Training Performance with Increased Coil Pre-stress of the 2-m Model Magnet of Beam Separation Dipole for the HL-LHC Upgrade

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KEK

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CERN

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Outline

- HL-LHC
- Overview of D1 magnet
- Unsatisfactory training performance of the first 2 m model (MBXFS01)
- Magnet reassembly with enhanced coil pre-stress (MBXFS01b)
- Training performance of MBXFS01b
- Coil deformation observed after magnet test

HL-LHC

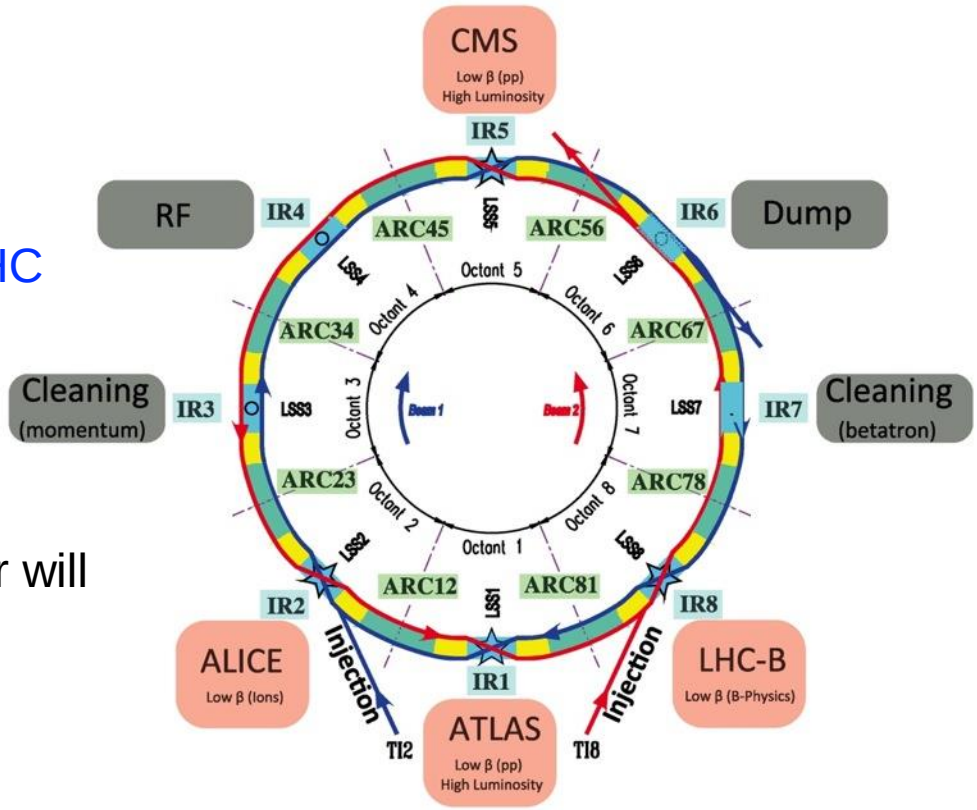
From LHC to HL-HC

Present LHC

p-p collision center-of-mass energy of 13 TeV since 2015

Japan participated in construction of the LHC since 1995.

- Final focus quadrupole magnets (KEK)
- ATLAS detector



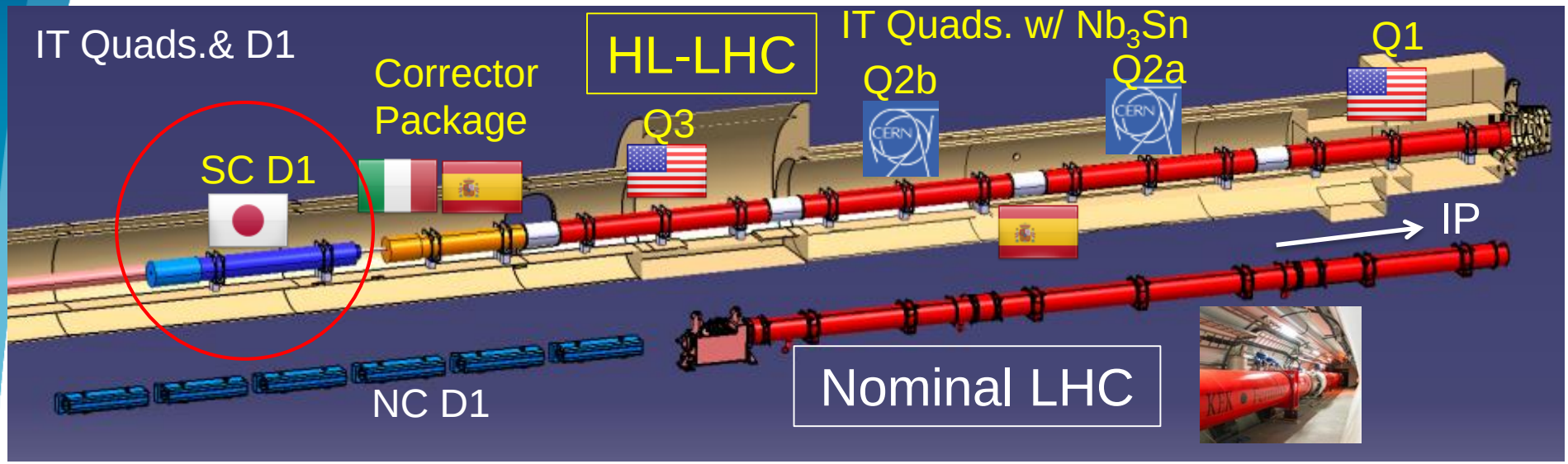
- Running time to halve the statistical error will be more than 10 years after 2020.
  → Increase of luminosity
- Radiation damage in low-β inner triplets
  → Replacement of superconducting magnets

Low-β triplets in the present LHC

High Luminosity LHC（HL-LHC）

Peak luminosity：5×10^{34} $cm^{-2}s^{-1}$（a factor of 5）
Integrated luminosity：3000 fb^{-1}（a factor of 10）

D1 magnet



Courtesy of P. Fessia

Development of magnet system around two interaction points is ongoing under international collaboration, aiming construction in around 2024.

KEK is in charge of **beam separation dipole（D1 magnet）**.

- Large aperture to obtain smaller β^*

  Coil aperture: ϕ70 mm → ϕ150 mm

- Stronger kick to accommodate shorter distance between D1 and D2 (recombination magnet)

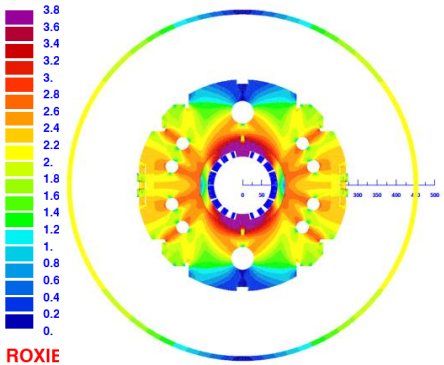
  Field integral: 26 Tm → 35 Tm

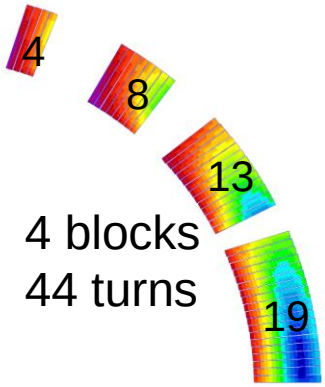
Normal conducting D1 in the current LHC will be replaced by Nb-Ti based superconducting magnets.

Overview of D1 magnet

Design parameters

	Production	2 m model
Coil aperture	150 mm	
Field integral	35 T・m	9.8 T・m
Nominal field	5.57 T	
Peak field	6.44 T (SS), 6.56 T (coil end)	
Operating current	12.0 kA	
Operating temperature	1.9 K	
Field quality	$<10^{-4}$ w.r.t B_1 (R_{ref}=50 mm)	
Load line ratio	75.4%（SS）, 76.6%(coil end）at 1.9 K	
Differential inductance	4.0 mH/m	
Conductor	Nb-Ti MB outer cable	
Stored energy	340 kJ/m	
Magnetic length	6.33 m	1.73 m
Coil mech. length	6.57 m	2.00 m
Magnet mech. length	6.72 m	2.15 m
Heat load	135 W (Magnet total) 2 mW/cm^3 (Coil peak)	
Radiation dose	> 25 MGy	



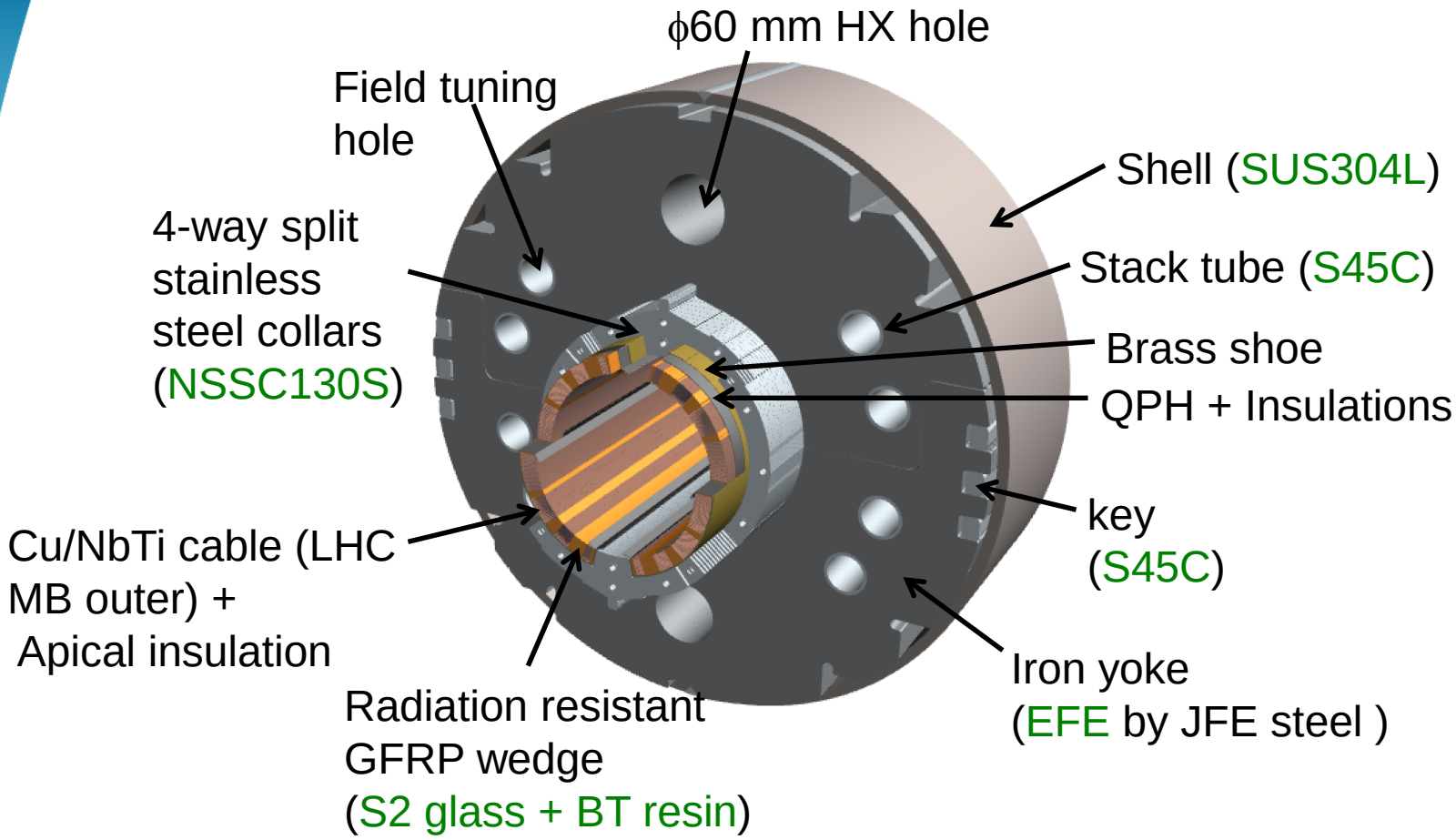


2 m model magnet of D1 is being developed in KEK.

Technical challenges

- Large aperture：Large coil-size change during fabrication, cooling and excitation
→ Precise prediction for appropriate pre-stress and good field quality
- Radiation resistance：Radiation resistant material for coil parts, cooling
- Iron saturation：Good field quality from injection to nominal current

Overview of D1

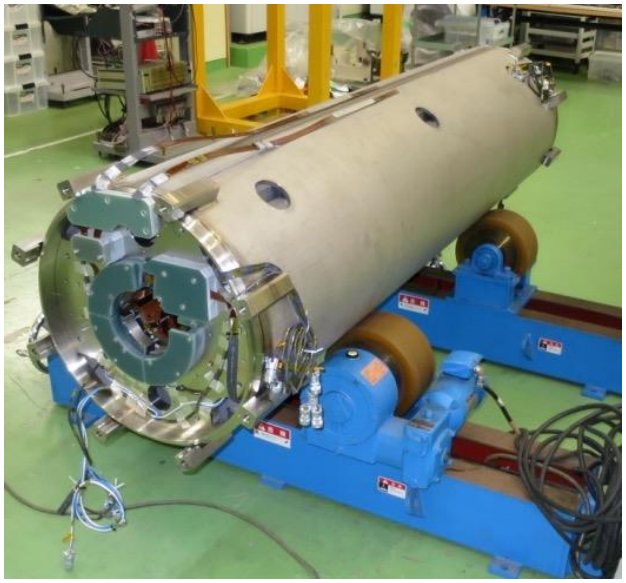


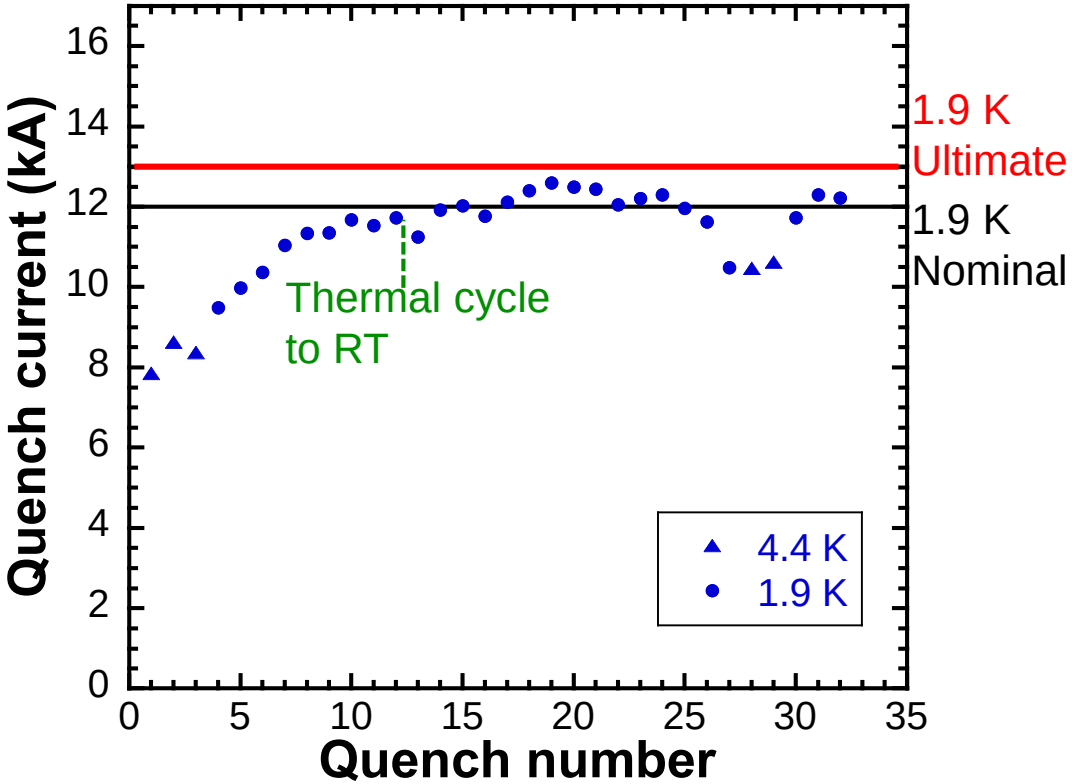
- A single layer coil to maximize iron volume and better cooling
- Nb-Ti/Cu cable with APICAL and PIXEO insulations, same as MB outer cable
- Radiation resistant GFRP for wedges and spacers
- Collared yoke structure to increase amount of iron yoke
- Design features for better cooling (Heat load 135 W in total, 2 mW/cm^3 at local peak)
  - Void spaces and packing factor of collar and yoke less than 100% for passage of superfluid He

Unsatisfactory training performance of the first 2 m model (MBXFS01)

Training performance of MBXFS01

Previous work



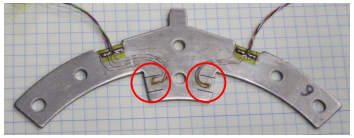


First 2 m model magnet (MBXFS01, model 01)
Fabricated and tested in 2015-2016

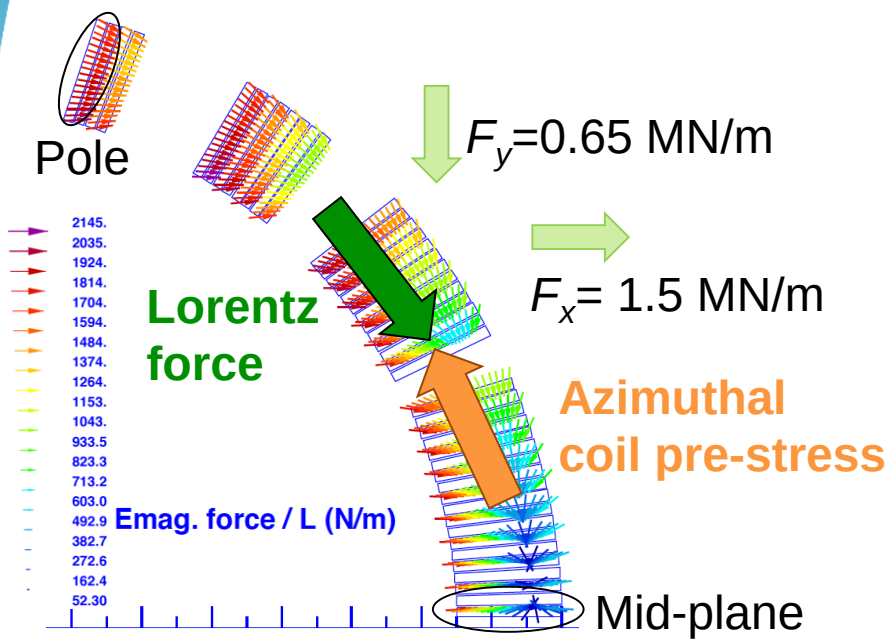
- Maximum quench current = 105% of the nominal current (I_{nom}=12.0 kA)
- Quench current did not reach the ultimate current of 13.0 kA (108% of I_{nom}, acceptance criteria).
- Erratic behavior after the maximum quench current

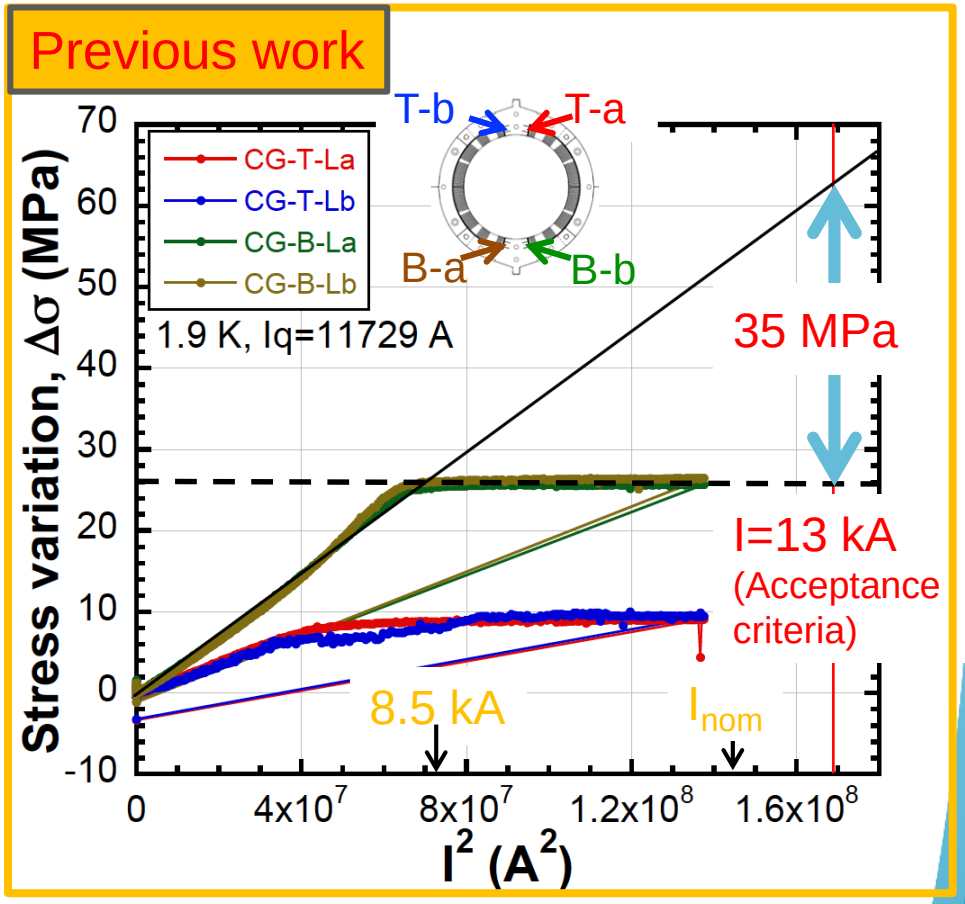
Training performance was not satisfactory.

Coil pre-stress in straight section during excitation



Lorentz force exerted on a coil



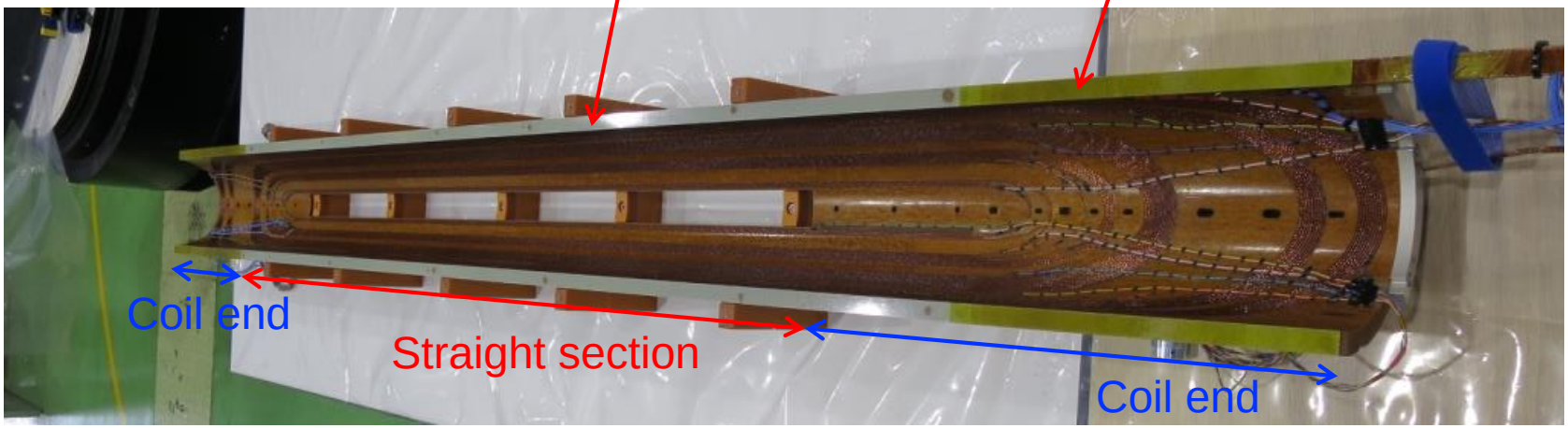


- Flattening of the measured curve→ Complete released of azimuthal coil pre-stress below 8.5 kA (< I_{nom}=12 kA).
- Pre-stress should be increased by 35 MPa.

Insufficient coil pre-stress is a main reason of unsatisfactory training performance.

Magnet reassembly with enhanced coil pre-stress (MBXFS01b)

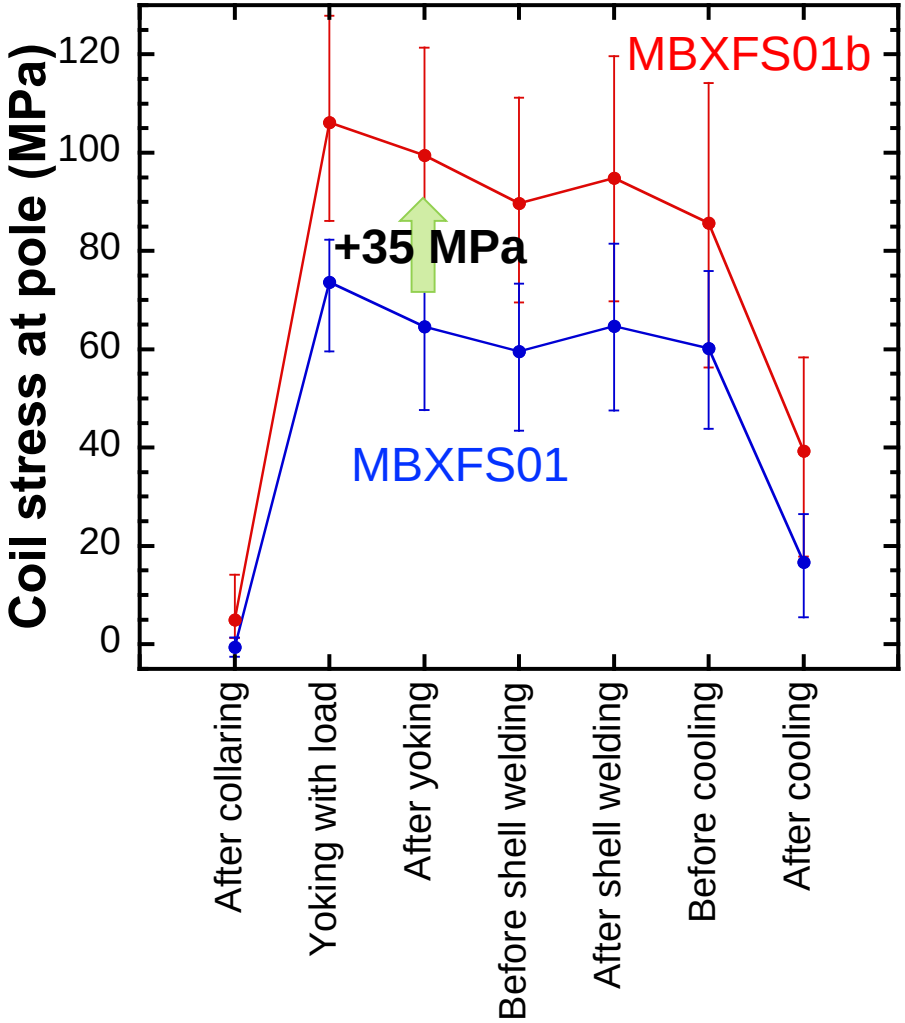
Enhancing azimuthal coil pre-stress

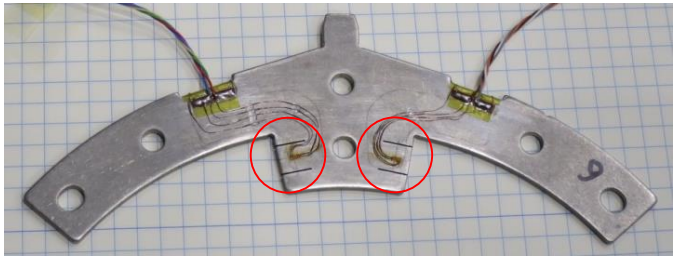


- Reassembly with enhanced azimuthal coil pre-stress
  → MBXFS01b, model 01b

- Coil pre-stress was increased by inserting the G10 shims to the Mid-plane.
- **Target pre-stress**
  - Straight section: 110 MPa with 0.8 mm-thick G10 shim determined based on coil size measurements
  - Coil end: 50-55 MPa with 0.9 mm-thick shim

Measured coil pre-stress during reassembly





Coil pre-stress measured using strain gauges on a collar pole in straight section

- Coil pre-stress was mainly applied in a yoking process.
- Pre-stress after yoking in MBXFS01b is 35 MPa higher than that in MBXFS01.

→ Coil pre-stress was able to be increased almost as expected.

Training performance of MBXFS01b

Magnet test program of MBXFS01b

- 1st test cycle
  - Training quench at 1.9 K → This presentation
  - Magnetic field measurement

Thermal cycle to RT

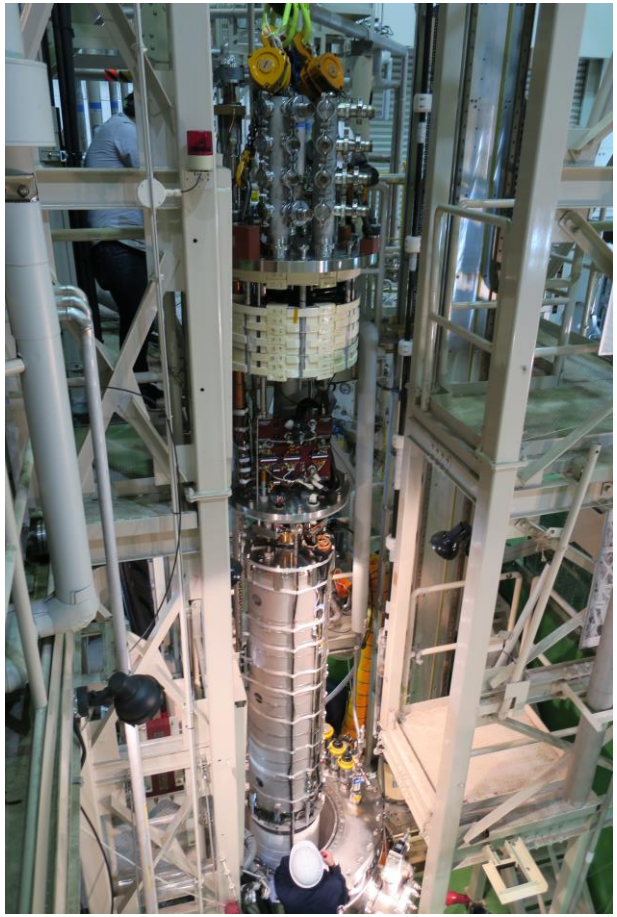
- 2nd test cycle
  - Training quench
    - Quench training memory
    - Ramp rate dependence
    - Temperature dependence

    This presentation
  - Magnetic field measurement
  - Heater test (Spot heater, QPH, Full energy dump)

Poster session on Tuesday afternoon

- Iron saturation and coil end effect on field quality by Enomoto
- Heater test results, quench simulation for QPH design by Suzuki

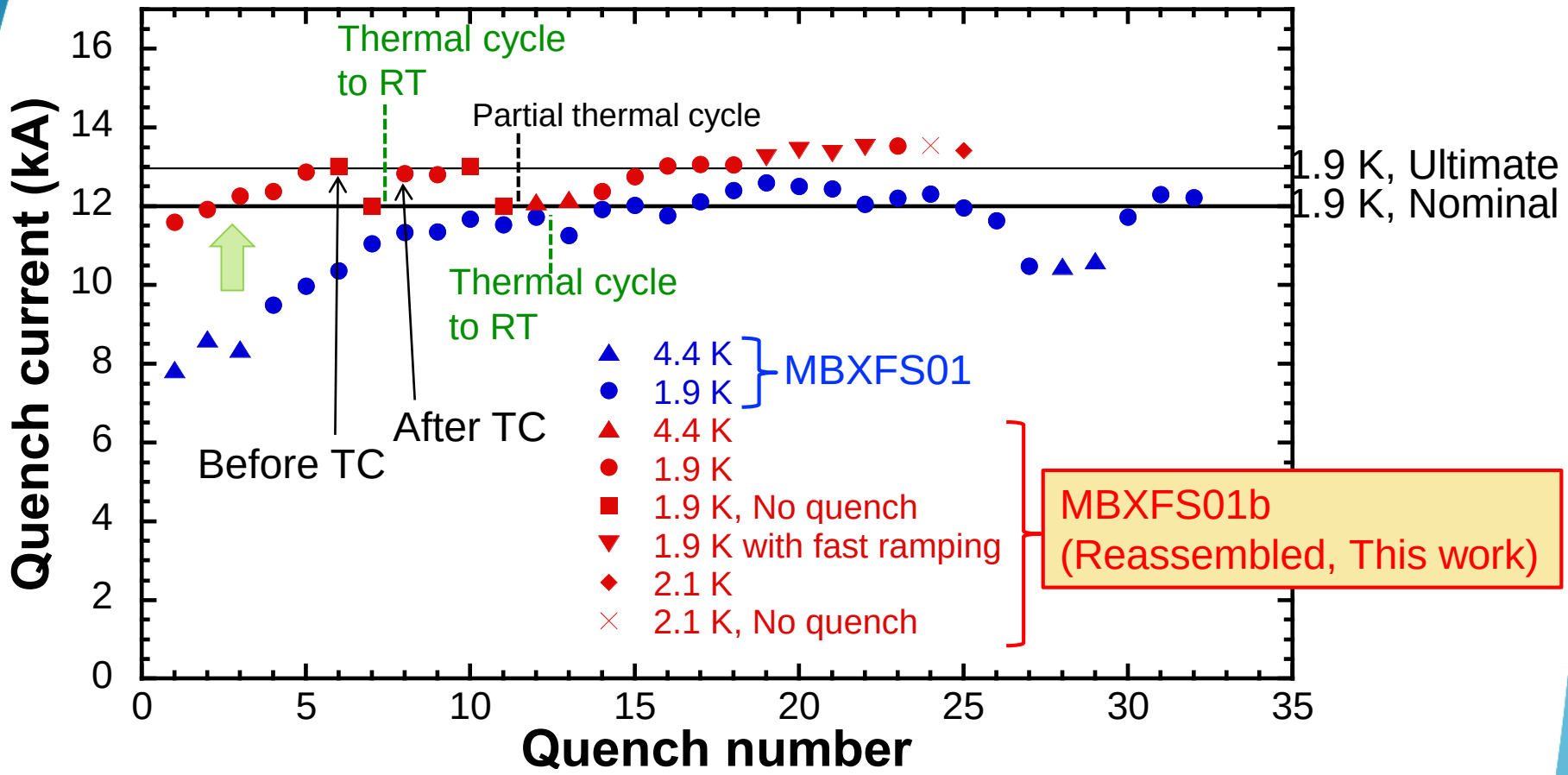
Conditions of training quench



- 9 m-deep vertical cryostat in KEK
- Energy extraction
  - Dump resistor :73 mΩ or 50 mΩ
- Quench detection
  - Voltage threshold: 0.1 V
  - Validation time: 10 ms
- Temperature: 1.9 K, 2.1 K and 4.4 K
- Ramp rate
  - Typically 10 A/s
  - 50–200 A/s for fast ramp test

- Quench origin and propagation: voltage taps, quench antennas
- Stress/strain measurements: collar (coil pre-stress), yoke, shell and bullet

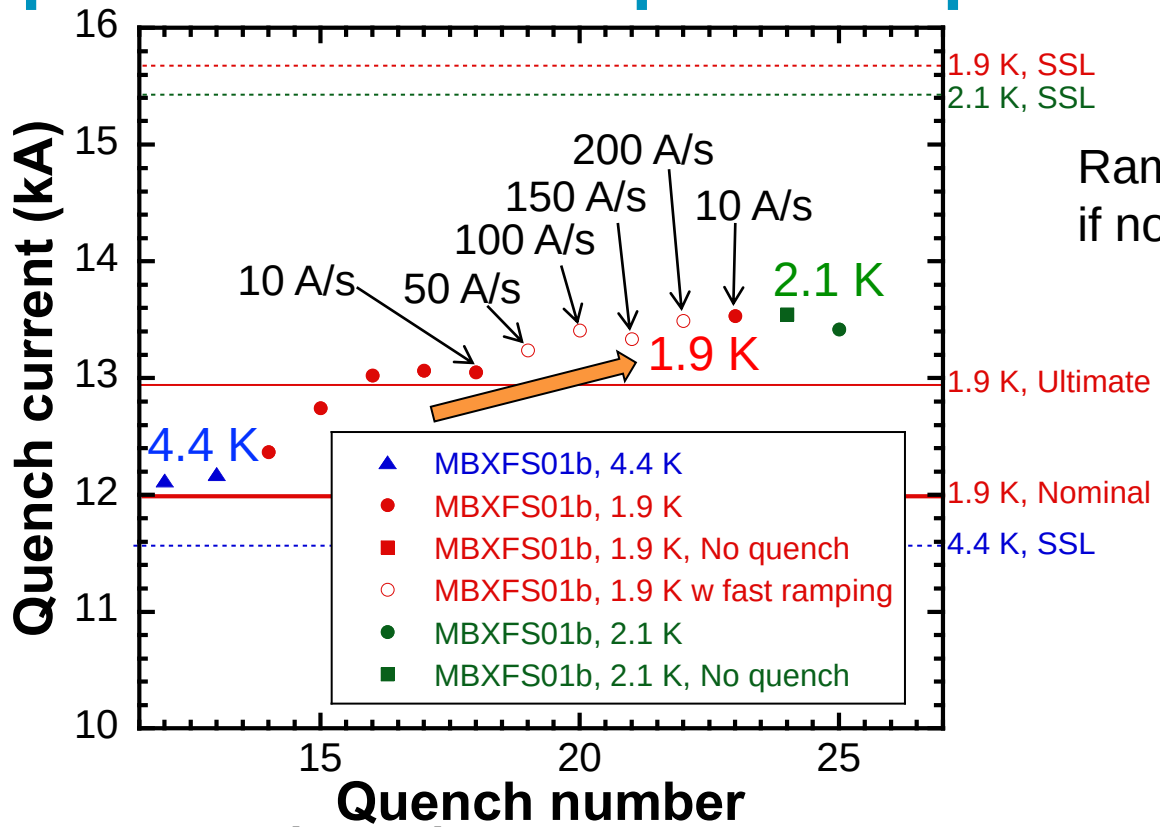
Training plot (comparison btw 01 and 01b)



- Smaller number of quenches to the nominal current (12 kA): 15 → 3 quenches
- 5 quenches to the ultimate current (13 kA) (Not achieved in MBXFS01)
- Current-holding at 13 kA for 1 min, 12 kA for 1 hr → OK
- Quench current before and after thermal cycle (TC) to RT: 108% and 107% of I_{nom}
  → Good training memory

Training performance is improved significantly in MBXFS01b.

Temperature and ramp rate dependence

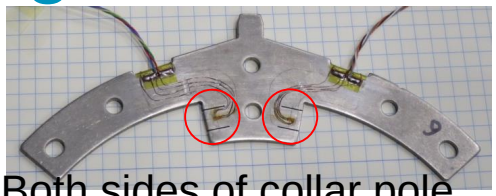


Ramp rate is 10 A/s if not stated.

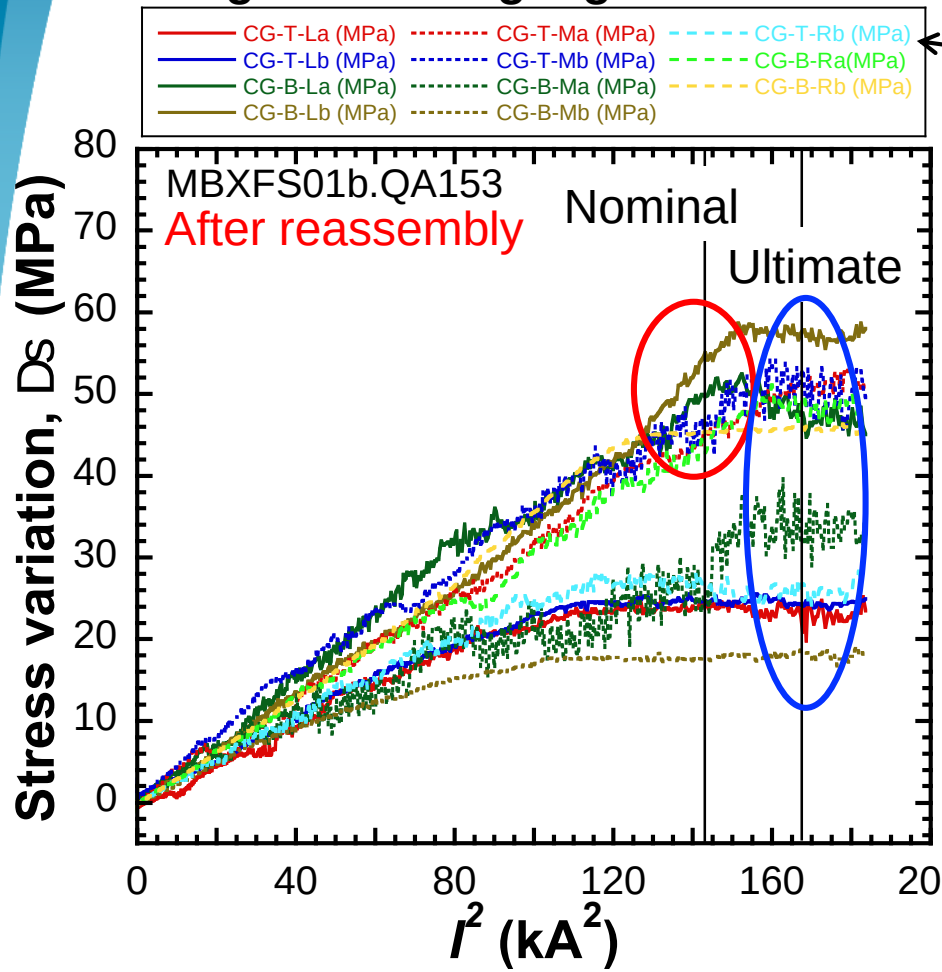
- **Temperature dependence**
  - I_q at 4.4 K ~ 100% of SSL
  - I_q at 2.1 K is comparable to I_q at 1.9 K
    → I_q is finally limited by mechanical support of the coils.
  - I_{max} through the tests = 13.548 kA (88% of SSL at 2.1 K)
- **Ramp rate dependence**
  - I_q increases despite of increasing ramp rate.
    → The magnet was still under training.

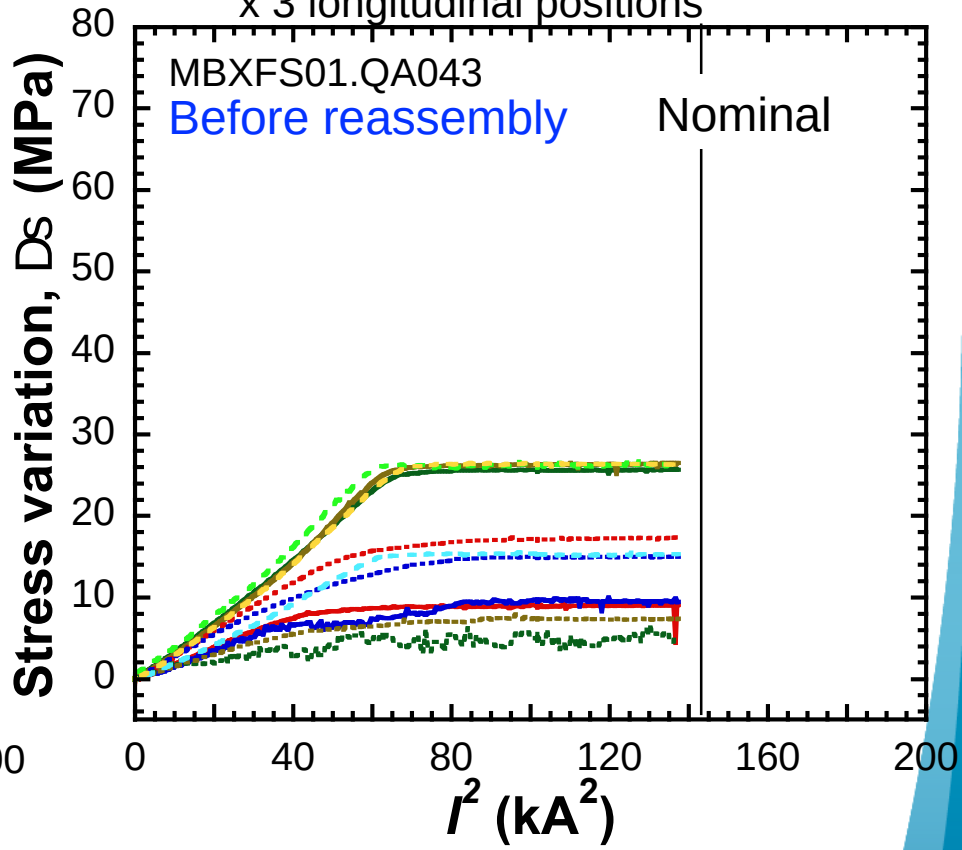
Coil pre-stress in the straight section

Coil pre-stress measured using the strain gauges at the collar pole



Both sides of collar pole
x 3 longitudinal positions



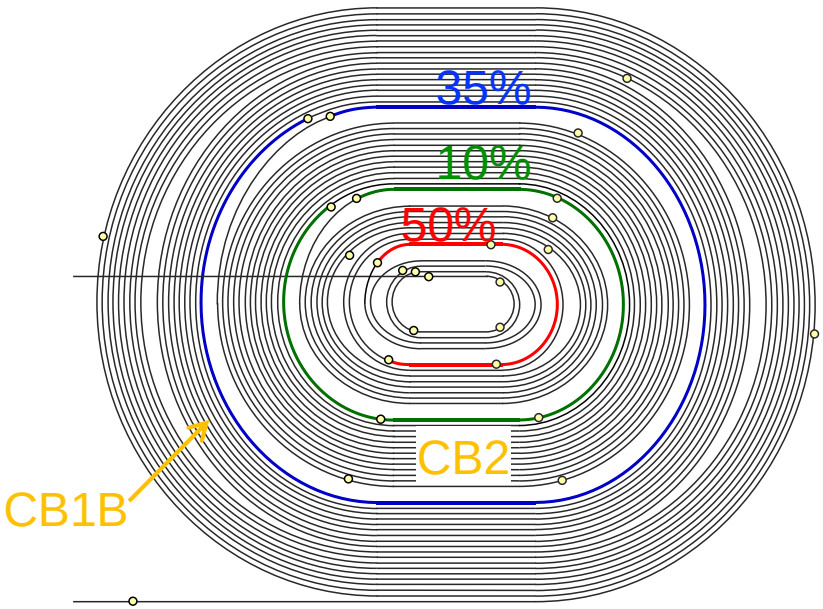


- Nominal current: Pre-stress still remains at half of measured points in MBXFS01b.
- Ultimate current: Pre-stress was relieved at all measured points.

→ Coil pre-stress is preferably increased by 15 MPa.

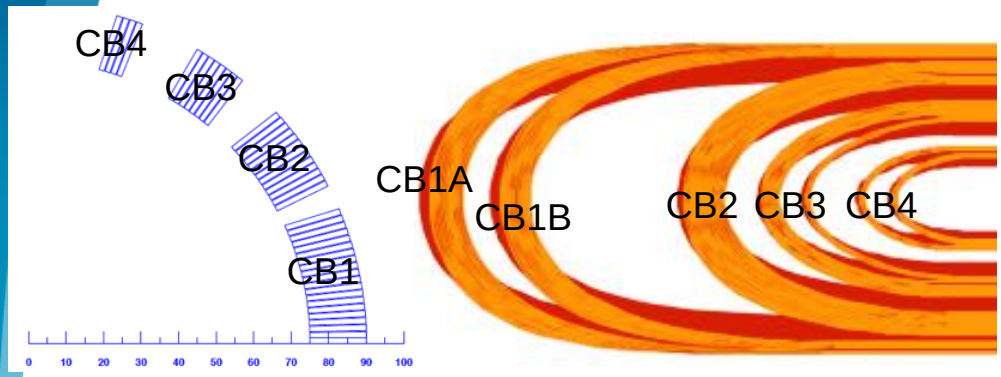
Quench start location

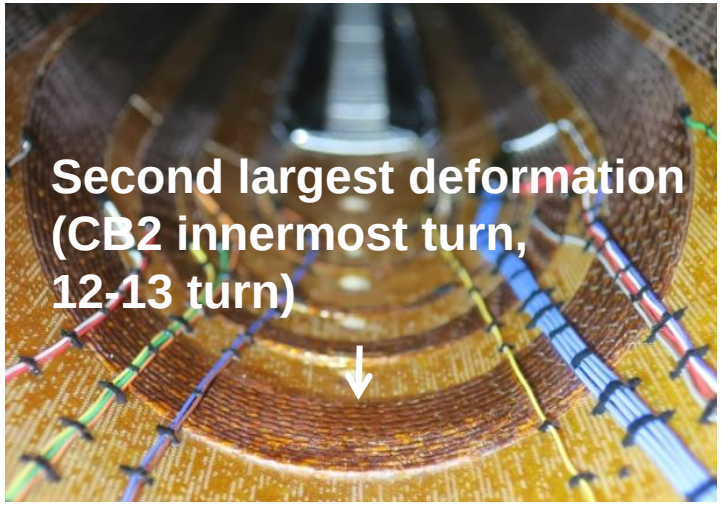
Run	Quench start location		
	Coil	CB No.	Turn No.
1st cycle			
01b.QA008	T	3	5th
01b.QA009	T	1	26-27th
01b.QA010	T	3	5th
01b.QA011	Failure in data acquisition		
01b.QA013	B	3	5th
2nd cycle-1			
01b.QA032	B	2, 3	12-13th
01b.QA033	B	3	5th
2nd cycle -2			
01b.QA138	B	3	5th
01b.QA139	T	3	5th
01b.QA140	B	1	26-27th
01b.QA141	T	1	26-27th
01b.QA142	T	1	26-27th
01b.QA145	T	3	5th
01b.QA146	B	1	26-27th
01b.QA147	B	3	5th
01b.QA148	T	3	5th
01b.QA149	B	2	13th
01b.QA150	T	1	26-27th
01b.QA151	B	3	5th
01b.QA154	T	1	26-27th

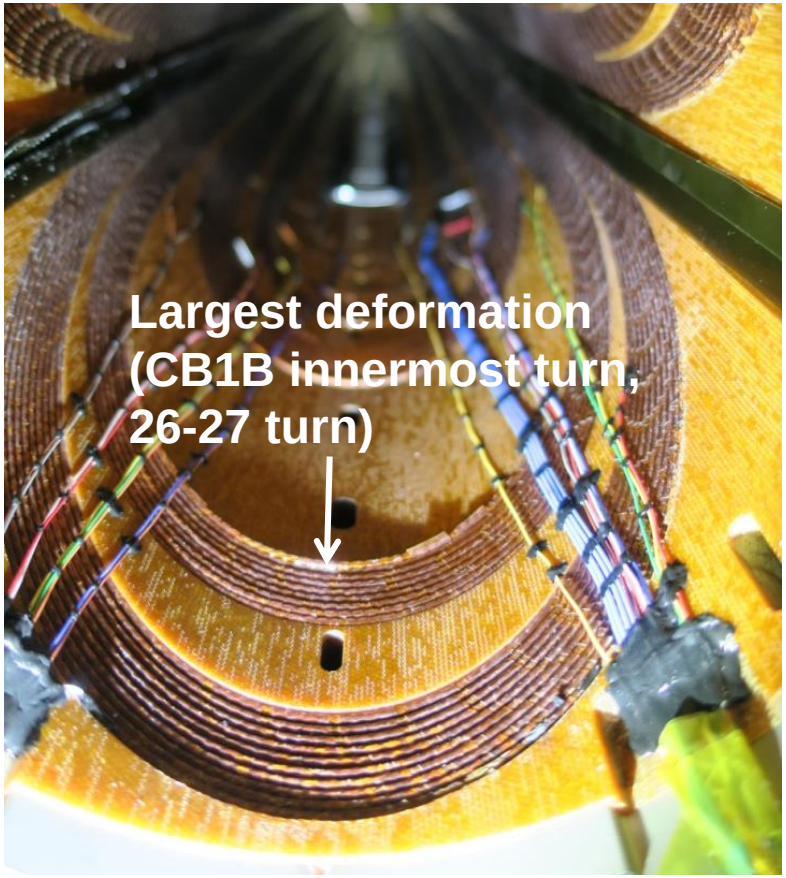


- Quench start location was identified from voltage tap signals.
- 50% at the 5th turn (peak field)
- The rest of quenches initiated at the innermost turn of CB1B and CB2.

Coil deformation at coil end (MBXFS01b)



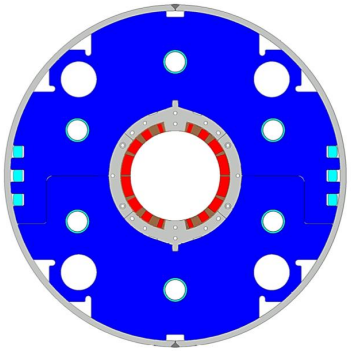


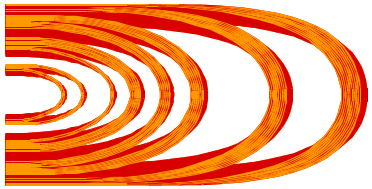


- Similarly to 01, coil deformation towards the coil bore was observed in the 01b.
- The largely deformed turns coincide with ones at which quench started, though it has not been clarified if such cable deformation can cause quench.
  → Mechanical support of the cable at coil end against Lorentz force should be reinforced.
- Countermeasures: Higher pre-stress, better matching btw cable/spacers, impregnation only at coil end

Summary

- The first 2 m model magnet of D1 with unsatisfactory training performance (MBXFS01) was disassembled and reassembled as MBXFS01b with enhanced azimuthal coil pre-stress.
- In MBXFS01b, training performance was significantly improved, suggesting that controlling coil pre-stress is extremely important in this magnet.
- Coil deformation was observed at coil end even with higher pre-stress. Various countermeasures will be applied in the next model magnet.
- Design updates of the second 2 m model have been almost completed. Coil winding will be started in 2017.





Acknowledgement

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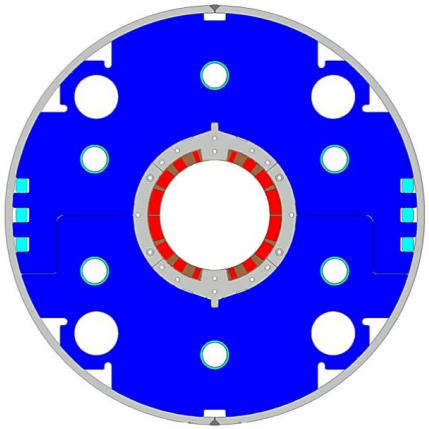
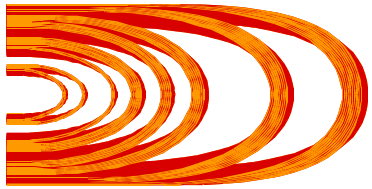
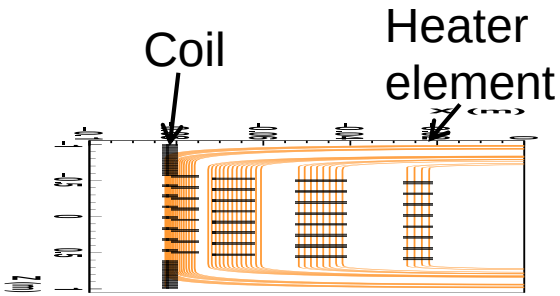
- The authors would like to express their gratitude to Profs. K. Tokushuku, K. Hanagaki and S. Yamaguchi at KEK and L. Rossi at CERN for their strong supports for this project. The authors are also very grateful for their colleagues at KEK and CERN, in particular, B. Auchmann, A. Ballarino, L. Bottura, P. Fessia, P. Francois-Oliver, S. Izquierdo Bermudez, G. Kirby, J.C. Perez, G. de Rijk, F. Savary, and R. van Weelderen for their kind suggestions and fruitful discussions. The authors also thank T. Kawashima, I. Murakami and A. Ueda for their technical supports.

Design updates for the second 2 m model

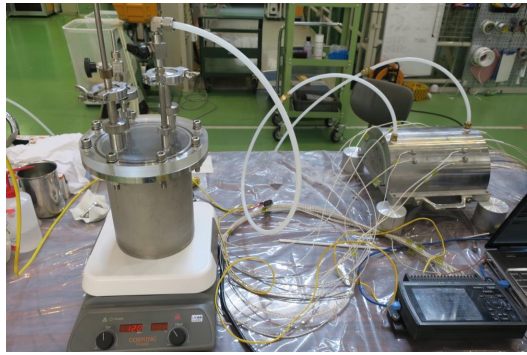




New magnet cross-section and coil end shape



Study for QPH pattern

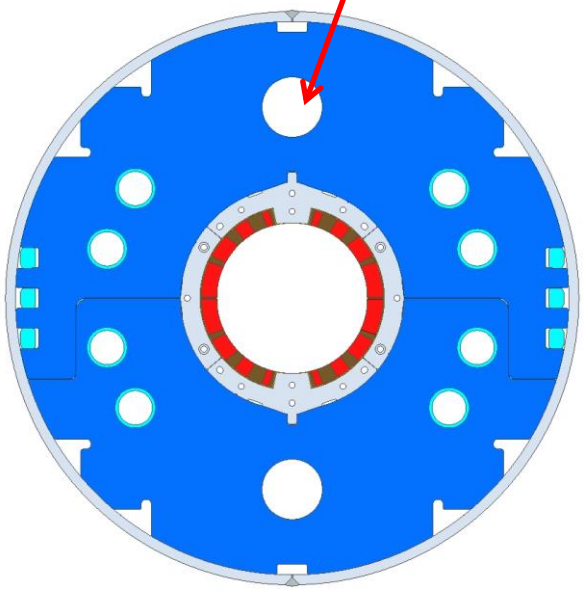


Impregnation test

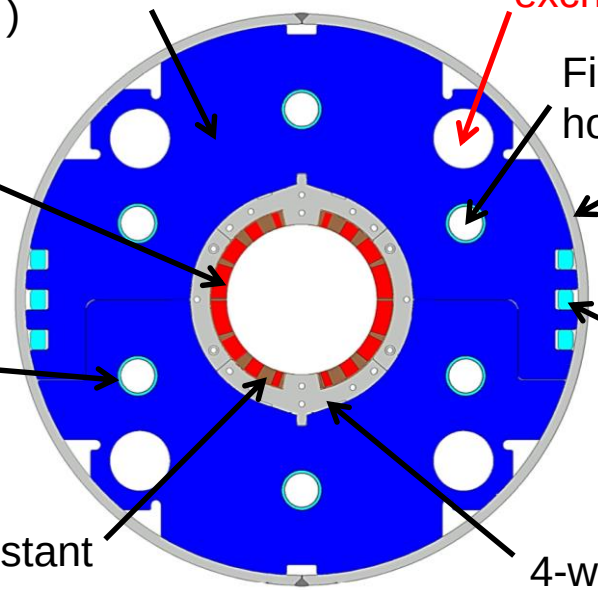
- New Iron cross-section to fulfill request from CERN to change heat exchanger hole conditions
- Update of magnetic design (2D cross-section, coil end)
- QPH design based on quench simulation
- Countermeasures against coil deformation
  - Increase in azimuthal coil pre-stress
  - Increase in axial pre-load
  - Improvement of matching between cable and end spacers
  - Impregnation only at coil end
- Fabrication will be started in Nov., 2017.

Update of magnet cross-section

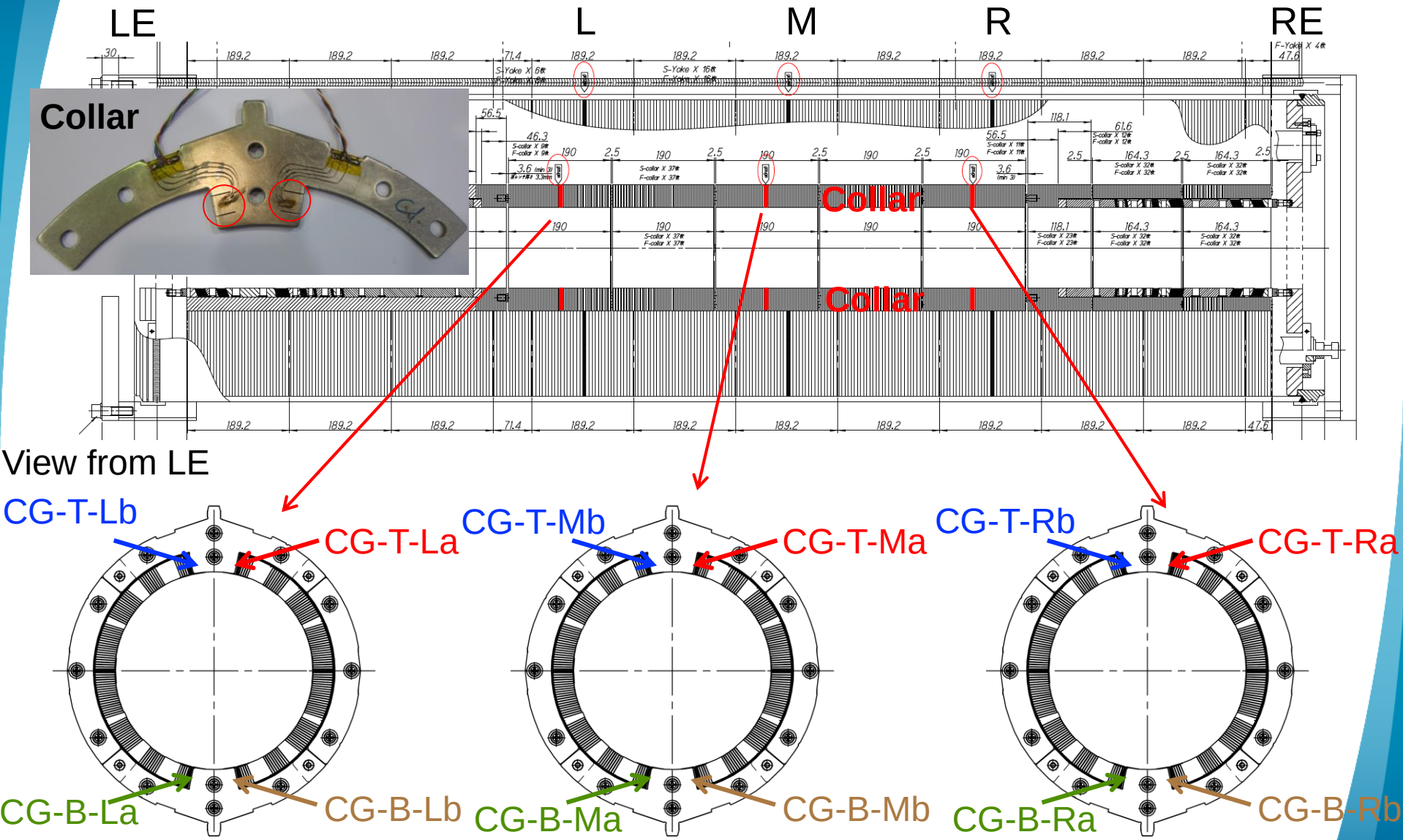
First model



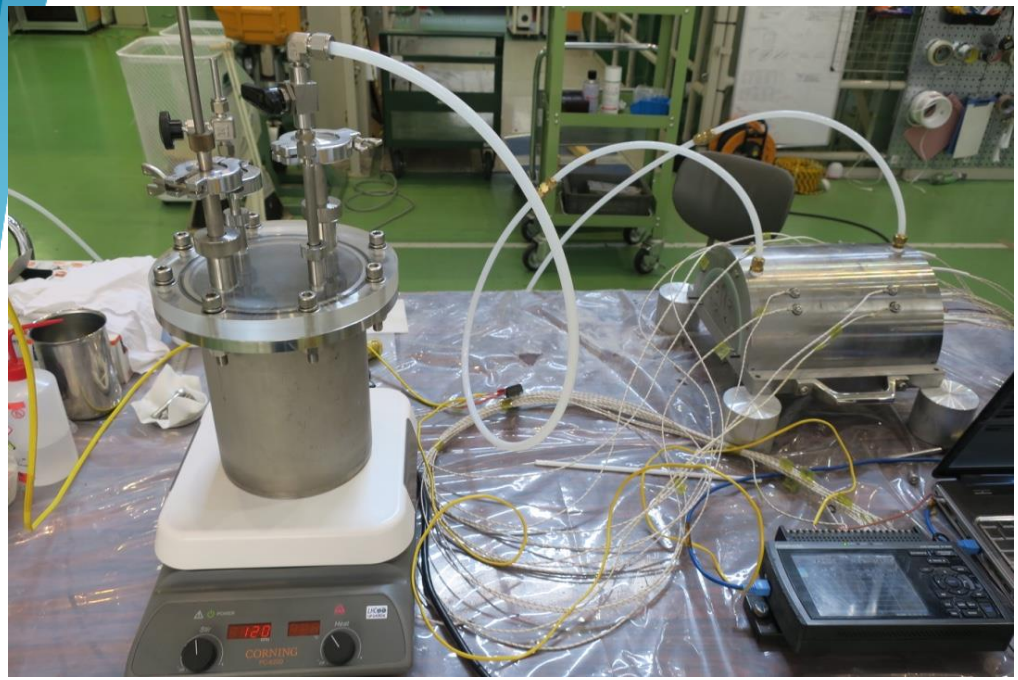
Second model



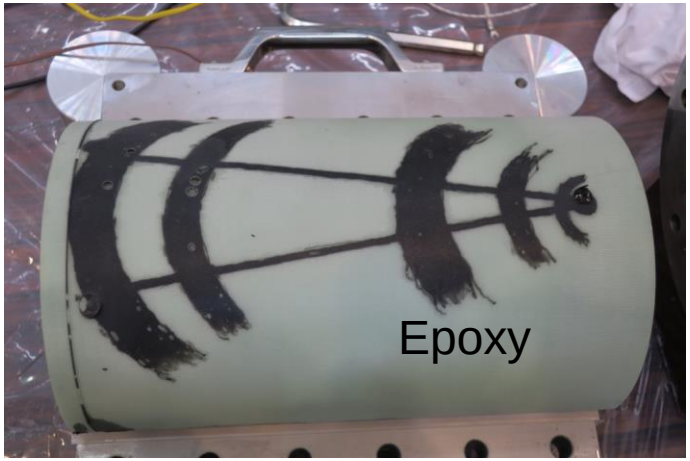
Position of collar plates with strain gauges



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

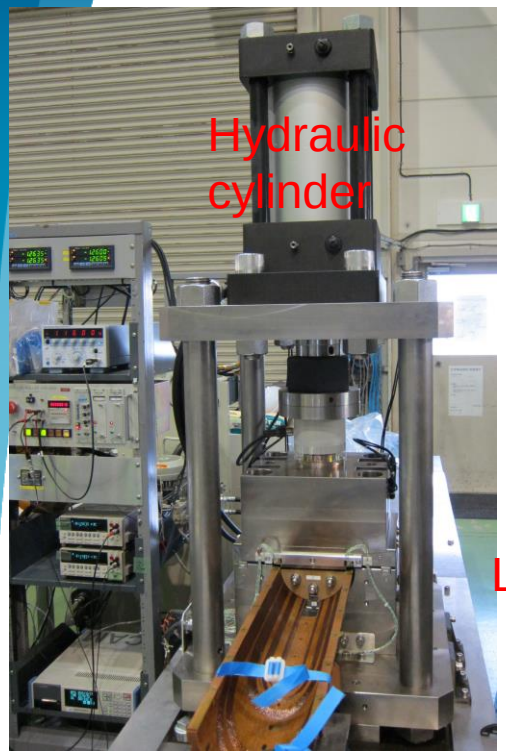


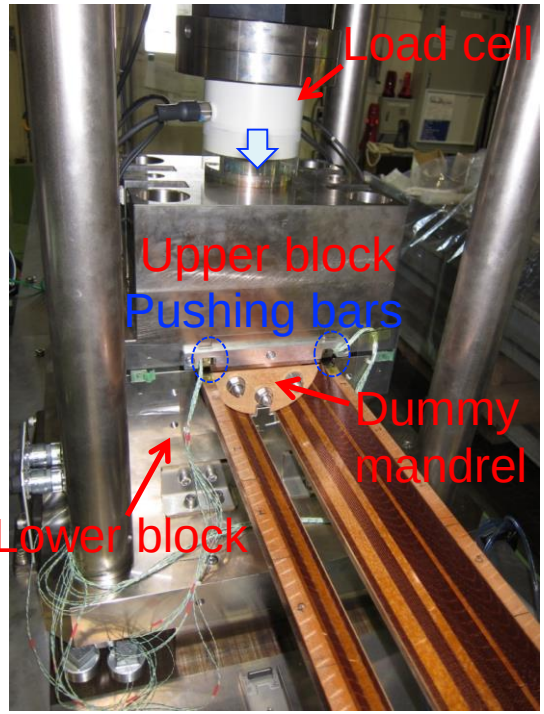
Tests with G10 dummy coil



- 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.

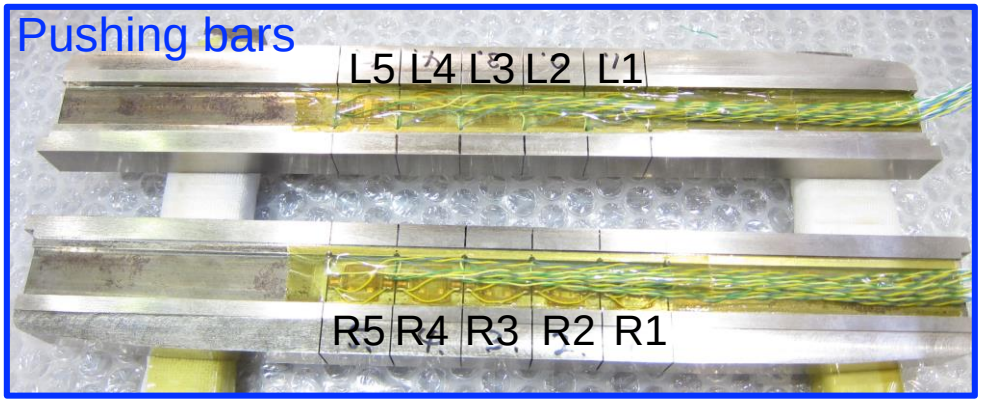
Coil size measurement

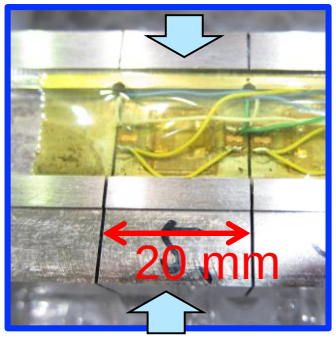


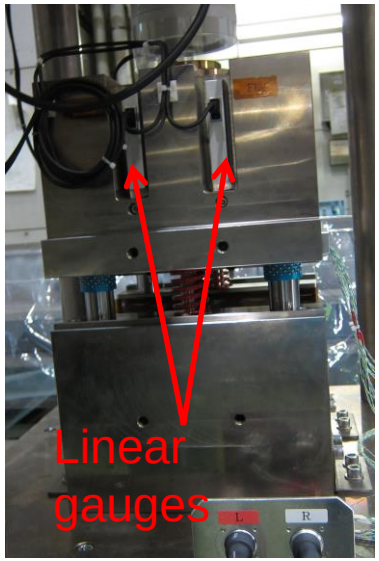


Measure the pressure to compress a coil to the final size and compare it with the target value of pre-stress

- 50 ton hydraulic press
- Two pushing bars with strain gauges
  → Pressure applied to the coil MPs every 20 mm can be measured.
- Four linear gauges
  → Coil deformation
- 5.4 m-long-bench
  → Longitudinal distribution





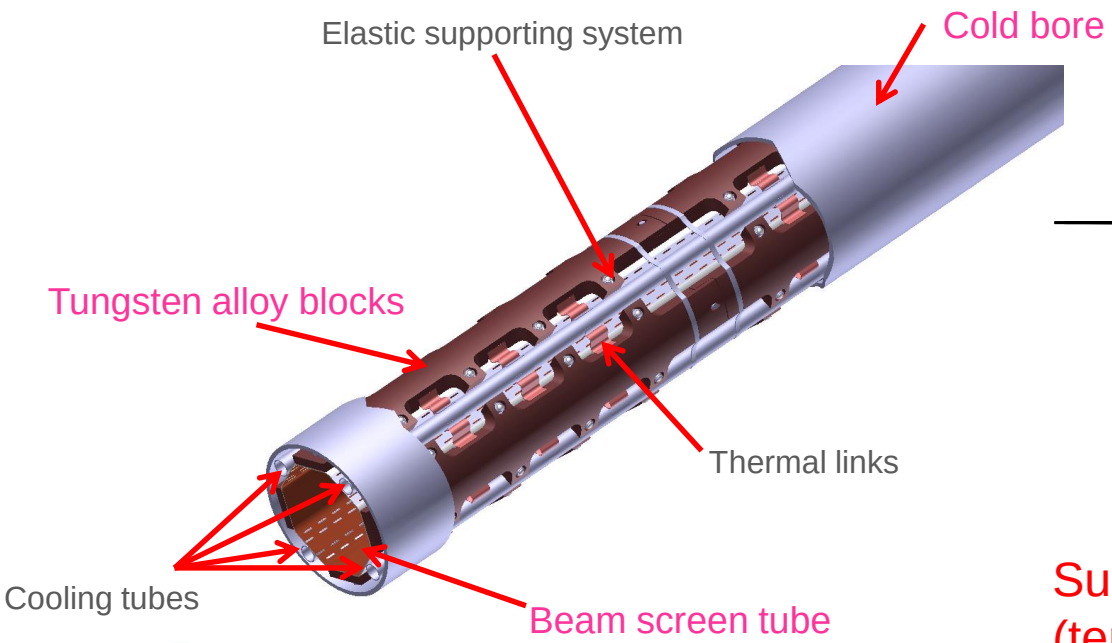


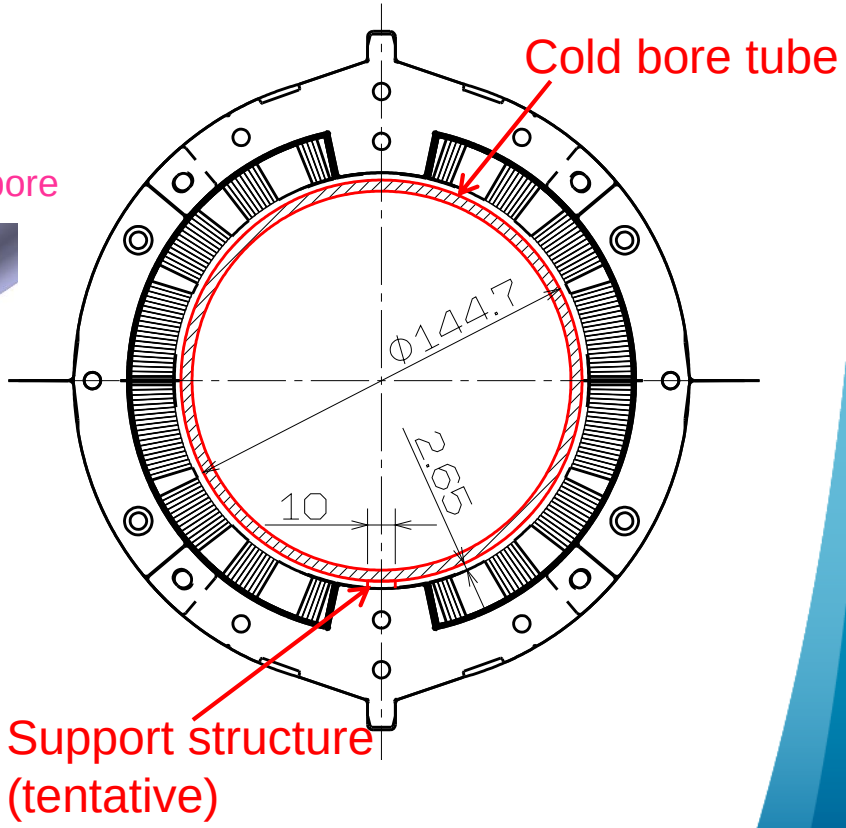
Thanks to Glyn Kirby

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

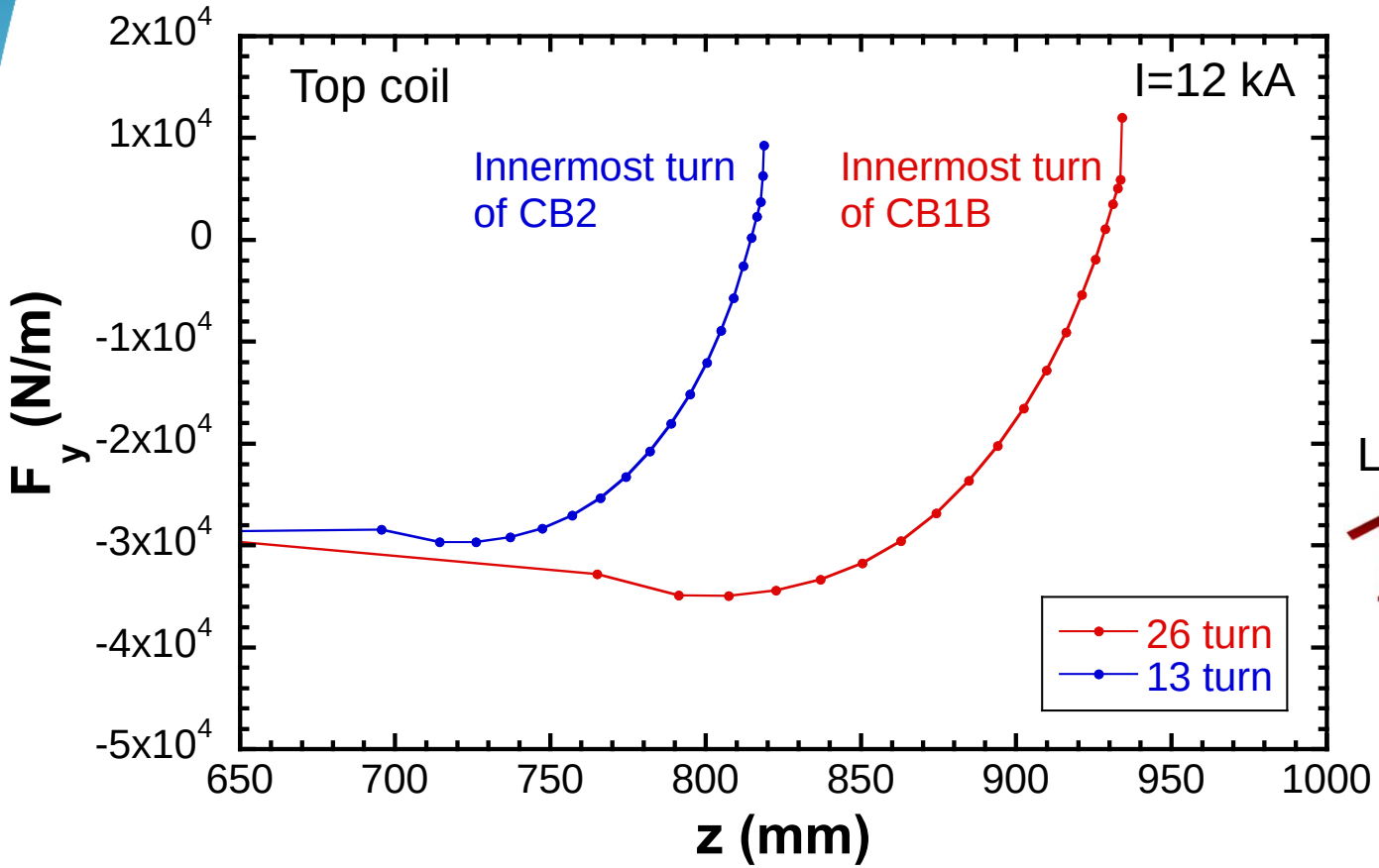
Beam screen for Q1-Q3

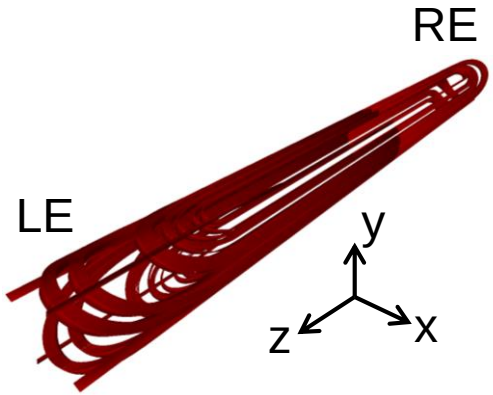




C. Garion, HL-LHC Collaboration meeting 2017

Lorentz force at coil end by ROXIE calculation



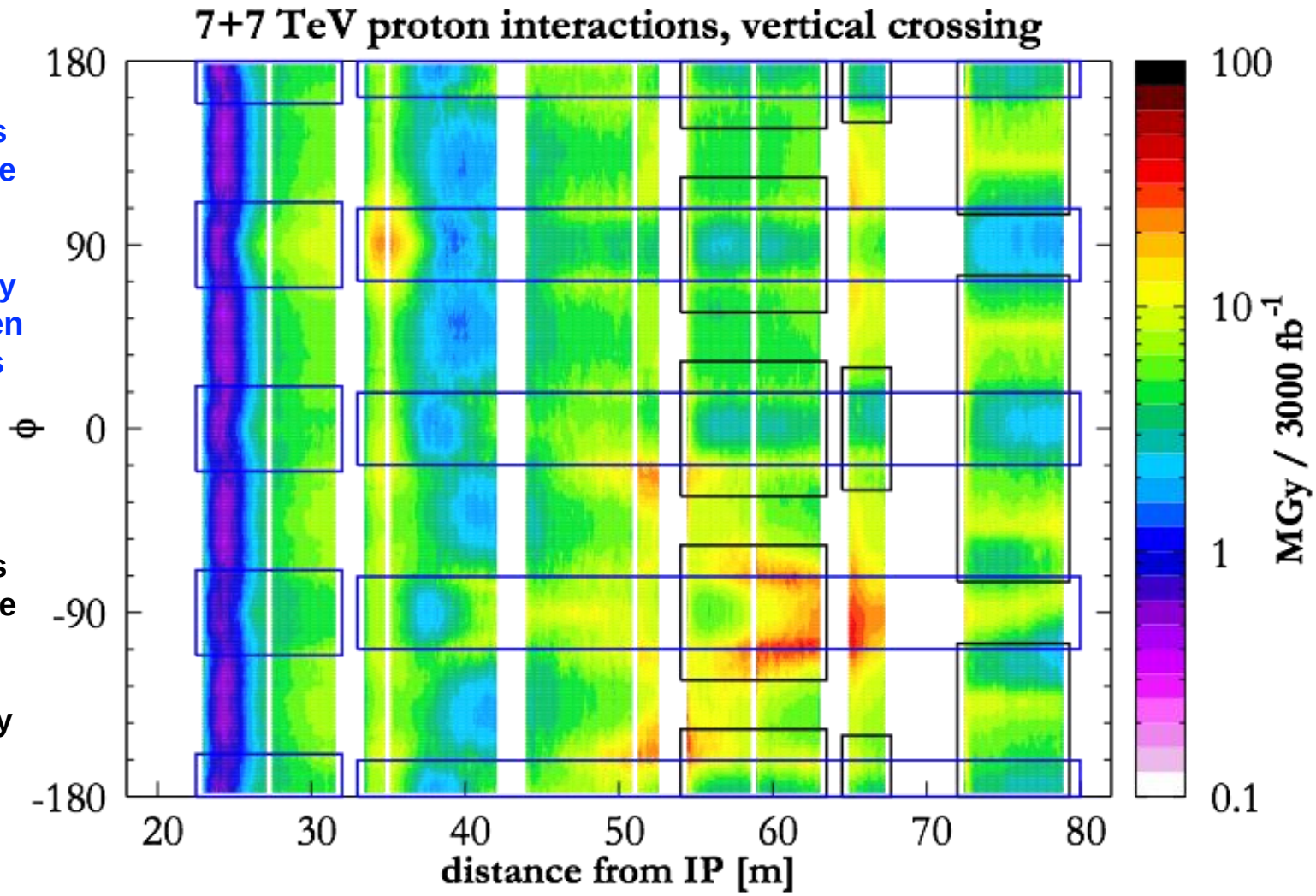


- Negative Fy will cause cable deformation towards the coil bore.
- In largely deformed turns, the values of Fy are 3 – 3.5x10^4 N/m.
- The amount of displacement will be determined by cable support and Lorentz force exerted on the curved section of the turn.

Φ-z distribution of the dose along IT—CP—D1

Blue rectangles indicate the azimuthal regions shielded by the tungsten absorbers

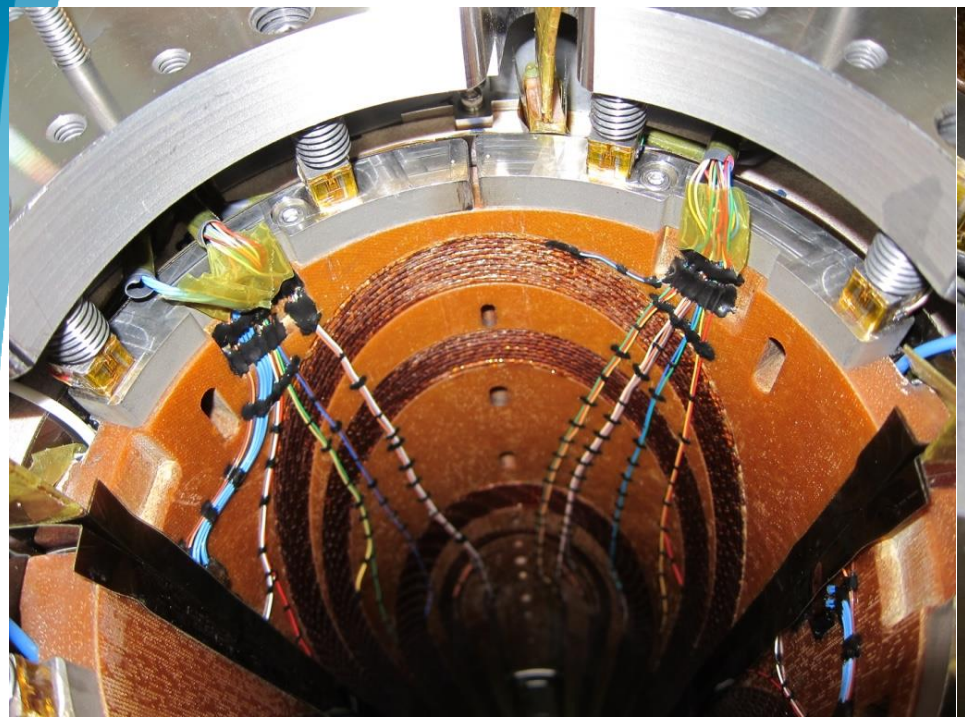
Black rectangles indicate the azimuthal regions covered by coils

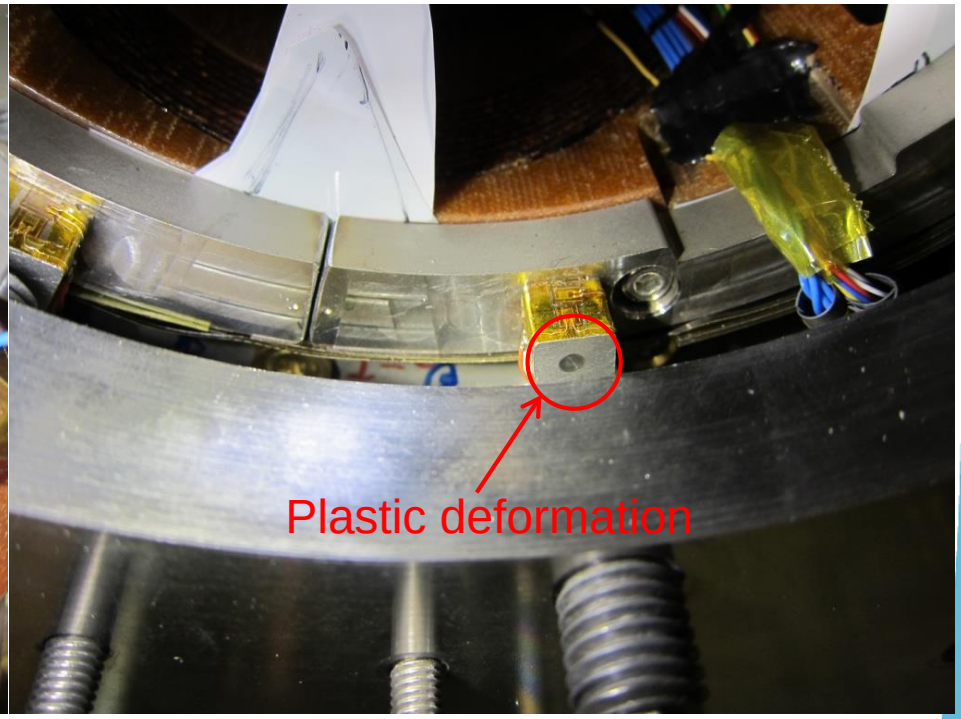


Owing to the IT magnetic configuration, through Q2 the losses move from the top to the bottom

F. Ceruttti, HL-LHC, WP3 meeting, 27 March 2014

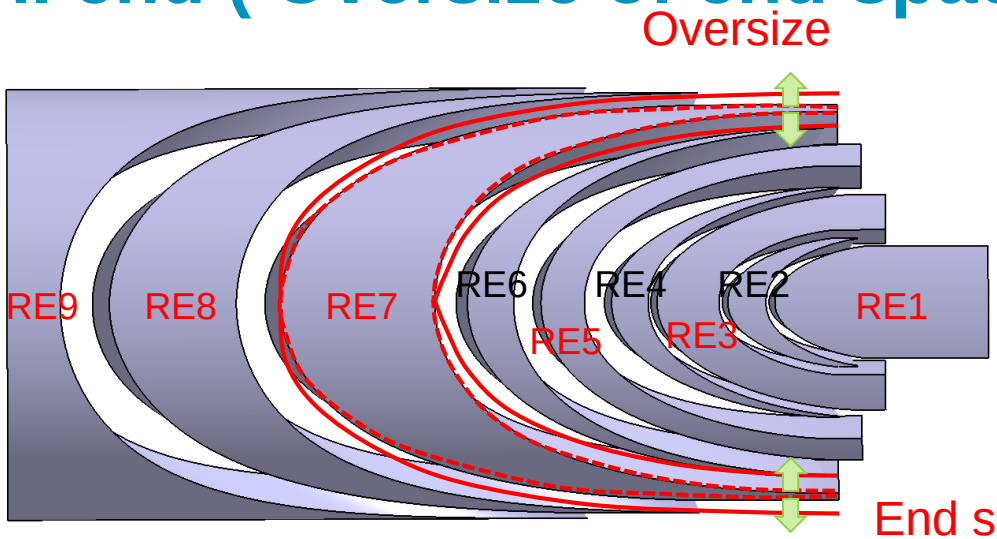
Countermeasures against coil deformation at coil end (Increase of axial pre-load)





- 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 (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.