Status of D1 Model Development

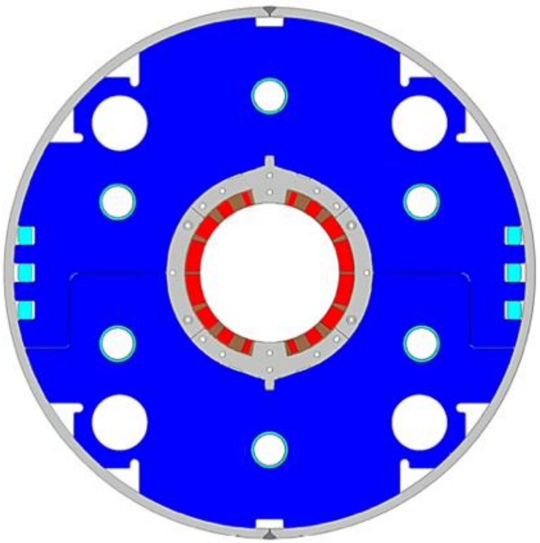
Tatsushi NAKAMOTO (KEK)

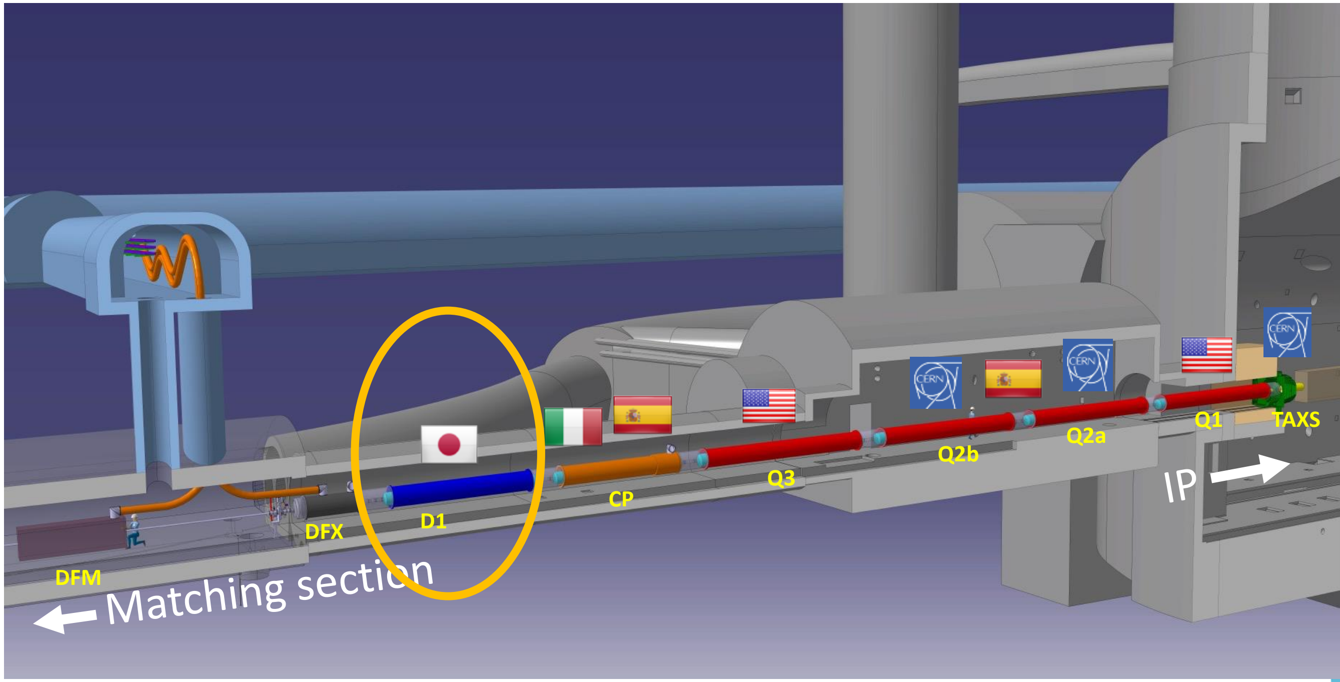
KEK

On behalf of CERN-KEK Collaboration for D1 Development for HL-LHC

8th HL-LHC Collaboration Meeting, CERN, Oct. 18, 2018

Japanese Contribution to HL-LHC: D1 magnets



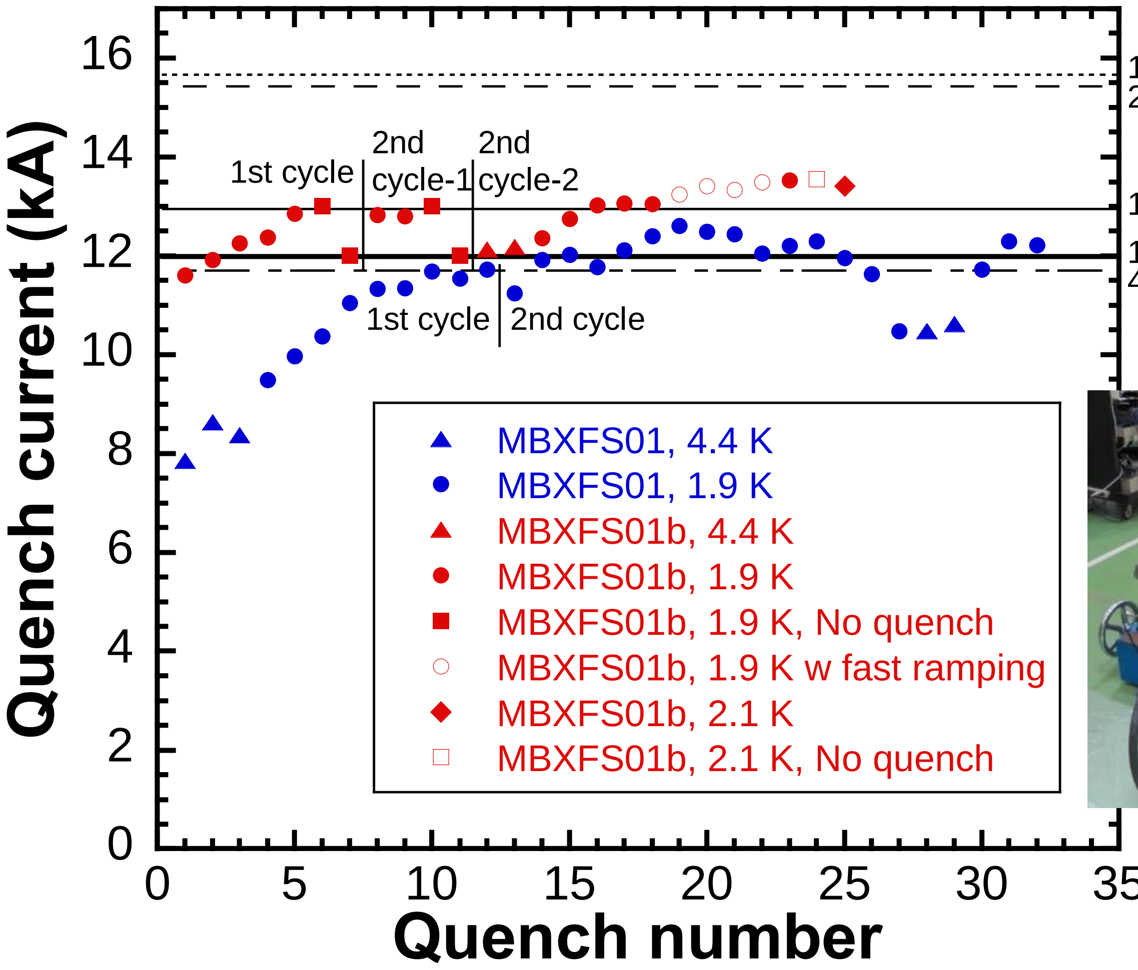


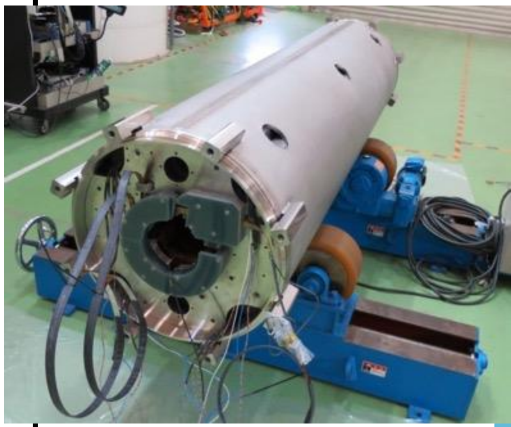
- Beam separation dipole (D1) by KEK
  - Design study of D1 for HL-LHC within the framework of the CERN-KEK collaboration since 2011.
  - 150 mm single aperture, 35 Tm (5.6 T x 6.3 m), Nb-Ti technology.
  - *Development 2-m long model magnets (3 units) at KEK*
- Deliverables for HL-LHC
  - *1 full-scale prototype cold mass (MBXFP)*
  - *6 series cold masses (MBXF1-6)*

Short summary of 2-m D1 models: MBXFS

- MBXFS1: Previous cross section. Insufficient quench performance.
  - ✓ Cold test at April 2016
- MBXFS1b: Increased coil prestress to improve quench performance.
  - ✓ Cold test at Feb. 2017.
- **MBXFS2: New cross section, improvement on prestress, QPH…**
  - ✓ **Cold test at Oct. 2018.**
- *MBXFS3: Reproducibility check.*
  - ✓ *Cold test foreseen at May 2019*

Performance of #1 and #1b: Training Quench



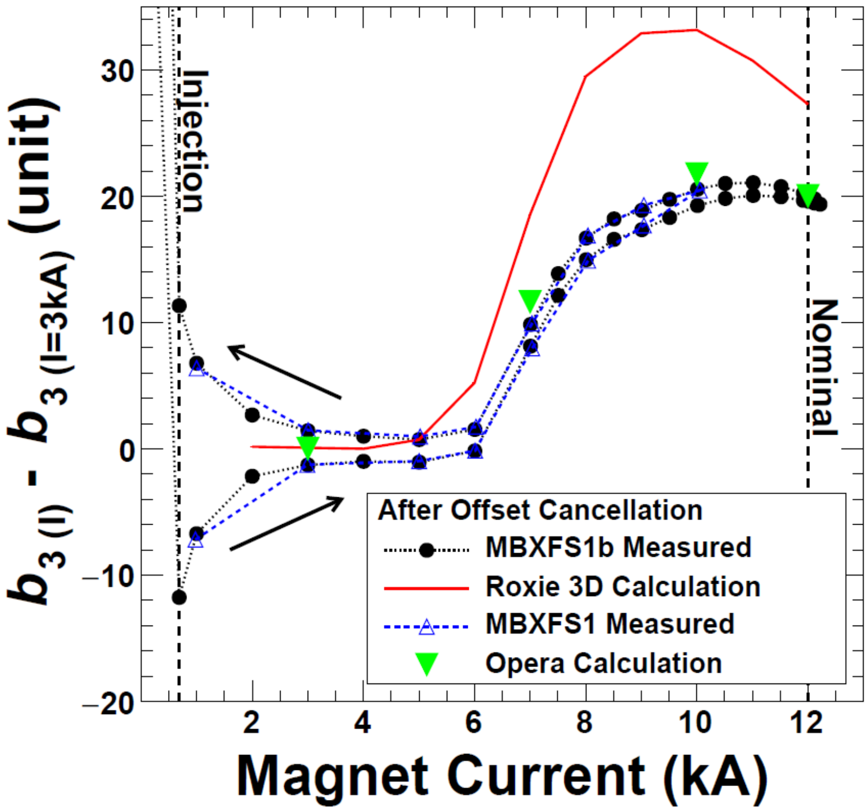


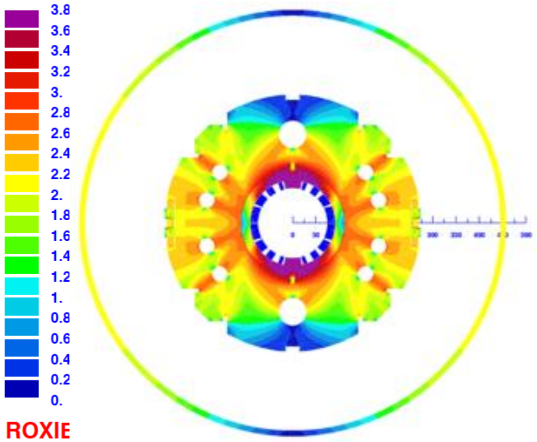
- **Training performance was significantly improved in the MBXFS1b.**
  - Same or better coil prestress level (target: 115MPa) in MBXFS2.

Performance of #1 and #1b: MFM

#1b

DC loop of b3 at magnet center
(offset cancelled)



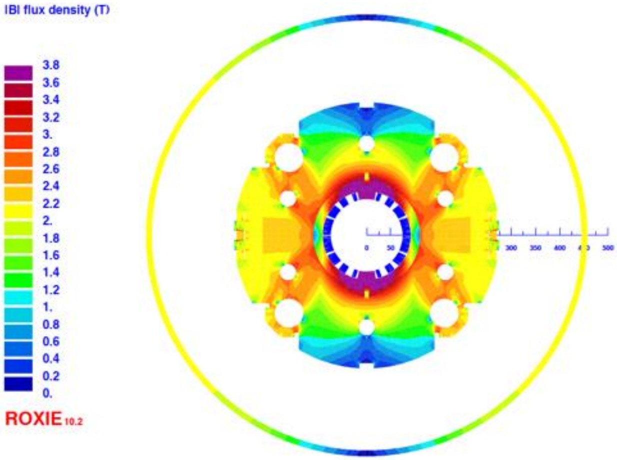


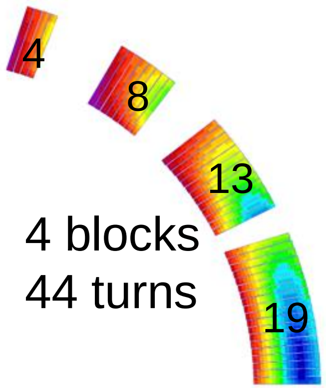
- Significant saturation (and stray field) effects on b_3.
  - ✓ Large difference between ROXIE3D and OPERA3D.
- Field error from coil geometry (< 5kA) has to be checked in MBXFS2.

Design modification from MBXFS1/1b to MBXFS2

Design overview from MBXFS2

	A series production	2 m model
Coil aperture	**150 mm**	
Field integral	**35 T m**	9.5 T m
Nominal field	5.57 T	
Peak field	6.45 T (SS), 6.58 T (coil end)	
Operating current	12.047 kA	
Operating temperature	1.9 K	
Field quality	<10^{-4} w.r.t B_1 (R_{ref}=50 mm)	
Load line ratio	75.6%（SS）, 76.7%(coil end）at 1.9 K	
Differential inductance	4.0 mH/m	
Conductor	Nb-Ti: LHC-MB outer cable	
Stored energy	340 kJ/m	
Magnetic length	6.26 m	1.67 m
Coil mech. length	6.58 m	2.00 m
Magnet mech. length	6.73 m	2.15 m
Heat load	**135 W (Magnet total)** **2 mW/cm³ (Coil peak)**	
Radiation dose	**> 25 MGy**	





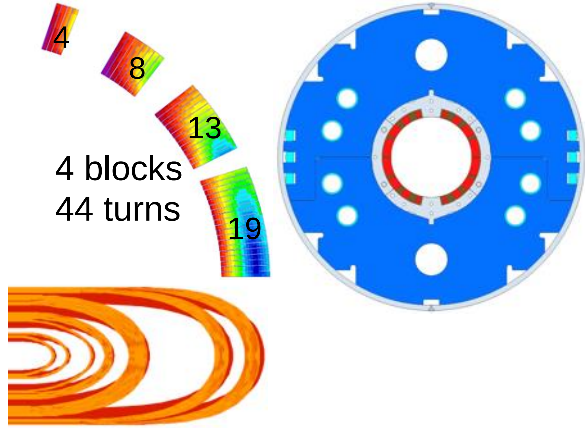
Technical challenges

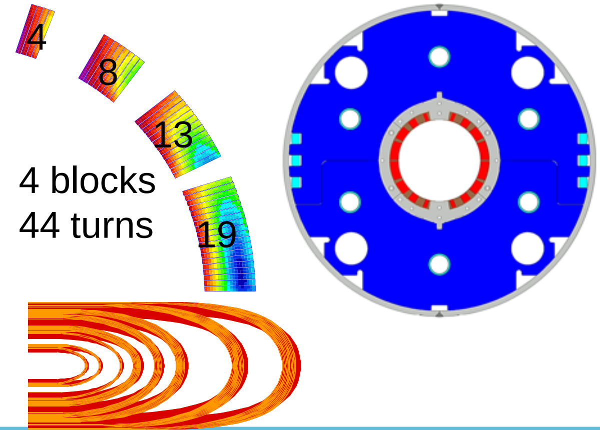
- **Large aperture: Management of coil size and pre-stress.**
- **Radiation resistance: Radiation resistant material for coil parts. Cooling capability.**
- **Iron saturation: Good field quality from injection to nominal current**

Updates from MBXFS1/1b to MBXFS2

- Four HX holes instead of two in yoke: REQUEST from CERN.
  - Yoke cross-section and coil block arrangement were modified
- Enhancement of mechanical support of coil blocks
  - Wet-winding with epoxy-blended cyanate ester at coil end
  - 15 MPa higher azimuthal coil pre-stress from 1b by increase in azimuthal thickness of GFRP
  - Increase in axial pre-load
  - Better fitting between end spacers and cable by updating ROXIE parameters to those taken from actual winding with more coil end block subdivision
- Newly designed QPH for reducing MIITs (max T)

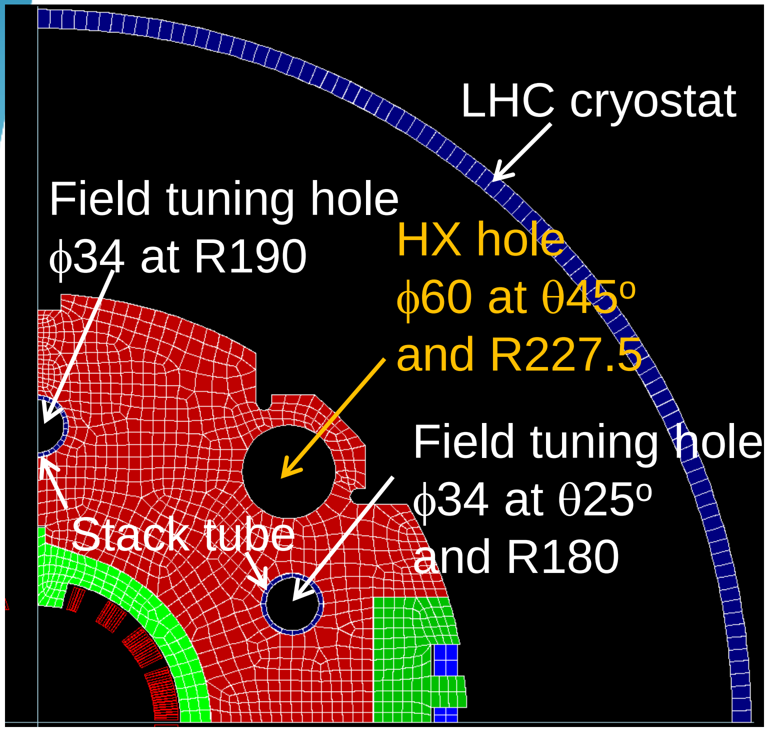
Design Parameters: 1st vs 2nd Models

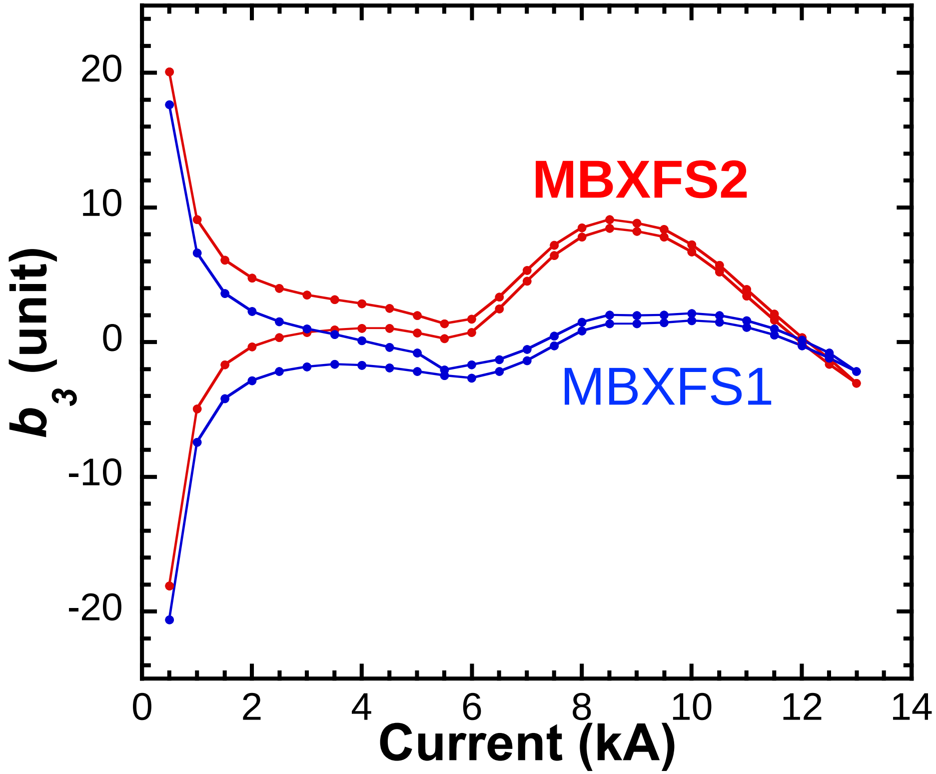




Item		MBXFS1, 1b	MBXFS2
Target pre-stress / load	lateral	#1: 80 Mpa, #1b: 110 MPa	115 MPa
	axial	Tightening torque of 12 Nm for four M12 bullets	Tightening torque of 20 Nm for four M12 bullets
Coil	2D	4 blocks (4+8+13+19)	
	Coil end	7 blocks	8 blocks
	Resin	100 % CE (BT-2160RX)	Epoxy + CE (EC-1HB w/ filler)
	length	525,1100,375mm	561.2,1025.5,413.3mm
QPH		straight	zigzag
Yoke		2 HX holes	4 HX holes
Cold tube Support		No	Yes
Nominal Current		12.000 kA	12.047 kA
Main Field		5.573	5.569
Coil Peak Field		6.56 T	6.58 T
Load line ratio		76.3%	%
Coil Mech. Length (full-scale)		6518 mm	6580 mm

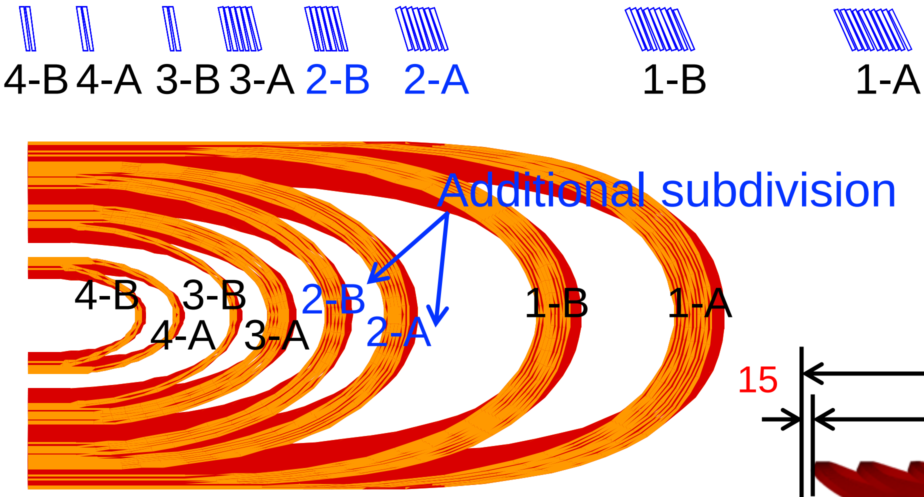
2D cross-section and coil end shape

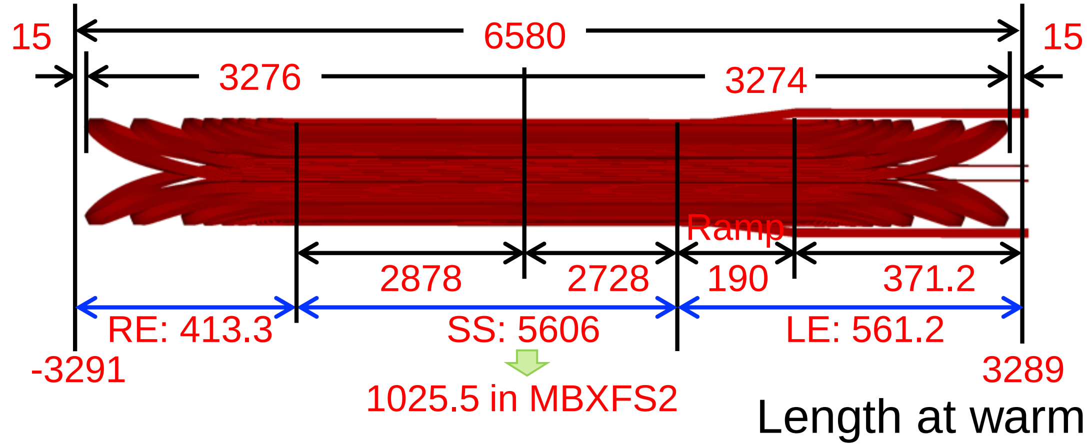




- Optimization of field tuning holes for good field quality from injection to nominal current
- Maximum b_3 during ramping-up is 8.5 units at 8.5 kA.
  - ✓ Note: b3 in ROXIE-2D is much different from ROXIE-3D due to end-effects.

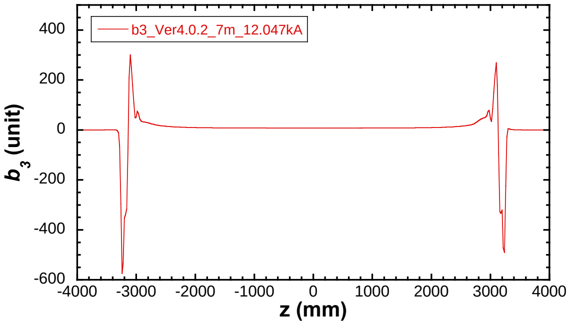
Modified coil end shape

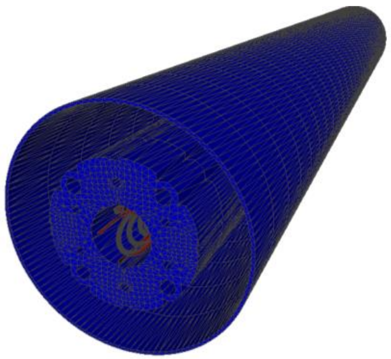




- Coil end block 2 was subdivided into 7+6 turns
- Minimizing multipole components integrated over 7 m-long magnet with LHC cryostat by adjusting axial position of coil end blocks
- MBXFS2 has the same cross-section and coil ends, but straight section is shortened.

Field integral in 7 m magnet by ROXIE 3D

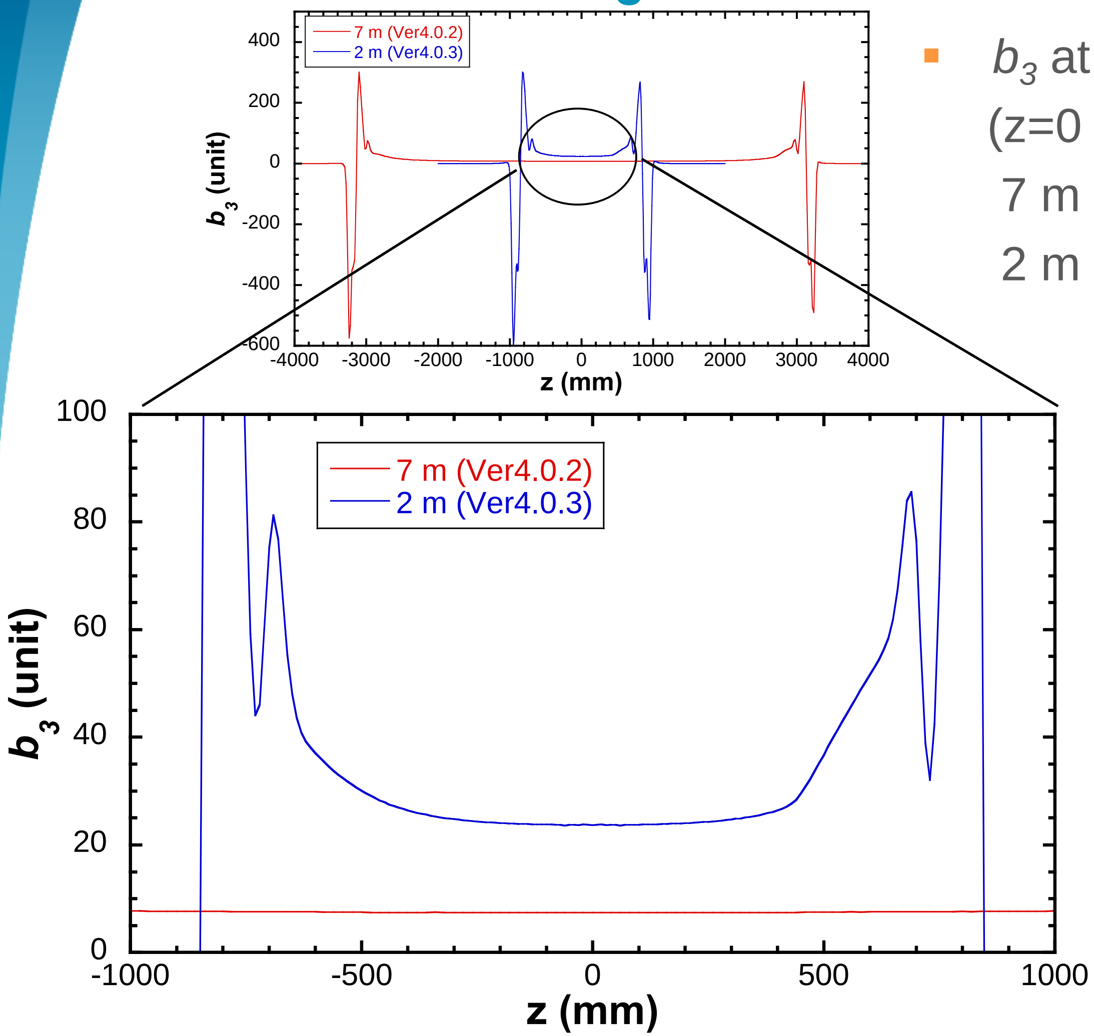




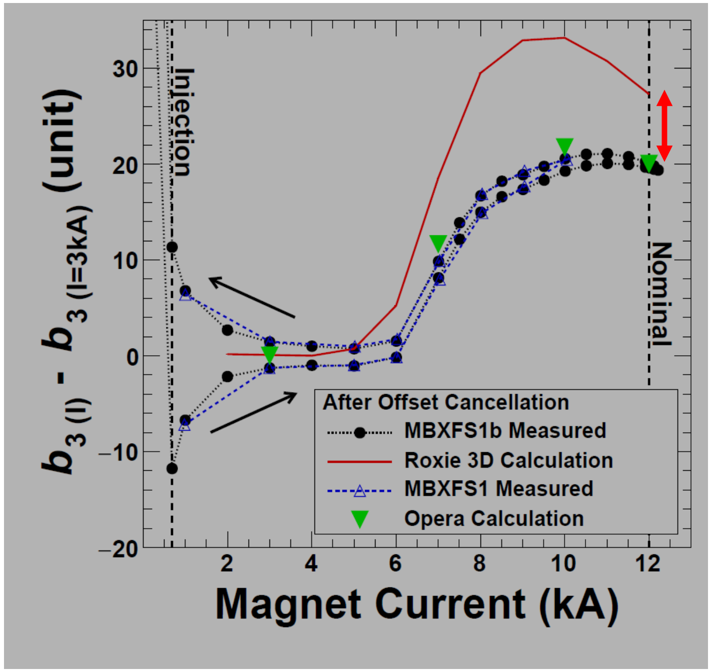
	RE (unit)	SS (unit)	LE (unit)	Total (unit)	2D (unit)	2D with 3D iron (unit)	Expected (unit)
z (mm)	-4000 ~ -2870	-2870 ~ 2720	2720 ~ 4000	-4000 ~ 4000			
BL (Tm)	1.422	31.343	2.262	35.027			35.027
b3 (unit)	-3.600	8.824	-2.128	3.096	-0.028	3.057	0.011
b5 (unit)	-0.280	0.049	0.300	0.069	-0.045	-0.228	0.251
b7 (unit)	-0.287	0.010	-0.059	-0.336	-0.054	-0.228	-0.162
b9 (unit)	-0.269	0.087	-0.167	-0.349	0.139	0.109	-0.320
b11 (unit)	-0.119	0.166	-0.087	-0.040	0.176	0.188	-0.052
b13 (unit)	-0.055	-0.620	-0.054	-0.729	-0.695	-0.696	-0.728
b15 (unit)	-0.035	-1.030	-0.060	-1.124	-1.157	-1.154	-1.127
b17 (unit)	-0.011	-0.726	-0.027	-0.764	-0.815	-0.814	-0.765
b19 (unit)	0.006	0.359	0.015	0.380	0.402	0.401	0.380
a1 (unit)	0.001	0.152	-5.532	-5.379	0.000	0.000	-5.379
a3 (unit)	0.000	0.039	1.808	1.847	0.000	0.000	1.847

- Target multipole coefficient in 3D optimization is taken into account the different iron models in 2D and 3D calculations.
  - ✓ b_3~b_9 can be controlled within 0.5 unit with respect to the target values.
  - ✓ Intrinsic a_1 and a_3 due to rotational symmetry.

Difference of b_3 between 2-m model and prototype



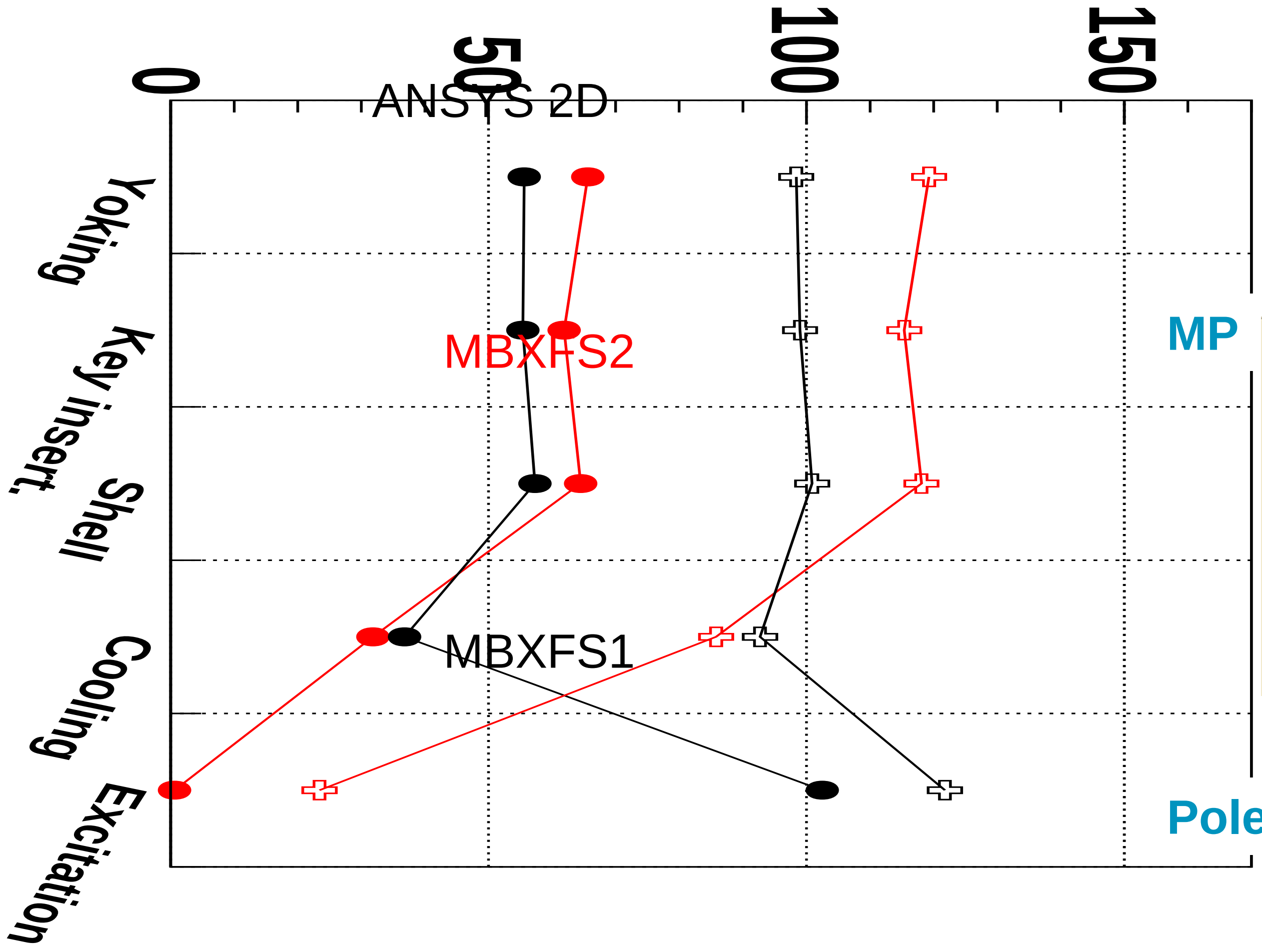
- b_3 at magnet center (z=0 in ROXIE)
  7 m magnet: 7.4 unit
  2 m magnet (MBXFS2): 23.7 unit

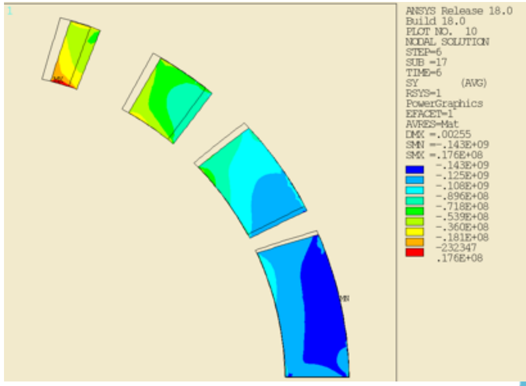


b3 of MBXFS1b w/ ROXIE3D & OPERA3D

For prototype and series, initial engineering design will be mainly performed by ROXIE3D, but final tuning of a coil geometry would be performed by using ***OPERA3D output***.

Target Coil Prestress at Assembly



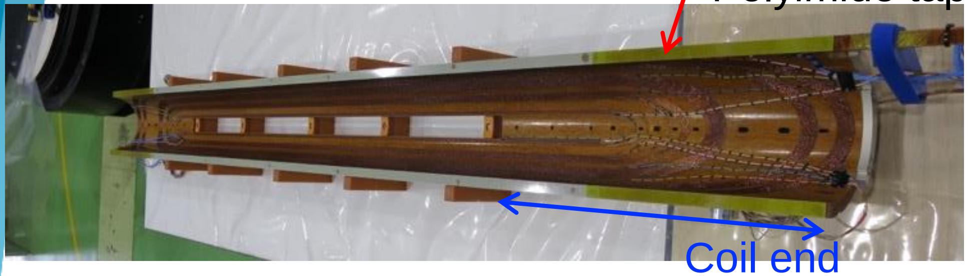


- MBXFS1: azimuthal stress at pole of 65 MPa
- MBXFS1b: 100 MPa with 0.8mm additional shim at MP
- MBXFS2: target of 115 MPa by oversize wedge (0.8 + 0.34 mm)

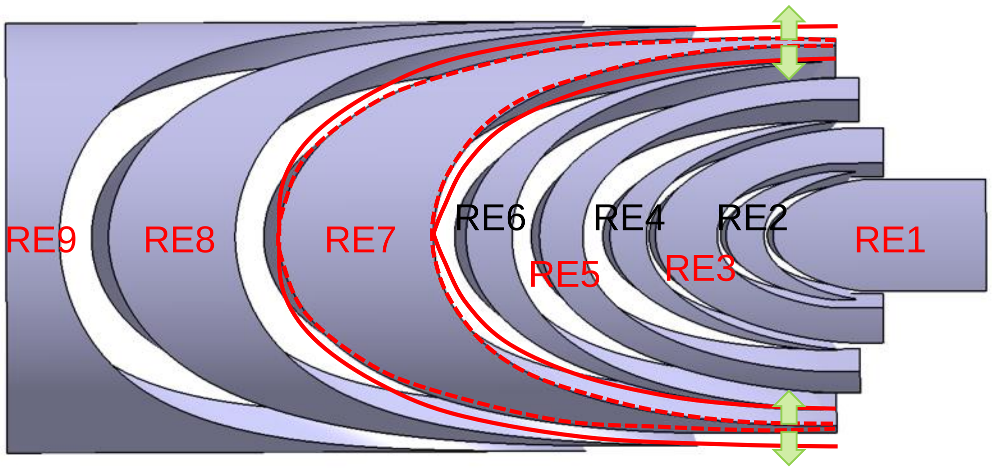
Oversizing of GFRP end spacers to increase azimuthal coil pre-stress at coil end

MBXFS1b

G10 shim +
Polyimide tapes = 0.9 mm



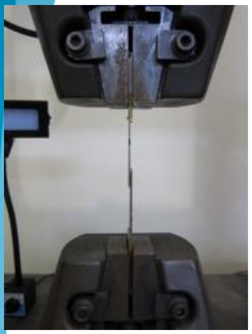
MBXFS2

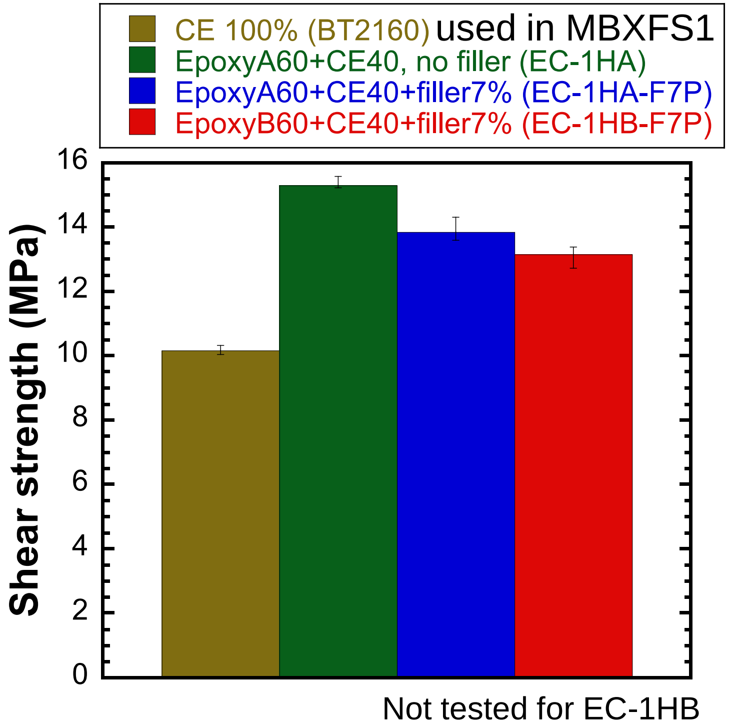


- End spacers were oversized in the azimuthal direction by the same amount as wedges. (0.24 mm thicker per quadrant than 1b)
- 3D mechanical analysis is ongoing. Coil pre-stress was tried to measure with strain gauges on end spacers in MBXFS2.

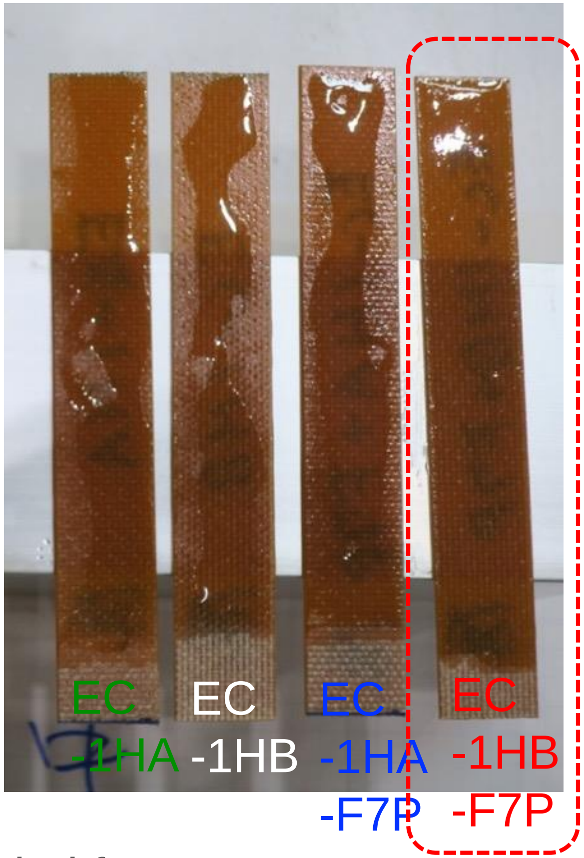
Wet-winding with epoxy-blended CE resin

Shear strength





Painting test

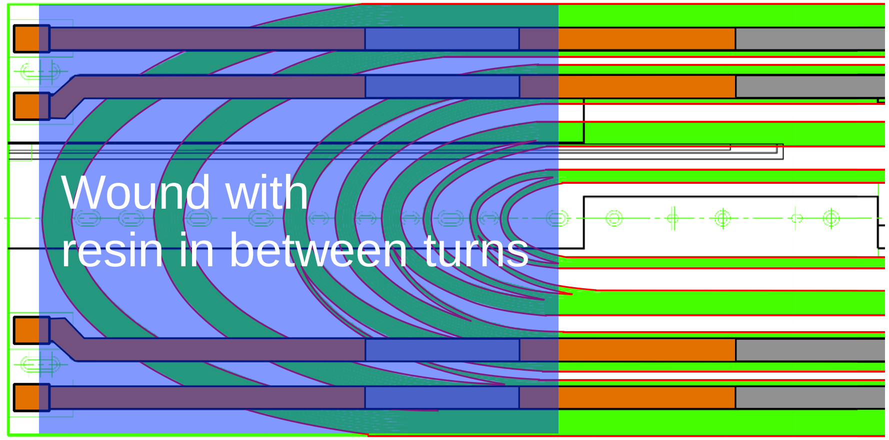


- Four kinds of epoxy-blended CE resins provided from ARISAWA were tested
  - Epoxy : CE = 60 : 40 for all resins
  - Viscosity: lower in epoxy A, higher in epoxy B
  - W or W/O filler (to control viscosity)

→ EC-1HB-F7P (Epoxy B + CE + 7wt% Silica filler) was selected from acceptable bonding strength with highest viscosity

Wet-winding

Coil S2-2, S2-3 used for assembly



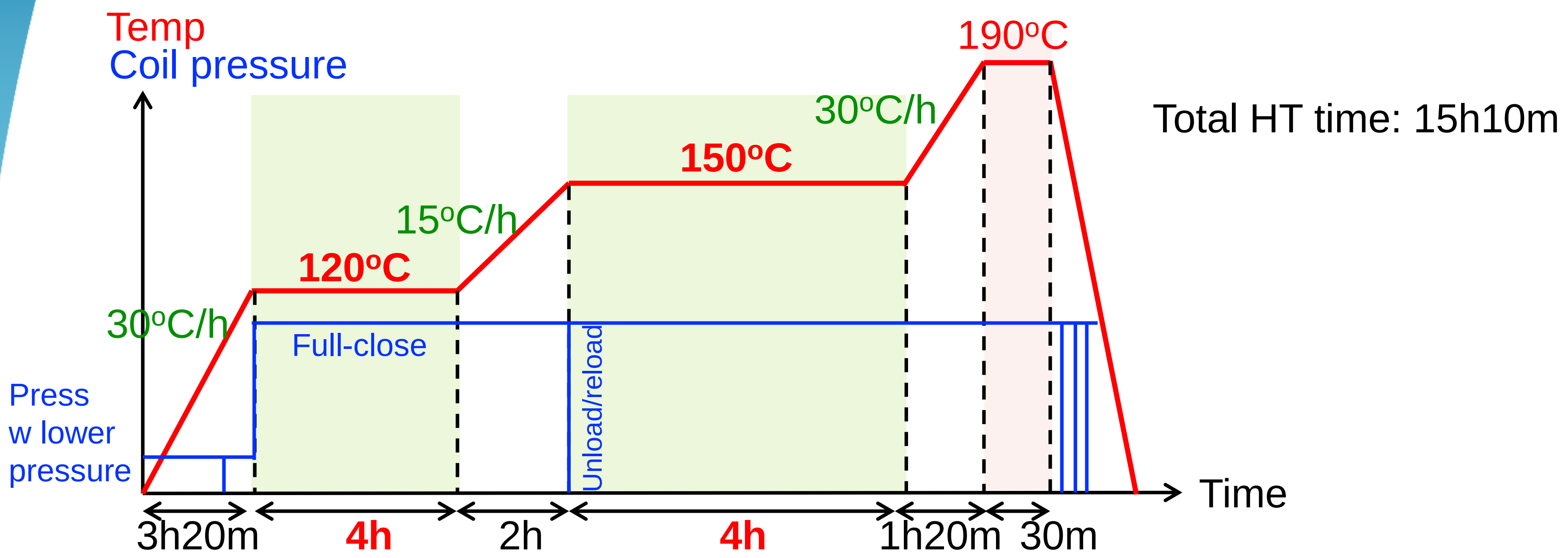
Cable surface

Wedges

End spacers

- Minimum amount of resin possible was painted on wedges, end spacers and cable surface to easily release a coil from curing mold and keep the coil surface smooth.
- Wet-winding was able to be completed without any severe problems.

New curing condition for Coil S2-2 and S2-3

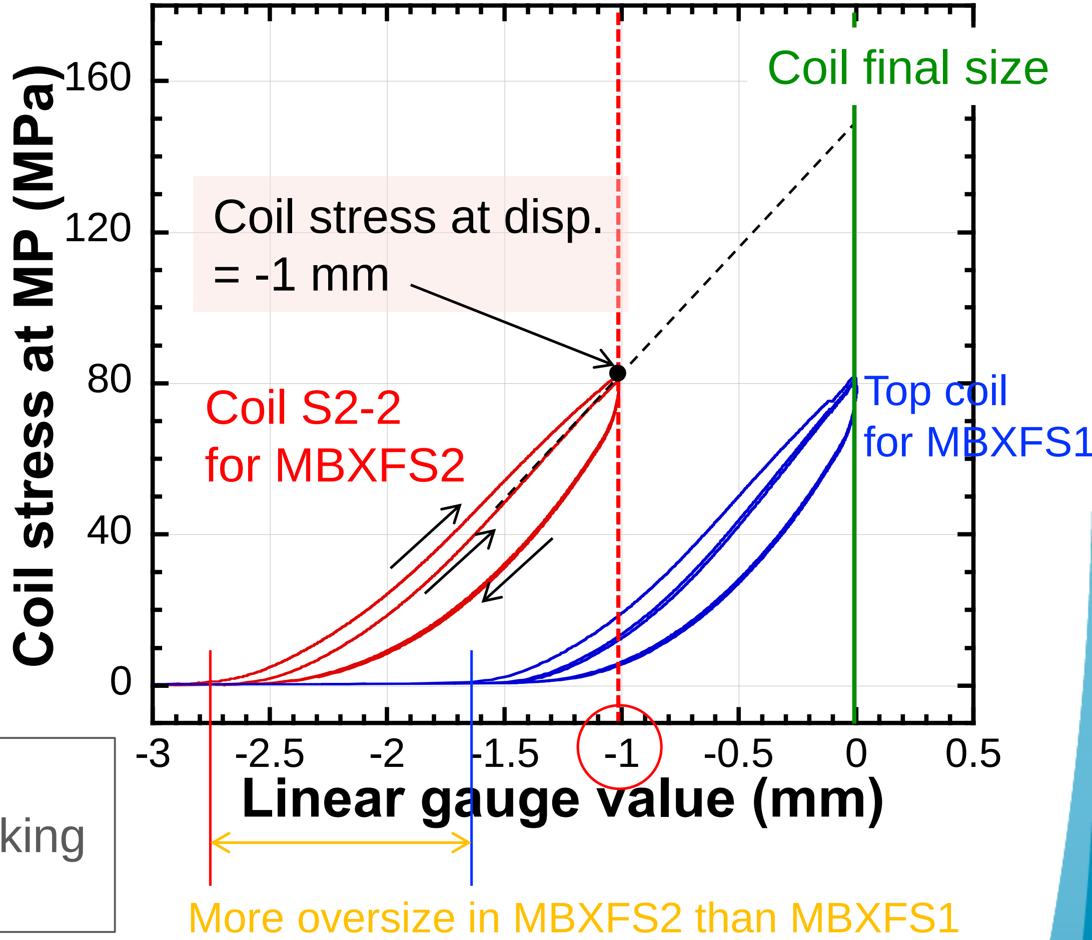


- Curing condition for epoxy-blended cyanate ester: 120ºC x 4h + 150ºC x 4h
- Self-fusing of polyimide insulation: 190ºC x 0.5h
- Coil pressure: lower at RT, while full-closing at 120ºC

Coil after curing

- Smooth and clean coil surface after curing
- No detachment of end saddle → Wet-winding was successful

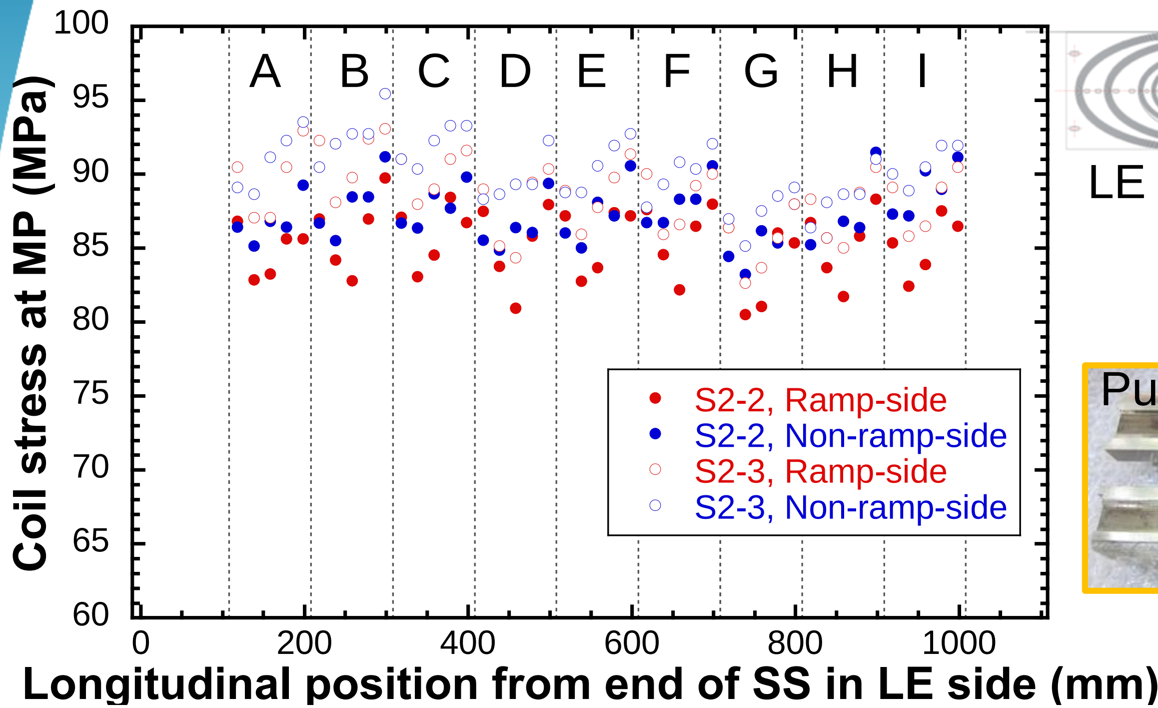
Coil size measurement

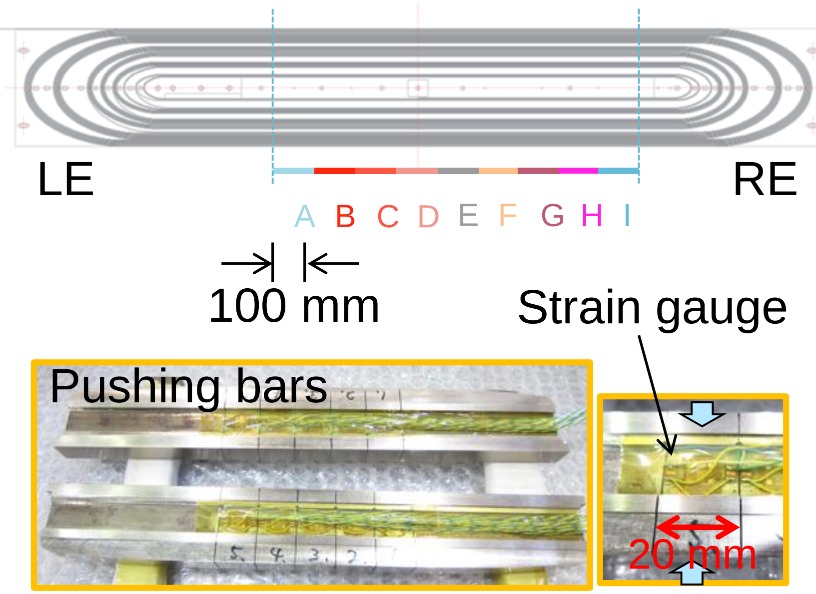


Purposes of coil size measurement
– Prediction of coil pre-stress after yoking
– Homogeneity of coil size over 2 m

- Due to limited load capacity of hydraulic press of 60 ton, coils for MBXFS2 with larger size than MBXFS1 were not able to be compressed to the final size after yoking.
- Coil stress at MP at the displacement of -1 mm was evaluated and its homogeneity over SS was checked.

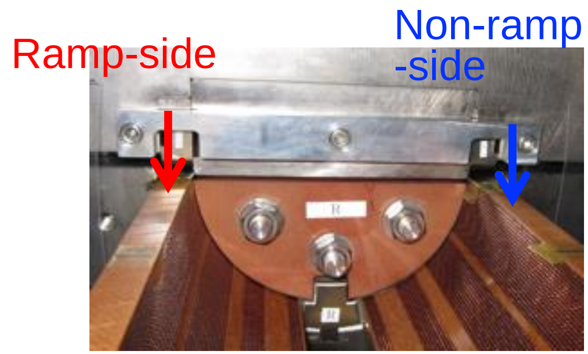
Variation of coil stress at displacement of -1 mm





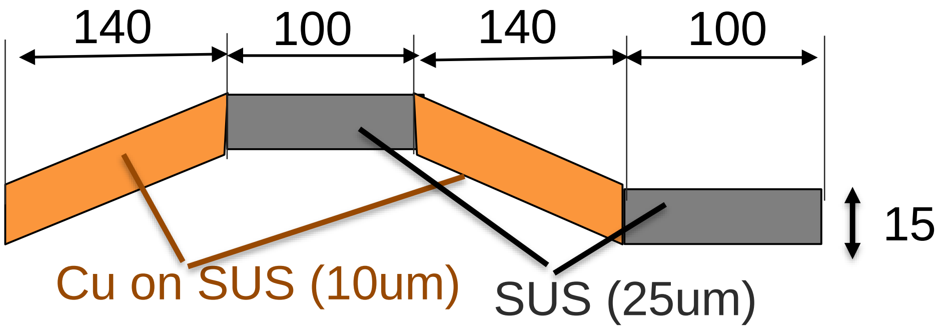
Average coil stress at each quadrant (MPa)

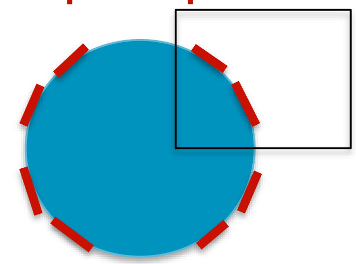
	Ramp-side	Non-ramp-side
Coil S2-2	85±2	87±2
Coil S2-3	89±2	90±3

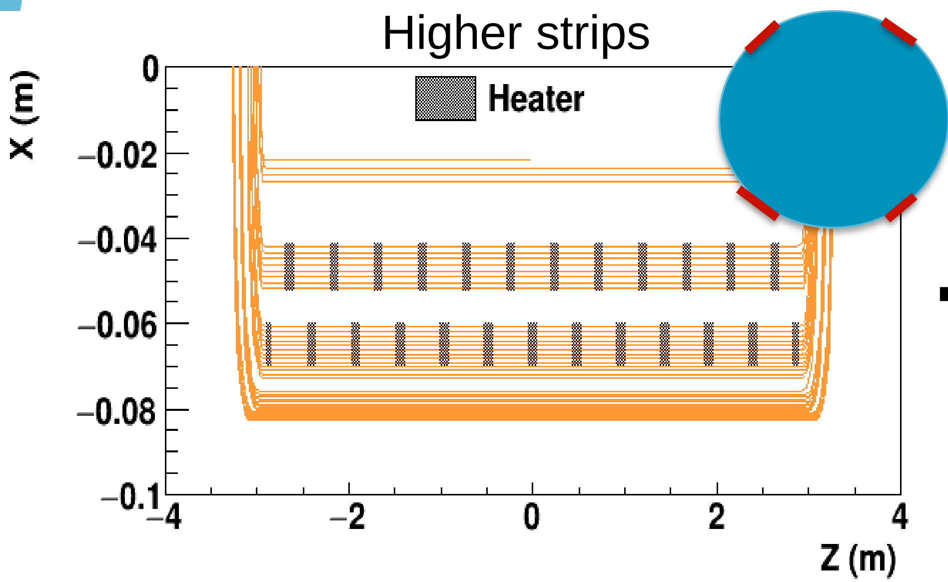


- Measured only for SS
- Longitudinal distribution of coil stress seems to be OK.

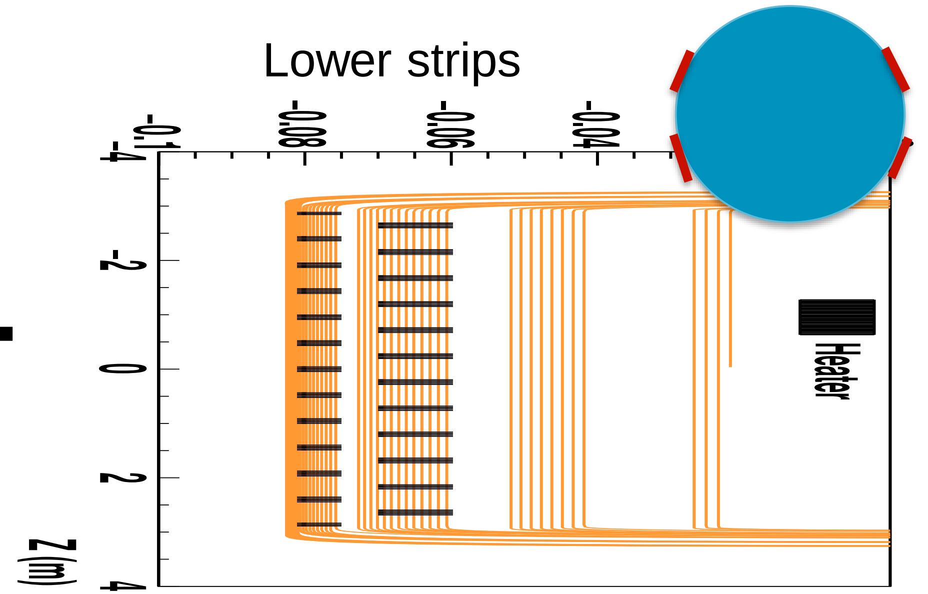
New QPH design





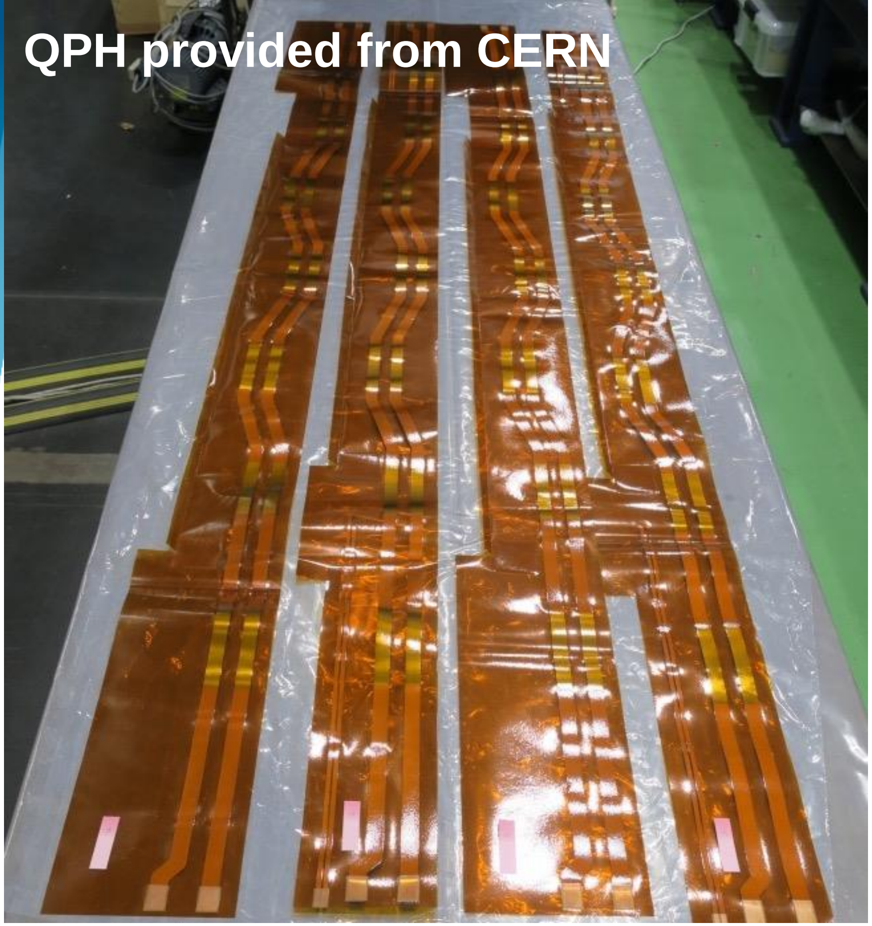


+

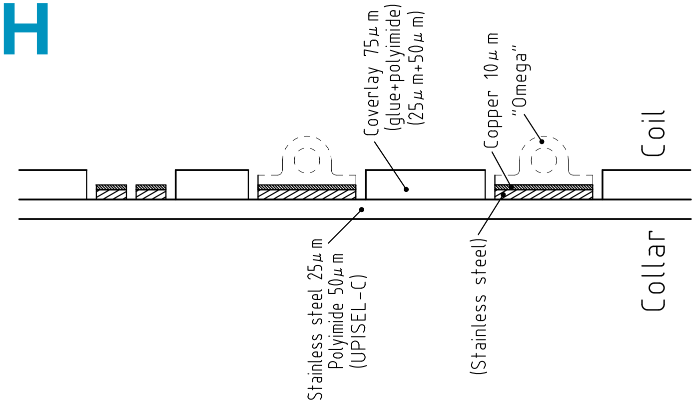


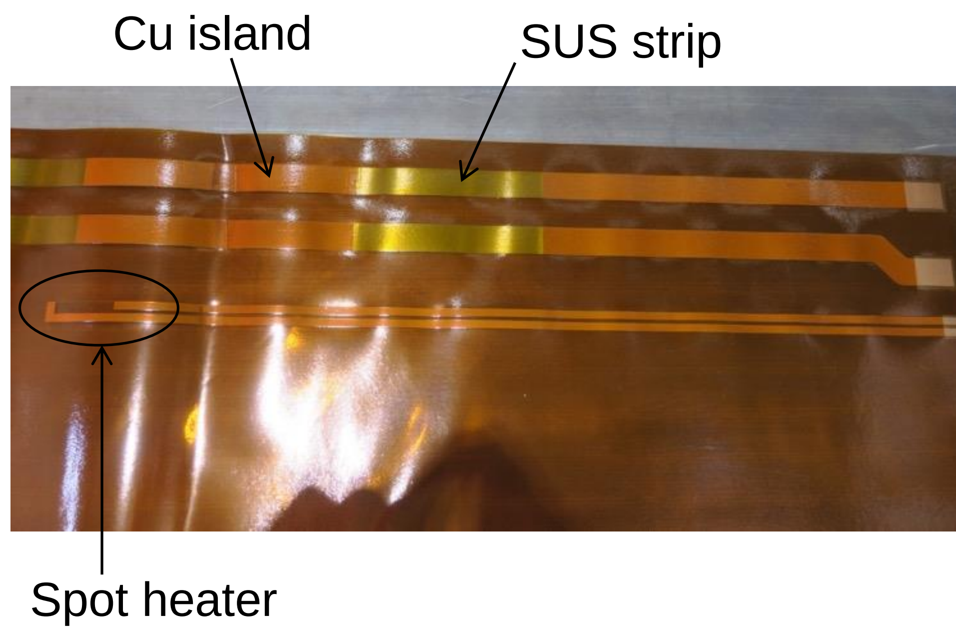
- Current scenario: the base material will be produced by CERN, and be patterned by Trackwise
- Composed of the two strips per quadrant, having a 'zig-zag' pattern for each
- Simulation results: max Temp. would be less than 300 K at 108 % I_{nom} and max voltage of 400 V at I_{nom}.

QPH



Thanks to Christian Scheuerlein,
Rui de Oliveira, Andrea Musso

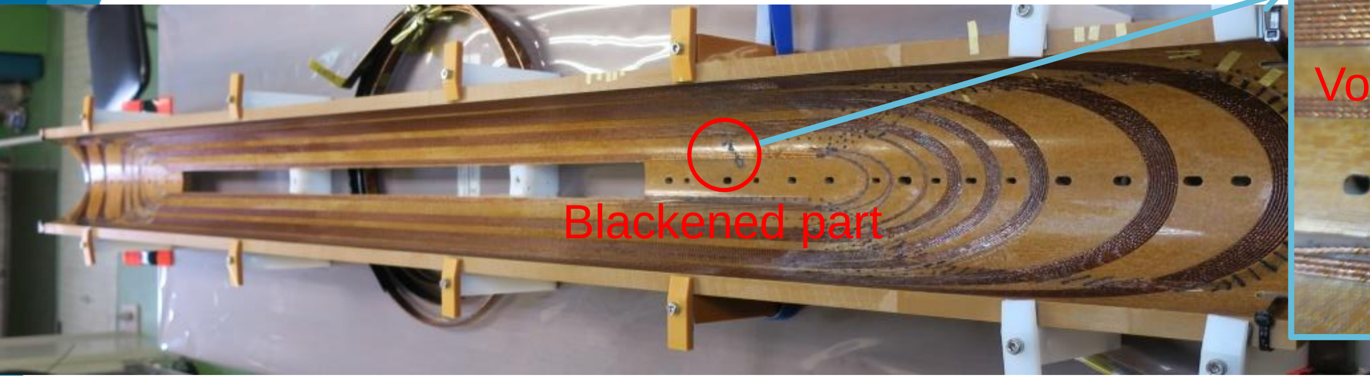


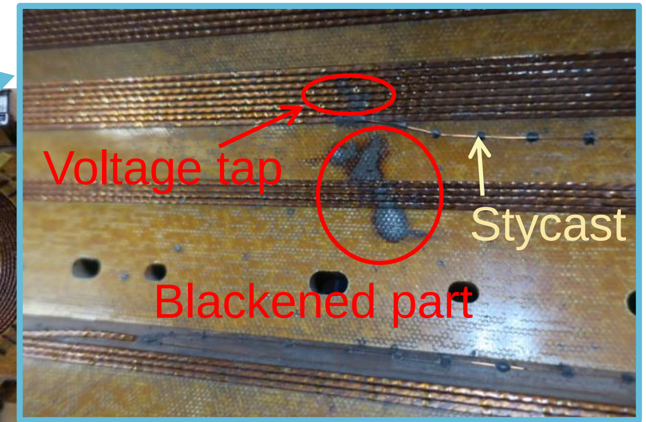


- Two heater strips per quadrant
- Meandering patterns with 25 μmt SUS strips and 10 μmt Cu islands
- QPH sheets for MBXFS2 were provided from CERN.

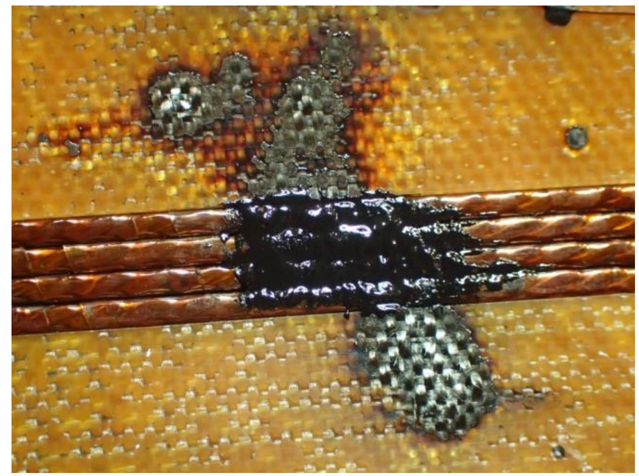
Coil S2-3

Non-conformity



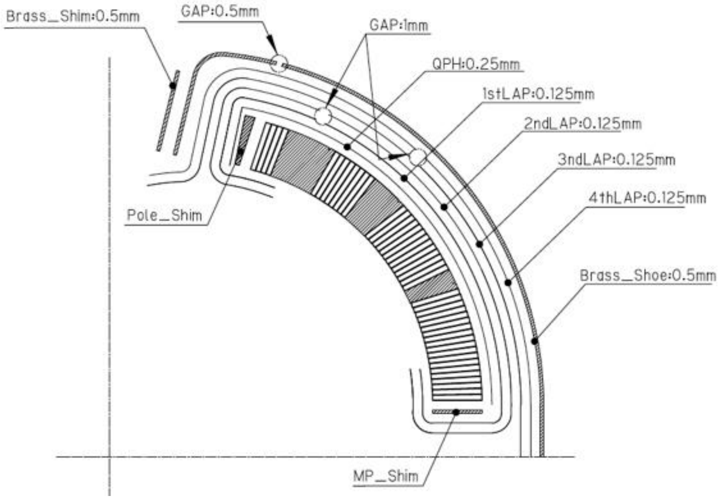


Repair



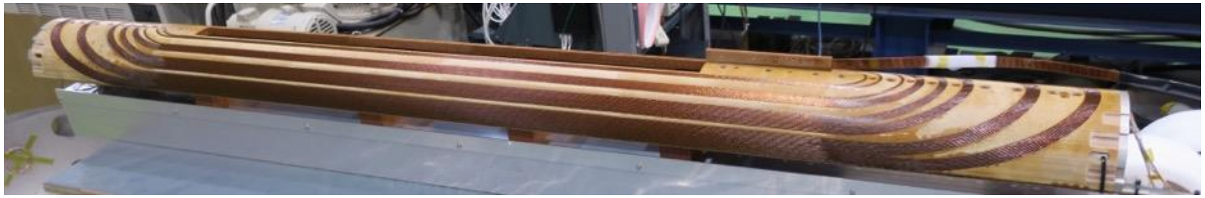
- Coil S2-3 after instrumentation was partly blackened due to insulation test in an incorrect manner by a worker from an outside company.
- After this incident, electrical inspection was performed. As long as we checked coil resistance, inductance and waveform of surge test up to 1 kV, electrical soundness seems to be no problem.
- After discussion with CERN, we reinforced cable insulation with Stycast and decided to use this coil for MBXFS2.

QPH and insulation wrapping

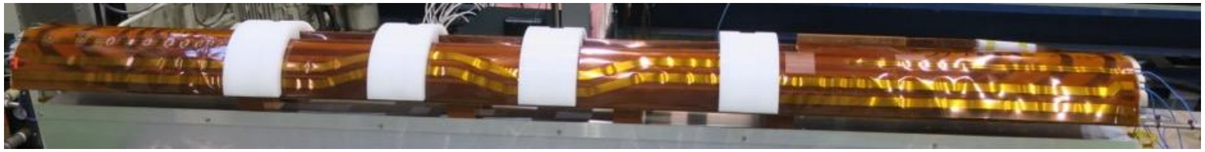


- QPH (0.15 mmt)+ dummy sheets (0.10 mmt)
- Ground insulation: 0.125 mmt x 4 layers
- Brass shim, brass shoe: 0.5 mm

Bare coil

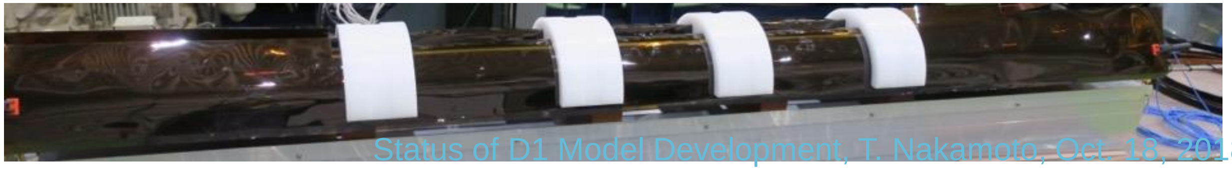


QPH



QPH dummy for thickness compensation

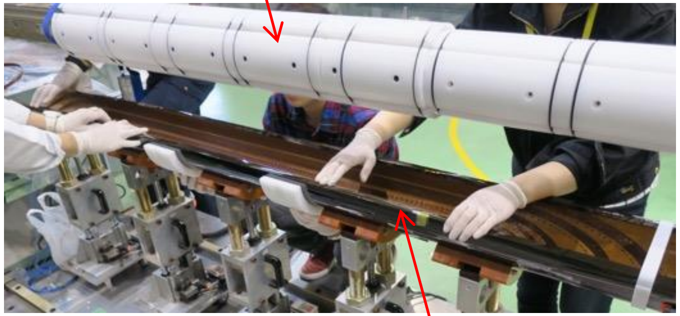
1st, 2nd layer of ground insulation



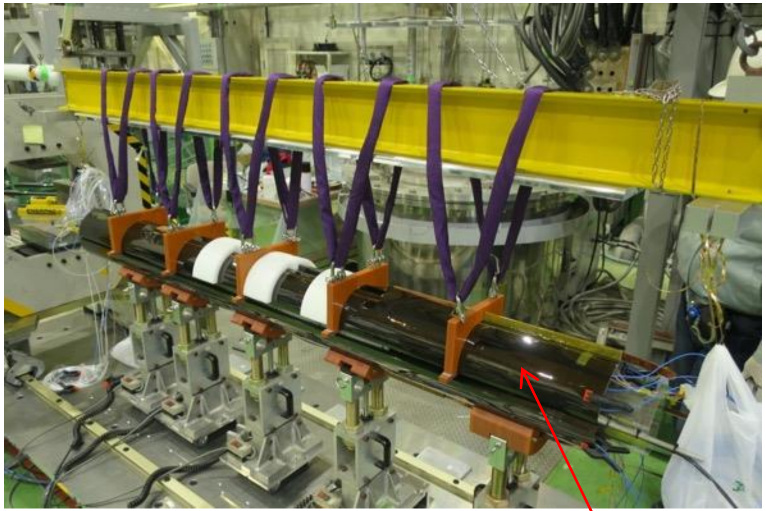
Insulation wrapping and brass shoe assembly

Top/Bottom coil assembly

Collaring mandrel



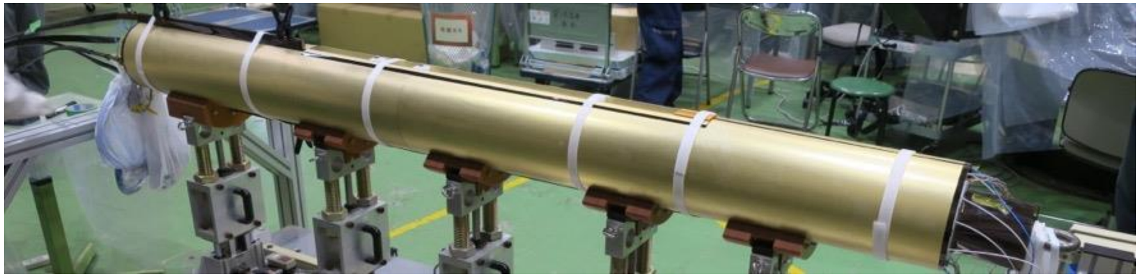
Bottom coil



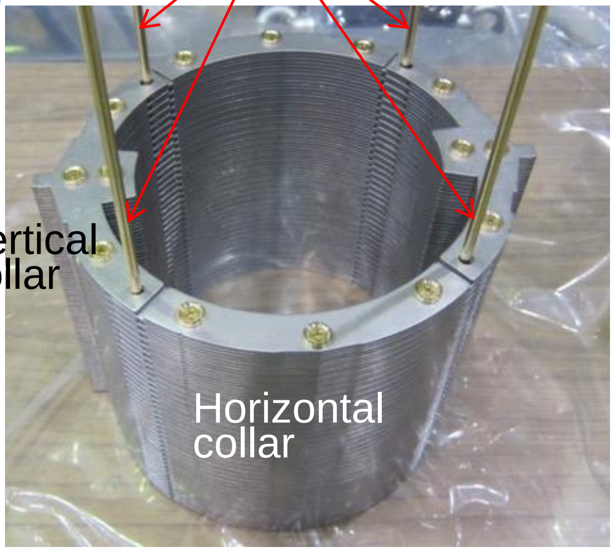
Top coil

3rd, 4th layer of ground insulation

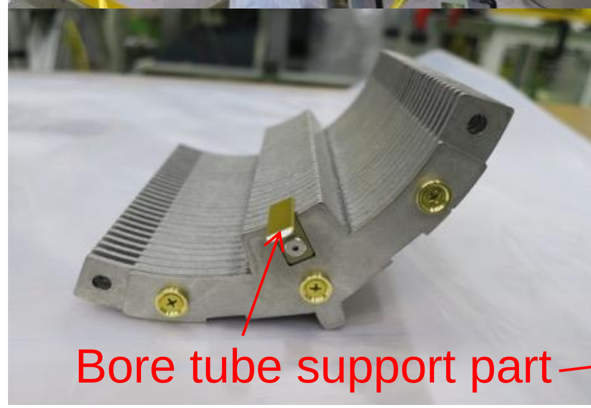
Brass shim, brass shoe

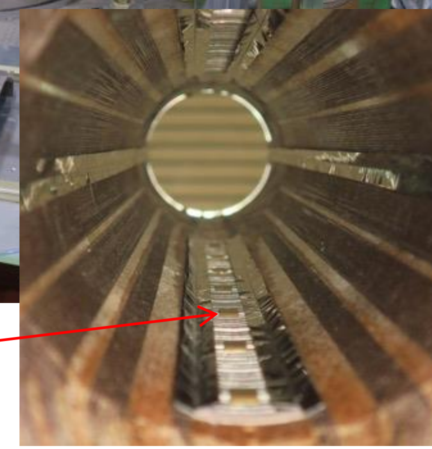


Collaring with four-split collar



Four-split collar

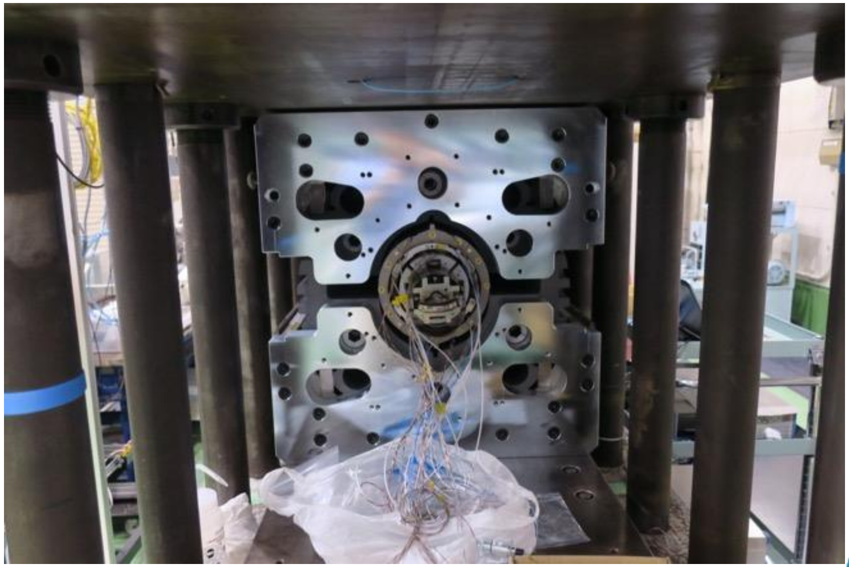




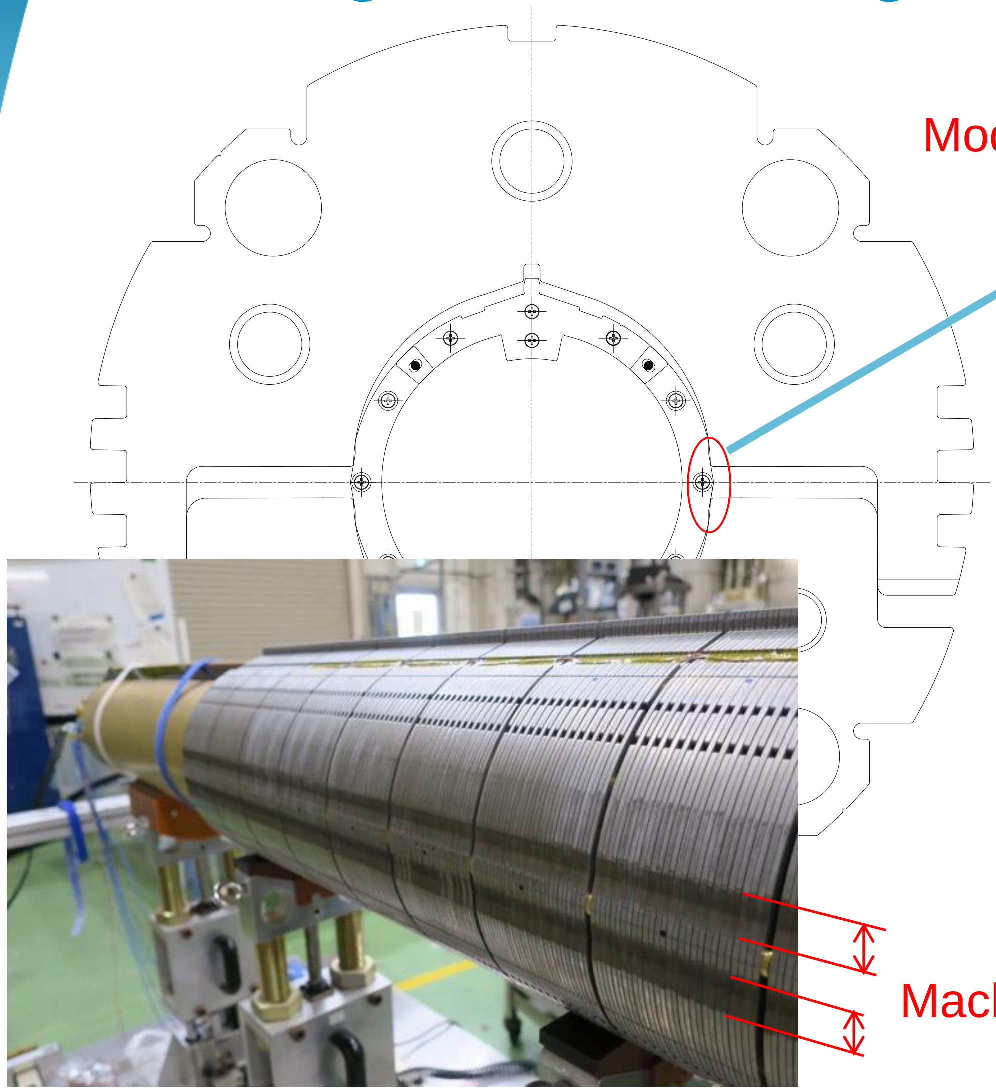
- Four-split collars are linked with “lock pins”.
- T-shaped brass parts with polyimide coating were introduced to support bore tube
- Large impact of larger coil oversize on collaring
  - Only thinner lock pins could be inserted due to limited load capacity (ϕ5.7 → ϕ5.5) → Larger collared coil diameter
  - Higher coil stress after collaring even with thinner lock pins
  - Collared coil deformed anisotropically

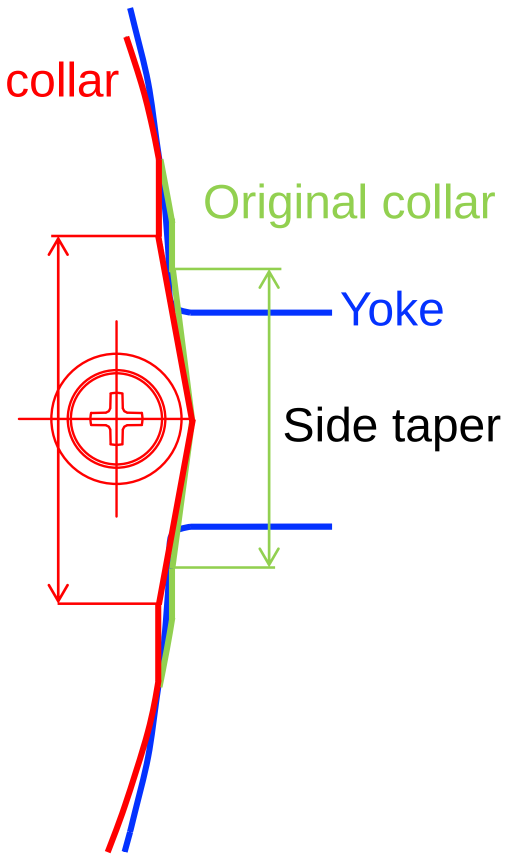
Collaring of was once completed.

Preparation for yoking



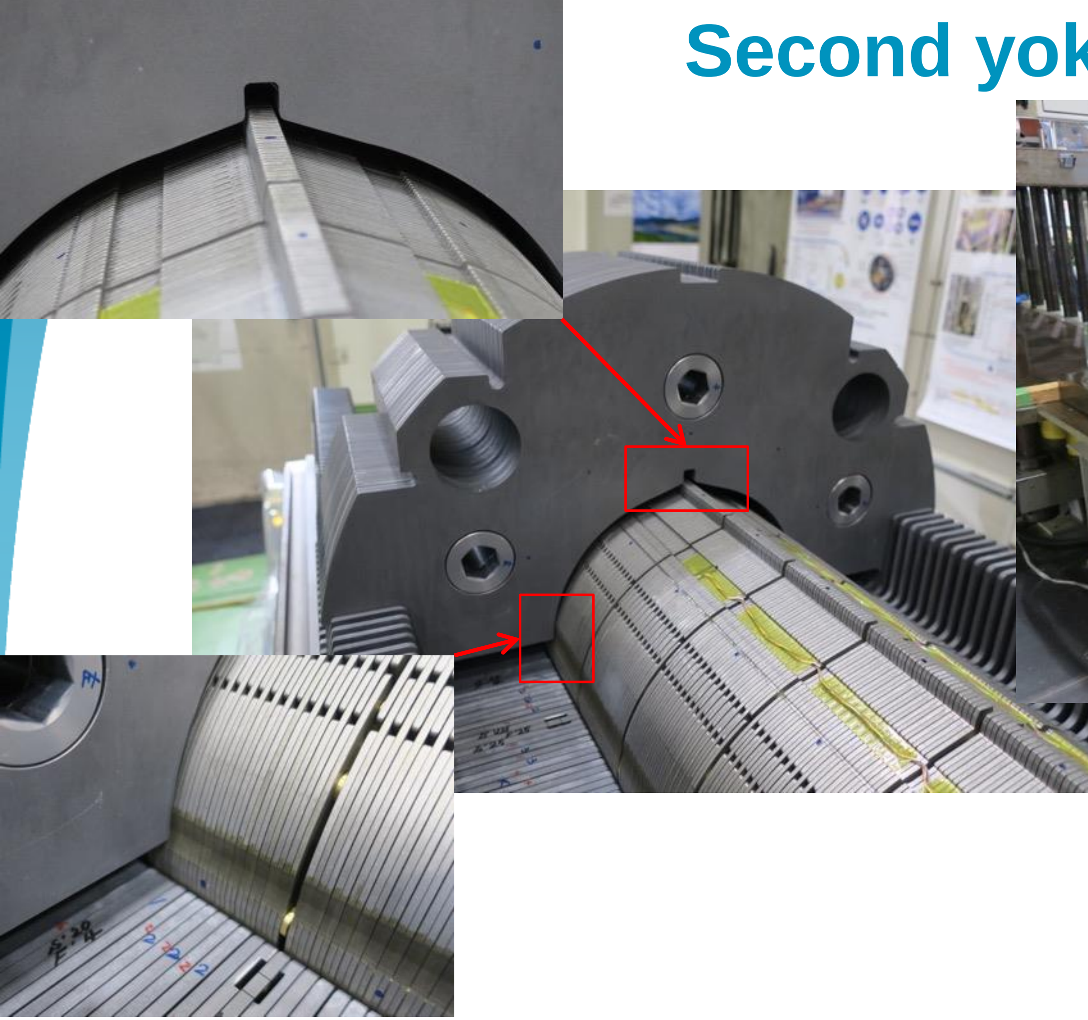
Enlarged Coil: Change of side collar shape





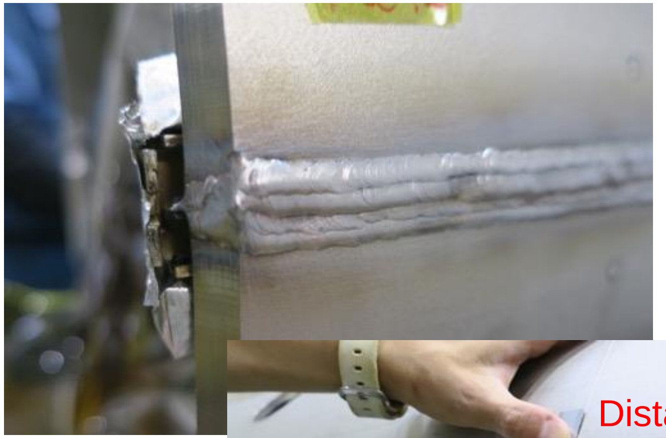
- To cope with a larger collared coil, side taper in horizontal collar was extended by wire-cutting.
- To decrease coil stress after collaring, further thinner lock pins (ϕ5.2) were used.

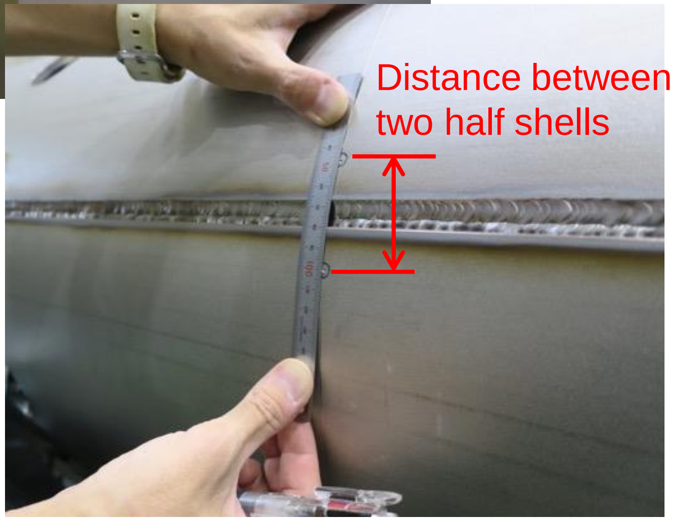
Second yoking



- Modified side collar functioned as expected and collared coil was properly aligned with respect to yoke.
- Yoking press and key insertion were successful.
- Collapsible collaring mandrel was removed.

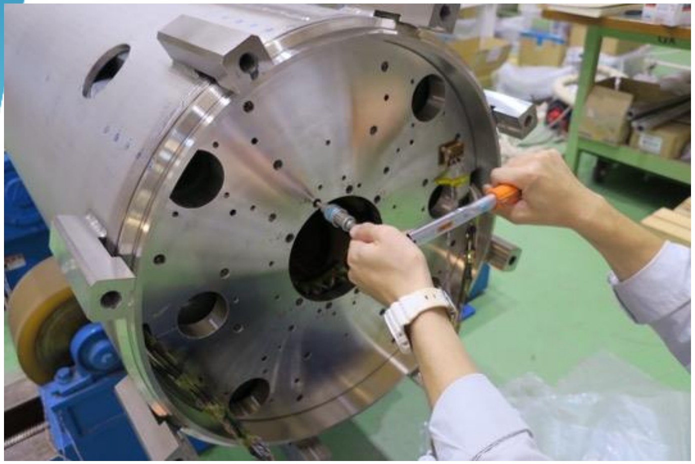
Shell welding

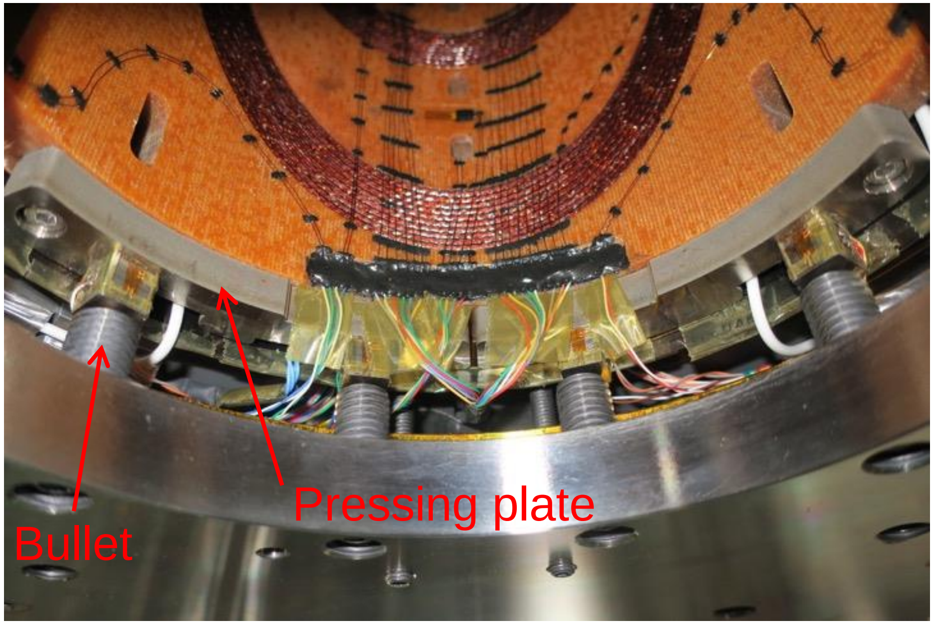




- Two half shells were manually welded from both sides with 11 passes.
- Azimuthal tensile strain by welding in MBXFS1b was 0.26% and this should be decreased.
- 0.5 mm longer circumferential length of half shells in MBXFS2
  → Azimuthal strain was able to be decreased to 0.17%.

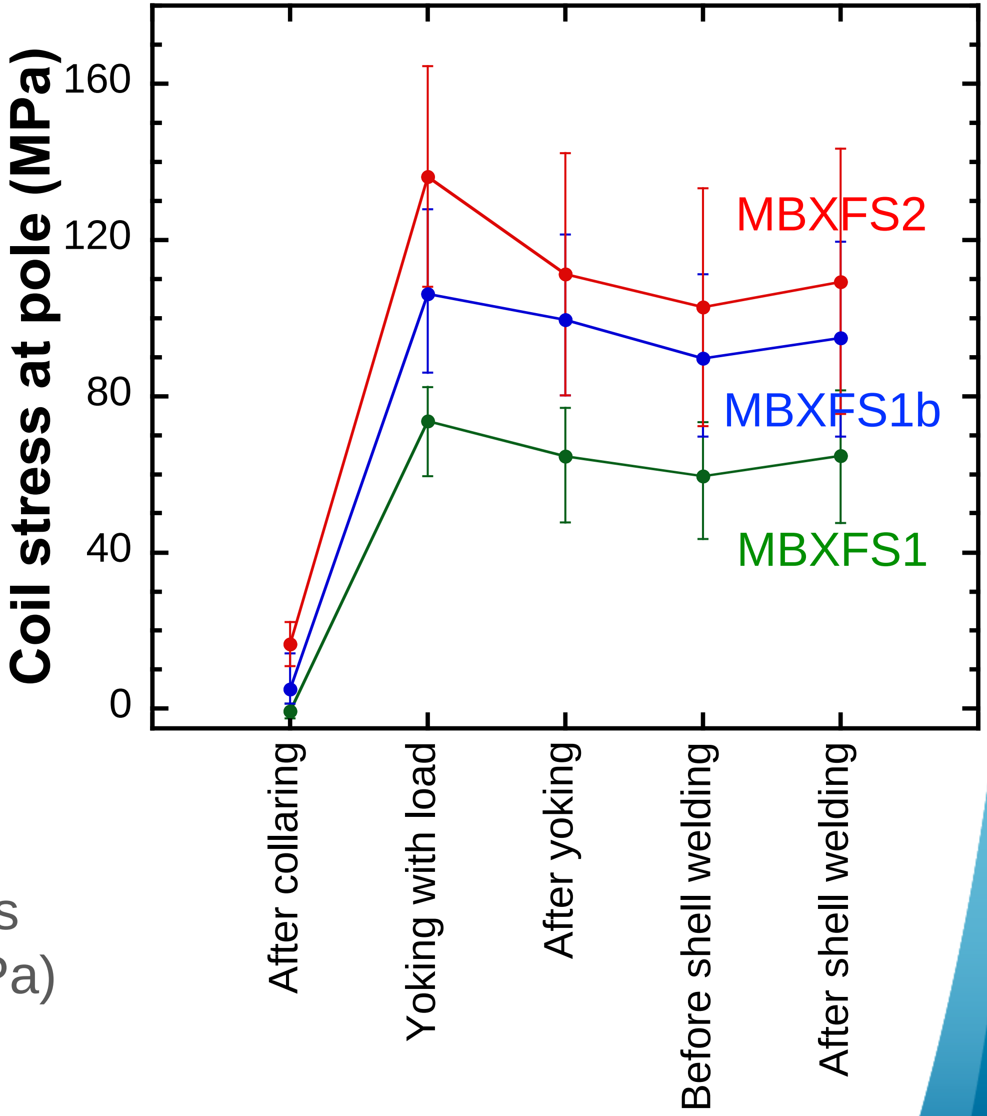
Axial pre-load





- Axial pre-load was applied with four bullets per coil
- Material of bullets and pressing plate was replaced from SUS304L to Ti6Al4V to prevent significant plastic deformation
- Tightening torque of M12 bullets:
  - MBXFS1b: 12 Nm >> 53 kN per coil
  - MBXFS2: 20 Nm >> 88 kN (S.G. meas. 30~43 kN per coil)

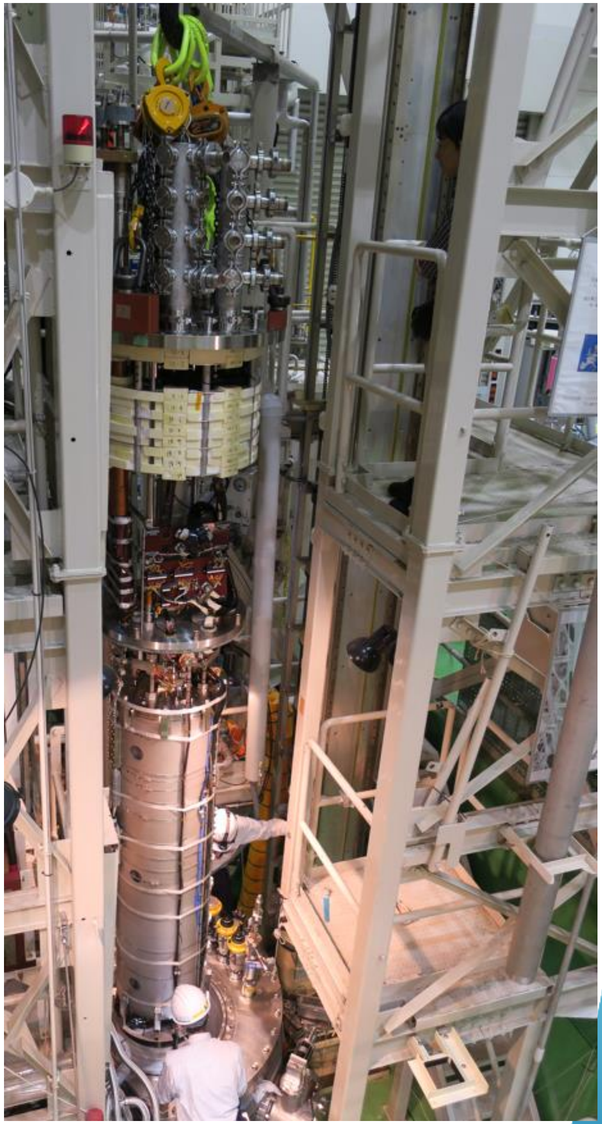
Completed magnet



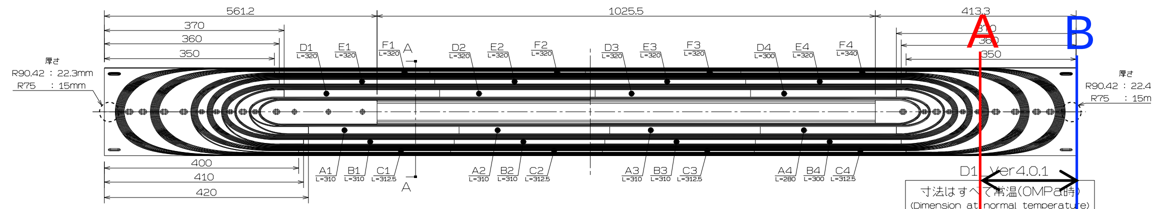
- Higher stress after collaring
- Stress after yoking of 111 MPa is close to the target value (115MPa)

Summary

- Development of beam separation dipole (D1) for HL-LHC has been carried out by KEK with a scope of Japanese in-kind contribution to the project.
- Modified 1st model magnet (MBXFS1b) with higher pre-stress showed improvement in training quench performance while the 1st model showed poor performance.
- Development of the 2nd model magnet (MBXFS2) has been carried out.
  - ✓ New cross section with 4 HX holes
  - ✓ New several features implemented: enhanced coil pre-stress, improved coil end shape & wet-winding, new QPH, etc.
  - ✓ The 2nd model is being cooled down to 1.9 K and the 1st ramp up to quench is anticipated very soon.
- The 3rd model development for reproducibility check is planned. The coil winding will be started after checking the MFM results of the 2nd model.



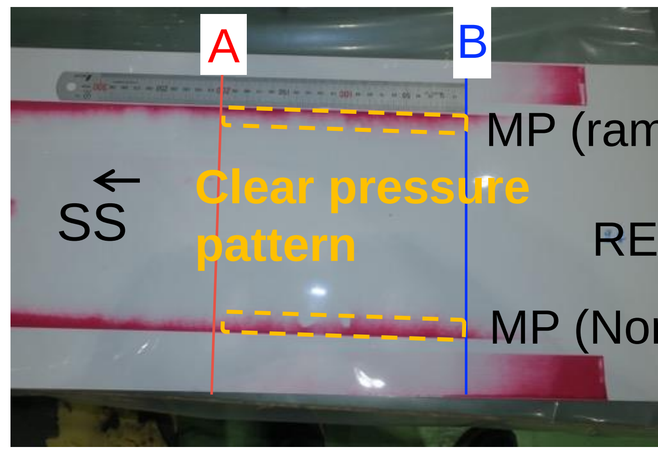
Curing press test for coil end



200 mm

Fuji paper test

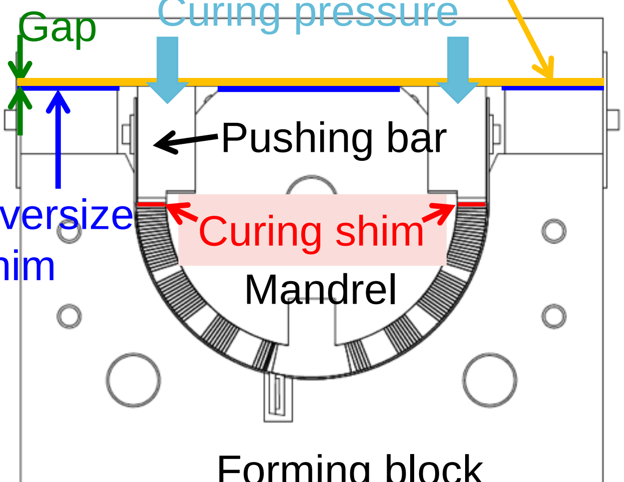
Coil S2-3
w new cuing shim



Pressure range:
10–50 MPa

MP (ramp-side)

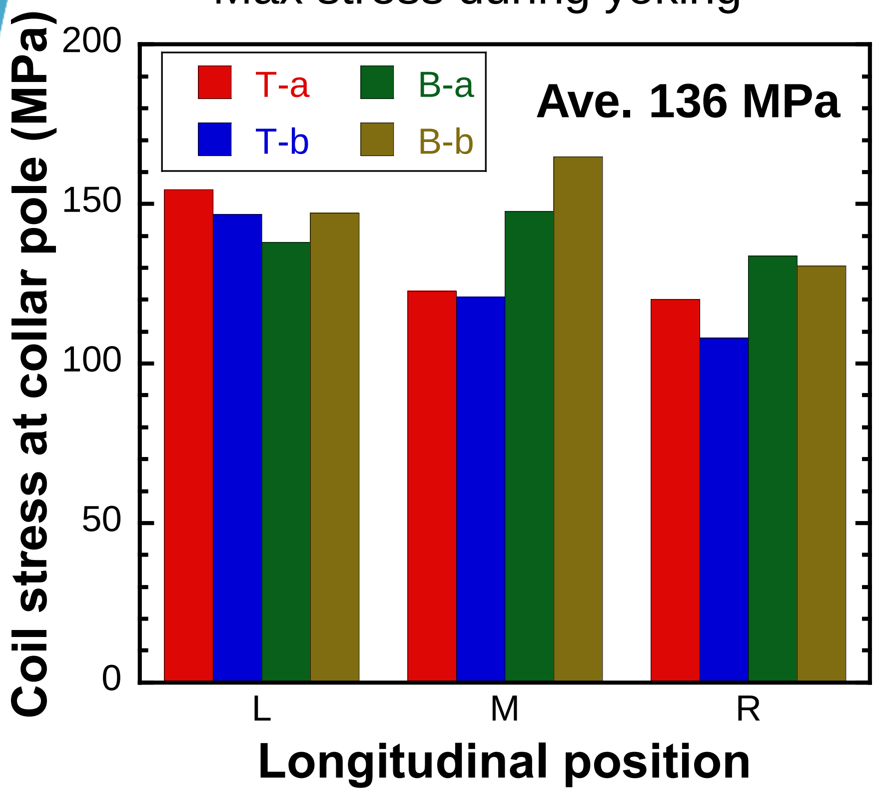
MP (Non-ramp-side)



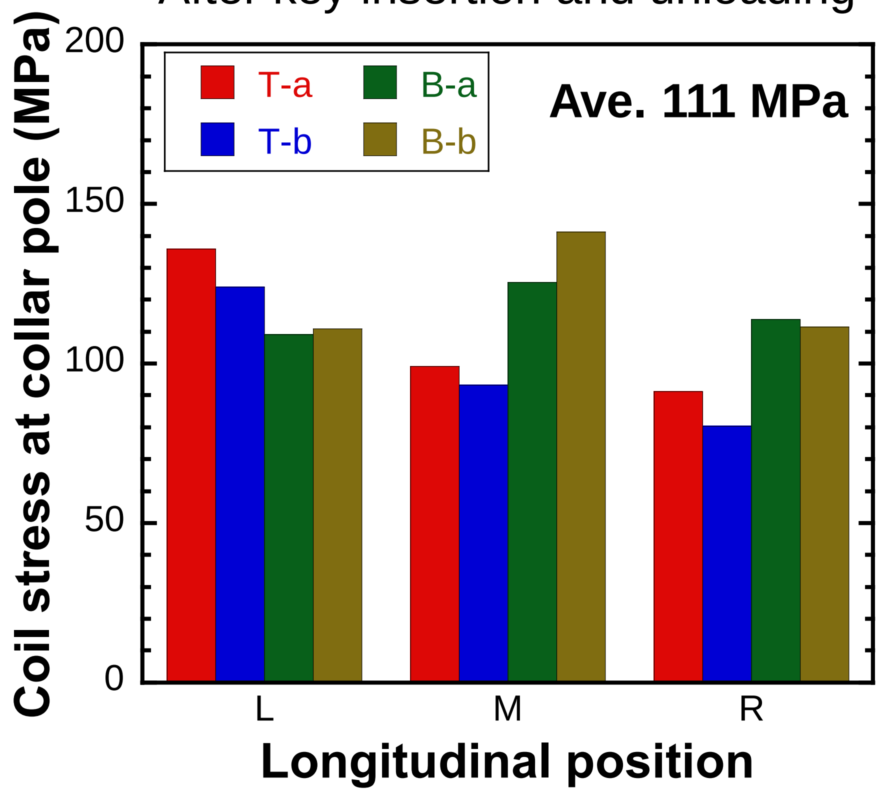
- Smaller coil size at coil end needs shimming for sufficient curing pressure.
- Thickness of a tapered shim was determined by iterative Fuji paper test and finally coil end was able to be pressed at around 50 MPa.

Azimuthal coil stress in SS

Max stress during yoking



After key insertion and unloading



- Average azimuthal coil stress after yoke key insertion is very close to the target value of 115 MPa.