FRIB Nb_3Sn ECR ion source magnet: Schedule, Cost, and Progress monthly report

Tengming Shen for the Supercon team
Lawrence Berkeley National Laboratory
July 2024 report

2024/07/15

- FRIB: Yoonhyuck Choi, Junwei Guo, Xiaoji Du, Dalu Zhang, Ting Xu, Machicoane, Guillaume, Maruta, Tomofumi, Jie Wei
- LBNL: Tengming Shen, Ye Yang, Philip Mallon, Ray Hafalia, Lianrong Xi, Mariusz Juchno, Paolo Ferracin, Soren Prestemon

The Indico site where the meeting slides can be downloaded: https://conferences.lbl.gov/event/1822/

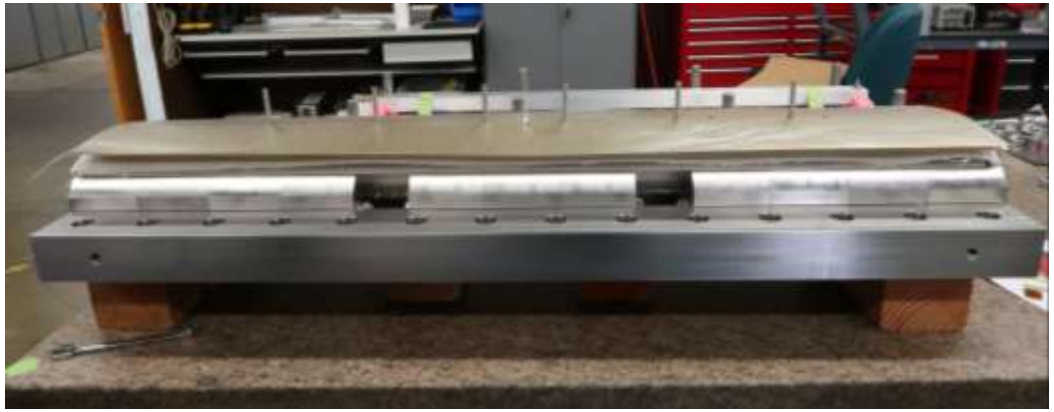
Access key: FRIB

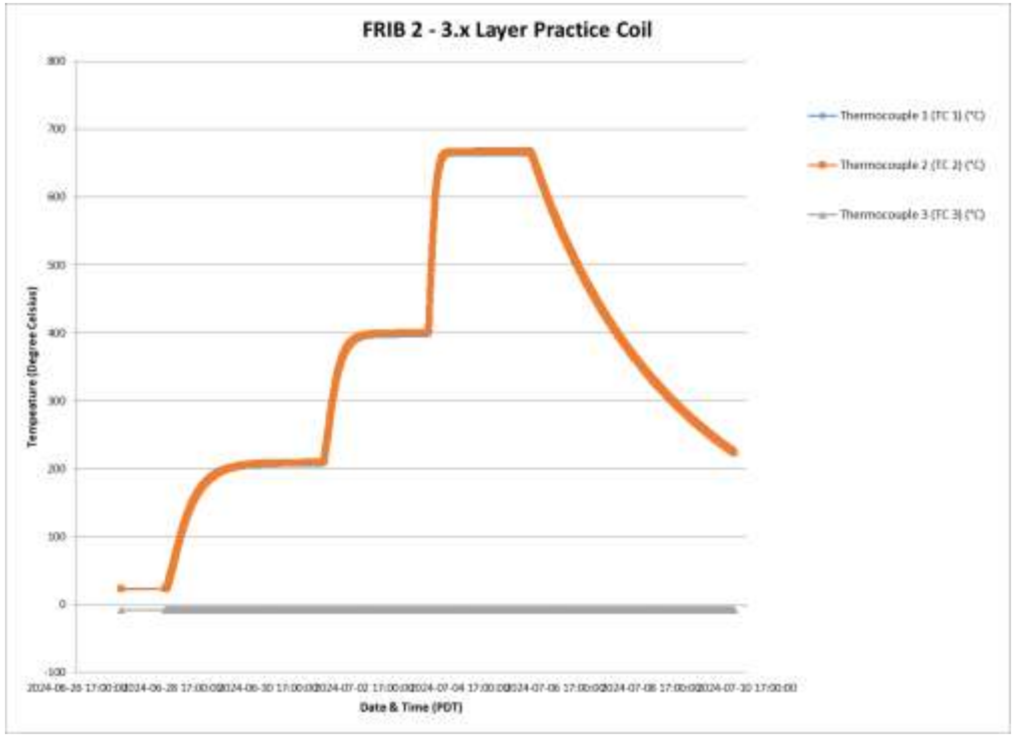
Past meetings slides are available at https://conferences.lbl.gov/category/109/

Progress since our last meeting (2024/06/17)

- Heat treatment of the 3.x layer practice coil has been completed.
- Impregnation tooling sent for fabrication. Estimated to arrive in the first week of August.
- 3D mechanical analysis completed.

Heat treatment of the 3.x layer practice coil has been completed

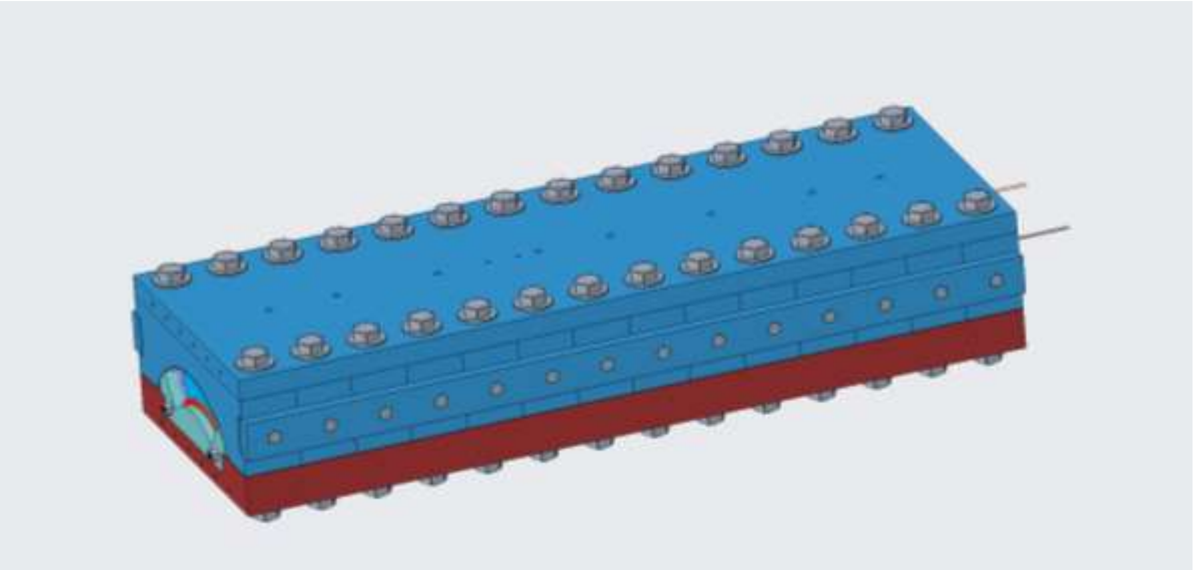




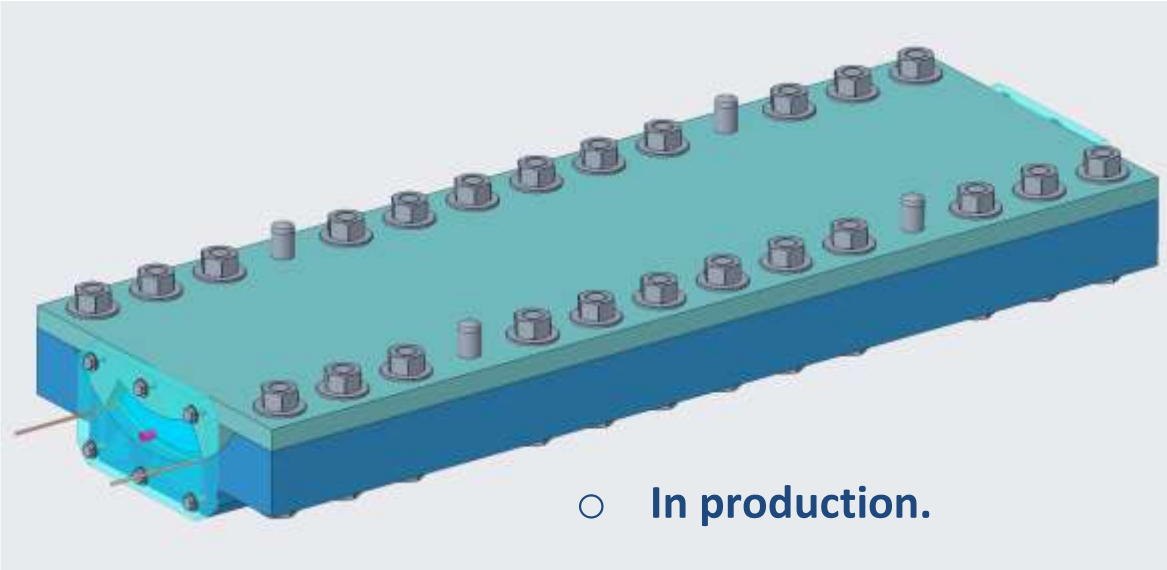
- Next steps: (1) Post reaction observation, (2) coil transfer to impregnation mold, (3) impregnation, (4) Cut-out observation.

Next step – transferring the practice coil into the impregnation mold for impregnation

The reacted coil in its tooling (mostly SS304)



The reacted coil in the impregnation tooling (mostly Aluminum)



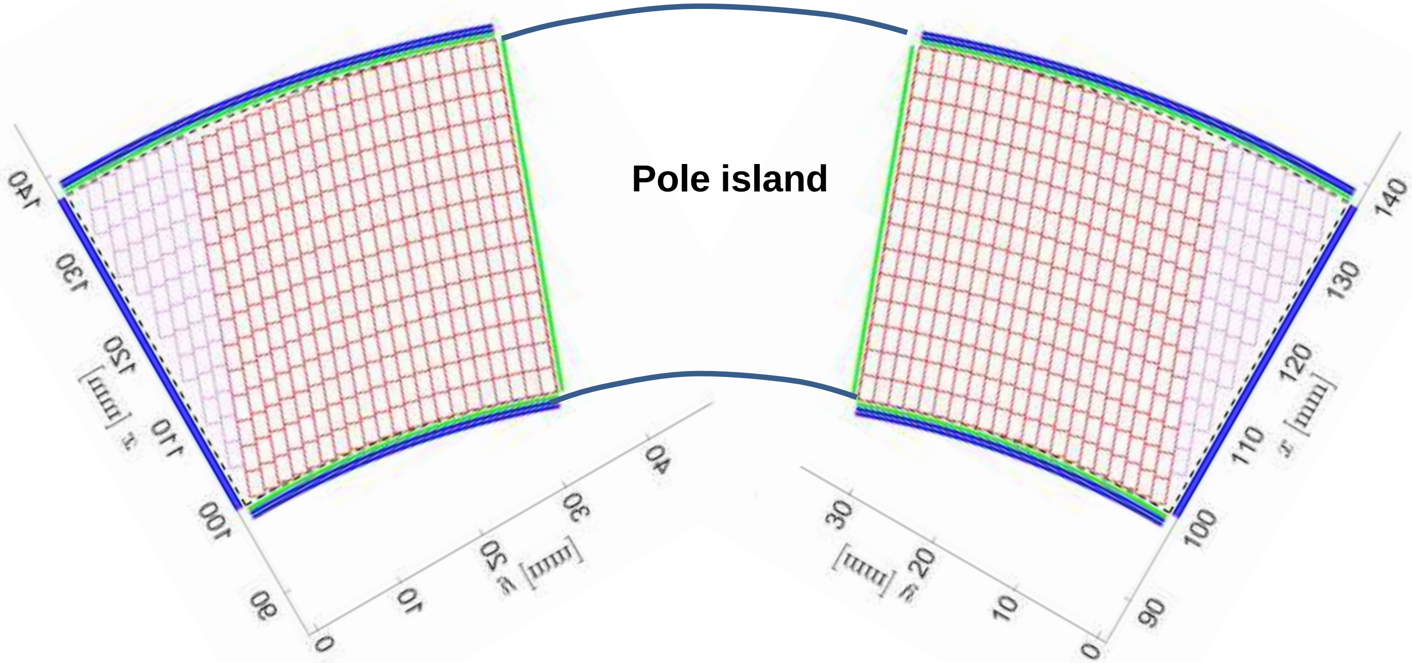
- In production.

A set of slides: https://docs.google.com/presentation/d/1FAAv_QD34foHT8IbBg2dZMK8RNcD6AAVxWchCaYS1-4/edit#slide=id.p

(Design: Lianrong Xu, Ray Hafalia)

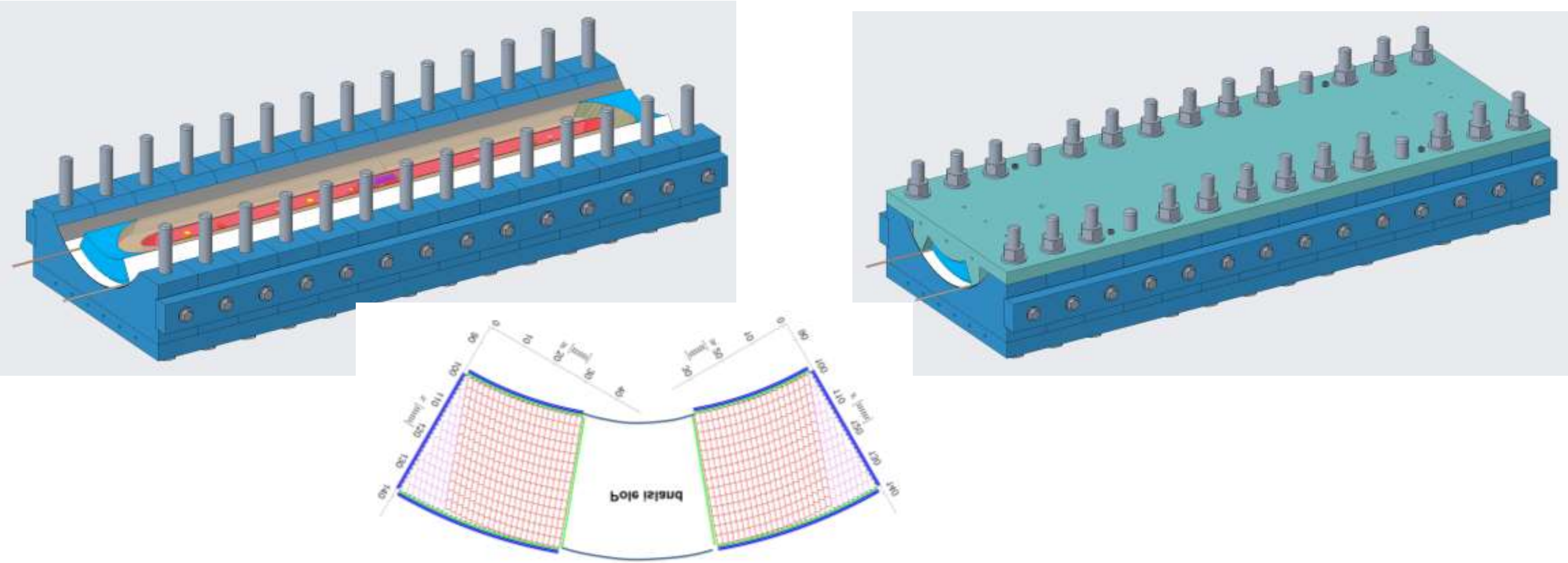
Prototype coil fabrication – ready to go and risk assessment

- Prototype coil pole island and tips have been fabricated, plasma spray coated. We are ready to go.



Risk: Winding partially filled layers and handling after reaction

Prototype coil fabrication – risk assessment

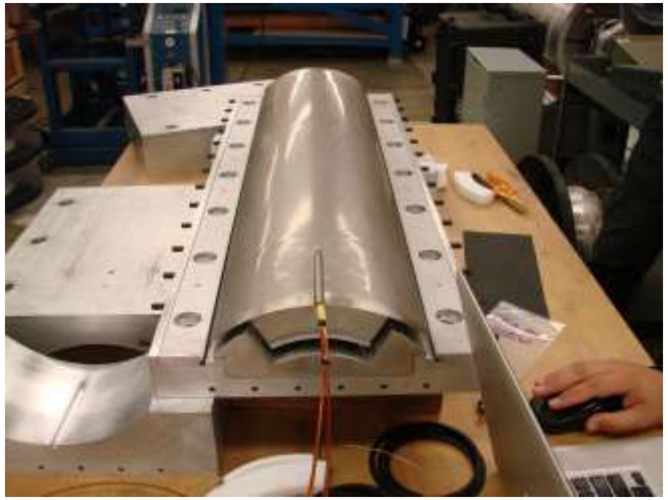


Full procedure available at: https://docs.google.com/presentation/d/1FAAv_QD34foHT8IbBg2dZMK8RNcD6AAVxWchCaYS1-4/edit#slide=id.p

(Design: Lianrong Xu, Ray Hafalia)

This risk is similar to lessons learned from Nb-Ti sextupole coil production

- Coil transfer into the impregnation tooling is a tricky step.
- Coils #4/#5/#6 had various issues, including turn-to-turn shorts, cross-over, and long training.

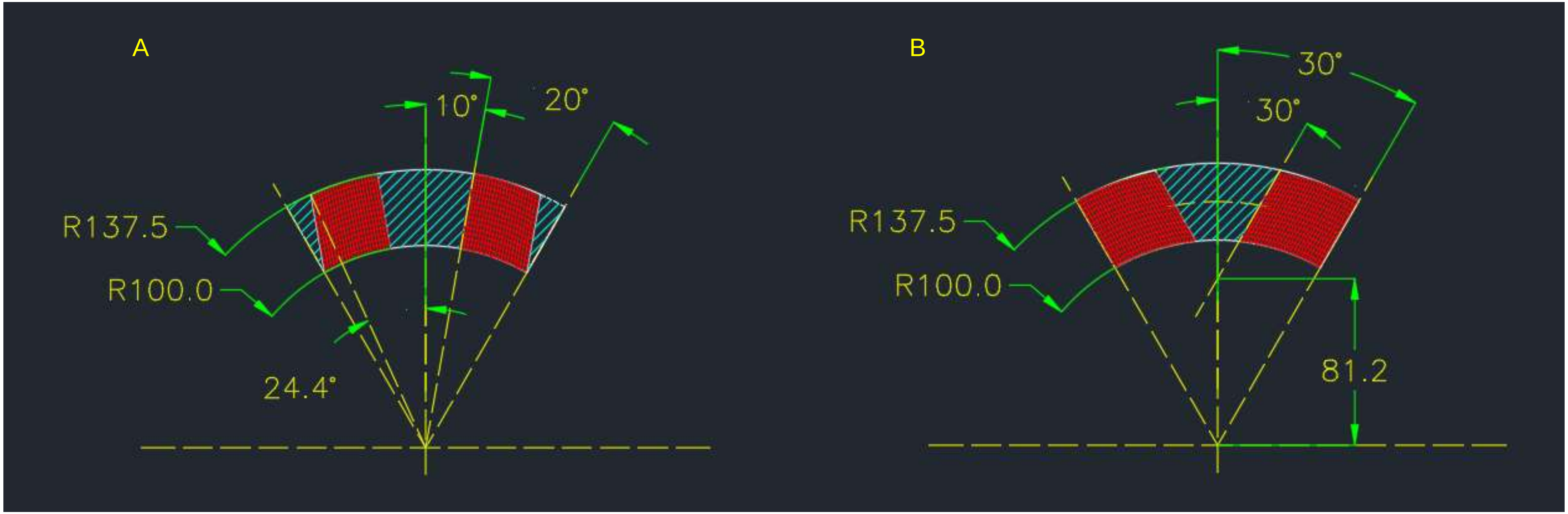


Alternative designs for the FRIB-II Nb_3Sn magnet

Ye Yang, Tengming Shen, Lianrong Xu

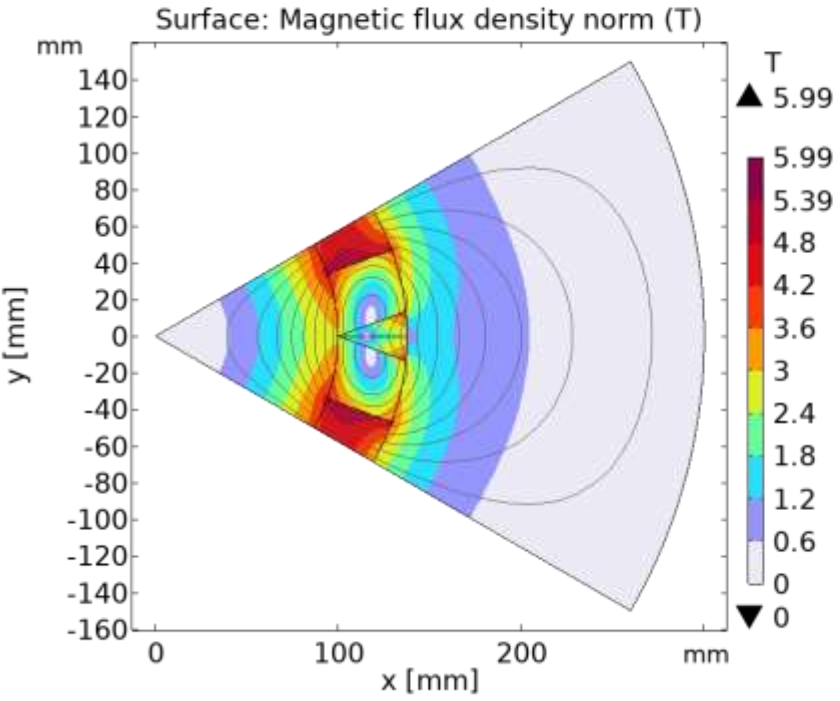
- Ver A, Jun.7.2024
- Ver B, Jun.25.2024

Options



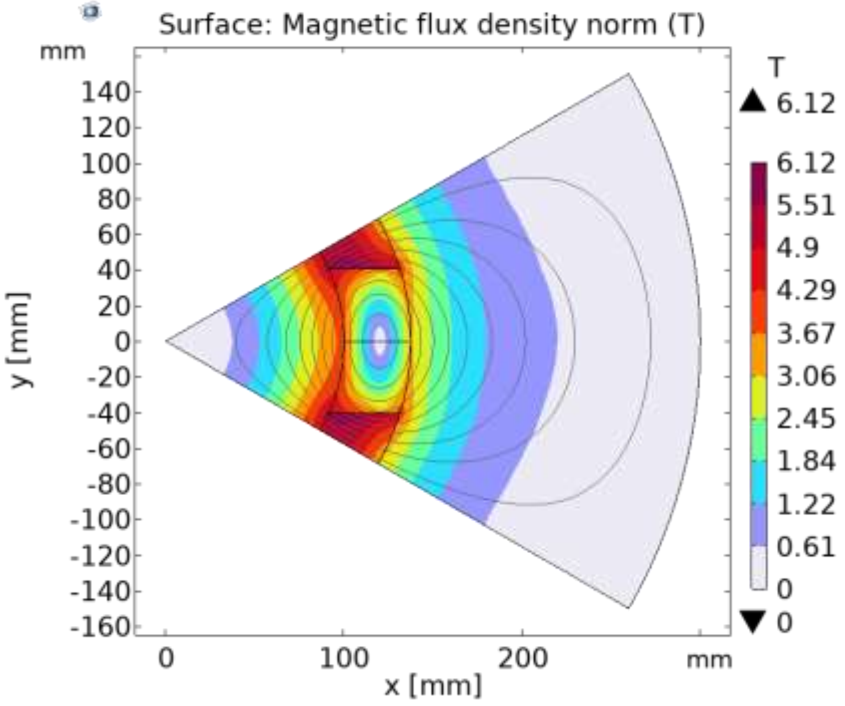
Field distribution

Case A



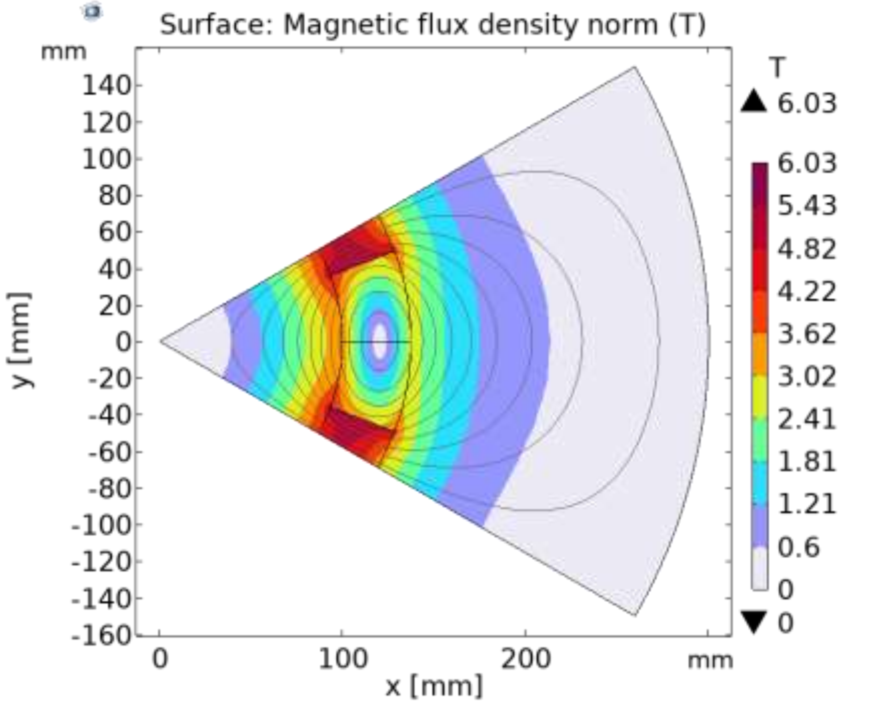
Bmax = 5.35T

Case B



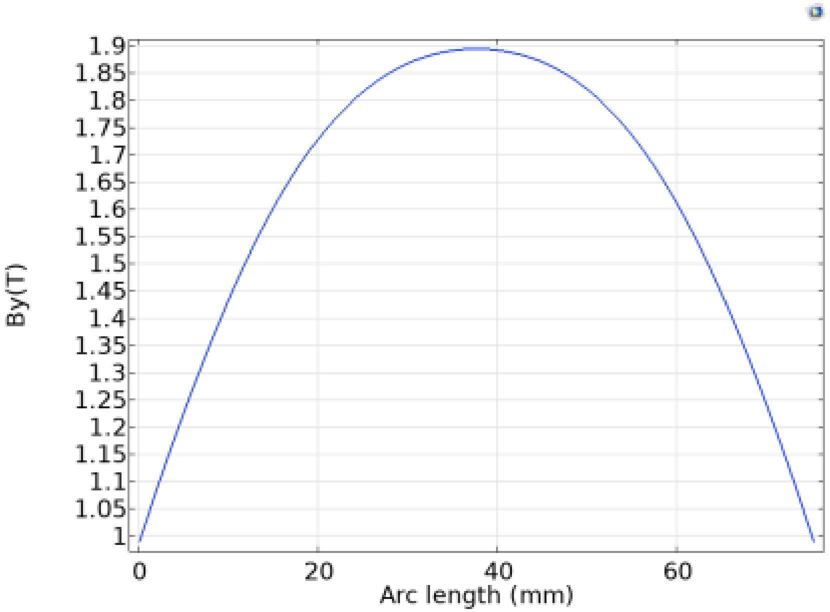
Bmax = 5.56T

Original

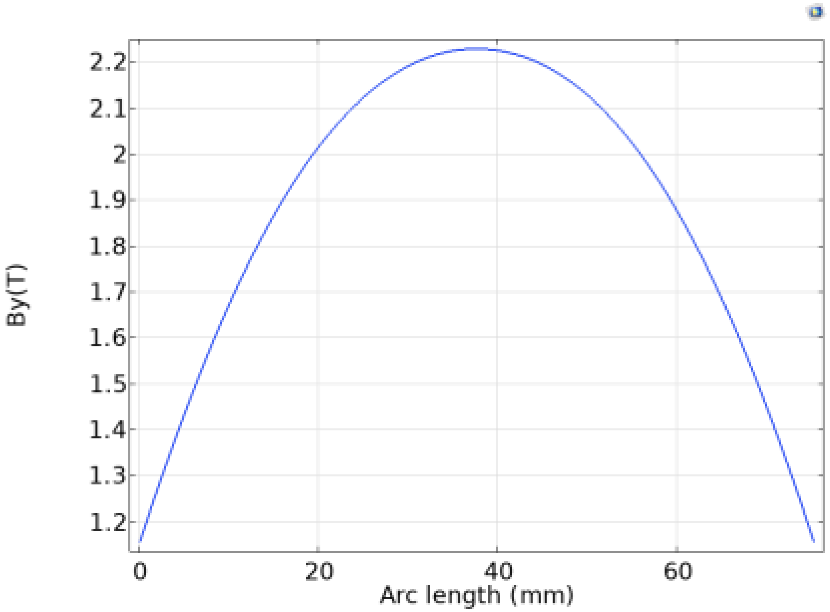


Bmax = 5.56T

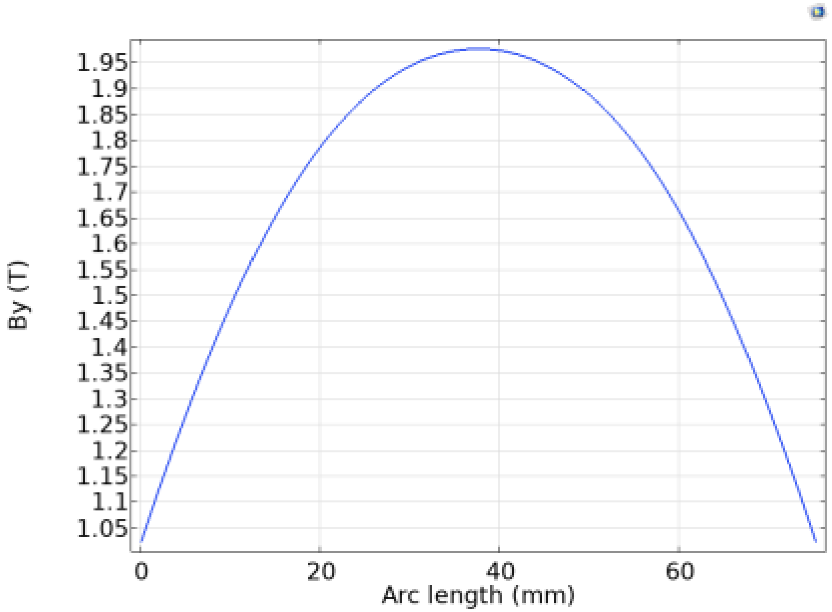
Radial field at R76 mm



By: 1.89 T

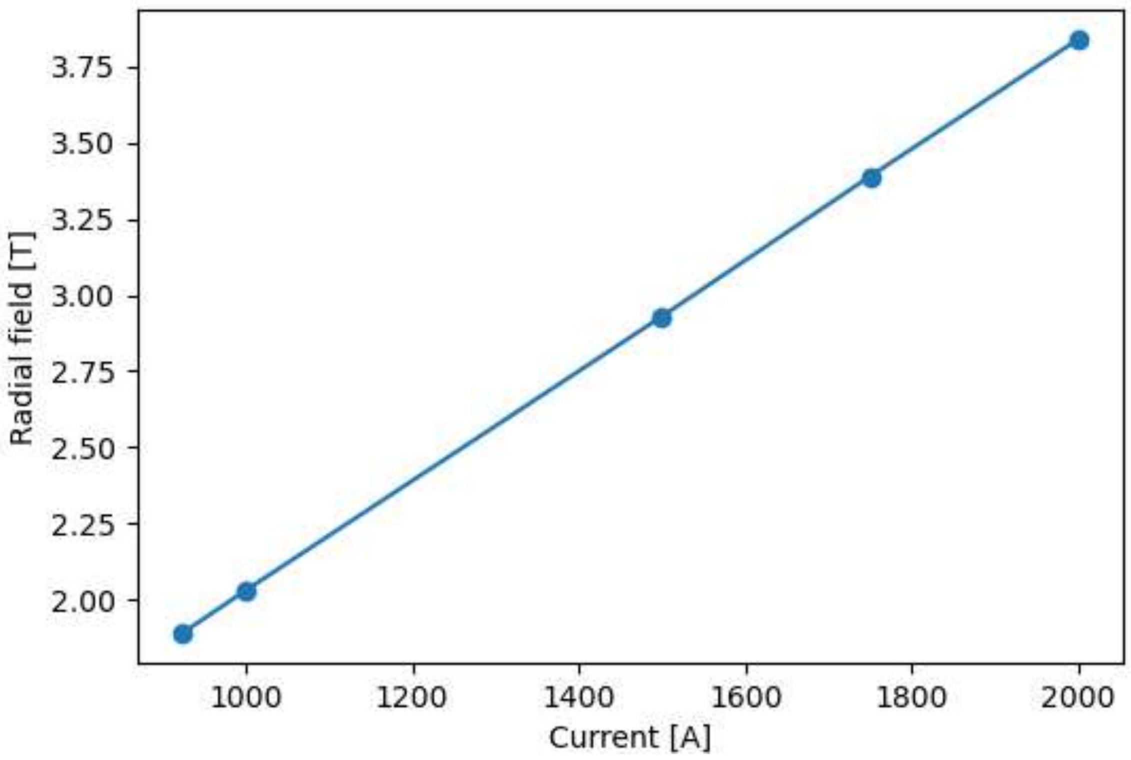


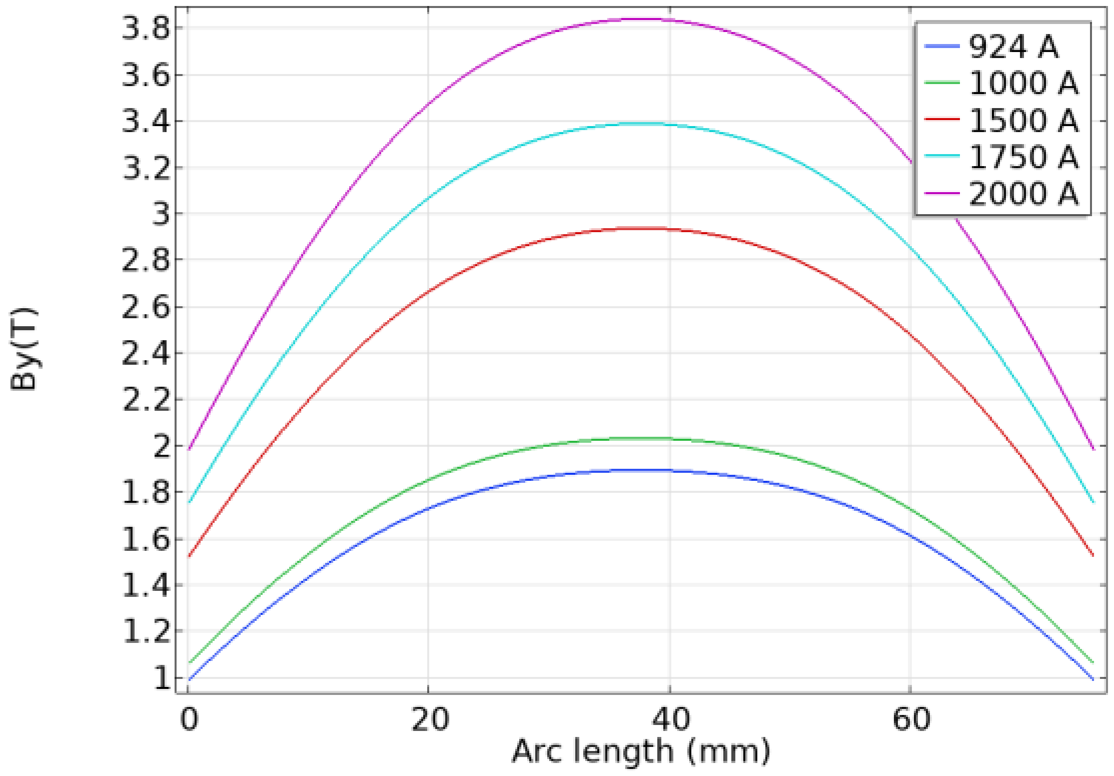
By: 2.23 T



By: 1.97 T

Transfer function of case A



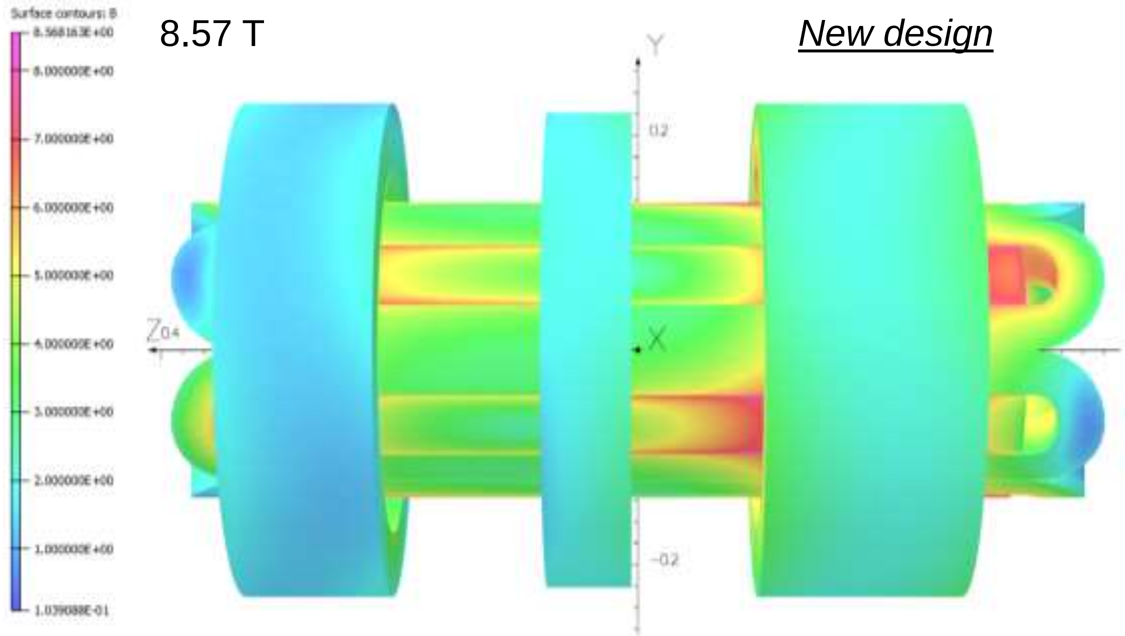


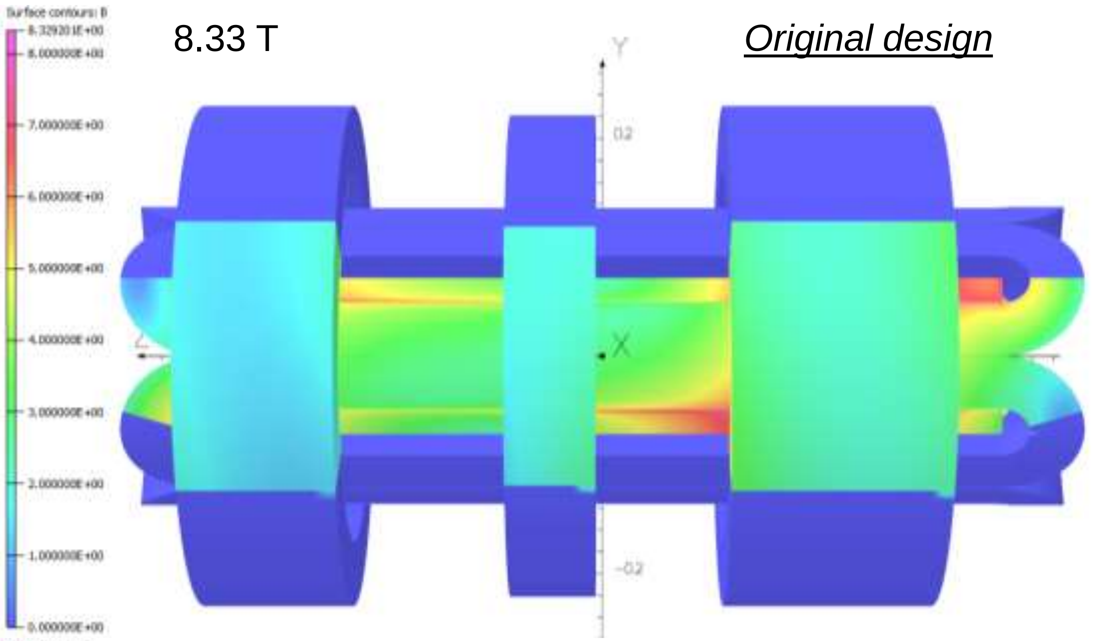
Radial field changes linearly even using the iron

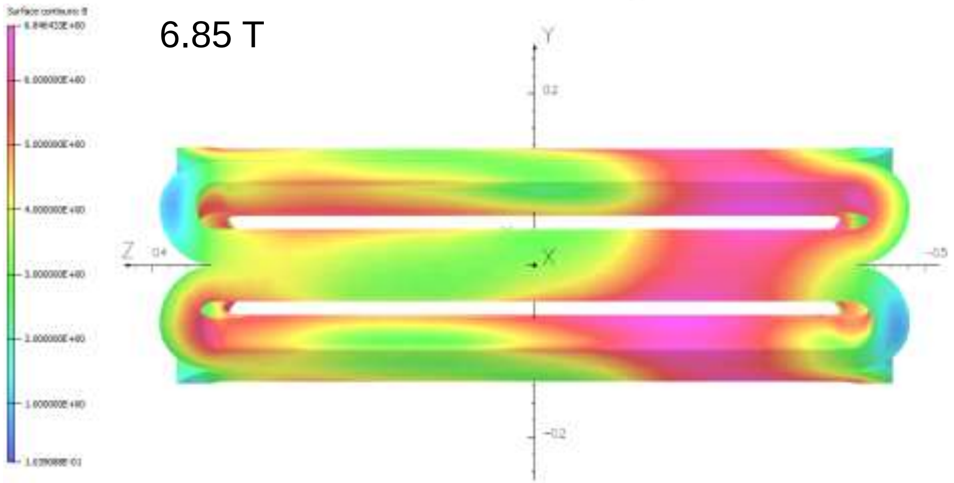
Result

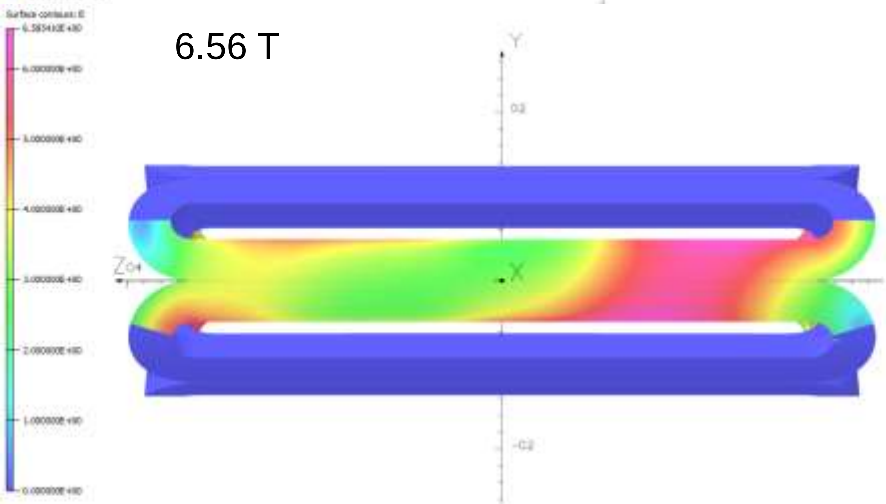
Item	Unit	Value		
Bare dimension	mm^2	2.35x1.25		
Insulated dimension	mm^2	2.60x1.55		
Design	-	A	B	Base
Layers	-	21	25	-
Turns per layer	-	14	14	-
Turns	-	294	350	317
Current	A	924		
Max. field	T	5.35	5.56	5.34
Br at 76mm	T	1.89	2.23	1.97

3D model with iron poles



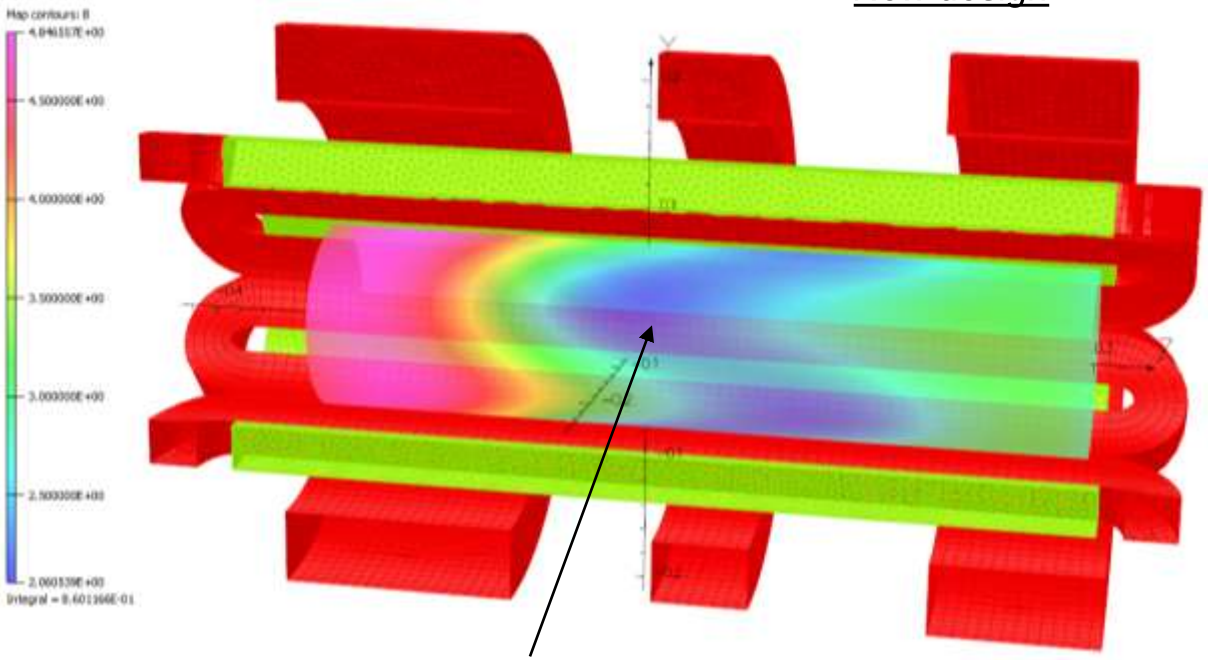






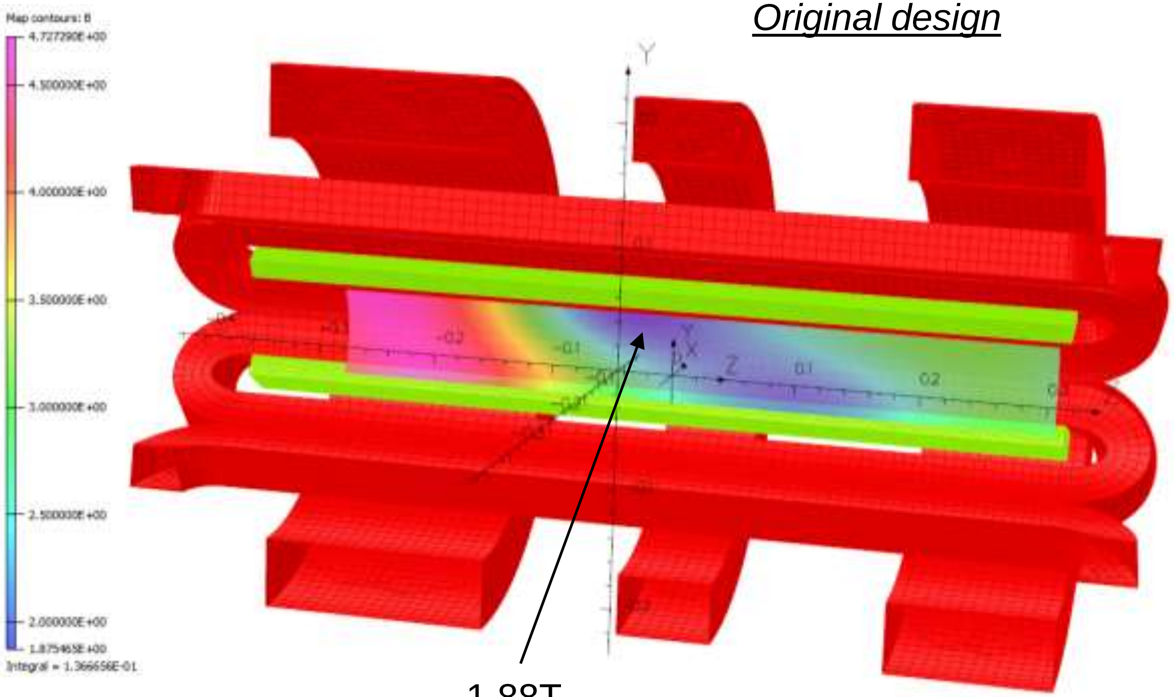
Minimum field at plasma chamber

New design



2.06T

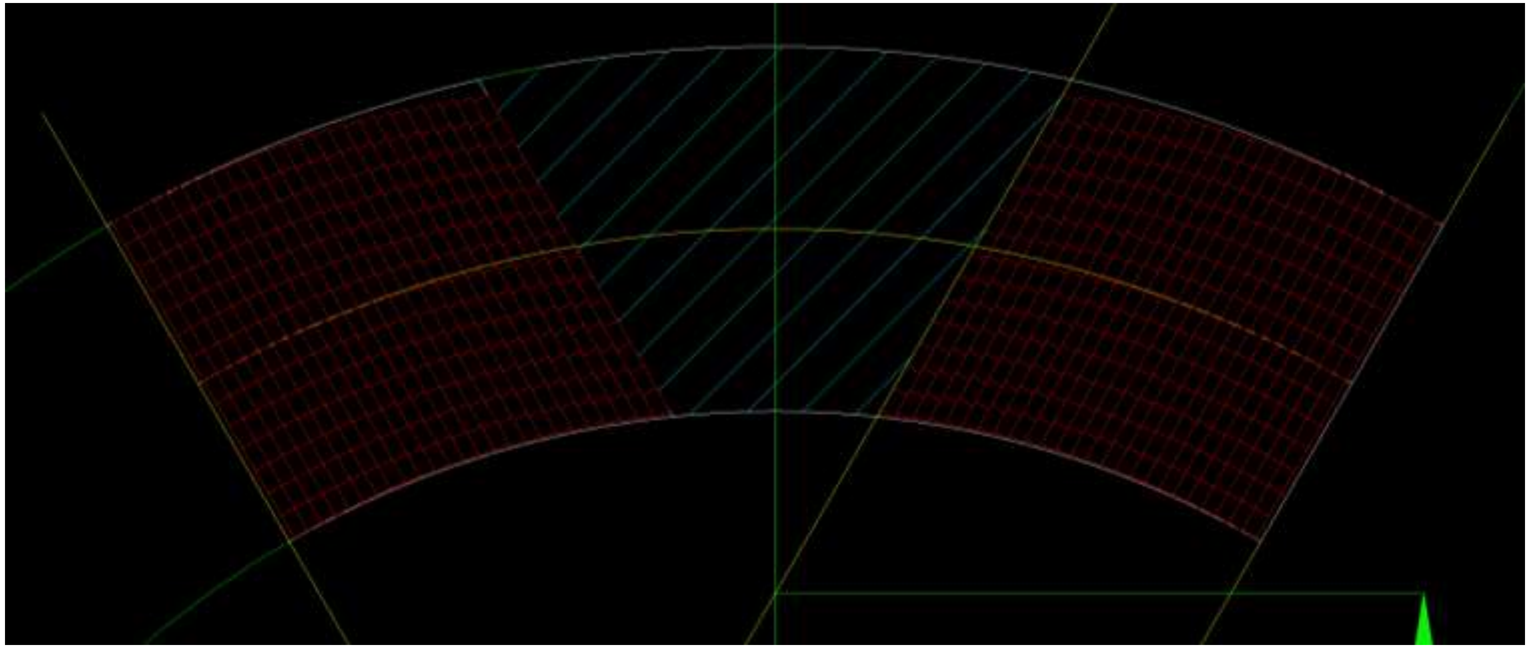
Original design



1.88T

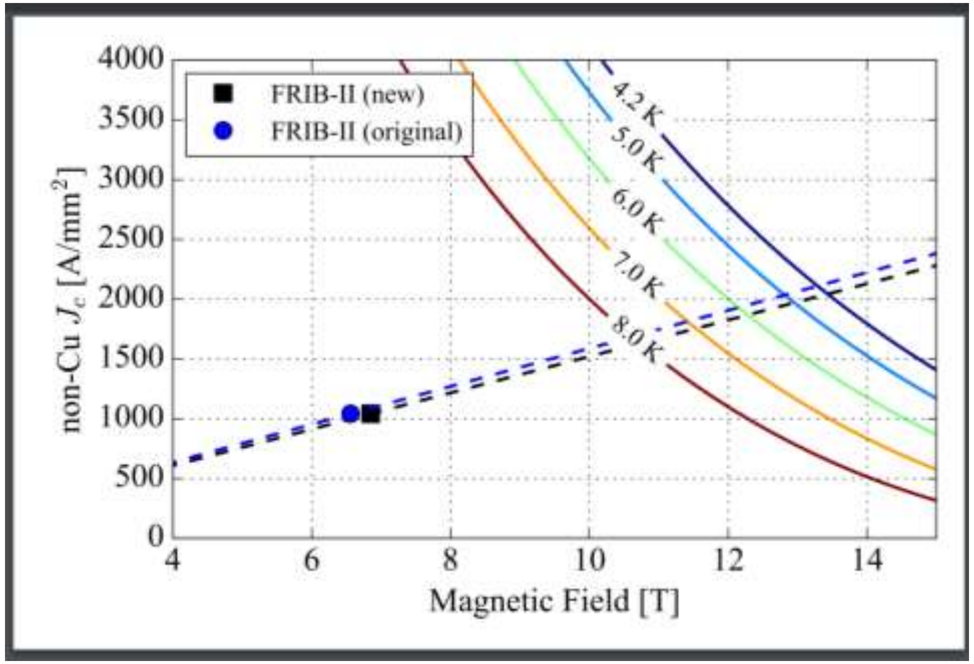
Rref: 71.85 mm

Back to the cross-section of the new design



Comparison

Item	Unit	New design	Original design
Turns	-	350	317
Current	A	924	924
Bmax on winding	T	6.85	6.56
|B| at Rref	T	2.06	1.88



The new design winding trial with Nb-Ti ECR sextupole strands

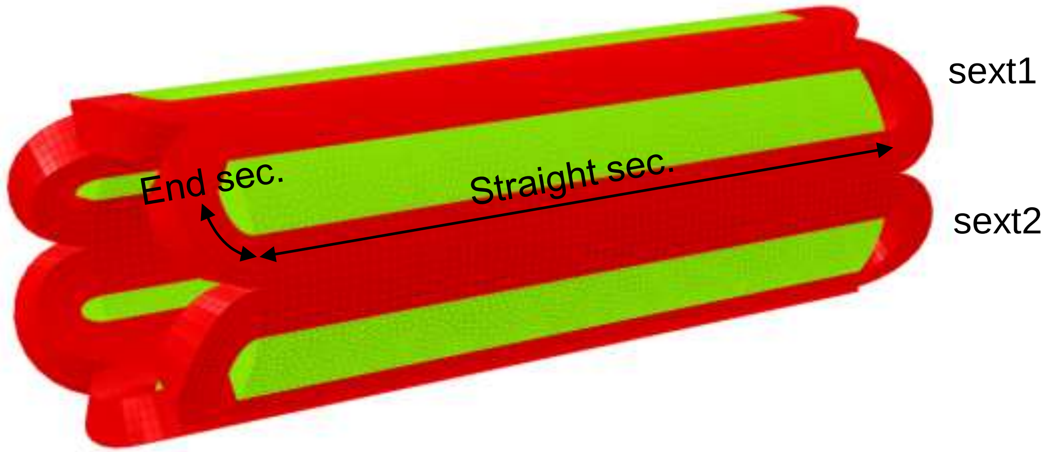
Summary and discussion of next steps

- We are ready to wind the prototype coil with the nominal design.
- The new design is quite interesting in reducing risks with coil fab for both Nb-Ti and in particularly Nb_3Sn.
- Switching to the new design will need to produce new poles and have a small impact on cost but a bigger impact on schedule (about 6 weeks).
- There might be hidden (unknown – unknown) risks.
  - We would like to ask you to allow us to perform winding evaluation and 3-D mechanical analysis and then decide on whether to switch to the new design.
- Proceeding to the new design with Nb_3Sn winding and coil transfer (from winding table into the reaction mold and from the reaction mold to the impregnation model) establishes a coil fabrication experience reference for Nb-Ti as well.

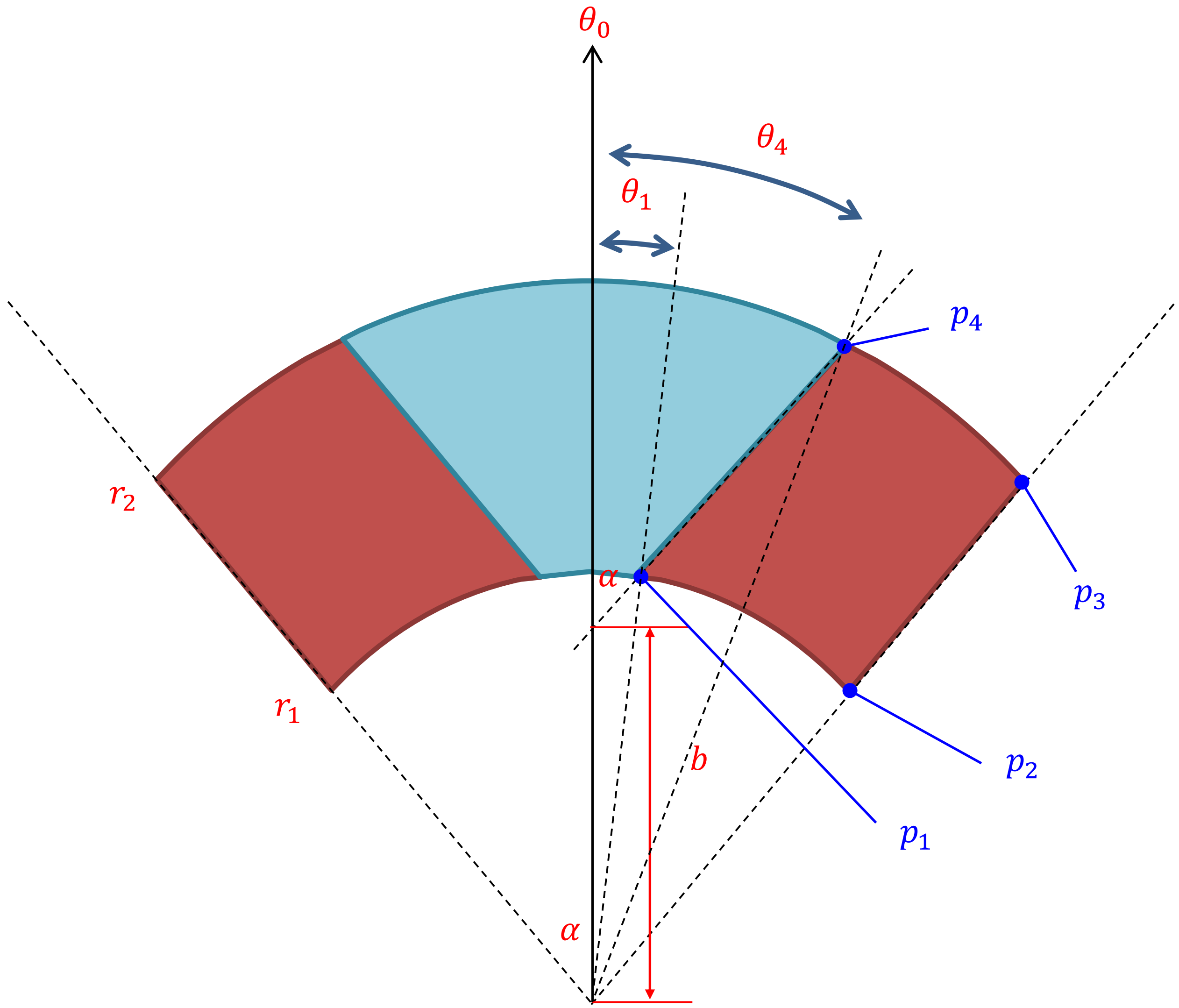
Supporting slides

Magnetic force

Item		Unit	Original	Alternative
sext1/straight	Fx	kN	98.8	151.3
	Fy	kN	-296.5	-459.4
	Fz	kN	0.1	0.0
sext1/end1 (extr side)	Fx	kN	25.2	29.6
	Fy	kN	-6.5	-5.4
	Fz	kN	9.8	12.5
sext1/end2 (inj side)	Fx	kN	-6.6	-9.3
	Fy	kN	-40.5	-41.4
	Fz	kN	-26.9	-33.2
sext2/straight	Fx	kN	105.0	128.4
	Fy	kN	321.1	307.3
	Fz	kN	0.1	0.0
sext2/end1 (extr side)	Fx	kN	-7.6	-10.7
	Fy	kN	36.7	37.8
	Fz	kN	25.0	30.7
sext2/end2 (inj side)	Fx	kN	25.1	28.4
	Fy	kN	2.6	2.3
	Fz	kN	-7.8	-10.4



Building the coil



- Needs the coordinate to generate conductor in OPERA
- P1 is a point intersected with circle

$$\begin{cases} x^2 + y^2 = r^2 \\ y = kx + b \end{cases}$$

$$(1 + k^2)x^2 + 2kbx + b^2 - r^2 = 0$$

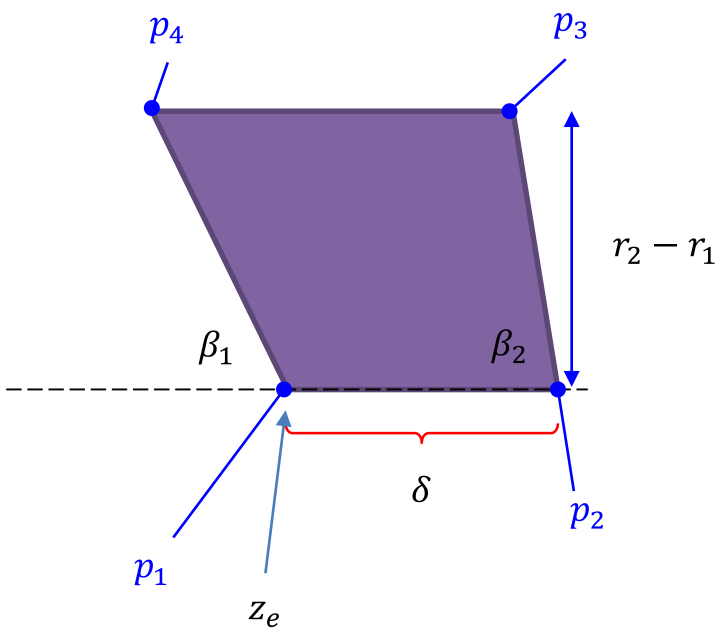
$$\Rightarrow \quad x = \frac{-2kb + \sqrt{4k^2b^2 - 4(1 + k^2)(b^2 - r^2)}}{2(1 + k^2)}$$

- The angle at each intersected point:

$$\theta = \cos^{-1}\{\frac{-2kb + \sqrt{4k^2b^2 - 4(1 + k^2)(b^2 - r^2)}}{2(1 + k^2)r}\}$$

$$k = \tan\alpha$$

Building the coil end



Parametric curve for the coil end:

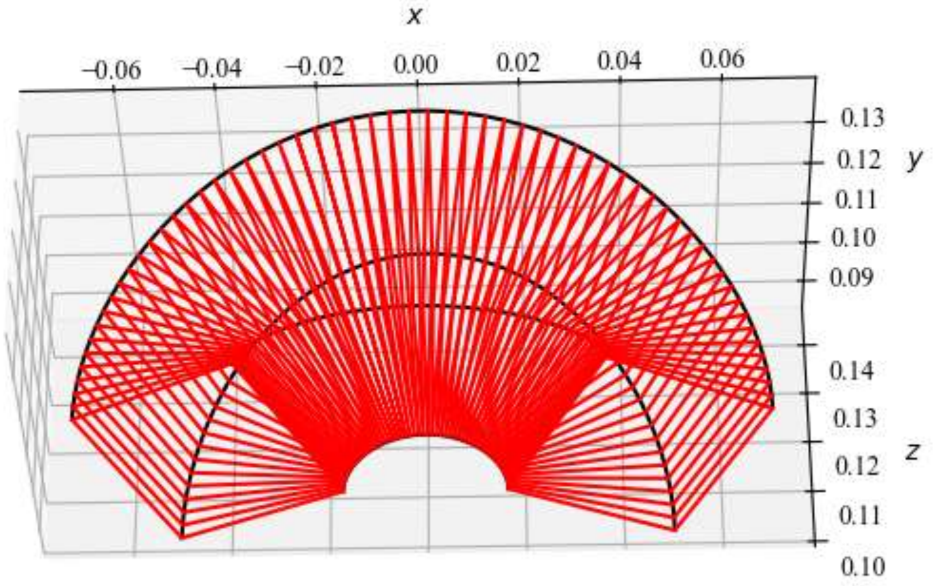
$$\theta_i = \theta_0 - \alpha_i \cos t$$

$$\begin{cases} x = r\cos\theta \\ y = r\sin\theta \\ z = z_0 + z_e \sin t \end{cases}$$

Coordinate at the corner for the end section:

- P1: $\begin{cases} r = r_0 \\ z = z_0 + z_e \sin t \end{cases}$
- P2: $\begin{cases} r = r_0 \\ z = z_0 + (z_e + \delta)\sin t \end{cases}$
- P3: $\begin{cases} r = r_1 \\ z = z_0 + \{z_e + \delta - (r_2 - r_1)\cot\beta_2\}\sin t \end{cases}$
- P4: $\begin{cases} r = r_1 \\ z = z_0 + \{z_e - (r_2 - r_1)\cot\beta_1\}\sin t \end{cases}$

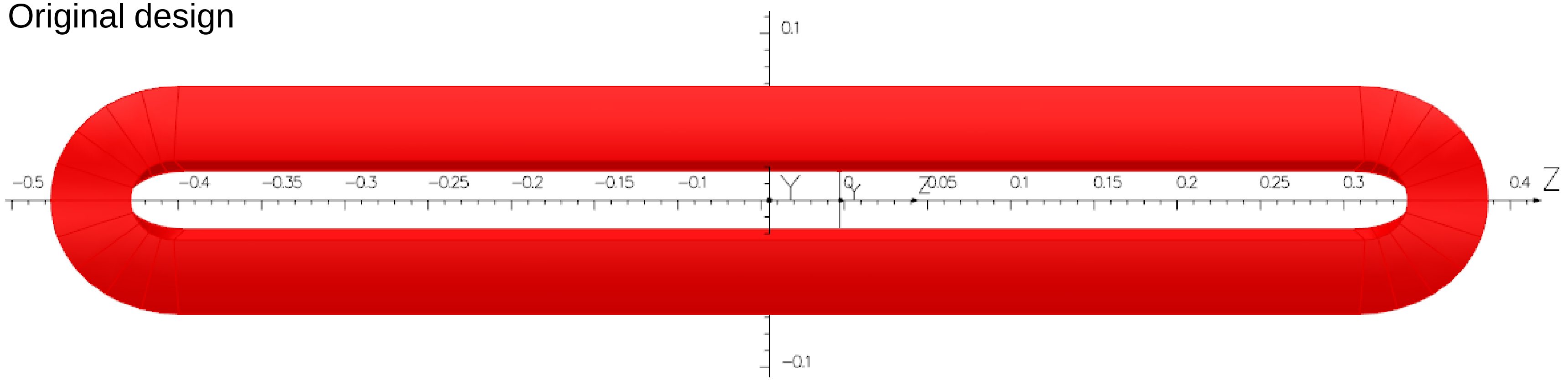
Genera



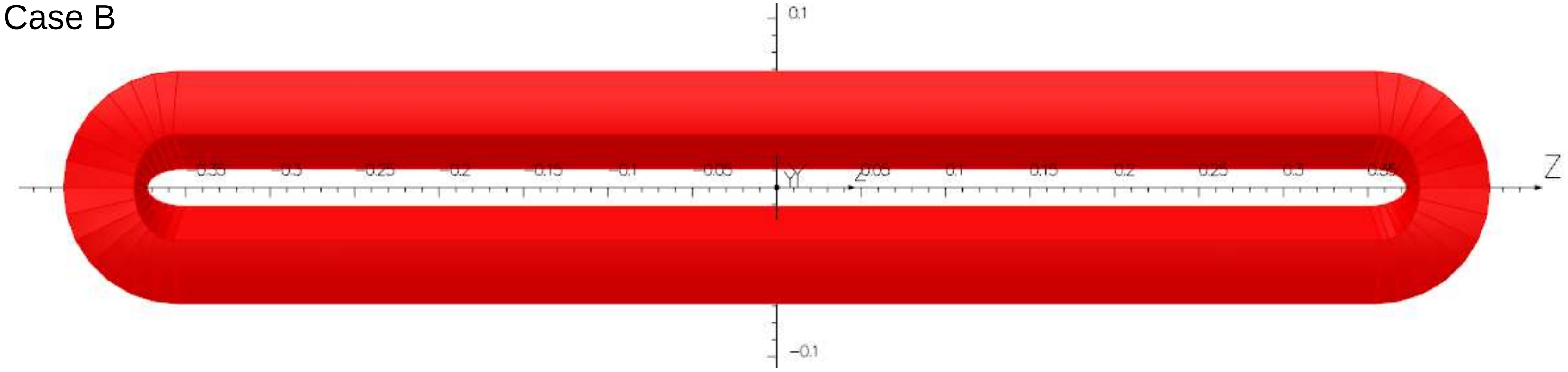

```
deg = np.pi/180
mm  = 1e-3

r0    = 100*mm
r1    = 137*mm
alpha = 30*deg
b     = 70*mm
z0    = 100*mm
ze    = 10*mm
sigma = 37*mm
theta0= 90*deg
beta1 = 85*deg
beta2 = 88*deg

plt.rcParams['font.family'] = 'Times New Roman'

def getTheta(alpha,b,r):
    k = np.tan(90*deg-alpha)
    x = (-2*k*b + np.sqrt((2*k*b)**2-4*(1+k**2)*(b**2-r**2))) / 2 / (1+k**2) / r
    theta = np.arccos(x)
    return theta

def getCorner(r0,r1,alpha,b,ze,sig,beta1,beta2):
    theta1 = getTheta(alpha,b,r1)
    theta2 = getTheta(alpha,b,r0)
    theta3 = 90*deg - alpha
    pts = {'r'     :np.array([r1,r0,r0,r1]),\
           'theta':np.array([theta1,theta2,theta3,theta3]),\
           'alpha':np.array([90*deg-theta1,90*deg-theta2,alpha,alpha]),\
           'z'     :np.array([ze-(r1-r0)/np.tan(beta1), ze, ze+sigma, ze+sigma-(r1-r0)/np.tan(beta2)])}

    print(pts['theta']/deg)
    return pts

def getEndPath(t0,t1,nt,pts,z0,z1,theta0):
    data = {}
    t    = np.linspace( t0, t1, nt )

    for i in range( len(pts['r']) ):
        data['p%i' %(i+1)] = {}
        theta = theta0 - pts['alpha'][i] * np.cos(t)

        data['p%i' %(i+1)]['x'] = pts['r'][i] * np.cos(theta)
        data['p%i' %(i+1)]['y'] = pts['r'][i] * np.sin(theta)
        data['p%i' %(i+1)]['z'] = z0 + pts['z'][i]*np.sin(t)

    return data

def getStraightPath(z0,z1,nz,r,gamma,theta):
    z = np.linspace( z0, z1, nz )
    x = r * np.cos(theta)
    y = gamma + (r-gamma) * np.sin(theta)
    x *= np.ones(nz)
    y *= np.ones(nz)
    return x, y, z
```

Single sextupole coil

Original design



Case B



Current density of the coil block

$$J = N\frac{I}{A} \quad \Rightarrow \quad J = NL\frac{I}{V}$$

$$V = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} |J(\xi,\eta,\zeta)| d\xi d\eta d\zeta \quad \Rightarrow \quad V = \sum_{i=0}^{N_\xi}\sum_{j=0}^{N_\eta}\sum_{k=0}^{N_\zeta} |J(\xi_i,\eta_j,\zeta_k)| w_i w_j w_k$$

$$J(\xi,\eta,\zeta) = \begin{pmatrix} \frac{\partial N_1}{\partial \xi} & \frac{\partial N_1}{\partial \xi} & \cdots & \frac{\partial N_{20}}{\partial \xi} \\ \frac{\partial N_1}{\partial \eta} & \frac{\partial N_1}{\partial \eta} & \cdots & \frac{\partial N_{20}}{\partial \eta} \\ \frac{\partial N_1}{\partial \zeta} & \frac{\partial N_1}{\partial \zeta} & \cdots & \frac{\partial N_{20}}{\partial \zeta} \end{pmatrix} \begin{pmatrix} x_1^e & y_1^e & z_1^e \\ x_2^e & y_2^e & z_2^e \\ \vdots & \vdots & \vdots \\ x_{20}^e & y_{20}^e & z_{20}^e \end{pmatrix}$$

$$L = \sqrt{(x_5^e - x_1^e)^2 + (y_5^e - y_1^e)^2 + (z_5^e - z_1^e)^2}$$

n	ξ_i, η_j, ζ_k	w_i
1	0.0	2.0
2	+/- 0.5773502692	1.0
3	+/- 0.7745966692 0.0	0.5555555556 0.8888888889
4	+/- 0.8611363116 +/- 0.3399810436	0.3478548451 0.6521451549

Shape function

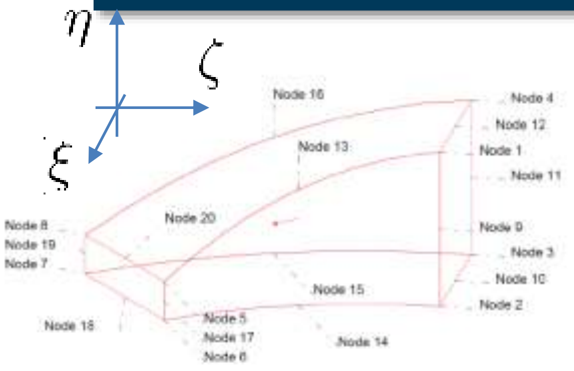


Figure 5.8 A 20-Node Brick

Node 1, (1, 1, 1), $\frac{1}{8}(1+\xi)(1+\eta)(1+\zeta)(-2+\xi+\eta+\zeta)$

Node 2, (1, -1, 1), $\frac{1}{8}(1+\xi)(1-\eta)(1+\zeta)(-2+\xi-\eta+\zeta)$

Node 3, (-1, -1, 1), $\frac{1}{8}(1-\xi)(1-\eta)(1+\zeta)(-2-\xi-\eta+\zeta)$

Node 4, (-1, 1, 1), $\frac{1}{8}(1-\xi)(1+\eta)(1+\zeta)(-2-\xi+\eta+\zeta)$

Node 5, (1, 1, -1), $\frac{1}{8}(1+\xi)(1+\eta)(1-\zeta)(-2+\xi+\eta-\zeta)$

Node 6, (1, -1, -1), $\frac{1}{8}(1+\xi)(1-\eta)(1-\zeta)(-2+\xi-\eta-\zeta)$

Node 7, (-1, -1, -1), $\frac{1}{8}(1-\xi)(1-\eta)(1-\zeta)(-2-\xi-\eta-\zeta)$

Node 8, (-1, 1, -1), $\frac{1}{8}(1-\xi)(1+\eta)(1-\zeta)(-2-\xi+\eta-\zeta)$

Node 9, (1, 0, 1), $\frac{1}{4}(1+\xi)(1-\eta^2)(1+\zeta)$

Node 10, (0, -1, 1), $\frac{1}{4}(1-\xi^2)(1-\eta)(1+\zeta)$

Node 11, (-1, 0, 1), $\frac{1}{4}(1-\xi)(1-\eta^2)(1+\zeta)$

Node 12, (0, 1, 1), $\frac{1}{4}(1-\xi^2)(1+\eta)(1+\zeta)$

Node 13, (1, 1, 0), $\frac{1}{4}(1+\xi)(1+\eta)(1-\zeta^2)$

Node 14, (1, -1, 0), $\frac{1}{4}(1+\xi)(1-\eta)(1-\zeta^2)$

Node 15, (-1, -1, 0), $\frac{1}{4}(1-\xi)(1-\eta)(1-\zeta^2)$

Node 16, (-1, 1, 0), $\frac{1}{4}(1-\xi)(1+\eta)(1-\zeta^2)$

Node 17, (1, 0, -1), $\frac{1}{4}(1+\xi)(1-\eta^2)(1-\zeta)$

Node 18, (0, -1, -1), $\frac{1}{4}(1-\xi^2)(1-\eta)(1-\zeta)$

Node 19, (-1, 0, -1), $\frac{1}{4}(1-\xi)(1-\eta^2)(1-\zeta)$

Node 20, (0, 1, -1), $\frac{1}{4}(1-\xi^2)(1+\eta)(1-\zeta)$

Derivative of the shape function

$$\frac{\partial N_1}{\partial \xi} = \frac{1}{8}(1+\eta)(1+\zeta)(-1+2\xi+\eta+\zeta)$$
$$\frac{\partial N_2}{\partial \xi} = \frac{1}{8}(1-\eta)(1+\zeta)(-1+2\xi-\eta+\zeta)$$
$$\frac{\partial N_3}{\partial \xi} = -\frac{1}{8}(1-\eta)(1+\zeta)(-1-2\xi-\eta+\zeta)$$
$$\frac{\partial N_4}{\partial \xi} = -\frac{1}{8}(1+\eta)(1+\zeta)(-1-2\xi+\eta+\zeta)$$
$$\frac{\partial N_5}{\partial \xi} = \frac{1}{8}(1+\eta)(1-\zeta)(-1+2\xi+\eta-\zeta)$$
$$\frac{\partial N_6}{\partial \xi} = \frac{1}{8}(1-\eta)(1-\zeta)(-1+2\xi-\eta-\zeta)$$
$$\frac{\partial N_7}{\partial \xi} = -\frac{1}{8}(1-\eta)(1-\zeta)(-1-2\xi-\eta-\zeta)$$
$$\frac{\partial N_8}{\partial \xi} = -\frac{1}{8}(1+\eta)(1-\zeta)(-1-2\xi+\eta-\zeta)$$
$$\frac{\partial N_9}{\partial \xi} = \frac{1}{4}(1-\eta^2)(1+\zeta)$$

$$\frac{\partial N_1}{\partial \eta} = \frac{1}{8}(1+\xi)(1+\zeta)(-1+\xi+2\eta+\zeta)$$
$$\frac{\partial N_2}{\partial \eta} = -\frac{1}{8}(1+\xi)(1+\zeta)(-1+\xi-2\eta+\zeta)$$
$$\frac{\partial N_3}{\partial \eta} = -\frac{1}{8}(1-\xi)(1+\zeta)(-1-\xi-2\eta+\zeta)$$
$$\frac{\partial N_4}{\partial \eta} = \frac{1}{8}(1-\xi)(1+\zeta)(-1-\xi+2\eta+\zeta)$$
$$\frac{\partial N_5}{\partial \eta} = \frac{1}{8}(1+\xi)(1-\zeta)(-1+\xi+2\eta-\zeta)$$
$$\frac{\partial N_6}{\partial \eta} = -\frac{1}{8}(1+\xi)(1-\zeta)(-1+\xi-2\eta-\zeta)$$
$$\frac{\partial N_7}{\partial \eta} = -\frac{1}{8}(1-\xi)(1-\zeta)(-1-\xi-2\eta-\zeta)$$
$$\frac{\partial N_8}{\partial \eta} = \frac{1}{8}(1-\xi)(1-\zeta)(-1-\xi+2\eta-\zeta)$$
$$\frac{\partial N_9}{\partial \eta} = -\frac{1}{2}\eta(1+\xi)(1+\zeta)$$

$$\frac{\partial N_1}{\partial \zeta} = \frac{1}{8}(1+\xi)(1+\eta)(-1+\xi+\eta+2\zeta)$$
$$\frac{\partial N_2}{\partial \zeta} = \frac{1}{8}(1+\xi)(1-\eta)(-1+\xi-\eta+2\zeta)$$
$$\frac{\partial N_3}{\partial \zeta} = \frac{1}{8}(1-\xi)(1-\eta)(-1-\xi-\eta+2\zeta)$$
$$\frac{\partial N_4}{\partial \zeta} = \frac{1}{8}(1-\xi)(1+\eta)(-1-\xi+\eta+2\zeta)$$
$$\frac{\partial N_5}{\partial \zeta} = -\frac{1}{8}(1+\xi)(1+\eta)(-1+\xi+\eta-2\zeta)$$
$$\frac{\partial N_6}{\partial \zeta} = -\frac{1}{8}(1+\xi)(1-\eta)(-1+\xi-\eta-2\zeta)$$
$$\frac{\partial N_7}{\partial \zeta} = -\frac{1}{8}(1-\xi)(1-\eta)(-1-\xi-\eta-2\zeta)$$
$$\frac{\partial N_8}{\partial \zeta} = -\frac{1}{8}(1-\xi)(1+\eta)(-1-\xi+\eta-2\zeta)$$
$$\frac{\partial N_9}{\partial \zeta} = \frac{1}{4}(1+\xi)(1-\eta^2)$$

Derivative of the shape function

$$\frac{\partial N_{10}}{\partial \xi} = -\frac{1}{2}\xi(1-\eta)(1+\zeta)$$
$$\frac{\partial N_{11}}{\partial \xi} = -\frac{1}{4}(1-\eta^2)(1+\zeta)$$
$$\frac{\partial N_{12}}{\partial \xi} = -\frac{1}{2}\xi(1+\eta)(1+\zeta)$$
$$\frac{\partial N_{13}}{\partial \xi} = \frac{1}{4}(1+\eta)(1-\zeta^2)$$
$$\frac{\partial N_{14}}{\partial \xi} = \frac{1}{4}(1-\eta)(1-\zeta^2)$$
$$\frac{\partial N_{15}}{\partial \xi} = -\frac{1}{4}(1-\eta)(1-\zeta^2)$$
$$\frac{\partial N_{16}}{\partial \xi} = -\frac{1}{4}(1+\eta)(1-\zeta^2)$$
$$\frac{\partial N_{17}}{\partial \xi} = \frac{1}{4}(1-\eta^2)(1-\zeta)$$
$$\frac{\partial N_{18}}{\partial \xi} = -\frac{1}{2}\xi(1-\eta)(1-\zeta)$$
$$\frac{\partial N_{19}}{\partial \xi} = -\frac{1}{4}(1-\eta^2)(1-\zeta)$$

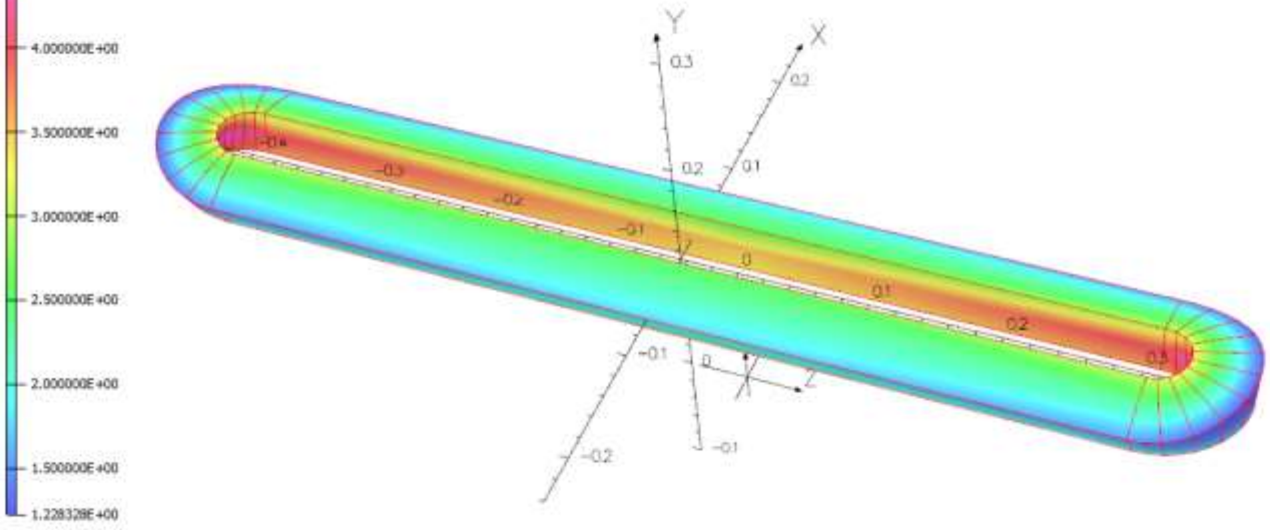
$$\frac{\partial N_{10}}{\partial \eta} = -\frac{1}{4}(1-\xi^2)(1+\zeta)$$
$$\frac{\partial N_{11}}{\partial \eta} = -\frac{1}{2}\eta(1-\xi)(1+\zeta)$$
$$\frac{\partial N_{12}}{\partial \eta} = \frac{1}{4}(1-\xi^2)(1+\zeta)$$
$$\frac{\partial N_{13}}{\partial \eta} = \frac{1}{4}(1+\xi)(1-\zeta^2)$$
$$\frac{\partial N_{14}}{\partial \eta} = -\frac{1}{4}(1+\xi)(1-\zeta^2)$$
$$\frac{\partial N_{15}}{\partial \eta} = -\frac{1}{4}(1-\xi)(1-\zeta^2)$$
$$\frac{\partial N_{16}}{\partial \eta} = \frac{1}{4}(1-\xi)(1-\zeta^2)$$
$$\frac{\partial N_{17}}{\partial \eta} = -\frac{1}{2}\eta(1+\xi)(1-\zeta)$$
$$\frac{\partial N_{18}}{\partial \eta} = -\frac{1}{4}(1-\xi^2)(1-\zeta)$$
$$\frac{\partial N_{19}}{\partial \eta} = -\frac{1}{2}\eta(1-\xi)(1-\zeta)$$

$$\frac{\partial N_{10}}{\partial \zeta} = \frac{1}{4}(1-\xi^2)(1-\eta)$$
$$\frac{\partial N_{11}}{\partial \zeta} = \frac{1}{4}(1-\xi)(1-\eta^2)$$
$$\frac{\partial N_{12}}{\partial \zeta} = \frac{1}{4}(1-\xi^2)(1+\eta)$$
$$\frac{\partial N_{13}}{\partial \zeta} = -\frac{1}{2}(1+\xi)(1+\eta)\zeta$$
$$\frac{\partial N_{14}}{\partial \zeta} = -\frac{1}{2}(1+\xi)(1-\eta)\zeta$$
$$\frac{\partial N_{15}}{\partial \zeta} = -\frac{1}{2}(1-\xi)(1-\eta)\zeta$$
$$\frac{\partial N_{16}}{\partial \zeta} = -\frac{1}{2}(1-\xi)(1+\eta)\zeta$$
$$\frac{\partial N_{17}}{\partial \zeta} = -\frac{1}{4}(1+\xi)(1-\eta^2)$$
$$\frac{\partial N_{18}}{\partial \zeta} = -\frac{1}{4}(1-\xi^2)(1-\eta)$$
$$\frac{\partial N_{19}}{\partial \zeta} = -\frac{1}{4}(1-\xi)(1-\eta^2)$$

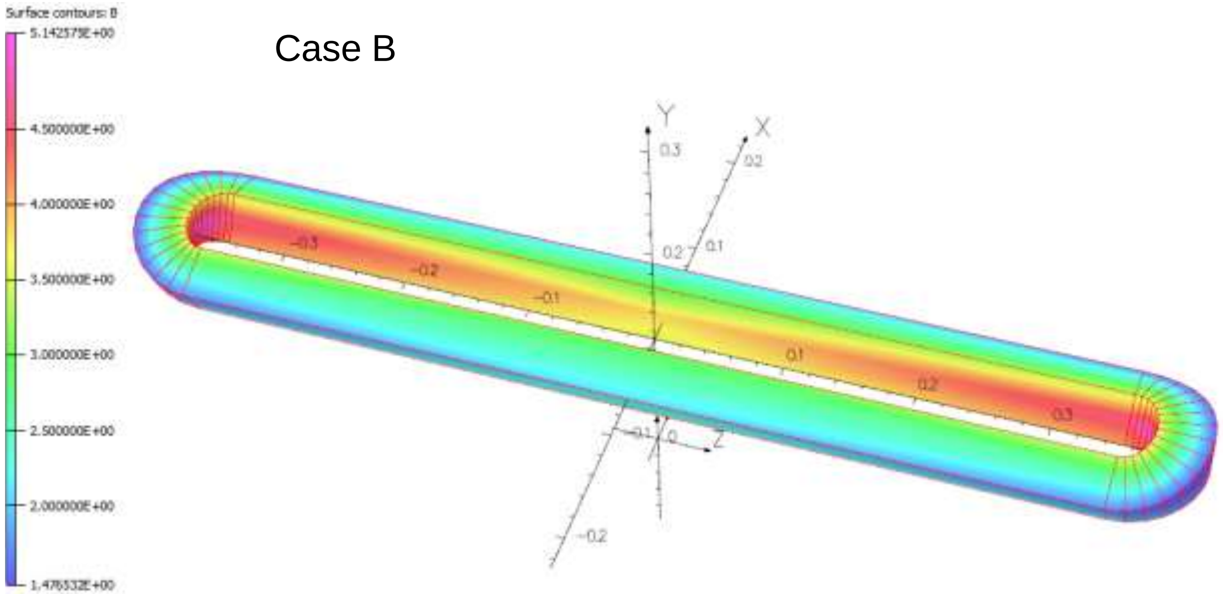
$$\frac{\partial N_{20}}{\partial \xi} = -\frac{1}{2}\xi(1+\eta)(1-\zeta)$$
$$\frac{\partial N_{20}}{\partial \eta} = \frac{1}{4}(1-\xi^2)(1-\zeta)$$
$$\frac{\partial N_{20}}{\partial \zeta} = -\frac{1}{4}(1-\xi^2)(1+\eta)$$

Comparison of the field on winding

Original design



Case B



- Peak field without iron pole:
  - Original design: 4.64 T
  - Case B: 5.14 T

	A [m^2]	J [A/m^2]
1	1.501709e-03	2.153546e+08
2	1.503282e-03	2.151292e+08
3	1.505521e-03	2.148093e+08
4	1.507202e-03	2.145697e+08
5	1.507606e-03	2.145123e+08
6	1.506979e-03	2.146015e+08
7	1.506260e-03	2.147040e+08
8	1.506260e-03	2.147040e+08
9	1.506979e-03	2.146015e+08
10	1.507606e-03	2.145123e+08
11	1.507202e-03	2.145697e+08
12	1.505521e-03	2.148093e+08
13	1.503282e-03	2.151292e+08
14	1.501709e-03	2.153546e+08
15	1.510577e-03	2.140904e+08