Design of the new D1 and relevant R&D

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Magnetic design

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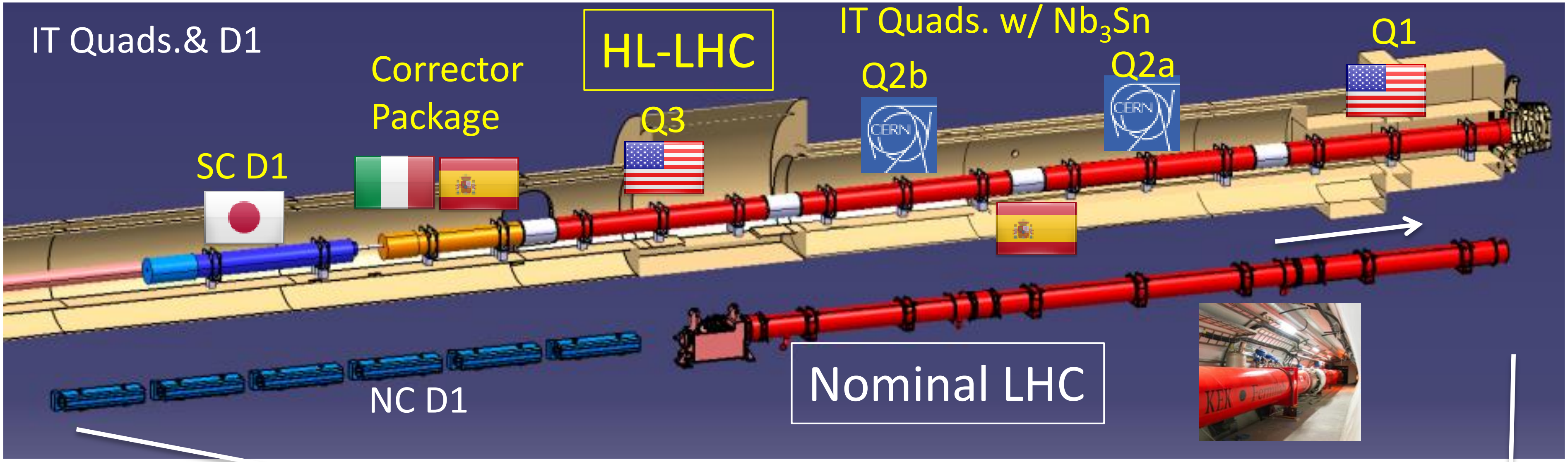
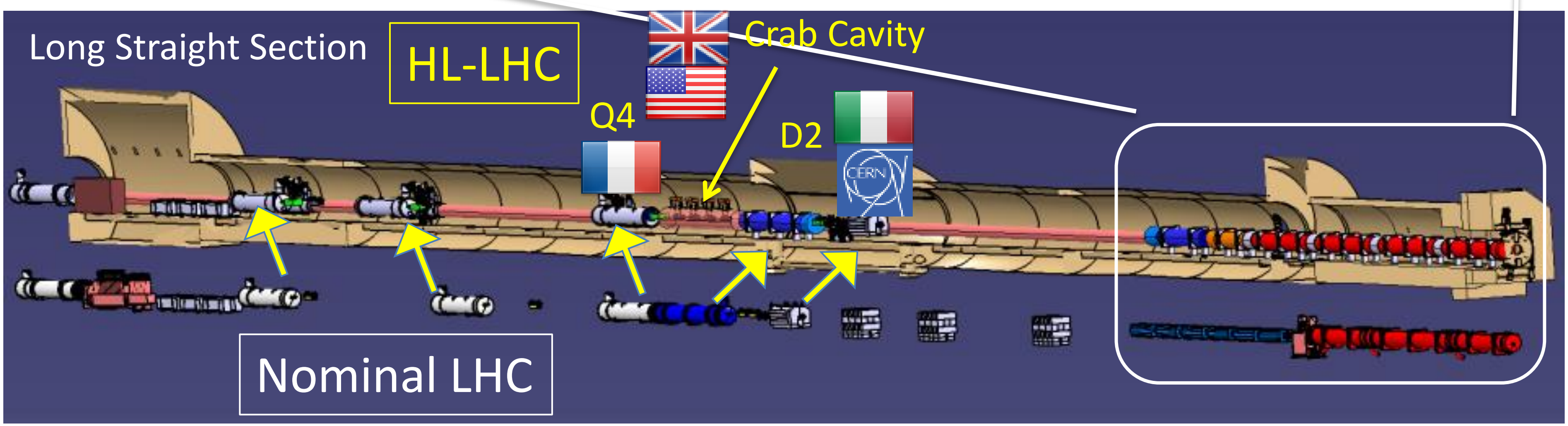
Next talk by Dr. Nakamoto

1. Plans
2. Procurement
3. Insulation
4. Quench protection heaters
5. Collars, yokes
6. Test facilities

Lay out around interaction points, ATLAS and CMS





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

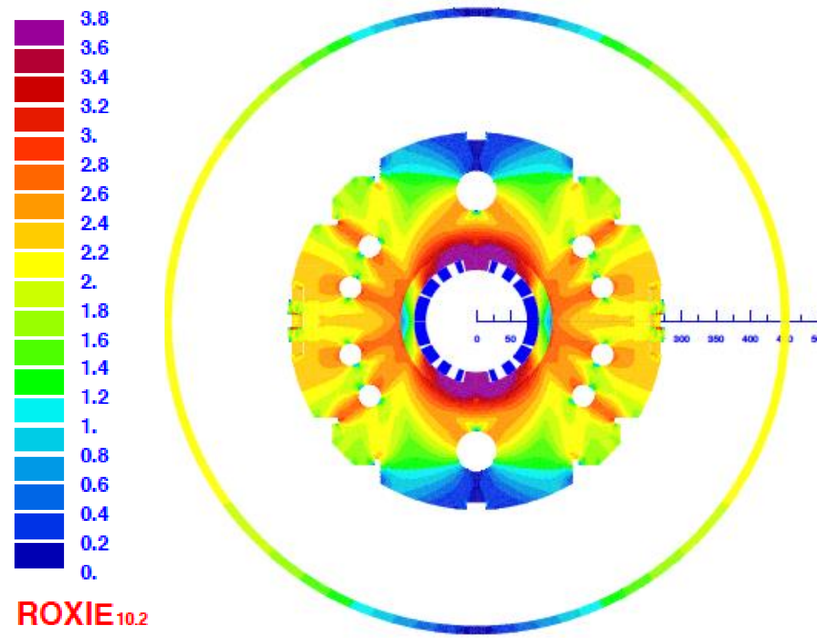
Replacement of current NC D1 by SC D1: Shortening magnet length by 15m

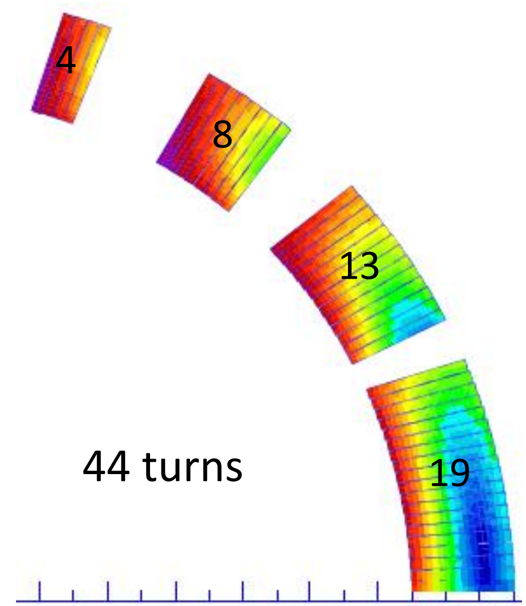
➡ Making room for new crab cavities

Latest design parameters of D1

- *Coil ID:* ***150 mm***
- *Integrated field:* ***35 T m*** *(26 Tm at present LHC)*
  - *5.58 T at 12 kA. L_{coil}=6.3 m*
- *T_{op}: 1.9 K by HeII cooling*
- *Load line ratio (SS):* ***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**

◆**Radiation resistance, cooling capability**

Comparison btw production mag. and 2-m model

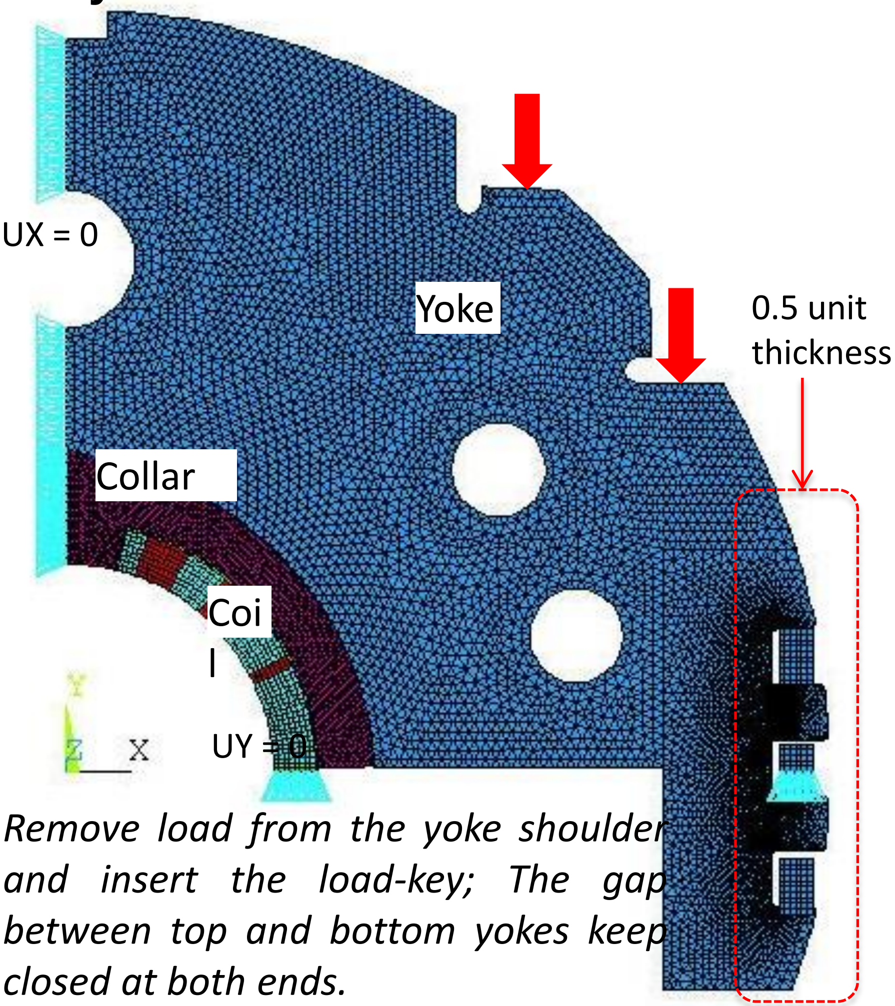
Design parameters	Production	2-m model
Field integral	35 T•m	10.3 T•m
Magnetic length	6.27 m	1.85 m
Coil mechanical length	6.46 m	2.00 m
Magnet mechanical length	6.96 m	2.50 m
Cold mass weight	12 tons	3.8 tons
Cable unit length per coil	568 m	175 m

Magnet design of new D1

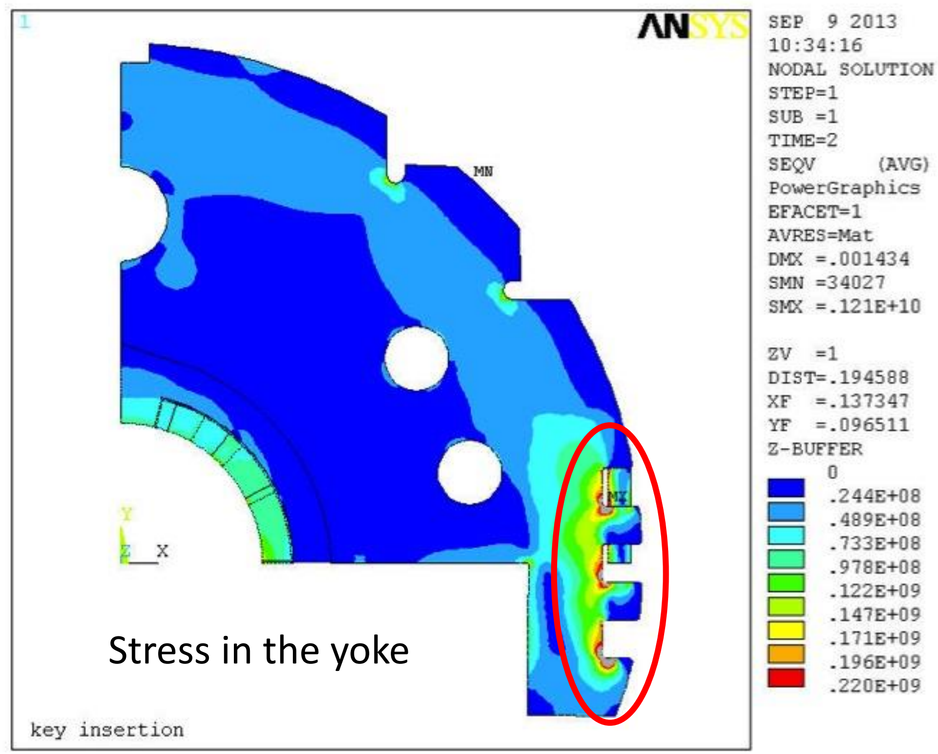
Mechanical analysis

- 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

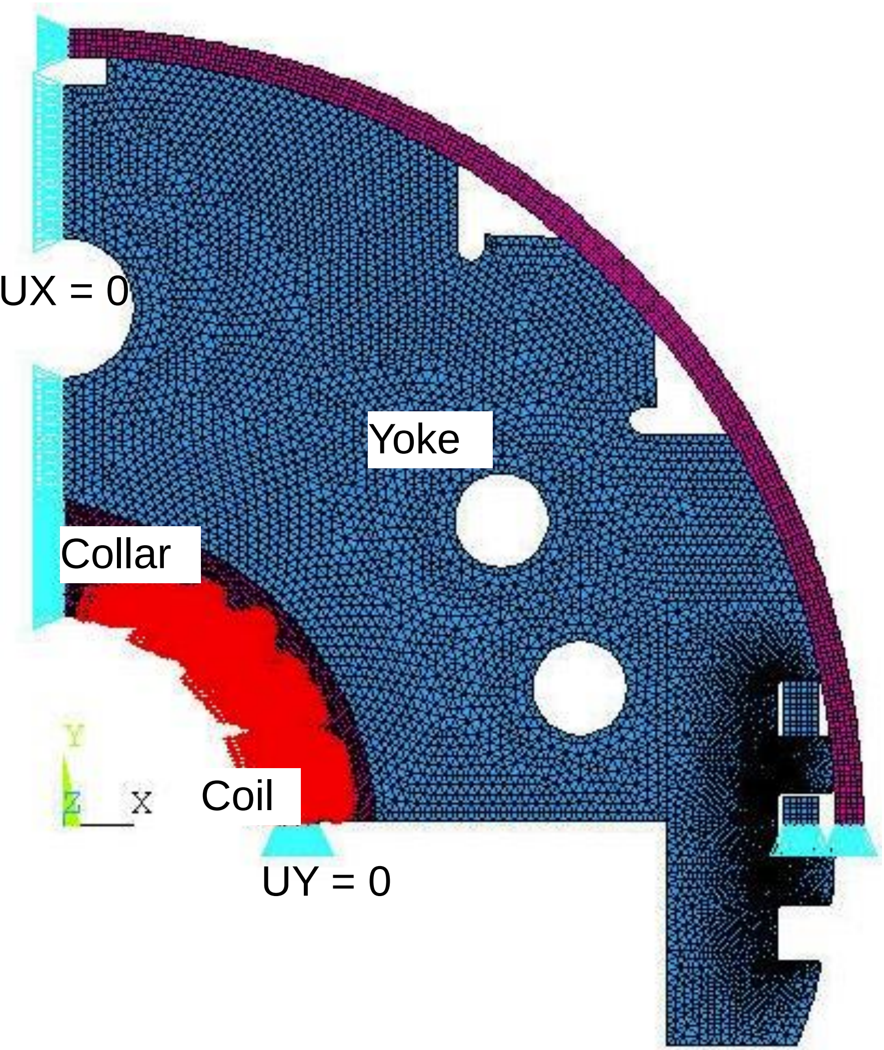


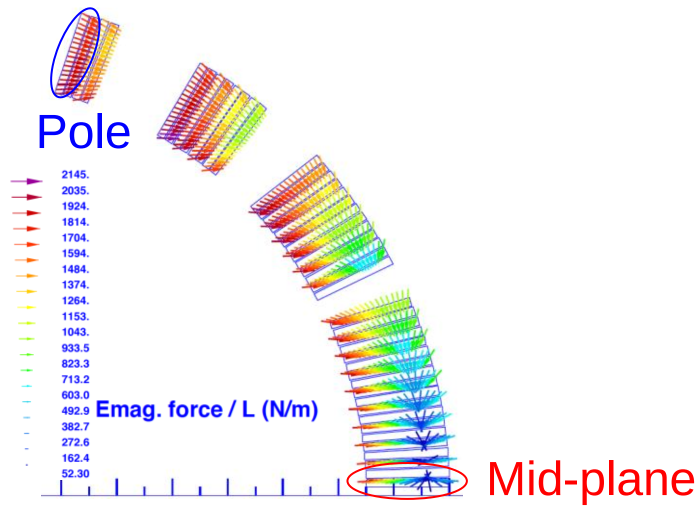
Remove load from the yoke shoulder and insert the load-key; The gap between top and bottom yokes keep closed at both ends.

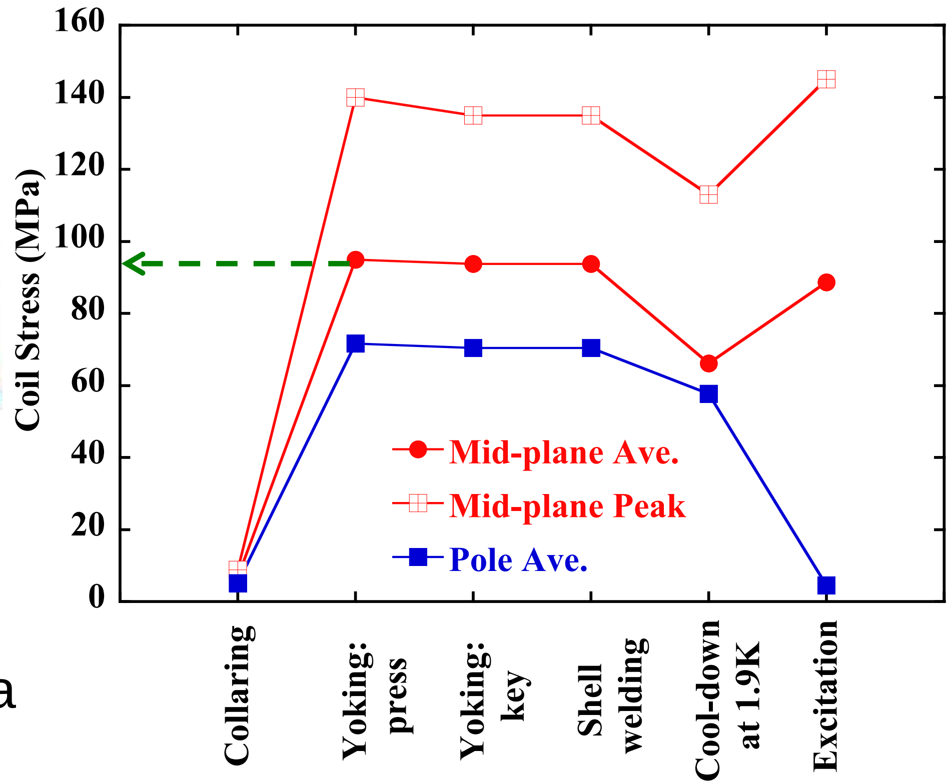


Coil stress

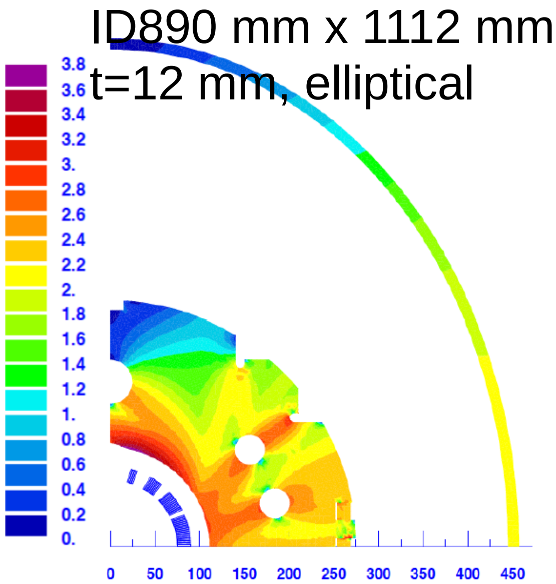
Excitation







Coil stress during yoking: 100 MPa



Consideration on possible error sources

(Change of b_3 by each factor)

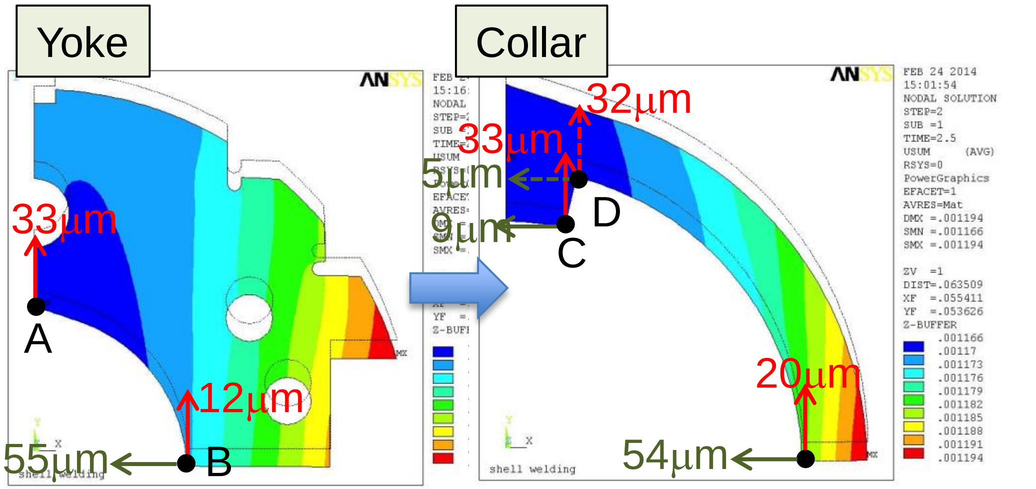
Impact of possible design changes

- 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

Impact of possible design changes on field quality

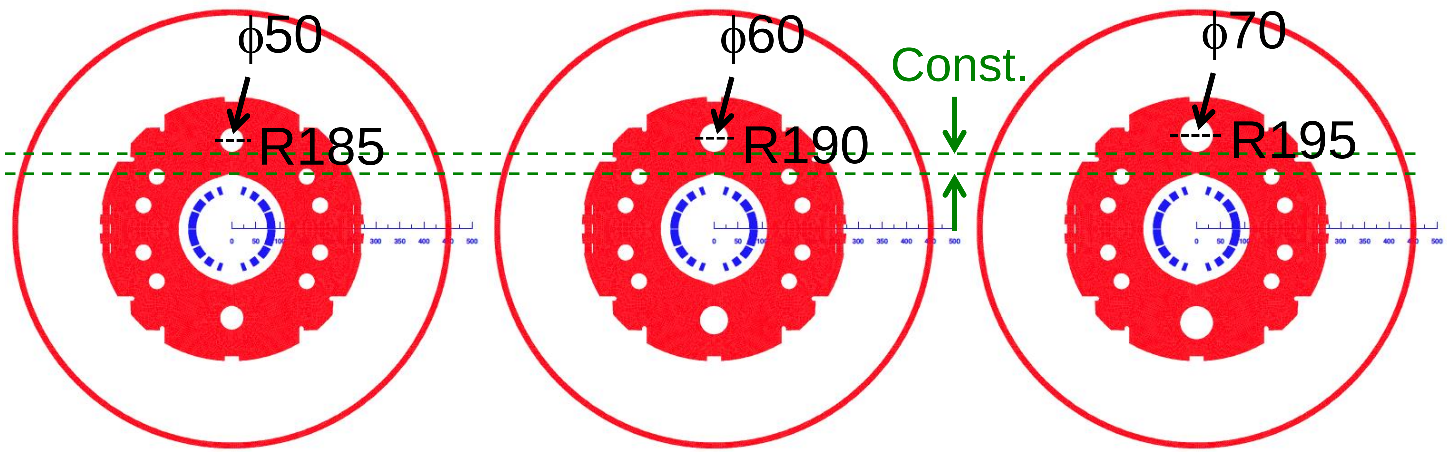
- **Diameter and position of HX holes**(ϕ50~70 in diameter)

  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

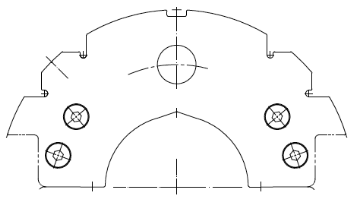


Now the diameter and position of the HX holes have been fixed to ϕ60 at R190

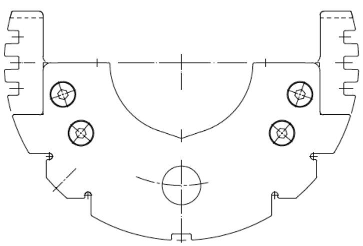
Systematic error

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

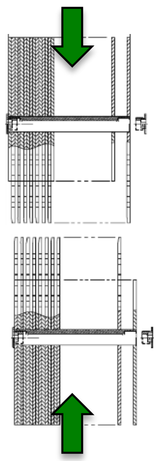
Spacer yoke（t=6）



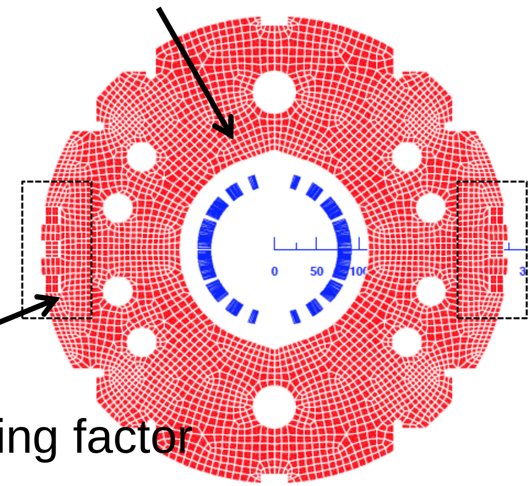
Fixing yoke（t=5.6）



Assembly of yoke stacks



Main body (PF=0.98)



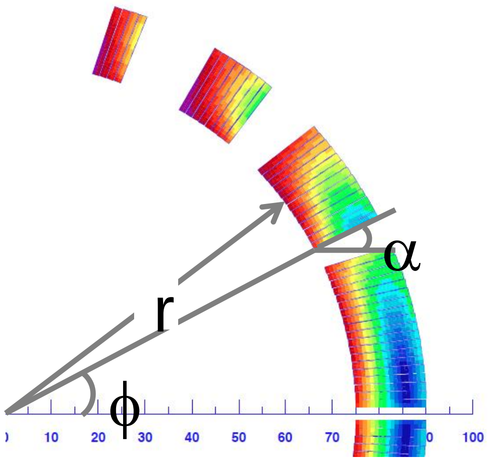
Slot region:
3.4% lower packing factor
than main body

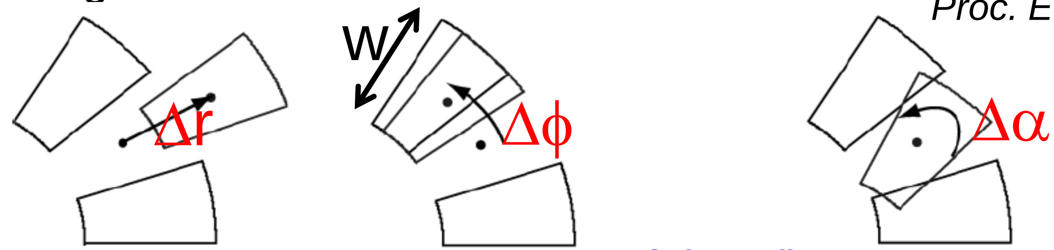
PF=0.98 for whole parts →
PF=0.98 for main body, 0.95 for slot region: Δb_3=-1.2 units

Random geometric error

Coil block displacement in 3 degrees of freedom was considered

Bellesia et al, Proc. EPAC 2006, 2601





r direction

$$\Delta r = d$$

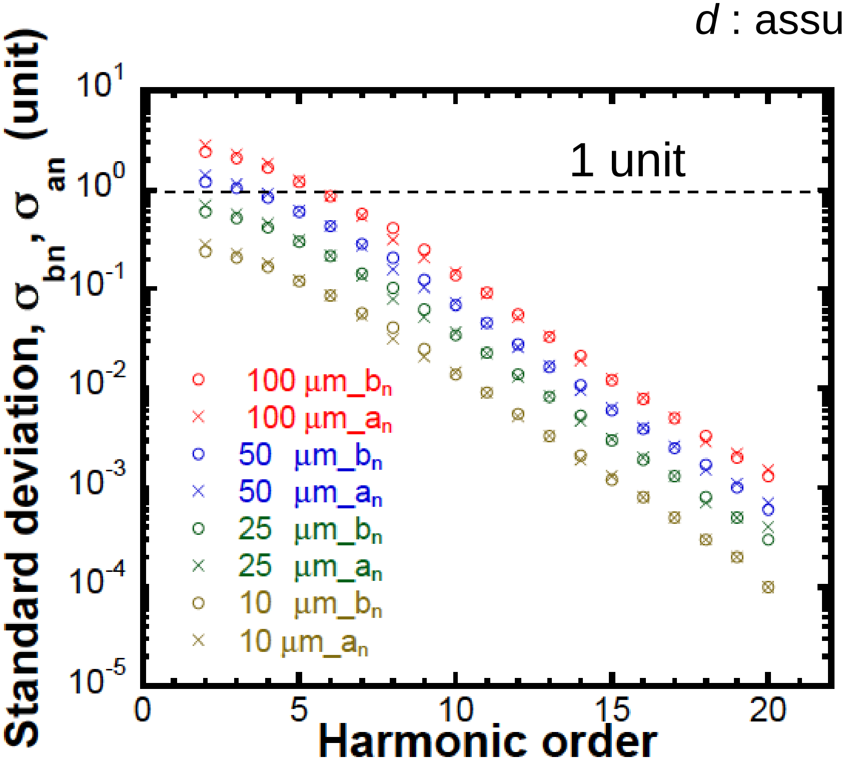
φ(position angle) direction

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

α(inclination angle) direction

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

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



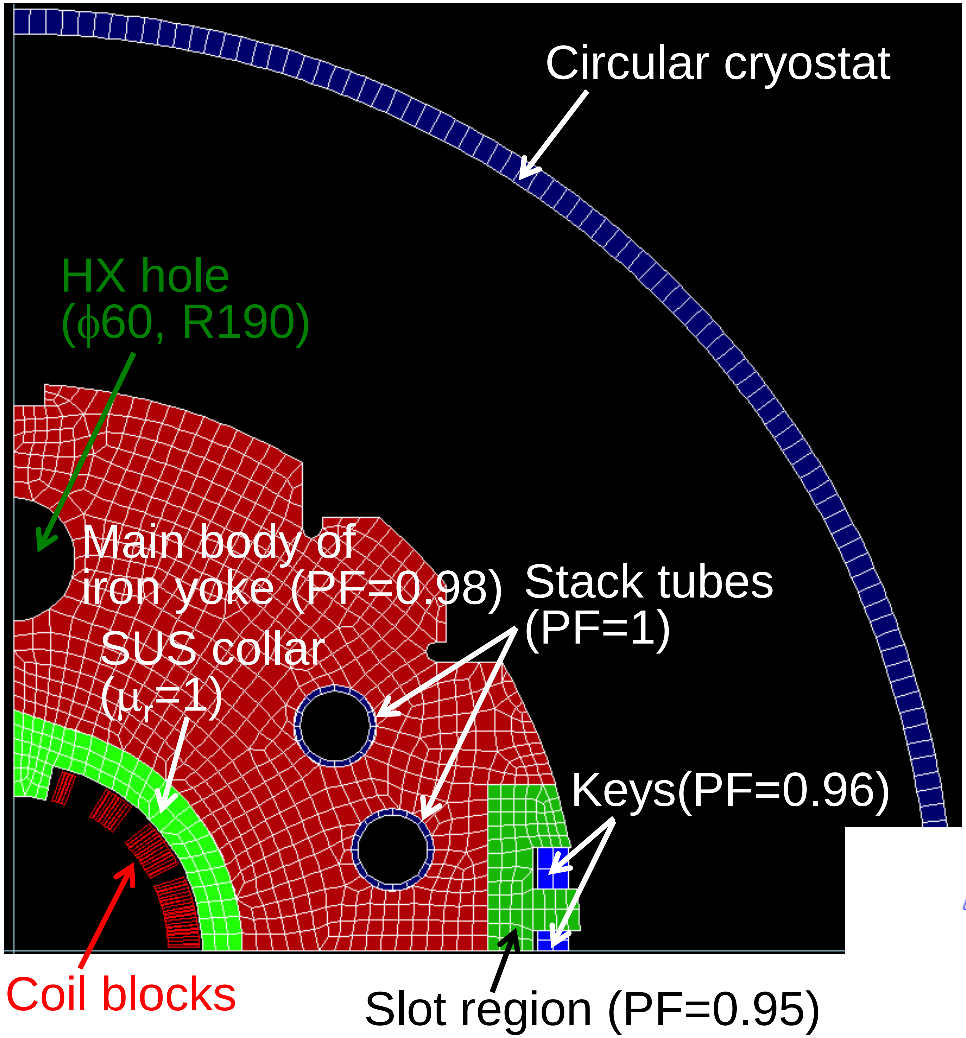
Given *d*

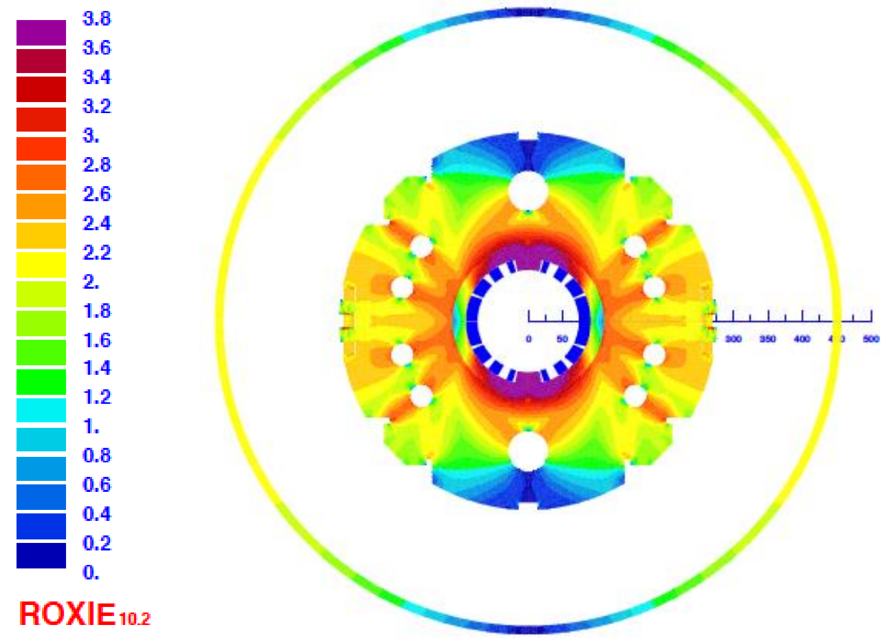
→ A thousand sets of (Δr, $\Delta\phi$, $\Delta\alpha$) are given by Monte-Carlo method

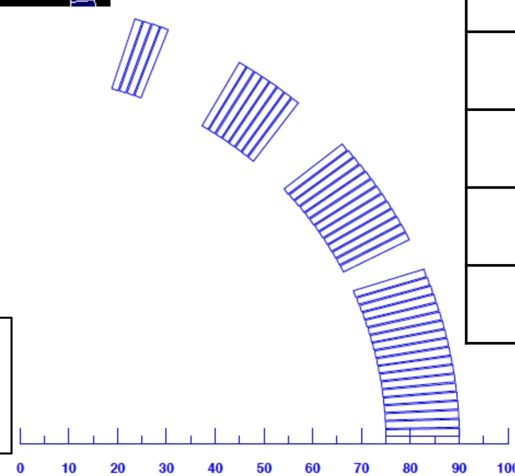
→ Calculation of standard deviation of b_i and a_i

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





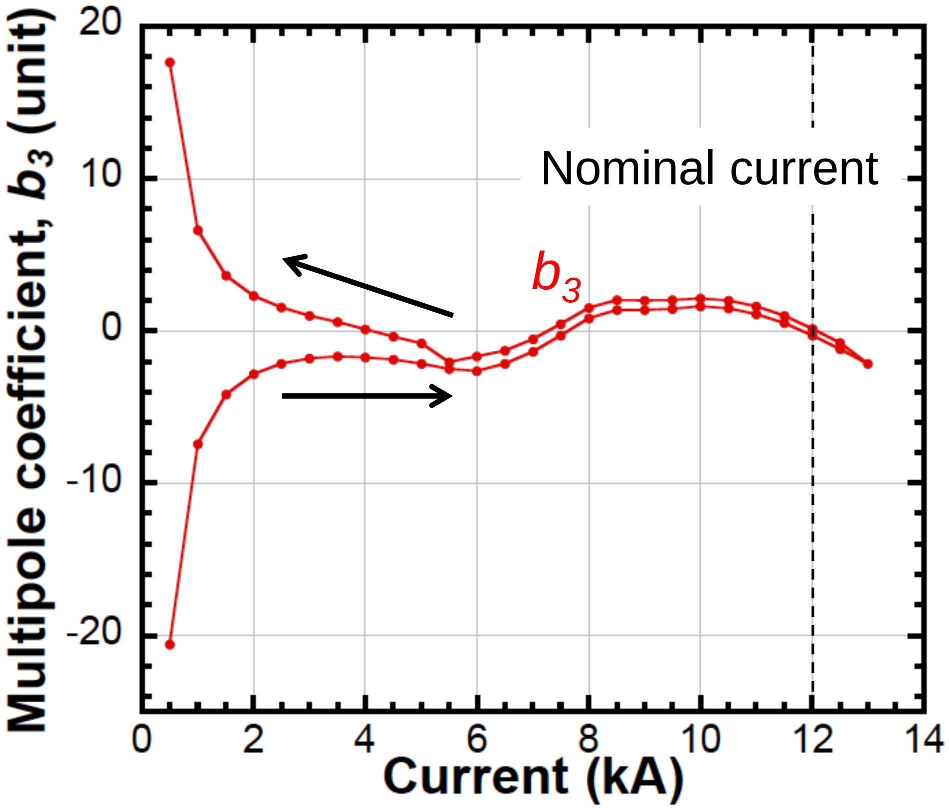


Main field (T)	5.573
b_3 (unit)	-0.059
b_5 (unit)	-0.097
b_7 (unit)	-0.111
b_9 (unit)	0.284
b_{11} (unit)	0.360

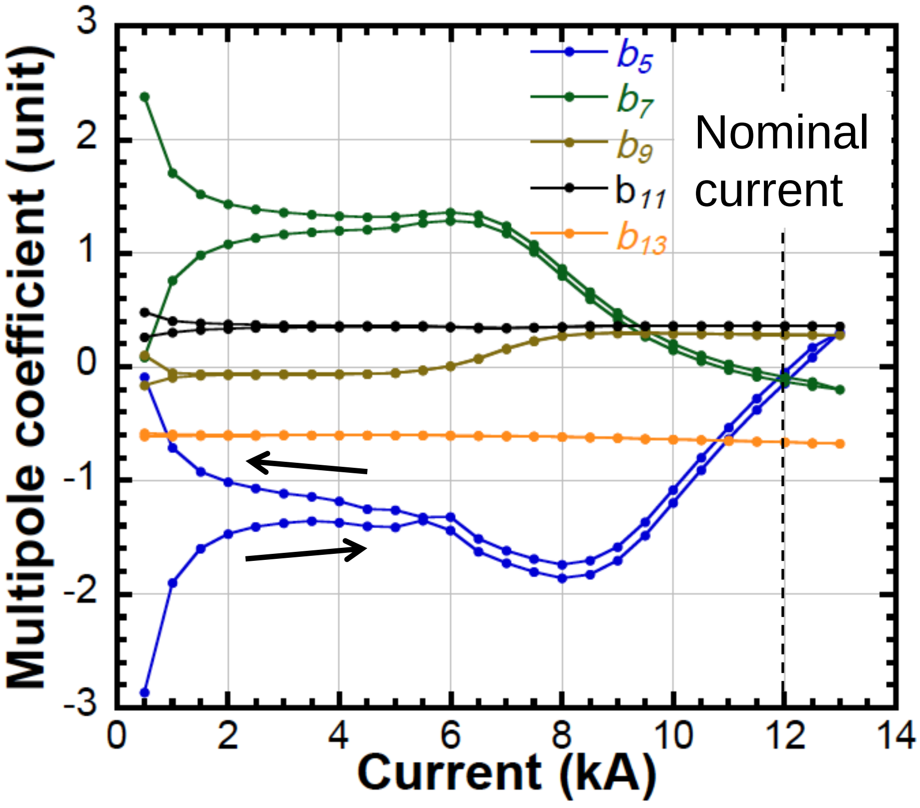
Coil block re-optimization in 2-D model has been completed

Variation of multipole coefficients

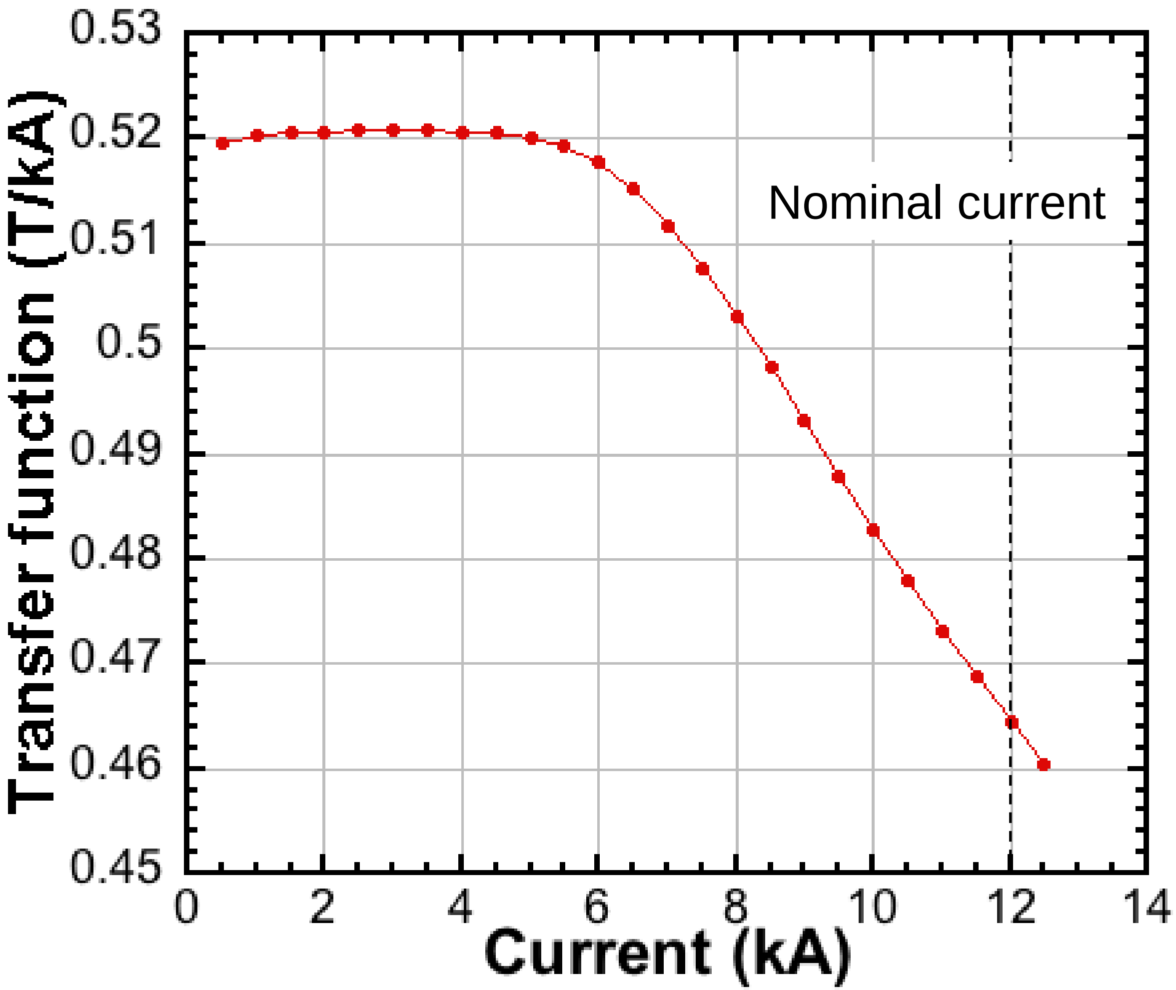
b_3



$b_5 \sim b_{13}$



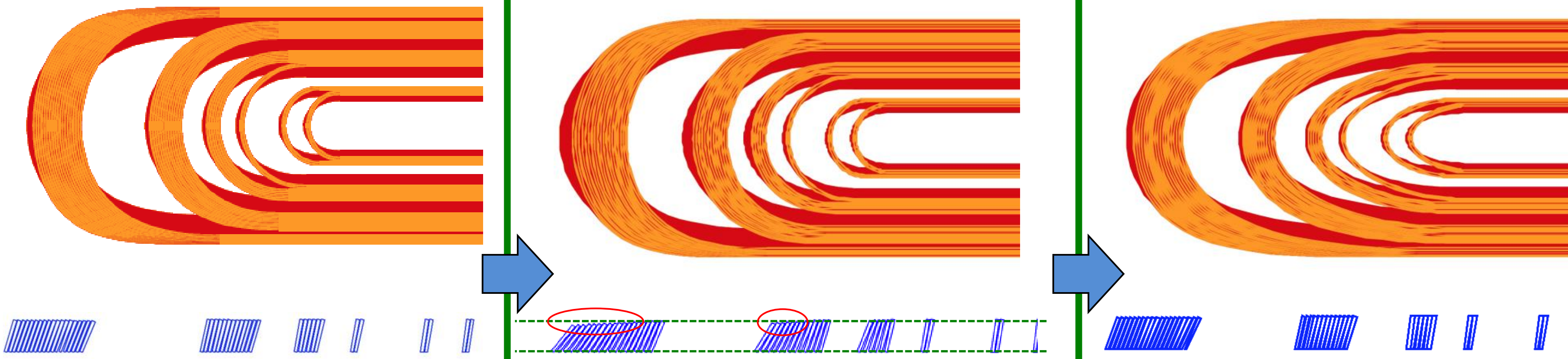
Transfer function



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

Coil end design

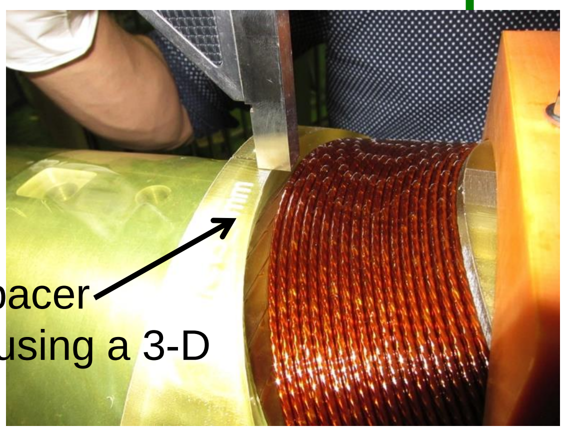
Old version | Coil end found in practice winding (2-m test coil) | Modified design



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

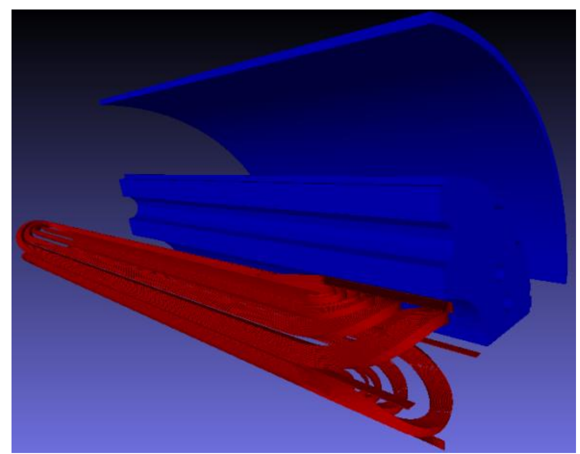
→ Difference in height between end spacer and cables

- Coil end will be modified to have longer length



End spacer made using a 3-D printer

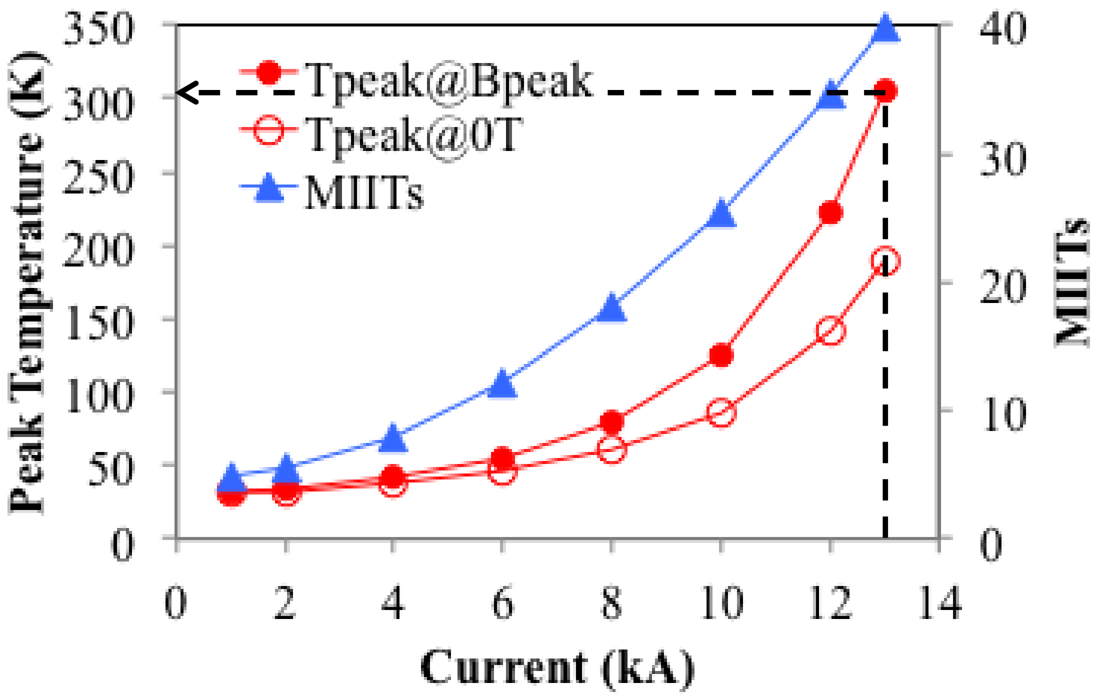
- Length of each coil block is being optimized to minimize multipole coefficients



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.

Fabrication of a test coil for the 2-m model

Purposes of test coil fabrication 1

To verify the following items

- Toolings for winding (Mandrel, Forming block, …)
- Operation test for winding machine, hydraulic press, heater,…
- Design of end spacers, winding and measurement of coil end
- Confirmation of curing cycle (temperature profile and homogeneity, pressure)
- Practice for quality assurance
  electrical tests of coil (ground fault, cable resistance, turn-turn insulation,…)

Once test coil fabrication is completed, it will be used for

- Commissioning of coil size measurement
- Practice for attaching voltage leads
- 200mm-long mechanical model

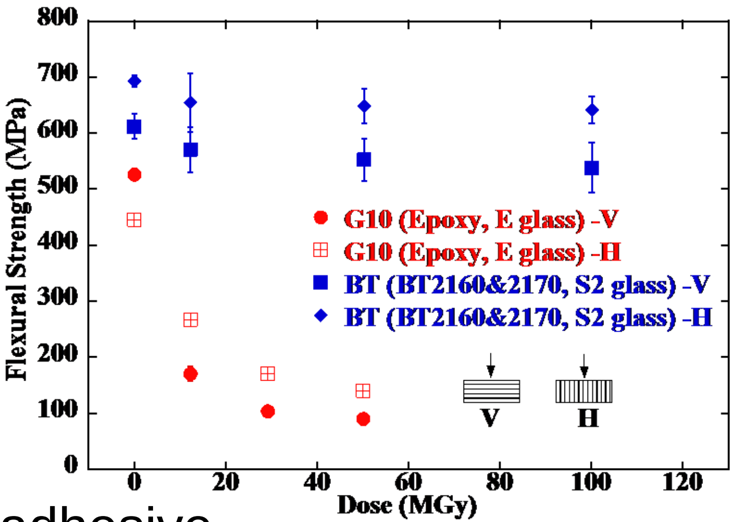
Purposes of test coil fabrication 2

- Radiation resistant GFRP end spacers and wedges

  End spacers and wedges made of BT resin + S2 glass fibre were used for the first time

  End spacers were machined in house

Can newly developed hard GFRP end spacers be accommodated to the cable by curing ?



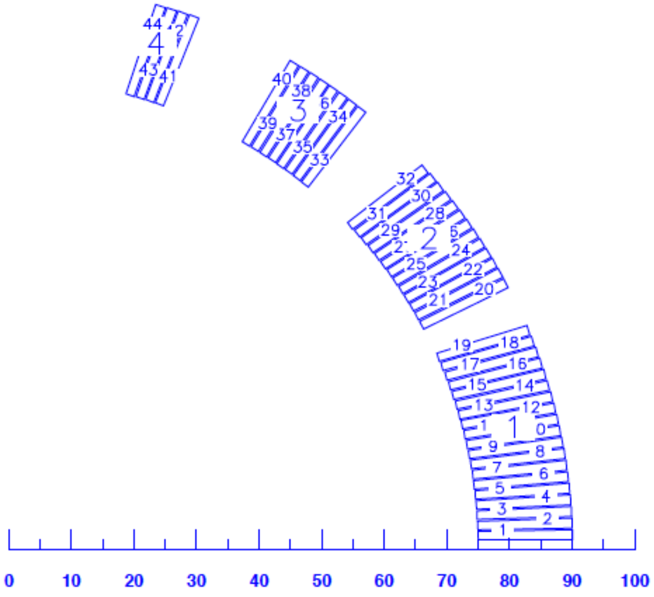
- Curing with radiation resistant cyanate ester adhesive

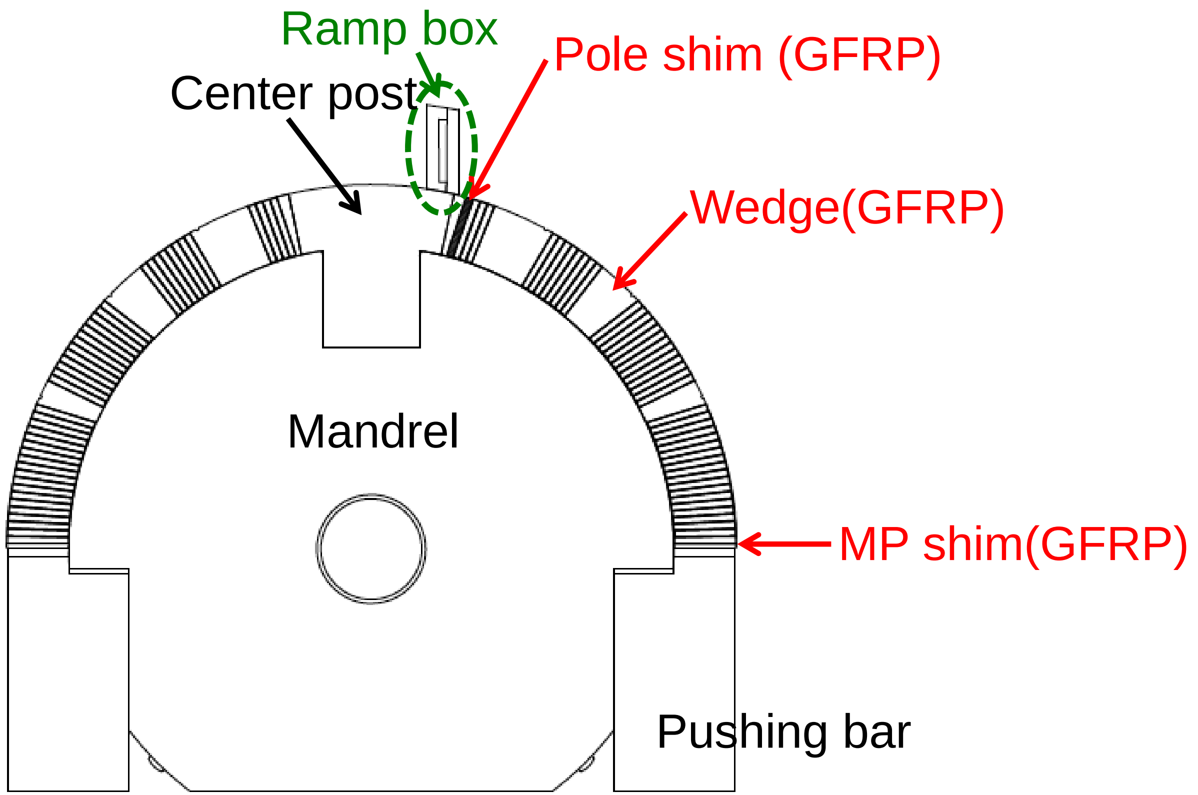
  Curing temperature around 200^{o}C is needed, while it should not influence on contact resistance between the strands (lower than melting point of Ag-Sn coating)

  To consider compromised heat treatment condition and check if bonding strength is strong enough even for a single layer coil

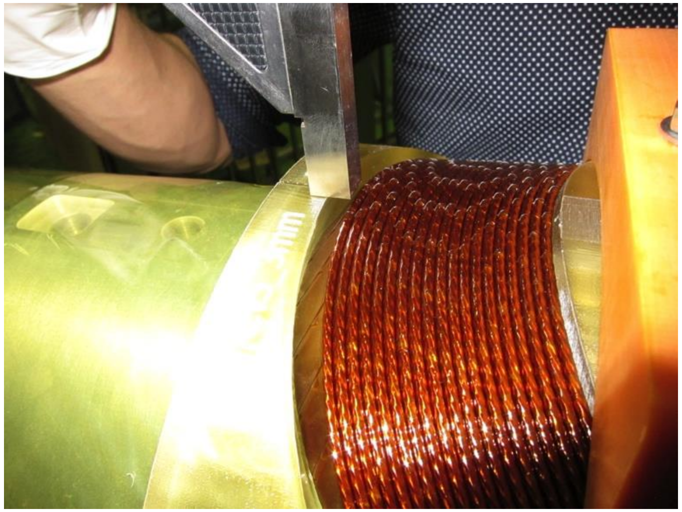
Coil structure

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)





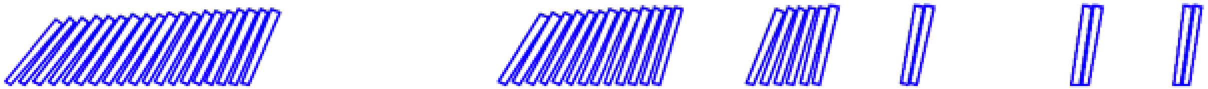
Coil end



Practice winding

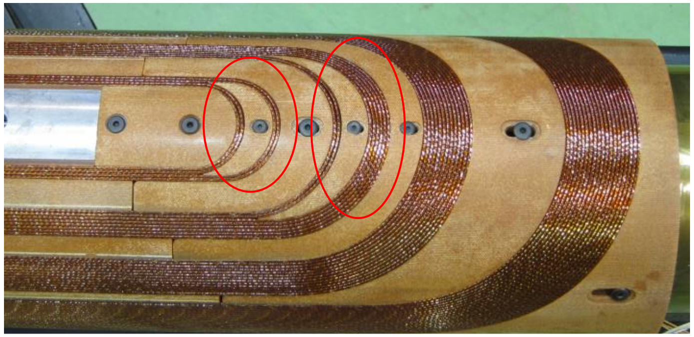
The cable angle was inclined too much and large gap between the cable and end spacer remained

End spacer was re-designed to accommodate to the inclined cable
(but further modification for the 2m-model coils should be needed)



Lead end

Return end



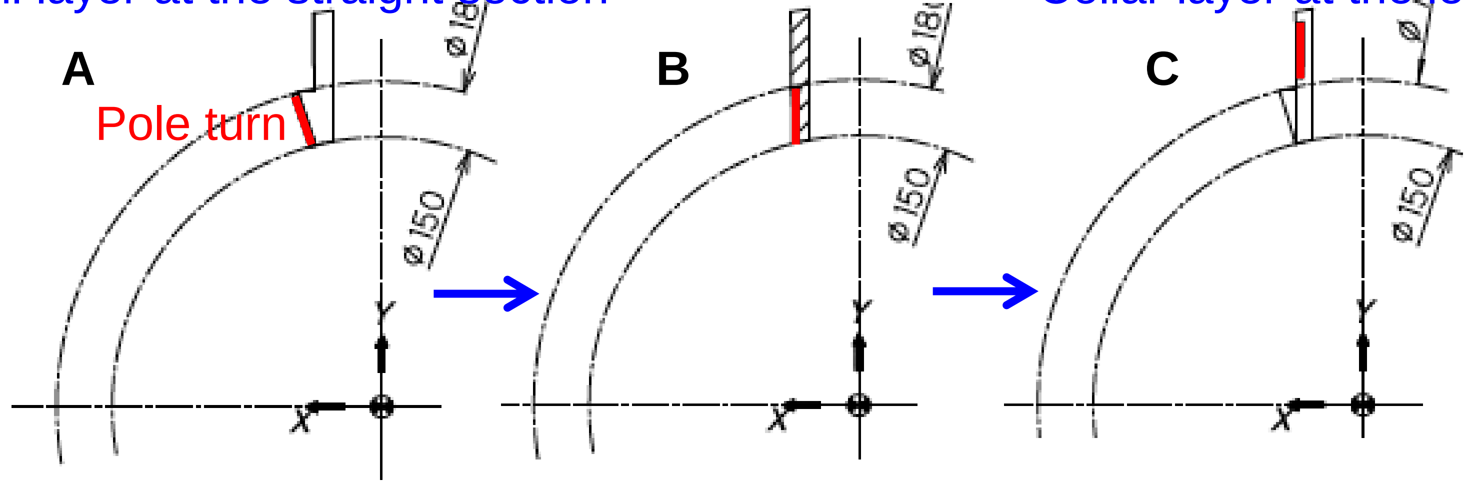
Inner 2 blocks were subdivided to reduce peak field

Layer jump

2D cross-sections of the layer jump

Coil layer at the straight section

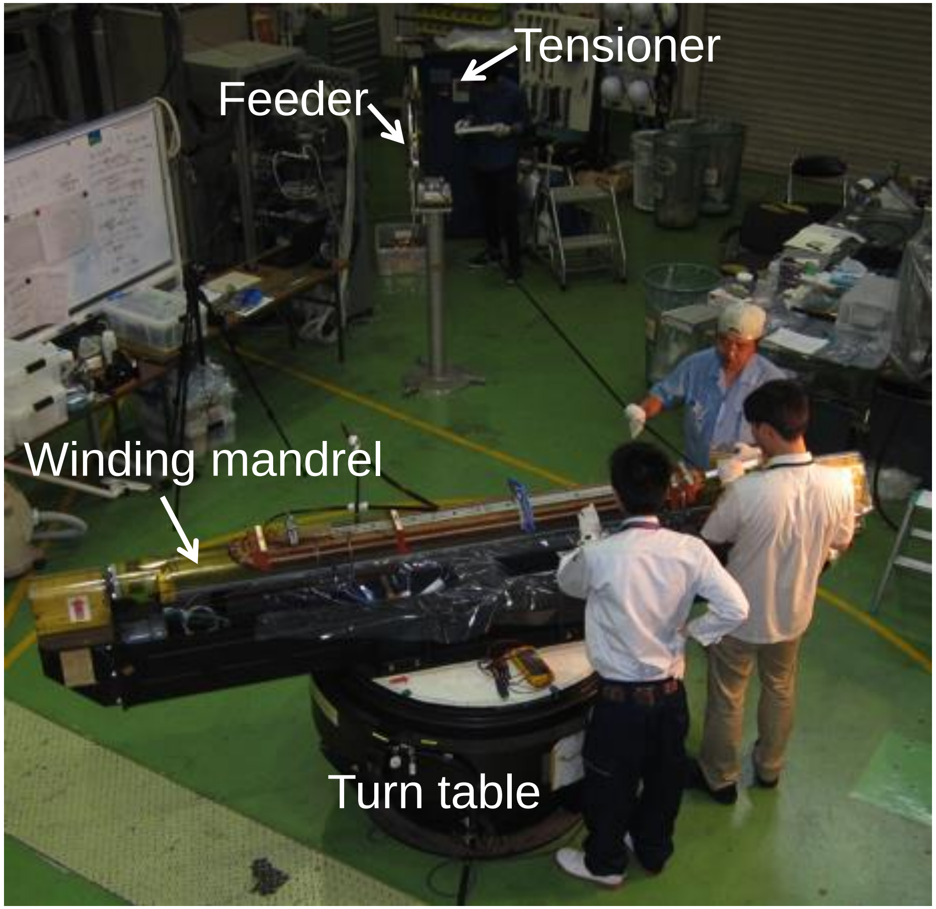
Collar layer at the lead end



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

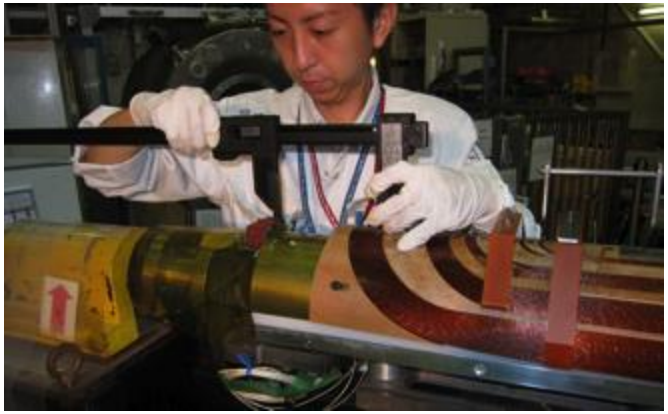
Coil winding

Winding machine

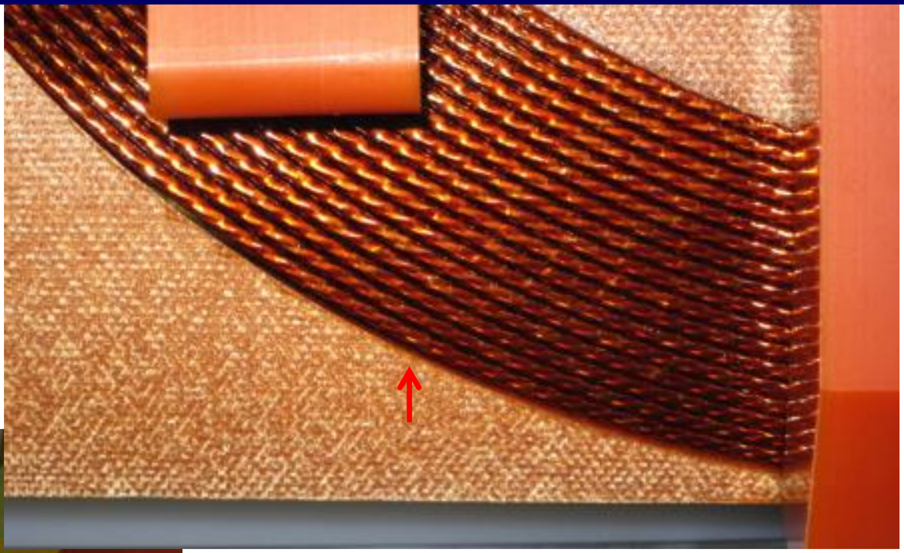


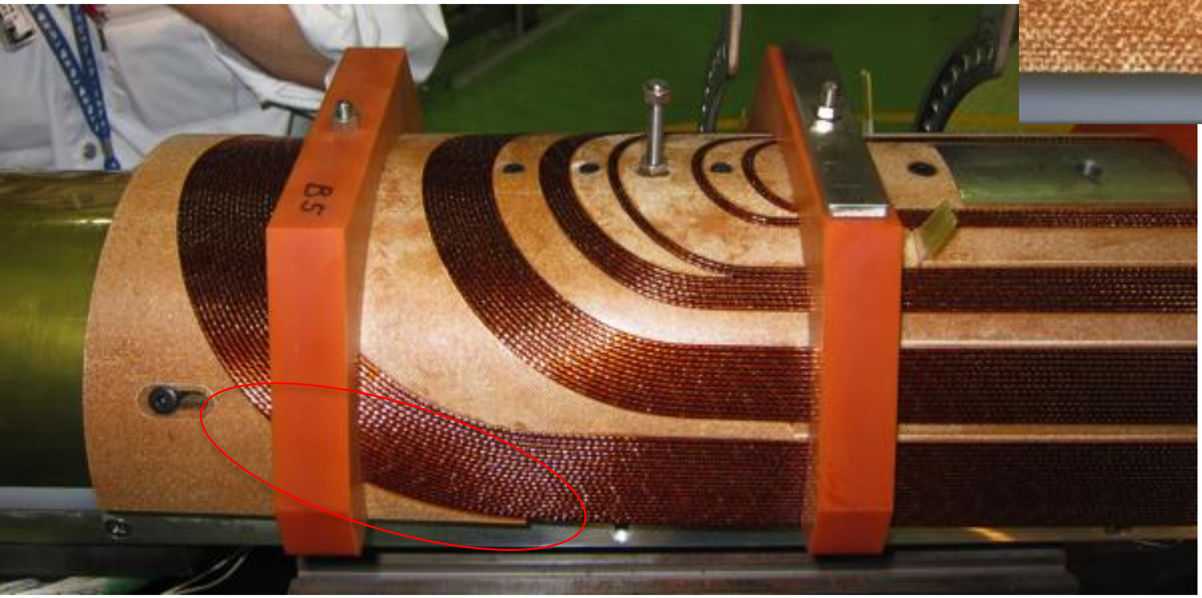
Winding tension: Started from 40.9 kgf, decreased by 0.25 kgf/turn

Measurement of cable positions and angles



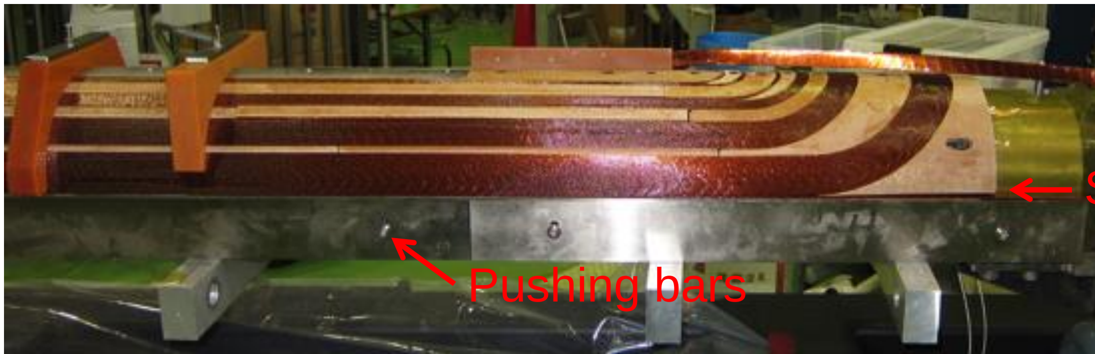
Fitting of end spacer to cable

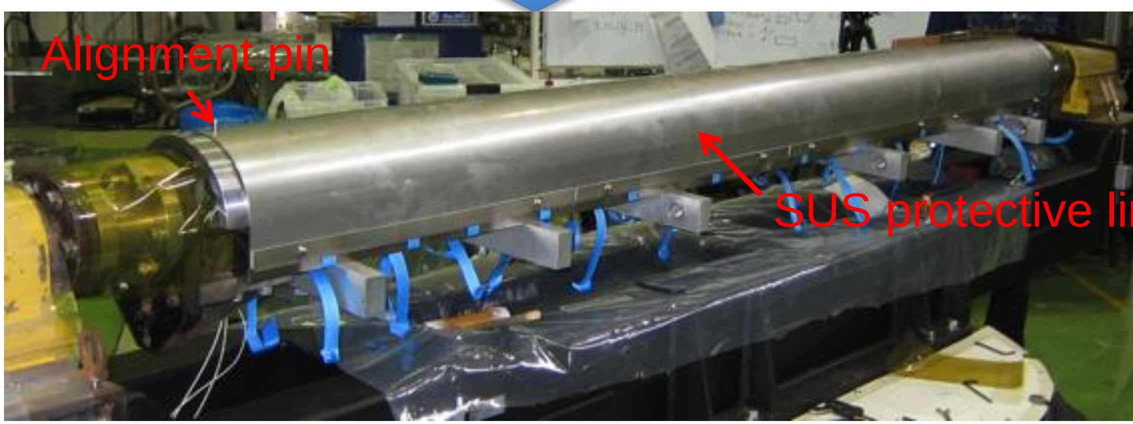




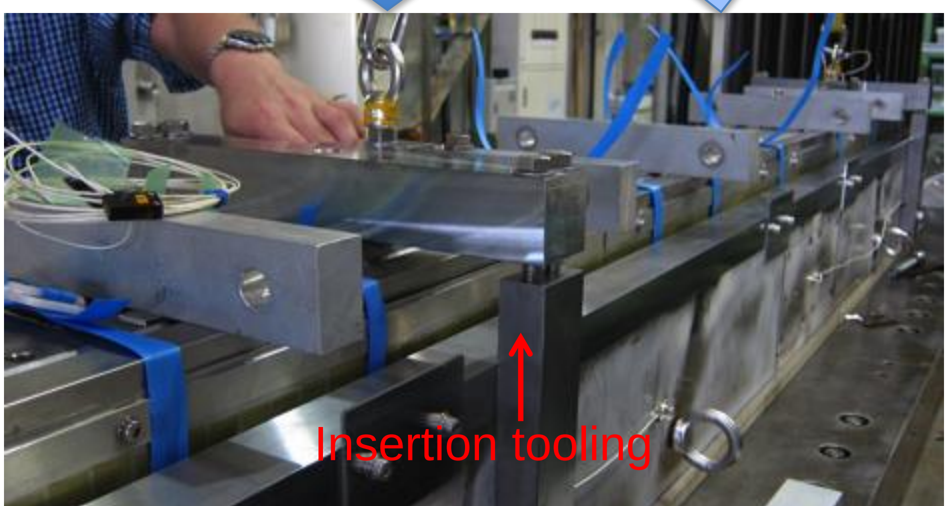
Gap between the end saddle and the cable remained
→ We checked if the gap can be closed after curing

Preparation for curing

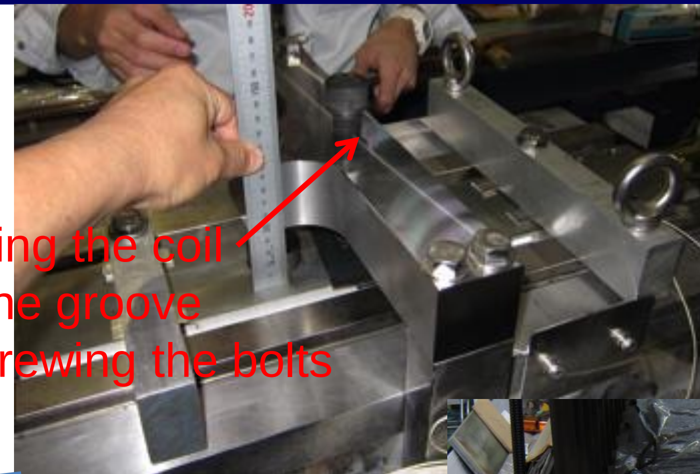


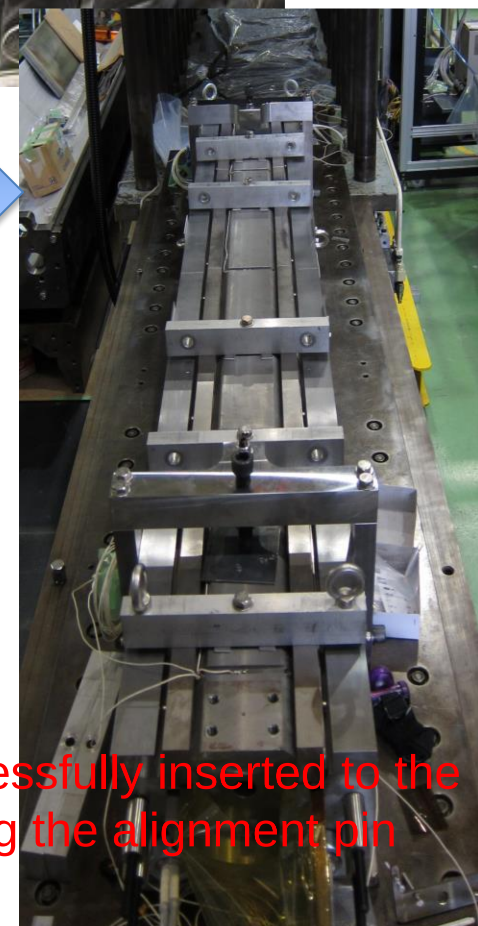


Transfer of coil into forming block



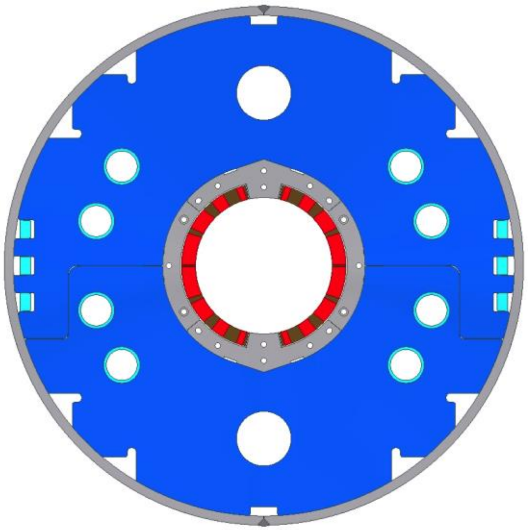
Pushing the coil
into the groove
by screwing the bolts





The coil was successfully inserted to the forming block using the alignment pin and jigs

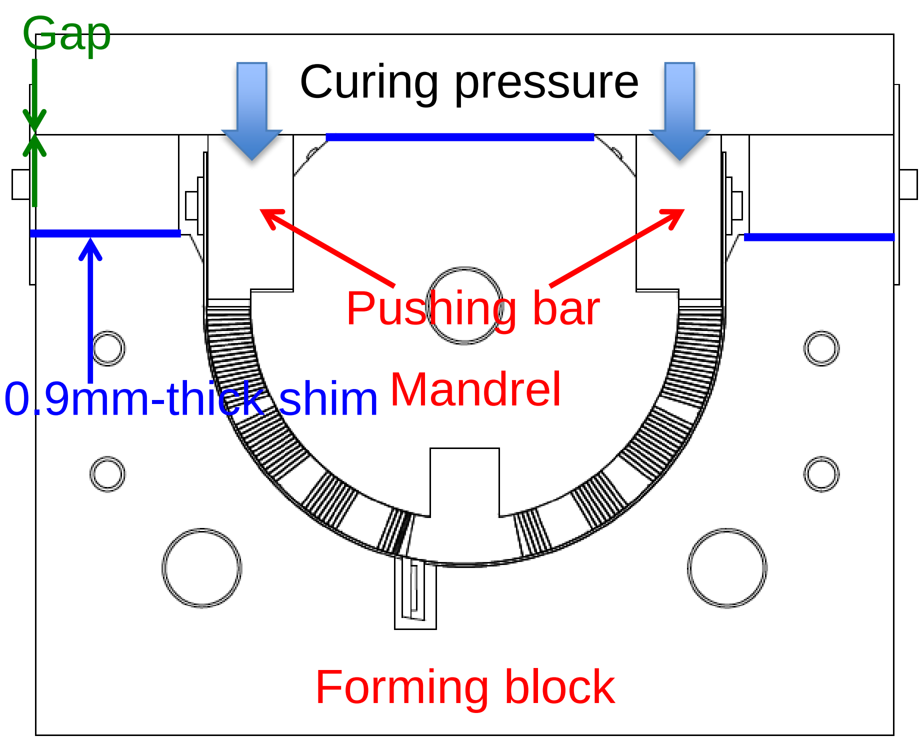
How much should coil be compressed in curing ?

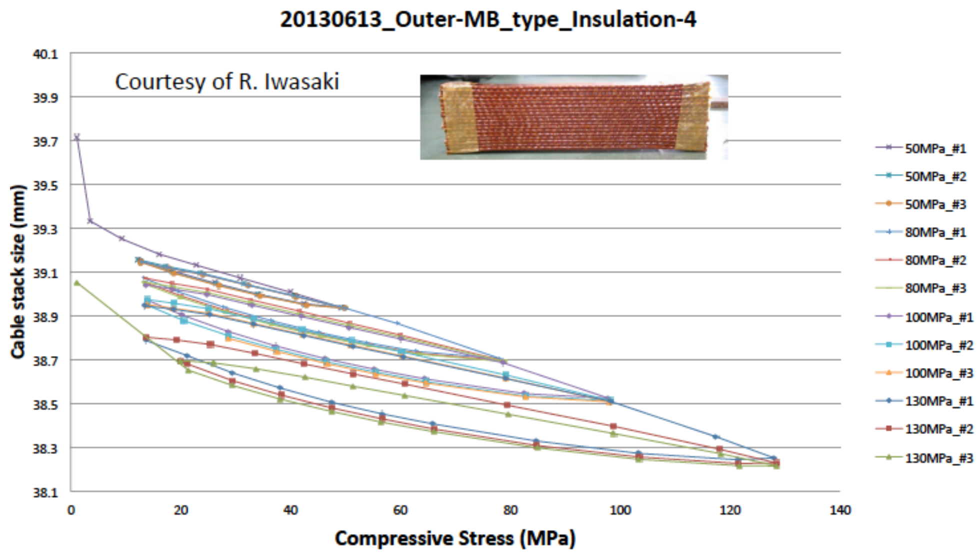


Final size of coil is determined by yoking

<u>Pressure applied to coil</u>
Curing: 50 MPa
Yoking: 100 MPa (max) → 80 MPa

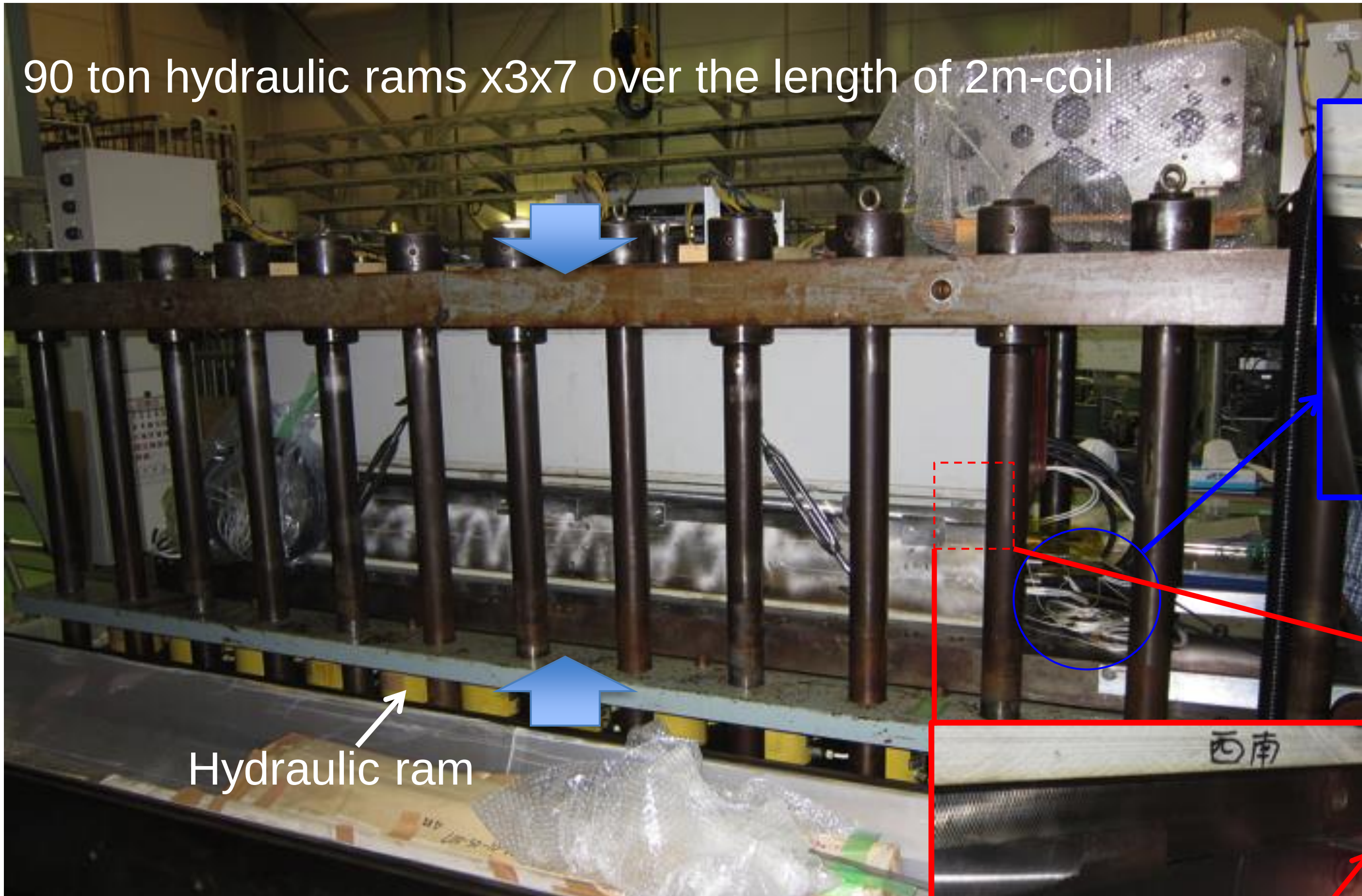
From the results of 10 stack measurement (22 cables), coil after curing should be larger by 0.9 mm than the final size



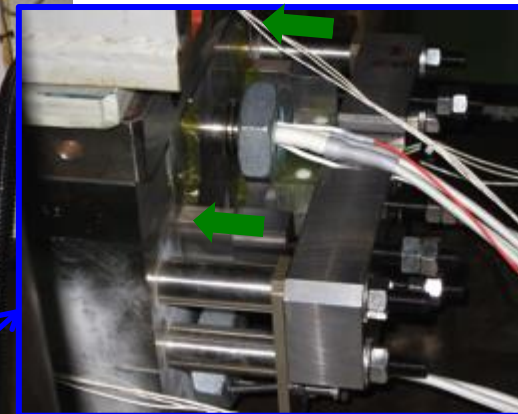


0.9 mm-thick shims were inserted and coil was compressed until the gap was closed

Curing press

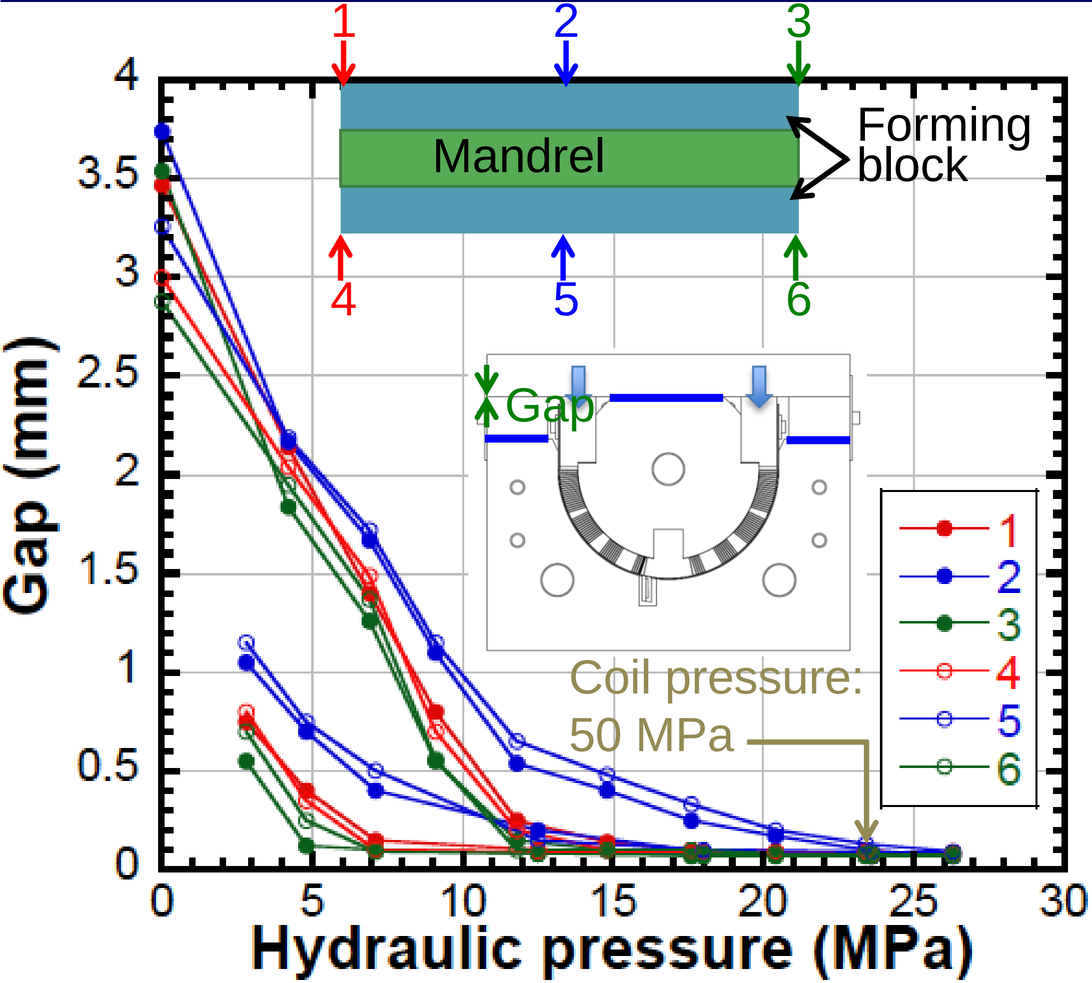


Longitudinal load
(5.2 tonf)

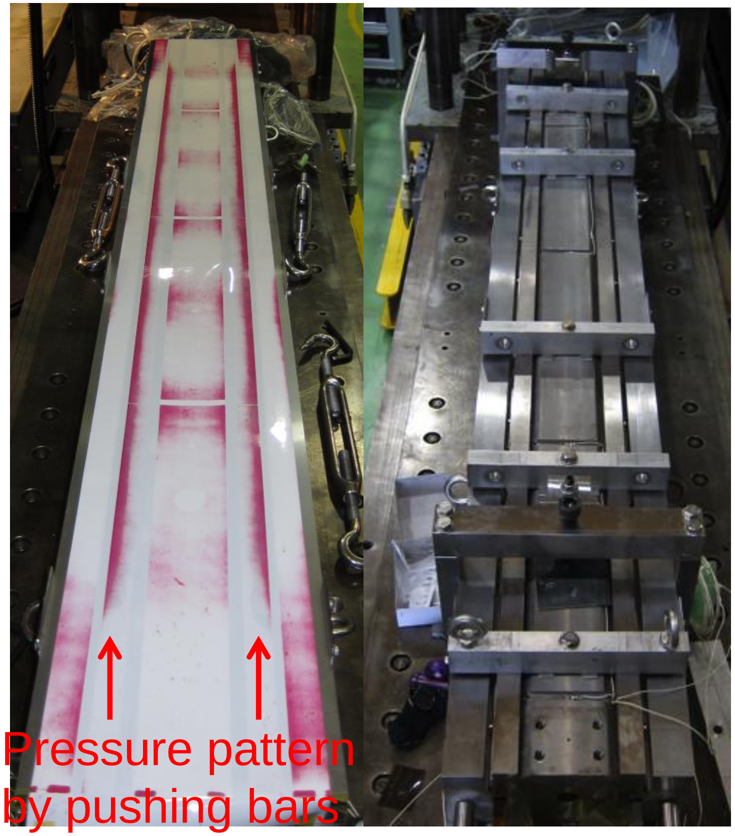


Vertical load was applied incrementally until the gap was closed

Determination of curing pressure



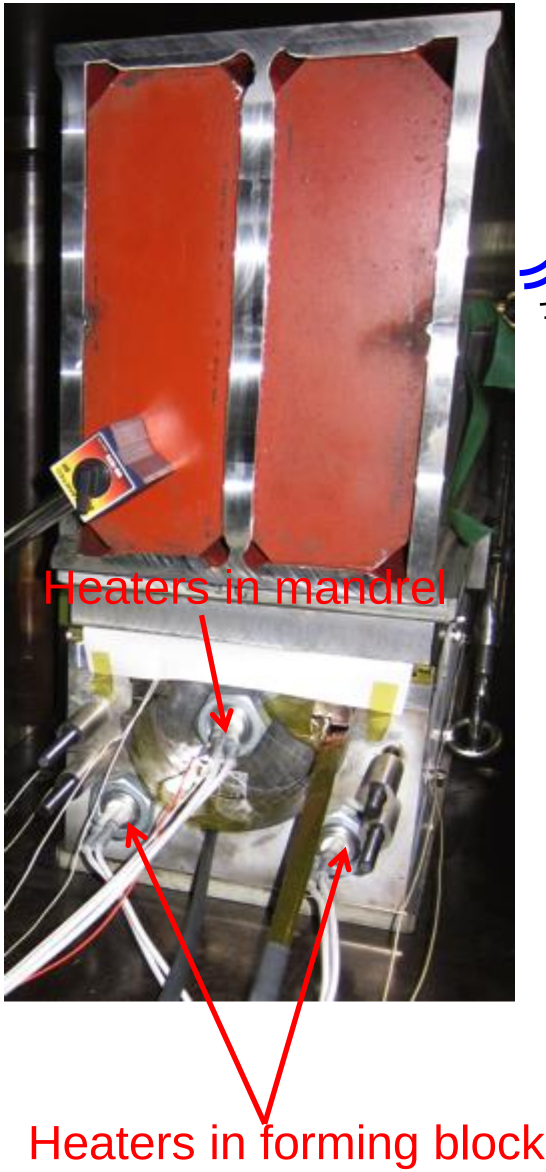
Check by Fuji paper

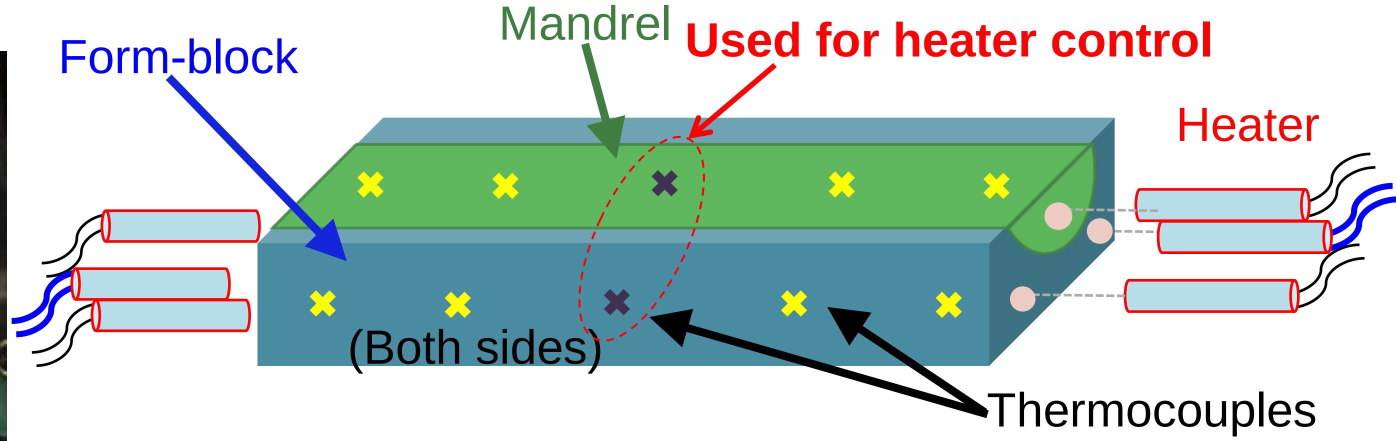


Gap was closed at hydraulic pressure of 23 MPa

Pressure in curing

Configuration of heater and thermometers





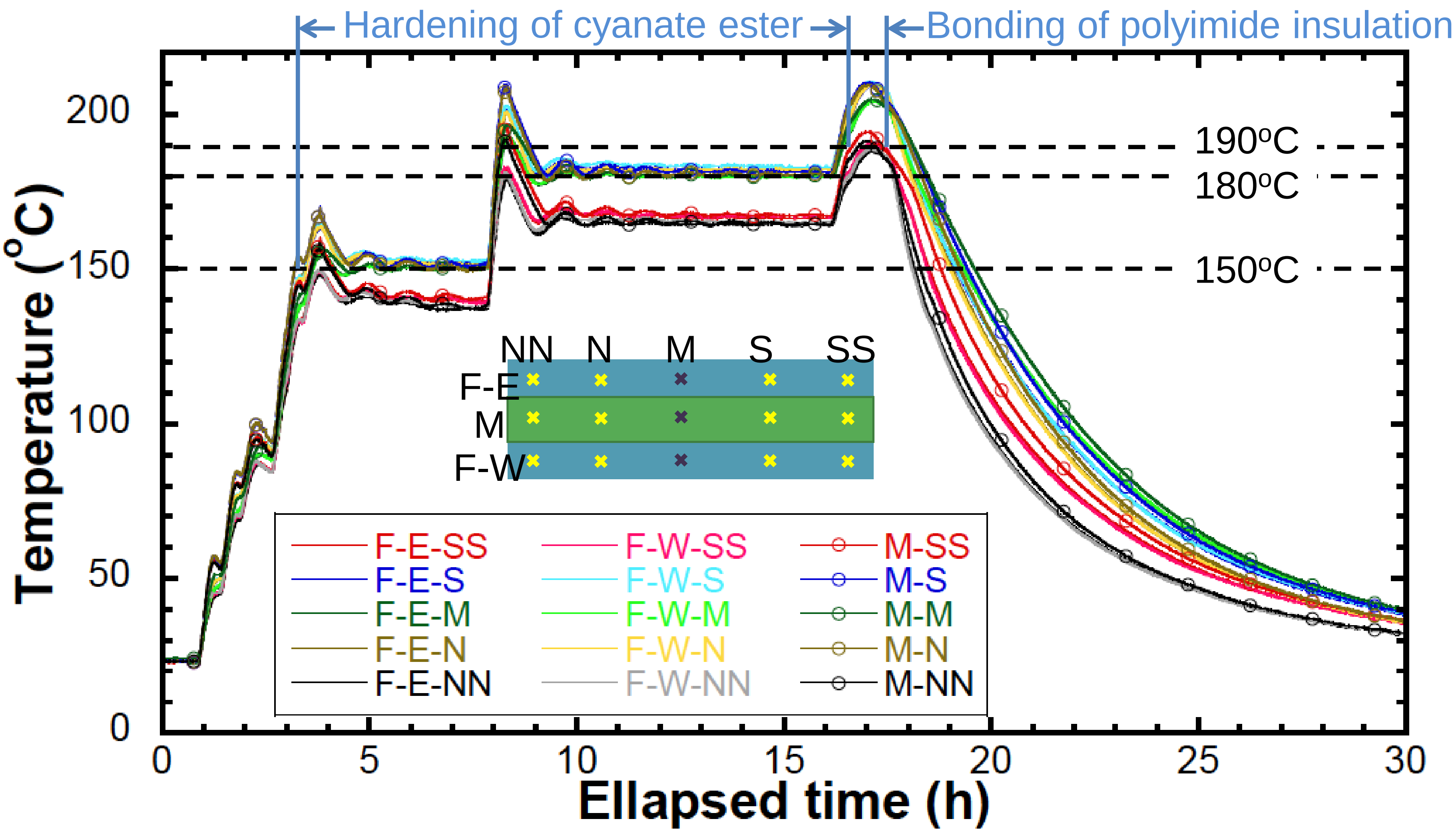
1m-long cartridge heater

- 4 in forming block
- 2 in winding mandrel

Thermocouples

- 10 in forming block
- 5 in winding mandrel
- 2 at cartridge heater for mandrel

Actual temperature trend in curing

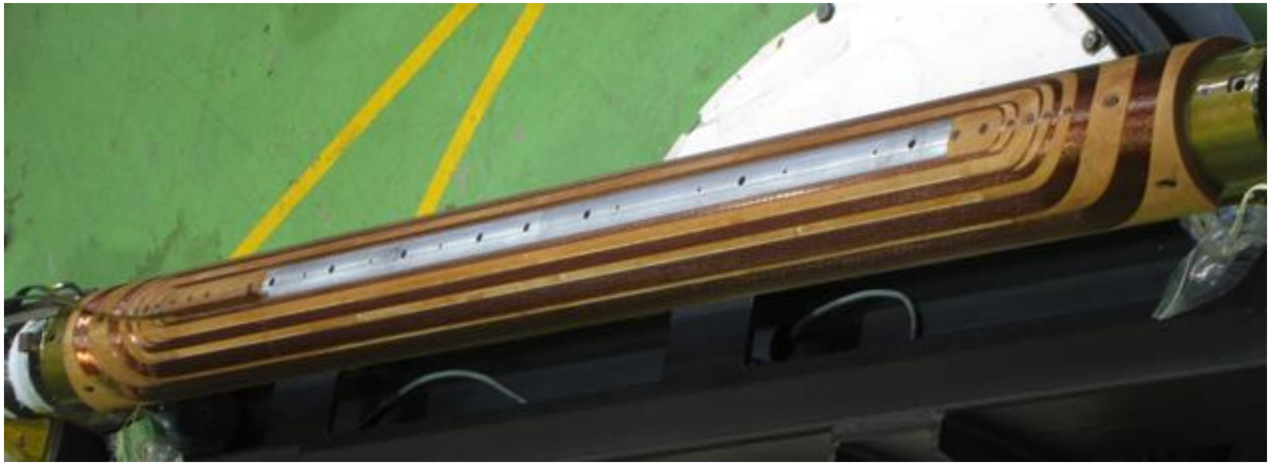


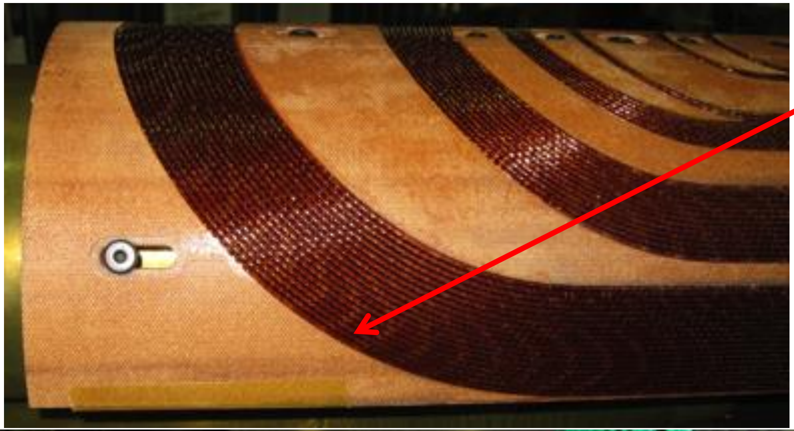
Temperature profile to harden cyanate ester (150ºC x 4h + 180ºC x 8h) was obtained as expected

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

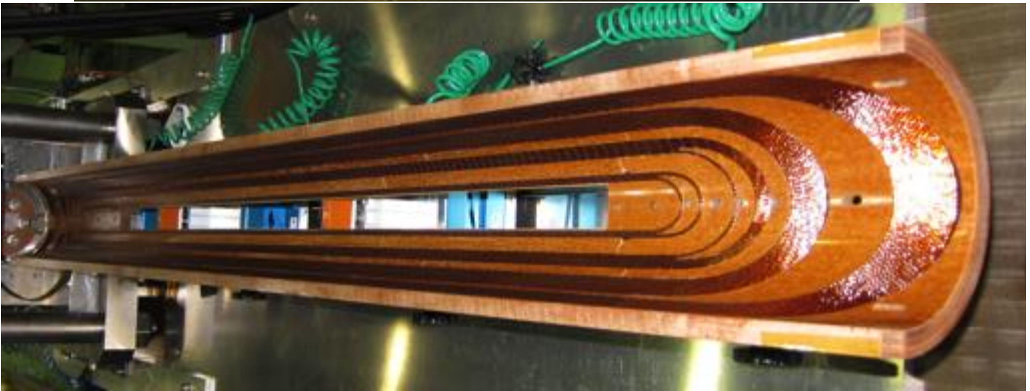
➡ Expected temperature profile was realized

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

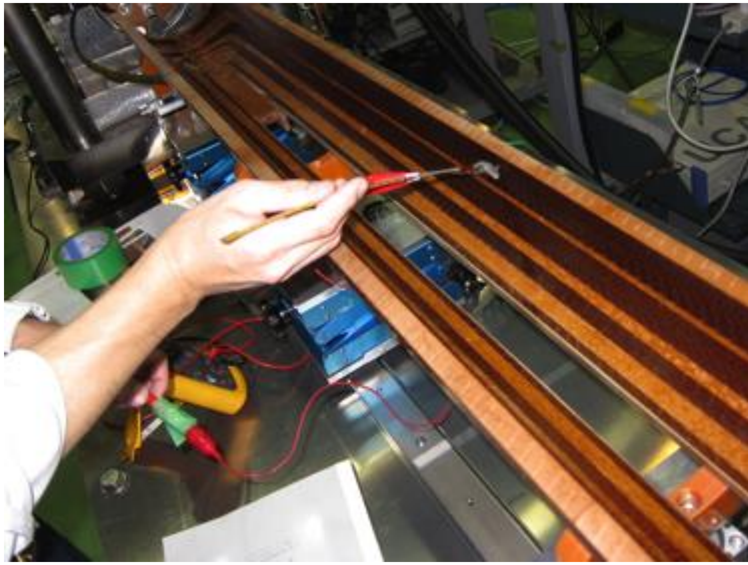


Bonding between the cable and the wedges is sufficiently strong
→ Effectiveness of heat treatment profile is verified

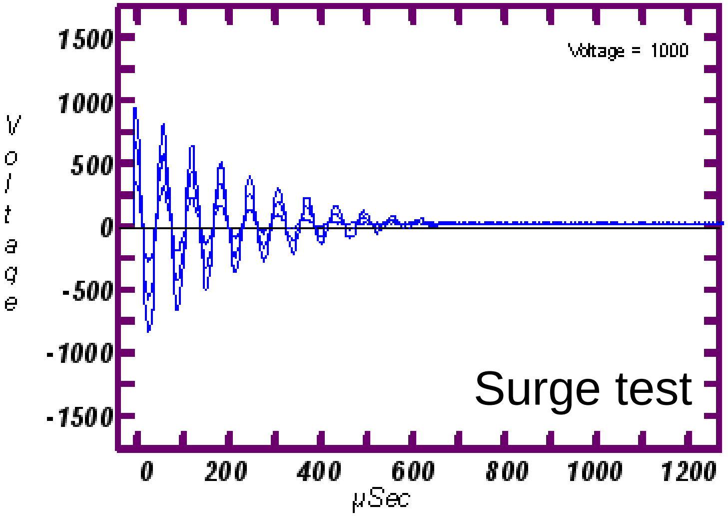
Electrical tests after curing

- 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

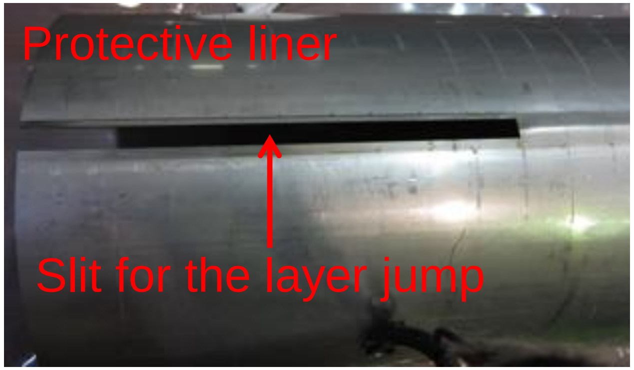


- No damage of cable insulation checked by a bundle of fine Nb-Ti filaments
- No turn-turn insulation failure at least up to 1 kV (Surge test)
- Coil inductance: 2.26 mH (calc. value = 2.28 mH)

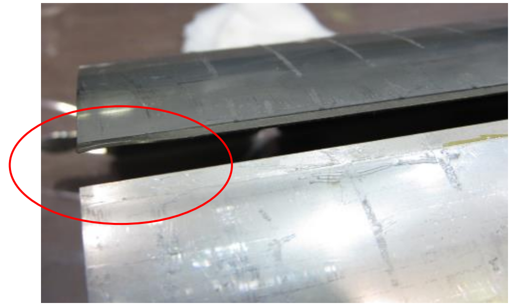


Electrical soundness of the coil was confirmed

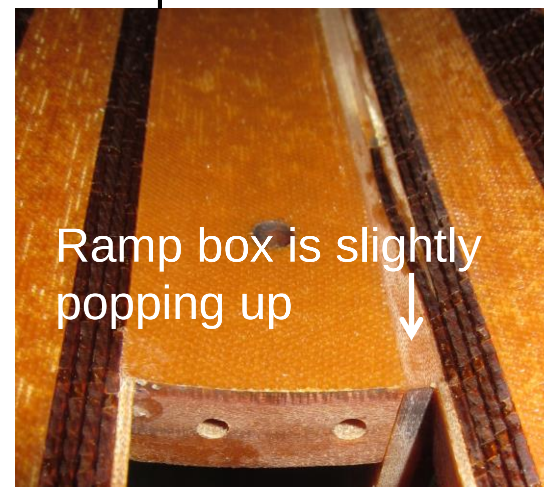
Issues to be modified 1

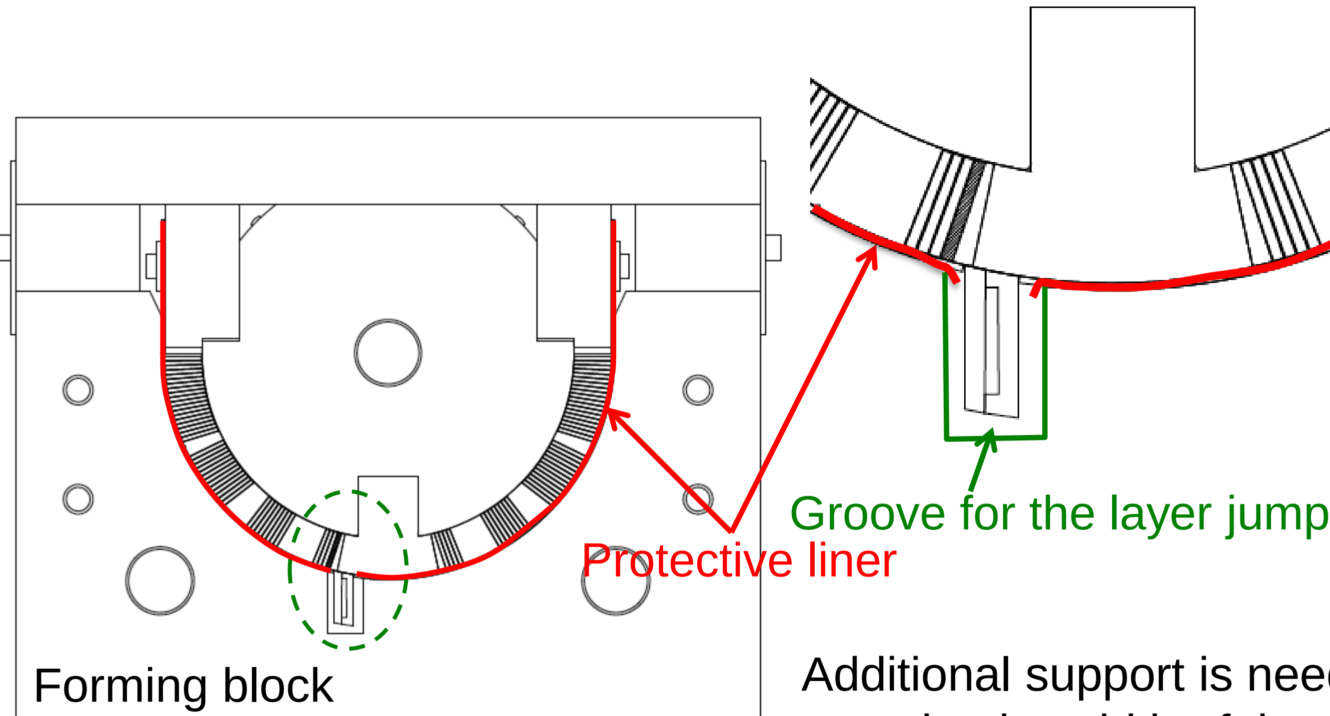


The protective liner deformed plastically after curing



Bottom surface of the ramp box

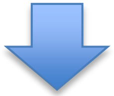




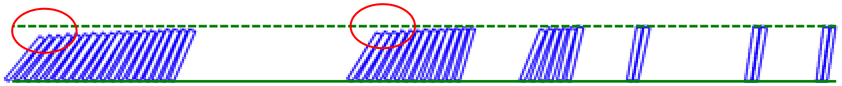
Additional support is needed for the layer jump to make the width of the groove narrower

Issues to be modified 2

There is difference in height at the boundary of the end spacer and the cable

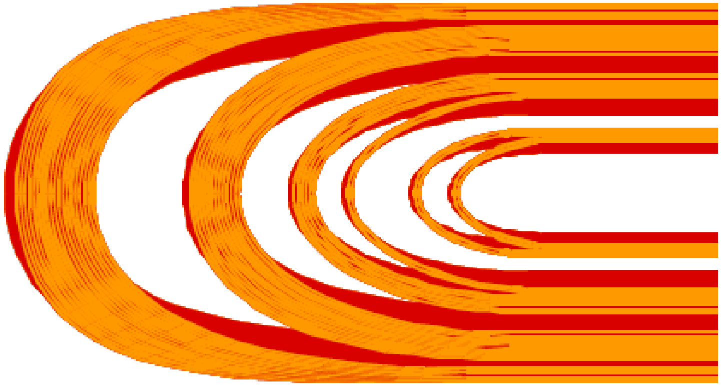


The leads for the QPH could be damaged



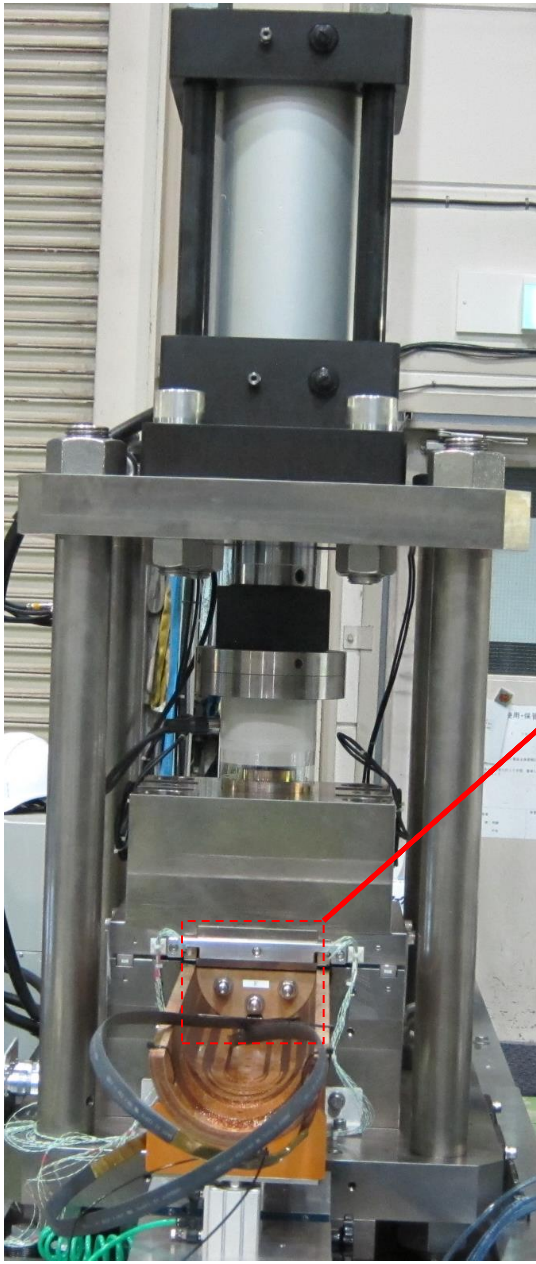
Approach 1: Modification of coil end shape

To make the cable more upright by elongating the length of coil end



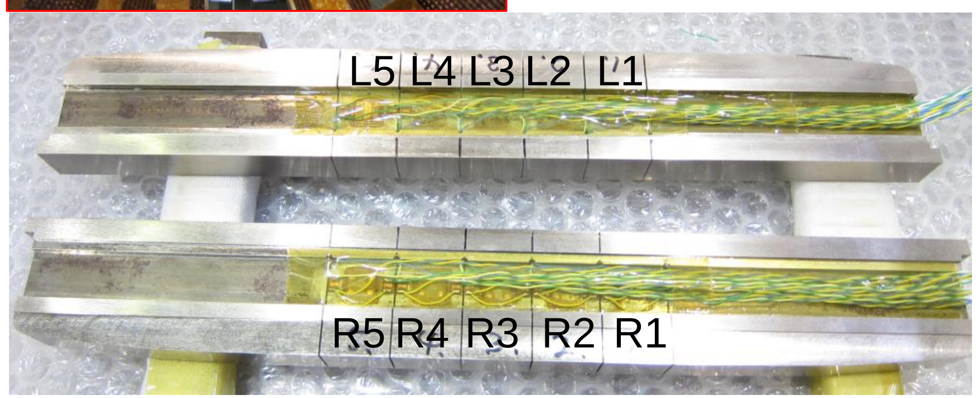
Approach 2: Filling the gap with shoe

Preparation for coil size measurement



Same system 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



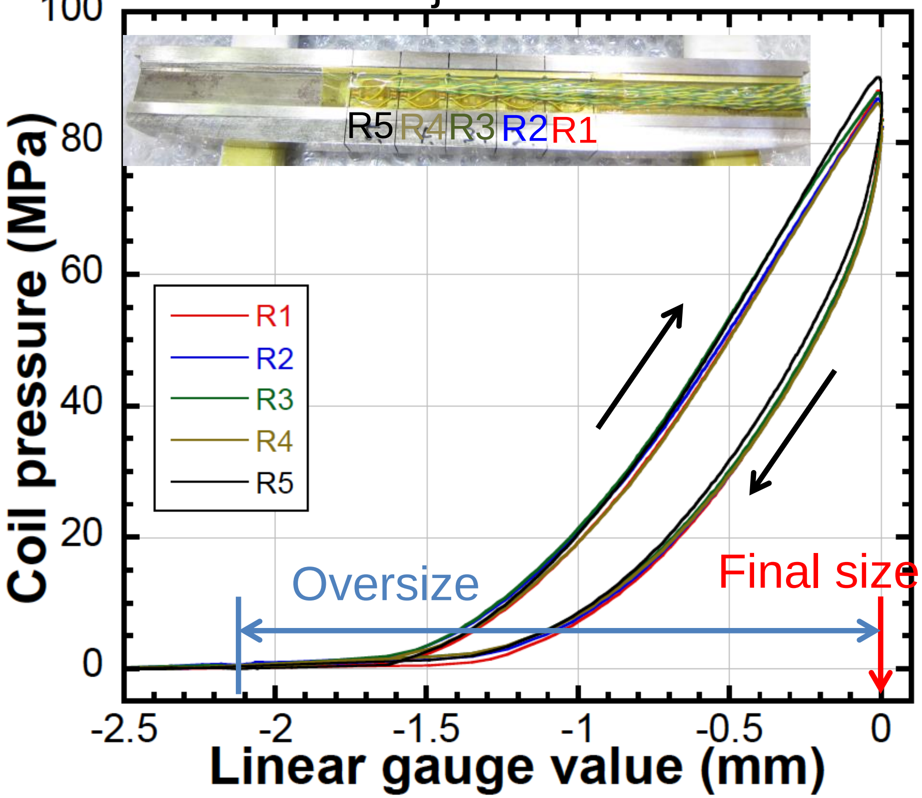
Pushing bars with strain gauges

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

Coil size measurement

Coil pressure – deformation

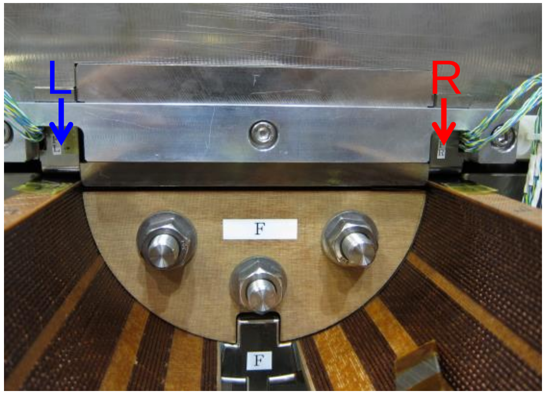
Results for adjacent 5 sections

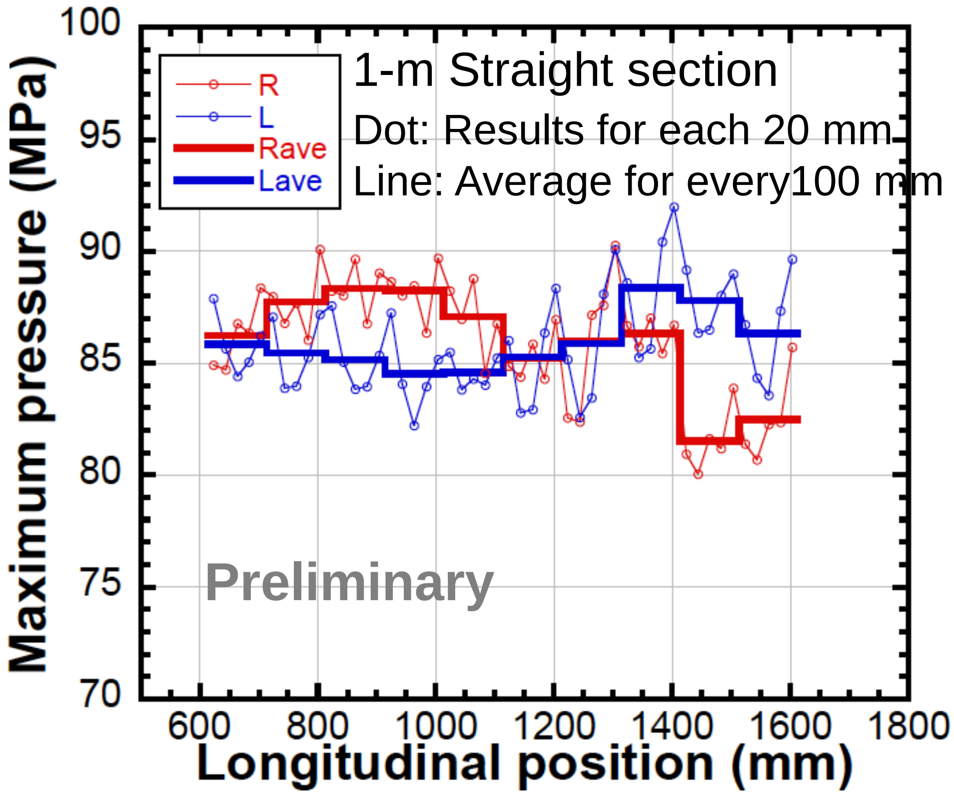


Measured maximum pressure: 80 – 92 MPa (After correction considering machine deformation: 90 – 100 MPa)

→ The size of our test coil is almost as designed

Coil stress at the final size along the coil length





Summary

- Iron model for ROXIE 2-D calculation was refined to include possible error sources. Arrangement of 2-D coil blocks has been optimized for HX holes with a diameter of ϕ60mm at R190.

- Quench protection studies were started. Peak temperature was estimated to be 305 K in a conservative scenario using R_{dump}=75 mΩ with quench detection threshold of 0.1 V and 10 msec.

- Fabrication of 2-m test coil was completed successfully. We confirmed that new radiation resistant GFRP can fit the cable after curing and tested curing temperature profile can work to obtain sufficient bonding strength for the single layer coil.

- Coil size measurement was started. The coil size of the test coil was suggested to be almost as designed.

- 200-mm mechanical short model will be assembled using the straight section of the test coil to verify collaring and yoking process.