HL-LHC MCBRD CCT Magnets: Review and Latest Progress in China

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For the CCT Magnet Team

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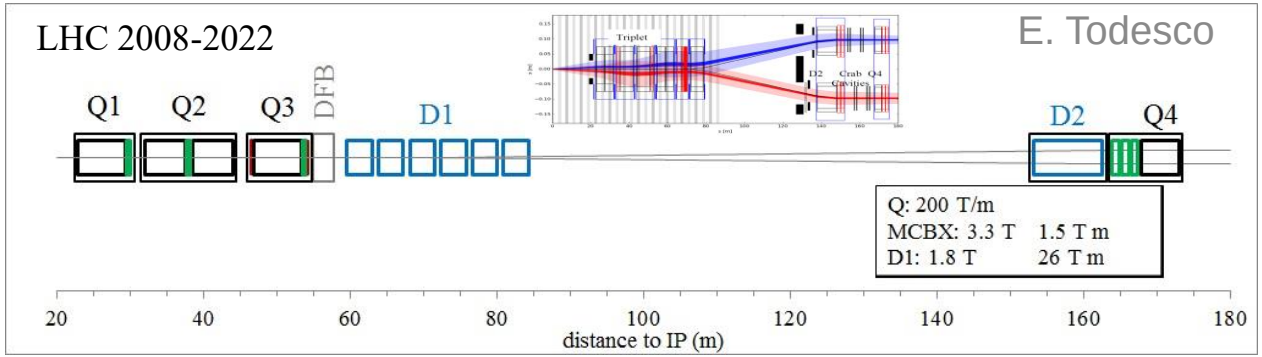
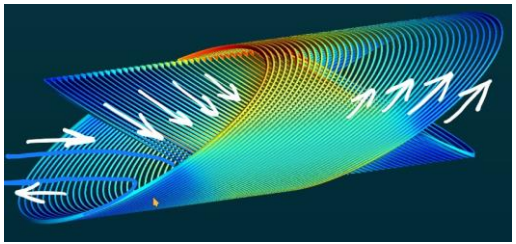
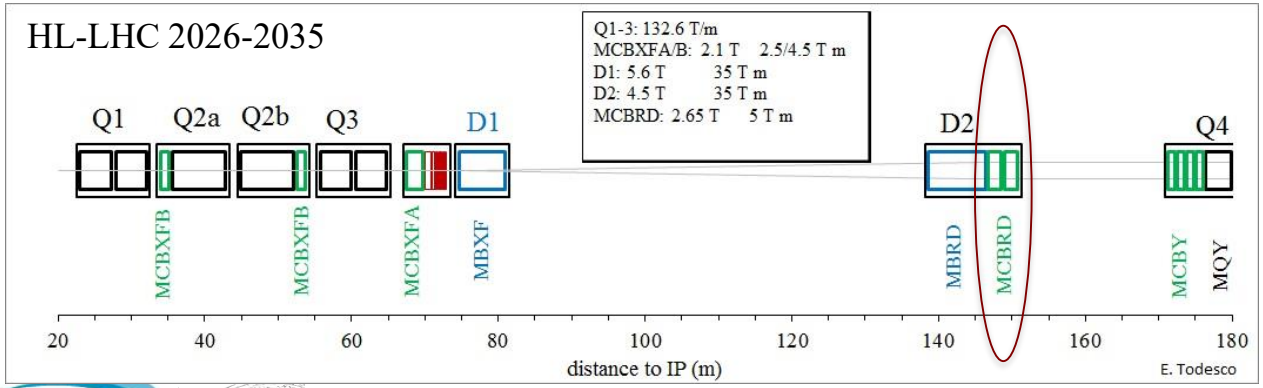
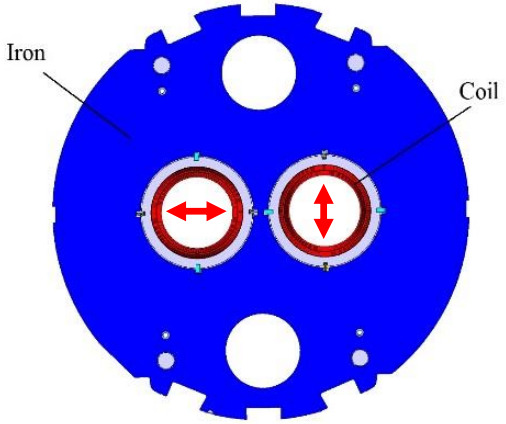
MCBRD: the HL-LHC D2 orbit correctors, 12+1 units, providing a 5 Tm integrated field in two apertures, vertical in one and horizontal in the other.



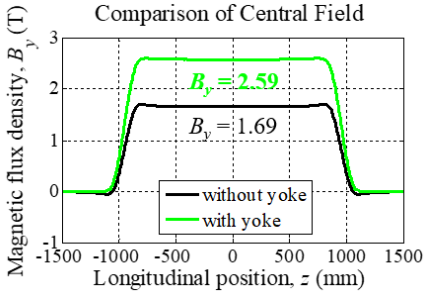


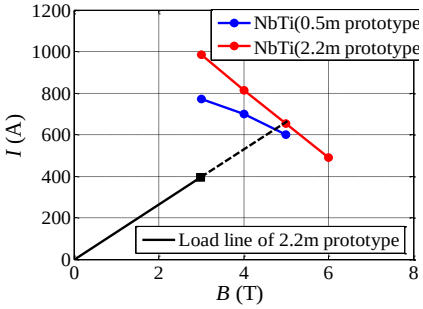


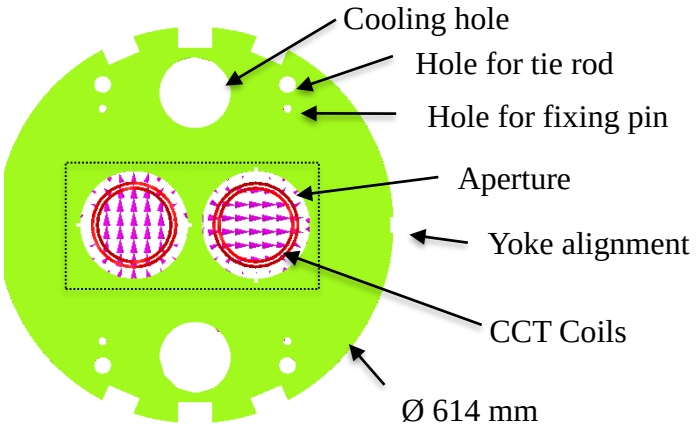


Main design parameters of the CCT magnet

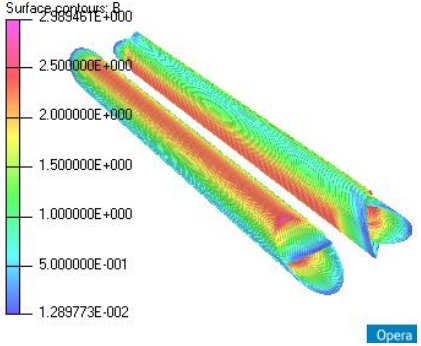
Items	Values
CCT skew angle	30°
No. of turns per layer	365
Slot size in former (mm)	2×5
Spacing per turn	5.222
Inside/Outside diameter of the former (mm)	Inner former:105.35/119.35 Inner former:120.80/134.85
Inside diameter of the groove/slot(mm)	1st layer: 109.15/119.15 2nd layer: 124.65/134.65
Reference radius (mm)	35
Diameter of aperture (mm)	105
Current (A)	395

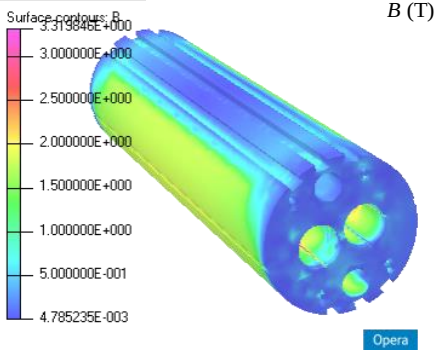






Items	Values
Diameter of yoke (mm)	614
Thickness of yoke lamination (mm)	5.8
Diameter of aperture (mm)	167
Position of aperture (mm)	94.19
Yoke key slot(mm)	8(3.01) ×6
Diameter of cooling hole (mm)	110
Position of cooling hole (mm)	205



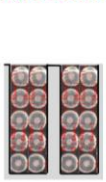


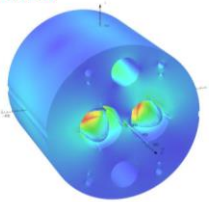
0.5-m model coils R&D in China in 2017-18

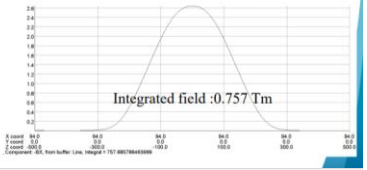
https://indico.cern.ch/event/765288/contributions/3178832/attachments/1768774/2881344/20181212-Short_Model_Prototype_and_Series_Program_of_MCBRD_in_China.pdf

Development of the 0.5-m Model in China

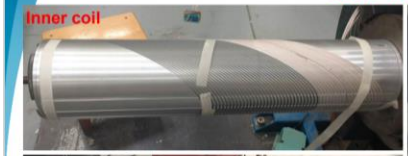
Bore field / T	2.64
Current / A	422
Layers	5+5
CCT angle /°	30
Turn width /mm	5.2(0.6)
Turns per layer	55
Integrated field / Tm	0.757
Peak field / T	3.1
Io/Ic	55%
Slot size in former	2 mm×5 mm, 0.6 mm for rib
Iron yoke size/mm	Φ614/539.4
ID and OD of two formers/ mm	The first layer: 105 /119 ; The second layer: 119 /133
Dia of wire / mm	0.825(767A@3T 700A@4T) 0.99(with insulation)





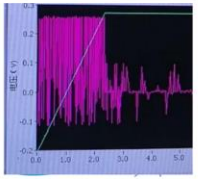


Coil Winding



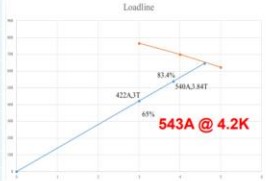
- 1# inner coil：the wire is 0.2-0.3 mm higher than the former.
- 2# inner coil：the wire is 0.1 mm higher than the former.

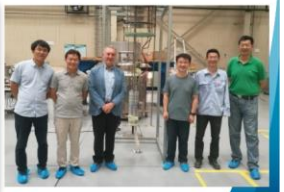
Test of the 1st 0.5m Model Coil



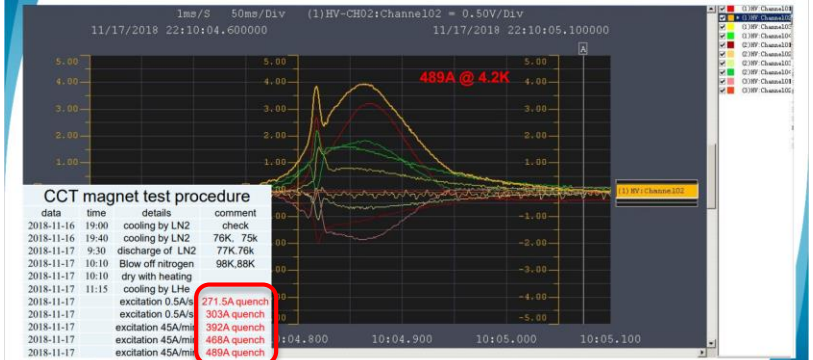
Test Procedures

data	time	details	comment
2018/7/14	8:40	cooling by LN2	check
2018/7/14	9:20	cooling by LN2	76K, 75k
2018/7/14	10:05	discharge of LN2	77K.76k
2018/7/14	11:00	dry under nitrogen	98K,88K
2018/7/14		dry with heating	
2018/7/14	12:20	cooling by LHe2	102K ,95k
2018/7/14	13:50	cooling by LHe2	41cm
2018/7/14	14:05	excitation 1A/s	
2018/7/14		excitation 2A/s	483A quench
2018/7/14	15:10	excitation 3A/s from 0 to 460A, 1A/s from 0 to 470A, pause, excitation	471A quench
2018/7/14	15:18	excitation 4A/s	469.4A
2018/7/14	15;28	excitation 4A/s	529A
2018/7/14	15:44	excitation 4A/s	543A
2018/7/14	15:49	excitation 4A/s	520A last 20 min, 551A quench





Test of the 2nd 0.5m Model Coil

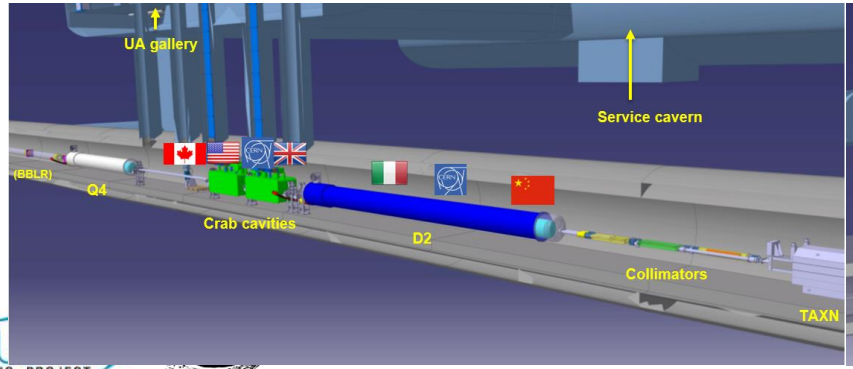


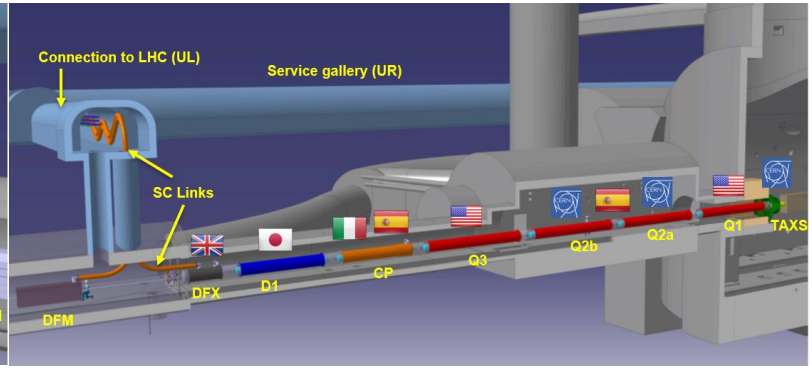
CCT magnet test procedure

data	time	details	comment
2018-11-16	19:00	cooling by LN2	check
2018-11-16	19:40	cooling by LN2	76K, 75k
2018-11-17	9:30	discharge of LN2	77K.76k
2018-11-17	10:10	Blow off nitrogen	98K,88K
2018-11-17	10:10	dry with heating	
2018-11-17	11:15	cooling by LHe	
2018-11-17		excitation 0.5A/s	271.5A quench
2018-11-17		excitation 0.5A/s	303A quench
2018-11-17		excitation 45A/min	392A quench
2018-11-17		excitation 45A/min	468A quench
2018-11-17		excitation 45A/min	489A quench

489A quench at the wire 1# of inner coil and 2# of outer coil

Agreement For CCT magnets signed in Sep 2018 at IHEP





Related partners

Contracts of the materials and components for the 12+1 CCT magnets

NbTi wires:	Contract with WST China.
Insulated wires:	Contract with CGP France.
Coil formers:	Contract with HE-Racing China.
Yoke laminations and end plates:	Contract with KEYE China with iron plates from CERN

Fabrication of the magnets: prototype by WST, series by BAMA

- Coil winding and impregnation, instrumentation, magnet assembly.

Performance test

- Coil stand-alone test at IHEP: training to 530 A, then magnet assembly;
- Magnet test at IMP at 4.2 K: training to 422 A with iron.
- Magnet test at CERN at 1.9 K: double-check the performance.

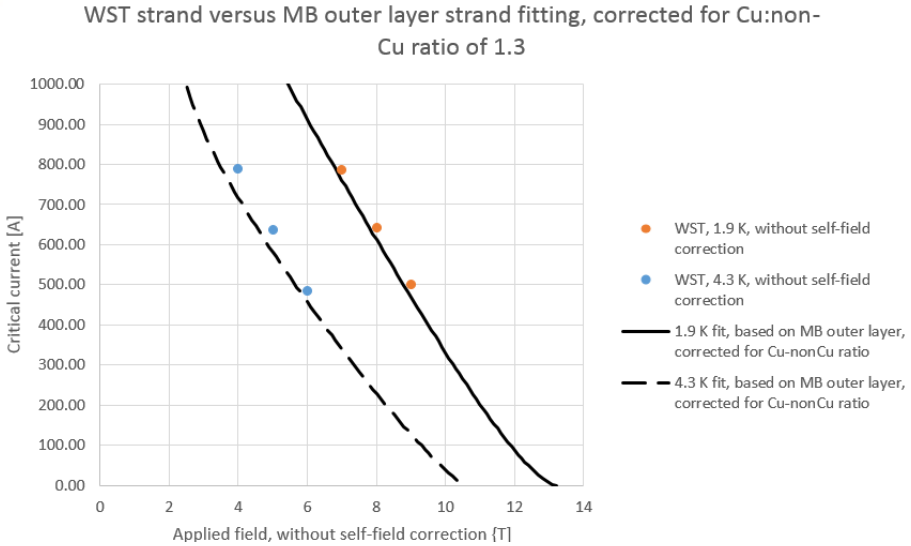
QA &QC: IHEP & CERN and related partners.

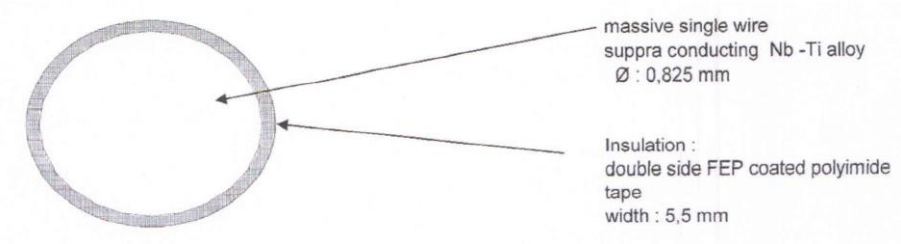
Superconducting wires

- NbTi bare wire from WST China:

  similar J_c but with lower Cu ratio than CERN wire： 1.2-1.3 instead of 1.9

- The insulation done by CGP France.





Overlap: 55±1 %

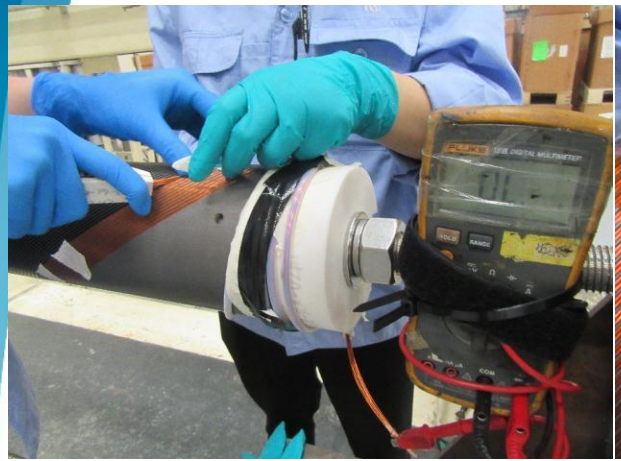
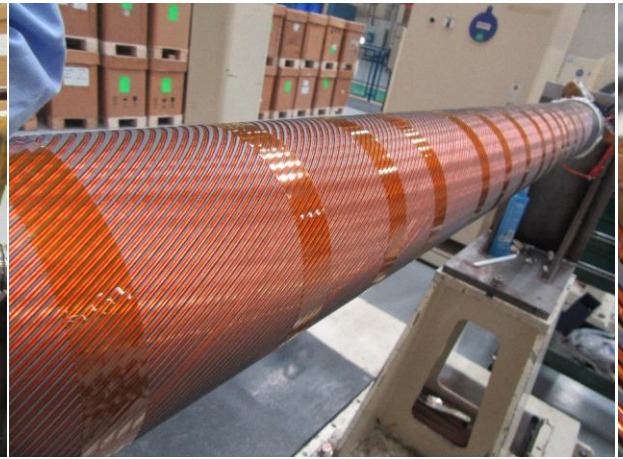
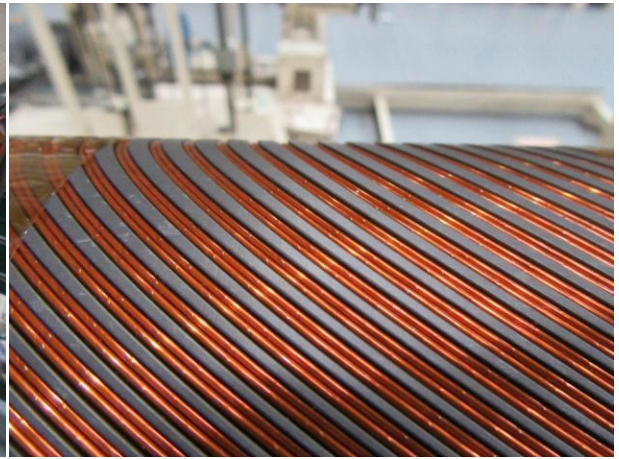
Outside diameter: 0.97±0.02 mm

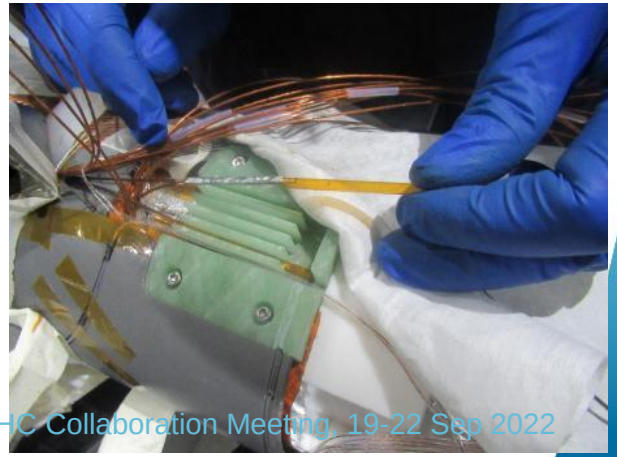
Bonding temperature: 240 ℃

Duration of thermal bonding treatment： 72 S

Electrical checks : > 10 KV insulation over the total length.

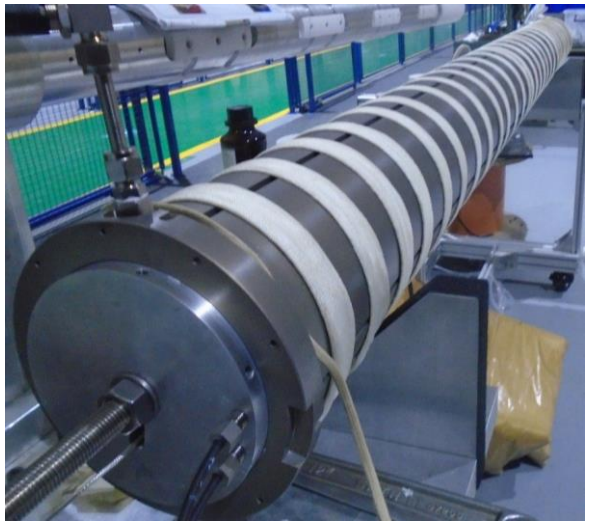
Coil fabrication

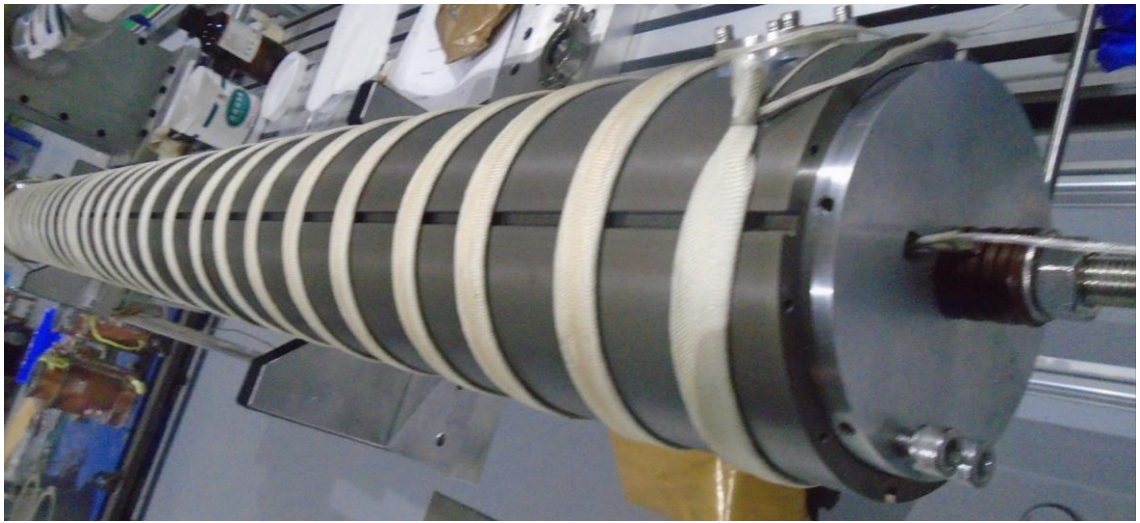




VPI

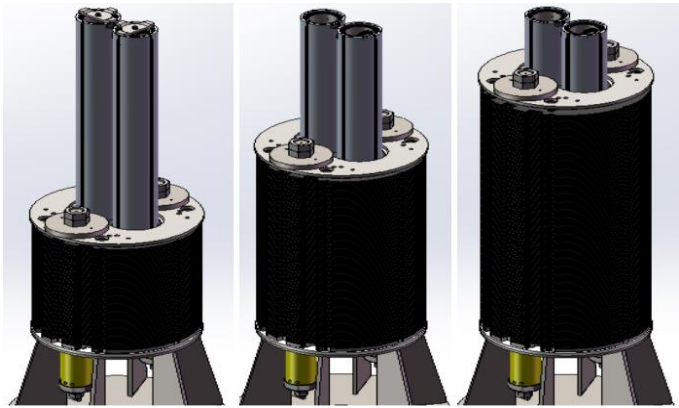
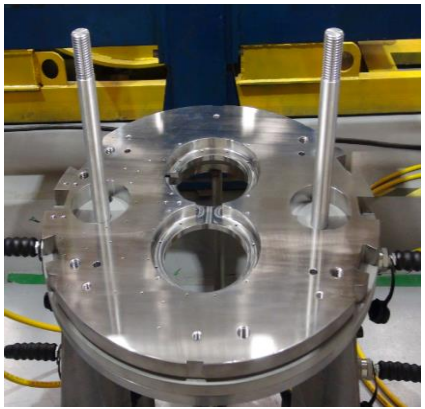
- Coil VPI for aperture V and H with pressure
  - ✓ Baking coil before vacuum impregnation at 80°C for 3 days.
  - ✓ Electrical test before and after VPI procedure

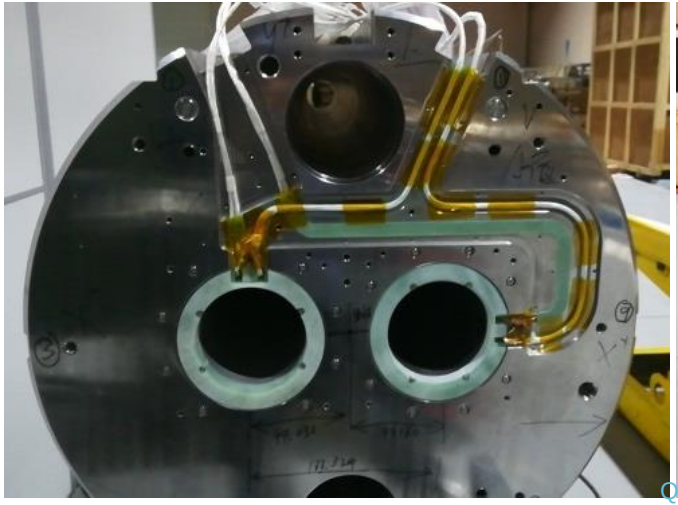
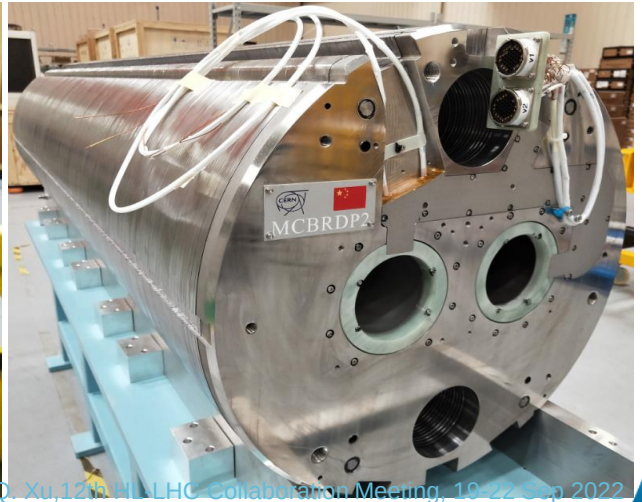




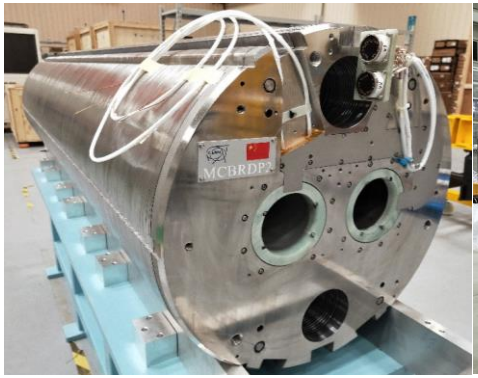
Aperture V coil after VPI

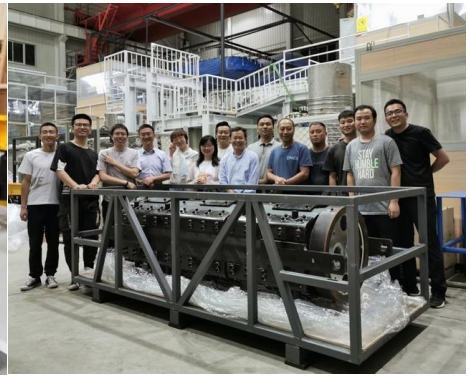
Magnet assembly

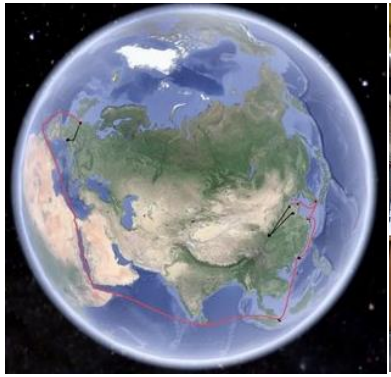




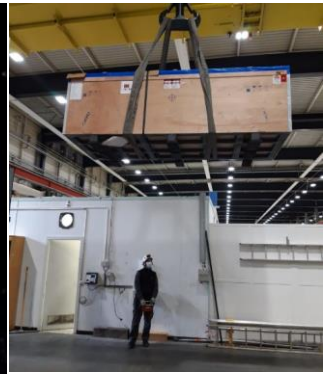
Fabrication completed in May, test completed in Aug. 2020



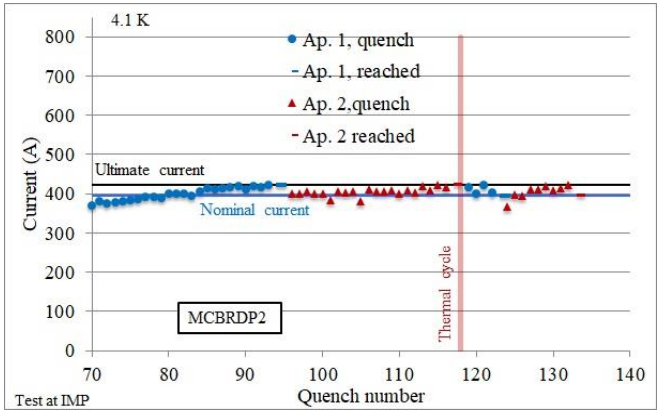


Delivery to CERN Aug-Oct 2020





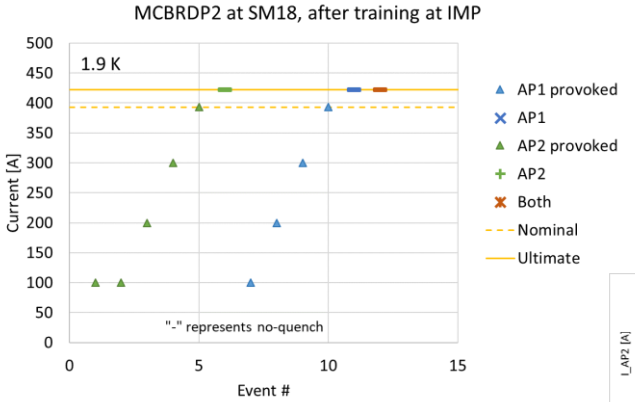
MCBRDP2 4.2 K Test at IMP:
both apertures reached the ultimate current.

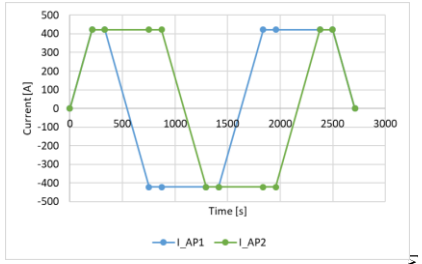


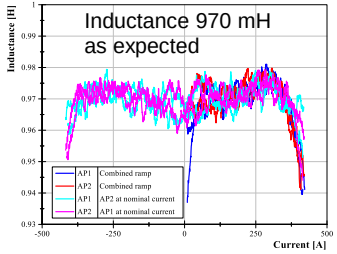
Test Setup at SM18 CERN

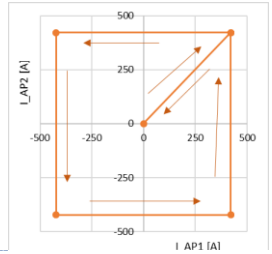
MCBRDP2 1.9 K test at CERN

Each aperture, individually and combined, arrived to ultimate current without quench

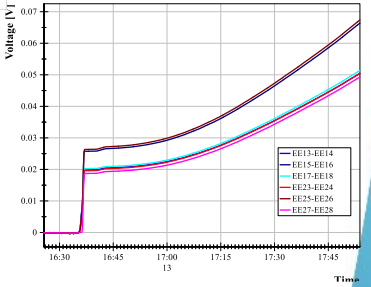


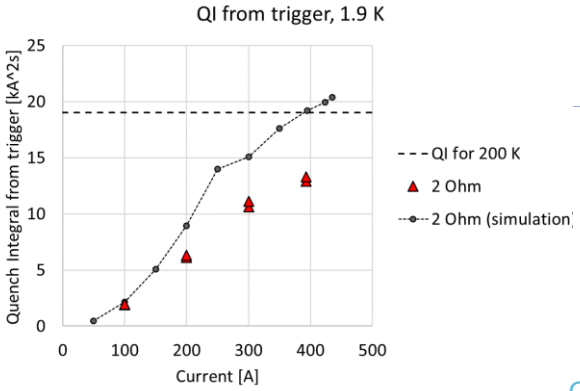


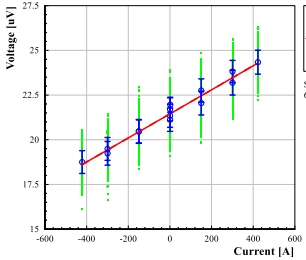




Segment	RRR
EE13-EE14	178
EE15-EE16	182
EE17-EE18	176
EE23-EE24	179
EE25-EE26	178
EE27-EE28	188





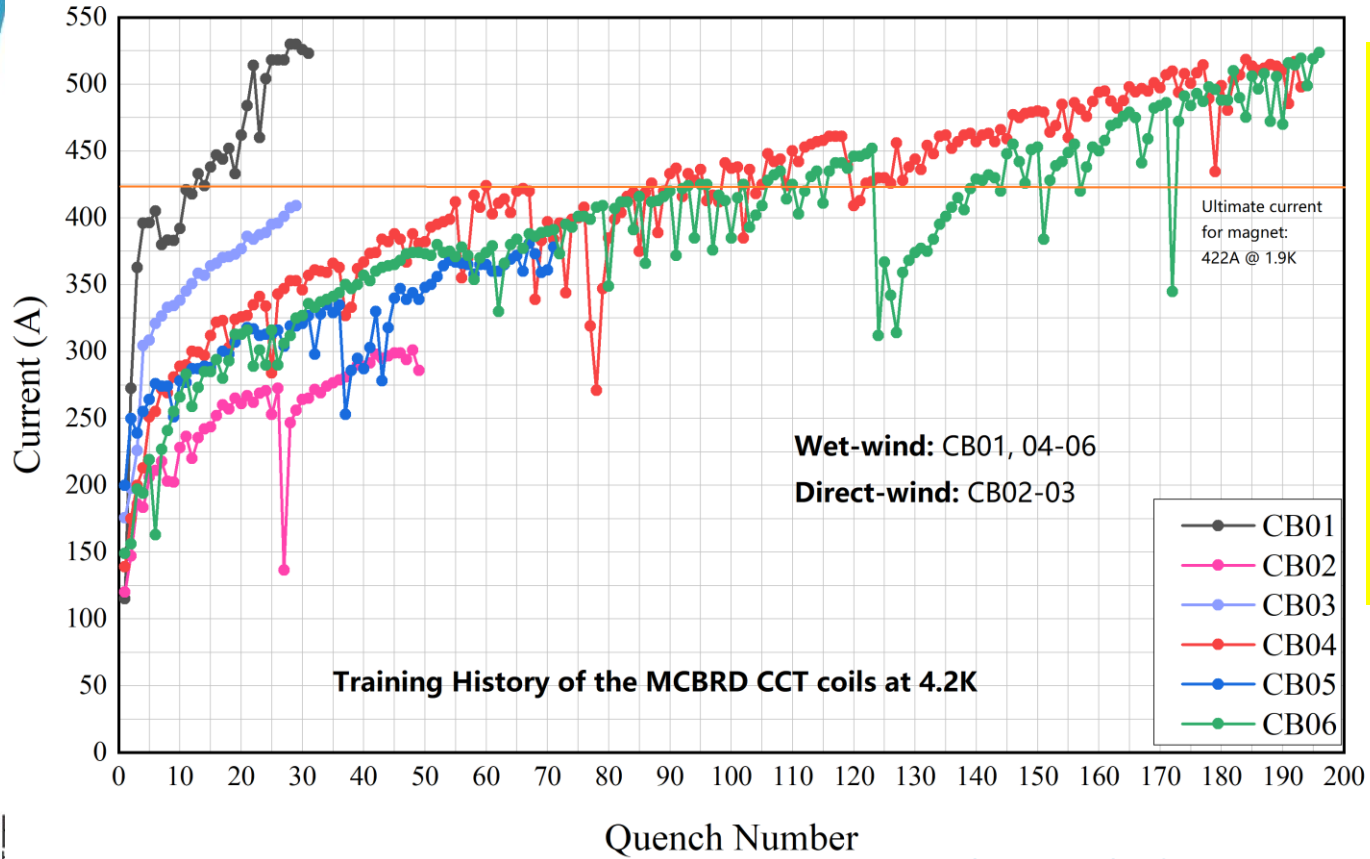


Splice	Meas. at IMP (394 A)	Meas. at SM18
EE14-EE15	6.77 nΩ	7.35 nΩ
EE16-EE17	5.49 nΩ	4.50 nΩ
EE24-EE25	5.36 nΩ	4.84 nΩ
EE26-EE27	6.36 nΩ	6.73 nΩ

Progress of series production

	Coil name	Winding method	Location	Coil stand-alone performance at 4.2 K	Magnet performance at 4.2 K
Magnet1	MCBRD_CB01	Wet wind	CERN	530 A	Both apertures reached ultimate current 422 A, and passed 4-hour stability test
	MCBRD_CB03	Direct wind	CERN	410 A (training stopped due to the availability of the test station)	
	MCBRD_CB02	Direct wind	CERN	Failed to reach the design current	
Magnet2	MCBRD_CB04	Wet wind	CERN	422 A (training stopped due to the availability of the test station)	Both apertures reached ultimate current 422 A, and passed 4*1 hour stability test
	MCBRD_CB06	Wet wind	CERN	530 A	
Magnet3	MCBRD_CB09	Direct wind with new channel size	IMP	530 A	Both apertures reached ultimate current 422 A, and stability test to be done this week
	MCBRD_CB12	Direct wind with new channel size	IMP	520 A (training stopped due to the availability of the test station)	

Training-history of Bama coils CB1-6



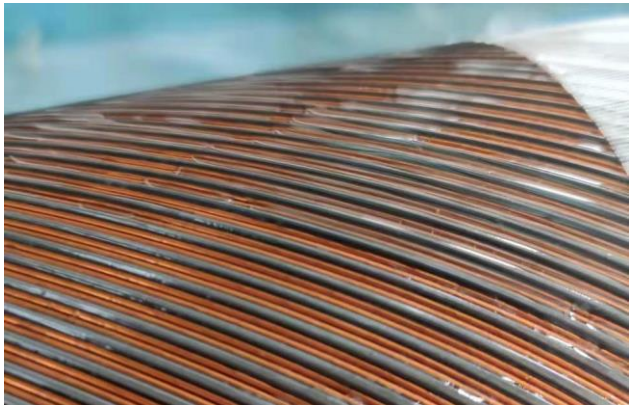
CB01 has the best training performance of all the 2.2m coils from China.

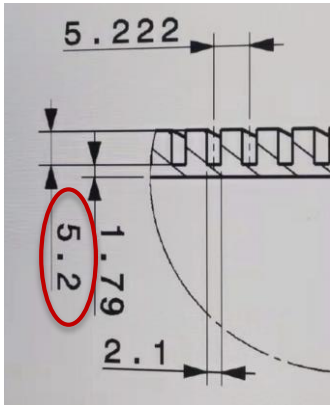
Wet-winded with a coil former whose machining error exceeds the tolerance：having the smallest depth of the channel

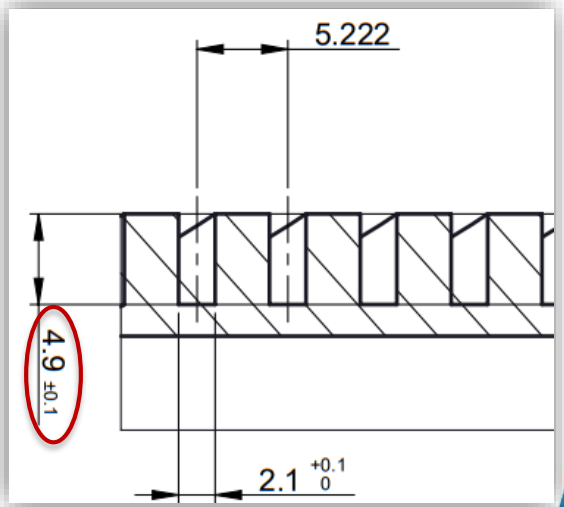
Field quality is good: ~5 units (measured at IMP)

Proposals *in the CERN-China SC meeting in Jan 2022*

- **Further optimize the channel size immediately**, try to make the conductor a bit higher (0.1~0.2 mm) than the former outer surface, then apply support stress outside of each layer by wrapping glass tapes.
- Wet wind **back to direct wind**, make the process simple, with a careful check of the VPI system at Bama before hand.
- **IHEP provides components of 2 magnets (insulated conductors, coil formers and iron plates) to CERN**. CERN fabricate the 2 magnets with the same procedures as in China, to have a **double-check of the performance at 4.2K.**

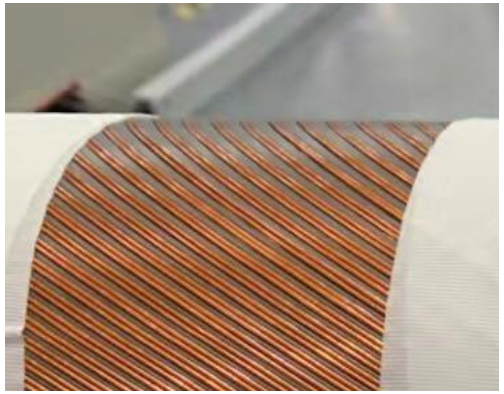


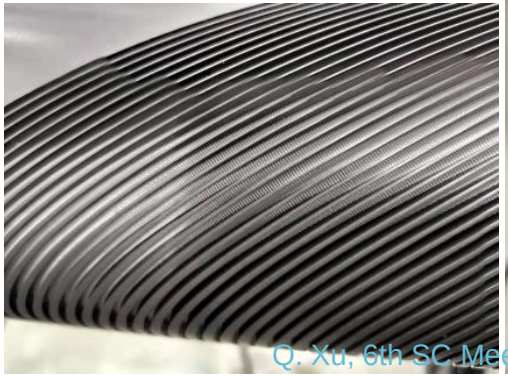




Direct winding of CB09

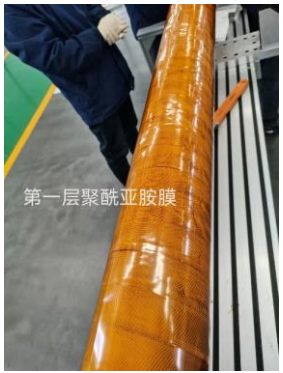
Using 3 layers of glass fiber to **reduce the channel depth from 5.2 mm to 4.8 mm;**
The conductor is ~**0.2 mm higher than the former surface** after winding.

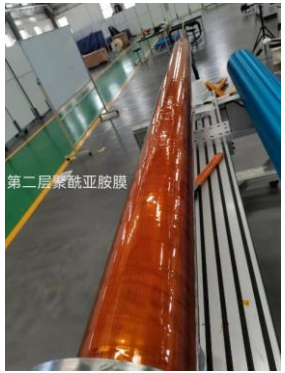


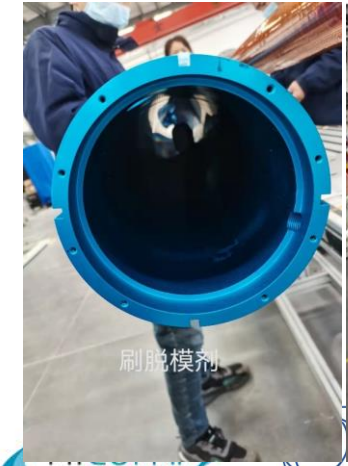


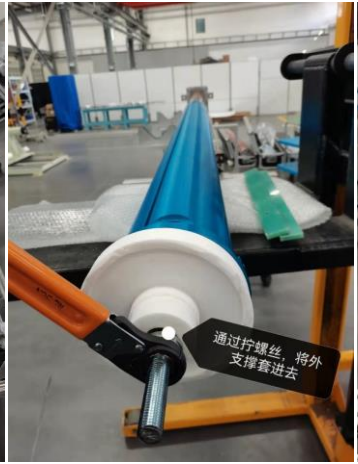
Direct winding of CB09

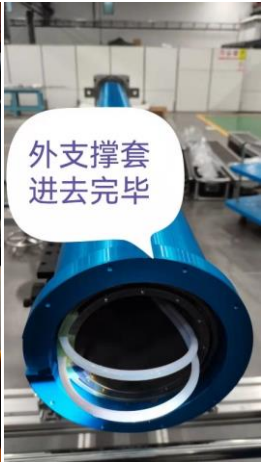




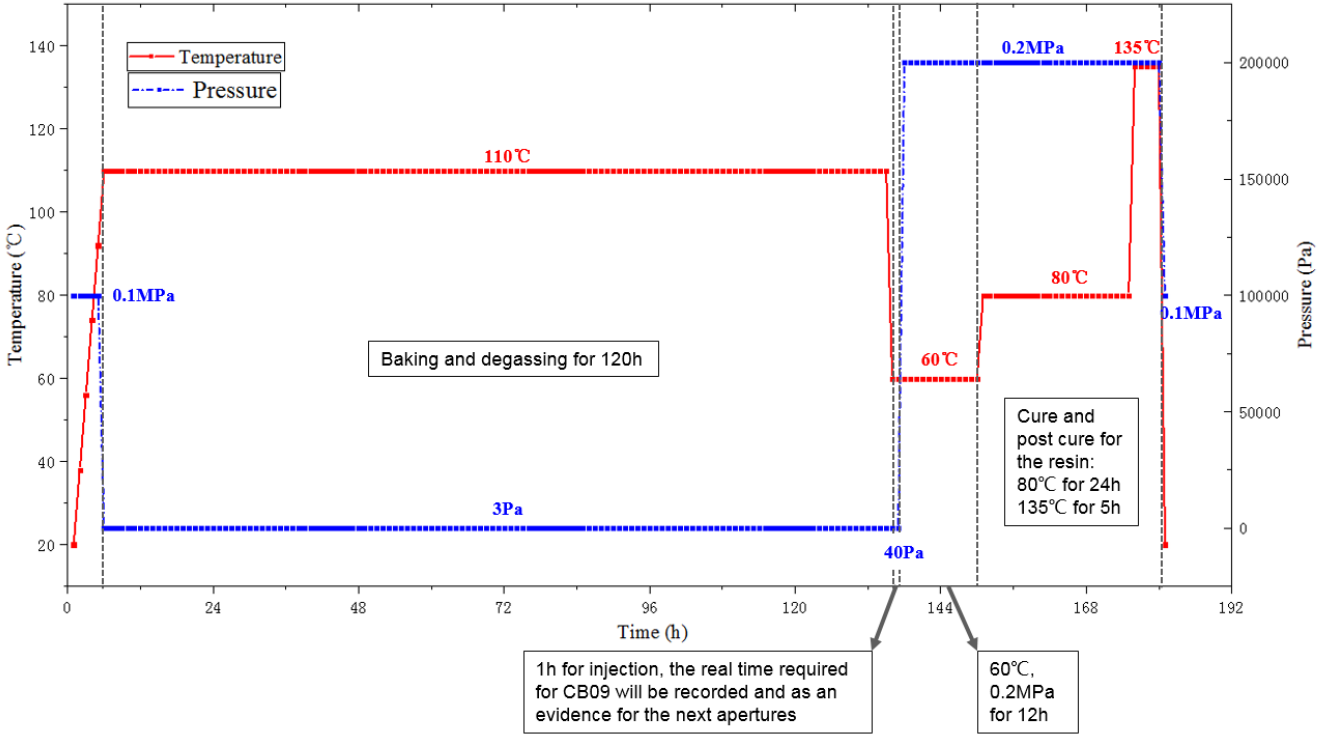




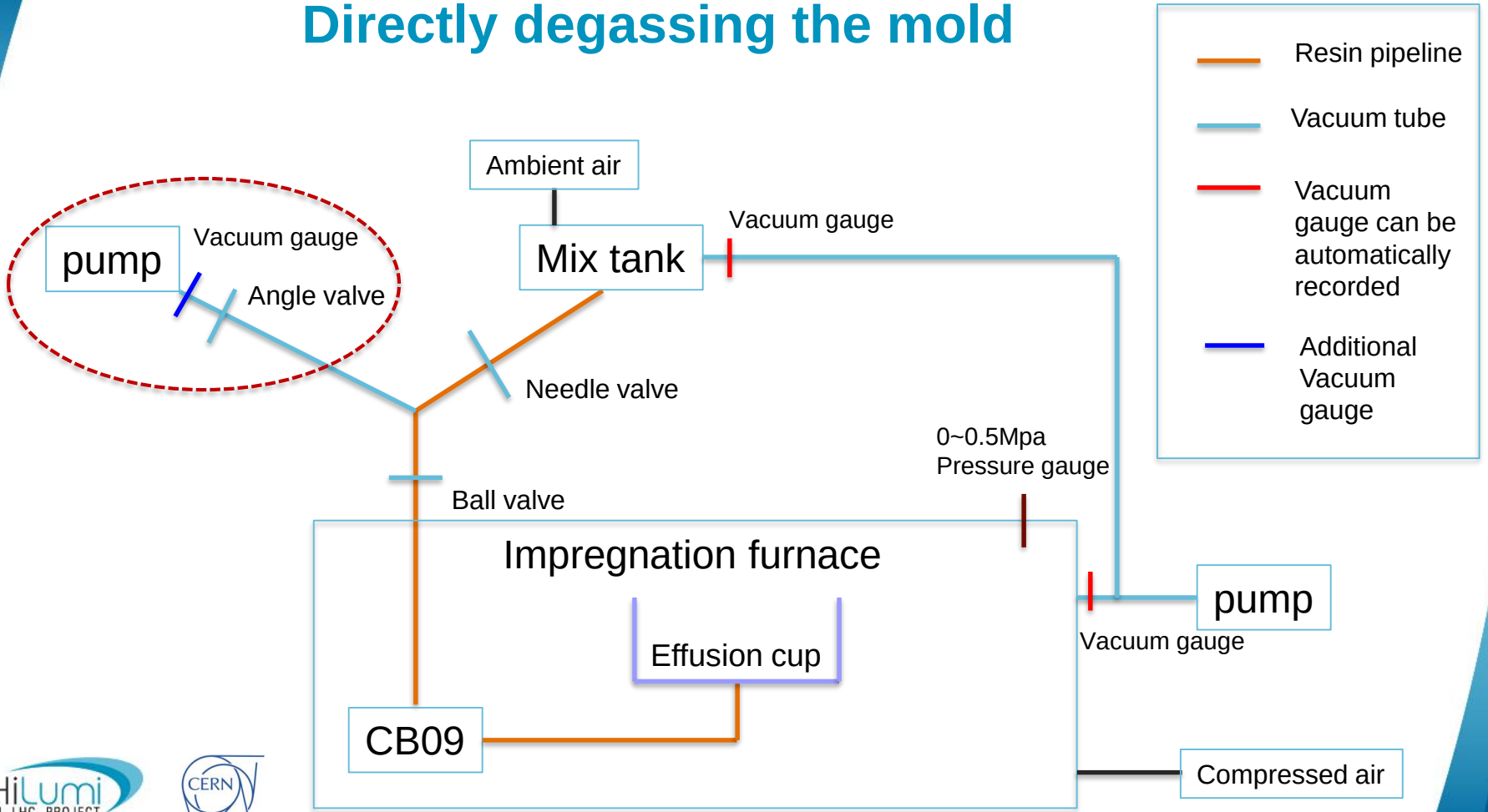




P-T setting of the VPI procedure

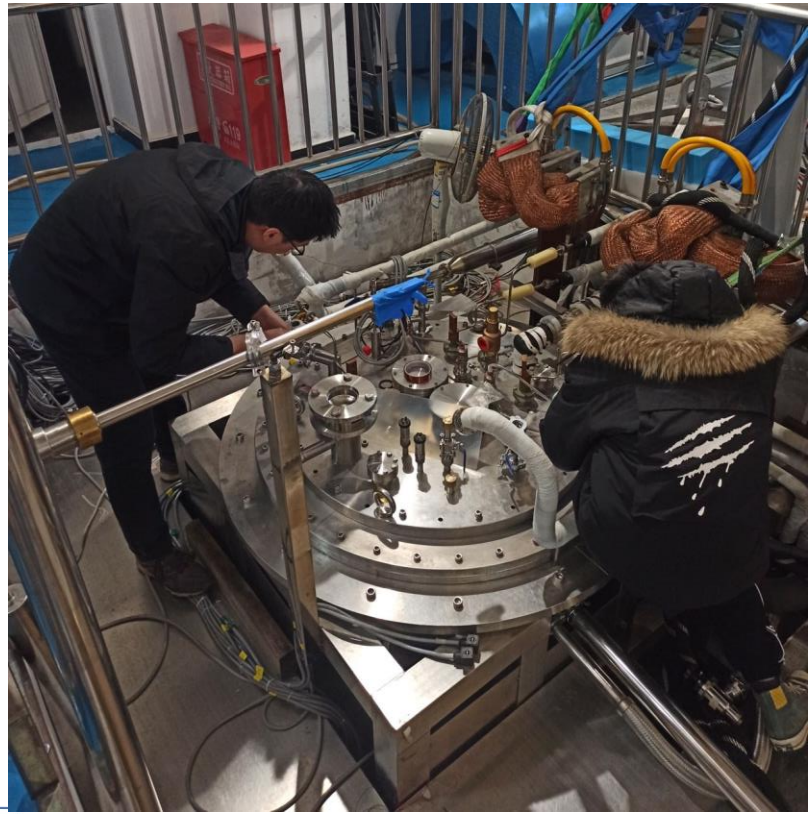


Directly degassing the mold



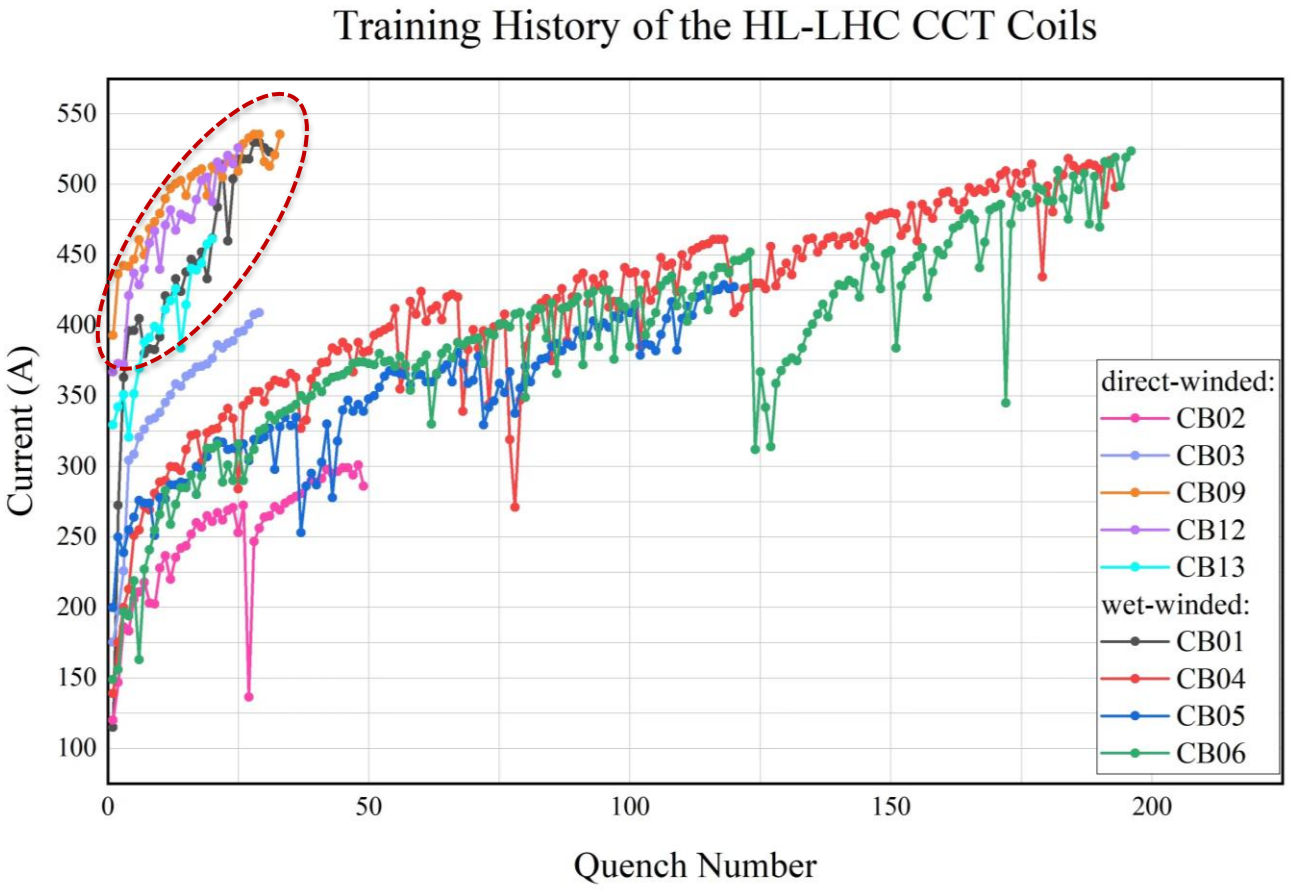
Directly degassing the mold

Stand-alone test of CB09 at IHEP



Stand-alone test of CB09 at IHEP

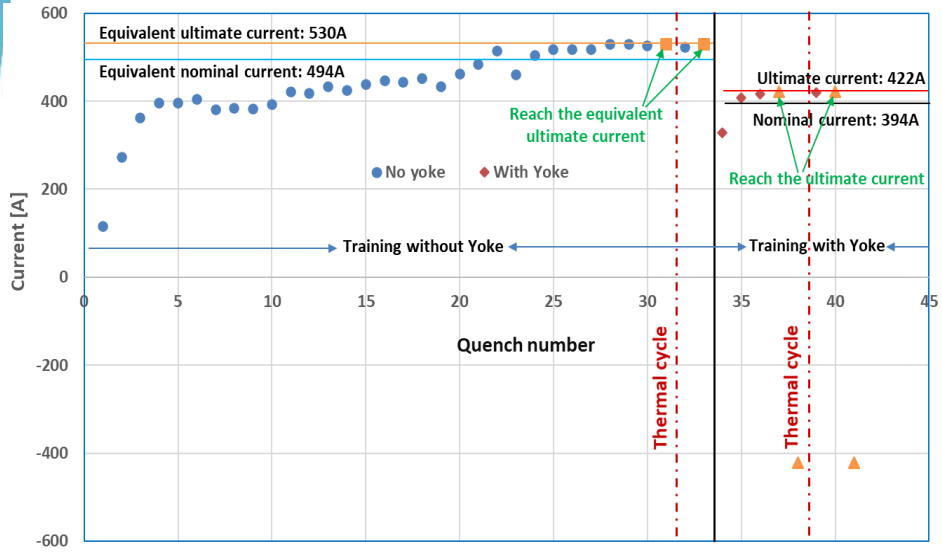
and followed by CB12, 13



Training of the 1st series magnet MCBRD01

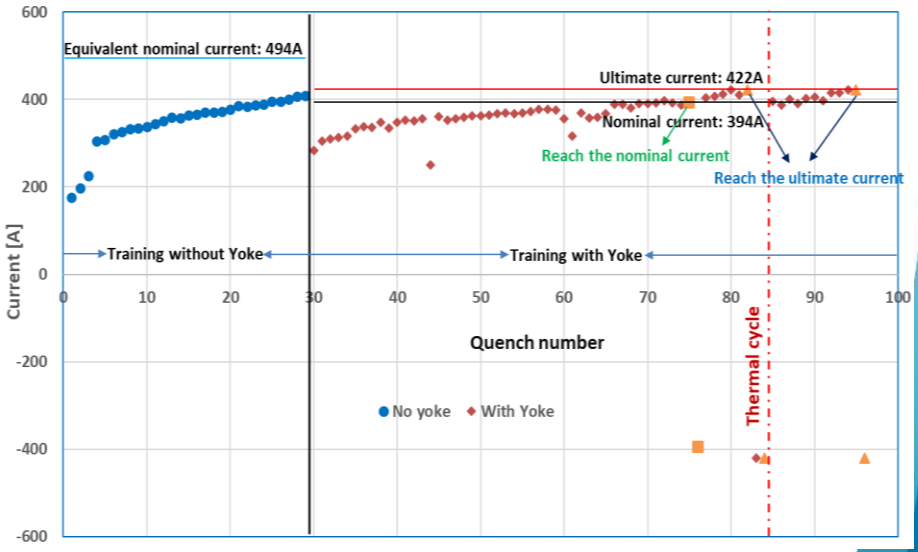
Aperture1 of the 1st series magnet

The 1st practice coil from Bama with new fabrication process wet wind plus 5-bar VPI.

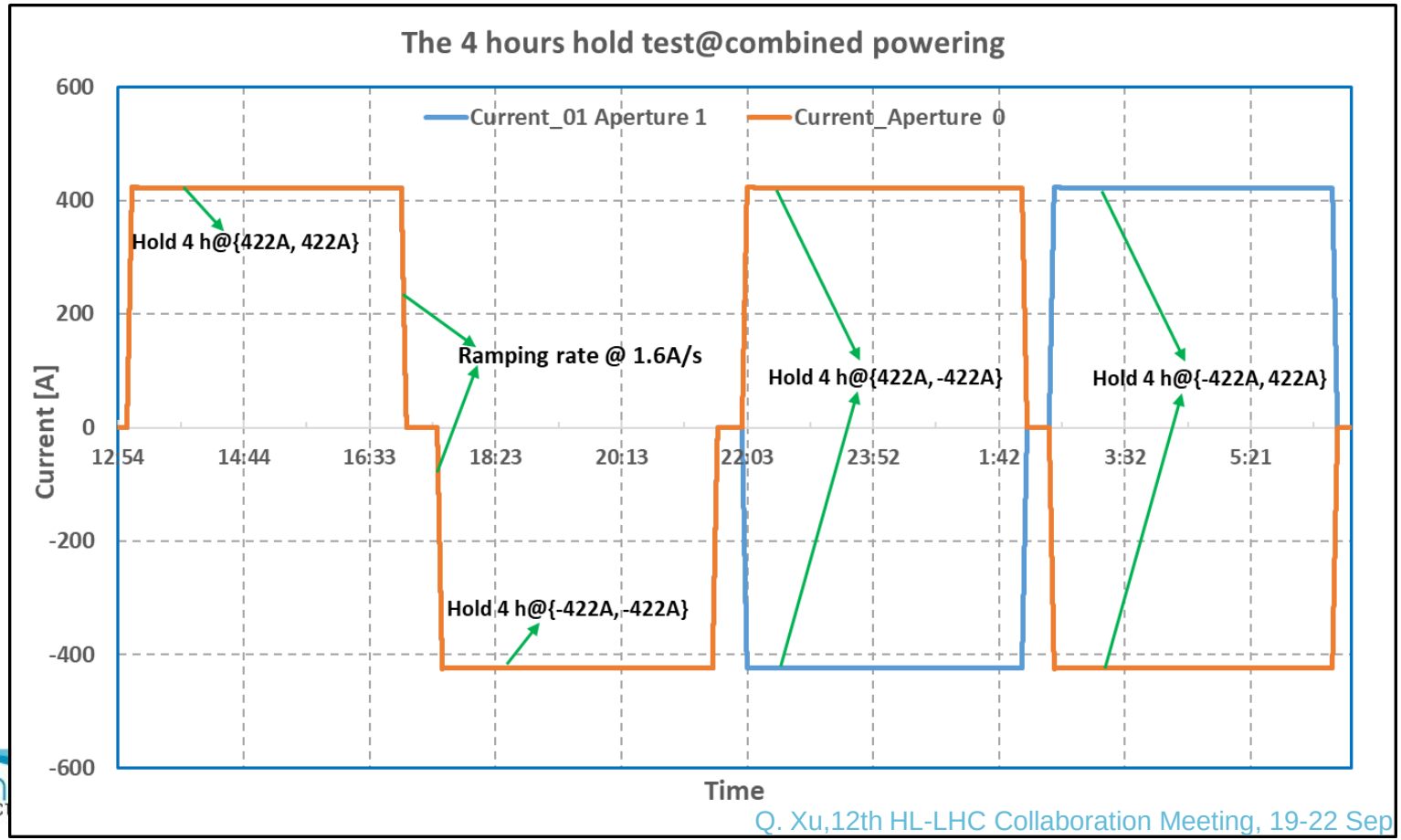


Aperture2 of the 1st series magnet

The 2nd coil from Bama with direct wind process plus 5-bar VPI, similar to the process of the 1st prototype.

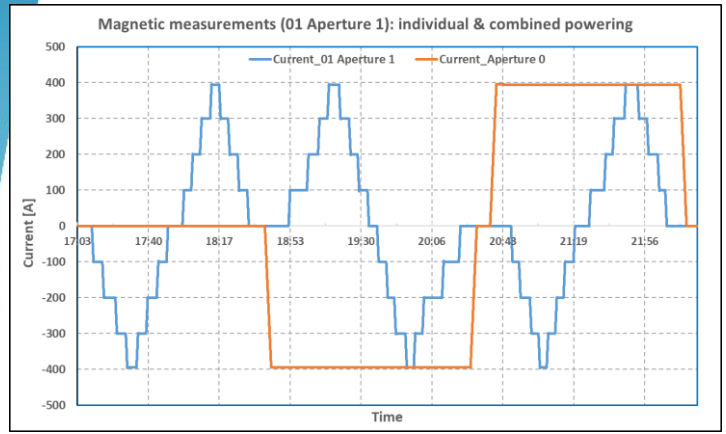


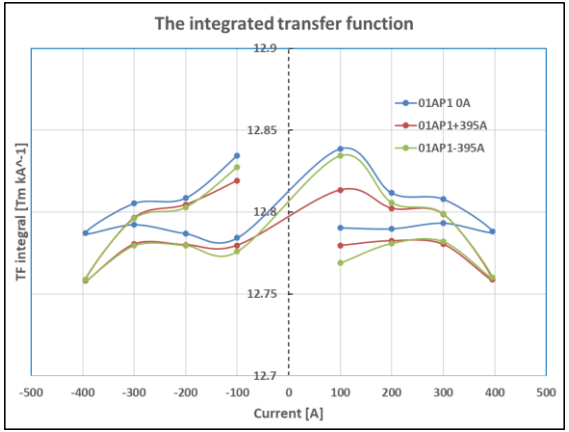
Holding test of the 1st series magnet

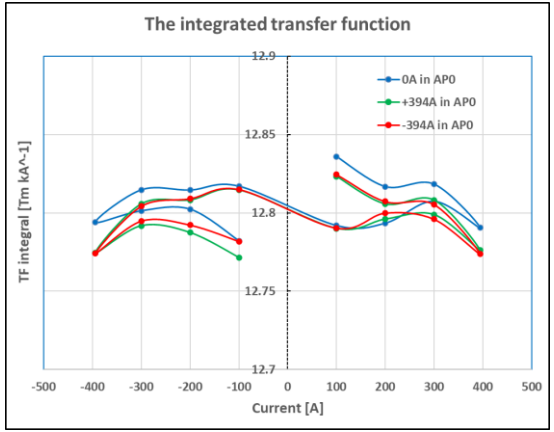


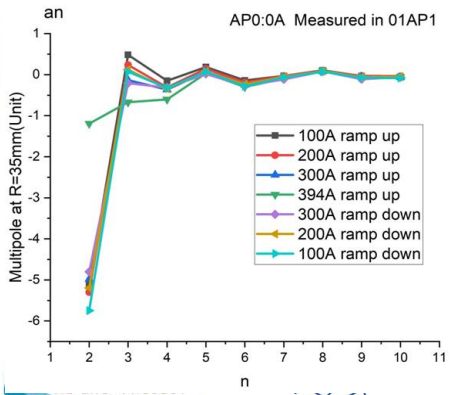
Field quality measurements at 4.1K

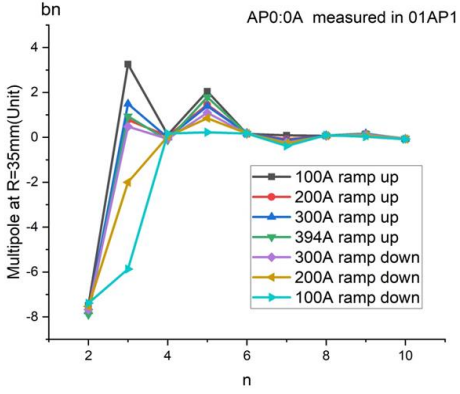
All field harmonics are within the 10-unit requirement, <5 units for most cases.

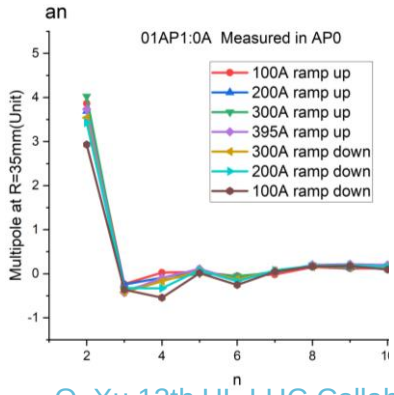


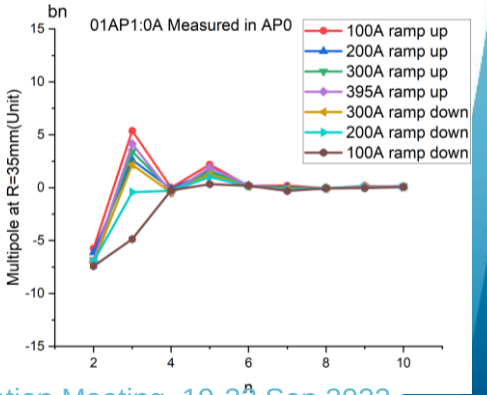








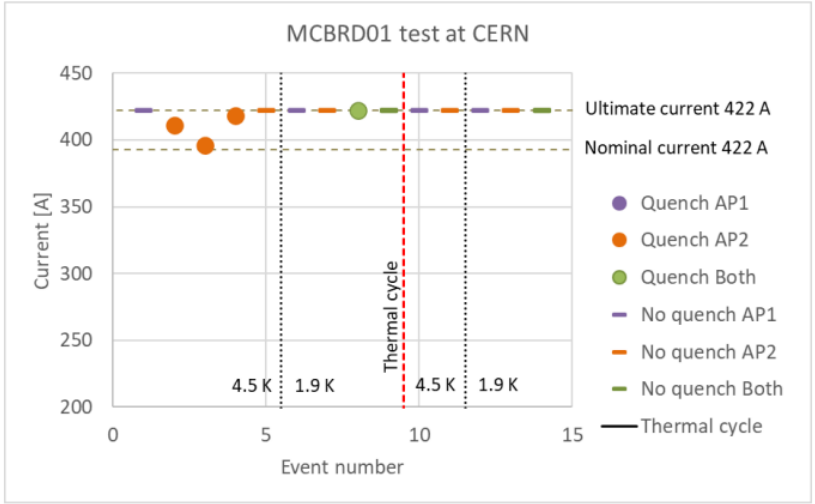




The 1st series magnet delivered to EU

The 1st magnet Packed and delivered to Sweden Uppsala University on Oct. 18 2021

MCBRD01 1.9 K Performance test at CERN



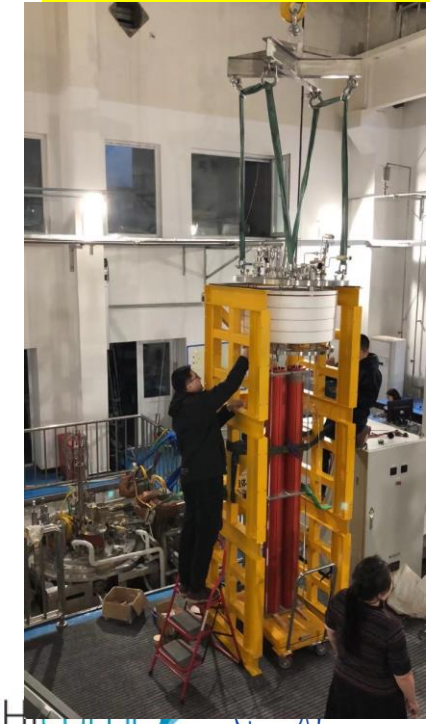
wire insulation damage at the end plate

"After the test in China, the magnet was shipped, connected to the bench at Freia, transported to CERN, connected to the CERN bench. After all this, the magnet showed a very good memory!"

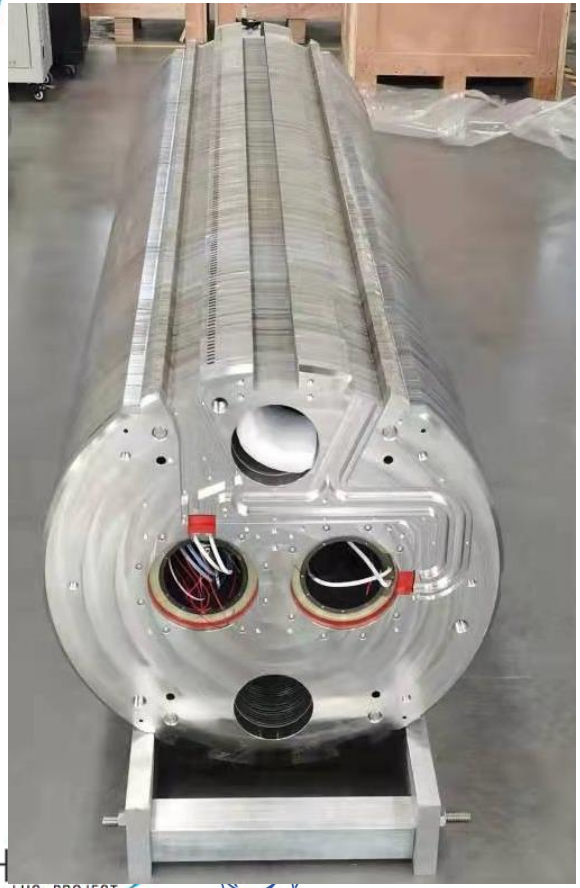
"the target voltage of 1620V from each aperture to ground according to the Electrical Design Criteria (EDMS 2363906) was not reached for any of the two apertures in magnet MCBRD01. The maximum voltage reached at 1100 V for aperture 1 to ground and 1500 V for aperture 2 to ground, but tripped at those levels"

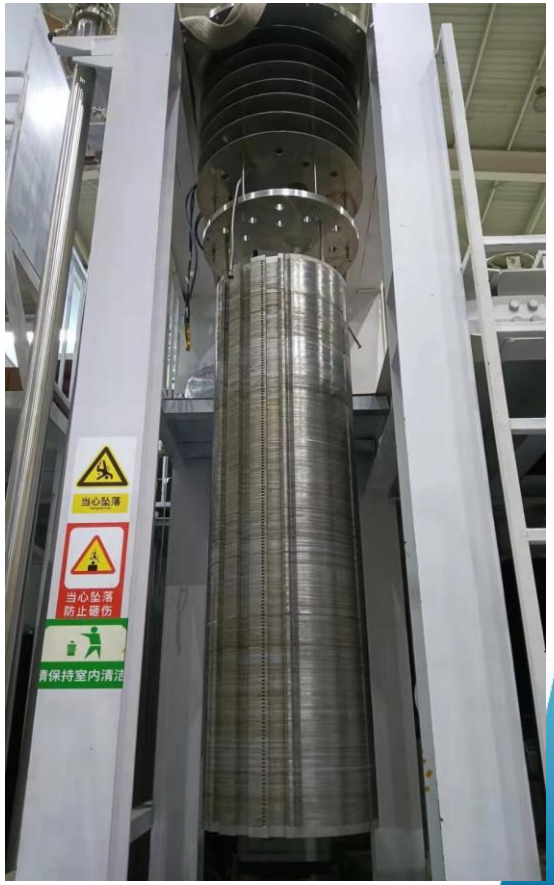
The 2nd series magnet MCBRD02

CB 04&06 trained stand-alone to 520 A at IHEP in Nov 2021.
To Bama for magnet assembly in Jan 2022.

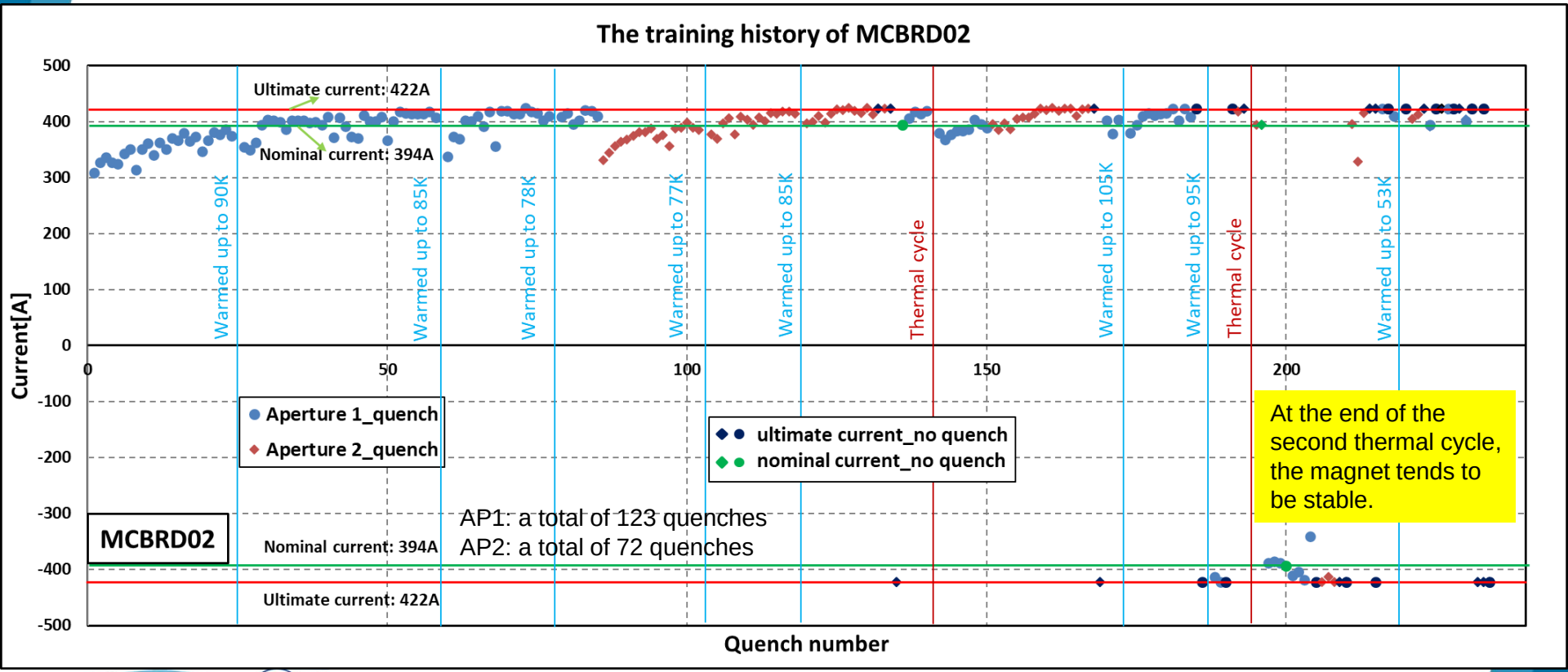


Magnet 2 assembled on the test platform at IMP

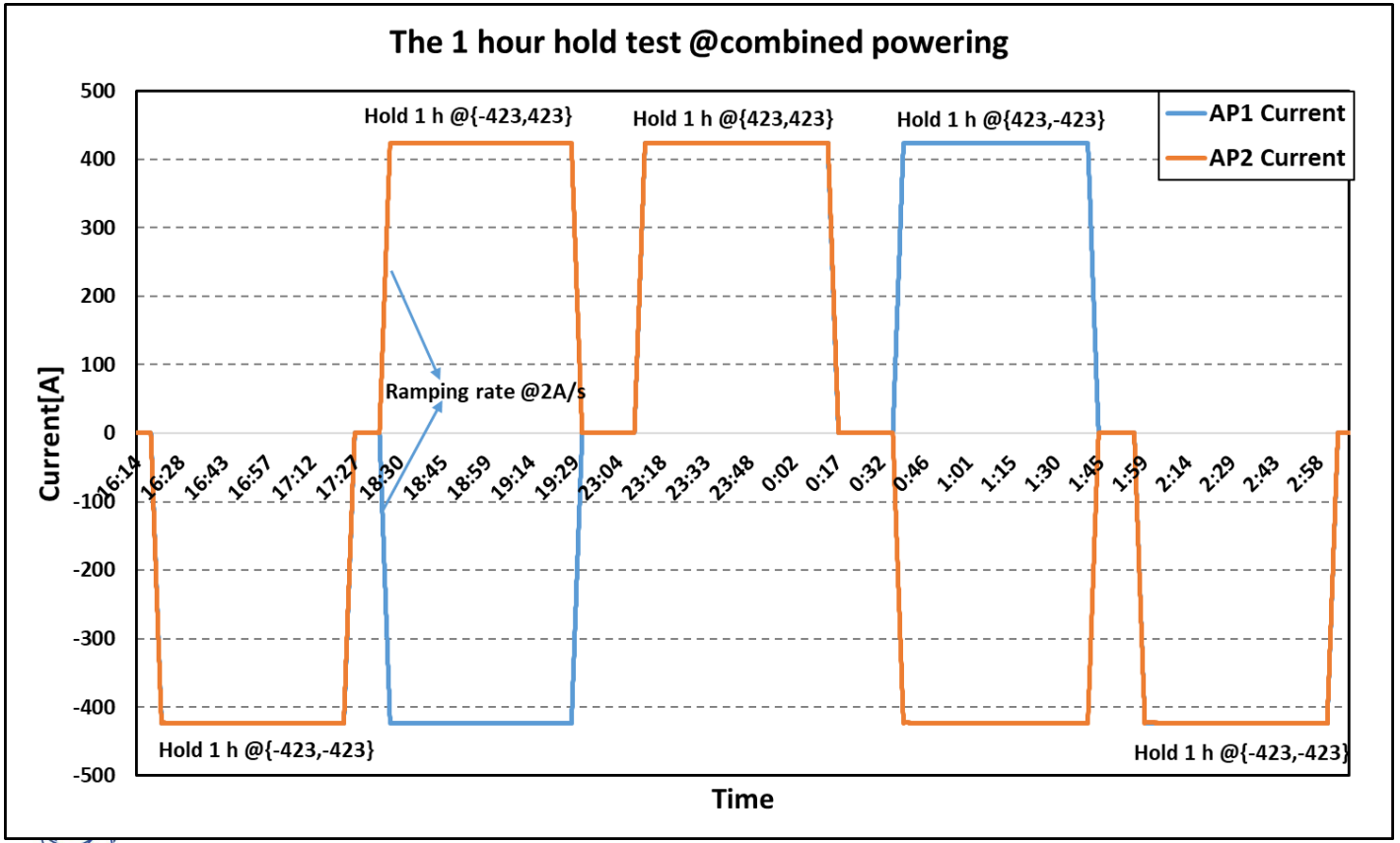




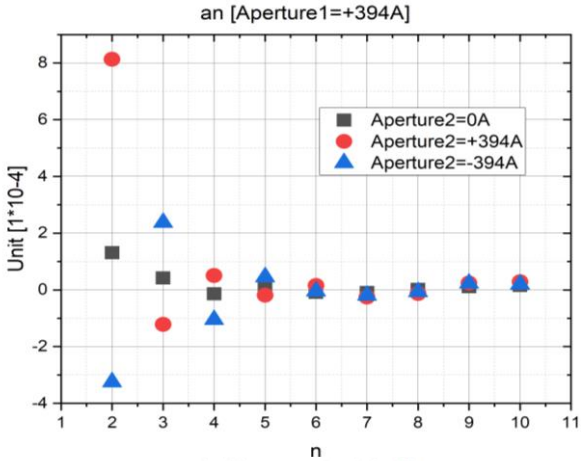
Training history of MCBRD02

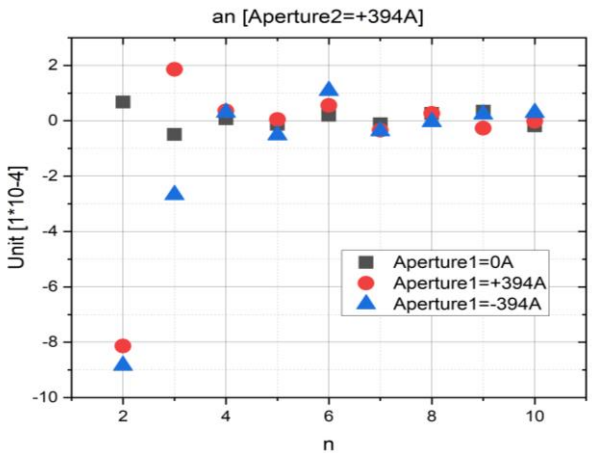


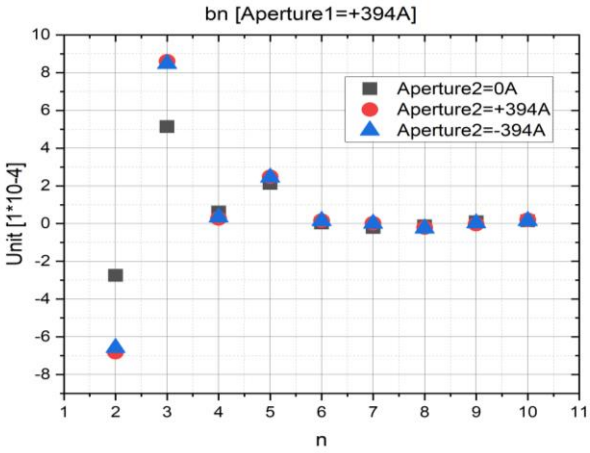
The holding test

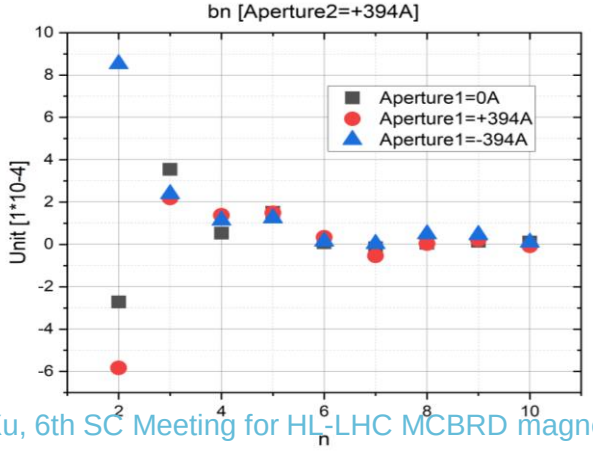


Crosstalk—Multipoles in the 2 Apertures









Electrical test before packaging

Table 11. The insulation test results (final tests)

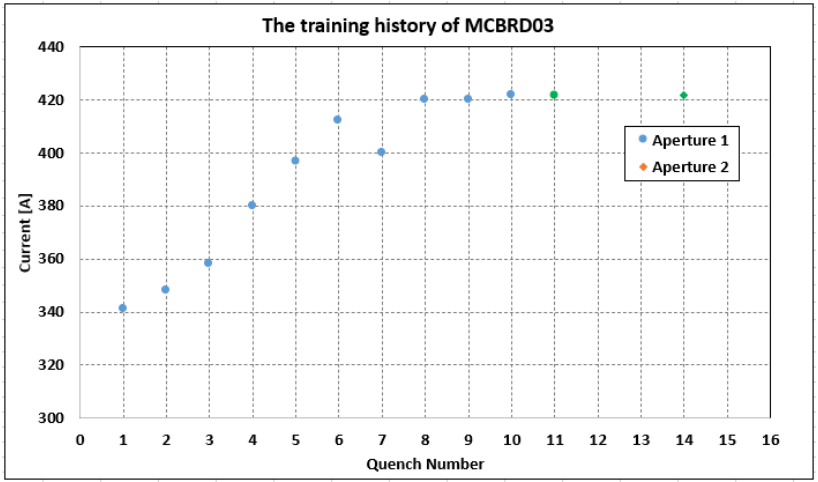
Equipment	Coil ID	Object	Function	Voltage/Current	Test Time	Resistance
Megger MIT 525	Aperture 1	Coil to Ground	IR	102V/1.28nA	30s	79.5GΩ
		Coil to Ground	IR	201V/1.28nA	30s	>100GΩ
		Coil to Ground	IR	308V/1.64nA	30s	188.1GΩ
		Coil to Ground	IR	340V/1.98nA	30s	172.2GΩ
		Coil to CCS322	IR	103V/0nA	30s	>100GΩ
		Coil to CCS322	IR	254V/0nA	30s	>500GΩ
		Coil to CCS323	IR	104V/0nA	30s	>100GΩ
		Coil to CCS323	IR	254V/0nA	30s	>500GΩ
	Aperture 2	Coil to Ground	IR	102V/0.54nA	30s	>100GΩ
		Coil to Ground	IR	201V/1.74nA	30s	>100GΩ
		Coil to Ground	IR	308V/2.07nA	30s	149.1GΩ
		Coil to Ground	IR	340V/2.13nA	30s	159.3GΩ
		Coil to CCS317	IR	101V/0nA	30s	>100GΩ
		Coil to CCS317	IR	254V/0nA	30s	>500GΩ
		Coil to CCS324	IR	101V/0nA	30s	>100GΩ
		Coil to CCS324	IR	254V/0nA	30s	>500GΩ
Test condition：23.7℃ & relative humidity 38.9% & before packaging						

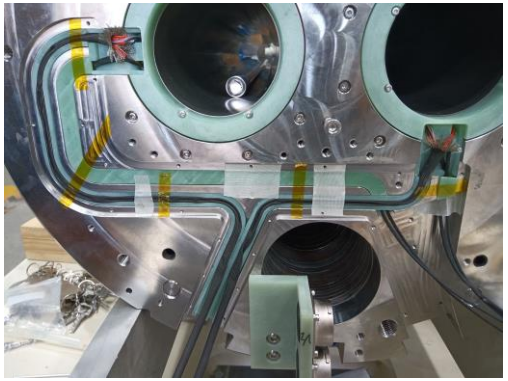
The magnet's two apertures pass all insulation tests.

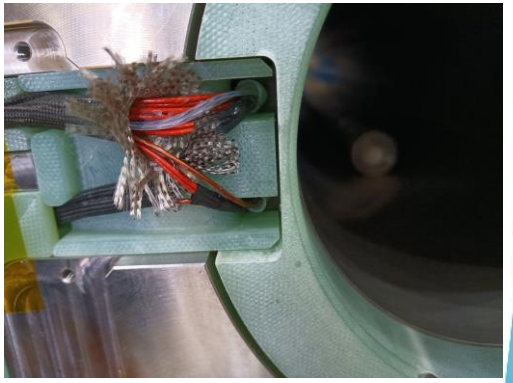
MCBRD02 Shipped to CERN in June 2022

The 3rd series magnet MCBRD03

- AP1(CB12，25 quenches 526A) reached ±422A after 11 quenches.
- AP2(CB09, 33 quenches 530A; after thermal cycle ＞500A) reached ±422A without any quenches.







Summary

- In total 3 series CCT magnets MCBRD01-03 have been fabricated. All of them reached the ultimate current and passed the field quality test (MCBRD 03 to be done this week)
- Long training “problem” has been solved with modifying the design parameters and improving the fabrication process.
- Wire insulation at the endplate of MCBRD01 is broken, caused low insulation strength, to be repaired at CERN. MCBRD03 passed 1620 V HV test in LHe at IMP Lanzhou.
- Components for 2 CCT magnets being shipped to CERN from IHEP, to verify the performance with WST wires and coil formers fabricated in China with CERN fabrication process, and also speed up the project progress.
- Schedule for the following magnets: every ~3 month per magnet.

Thanks for your attention