Test results of the first 2-m long model magnet for D1

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On behalf of CERN-KEK Collaboration for HL-LHC

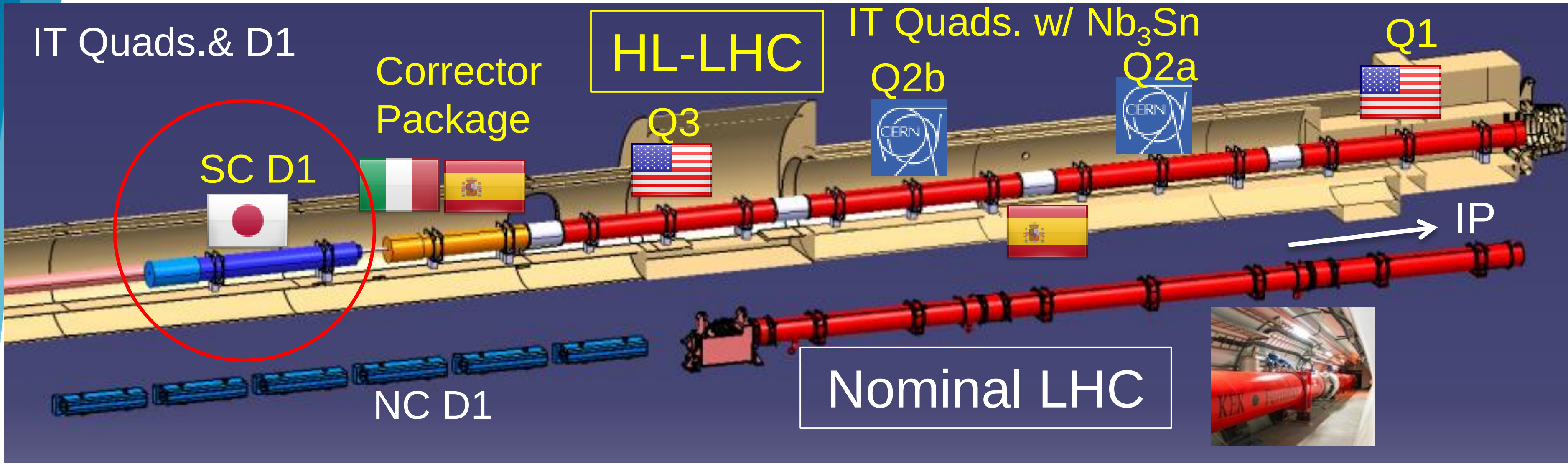
6th HL-LHC Collaboration meeting, Paris, 14 - 16 Nov 2016

Outline

- Overview of D1
- Cold test results of the 1st 2 m model of D1 (MBXFS01)
  - Quench performance
  - Field quality
- Reassembly of the 1st 2 m model with higher pre-stress (MBXFS01b)
- Further plan

Overview of D1

D1 magnet



Courtesy of P. Fessia

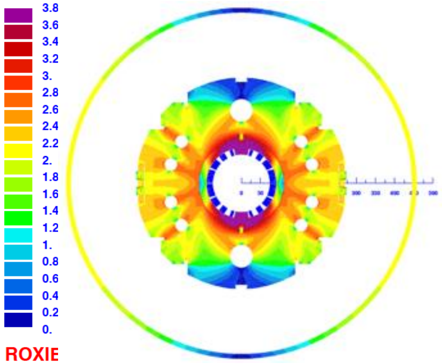
- Large aperture to obtain smaller β^*

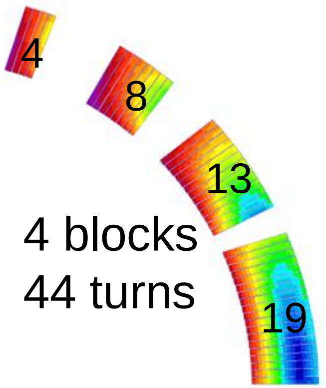
  Coil aperture: ϕ70 mm → ϕ150 mm
- Stronger kick to accommodate shorter distance between D1 and D2 (recombination magnet)

  Field integral: 26 Tm → 35 Tm
- Normal conducting D1 in the current LHC will be replaced by Nb-Ti based superconducting magnets.
- KEK is in charge of development of D1 since 2011.

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	

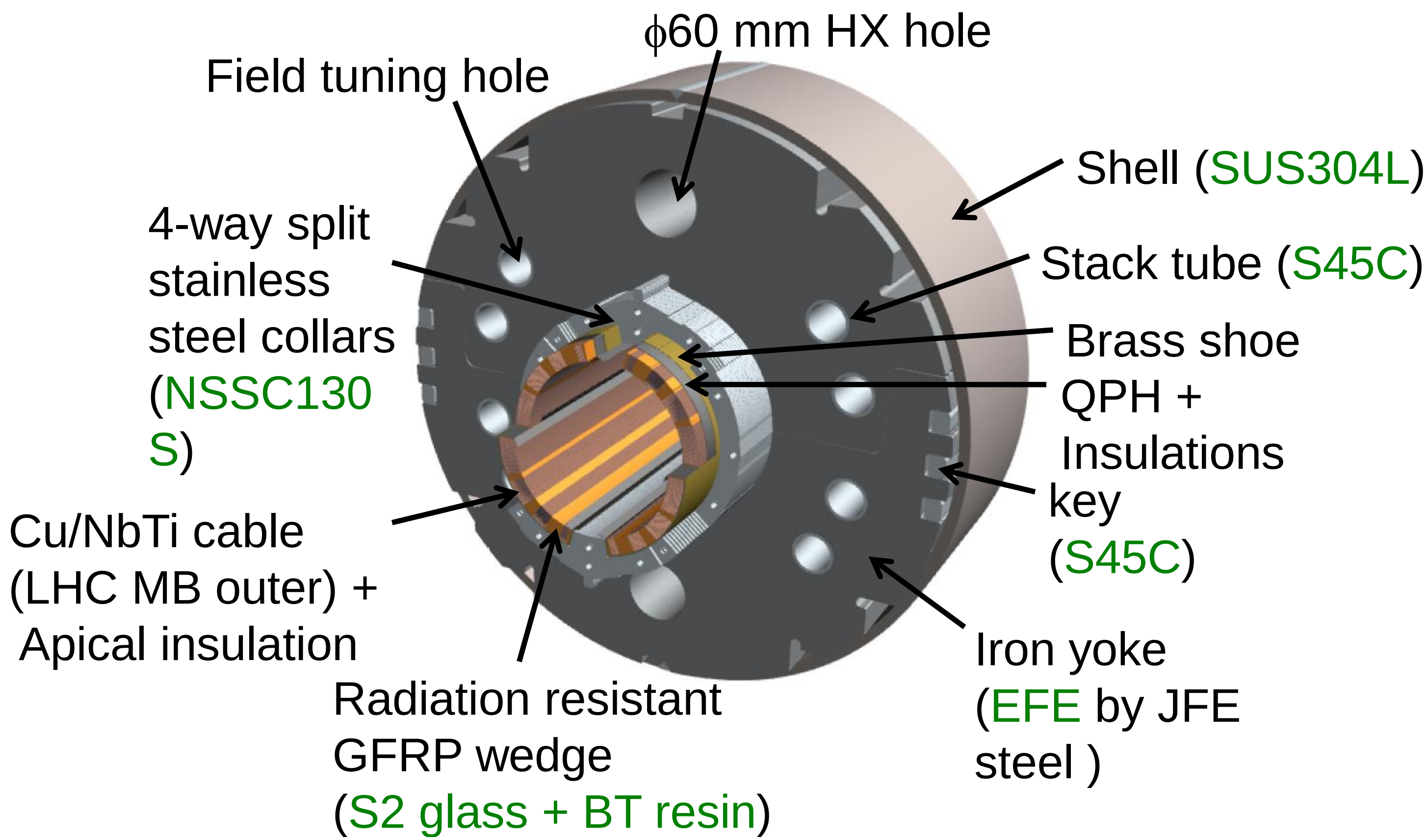




Technical challenges

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

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
- Newly developed radiation resistant GFRP for wedges and end 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

Fabrication of the 1st 2 m model in KEK

- Jul 2015 – Mar 2016

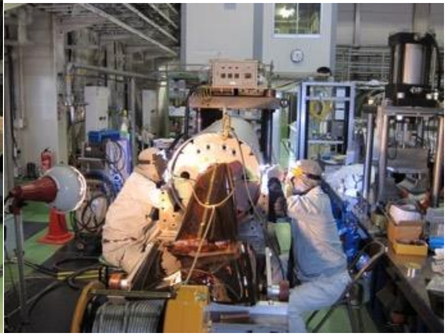
Coil winding

Curing

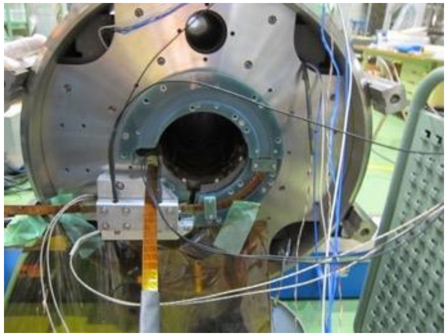
Coil size meas.

Collaring

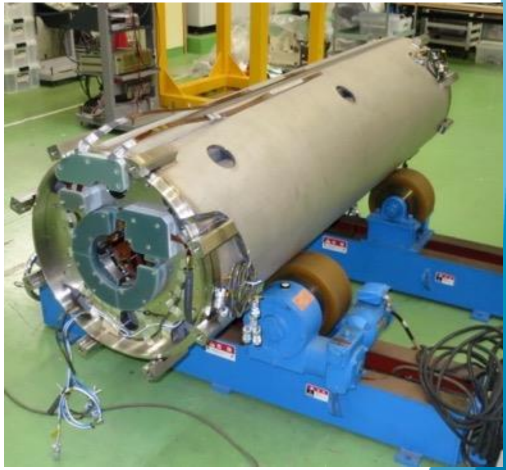
Yoking



Shell welding

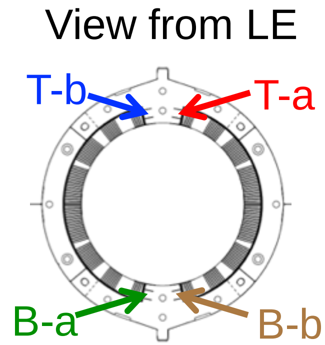


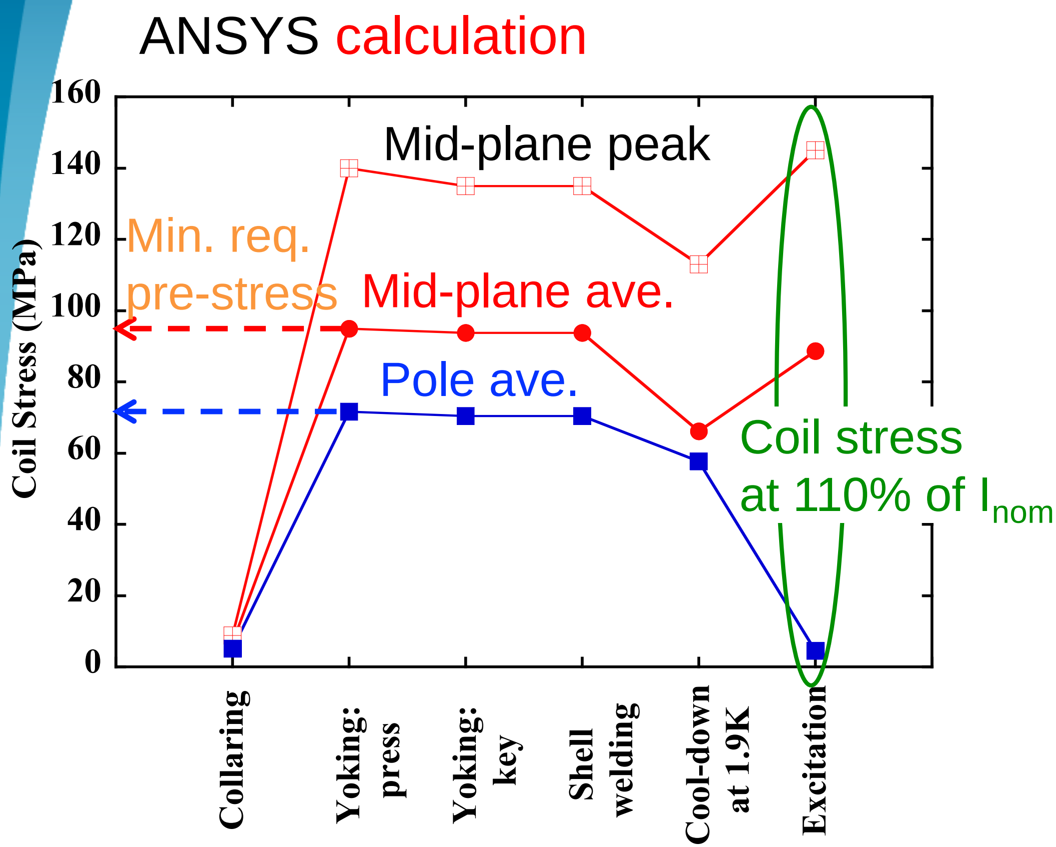
Splice work

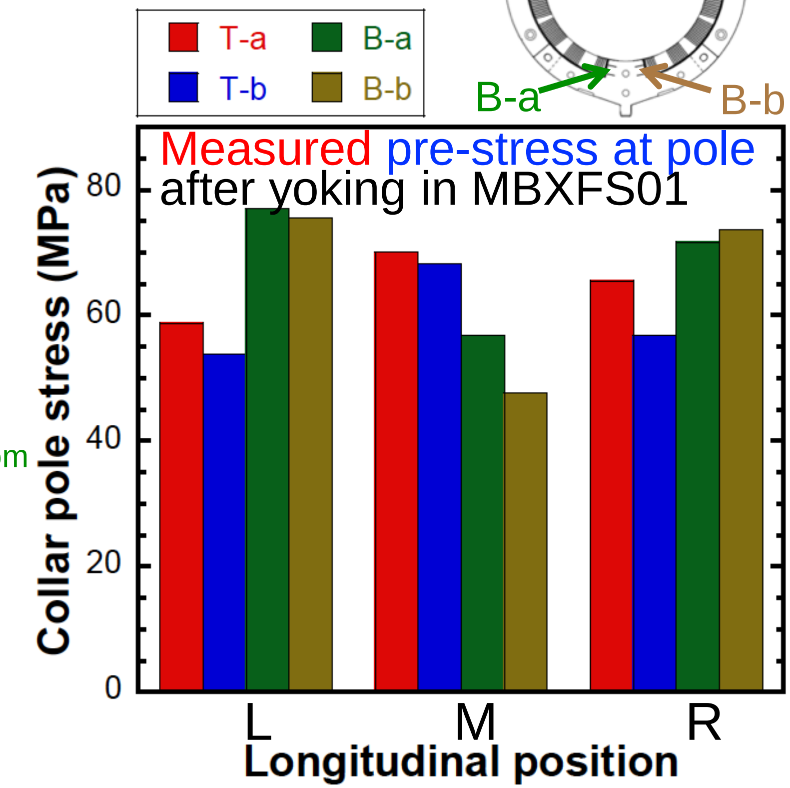


Completion of fabrication

Target of coil pre-stress







- Required pre-stress to keep the coils in compression even after excitation to 110% of the nominal current:
  - Min required pre-stress: 70 MPa at pole, 94 MPa at MP
- The target pre-stress at pole :80 MPa
- Measured coil pre-stress at pole after yoking in MBXFS01: 65 MPa

Cold test results of the 1st 2 m model

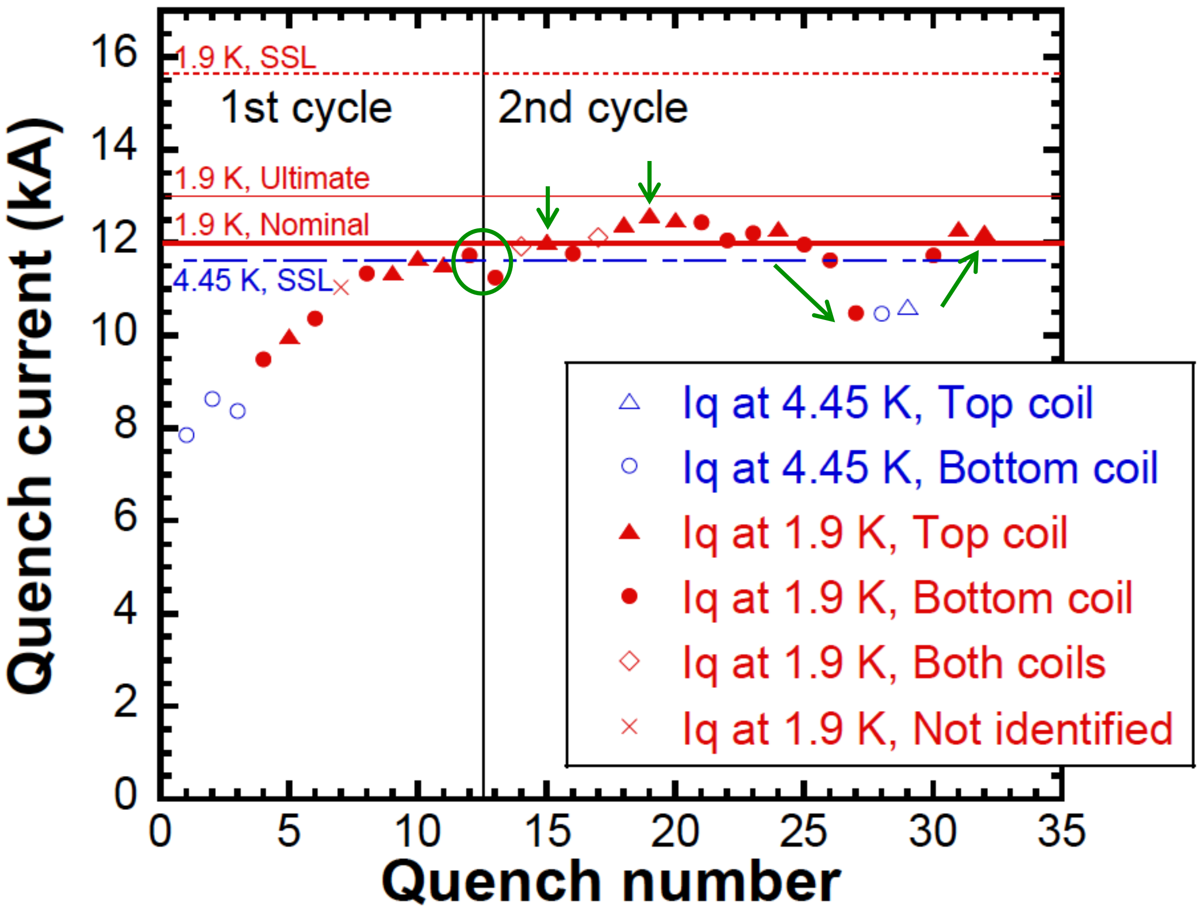
Training quench tests

1st cycle: April 2016
2nd cycle: May – June 2016
in the 9 m deep vertical cryostat in KEK

Training quench

- Temperature: 4.45 K and 1.9 K
- Energy extraction with a dump resistor of 73 mΩ
- Threshold voltage: 0.1 V
- Detection time: typically 10 msec
- Ramp rate to quench: 10 A/sec

Training plot



- Max. quench current = 105% of I_{nom}, but lower than the ultimate
- Good training memory between the 1st and 2nd test cycles
- An erratic behaviour
  - Decrease of I_q after I_q, max (No cable damage)
  - Recovery to more than I_{nom} at the last two quenches

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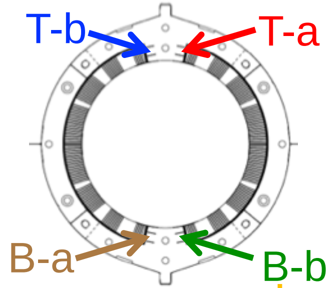
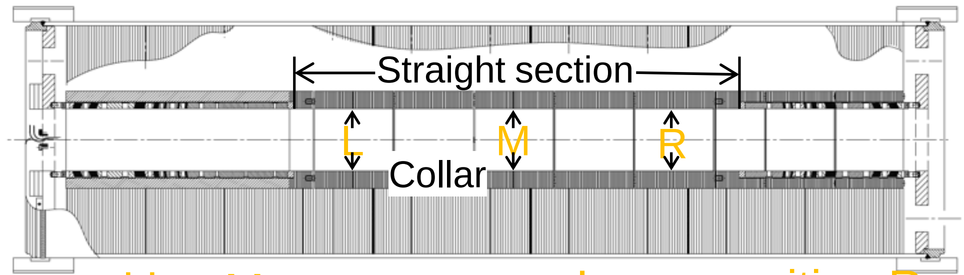
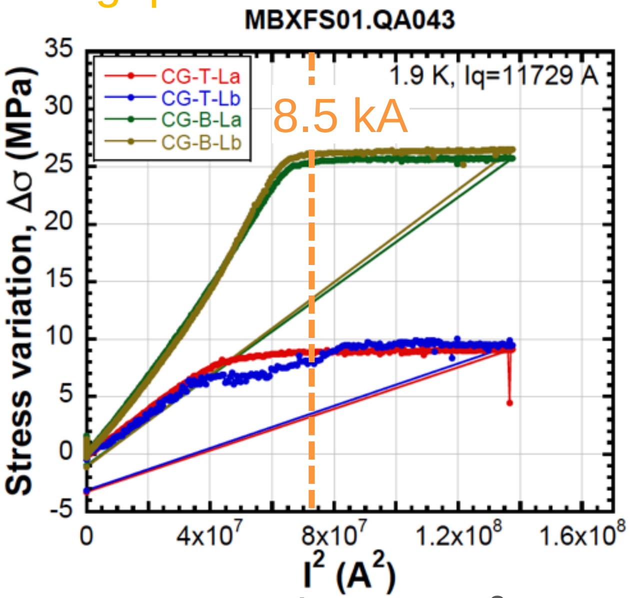
Variation of coil stress at pole during excitation

View from LE

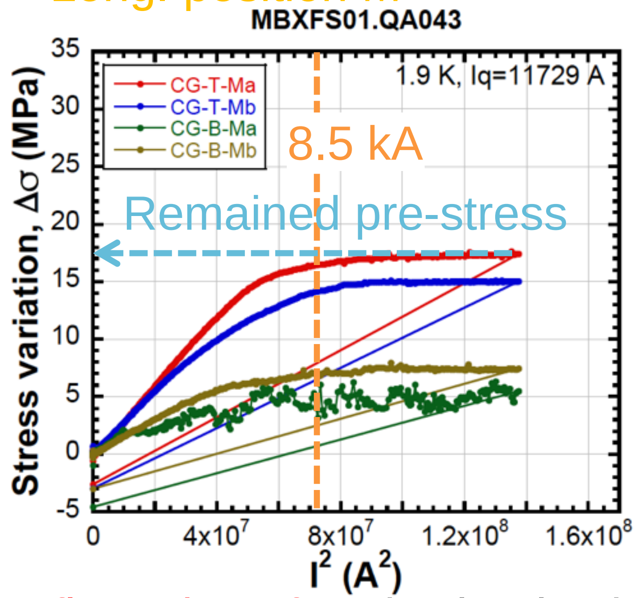




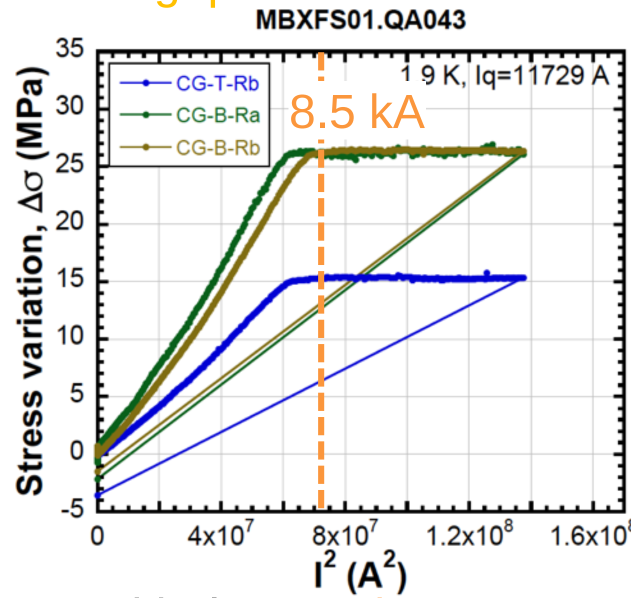
Long. position L



Long. position M



Long. position R



- In the $\Delta\sigma - I^2$ curves, flattening of $\Delta\sigma$ is clearly observed below 8.5 kA.

Compressive pre-stress of the coils are completely released.

- Remained pre-stress at cold: 17 MPa << 65 MPa after yoking

→ Large stress release by cooling

- Coil stress at cold should be increased by around 35 MPa.

Possible reasons of lower pre-stress

Straight section

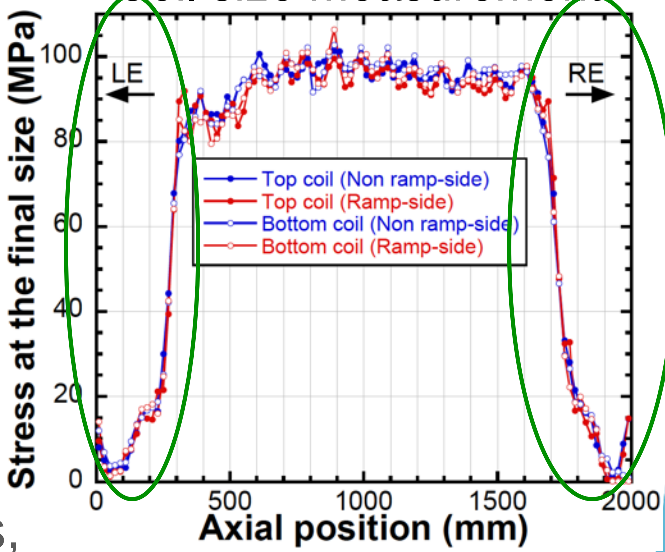
Large stress release during cooling-down

Measured values: 44 MPa >> ANSYS calculation: 13 MPa

Lower Young's modulus in ANSYS calculation

→ Underestimate of stress release by cooling

Coil size measurement



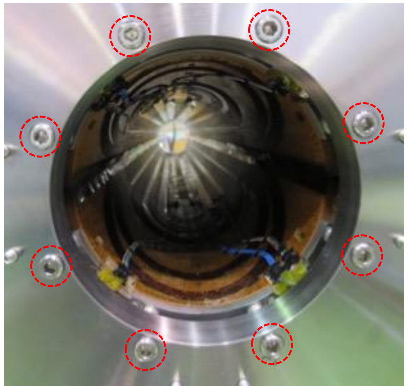
Coil end

Very low azimuthal pre-stress at coil end was confirmed in coil size measurement.

→ Insufficient cable support

Axial preload

Coils were longitudinally supported by the bullets, but longitudinal stress to the coils were not monitored.



Enhancement of pre-stress will be a key to improve quench performance.

Magnetic field measurement

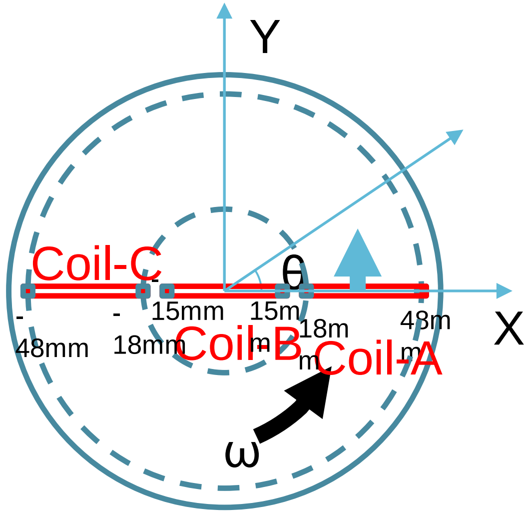
- DC loop: I=0–10 kA
- z scan: I=688(injection) , 3, 5, 7, 10 kA

} Maximum current < I_{nom} to avoid quench during MFM

- 7m long GFRP shaft
- Anti-cryostat: ϕ141.3 mm (OD)
- “Warm” bore: ϕ108.3 mm (ID)

Rotating coils

“Warm” bore



Coil A: dipole

Coil A – Coil B: dipole bucking

Coil C: spare

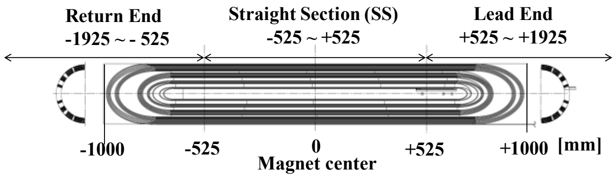
- Size of coils made of PCB
  - Long: 350 mm x 30 mm
  - Short: 80 mm x 30 mm
- Number of turns: 20

Field integral at 10 kA

n	RE		SS		LE		Total	
	$\widetilde{b_n}$	$\widetilde{a_n}$	$\widetilde{b_n}$	$\widetilde{a_n}$	$\widetilde{b_n}$	$\widetilde{a_n}$	$\widetilde{b_n}$	$\widetilde{a_n}$
1	1937.51 (1965.25)	2.53 (0.00)	6031.67 (6080.50)	−0.46 (0.27)	2030.82 (1954.25)	−28.55 (−17.11)	10000.00 (10000.00)	−26.47 (−16.80)
2	0.25 (0.00)	−2.50 (0.00)	−0.36 (0.00)	−0.23 (0.00)	0.25 (0.00)	−0.93 (0.00)	−0.17 (0.00)	−3.67 (0.00)
3	−9.26 (−7.70)	−0.24 (0.00)	18.76 (21.41)	0.29 (0.13)	−5.19 (−5.50)	6.74 (5.74)	4.30 (8.21)	6.78 (5.88)
4	0.21 (0.00)	−0.26 (0.00)	0.00 (0.00)	0.19 (0.00)	0.07 (0.00)	0.23 (0.00)	0.28 (0.00)	0.17 (0.00)
5	−1.12 (−1.73)	−0.07 (0.00)	−1.14 (−0.66)	0.05 (−0.02)	1.42 (−0.08)	−0.52 (−0.52)	−0.84 (−2.46)	−0.54 (−0.54)
6	0.14 (0.00)	−0.13 (0.00)	−0.04 (0.00)	0.03 (0.00)	−0.04 (0.00)	−0.02 (0.00)	0.06 (0.00)	−0.12 (0.00)
7	−1.34 (−1.49)	−0.01 (0.00)	0.18 (0.20)	0.08 (0.03)	−0.62 (−0.70)	0.36 (0.39)	−1.78 (−1.99)	0.43 (0.41)
8	0.12 (0.00)	−0.12 (0.00)	−0.10 (0.00)	−0.08 (0.00)	−0.19 (0.00)	0.07 (0.00)	−0.18 (0.00)	−0.12 (0.00)
9	−1.16 (−1.32)	−0.06 (0.00)	−0.02 (0.09)	−0.09 (−0.01)	−0.92 (−1.01)	0.00 (−0.15)	−2.09 (−2.23)	−0.16 (−0.16)
10	0.06 (0.00)	−0.05 (0.00)	−0.08 (0.00)	−0.03 (0.00)	−0.08 (0.00)	0.02 (0.00)	−0.10 (−0.81)	−0.06 (0.00)

Measurement
(ROXIE cal.)

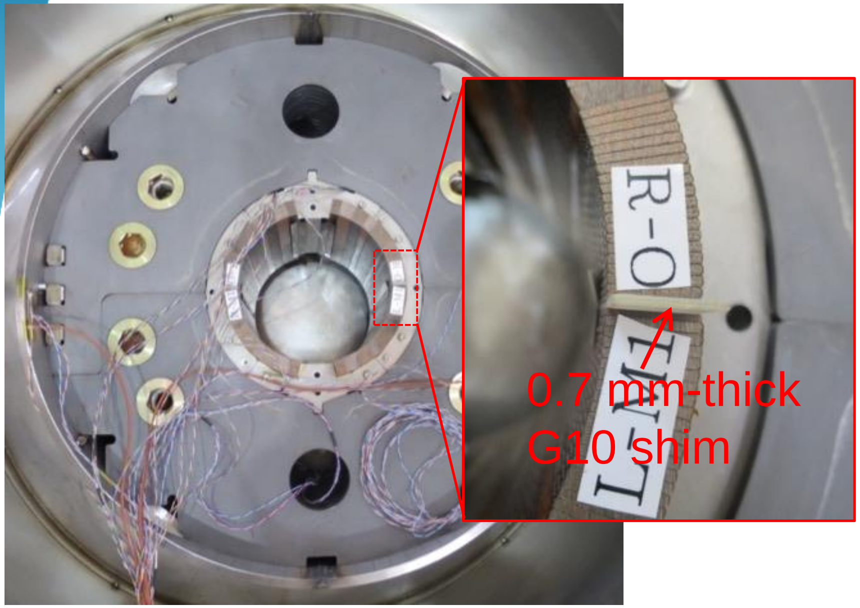
$$\widetilde{b_n(I)} = \frac{\int B_n(I)dz}{\int_{all} B_1(I)dz} \times 10^4$$

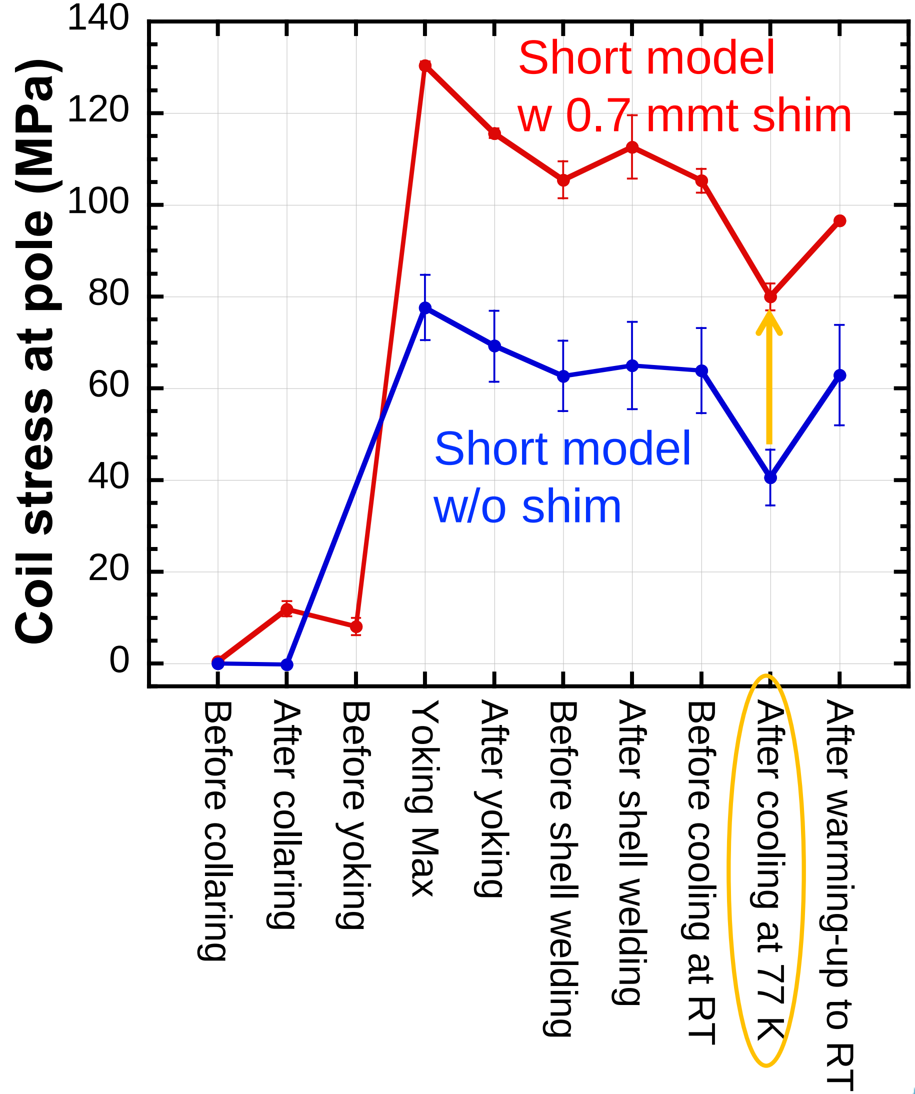


- ROXIE3D calculations generally agree with the measurements.
  - Need improvement of ROXIE models for b_3 and b_5
- Skew and un-allowed multipoles are sufficiently small.

Reassembly of the 1st model with higher pre-stress (MBXFS01b)

Mechanical short model with higher pre-stress





- We decided to reassemble the 2 m model with enhanced pre-stress (MBXFS01b) by inserting additional shims to the MP.
- Mechanical short model assembly to estimate thickness of shim at MP to increase pre-stress at cold by 35 MPa
- Shim thickness for MBXFS01b

  → 0.8 mm per quadrant

  (Target pre-stress at RT: 140 MPa)
- We should allow compromised field quality in MBXFS01b.

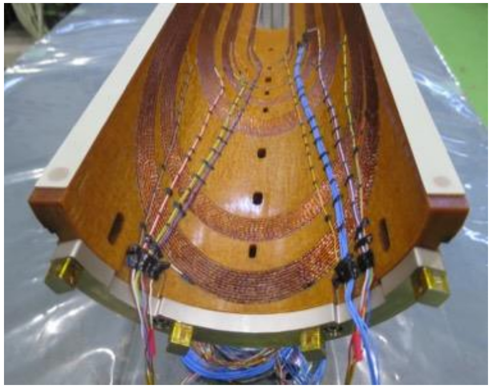
Current status of MBXFS01b

- MBXFS01 was disassembled and 0.8 mm-thick G10 shims were bonded to the MP of each coil to increase pre-stress.
- Implementation of strain gauges to monitor axial pre-stress
- Increase of the number of voltage taps on the coils (29 → 42 per coil)

Reassembly was just started last week !

Disassembly of MBXFS01

A coil for MBXFS01b
with additional MP shims



Strain gauges to monitor axial preload

Further plan

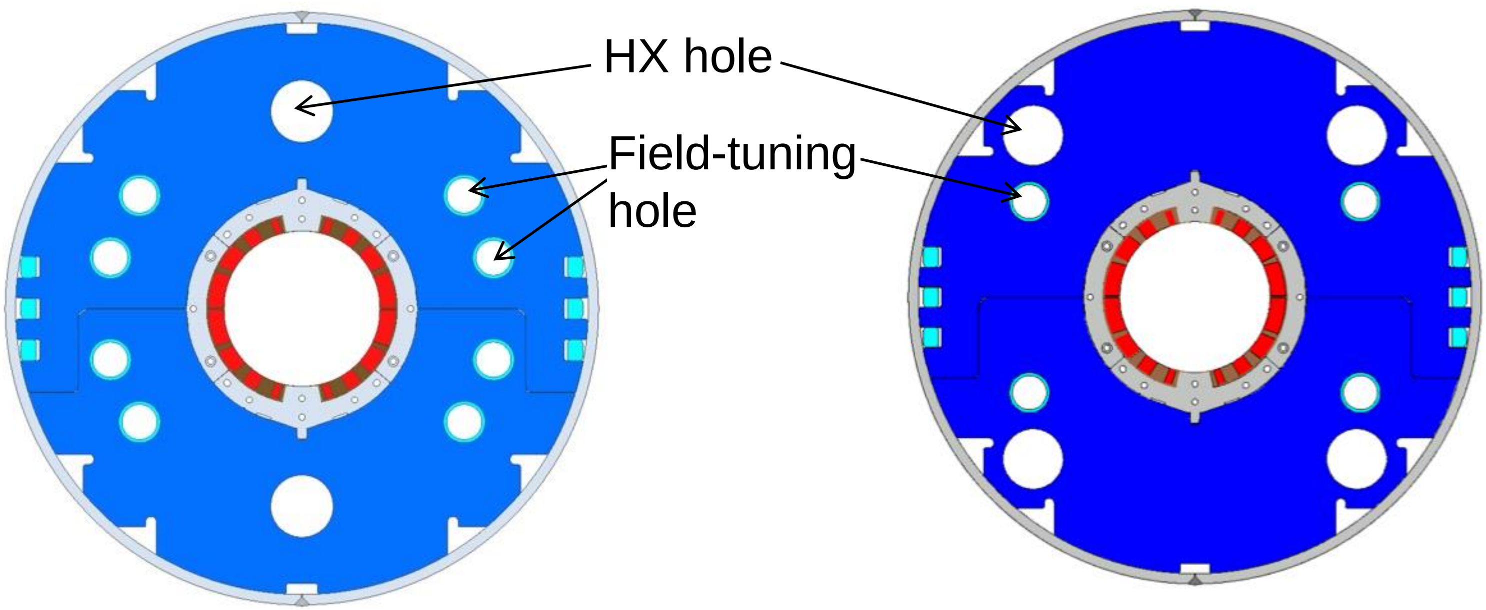
Plan for the 2nd 2 m model (MBXFS02)

- Change of iron yoke cross-section

  HX hole position will be changed so as to be in line with that for the inner triplets

- Modification of design of wedges and end spacers to realize sufficient pre-stress and good field quality simultaneously

Now iterative electro-magnetic analysis is underway.



MBXFS01

Tentative magnet cross-section for MBXFS02

Schedule

- MBXFS01b (w/ higher pre-stress)
  - Reassembly: Nov 2016 - Jan 2017
  - Cold test: End of Jan - Mar 2017

- MBXFS02 (w/ new cross section)
  - Design: Sep. 2016 - Jan. 2017
  - Construction: Jan. 2017 – Sep. 2017
  - Cold test: Oct. 2017 – Nov. 2017

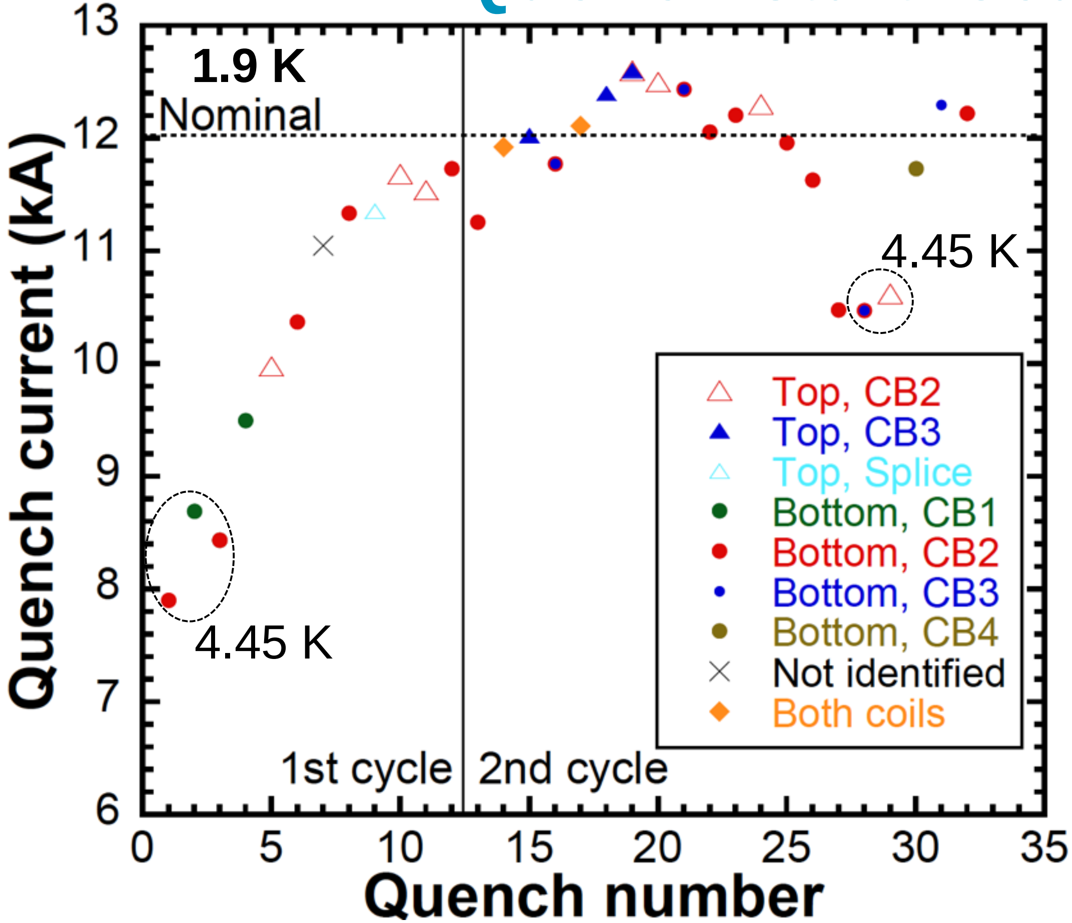
- MBXFS03 (w/ new cross section) >> TBD
  - Nov. 2017 - July 2018

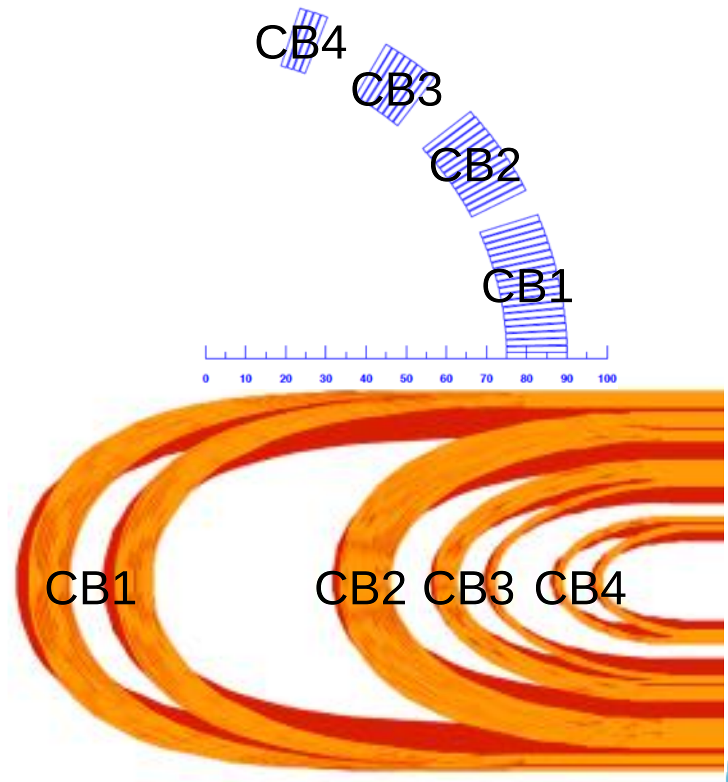
Summary

- The first 2 m model of D1 (MBXFS01) was fabricated and tested at cold in KEK.
- Quench current reached the nominal current, but the ultimate current was not achieved.
- Unsatisfactory quench performance will be attributed to insufficient coil pre-stress.
- Generally, good agreement was confirmed between measured and calculated magnetic field quality. But to fully understand the measured results, further analysis is needed.
- Reassembly with higher pre-stress has been already started and cold test of MBXFS01b is scheduled in early 2017.

Backups

Quench start location



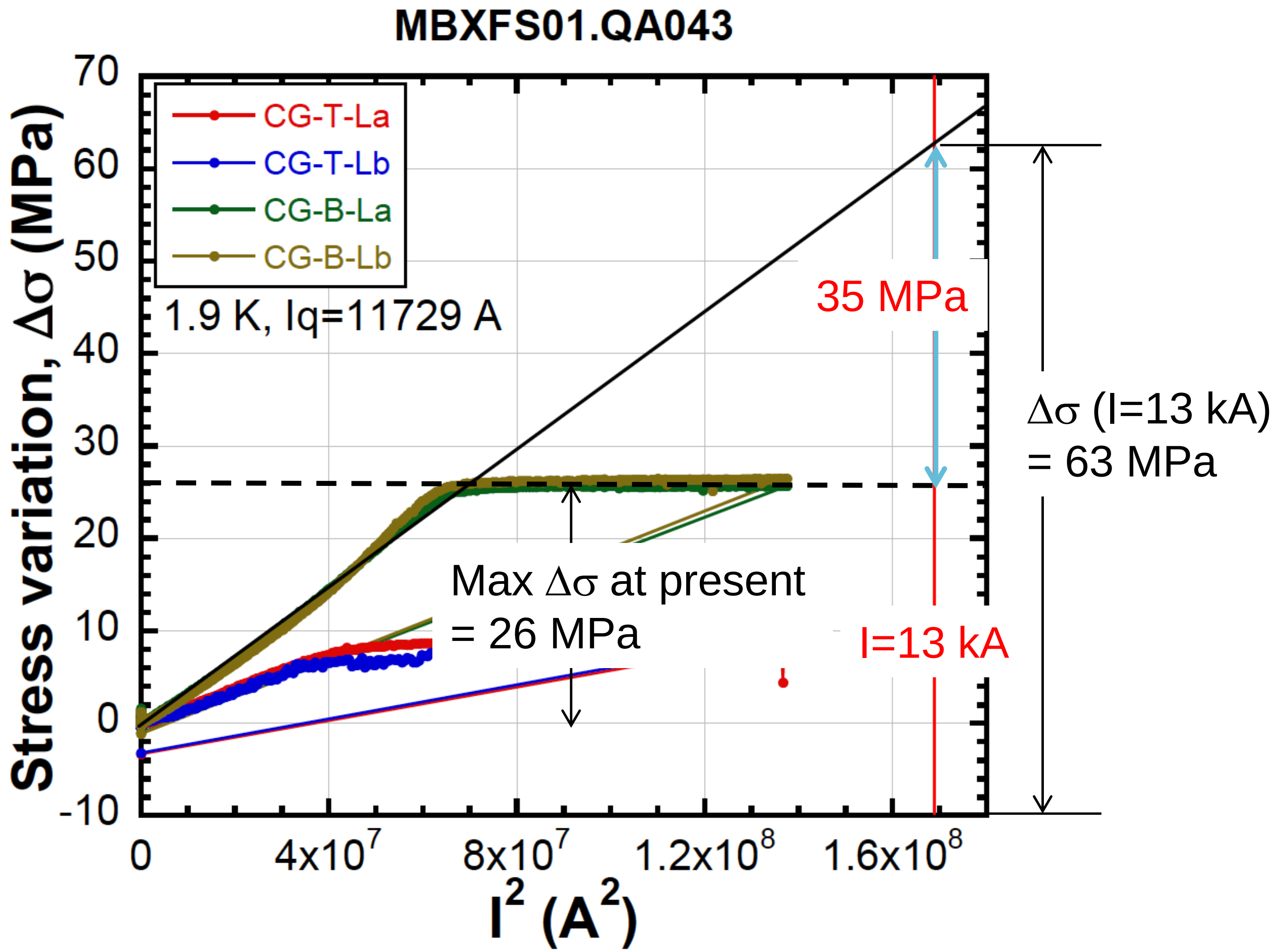


Number of quenches starting at each location

	CB1	CB2	CB3	CB4	Splice
Top	0	8	4	0	1
Bottom	3	14	3	1	0
Both	0	2	0	0	0

More detailed quench start location (straight section or coil end) has not been identified.

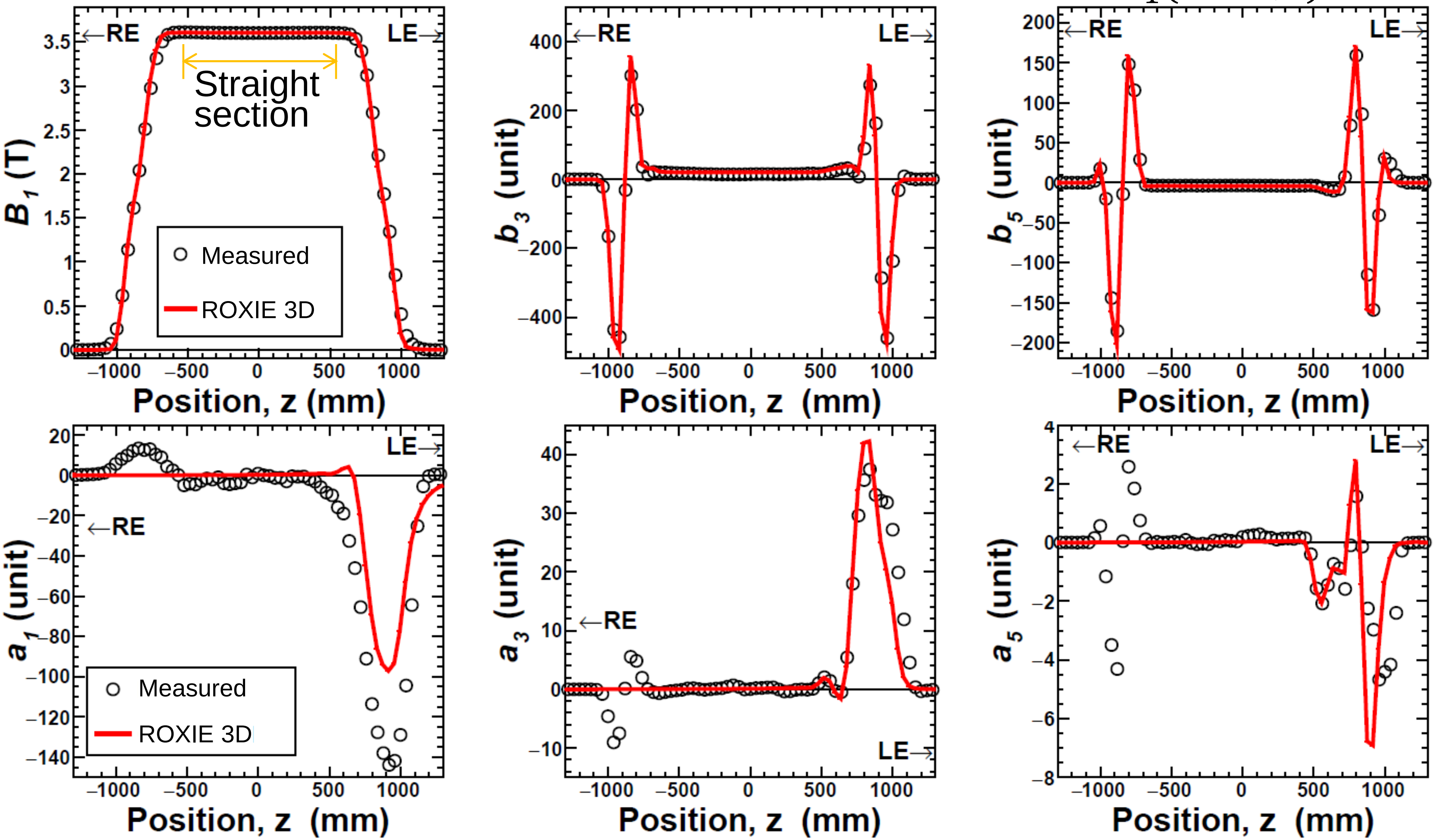
How much pre-stress should we add ?



- As rough estimation, pre-stress should be increased to be more than 65 MPa.

Z scan: I = 7 kA

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



- B_1, b_3 and b_5: Good agreement between measurements and calculations
- a_1, a_3 and a_5: Large difference at coil ends → Additional tilt ?