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Improvement in Training Performance by Enhancing Coil Mechanical Support in Beam Separation Dipole Model Magnet for the HL-LHC Upgrade

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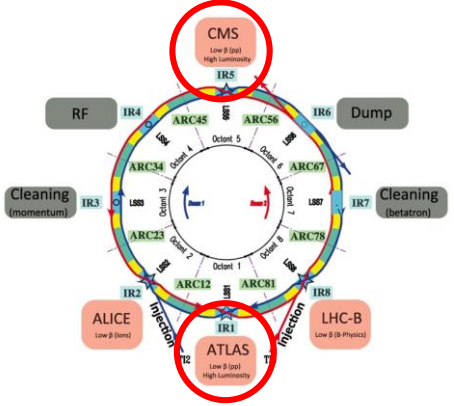
Outline

- MBXF for HL-LHC
- Mechanical support in MBXFS3
- Test result of MBXFS3
  - Training performance
  - Coil stress in the straight section (SS)
  - Quench start location
  - Field quality

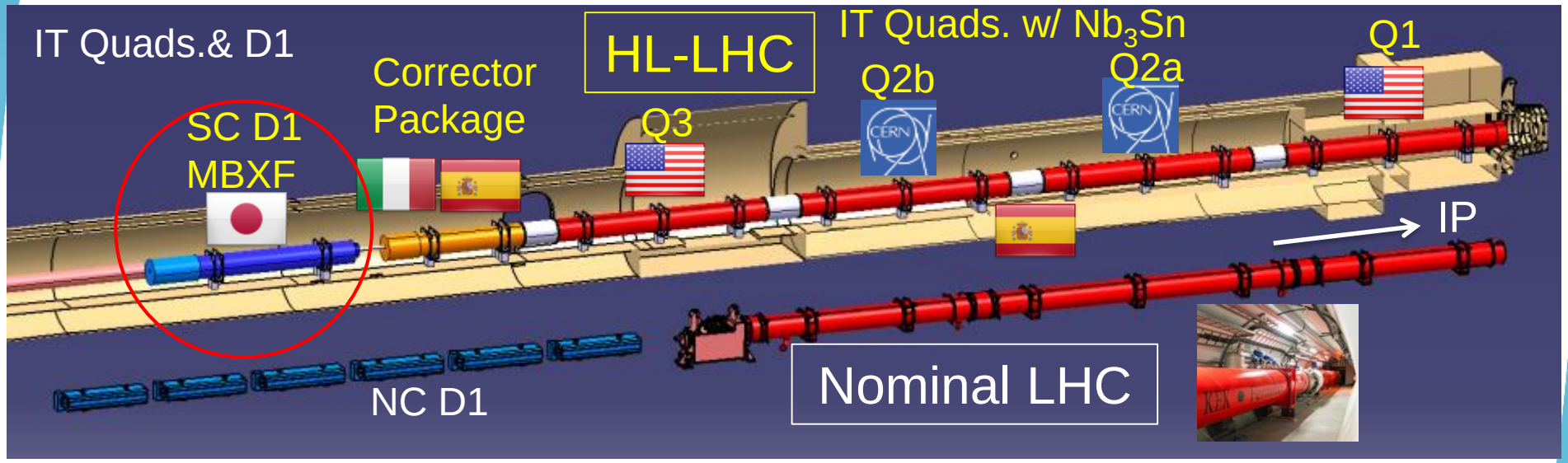
MBXF for HL-LHC

MBXF for HL-LHC



High Luminosity LHC（HL-LHC）

Peak luminosity：$5x10^{34}$ $cm^{-2}s^{-1}$（a factor of 5）
Integrated luminosity：3000 fb^{-1}（a factor of 10）



Courtesy of P. Fessia

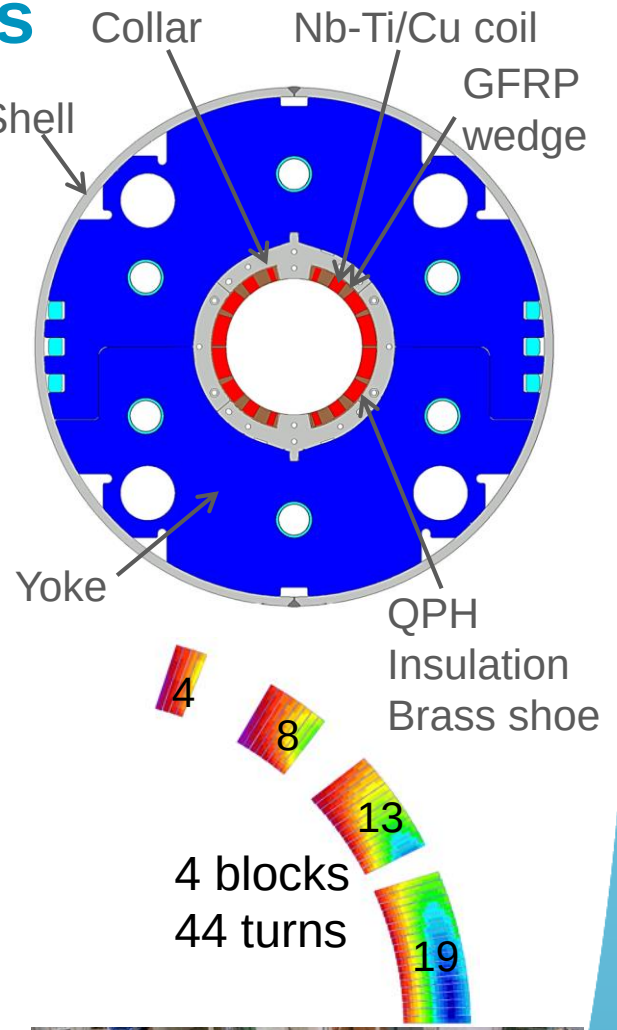
KEK is in charge of developing **beam separation dipole（D1 magnet, MBXF）.**

- 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.

Design parameters

	A series production (7m)	MBXFS2 (2 m)
Coil aperture	**150 mm**	
Field integral	**35 T m**	9.5 T m
Field (3D)	Nominal: 5.60 T, Ultimate: 6.04 T	
Peak field (3D)	Nominal: 6.58 T, Ultimate: 71.4 T	
Current	Nominal : 12.05 kA, Ultimate 13.14 kA	
Operating temperature	1.9 K	
Field quality	$<10^{-4}$ w.r.t B_1 (R_{ref}=50 mm)	
Load line ratio (3D)	Nominal: 76.5%, Ultimate: 83.1% at 1.9 K	
Differential inductance	Nominal: 4.0 mH/m	
Conductor	Nb-Ti: LHC-MB outer cable	
Stored energy	Nominal: 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/cm^3 (Coil peak)	
Radiation dose	**> 25 MGy**	



Large-aperture single layer coil →

Mechanical support of a coil is challenging

Production magnet: 7 m-long

Three 2 m model magnets have been fabricated at KEK

Model magnet development in KEK

MBXFS1

- Insufficient training performance due to lack of azimuthal pre-stress
- Field quality could not be evaluated at nominal current due to low quench current

MBXFS1b

- Re-assembled magnet with enhanced coil pre-stress
- Significant improvement of training performance
- Field quality could not be quantitatively discussed due to shim insertion

MBXFS2

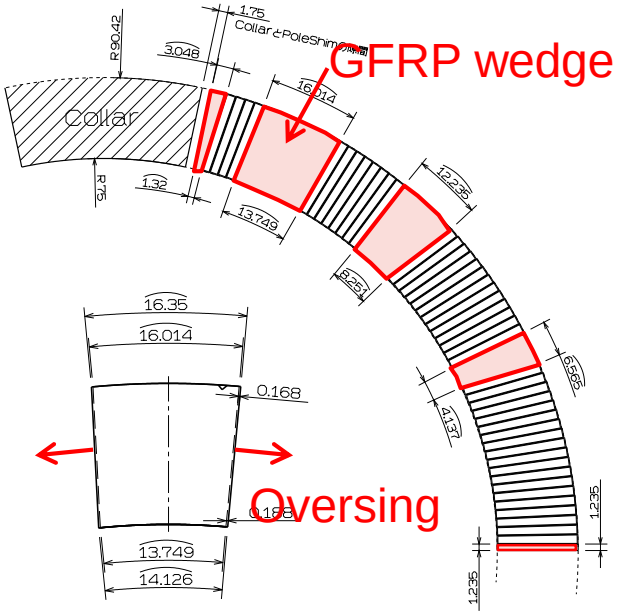
- Significant change in yoke design → Magnetic and mechanical design update
- Wet-winding at coil end for coil end support
- Successful validation of QPH with meandering heater strips
- Large b_3 offset of 19 unit from calculation
  → Incorrect way of wedge oversizing (thicker cable insulation in ROXIE calc.), coil deformation

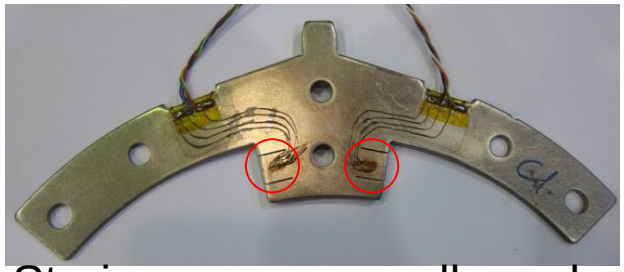
MBXFS3

- Same basic design as MBXFS2 → Reproducibility check
- Same wedge design as MBXFS2 → Similar large b_3 offset is expected
- Further enhancement of mechanical support at coil end
- 1st cold test cycle has been completed

Mechanical support in MBXFS3

Mechanical support in the SS in MBXFS3





Strain gauges on collar pole

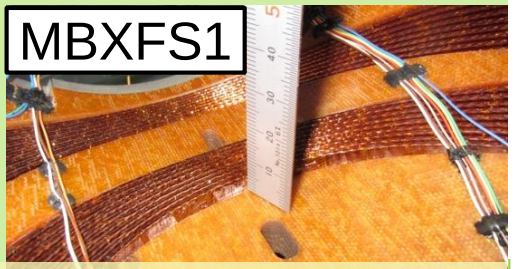
GFRP oversize and coil pre-stress

	MBXFS1	MBXFS1b	MBXFS2	MBXFS3
Total GFRP arc length w.r.t MBXFS1 (mm)	–	0.8	1.14	1.14
Target azimuthal pre-stress (MPa)	80	110	115	115
Measure pre-stress after yoking (MPa)	65	100	111	114

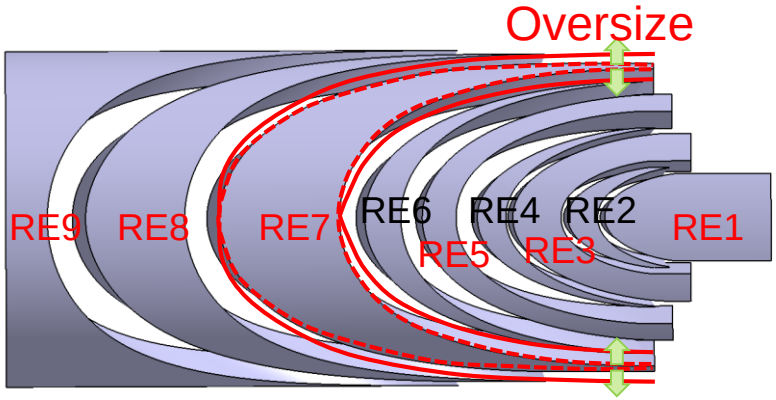
Wedge design same as MBXFS2, Similar measured pre-stress

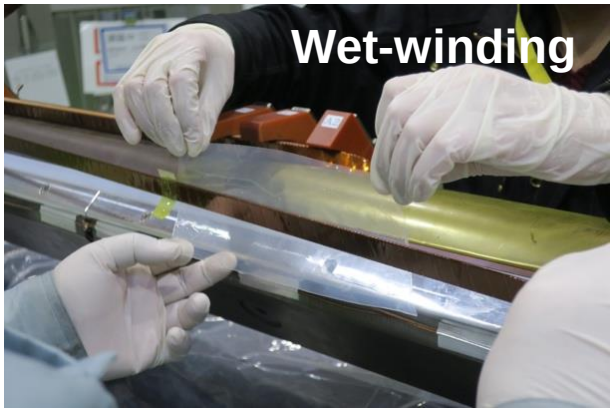
Mechanical support at coil end

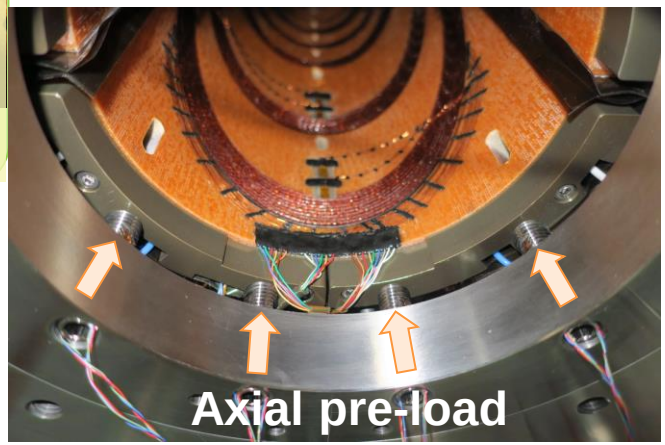
Cable deformation

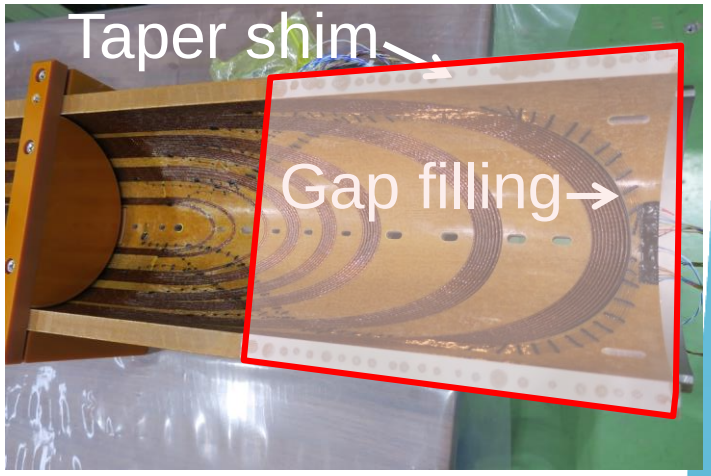


Max displacement
3.4 mm in MBXFS1
→ ~1 mm in MBXFS2







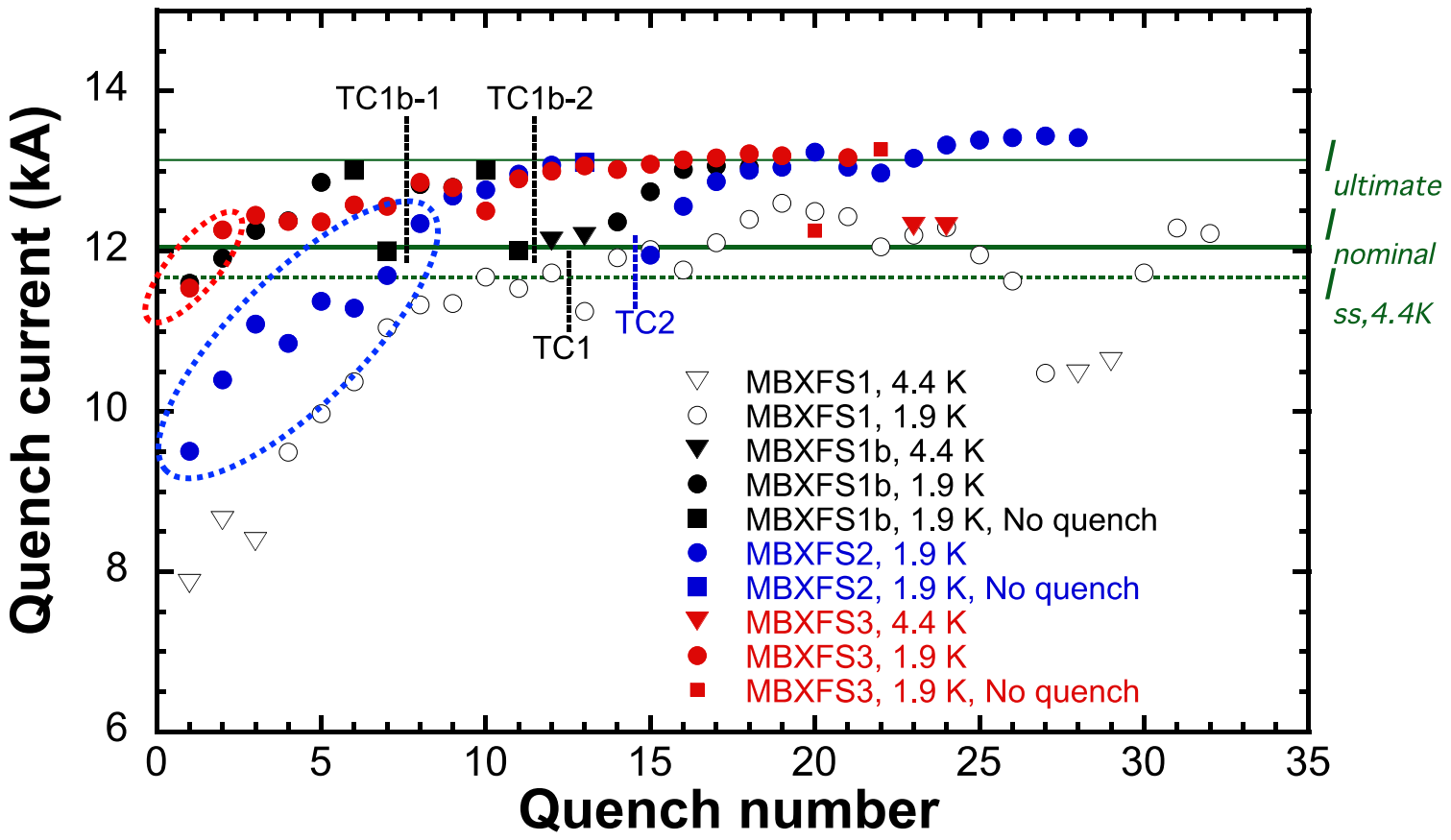


Mechanical support at coil end

	MBXFS1	MBXFS1b	MBXFS2	MBXFS3
Oversize of end spacers (mm)	–	0.9	1.14	1.14
Additional shim on end saddle	–	–	–	t0.7 mm at max
Wet-winding	No	No	Yes	Yes
Tightening torque of bullets (Nm)	14	14	20	24
Gap filing with epoxy resin	No	No	No	Yes

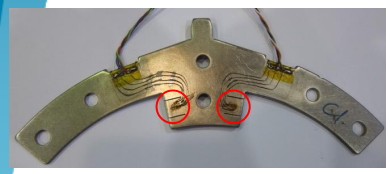
Test result of MBXFS3

Training history

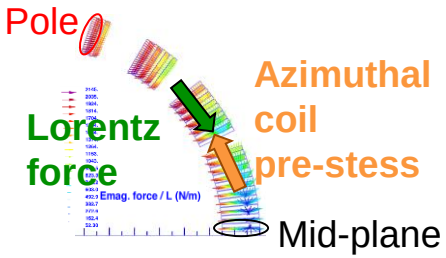


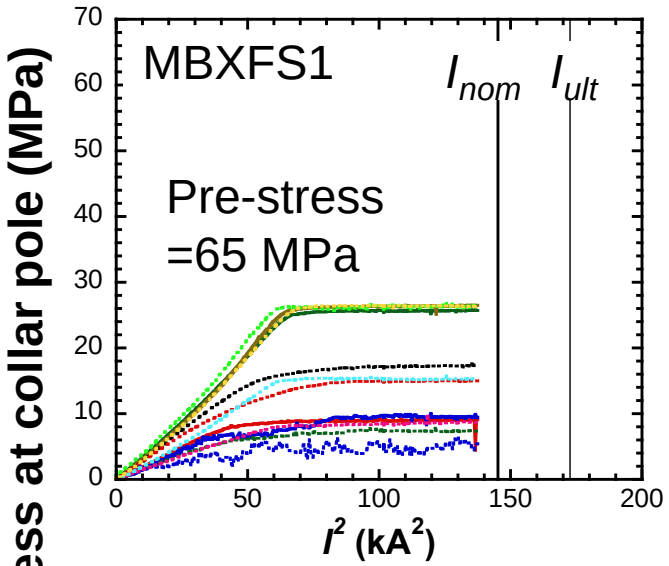
- Number of quenches to nominal (12.05 kA):8 in MBXFS2 → 2 in MBXFS3
  Significant improvement in training up to nominal current in MBXFS3
- The ultimate current (13.14 kA) was achieved at the 16th quench.
- Current holding: 12.3 kA for 1hour, 13.3 kA for 35 min
- 4.4 K training: $I_{q,4.4K}$=12.3 kA up to short sample limit
  → Quench current at 1.9 K is limited by mechanical support

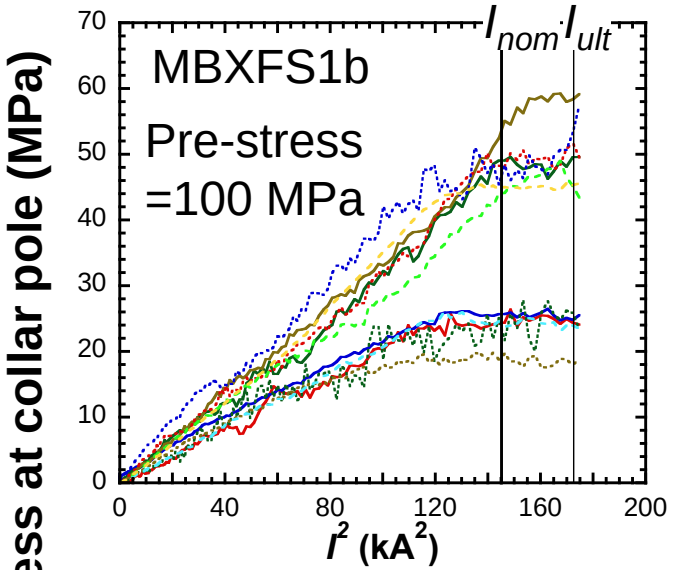
Coil stress in the straight section

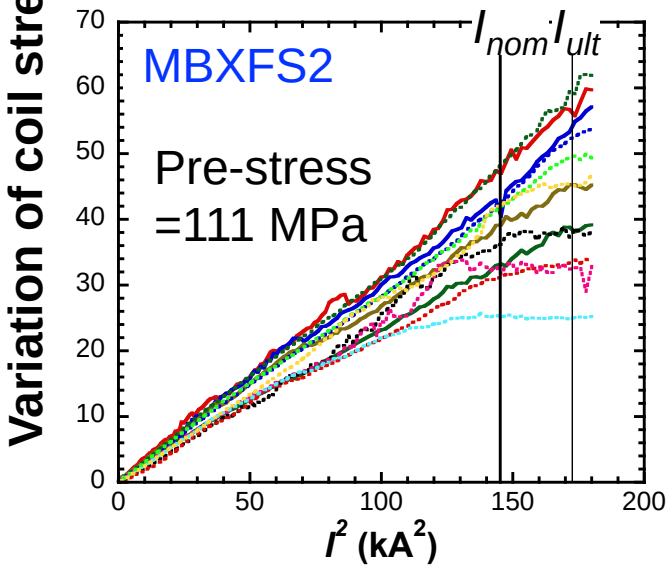


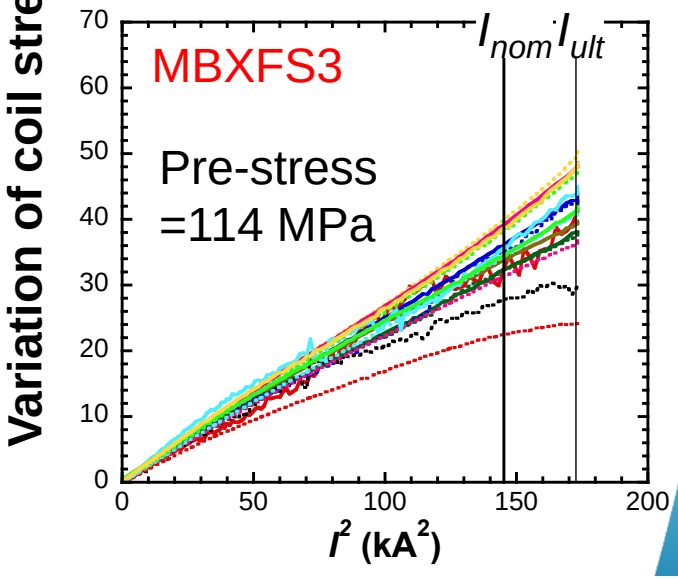
Strain gauges on collar pole









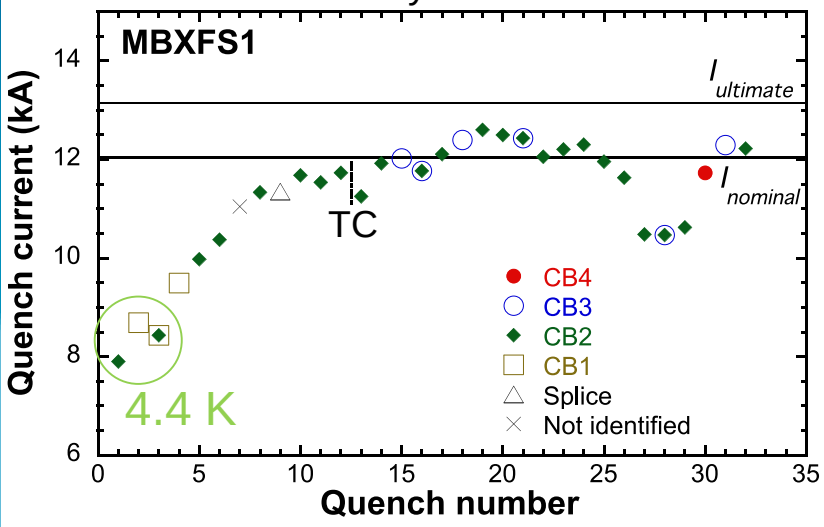


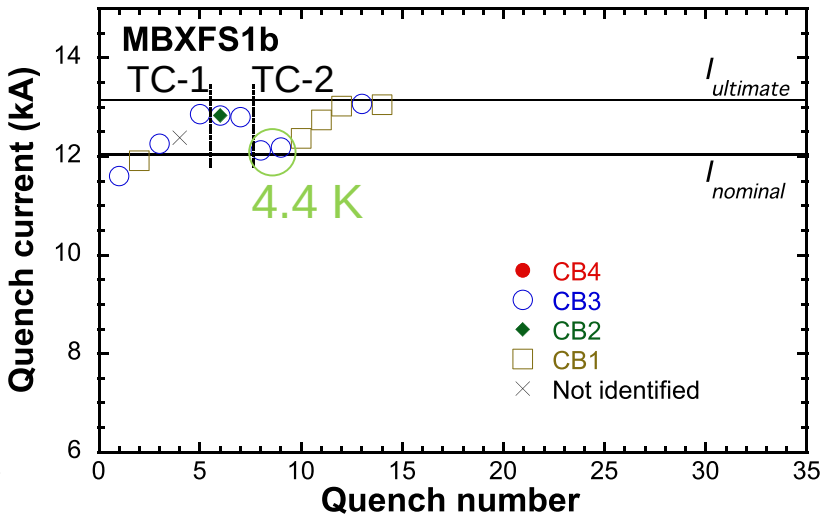
Sufficient azimuthal coil pre-stress in MBXFS3 same as MBXFS2

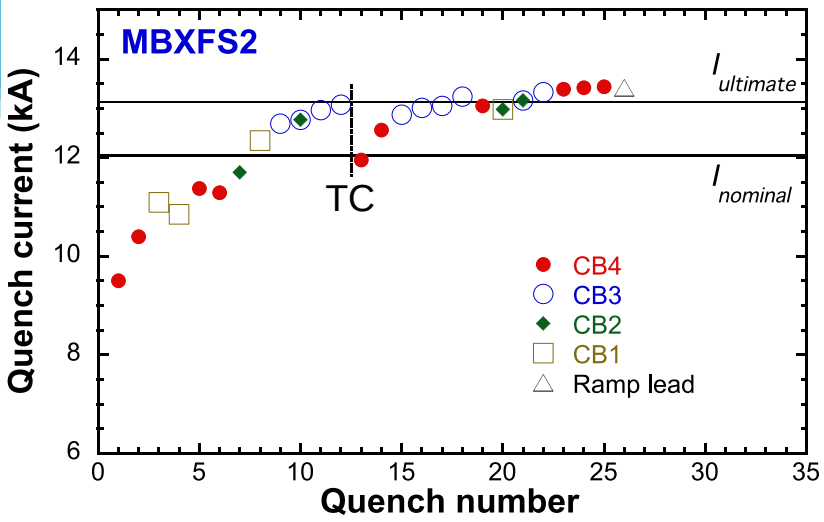
Quench start location

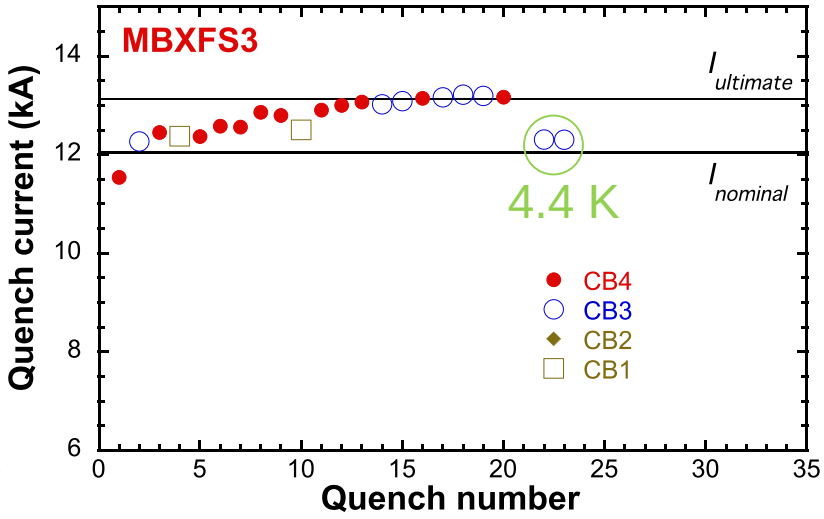
TC: Thermal cycle

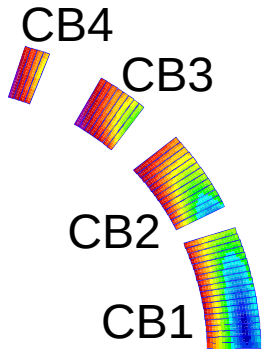
T=1.9 K if not stated

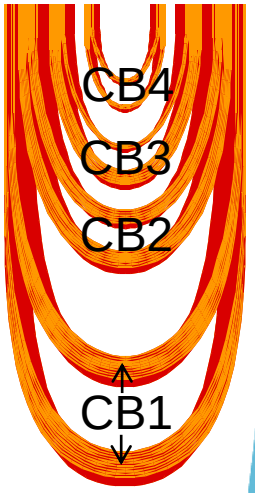






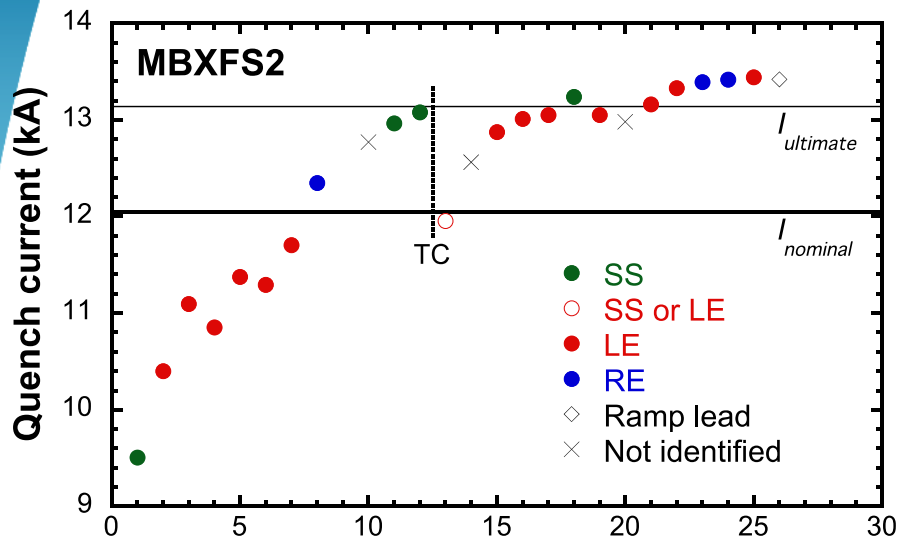


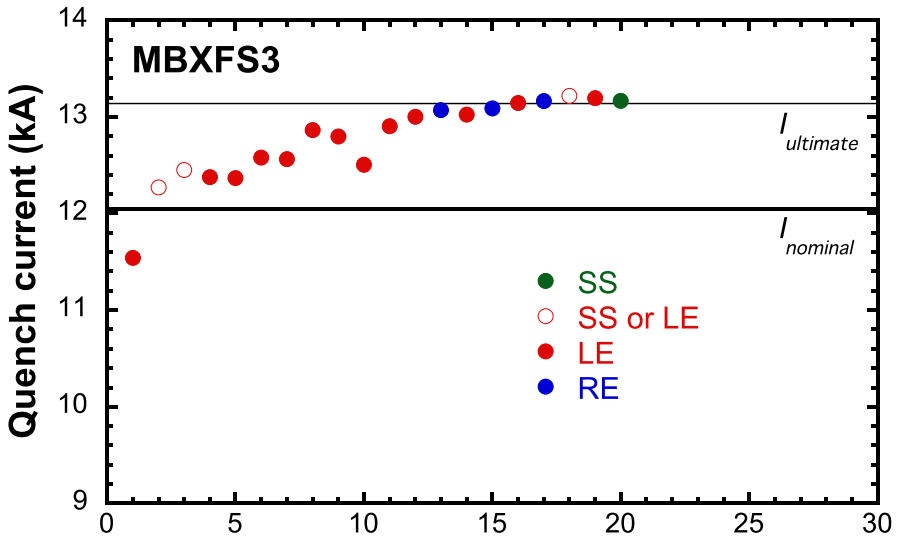


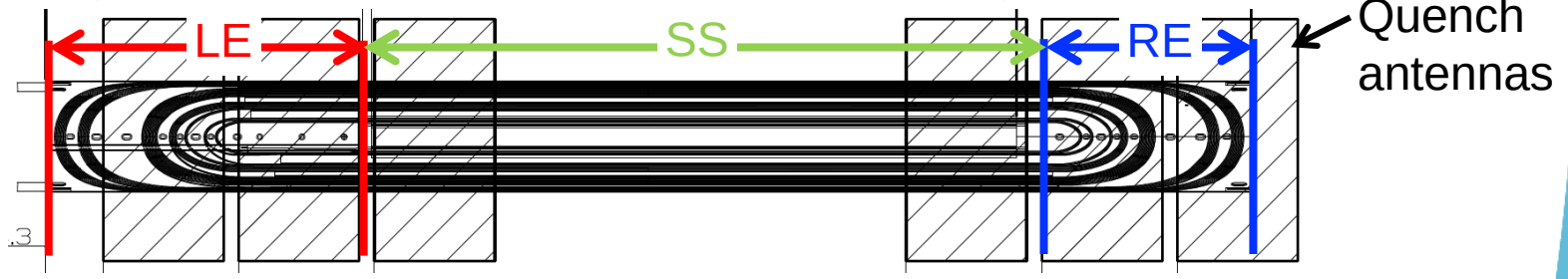


- CB1, 2 → Low field coil blocks, CB3, 4→ High field coil blocks
- Quench start location moves from lower field (CB1, 2) in MBXFS1 to higher field coil blocks (CB3, 4) in MBXFS2 and 3 by wet-winding at coil end and end spacer oversizing.

Longitudinal quench start location



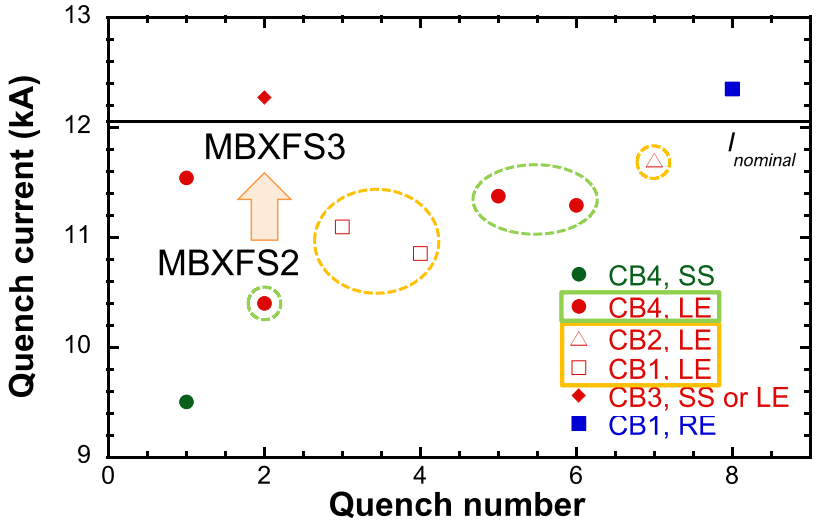


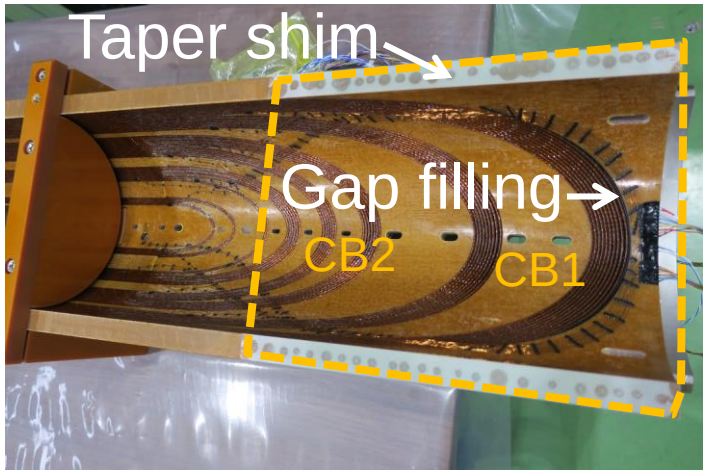


- Longitudinal quench start location was identified by voltage tap signals and quench antennas.
- In MBXFS2 and 3, training started from quench at LE side.
- Stress and strain measurements during excitation suggest that lower azimuthal coil pre-stress at LE can be one of the reasons of frequent quench at LE.

Summary of improvement in training by enhanced mechanical support

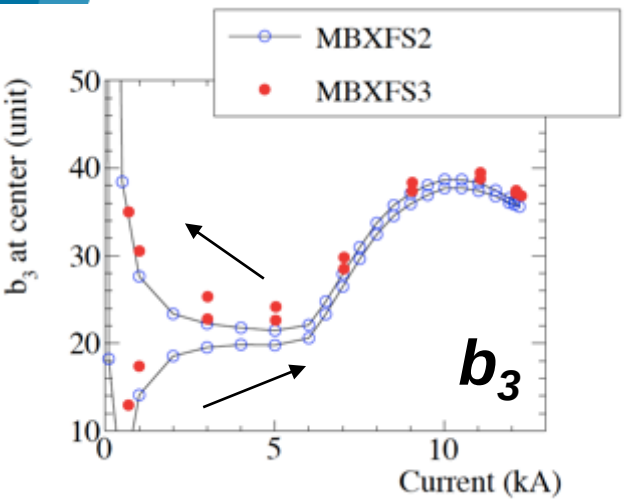
- **MBXFS1 → MBXFS1b**
  - Max. quench current > ultimate current
  - Increase in coil pre-stress both in the SS and at coil end
- **MBXFS1, 1b → MBXFS2**
  - Quench start location from lower field to higher field coil blocks
  - Wet-winding at coil end and end spacer oversizing
- **MBXFS2 → MBXFS3**
  - Improvement in training up to the nominal current
  - Coil end shimming and gap filling

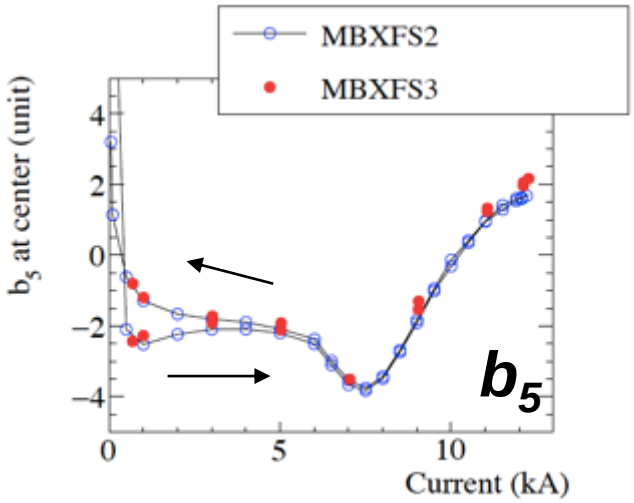


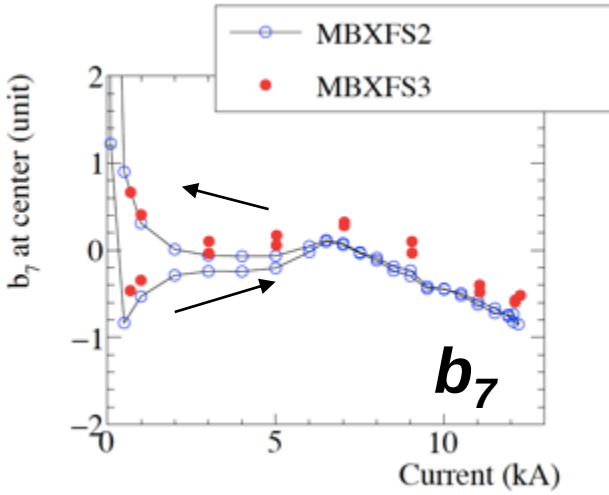


Field quality of MBXFS3

At magnet center







		MBXFS2*	MBXFS3*	Δb_3
b_3 (units)	3 kA (Geometric)	20.89	24.03	3.1
	12.05 kA (Saturation)	36.04	37.32	1.3

(*) Average of ramp-up / down

- Δb_3 = 3 unit at 3 kA is taken into consideration as fabrication error in magnetic design of a full-scale prototype magnet
- Δb_5, Δb_7 are less than 1 unit.

Summary

- Third 2 m-long model magnet of beam separation dipole (MBXFS3) for the HL-LHC upgrade was fabricated and tested at KEK.
- Quench current reached nominal current after the second quench. Current-holding above the ultimate current was also successful.
- Quench started more frequently at LE than RE and SS.
- Coil end shimming and gap filling can improve training performance up to the nominal current.
- Measured field harmonics in MBXFS3 reproduced the results of MBXFS2 within Δb_3=3 unit at 3 kA.
- A 7 m-long prototype (MBXFP) will be constructed by Hitachi in 2020. KEK has completed modification of coil cross-section to fulfill the requirement of field quality. Preparation for prototype construction is ongoing.

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