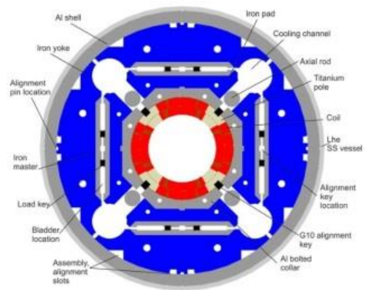
The HL LHC interaction region magnets towards series production

E. Todesco (CERN)
On behalf of HL-LHC WP3 and TE-MSC

14 October 2019 - FNAL

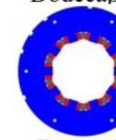
THE HL-LHC IR REGION MAGNETS

- 100 magnets of 11 different types, done via 6 collaborations
- To be ready by 2024

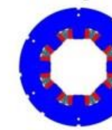


Triplet [G. Ambrosio, P. Ferracin et al.]

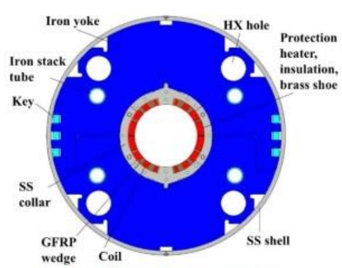
Dodecapole



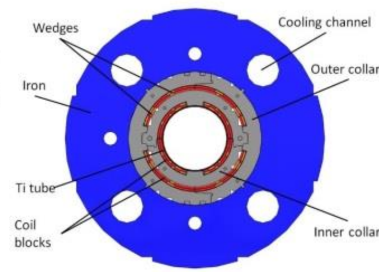
Decapole



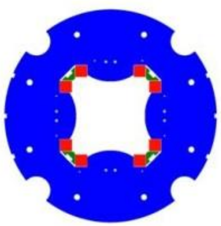
Octupole



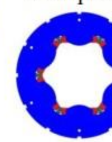
D1 [T. Nakamoto, et al.]



MCBXF [F. Toral, et al.]

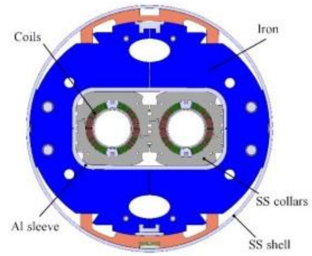


Skew quad

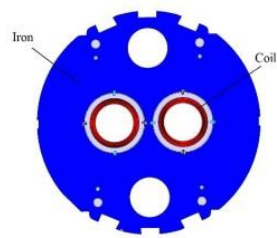


Sextupole

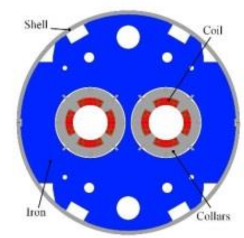
[M. Sorbi, M. Statera, et al.]



D2 [P. Fabbricatore, S. Farinon, et al.]

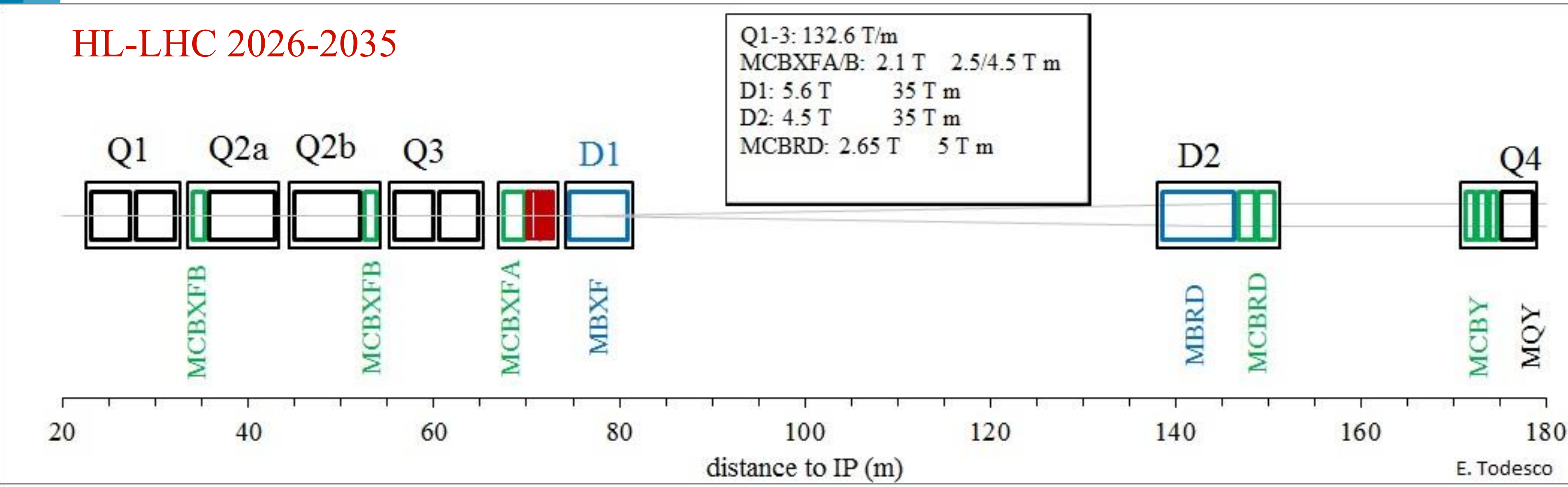


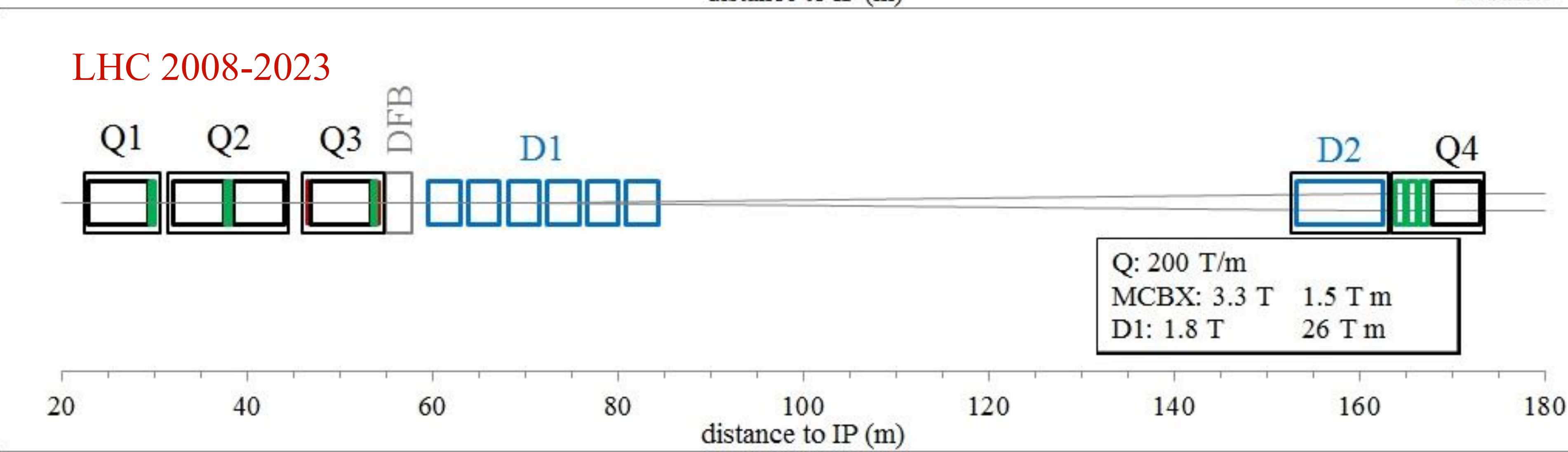
D2 correctors [G. Kirby, Q. Xu, et al.]



MQYY [H. Felice, et al.]

THE HL-LHC IR REGION MAGNETS





HL-LHC WP3: IR magnets

E. Todesco

P. Ferracin (Deputy)

September 2019

Nb_3Sn magnets

Triplet Q1/Q3
G. Ambrosio, S. Feher (FNAL)
P. Ferracin (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)
A. Musso (CERN WPE)

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

Nb-Ti and resistive main magnets

Separation dipole D1
T. Nakamoto (KEK)
A. Musso (CERN WPE)

Recombination dipole D2
P. Fabbricatore (INFN Genova)
A. Foussat (CERN WPE)

MQYY
H. Felice (CEA)
A. Foussat (CERN WPE)

MBW and MQW
P. Schwarz (CERN WPE)

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

IHEP

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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INFN

TE-MSC

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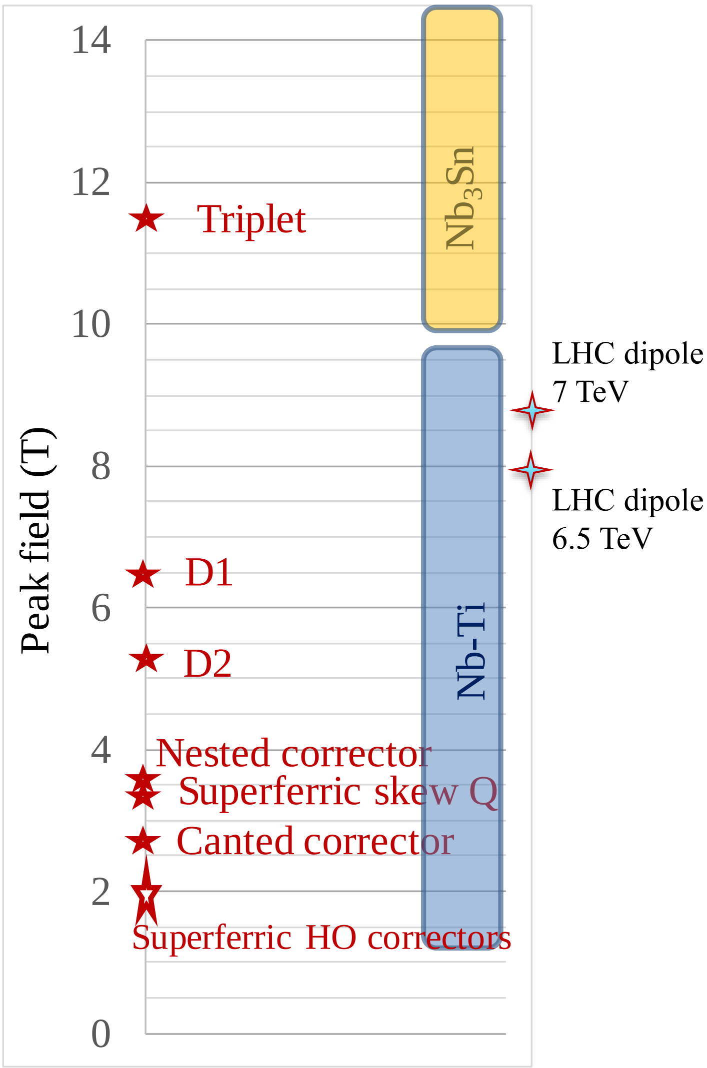
G. NINET
P. VIRET
G. WILLERING

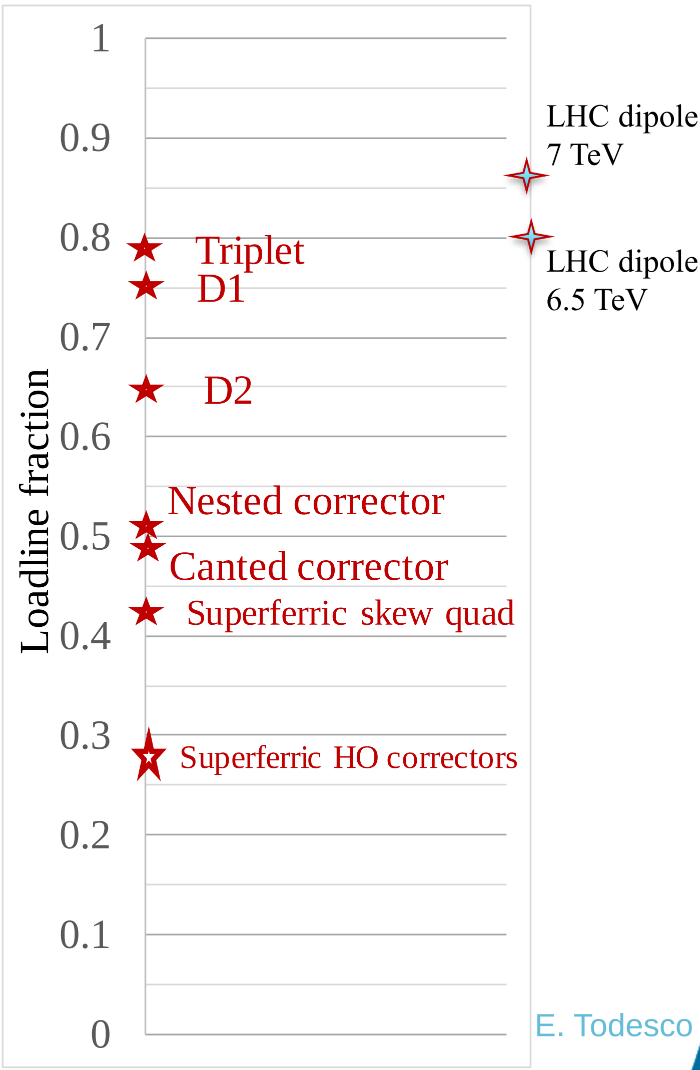
SEPTEMBER 2019

FEATURES

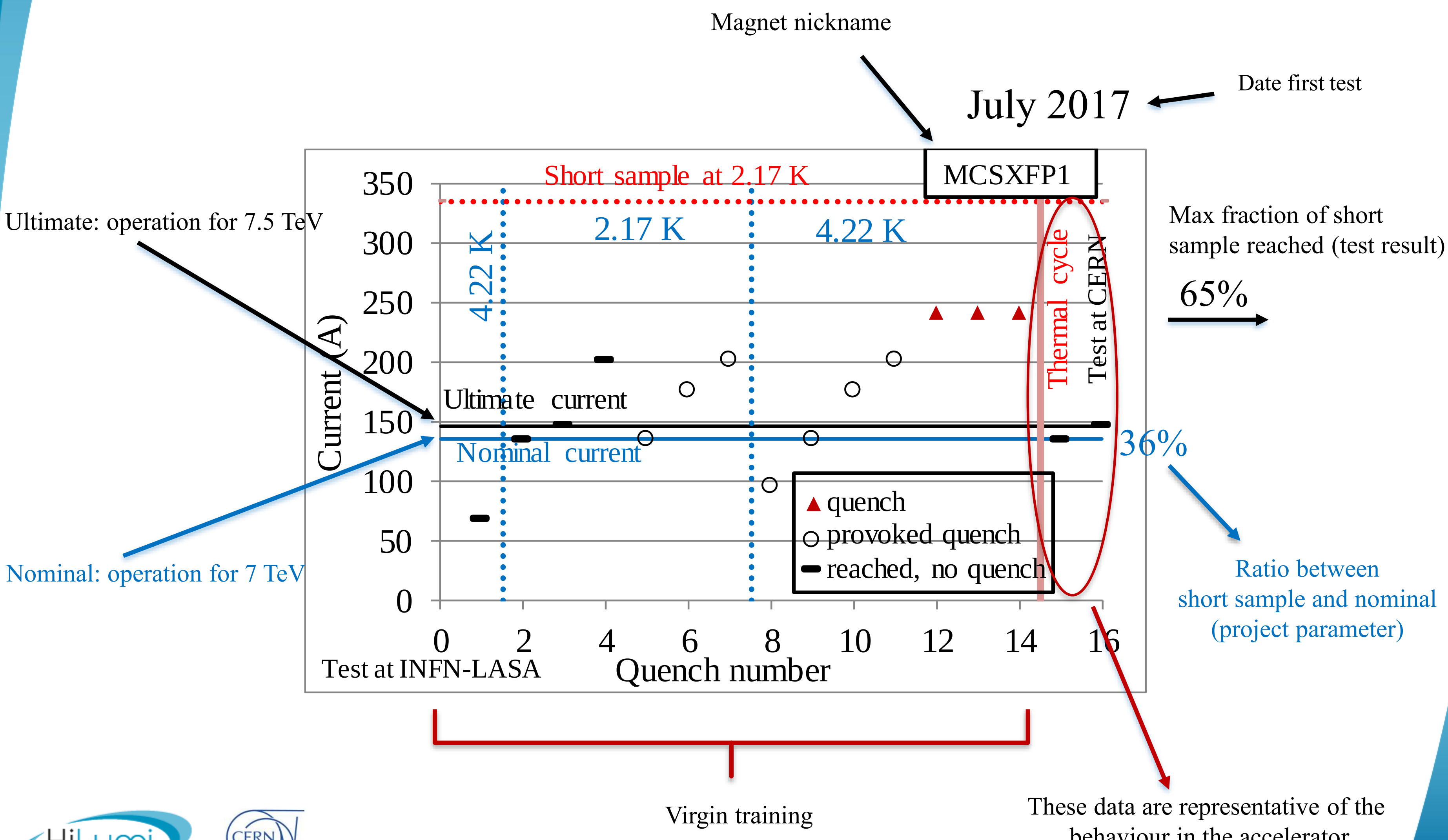
Peak field from 2 to 12 T



Operating at 30 to 80% of max current (usually called short sample current)



HOW TO READ A PERFORMANCE PLOT

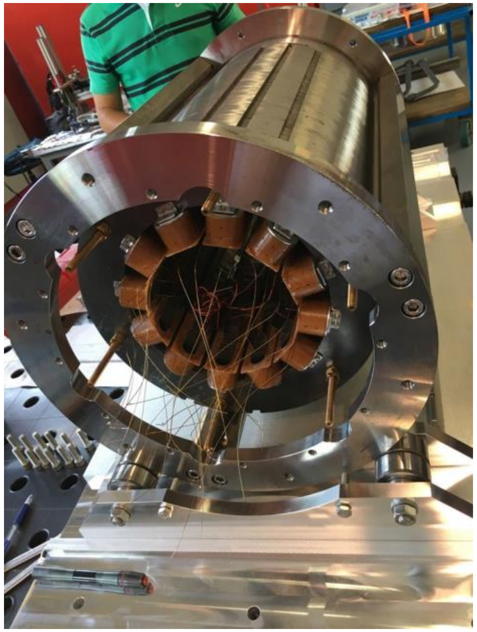


SUMMARY

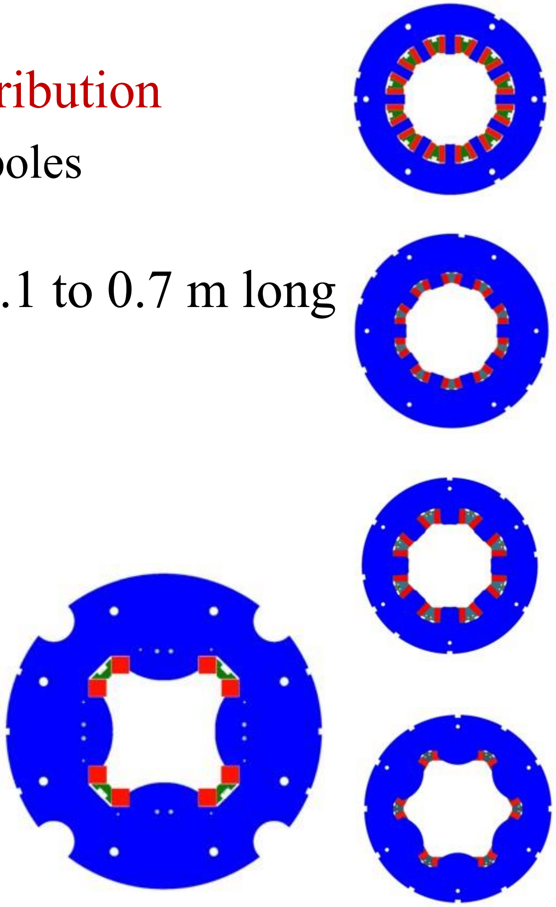
- Where are we with validation of the design
- Open points
- Understood issues
- Conclusions

HIGH ORDER CORRECTORS DESIGN

- The high order corrector are based on a superferric design, first developed by CIEMAT for S-LHC
- Design, prototypes and series as INFN-LASA contribution
- Nb-Ti winding of a single insulated strand, around iron poles
  - Both winding and iron at 1.9 K
- 2-3 T peak field magnet, 25-45% on the loadline, 0.1 to 0.7 m long



The dodecapole: magnet (left), coil (right)
(M. Statera, A. Musso, et al.)

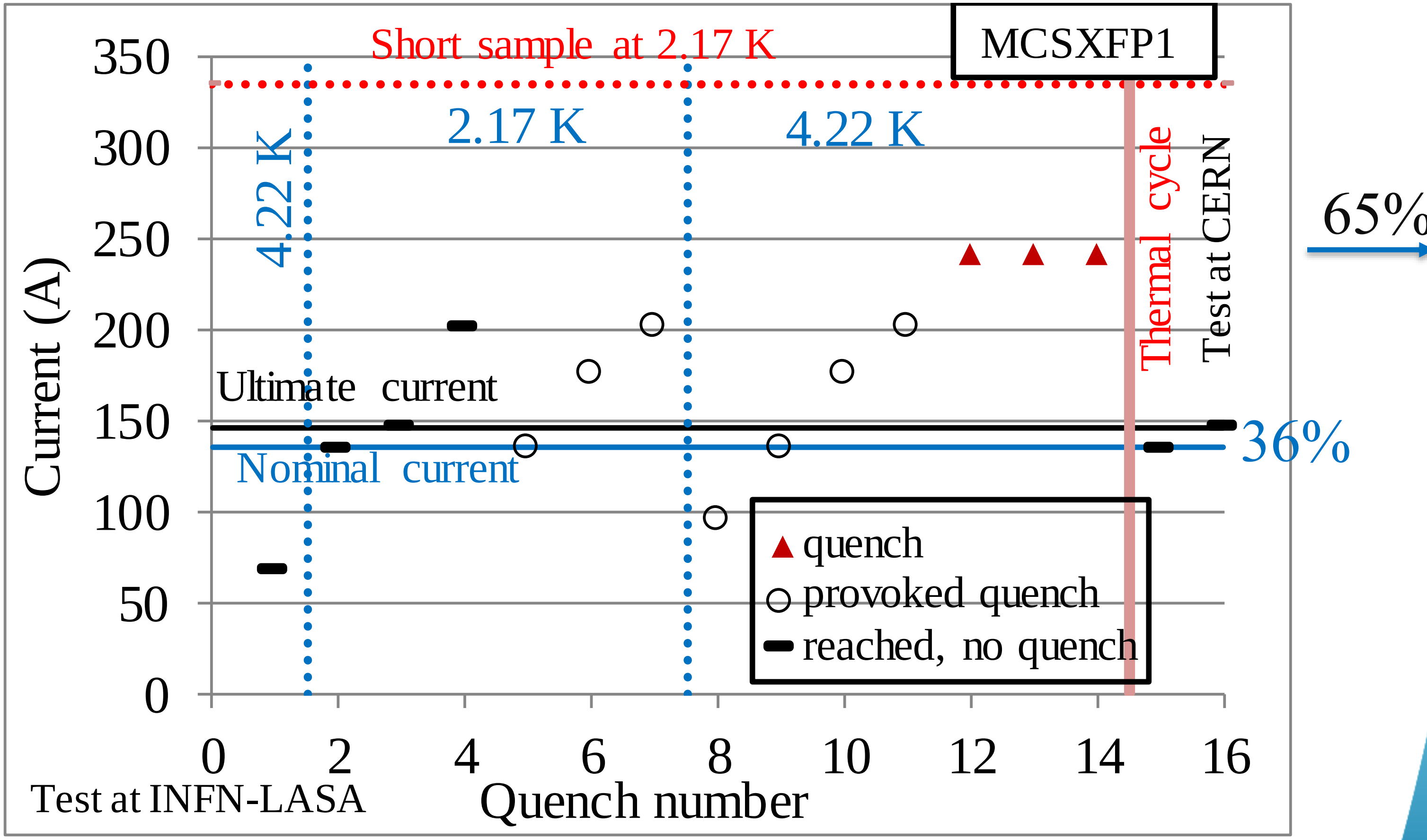


Magnet cross-sections
(G. Volpini, M. Sorbi)

HIGH ORDER CORRECTOR RESULTS

- Design succesfully validated on prototypes
  - Sextupole …

February 2016

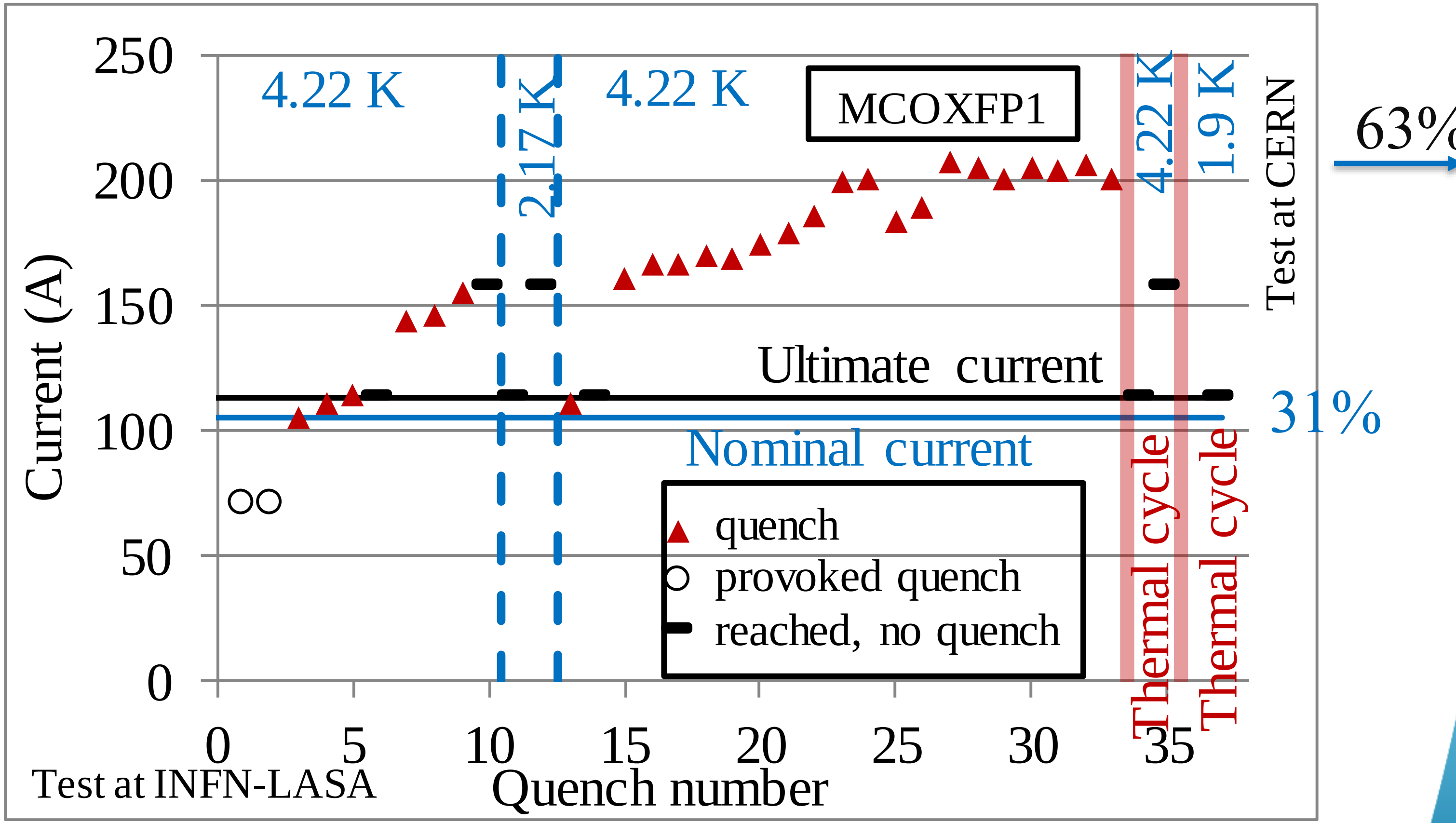


Sextupole training [G. Volpini, M. Sorbi, et al.]

HIGH ORDER CORRECTOR RESULTS

- Design succesfully validated on prototypes
  - Octupole …

March 2017

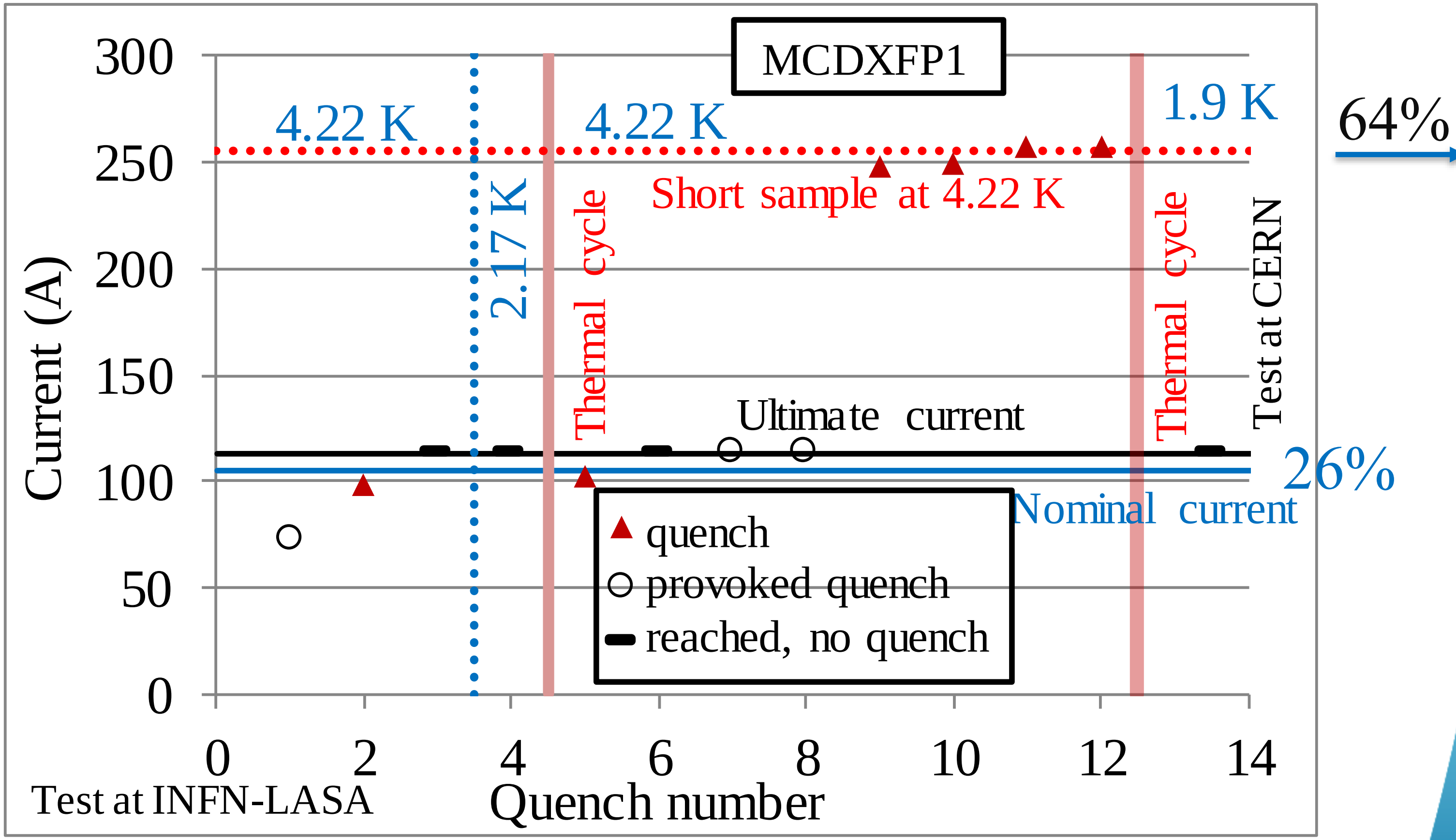


Octupole training [G. Volpini, M. Sorbi, et al.]

HIGH ORDER CORRECTOR RESULTS

- Design succesfully validated on prototypes
  - Decapole …

September 2017

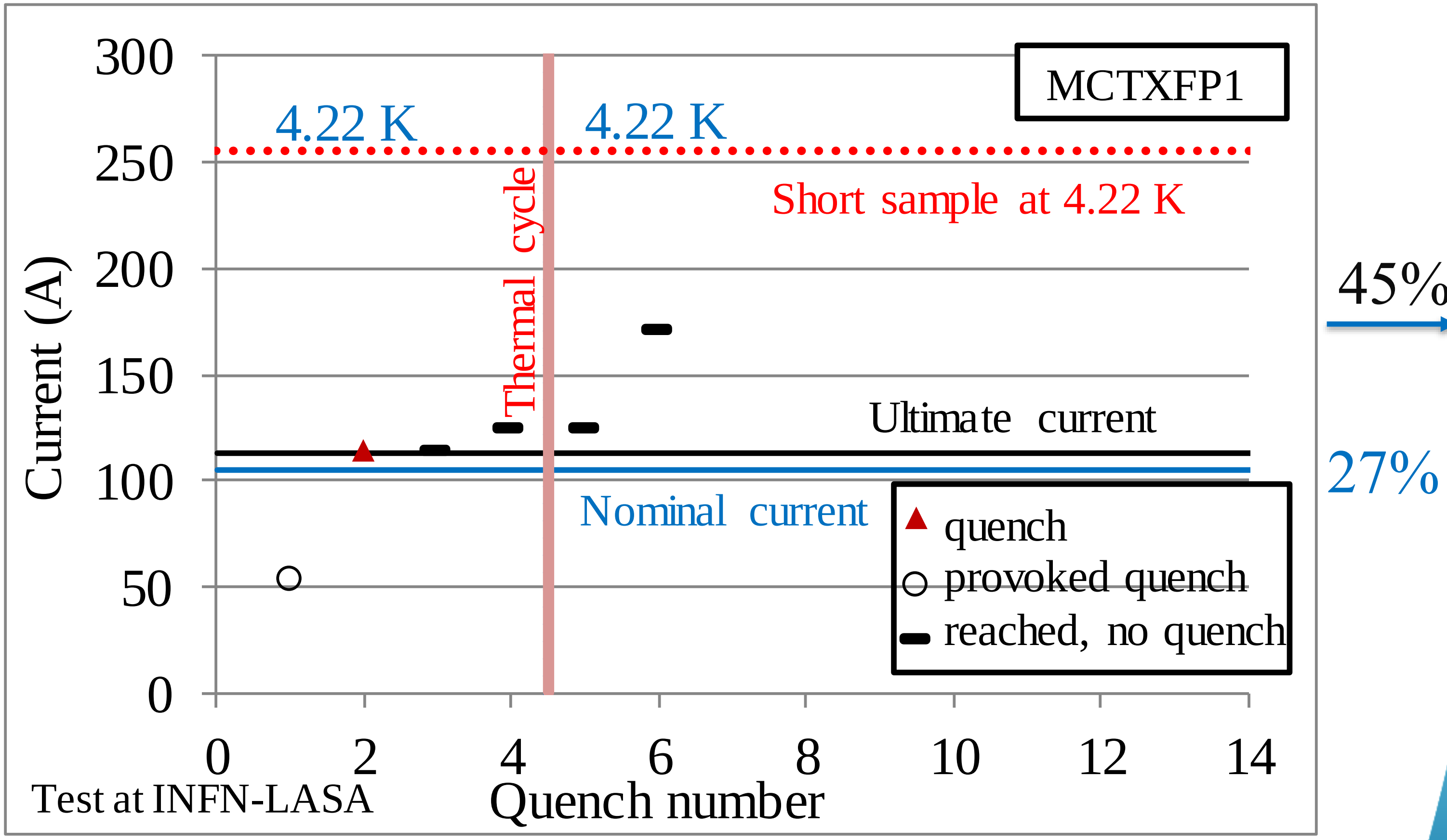


Decapole training [M. Sorbi, M. Statera, A. Musso et al.]

HIGH ORDER CORRECTOR RESULTS

- Design succesfully validated on prototypes
  - Dodecapole … (first done in industry)

October 2018

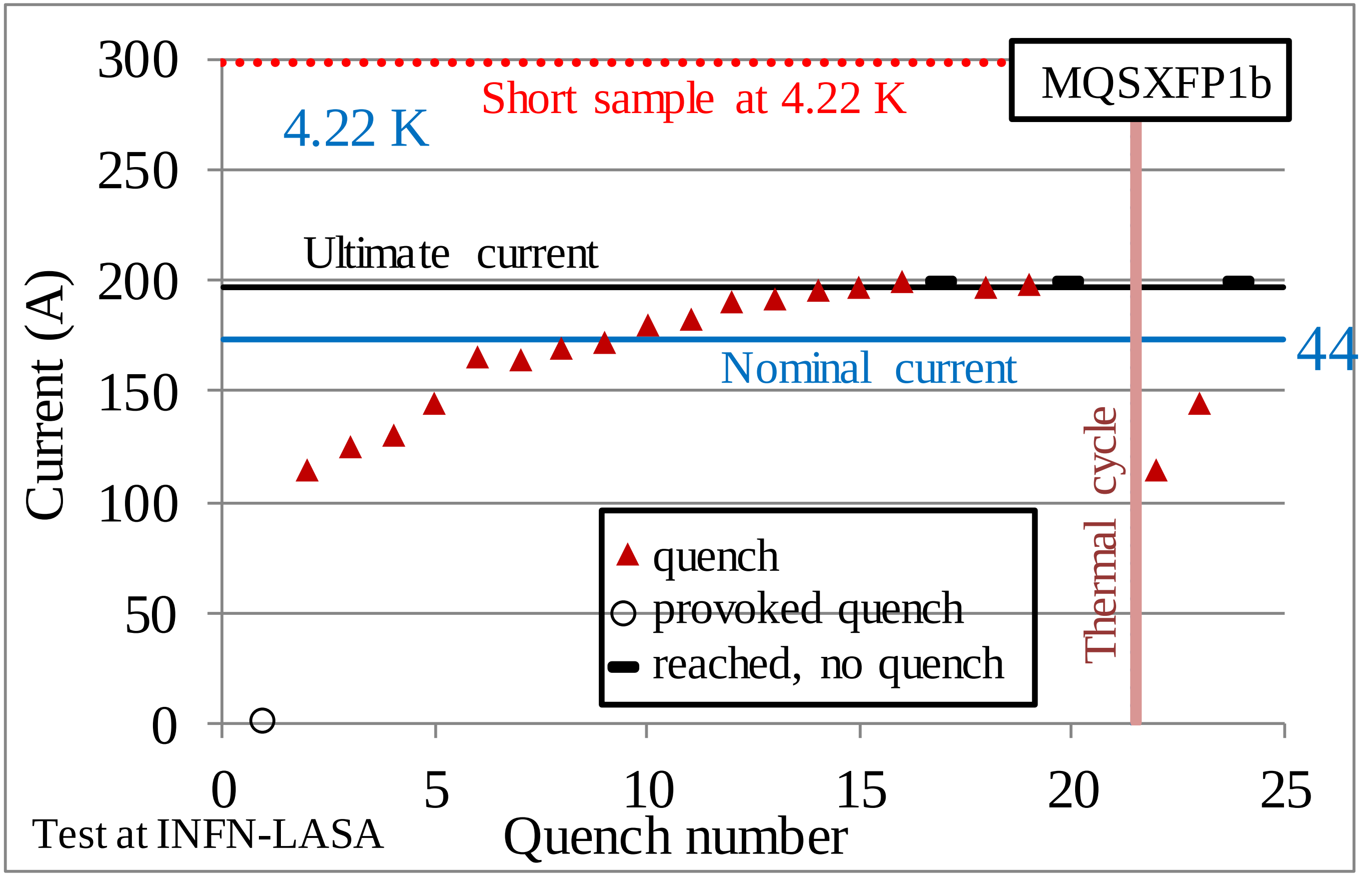


Dodecapole training [M. Sorbi, M. Statera, A. Musso et al.]

HIGH ORDER CORRECTOR RESULTS

- Design succesfully validated on prototypes
  - … and skew quadrupole

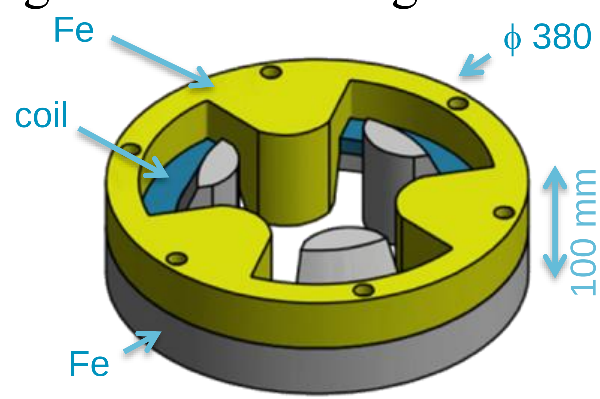
February 2019

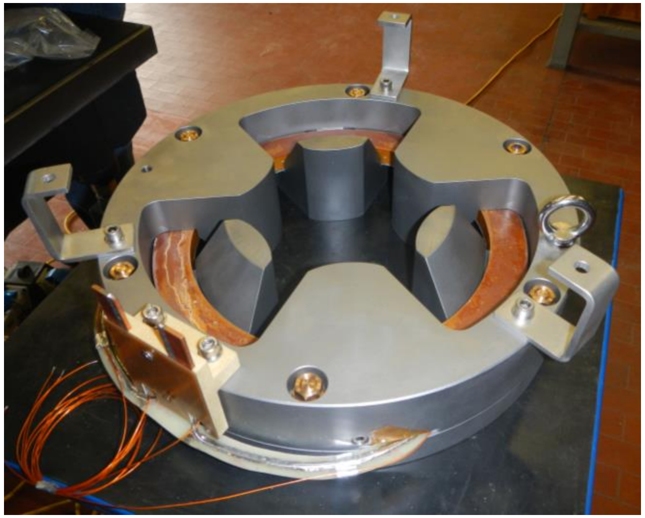


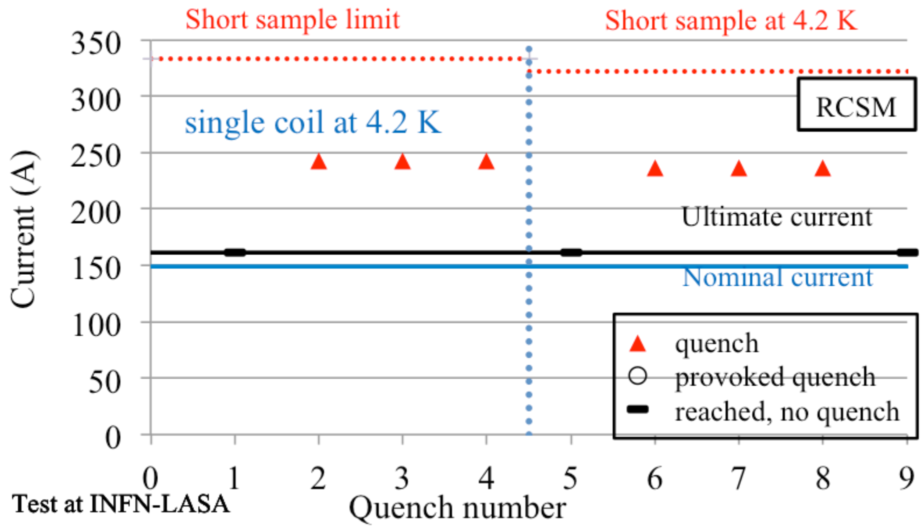
Decapole training [M. Sorbi, M. Statera, A. Musso et al.]

HIGH ORDER CORRECTOR RESULTS

- The RCSM (round coil superferric magnet)
  - INFN and CERN explored the possibility of using a corrector design based on round coils in MgB_2
  - Not adopted due to the lower efficiency in producing integrated gradient
  - LASA developed and tested a sextupole that reached 75% of short sample

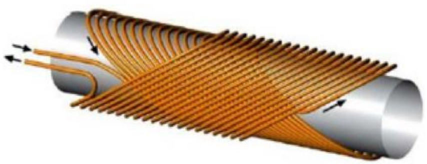






RCSM magnet (left) and power test (right) [M. Sorbi, M. Statera, G. Volpini et al.]

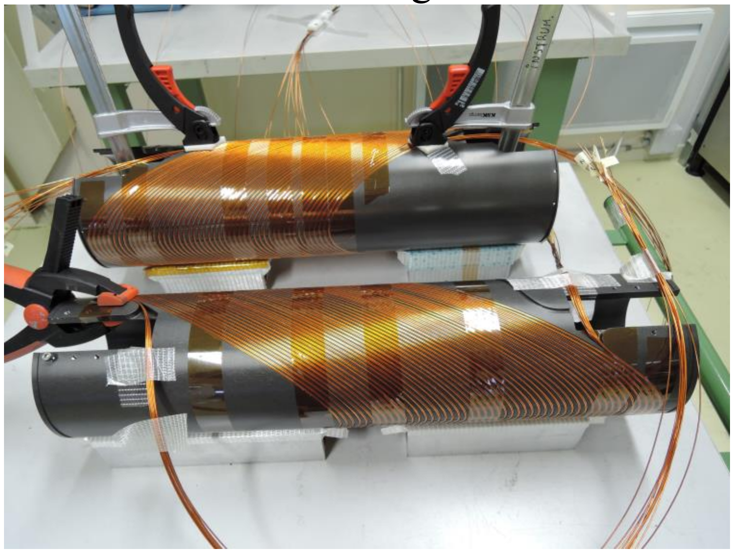
D2 CORRECTOR DESIGN



- Dipole corrector magnet based on canted cos theta design
  - 3 T peak field magnet, 50% on the loadline, 2-m-long
  - Uses more conductor but has a very simple tooling and faster construction
  - Interesting for 2-5 T range

(D. I. Meyer, 1970 – S. Caspi, 2015)
(H. Meinke, et al 2003)

- Nb-Ti winding of a single insulated strand, inside a groove taking 10 strands, made on an Al cylinder
  - CERN (927 lab) developed the design and manufactured short model and prototypes
  - China (IHEP) is developing a prototype based on CERN design and will provide the series magnets



The short model winding (G. Kirby, et al.)

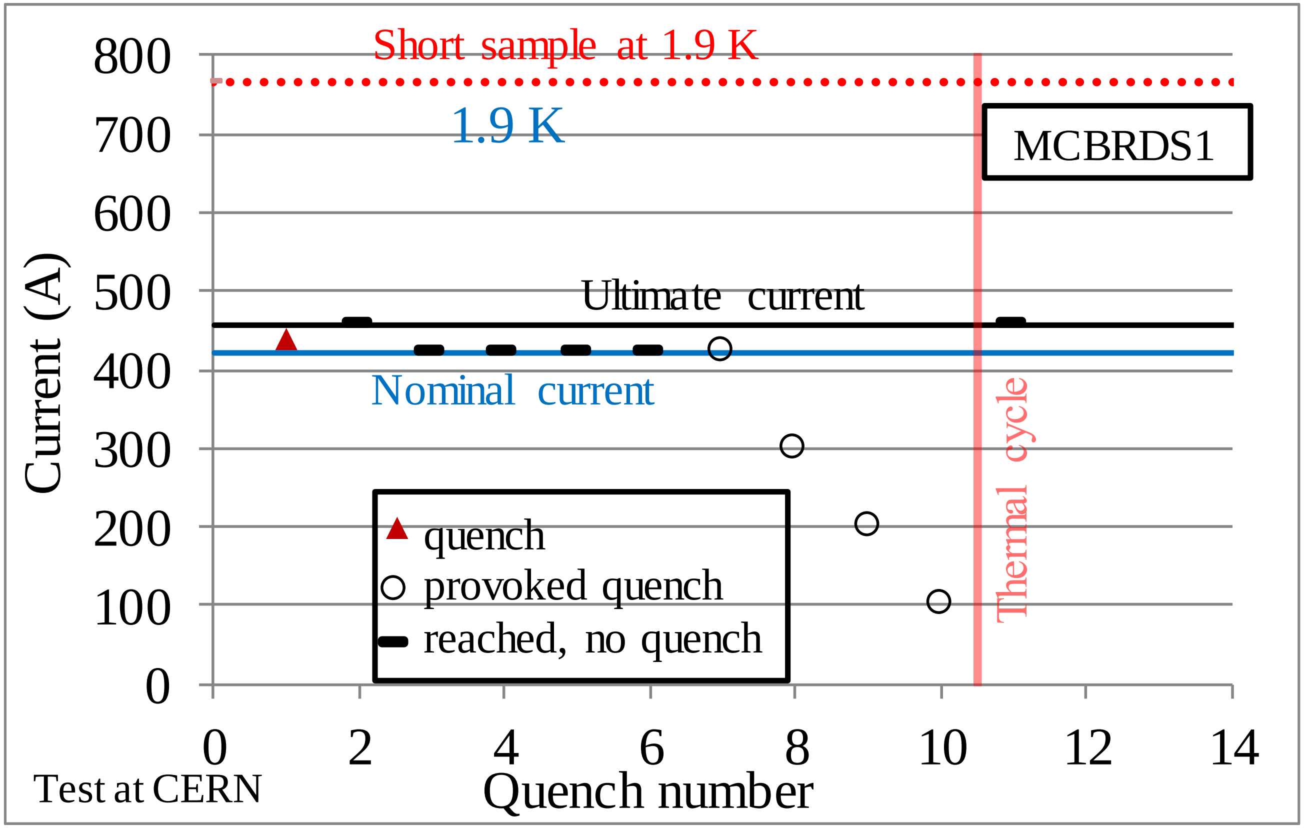
Test in SM18 (F. Mangiarotti, et al.)

Detail of winding (J. Mazet, et al.)

D2 CORRECTOR RESULTS

- Design succesfully validated on one short model (double aperture) and on one prototype (double aperture)

August 2017



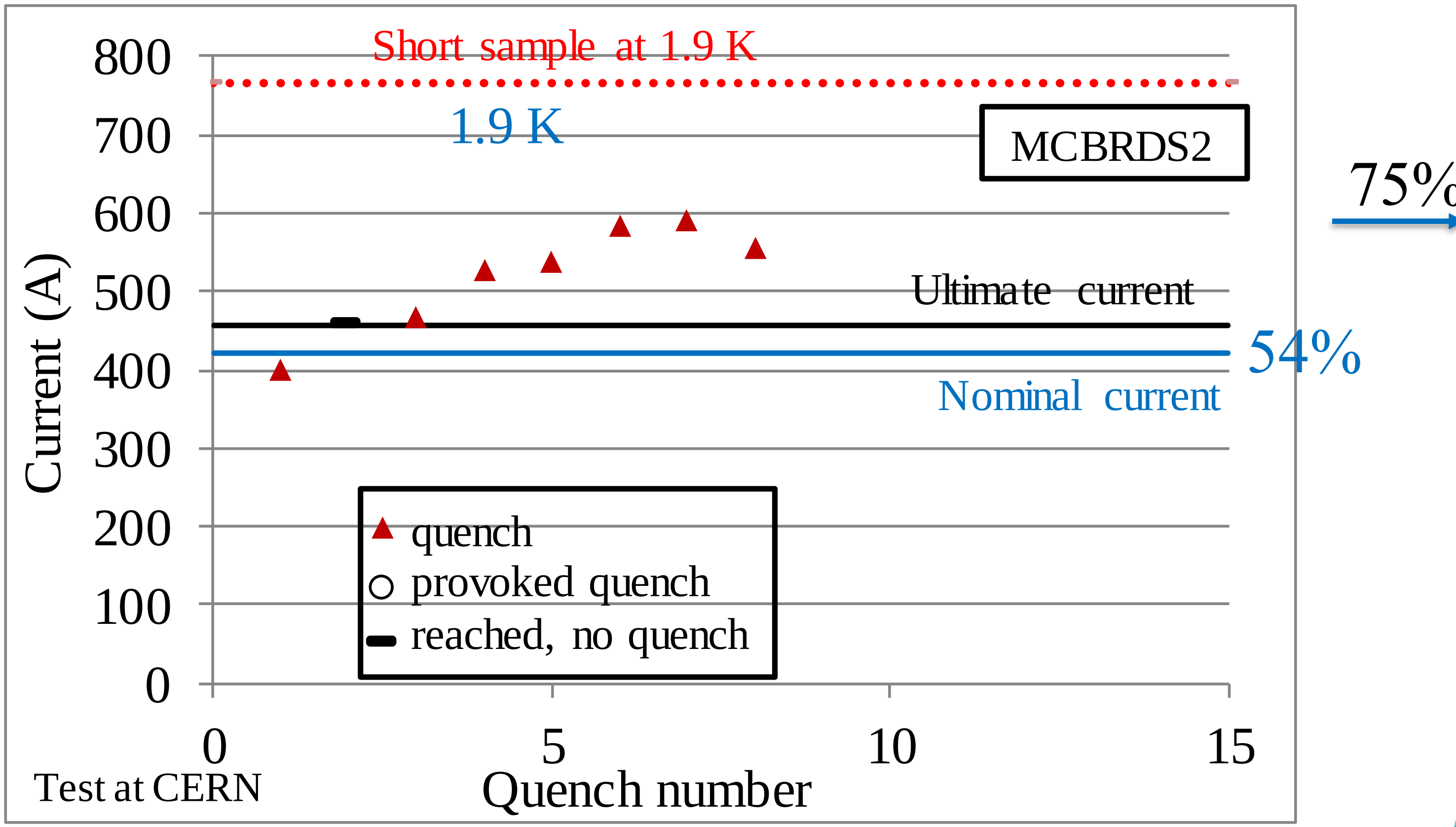
54%

Training of D2 corrector short model first aperture (F. Mangiarotti, G. Kirby, et al.)

D2 CORRECTOR RESULTS

- Design succesfully validated on one short model (double aperture) and on one prototype (double aperture)

May 2018

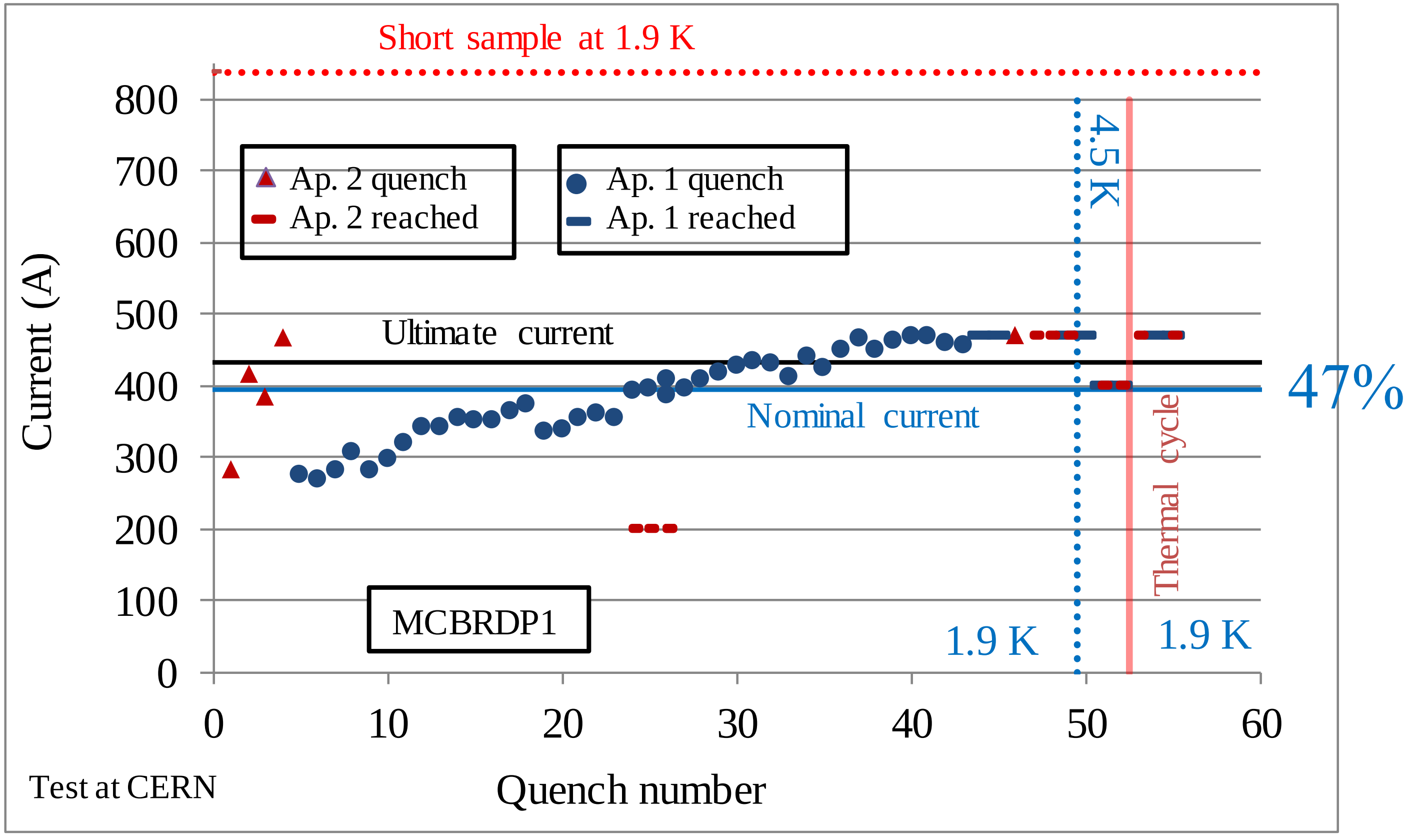


Training of D2 corrector short model second aperture (F. Mangiarotti, G. Kirby, et al.)

D2 CORRECTOR RESULTS

- Design succesfully validated on one short model (double aperture) and on one prototype (double aperture)
  - Long training in one aperture but good memory

November 2018



Training of D2 corrector prototype (F. Mangiarotti, G. Kirby, et al.)

D2 CORRECTOR

- First collaboration of CERN with China for accelerators
  - IHEP is steering the collaboration, prototype and series to be done in WST, tested in IMP

Signature of collaboration agreement

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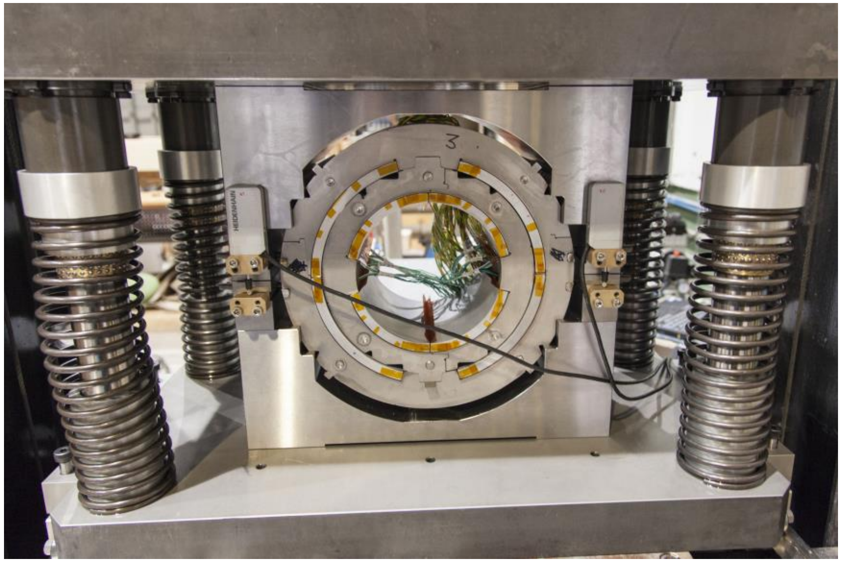
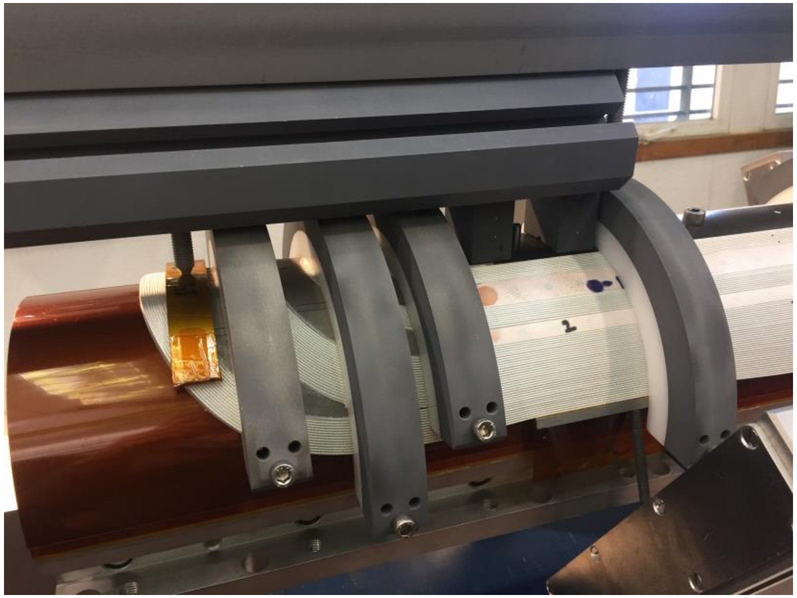
NESTED CORRECTOR: DESIGN

- Dipole corrector magnet based on Rutherford cable
  - 3.5 T peak field magnet, 50% on the loadline, 1.5 and 2.5-m-long
  - Horizontal and vertical dipole, nested
  - Double collaring with mechanical lock on the straight part
  - Nb-Ti Rutherford cable with impregnation
- Design, prototypes and series as CIEMAT contribution



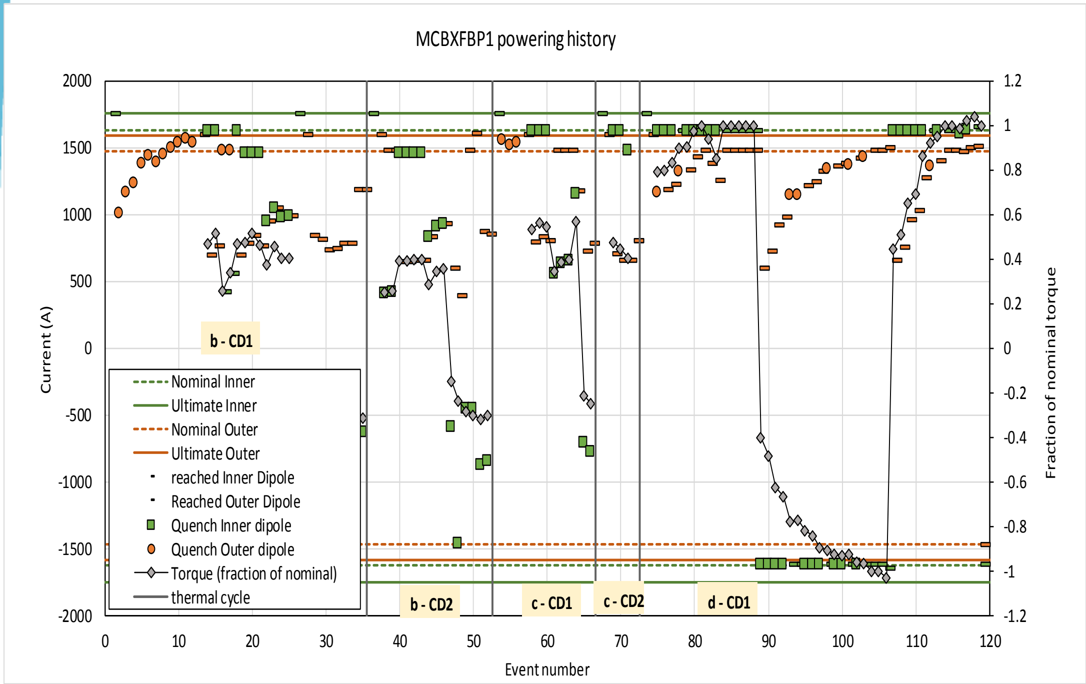
Collaring test (F. Toral, J. C. Perez, et al.)



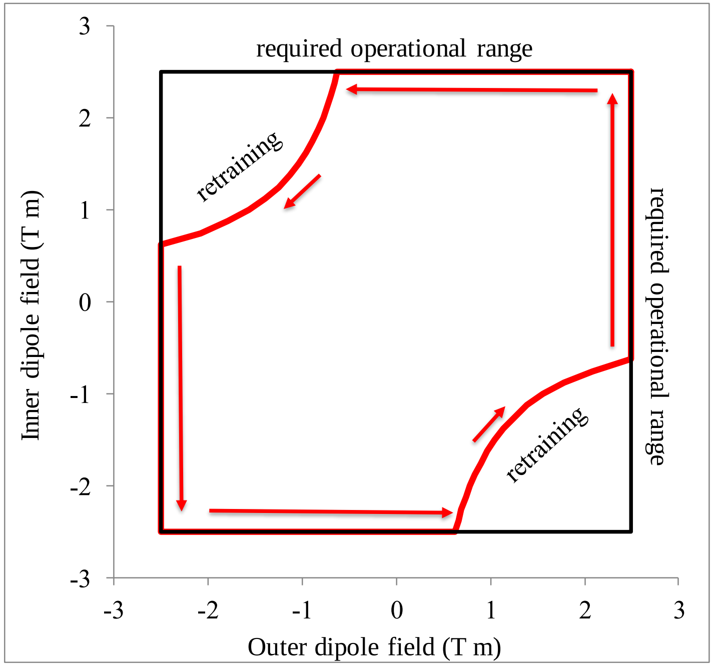
Coil winding (F. Toral, J. C. Perez, et al.)

NESTED CORRECTOR RESULTS

- The first prototype reaches performance on 80% of required operational range
  - The other 20% accessible via training
  - Main critical part is the head support given by shimming (see next section)
  - Iteration on shimming to improve performance and to check reproducibility on the second prototype



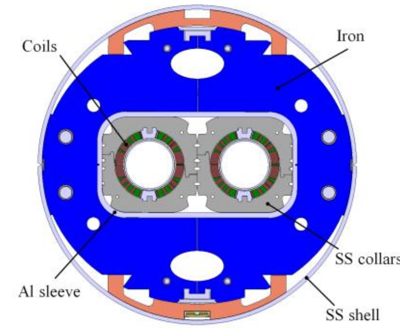
Training of nested corrector short prototype
(G. Willering, J. C. Perez, F. Toral, et al.)



Operational cycle preformed without quenches after training(in red)
(G. Willering, J. C. Perez, F. Toral, et al.)

D2 RECOMBINATION DIPOLE DESIGN

- The D2 dipole is a 4.5 T two in one aperture dipole «a la LHC»
  - Same cable, same SS collars, but only one layer of cable and 105 mm aperture
  - 5.5 T peak field magnet, 65% on the loadline, 7-m-long
  - Novel features
    - Small coil asymmetry to compensate aperture cross-talk
    - Al sleeve to lock the two apertures
  - Design, prototypes and series as INFN-Ge contribution



Magnet cross-section
(P. Fabbricatore, S. Farinon, et al.)

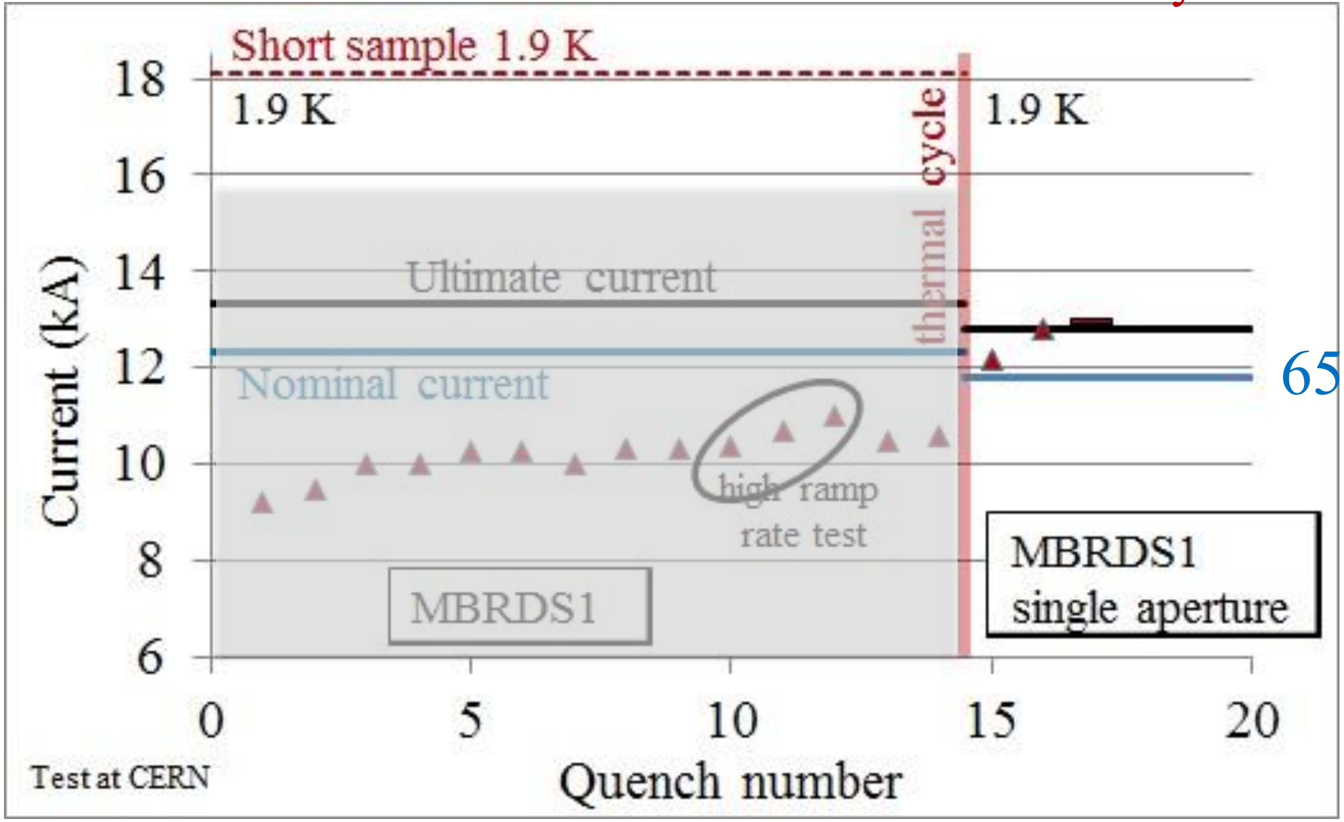
Two apertures assembled in Al sleeve [P. Fabbricatore, S. Farinon, et al.]

Ready for test in SM18

D2 RECOMBINATION DIPOLE RESULTS

- Design validated on one aperture of one short model
  - Fine tuning of design to improve robustness of assembly
  - One aperture had a major assembly fault (see next section)

February 2019

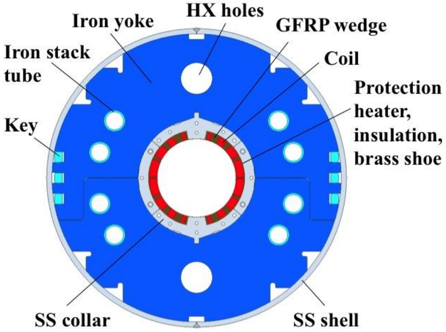


65%

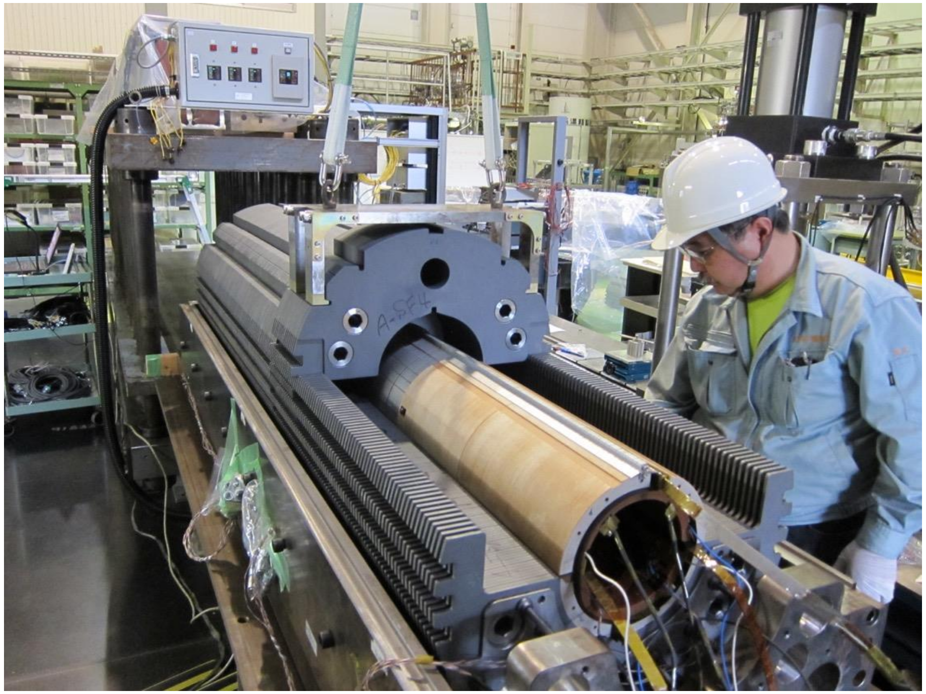
Training of recombination dipole short prototype
(G. Willering, A. Foussat, P. Fabbricatore, et al.)

D1 SEPARATION DIPOLE DESIGN

- The D1 dipole is a 5.6 T large aperture dipole
  - Same LHC cable but one layer of cable and 150 mm aperture
  - 6.5 T peak field magnet, 75% on the loadline, 6-m-long
  - Mechanical structure «a la MQXA»
    - Iron mechanical support, thin collar spacers
  - Design, prototypes and series as KEK contribution



Magnet cross-section (T. Nakamoto, et al.)



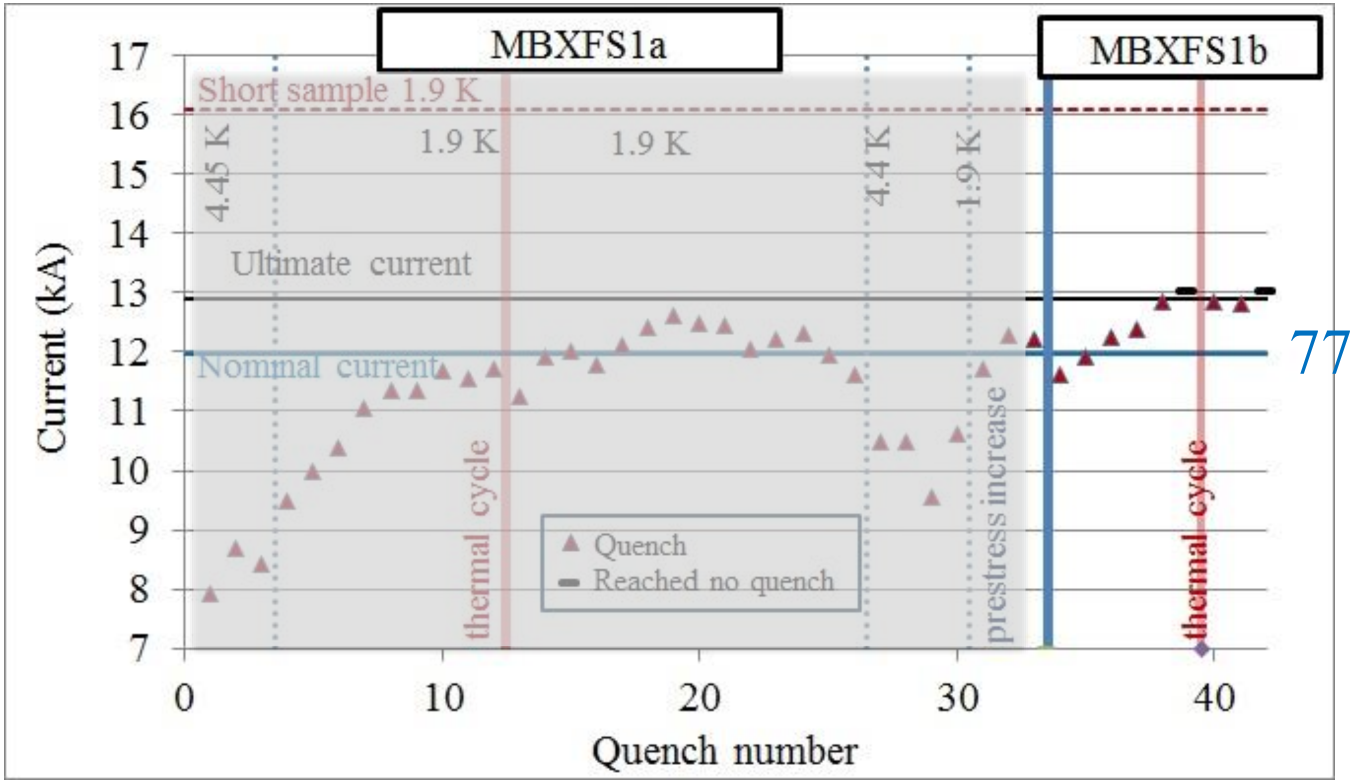
Collaring with iron [T. Nakamoto, M. Sugano, et al.]

Ready for test in KEK

D1 SEPARATION DIPOLE RESULTS

- Design succesfully validated on three short models
  - First assembly of first short model had assembly issues (see next section) – second assembly OK

April 2016



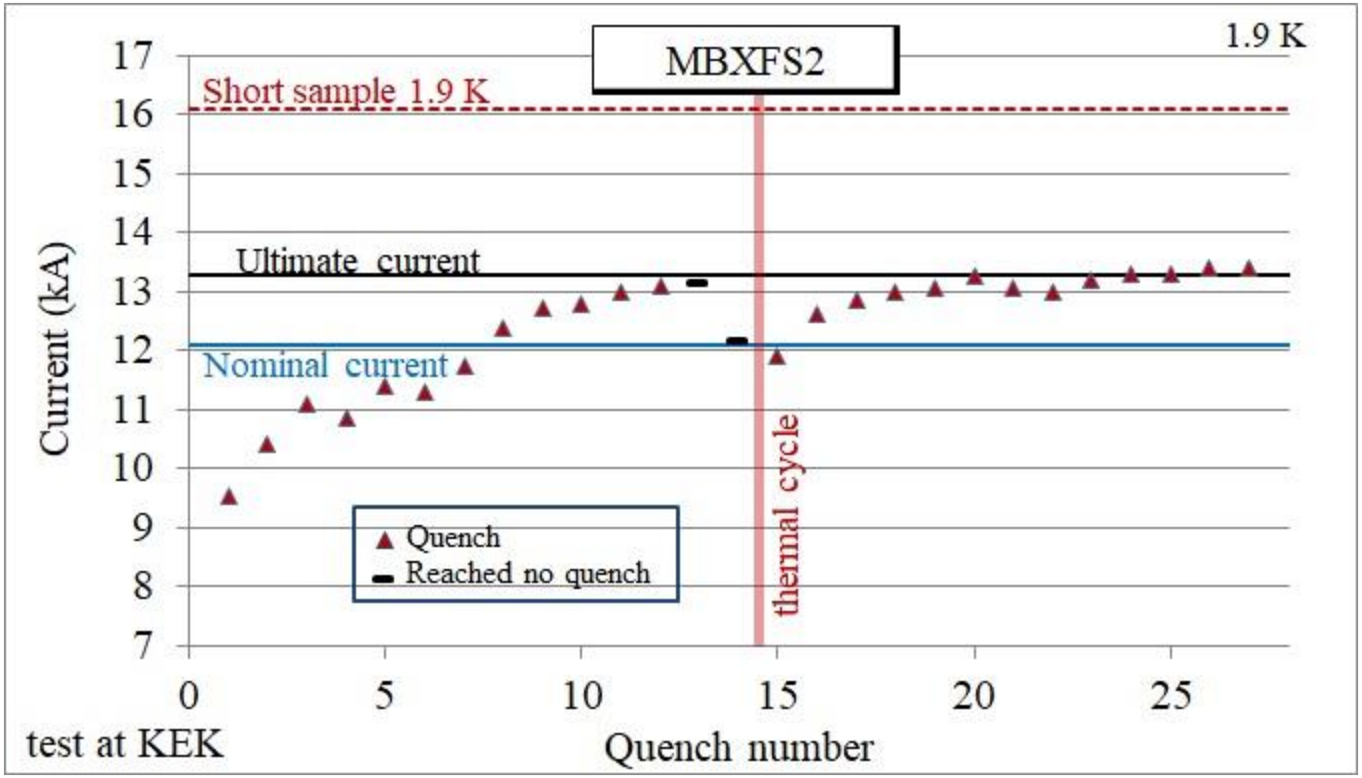
77%

Training of separation first dipole short prototype
(T. Nakamoto, M. Sugano, A. Musso, K. Suzuki, et al.)

D1 SEPARATION DIPOLE RESULTS

- Design succesfully validated on three short models
  - Second model OK

October 2018



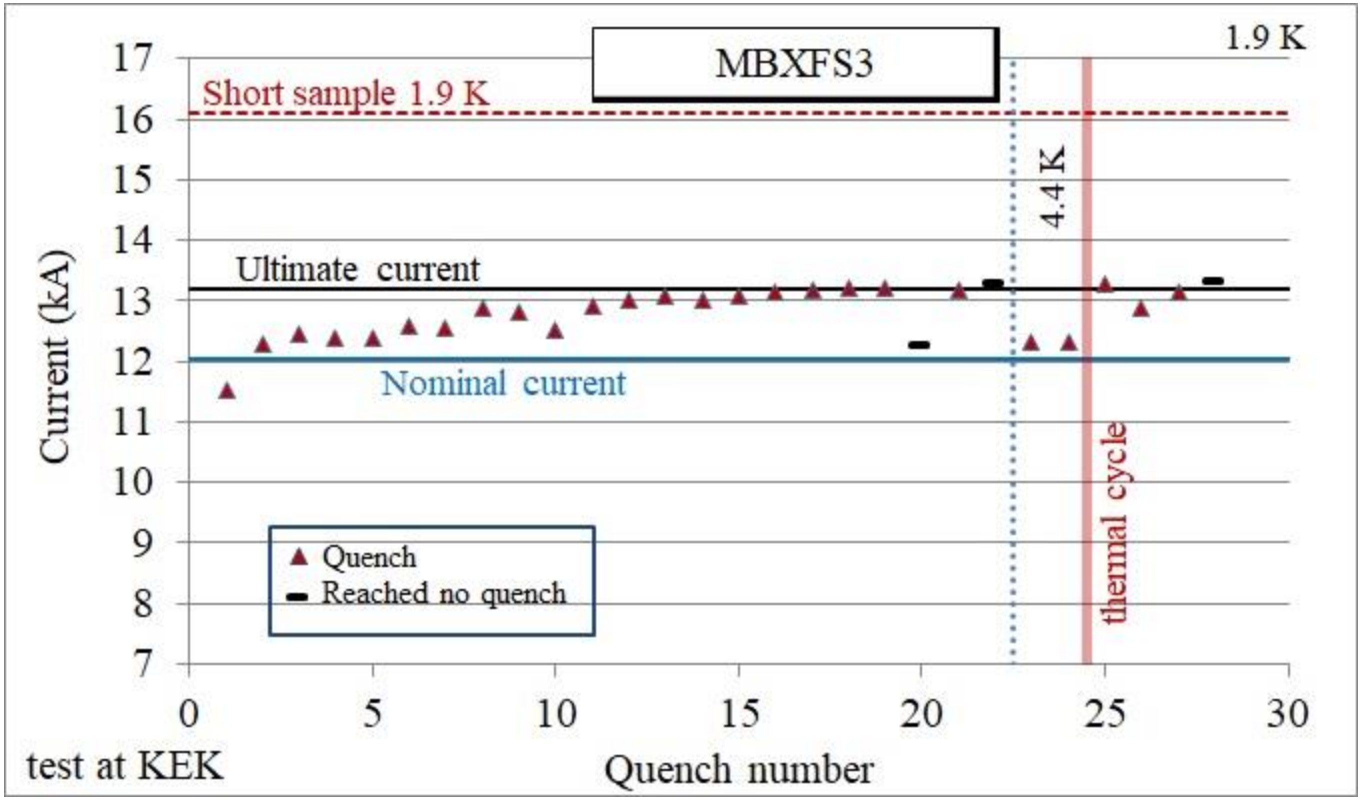
77%

Training of separation second dipole short prototype
(T. Nakamoto, M. Sugano, A. Musso, K. Suzuki, et al.)

D1 SEPARATION DIPOLE RESULTS

- Design succesfully validated on three short models
  - Third model OK

September 2019



77%

Training of separation third dipole short prototype
(T. Nakamoto, M. Sugano, A. Musso, K. Suzuki, et al.)

TRIPLET DESIGN

- The MQXF is a 11.5 T peak field, 150 mm aperture, Nb_3Sn quadrupole
  - 78% on the loadline, 7.15 and 4.2-m-long (CERN and US version)
  - First Nb_3Sn magnet to be operated in a particle accelerator after the 11 T
  - First magnet to be operated in a particle accelerator with Al shell and b&k
    - Part of the preload given during cool-down, avoiding peak stresses during collaring
  - First magnet to be operated in a particle accelerator protected by CLIQ
  - Design as a joint venture CERN-US, based on LARP experience

Beam screen insertion in short model
[P. Ferracin, J. C. Perez, et al.]

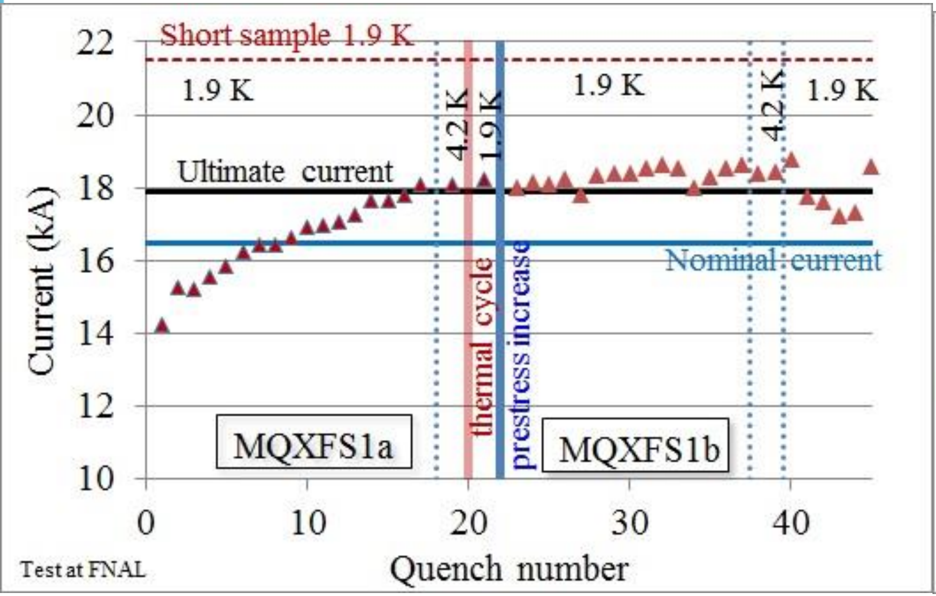
Assembly of the coils
[P. Ferracin, F. Lackner, et al.]

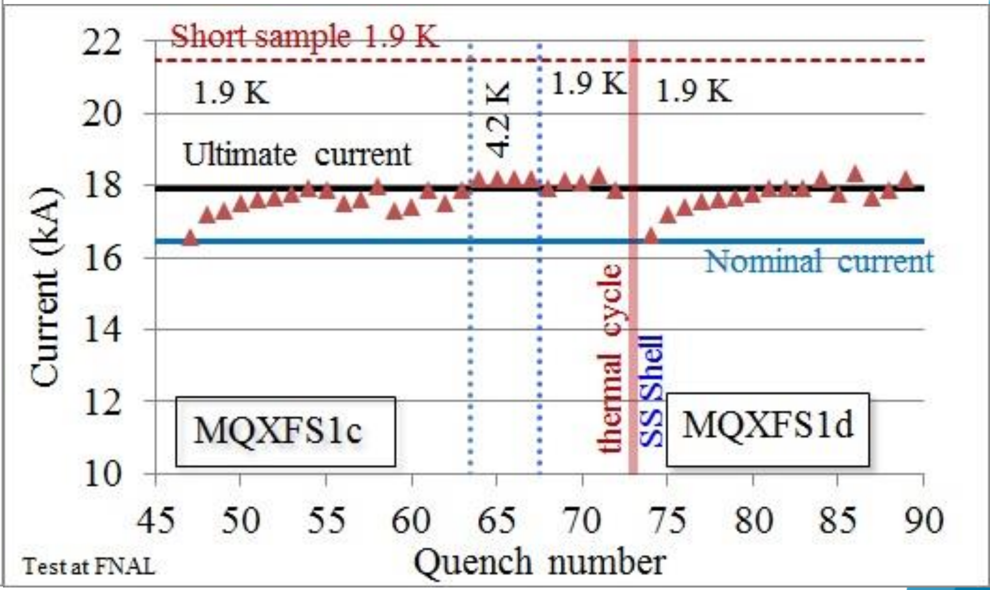
TRIPLET RESULTS

- Design succesfully validated on three short models: first
  - First «Frankenstein» model (2 coils from CERN and 2 from US, different strands
  - No quenches below nominal after thermal cycle
  - Large margin at 4.2 K
  - More than 100 quenches and five thermal cycles

US HL-LHC AUP

October 2016



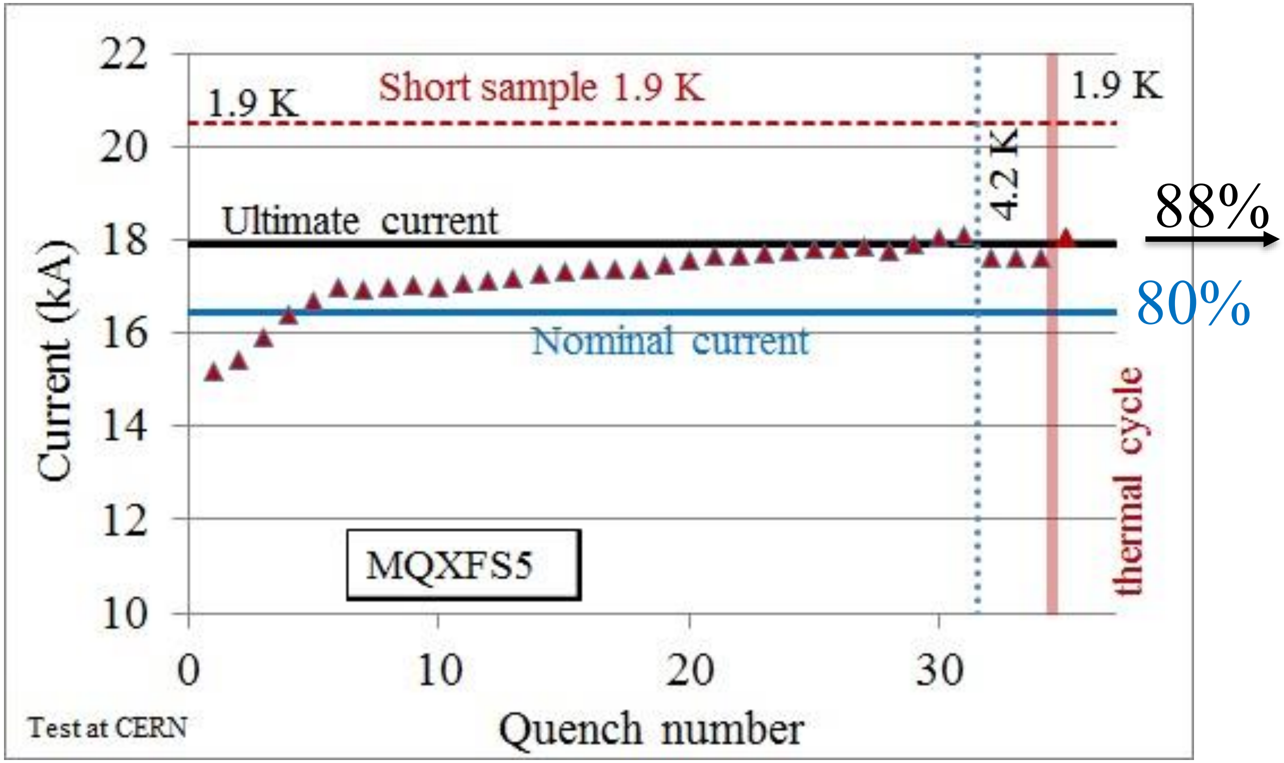


Training of first short model quadrupole
(G. Ambrosio, P. Ferracin, S. Feher, S. Stoynev, et al.)

TRIPLET RESULTS

- Design succesfully validated on three short models: second
  - No quenches below ultimate after thermal cycle
  - Large margin at 4.2 K

July 2017

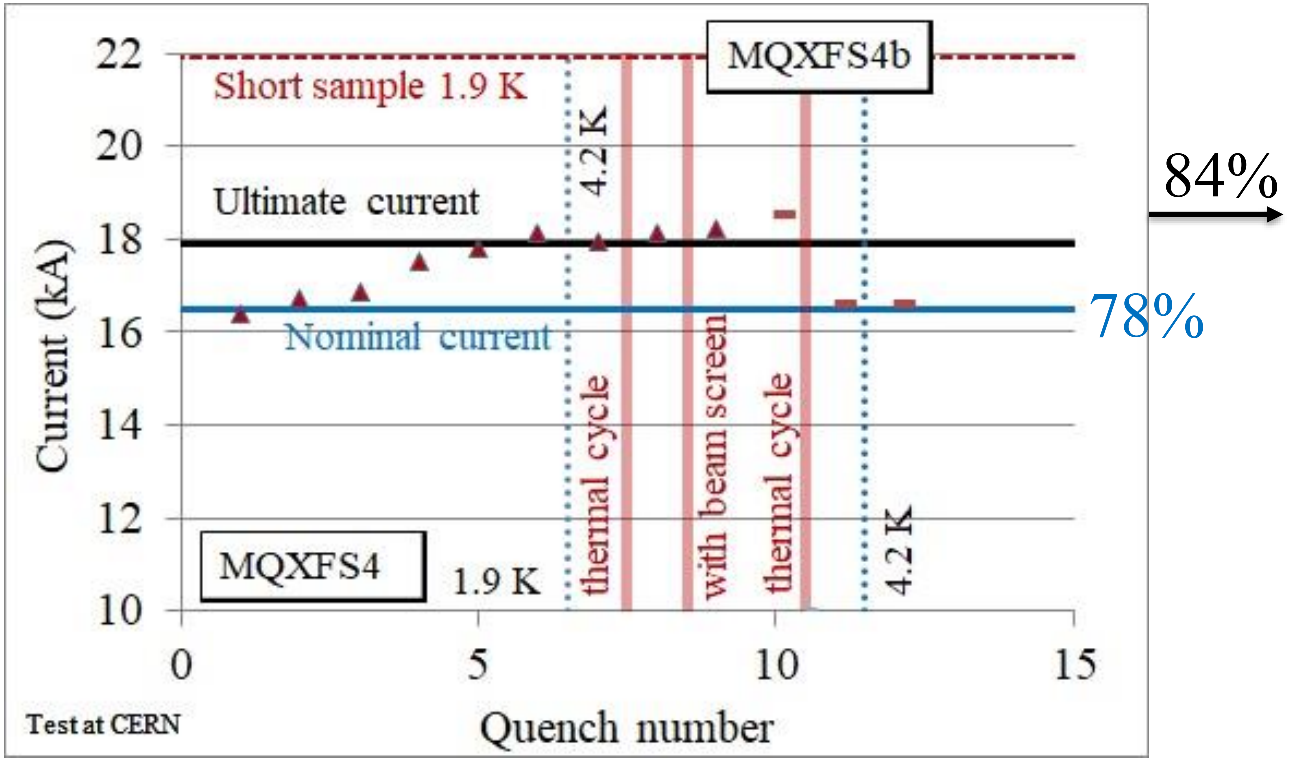


Training of MQXFS5
(P. Ferracin, J. C. Perez, H. Bajas, et al.)

TRIPLET RESULTS

- Design succesfully validated on three short models: third
  - No quenches below ultimate after thermal cycle
  - Large margin at 4.2 K
  - Four thermal cycles

July 2018

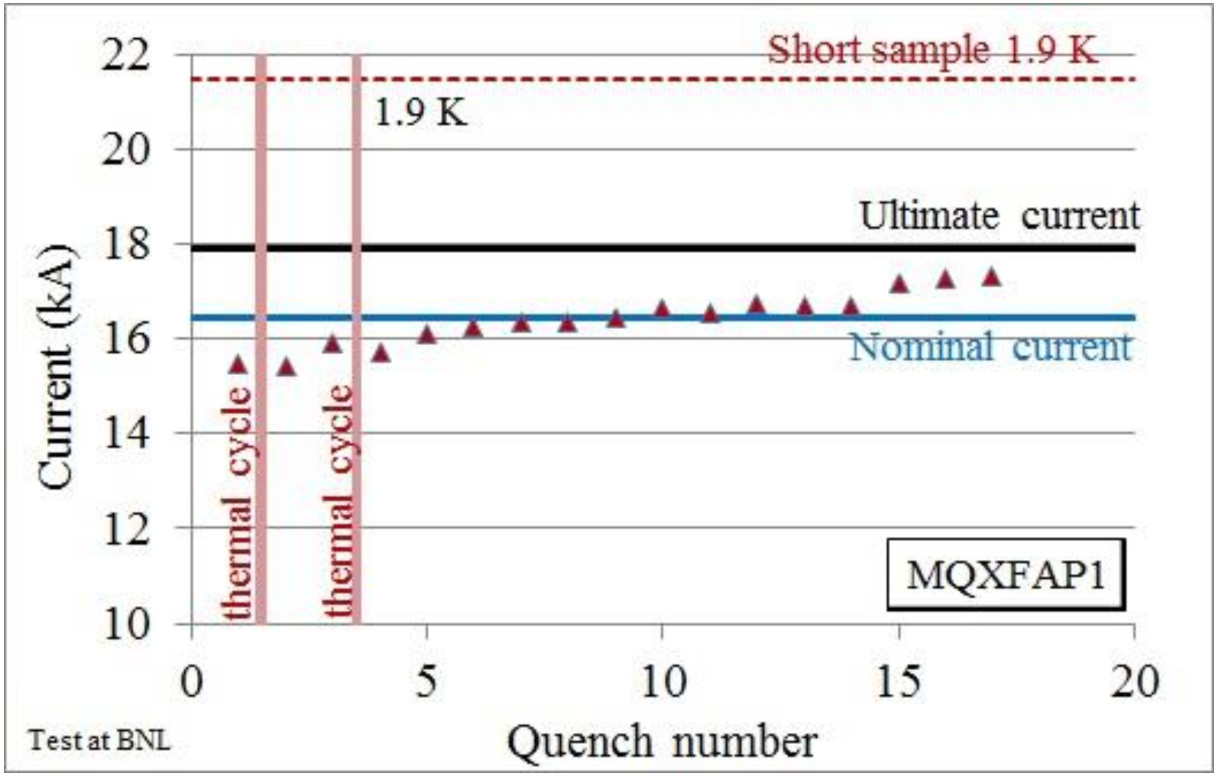


Training of MQXFS4
(P. Ferracin, J. C. Perez, F. Mangiarotti, et al.)

TRIPLET RESULTS

- Design succesfully validated on one prototype to nominal
  - 4-m-long magnet has similar training of short models
  - Test interrupted by short (see next section)

August 2017



Training of MQXFP1
(G. Ambrosio, P. Ferracin, S. Feher, J. Muratore, et al.)

A FEW WORDS ABOUT COLLABORATIONS

US HL-LHC AUP

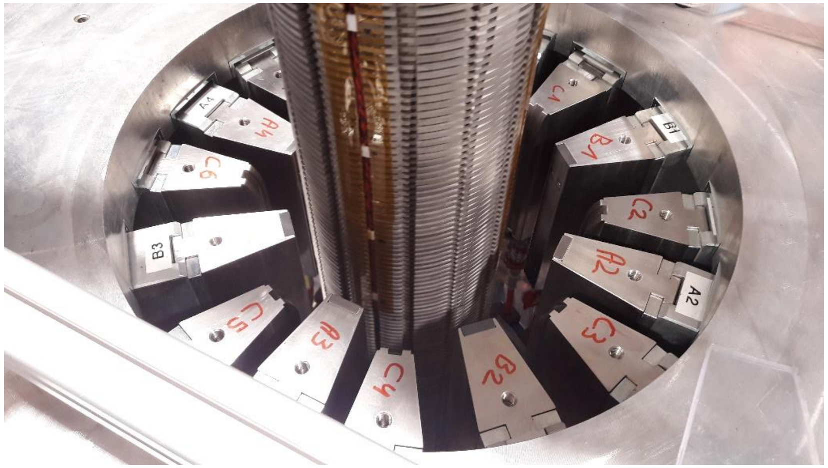
HiLumi HL-LHC PROJECT

LARGE APERTURE Q4 (MQYY)

- A large, double aperture Nb-Ti magnet to replace MQY (Q4 in the LHC)
  - Initially in the baseline, then removed after project streamlining
  - Coil manufactured at CEA, collaring in 927
  - Test foreseen in CEA in 2020

  - QUACO initiative in construction phase: two prototypes in the EU industry [M. Losasso, I. Bejar Alonso]

Coils ready for assembly
[D. Simon, H. Felice, M. Segreti, et al.]



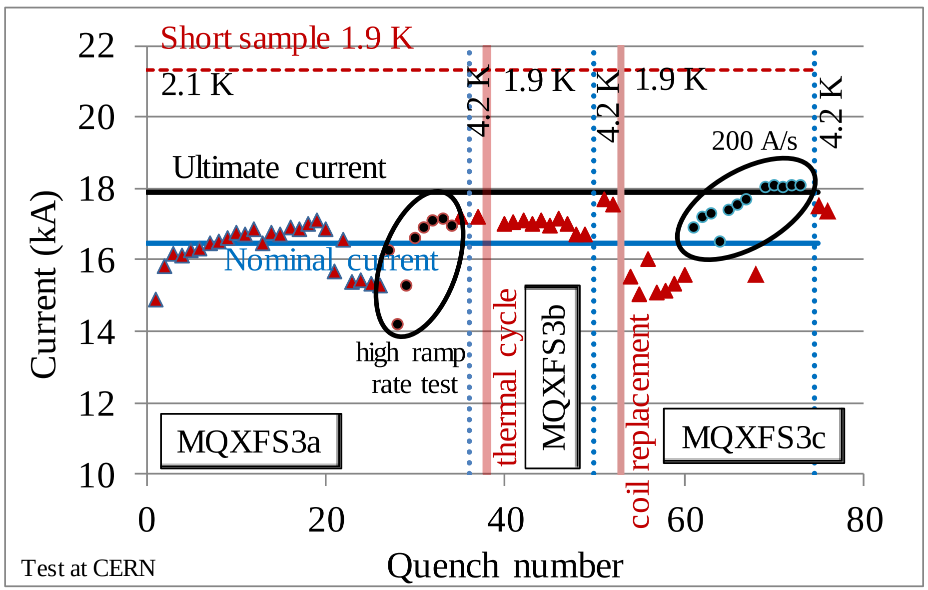
Collaring
[D. Simon, H. Felice, J. C. Perez, et al.]

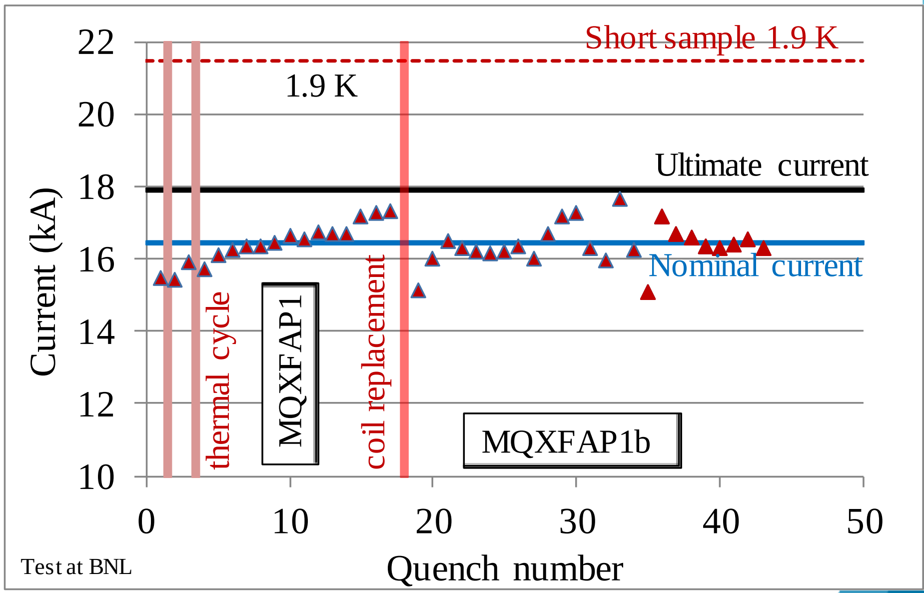
SUMMARY

- Where are we with validation of the design
- Open points
- Understood issues
- Conclusions

COIL REPLACEMENT

- We have two cases of coil replacement in MQXF not working as expected
  - Magnet limited by one coil, that coil is replaced, and coil previously «well behaving» limit performance

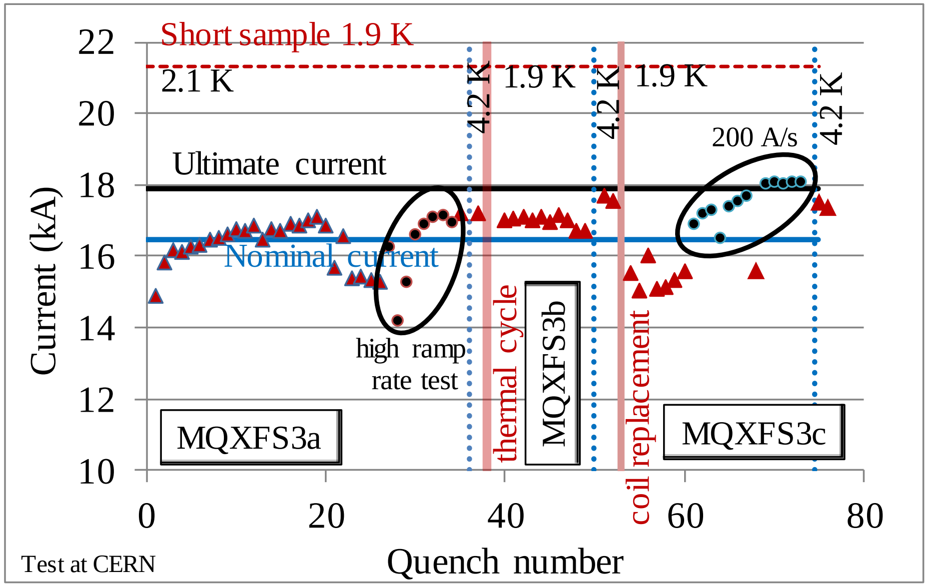


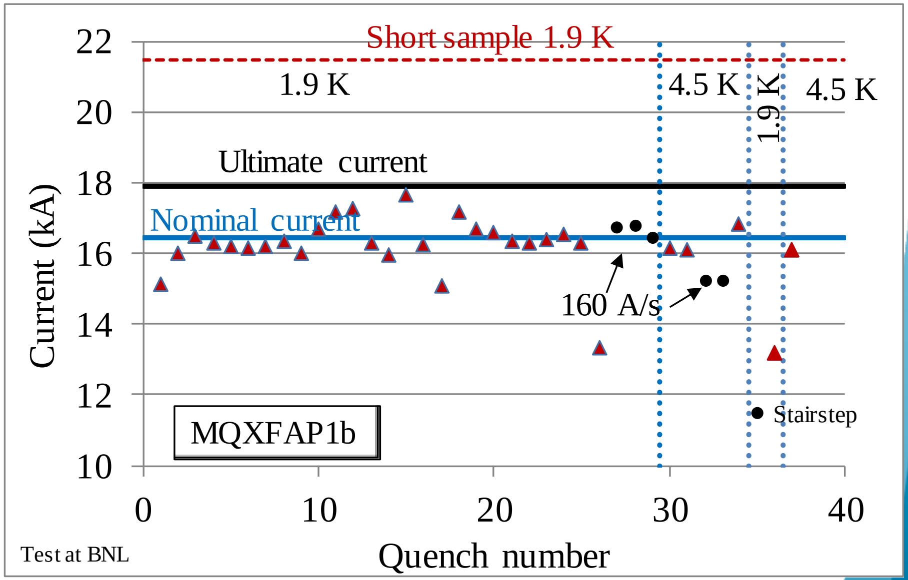


The two cases seen in MQXF program of coil replacement

REVERSE BEHAVIOUR

- By reverse behaviour we indicate 4.5 K performance better than 1.9 K, and high ramp rates better than low ramp rate
  - Seen in in one short and one long magnet
  - Indication that we are touching instabilities (B. Bordini, et al., several works since 2005 published on IEEE TAS)





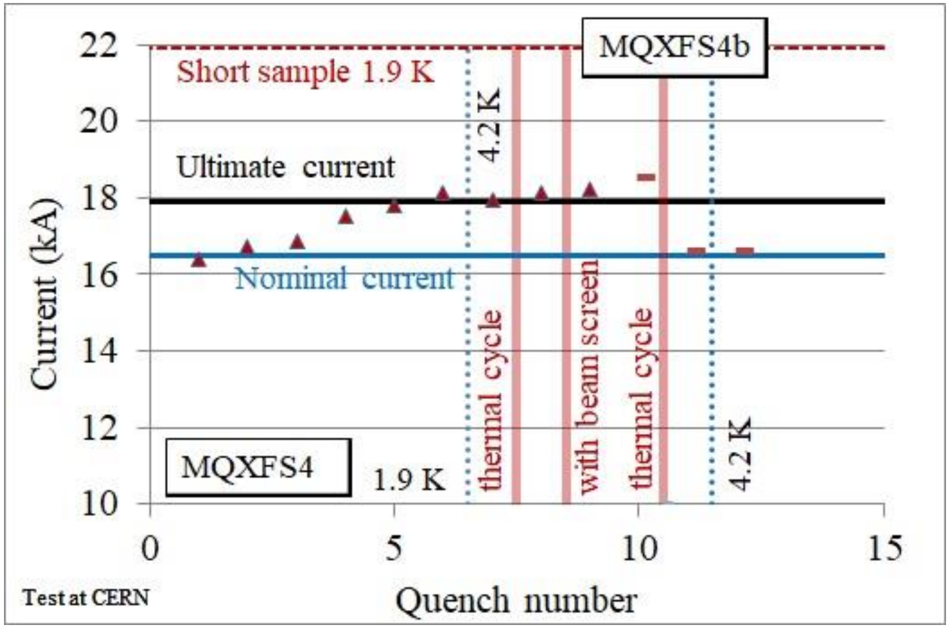
The two cases seen in MQXF program of reverse behaviour

ELECTRICAL INTEGRITY

- Quench heater location
  - We have in the baseline quench heaters impregnated in the coil heads
  - We (together with US AUP) found evidence of a possible mechanism of loss of electrical integrity between coil and heaters
  - Questions also coming from the experience of the 11 T program, where the removal of heaters from impregnation was decided early 2019
    - Remember that 11 T has double voltage requirements w.r.t. MQXF because of the energy extraction
  - We are considering the option of removing the quench heaters from impregnation to make the design more robust
  - Tests on short and long magnets are being done, a roadmap is identified, decision to be taken at the end of the year

DEGRADATION

- Performance degradation
  - Worries on degradation of magnet performance started eraly 2019, based on tests on a 11 T short model (SP109)
    - Later dissipated by test on SP107, and noting that 109 had non conform coils
  - First short model MQXFS1 had many thermal cycles (8) and more than 150 quenches, showing ability to go to nominal without quenches and to be retrained to ultimate
  - Special endurance test on MQXFS4 to have a clean test of long term behaviour (thermal cycles, powering cycles, high MIITs)
  - Test is ongoing, showing at the moment no issues

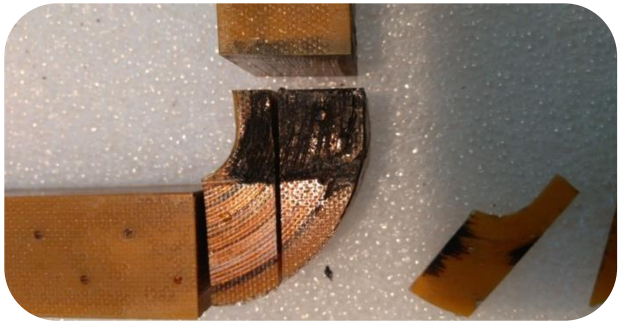


SUMMARY

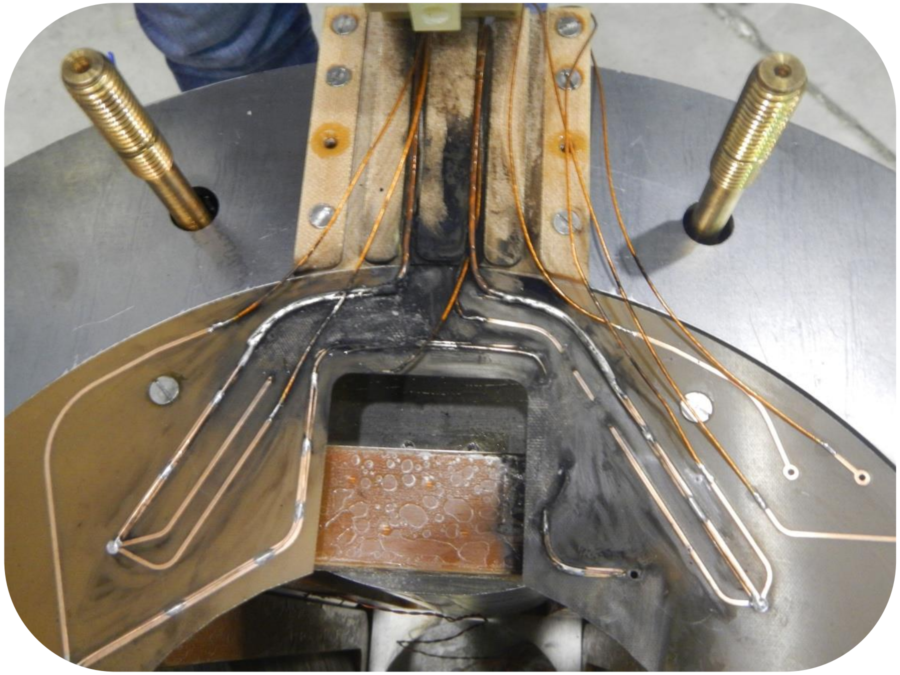
- Where are we with validation of the design
- Open points
- Understood issues
- Conclusions

ELECTRICAL SHORT - 1

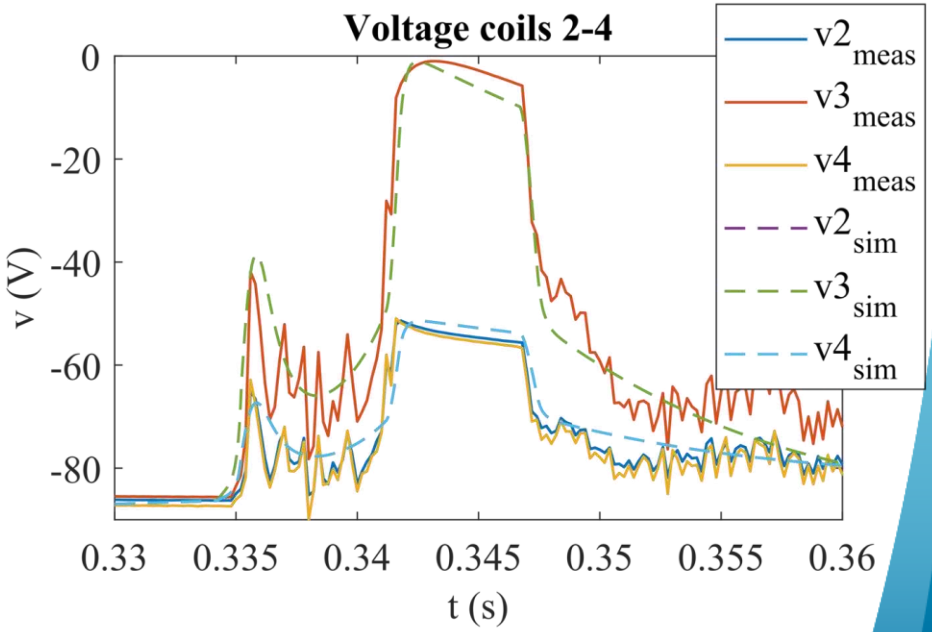
- The skew quadrupole had electrical short during test
  - Facts: inter-turn short during a quench
  - Origin: weakness in the coil design, cured
  - Consequence: one coil lost
  - New assembly worked succesfully



Origin of the short on PCB [M. Statera, et al.]



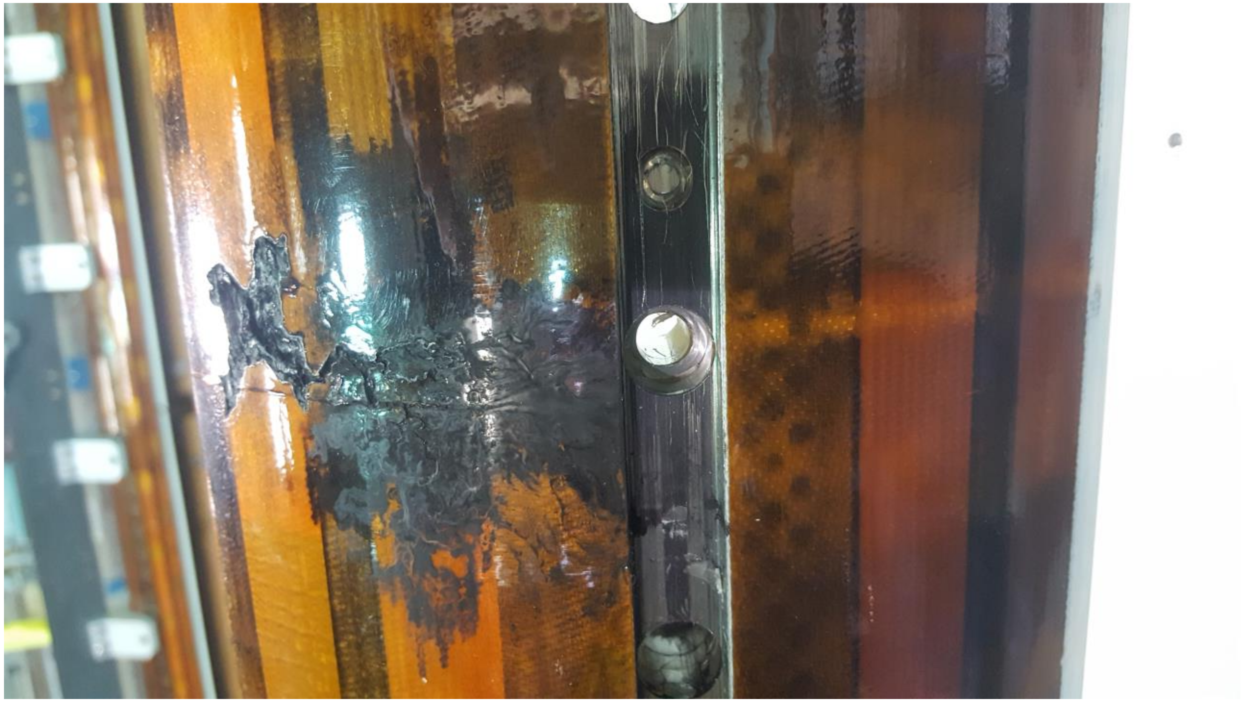
Impact of the short on PCB [M. Statera, et al.]



Simulation vs. measurements of the electrical short
[M. Statera, M. Prioli, et al.]

ELECTRICAL SHORT - 2

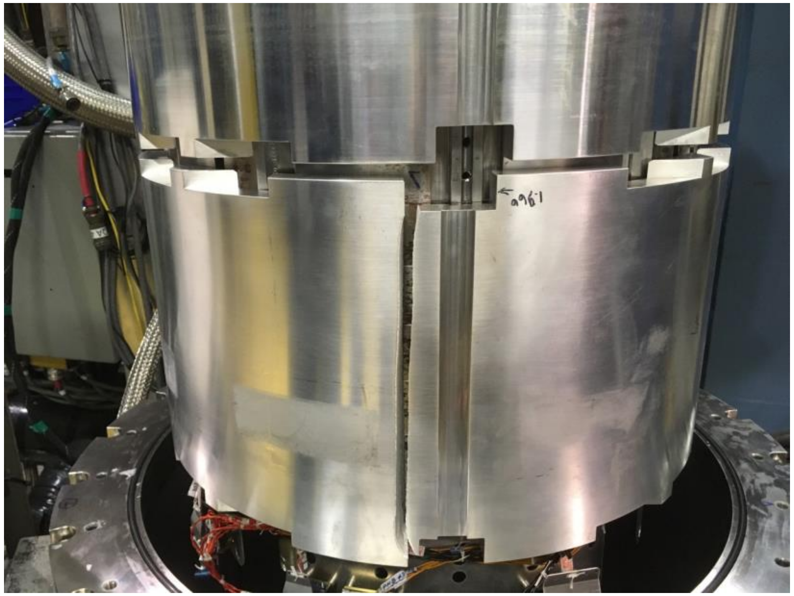
- The first US MQXF prototype had electrical short during test
  - Facts: double short between quench heater and coil
  - Origin: weakness in the coil impregnation (early production) – enhanced by non conform electrical test
  - Consequence: one coil lost
  - Analysis in https://edms.cern.ch/document/2037314 [E. Ravaioli et al.]



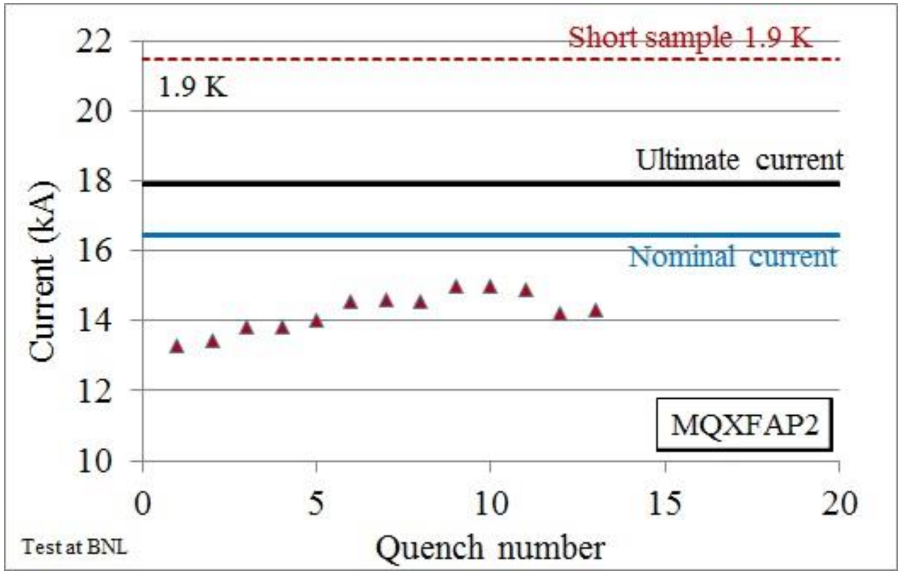
Electrical short circuit in MQXFAP1 [G. Ambrosio, et al.]

SHARP CORNERS

- The 2nd MQXFA prototype had a broken Al shell during test
  - Facts: broken shell during cool down or during quench
  - Origin: very sharp corners in Al shell – cured
  - Consequence: four coil losts
  - Note: the general issue of sharp corners in Al shells was addressed in a review
  - Note: the MQXFAP2 NC was considered not critical and was not escalated up
  - Note the resiliance of the magnet, that anyway reaches 65% of short sample



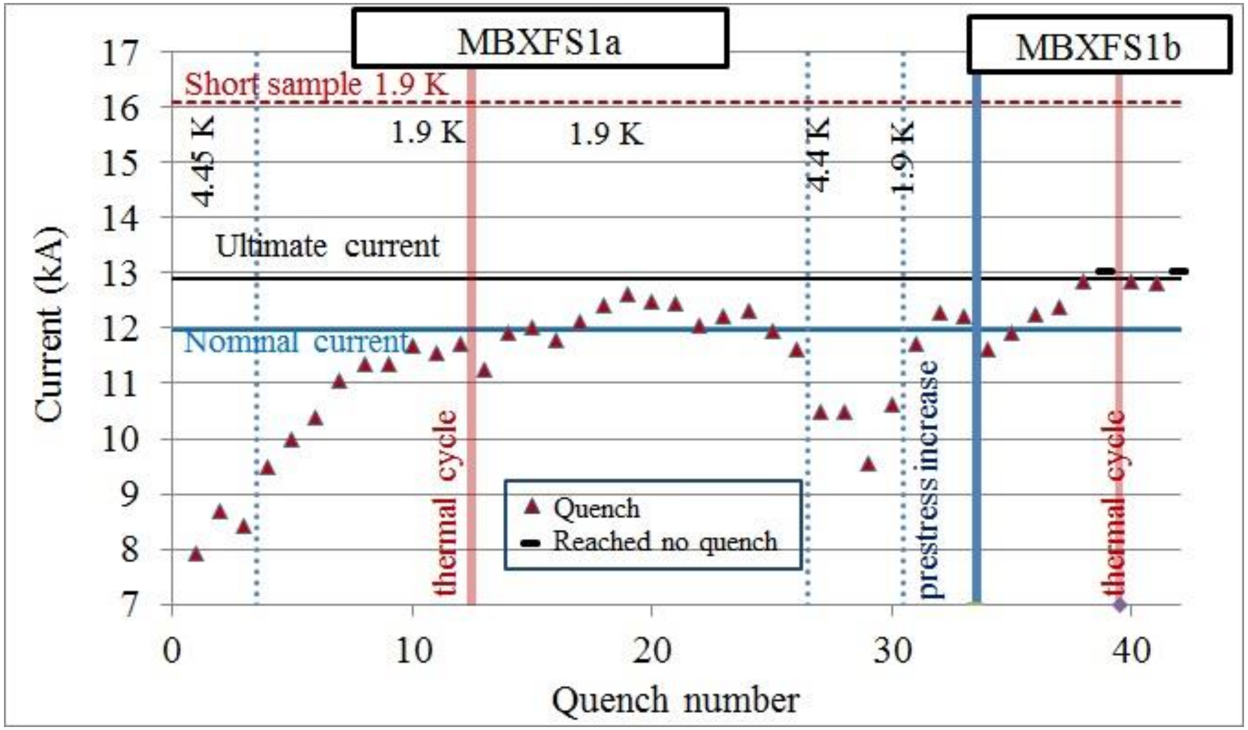
Broken shell in MQXFPA2



Test of MQXFPA2 [J. Muratore, S. Feher et al.]

NOT ENOUGH PRESTRESS IN HEADS - 1

- The first D1 short model did not reach ultimate field
  - Facts: coil ends collapsing few mm inside the aperture
  - Origin: not enough prestress in coil ends
  - Consequence: erratic performance, but coils not damaged - cured after prestress increase

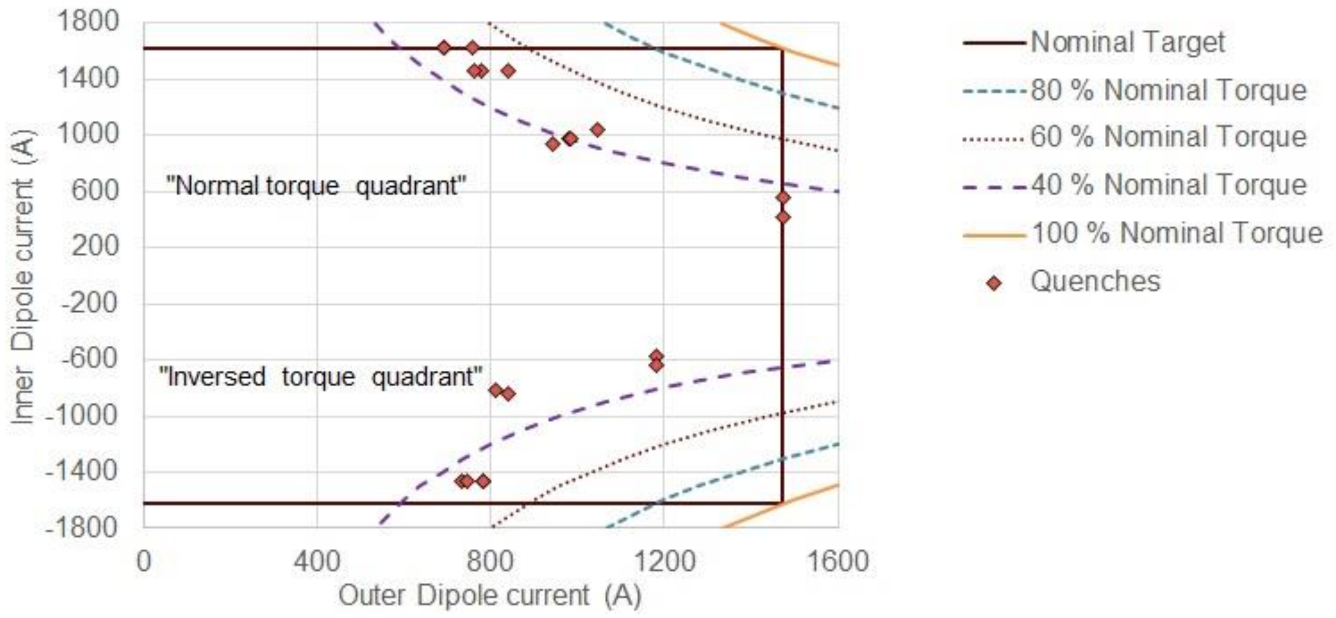


Training of first separation dipole short prototype
(T. Nakamoto, M. Sugano, A. Musso, K. Suzuki, et al.)

Conductor in the heads protruding inside the aperture
(T. Nakamoto, M. Sugano, et al.)

NOT ENOUGH PRESTRESS IN HEADS - 2

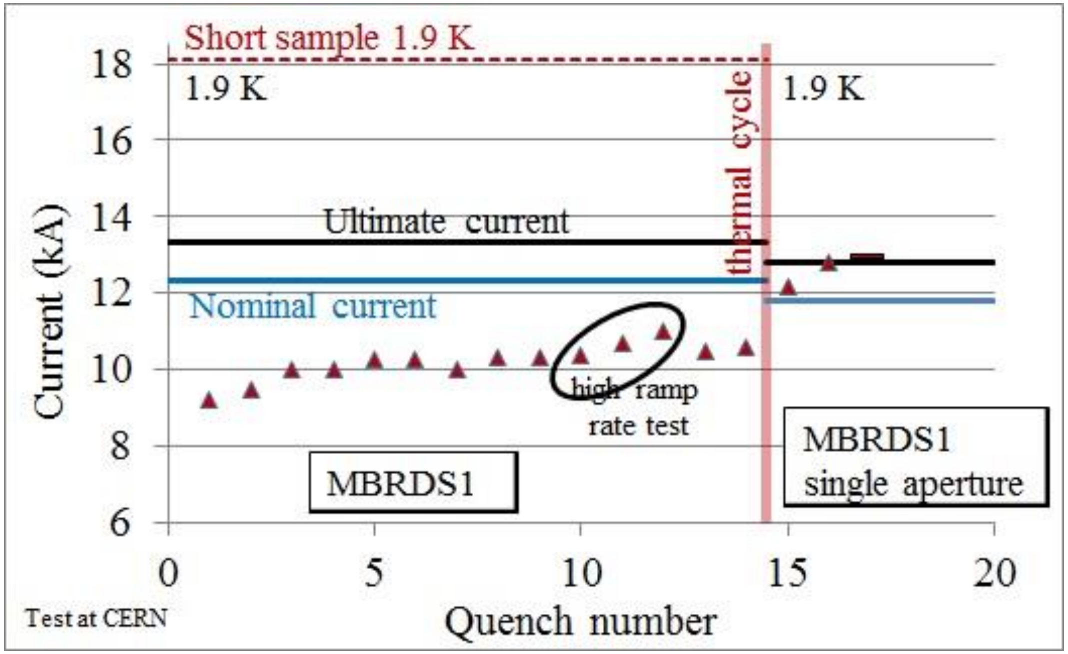
- The first MCXBF prototype did not reach ultimate field in both planes simultaneously
  - Facts: coil ends with a ~0.5 mm gap
  - Origin: not enough prestress in coil ends
  - Consequence: blocked at 30% of torque –greatly improved after prestress increase



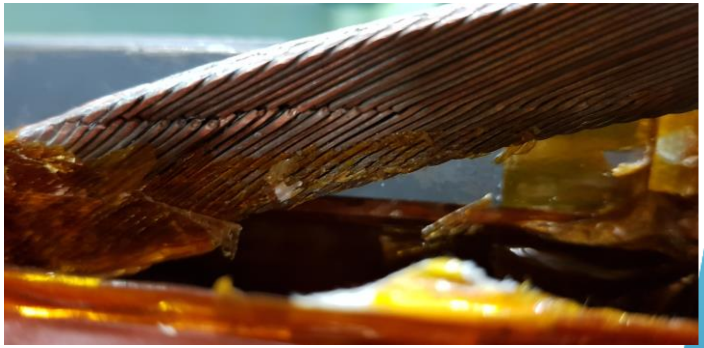
MCBXF magnet performance blocked above 30% of nominal torque
(F. Toral, G. Willering, J. C. Perez, et al.)

ASSEMBLY FAULT

- The first D2 short model did not reach nominal field in one aperture
  - Facts: cable had half of the strands cut during assembly
  - Origin: misplacement of layer jump during assembly procedure
  - Consequence: coil lost



Training of recombination dipole short prototype
(G. Willering, P. Fabbricatore, et al.)



Disassembly of the faulty coil

CONCLUSIONS

- HL-LHC WP3 magnets include novel technologies for accelerator magnets
  - Nb_3Sn quadrupole, Al shell structure – a prima in magnets installed in accelerator
  - CLIQ protection – a prima in superconducting magnets
  - A double helix magnet as orbit corrector – technology useful for many applications
  - A double collared nested corrector – a prima in magnet design
  - A MgB_2 corrector based on an exotic design from former USSR (not in the baseline)

- Design of all HL LHC WP3 magnets has been validated, with few caveats
  - For MQXF, we rely on 3 short models (to ultimate) and one prototype (well above nominal): validation on next US and CERN prototypes is a crucial step
  - For MQXF, the heater inclusion in impregnation is the only open point of design
  - For MCBXFB, the last corners of the operational space has still to be conquered
  - For D2, the second aperture is very welcome to fully validate the field quality

- Now, reproducibility of performance is the next challenge

THANKS

BESIDE THE PREVIOUSLY QUOTED COLLEAGUES FROM TE-MSC

- TE-MPE: E. Ravaioli, M. Mentink, F. Rodriguez Mateos, R. Denz, A. Verweij, D. Wollmann, et al.
- TE-VSC: V. Baglin, C. Garion, M. Morone, G. Riddone, et al.
- TE-CRI: R. van Weelderen, S. Claudet
- TE: L. van den Boogaard, M. Jimenez, et al.
- AB-ABP: G. Arduini, M. Giovannozzi, R. Tomas Garcia, R. de Maria et al.
- EN-MME: D. Perini, P. Moyret, A. Dallocchio, et al.
- AT-DO: I. Bejar Alonso, B. Almeida Ferreira, L. Tavian, M. Alcaide Leon, B. Di Girolamo, B. Delille, P. Martinez Urios, O. Bruning, P. Fessia, L. Rossi, et al.

AND THE COLLABORATIONS

- US-AUP: G. Apollinari, R. Carcagno, G. Ambrosio, S. Feher, M. Baldini, P. Joshi, S. Prestemon, J. Muratore, S. Stoynev, V. Marinozzi, K. Amm, P. Wanderer et many al.
- INFN-LASA: M. Statera, M. Sorbi, et al.
- INFN-Ge: P. Fabbricatore, S. Farinon, A. Bersani, B. Caiffi, et al.
- CIEMAT: F. Toral, J. Garcia Matos, et al.
- IHEP: Q. Xu, S. Wei, et al.,
- KEK: T. Nakamoto, M. Sugano, K. Suzuki, A. Yamamoto, et al.
- CEA: H. Felice, D. Simon, et al.

INDUSTRIAL PARTNERS

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