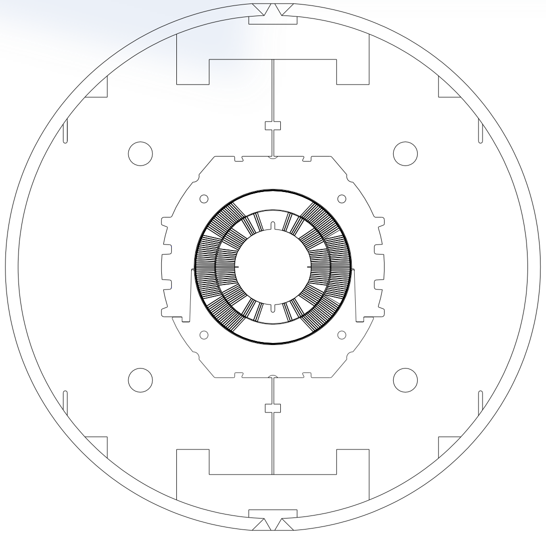
Magnet Design Goals

3 different structures



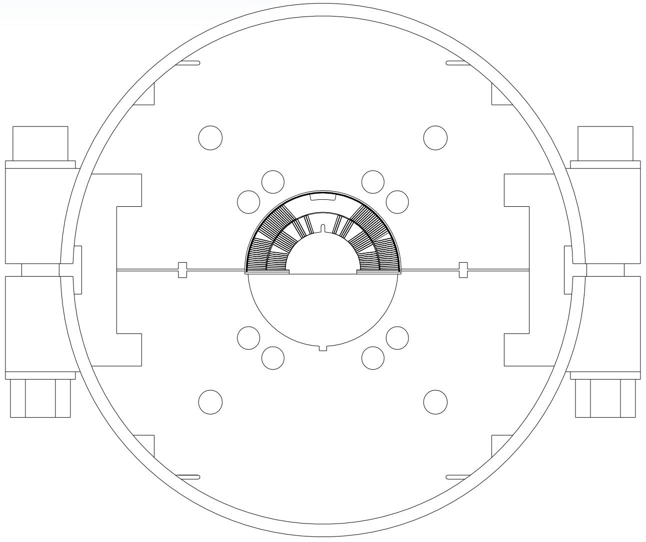
Twin Aperture Magnet

Primary Goal



Single Bore Magnet

Collared Coils Test Bench



Mirror Magnet

Nb_3Sn Coil Test Structure

Single Bore Magnet Mechanical Concept

Coil mechanical support is provided by stainless collars, vertically split iron yoke, aluminium clamp and welded stainless steel skin.

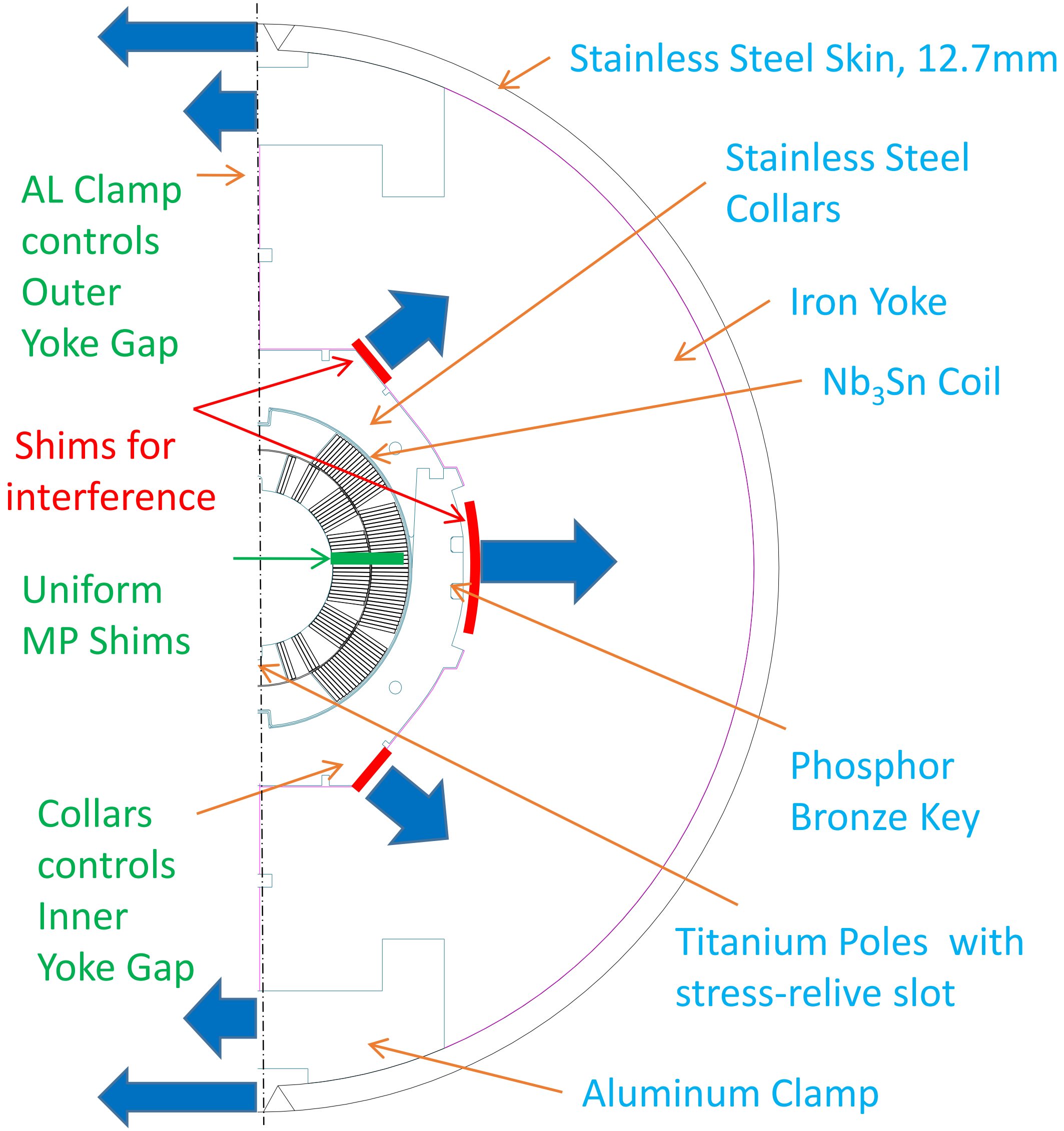
Strong collars and iron yoke create the “rigidity belt” around Nb_3Sn coil for conductor protection.

Coil midplane shims generate initial coil azimuthal prestress at collaring stage.

Skin and clamp tensions deform the iron, reduce the vertical collars spring-back and finalized coil compression.

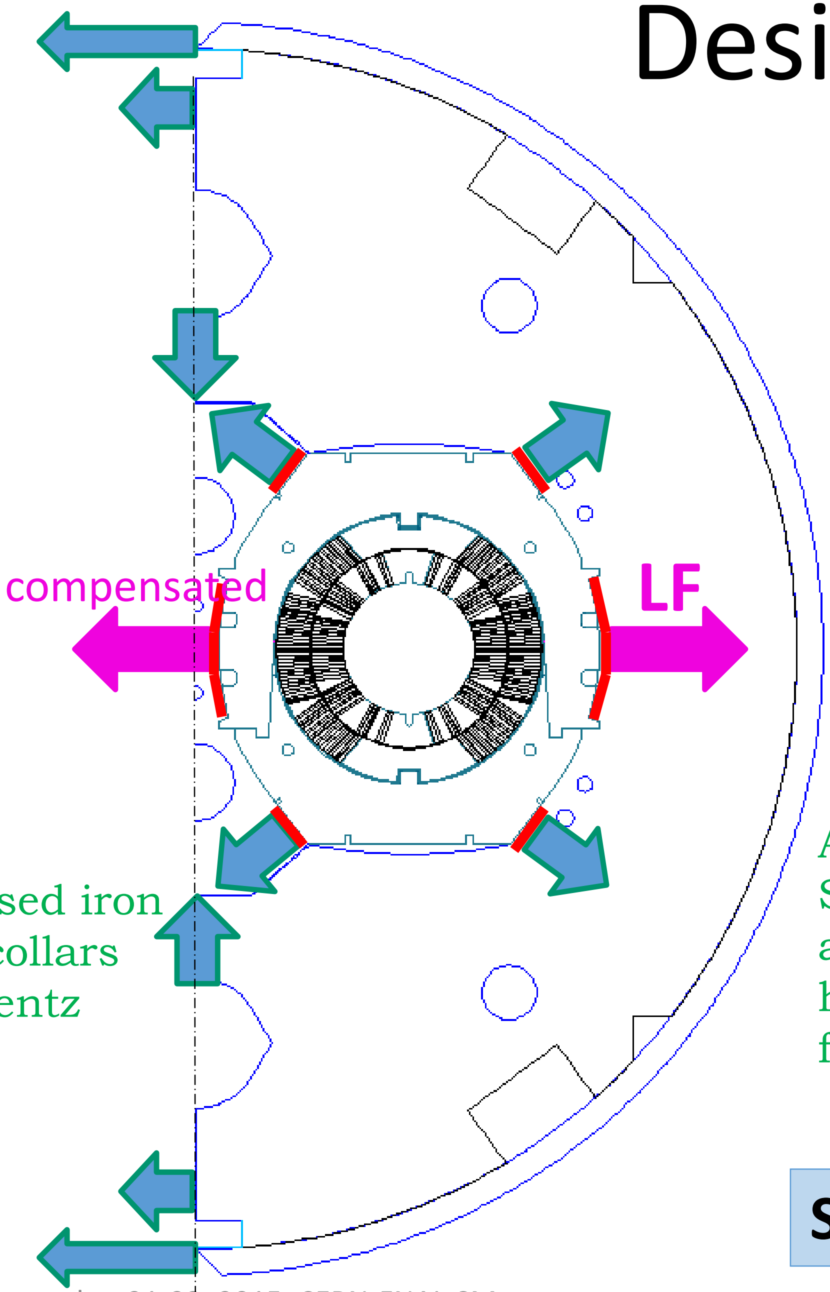
Collar-yoke-clamp-skin interferences support horizontal LF action.

Coil and inner layer pole in contact at 12T and stress in materials below yield point.

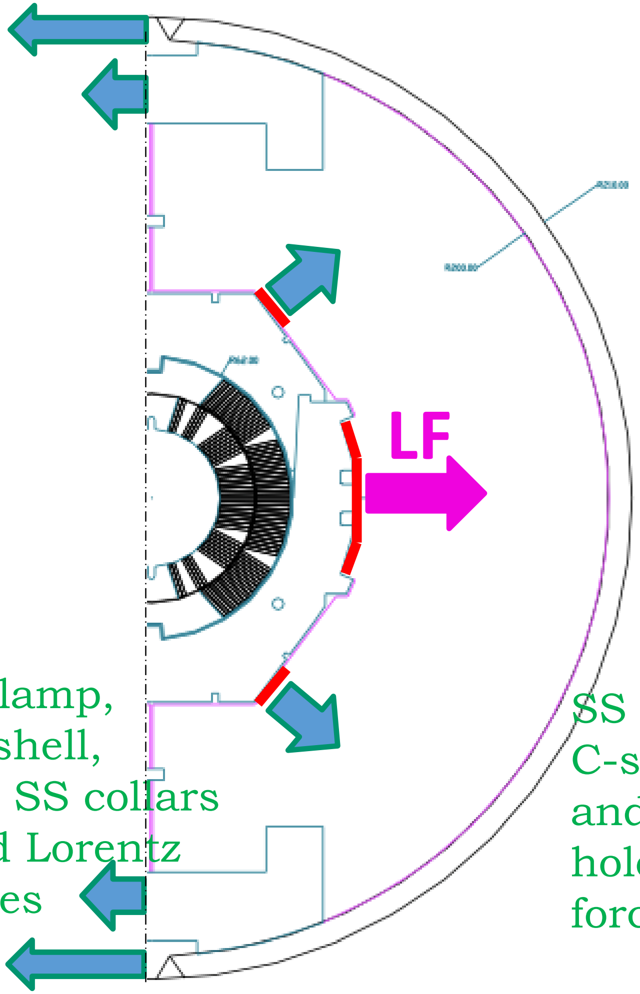


Design Concepts

Twin Aperture Magnet

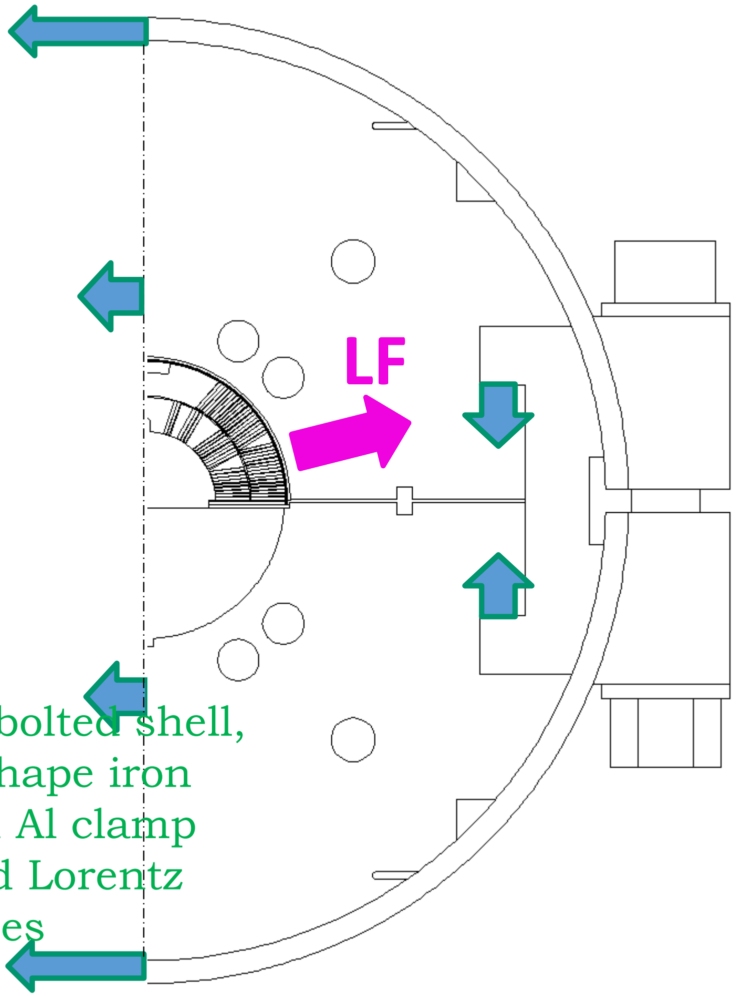


SS shell, compressed iron and SS collars hold Lorentz forces



Al clamp, SS shell, and SS collars hold Lorentz forces

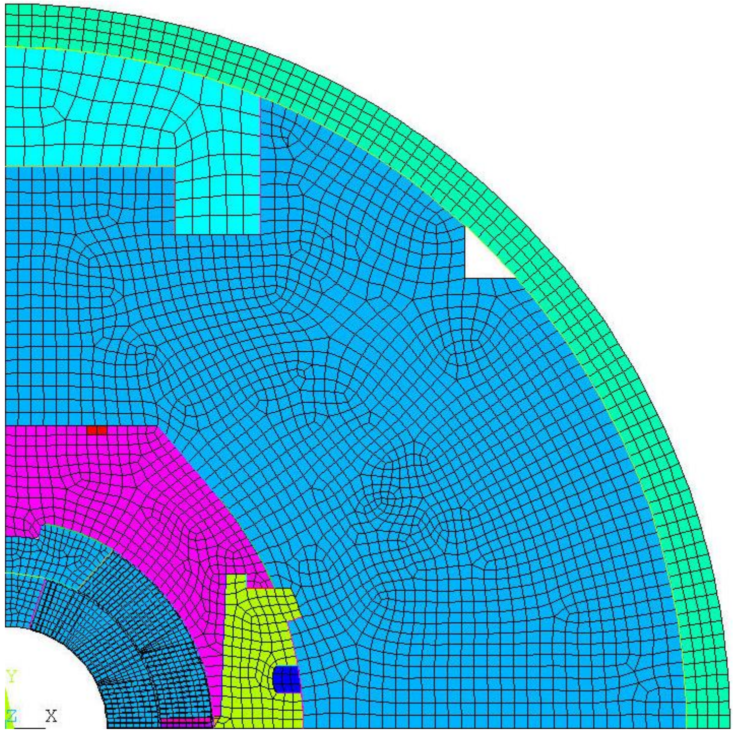
Single Bore Magnet



SS bolted shell, C-shape iron and Al clamp hold Lorentz forces

Mirror Magnet

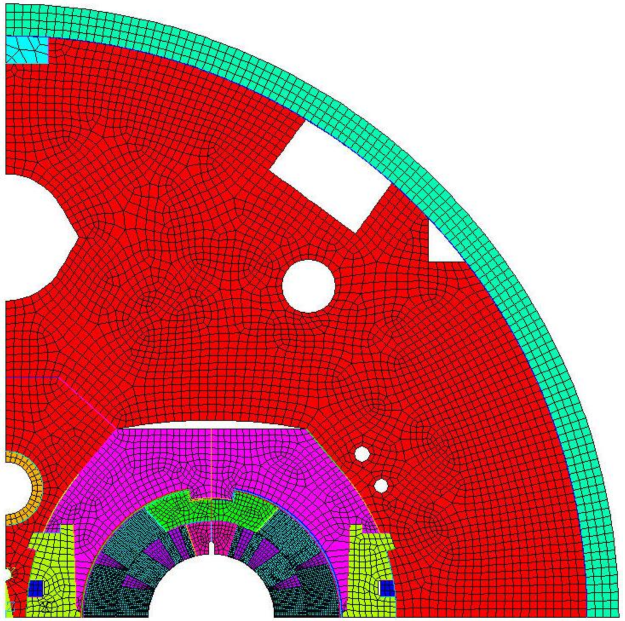
Single Bore Magnet FEA Model



The design components are represented with 4-node plane quadrilateral elements (PLANE 42). Material interfaces are modelled with contact elements (CONTACT 169-172).

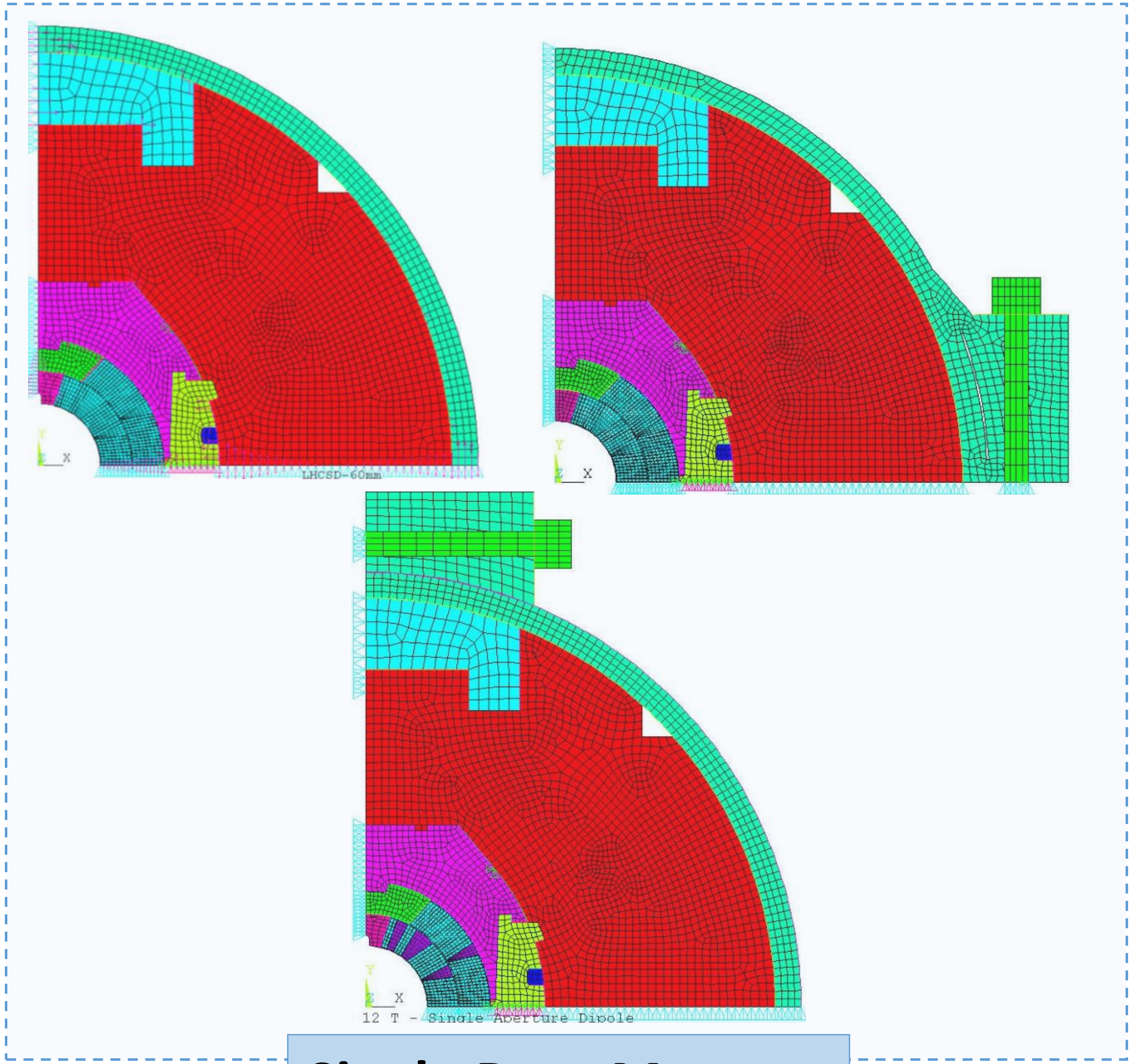
- The 2D ANSYS parametric model of the dipole includes the coil, the two layers of collars (front and lock-leg), the key, the iron yoke, the clamp and the skin.
- The model has a quarter symmetry.
- The coil inner and outer layers, and interlayer insulation are glued together.
- The Ti coil poles freely separates from the coil.
- The coil is surrounded by two layers of stainless steel collars
- Front and leg collars have symmetric boundaries along X-axis (CP and CE equations simulate line motion).
- The phosphor bronze key locks collar laminations fixing the coil azimuthal prestress.
- Clamped iron yoke supports the collars, and the welded stainless steel skin restrains the iron yoke from outside.

FEA Models

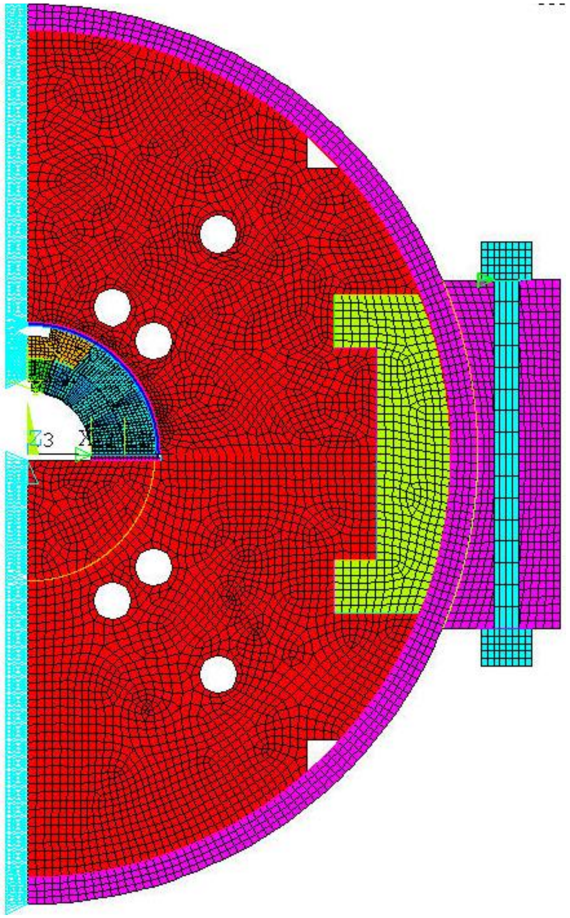


Twin Aperture Magnet

Includes identical (coil, collars) and different (iron, skin) parts



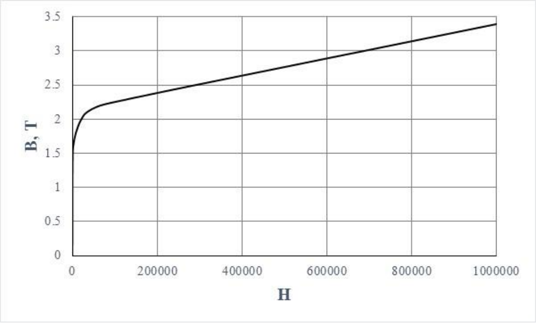
Single Bore Magnet



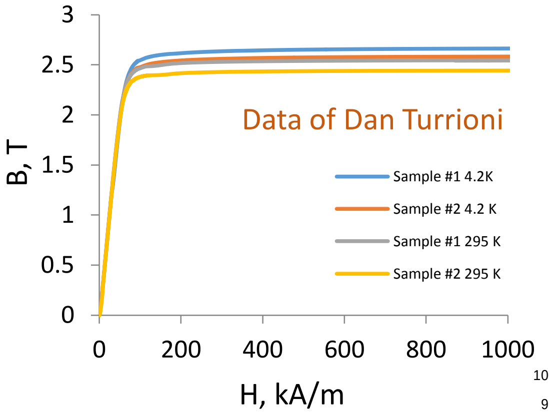
Mirror Magnet

Material Properties

BH for 1045 Iron used in ANSYS



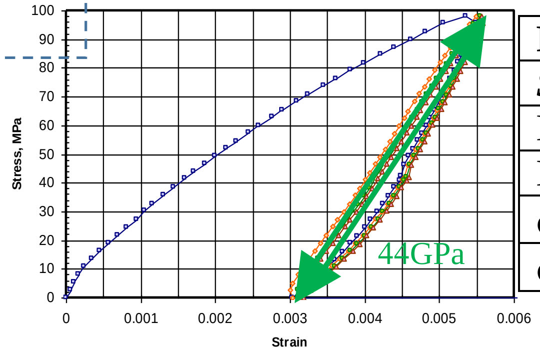
Measured 1045 Iron Magnetization



Structural element	Material	Thermal contraction (300-2 K), mm/m	Elasticity modulus, GPa		Yield stress, MPa	
			warm	cold	warm	cold
Clamp	7075-T6	4.1	70	85	460	650
Pole blocks	Ti-6Al-4V	1.7	115	125	650	>900
Collar	316LN	2.7-2.9	190	210	520	900
Key	Phosphor Bronze	3.3	110	123	380	>500
Yoke	Soft Iron	2.05	205	225	180-305	600
Skin	304L	2.9	190	210	340	600

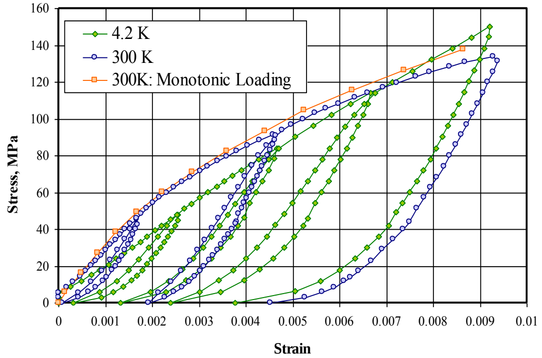
Coil data from HFM dipole programs

Cyclic Loading Tests

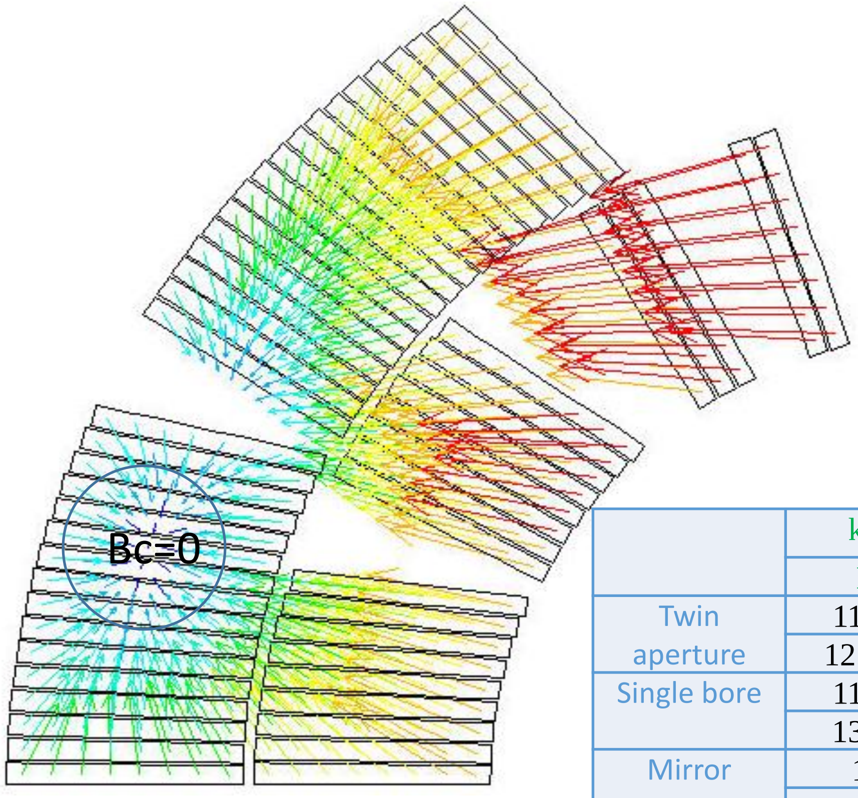


Parameter	**unit**	**2D Model**	
Straight section		*293 K*	*4.3 K*
Ey – Azimuthal direction	GPa	44	44
Ex – Radial direction	GPa	44	55
αx	E-3	2.6	
αy	E-3	3.5	

Load-Unload-Reload Tests



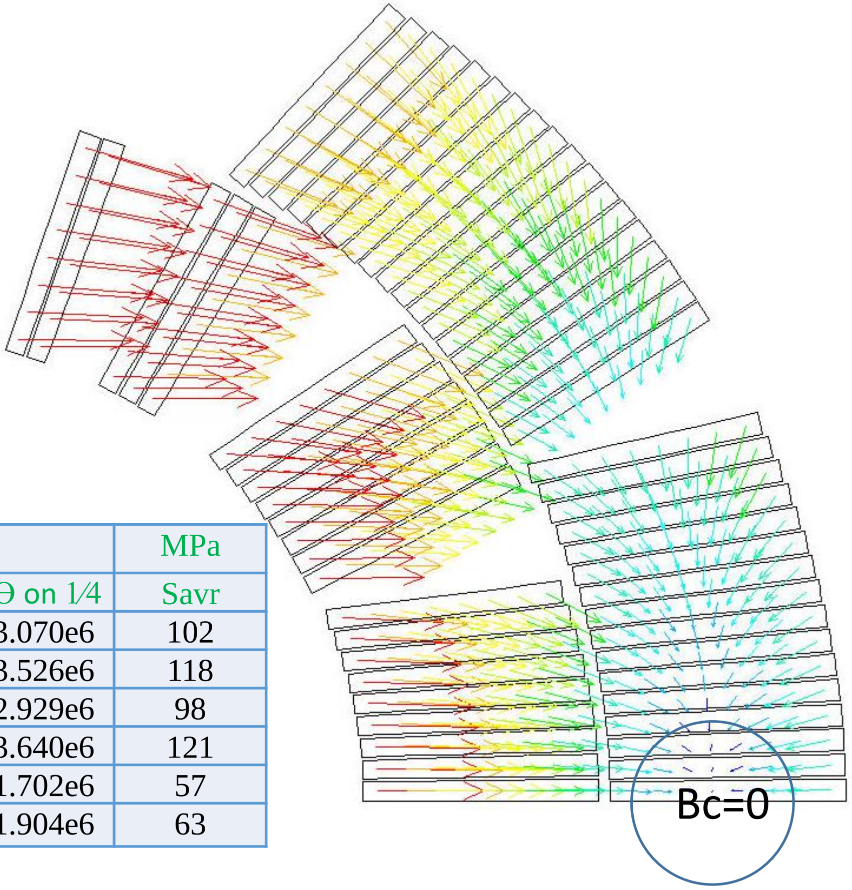
Electromagnetic Forces in the Magnet



Mirror Magnet

	kA	T	N per m				MPa
	Ic	Bo	Fx on ½	FY on 1/4	FR on ½	FΘ on 1/4	Savr
Twin aperture	11.85	11.2	6.296e6	-1.589e6	2.736e6	-3.070e6	102
	12.755	12	7.173e6	-1.836e6	3.077e6	-3.526e6	118
Single bore	11.85	10.8	2.327e6	-2.929e6	2.327e6	-2.929e6	98
	13.32	12	2.744e6	-3.640e6	2.744e6	-3.640e6	121
Mirror	13	10.77*	2.984e6	-1.638e5	1.638e6	-1.702e6	57
	14	11.45*	3.344e6	-1.699e5	1.812e6	-1.904e6	63

* Bconductor



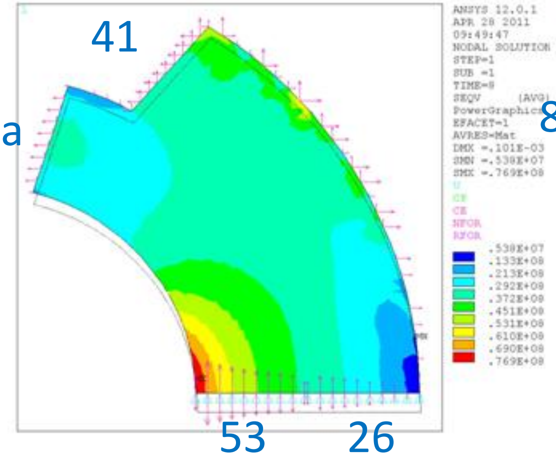
Single Bore Magnet

Single-Bore Dipole: Coil Stress

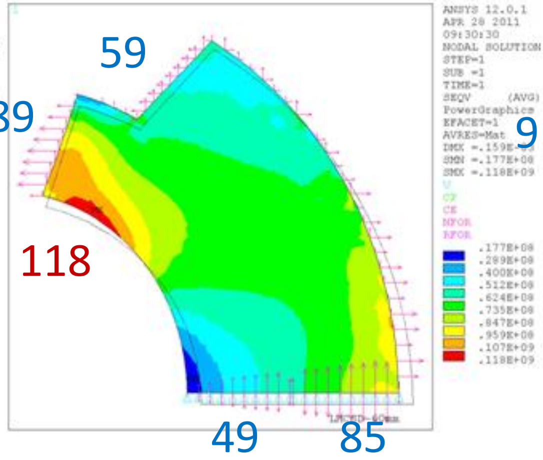
Avg.=28MPa

Max Seqv.
=77MPa

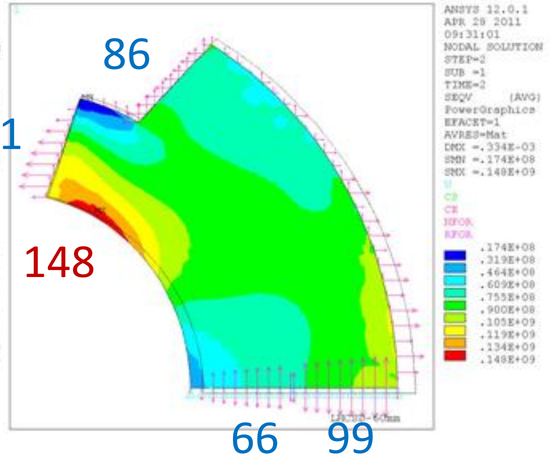
After Collaring

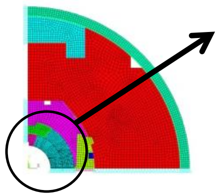


After Skin Welding

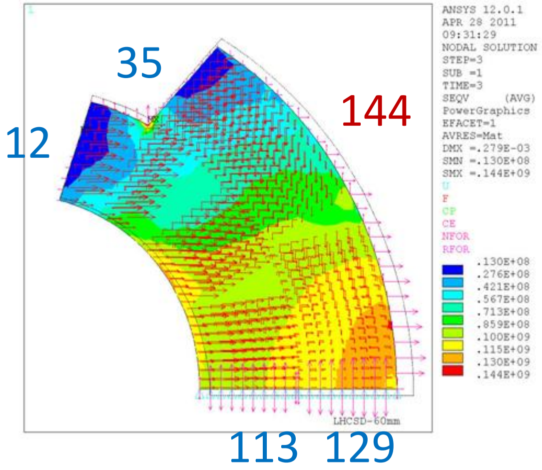


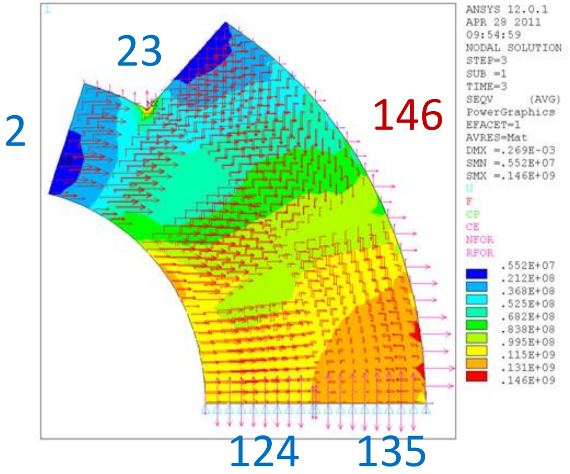
After Cooling Down, 300-2K





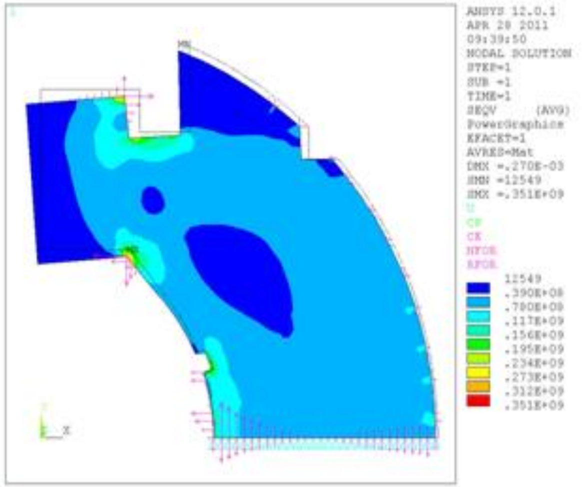
After 11T, 2K





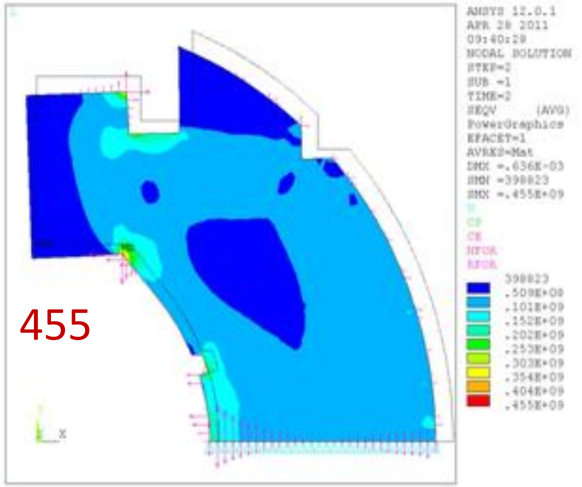
After 12T, 2K

Single Bore Dipole: Iron Yoke Stress



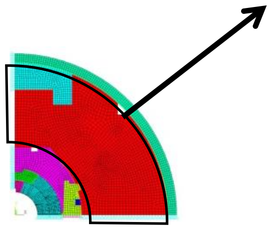
After Skin Welding

Max Seqv.
=351MPa



After Cooling Down, 300-2K

455



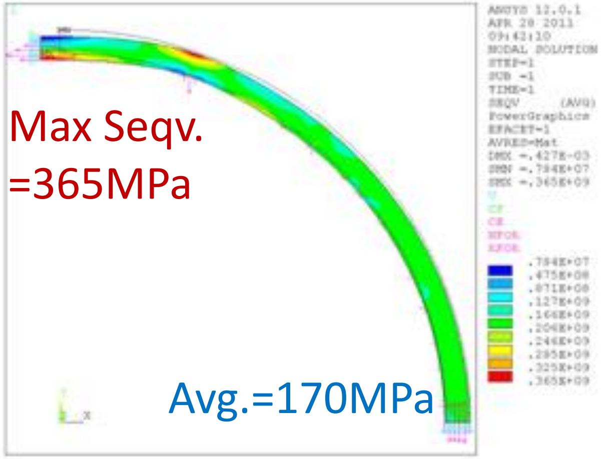
After 11T, 2K

362

After 12T, 2K

387

Single Bore Dipole: Skin Stress



Max Seqv.
=365MPa

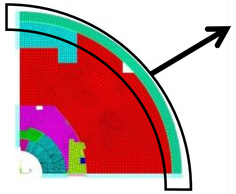
Avg.=170MPa

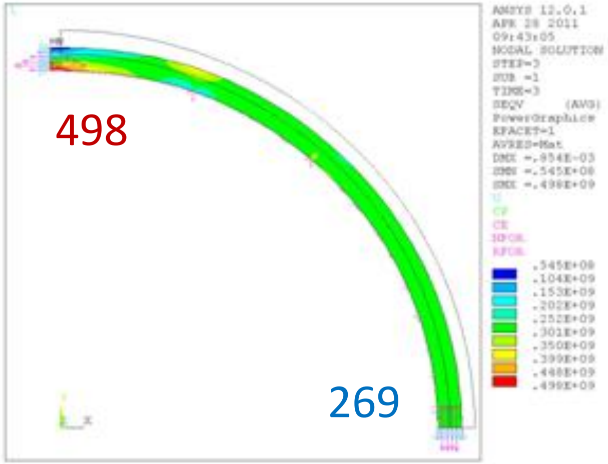
After Skin Welding

489

266

After Cooling Down, 300-2K





498

269

After 11T, 2K

499

270

After 12T, 2K

Single Bore Dipole FEA Results

	Coil average stress, MPa			
	Inner pole	Outer pole	Inner midplane	Outer midplane
Collaring	28	41	53	26
Assembly	89	59	49	85
Cooldown	91	86	66	99
I_{nom}=11.85 kA	12	35	113	129
B_{max}=12 T	2	23	124	135

	Maximum stress, MPa					
	Inner/outer poles	Collar	Key	Yoke	Al clamp	Skin/avg/max
Collaring	133/90	527	362	n/a	n/a	n/a
Assembly	510/180	412	132	351	261	170/365
Cooldown	588/263	562	124	455	287	266/489
I_{nom}=11.85 kA	100/128	476	184	362	282	269/498
B_{max}=12 T	50/136	494	202	387	281	270/500

Single Bore Coil: IR Deflections

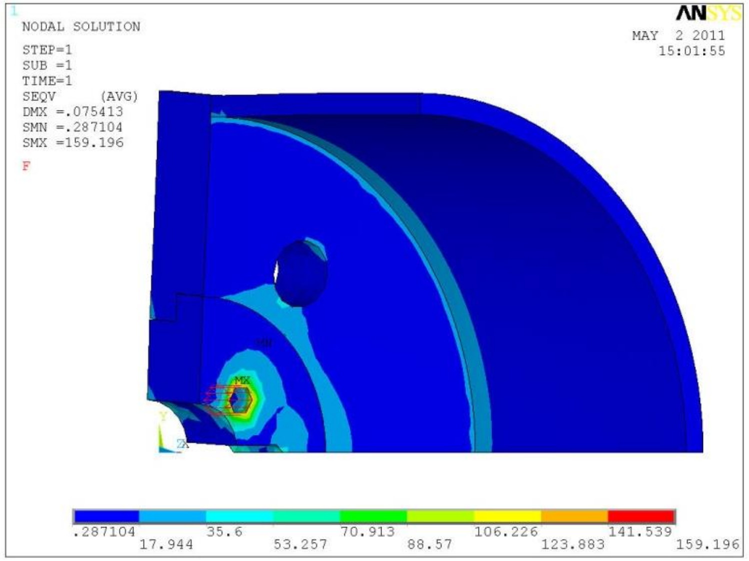
Magnet cross-section is deformed due to the coil prestress, cool-down and Lorentz forces action. Bore deflections from the warm unstressed round geometry (magnetic design) calculated for the above mentioned effects at room and helium temperatures in the dipole straight section are summarized below:

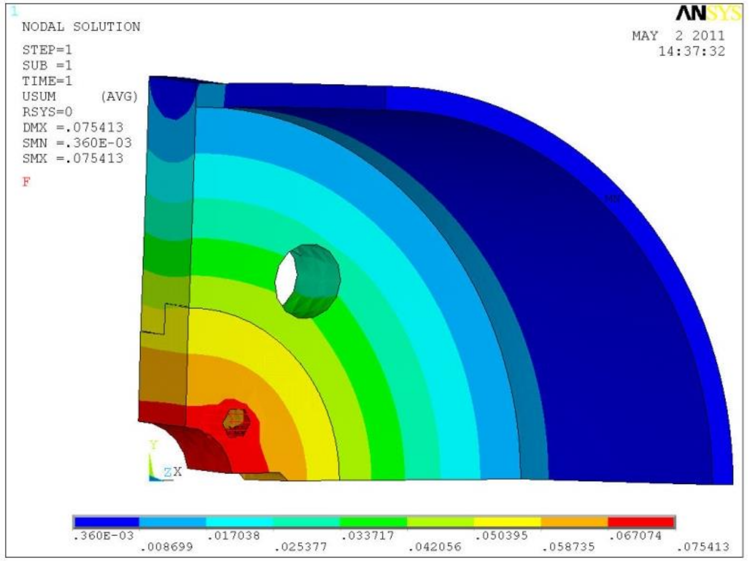
	Bore radial deflection, µm		
	Pole	Midplane	45 degree
Collaring	58	-11	58
Assembly	87	-122	13
Cooldown	-21	-240	-96
I_{nom}=11.85 kA	-51	-163	-74
B_{max}=12 T	-57	-149	-70

At the nominal operating current of 11.85 kA the radial cross-section deflection from the magnetic design in the magnet midplane is ~165 µm.

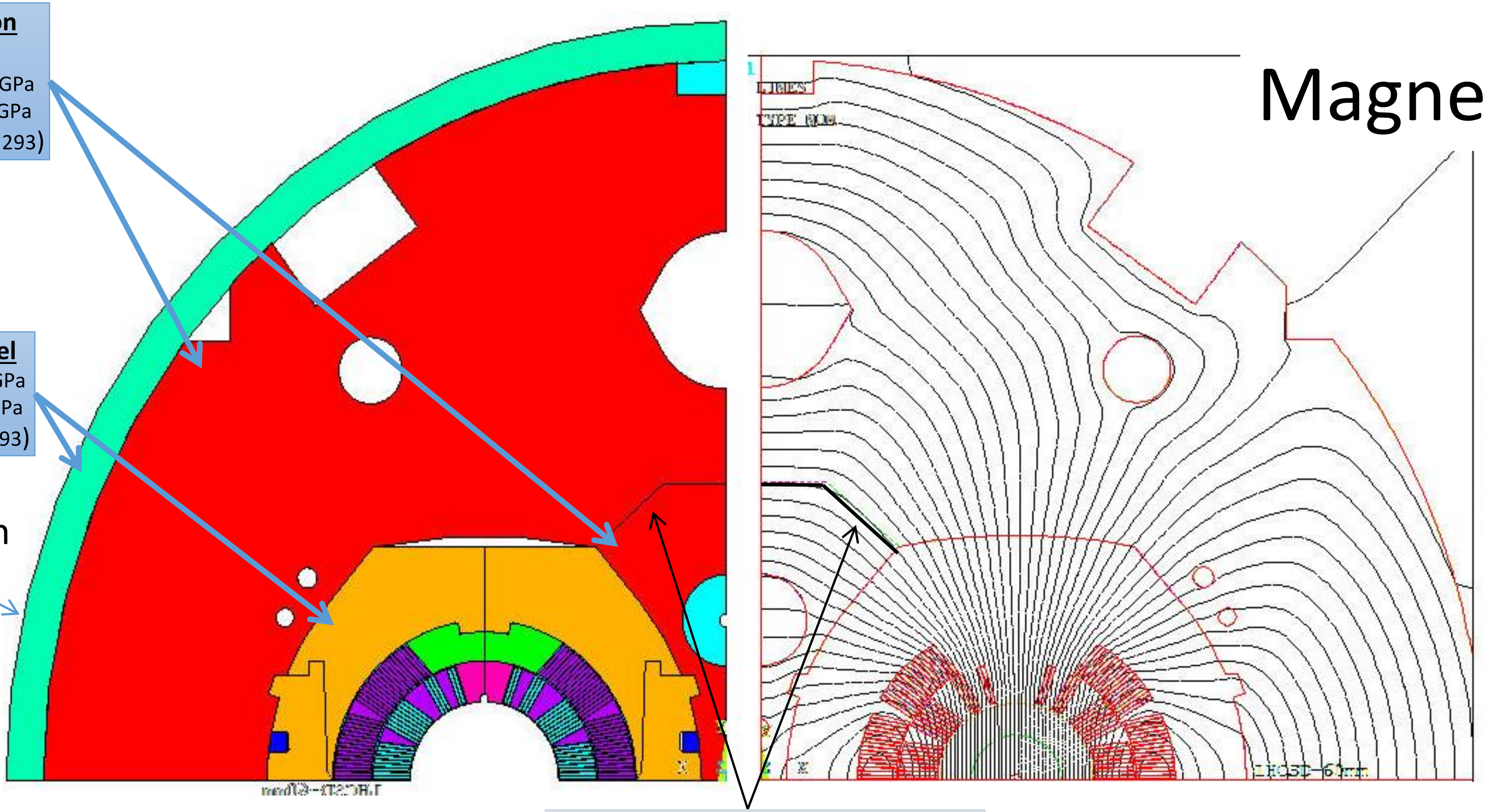
End Plate Deformation and Stress

- The 50-mm end plate deflection and coil end motion under the nominal LF is about 75 μm.
- The maximum stress in the end plate is 160 MPa.
- Taking into account that usually only 20% of the Lorentz force is transferred to magnet end plates, the coil end motion is even smaller.





FNAL 2in1 FEA Model



Low Carbon Steel
E(**293K**) = 210 GPa
E(**4.2K**) = 225 GPa
α= 2.05/(1000*293)

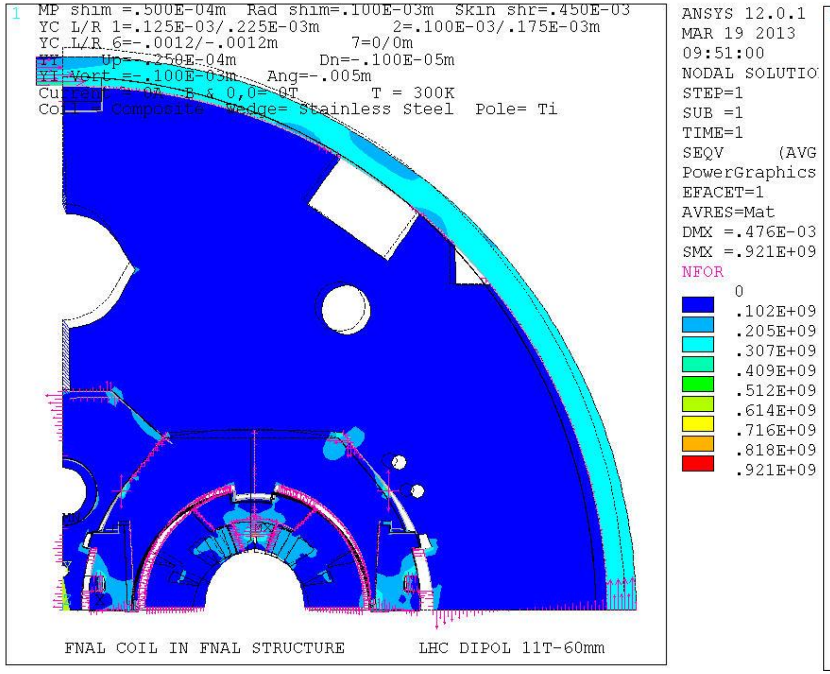
304L St. Steel
E(**293K**) = 195 GPa
E(**4.2K**) = 215 GPa
α= 2.7/(1000*293)

15mm Skin

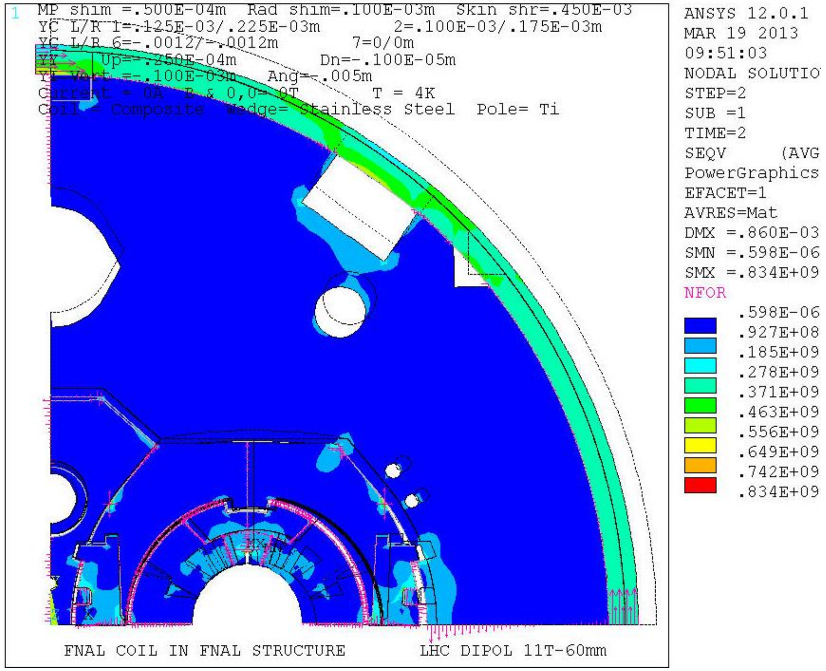
Magnetic flux

Iron cut along flux line

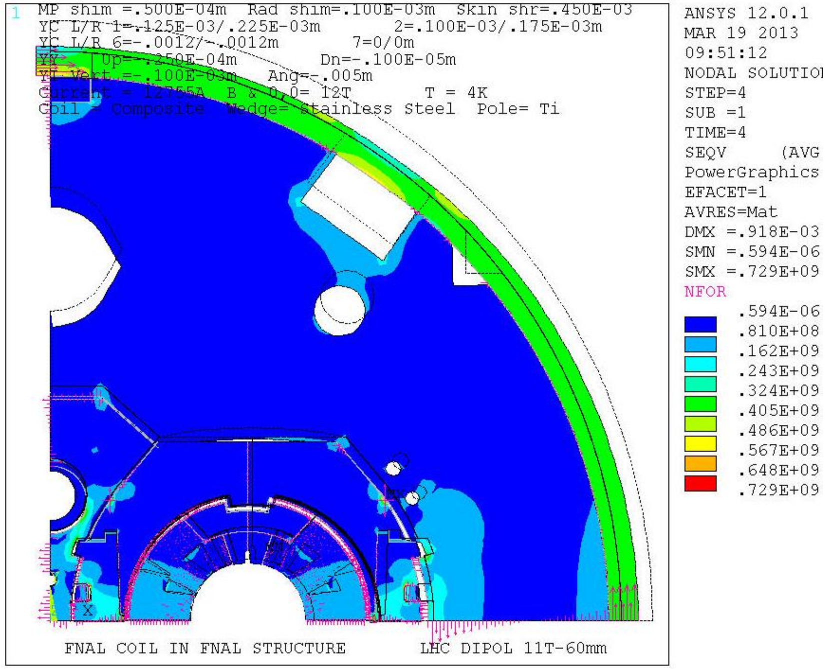
Twin Aperture Dipole Structure



300K



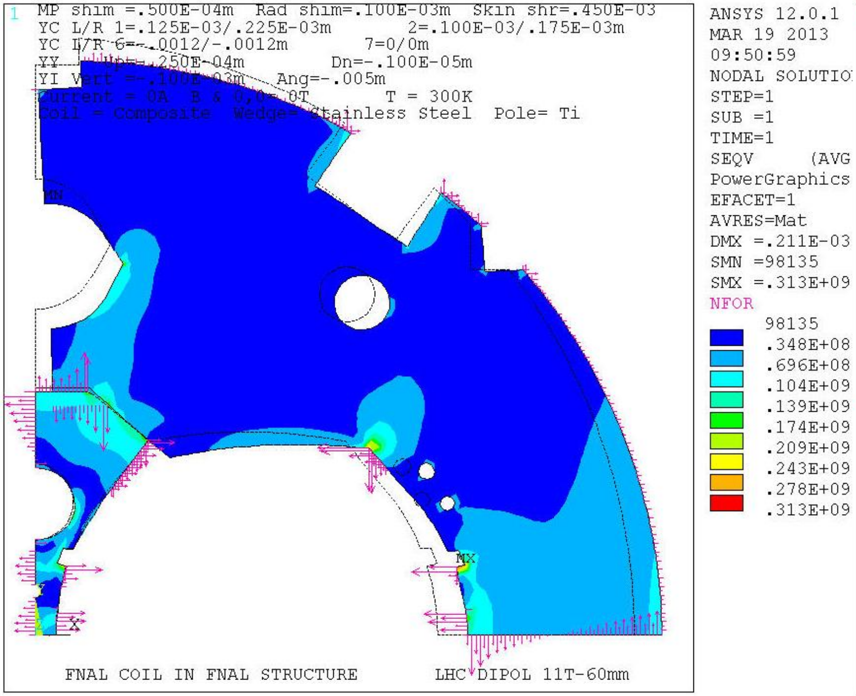
4K



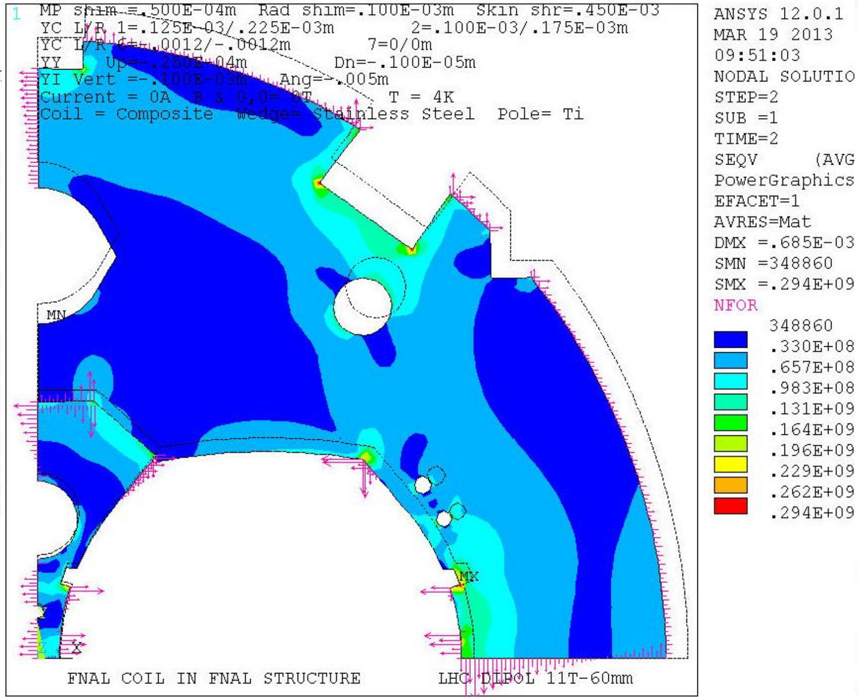
4K 12T

Seqv, Pa

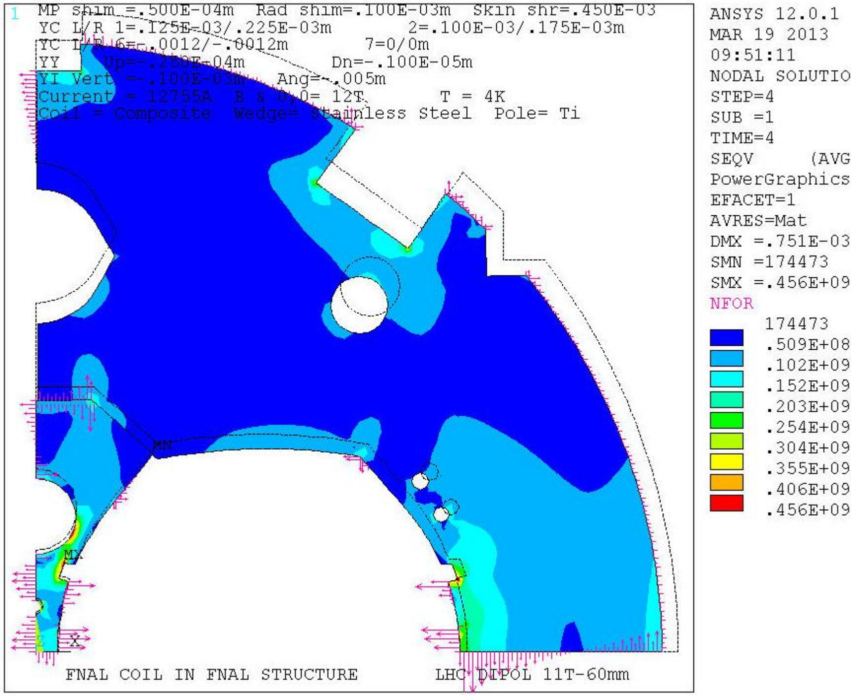
Twin Aperture Dipole Iron



300K



4K

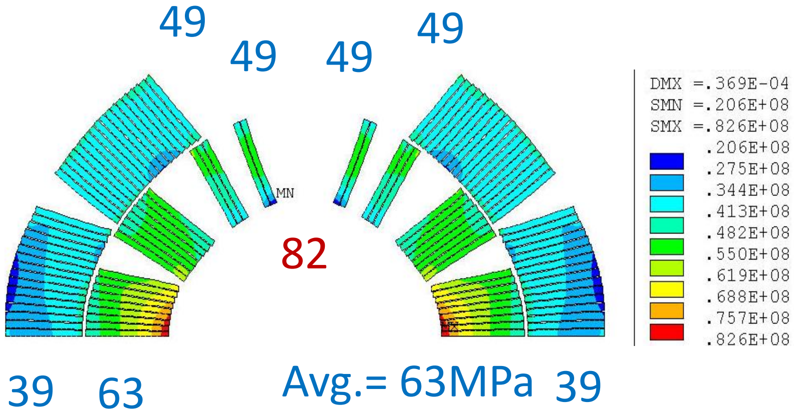


4K 12T

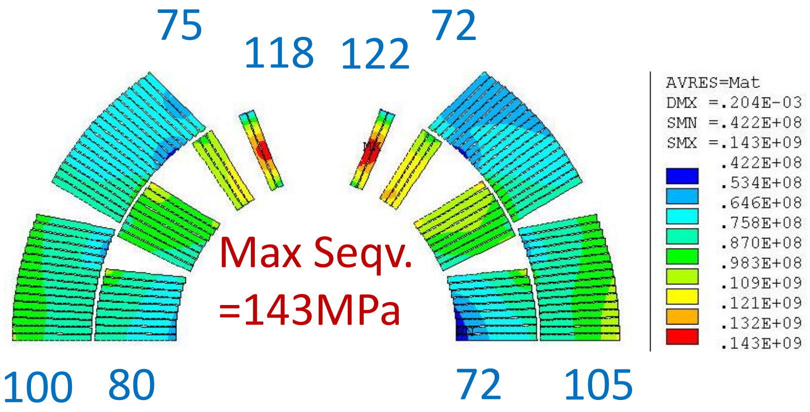
Seqv, Pa

Twin Aperture Dipole: Coil Stress

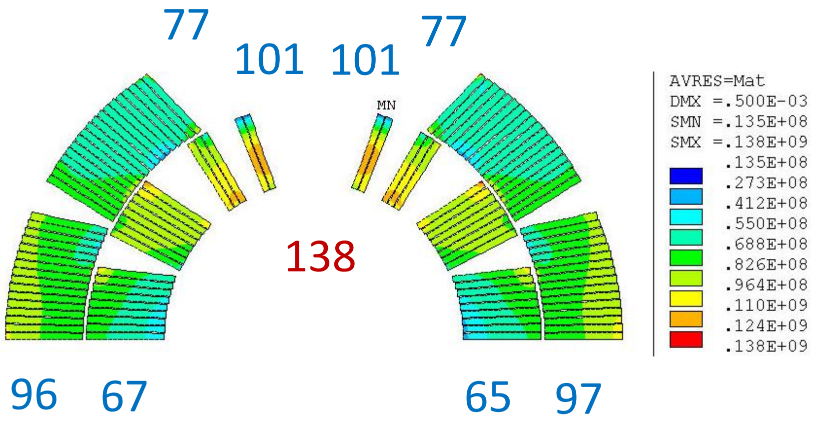
After Collaring

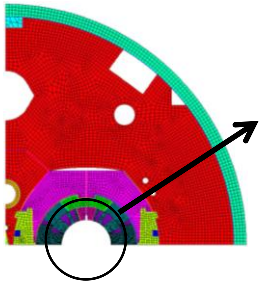


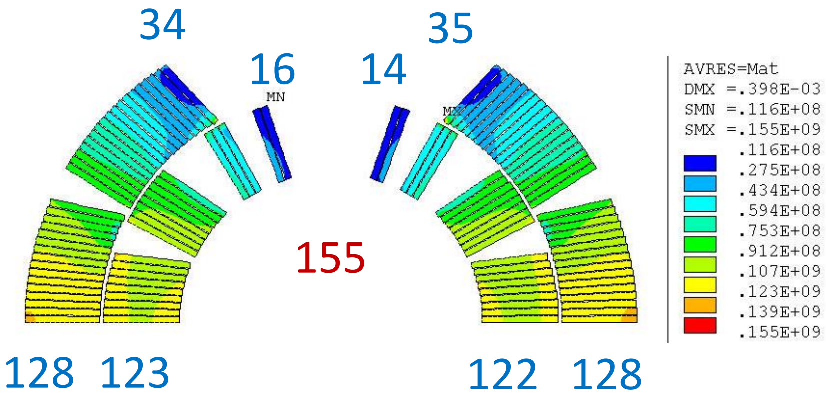
After Skin Welding



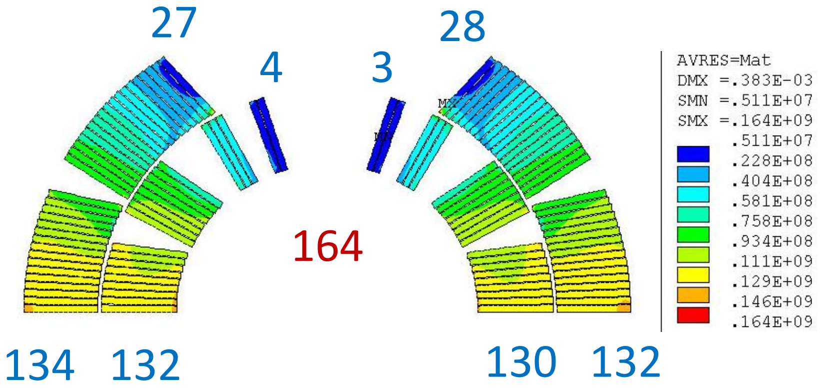
After Cooling Down, 300-2K





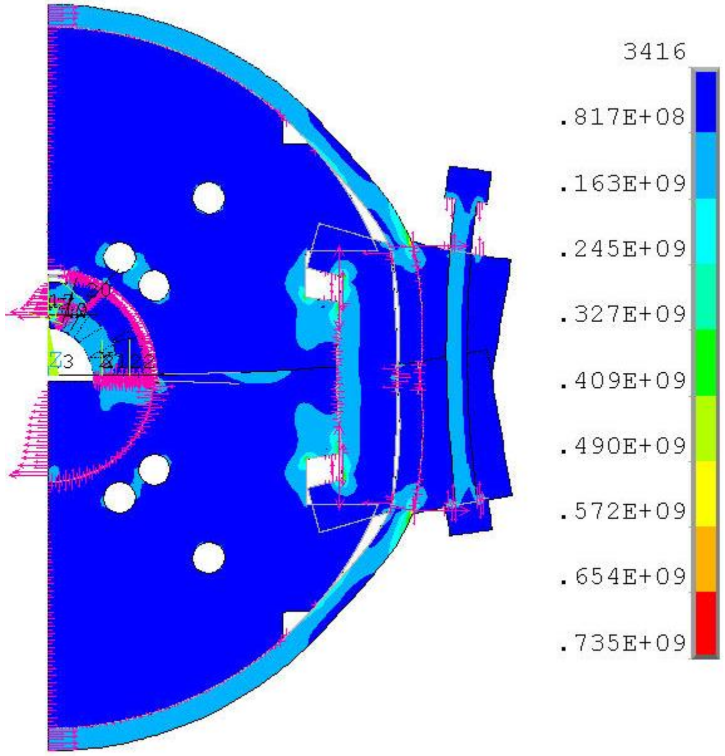


After 11T, 2K

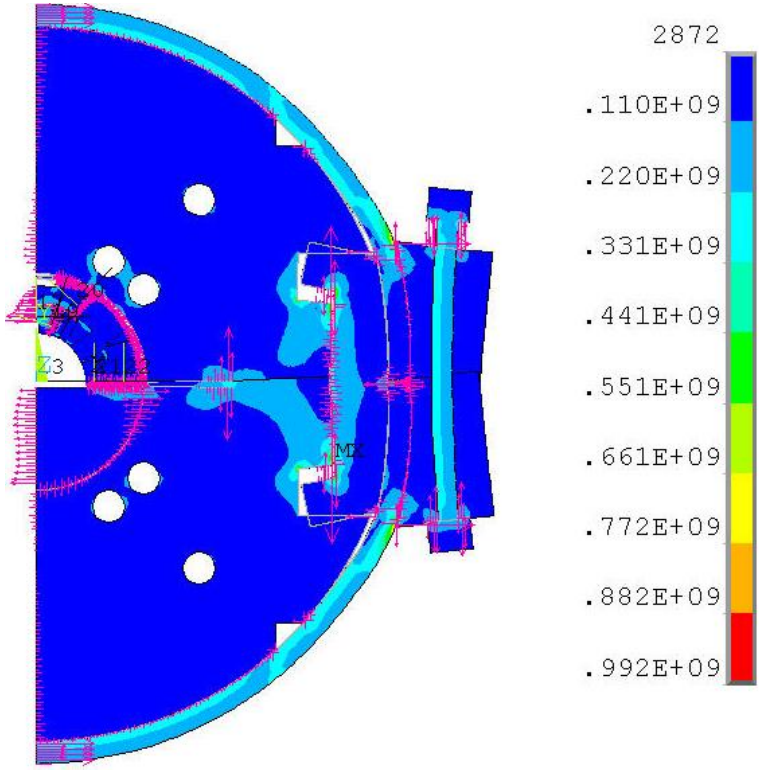


After 12T, 2K

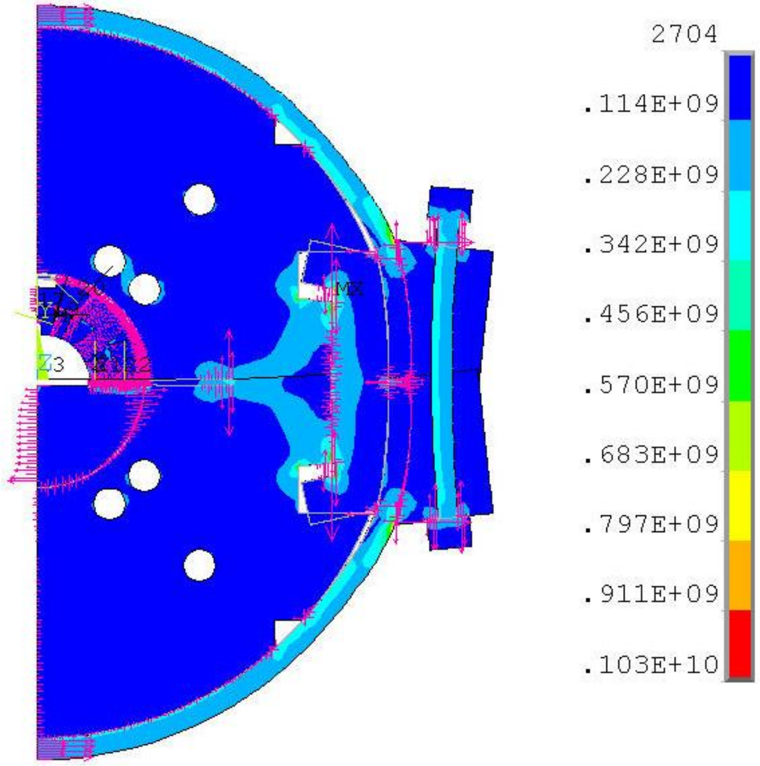
Mirror Structure



300K



4K



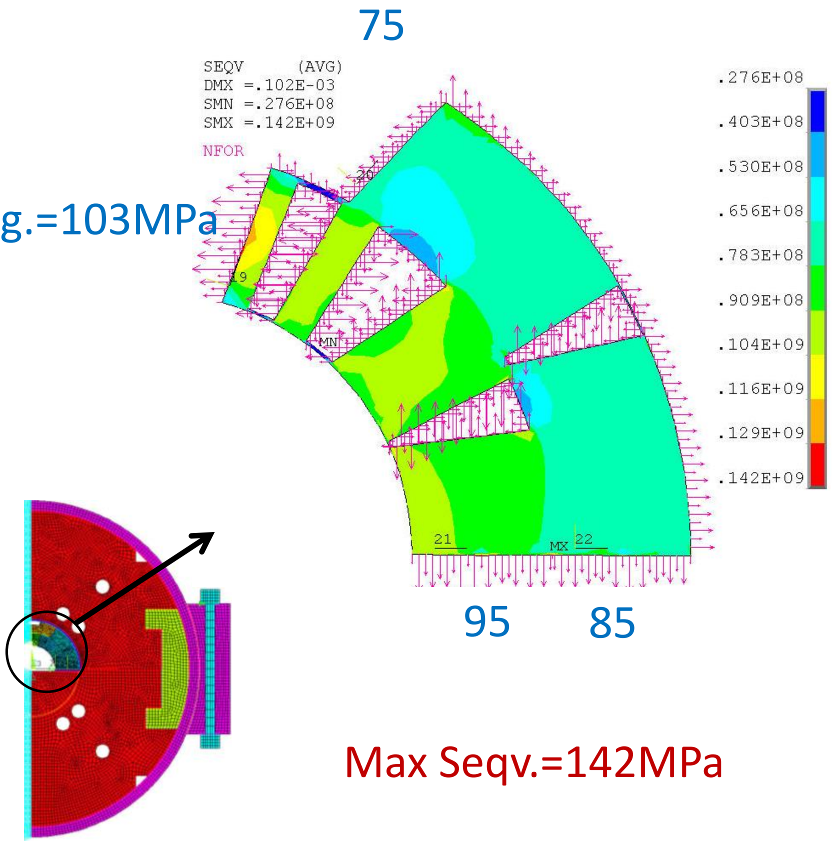
4K 11T

Seqv, Pa

Mirror Magnet: Coil Stress

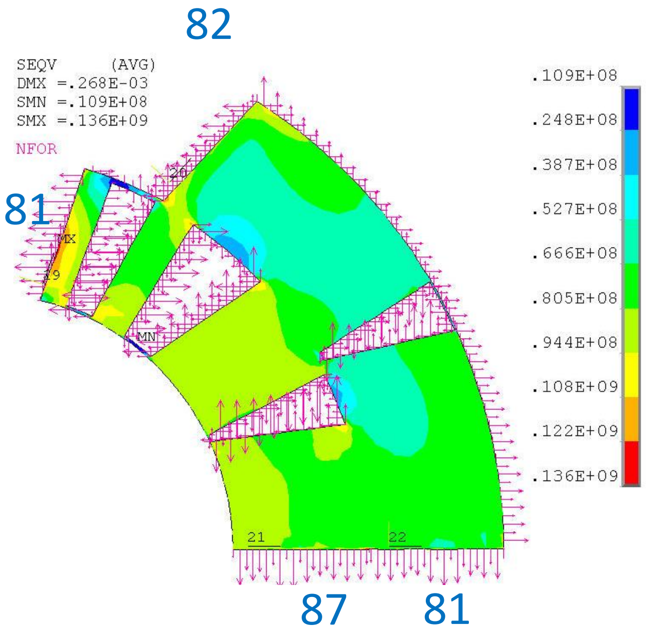
After Skin Bolting

Avg.=103MPa



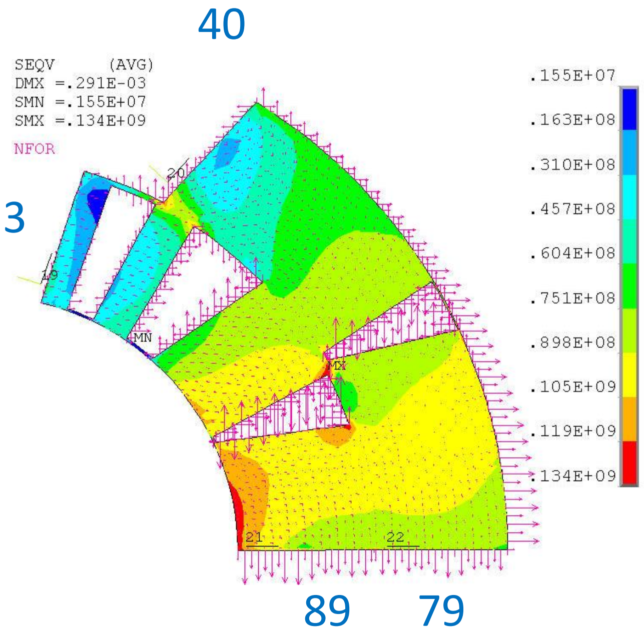
Max Seqv.=142MPa

After Cooling Down, 300-2K



136

At B=8.35T, 2K



134

Summary

All mechanical designs provides the coil prestress required for the operating current range

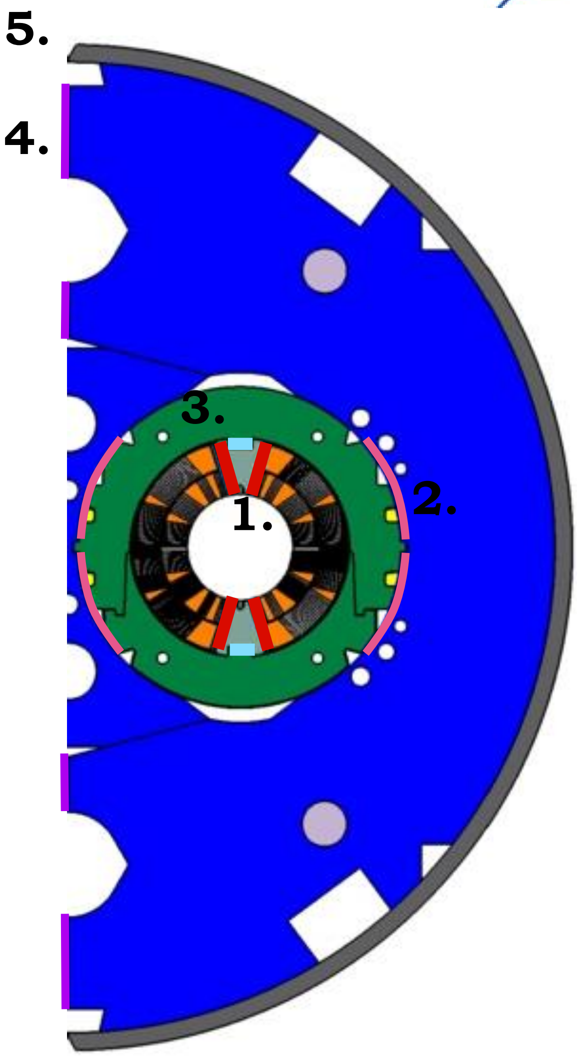
All designs restricts turn radial, azimuthal and longitudinal motion under the Lorentz forces up to 12T

The maximal mechanical stresses in the major elements of coil support structure are below the limits for the materials used

Back Up Slides

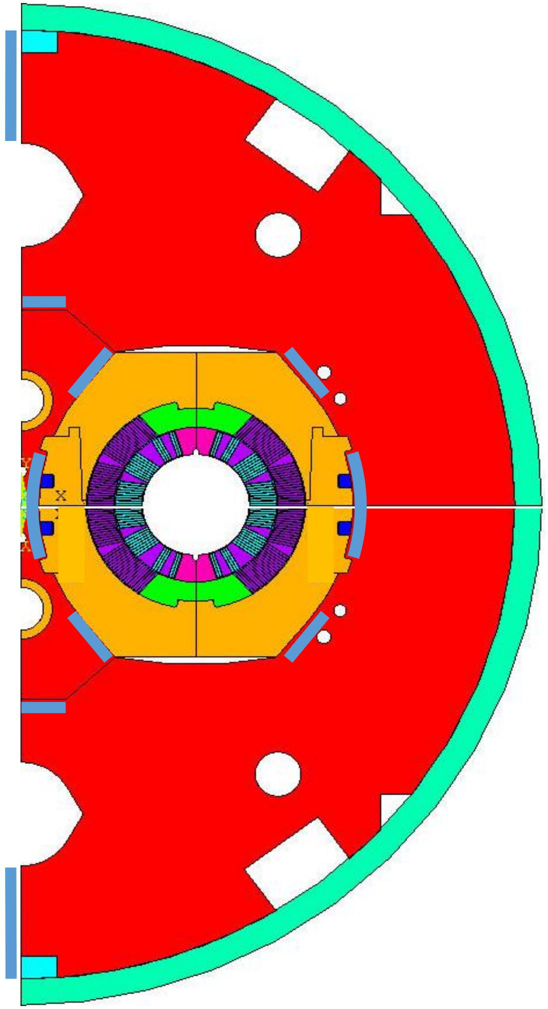
Outline of CERN 2in1 Concept

- OD of 2in1 magnet is fixed
- Close-iron concept persuade by CERN (working design, tooling, assembly experience) => “Close-iron” or “Iron Ring” concept
- Collared coil shrinks more than the rigid “Iron Ring”
  => need interference
- Collared coil-Yoke interference use to compensate difference in collars and yoke thermal-contractions, plus needed push against LF action.
  => fades down from 0 (MP) to ~35-40 degree (coil top horiz.)
- Interference value not sufficient
  => need additional mechanism for coil pre-stress
- Removable pole concept has been introduced
  => removable pole for coil pre-stress
- New (Removable pole) concept require new coil and collared coil designs

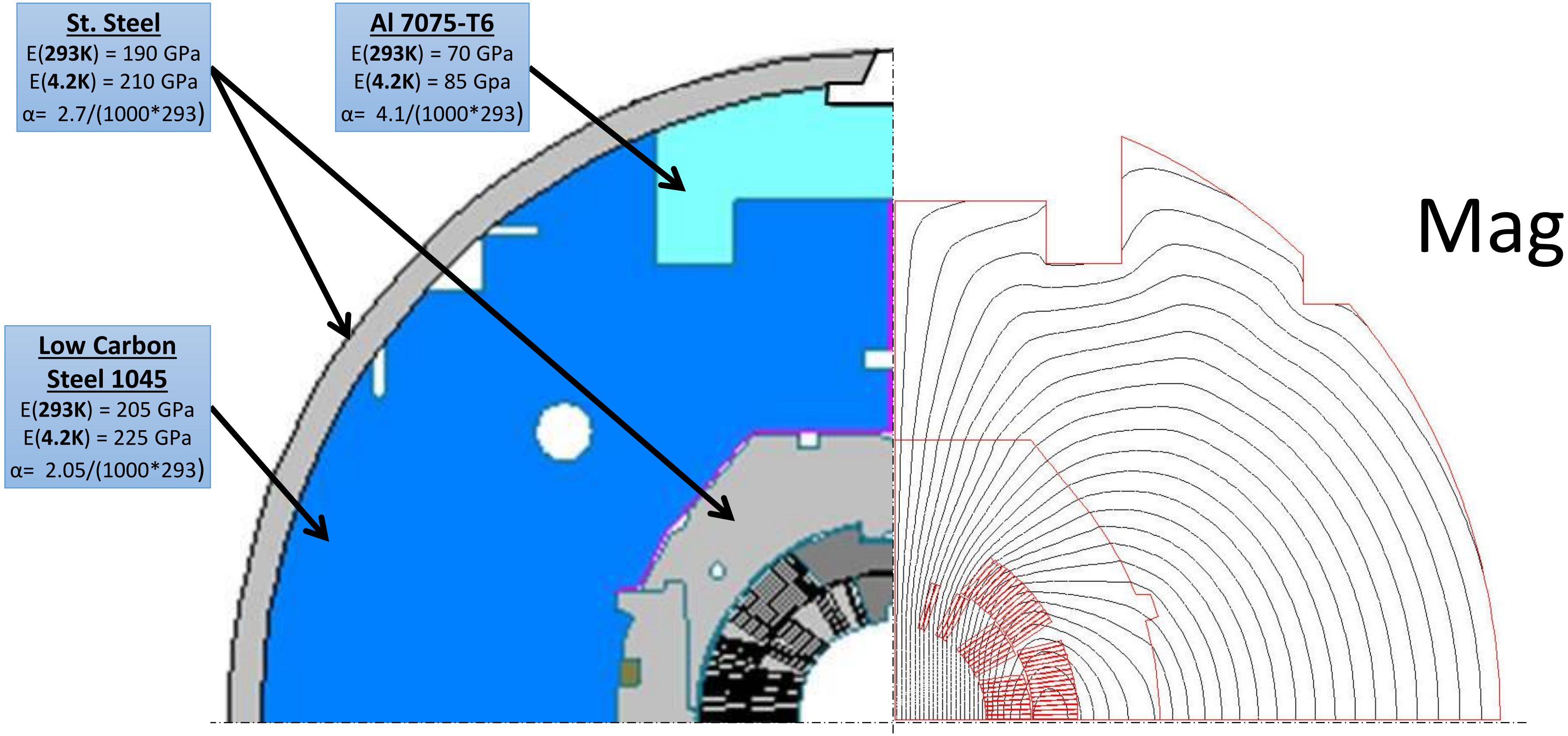


Outline of FNAL 2in1 Concept

- Integrated Pole design concept for coil is fixed by FNAL (working design, tooling, assembly experience)
  => require different approach (not CERN “Iron Ring”)
- “Controlled Yoke Gap” concept was introduced (TQ design) to deliver additional coil pre-stress
  => Controlled by collars Yoke Gap for coil pre-stress
- New (Controlled Yoke Gap) concept require new yoke and collars design



FNAL Single Bore Magnet FEA Model



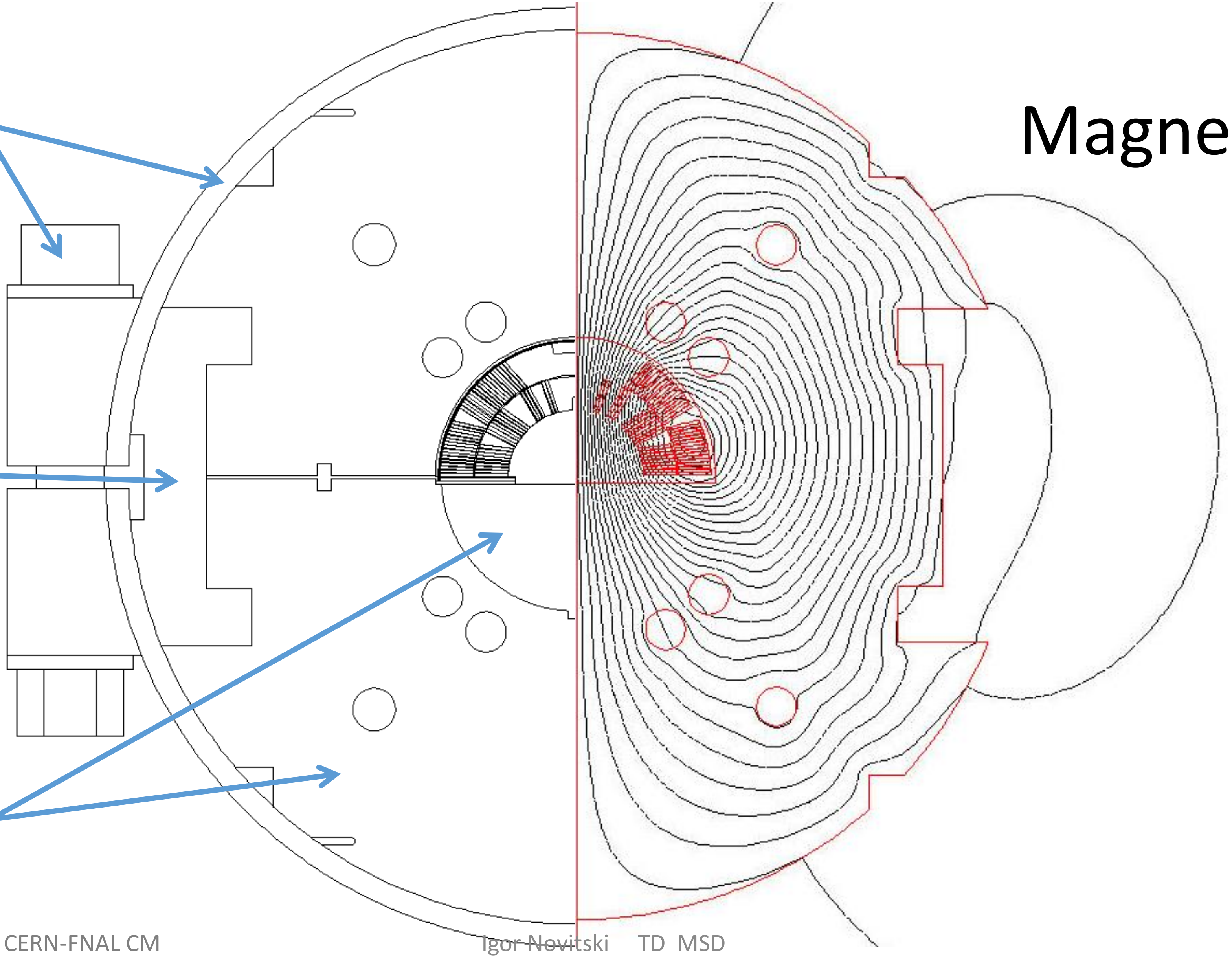
St. Steel
E(**293K**) = 190 GPa
E(**4.2K**) = 210 GPa
α= 2.7/(1000*293)

Al 7075-T6
E(**293K**) = 70 GPa
E(**4.2K**) = 85 Gpa
α= 4.1/(1000*293)

Low Carbon Steel 1045
E(**293K**) = 205 GPa
E(**4.2K**) = 225 GPa
α= 2.05/(1000*293)

Magnetic flux

FNAL Mirror Magnet FEA Model



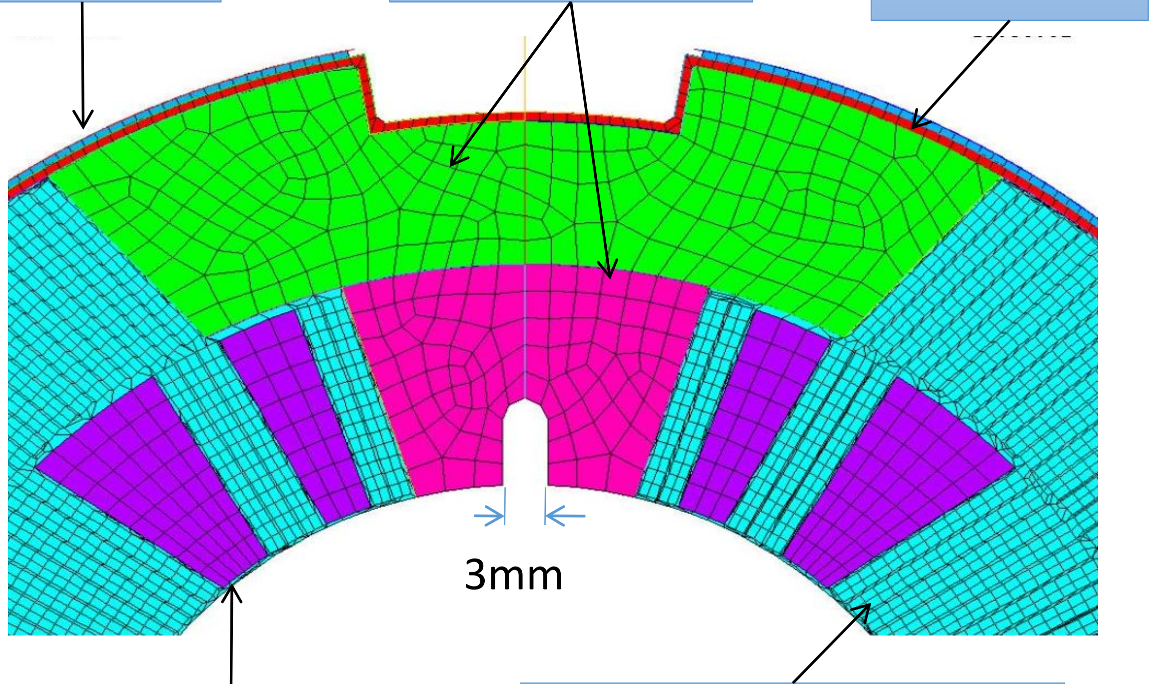
Magnetic flux

304L St. Steel
E(**293K**) = 190 GPa
E(**4.2K**) = 210 GPa
α= 2.9/(1000*293)

Al 7075-T6
E(**293K**) = 70 GPa
E(**4.2K**) = 85 GPa
α= 4.1/(1000*293)

Low Carbon Steel
E(**293K**) = 205 GPa
E(**4.2K**) = 225 GPa
α= 2.05/(1000*293)

FNAL Coil Model
Material Properties



St. Steel Shell
E(**293K**) = 190 GPa
E(**4.2K**) = 210 GPa
α= 2.9/(1000*293)

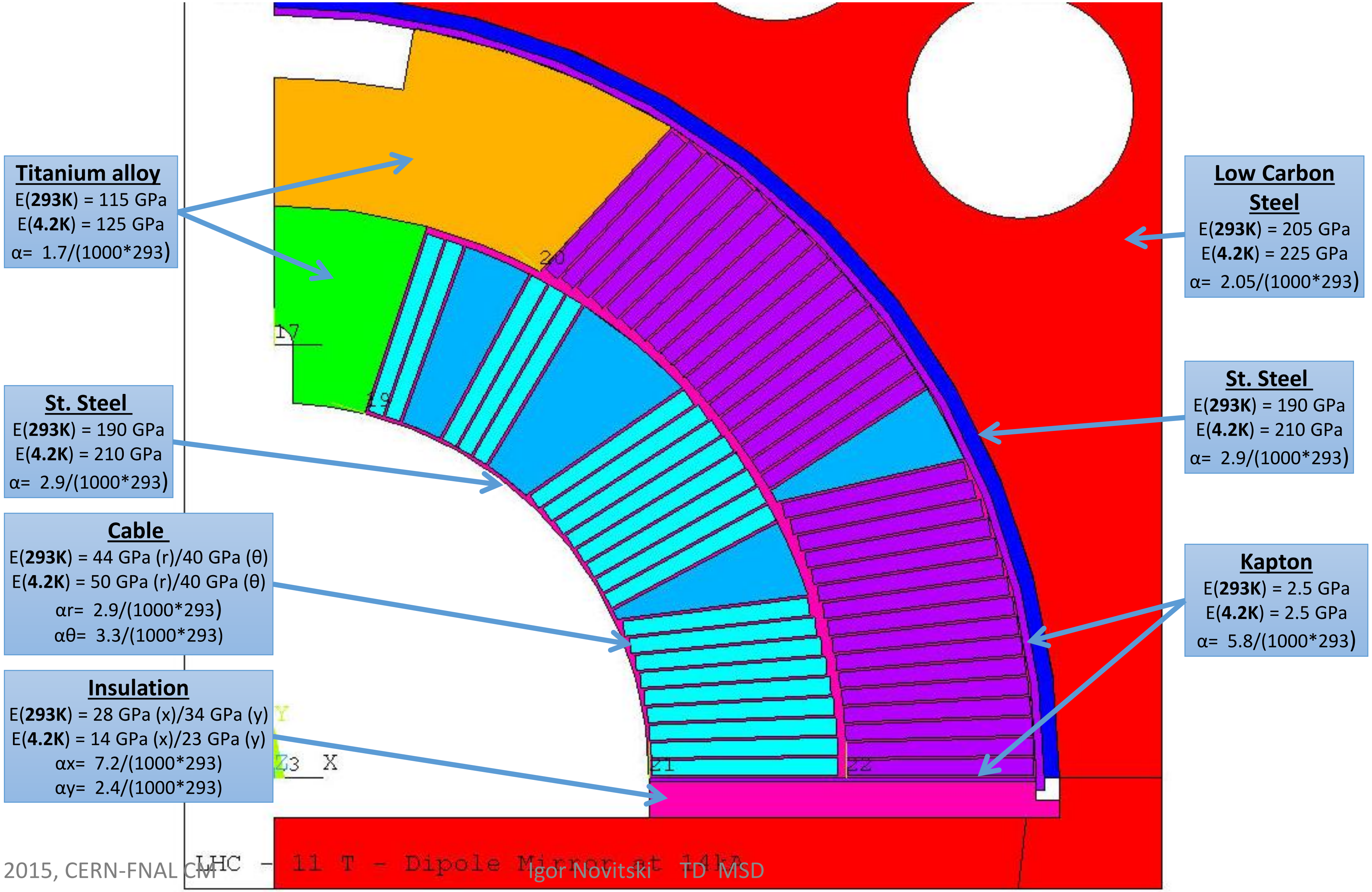
Titanium Alloy Poles
E(**293K**) = 115 GPa
E(**4.2K**) = 125 GPa
α= 1.7/(1000*293)

Kapton Gl
E(**293K**) = 2.5 GPa
E(**4.2K**) = 2.5 GPa
α= 5.8/(1000*293)

St. Steel Wedges
E(**293K**) = 190 GPa
E(**4.2K**) = 210 GPa
α= 2.9/(1000*293)

Cable and Insulation Composite
E(**293K**) = 40 GPa (x)/40 GPa (y)
E(**4.2K**) = 45 GPa (x)/40 GPa (y)
αy= 3.3/(1000*293)
αx= 2.9/(1000*293)

Coil Model Material Properties



Titanium alloy
E(**293K**) = 115 GPa
E(**4.2K**) = 125 GPa
α= 1.7/(1000*293)

St. Steel
E(**293K**) = 190 GPa
E(**4.2K**) = 210 GPa
α= 2.9/(1000*293)

Cable
E(**293K**) = 44 GPa (r)/40 GPa (θ)
E(**4.2K**) = 50 GPa (r)/40 GPa (θ)
αr= 2.9/(1000*293)
αθ= 3.3/(1000*293)

Insulation
E(**293K**) = 28 GPa (x)/34 GPa (y)
E(**4.2K**) = 14 GPa (x)/23 GPa (y)
αx= 7.2/(1000*293)
αy= 2.4/(1000*293)

Low Carbon Steel
E(**293K**) = 205 GPa
E(**4.2K**) = 225 GPa
α= 2.05/(1000*293)

St. Steel
E(**293K**) = 190 GPa
E(**4.2K**) = 210 GPa
α= 2.9/(1000*293)

Kapton
E(**293K**) = 2.5 GPa
E(**4.2K**) = 2.5 GPa
α= 5.8/(1000*293)

Single Bore Coil Stress

	Coil average stress, MPa			
	Inner pole	Outer pole	Inner midplane	Outer midplane
Collaring	28	41	53	26
Assembly	89	59	49	85
Cooldown	91	86	66	99
I_{nom}=11.85 kA	12	35	113	129
B_{max}=12 T	2	23	124	135

The expected prestress variation with respect to the nominal coil prestress at the ±50 μm azimuthal coil size variation is within ±10 MPa in the inner layer and within ±23 MPa in the outer layer.

Analysis shows that at the maximum design field of 12 T the minimal coil prestress in pole regions is 2-23 MPa.

The maximum coil prestress at room temperature does not exceed 160 MPa, which is acceptable for the Nb_3Sn cable and coil insulation.

Single Bore Structure: Maximum Stress

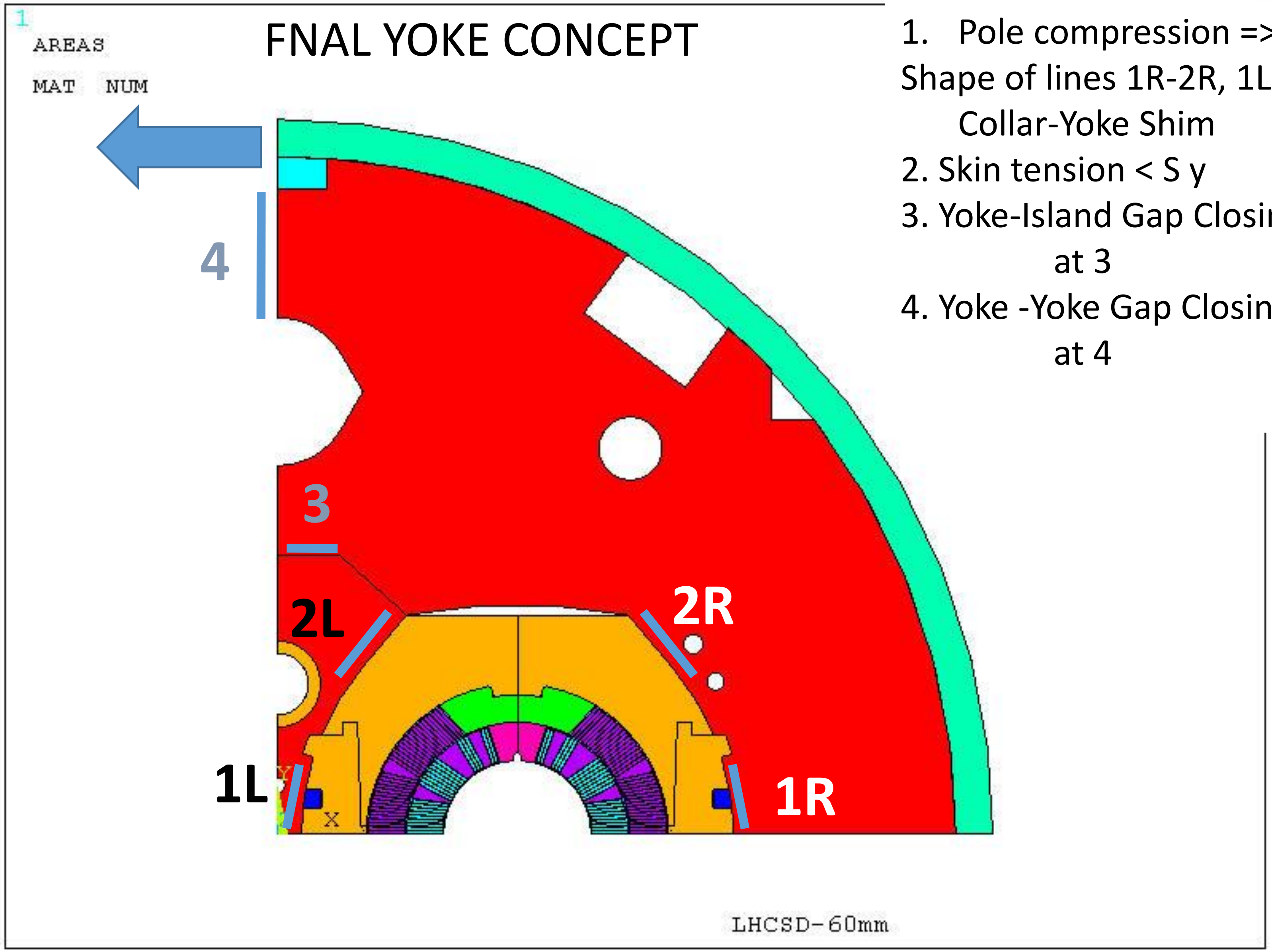
	Maximum stress, MPa					
	Inner/outer poles	Collar	Key	Yoke	Al clamp	Skin/avg/max
Collaring	133/90	527	362	n/a	n/a	n/a
Assembly	510/180	412	132	351	261	170/365
Cooldown	588/263	562	124	455	287	266/489
I_{nom}=11.85 kA	100/128	476	184	362	282	269/498
B_{max}=12 T	50/136	494	202	387	281	270/500

The maximum stress in the collars and compression in the iron yoke achieves the material yield stress in small regions near key grooves and iron yoke corner (model singularities, mesh size).

To minimize the stress concentrations, the key grooves and iron corners have been rounded.

All stress values are below yield stress of corresponding materials.

FNAL YOKE CONCEPT



1. Pole compression =>
Shape of lines 1R-2R, 1L-2L and
Collar-Yoke Shim
2. Skin tension < S y
3. Yoke-Island Gap Closing
at 3
4. Yoke -Yoke Gap Closing:
at 4

Twin Aperture Dipole FEA Results

3F

ALST	ALSS	YSTO	RCOU	COTH	ALHO
32.	40.	22.	105.	16.	21.

RSHM1	RSHM2	INCY	SKWL	RIN10	RIN20	RIN70	B0	Ic	Rshim
0.000050	0.000050	-0.000100	0.000450	0.000225	0.000175	0.000000	11.99	0.00	0.000100

LSHM1	LSHM2	YGPU	YGPD	LIN10	LIN20	LIN70	YYY		
0.000050	0.000050	-0.000025	-0.000001	0.000125	0.000100	0.000000	-0.005000	uniform	no clamp

Load	PoleR1	PoleR2	MidpR1	MidpR2	PoleL1	PoleL2	MidpL1	MidpL2	Smin	Smax	Skma	Skav	Iron	Collar	Skey
After Skin Welding at 300K															
1.	122.8	71.9	72.0	105.1	117.9	75.1	79.6	100.4	42.2	143.1	372.8	213.3	312.8	625.4	275.1
After Cooling Down to 2K															
2.	100.9	77.0	65.3	97.2	100.8	77.0	67.3	96.0	13.5	137.9	541.9	357.8	294.2	674.7	314.1
At Field Bnom, at 2K															
3.	14.4	35.0	121.6	127.6	16.0	33.8	123.1	128.1	11.6	154.9	557.7	361.8	432.1	725.5	352.3
At Field Bmax, at 2K															
4.	2.8	28.1	130.2	132.4	4.2	27.0	132.1	133.5	5.1	164.1	560.6	362.5	456.5	728.7	355.1

Twin Aperture Dipole FEA Results

```
ALST ALSS YSTO RCOU COTH ALHO
 32.   40.  22.   105.   16.   21.

      RSHM1     RSHM2    INCY      SKWL      RIN10     RIN20     RIN70     B0    Ic     Rshim  Y-Y: 0.057,0.096
     0.000025  0.000025  0.000000  0.000350  0.000100  0.000100  0.000000 11.99 12.76  0.000100  gap: l-1, r-2 20%
      LSHM1     LSHM2    YGPU      YGPD      LIN10     LIN20     LIN70     YYY
     0.000025  0.000025  0.001000  0.001000  0.000100  0.000100  0.000000 -0.005000     uniform    no clamp
```

2F

Load	PoleR1	PoleR2	MidpR1	MidpR2	PoleL1	PoleL2	MidpL1	MidpL2	Smin	Smax	Skma	Skav	Iron	Collar	Skey
After Skin Welding at 300K															
1.	101.5	66.6	72.4	85.8	104.5	64.5	71.0	86.7	41.9	121.4	305.1	179.7	271.9	519.8	257.1
After Cooling Down to 2K															
2.	108.1	89.0	82.0	103.0	112.9	85.4	79.6	104.3	15.7	148.3	396.4	273.5	345.8	613.7	165.9
At Field B=11.22T , at 2K															
3.	15.8	42.8	134.4	128.1	21.9	38.3	131.6	131.1	3.9	152.3	430.4	286.9	577.5	485.5	224.8
At Field B=12T, at 2K															
4.	3.3	35.5	142.4	132.2	9.2	31.2	139.9	135.8	4.3	161.9	434.7	288.7	623.6	501.5	232.1
In Collaring Press															
5.	60.3	86.3	111.2	52.6	60.4	86.4	111.2	52.6	10.9	157.8					
Collared Coil															
6.	48.7	48.7	63.4	39.1	48.7	48.7	63.4	39.1	20.6	82.6					

Mirror Magnet FEA Results

```
ALST ALSS YSTO RCOU COTH ALHO     SHM1     YGAP     INC1     SKDL     IN30     IN60     IN90   B0   Ic
 32.  40.  22. 105.  16.  21.           0.000025 -0.000125  0.000300  0.000600  0.000075  0.000075  0.000050  8.35 14.00
KAPTON, yoke stopper at 60-115, glued poles
 Load    Pole 1   Pole 2   Midp 1   Midp 2    Smin     Smax     Skma     Skav     Iron   Spole1   Clamp    Sbol
 Load    P1 min   P1 max   P2 min   P2 max   M1 min  M1 max   M2 min   M2 max
 Load    P1 cav   P2 cav   M1 cav   M2 cav
  1.    103.8     75.9     95.2     85.2     27.6    141.6    560.7    102.0    697.3    735.3    431.7    179.7
  1.   -147.6    -47.0   -104.1    -66.0   -119.7    -66.8   -110.2    -58.7
  1.     99.2     71.4     92.9     83.0
  2.     81.0     82.5     87.4     81.2     10.9    136.2    885.7    215.4    992.0    566.3    661.3    361.2
  2.   -120.6    -31.4   -115.8    -58.0   -107.2    -61.4   -104.5    -57.2
  2.     78.2     76.9     85.3     79.1
  3.     -3.0     40.3     98.7     79.0      1.5    134.0    895.4    218.1   1025.2    108.2    683.9    365.0
  3.     -3.0     12.2    -75.6    -15.5   -124.4    -73.3    -99.5    -53.6
  3.     -2.0     36.8     96.4     77.0
```

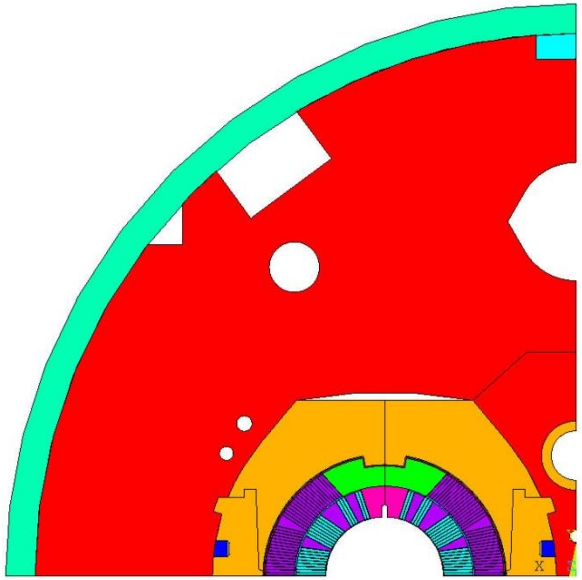
```
 KAPTON, yoke stopper at 60-115, clamped yoke, glued poles
 Load    Pole 1   Pole 2   Midp 1   Midp 2    Smin     Smax     Skma     Skav     Iron   Spole1   Clamp    Sbol
 Load    P1 min   P1 max   P2 min   P2 max   M1 min  M1 max   M2 min   M2 max
 Load    P1 cav   P2 cav   M1 cav   M2 cav
  1.     73.4     42.9     52.8     57.1     19.4    101.3      0.0      0.0    937.0    554.9    467.0      0.0
  1.   -106.8    -38.7    -65.2    -37.5    -66.3    -35.0    -73.6    -41.1
  1.     70.2     40.4     51.5     55.7
```

MP Shim = 25um

Rad Shim= 50um

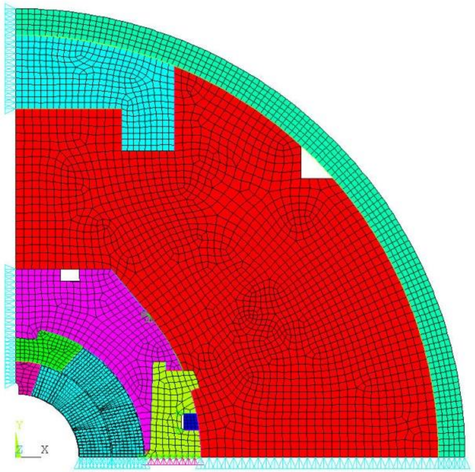
RT Yoke-Yoke Dap=125um

Design Goals



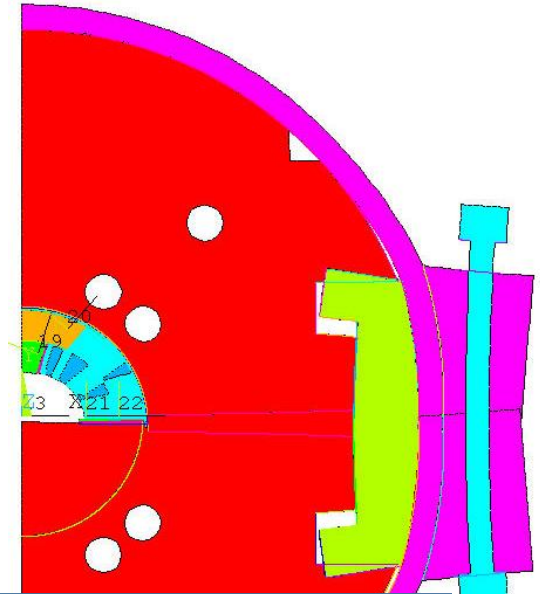
MP Shim = 0.025mm
Radial Shim = 0.1mm
Bending Shim = 0.1mm
Skin shrink. = 0.35m

Twin Aperture Magnet



MP Shim = 0.125mm
Radial Shim = 0.0mm
Bending Shim = 0.2mm
Clamp-Yoke Int = 0.3mm
Skin shrink. = 0.4mm

Single Bore Magnet



MP Shim = 0.025mm
Radial Shim = 0.05mm
Bending Shim = 0.075mm
Clamp-Yoke Int = 0.3mm
Yoke-Yoke gap = 0.125mm

Mirror Magnet