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

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G. Ambrosio, S. Feher, T. Nakamoto, Q. Xu, F. Toral, S. Farinon, M. Statera
A. Foussat, J.-C. Perez, E. Gautheron, H. Felice, A. Devred, et al,

Uppsala, 19 September 2022

List of contributors (from East to West)

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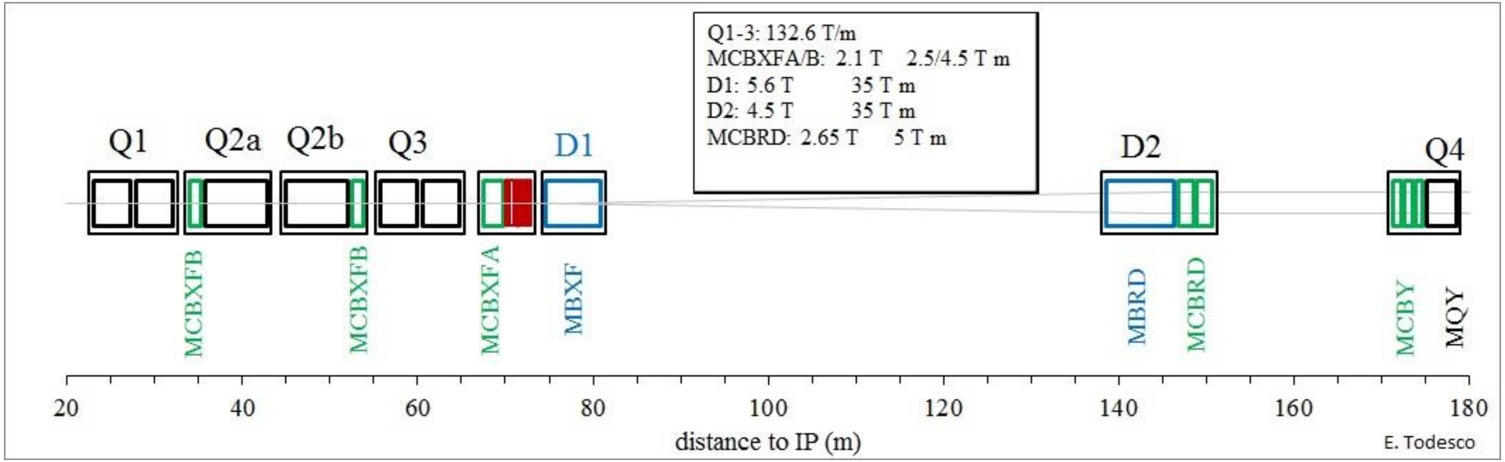
- Summary of Nb-Ti magnets
- Summary of MQXFA
- Status of MQXFB

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)

Structure

HL-LHC WP3: IR magnets
E. Todesco
D. Duarte Ramos (Deputy)

September 2021

Nb_3Sn magnets

Triplet Q1/Q3
G. Ambrosio, S. Feher (FNAL)
S. Izquierdo Bermudez (CERN WPE)

Triplet Q2
S. Izquierdo Bermudez (CERN WPE)

Nb-Ti correctors

Orbit correctors
F. Toral (CIEMAT)
J. Carlos Perez (CERN WPE)

High order correctors
M. Statera (INFN LASA)
E. Gautheron (CERN WPE)

D2 correctors
Q. Xu (IHEP)
G. Kirby, A. Foussat (CERN WPE)

D1-DFX Connection module
Y. Leclercq (CERN WPE)

Nb-Ti and resistive main magnets

Separation dipole D1
T. Nakamoto (KEK)
H. Felice (CERN WPE)

Recombination dipole D2
S. Farinon (INFN Genova)
A. Foussat (CERN WPE)

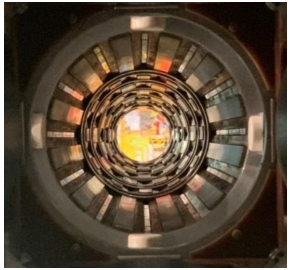
MQYY
D. Simon (CEA)
A. Foussat (CERN WPE)

MBW and MQW
P. Schwarz (CERN WPE)

Q4, Q10 in IR1 and IR5
H. Prin (CERN WPE)

Nb-Ti magnets

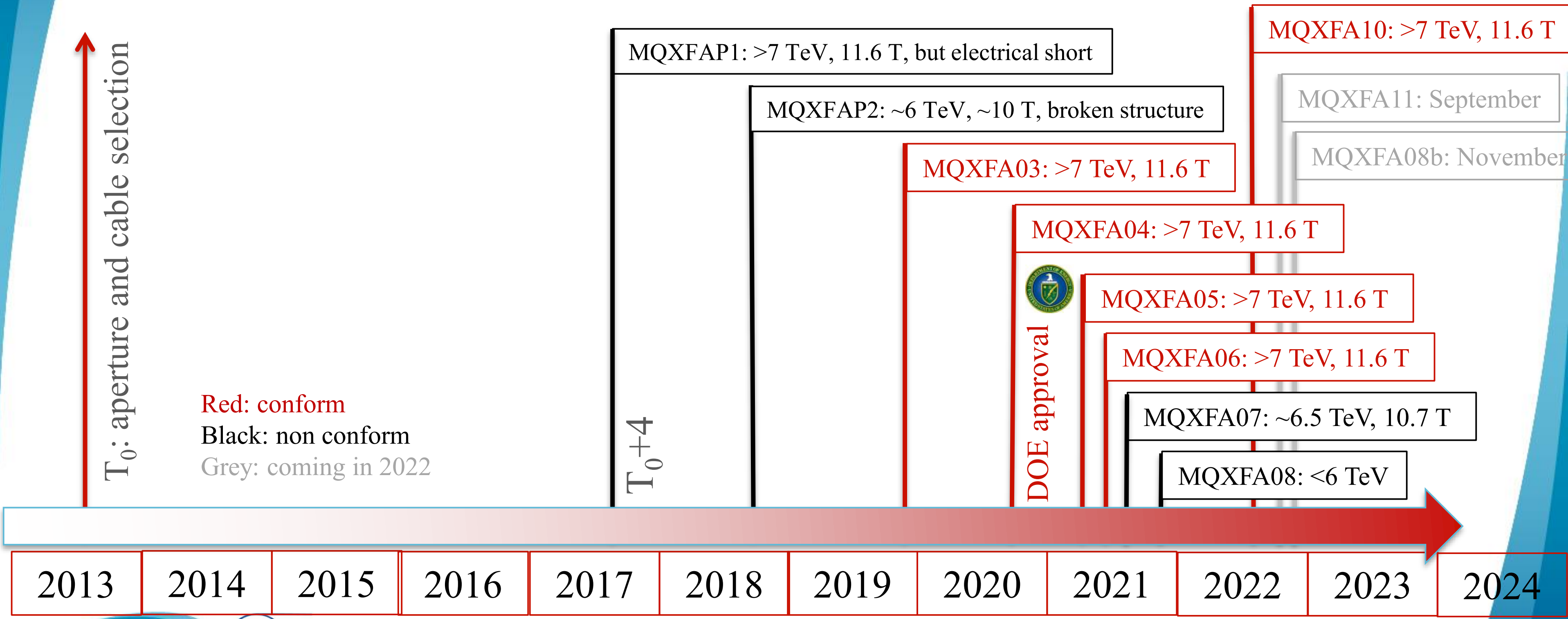
- D1: prototype cold mass completed, to be shipped at CERN end of 2022
  - See talk by T. Nakamoto
- D2: prototype cryomagnet completed, test is ongoing
  - See talk by A. Bersani
- D2 correctors: test of 3rd series magnet ongoing in China
  - See talk by Q. Xu and A. Foussat
- Nested correctors: first magnet fully manufactured in Elytt being completed, to be tested at CERN end of September
  - See talk by F. Toral
- High order correctors: production completed, 2/3 of the magnets tested and accepted – cold mass production started at CERN
  - See talk by M. Statera



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

US HL-LHC AUP

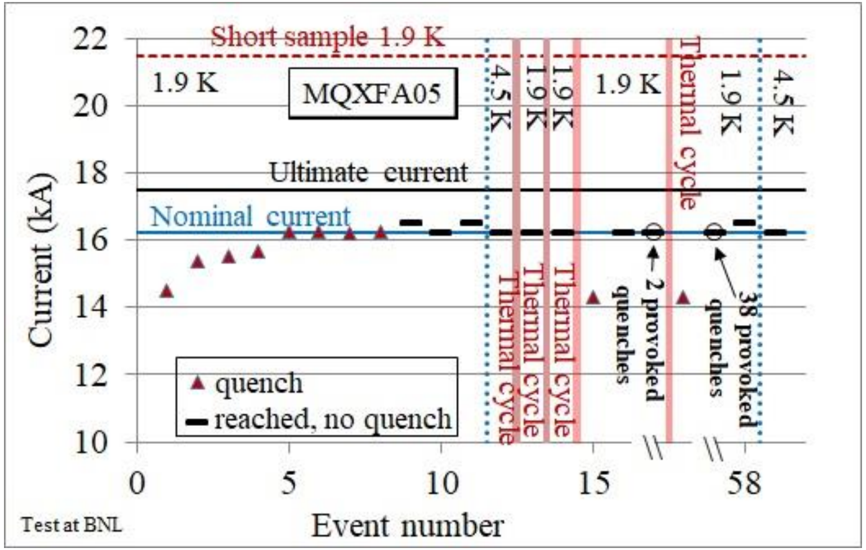
- 132.6 T/m at 7 TeV, corresponding to 11.4 T peak field

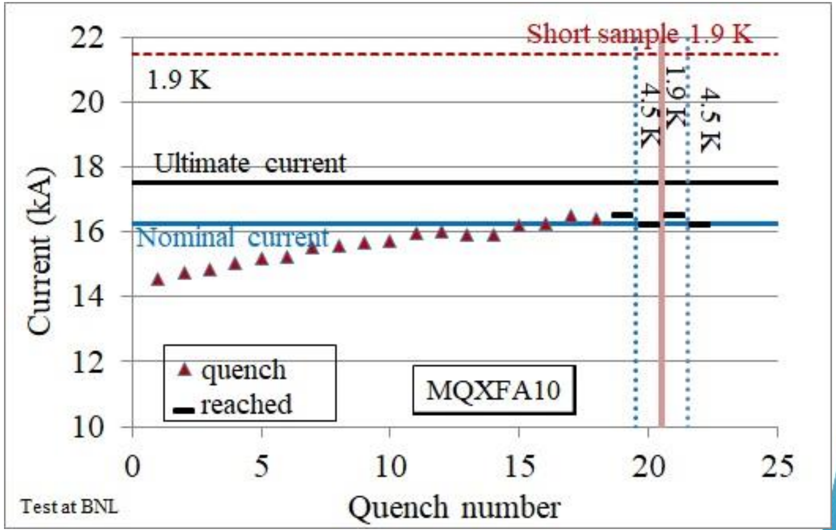


9 magnet tested, 14 more new magnets to test (9 and 11-23), plus re-assemblies

Status of MQXFA (see G. Apollinari and Ambrosio talks)

- Successful endurance test of MQXFA05
  - 5 thermal cycles, 50 quenches at nominal current (43 triggered)
- Successful test of MQXFA10: first conform magnet after the MQXF07 and MQXF08 issues

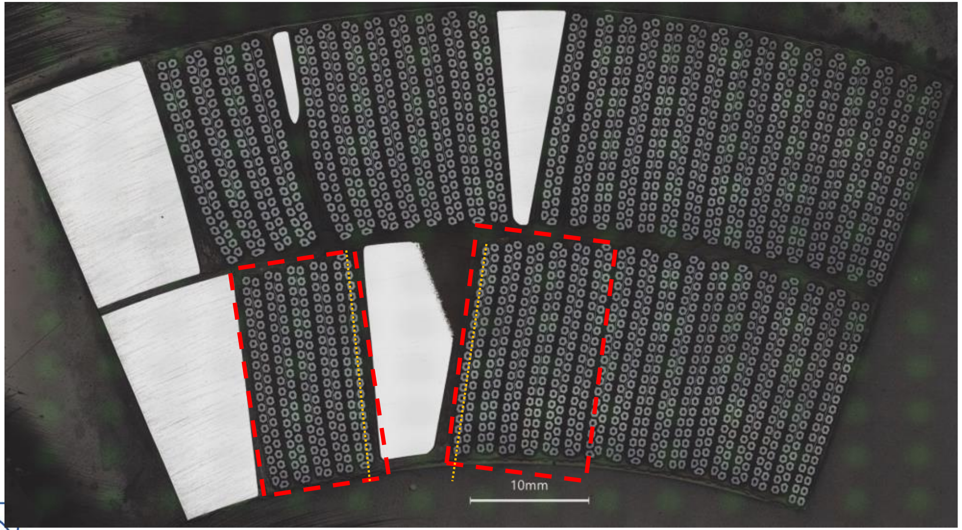


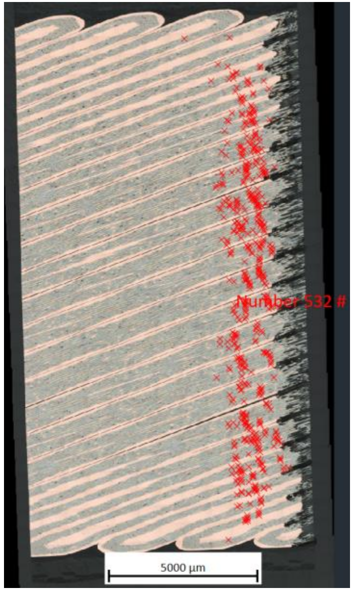


Endurance test of MQXFA05 and test of MQXFA10 (PE: G. Ambrosio, S. Feher, test eng.: B. Ahia)

Status of MQXFA (see G. Apollinari and Ambrosio talks)

- MQXFA07 limiting coil has been inspected via tomography / metallography at CERN
  - Result confirms the initial hypothesis on the location of the performance limitation: the transition between end spacers and wedge, with a large number of longitudinal cracks in the filaments (see talk by A. Moros on Thursday at 9h)
  - Feedback on the assembly procedures was implemented starting from MQXFA10 that reached performance





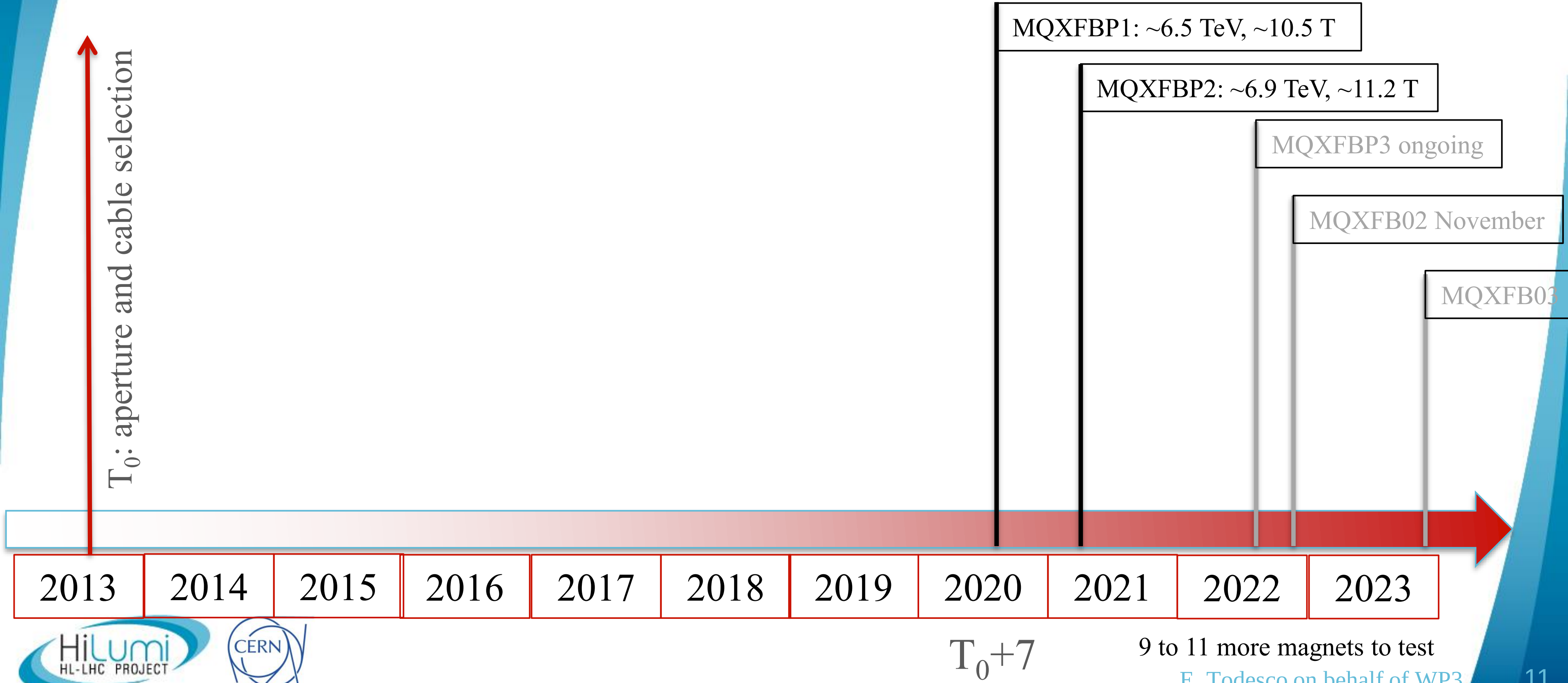
Presence of cracks (red crosses) in coil 214 (M. Crouvizier, A. Moros, S. Sgobba)

CONTENTS

- Summary of Nb-Ti magnets: D1, D2 and correctors
- Summary of MQXFA
- Status of MQXFB

A summary of the MQXFB program

- 132.6 T/m at 7 TeV, corresponding to 11.4 T peak field



Root cause analysis

- As shown in Chamonix, January 2022

Plans for MQXFB: root cause analysis

- Three possible root causes have been identified for the performance limitation of prototypes MQXFBP1 and MQXFBP2 at CERN
- 1) Cold mass assembly
  - Non-optimum mechanical coupling between welded outer stainless steel and magnet structure (aluminum rings)
- 2) Magnet assembly
  - Non-optimum magnet assembly parameters and processes (*e.g.*, keying and bladdering) leading to unbalanced and/or excessive peak stresses on coils
- 3) Coil manufacturing
  - Issues during coil manufacturing and/or handling leading to coil non-uniformities and/or deformation
- We cannot exclude that it may also be a combination of two of the three, or of all of them
- MQXFA program has demonstrated that coil manufacturing/handling (Cause 3) and magnet assembly (Cause 2) can be successfully developed and applied to coil and magnet assembly up to 4.2 m; MQXFA next step is qualification of cold mass assembly (Cause 1), with the difference that AUP cold mass includes 2 × 4.2-m-long magnets compared to 1 × 7.15-m-long magnet at CERN (see slide 3)

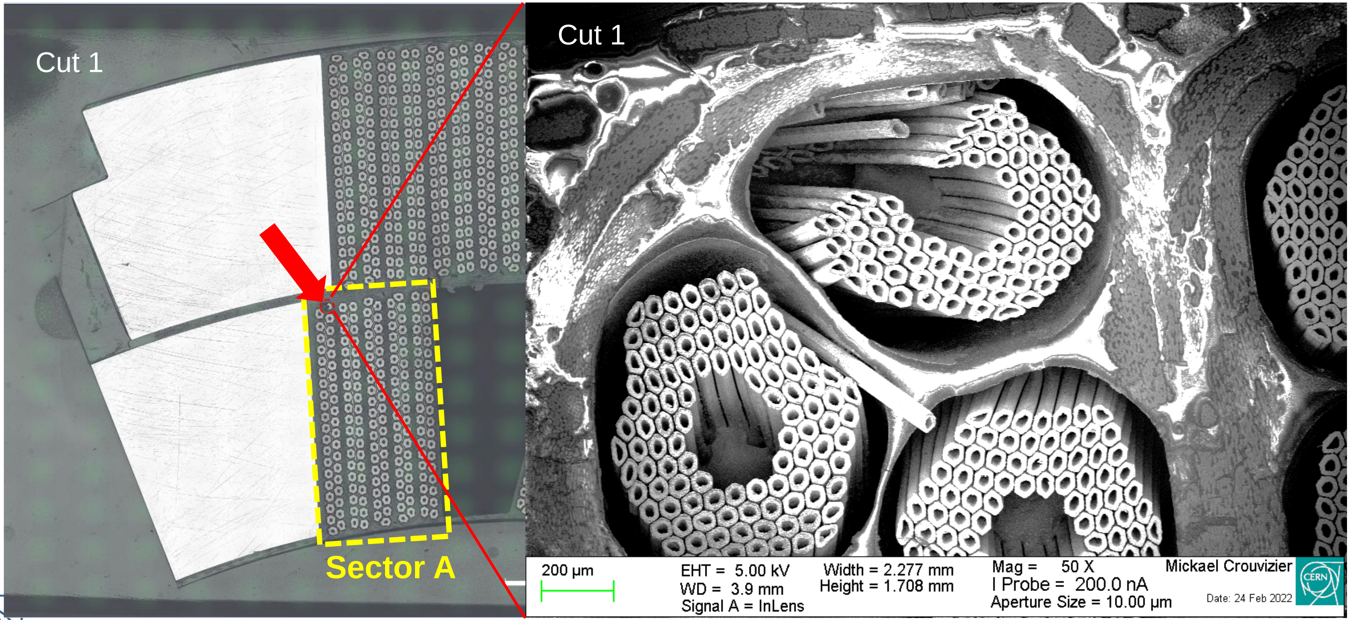
E. Todesco on behalf of WP3 13

MQXFB ongoing plan

- MQXFBP1: limited at 15 kA (~6.5 TeV), disassembled and limiting coil (108) inspected
- MQXFBP2: limited at 16 kA (~6.8 TeV), being assembled in final cold mass with corrector and to be used in the string
- MQXFBP3 (previously called MQXFB01): under test, nominal +300 A reached with one training quench
  - Old coils, old magnet assembly procedure, first magnet with optimized welding of SS shells
- MQXFB02: Test cold mass being completed (without corrector) – first magnet with new assembly procedures with peak stress of 65 MPa during assembly – test in November 2022
  - Old coils, new assembly procedure, second magnet with optimized welding of SS shells
- All these magnets have coils manufactured before the April 2021 stop of production
  - Coil production has been paused from April 2021 to May 2022 (see next slides)

Advancements on MQXFBP1 diagnosis

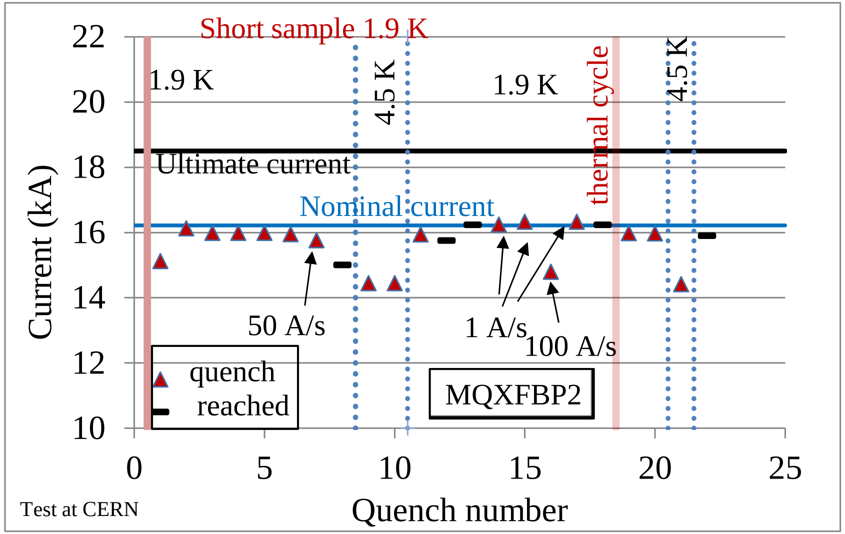
- MQXFBP1 performance limitation (6.5 TeV) analysis had a significant breakthrough in January 2022 (see talk of A. Moros on Thursday 9h): analysis of limiting coil 108
  - Broken filaments in a strand always in the same position of the cross-section, in several sections close to the transition in the poles –in agreement with voltage tap and quench antenna localization

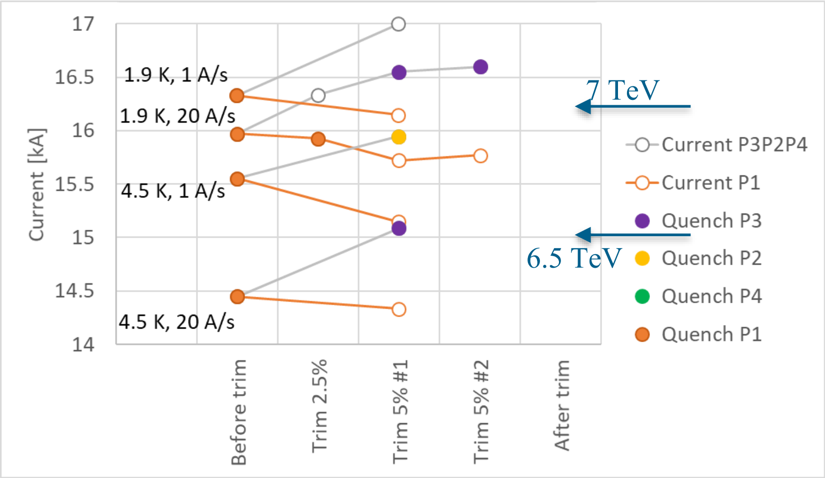


Broken filaments in coil 108, limiting MQXFBP1 (M. Crouvizier, A. Moros, S. Sgobba, et al.)

MQXFBP2

- MQXFBP2 had a performance limitation at ~16 kA (~6.8 TeV equivalent)
  - Since the phenomenology is very similar to MQXFBP1, it is likely that we have the same issue described in the previous slides
  - Trimmed powering developed in fall 2021: 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





Training of MQXFBP2 and trimmed powering (PE: S. Izquierdo Bermudez, test eng.: F. Mangiarotti, et al.)

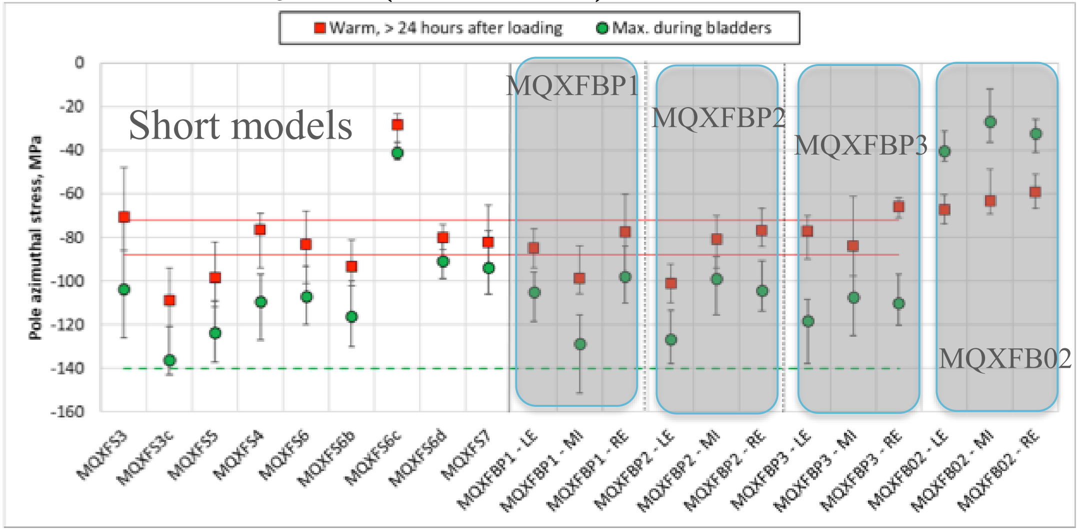
MQXFBP2b

- MQXFBP2b: to debug the final cold mass assembly, cryostating and horizontal test in March 2023
- If it keeps the same perfomance to be used in the string, ready by fall 2023

MQXFBP2 on assembly bench with nested corrector MCBXFBP1 (H. Prin, et al.)

MQXFBP3

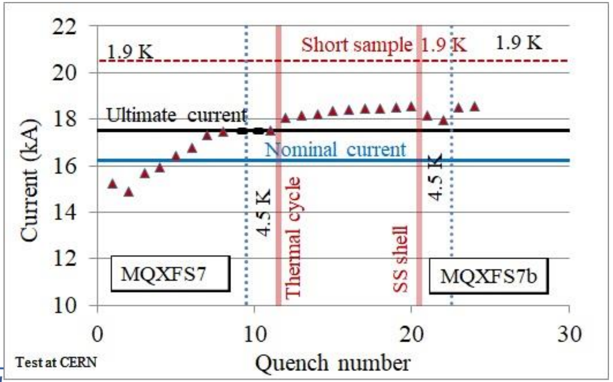
- MQXFBP3 history
  - Coils produced in March to October 2020
  - Assembly in November 2020-January 2021, with max. measured peak stress of the order of 140 MPa
  - SS shell welding with strong interference done in February 2021, as planned – Magnet not tested after the limitation seen in April 2021 in MQXFBP2 – optimized SS shell welding done in April 2022 after successful test on short model MQXFS7 (see next slide)

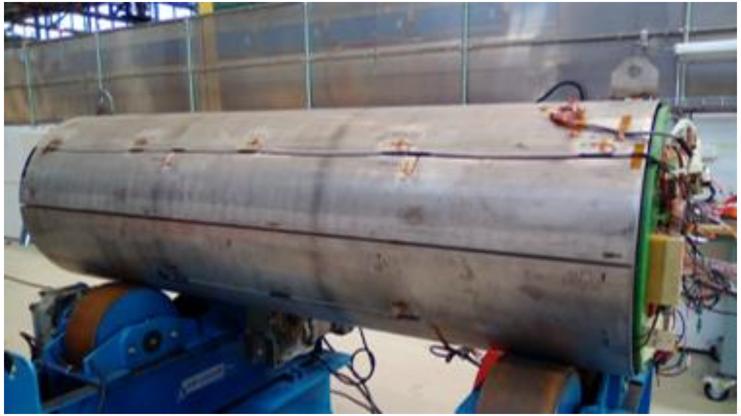


Peak load during assembly in short model and (S. Izquierdo Bermudez, M. Guinchard, et al.)

New procedure for welding and fixed point

- The stainless steel shell welding history (see talk of H. Prin on Thursday at 11h50)
  - After performance limitation seen in April 2021 in MQXFBP2, it was decided to review the design principles (no mechanical coupling between SS shell and magnet)
  - Neither LARP, nor AUP, ever tested bladder and key magnets integrated with SS shell, in H position
  - AUP put on hold the welding of MQXFA03 and MQXFA04 in June 2022
  - New Functional Requirement Specifications have been adopted and agreed for MQXFA/B, including requirements on the fixed point magnet/SS shell
  - MQXFB procedures validated on a short model at CERN in August 2021

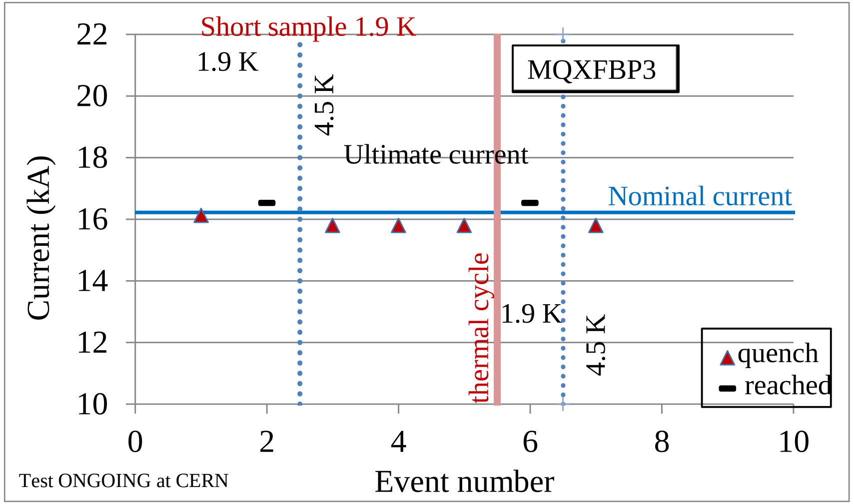


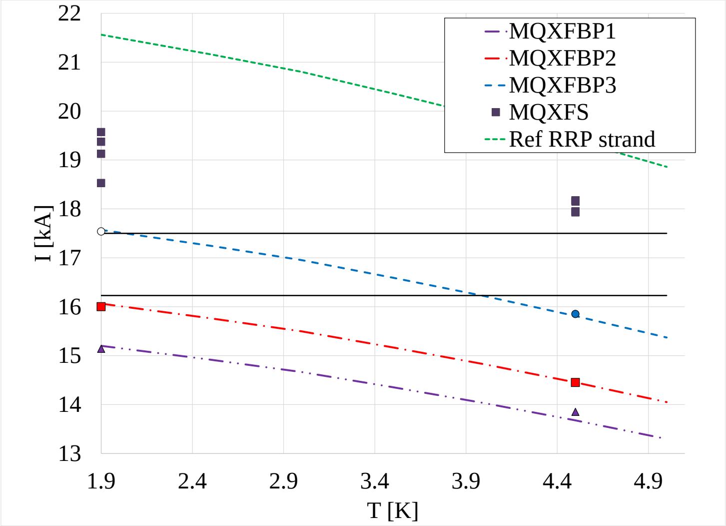


Test results of MQXFS7 with new procedure for SS shell welding (S. Izquierdo Bermudez, H. Prin, F. Mangiarotti, et al.)

MQXFBP3

- MQXFBP3 is under test
  - Nominal plus 300 A reached during first powering with one training quench
  - At 4.5 K, we see the same type of limitation observed in MQXFBP1 and MQXFBP2 but at much higher levels
  - Three cool-down foreseen: if performance is confirmed, assembly in final cold mass in winter, test in spring 2023

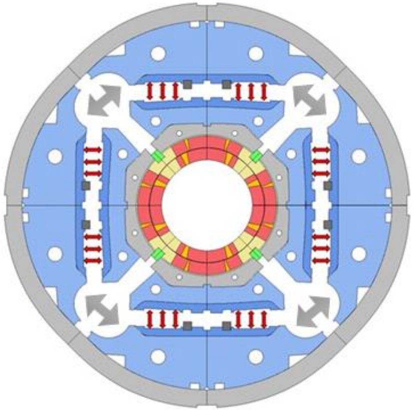




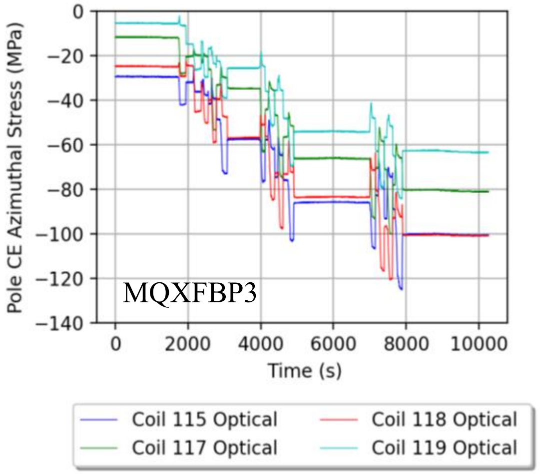
Test results of MQXFBP3 and comparison to MQXFBP1 and MQXFBP2, and short models
(PE: S. Izquierdo Bermudez, test eng.: F. Mangiarotti, et al.)

MQXFB02 and magnet assembly

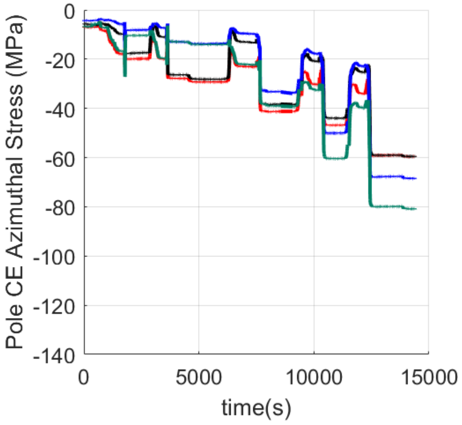
- An optimized procedure of bladder and key loading has been developed at CERN during the prototype phase in 180, and tested in November-December 2021 (see J. Ferradas talk on Thursday at 11h)
  - This procedure is based on stretching the outer structure via additional bladders in the HX holes
  - It eliminates the overshoot during loading (−30 MPa, as high as 50 MPa), and minimizes peak stress
  - This is a major advancement for the bladder and key technology applied to long quadrupole magnets



Loading via additional bladders



Standard loading procedure in MQXFBP3

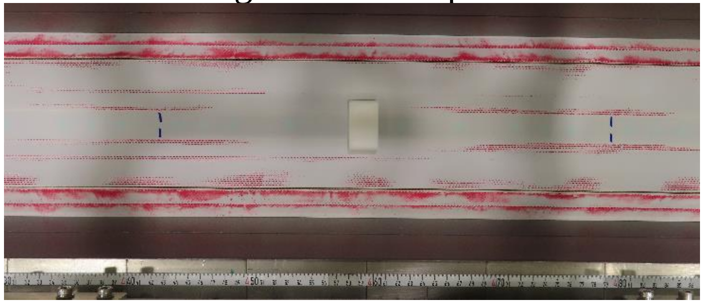


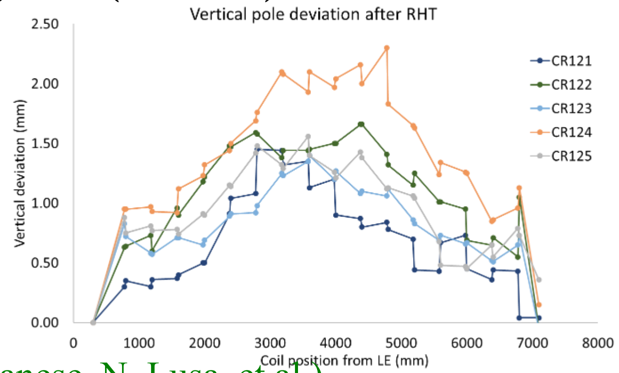
Improved loading procedure in MQXFB02

[N. Bourcey, S. Ferradas, S. Izquiredo, A. Milanese et al]

Coil manufacturing

- Several actions ongoing to improve the coil manufacturing
  - Analysis of 108 (limiting coil of MQXFBP1) shows that breakages are close to pole transitions
  - Analysis of 126 shows that (few) events are also present in a virgin coil (not tested)
  - Efforts are focusing on the «hump»





The hump (S. Izquierdo Bermudez, A. Milanese, N. Lusa, et al.)

- Fast-tracks have been defined to assess the performance of the two coils manufactured after the 1 year long pause
  - MQXFBMT4 and MQXFBMT5, where new coils are assembled with existing coils – to be tested in April and August 2023
- MQXFB03, the first magnet using 4 coils manufactured after the pause, will be tested at the end of the year 2023

CONCLUSIONS

- Correctors are well underway
  - Manufacturing of coils in Elytt for the nested corrector had a first important validation step
  - BAMA is solving the issues with long training and quality of the production is improving
  - INFN-LASA will celebrate in December the end of the acceptance tests for the last production batch
- Cold mass manufacturing procedures succesfully applied to all types of main magnets
- MQXFA
  - Successful endurance test of the first Nb_3Sn full length magnet – major milestone
  - Issues with MQXFA07 and MQXFA08 performance seem to be understood and MQXFA10 is conform
  - Next critical steps before end of the year: test of the first cold mass in horizontal position and validation of coil replacement in MQXFA08b
- MQXFB
  - Last prototype has achieved nominal plus 300 A – reliability being assessed in the coming months
  - Repeatability of this result to be assessed in test of MQXFB02
  - Efforts still ongoing to improve coil manufacturing

D1 (see T. Nakamoto talk)

- After the test of the prototype in vertical KEK test station (May 2021), past year has been dedicated to cold mass manufacturing and test facility upgrade
  - Shipping to CERN before the end of 2022, and horizontal test in SM18 in early 2023
- The winding at Hitachi of the coils of first (MXBF5) and second (MBXF1) series magnet has been completed (1/3 of total production!)
  - These coils had a fine tuning of cross-section to correct 5 units of b_3 and -5 of b_5
- Collaring of MBXF5 completed, but issue with procedures has been found → decollaring
  - Vertical test of MBXF1 expected for end of 2022

Cold mass of MBXFP1 (T. Nakamoto, M. Sugano, K. Suzuki, H. Felice, et al)

D2 (see B. Caiffi talk)

- D2 prototype (fully made in ASG) test at 1.9 K in SM18 is ongoing
  - Final cold mass configuration, with one D2 corrector from CERN and one from China in-kind contribution
  - First use of cryostating tooling for HL-LHC at CERN
- Manufacturing of first series coil completed
  - Fine tuning of cross-section to optimize b_3 and b_5
  - First series magnet at CERN in mid 2023,

  test in early 2024

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)

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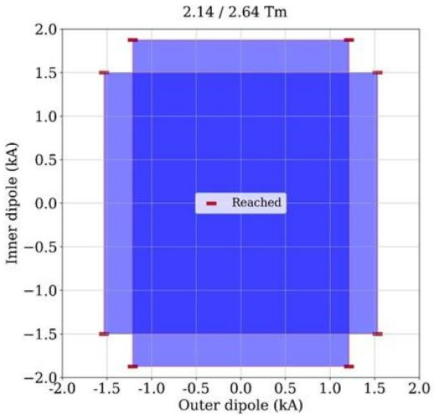
- The performance limitation seen on the retraining after change of torque in prototype MCBXFBP1 and MCBXFBP2 (short nested correctors) was overcome after a design iteration executed on MCBXFB01
- The second prototype had the inner layer changed with a new inner layer made by Elytt, both to validate the first production coils and to verify the reproducibility of the design change
  - Magnet reached performance at 7.5 TeV equivalent without retraining after thermal cycle – second magnet conform
- First short corrector fully manufactured in Elytt is being completed (MCBXFB02)
  - To be tested in October 2022 at CERN
- First long prototype to be assembled in October at CERN

ELYTT ENERGY



Test results of MCBXFP2c
(S. Ferradas Troitino, F. Toral, J. C. Perez, C. Martins, et al)

HiLumi HL-LHC PROJECT
CERN

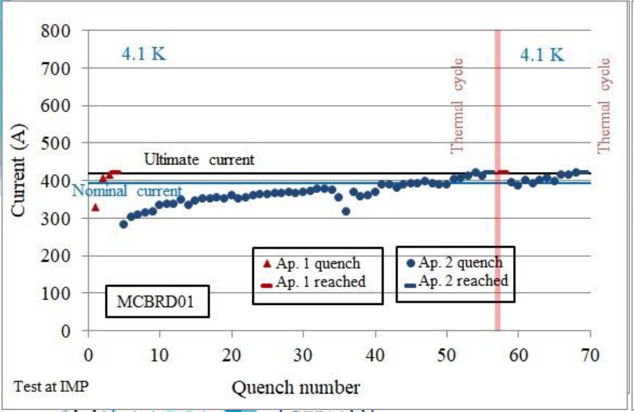
D2 correctors (see Q. Xu) talk

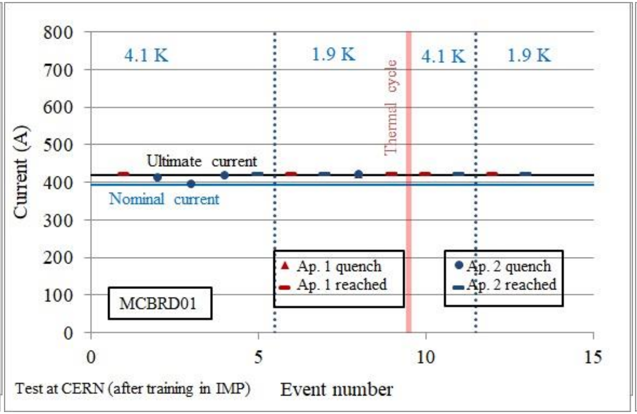
IHEP

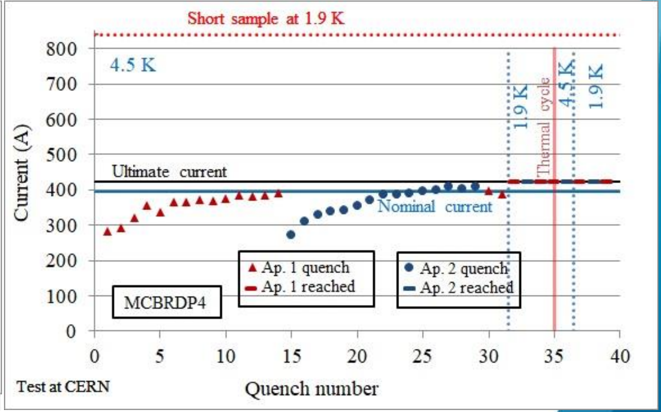
IMP

Superconductor Technology
苏州八匹马超导科技有限公司

- D2 correctors (see also A. Foussat talk on Wednesday at 9h)
  - Issue of very long training at 4.5 K observed in inital production at BAMA has been solved (iteration on impregnation prodecures, and size of the channel gap)
  - First fast training coils to be tested in MCBRD03
  - MCBRD01 and 02 reached performance at 4.5 K in IMP (non conformity in retraining and HV test)
  - MCBRD01 retested at CERN at 1.9 K and achieved training requirements – pending issue on insulation
  - MCBRD02 to be tested at CERN in October 2022
  - Additional magnet completed at CERN (MCBRDP4) - conform







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

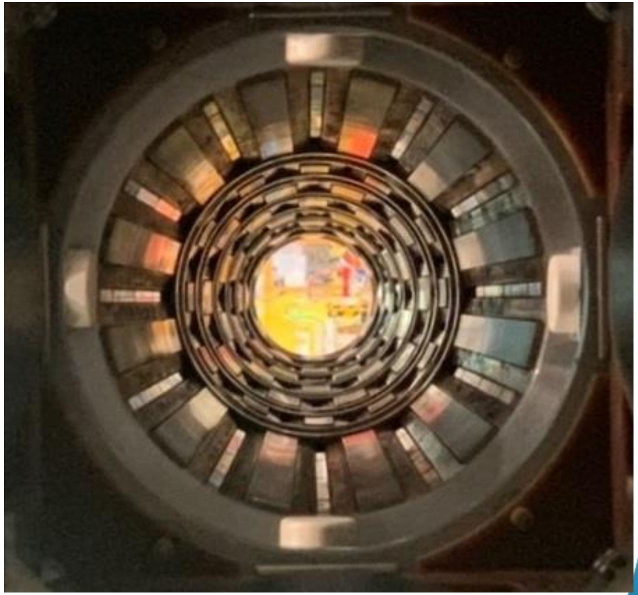
Training of MCBRDP4
(WPE: A. Foussat, G. Kirby, test: G. Willering et al)

HL-LHC PROJECT

CERN

High order correctors (see M. Statera talk)

- Production completed in SAES-RIAL vacuum (54 magnets)
  - 37 magnets tested and accepted (2/3)
  - Cold mass assembly operations started at CERN, including alignment



The nine high order correctors assembled in the prototype cold mass
(M. Statera, E. Gautheron, H. Prin, et al)