Status and challenges of interaction region magnets for HL-LHC, with focus on Nb_3Sn triplet

E. Todesco, TE-MSC, CERN

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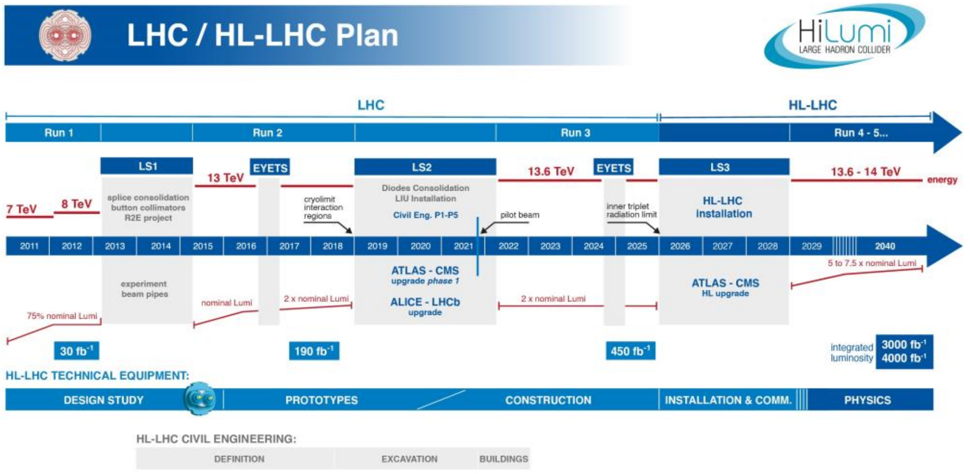
The HL-LHC project



- Luminosity upgrade of LHC
  - Studies since 2000
  - Investment of DOE on Nb_3Sn and on crab cavities (LARP)
  - HiLumi design studies in 2012-2014
  - Project started in 2015, led by L. Rossi
  - Installation in 2026-28
  - Larger aperture triplet and crab cavities are the enabling technologies

- 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

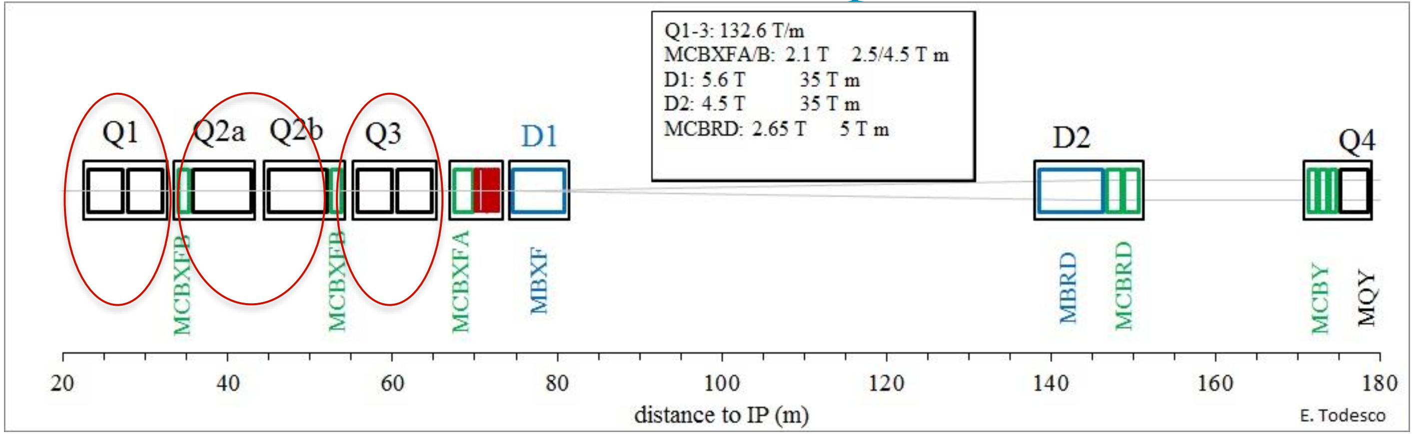
www.cern.ch/hilumi/wp3

List of WP3 contributors (from East to West)

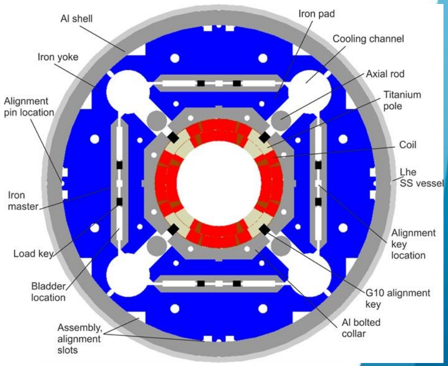
- KEK: T. Nakamoto, M. Sugano, K. Suzuki, N. Kimura et al.
- IHEP: Q. Xu, Y. Wang, D. Ni, W. Wu, L. Li, Q. Peng, et al.
- FREIA: K. Pepitone, R. Ruber, et al.
- INFN-LASA: M. Statera, M. Sorbi, M. Prioli, S. Mariotto, et al.
- INFN-Genova: P. Fabbricatore, S. Farinon, B. Caiffi, A. Bersani, R. Cereseto, 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

Focus on the triplet



- MQXF Nb_3Sn quadrupoles: US manufactures 20, 4.2-m-long MQXFA (Q1/Q3)
- CERN manufactures 10 7.2-m-long MQXFB (Q2a and Q2b)
- Longest Nb_3Sn accelerator magnet so far (4.2 m for Q1/3, 7.2 m for Q2)
  - Previous record was 4-m-long LQ done by LARP
  - First use of Al rings structure and b&k for magnets to be installed
    S. Caspi, et al. IEEE TAS 11 (2001)
  - First use of CLIQ as protection system Ravaioli, Kirby, et al IEEE TAS **24** (2014)



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

Contents

- MQXF design in a nutshell
- The short model program (MQXFS)
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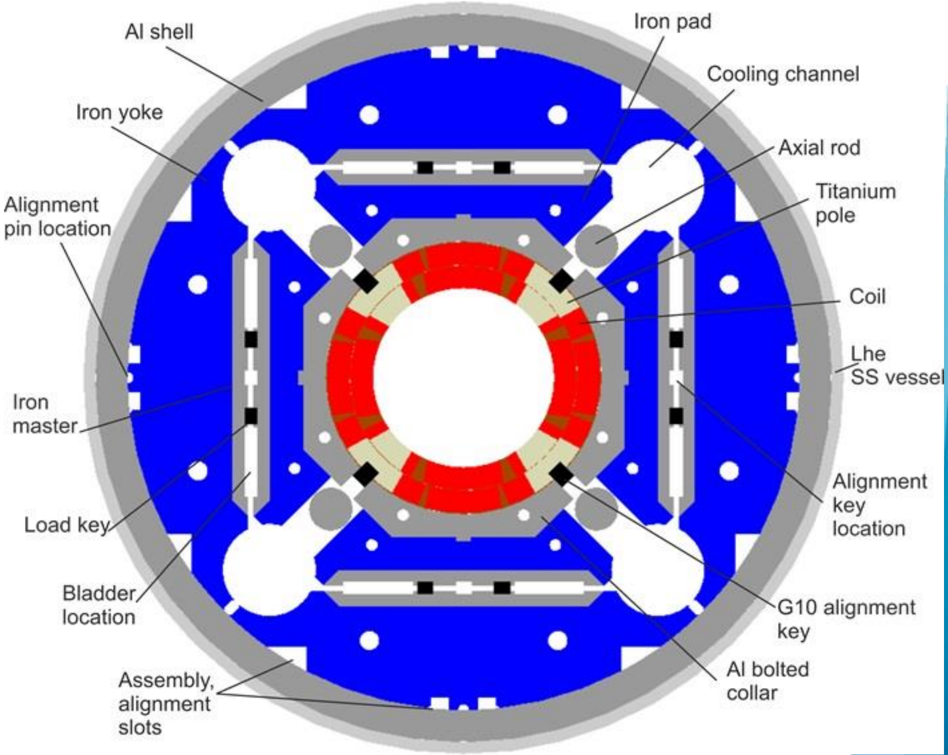
- Some lessons learnt in the view of Nb_3Sn dipoles for FCC-hh

MQXF design in a nutshell

- Large aperture: 150 mm diameter
- Operational parameters (at 7 TeV)
  - 132 T/m gradient, 462 A/mm^2 overall j
  - 11.3 T peak field in the coil
  - 5 K of temperature margin
    - Present LHC triplet has ≈2 K
  - 110 MPa of accumulation of stress in the midplane due to e.m. forces
  - Operates at 77% on the loadline
    - Present LHC triplet is at 82%-78%
- Conductor: 40 strand cable, 0.85 mm strand
  - High j_c Nb_3Sn strand RRP, 1280 A/mm^2 at 15 T, 4.22 K (10% more systematically achieved)
  - Production of more than 3000 km of 0.85 mm diameter strand, with UL of 500 and 800 m



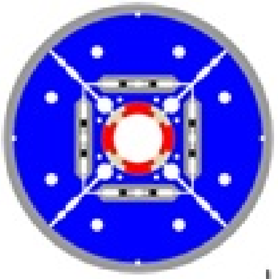
MQXF cross-section
(P. Ferracin, G. Ambrosio, et al.)

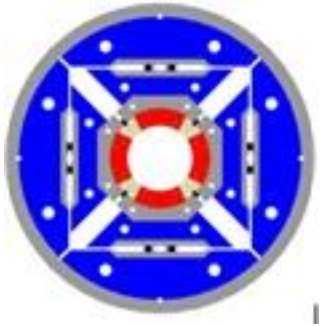
MQXF design in a nutshell

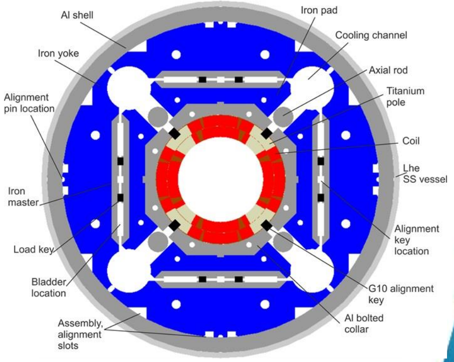
- MQXF is the third generation of LHC IR quadrupoles of LARP
  - First target was 200 T/m in 90 mm aperture (TQ), 2003
    - Two versions: TQS based on Al shell, and TQC, based on collars
  - Then in 2007 target moved to 170 T/m in 120 mm aperture (HQ), including also alignment features
    - Based on Al shell structure, considered to be more efffective
    - Three models built
  - Then in 2013 final aperture of 150 mm was selected
- Aperture increase was associated to larger coil width and lower operational current densities
  - Note that TQ was not compatible with protection contraints

	MQXF	HQ	TQ
Gradient (T/m)	132	170	200
Peak field (T)	11.4	12.1	10.0
Coil width (mm)	36	29.5	18.6
Aperture (mm)	150	120	90
Overall j (A/mm^2)	462	593	739
Stress at r (MPa)	86	91	75

$$s_{qq}(r) = \frac{G r^2 j}{4}$$


TQS


HQ



MQXF

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MQXF short model synoptic

- 7 short models built, 6 conform

11.6 T peak field corresponds to the gradient requirement for 7 TeV operation (also called nominal)

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: ≥13.2 T

MQXFS8: ≥13.1 T

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

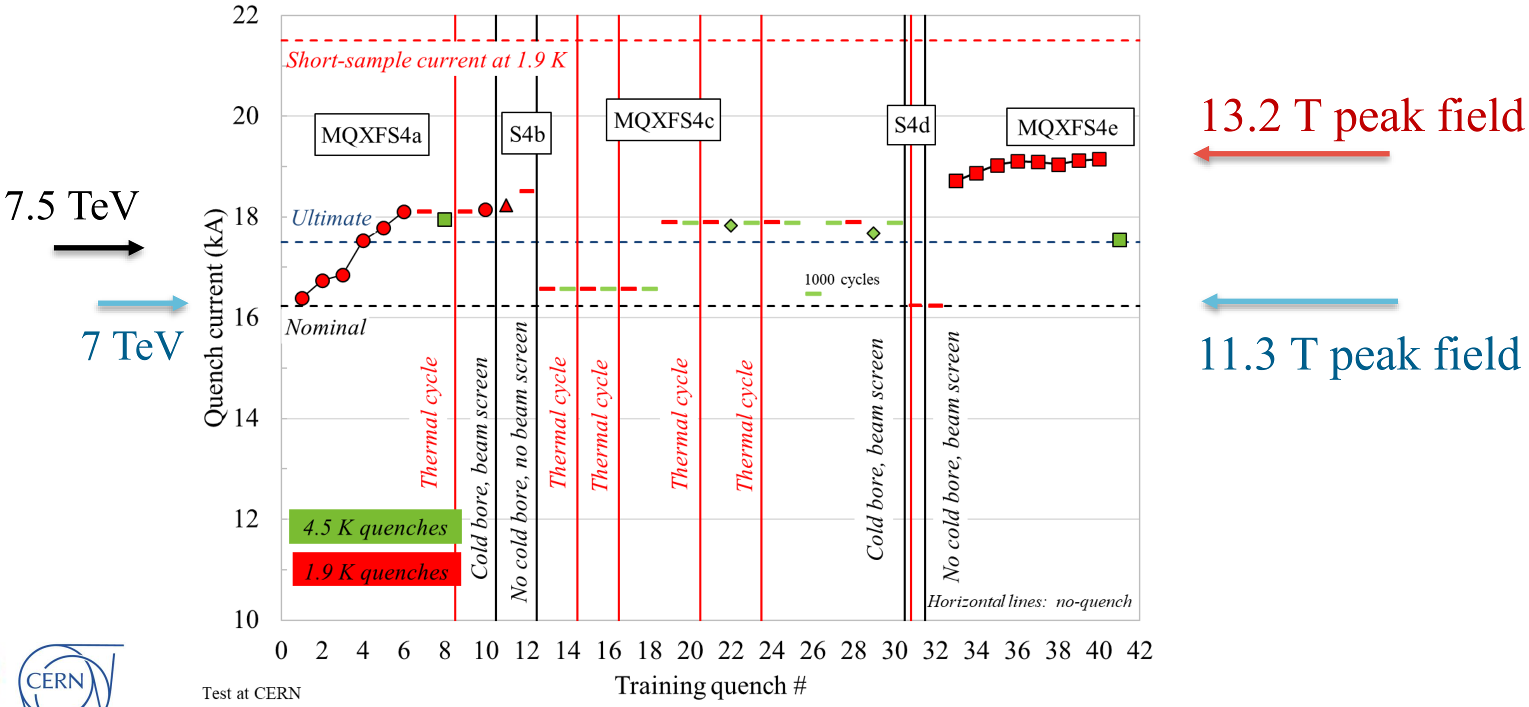
T_0+3

MQXF short model timeline

- 29 coils manufactured, with few variants
  - 3 at FNAL (RRP), 14 (RRP) + 12 (PIT) at CERN
- Assembled in 7 models
  - Structures were totally reused
  - Mixing CERN and FNAL coils, mixing RRP and PIT
  - Successive assemblies varying preload (0.1 mm difference in key giving 20 MPa)
- Main results
  - Absence of retraining after thermal cycle to nominal current (and above)
  - Margin in temperature: reaching nominal current at 4.5 K (>2.6 K margin demonstrated)
  - Endurance tests on two magnets, 100s of quenches, 10 thermal cycles
  - Margin in field (and forces): systematic ability of reaching coil peak fields above 13 T (25% more e.m. forces and stresses)
  - Reaching systematically >90% short sample at 1.9 K and at 4.5 K
  - Reproducibility: only one magnet not reaching nominal current out of seven

MQXF short model results

- Typical pattern of training of a short model
  - The MQXFS short model program is a good paradigm of what should be achieved by a magnet in the short version before scaling up the length – see last part of these slides



MQXFS4 training and endurance (S. Izquierdo Bermudez, F. Mangiarotti, et al.)

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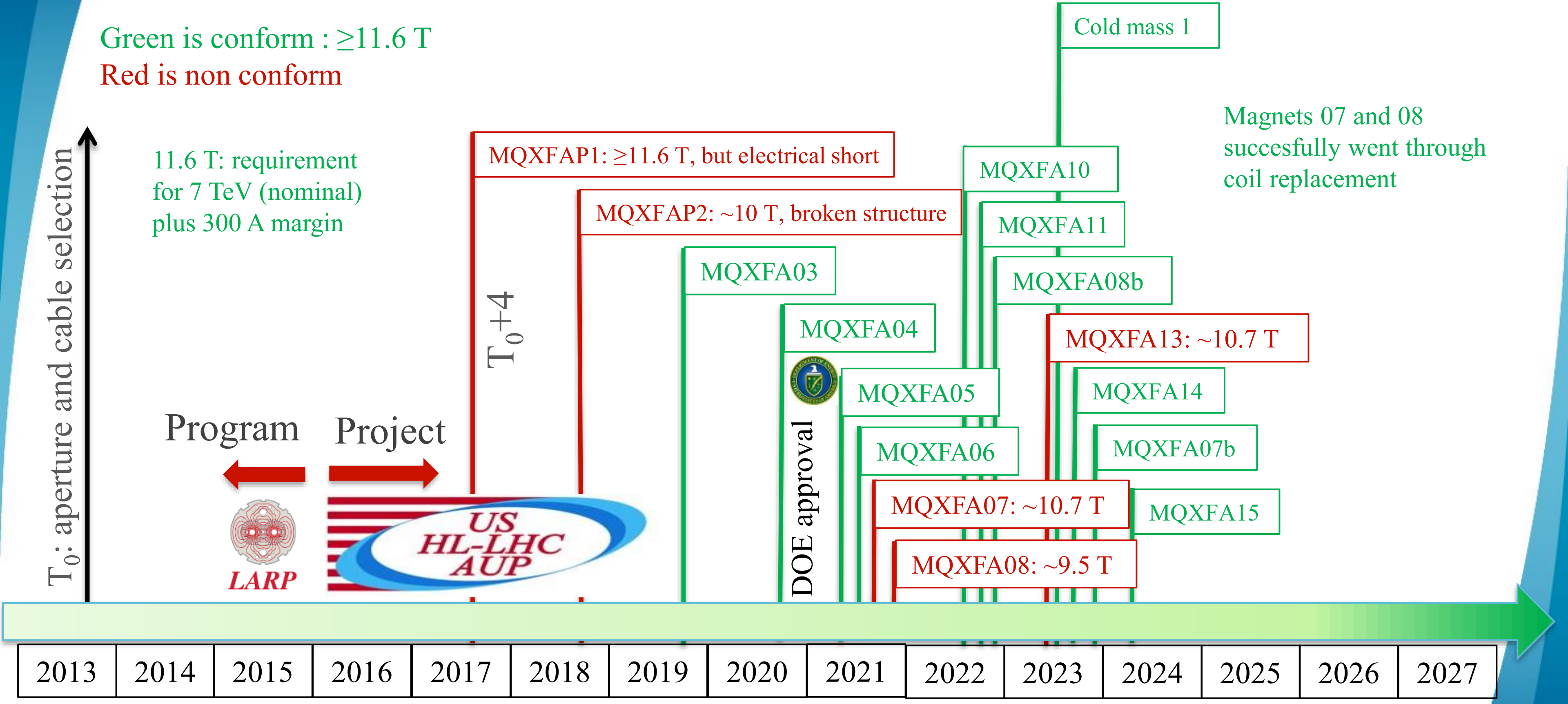
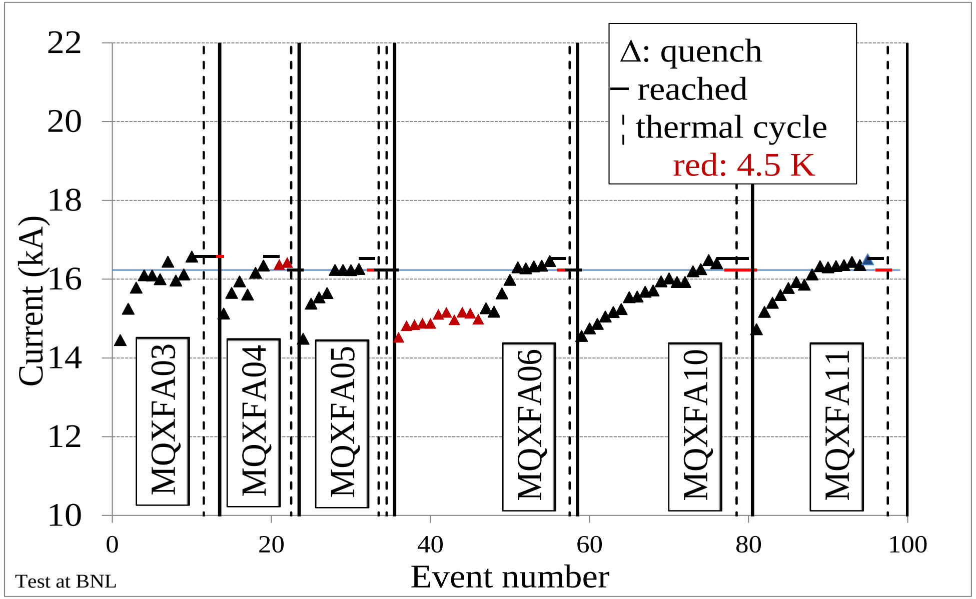
MQXFA synoptic



11 magnet tested, 10 more new magnets to test (9,12,16-23), plus MQXFA13 reassembly

MQXFA conform magnets

- MQXFA program confirms
  - Ability to 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

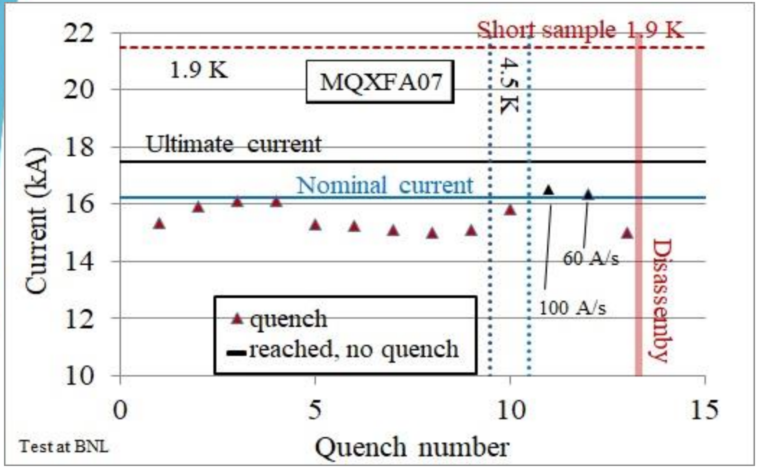


Powering test of first six conform MQXFA magnets
(J. Muratore, B. Ahia, S. Feher et al.)

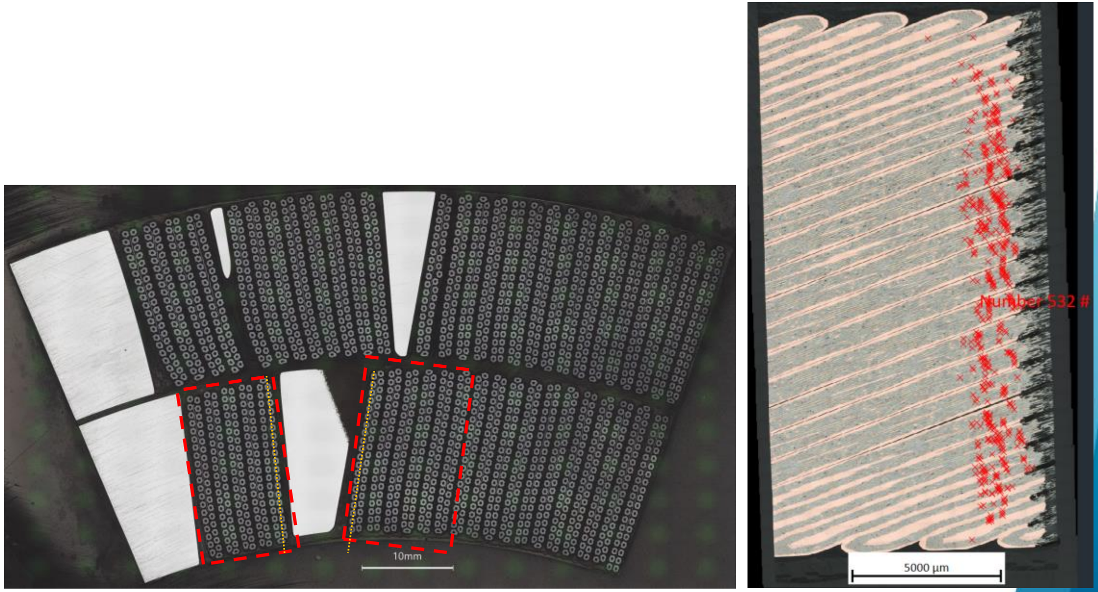
Non conform MQXFA11 transport

MQXFA performance limitations

- MQXFA07 and 08 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



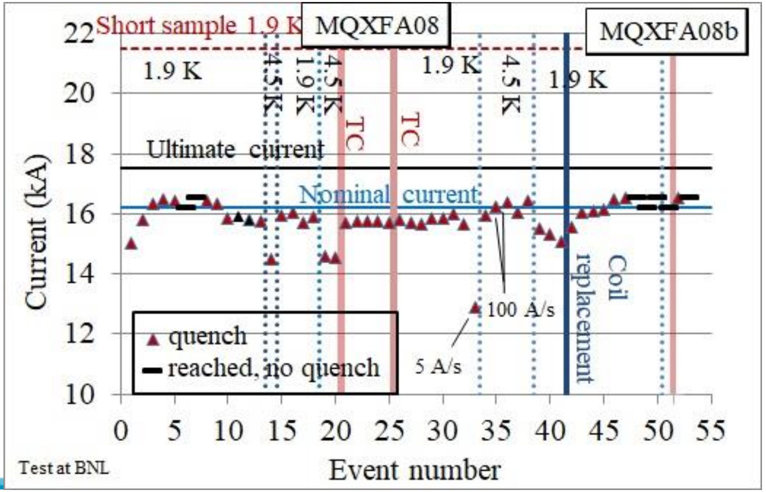
Power test of MQXFA07 (J. Muratore, S. Feher, G. Ambrosio et al.)



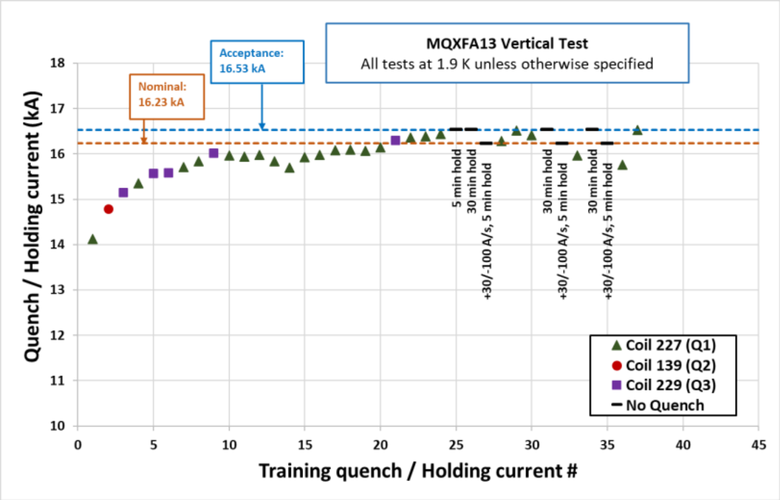
Presence of cracks (red crosses) in coil 214 (M. Crouvizier, A. Moros, S. Sgobba)

Overcoming performance limitations

- Both 07 and 08 went through a coil replacement and then reached performance
  - Iteration on assembly parameters, alingment key (see last part)
- MQXFA13 also showed performance issues, coil replacement is ongoing
  - Performance: out of 11 built, 8 conform 3 non-conform (excluding prototypes)
    - Two out of these three non-conform magnets were reassembled and now ok



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



Power test of MQXFA13 (A. Ben Yahia, S. Feher, G. Ambrosio et al.)

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MQXFB synoptic

Green: conform ≥ 11.6 T
Red: non conform
Grey: to come

T_0: aperture and cable selection

MQXFBP1: ~10.5 T
MQXFBP2: ~11.2 T
MQXFBP3
MQXFB02*
MQXFB03
MQXFB04
MQXFB05

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

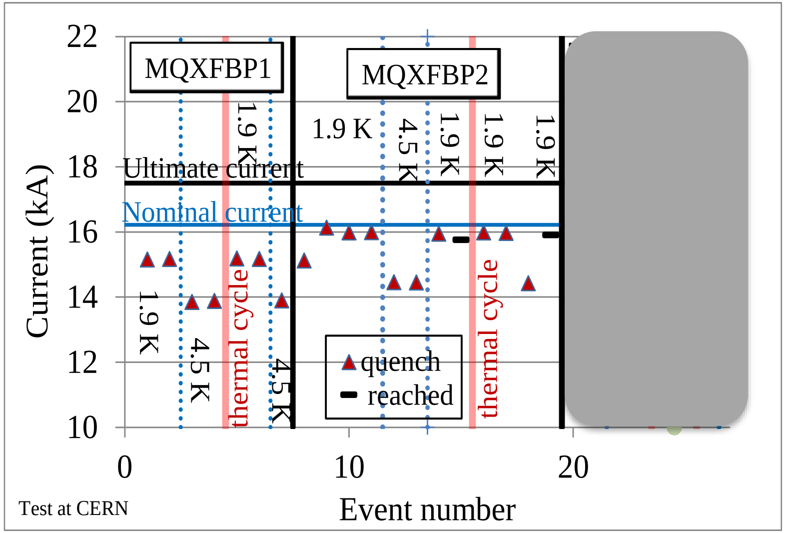
T_0+7

7 to 9 more magnets to test

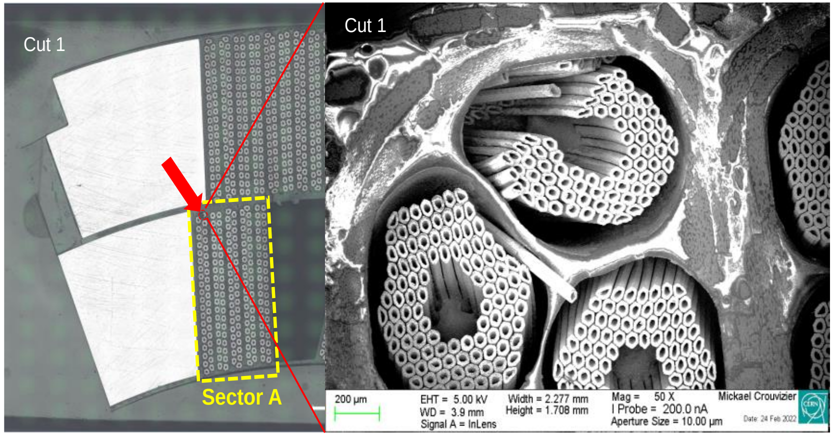
* NC HV test, to be disassembled

MQXFB performance limitations

- MQXFBP1 and MQXFBP2 were limited just 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



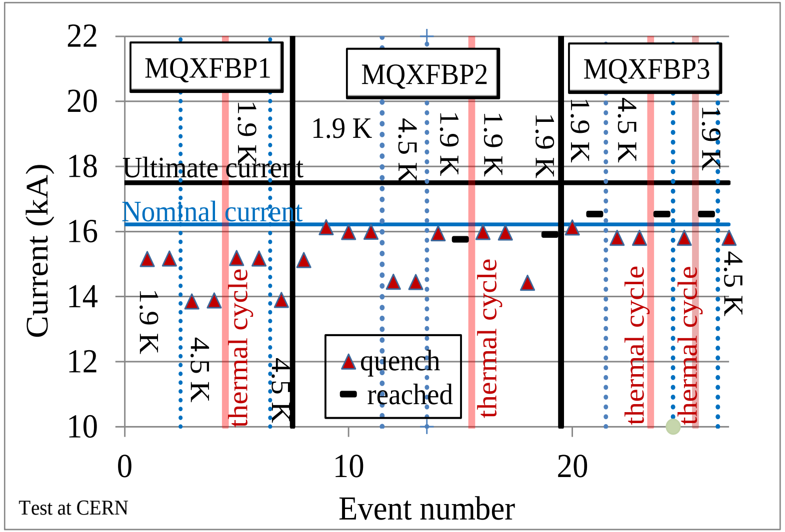
MQXFB prototype performance
(F. Mangiarotti, S. Izquierdo Bermudez, et al.)



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

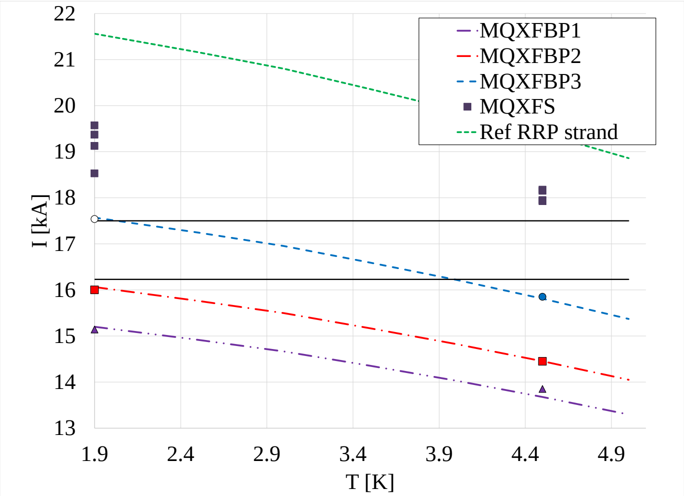
MQXFB performance limitations

- MQXFBP3 reached nominal current plus 300 A
  - But at 4.5 K the limitation is still 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



MQXFB prototype performance

(F. Mangiarotti, S. Izquierdo Bermudez, et al.)

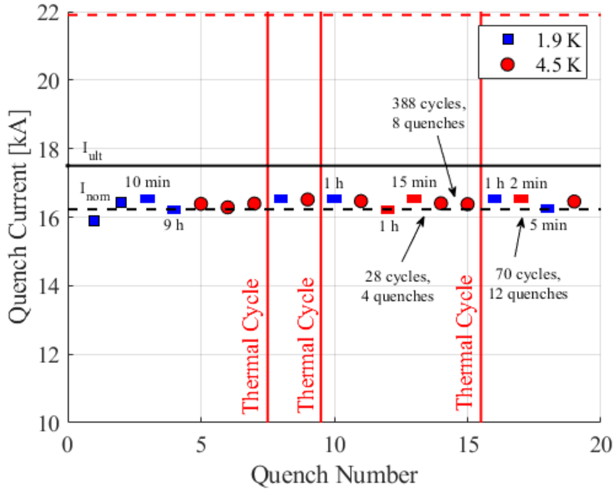


Comparison of performance of MQXFB prototypes

(S. Izquierdo Bermudez)

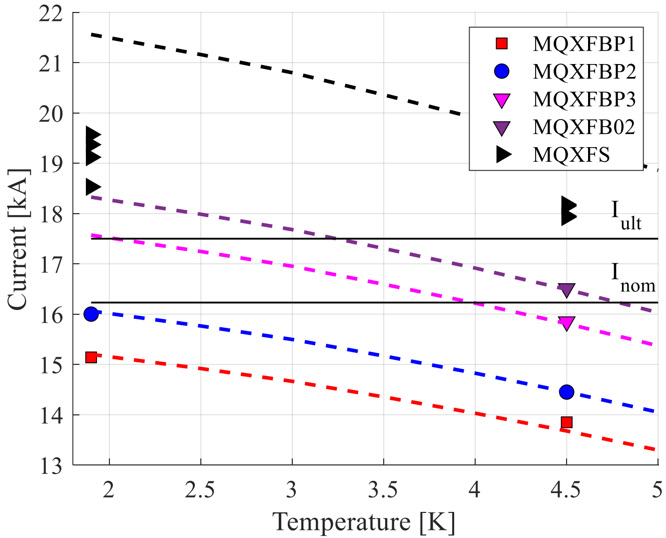
MQXFB performance limitations

- MQXFB02 reached nominal current plus 300 A
  - But at 4.5 K the limitation barely visible, corresponding to 82% of short sample and 2.6 K temperature margin - 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 (MQXFB02), (iii) coil manufacturing



MQXFB02 performance

(F. Mangiarotti, S. Izquierdo Bermudez, et al.)

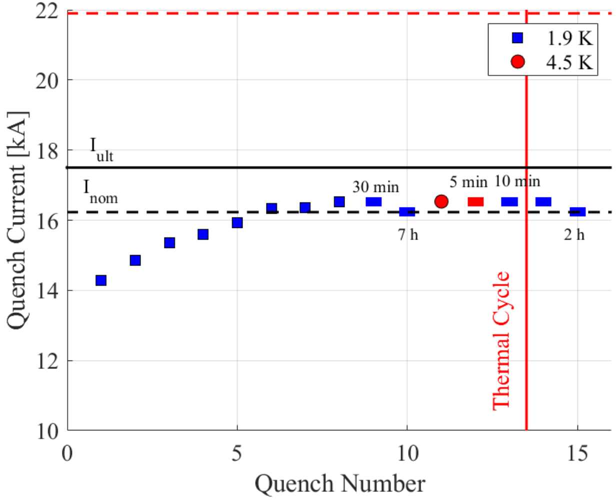


Comparison of performance of MQXFB prototypes

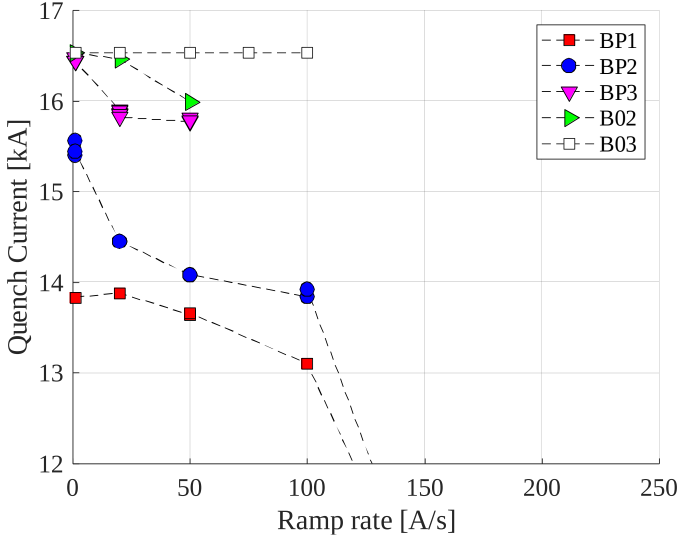
(S. Izquierdo Bermudez)

MQXFB performance limitations

- MQXFB03 reached nominal current plus 300 A, and showed to limitations at 4.5
  - This magnet implemented modification of coil fabrication (removal of the binder from the outer layer, curing an oversize in the coil azimuthal length and other indicators)
  - Note that US magnets did not have these indicators (neither limitations in performance, and therefore kept the binder



MQXFB03 performance
(F. Mangiarotti, S. Izquierdo Bermudez, et al.)

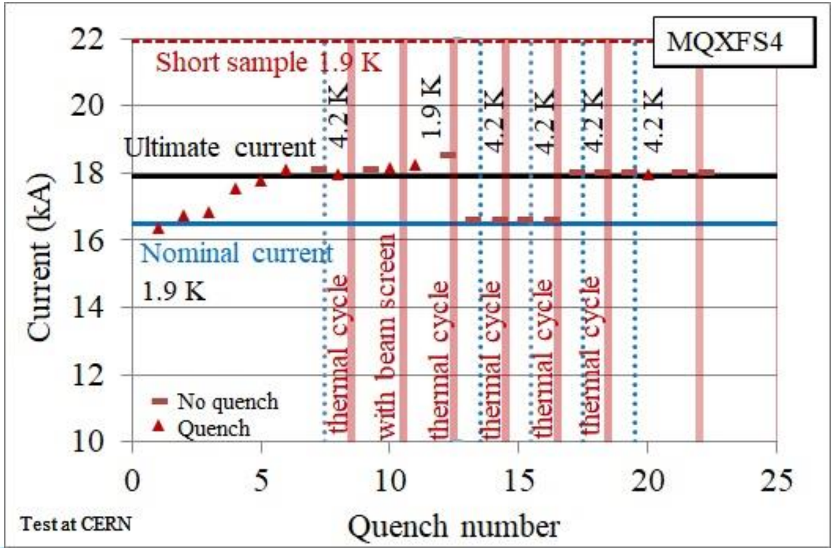


Ramp rate comparison of prototypes
(S. Izquierdo Bermudez)

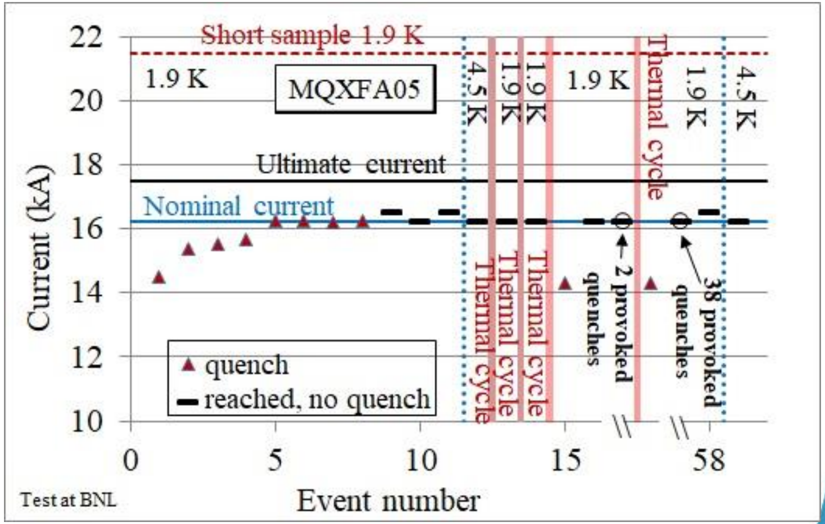
Contents

About long term stability

- 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.)

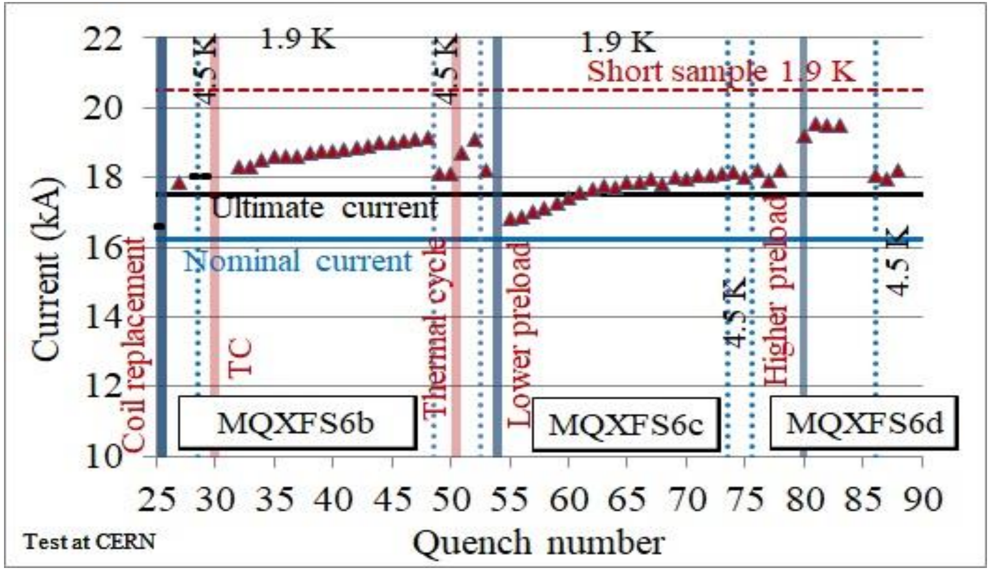


Long magnet endurance test
(B. Ahia, S. Feher, G. Ambrosio, et al.)

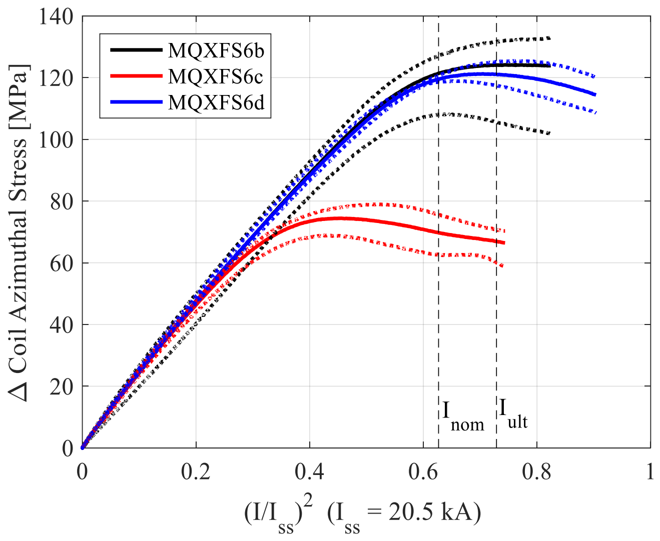
About low preload

- The structure based on Al shells aims at full preload just below nominal current
  - Very low preload has also been tested, corresponding to preload at 70% of nominal current: magnet was tsill able to operate at nominal current, but nearly 2 kA of maximum reachable current were lost

(S. I. Bermudez, et al., IEEE TAS 32 (2022) 4007106)



Power tests

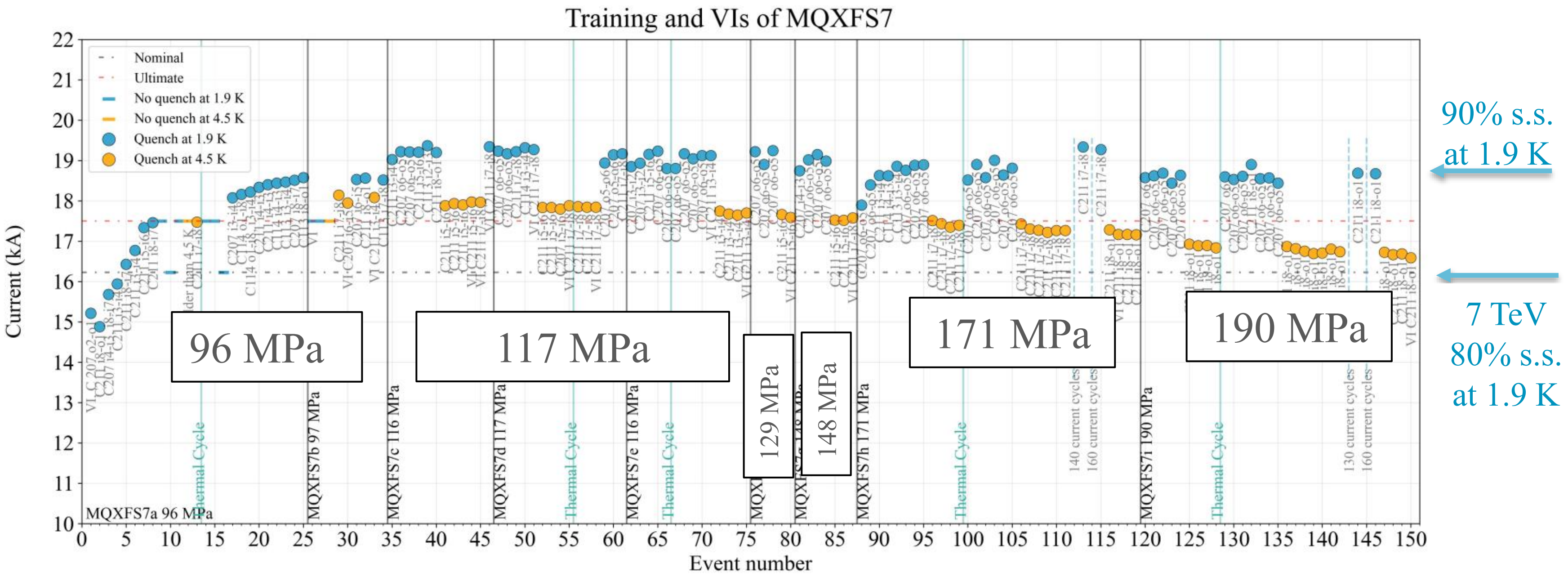


Coil unloading during powering

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

About high preload

- Similar to what done in TQ magnet, higher preload were explored (up to 200 MPa)
  - Test is ongoing, at 200 MPa nominal performance is still reachable, but signs of performance degradation in the range above 90% of short sample limit – we are now going back to 120 MPa



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

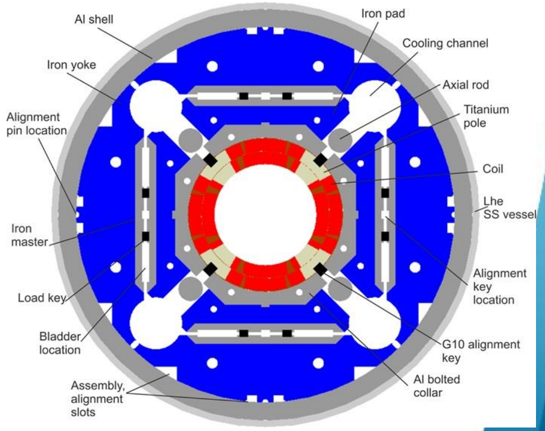
About training: a red haring ?

- In the communuty, a lot of emphasis has been put on training of Nb_3Sn
  - Typical statement: «Training in Nb_3Sn magnets is slow, and this is not acceptable for a machine made of 4000 magnets as FCC-hh »
  - This mainly comes from the experience on LHC, were operation at 6.8 TeV (83.5% of short sample) requires about 600 retraining quenches
- MQXF shows a long virgin training, especially above 80% of short sample – more significant than Nb-Ti LHC dipoles
- On the other hand, training after thermal cycle appears absent in MQXF up to nominal (but this is 77% of short sample – not directly comparable to LHC dipoles)
- One should not forget that there are two types of training: virgin training and training after thermal cycle
  - Virgin training is part of magnet construction and test: even though one trains in the test station for two weeks, the magnet construction takes one year … so virgin training is probably not a driving factor
- We are gathering a lot of statistics, and at the end of the MQXF production we will be able to better assess the relevance of training in Nb_3Sn

About mechanical design

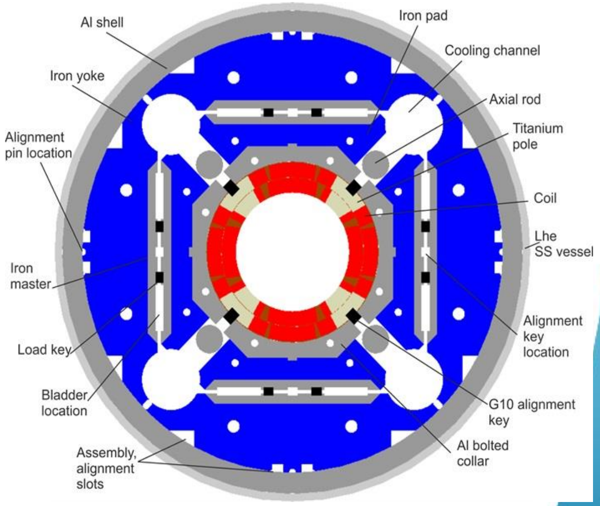
- The principle of the TQ structure is open gap, i.e. there are no stoppers preventing the force from the Al shell to go on the coils
  - This structure has the advantage of simplicity, as the cool-down effect is not related to tolerances of the stoppers and is fully reproducible …
  - … and having measurements of strain at cryogenic temperature in absolute is very tricky
- In MQXF, alignment features were introduced (alignment keys)
- After some iterations the interference between

alignement key and collars has been removed
  - Even with this lack of interference, field quality is very good:
  - It corresponds to a coil positioning of 20 μm
- Different structures can do the same work …
- … for MQXF we decided to reuse all concepts validated in LARP
- This was a risk minimization



About mechanical observables

- There is a wide range of assembly parameters for preload
  - Note that the « exact » state of stress in the coil is an ill defined quantity, as the coil is a composite structure and it cannot be measured directly
  - It is not a surprise that experiments on different settings can vary up to a factor two (i.e. degradation is in the 100-200 MPa range)
  - Another point is how much degradation we can accept ?
    - Working at 80%, we can survive 50% of degradation …
    - … but should be stable in time ! Tricky point
- A fundamental point is to have reliable observables
  - Coil size, shimming size and keys size
  - Strain gauges in the coil and in the shell, used at room temperature during assembly
  - Seeing the coil unloading during powering is an essential tool to validate the control of the mechanical aspects

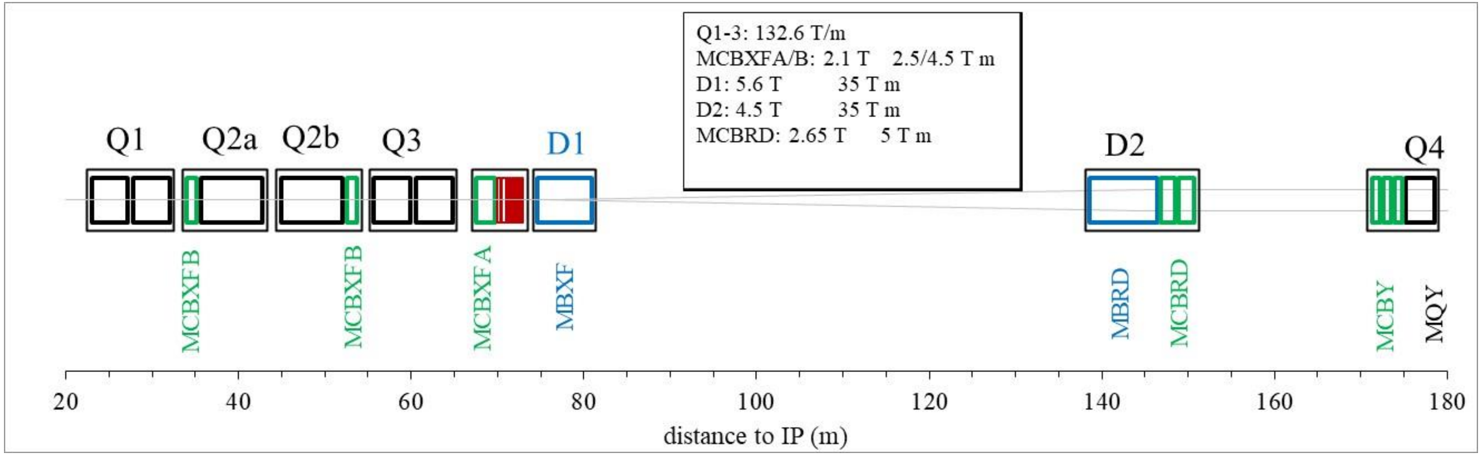


Targets for FCC-hh Nb_3Sn magnets

- Based on the HL-LHC experience, one can set the targets for FCC-hh dipole
  - This is needed to clarify the ambiguities between 16 T, 14+ T, margins, requirements, etc
- We set 14 T operational field, at 80% on the loadline (20% margin)
  - This gives 5 K temperature margin, and according to HL-LHC experience should guarantee the possibility of operating 14 T also at 4.5 K (proving tht half of the theoretical temperature margin is there)
  - 4.5 K is an interesting option for energy saving – it implies having most of the correctors and other main magnets in Nb_3Sn (with Nb-Ti at 4.5 K you lose a lot)
- A 14 T dipole with the FCC 91 km tunnel can give 90 TeV c.o.m. collision energy
- For the short model magnets, one should prove more
  - Before scaling in length one should have consistent margins in the design!
- Targets for short models
  - As a first target, 85% of short sample at 4.5 and at 1.9 K
  - This means able to reach 15 T at 1.9 K
  - This proves the margin in the mechanics for 13% larger forces and stresses
  - A second target, for a second phase, to reach 90%

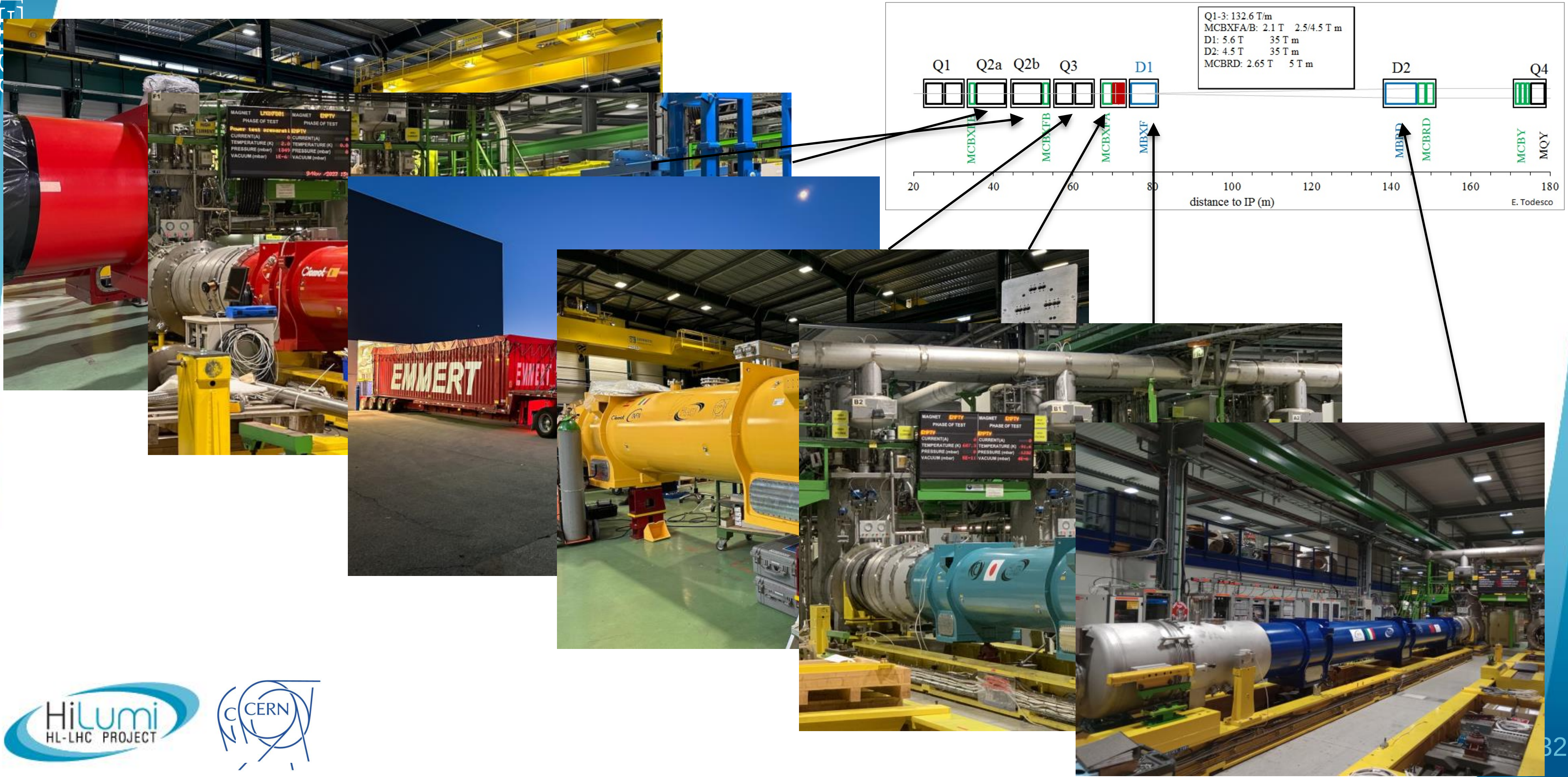
2013 status

In summer 2013 we defined the HL-LHC baseline, based on preparatory work by LARP, S-LHC, Phase-I and Phase-II upgrade, HL-LHC design study



E. Todesco, H. Allain, G. Ambrosio, G. Arduini, F. Cerutti, R. De Maria, L. Esposito, S. Fartoukh, P. Ferracin, H. Felice, R. Gupta, R. Kersevan, N. Mokhov, T. Nakamoto, I. Rakno, J. M. Rifflet, L. Rossi, G. L. Sabbi, M. Segreti, F. Toral, Q. Xu, P. Wanderer, and R. van Weelderen: "A first baseline for the magnets in the high luminosity LHC insertion regions" *IEEE Trans. Appl. Supercond.* **24** (2014) 4003305 (presented in ASC 2013, published on 2014)

Ten years later …



HiLumi HL-LHC PROJECT

CERN

Conclusions

- The Nb_3Sn magnets for HL-LHC had an very fast development timeline: 15 years from aperture and cable selection (2013) to installation (2028), for a new technology
- This was possible thanks to
  - Total synergy between AUP and CERN, building the same magnet
  - Reusing all concepts developed by LARP in 2003-2013

- The project is proving the Nb_3Sn technology for 7-m-long accelerator magnets operating at 11.3 T peak field
  - Protection and field quality (not discussed here)
  - Large margin in mechanics proved for short models (up to 13 T)
  - Large temperature margin proved in long magnets (up to 2.6 K out of 5 K)
  - Endurance and long term stability

Conclusions

- Scaling in length to 7 m is a fundamental new contribution of HL-LHC to the Nb_3Sn technology for accelerators
  - What could have been seen as a daring decision in 2013 is shown today to be an investement for CERN long term activities
- Scaling in length has been non trivial on both sides of the ocean – first two prototypes failed to reach performance both in the US and at CERN
  - Proved in 2019 for US 4-m-long magnets, after two prototypes failing to reach performance
  - Proved in 2023 for CERN 7-m-long magnets, after four magnets, two of which compatible with operation but still showing limitations
- The short model program is an ideal testbed for R&D related to High Field Magnet program, in particular for the relation between preload and performance
  - Very wide ranges – preload matters, but well above operational levels – Nb3Sn degradation starts to be visible at 200 MPa
- HL-LHC experience can set targets for the FCC-hh 14 T dipole performance