Status of interaction region magnets (WP3) with focus on MQXFB

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A. Foussat, J.-C. Perez, E. Gautheron, A. Devred, et al,

13th HL-LHC Collaboration Meeting, 25 September 2023

List of contributors (from East to West)

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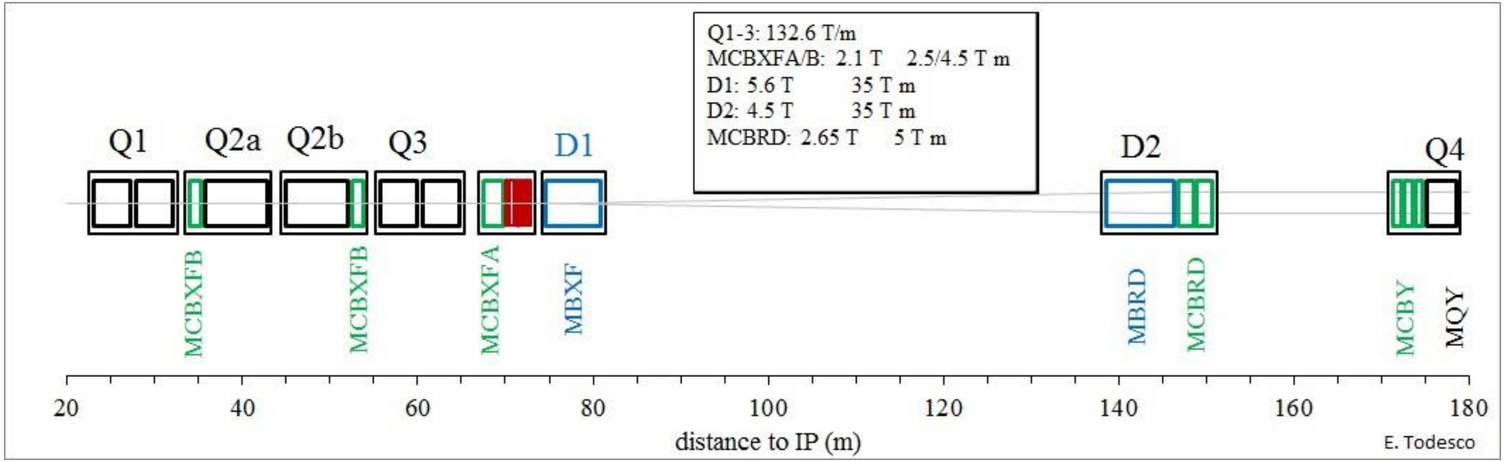
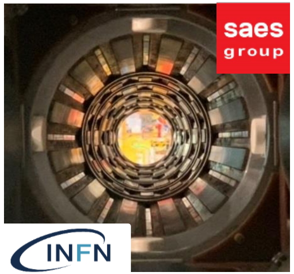
- CIEMAT: F. Toral, C. Martins Jardim, J. Garcia Matos, et al.
- AUP: G. Ambrosio, S. Feher, R. Carcagno, G. Apollinari, B. Ahia, P. Joshi, K. Amm, M. Yu, A. Nobrega, J. Schmalzle, M. Anarella, A Vouris, G. Chlachidze, S. Stoynev, R. Bossert, M. Baldini, P. Ferracin, D. Cheng, S. Prestemon, G. L. Sabbi, L. Cooley, V. Lombardo et al.,

Interaction region magnets



- **MQXF**: Nb_3Sn quadrupole (24 magnets to install)
- **D1**: Nb-Ti separation dipole (4 magnets to install)
- **D2**: Nb-Ti recombination dipole (4 magnets to install)
- **MCBXFA/B**: Nb-Ti nested correctors (12 magnets to install)
- **MCBRD:** Nb-Ti CCT correctors (8 magnets to install)
- **High order correctors:** Nb-Ti superferric correctors (36 magnets to install)

High order correctors
[M. Statera, E. Gautheron et al.]



D1
[T. Nakamoto, J. C. Perez et al.]

D2
[S. Farinon, A. Foussat, et al.]

Nested correctors
[F. Toral, J. C. Perez et al.]

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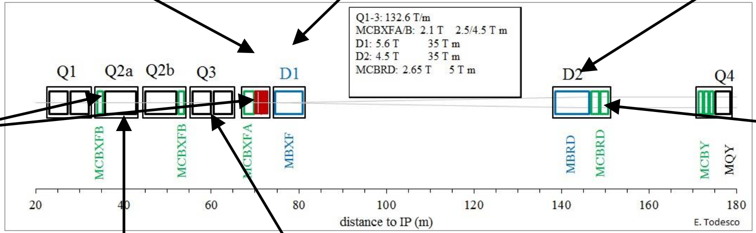
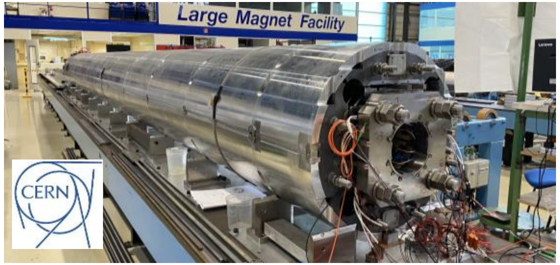


CCT correctors [Q. Xu, A. Foussat et al.]

IHEP
IMP
苏州八匹马超导科技有限公司

Q2 [S. Izquierdo Bermudez et al.]



Q1/Q3 [G. Ambrosio, S. Feher, S. Izquierdo Bermudez et al.]

US HL-LHC AUP

BERKELEY LAB

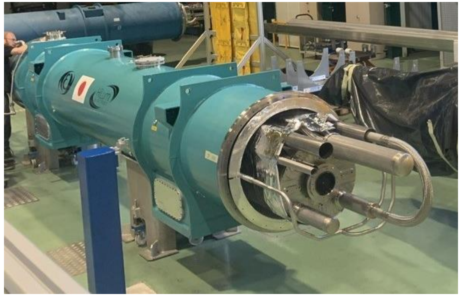
Brookhaven National Laboratory

Contents

- **Summary of Nb-Ti magnets**
- Summary of MQXFA
- Status of MQXFB

Nb-Ti magnets

- **D1** (See talk by T. Nakamoto):
  - Prototype and first series magnet reached requirements (vertical test)
  - 1st cryo-assembly completed, test in October 2023 at CERN
- **D2** (See talk by A. Pampaloni):
  - D2 prototype reached requirements – test completed
  - 1st series magnet expected at CERN in October 2023
- **D2 correctors** (see talk by E. Todesco):
  - The performance of the first two magnets (MCBRD01/02) is close to requirements, MCBRD03 reached performance at 4.5 K in IMP, MCBRD04 reached performance at 4.5 K in IMP, thermal cycle pending
- **Nested correctors** (see talk by F. Toral):
  - Three (out of 12) short nested series magnets produced and qualified for installation
  - Prototype long magnet also qualified for installation
- **High order correctors:** production completed, all magnets tested and accepted
  - 1st cold mass production completed at CERN, cryo-stating ongoing
  - Assembly of the second cold mass started



MBXFP1 in the cryostat

D2 prototype in the test bench

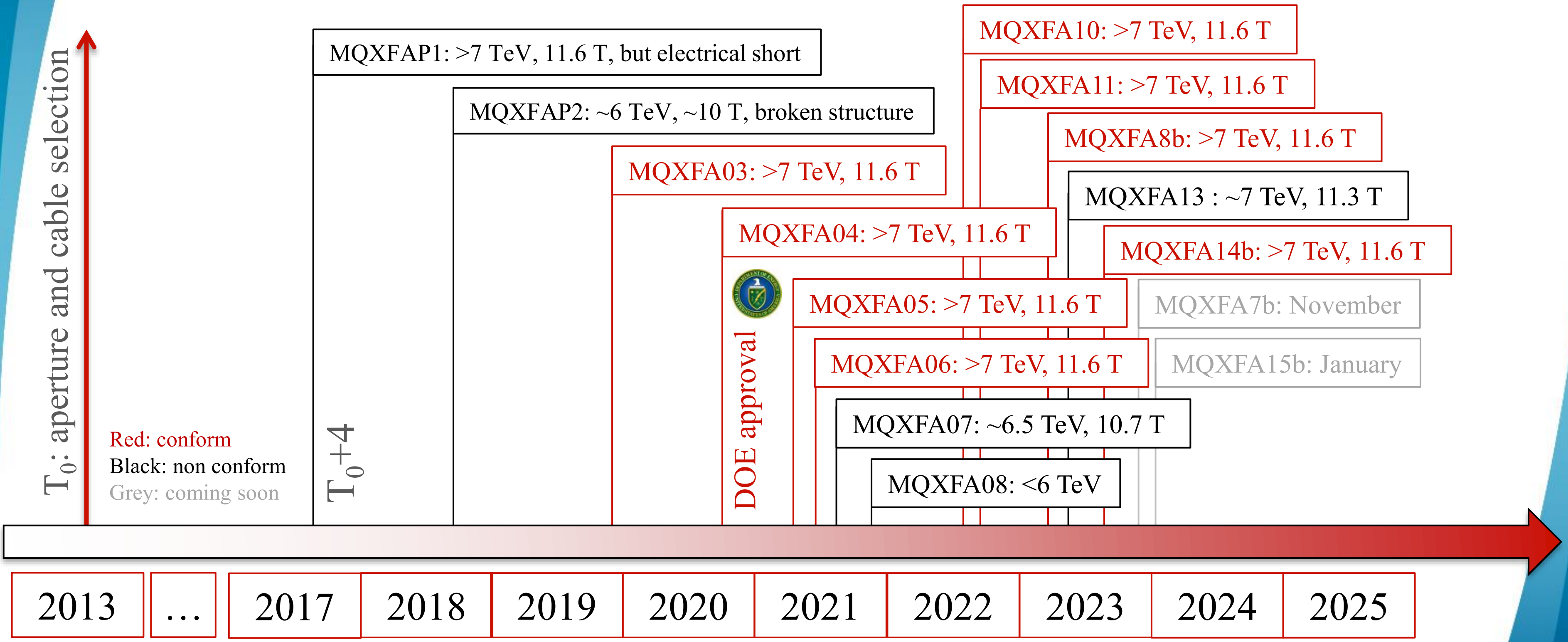
Corrector package in the cyostating bench

Contents

- Summary of Nb-Ti magnets
- **Summary of MQXFA**
- Status of MQXFB

MQXFA program (see G. Apollinari and G. Ambrosio)

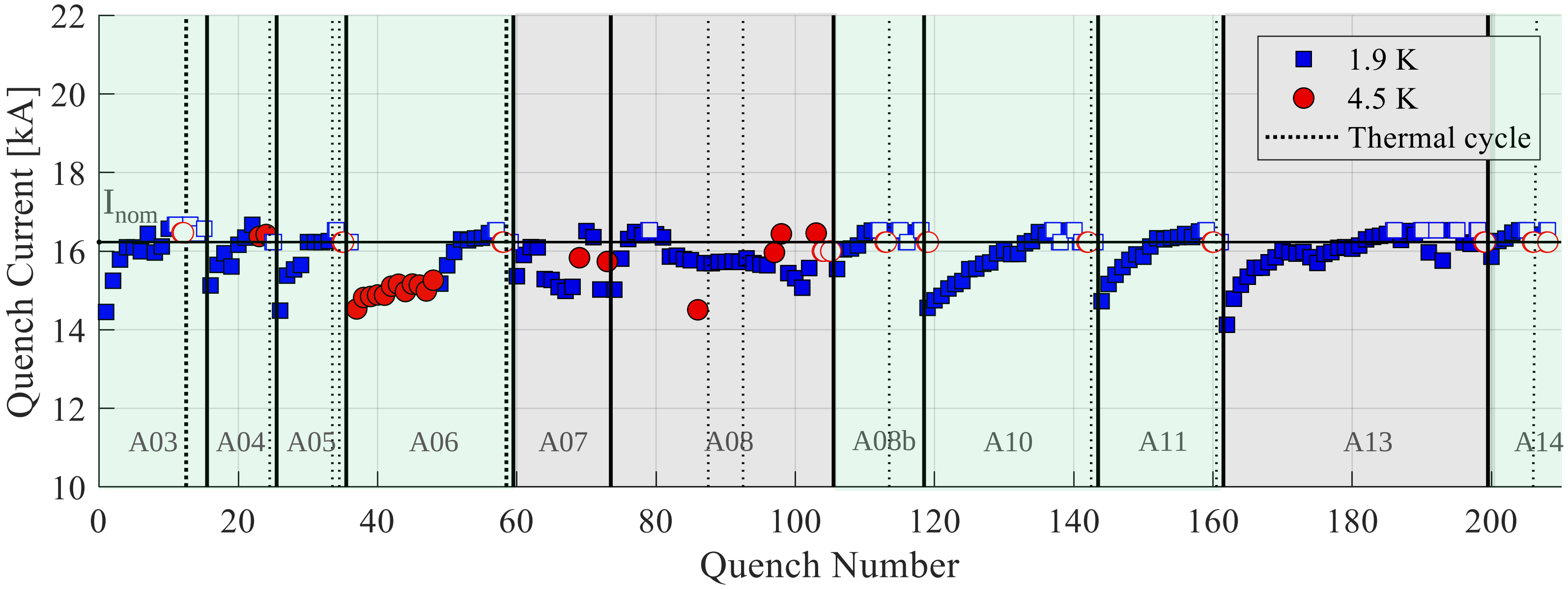
- 132.6 T/m at 7 TeV, corresponding to 11.3 T peak field



13 magnet tested, 8 conform, 3 non-conform, 12 more new magnets to test (7b, 12b, 13b,15-23)

MQXFA Test Results

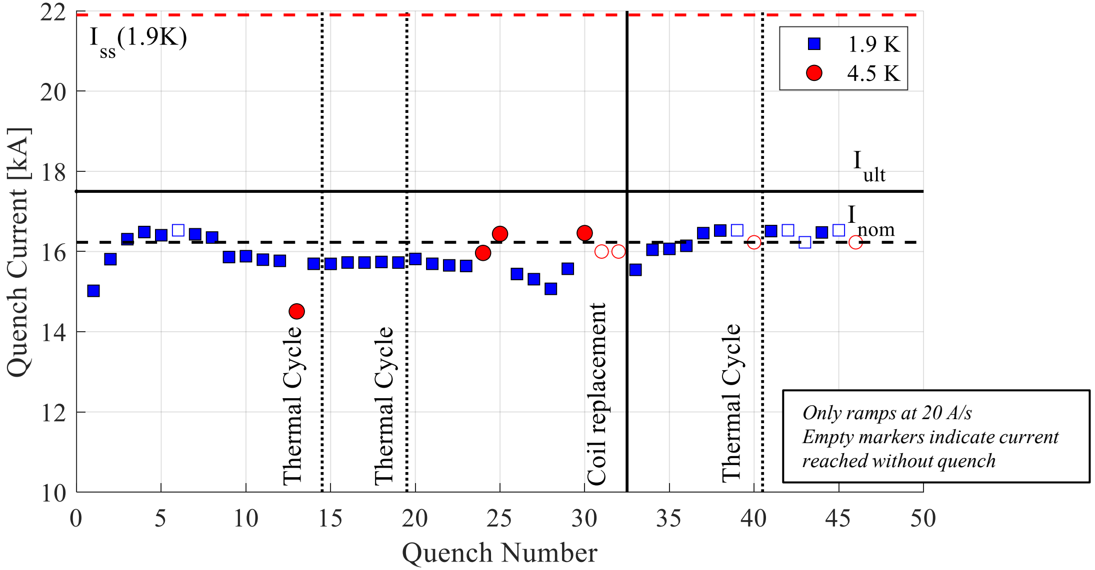
- MQXFA03-06, A10, A11, A08b and 14b reached performance and met all requirements
  - Operation at nominal current plus 300 A at 1.9 K, nominal current at 4.5 K
  - Good memory, i.e. no retraining after thermal cycle
- MQXFA07 and MQXFA08 showed performance limitations with reverse behavior
- MQXFA13 showed long training and erratic behavior close to nominal current, the weak coil will be replaced



Powering test of MQXFA magnets (B. Ahia, S. Feher, G. Ambrosio et al.)

Removing performance limitations

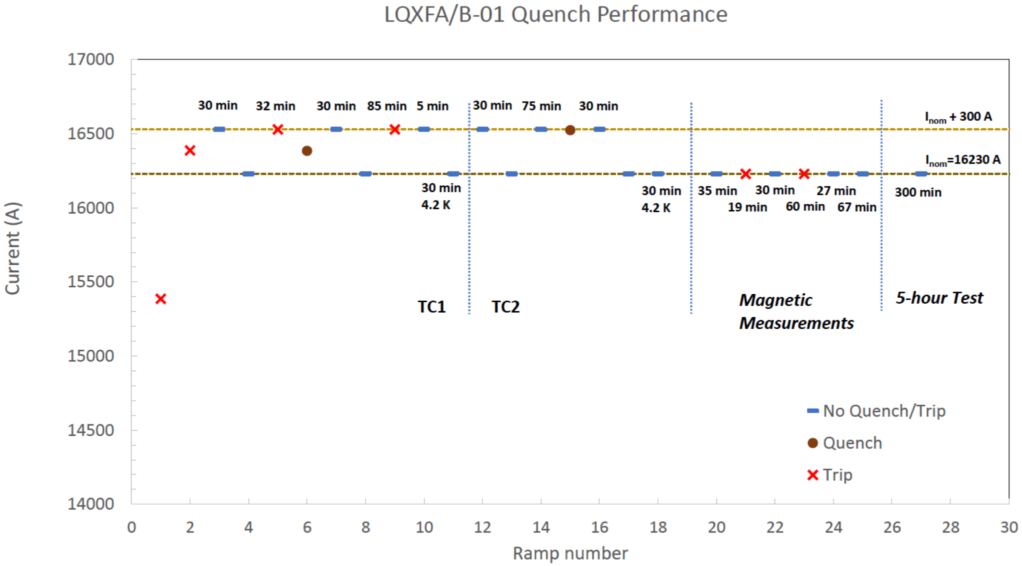
- MQXFA08 limiting coil was replaced, and the magnet reached performance requirements
  - First long magnet with coil replacement
  - Same procedure will be applied to MQXFA07 and to MQXFA13



Power test of MQXFA08 (J. Muratore, A. Yahia, S. Feher, G. Ambrosio et al.)

MQXFA program

- First cold mass reaching performance – no retraining after thermal cycle



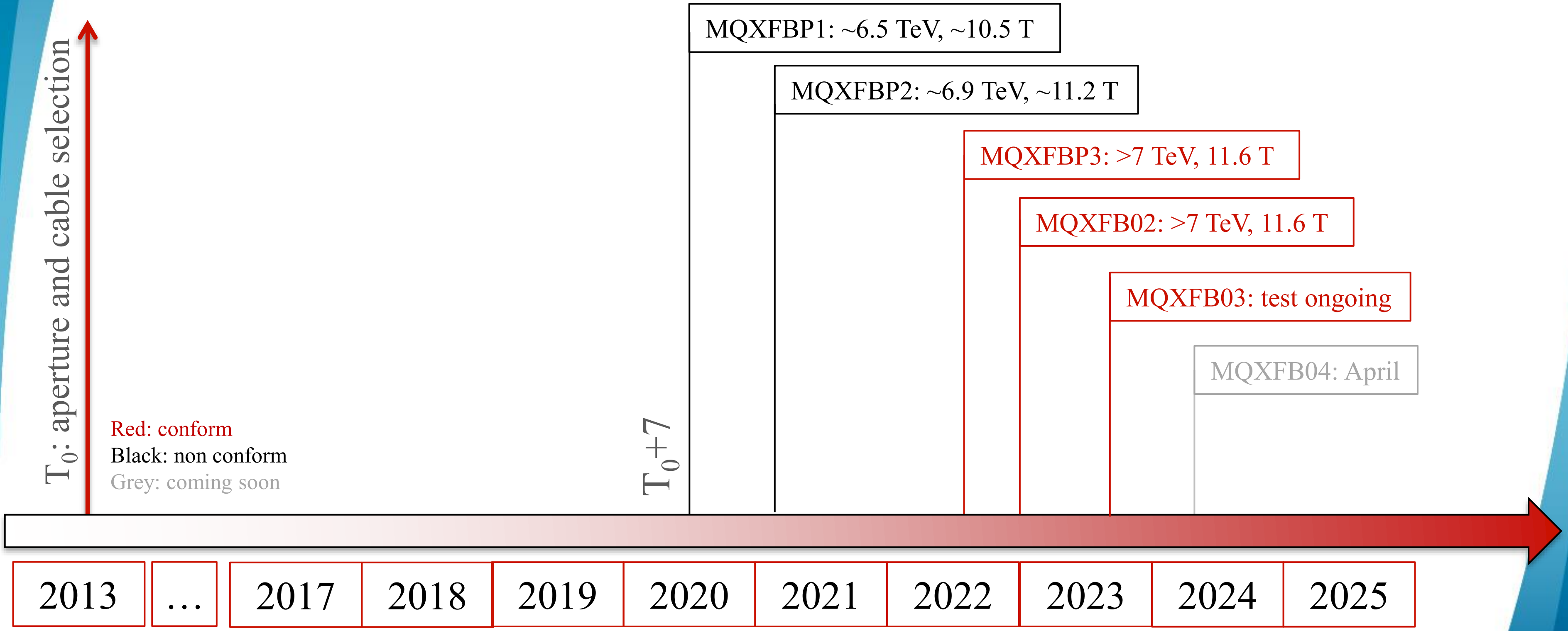
Quench performance of LQXFA01 (G. Ambrosio, S. Feher, et al.)

Contents

- Summary of Nb-Ti magnets
- Summary of MQXFA
- **Status of MQXFB**

A summary of MQXF program

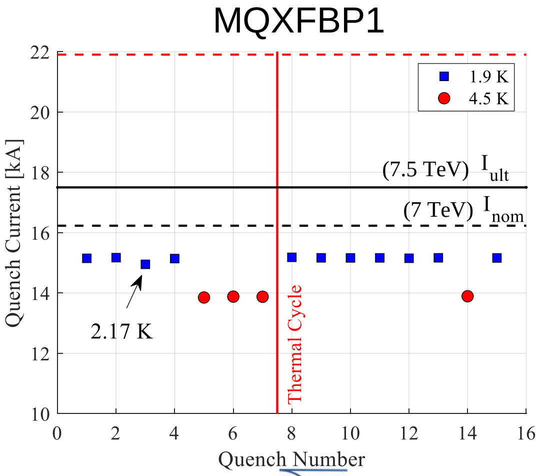
- 132.6 T/m at 7 TeV, corresponding to 11.3 T peak field

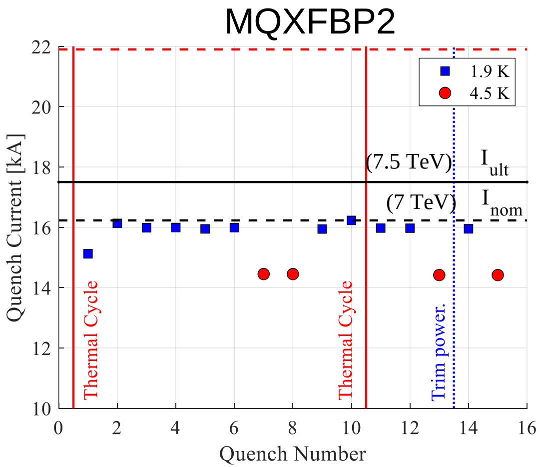


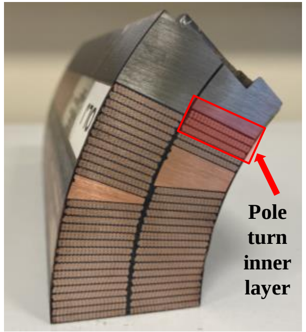
7 to 9 more magnets to test

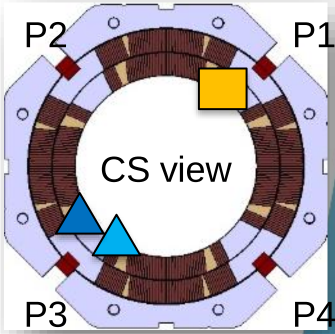
MQXFBP1&BP2 Prototypes Performance

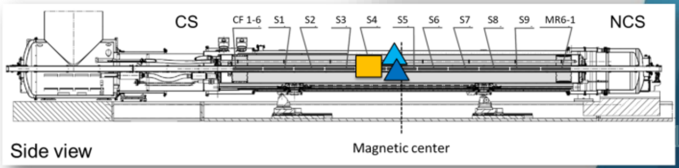
- **MQXFBP1** and **BP2** were **limited below nominal current** at 1.9 K (~15 and ~16 kA respectively).
- 4.5 K behaviour compatible with magnet on the critical surface (70% of the short sample limit in MQXFBP1, 73 % in MQXFBP2).
- No retraining after thermal cycle and **magnet performance did not degrade with temperature cycles, quenches and current cycles.**
- In all the cases, the quench location was on the inner layer pole turns near the mechanical center of the magnet.
- **Power circuit modification** (the so-called trimmed powering) to evaluate the performance of non-limiting coils → **other two coils** also limited with **similar** mechanism (straight part), at 16.5-17 kA – no quenches in the heads, and no degradation with thermal cycle











F. J. Mangiarotti et al., "Power Test of the First Two HL-LHC Insertion Quadrupole Magnets Built at CERN," in IEEE Transactions on Applied Superconductivity, vol. 32, no. 6, pp. 1-5, Sept. 2022, Art no. 4003305, doi: 10.1109/TASC.2022.3157574.

Overview on main findings and strategy definition

In Spring 2021, we stopped the production to identify and address possible root causes for the performance limitation:

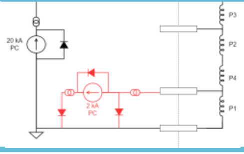
1. Cold mass assembly
2. Magnet assembly
3. Coil manufacturing

It may also be a combination of two of the three, or all of them

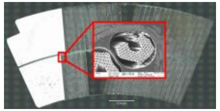
Limiting performance BP1

Very similar phenomenology in BP2 → systematic problem?

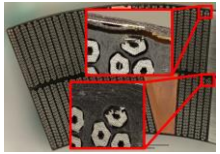
3 out of the 4 coils in BP2 show same type of limitation



Very localized defect in the limiting coil of BP1



Similar defect in a virgin coil (never assembled in a magnet)

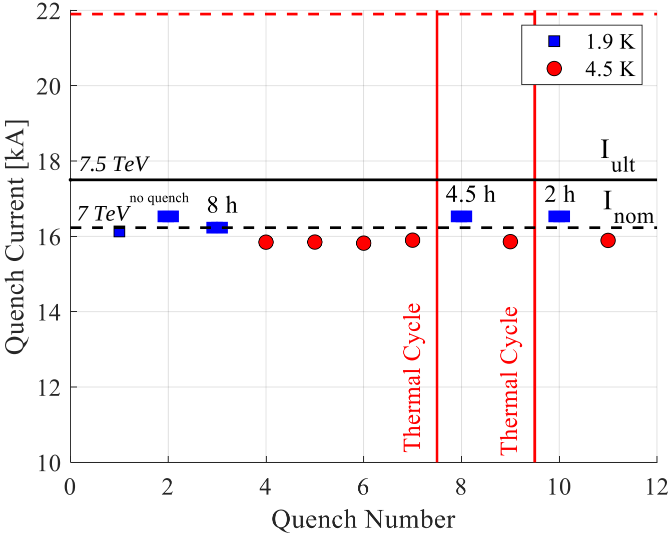


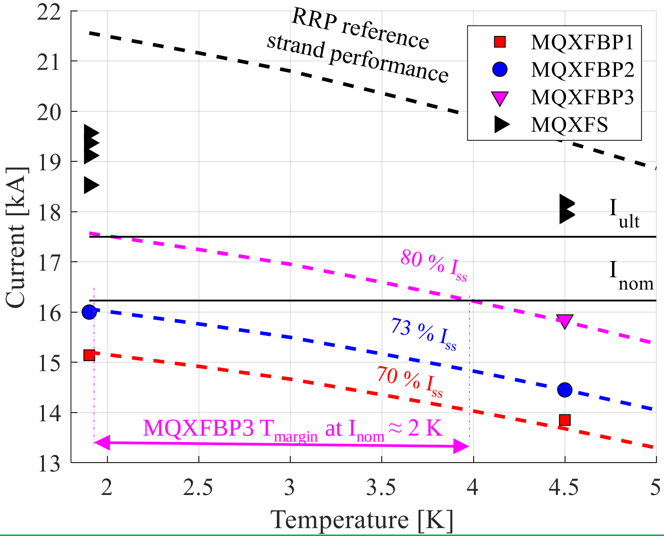
2020				2021				2022				2023			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
				STOP	Identify and assess potential root causes			Cold mass: BP3			✓				
									Magnet assembly: B02				✓		
										Coil fabrication: B03					Test ongoing

- BP2 coils
- BP3 coils
- BP3 magnet
- BP3 cold mass
- B02 coils

MQXFBP3: Cold mass assembly

- Optimized welding procedure, to **decouple the stainless steel vessel and and magnet**
- MQXFBP3 **reached the target current at 1.9 K** (I_{nom} + 300 A) after one quench
- At 4.5 K, we see the same type of limitation observed in MQXFBP1 and MQXFBP2 but at higher levels.
  - Quench level extrapolation for MQXFBP3 at 1.9 K: above ultimate current with a **temperature margin** at nominal current of **2 K** (0.35 K needed for operation[1]).
- No re-training after thermal cycle. Magnet performance does not change with thermal and current cycling

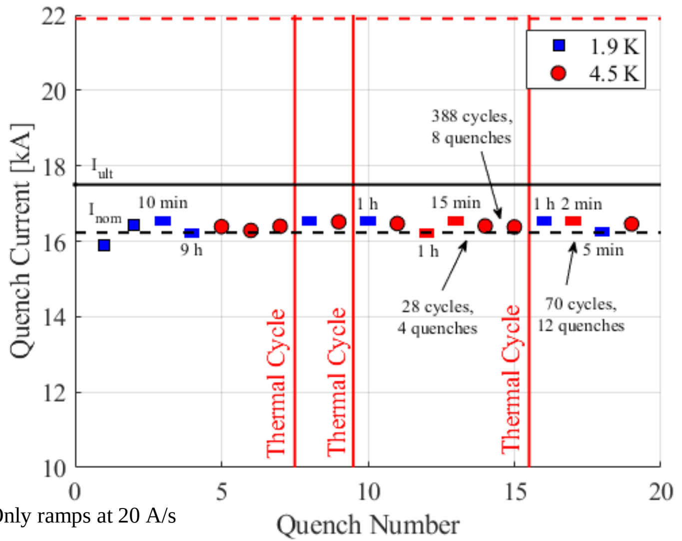




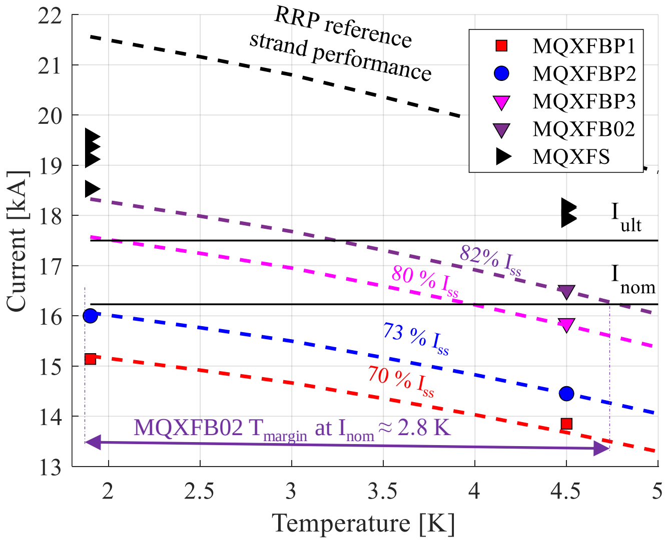
[1] Borges de Sousa et al, "Numerical Assessment of the Inhomogeneous Temperature Field and the Quality of Heat Extraction of Nb_3Sn Impregnated Magnets for the High Luminosity Upgrade of the LHC "

MQXFB02: Magnet Assembly

- Optimized **procedure of bladder and key loading**, to **eliminate the overshoot of coil azimuthal stress during loading**
- MQXFB02 **reached the target current at 1.9 K** (I_{nom} + 300 A) after two quenches.
- At 4.5 K, we see the same type of limitation observed in MQXFBP1&P2&P3 but above nominal current
  - Quench level extrapolation for MQXFB02 at 1.9 K: above ultimate current with a **temperature margin** at nominal current of **2.8 K** (0.35 K temperature margin needed for operation).
- No retraining after thermal cycle. **Endurance** test show no degradation after **3 thermal cycles**, ≈ **50 quenches** and **500 current cycles**.

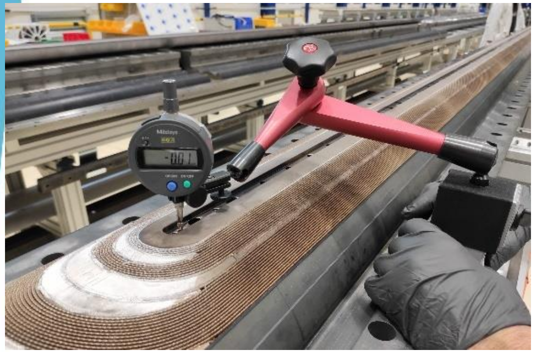


Only ramps at 20 A/s

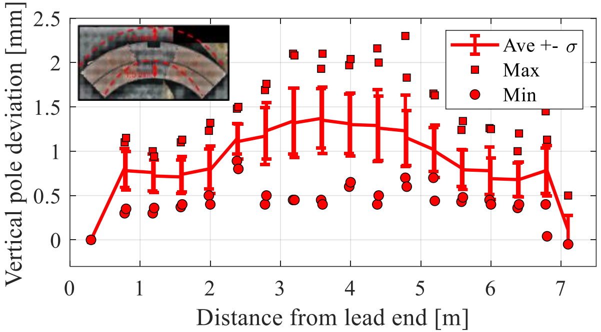


MQXFB03: Coil fabrication

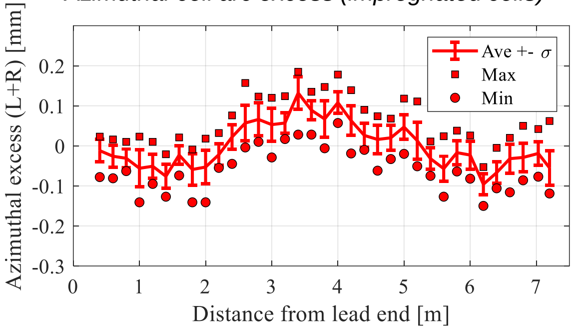
- **After reaction**, a vertical deflection of the outer layer pole with respect to the base plate of 1-2 mm is typically observed after the opening of the reaction fixture.
- **After impregnation**, the coil is azimuthally bigger in the middle (≈ 0.1 mm per mid-plane).
- Pole to pole transitions, where collapsed filaments are found in destructive inspections, have been identified as stress concentration region during the closure of the impregnation fixture



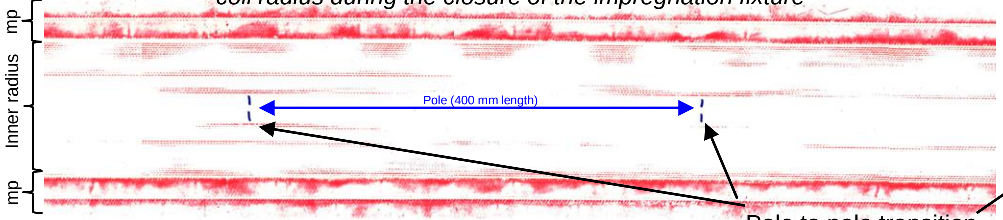
Vertical pole deflection (reacted coils)



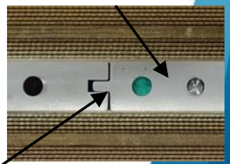
Azimuthal coil arc excess (impregnated coils)



Pressure sensitive film imprints (2.5 – 10 MPa)of the inner coil radius during the closure of the impregnation fixture

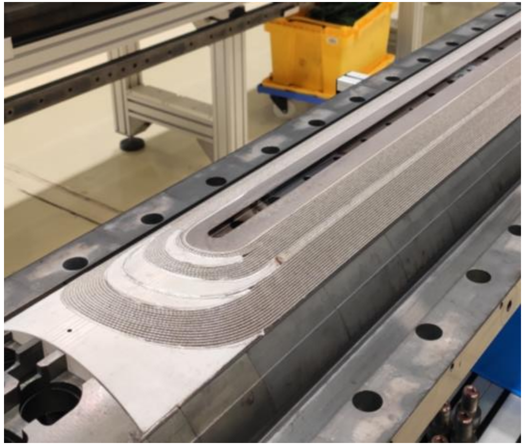


Ti pole
(400 mm length)

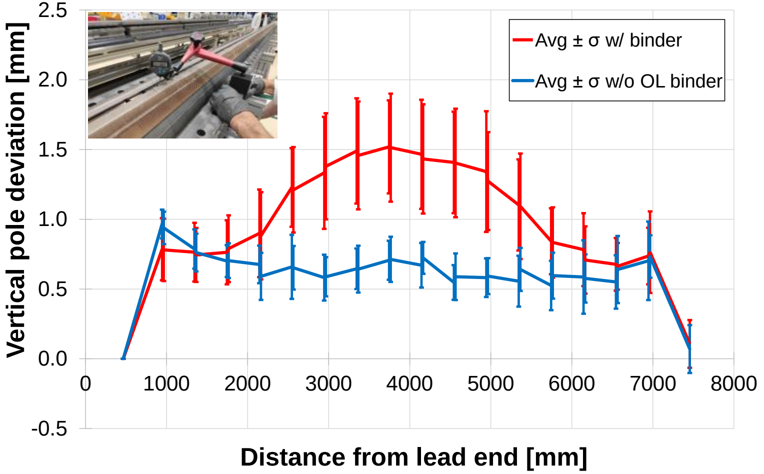


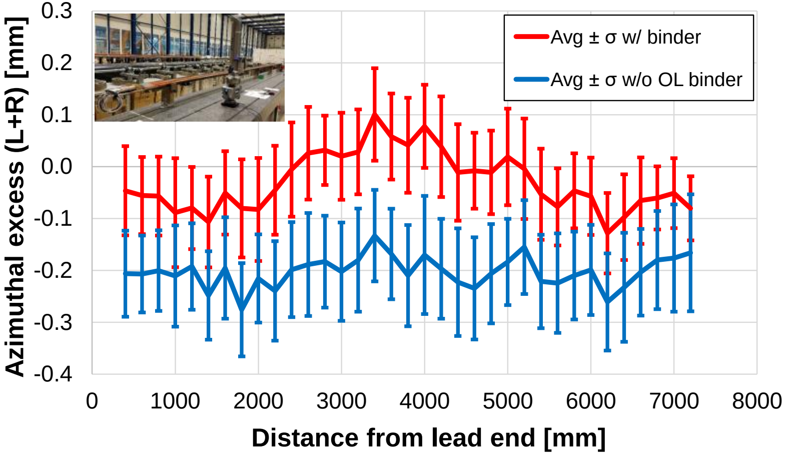
Pole to pole transition

New generation coils



- Modifications aimed at reducing the friction between coil and reaction mold
  - Pole gap increase
  - Partial compensation of the curing cavity
  - **Removal of the ceramic binder from the outer layer of the coil**
- New generation coil measurables point to a coil which is more ‘relaxed’ after RHT
  - No coil ‘hump’ after reaction
  - No bigger coil azimuthal size towards the middle after impregnation
  - More homogeneous torque required to close the impregnation fixture



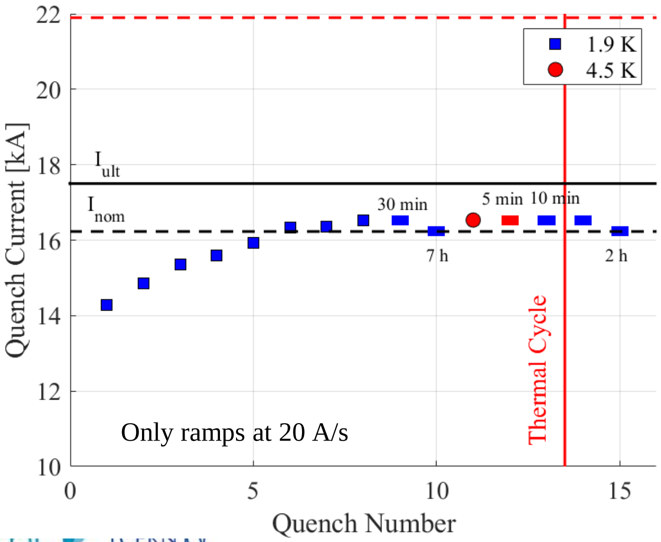


More details on Wednesday in the parallel session

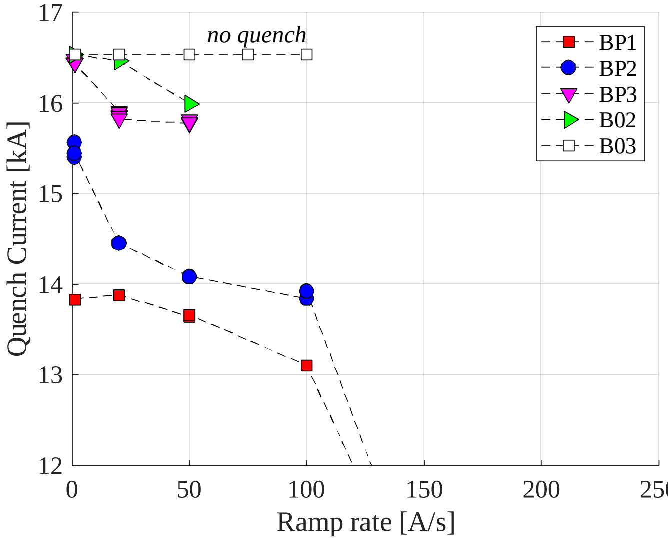
MQXFB03 Test Results

- MQXFB03 **reached the target current at 1.9 K** (I_{nom} + 300 A) after eight quenches. It operated during 1 hour at target current and 7 hours at I_{nom}
- Stable operation at **4.5 K at target current** (I_{nom} + 300 A), no sign of conductor limitation as observed in previous magnets
  - The magnet reaches target current at 4.5 K at 100 A/s (nominal 20 A/s), a good indication that we still have margin.
- Good memory after thermal cycle (test still ongoing)

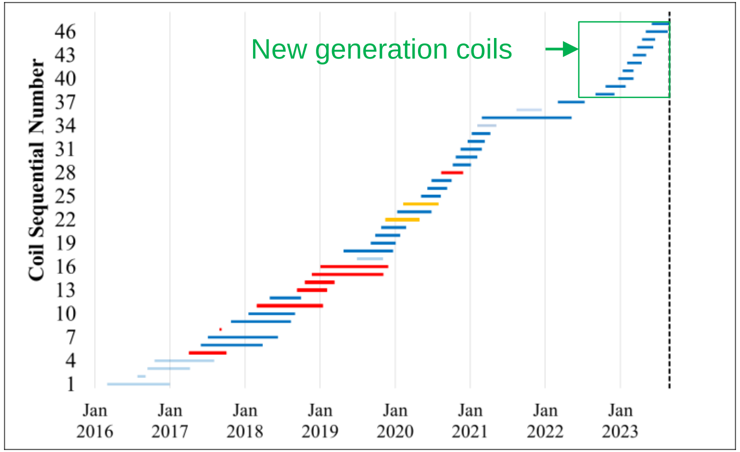
Training of MQXFB03



Ramp rate dependency at 4.5 K



MQXFB – Next steps



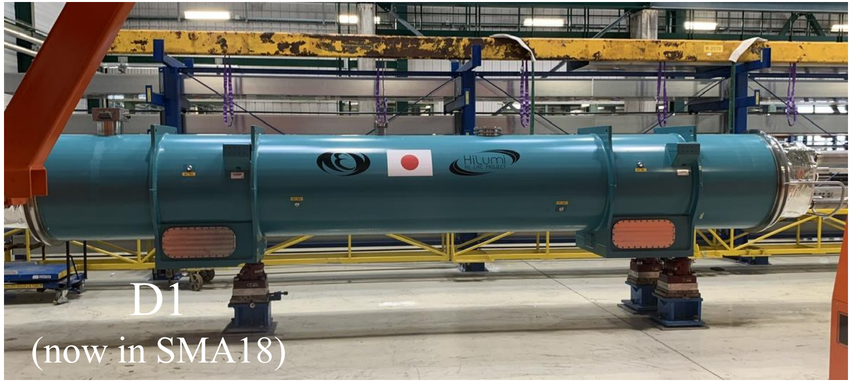
- *Coil fabrication:*
  - 10 'new generation' coils have been completed
  - Coil fabrication ongoing, with a pace of ≈ 1 coil/month
- *Magnet assembly*
  - Assembly of MQXFB04, with 4 new generation coils ongoing. Test expected in Spring 2024.
- *Cold mass and cryo-assembly*
  - MQXFBP2b and MQXFBP3b have been assembled in Q2 cold mass configuration, BP2b is ready to be tested in SM18 (and then, the string). Cryostating of BP3b almost copleted.
  - MQXFB02b Q2-type cold mass completed, but disassembly needed due to an electrical non-conformity
  - From MQXFB04, the plan is to go directly to Q2 cold mass
- **Next critical steps:**
  - Demonstrate reproducibility of the performance with MQXFB04
  - First test of a Q2 final cryo-assembly

Conclusions

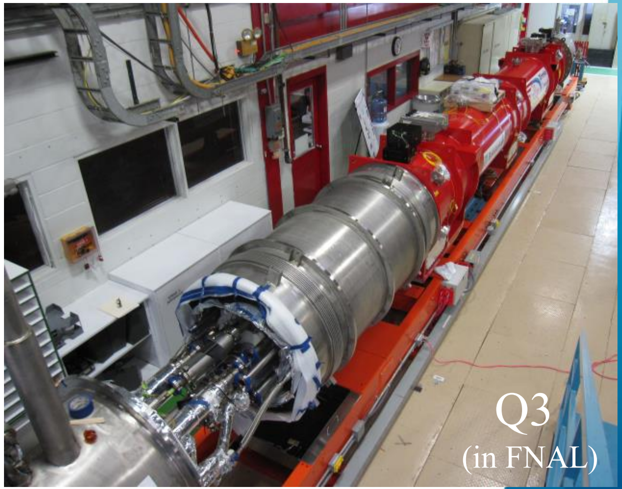
- Cold mass manufacturing procedures successfully applied to all types of magnets

- MQXFA
  - Successful test of the **first cold mass in horizontal position** – major milestone
  - **Coil replacement** validated in MQXFA08b
  - AUP completed cable and (almost) coil production. **8 magnets** (out of 11 (+2) magnets tested) **are accepted** (reached I_{nom} + 300 A at 1.9 K, I_{nom} at 4.5 K, > 2.6 K temperature margin (0.35 K needed)).

- MQXFB
  - Three MQXFB magnets reached HL-LHC requirements (MQXFBP3, MQXFB02 and MQXFB03).
  - **Endurance** test in **MQXFB02** show no degradation after **3 thermal cycles**, ≈ **50 quenches** and **500 current cycles**.
  - **MQXFB03**, produced using **new generation coils**, does not show performance limitation: **first 7.2 m length magnets with no signs of conductor degradation!**
  - Next critical step: demonstrate **reproducibility of the performance** with **MQXFB04**



The string is taking the right colors!



Thanks

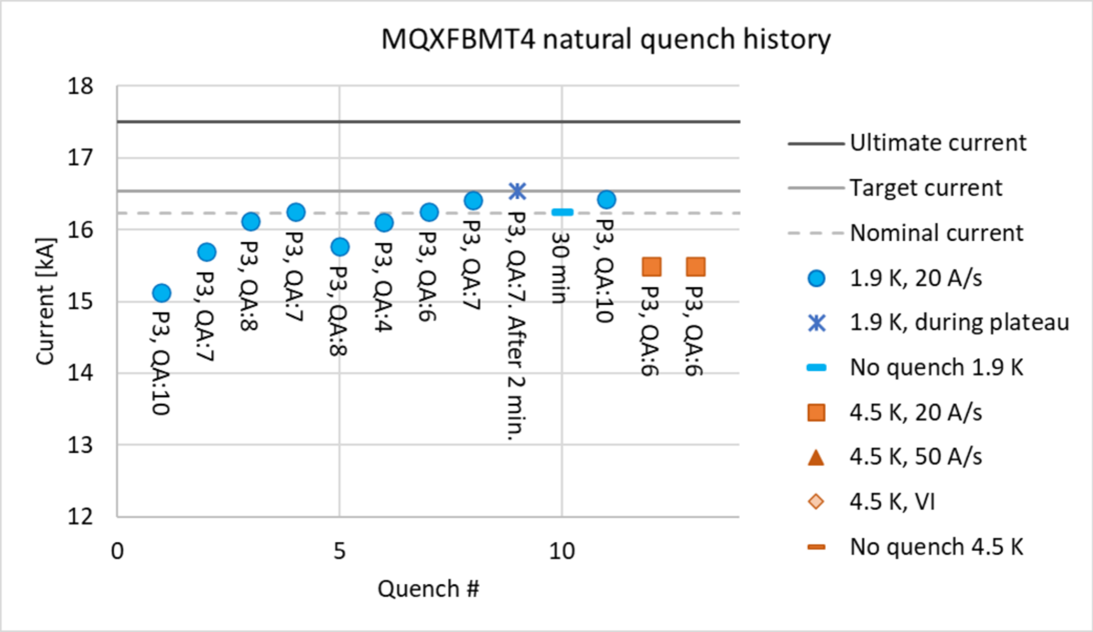
Additional slides

Readiness for the string

- Readiness dates for the string:
  - Q1: magnet cold mass being welded → Available in September 2024
  - Q2a: MQXFBP3b completed – H test in January → Available April 2024
  - Q2b: MQXFBP2b completed – H test in October → Available April 2024
  - Q3: magnet test being completed → Available in July 2024
  - CP cryostating phaseII ongoing → Available August 2024
  - D1 cryostating completed → Available March 2024

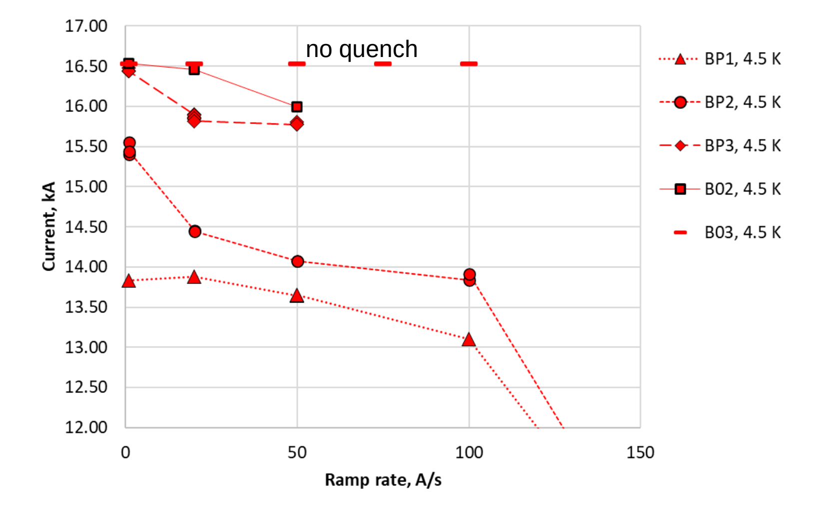
Plan B: MQXFBMT4

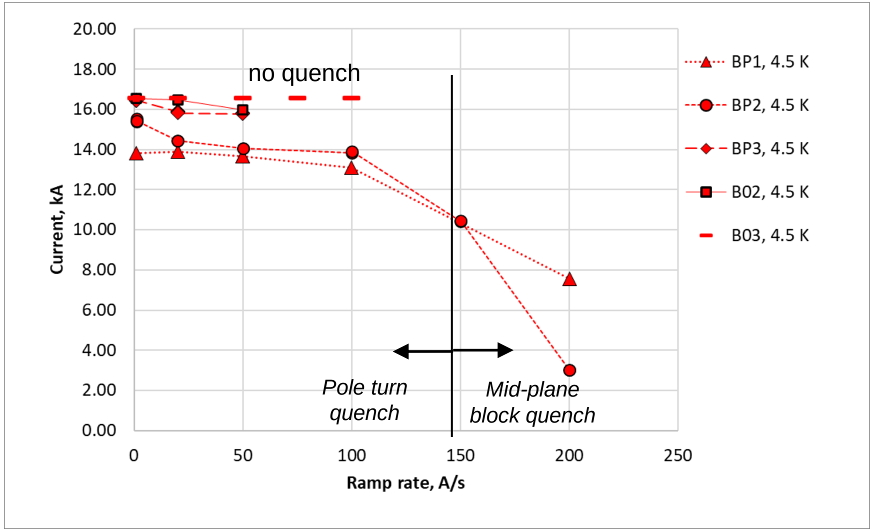
- A coil produced with minor modifications with respect to MQXFB02 (CR127) was assembled with the 3 non-limiting coils of MQXFBP1.
- Objectives:
  - Improve our understanding on the phenomenology for conductor limitation, in case MQXFB03 coils do not reach performance and we need to go back to the 'old' coil fabrication process
  - Practice coil replacement
- Results:
  - Longer training than previous magnets, always the new coil (CR127) is the quenching coil
  - Performance limitation at 15.5 kA at 4.5 K in CR127



Ramp rate dependency MQXFB magnets

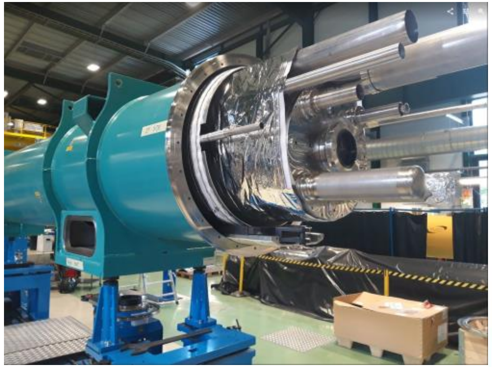
- MQXFB03 is able to reach target current at 4.5 K at 100 A/s



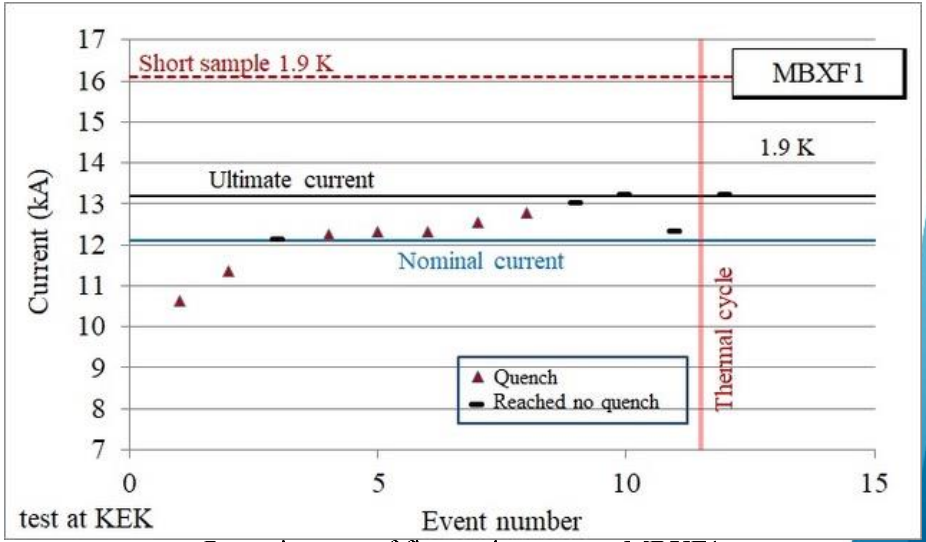


D1 (see T. Nakamoto talk)

- MBXFP1 (prototype) in the cryostat, ready to be connected to the test bench
  - After cold test, ~15 weeks of work (phase 2 cryo-stating for delivery to the string)
- MBXF1 (first series) reached requirements (vertical test)
- MBXF5 (second series) tests in October
- MBXF2 magnet assembly on-going
- Half of the coils are completed



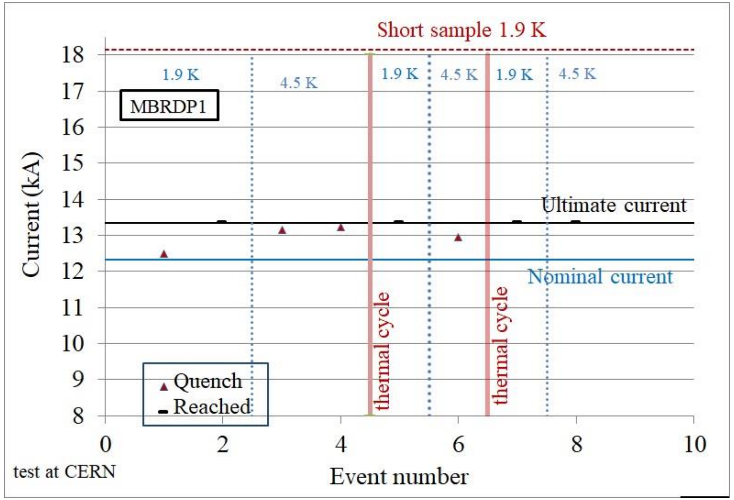
MBXFP1 in the cryostat



Powering test of first series magnet MBXF1
(T. Nakamoto, M. Sugano, K. Suzuki, J. C. Perez, et al)

D2 (see A. Pampaloni talk)

- D2 prototype (fully made in ASG) reached requirements
- Manufacturing of the first series magnets close to completion, expected at CERN in October 2023
  - RT magnetic measurements show that the iteration on field quality was successful
- Half of the series coils are completed, collaring of the second series magnet on-going



D2 cold mass on the test bench in SM18 (S. Farinon, B. Caiffi, A. Bersani, A. Foussat, et al)

Nested correctors (see F. Toral talk)

- The performance limitation seen on the retraining after change of torque in prototype MCBXFBP1 and MCBXFBP2 (short nested correctors) was overcome after a design iteration executed on MCBXFB01
- Three (out of 12) short nested series magnets produced and qualified for installation
  - From MCBXFB02, magnets fully manufactured in Elytt
  - Endurance test of MQXFB02 showed no degradation of the performance after 2000 cycles
- Prototype long magnet also qualified for installation

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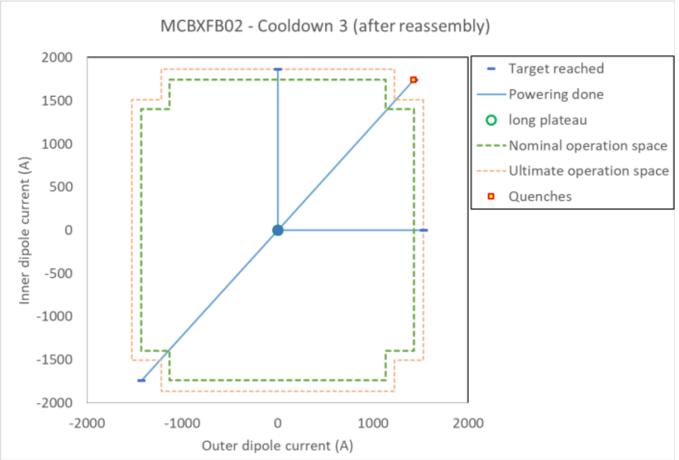
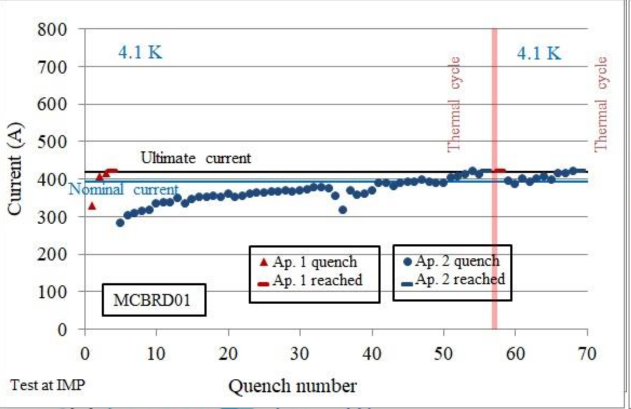
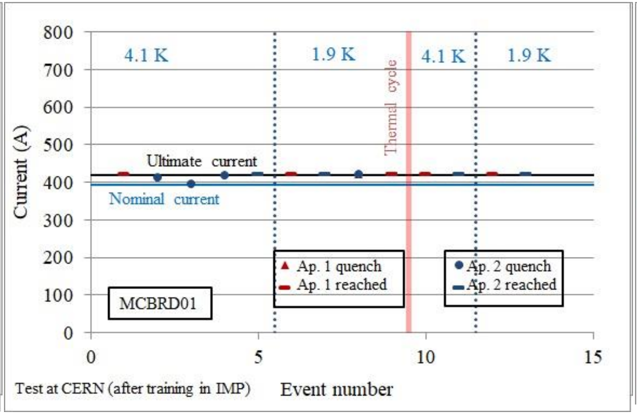


Test results of MCBXFB02
(G. Willering, F. Toral, J. C. Perez, C. Martins, et al)

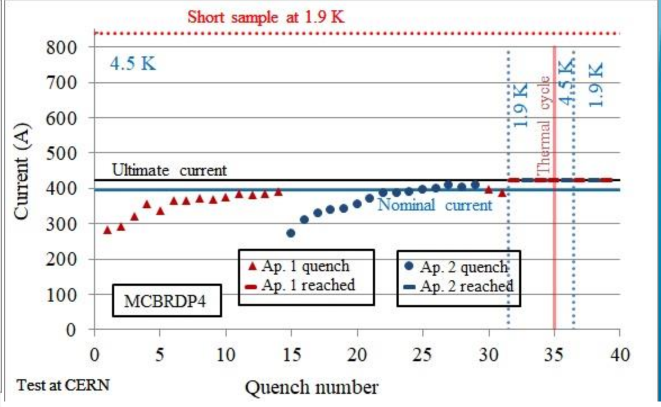
D2 correctors (see Q. Xu talk)

- Issue of very long training at 4.5 K observed in initial production at BAMA has been solved (iteration on impregnation procedures, and size of the channel gap)
- MCBRD01 and 02 reached performance at 4.5 K in IMP (nonconformity in retraining and HV test) (quarantine, non-conformed procedures, performance close to requirement)
- MCBRD03 reached performance at 4.5 K in IMP, good memory after thermal cycle
- MCBRD04 being tested IMP
- At CERN:
  - 3 prototype magnets have been completed and are conformed (MCBRDP2-3-4).
  - 2 magnets being built with components from IHEP (MCBRD11/12)





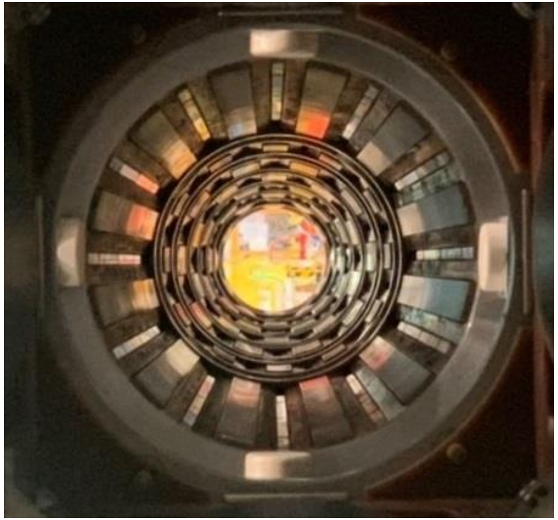
Training of MCBRD01 (PE: Q. Xu, test: W. Wu, G. Willering et al)



Training of MCBRDP4
(WPE: A. Foussat, G. Kirby, test: G. Willering et al)

High order correctors

- Production completed in SAES-RIAL vacuum (54 magnets)
  - All magnets delivered and accepted M. Statera, et al., IEEE TAS 32 (2022)
  - First corrector package cold mass completed, and being cryostated



(M. Statera, E. Gautheron, H. Prin, D. Duarte et al)