Status Report on D1 Magnets

Tatsushi NAKAMOTO, KEK

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

CERN-KEK Committee, 17th Meeting, Dec. 8, 2022

Acknowledgement

- KEK (in particular)

M. Sugano, K. Suzuki, Y. Arimoto, R. Ueki, Y. Ikemoto, H. Kawamata,
N. Okada, R. Okada, H. Ohhata, A. Terashima, K. Tanaka, N. Ohuchi, T. Ogitsu.

- Univ. of Tokyo

N. Kimura.

- CERN (in particular)

E. Todesco (WPL), H. Felice (exWPE), J. C. Perez (WPE), H. Prin, D. Duarte Ramos,
C. Scheuerlein, H. G. Gavela, A. Devred.

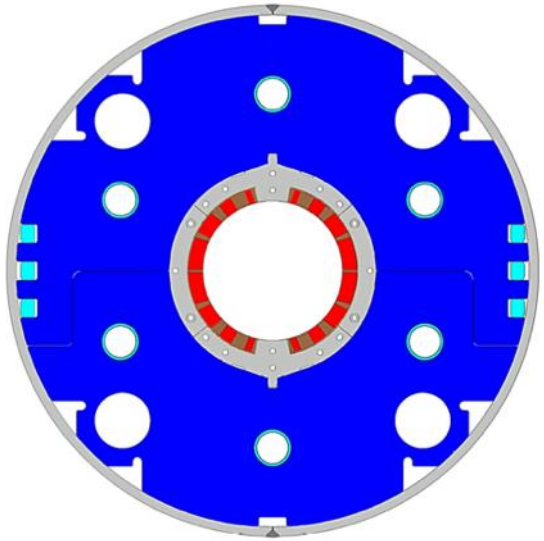
- Hitachi

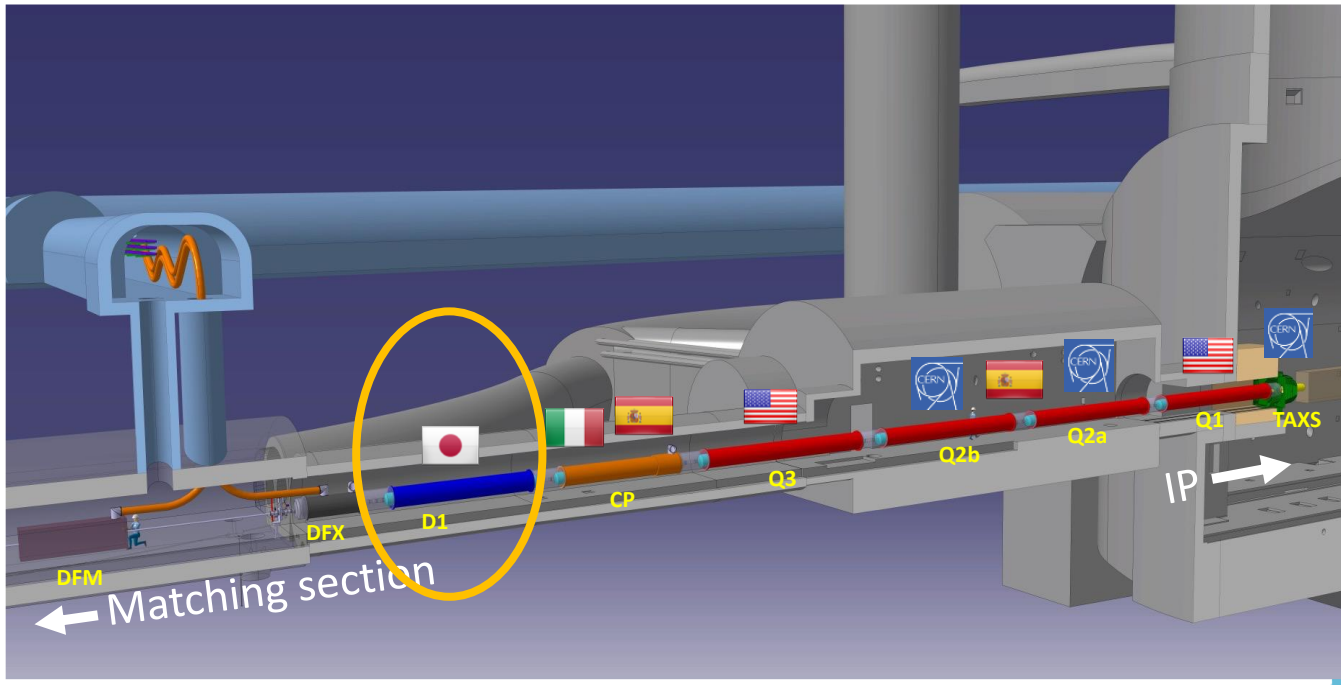
M. Yanagisawa, A. Yokogi, H. Togashi, T. Tahara, T. Chiba

- Fusac Technologies

T. Ichihara.

Japanese Contribution to HL-LHC: D1 magnets



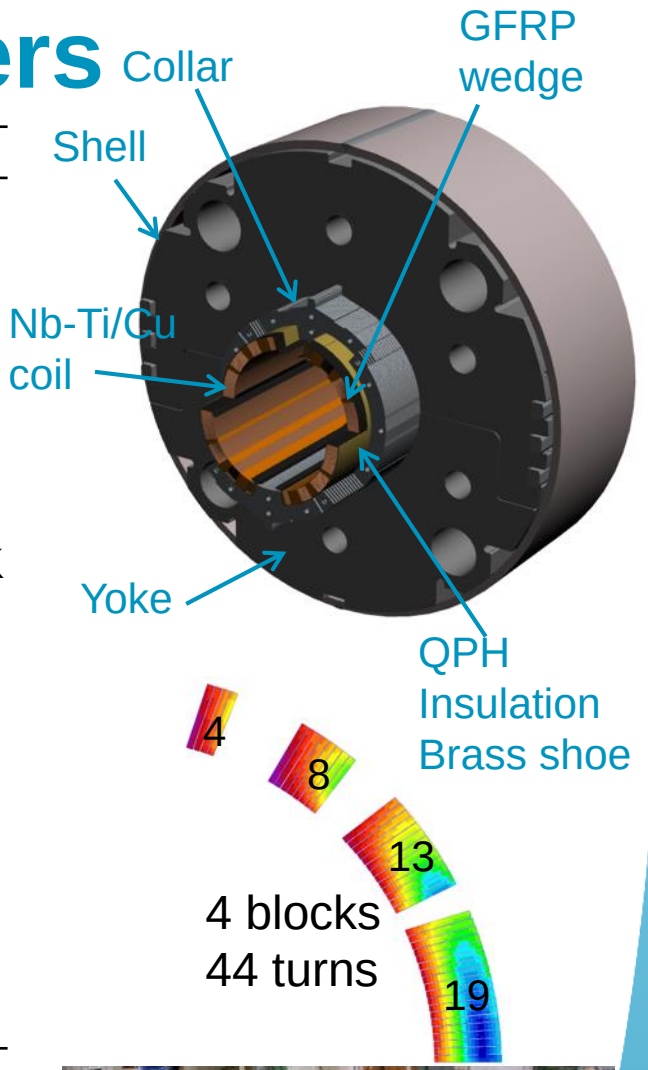


- Beam separation dipole (D1) by KEK
  - Design study of D1 for HL-LHC within the framework of the CERN-KEK collaboration since 2011.
  - 150 mm single aperture, 35 Tm (5.6 T x 6.3 m), Nb-Ti technology.
  - Development 2-m long model magnets (3 units) at KEK
- Deliverables for HL-LHC
  - *1 full-scale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

7 units x 7-m long cold masses

Design parameters

	prototype, series production (7m)
Coil aperture	**150 mm**
Field integral	**35 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 : 12.11 kA, Ultimate 13.23 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
Coil mech. length	6.58 m
Magnet mech. length	6.73 m 12 ton
Heat load	**135 W (Magnet total)** **2 mW/cm^3 (Coil peak)**
Radiation dose	**> 25 MGy**



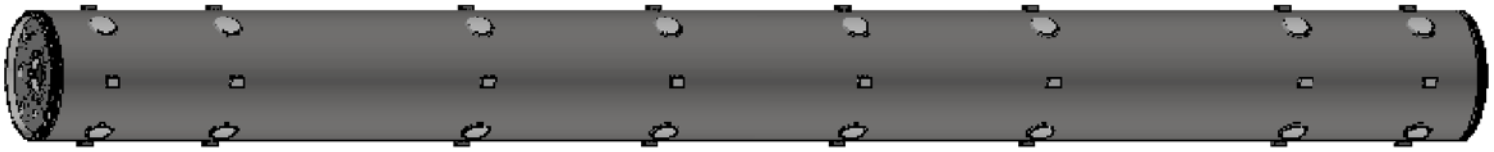
Large-aperture single layer coil →
Mechanical support of a coil is challenging

Three 2 m model magnets were developed at KEK.

D1 Prototype Cold Mass: MBXFP1

Full-scale D1 Prototype

- Magnet technology developed through 2m-long model magnet program (2011-2019) by KEK has been transferred to Hitachi.
- **Objective:** *Validation of design, manufacturing procedure and performance of a full-scale magnet constructed by Hitachi.*
- Cold test of the D1 prototype magnet at 1.9 K at the 9-m deep vertical cryostat at KEK was carried out in June to Sep. 2021.



D1 magnet for vertical cold test (Yoked magnet w/ shell, end-ring)

D1 cold mass to be delivered to CERN

Testing of D1 Prototype at KEK

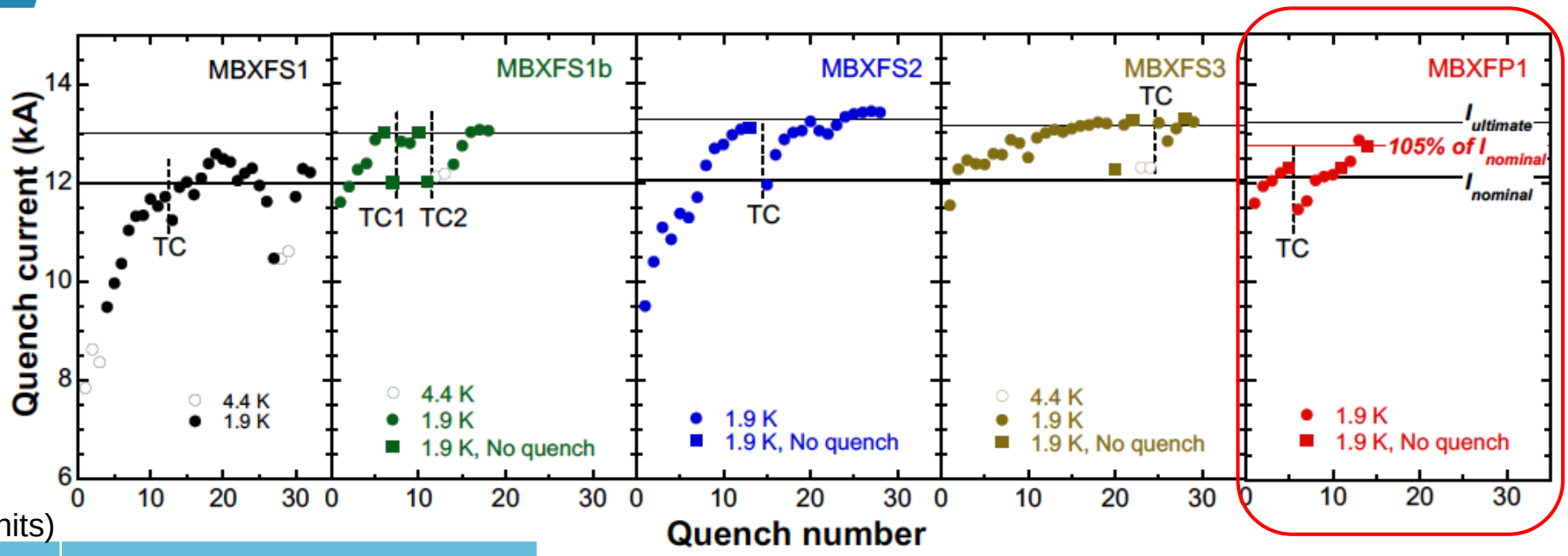
- Lifting up the D1 magnet

- Insertion into vertical cryostat

Test Report of MBXFP1
EDMS 2747573

Vertical Cold Test Results

Prototype



(units)

	Field Integral at 12.1 kA		
	Calculation		Meas.
	CERN H-Cryo.	**KEK V-Cryo.**	**KEK V-Cryo.**
b_3	-0.5	**-6.5**	**-12.7**
b_5	4.9	**4.8**	**6.5**
b_7	0.3	**0.3**	**0.5**
b_9	0.5	**0.5**	**0.8**
b_{11}	-0.2	**-0.2**	**-0.2**
b_{13}	-0.8	**-0.8**	**-1.0**
b_{15}	-1.3	**-1.3**	**-1.4**

Training behavior

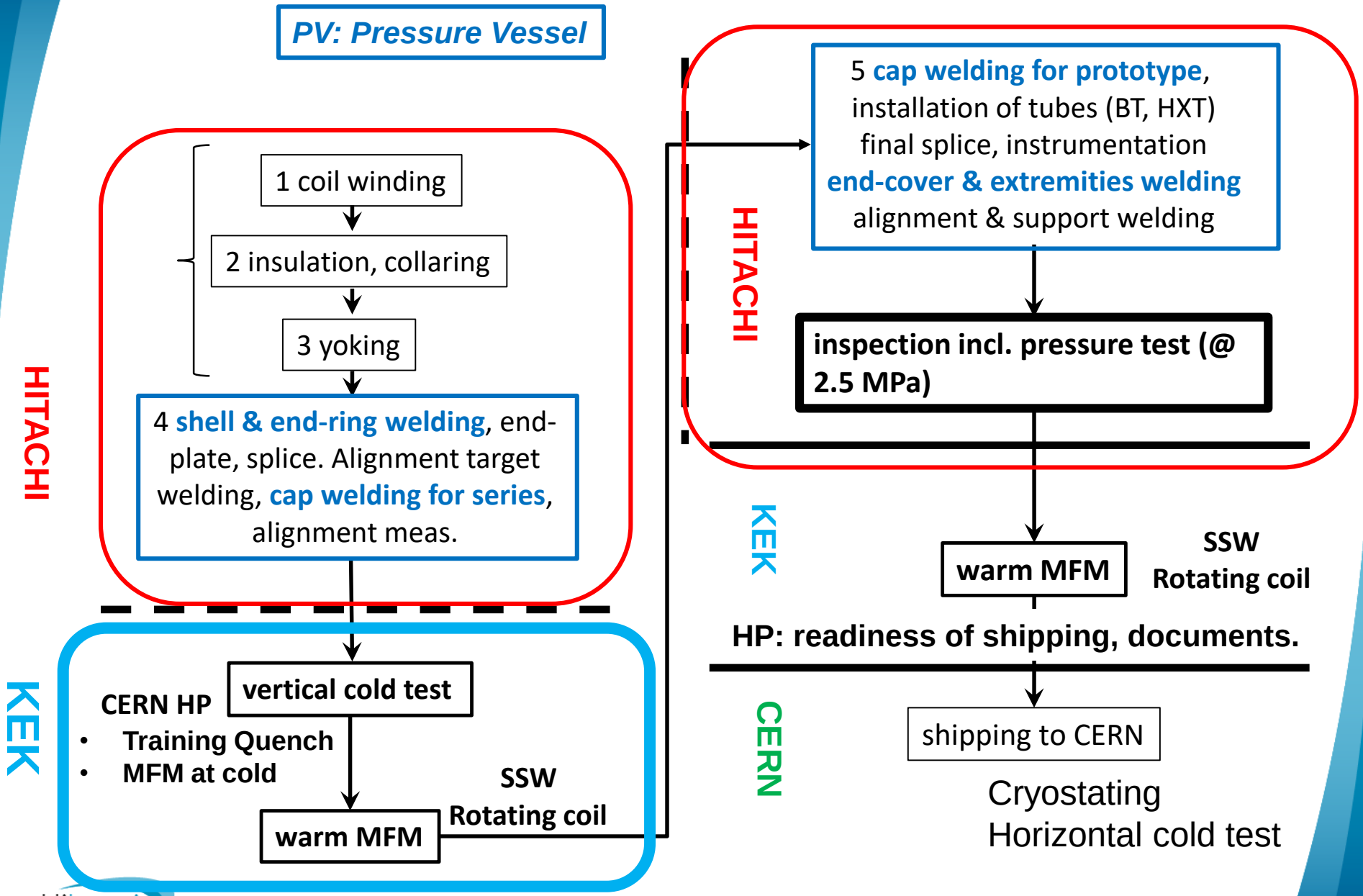
- The maximum current was 12.87 kA which was limited by allowable terminal voltage of DCCB.
- Good performance was confirmed while the ultimate was not demonstrated.

Field quality

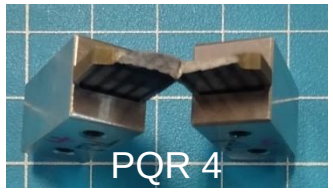
- Some discrepancies observed in b_3 and b_5.
  - Larger discrepancy observed in b_3 integral comes from the coil ends.
- A fine tuning of the coil cross section for series production magnets.

Flow of D1 Cold Mass Production

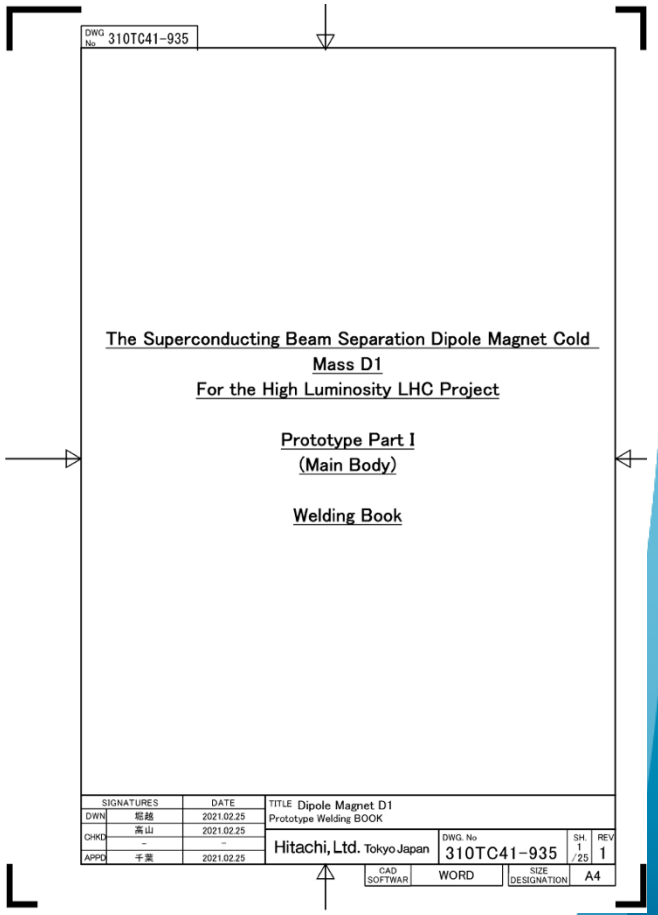
PV: Pressure Vessel



Welding Qualification for Manufacturing the D1 Pressure Vessel



- Welding Book Part. 1 for Main body: **EDMS 2492330 Released.**
  - Welding for the magnet (shell, end-ring).
  - PQR 1, 2 for t=10mm: Completed.
- Welding Books Part. 2 for End dome & Part 3 for Extremities are completed.
  - Welding for End-cover, CBT, HX and the extremities.
  - PQR 4, 5 for t=1 to 3 mm: Charpy V notch test required in EDMS 1891856 Rev. 4.31, but not-appropriate for shin plates. Quite a long time for establishing qualification regulation…
    - Charpy Test for PQR 4 (t=2 mm) was completed on Jan. 11.
    - Charpy Test for PQR 5 (t=1 mm) was finally completed on Feb. 1, 2022.
  - PQR 6, 7, 8: Lip weld joints, not specified in ASME or EN. Special agreement with CERN for welding qualification.
    - PQRs were completed including the burst-test.


DWG No 310TC41-935

The Superconducting Beam Separation Dipole Magnet Cold Mass D1
For the High Luminosity LHC Project

Prototype Part I
(Main Body)

Welding Book

SIGNATURES		DATE
DWN	堀越	2021.02.25
CHKD	高山	2021.02.25
	-	-
APPD	千葉	2021.02.25

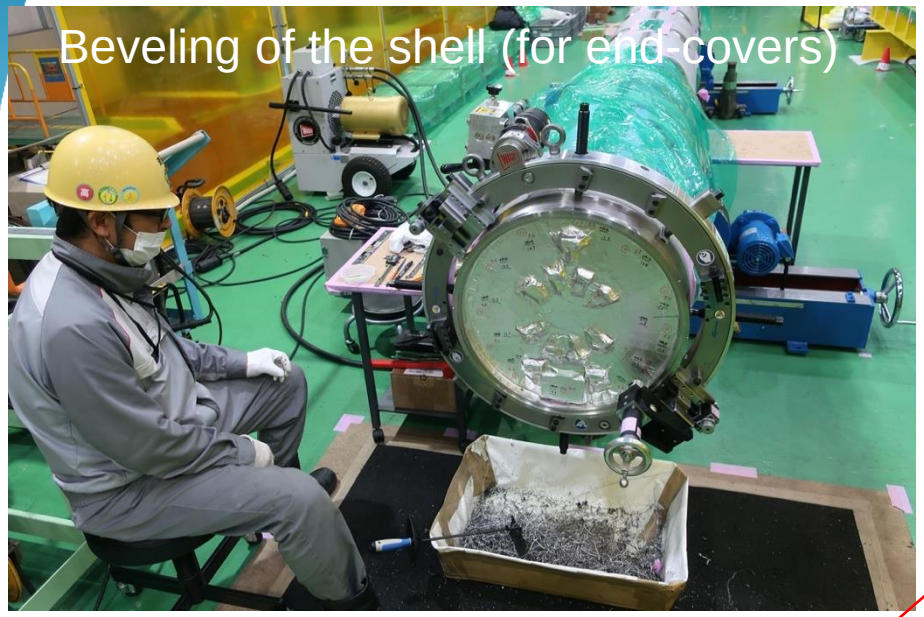
TITLE Dipole Magnet D1
Prototype Welding BOOK

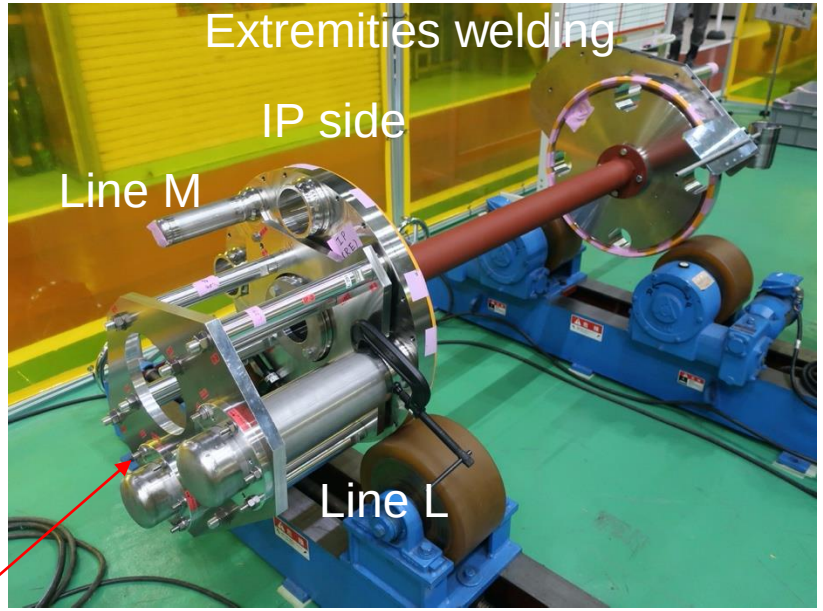
Hitachi, Ltd. Tokyo Japan

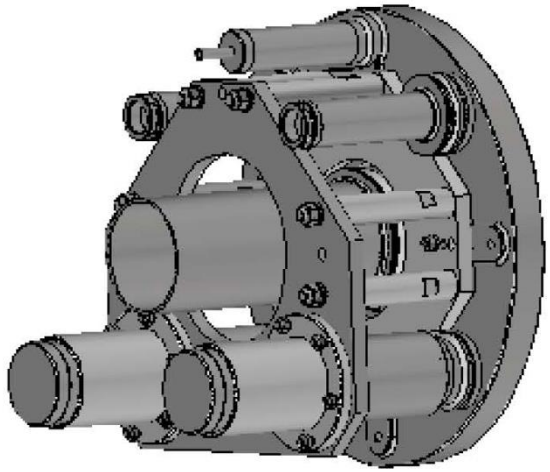
DWG. No 310TC41-935 | SH. 1 /25 | REV. 1

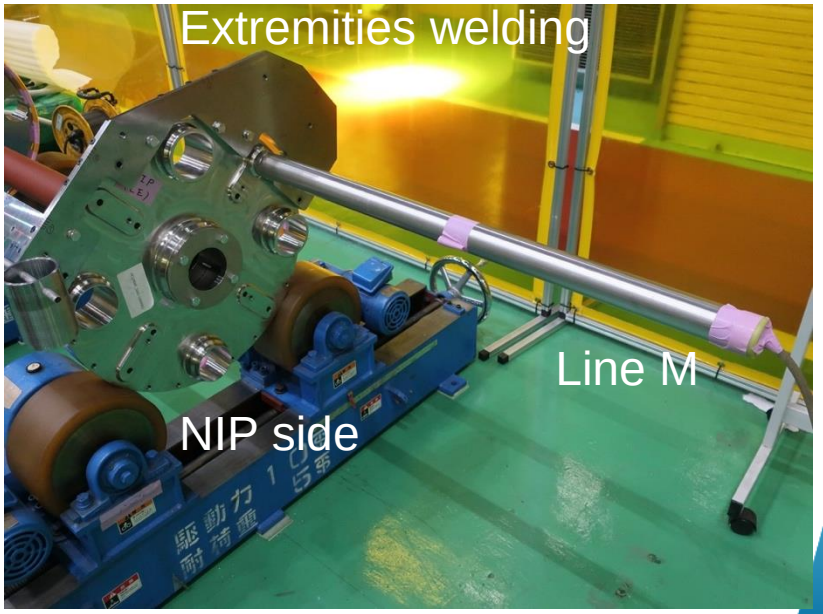
CAD SOFTWAR: WORD | SIZE DESIGNATION: A4

Extremities Welding





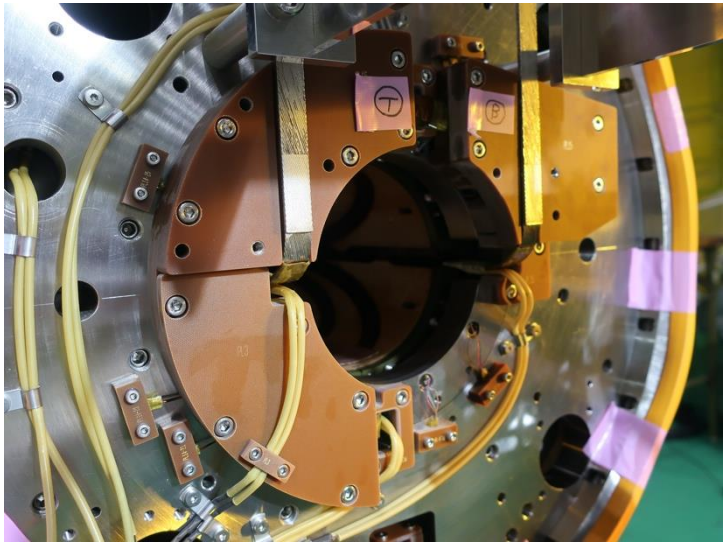


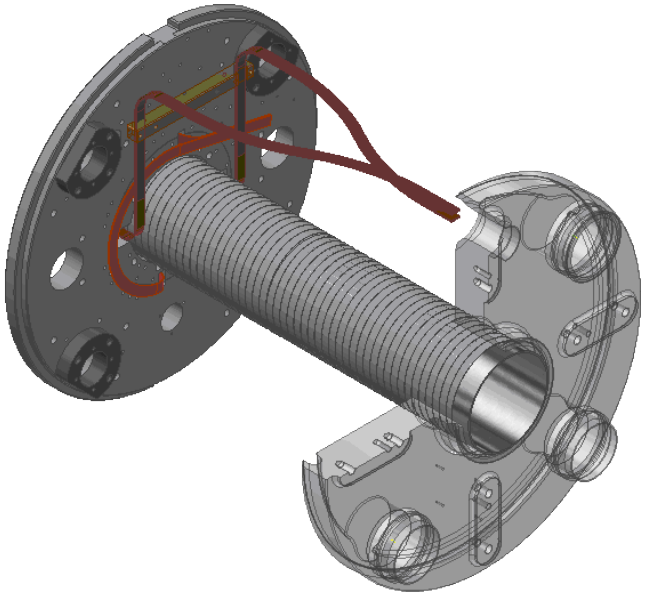


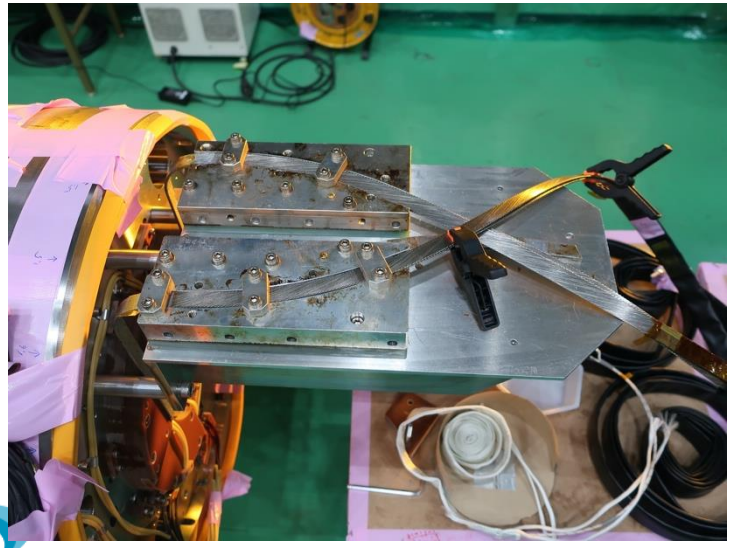
Extremities Position Adjustment Tooling
(Lines M, L, X, V for NIP and IP sides)

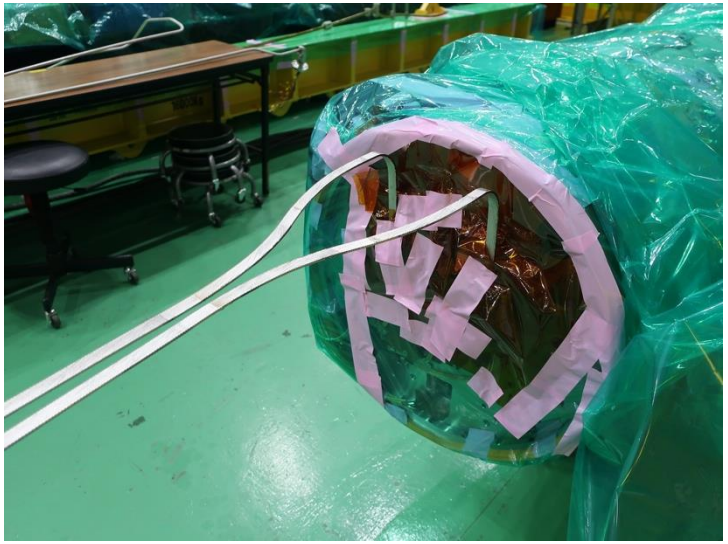
SC Bus Leads and “Spider”

- SC bus leads and “Spider”: thanks to Herve and Rosario.
- Vtap installation and wire routing.

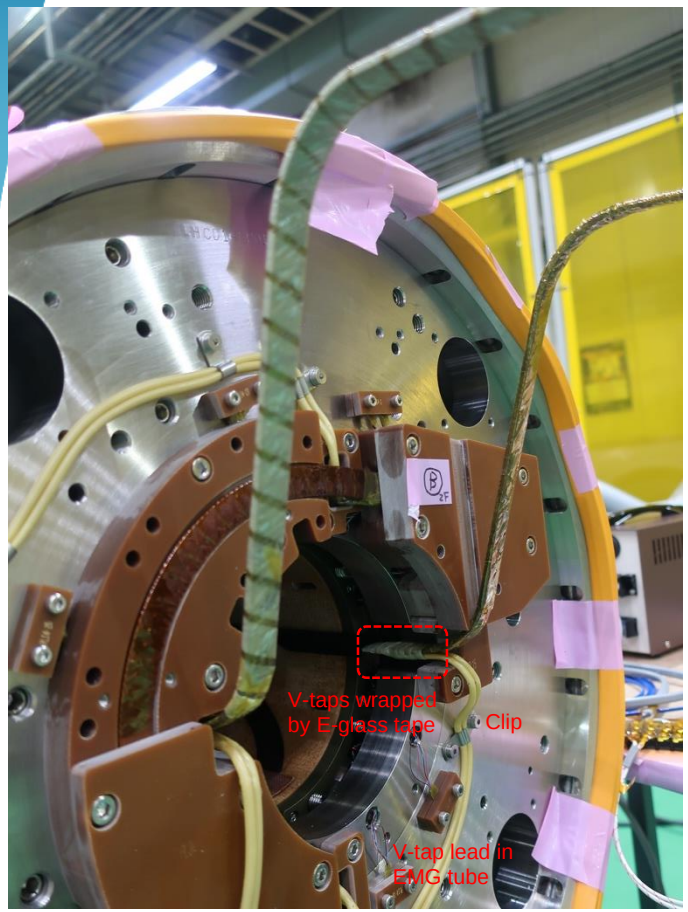


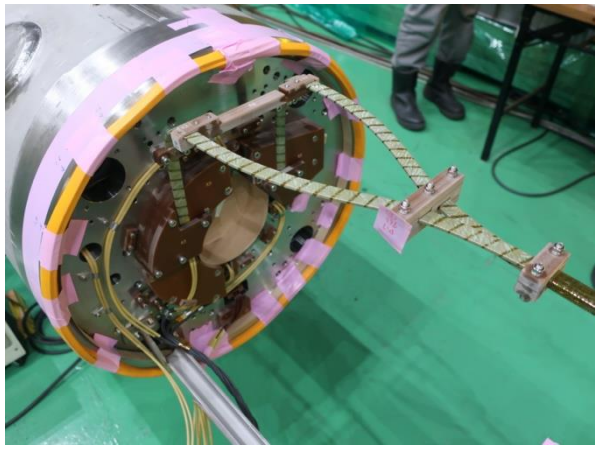


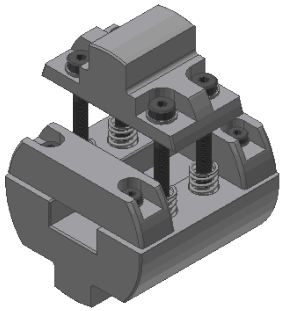


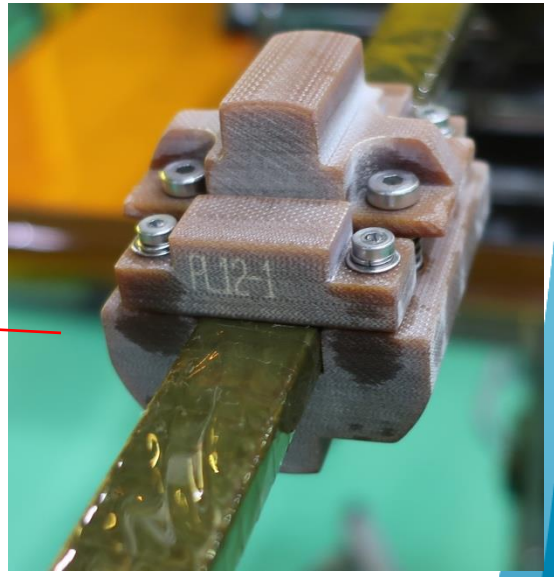


SC Bus Leads and "Spider"

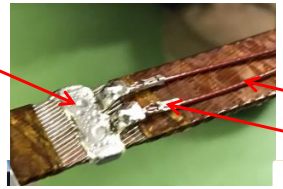






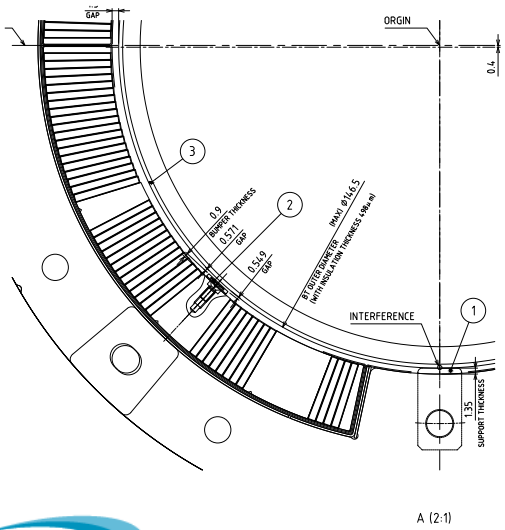


Spider for centering the bus-leads in Line M

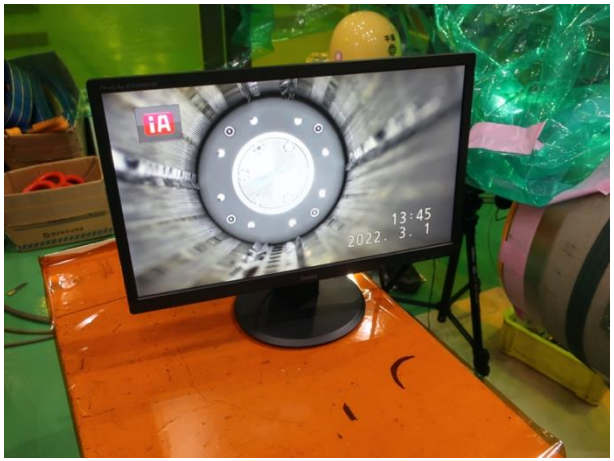


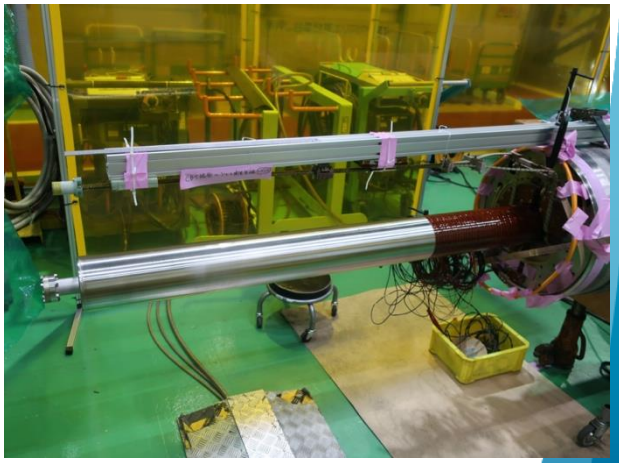
Insertion of CBT

- The allowed gap between CBT and inner surface of the coil structure is approximately ~1 mm.
- Insertion was very smooth and applied load was consistent with prediction (weight of CBT, friction of pinion): impedance induced in the bore was negligible.
- Hipot test at 2 kV was successfully passed.

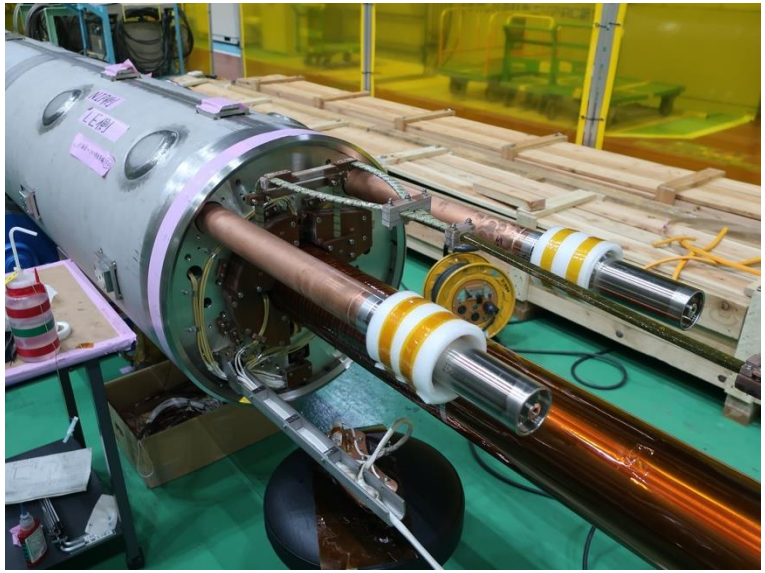


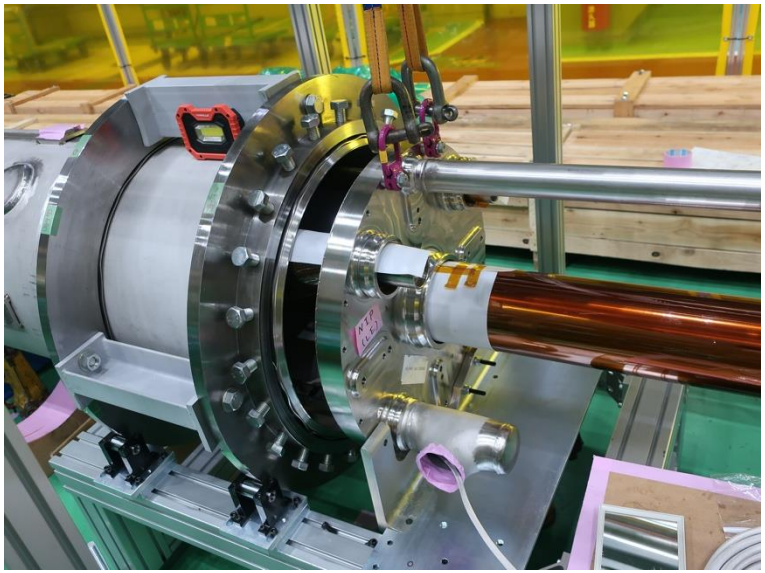
A (2:1)





End-dome, End-cover

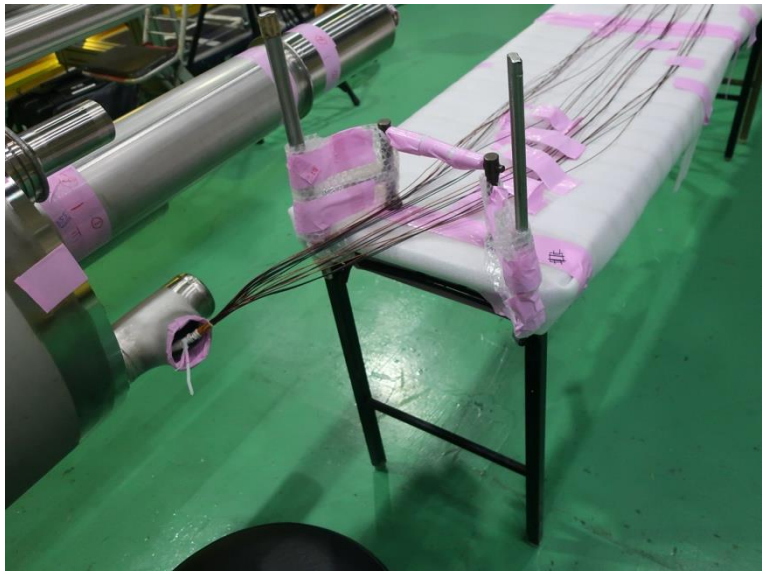




- Outer-rings to correct the formed and longitudinally-welded end-dome.
- Position of the end-cover was precisely aligned with respect to the mechanical fiducial of the magnet defined by the 32 alignment markers using the laser tracker.

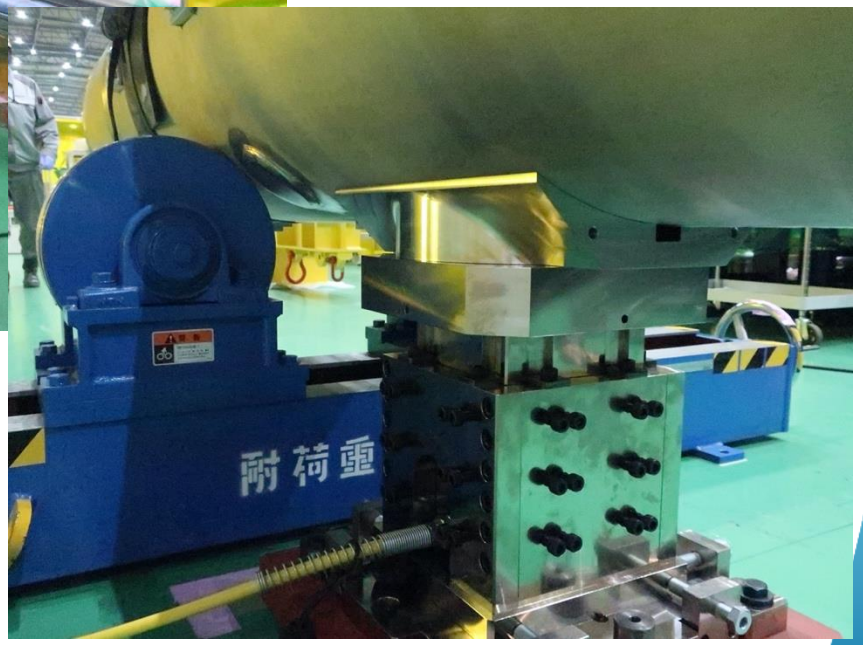
IFS Line

Instrumentation wires, routing



- Hipot test at 3.1 kV between IFS tube and wires was passed.

Saddle

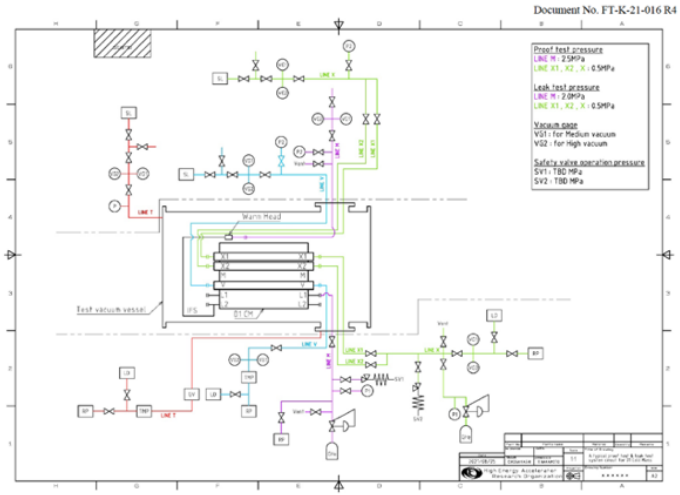


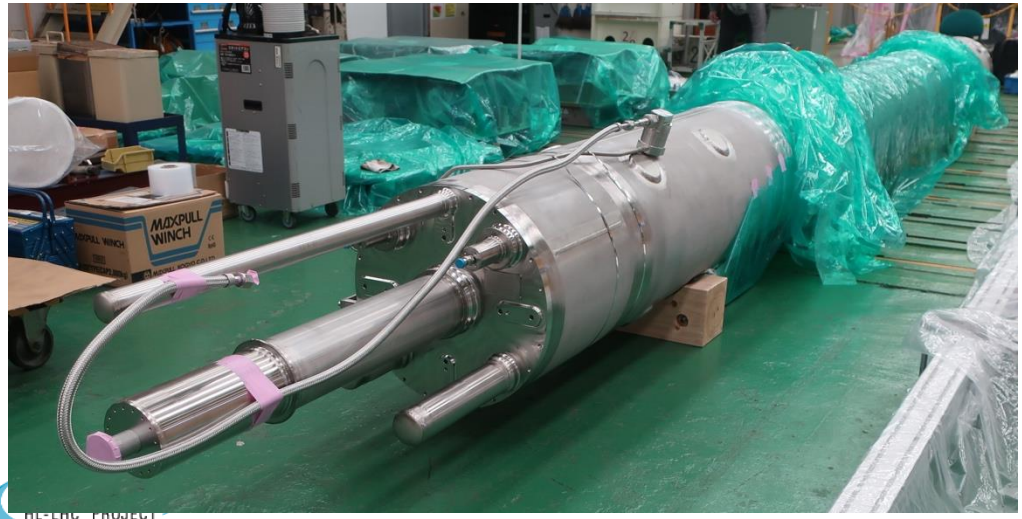
- Position of the support saddles was precisely aligned with respect to the mechanical fiducial of the magnet defined by the 32 alignment markers using the laser tracker.

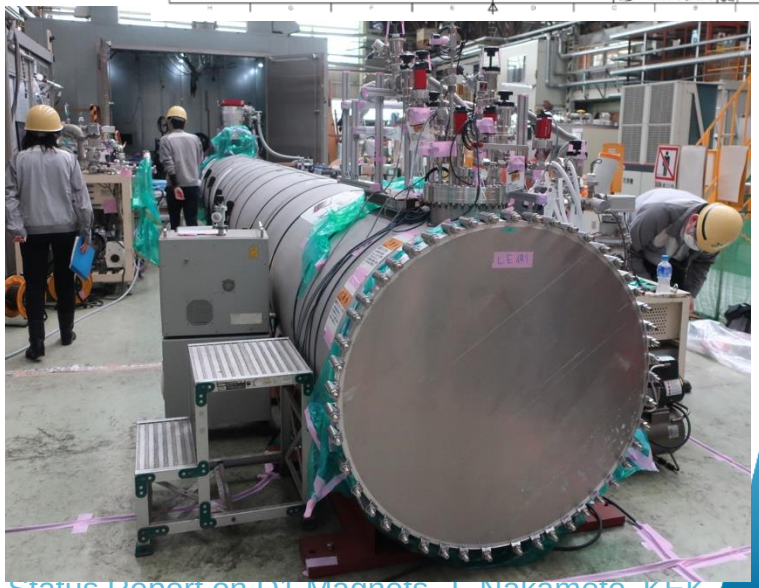
Pressure Proof Test and Leak Test of the D1 Prototype

- A dedicated SS vacuum chamber (10 m long, ID 1000mm) was prepared for the pressure proof test (PPT) and leak test (LT) at Hitachi.
- "Guideline of Proof Test and Helium Leak Test for D1 Cold Masses": EDMS 2681049.
- Test condition and criteria:
  - PPT at 2.5 MPa_{Abs} for cold mass,
  - LT at 2.0 MPa_{Abs}
    - ✓ Vacuum chamber: < 1 e-10 Pam^3/sec
    - ✓ Cold bore tube: < 1 e-11 Pam^3/sec
    - ✓ HX tubes : < 1 e-6 Pam^3/sec

All passed.





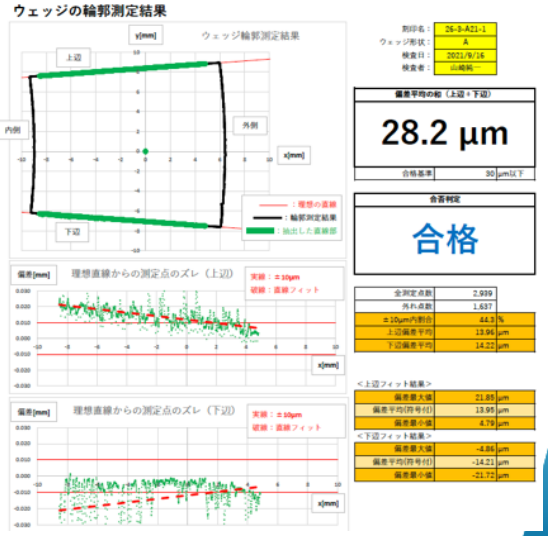


Series Production: MBXF1 and MBXF5

Summary of results of coil size measurement

Magnet	Coil	Total average (MPa)	Max value (MPa)	Min value (MPa)	Standard deviation (MPa)	Cable thickness (44 stack) wrt S2-4 cable (mm)*
MBXFP1	LPT-1	112	116	106	2.0	0.262
	LPB-1	110	113	108	1.4	0.256
MBXF5	LT-1	122	125	119	1.5	0.418
	LB-1	122	125	118	1.8	0.422
MBXF1	LT-2	117	120	114	1.3	0.397
	LB-2	125	128	112	1.6	0.403

- **Target range of the total average: 115±10 MPa.**
- Thickness of the insulated SC cables from 19 spools was determined by the “10-stack measurement” before the coil winding.
- Dimension control of the wedge thickness: <30 μm
- All the prestresses are within the target range.
  - Check for the LB-2 coil with higher value is underway.



MFM of MBXF5 after yoking

- Experimental check of **new coil cross section for the series magnets.**
  - Fine tuning of b_3 and b_5 with respect to the MBXFP1.
- Warm field measurement at Hitachi Rinkai-work.

R_{ref}=50 mm

Measurement

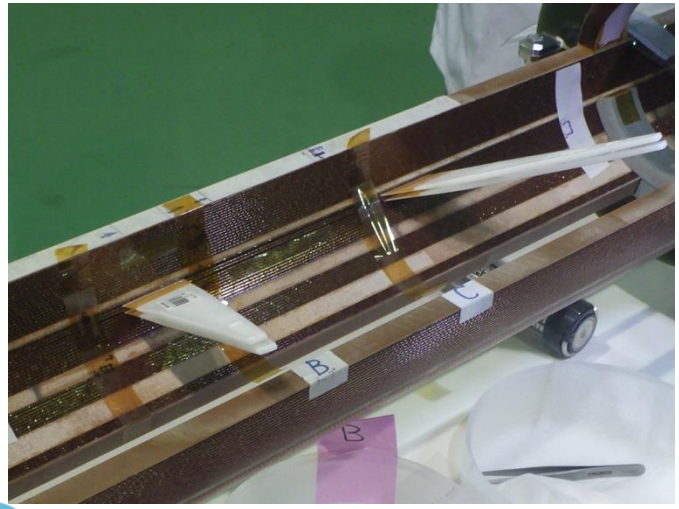
Calculation

	Data						Roxie2D					
n	MBXFP		MBXF5		MBXF5-MBXFP		MBXFP (v11.D)		MBXF5 (v13.A)		MBXF5-MBXFP	
	an	bn	an	bn	an	bn	an	bn	an	bn	an	bn
2	-1.4	0.8	-1.7	-0.3	-0.3	-1.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	-4.9	-0.6	-0.1	-0.6	4.8	0.0	-7.3	0.0	-2.7	0.0	4.6
4	0.1	0.4	0.0	0.0	-0.1	-0.4	0.0	0.0	0.0	0.0	0.0	0.0
5	-0.1	2.9	0.0	-2.8	0.1	-5.7	0.0	2.7	0.0	-2.8	0.0	-5.5
6	0.3	0.1	0.1	0.2	-0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	1.0	0.1	0.0	0.1	-1.0	0.0	1.1	0.0	0.1	0.0	-1.0
8	0.4	0.1	0.1	0.0	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.6	0.1	0.1	0.1	-0.5	0.0	0.6	0.0	0.0	0.0	-0.6
10	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0
12	-0.2	-0.1	0.0	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	-0.6	0.0	-0.5	0.0	0.0	0.0	-0.6	0.0	-0.6	0.0	0.0
14	-0.5	-0.3	0.1	0.0	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	-1.0	0.1	-1.0	0.2	0.0	0.0	-1.2	0.0	-1.0	0.0	0.1
16	-0.3	-0.2	-0.1	-0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
17	0.1	-0.6	0.0	-0.5	-0.1	0.1	0.0	-0.7	0.0	-0.7	0.0	0.0
18	0.3	0.1	0.1	0.1	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.3	-0.1	0.1	0.0	-0.2	0.0	0.4	0.0	0.4	0.0	0.0
20	0.0	0.0	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

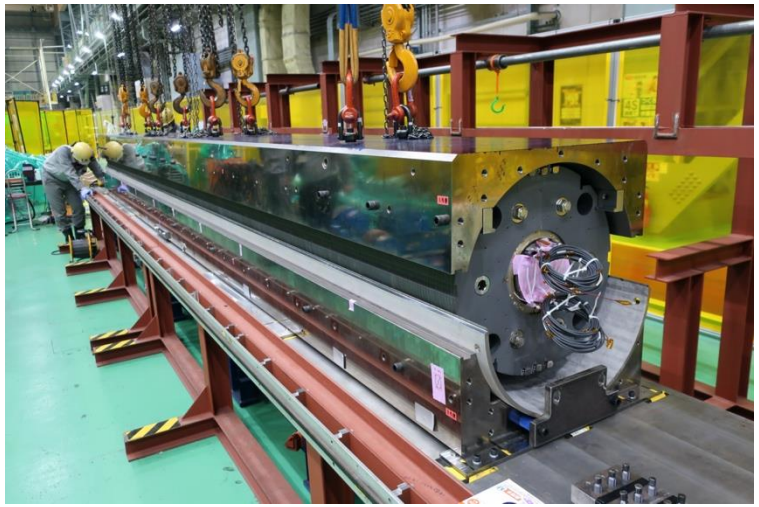
- ✓ Tuning of Multipoles: Consistent with the 2D model
- ✓ KEK proposes to give Hitachi a green-light to resume fabrication of the wedges of MBXF2.

Status of Manufacturing

- MBXF5
  - NC: potential coil insulation damage was found after removal of the collaring-mandrel after yoking process. EDMS 2753776.
  - The yoked magnet was fully disassembled and the coil insulations were repaired.
  - The inspection tests to confirm the electrical insulation and the mechanical property of the coils are underway.
  - The magnet re-assembly is foreseen in January 2023 after review of the repair work.
- MBXF1
  - Shell welding was completed and RT is underway.
  - The vertical cold test is planned around April 2023.
- MBXF2
  - Coil winding will be started in February 2023.



Insulation repair of MBXF5 coil



MBXF1 in preparation for shell welding

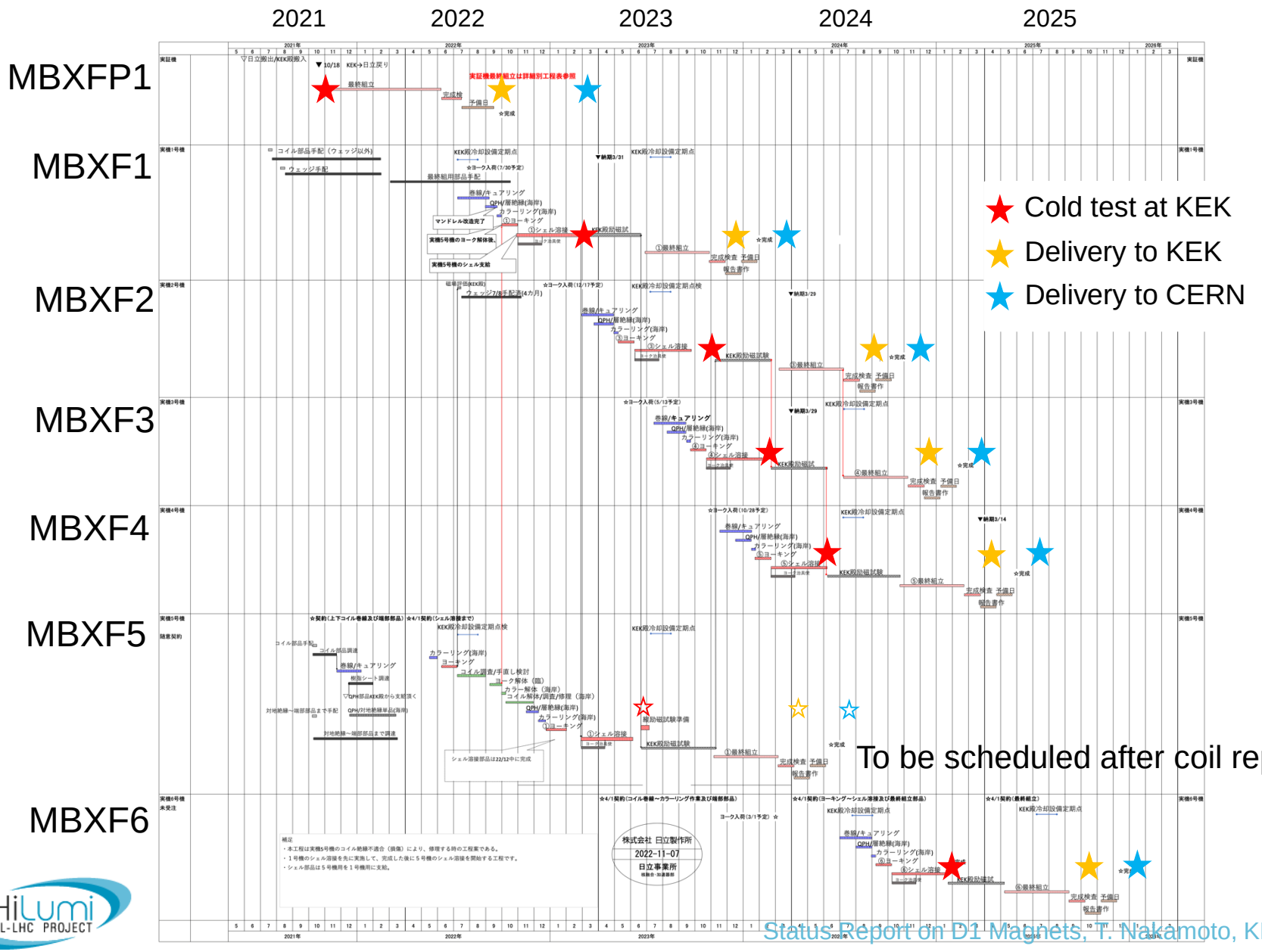
Components delivered from CERN

	Item Code	0	1	2	3	4	5	6	7
		SC cables	QPH Laminate	Cold bore tube	End-cover	HX tube	Extremity parts	Cryo Heaters	Thermometers
Until Dec. 2019		19	14	0	0	0	0	0	0
March, 2020	ID 8294098, delivery on August 18	0	0	1	0	0	9 IFS pipes (obsloleted)	0	0
April, 2020	ID 8302253, delivery on July 3	0	0	0	3	0	3	4 (obsloleted)	8
Oct., 2020	ID 8455728, delivery on Nov. 4	0	0	0	11	0	3	10 (obsloleted)	20
Dec., 2020	ID 8477112, delivery on Jan. 12, 2021	0	0	3	0	4	6 IFS pipes	0	0
Aug., 2021	ID 8842597, delivery on Aug. 6, 2021	0	4	0	4	0	3	2	0
Oct. 2021	ID 8942303, delivery on Oct. 15, 2021	0	0	0	0	0	*	4	0
May. 2022	ID 9228712, delivery on May 9, 2022	0	1 Compensation	~~0~~	0	0	0	0	0
Nov, 2022	ID 9328931, delivery on Nov. 16, 2022	0	0	4	0	8	0	0	0
Jan., 2023	Production underway	0	6 QPH (2eq)	0	0	0	0	0	0
XXX, 2023		2	TBD	0	0	2	**	8	0
Total # (unit, set)		21	18+2eq	8	18	14	9	14	28

- EDMS 2326071 v.1.0, EDMS 2209761 v.1.0
- Issues of QPH laminate: defected insulation, delamination
  - CERN PCB group will produce 6 pieces of QPH for D1. Delivery is foreseen in January 2023.
- Nearly completed, but still a few deliveries from CERN will be required to cover a full series production of the D1.

Production Schedule

Plan by Hitachi in Nov. 2022



Summary

- The D1 prototype cold mass was completed and delivered to KEK in September 2022.
  - To be delivered to CERN in March 2023.

- A series production of the D1 was started in 2021.
  - MBXF5
    - NC: potential coil insulation damage was found after removal of the collaring-mandrel after yoking process. EDMS 2753776.
    - The coil insulations were repaired. The magnet re-assembly is foreseen in January 2023 after review of the repair work.
  - MBXF1
    - Shell welding was completed and RT is underway.The vertical cold test around April 2023.
  - MBXF2
    - Coil winding will be started in February 2023.

Additional Helium Gas Storage Bag

- Limitation of helium gas recovery at quenches of MBXFP1.
- Present capacity: 280 m^3 (#2: 80 m^3, #4: 200m^3)
- Helium gas at 13.23 kA w/ **Varistors**: 294 m^3 (prediction)
- Plan: new Helium gasbag (#4b, 40 m^3)
  - Total capacity: 320 m^3 > 294 m^3
  - #4b Gasbag to be installed next to #4 Gasbag in the same tent warehouse
  - The gasbag is already available. The drawings are being prepared in a rush.

In the event of MBXFP1 quench