Status and challenges of interaction region magnets for HL-LHC

E. Todesco, on behalf of HL-LHC WP3, CERN TE-MSC, and several collaborations

Honolulu, 24 October 2022

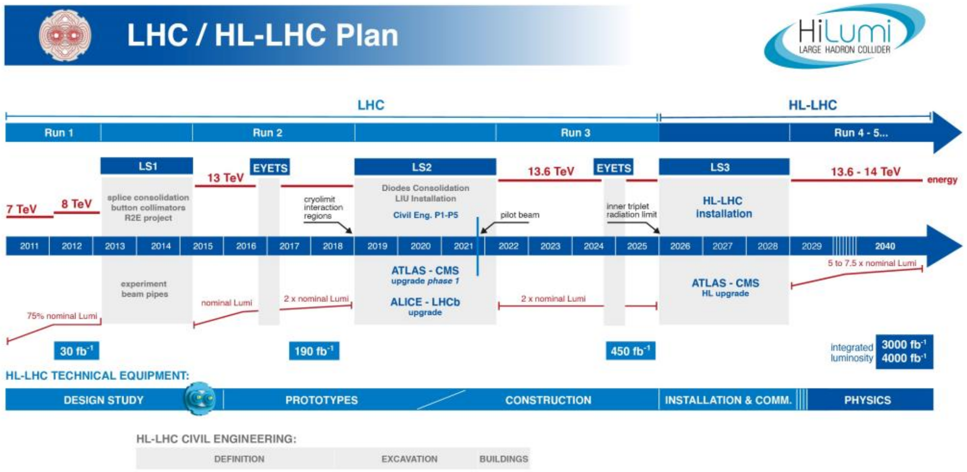
List of contributors (from East to West)

- KEK: T. Nakamoto, M. Sugano, K. Suzuki, N. Kimura et al.
- IHEP: Q. Xu, Y. Wang, D. Ni, W. Wu, L. Li, Q. Peng, et al.
- FREIA: K. Pepitone, R. Ruber, et al.
- INFN-LASA: M. Statera, M. Sorbi, M. Prioli, S. Mariotto, et al.
- INFN-Genova: P. Fabbricatore, S. Farinon, B. Caiffi, A. Bersani, R. Cereseto, et al.
- CERN: S. Izquierdo Bermudez, E. Gautheron, G. Kirby, A. Foussat, J. Carlos Perez, F. Rodriguez Mateos, N-Lusa, E. Ravaioli, M. Bednarek, J. Ferradas Troitino, F. Mangiarotti, M. Bajko, L. Bottura, A. Devred, H. Felice, G .Willering, S. Ferradas Troitino, M. Duda, H. Prin, A Milanese, J. Ferradas Troitino, E. Takala, R. Principe, A. Ballarino, D. Tommasini, B. Bordini, J. Fleiter, V. Parma, F. Savary, D. Duarte Ramos, Y. Leclercq, M. Struik, L. Fiscarelli, S. Russenschuck, C. Petrone, G. de Rijk, L. Rossi, P. Fessia, S. Riebe, H. Garcia Gavela, G. Vandoni, L. Quain Solis, A. Dallocchio, D. Perini, P. Moyret, S. Sgobba, A. Moros, M. Crouvizier, B. Bulat, M. Guinchard and its team, et al.
- CEA: H. Felice, D. Simon, et al.,
- 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.,

In red: management at CERN and in collaborations

The HL-LHC project

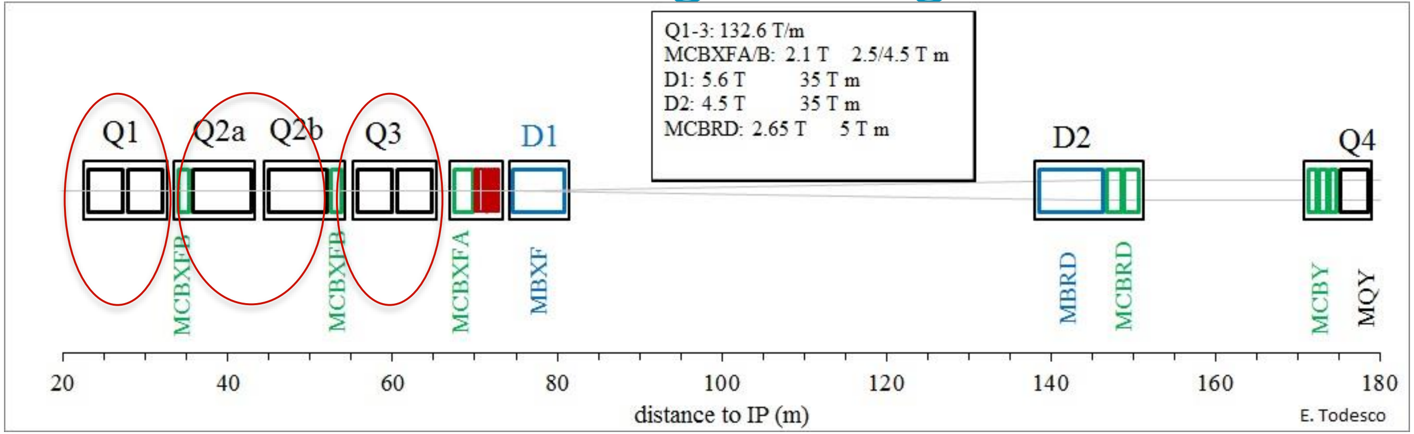
- Luminosity upgrade of LHC
  - Studies since 2000
  - Investment of DOE on Nb_3Sn (LARP) and on crab cavities
  - HiLumi design studies in 2012-2014
  - Project started in 2015
  - Installation in 2026-28
  - Larger aperture triplet and crab cavities are the enabling technologies
  - SC technologies: interaction region magnets (this talk), MgB_2 link to power the main magnets (A. Ballarino), 11 T dipoles (A. Devred, D. Perini, installation on hold)



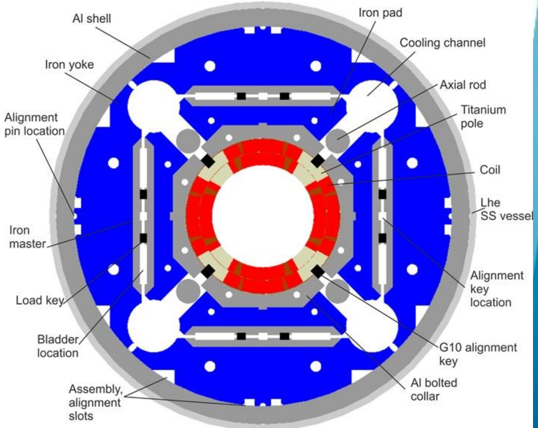
- IR magnets: replacing magnets in the 160 m left and right of ATLAS and CMS with larger (double) aperture magnets
  - 220 MCHF budget (w/o personnel), including 8 collaborations/in kind contributions

www.cern.ch/hilumi/wp3

Interaction region magnets



- MQXF Nb_3Sn quadrupoles
  - High j_c Nb_3Sn strand RRP, 1280 A/mm^2 at 15 T, 4.22 K
  - 11.3 T conductor peak field, 150 mm aperture, 110 MPa accumulation of stress
  - Loadline fraction of 77% at nominal current (7 TeV energy)
- Longest Nb_3Sn accelerator magnet so far (7.17 m)
  - First use of Al rings structure and b&k for magnets to be installed
    Caspi, et al. IEEE TAS 11 (2001)
  - First use of CLIQ as protection system Ravaioli, Kirby, et al IEEE TAS **24** (2014)
- Mini-series of 30 magnets, manufactured in US labs and at CERN



MQXF cross-section
(P. Ferracin, G. Ambrosio, et al.)

MQXF short model synoptic

- 6 short models built, 5 conform

T_0: aperture and cable selection

MQXFS1: ≥12.9 T

MQXFS3: ~10.6 T

MQXFS5: ≥12.7 T

MQXFS4: ≥13.1 T

MQXFS6: ≥13.4 T

MQXFS7: ≥12.7 T

MQXFS8

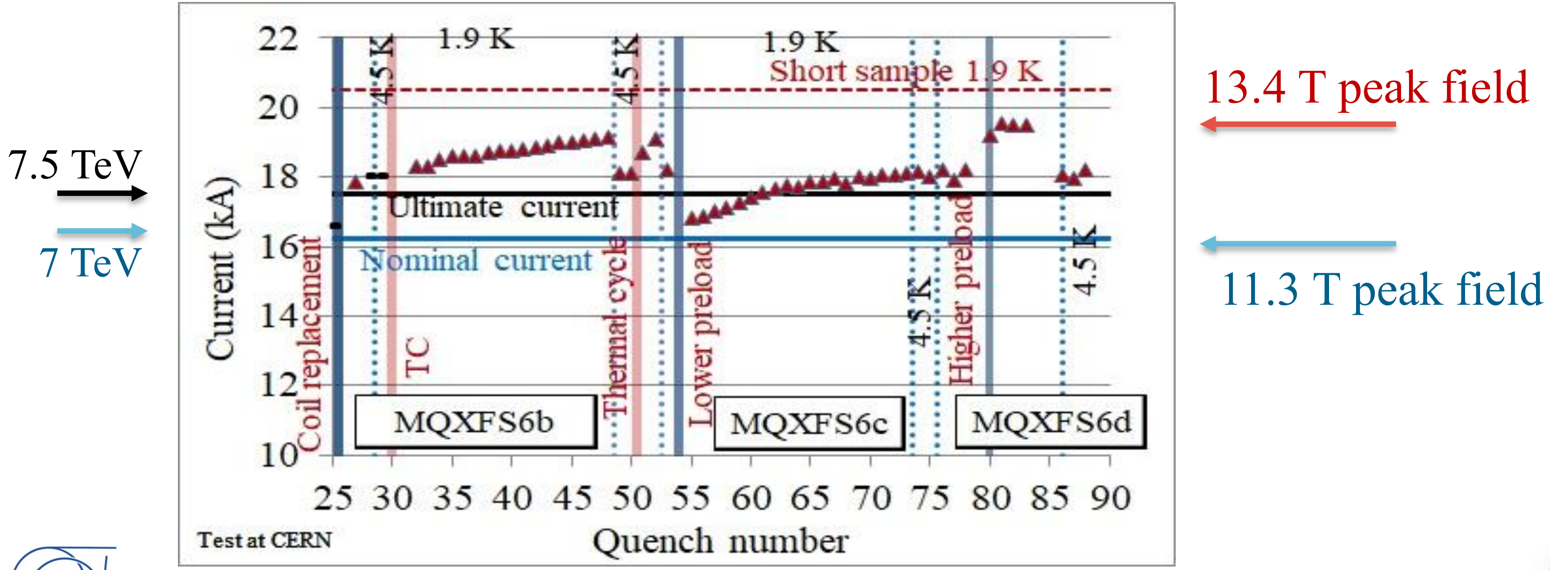
RED indicates conform magnets

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

T_0+3

MQXF short model results

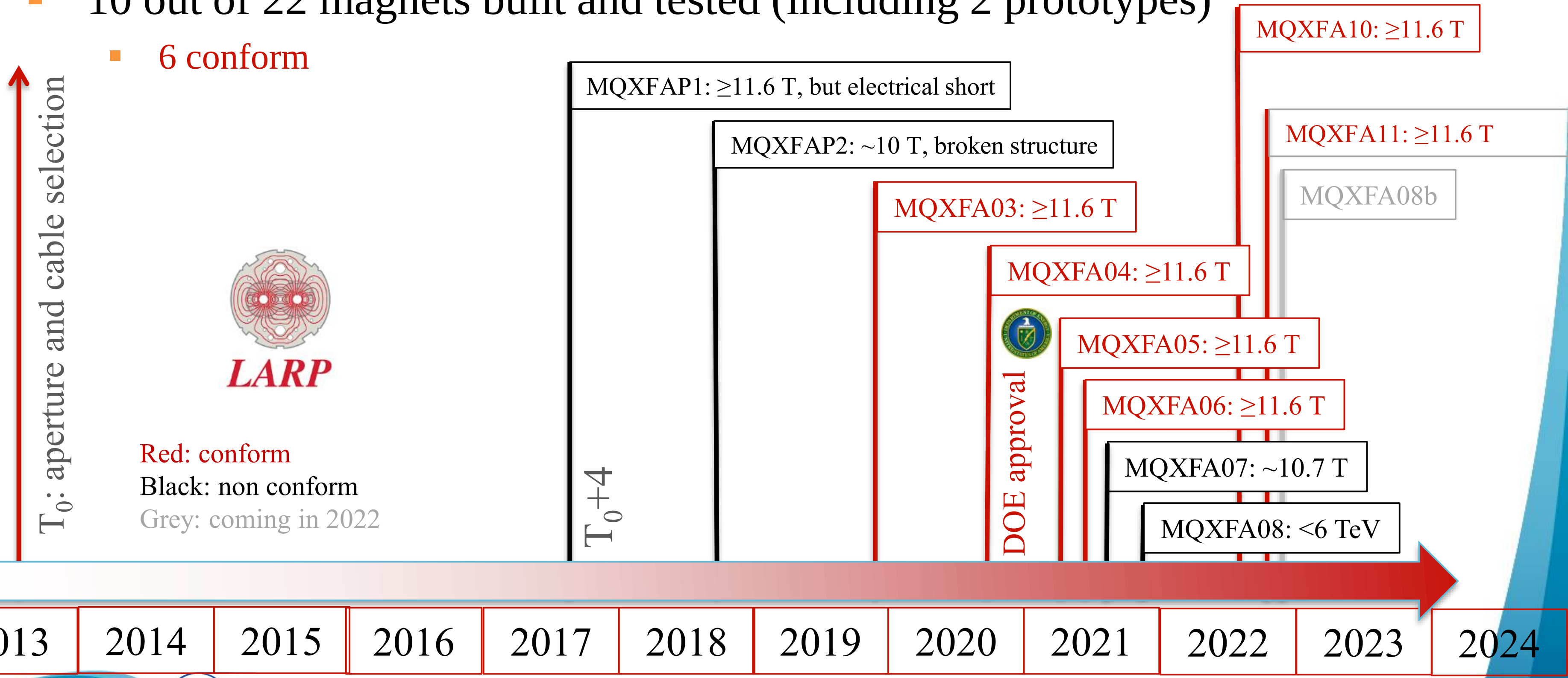
- Ability to operate at nominal current both at 1.9 K and at 4.5 K
- Large margin: ability to achieve 1 to 2 T conductor peak field in excess of what required
- Perfect memory: no retraining after thermal cycle up to ultimate current
- Reproducibility: 5 out of 6 magnets reached operation >7.5 TeV



Preload experiment on MQXFS6 (S. Izquierdo Bermudez, F. Mangiarotti, et al.)

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

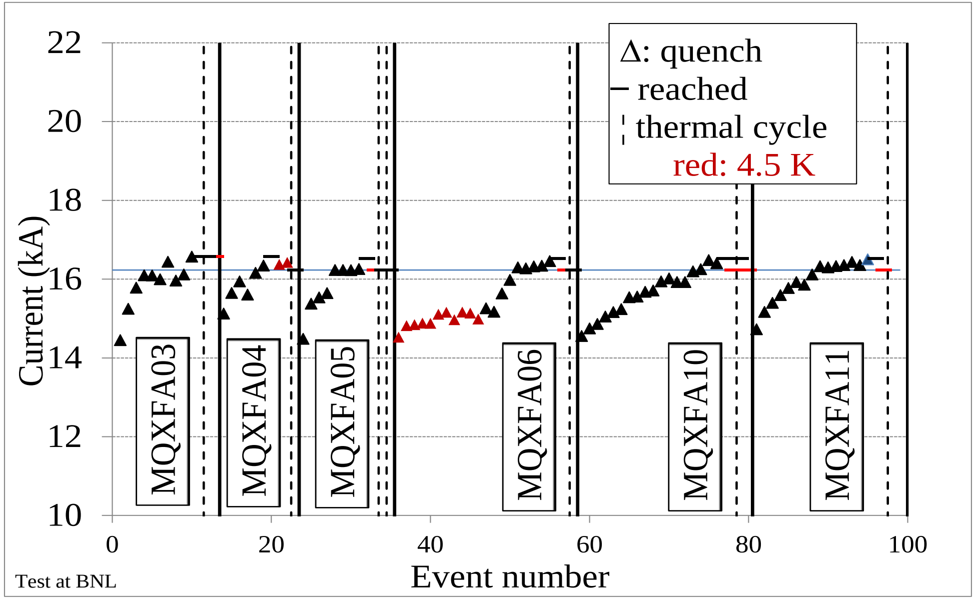
- 10 out of 22 magnets built and tested (including 2 prototypes)
  - 6 conform



10 magnet tested, 13 more new magnets to test (9 and 12-23), plus re-assemblies

MQXFA conform magnets (see talk by G. Ambrosio)

- MQXFA program confirms
  - Operation at nominal current plus 300 A, both at 1.9 K and 4.5 K
  - Perfect memory, i.e. no retraining, and some robustness

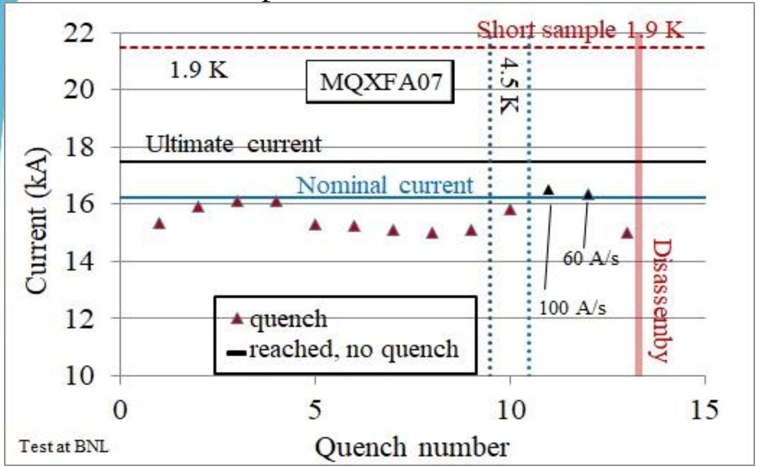


Powering test of conform MQXFA magnets (J. Muratore, B. Ahia, S. Feher et al.)

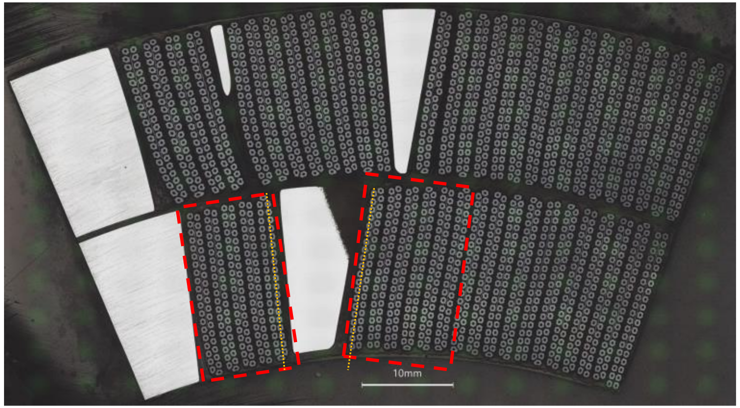
Non conform MQXFA11 transport

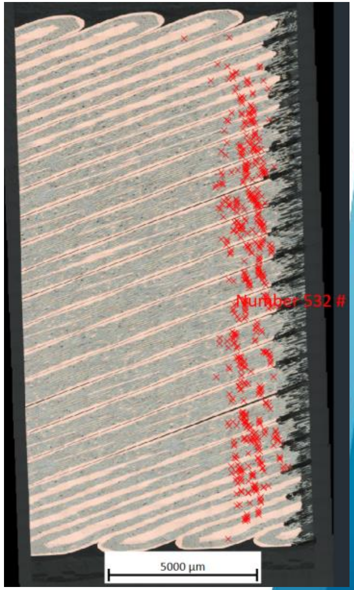
MQXFA performance limitations (see talk by G. Ambrosio)

- MQXFA07 and MQXFA08 showed performance limitations with reverse behaviour
  - Issue identified in an asymmetry in the assembly, at the transition straight part-end
  - MQXFA07 limiting coil has been inspected via tomography/mterialography at CERN: large number of longitudinal cracks in the filaments in that region (see talk by S. Sgobba)
  - Feedback on the assembly procedures was implemented starting from MQXFA10 that reached performance



Power test of MQXFA07 (J. Muratore, S. Feher, G. Ambrosio et al.)





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

MQXFB synoptic (see S. Izquierdo Bermudez talk)

- 3 prototypes tested

T_0: aperture and cable selection

MQXFBP1: ~10.5 T

MQXFBP2: ~11.2 T

MQXFBP3: ≥ 11.6 T

MQXFB02

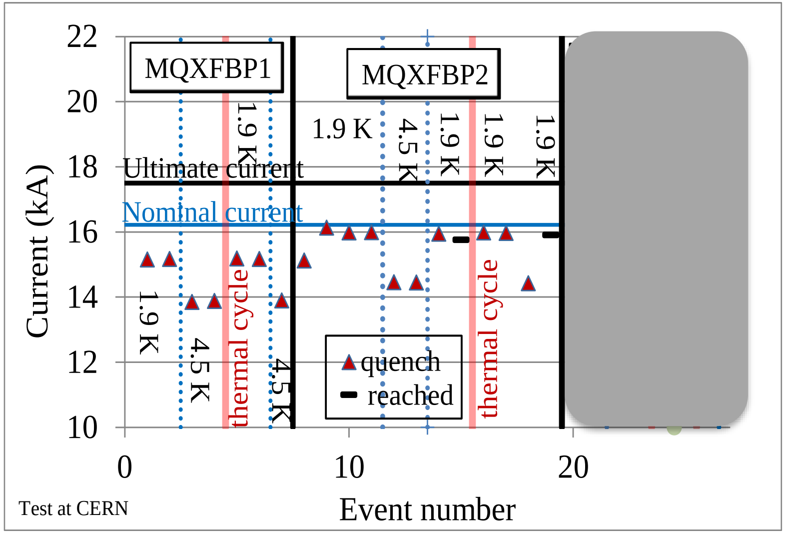
2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

T_0+7

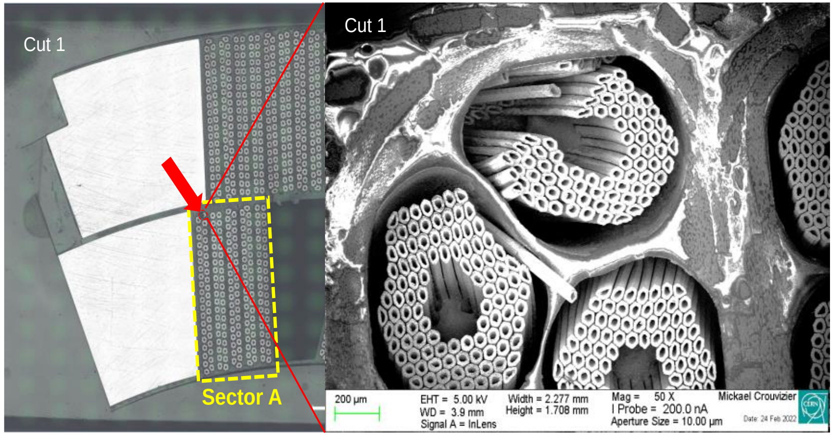
9 to 11 more magnets to test

MQXFB performance limitations

- MQXFBP1 and MQXFBP2 were limited below nominal current
  - Contrary to MQXFA, no reverse behaviour, i.e., 4.5 K performance consistent with 1.9 K (70% and 74% of short sample) – quenches in straight part
  - MQXFBP1 was disassembled, and longitudinally broken filaments were found in the limiting coil, in agreement with quench antenna and voltage tap locations



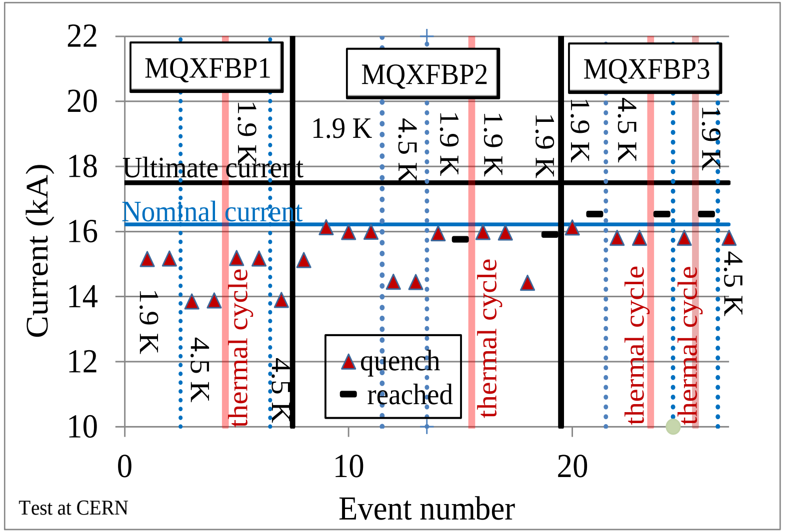
MQXFB prototype performance
(F. Mangiarotti, S. Izquierdo Bermudez, et al.)



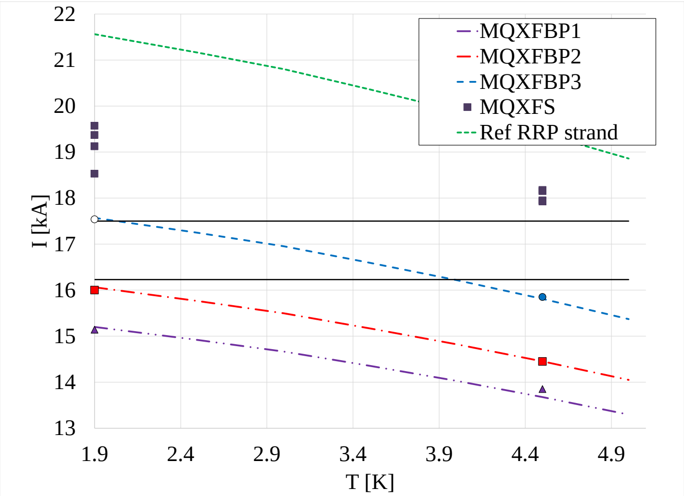
Broken filaments in coil 108, limiting MQXFBP1
(M. Crouvizier, A. Moros, S. Sgobba, et al.)

MQXFB performance limitations

- MQXFBP3 reached nominal current plus 300 A
  - But at 4.5 K the limitation is visible, corresponding to 80% of short sample
  - No degradation after thermal cycles
  - A three bullet plan was defined to address possible causes: (i) integration in LHe vessel (addressed in MQXFBP3), (ii) assembly, (iii) coil manufacturing (see talk by S. Izquierdo Bermudez)



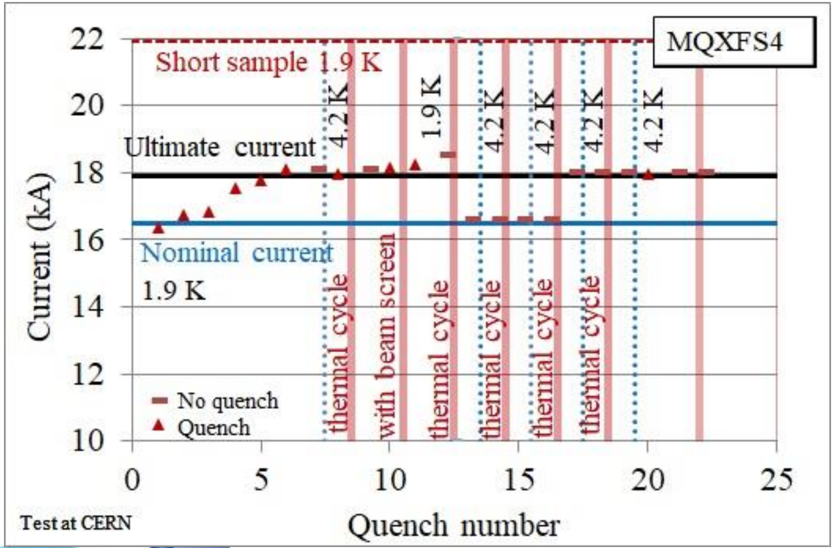
MQXFB prototype performance
(F. Mangiarotti, S. Izquierdo Bermudez, et al.)



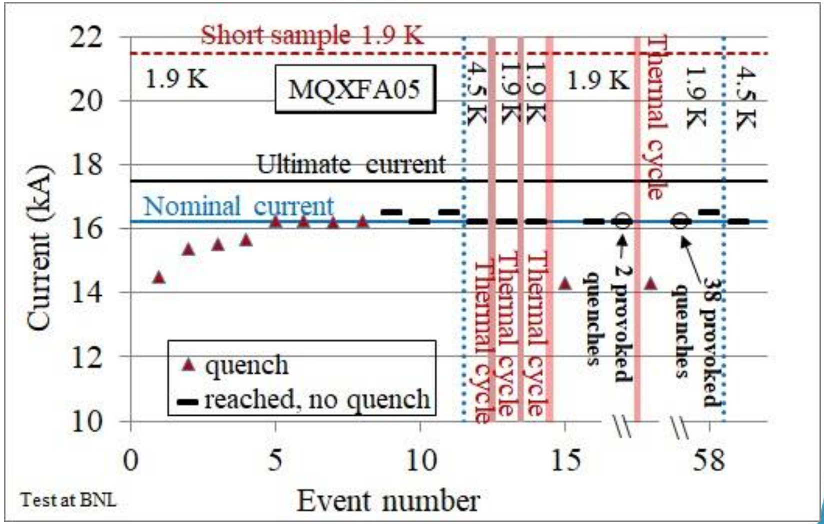
Comparison of performance of MQXFB prototypes
(S. Izquierdo Bermudez)

Endurance tests

- Degradation of Nb_3Sn magnets after thermal cycle has become a major concern in the community after the results in 2018-2020 of the 11 T long magnets
  - Three short models succesfully went through endurance tests: MQXFS1, MQXFS4, MQXFS6
  - One full-length MQXFA magnet (without integration in the LHe vessel) succesfully went through endurance tests – no degradation observed after thermal cycles and quenches

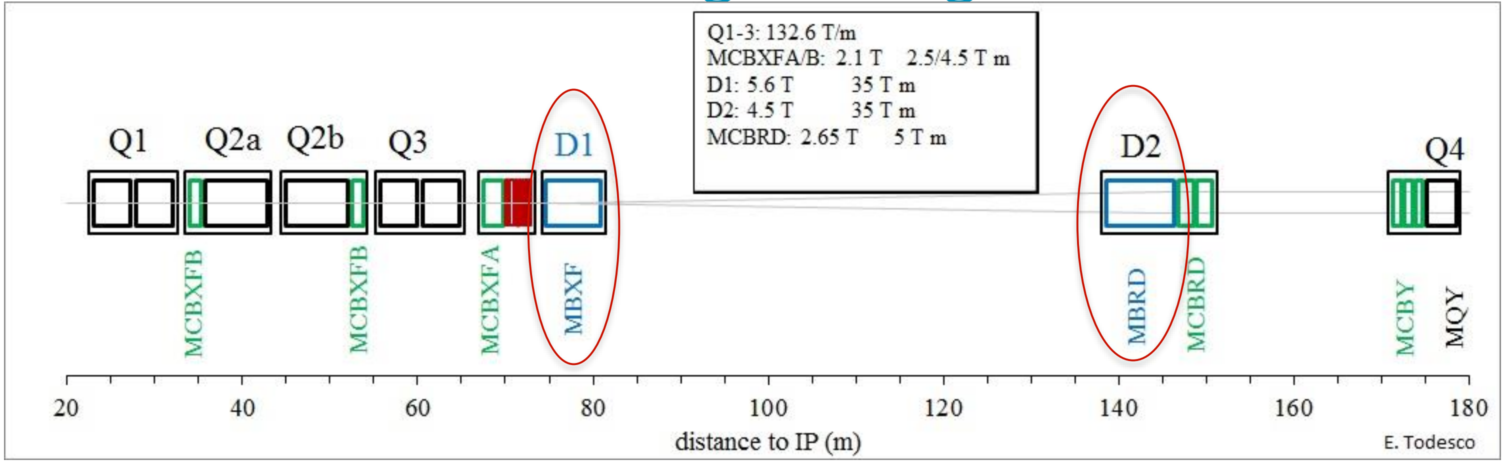


Short magnet endurance test
(P. Ferracin, F. Mangiarotti , et al.)



Long magnet endurance test
(B. Ahia, S. Feher, G. Ambrosio, et al.)

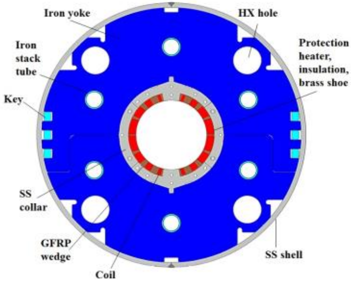
Interaction region magnets

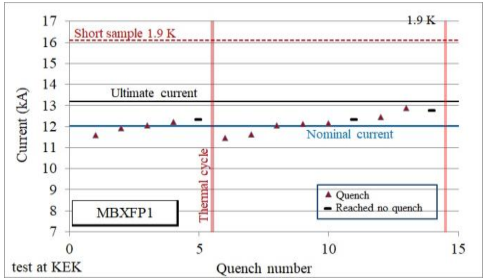


- D1: Nb-Ti separation dipole (4 magnets to install)
- D2: Nb-Ti recombination dipole (4 magnets to install)

D1 synoptic

- 5.6 T magnet, 150 mm aperture, 100 MPa midplane stress
  - 3 short models, 3 successful, with one iteration on preload
  - Prototype tested vertical, reached ultimate current but with retraining
  - 3 cross-section iteration on field quality
  - Series started





T_0: aperture and cable selection

MBXFS1: ~5.6 T

MBXFS1b: ≥6.1 T

MBXFS2: ≥6.1 T

MBXFS3: ≥6.1 T

MBXFP1: ≥6.1 T

MBXF1

2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

T_0+3

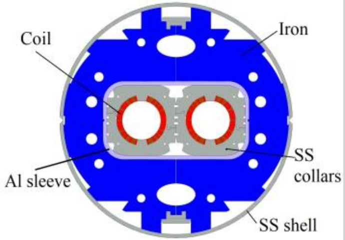
Contract

Hitachi

6 more magnets to test

D2 synoptic (see S. Farinon talk)

- 4.5 T magnet, 105 mm aperture, e.m. cross-talk
  - One short model, issues in one aperture, repaired
    target field reached but retraining – issues in cable exit
  - Prototype tested vertical, conform
  - 2 cross-section iterations on field quality
  - Series started



T_0: collaboration agreement

Contract to ASG

MBRDS1: ≥4.8 T, but in one aperture

MBXFS1c: ≥4.8 T, but retraining

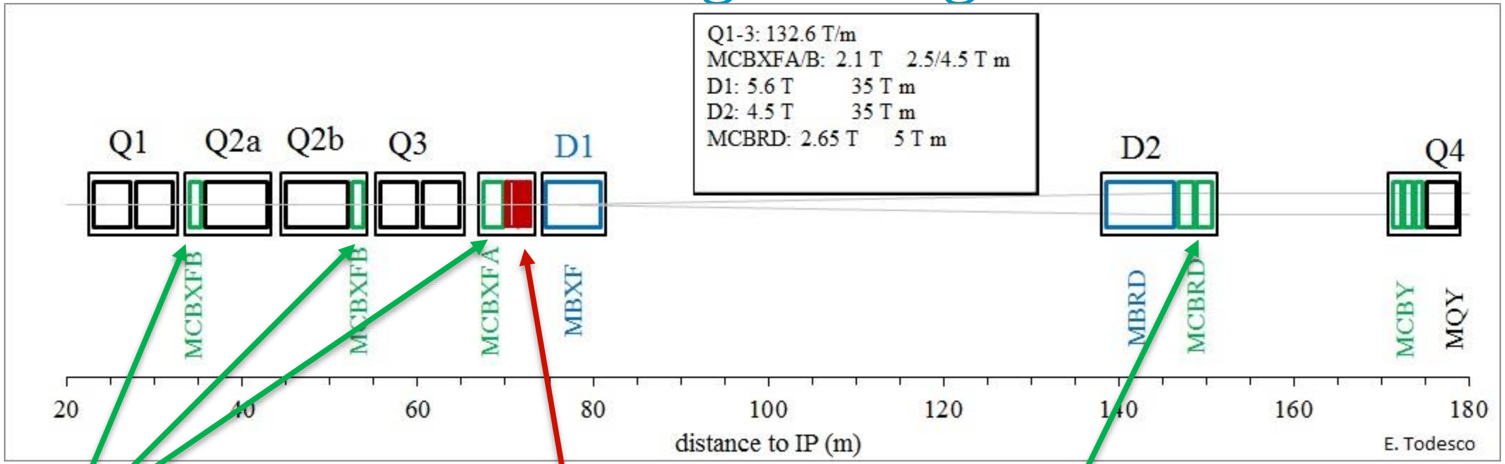
MBRDP1: ≥4.8 T

MBRD1

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024

T_0+5 6 more magnets to test T_0+8

Interaction region magnets



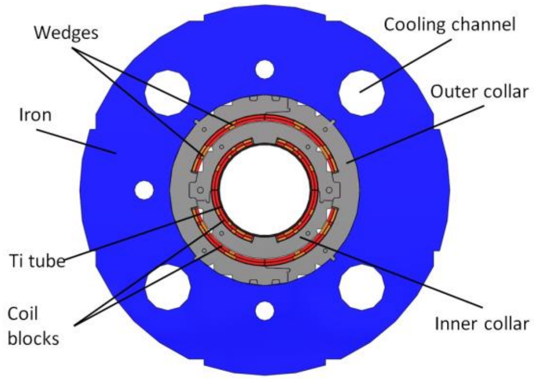
MCBXFA/B: Nb-Ti nested correctors (12 magnets to install)

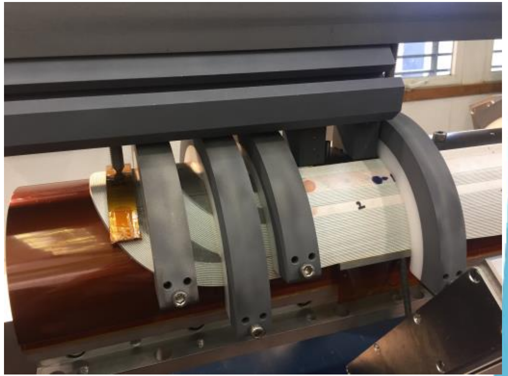
MCBRD: Nb-Ti CCT correctors (8 magnets to install)

High order correctors: Nb-Ti superferric correctors (36 magnets to install)

Nested corrector synoptic (see F. Toral talk)

- 2.1 T magnet in each plane, mechanical lock of torque
  - Double collaring design, allowing stress management and preload
  - Prototypes not fully conform, succesful iteration in the design
  - Production started in Elytt, first magnet succesfully tested





T_0: collaboration agreement

MCBXFBP1: ~7 TeV

MCBXFBP2: ~7 TeV

Contract To Elytt

MCBXFB01: ≥7.5 TeV

MCBXFBP2c: ≥7.5 TeV

MCBXFB02: ≥7.5 TeV

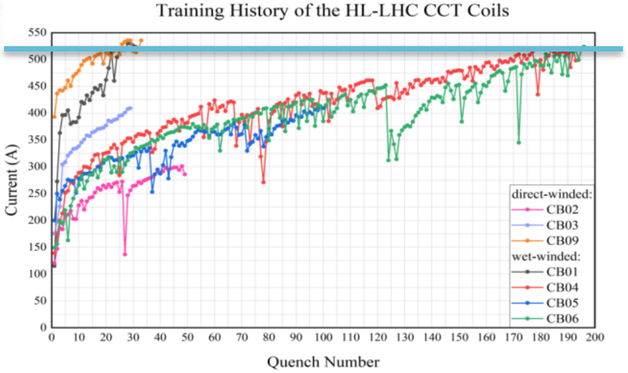
2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

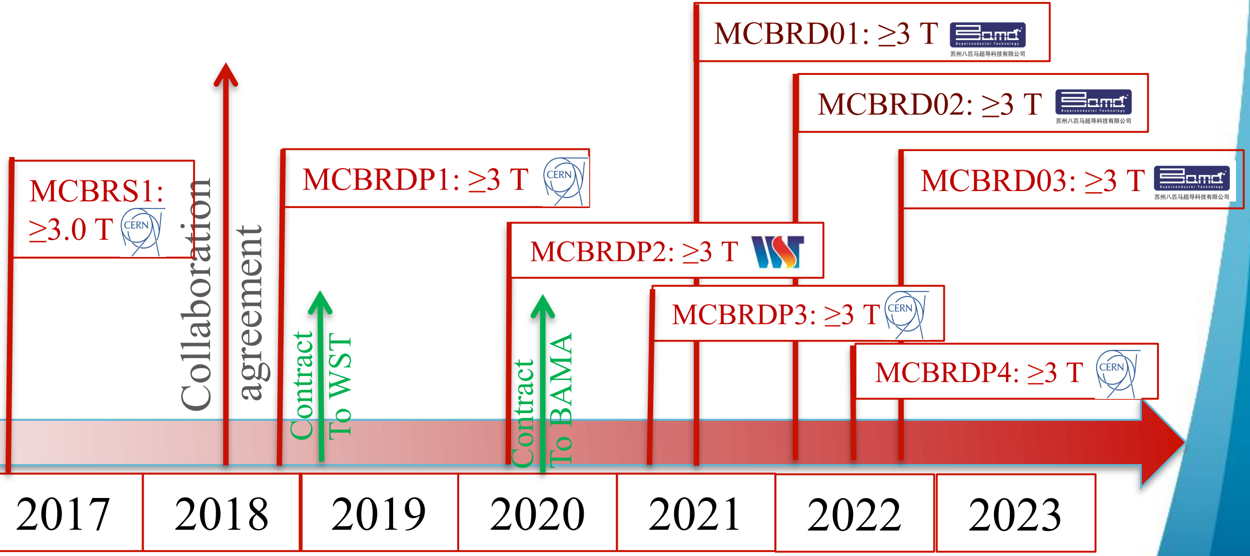
T_0+4

17 more magnets to test

CCT corrector synoptic

- Based on CCT design, 2.8 T dipole, ~0.5 loadline fraction
  - First implementation for CERN of this design, successful
  - Four successful prototypes, series not attributed to firm developing the prototype
  - Long training of series magnets, issue cured with improvement of impregnation and reduction of slot

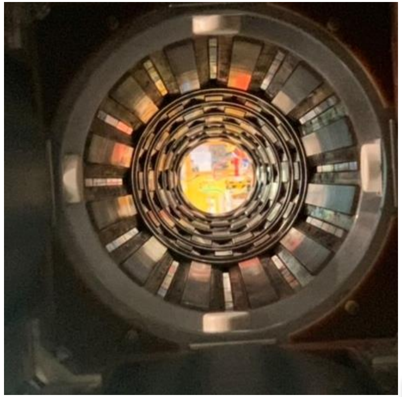




7 to 9 more magnets to test

Nested corrector synoptic (see M. Statera talk)

- Superferric magnets, Nb-Ti coils, ~0.2 loadline fraction
  - Prototypes developed in LASA, based on CIEMAT and Phase-I upgrade work
  - Production completed, 4/5 tested and accepted



T_0: collaboration agreement

Contract To SAES

Sextupole

Octupole

Decapole

Dodecapole

Skew quadrupole

Production of 54 correctors

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

7 more magnets to test

CONCLUSIONS

- The interaction region magnets are in different phases: ending prototype phase (MQXFB, D1, D2), beginning production (CCT and nested corrector), mid of production (MQXFA), ending production (HO correctors)
- For the Nb_3Sn quadrupole, having 11.3 T conductor field and 150 mm aperture:
  - MQXFA (4.2-m-long magnet in US)
    - 6 magnets qualified out of 16 to be installed plus 4 spares – cold mass still to be tested
    - Successful endurance test of the first Nb_3Sn full length magnet – major milestone
    - Issues with MQXFA07 and MQXFA08 performance seem to be understood and MQXFA10/11 are conform – next steps: integration in Lhe vessel and coil replacement
  - MQXFB (7.2-m-long magnet at CERN
    - Performance limitations below requirements seen in the first two prototypes
    - 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
- Nb-Ti magnets are well underway and pose no special issues