New design updates for the D1 magnet and strategy for the model-02

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KEK

WP3 meeting, 9 August 2017

Outline

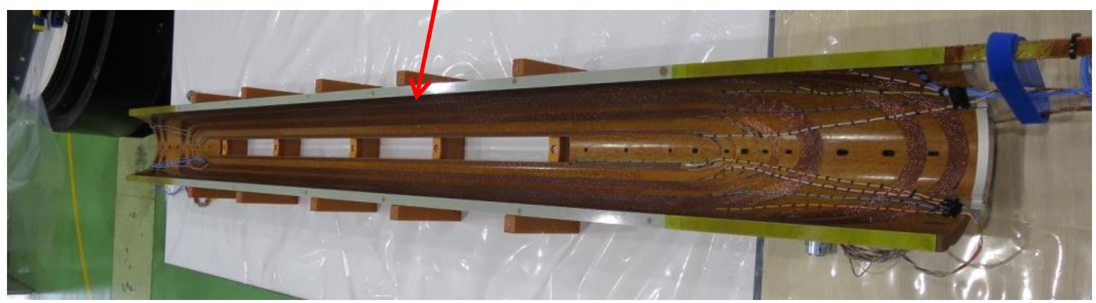
- Brief summary of test results of MBXFS01b
- Design updates from 1st to 2nd model
  - Design parameters
  - Magnetic design update
  - Enhancing mechanical support of a coil
  - Other items
- Schedule

Brief summary of test results of MBXFS01b

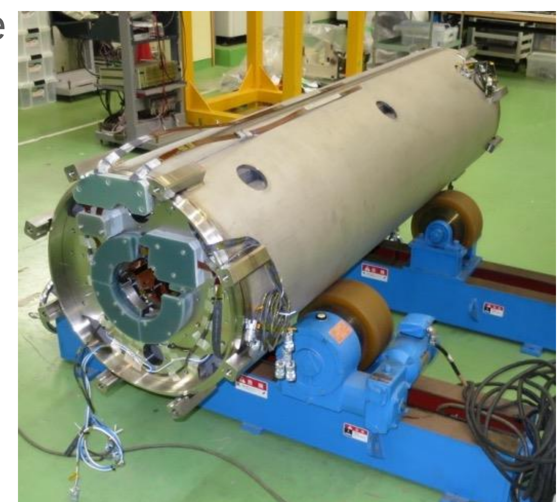
History of 2 m model magnet development of D1

- MBXFS01
  - Fabricated in Aug, 2015 – Mar, 2016, Magnet test in Apr – Jun, 2016
  - Unsatisfactory training performance due to lack of azimuthal coil pre-stress

0.8 mm-thick G10 shim

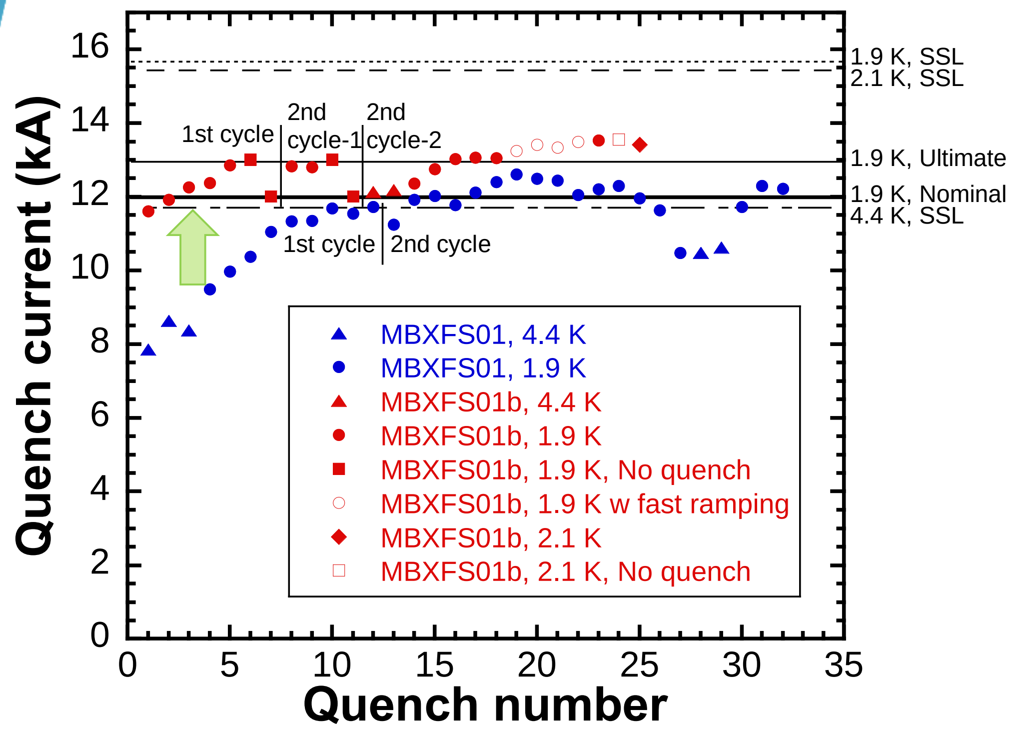


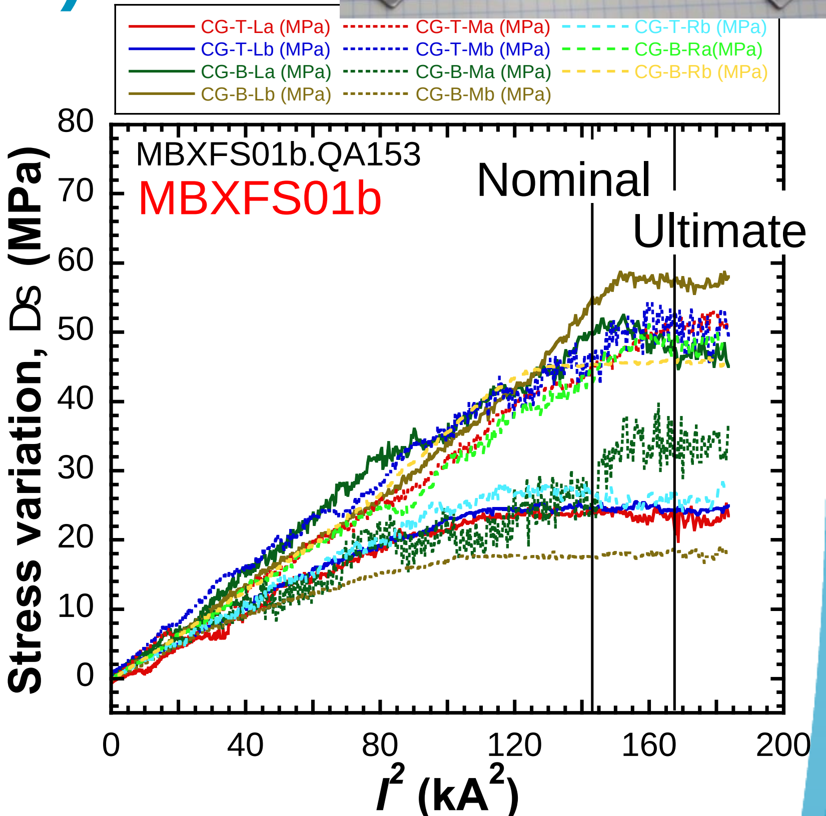
- MBXFS01b
  - Reassembly in Nov, 2016 – Jan, 2017, Magnet test in Feb – April, 2017
  - Increase of azimuthal coil pre-stress by inserting a G10 shim covering coil MP
  - Substantial improvement of training performance



- MBXFS02

Training performance (MBXFS01b)



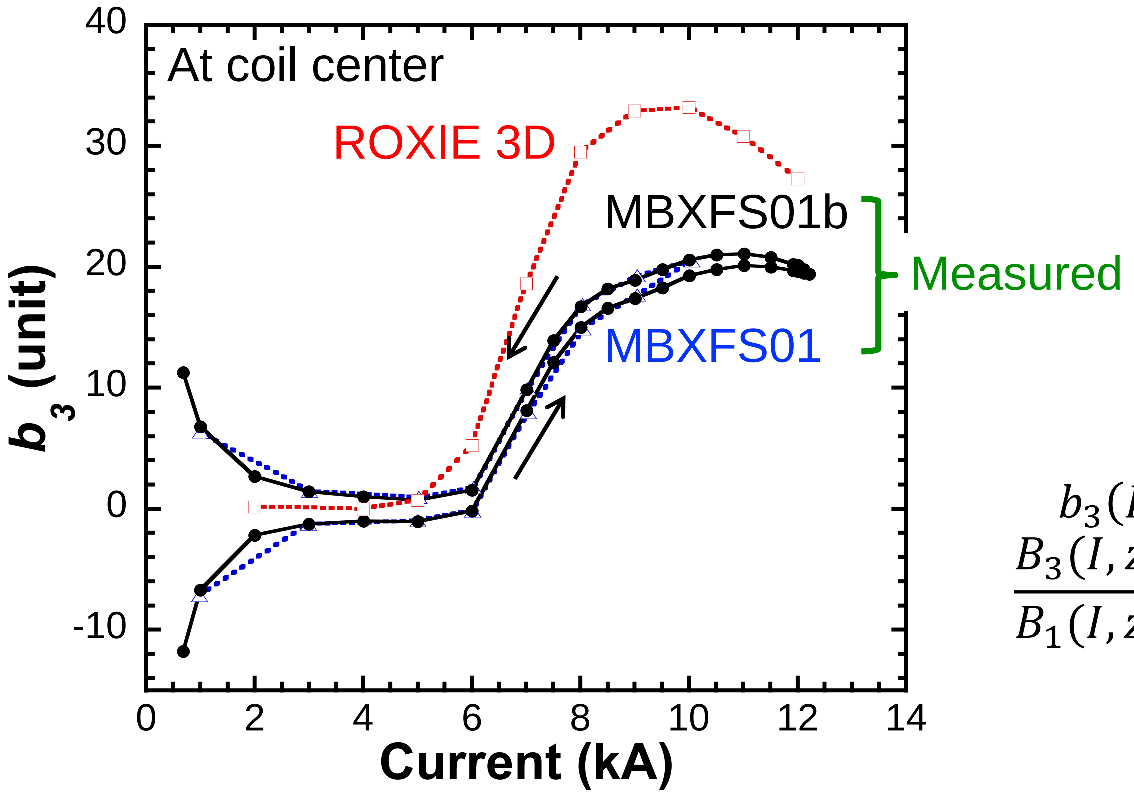


- Substantial improvement of training performance from 01 to 01b by increasing azimuthal coil pre-stress
  - Nominal at the third quench, ultimate after five quenches, good training memory
- Even in 01b, azimuthal coil pre-stress was relieved at the ultimate current.

→ Increase of azimuthal coil pre-stress by 15 MPa is necessary.

Variation of b3 at coil center (MBXFS01b)

The baseline of each curve was offset so that variation of b3 can be compared.

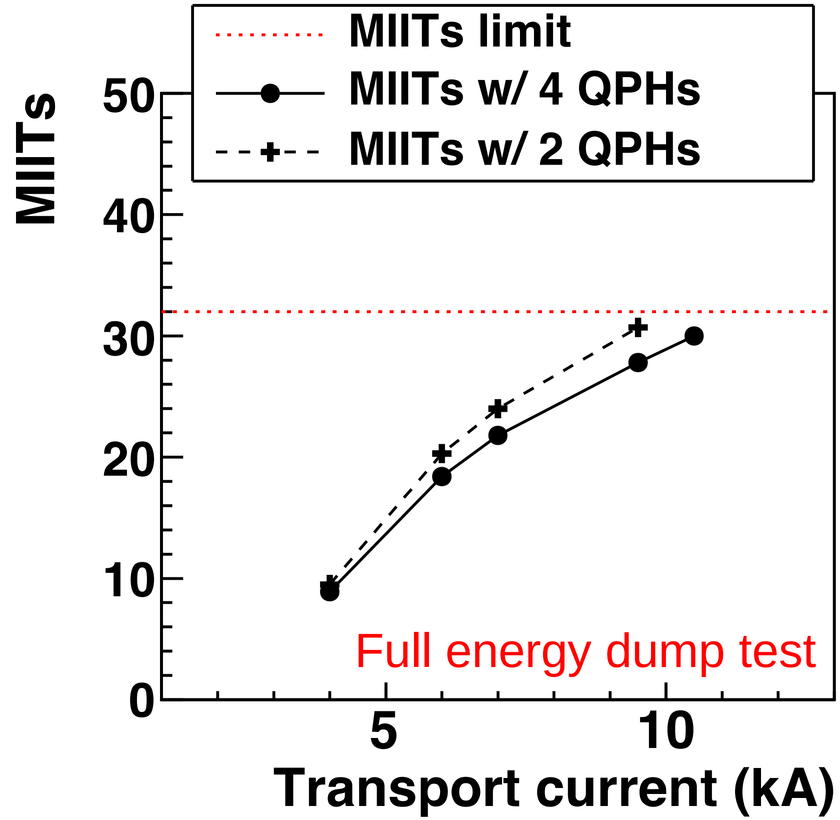


$$b_3(I, z=0) = \frac{B_3(I, z=0)}{B_1(I, z=0)} \times 10^4$$

- Good reproducibility between 01 and 01b
- Difference between measured b3 and ROXIE 3D calculations by more than 10 unit

→ The reason of this discrepancy has not been clarified.

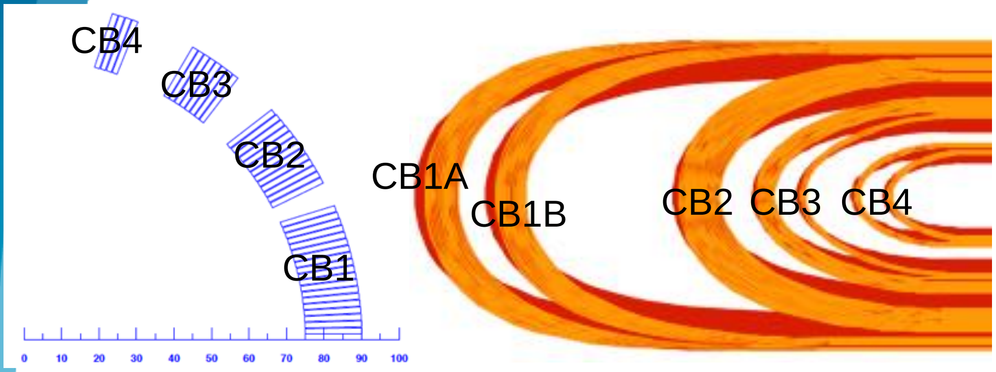
Quench protection (MBXFS01b)

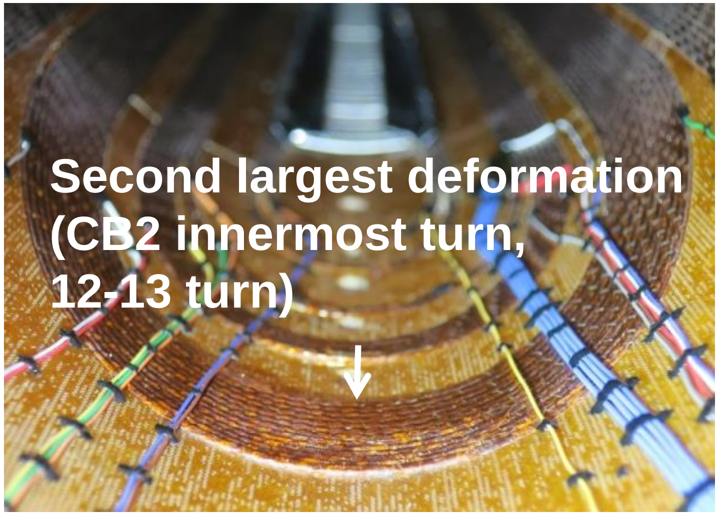


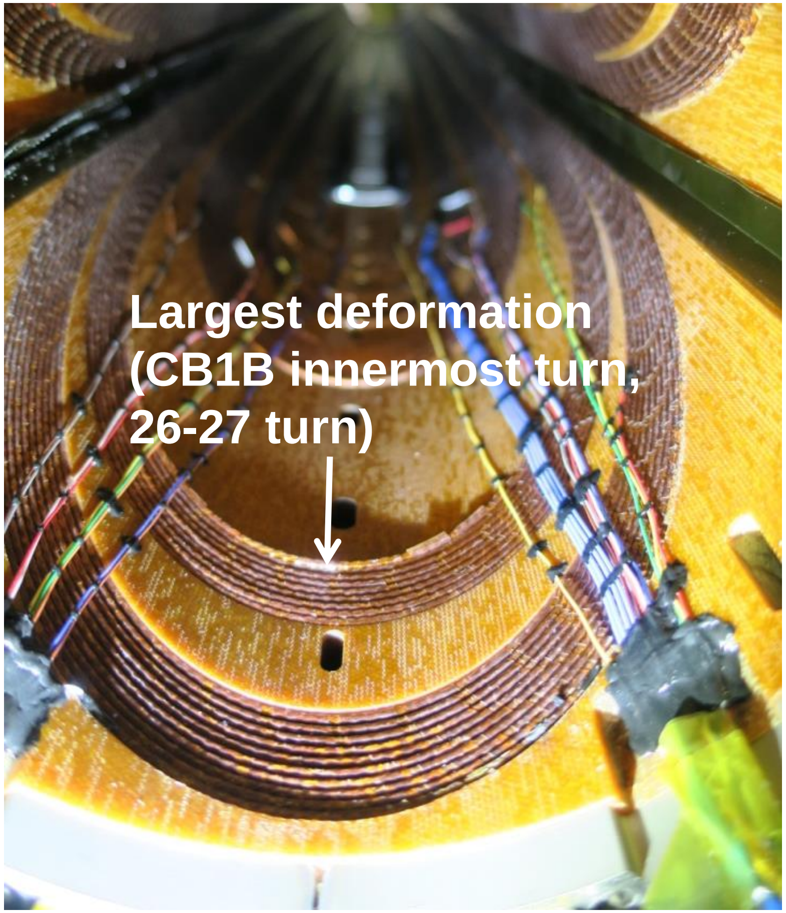
QPH implemented in the 1st model

- As a result of full energy dump test, MIITs reached the allowable limit (MIITs=32 at 300 K) even at 10.5 kA (while I_{nom}=12 kA).
- QPH should be designed so that quench can be provoked in more turns.
- Quench simulation is necessary to design QPHs.

Coil deformation at coil end (MBXFS01b)

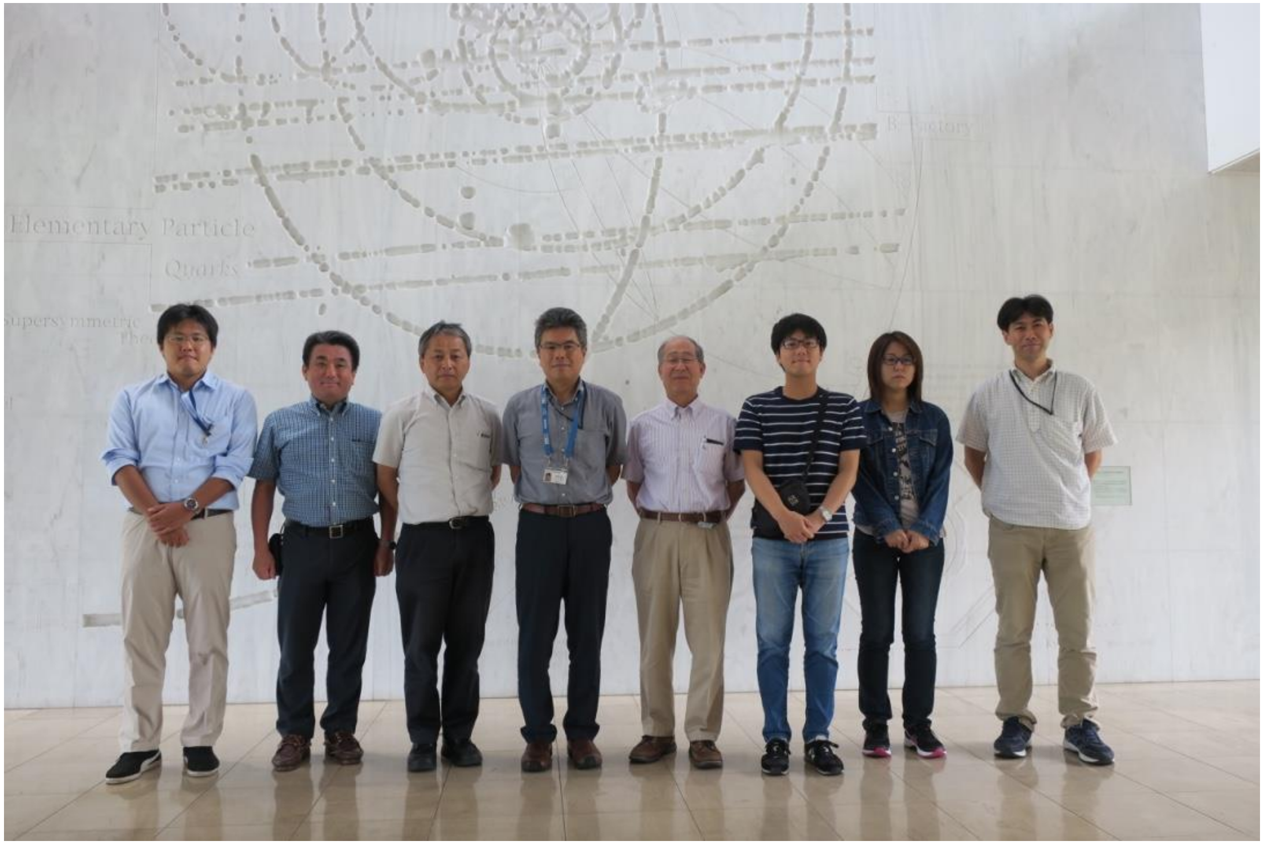






- Similarly to 01, coil deformation towards the coil bore was observed in the 01b.
- Largely deformed turn in 01b is the same as 01.
- The largely deformed turns coincide with ones at which quench started, though it has not been clarified if such cable deformation can cause quench.
  → Mechanical support of the cable at coil end should be reinforced.

2nd D1 magnet review (internal)



9 August, 2017
at KEK

Reviewers:
Toru Ogitsu
Akira Yamamoto
Kiyosumi Tsuchiya

Review report will be submitted at the end of August.

- Recommendations from the reviewers
  - Countermeasures against coil deformation at coil end
  - New design of QPH
  - Field quality study for the 2nd model

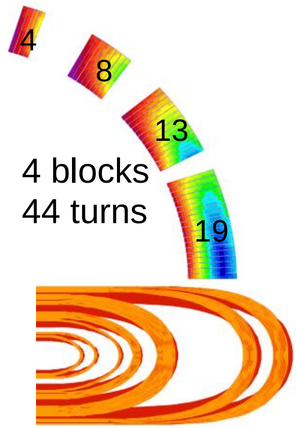
Design parameters
Comparison between 1st and 2nd model

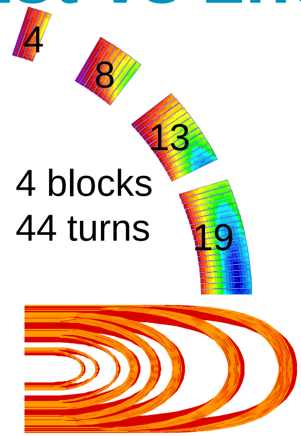
Strategy for the 2nd model (MBXFS02)

- Magnetic design
  - Change of HX holes to be in line with those in Q1-Q3

    (two holes at 90º → four holes at 45º) **REQUEST from CERN**
  - Optimization of iron shape, 2D coil block arrangement and coil end design
- Mechanical design
  - Increase of azimuthal coil pre-stress
  - Countermeasures against coil deformation at coil end
- Quench protection
  - Newly designed QPH will be implemented.
- Field quality
  - To reproduce measured results, field calculation model will be improved.

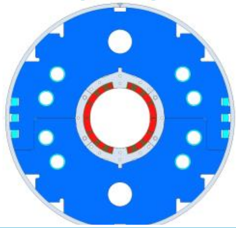
Design Parameters: 1st vs 2nd Models

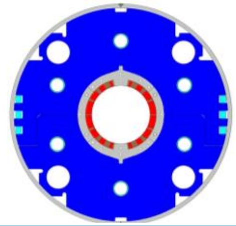




Item		1st model	2nd model	Remarks
Target pre-stress / load	lateral	01: 80 MPa 01b: 110 MPa	115 MPa	At pole in assembly. Both at S.S and coil ends.
	axial	51 kN/coil	? kN/coil	In assembly. Strain gauges on end spacers.
Coil	2D	4 blocks (4+8+13+19)		Small changes in position
	Coil end	7 blocks	8 blocks	Inclination angle, z/z0.
	Resin	100 % CE (BT-2160RX)	Epoxy + CE (EC-1HA, B?)	Radiation resistance proved for the ITER TF magnet. Study on heat cycle.
	length	525,1100,375 mm	561.2,1025.5,413.3 mm	LE, SS, RE

Design Parameters: 1st vs 2nd Models



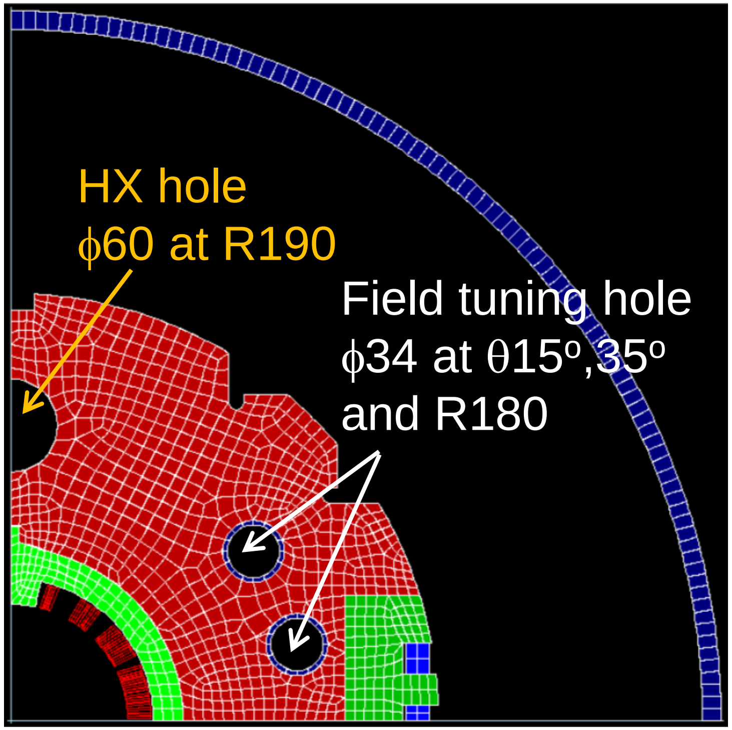


Item	1st model	2nd model	Remarks
QPH	straight	zigzag	Quench simulation underway
Insulation	4 x 0.125 mm polyimide sheets		No change
Collar	4-way split collars		No change
Yoke	2 HX holes	4 HX holes	PF 98% (t 0.6 mm SUS316L sheets in yoke laminations)
Shell	Two halves shell welded, vertically split, 10 mm thick SUS304L		Small change in arc length
Splice Box	4 layers GFRP		Need modification for the 4 HX holes
Cold tube Support	No	Yes	Design underway.
V-taps & wires	42 taps/coil, ϕ2mm wire	? taps/coil, ϕ0.4mm wire	Number of V-taps will be decreased.
Strain gages	Pole 12, Bullet 16, Coil end 0, Yoke 6, Shell 4	Pole 12, Bullet 8, Coil end 12, Yoke 6, Shell 4	

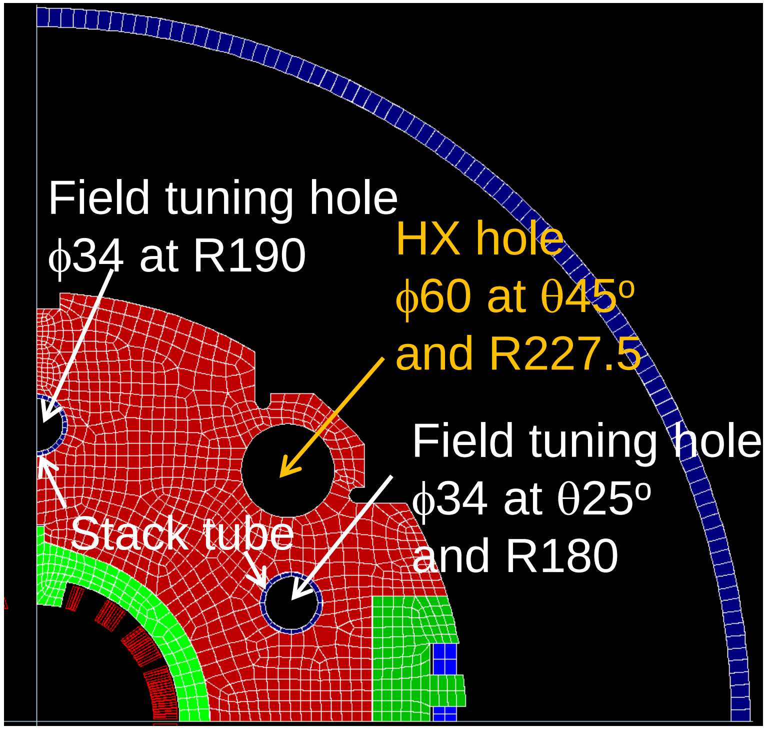
Magnetic design

Magnetic design

1st model



2nd model

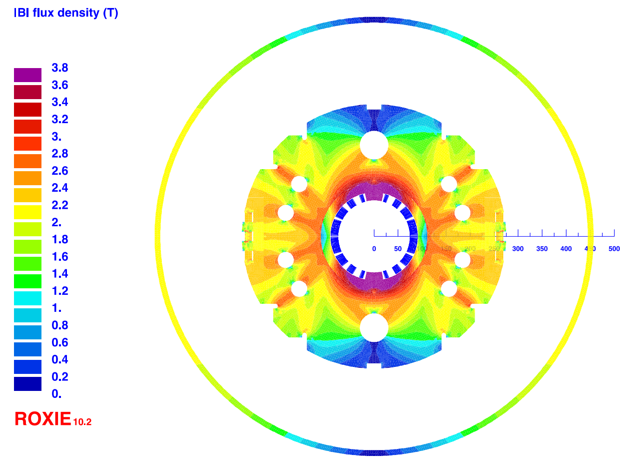


- Change of HX holes: 45º, ϕ60, R227.5
- A number of calculations using ROXIE 2D were performed to determine a new iron cross section. In these calculations, size and position of the field tuning holes were systematically changed mainly to minimize iron saturation effect on multipole coefficients.
- One of the cross sections with four HX holes was selected for the 2nd model and the later magnets. This result was compared with the 1st model with two HX holes.

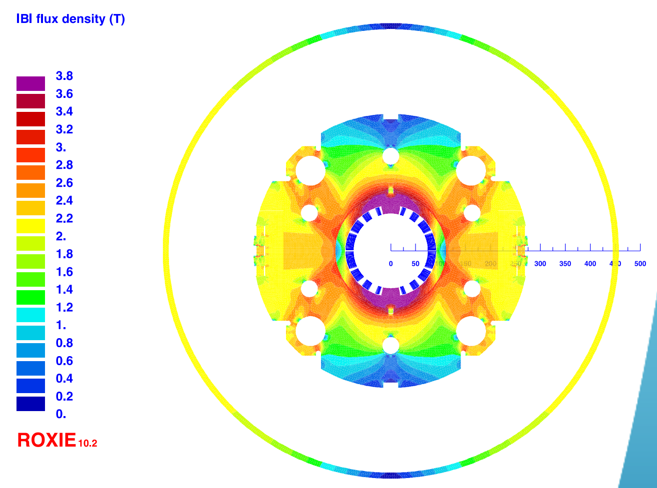
Field quality at nominal current by ROXIE 2D

	1st model Ver3.0.0	2nd model Ver4.0.1
Nominal current (kA)	12.0	12.047
Main field (T)	5.573	5.569
b3 (unit)	-0.059	-0.028
b5 (unit)	-0.097	-0.045
b7 (unit)	-0.111	-0.054
b9 (unit)	0.284	0.139
b11 (unit)	0.360	0.176
b13 (unit)	-0.663	-0.695
b15 (unit)	-1.115	-1.157
b17 (unit)	-0.788	-0.815
b19 (unit)	0.399	0.402

1st model



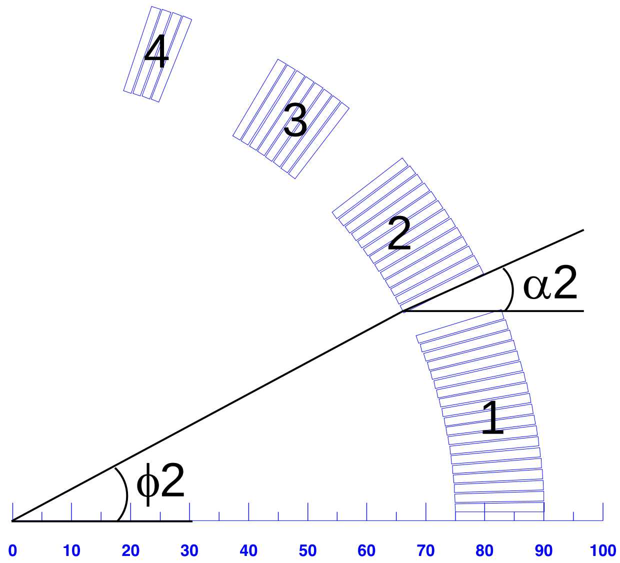
2nd model



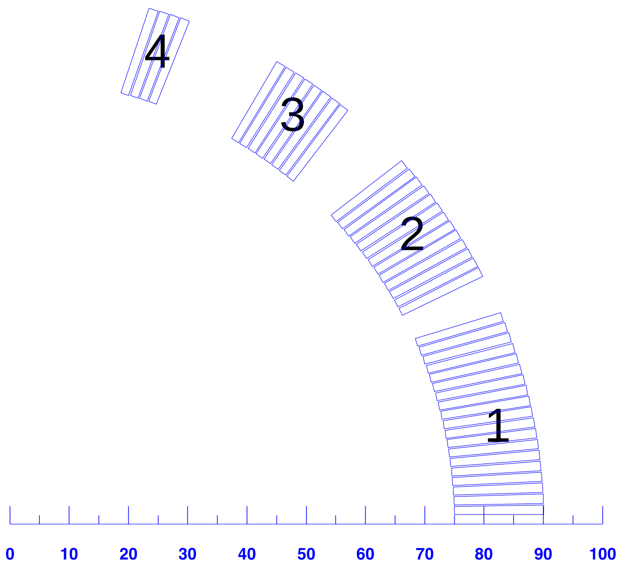
Nominal current in the modified model was determined to generate the main dipole field of 5.57 T.

Coil block arrangement

1st model



2nd model

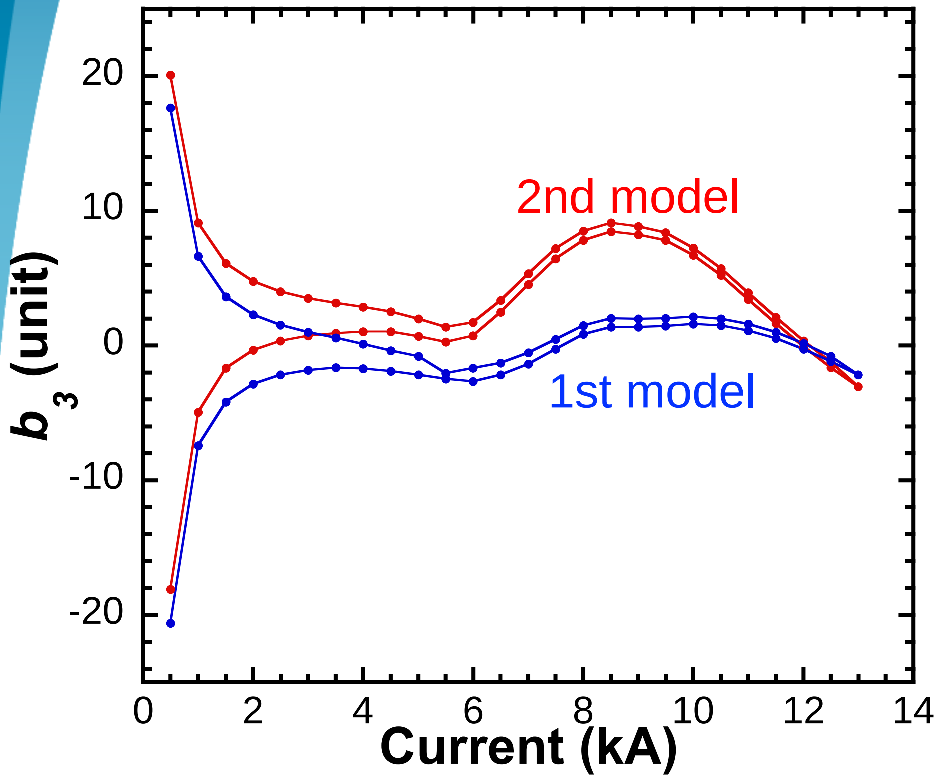


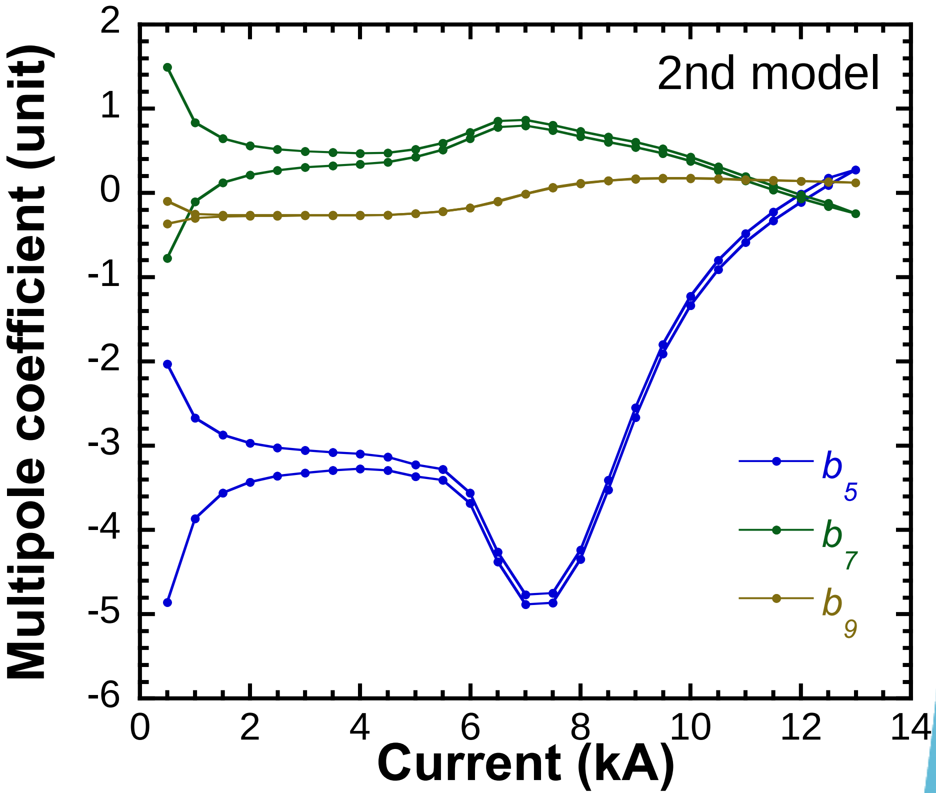
ROXIE coil parameters
after optimization at I_{nom} (deg)

	1st model	2nd model
ϕ1	1.0255	1.1346
ϕ2	27.8582	27.8721
ϕ3	50.3081	50.2969
ϕ4	70.6354	70.6992
α2	26.0000	26.0000
α3	52.3508	52.4212
α4	68.0015	68.0015

Coil block arrangement in the 2nd model is not much different from the 1st model.

Variation of b_n with current

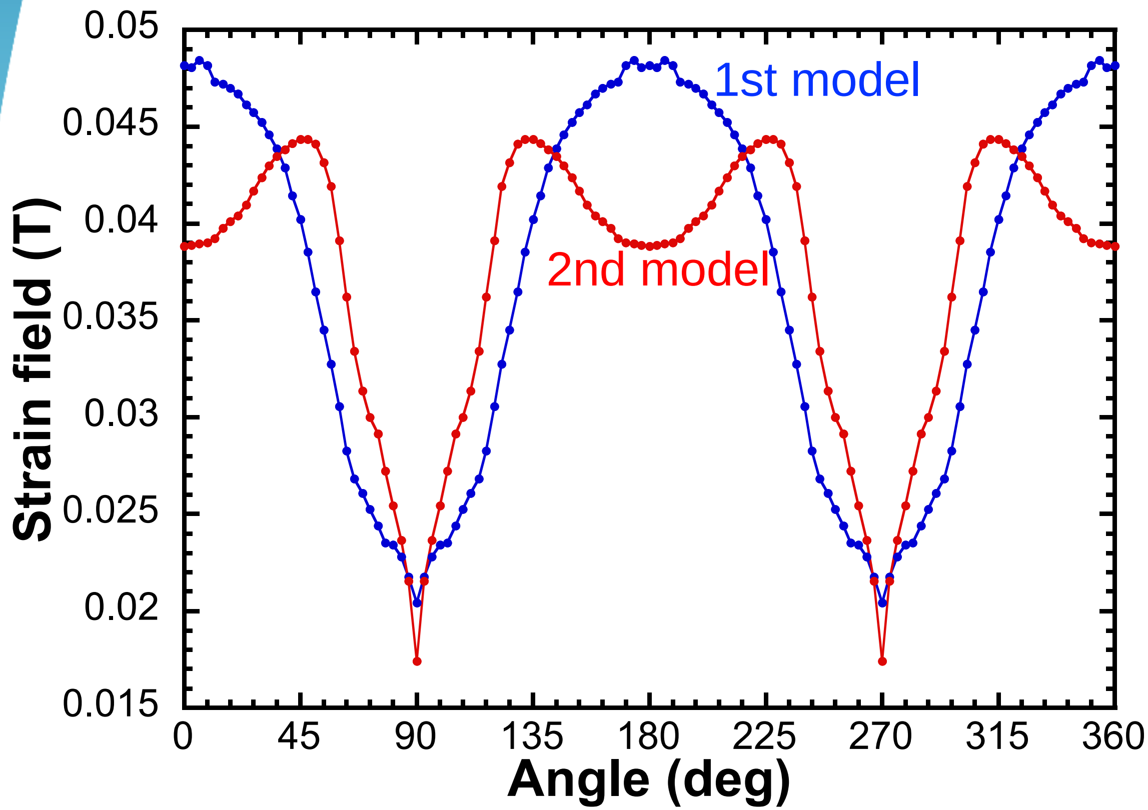


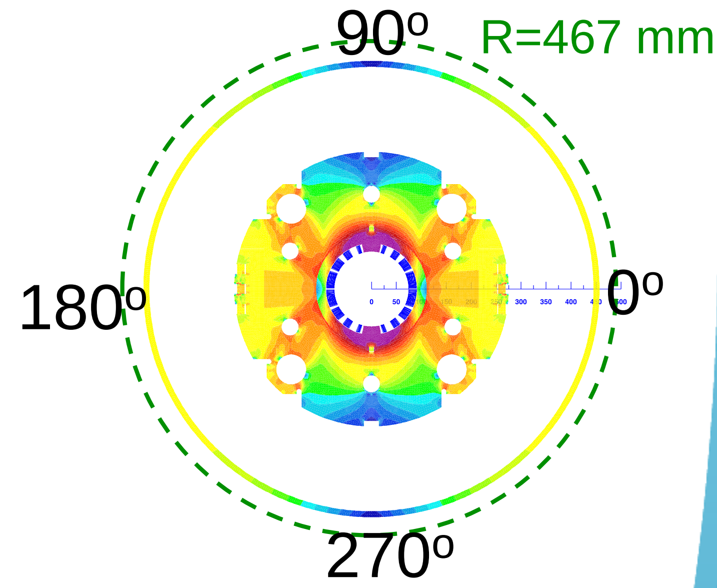


Saturation effect on b_3 is larger in the modified model.
(Maximum b_3 during ramping-up is 8.5 units at 8.5 kA.)

Stray field

Stray field at R=467 mm (10 mm from the outer surface of LHC cryostat)





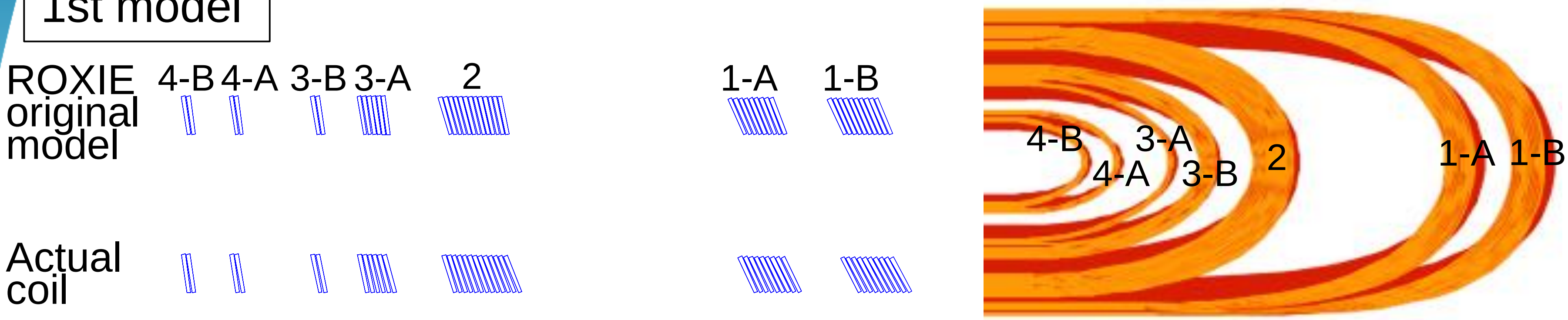
Maximum stray field along R=467 mm

1st model: 48 mT at 90°

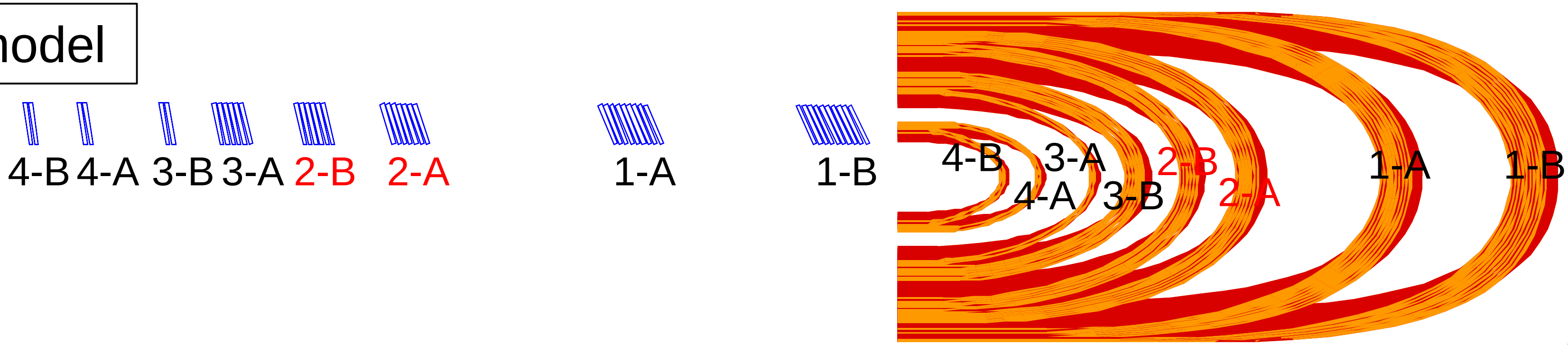
2nd model: 44 mT at 45°

Coil end design

1st model



2nd model

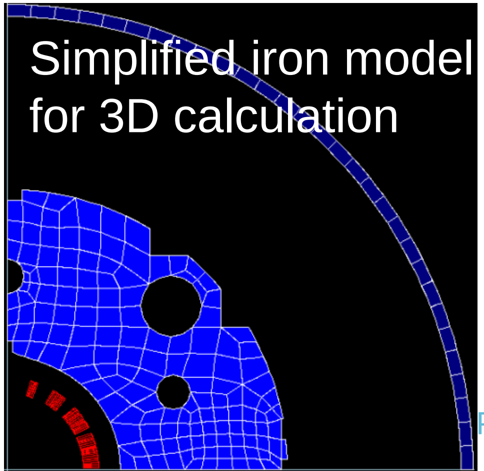


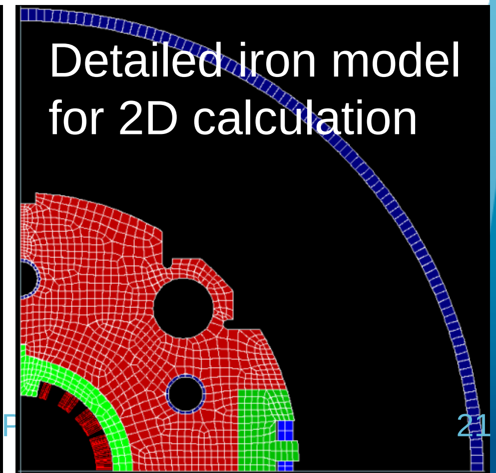
- Coil end shape was re-optimized for the 7 m production magnet and this will be applied to the 2nd model.
- In the 1st model, the cable was inclined more than the original design. In the 2nd model, the measured cable angles were reflected to the design parameters to realize better fit between the cable and the end spacers.
- The second coil block will be also subdivided to make it easier to predict the cable angle and increase the adjustable parameters for minimizing multipoles.

Field integral in 7 m magnet by ROXIE 3D

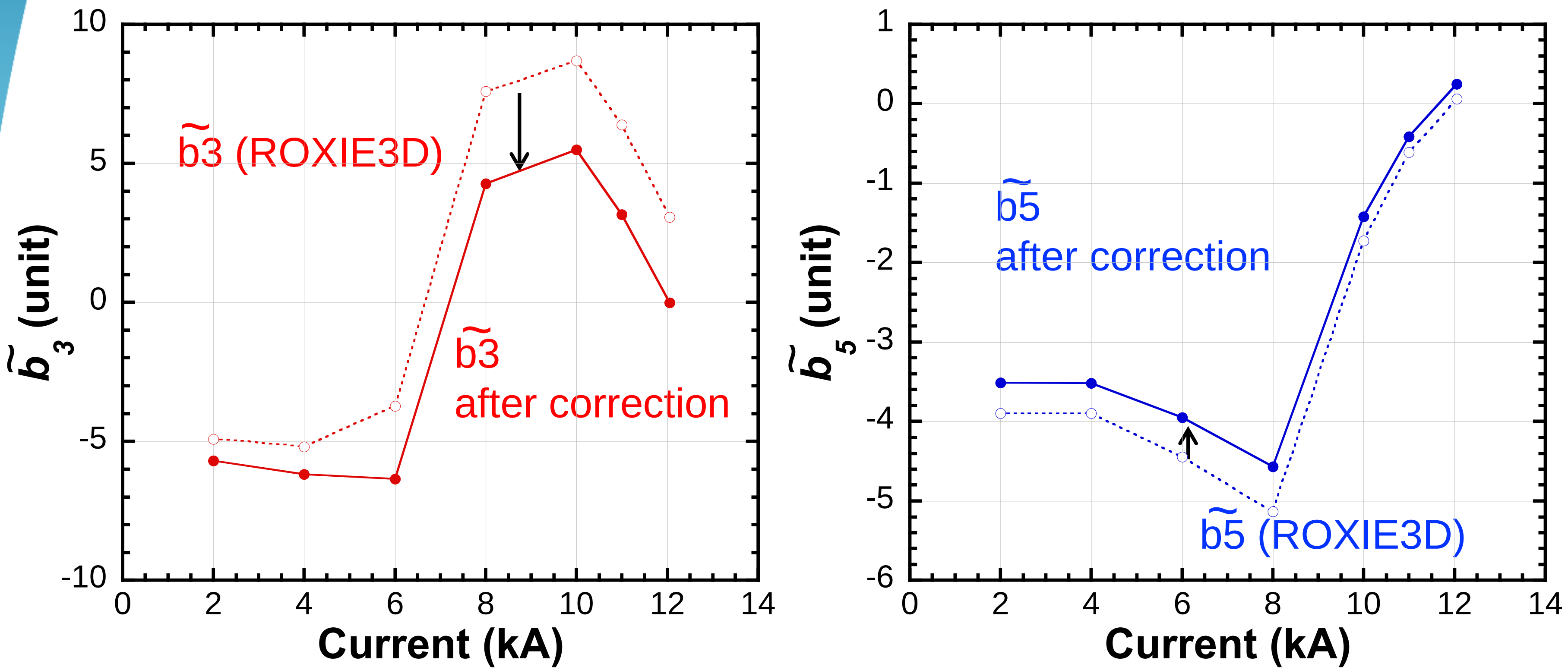
	RE (unit)	SS (unit)	LE (unit)	Total (unit)	Target value (unit)	Difference (unit)
z	-4000~-2870	-2870~2720	2720~4000	-4000~4000		
BL (Tm)	1.422	31.344	2.262	35.027		
b3 (unit)	-3.607	8.805	-2.132	3.066	3.057	0.009
b5 (unit)	-0.281	0.048	0.298	0.065	-0.228	0.292
b7 (unit)	-0.287	0.016	-0.058	-0.330	0.067	-0.397
b9 (unit)	-0.269	0.091	-0.167	-0.345	0.109	-0.454
b11 (unit)	-0.119	0.167	-0.086	-0.038		
b13 (unit)	-0.055	-0.620	-0.054	-0.729		
b15 (unit)	-0.035	-1.030	-0.060	-1.124		
b17 (unit)	-0.011	-0.726	-0.027	-0.765		
b19 (unit)	0.006	0.359	0.015	0.380		
a1 (unit)	0.001	0.148	-5.539	-5.391		
a3 (unit)	0.000	0.039	1.808	1.847		

- The 2D calculation results with the simplified iron model was set as a target.
- b3-b9 can be controlled within 0.5 unit with respect to the target values.





Current dependence of integrated b3 and b5 over 7m magnet calculated by ROXIE 3D



Integrated bn: $$\widetilde{b_n} = \frac{\int_{7m} B_n dz}{\int_{7m} B_1 dz} \times 10^4$$

b̃n after correction =
b̃n (ROXIE3D) – {bn(ROXIE2D, 3D iron) – bn(ROXIE, 2D iron)}

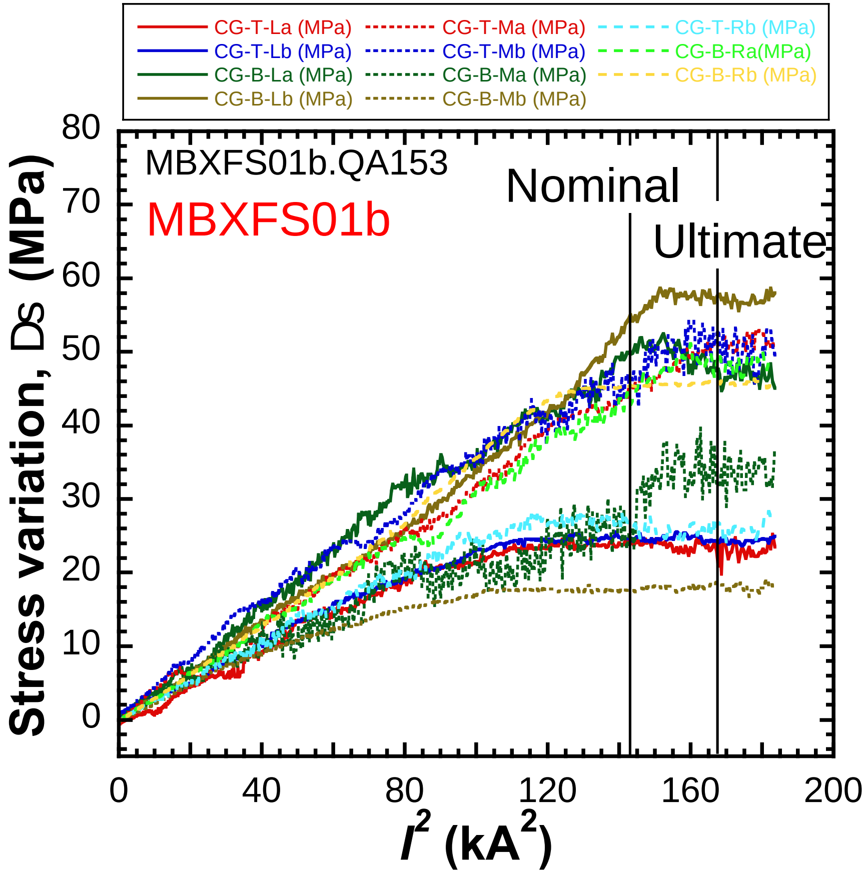
Other parameters

		1st model	2nd model
Nominal current		12.000 kA	12.047 kA
Peak field	SS	6.44 T	6.45 T
	Coil end	6.56 T	6.58 T
Load line ratio	SS	75.4%	75.6%
	Coil end	76.3%	76.7%
Coil mechanical length (7 m model, at warm)		6518 mm	6580 mm

- Peak field and load line ratio are almost the same.
- Coil mechanical length is 62 mm longer than the previous design. (Still feasible for the test in the KEK vertical cryostat)

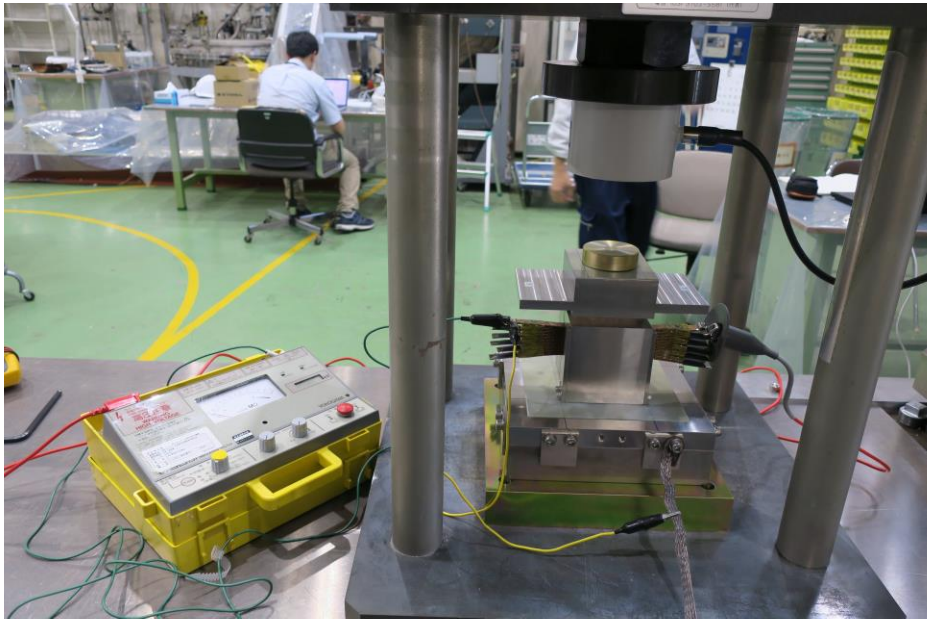
Enhancing mechanical support of a coil

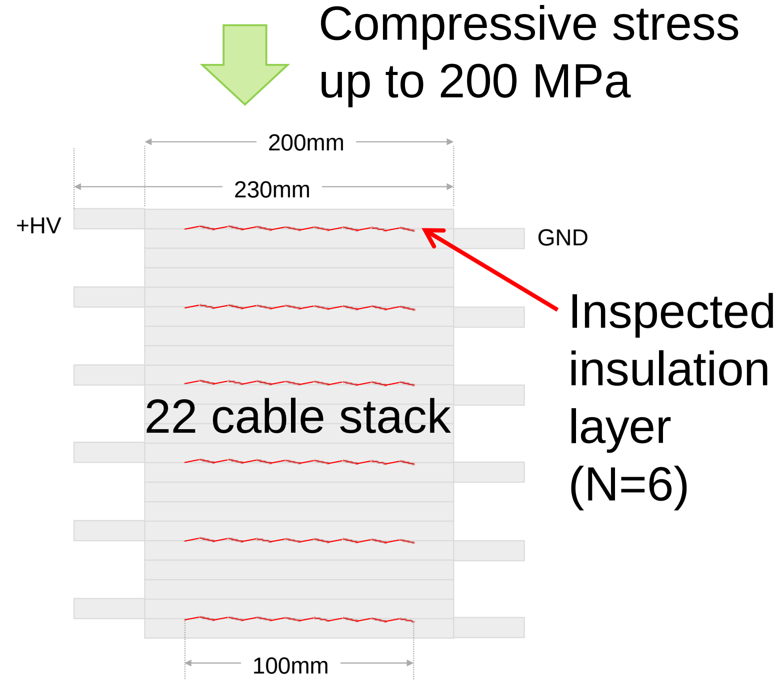
Azimuthal coil pre-stress in SS



- Coil pre-stress at pole after yoking in 01b: 100 MPa
- Target in the 2nd model: 115 MPa (at pole)
  - Insulation endurance → Hi-pot test under compression
  - Change of cable size → 10 stack measurement
  - Oversizing of wedges

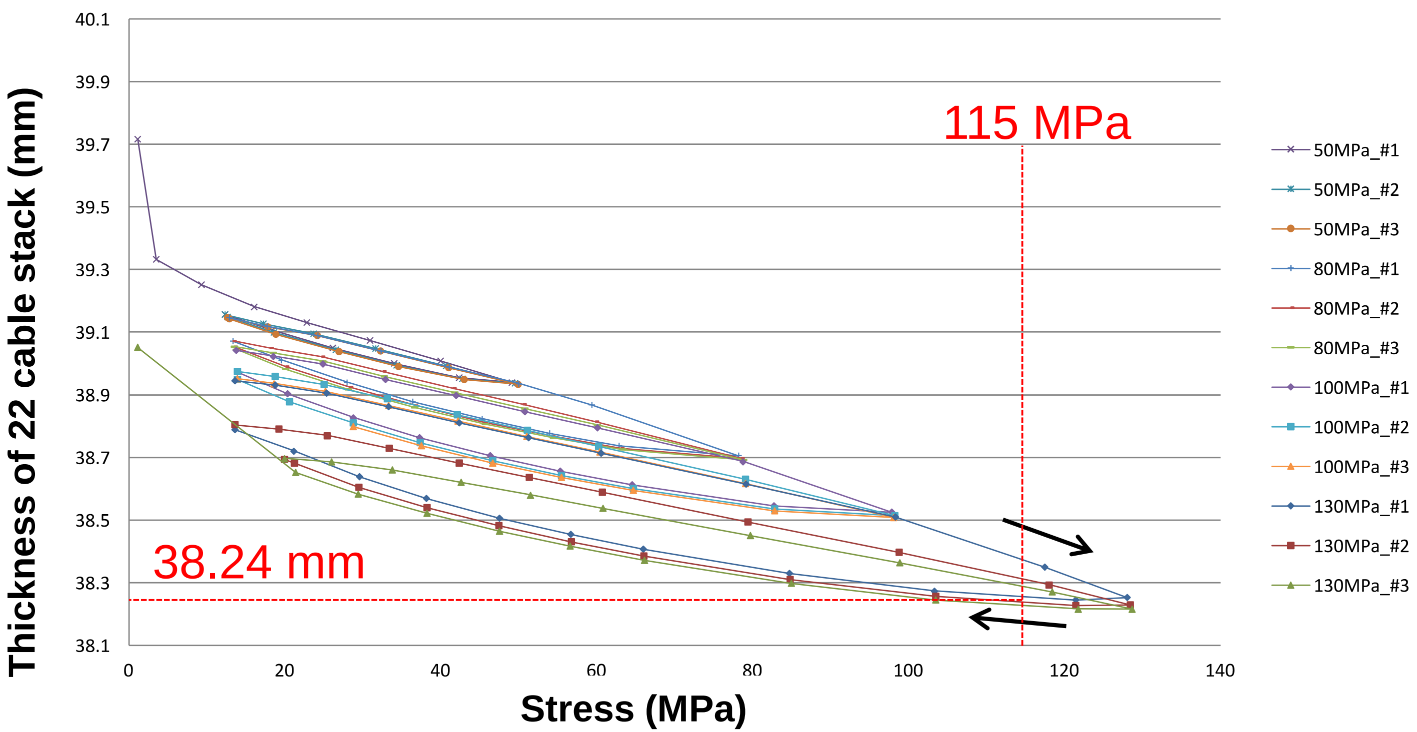
Increase of azimuthal coil pre-stress in SS (Cable 10 Stack: Insulation Endurance)





- Hi-pot test under compressive stress for a 22 cable
- No degradation of insulation resistance up to 200 MPa at 3 kV for 1 min
- Degradation of electrical insulation due to creep deformation should be also checked.

Increase of azimuthal coil pre-stress in SS (Cable 10 stack measurement)

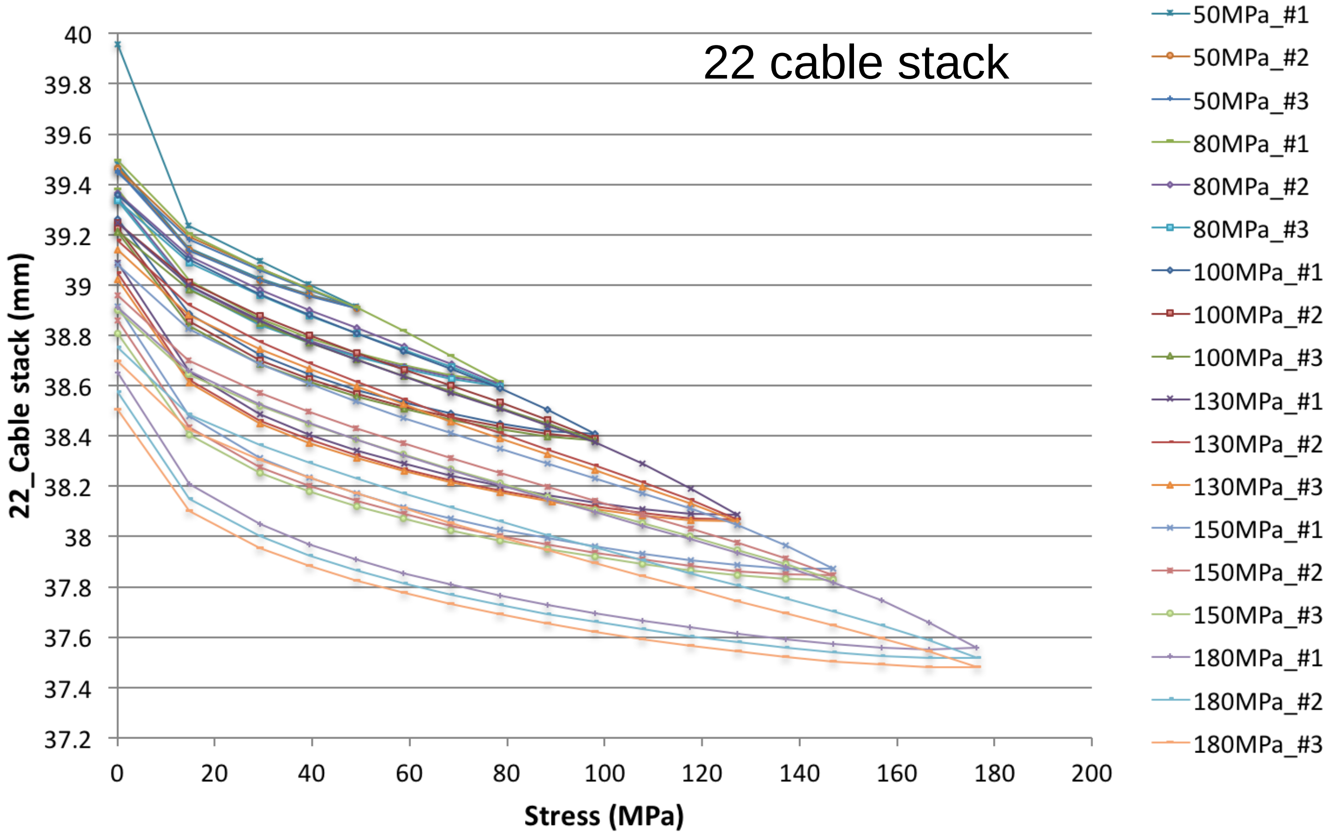


- Thickness of 22 cable stack at 115 MPa (target pre-stress) =38.24 mm
- Azimuthal thickness of cable insulation = 0.130 mm

  → Input for ROXIE calculation

HiLumi HL-LHC PROJECT

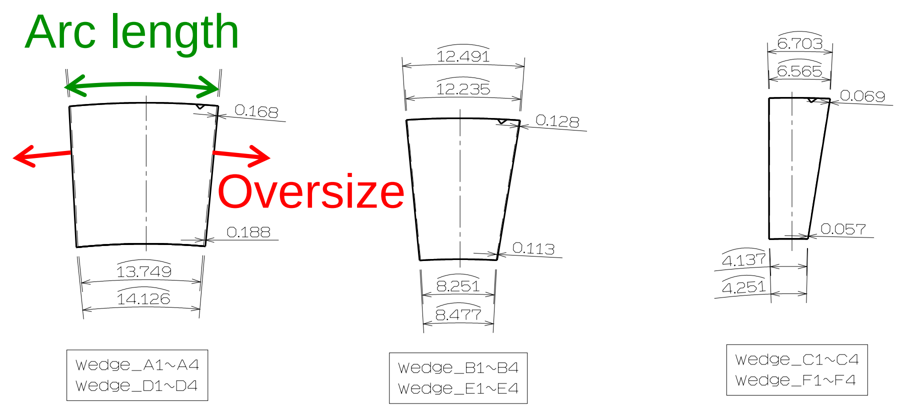
Increase of azimuthal coil pre-stress in SS (Cable 10 stack: Size Meas. up to 180 MPa)

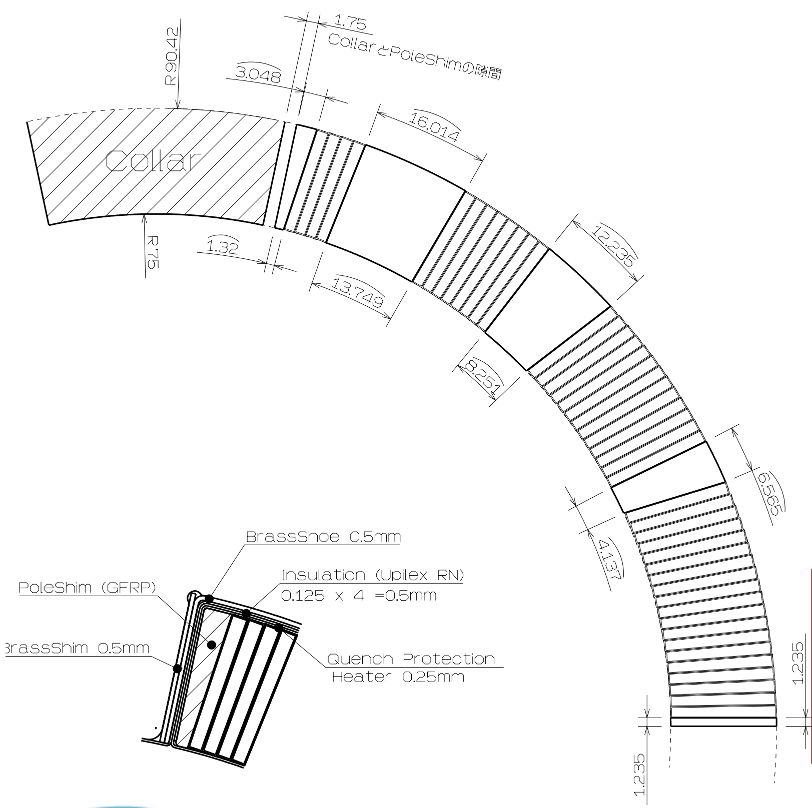


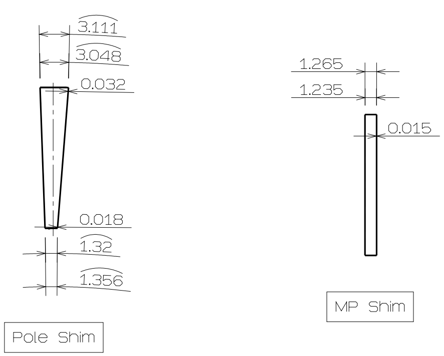
- Creep deformation becomes more remarkable above 130 MPa.

Increase of azimuthal coil pre-stress in SS (Oversize of wedges)

Type		ΔL	ΔL/2
A(orD)	16.014	0.33627	0.16813
	13.749	0.37712	0.18856
B(orE)	12.235	0.25692	0.12846
	8.251	0.22631	0.11315
C(orF)	6.565	0.13785	0.06892
	4.137	0.11347	0.05673
PoleShim	3.048	0.06400	0.03200
	1.32	0.03620	0.01810
MPShim	1.235	0.02990	0.01495
	1.235	0.02990	0.01495

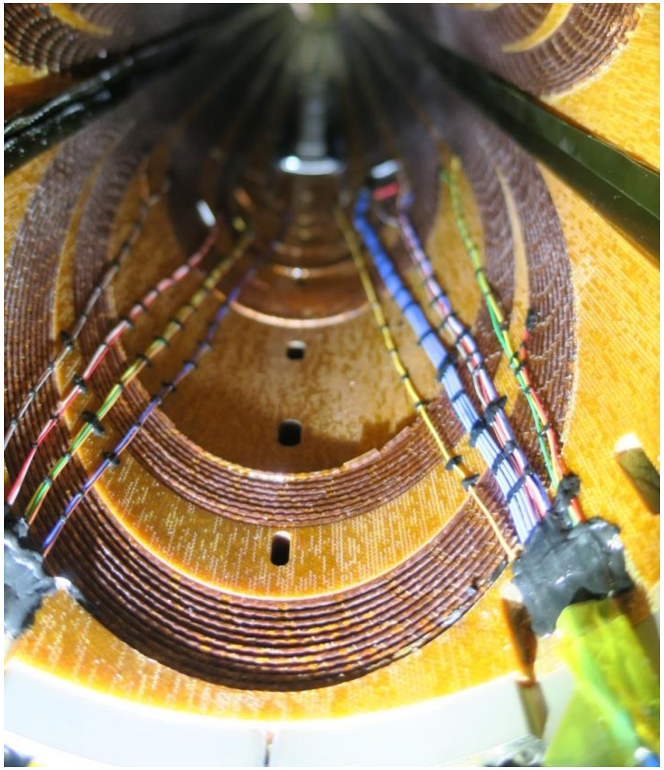






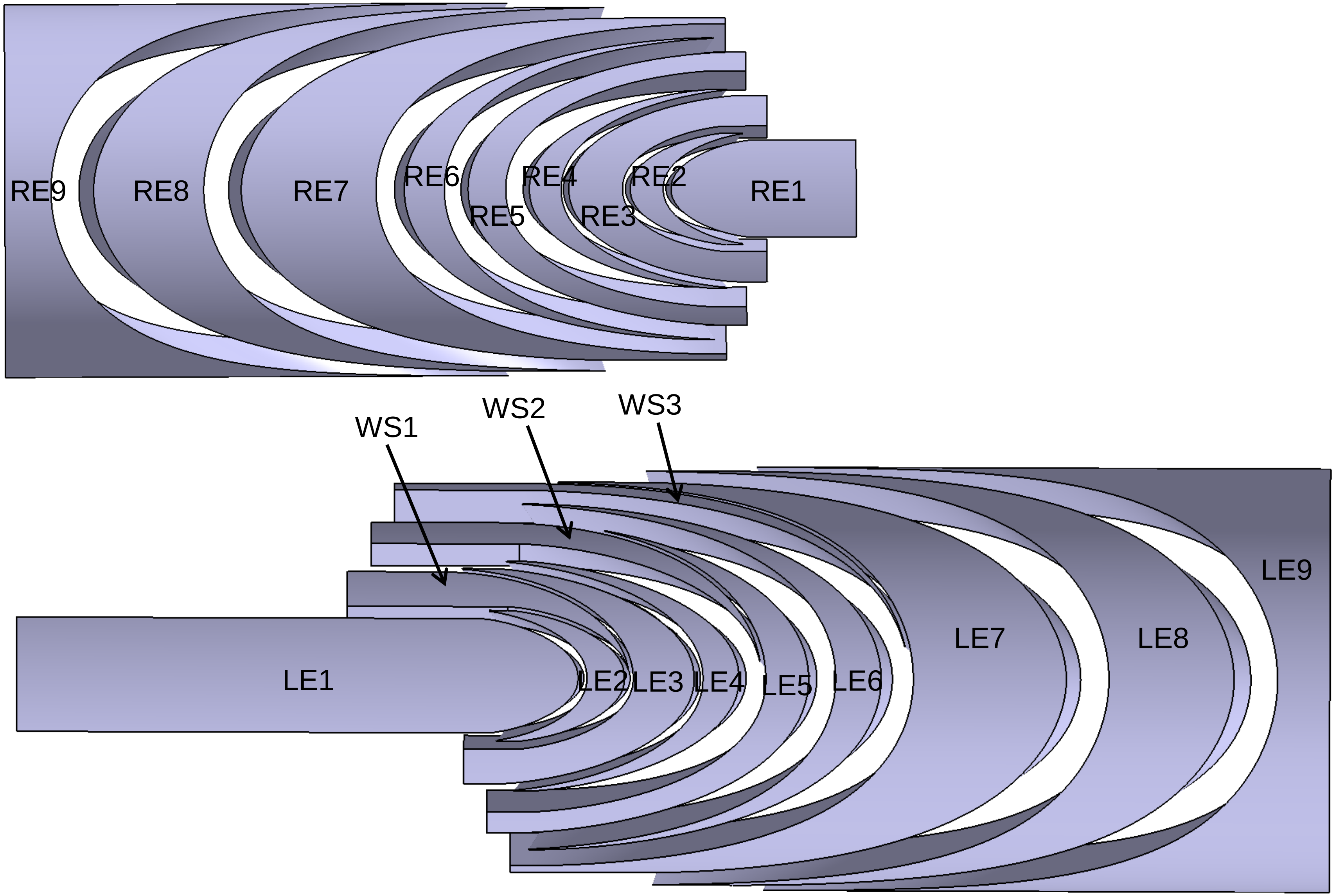
Total arc length of wedges per quadrant is enlarged by 1.14 mm wrt that of model-01 to reach the target pre-stress of 115 MPa at pole.

Countermeasures against coil deformation

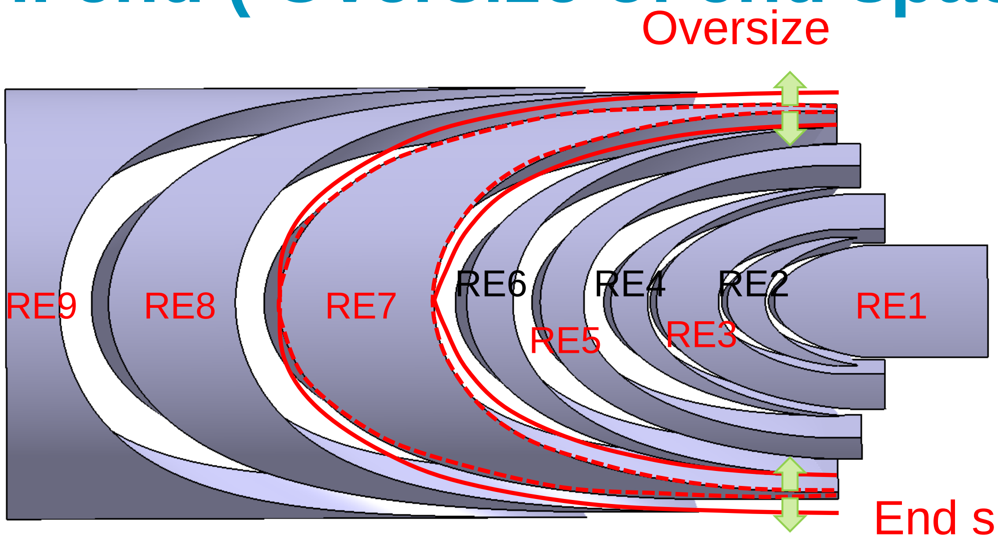


- Improvement of fitting between cable and end spacers
  → Measured cable angles in 01 were reflected to coil end design.
- Increase of azimuthal coil pre-stress at coil end
- Increase of axial pre-load
- Impregnation of coil end

Countermeasures against coil deformation at coil end (Catia model of end spacers)



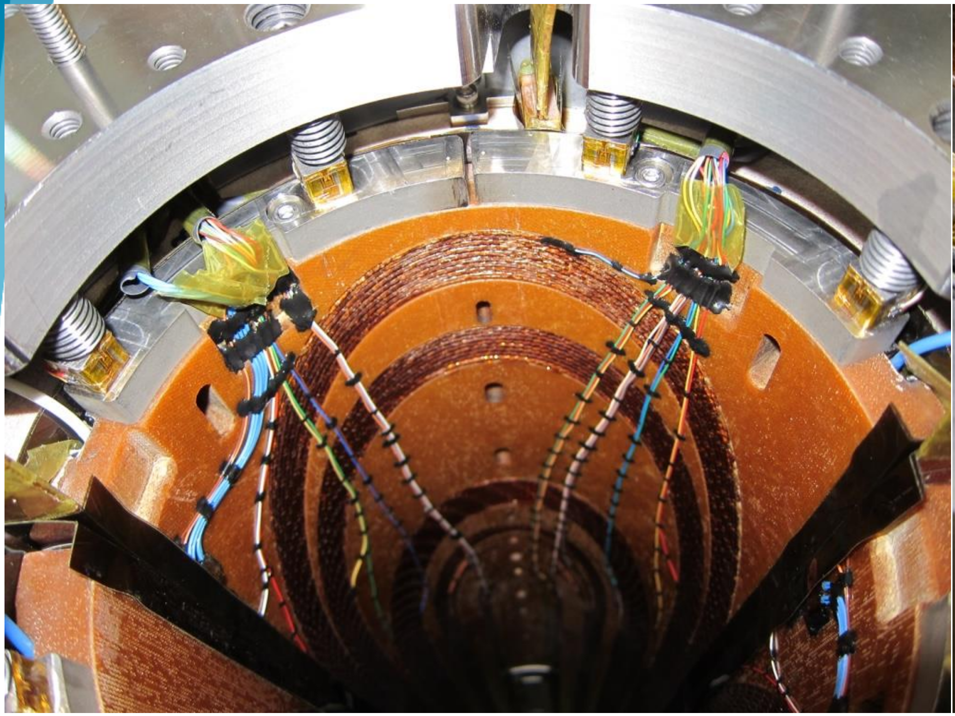
Countermeasures against coil deformation at coil end (Oversize of end spacers)

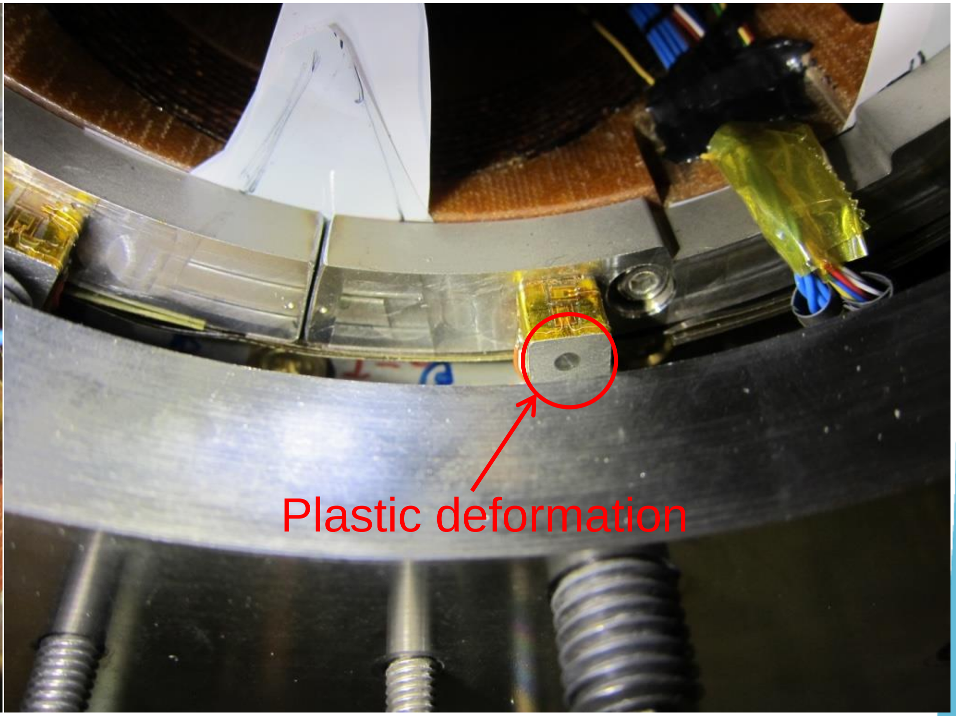


End spacer shown in red will be oversized.

- In the1st model, end spacers were not oversized except for the end saddles.
- In the 2nd model, part of end spacers will be oversized in the similar way to wedges.
  - Total oversize at each z position is controlled to be the same as that of wedges.
  - At the end of end saddles, oversize is set to be 0.6 mm so that pre-stress of full GFRP part is 115 MPa.
- Strain gauges will be implemented on the end spacers to monitor coil pre-stress at coil end.

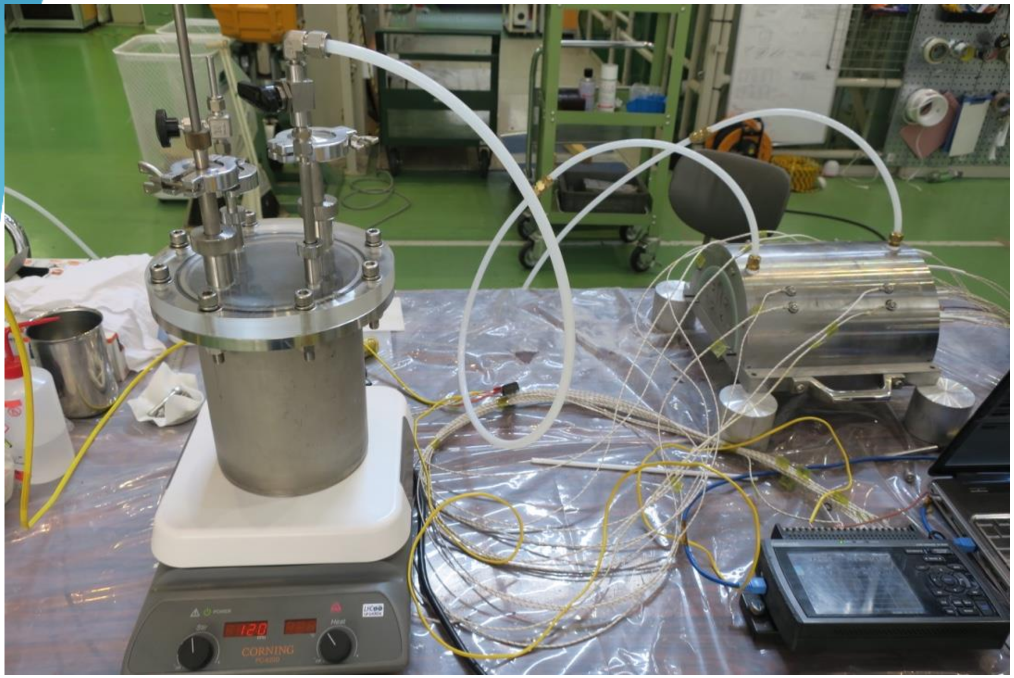
Countermeasures against coil deformation at coil end (Increase of axial pre-load)



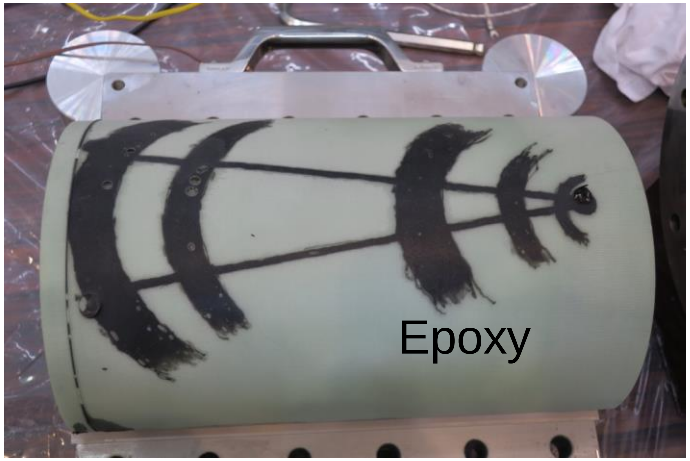


- In the 1st model, axial pre-load was determined empirically.
- Pre-load will be increased to help mechanical support of a cable.
  (Target value has not been decided.)
- The blocks which are pushed by the bullets were plastically deformed in 01b. Material should be changed from SUS304L.

Countermeasures against coil deformation at coil end (Coil end impregnation)



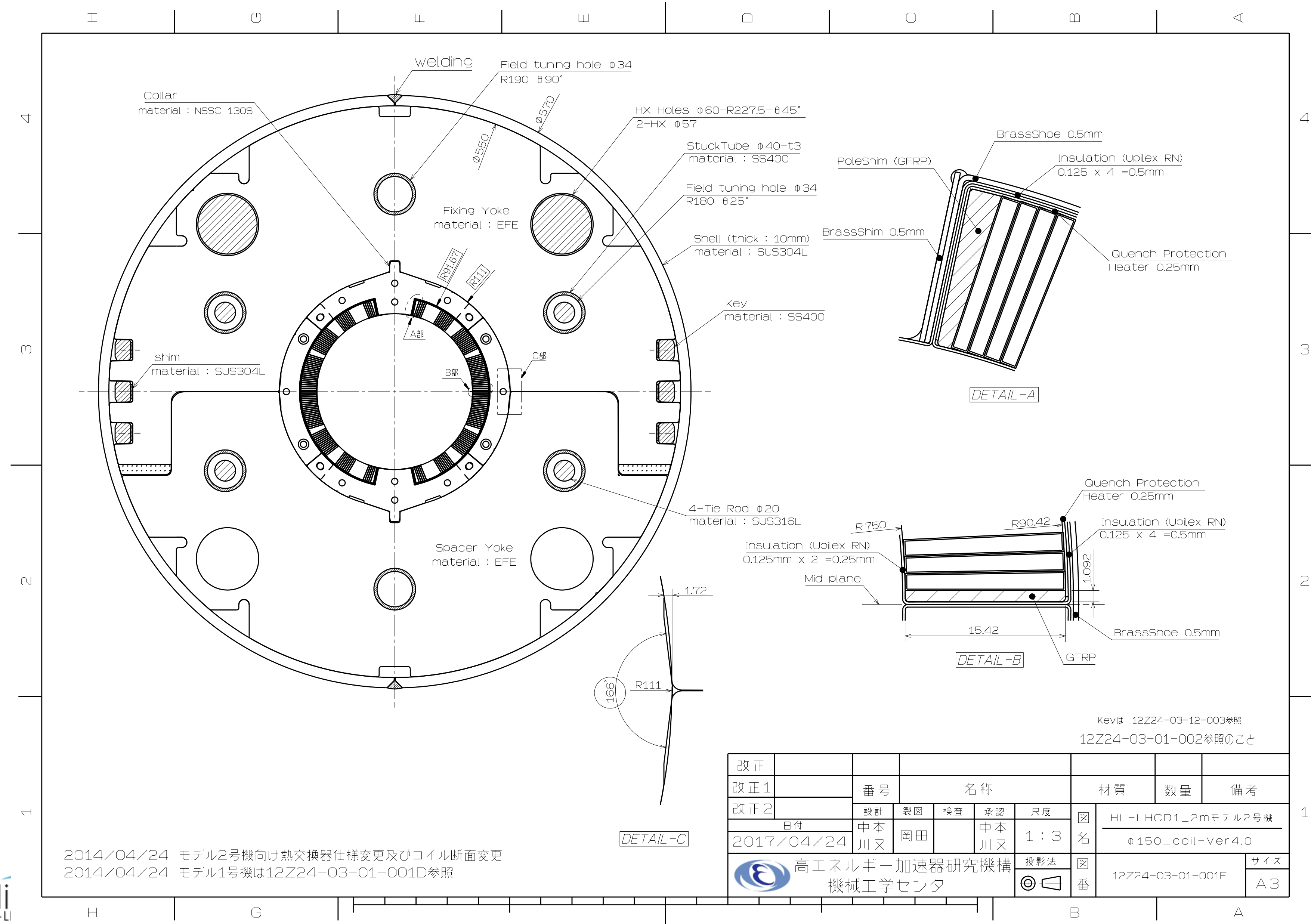
Tests with G10 dummy coil



- The aims of impregnation at coil end
  - Filling space between cable and end spacer for better transmitting pre-stress
  - Reinforcing inter-turn bonding to behave a coil block as one body
- Low radiation heat at impregnated part thanks to beam screen
  → Not compromise cooling
- New epoxy-blended CE provided from ARISAWA are under testing.

Other items

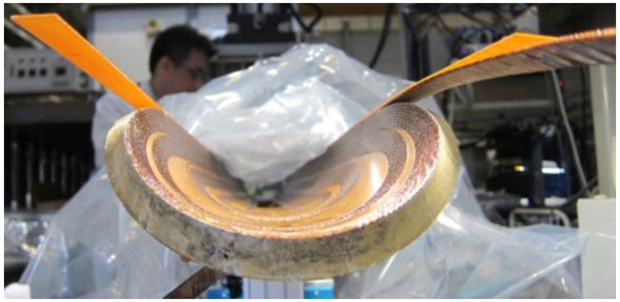
Iron yoke

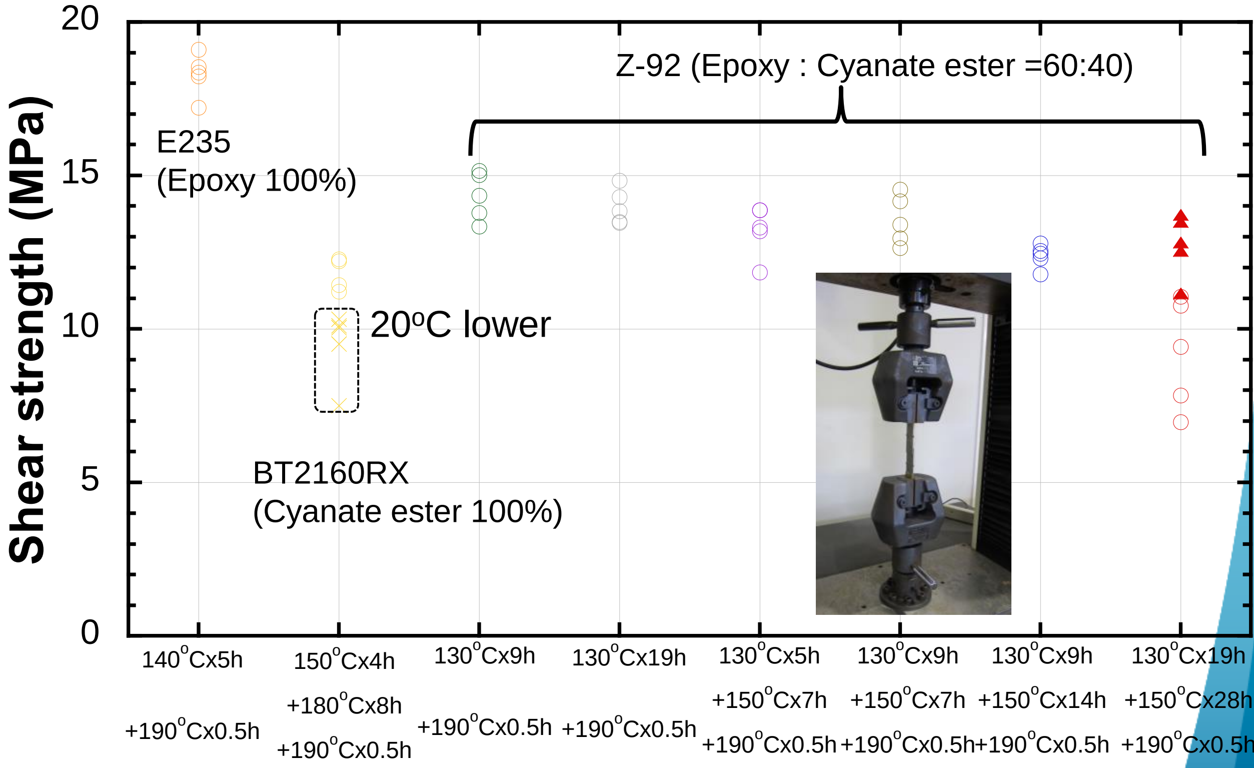


welding
Field tuning hole φ34
R190 θ90°
Collar
material : NSSC 130S
HX Holes φ60-R227.5-θ45°
2-HX φ57
StuckTube φ40-t3
material : SS400
Field tuning hole φ34
R180 θ25°
Fixing Yoke
material : EFE
Shell (thick : 10mm)
material : SUS304L
Key
material : SS400
shim
material : SUS304L
4-Tie Rod φ20
material : SUS316L
Spacer Yoke
material : EFE
PoleShim (GFRP)
BrassShoe 0.5mm
Insulation (Upilex RN)
0.125 x 4 =0.5mm
BrassShim 0.5mm
Quench Protection
Heater 0.25mm
DETAIL-A
R750
R90.42
Insulation (Upilex RN)
0.125mm x 2 =0.25mm
Mid plane
15.42
1.092
BrassShoe 0.5mm
GFRP
DETAIL-B
1.72
R111
166°
DETAIL-C
Keyは 12Z24-03-12-003参照
12Z24-03-01-002参照のこと
2014/04/24 モデル2号機向け熱交換器仕様変更及びコイル断面変更
2014/04/24 モデル1号機は12Z24-03-01-001D参照
改正
改正1
改正2
日付
2017/04/24
番号
名称
材質
数量
備考
設計
製図
検査
承認
尺度
中本 川又
岡田
中本 川又
1 : 3
図名
HL-LHCD1_2mモデル2号機
φ150_coil-Ver4.0
高エネルギー加速器研究機構
機械工学センター
投影法
図番
12Z24-03-01-001F
サイズ
A3

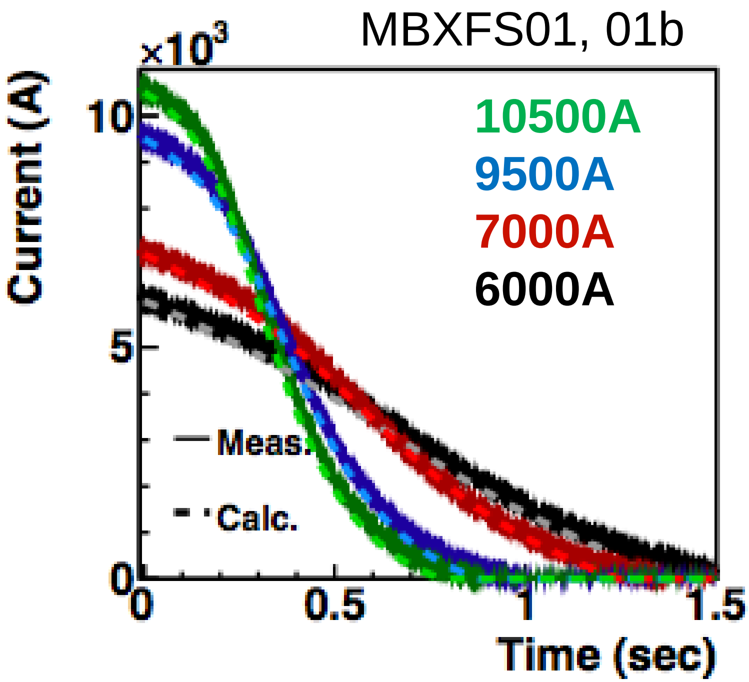
Study of resin – Z-92

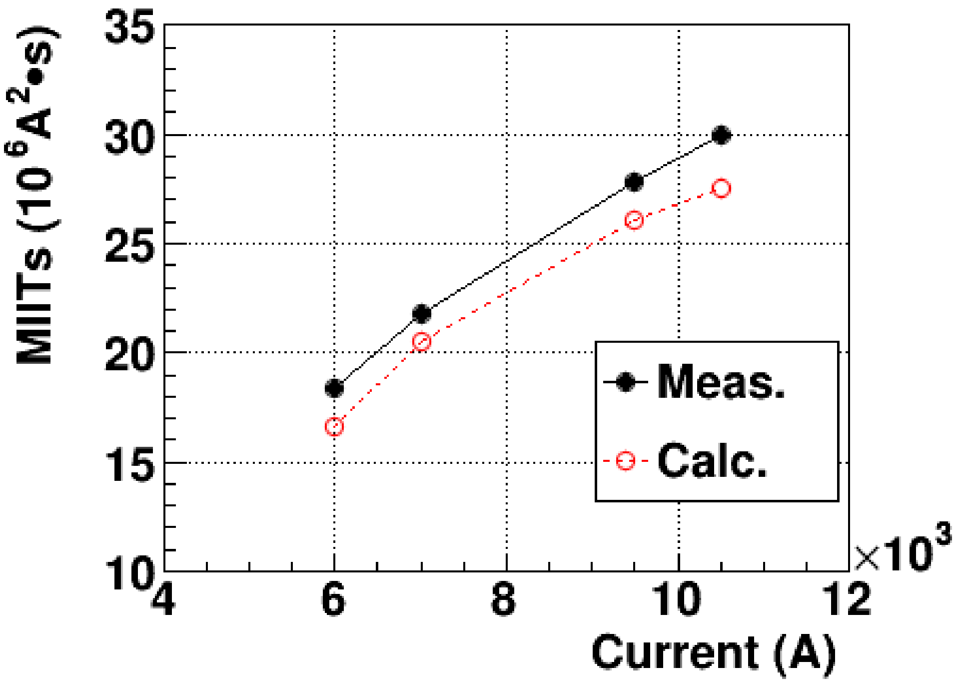
- To avoid detachment of end saddles occurred in the 1st model, epoxy-blended cyanate ester will be used as adhesive between GFRP parts and cables instead of 100% cyanate ester.
- Z-92 proven in ITER TF coils
- Recommended curing cycle for Z-92 : 130ºCx19h +150ºCx28h
- Study for preferable curing conditions (shorter time and lower temp.)
  - Shear test





Quench simulation

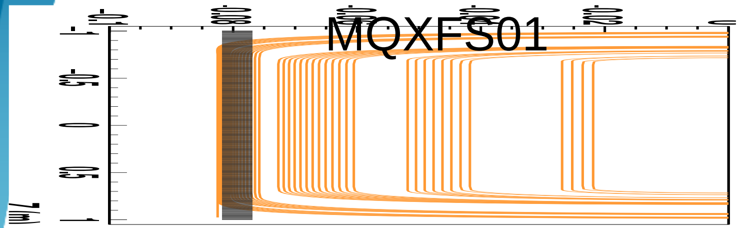


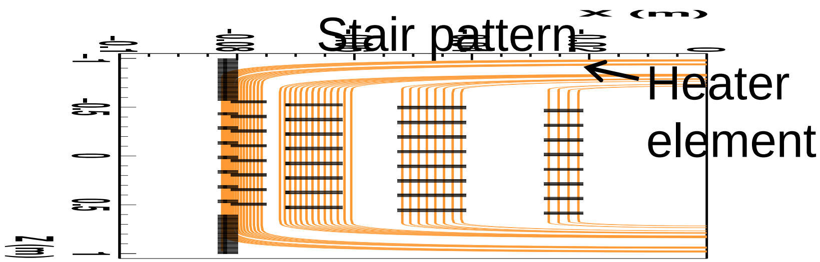


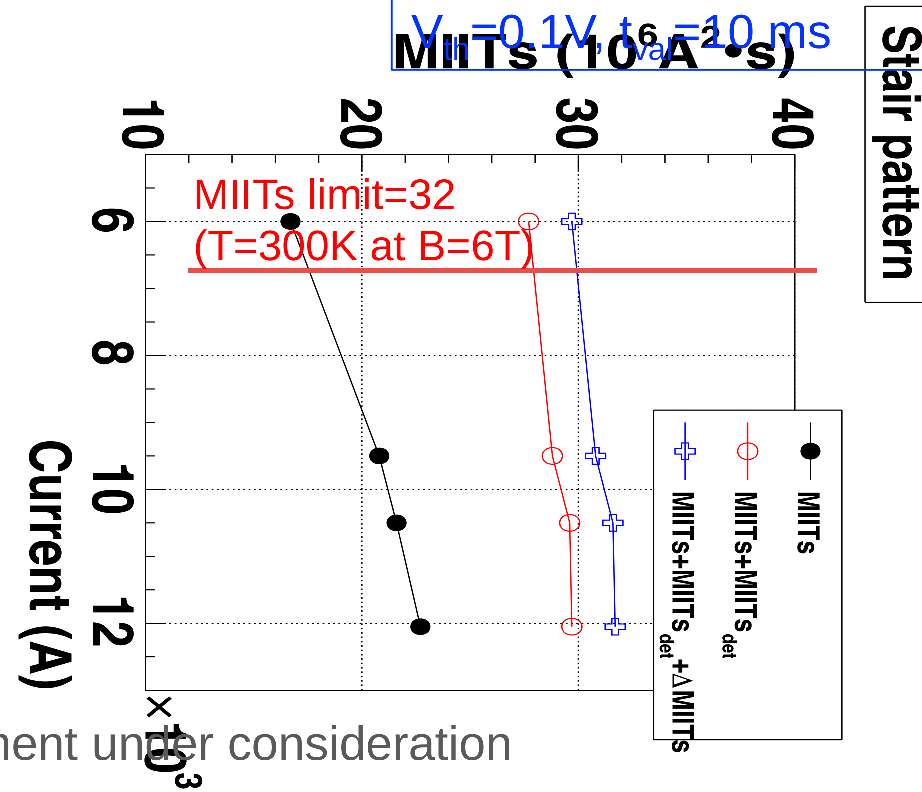
- Original simulation code based on finite difference method
- Good agreement between measured and calculated current dump
- Right: Calculated MIITs is, however, lower than the measured one (**ΔMIITs~2**)
  - This is possibly because the delay time is not reproduced well in our simulation

Design of QPH (ongoing)

Quench detection conditions:
V_{th}=0.1V, t_{val}=10 ms





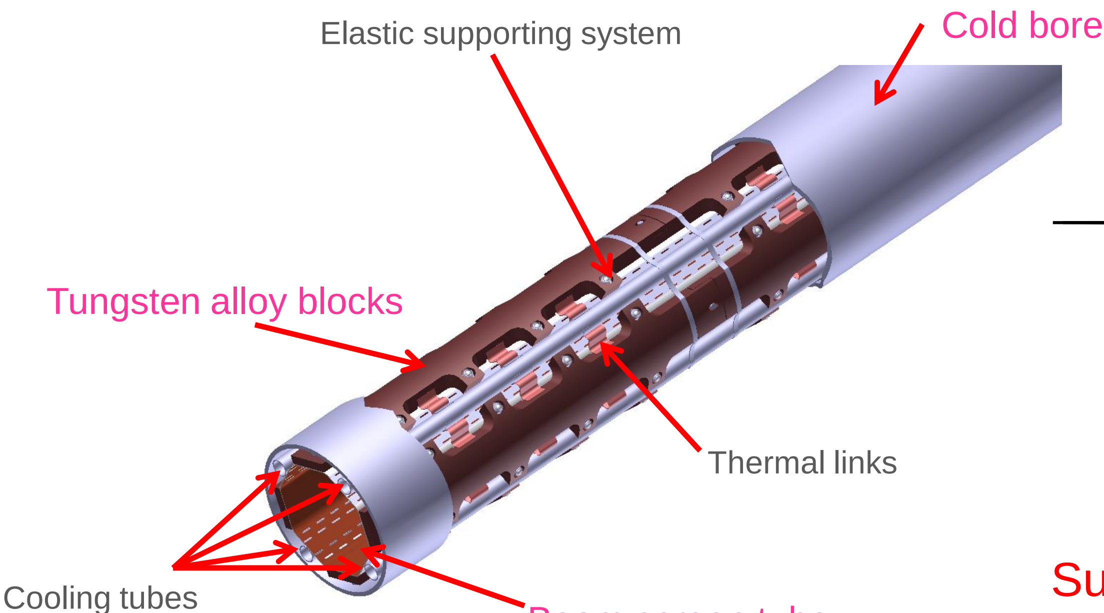


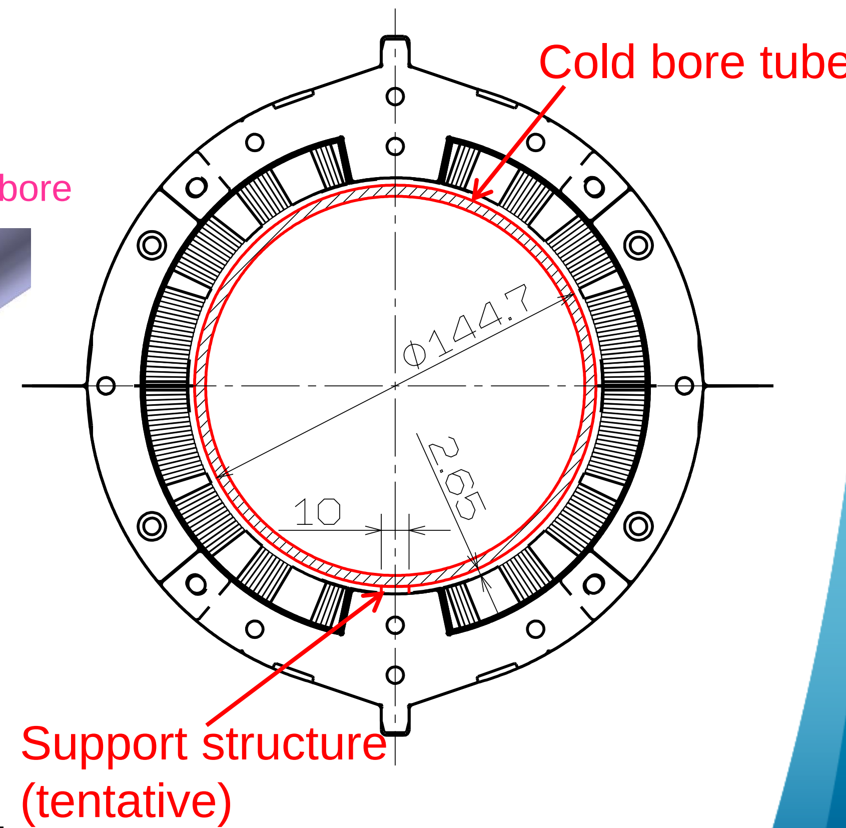
- Various patterns of heater element under consideration
- ‘Stair’ pattern covers almost all turns.
- Confirm all the computed MIITs in stair pattern are below 32 even considering the detection time (MIITs$_{det}$) and uncertainty in the simulation (ΔMIITs=2)
- As soon as QPH design is fixed, we will order the QPHs for the 2nd model to both CERN and ARISAWA (a Japanese company).

Cold tube support

- Plan: cold test of the 2nd model at CERN in 2018
- Behavior of the insulated cold tube with the tungsten shield during the quench will be studied. (C. Garion)
- New mechanical feature to support the cold tube in horizontal position
- A gap between the cold tube and the inner coil surface: ~1.5 mm

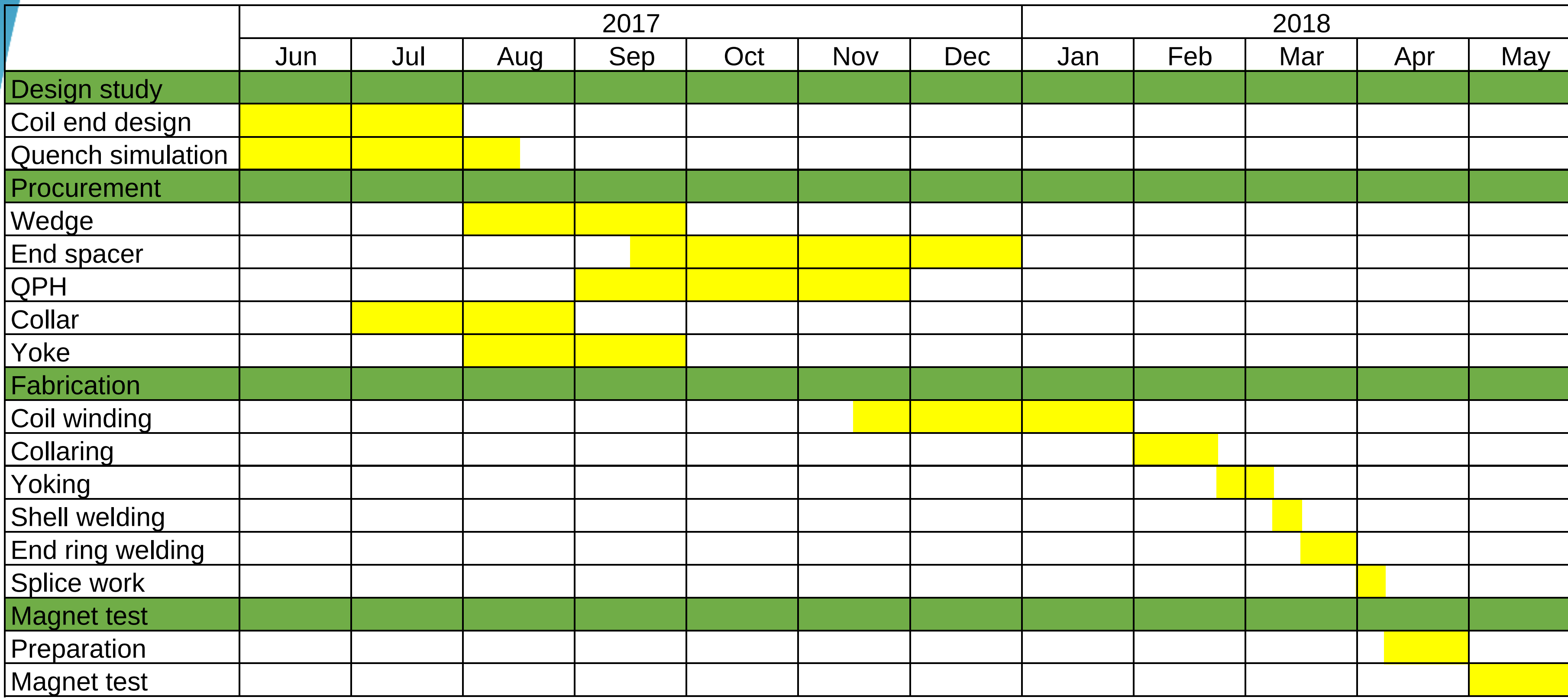
Beam screen for Q1-Q3





C. Garion, HL-LHC Collaboration meeting 2017

Schedule



- Four coils will be wound.
  (one test coil + two coils for magnet assembly + one spare)
- Fabrication of end spacers will limit the schedule.

Summary

- Design updates for the 2nd model are almost fixed.
- Magnetic design update with new iron yoke cross-section was completed.
- Azimuthal coil pre-stress in straight section will be increased by 15 MPa than that of 01b.
- To prevent cable deformation at coil end, oversizing end spacers, increase of axial pre-load and impregnation at coil end will be applied.
- Quench simulation to design QPH is ongoing.
- Coil winding will start in November, 2017 and fabrication of the 2nd model will be finished in April, 2018.

Azimuthal coil pre-stress in 01 and 01b

	Target (at pole)	Analytical calculation	Coil size meas. (at MP)	Strain gauge after yoking (at pole)
01	80	54	92	65
01b	110	93	137	100
Diff.	30	45	45	35