Mechanical Design Study of a 20 T Common-coil Dipole for SppC

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Outline

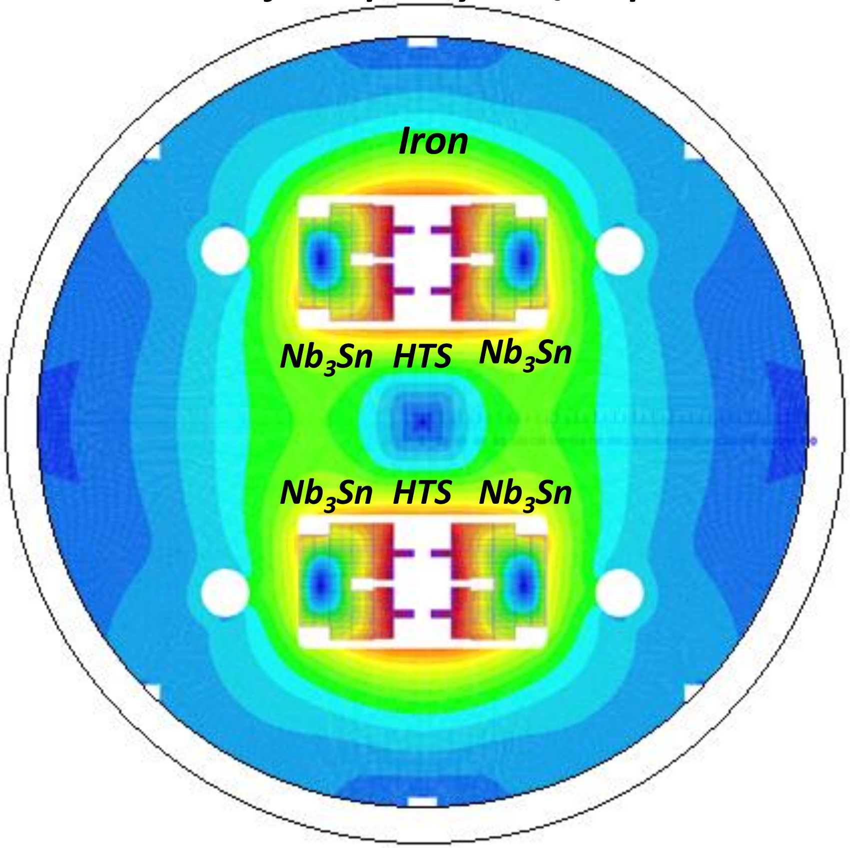
- ✓ Introduction of the possible 20 T common-coil dipole for SppC
- ✓ Mechanical design and stress analysis of the 20 T common-coil dipole
- ✓ Further work remain to be done
- ✓ Main challenges

Introduction of the Possible 20 T Common-coil Dipole

20-T Nb_3Sn + HTS common coil dipole for SppC

Space for beam pipes: 2 * Φ50 mm, with the load line ratio of ~80% @ 1.9 K and the yoke diameter of 800 mm

With 10^{-4} field quality @ 2/3 aperture

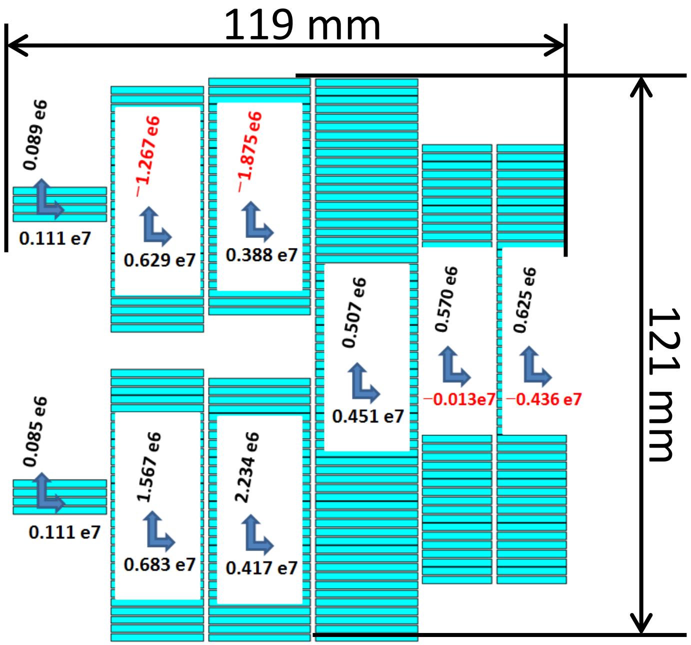


Magnetic design has been carried out by Dr. Xu Qingjin. FCC week 2015.03.26.

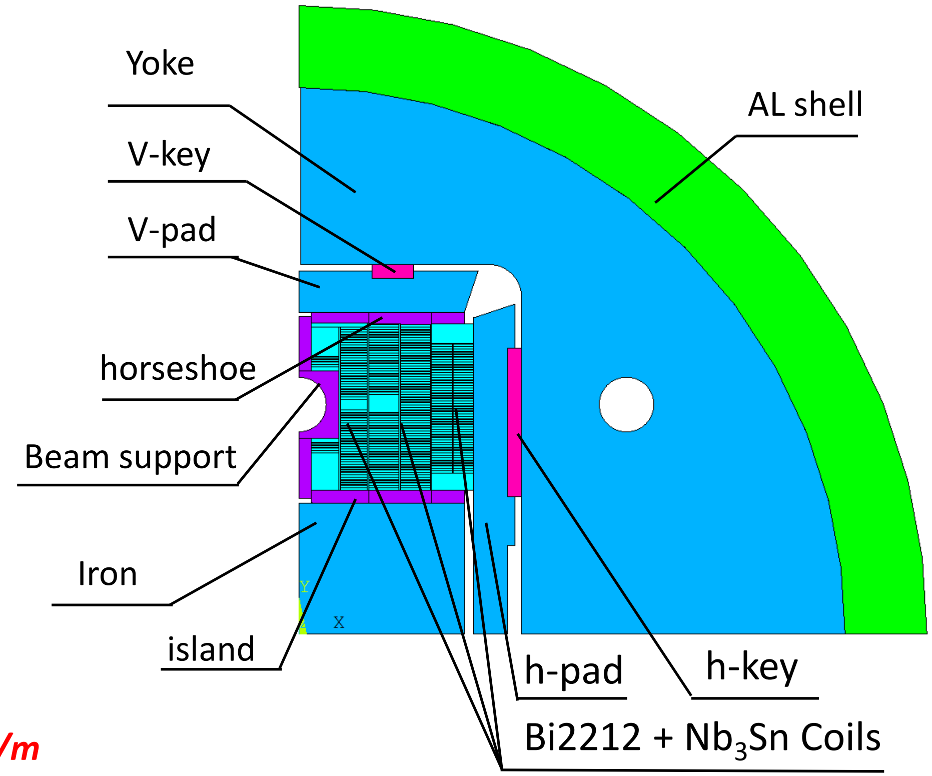
Main Design Parameters

Number of apertures	(-)	2
Aperture diameter	(mm)	50
Inter-aperture spacing	(mm)	330
Operating current	(A)	14700
Operating temperature	(K)	1.9
Operating field	(T)	20
Peak field	(T)	20.4
Margin along the loadline	(%)	~20
Stored magnetic energy	(MJ/m)	7.8
Inductance (magnet)	(mH/m)	72.1
Yoke ID	(mm)	260
Yoke OD	(mm)	800
Weight per unit length	(kg/m)	3200
Energy density (coil volume)	(MJ/m^3)	738
Winding pack current density	(A/mm^2)	400
Force per aperture – X/Y	(MN/m)	23.4/2.4
Peak stress in coil	(MPa)	240
Fringe Field @ r = 750 mm	(T)	0.02

Mechanical Design and Stress Analysis



Lorentz force distribution on each coil



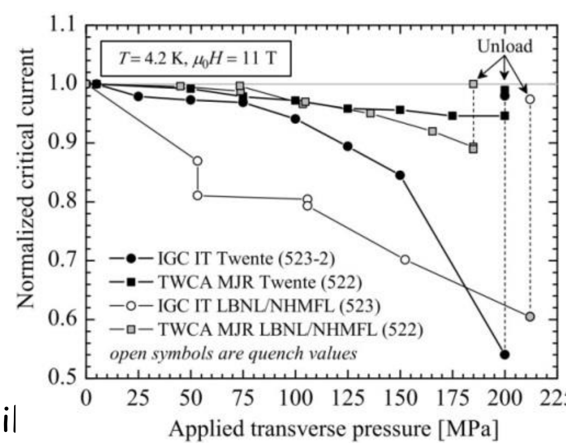
Total lorentz force per aperture: ***Fmag_x=23.4 MN/m***
Fmag_y=2.38 MN/m

Shell based structure with bladder and key technology

Assuming the preload on the coils after cooling down is 23.4 MN/m, then the average horizontal compressive stress in coils equals to:

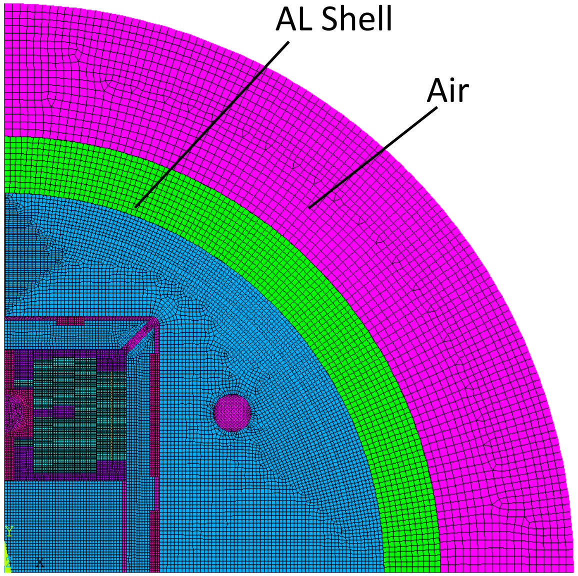
$$[\sigma] = \frac{23.4\ MN/m}{0.121\ m} = 193.4\ MPa$$

To ensure that the stress in coils is homogeneous, it is necessary to keep the similar average rigidity of the coil from left to right and from top to bottom.



D.R.Dietderich,A. Godeke, "Nb3Sn research and development in the USA – Wires and cables," Cryogenics 48 (2008) 331–340

Mechanical Design and Stress Analysis



2D electromagnetic analysis model

Element

```
et,1,plane13
et,4,infin9
keyopt,1,1,0        !freedom az
keyopt,1,3,2        !plane stress
```

Degrees of freedom coupling

```
cmsel,s,elem1
cmsel,s,nod1
ceintf,0,az,,,,,,0     !coupling 1
…
                       !coupling36
```

Far field boundary condition

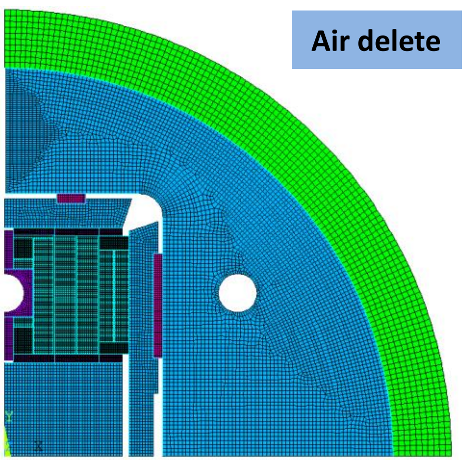
```
lsel,s,,,40025
type,4
lmesh,all
```

Flux parallel

```
dl,,,asym        !for left and bottom side
```

Excitation

```
bfe,,js,,,,cur/(w_rf1*h_rf1)     !for coil 1
…
                                 !for coil 3
```



2D structural analysis model

Air delete

Element

```
et,2,targe169
et,3,conta172
et,5,conta172
et,6,conta172
keyopt,1,1,3      !UX and UY
keyopt,3,9,1
!exclude both initial penetration, gap and
 offset
keyopt,5,9,1
keyopt,5,12,5 !bonded (always)
keyopt,6,9,3   !include offset only
keyopt,6,12,2 !no separation(slide permit)
```

Contact pairs

```
real,1
lsel,s,,,2428
nsll,s,1
type,2
esurf,all
lsel,s,,,2411
nsll,s,1
type,5
esurf,all
!contact pairs 1
…
!contact pairs38
```

Constraints

```
lsclear,all
dl,all,,symm
!for left and bottom
side
```

Loa1:Interference

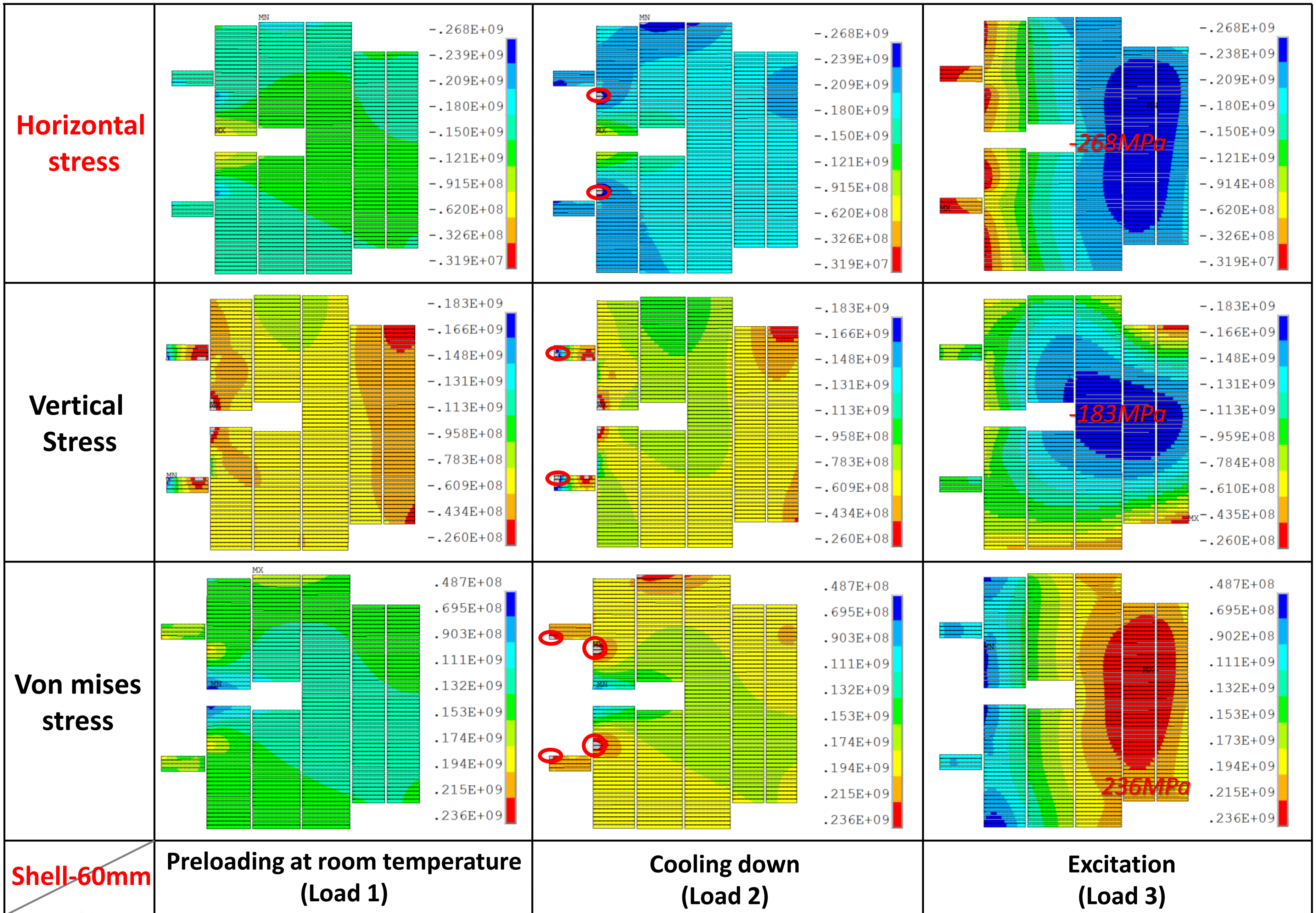
```
r,18
rmore,,,,-,
```

Load2:Cooling down

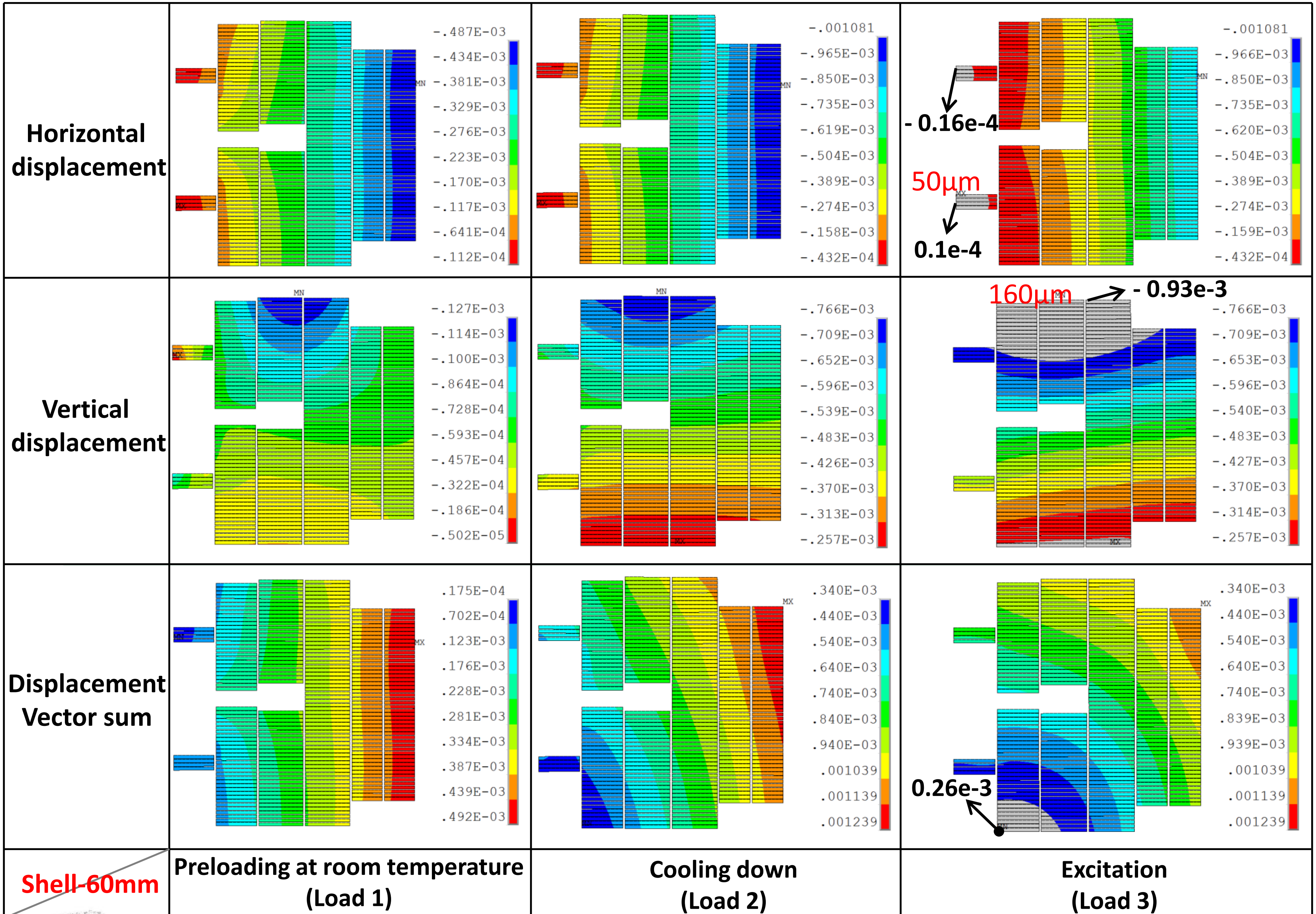
```
tunif,293
tref,293
allsel
bfa,all,temp,4.3
```

Load3:Lorentz force

```
ldread,forc,,,,,,-,rst
```



○ *where stress concentration occurs.* *(The stress concentration disappears after excitation* ☺ *)*



The difference of displacement between load 2 and 3 is much larger than 20 μm. Influence the filed uniformity!!

Mechanical Design and Stress Analysis

	AL Shell thickness (mm)	Inteference (mm)	Fx1 ($\times 10^7$N/m)	Fx2 ($\times 10^7$N/m)	Fx3 ($\times 10^7$N/m)	$\overline{\sigma_{AL}}$ (MPa)
1	40	5.0	1.9168	2.3978	2.4680	626.3
2	50	4.0	1.8655	2.3821	2.4663	501.0
3	60	3.4	1.8091	2.3954	2.4896	423.4
4	80	2.6	1.6816	2.3888	2.5033	321.6
5	100	2.1	1.5592	2.3654	2.4991	258.8

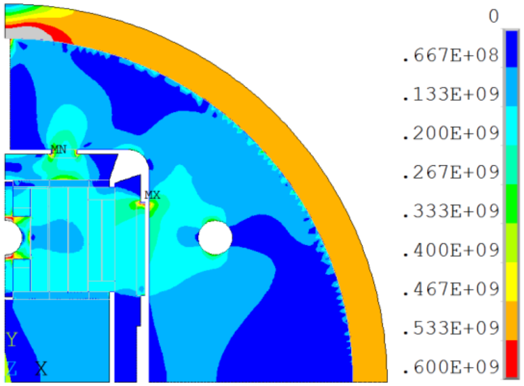
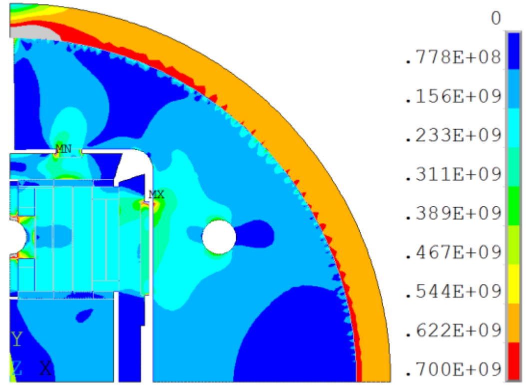
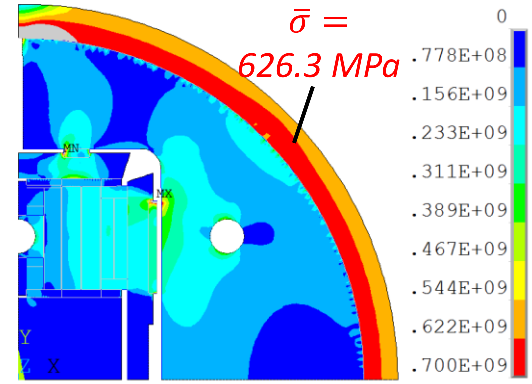
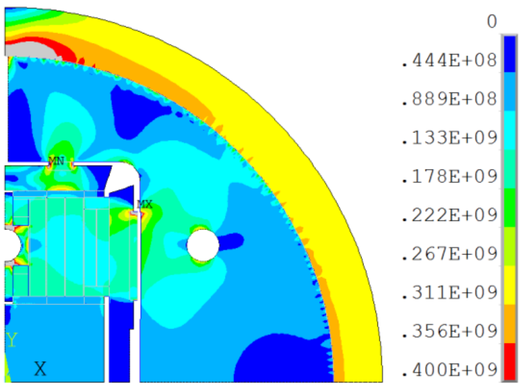
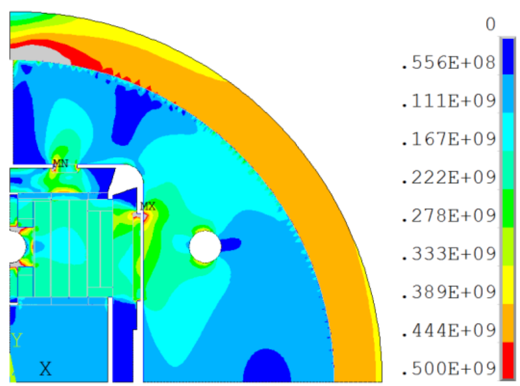
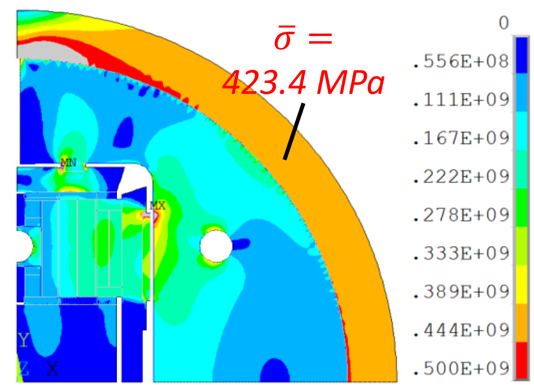
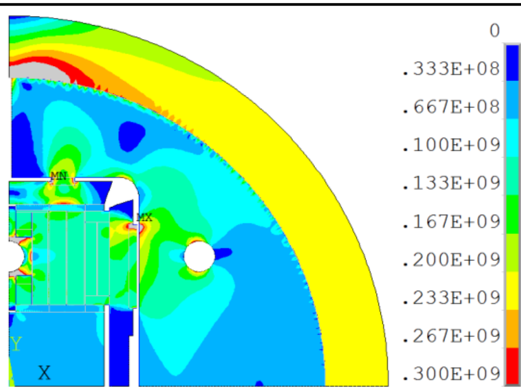
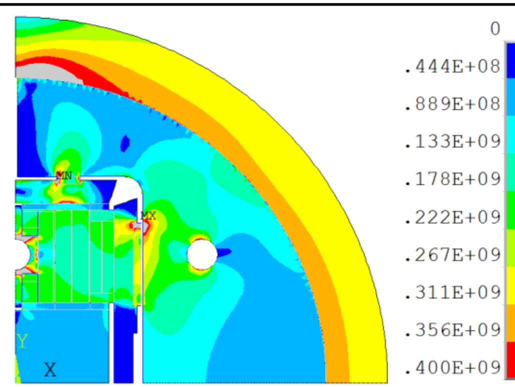
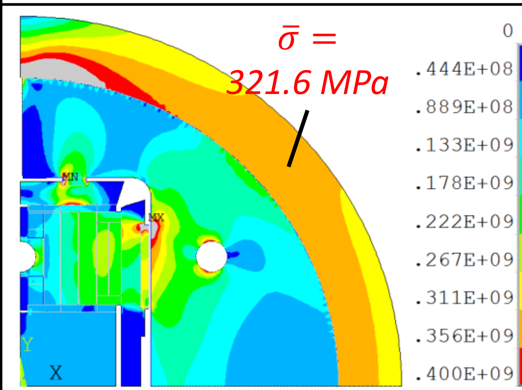
Fx1: horizontal force transmitted by h-key after load 1;

Fx2: horizontal force transmitted by h-key after load 2;

Fx3: horizontal force transmitted by h-key after load 3;

$\overline{\sigma_{AL}}$: average von mises stress on AL shell after load 3.

Large interference is required by applying the preload with water pressurized bladder because the AL shell is not that rigid and the horizontal magnetic force is so large.

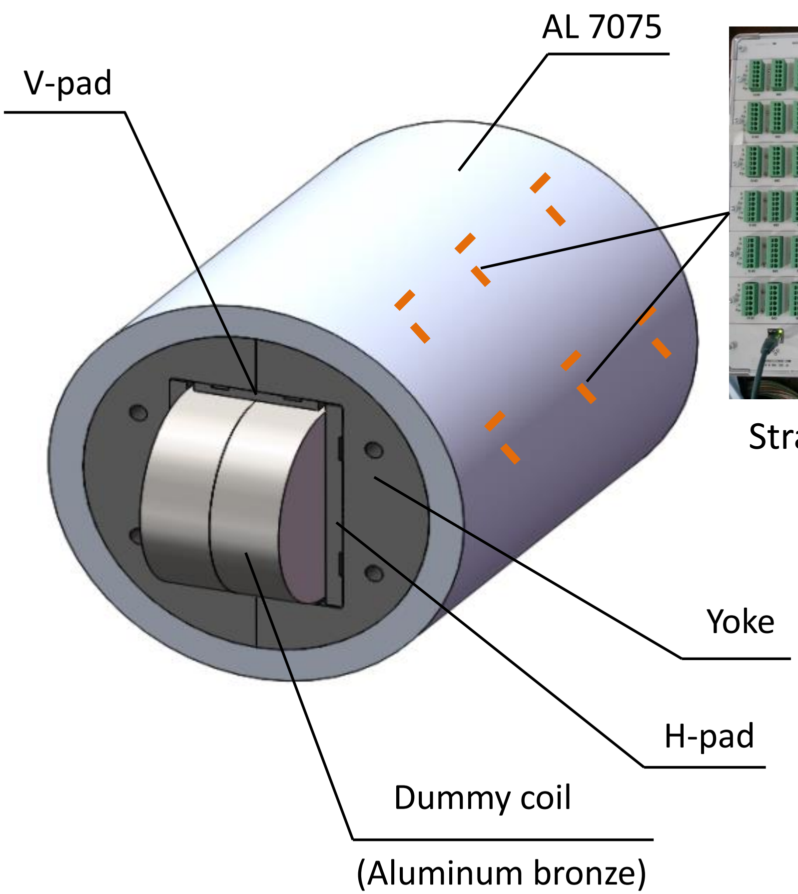
Von-mises stress	Preloading at room temperature (Load 1)	Cooling down (Load 2)	Excitation (Load 3)
Shell-thick 40mm			
Shell-thick 60mm			
Shell-thick 80mm			

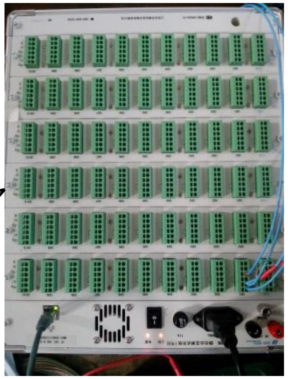
Mechanical Design and Stress Analysis

Material	Yield strength （MPa）			Young's modulus (GPa)
	300K	77K	4K	
316LN annealed	310	607	815	200
304L annealed	400	460	550	200
AL 6061-T6	300	360	380	
AL 7075-T6	502	589	648	63.2-74.4
AL 7475-T761	460	549	572	66.3-76.4
AL 2219-T87	397	484	539	67.8-77.9
AL 2090-T8E41	488	551	614	74.0-84.1

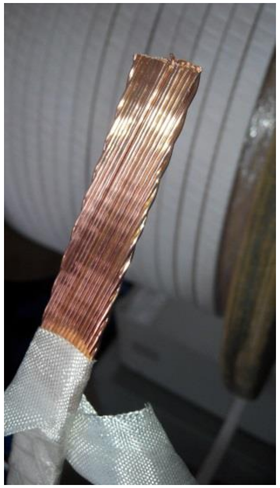
AL 7075 seems to be a promising material whose yield strength at 4 K is beyond 600 MPa.

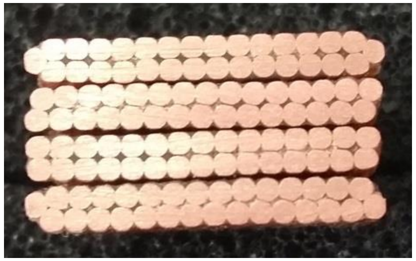
Further Work Remain to be Done





Strain indicator

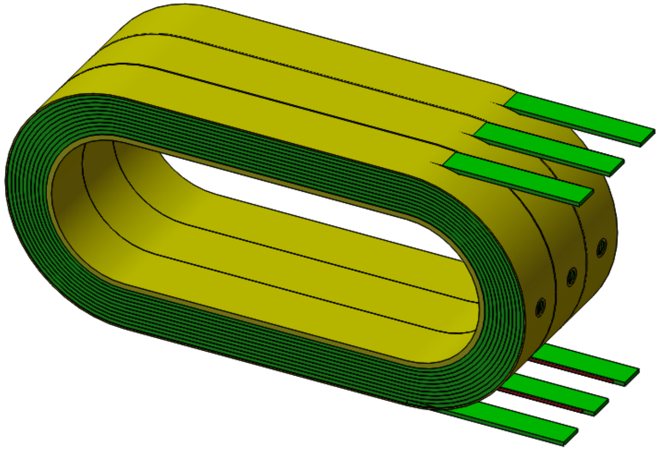




cross-section view

(30 strands, ϕ1.06 mm, 16.5mm x 2 mm)

"copper" Rutherford cable



Three block coils bonded together

- ✓ ***Test the yield strength of AL 7075 and other promising alum-inium alloys.***
- ✓ ***Test whether the AL shell can restore its original shape after unloading.***
- ✓ ***Test whether the bonded three coils can slide freely between the pads .***

Main Challenges

- ✓ The outer diameter of the dipole is limited to be **900 mm**, however, our present design parameter is 920 mm by setting the shell thickness to be 60 mm;
- ✓ we need to apply the preload of more than **23.4 MN/m per aperture**;
- ✓ We hope that the preload can be totally applied to the coils;
- ✓ The stress in shell is so large that we need to do experiments to judge whether **AL 7075** is a promising material;
- ✓ The present peak transverse pressure in coils is **268 MPa**; the present peak von-mises stress in coils is **236 MPa**. We need to validate whether this magnitude of stress will cause severe J_c degradation of Nb_3Sn rutherford cables;
- ✓ The displacement of coils after excitation shall be limited to ensure the uniformity of the magnetic field. (The present analysis results indicate that the maximum horizontal displacement and vertical displacement is respectively 50 μm and 160 μm)