D1 Status

Tatsushi NAKAMOTO, KEK

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

CERN-KEK Committee, 14th Meeting. Nov. 18, 2019. KEK

Acknowledgement

- KEK (in particular)

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- Hitachi

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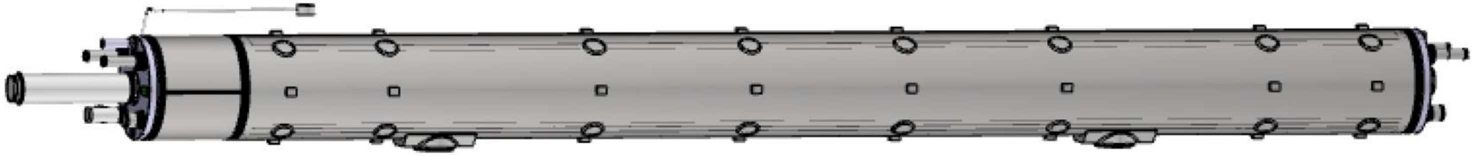
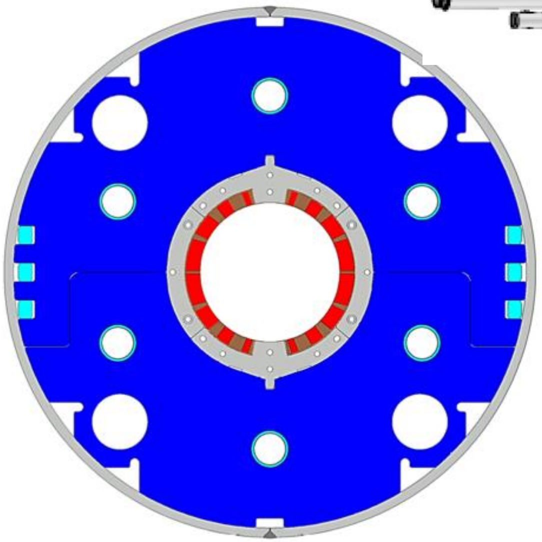
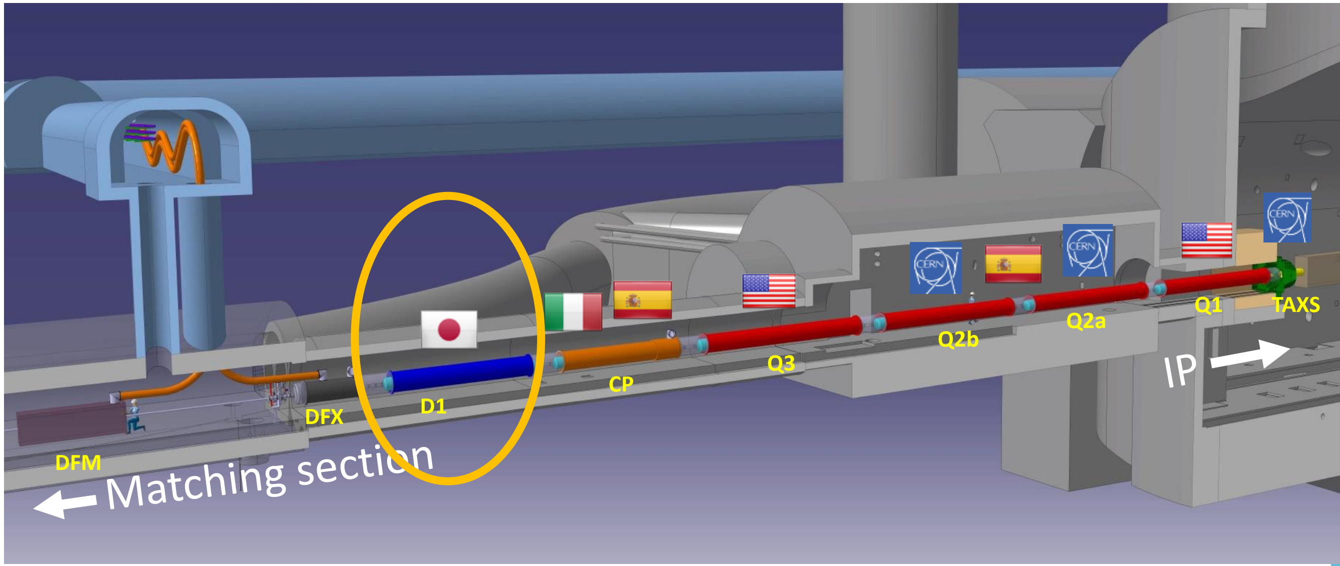
- Fusac Technologies

T. Ichihara.

Japanese Contribution to HL-LHC: D1 magnets





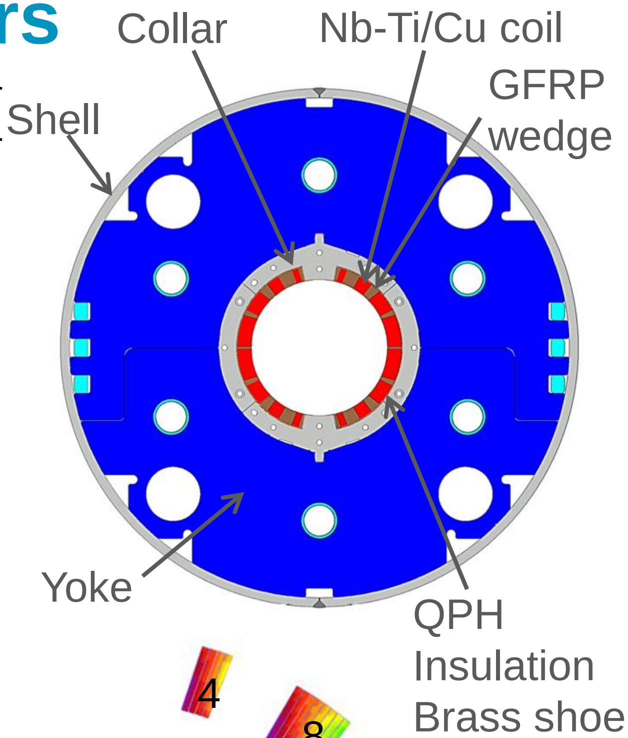


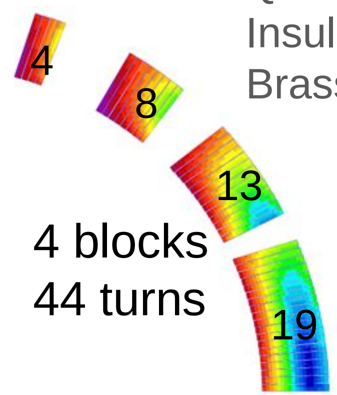
- Beam separation dipole (D1) by KEK
  - Design study of D1 for HL-LHC within the framework of the CERN-KEK collaboration since 2011.
  - 150 mm single aperture, 35 Tm (5.6 T x 6.3 m), Nb-Ti technology.
  - Development 2-m long model magnets (3 units) at KEK
- Deliverables for HL-LHC
  - *1 full-scale prototype cold mass (LMBXFP)*
  - *6 series cold masses (LMBXF1-6)*

7 units x 7-m long cold masses

Design parameters

	A series production (7m)	MBXFS3 (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: 7.14 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**	





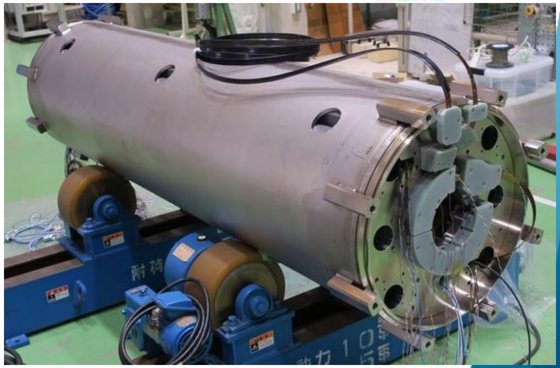
4 blocks
44 turns

Large-aperture single layer coil →

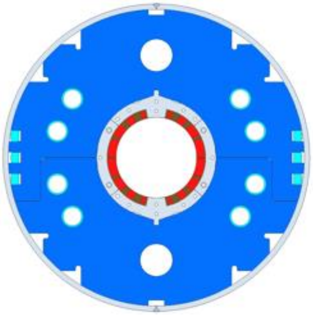
Mechanical support of a coil is challenging

Production magnet: 7 m-long

Three 2 m model magnets have been developed at KEK



Model magnet development in KEK

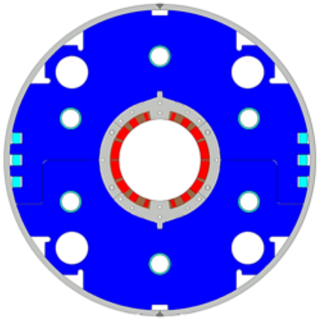


MBXFS1 cold test at Apr. 2016

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

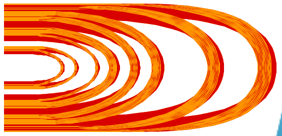
MBXFS1b cold test at Feb. 2017

- Improvement of training performance due to enhanced coil pre-stress
- Field quality could not be quantitatively discussed due to shim insertion



MBXFS2 cold test at Nov. 2018

- 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 ~20 unit** from calculation



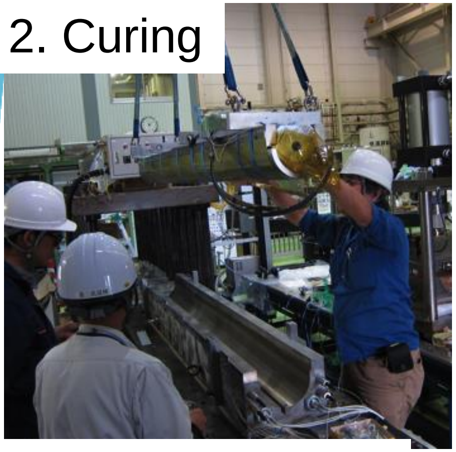
MBXFS3 cold test at Sep. 2019

- Basically same design as MBXFS2 → Reproducibility check
- Identical wedge as MBXFS2 → a systematic large b_3 offset is expected
- Further enhancement of mechanical support at coil end.

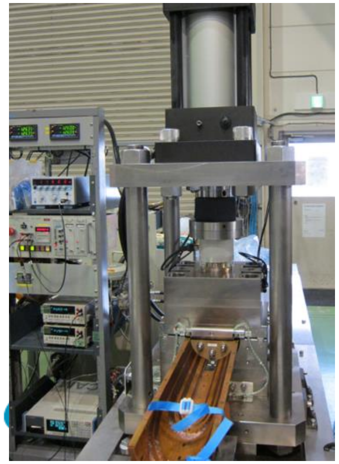
Fabrication steps

1. Coil winding

2. Curing

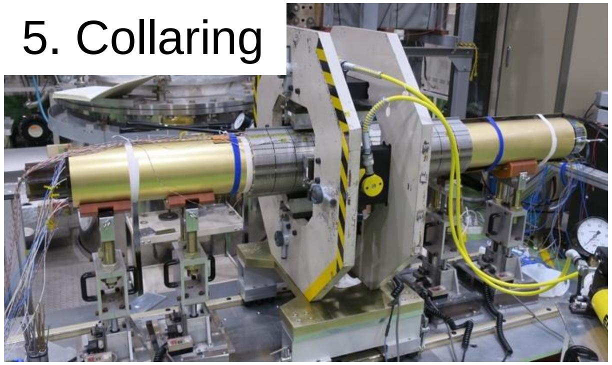


3. Coil size meas.



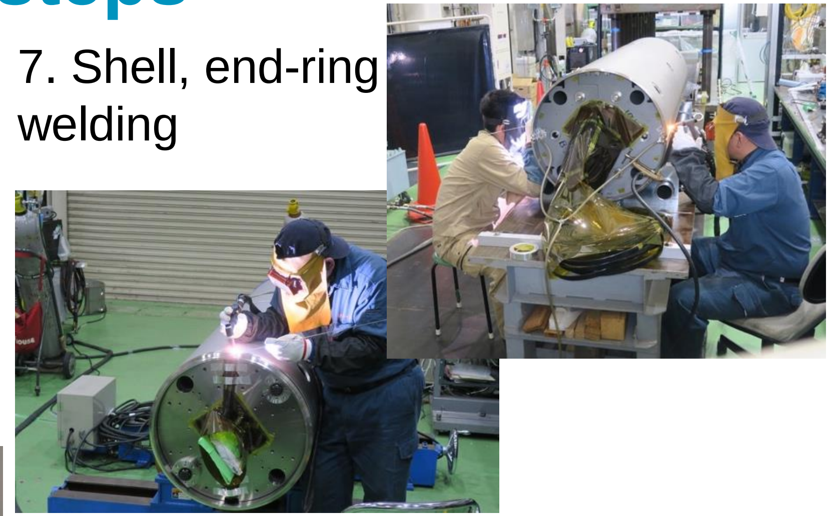
4. QPH, insulation wrapping

5. Collaring

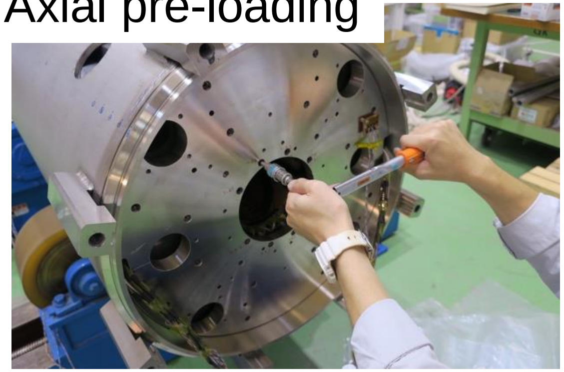


6 .Yoking

7. Shell, end-ring welding



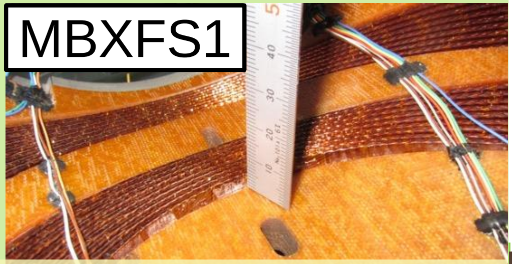
8. Axial pre-loading



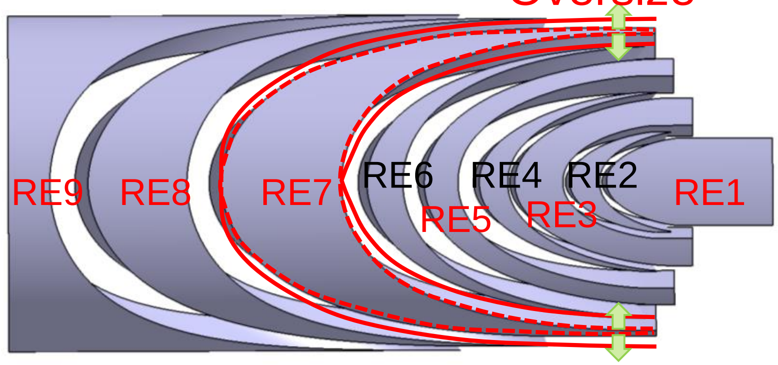
9. Splicing

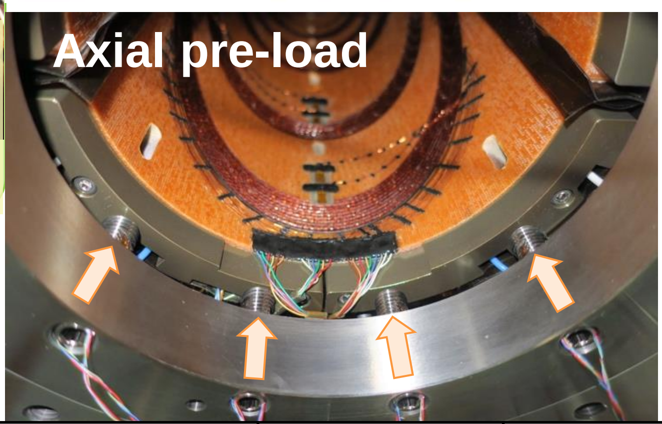
Mechanical support at coil end

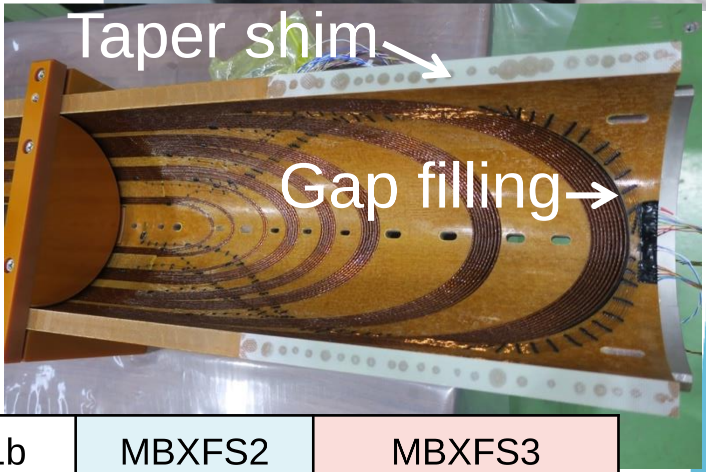
Cable deformation



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

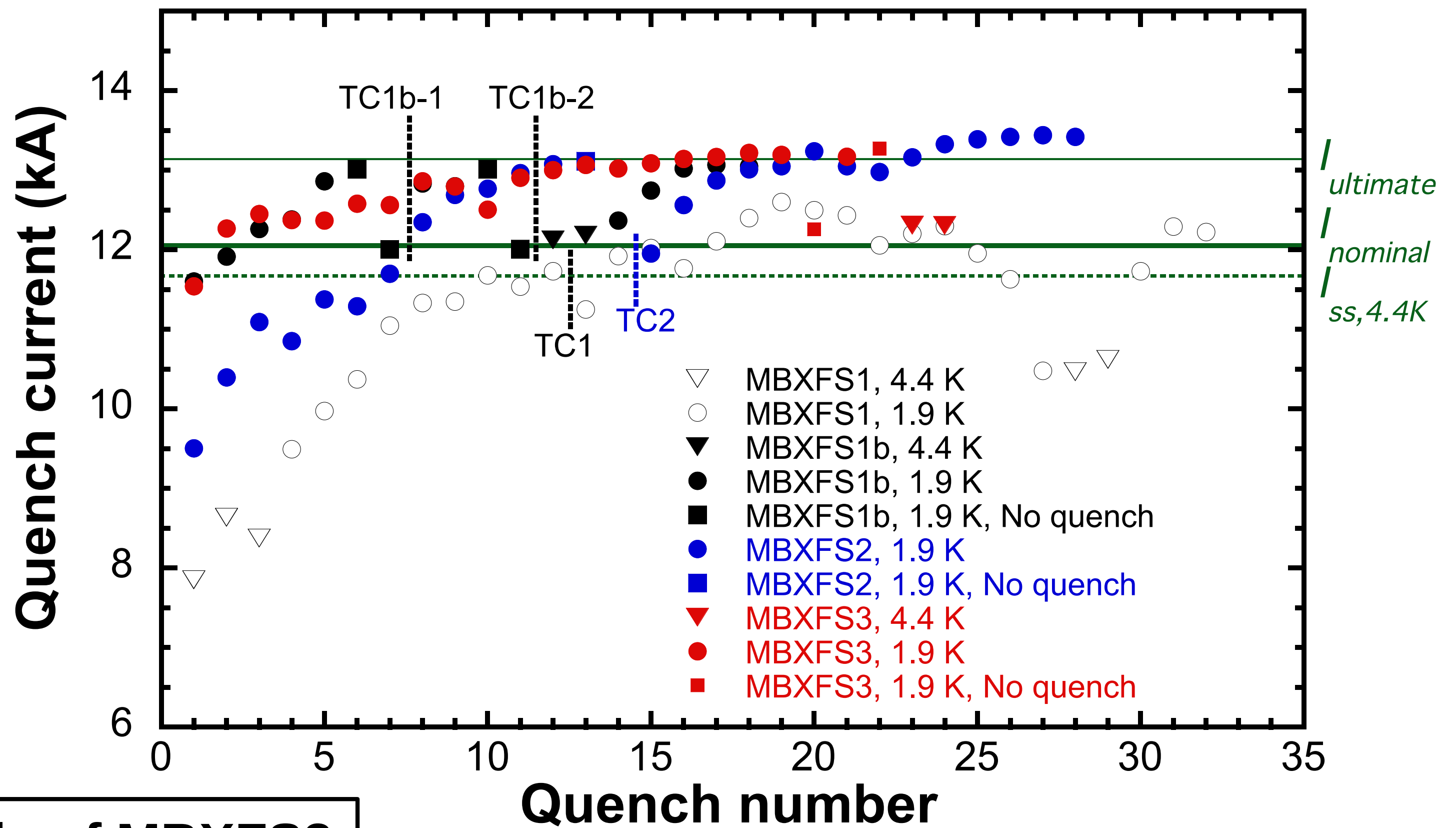






	MBXFS1	MBXFS1b	MBXFS2	MBXFS3
Oversize of end spacers wrt MBXFS1 (mm)	–	0.9	1.14	1.14
Wet-winding	No	No	Yes	Yes
Tightening torque of bullets (Nm)	14	14	20	24
Axial pre-load per coil end (kN)	–	–	30 – 43	25 – 40
Additional shim on end saddle	–	–	–	t0.7 mm at max
Gap filing with epoxy resin	No	No	No	Yes

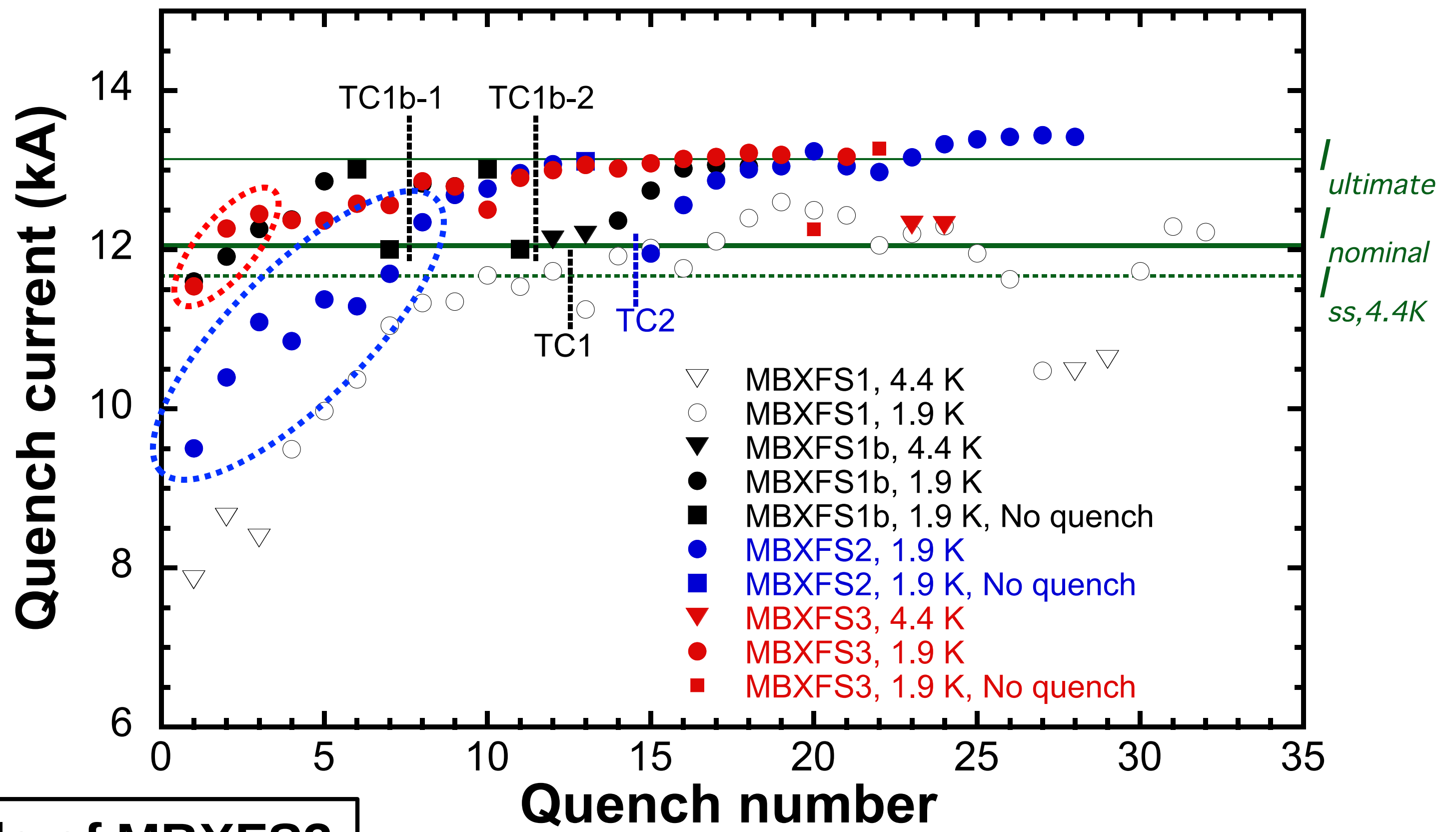
Training history



1st cycle of MBXFS3

- 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

Training history



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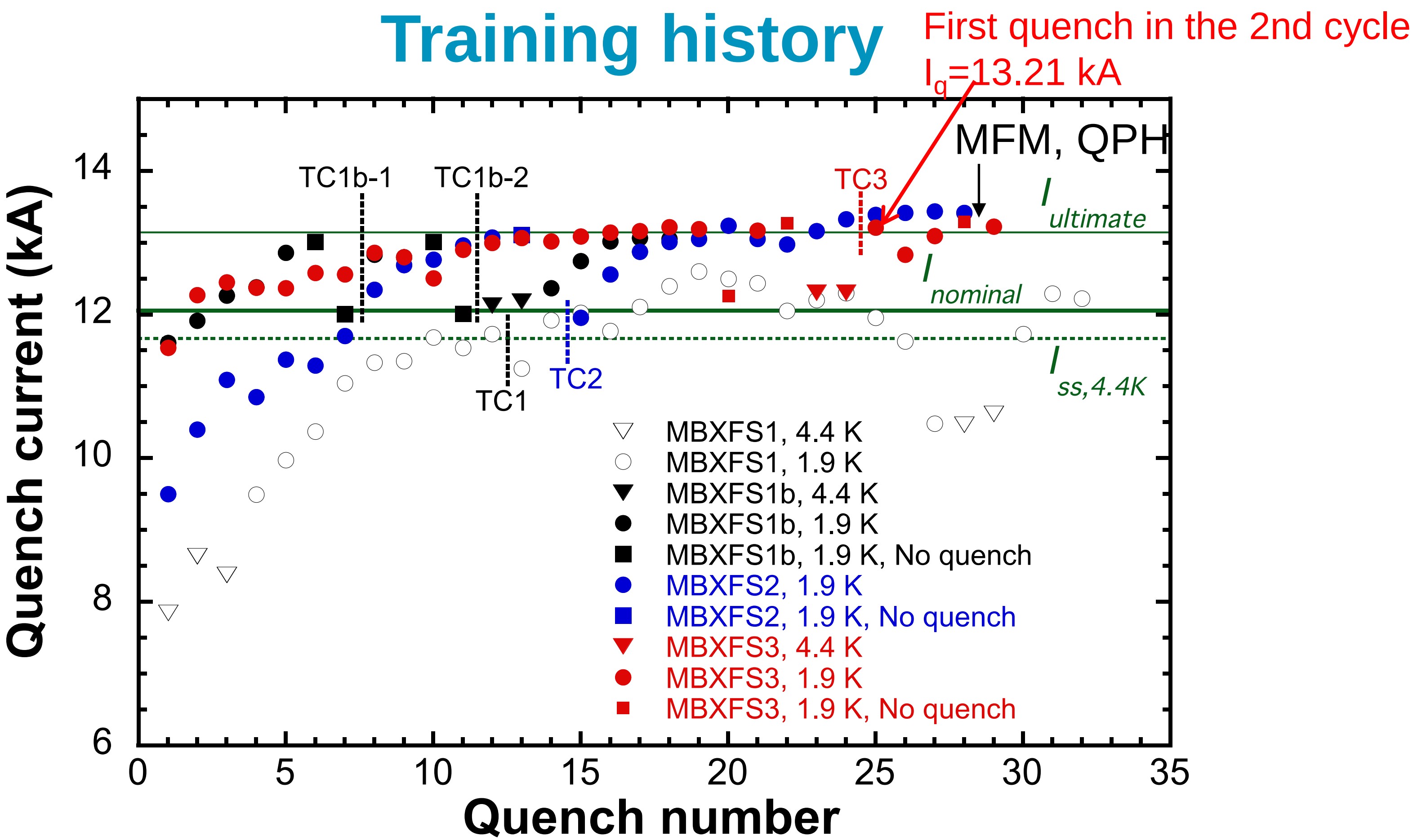
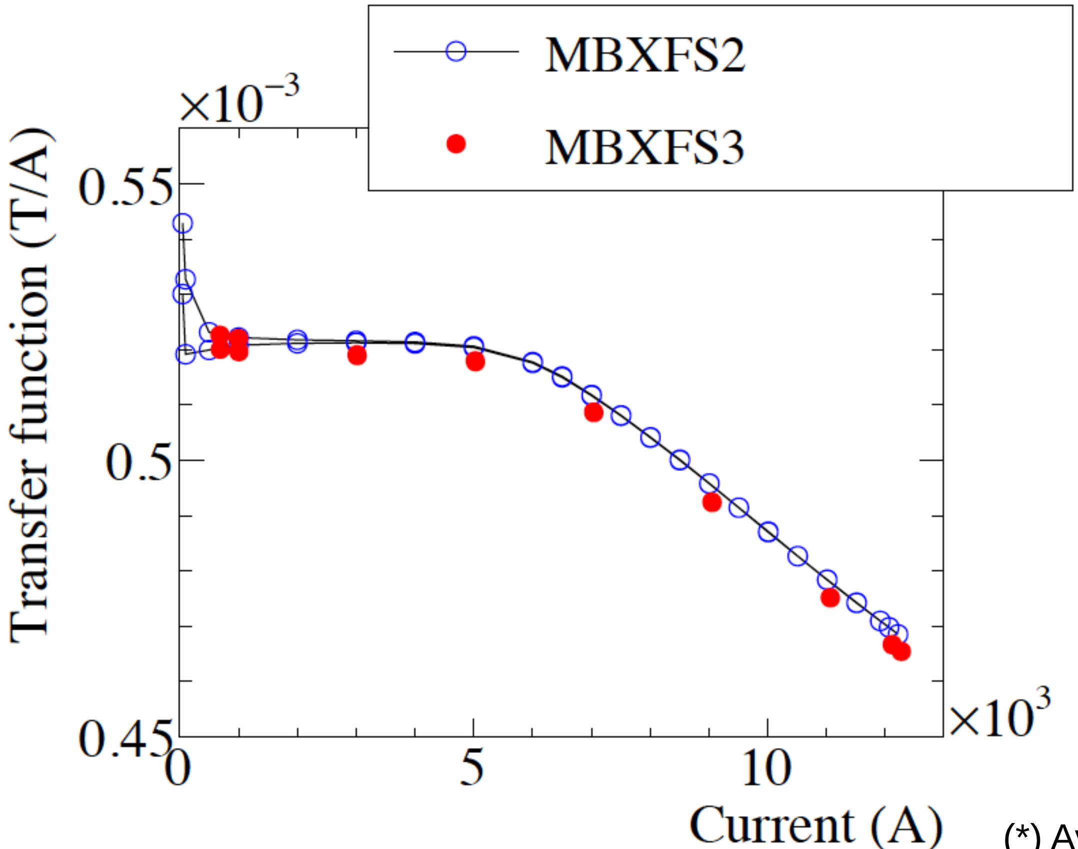


2nd cycle of MBXFS3

- The first quench current after full thermal cycle exceeded the ultimate current. (I_q=13.21 kA beyond the ultimate of 13.14 kA)
- Very good training memory

MFM: Transfer function

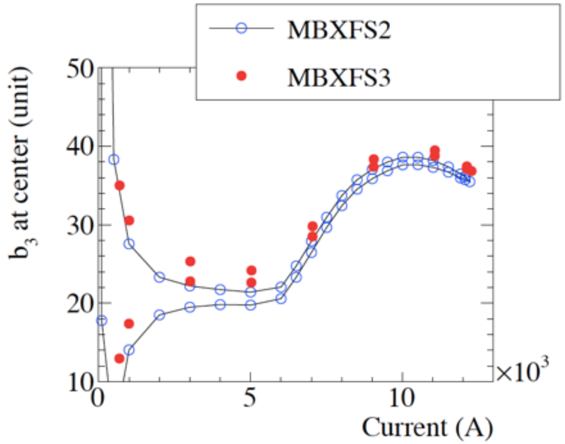


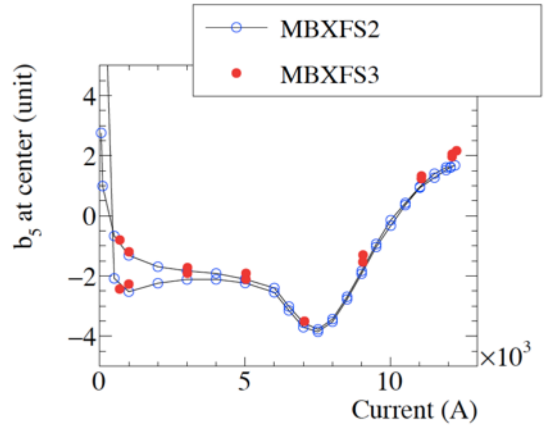
(*) Average of ramp-up / down

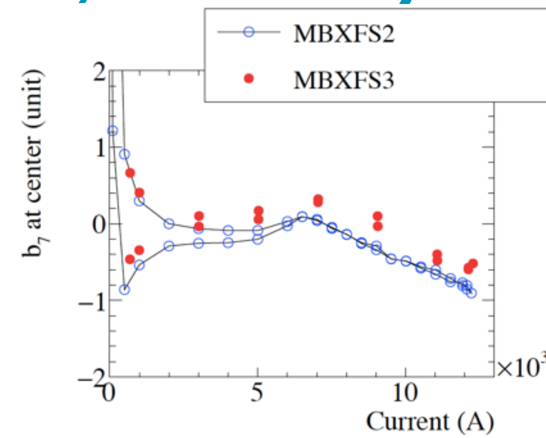
	MBXFS2		MBXFS3	
	Data*	Calc.	Data*	Calc.
TF (T/kA) @ 12 kA	0.4698	0.4684	0.4667	0.4681

TFs of MBXFS2 and 3 agree within 0.7 % at nominal operating current

MFM: at the magnet center (I=3kA, 12.05kA)







(*) Average of ramp-up / down

	MBXFS2		MBXFS3	
	3 kA*	12.047 kA*	3 kA*	12.047 kA*
b_3 (units)	**20.84**	**35.94**	**24.05**	**37.28**
b_5 (units)	-1.98	1.61	-1.82	2.01
b_7 (units)	[illegible]	[illegible]	[illegible]	-0.58
b_9 (units)	[illegible]	[illegible]	[illegible]	0.50
b_{11} (units)	0.20	0.21	0.21	0.23
b_{13} (units)	-0.50	-0.53	-0.51	-0.52
b_{15} (units)	-0.96	-1.02	-1.01	-1.10

Inadequate design of wedge oversizing for coil prestress enhancement was the cause of a large b3.

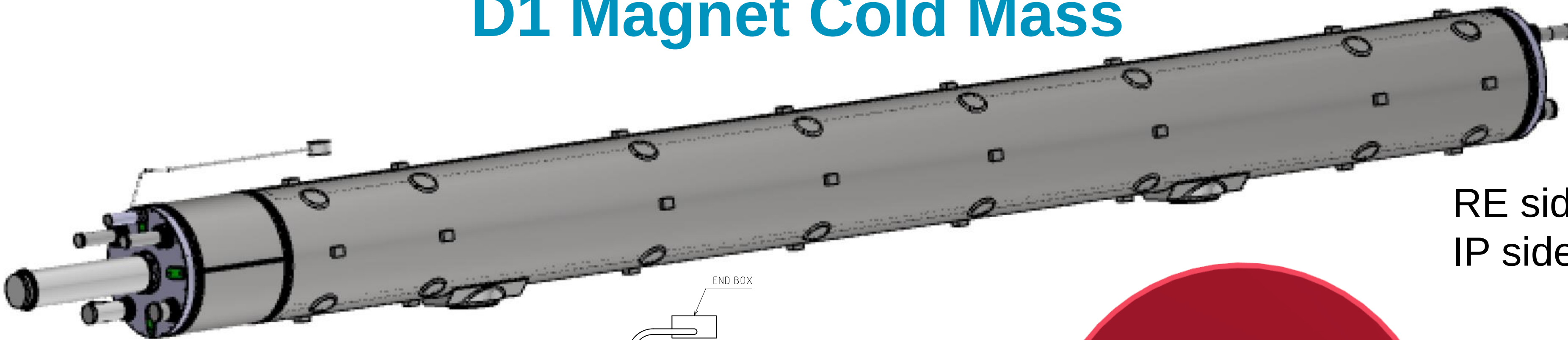
#2-#3 comparison:

Good agreement in the higher allowed multipole (n≥5)

~3 unit difference observed in the geometrical b3, and reduced to ~1 unit at $I_{nominal}$

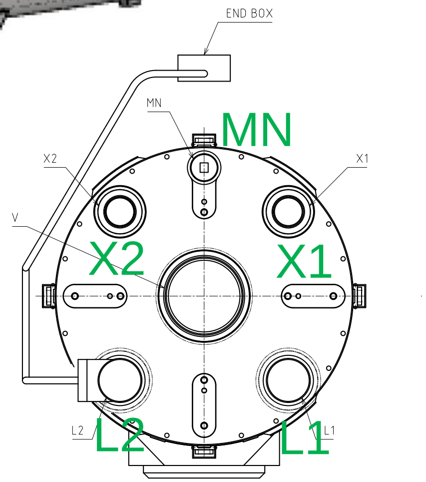
Status of Prototype

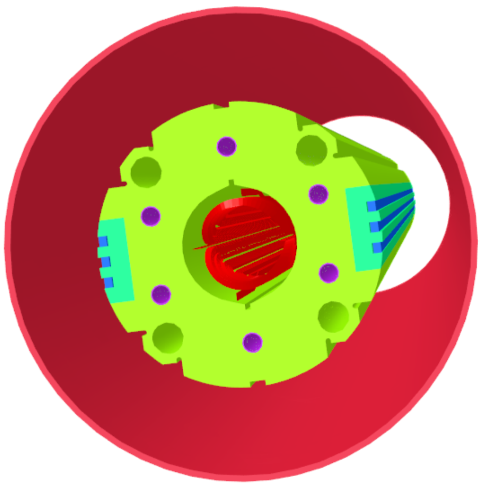
D1 Magnet Cold Mass



RE side
IP side

LE side
NIP side



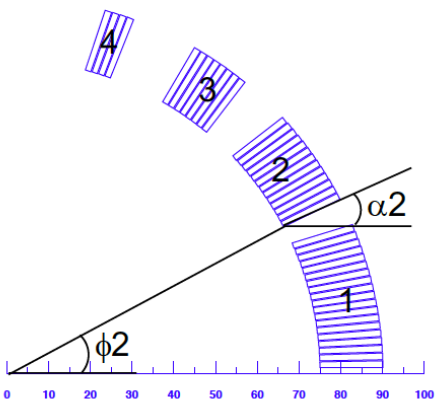


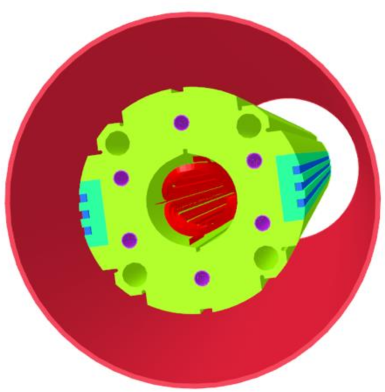
Design Parameters

- Nominal current and field, field integral: **12070 A, 5.58T, 35 Tm**
- Design pressure and operating temperature: 2.0 MPa, 1.9 K
- Pressure test at 2.5 MPa
- He leak rate below 1×10^{-10} Pa m^3/s
- Cold mass length and distance between saddles: 7370 mm and 3900 mm
- Outer diameter: < 630 mm ➡ Shell OD: 570 mm + markers
- The detail of extremities given by CERN
  - ➢ Two HeII HX pipes in line with MQXF (X1, X2)
  - ➢ Two HeII conduction lines (L1, L2)
  - ➢ Bus bars interconnection line (MN)

Design for MBXFP1

- For 7m long full-scale prototype, the ROXIE model with appropriate **azimuthal insulation thickness of 0.122 mm** including the prestress enhancement is used for the design.
  - In addition, the effects of oval structural deformation, coil deformation due to Lorenz force and unpredictable iron saturation effect in 3D model at 12 kA are taken into account for the 7m long full-scale prototype.





	MBXFS2 and 3	MBXFP1 v7.1.0
Target b3 at 3kA	0	-5
$\phi 1$	1.1346	1.2962
$\phi 2$	27.8721	27.9747
$\phi 3$	50.2969	50.4743
$\phi 4$	70.6992	70.841
$\alpha 2$	26.0000	27.4005
$\alpha 3$	52.4212	52.34
$\alpha 4$	68.0015	68.9141
Azimuthal insulation thickness (mm)	**0.130**	0.122

B1=5.578 T @ 12070A

	Acceptance criteria		Expected total integral
	LL	UL	v. 7.1.0
b_2	-0.800	0.800	**0.00**
b_3	-2.900	2.900	$\mathbf{0.01^{+1.61}_{-1.06}}$
b_4	-0.500	0.500	**0.00**
b_5	-1.500	1.500	**0.19**
b_6	-0.240	0.240	**-0.01**
b_7	-0.660	0.660	**-0.63**
b_8	-0.110	0.110	**-0.01**
b_9	-0.260	0.260	**-0.22**
b_{10}	-0.030	0.030	**0.00**
b_{11}	-0.076	0.076	**-0.31**
a_2	-0.800	0.800	**-0.02**
a_3	-2.900	2.900	**1.61**
a_4	-0.500	0.500	**0.00**
a_5	-1.500	1.500	**-0.14**
a_6	-0.240	0.240	**0.00**
a_7	-0.660	0.660	**0.14**
a_8	-0.110	0.110	**-0.01**
a_9	-0.260	0.260	**-0.03**
a_{10}	-0.030	0.030	**0.00**
a_{11}	-0.076	0.076	**0.02**

Opera

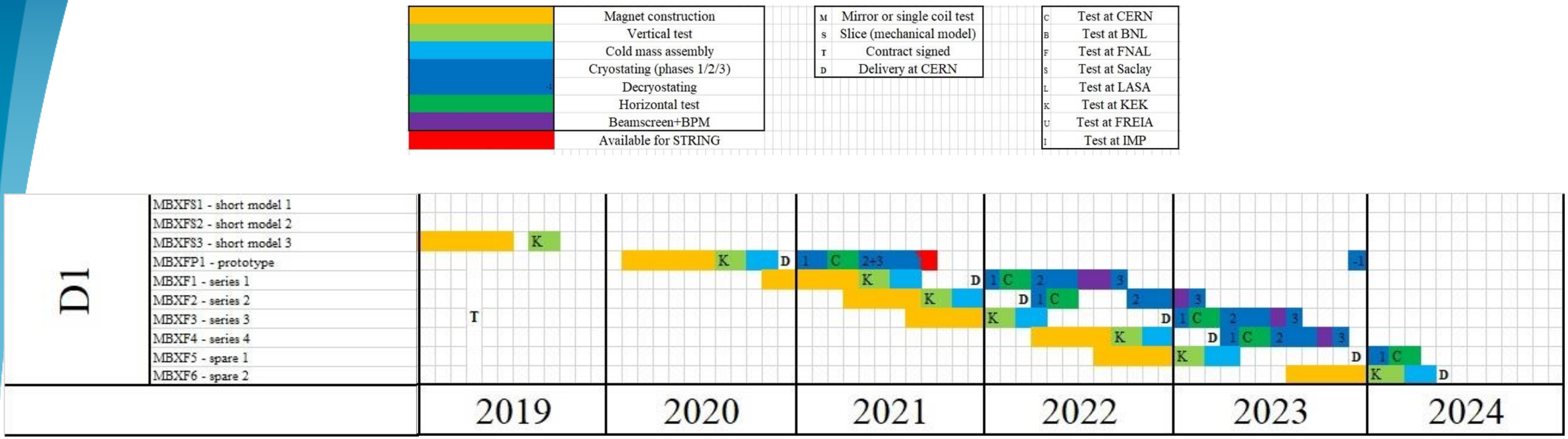
HiLumi HL-LHC PROJECT

Overview of Production of D1 Prototype and Series

- Production of 7-m cold masses (prototype and series) by a manufacturer.
  - Involvement of Japanese firms already in model magnet development:
    >> smooth technical transfer, accurate (lower) cost estimate.
  - A Multi-year contract given to **Hitachi (May 2019)**
    - Covering construction of **1 prototype & 4 series cold masses**
    - Another contract for **2 remaining cold masses will be made in JFY 2021 and 2022.**
    - To be fitted to the delivery schedule.
- Raw materials procured by KEK: timely provision to the manufacturer.
  - Due to some reasons: budget limitation, PED, cobalt content.
    - Low cobalt iron and stainless steel, radiation resistant GFRP, etc.
- Supplies from CERN:
  - insulated SC cables,
  - base laminates of QPH
  - HX tubes
  - insulated beam tubes
  - end-covers
  - Extremity parts such as flare flanges (under discussion).

Agreement of money transfer using Mixed Flow Budget Code in preparation.

Schedule



- Contract with Hitachi in May 2019.
- Some initial delay for start-up at Hitachi was observed.
  - KEK and CERN expressed big concerns about the schedule delay.
  - Hitachi has been pursuing the schedule recovery plan underway.
- Prototype
  - The fabrication will start in Feb. 2020 and the vertical cold test is planned in August.
  - Need a revision of cold mass assembly schedule in Oct. 2020.
- 1st series
  - Fabrication will only start after the vertical cold test of the prototype.

Summary

2-m long model development

- KEK has developed three 2 m-long model magnets (MBXFS1, 2 and 3) with one variant (MBXFS1b) of the beam separation dipole D1 for the HL-LHC upgrade.
- The latest 3rd model with an improvement of mechanical support showed a good training performance
  - 1st cycle;
    - Reaching the nominal current after the first quench.
    - Achievement of current hold (10 min.) w/o quench at the ultimate current.
  - 2^{nd} cycle
    - the first quench beyond the ultimate. Excellent training memory.
- It was concluded that a large b_3 around 20 unit consistently observed in MBXFS2 and 3 was caused by the inadequate design of coil wedges.

7-m long prototype and series magnet cold mass

- New coil cross section with minimal b_3 has been designed and be implemented in the prototype.
- Contract of D1 cold mass production was given to Hitachi. The coil fabrication will be started in Feb. 2020.
  - Documentation, drawings, procurement are underway at KEK and Hitachi.
- Renovation of test facility at KEK is on-going.