High Luminosity LHC

D1 Development Status

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KEK

4th Joint HiLumi LHC-LARP Annual Meeting
17-21 November 2014, KEK

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Participants & Supports

KEK
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Q. Xu (left March 2014), N. Higashi, N. Okada, R. Okada,
Y. Ikemoto, M. Iio, T. Ogitsu, K. Sasaki, N. Kimura, M. Yoshida,
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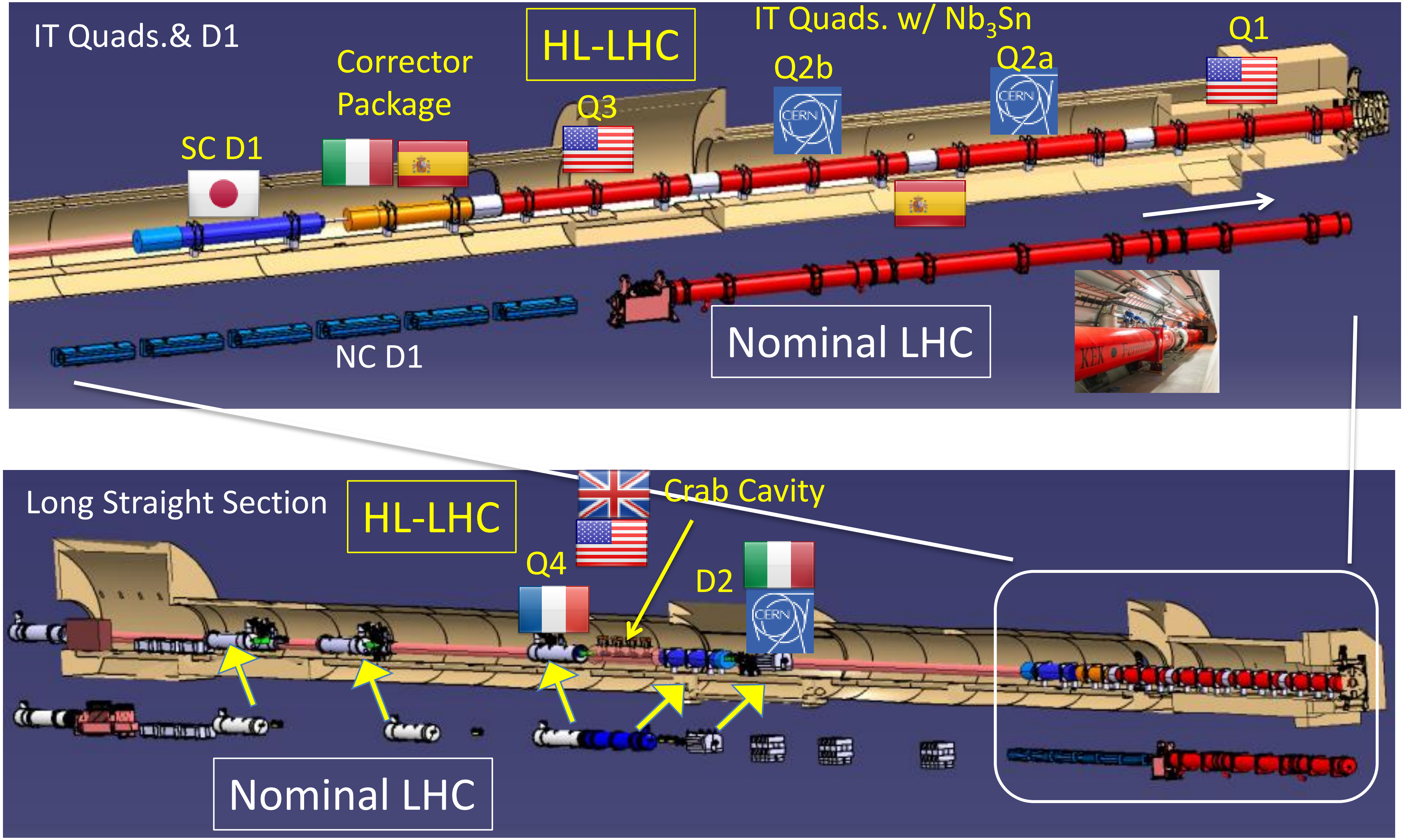
CERN
E. Todesco, A. Musso, G. Kirby, F. Savary, A. Ballarino,
P. Fessia.

Layout of IR Magnets



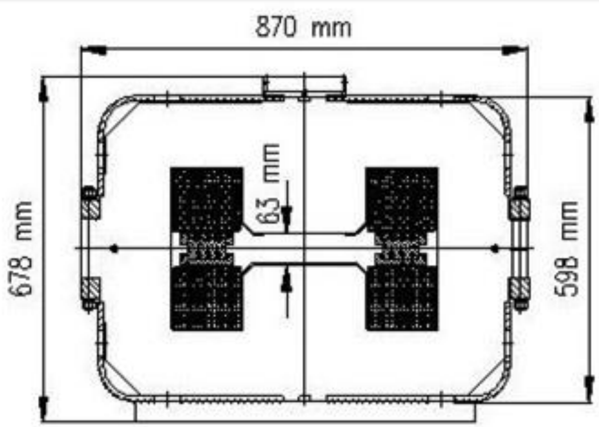
Aperture increase in IT Quads:70mm→150mm ➡Large bore also for the new D1

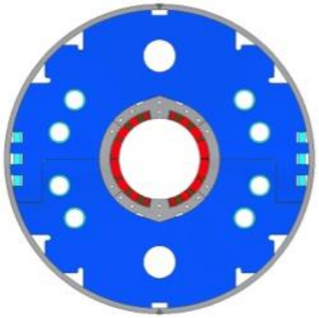
Replacement of current NC D1 by SC D1: Shortening magnet length by 15m

➡ Making room for new crab cavities

NC vs SC

Beam separation dipole, D1		
	LHC	HL-LHC
Aperture	52mm gap	150mm
Nominal Field (Peak Field)	1.4 T	5.6 T (6.5 T)
Magnetic Length	3.4 m x 6 ~21m	6.27 m
Stored Energy	0.014 MJ/m	0.34 MJ/m

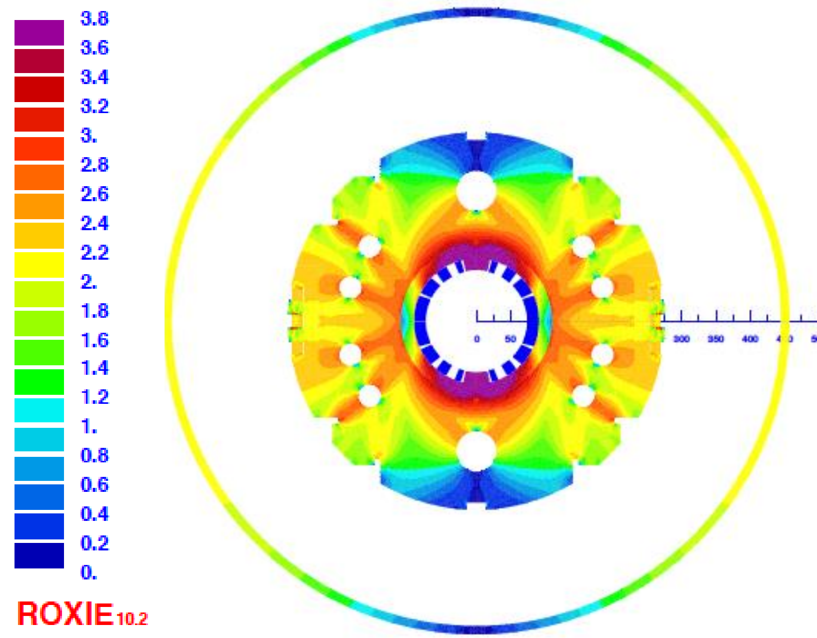


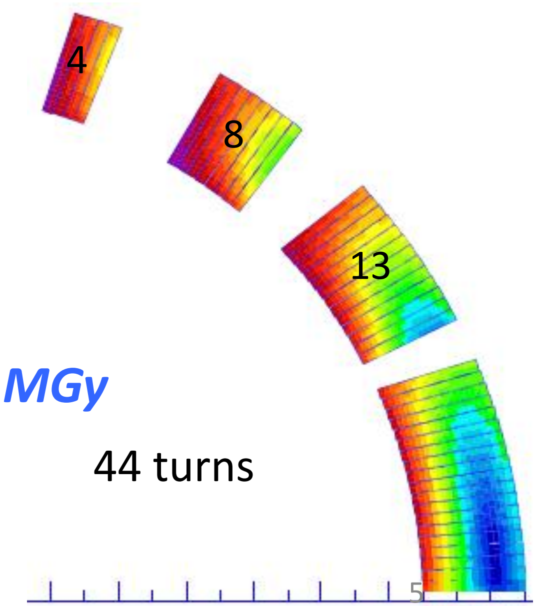


Latest Design Parameters of D1

- *Coil ID:* ***150 mm***
- *Integrated field:* ***35 T m*** *(26 Tm at present LHC)*
  - *5.59 T at 12 kA.* L_{coil}*=6.3 m*
- T_{op}*:* *1.9 K by HeII cooling*
- *Op. point (2D coil):* ***75 %***
- *Coil layout:* *1 layer of 15.1 mm cable*
  - *Better cooling. Saving space for iron yoke.*
- *Conductor:* ***Nb-Ti LHC MB outer cable***
- *Structure:* *Collared yoke structure by keying*
  - *RHIC dipole, LHC MQXA, J-PARC SCFM*
  - *Enhancing iron material for stray field issue*
- *Field quality:* $< 10^{-4}$ *at* R_{ref} *= 50 mm*
- *Cold mass OD:* *550 +10 x 2 = 570 mm*
- *Cryostat OD:* *914 mm, same as MB cryostat*
- *Radiation, energy deposition:*

135 W in total, 2 mW/cm³ at local peak, Radiation dose >25 MGy





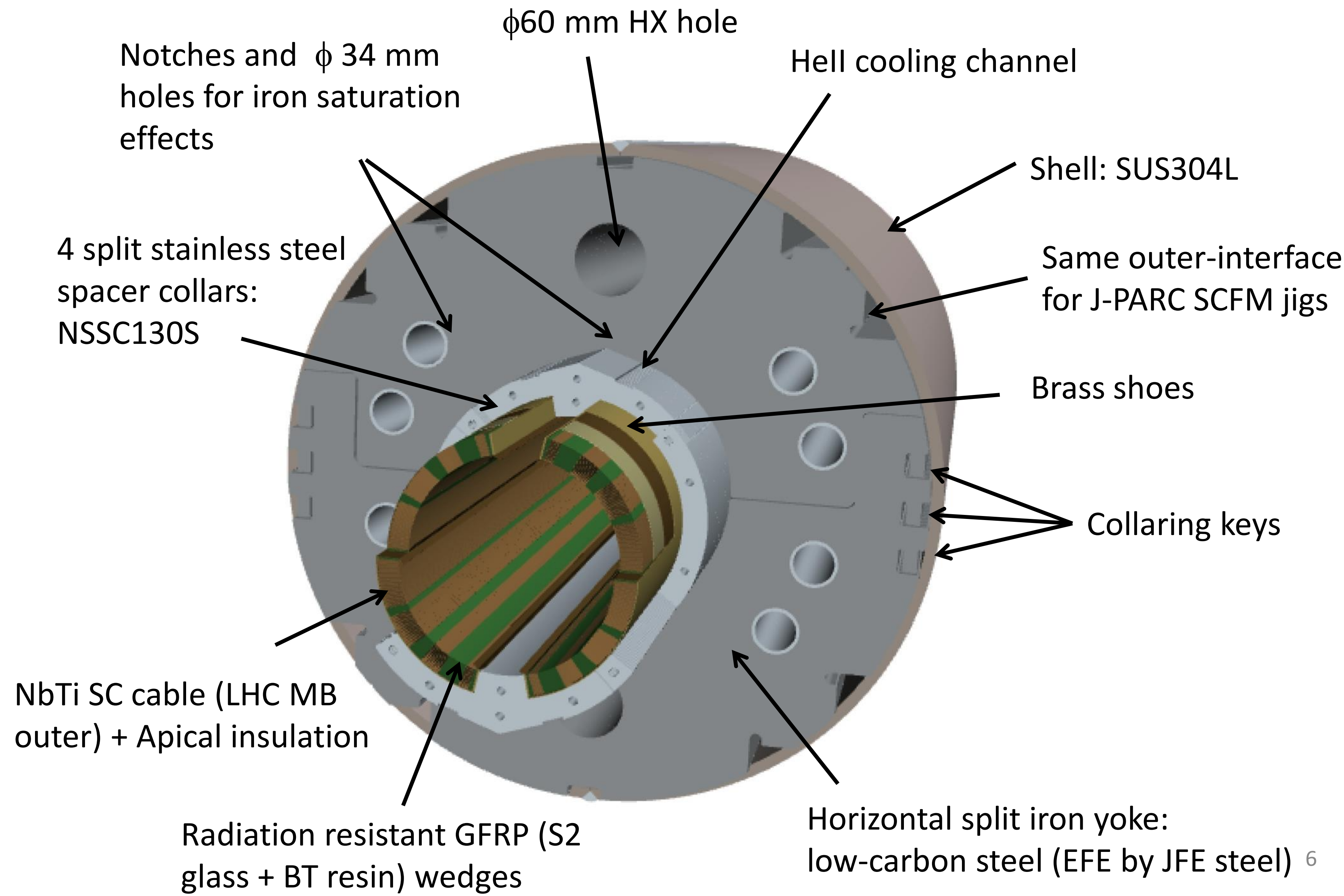
◆**Stress management**

◆**High saturation, stray field, flux return cryostat**

◆**Radiation resistance, cooling capability**

2m-long Model Magnet - Overview

Single-layer coil, 4-split spacer collars, collared yoke by keying



Deliverables

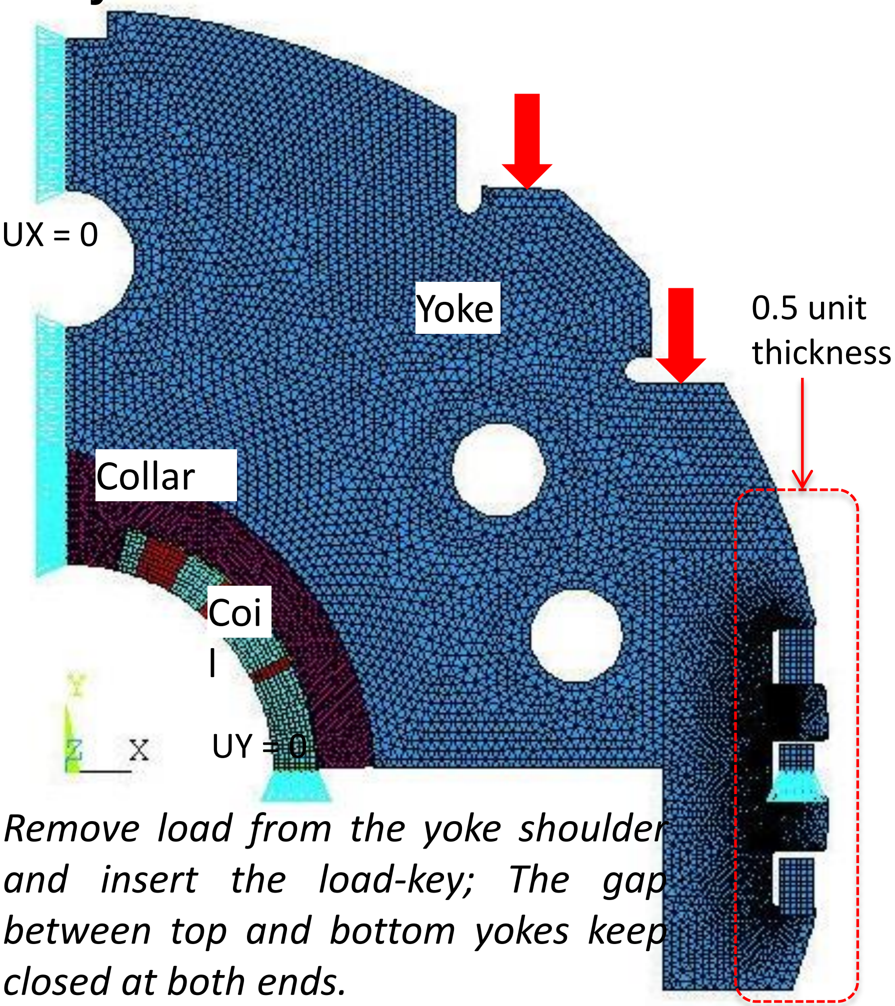
One 2m long model magnet will be built and tested at KEK.
The second model development is also planned.

Design parameters	Production	2-m model
Field integral	35 T•m	10.3 T•m
Magnetic length	6.27 m	1.85 m
Coil mechanical length	6.46 m	2.00 m
Magnet mechanical length	6.96 m	2.50 m
Cold mass weight	12 tons	3.8 tons
Cable unit length per coil	568 m	175 m

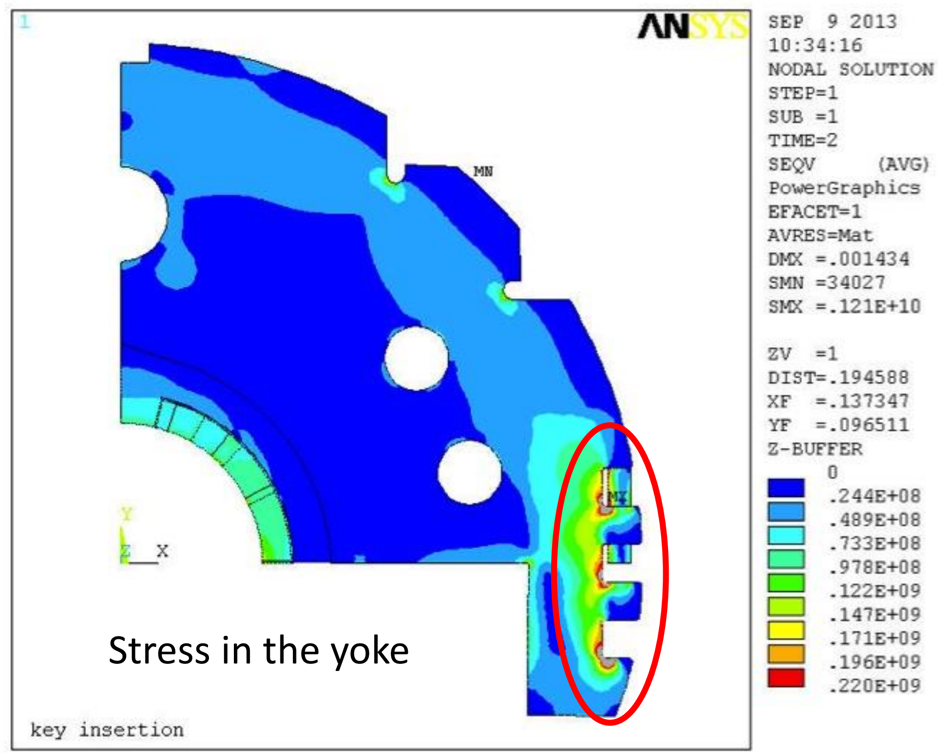
Mechanical Analysis: Yoking

- Mechanical analysis during the assembly process, cooling and excitation using ANSYS has been completed
- Highest stress arisen at key slots in the yoke < 220 MPa
  → The assembly scheme would be feasible

Key insertion

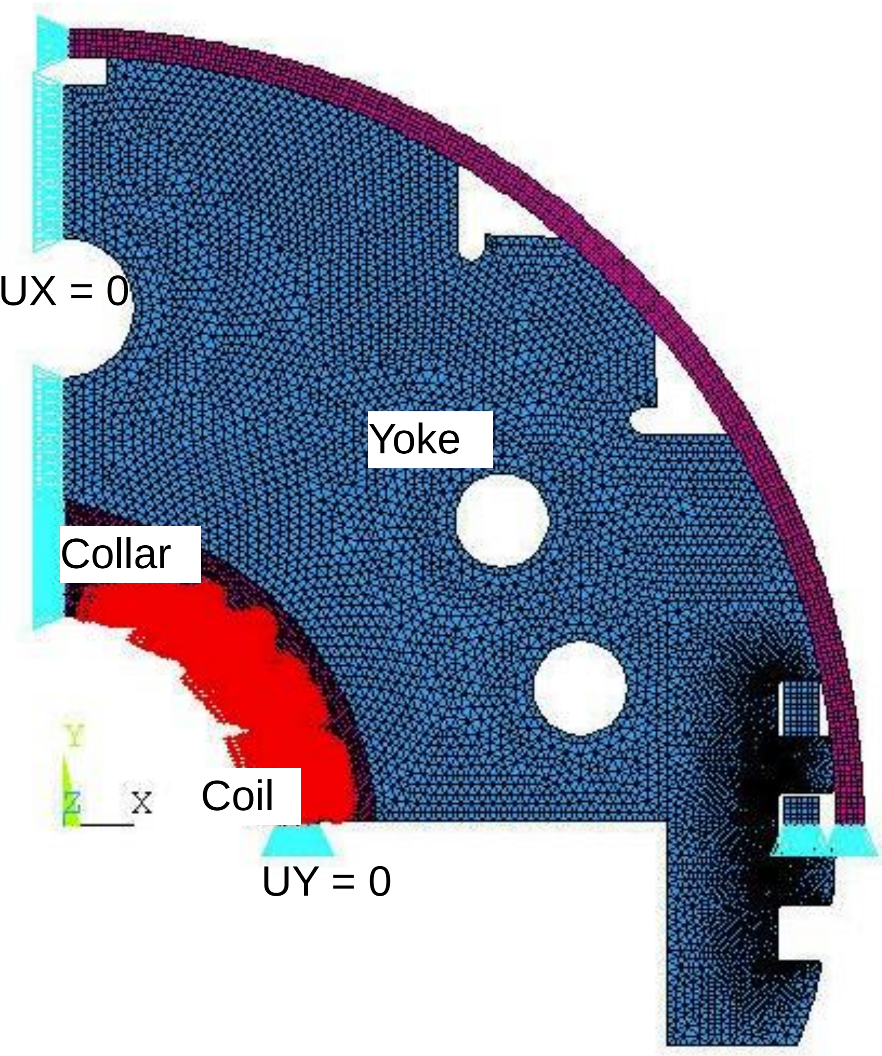


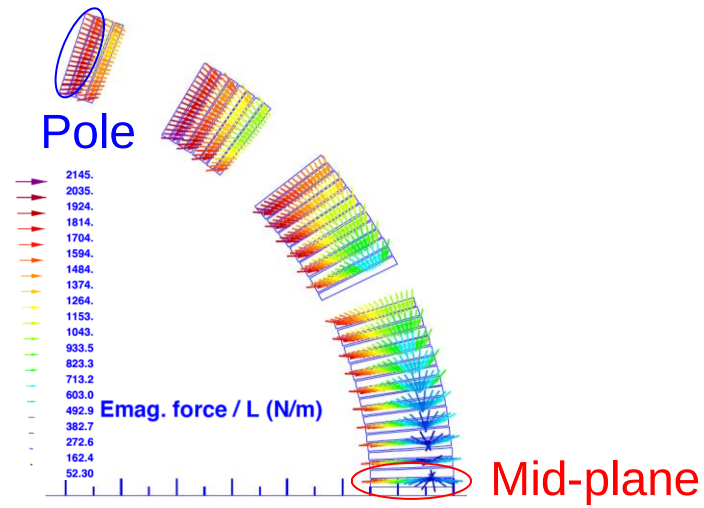
Remove load from the yoke shoulder and insert the load-key; The gap between top and bottom yokes keep closed at both ends.

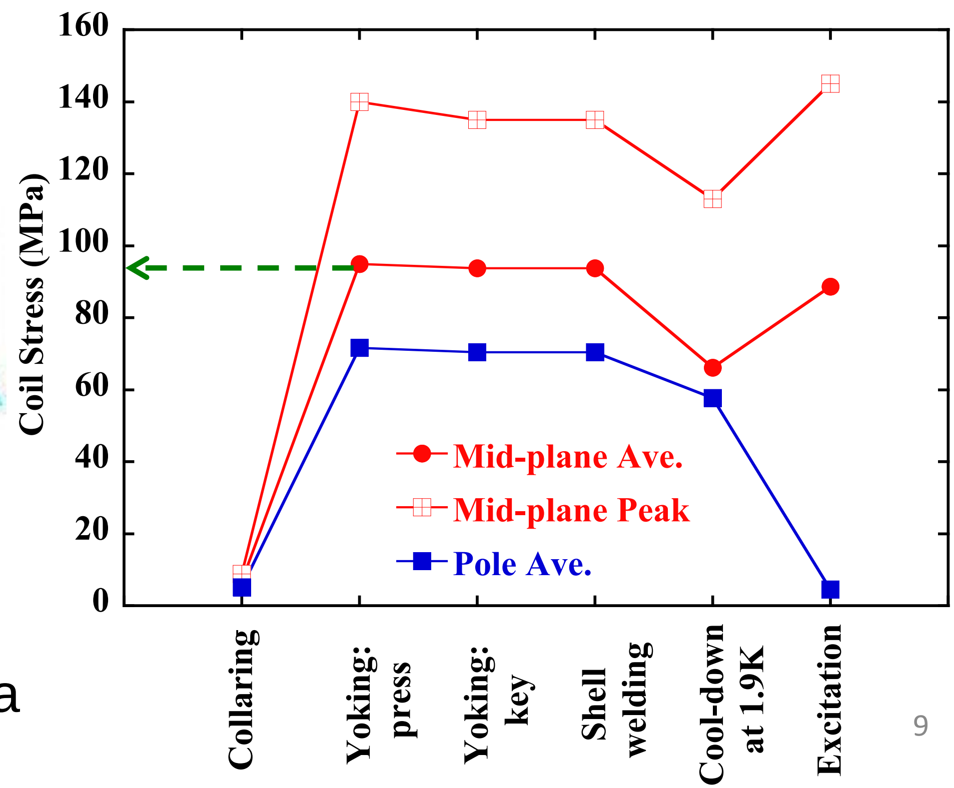


Mechanical Analysis: Coil Stress

Excitation

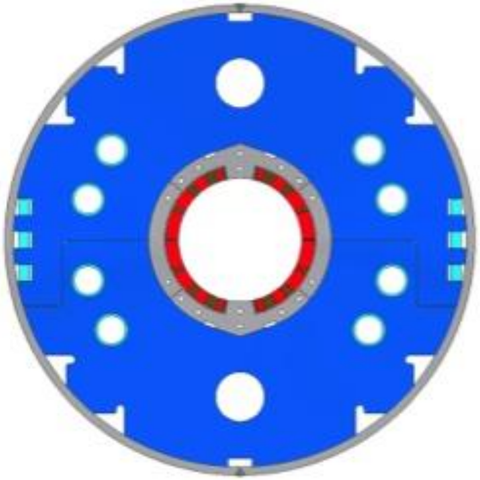


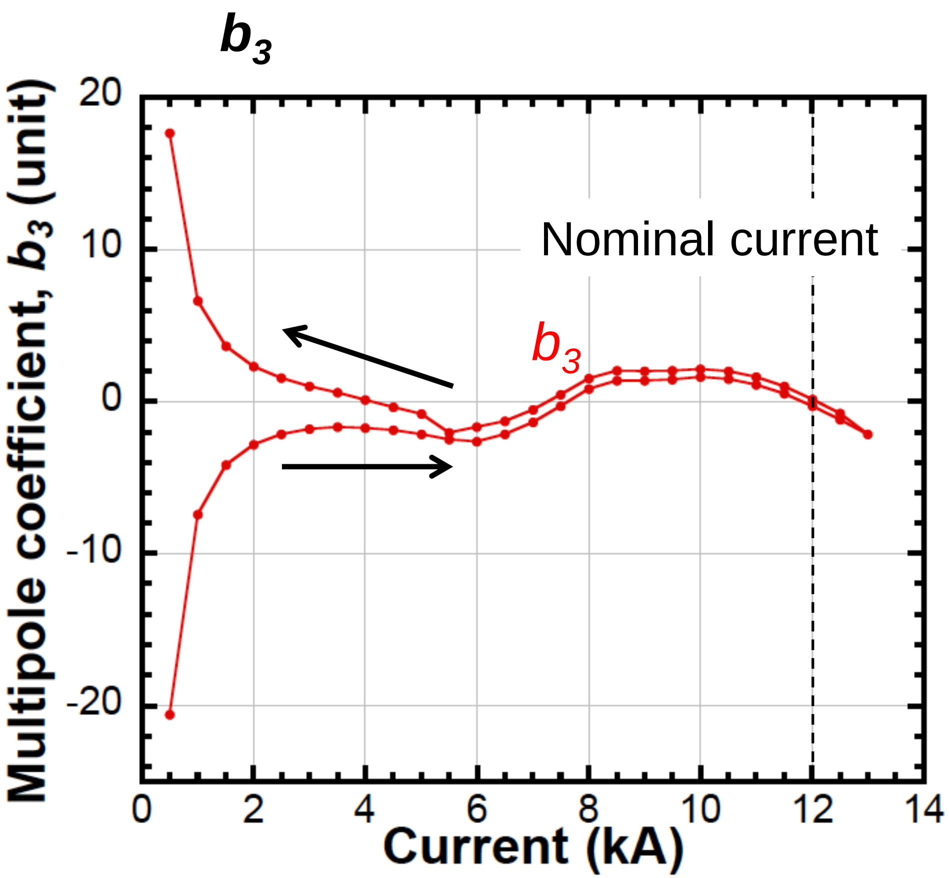


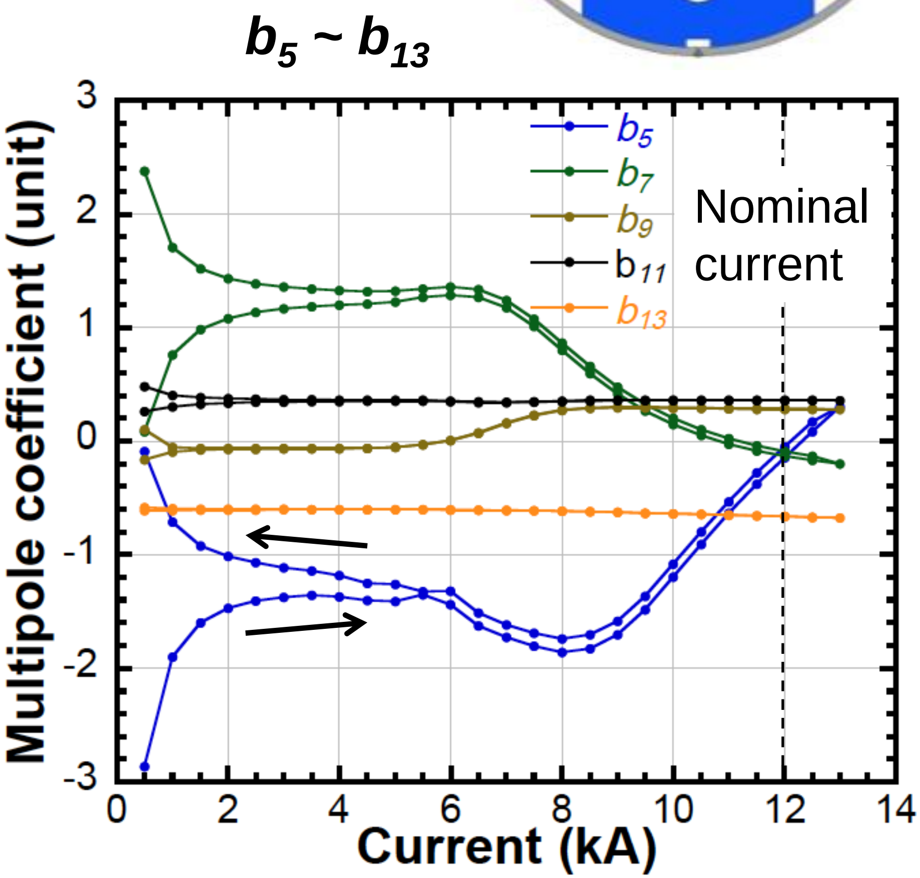


Coil stress during yoking: 100 MPa

Magnetic Design by ROXIE:
Variation of multipole coefficients

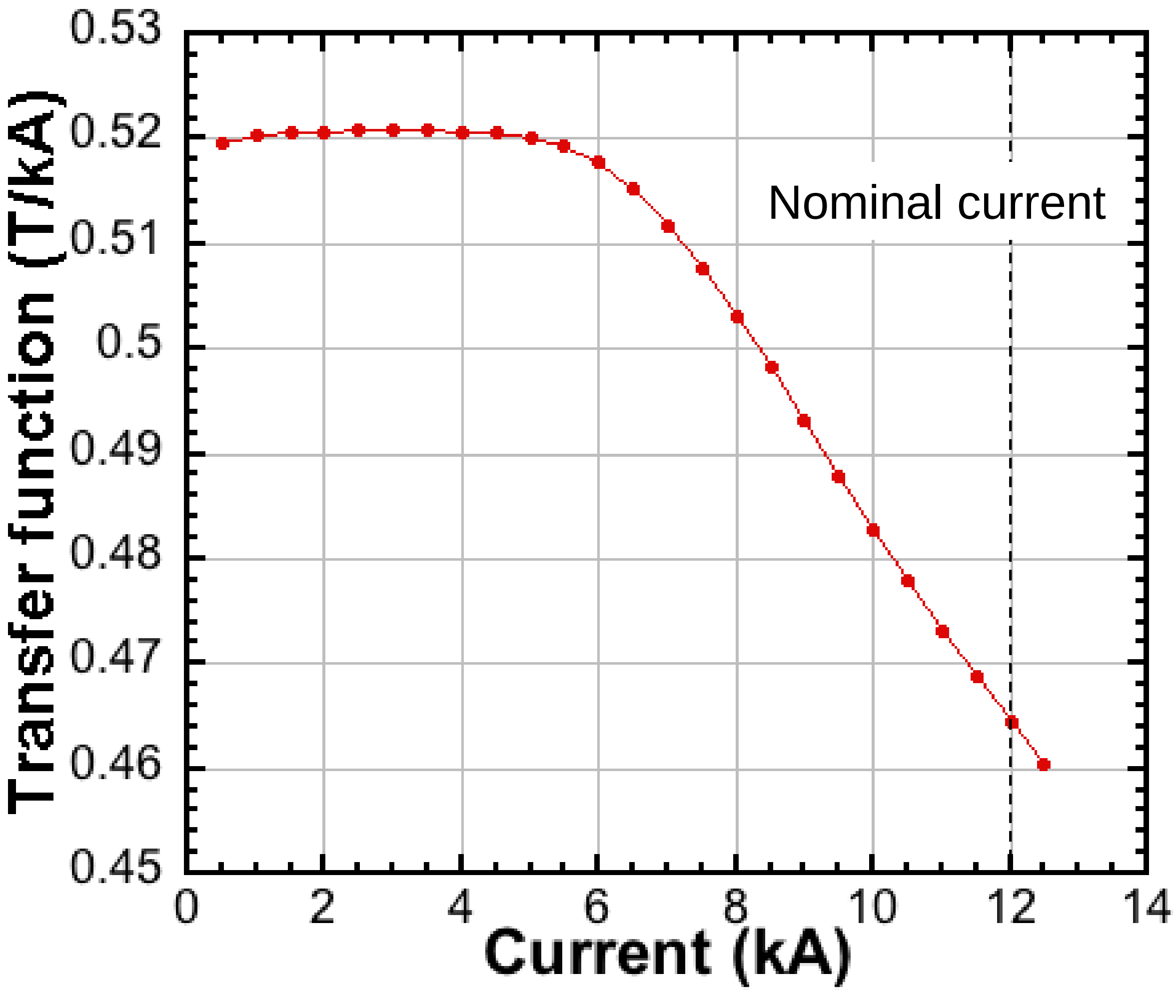






Magnetic Design by ROXIE:

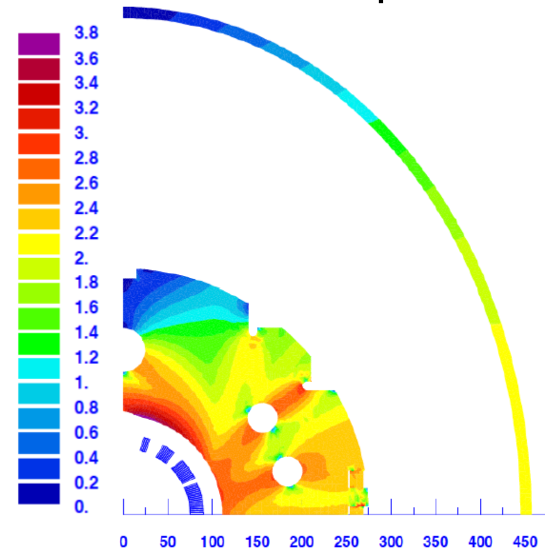
Transfer Function



Transfer function starts to decrease at 6 kA and the value at the nominal current is lower by 10% than one at low field

Magnetic Design by ROXIE:
Possible Error Sources

ID890 mm x 1112 mm, t=12 mm, elliptical



(Change of b_3 by each factor)

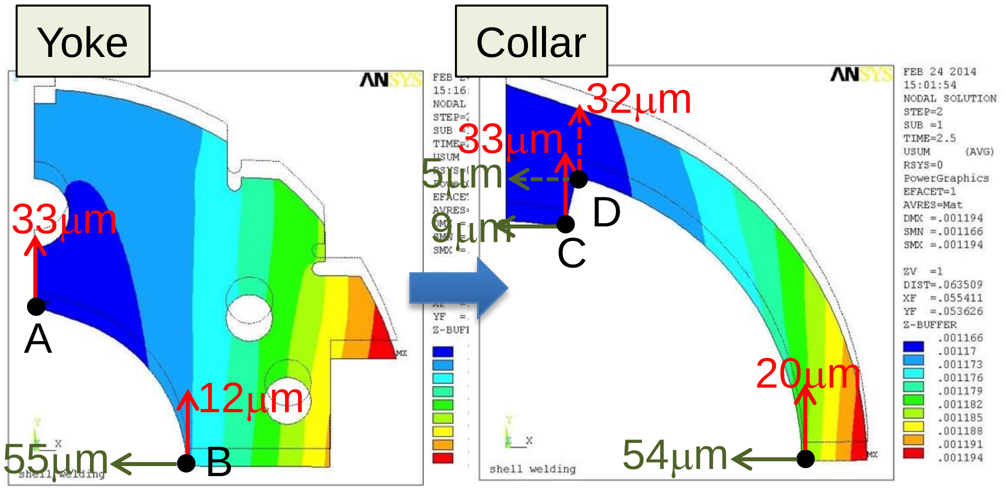
Impact of possible design changes

- Diameter and position of HX holes (-5.1 units)
- Shape of cryostat (Elliptical cryostat option) (-2 units)

Systematic errors

- Packing factor of iron yoke (-1.2 units)
- Relative permeability of stainless steel collar (-0.6 units)
- Mispositioning of coil blocks during yoking (-1 unit)

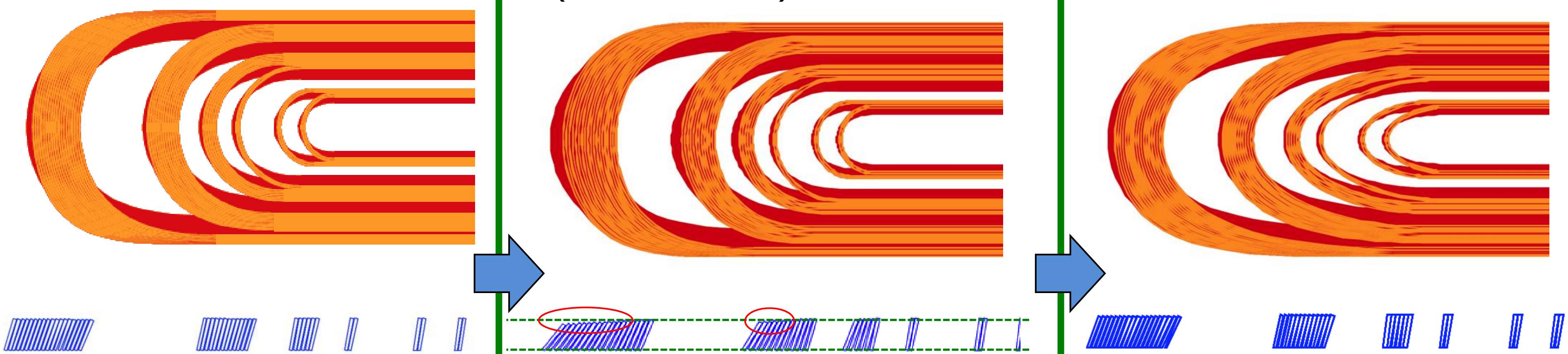
Random geometric error



Thanks to Susana Izquierdo Bermudez for her technical support in ROXIE

Coil End Design by ROXIE

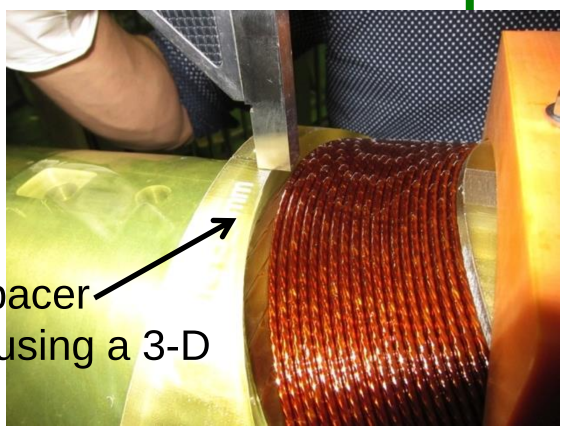
Old version | Coil end found in practice winding (2-m test coil) | Modified design



Due to insufficient length between straight section to end, cables at the coil end tend to be inclined to relieve strain energy

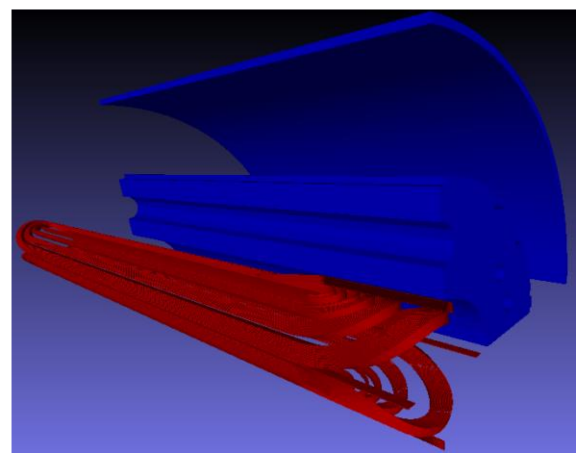
→ Difference in height between end spacer and cables

- Coil end will be modified to have longer length



End spacer made using a 3-D printer

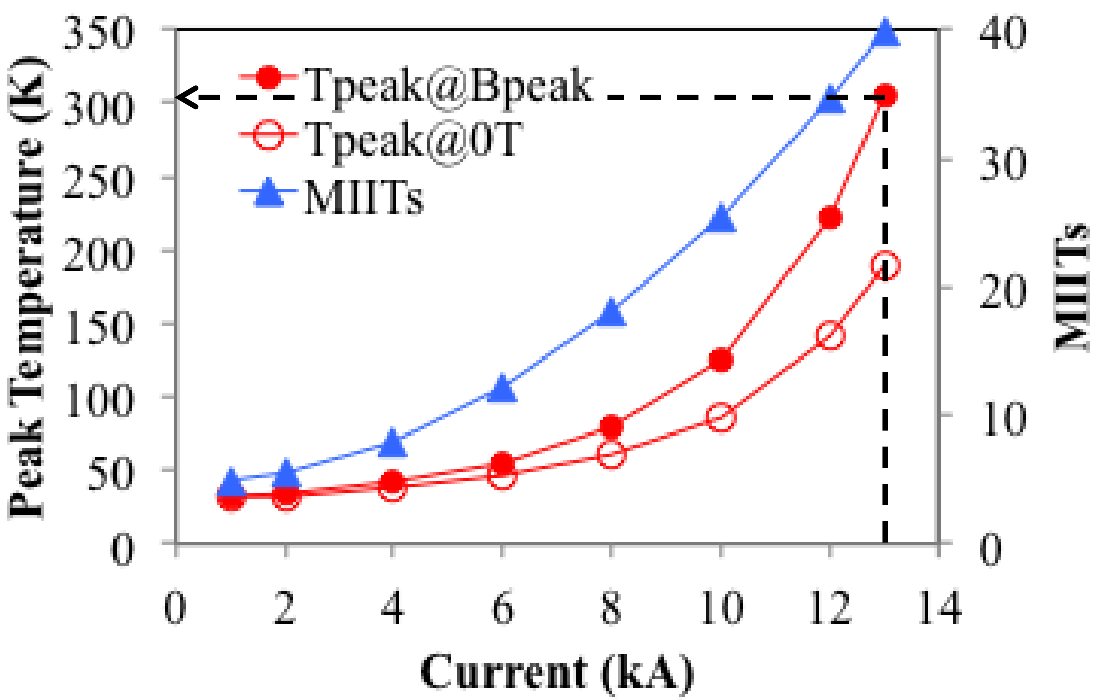
- Length of each coil block is being optimized to minimize multipole coefficients



Quench Protection Study with R_{dump}=75 mΩ

Calculation condition

- R_{dump}=75 mΩ: Already implemented for the MB circuit in the LHC
- Quench detection threshold: 0.1 V, 10 msec
- Cable resistance was neglected in calculation of detection time & time constant of current decay, τ → A conservative scenario
- Quench starts around lead out (B ~ 0 T) → Worst case



Peak temperature at B_{peak} (at I_{max}=13kA) = 305 K

- Further study will be made with 3D field map soon.
- QPH would not be necessary in the production magnet, but it will be decided after quench test using 2-m model magnet.

SC Cable Supply & Schedule

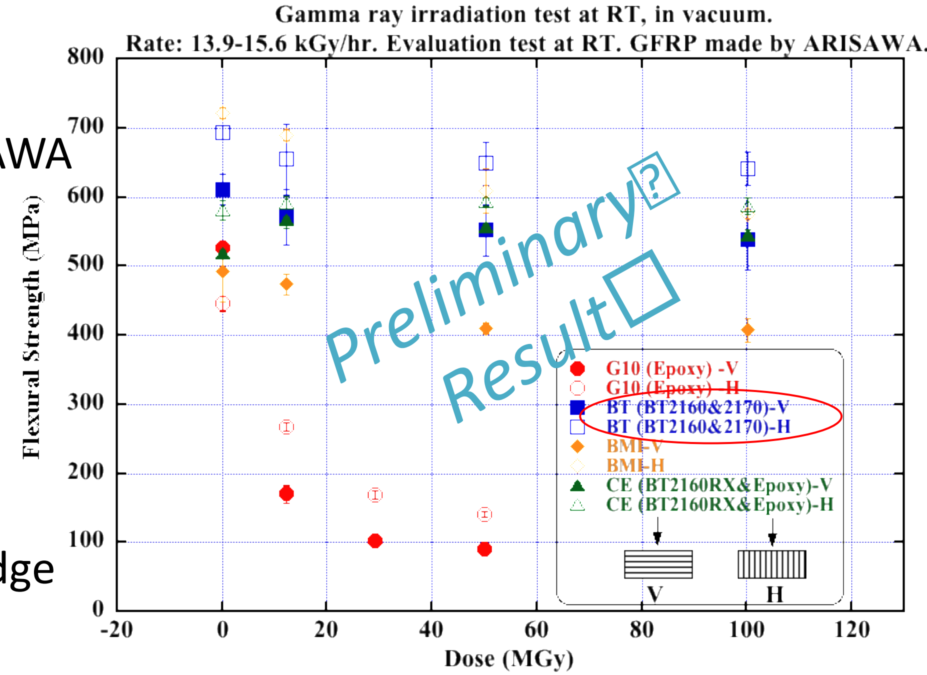
NbTi LHC MB outer cable supplied by CERN for the new D1 .

Delivery Date	Objective	Requirement	Remark
Feb. 2013	10 stack meas. (a piece length > 0.3 m)	~50 m w/ MB type insulation	Both MB inner and outer cables w/ MB type insulation
~~Jan. 2014~~ **May 2014**	1 practice coil* + 2 real coils for the 1^{st} 2-m long model + 1 spare coil	220 m** x 4	LHC MB outer cables w/ MB type Apical insulation
April. 2015	*2 practice coils + 2 real coils for the 2nd 2-m long model*	*220 m x 4*	*LHC MB outer cables w/ MB type Apical insulation*
JFY2016 (prospect)	*6 or 7 full-scale magnets + 4 practice/spare coils*	*600-640 m x 18*	*LHC MB outer cables w/ MB type Apical insulation*

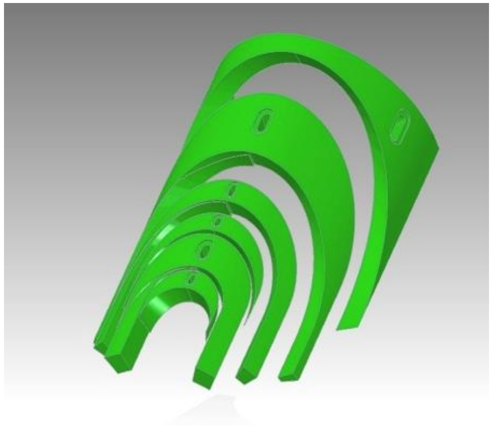
Done!!

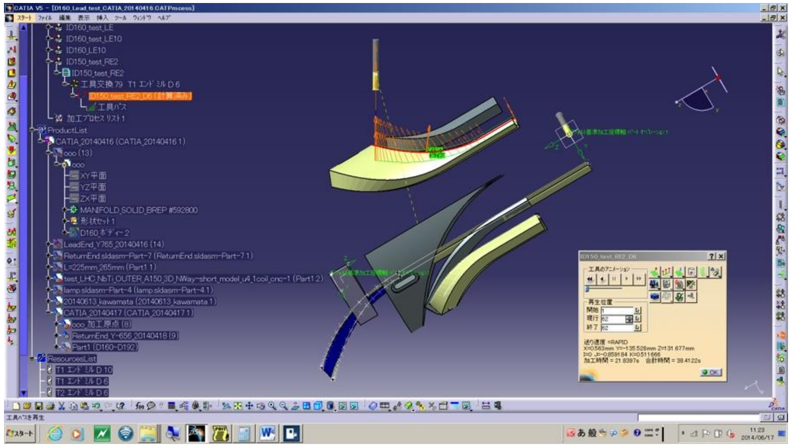
TBD

GFRP End Spacers, Wedges



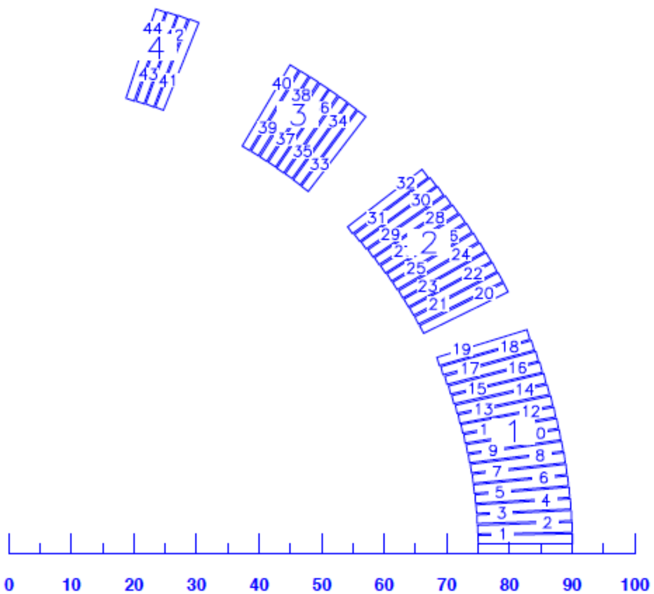
- GFRP: MGC BT2160/2170 + S2 glass by ARISAWA
  - Radiation resistance beyond 50 MGy
  - similar modulus as G10: 29 GPa
  - But 30 % higher mechanical strength
- End-spacers: manufactured in-house
  - Design by ROXIE
  - Modeling with NX, Drawing with Solid Edge
  - CAD/CAM CATIA V5
- Wedges
- Adhesion: Cyanate Ester (MGC BT2160RX)

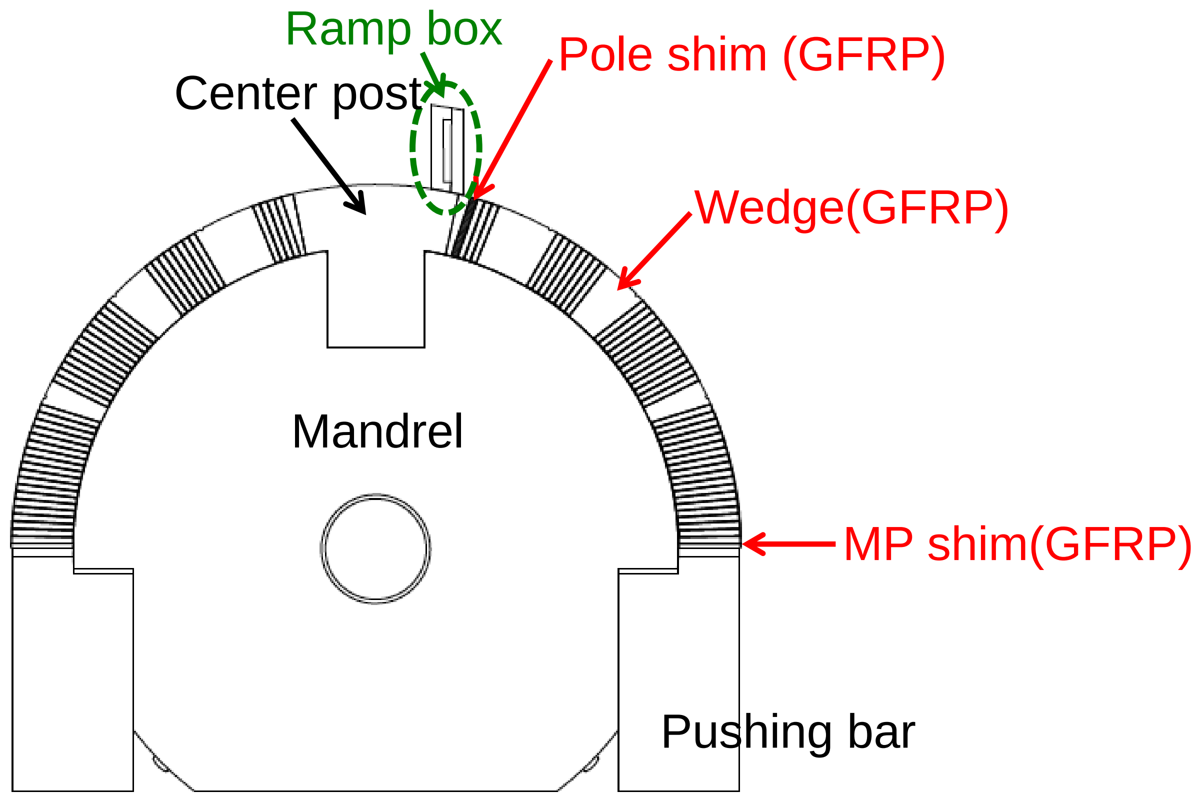




Coil Structure

Cable: NbTi MB cable with APICAL and PIXEO insulation supplied by CERN
Coil configuration:
- Single layer coil
- 44 turns, 4 coil blocks
- Coil length: 2020 mm (between the end saddles)
- 2D cross-section optimized for HX-hole of 50 mm (old version)



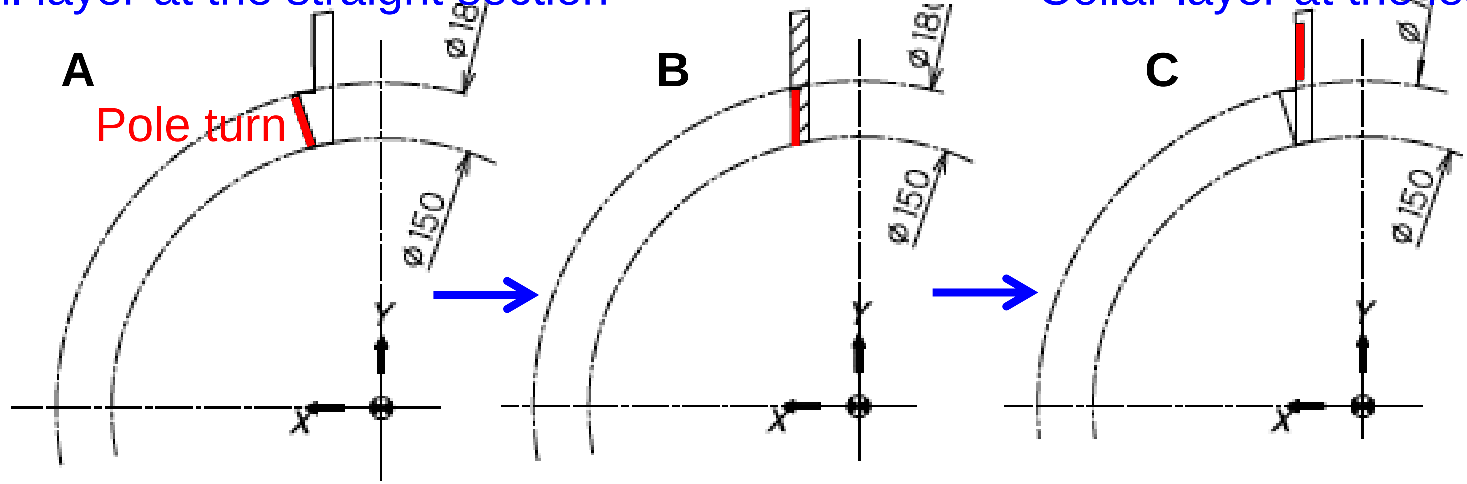


Layer Jump

2D cross-sections of the layer jump

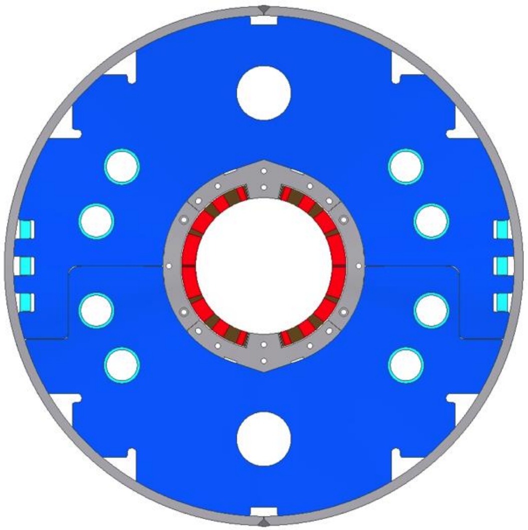
Coil layer at the straight section

Collar layer at the lead end



Ramp box was designed in such a way that the layer jump turn go out uprightly

Coil Size Control at Curing



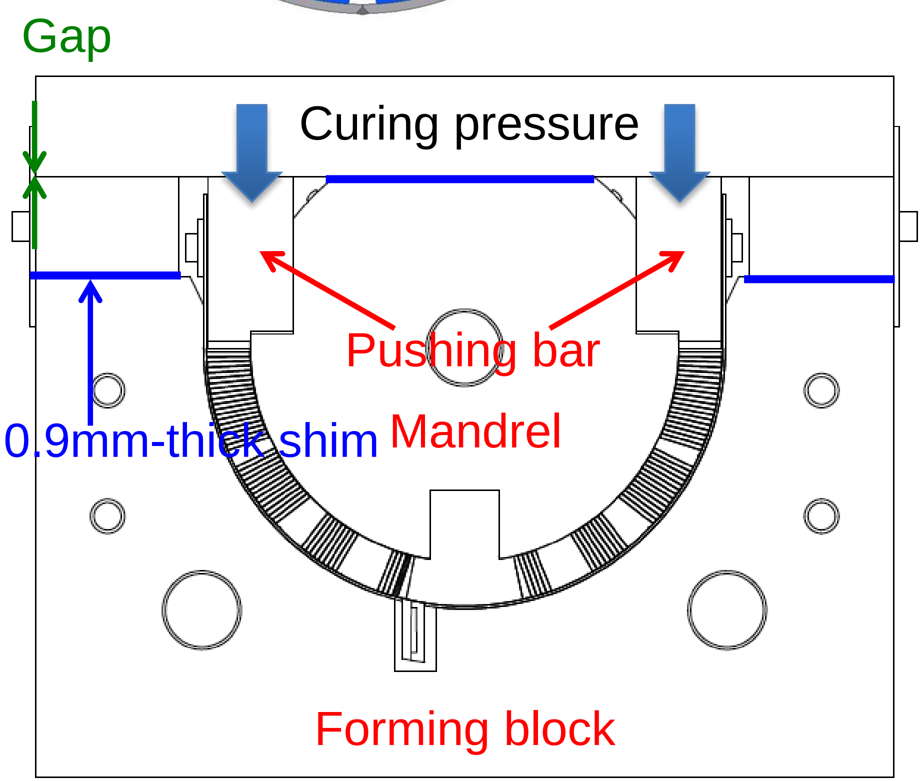
Final size of coil is determined by yoking

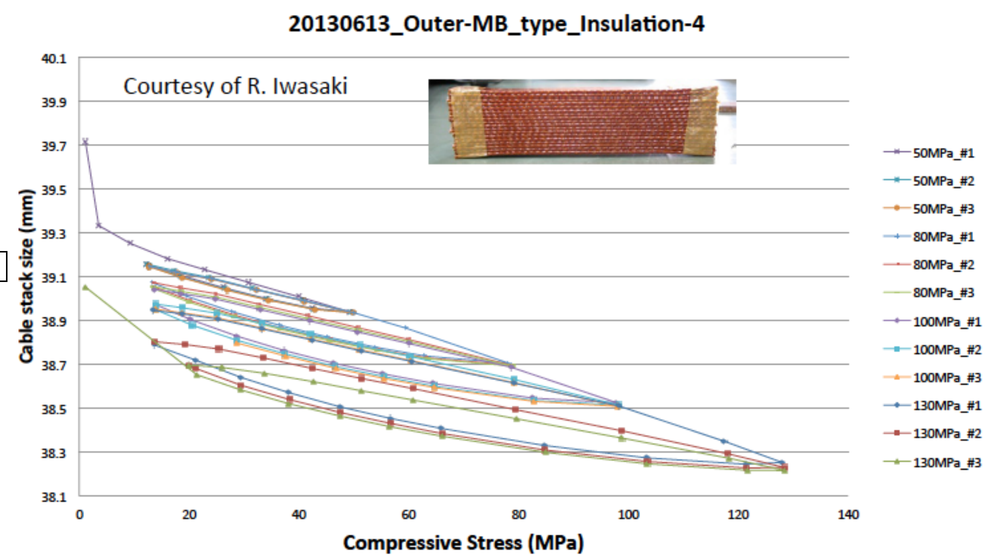
<u>Pressure applied to coil</u>

Curing: 50 MPa

Yoking: 100 MPa (max) → 80 MPa

From the results of 10 stack measurement (22 cables), coil after curing should be larger by 0.9 mm than the final size

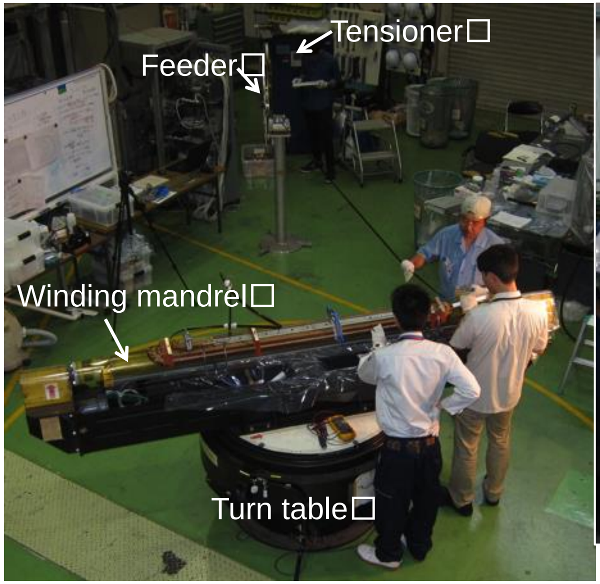


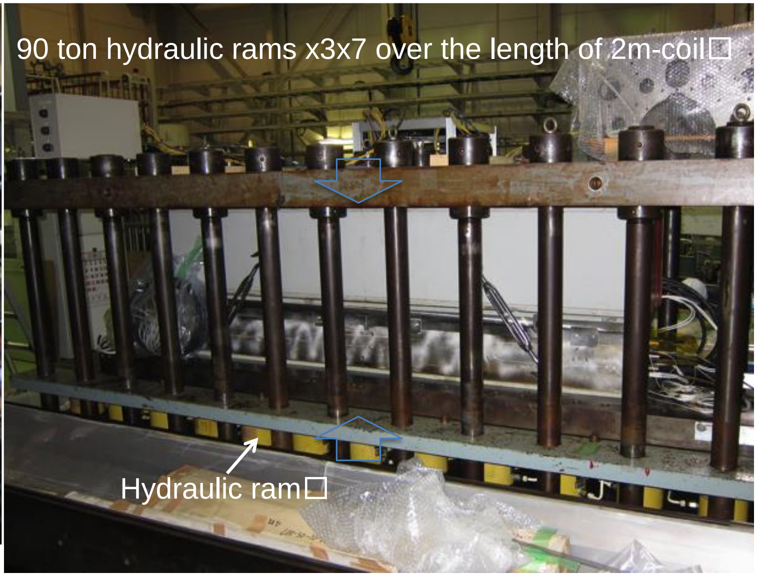


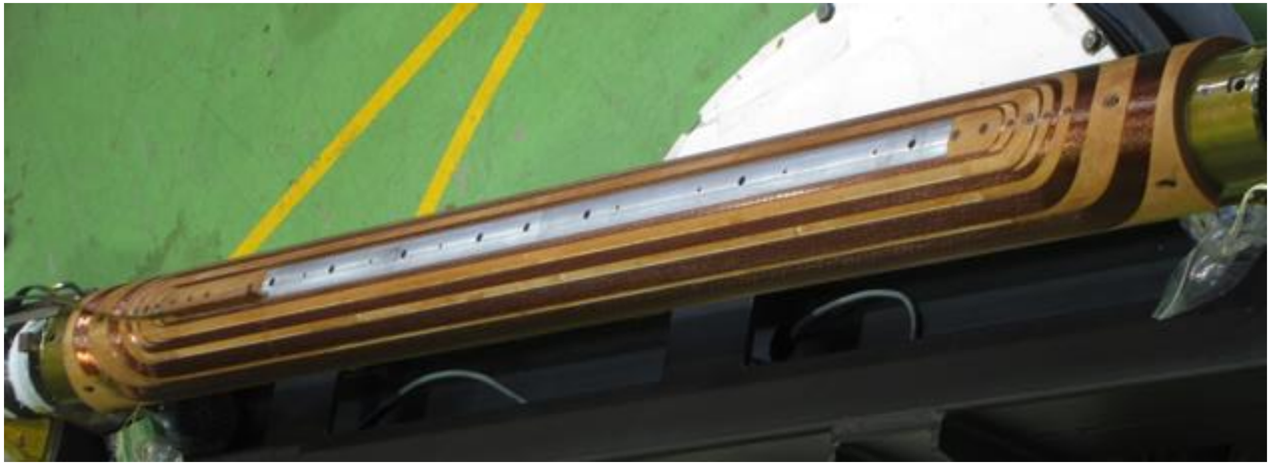
0.9 mm-thick shims were inserted and coil was compressed until the gap was closed

Test Coil Fabrication

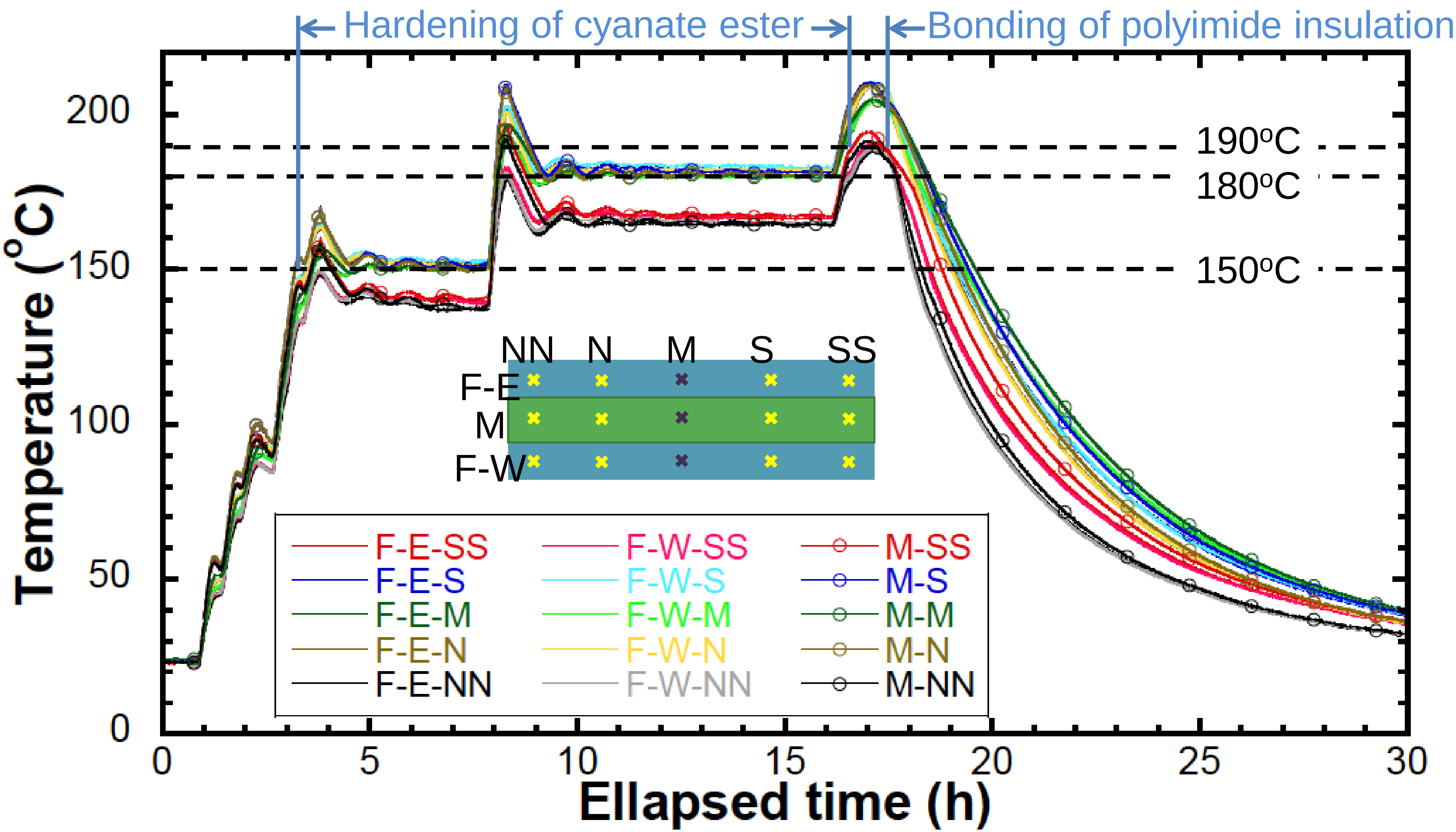
Demonstration of coil fabrication with a first 2m (test) coil.







Temperature Trend at Curing

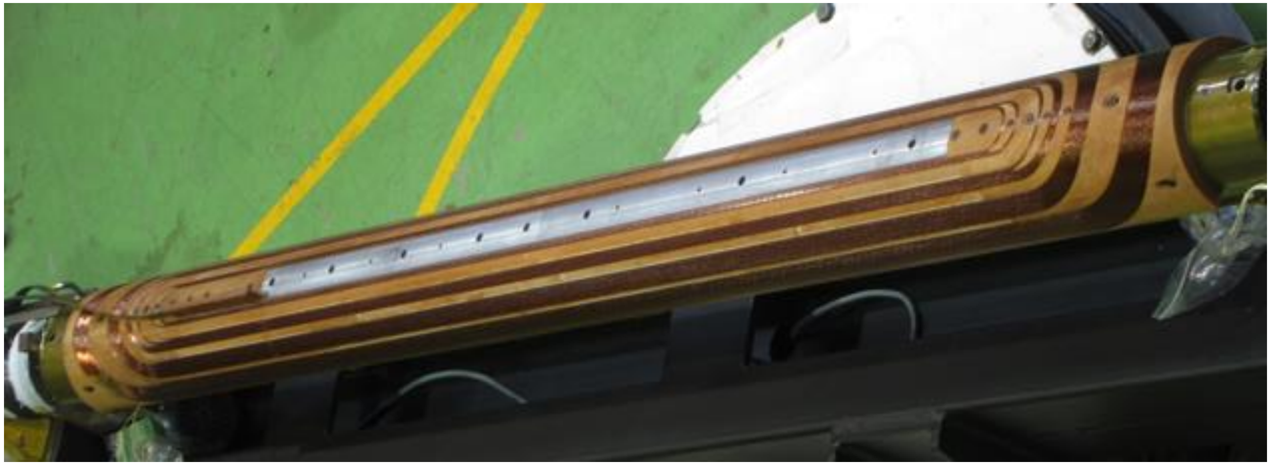


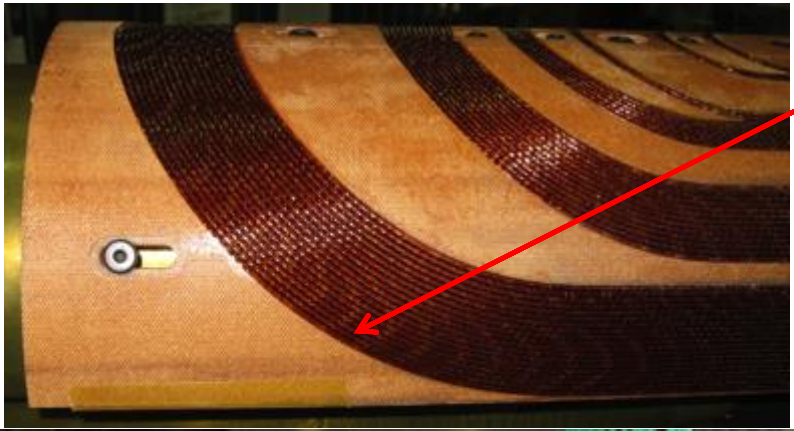
Temperature profile to harden cyanate ester (150ºC x 4h + 180ºC x 8h) was obtained as expected

Max. temperature could be controlled at 190 - 210ºC (< 220ºC)

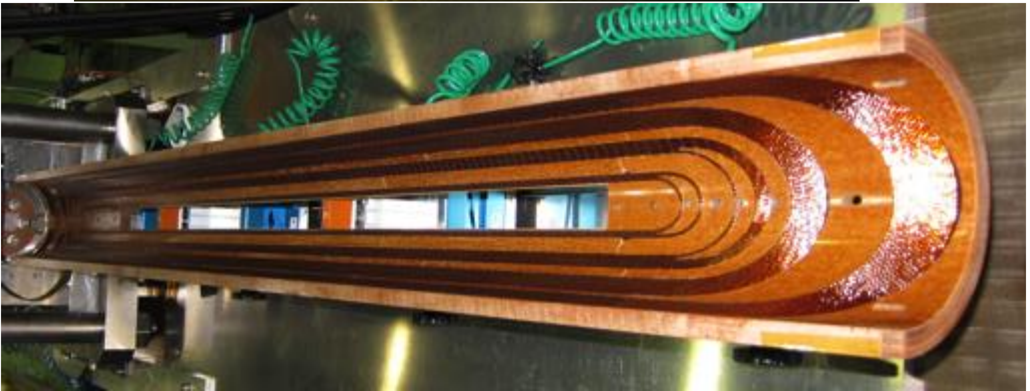
➡ Expected temperature profile was realized

Coil after Curing





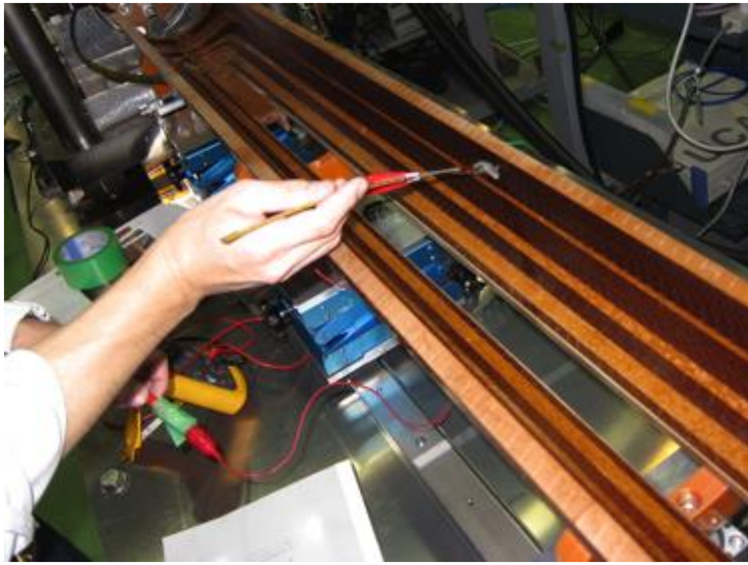
The gap between the end saddle and the cable was closed after curing
→Hard BT resin + S2 glass GFRP can be accommodated to the cable



Bonding between the cable and the wedges is sufficiently strong
→ Effectiveness of heat treatment profile is verified

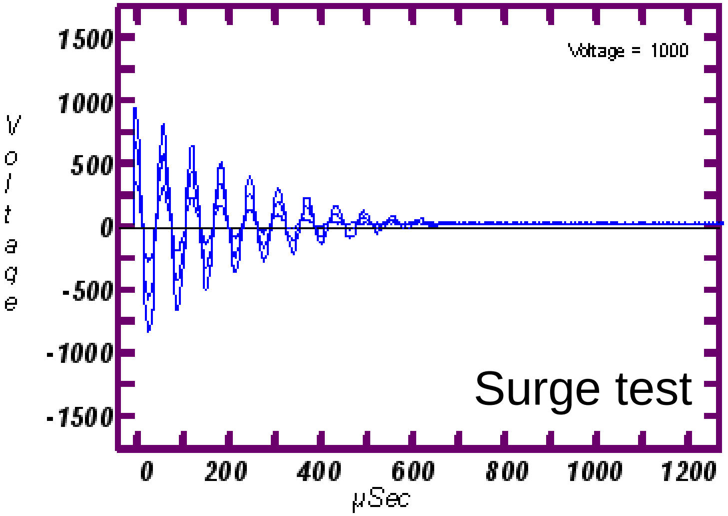
Electrical Tests for QA

- No ground fault throughout winding and curing
- No change of cable resistance (for 44 turn)



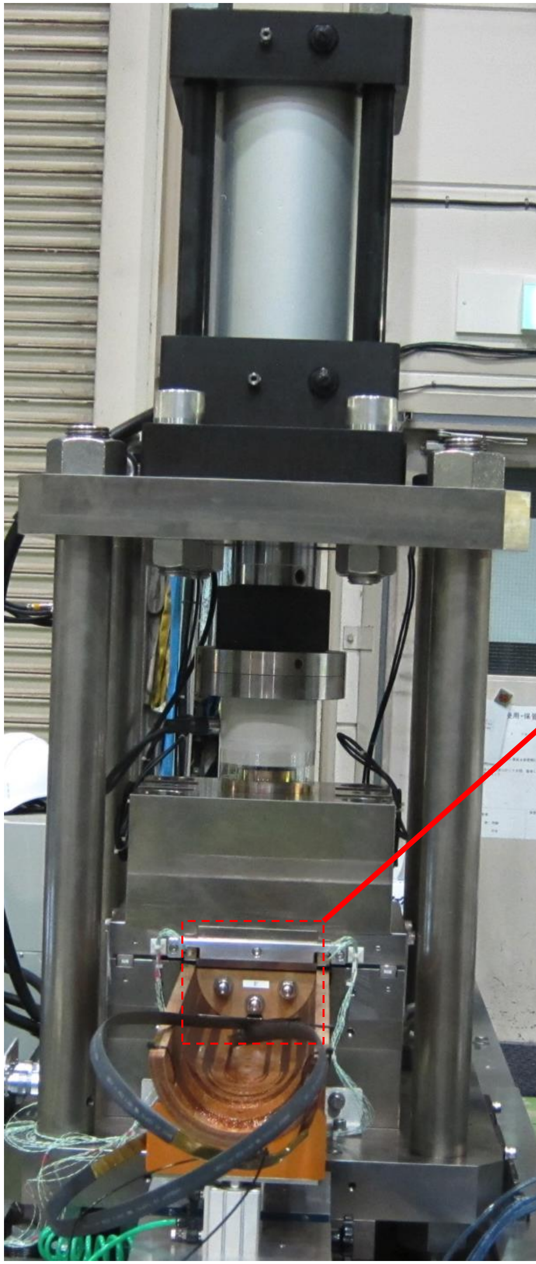
After winding	242.9 mΩ
Under curing pressure, before curing	242.5 mΩ
After curing	242.2 mΩ

- No damage of cable insulation checked by a bundle of fine Nb-Ti filaments
- No turn-turn insulation failure at least up to 1 kV (Surge test)
- Coil inductance: 2.26 mH (calc. value = 2.28 mH)



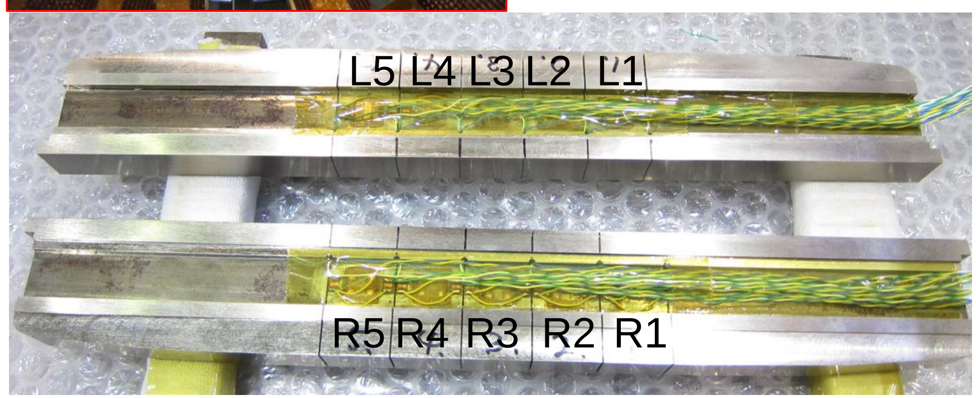
Electrical soundness of the coil was confirmed

Coil Size Measurement



Similar apparatus as CERN (Thanks to G. Kirby)

- 50 ton hydraulic press
- Coil pressure up to 90 MPa
- Continuous measurement using the 5.4 m-long bench
- Two pushing bars each having 5 x 20mm-wide fingers
- 4 x linear gauges to measure coil deformation



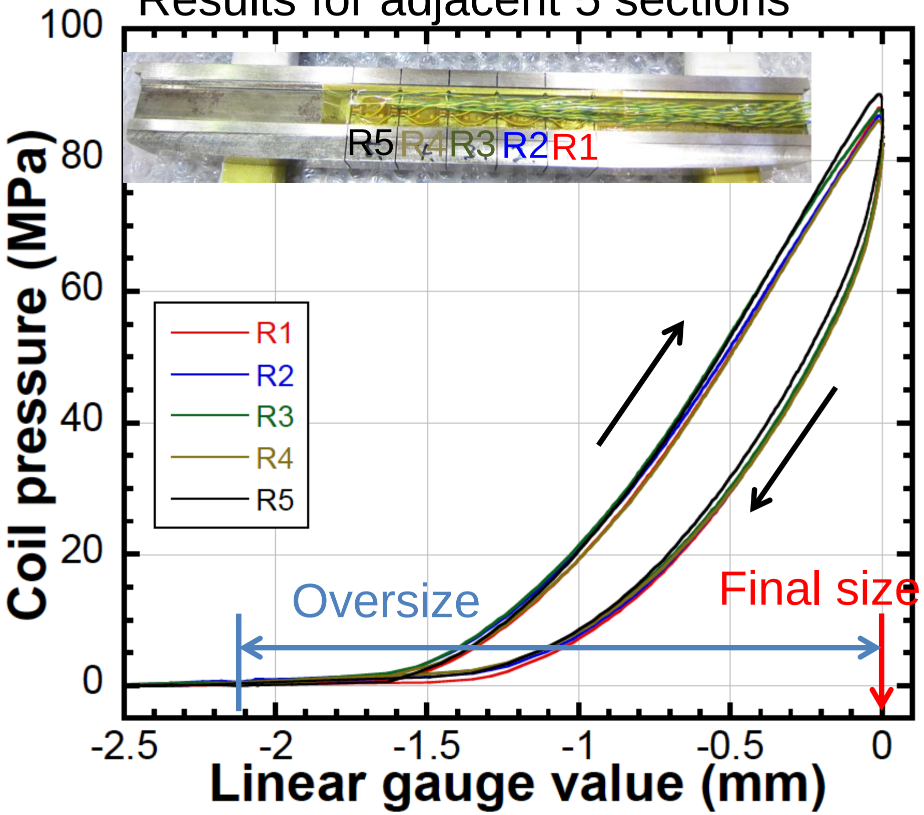
Pushing bars with strain gauges

Maximum pressure to compress the coil to the final size was measured

Coil Size Measurement: Results of Test Coil

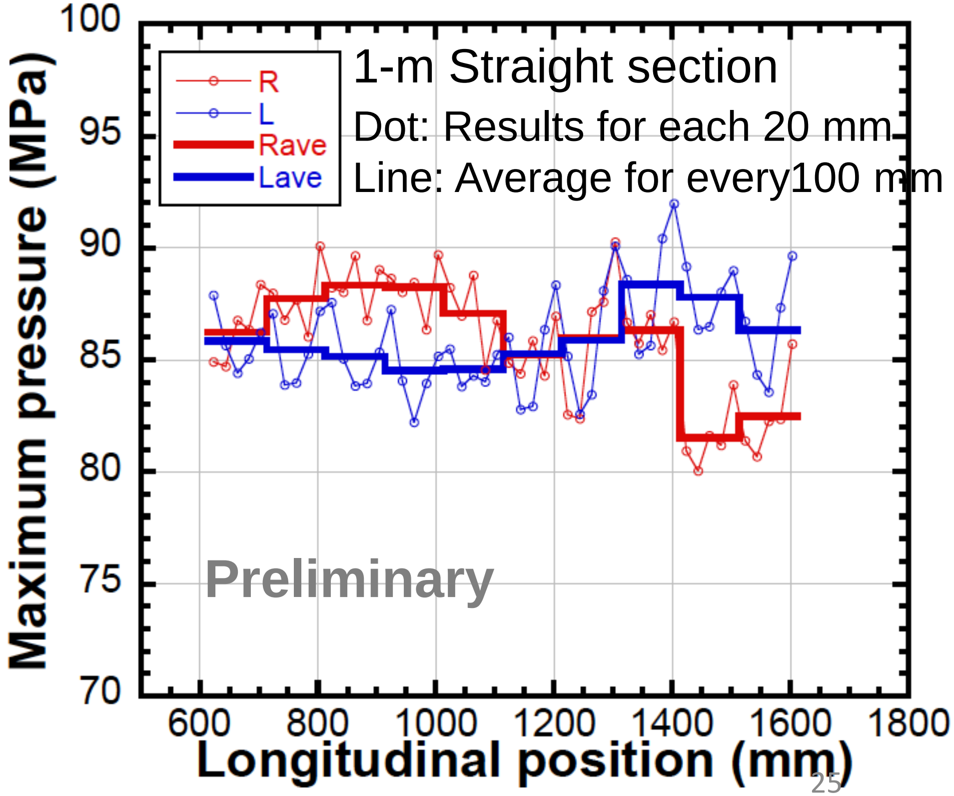
Coil pressure – deformation

Results for adjacent 5 sections



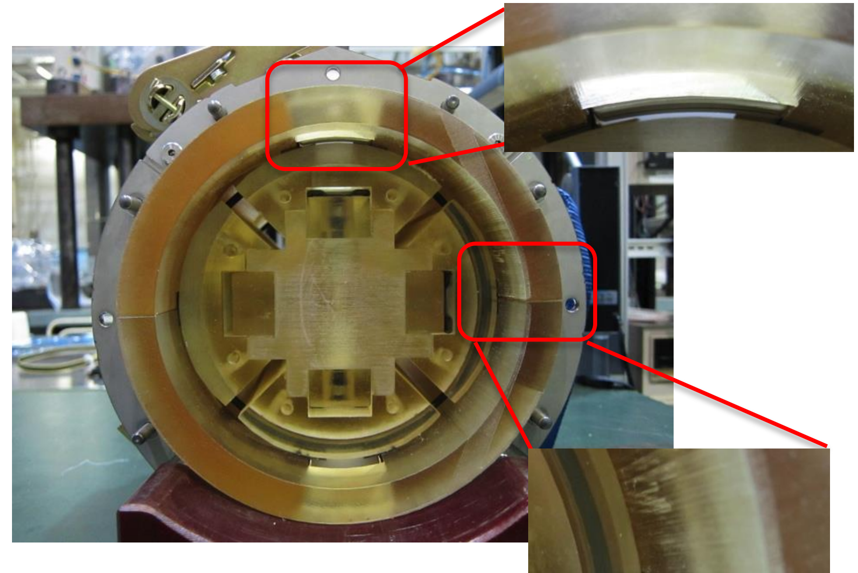
Measured maximum pressure: 80 – 92 MPa
(After correction considering machine deformation: 90 – 100 MPa)
→ The size of our test coil is almost as designed

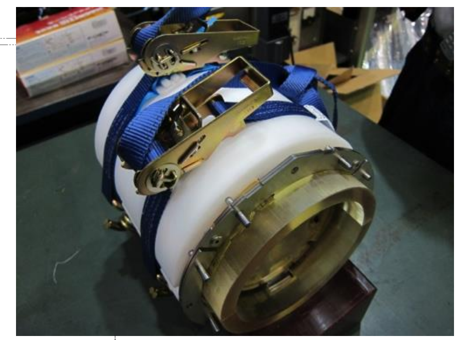
Coil stress at the final size along the coil length

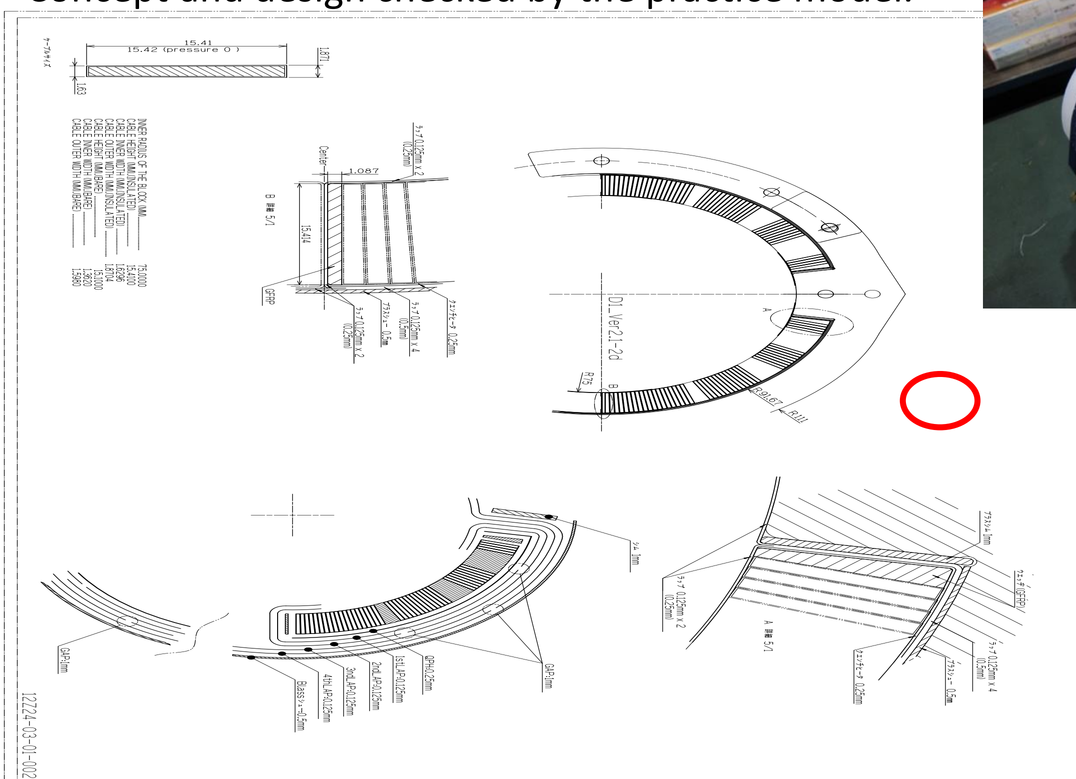


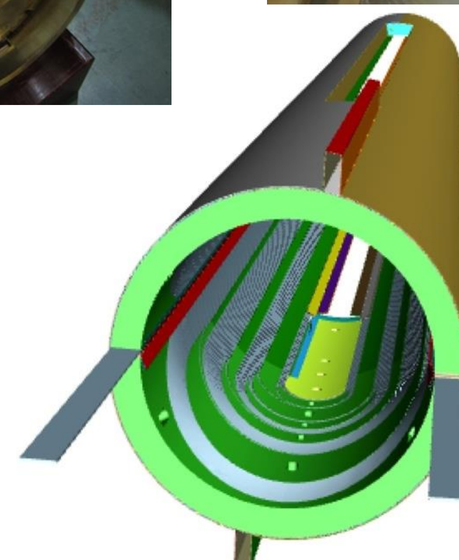
Ground Insulation

- Ground Insulation: same concept as MQXA
  - 4 layer of 0.125 mm thick Polyimide insulation (Upilex-RN)
  - Large shrinkage of the coil during the assembly should be taken into account.
- Brass shoes to intervene laminated collar sheets and the insulated coil.
- Collaring mandrel ensuring the proper coil form.
- Concept and design checked by the practice model.









QPH & Spot Heater

- QPH might not be necessary for the D1 because peak temperature is estimated to be 300K by a conservative scenario.

- Quench Protection Heater (0.25 mm think) for model magnet R&D
  - Still searching for manufacturer in Japan.
  - Possibility of supply from CERN
  - Necessity??

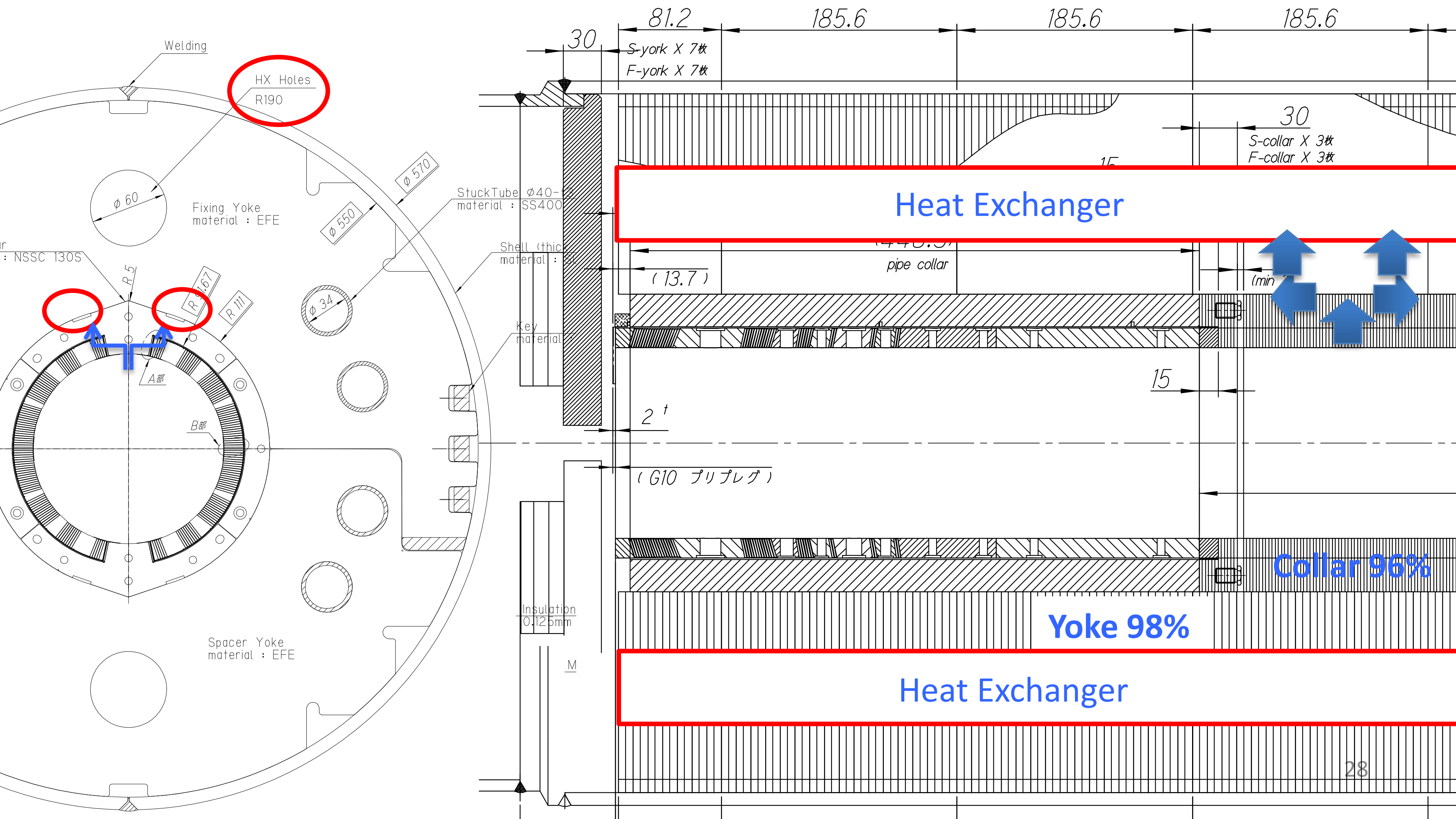
- Spot heaters will be implemented in the model magnet for the quench protection study.
  - higher field at the straight section
  - lowest field at the coil end (probably at lead-out)

- CLIQ might secure the quench protection?
  - Experimental study with the 1st model magnet

Requirement for Cooling

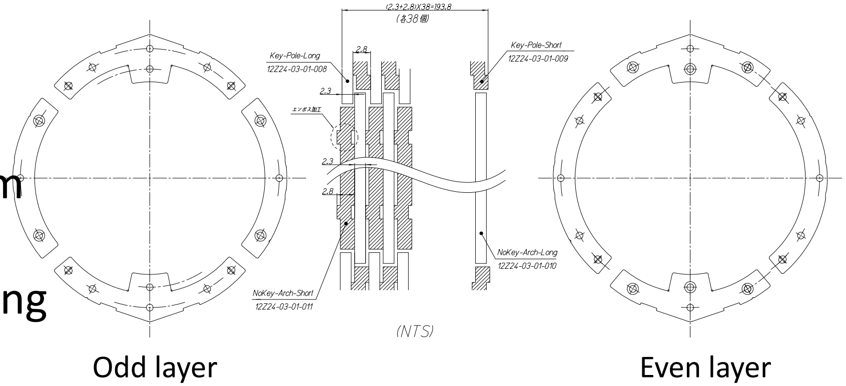
Suggestion by Rob:
- 2 x ϕ57 HeII HXs
- Radial gap of 4 % up to HX holes.
- Longitudinal free area >100cm^2

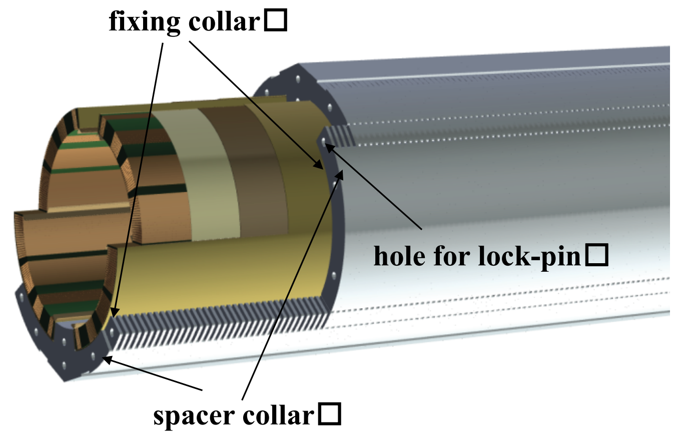
- New 2 HX holes: ϕ60 @R=190
- Collar lamination w/ 0.2mm gap by emboss
- Longitudinal grooves on collar: d2 x w20, both sides of triangle notch.
- Yoke packing factor of 98 %
- Free area: 153 cm^2

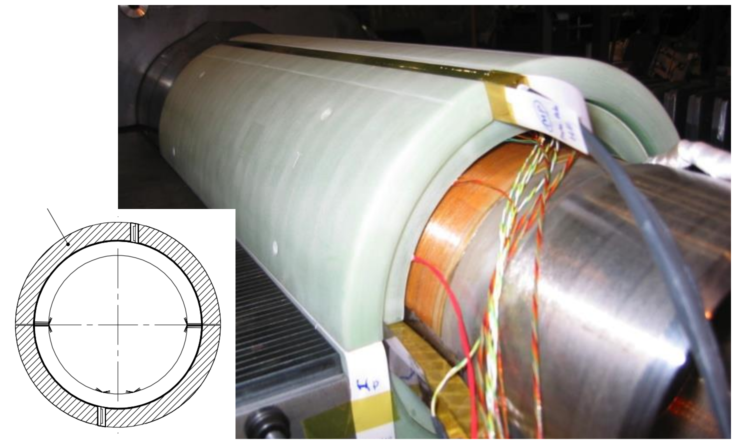


Collars

- Stainless steel: NSSC 130S (same as YUS130S)
  - 12 tons of NSSC-130S sheets (2.3mm & 2.6mm thick) delivered. This can cover the model magnet development and >30% of the 7-m long full-scale magnets production.
  - Specification, once set for the LHC MB, is fulfilled. Very low permeability of 1.002 confirmed at RT/4.2K.
- 4-way split collar concept for the dipole coil to avoid the unwanted warp at the fine-blanking process.
  - Collars work as spacers between the coil and the yoke.
  - A sub-stack of the collars is laminated by the 2.3mm thick “fixing collar” and the 2.6mm thick “spacer collar”. Similar with MQXA.
  - Four sub-stacks are connected by lock pins and provide the coil pre-stress below 5 MPa.
  - Emboss of 0.2mm
- Procurement of fine-blanking dies is on-going.
- Radiation resistant GFRP collar at lead end, same design concept as the J-PARC SCFM.



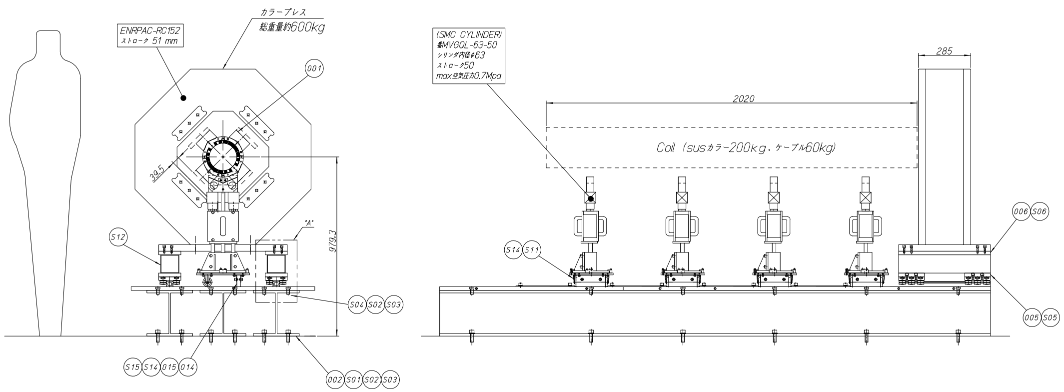


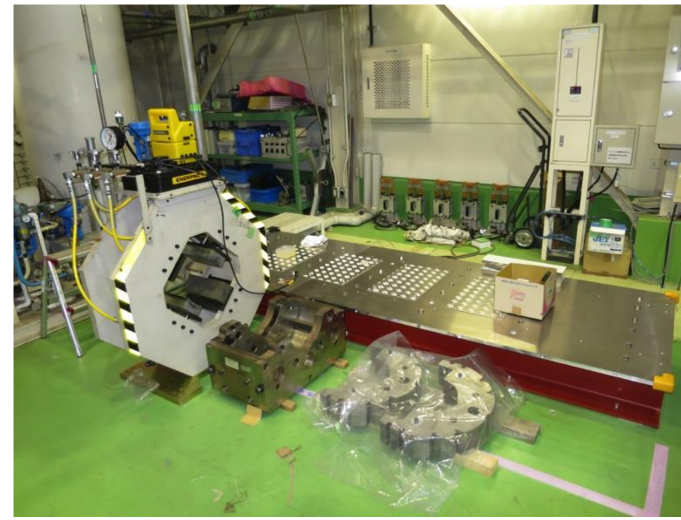


e.g.) GFRP collar to clamp the ramp box and the lead-out on the single layer coil for J-PARC SCFM.

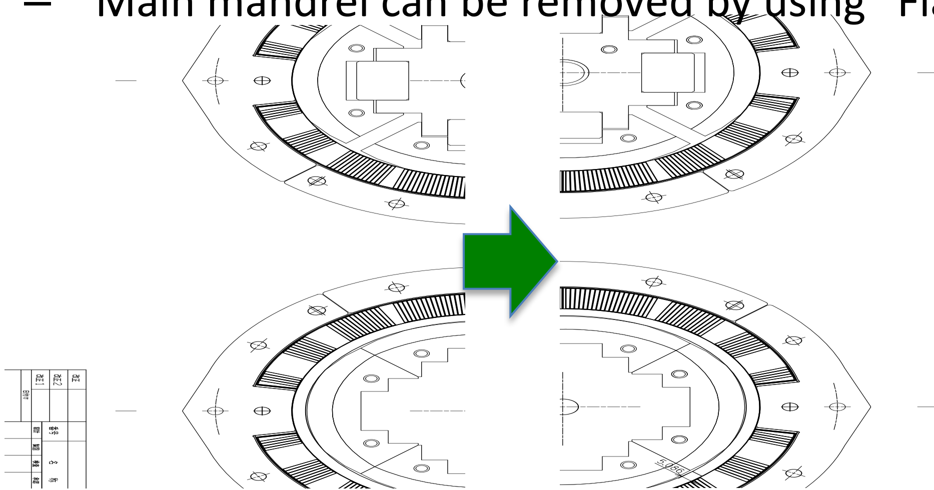
Collaring Press and Mandrel

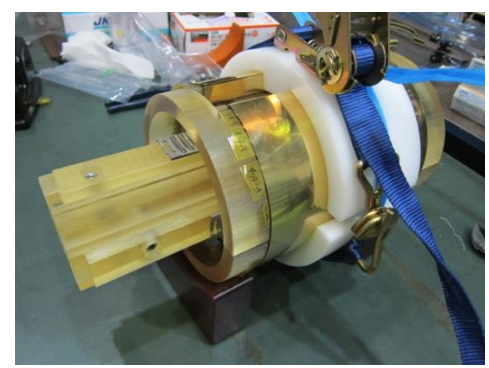
- Horizontal collaring press in preparation.
  - coil pre-stress below 5MPa.
  - coil deformation controlled by the collaring mandrel.





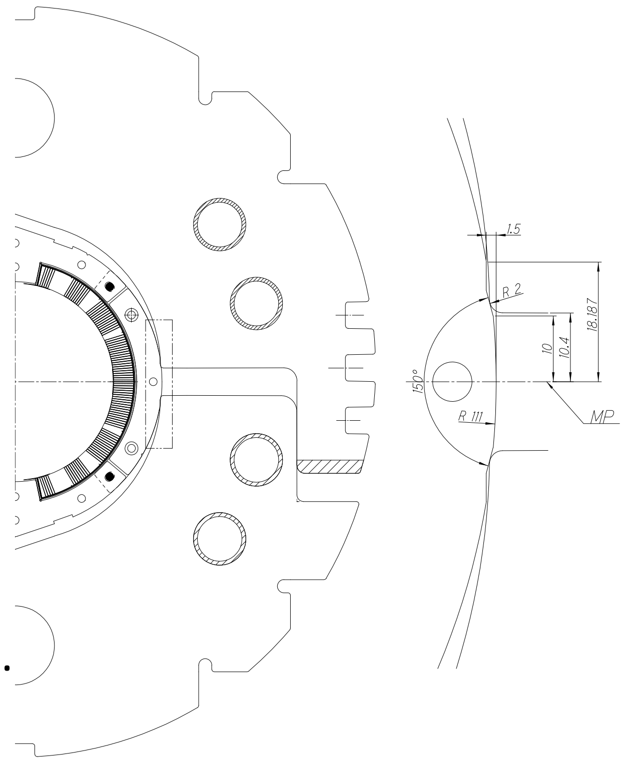
- Demonstration of collaring mandrel
  - 3D rapid prototyping.
  - Main mandrel can be removed by using “Flat Roller” after yoking.

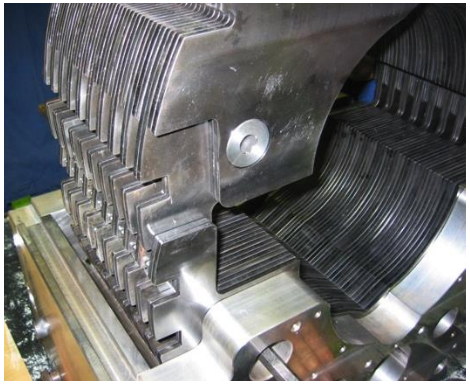




Yokes

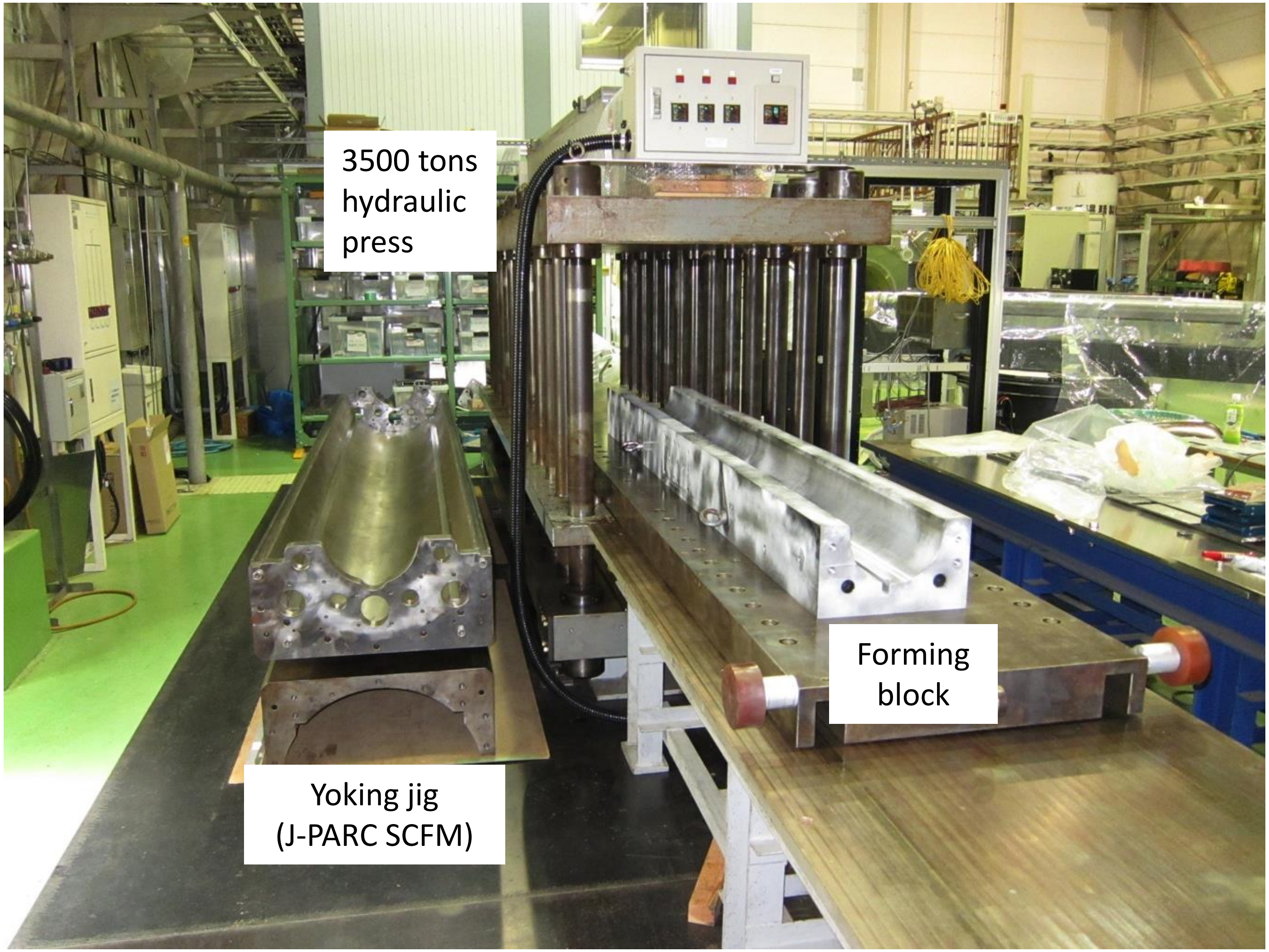
- Low carbon steel: EFE by JFE steel
  - 15 tons of EFE sheets (5.6mm & 6mm thick) delivered for the model magnet.
  - Another 15 tons will be procured within this year.
  - Y.S.: > 240 MPa. Magnetic property: OK.
- Yoke is locked by 3 keys at each side. The coil pre-stress of 90-100 MPa will be given by the yoking.
- Mechanical short model study: Demonstration of mechanical structure
  - Concept of 4-way split collars and pre-alignment feature.
  - Increase of thickness difference (5.6mm & 6.0mm): help for yoke stacks assembly.
  - Coil pre-stress measurement at assembly and cool-down to LN_2 temperature
- For model magnet:
  - KEK placed an order of fine-blanking dies. Yoke stacks will be delivered by Feb. 2015.
  - Holes on the yoke sheet are not finalized and will be machined for the model magnets.





assembly of top and bottom yoke stacks for J-PARC SCFM

Presses, Jigs

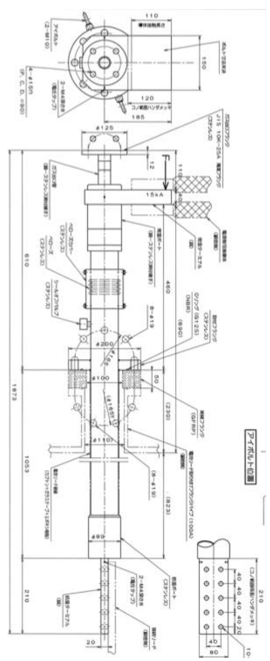


3.6 m long hydraulic press for coil curing and yoking is ready.

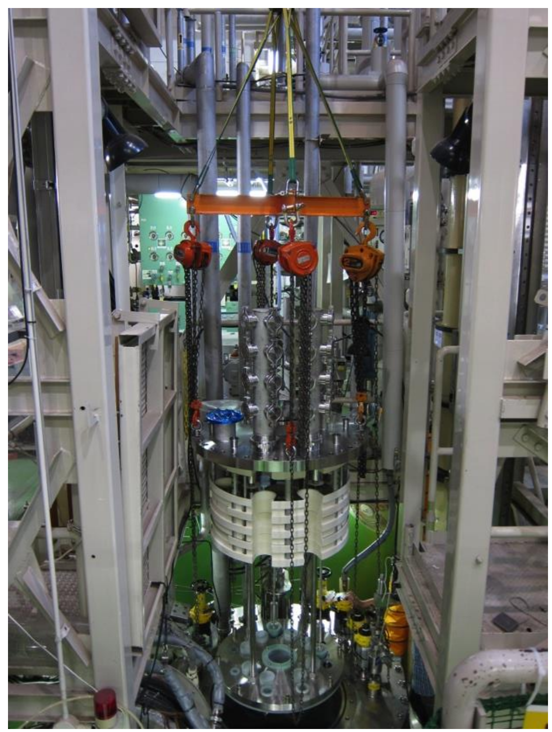
Preparatory Work for Cold Tests

- Modification and procurement of the cryostat for "12 kA, 150 mm aperture" D1 magnet.
  - Old Spec. of 9m-deep vertical cryostat: 7.5kA, 70 mm aperture dedicated for MQXA.
  - New header w/ larger warm bore.
- New 15 kA CLs to be delivered in March 2015
- Upgrade of PC and bus lines. (7.5 kA >> 15 kA).
  - New 15kA-DCCT procured by KEK is being calibrated at CERN.
  - New dump resistor of 75 mΩ with grounding at the middle.
- New DAQ systems

New 15kA bus lines



New 15kA-CLs



New header, cold tube, quench antenna

Deliverables and Near-term Plan

One 2m long model magnet will be built and tested at KEK.

The second model development is also planned.

Up to now, 2m long test coil fabricated. Coil size measurement done.

- Dec. 2014 A short mechanical model
- April 2015 1st 2m long model
  - Field optimization by ROXIE and end spacer design are underway.
  - Coil winding would start at Jan. 2015.
- June 2015 Commissioning of test stand
  - A new header (cryostat flange) for D1. To be inspected by local government.
  - A new pair of 15kA CLs
  - Upgraded 15kA P/C and buses
- Sep. 2015 Cold test of 1st model
- Dec. 2015 2nd 2m long model
- Feb. 2016 Cold test of 2nd model

Summary

- KEK has been engaged in the FP7 HiLumi-LHC design study. R&D of the beam separation dipole magnet, D1, including the 2-m model is underway.
  - Coil ID of 150 mm
  - 35 Tm w/ nominal field of 5.6 T at 12kA under 2 mW/cm^3 (local peak), 25MGy
- Conceptual design is mostly completed and the 1st test coil was fabricated at KEK. Coil size measurement results showed that the coil was made as designed.
- The 1st 2m model will be fabricated spring 2015 and the cold test is anticipated in September 2015.

Impact of possible design changes on field quality

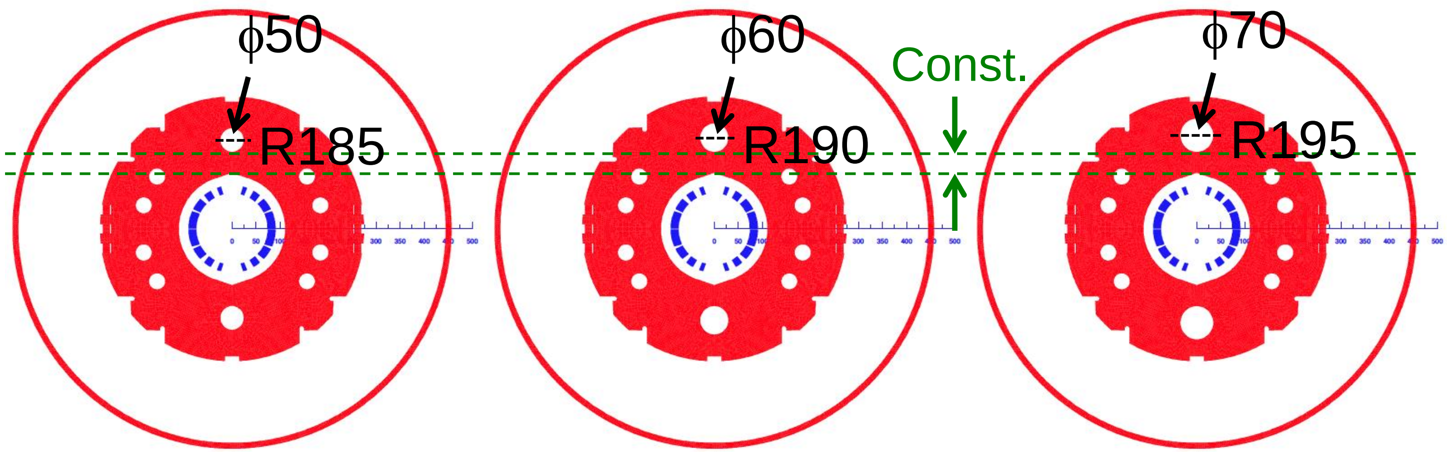
- **Diameter and position of HX holes**(ϕ50~70 in diameter)

  ϕ50 → ϕ60 : Δb_3=+2.0 units

  R185 → R195 with keeping ϕ50 : Δb_3=-5.1 units

  These errors can be corrected by small re-arrangement of the coil blocks

  → NO significant design changes in wedges, collars, and the number of blocks and cables are needed

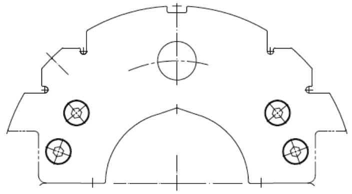


Now the diameter and position of the HX holes have been fixed to ϕ60 at R190

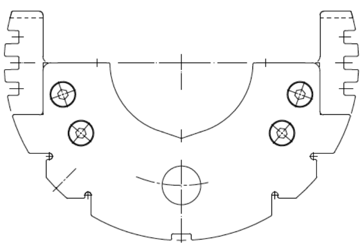
Systematic error

- **Packing factors (PFs) of iron yoke**

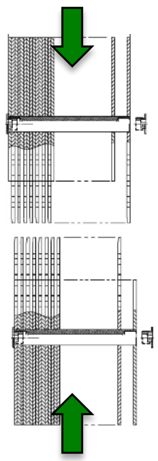
Spacer yoke（t=6）



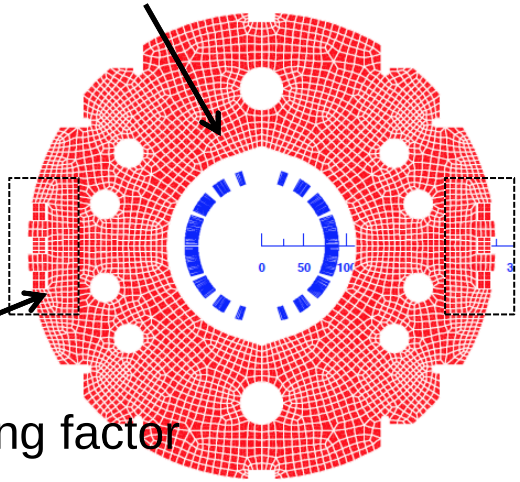
Fixing yoke（t=5.6）



Assembly of yoke stacks



Main body (PF=0.98)



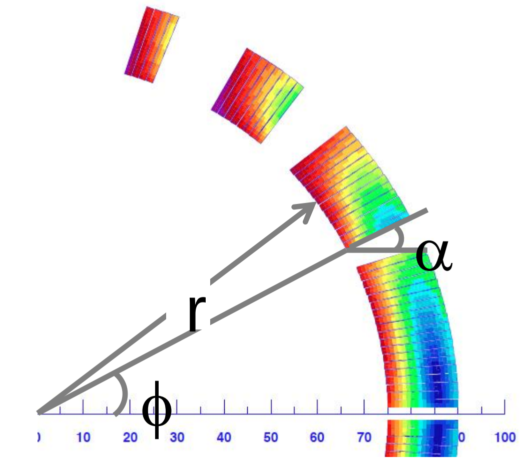
Slot region:
3.4% lower packing factor
than main body

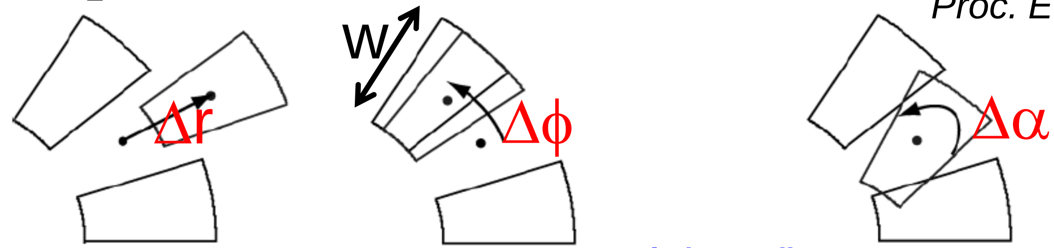
PF=0.98 for whole parts →
PF=0.98 for main body, 0.95 for slot region: Δb_3=-1.2 units

Random geometric error

Coil block displacement in 3 degrees of freedom was considered

Bellesia et al, Proc. EPAC 2006, 2601





r direction

$$\Delta r = d$$

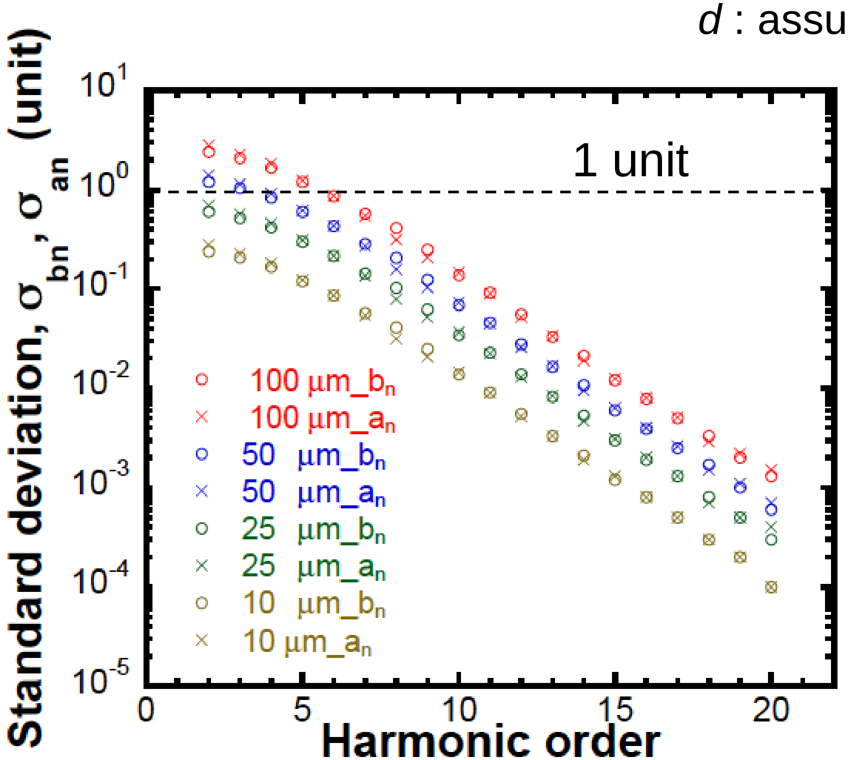
φ(position angle) direction

$$\Delta \phi = \frac{d}{r + \frac{w}{2}}$$

α(inclination angle) direction

$$\Delta \alpha = \frac{2d}{w}$$

d : assumed displacement, *r* : coil aperture, *w* : cable width



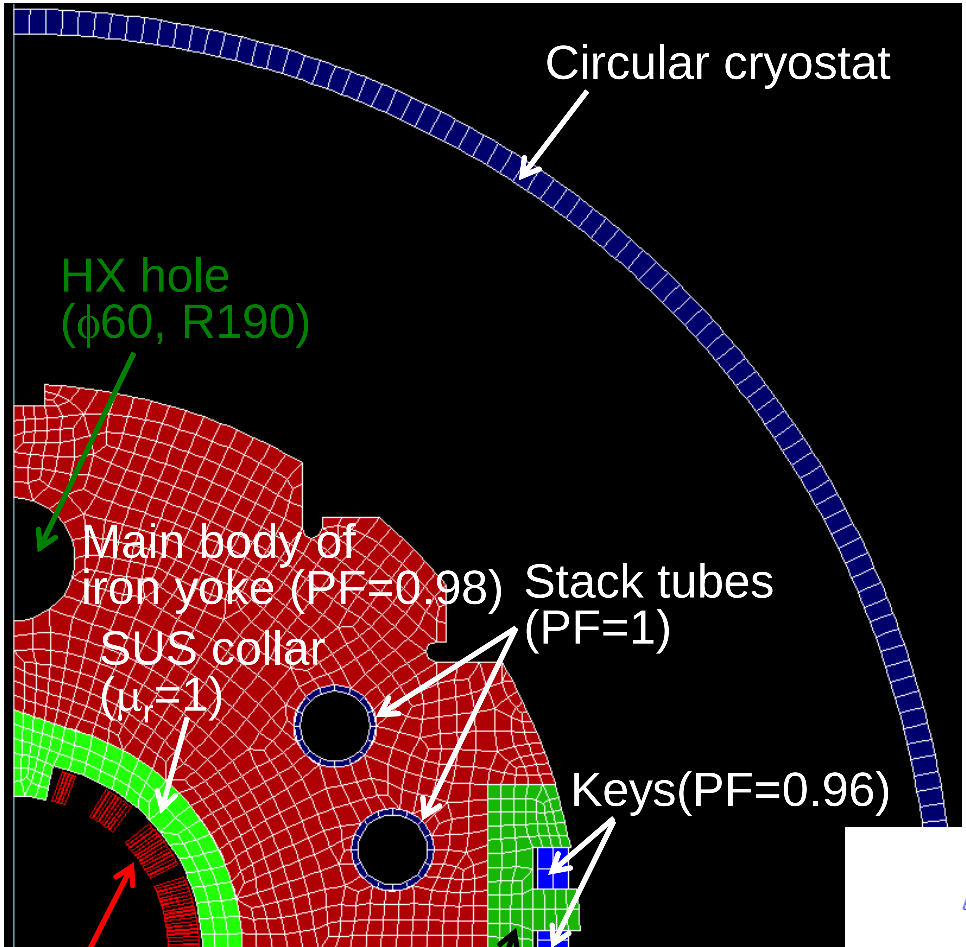
Given *d*

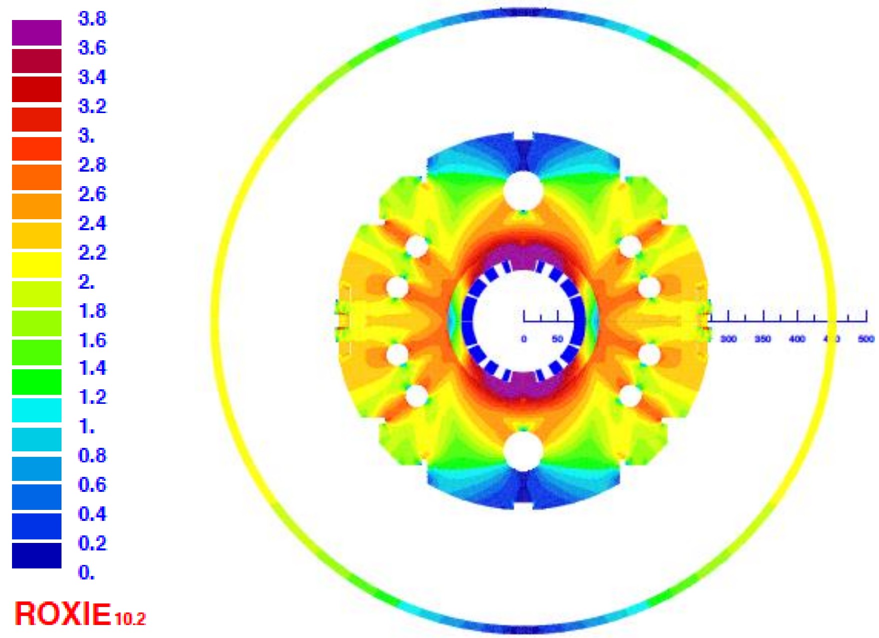
→ A thousand sets of $(\Delta r, \Delta\phi, \Delta\alpha)$ are given by Monte-Carlo method

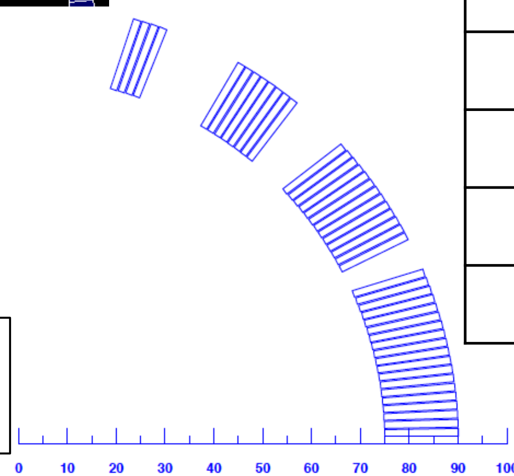
→ Calculation of standard deviation of b_i and a_i

Displacement, *d* (µm)	Stand. dev. of b_3 (unit)
100	2.067
50	1.033
25	0.516
10	0.206

Coil block re-optimization with full iron model







Main field (T)	5.573
b_3 (unit)	-0.059
b_5 (unit)	-0.097
b_7 (unit)	-0.111
b_9 (unit)	0.284
b_{11} (unit)	0.360

Coil block re-optimization in 2-D model has been completed