The HL-LHC Nb-Ti magnets towards series production

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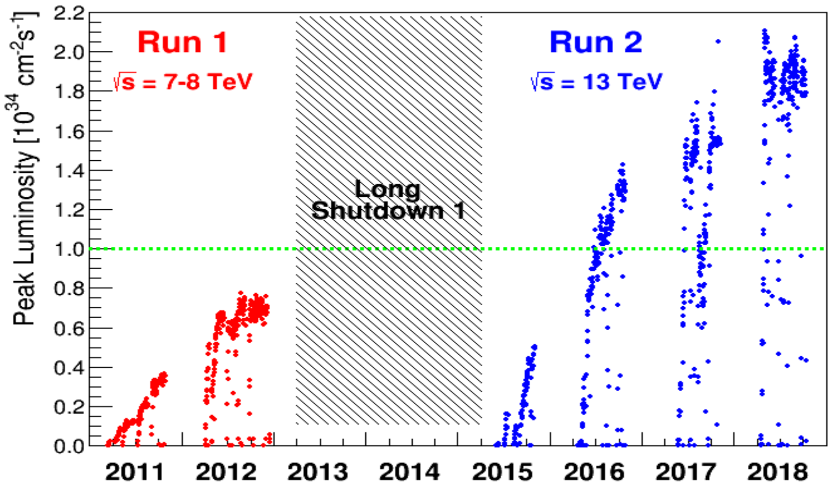
LHC

- LHC timeline
  - Commissioning in 2008
  - Incident and repair in 2009
  - RunI 2010-2012, limited at 3.5+3.5 and then 4+4 TeV (equivalent dipole field of 4.7 T) by magnet splices
  - Higgs discovery in 2012

LHC

- LHC timeline
  - 2013-2014 Long Shutdown 1: consolidation of splices
  - RunII 2015-2018, limited at 6.5+6.5 TeV (equivalent dipole field of 7.7 T) by magnet training
  - Reaching ultimate luminosity!

LHC luminosity ramp up in the 10's
(M. Lamont, J. Wenninger,
and many many others)



  - 2020-2021 Long Shutdown 2: upgrade of injectors, consolidation of diode boxes to be able tu have massive training
  - 2022-2024: RunIII, possibly at 7 TeV

HL-LHC

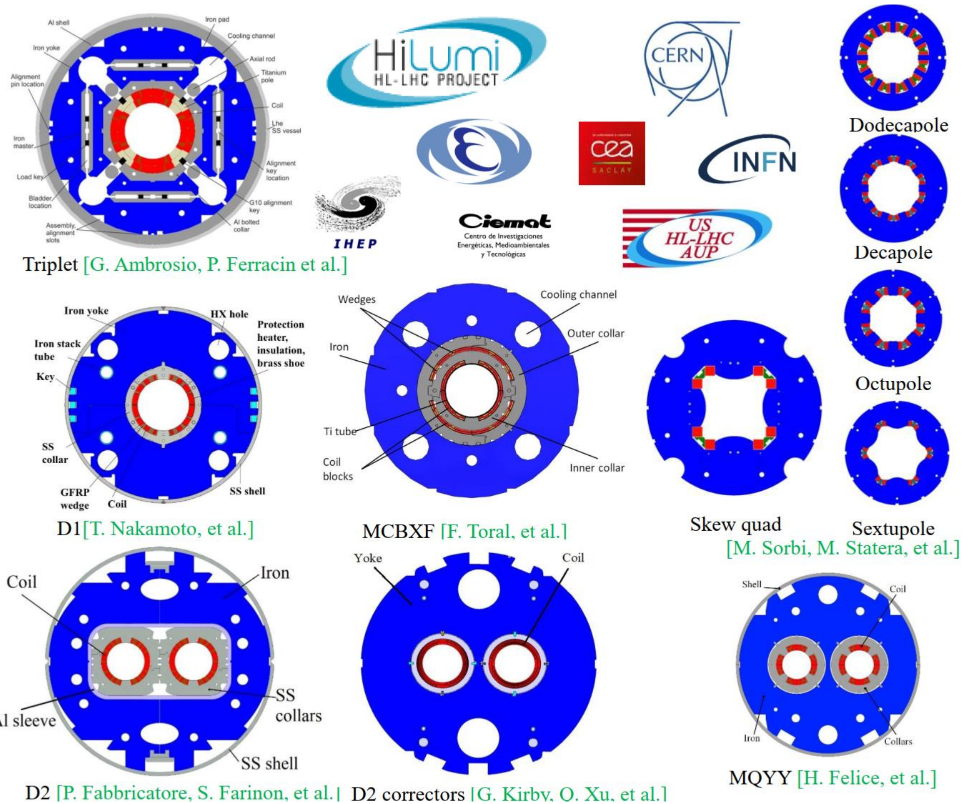
- After 2025, interaction region magnet will reach the limits of radiation resistance relative to an total luminosity of 300 fb^{-1}
  - In 2011, a design study was launched by L. Rossi to see how to replace these magnets and improve the machine performance in terms of luminosity, to be able to accumulate another 3000 fb^{-1} in the next ten years
    - Note: we do not increase the energy, since this would require replacing the arc magnets
    - Here we replace « just » a few hundred meters of magnet around ATLAS and CMS experiments
  - The key to the higher luminosity: larger magnet aperture to allow focusing more the beam
  - The HL-LHC project was approved in 2014-2015, the interaction region magnet part is now in the transition between prototype and series
    - Here we report about this transition, a crucial phase of the project
    - Review paper has just been published in SUST

Summary

- The main parameters of HL LHC interaction region magnets
- Where are we with the validation of the design
- Conclusions

The HL-LHC interaction region magnets

- 150 magnets of 11 different types, done via 6 collaborations



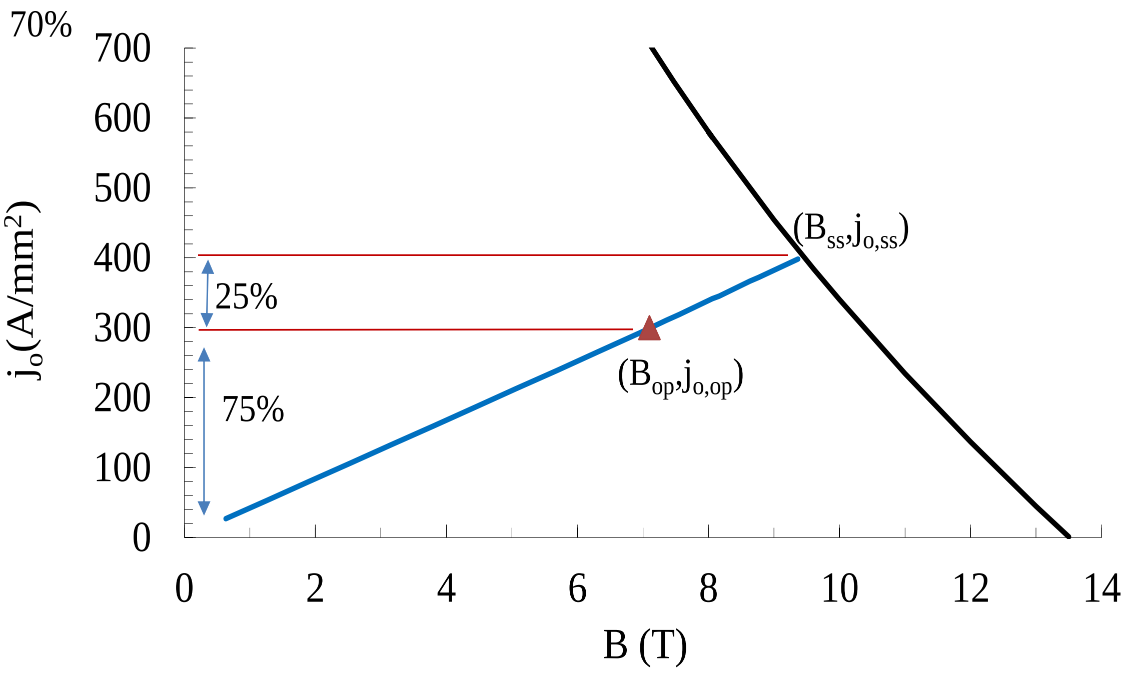
Superconducting magnets for accelerators

- Some features of accelerator superconducting magnets
  - Cheap: needed in large quantities
  - Compact: very large overall current density (order of 400 A/mm^2), much larger than in other devices
  - High performance: the field is pushed to large values, but compatible with previous two contraints
  - Reliability: one missing main magnets stops the machine
- Development has long times and needs to go in parallel
  - If you go in series (make a model, test, design changes, a second model, test, go for prototypes, …) it will take 30 years

HiLumi HL-LHC PROJECT CERN

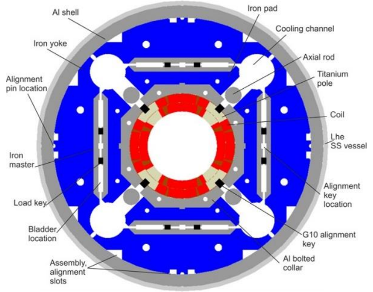
Recall of loadline fraction concept

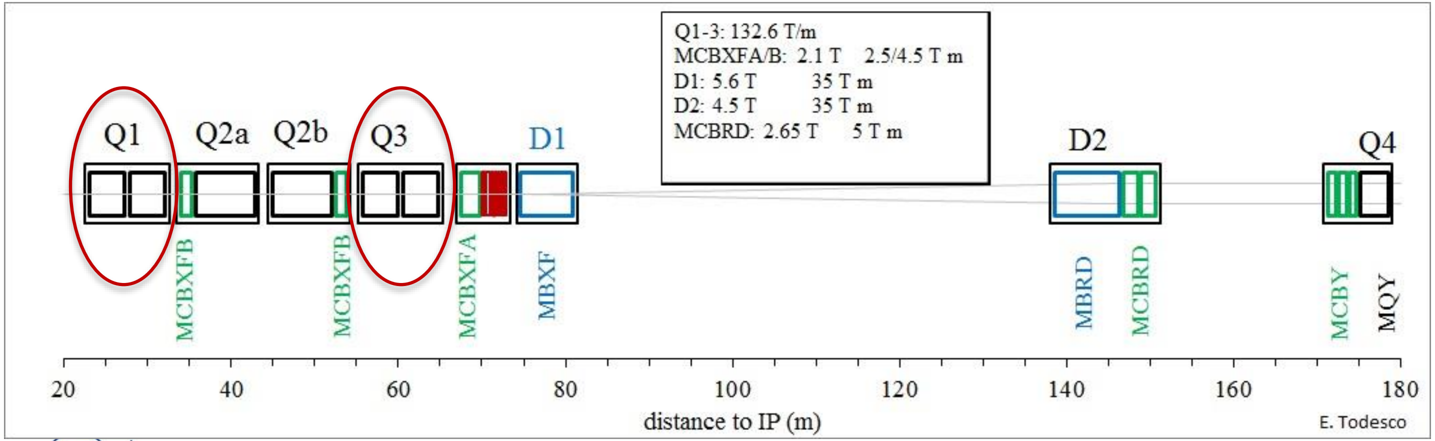
- Example of a magnet with 0.75 loadline fraction
  - i.e. operating at 75% of maximum theoretical performance
  - Also quoted as 25% loadline margin



The HL-LHC interaction region magnets

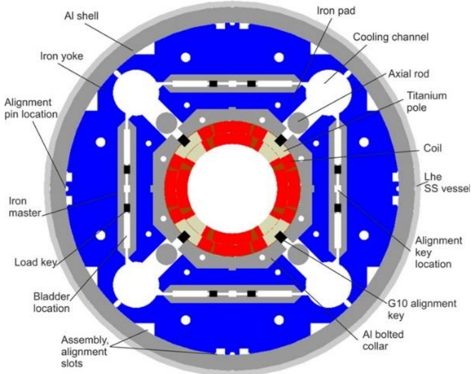
- Q1/Q3: Nb_3Sn triplet quadrupoles provided by US collaboration
  - 11.4 T peak field
  - 78% on the loadline, 110 MPa compression due to e.m. forces
  - Bladder and key loading, Al shell structure
  - 4.2 m long magnets

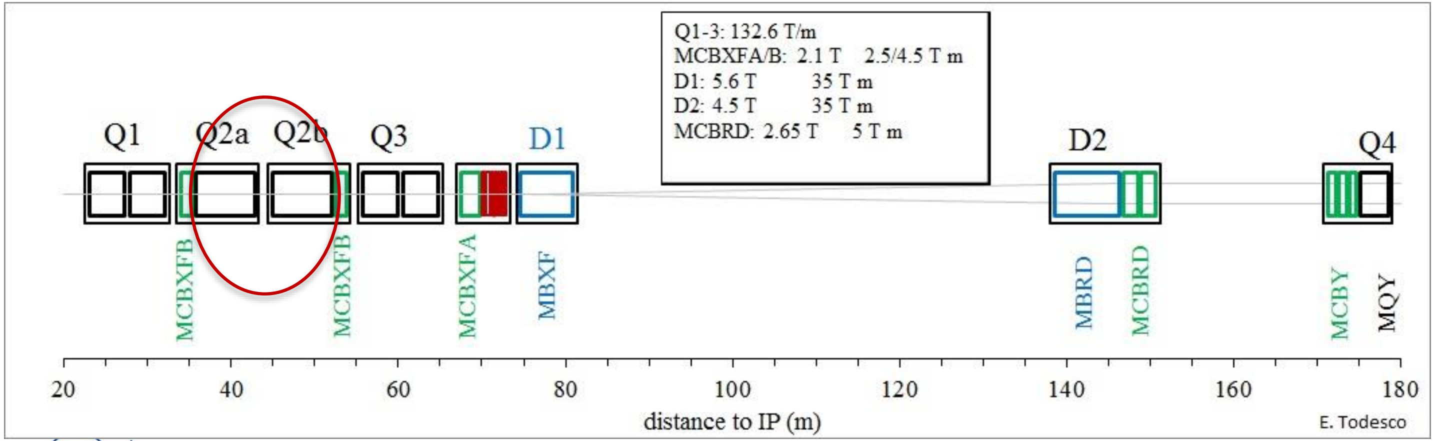




The HL-LHC interaction region magnets

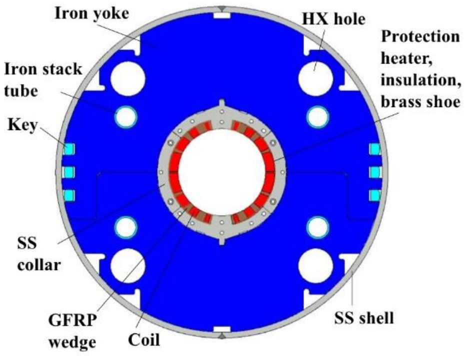
- Q1/Q3: Nb_3Sn triplet quadrupoles made at CERN 180
  - 11.4 T peak field
  - 78% on the loadline, 110 MPa compression due to e.m. forces
  - Bladder and key, Al shell structure
  - 7.15 m long magnets

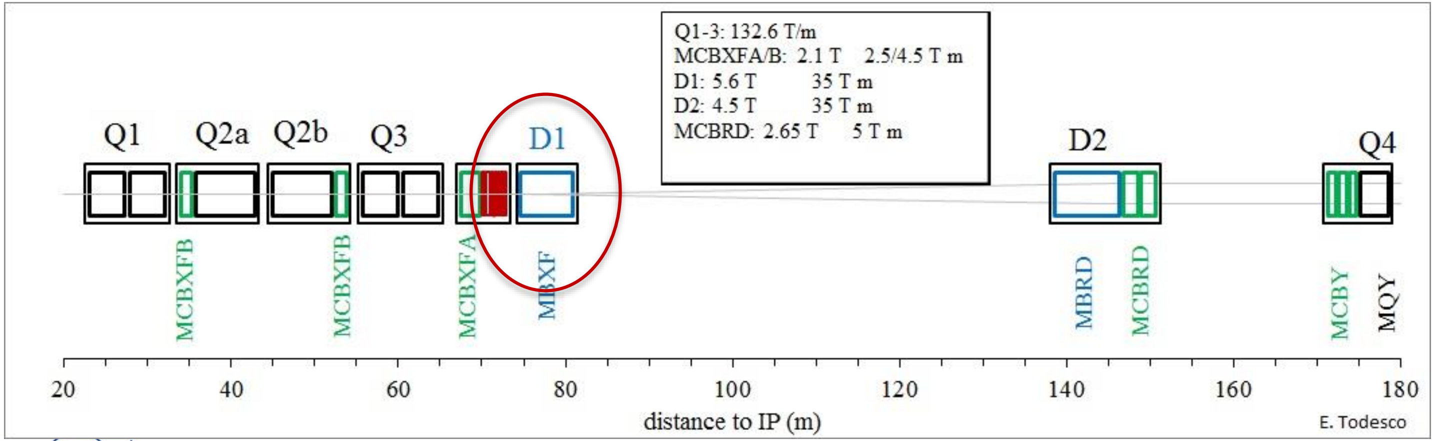




The HL-LHC interaction region magnets

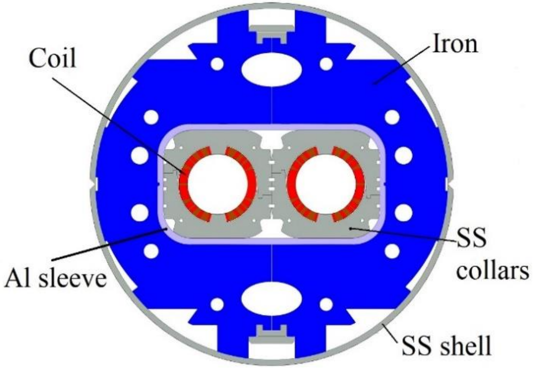
- D1: large aperture dipole provided by KEK
  - 5.6 T bore field
  - 75% on the loadline, 100 MPa compression due to e.m. forces
  - Same cable as the LHC dipole, one layer
  - Structure based on iron yoke and thin spacers

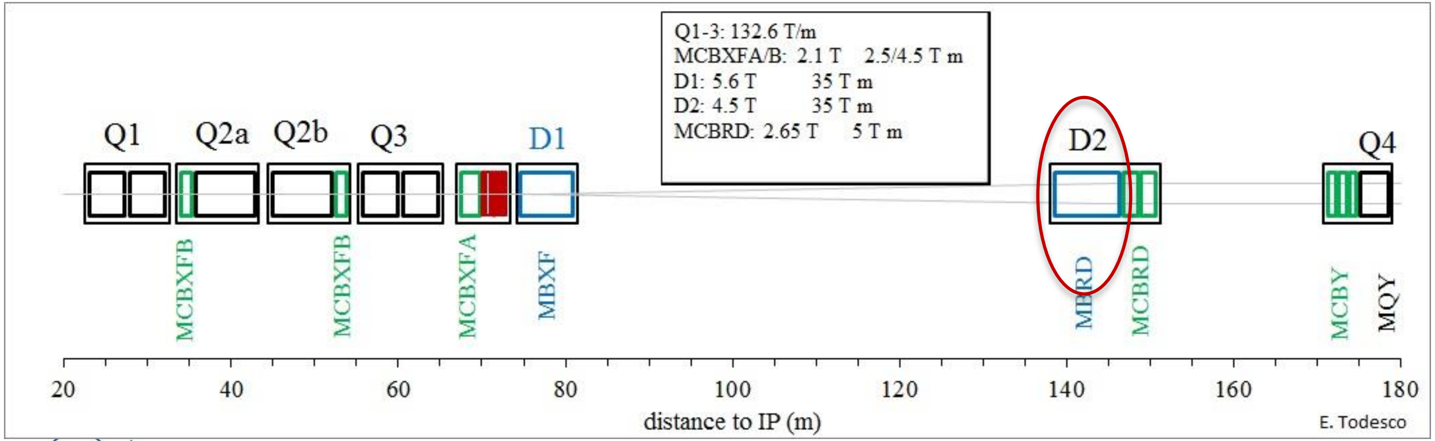




The HL-LHC interaction region magnets

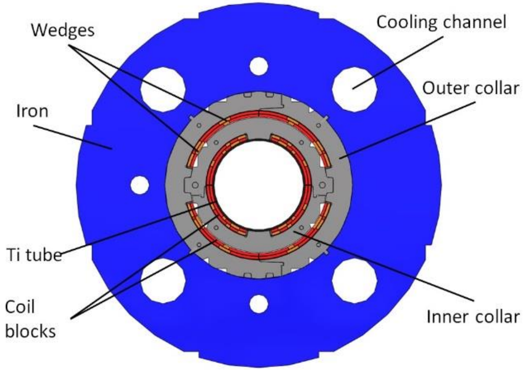
- D2: large aperture dipole provided by INFN Genova
  - 4.5 T bore field
  - 67% on the loadline
  - Same cable as the LHC dipole, one layer
  - Structure based on stainless steel self supporting collars

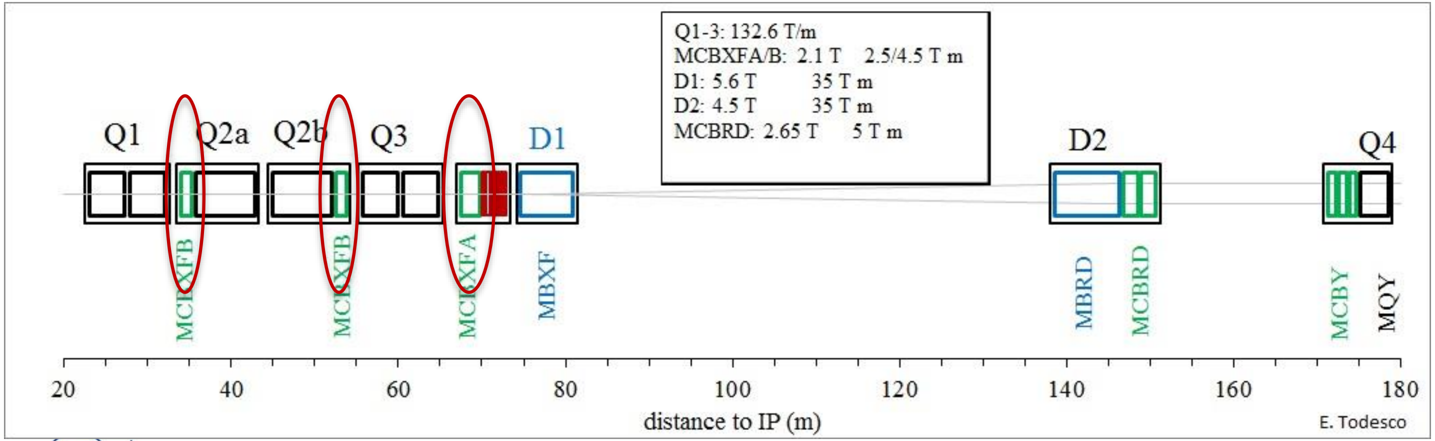




The HL-LHC interaction region magnets

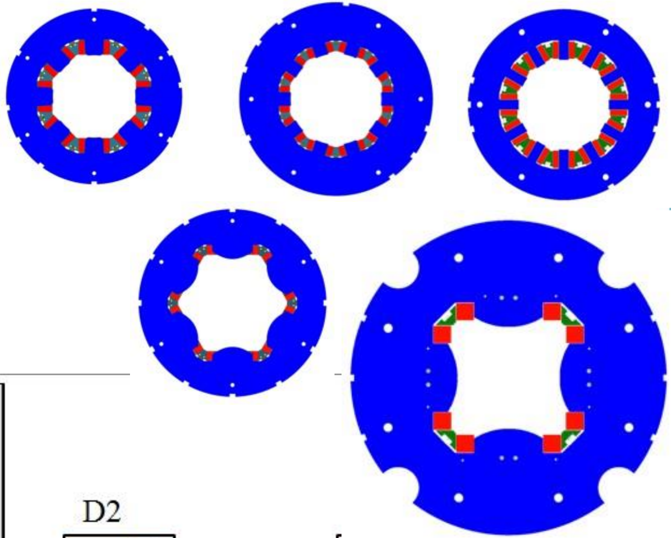
- MCBXF: nested correctors provided by CIEMAT
  - 2.1 T bore field in each direction (large torque)
  - 50% on the loadline
  - 4.5 mm width Rutherford cable, two layers for each dipole
  - Stainless steel self supporting collars, with double collaring

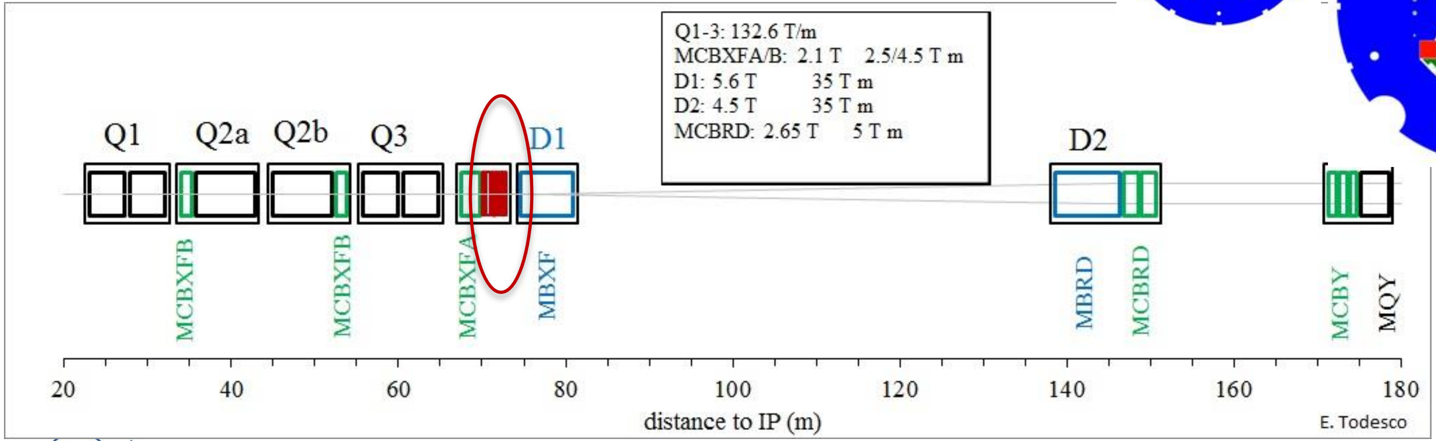




The HL-LHC interaction region magnets

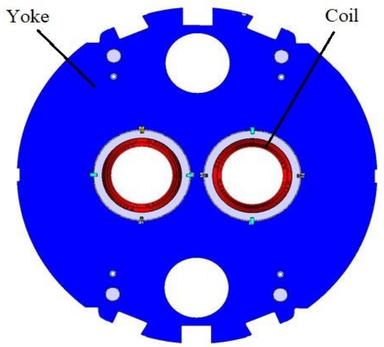
- High order correctors provided by INFN LASA
  - 2-3.5 T peak field
  - 30%-50% on the loadline
  - Superferric design, Nb-Ti coils and iron at 1.9 K

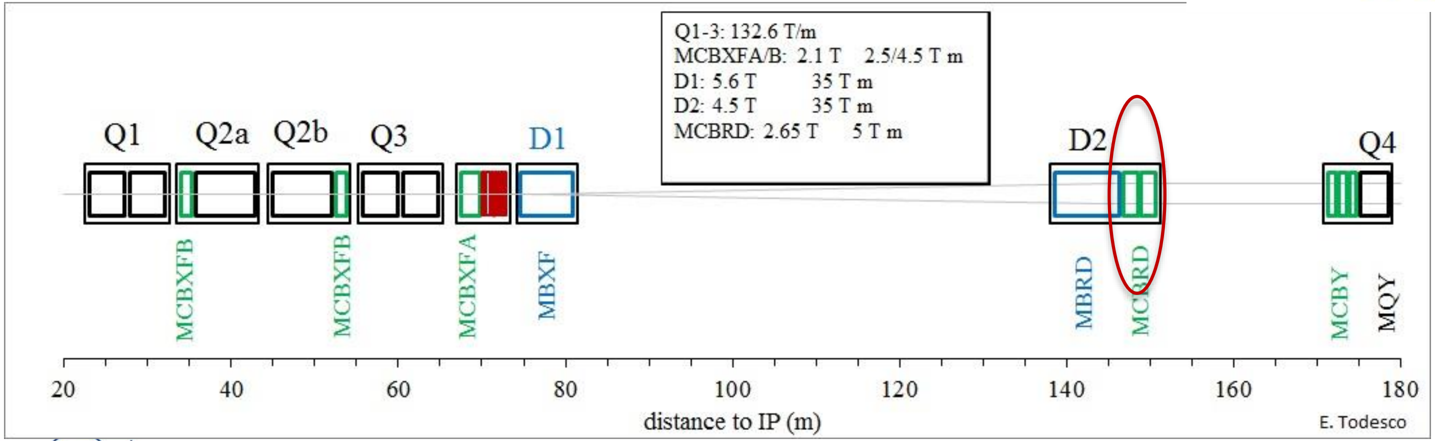




The HL-LHC interaction region magnets

- D2 corrector provided by IHEP (aka MCBRD)
  - 2.6 T bore field
  - 50% on the loadline
  - Canted cos theta design, Nb-Ti wire

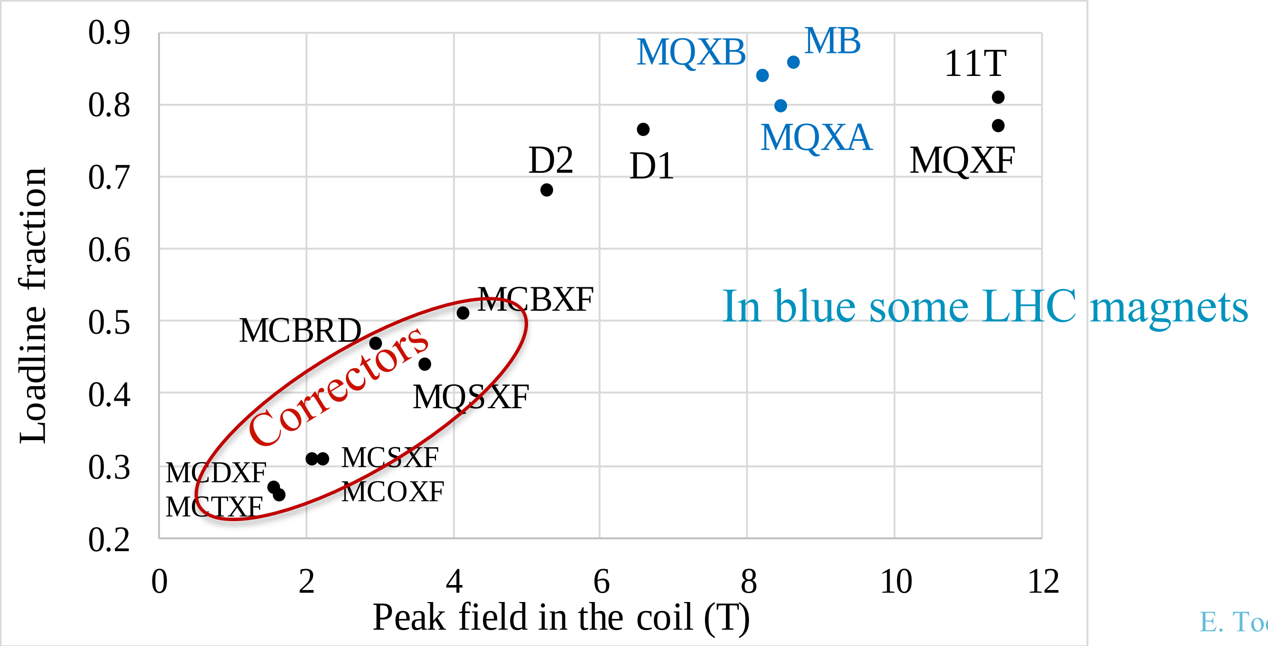




Peak field versus loadline fraction

- We also include the LHC main dipole (MB) and IR region quads (MQXA and MQXB)

- We placed the triplet (MQXF) at 77% (most critical decision)
- Correctors are at 50% or lower (more margin)



Stress estimates

- Accumulation of midplane stress on the bore is given by product of field, aperture and current density
  - Since aperture is large, we are exploring unprecedented levels of stress accumulation in the midplane, both in a 5 T magnet (D1) and in a quadrupole (MQXF)

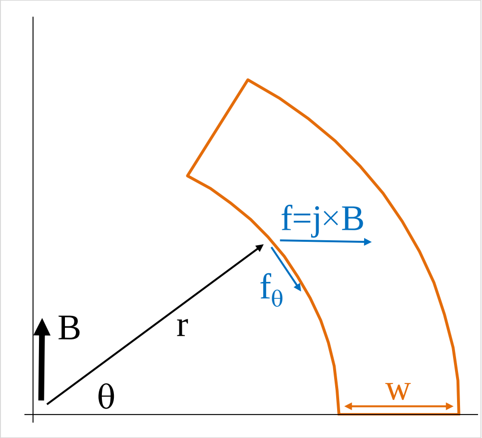
On the bore edge:

Dipole:

- $\sigma=1/2\ B\ r\ j\ F_d(w,r)$

Quadrupole

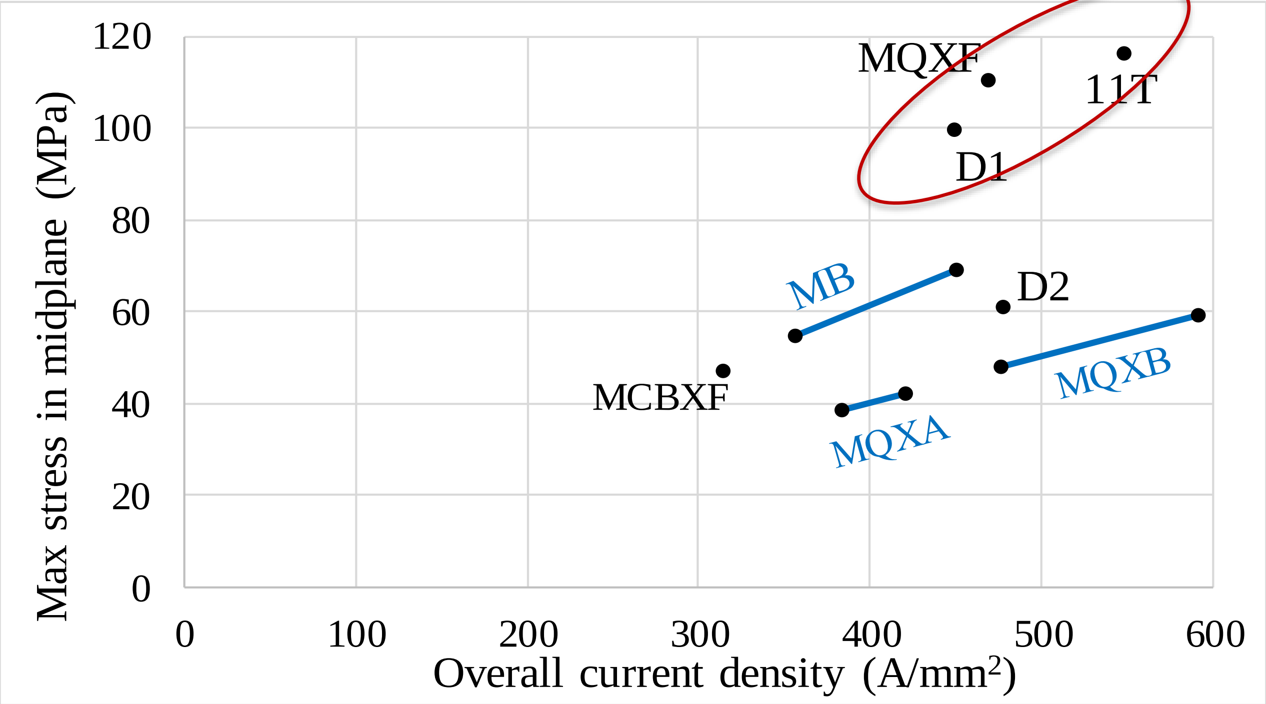
- $\sigma=1/4\ G\ r^2\ j\ F_q(w,r)$



- Max stress achieved in the coil, with a corrective factor *F* depending on *w/r*

Max stress versus overall current density

- Overall current density = over the insulated cable
- For D1 and MQXF (and also 11 T) we are at 100-120 MPa



Summary

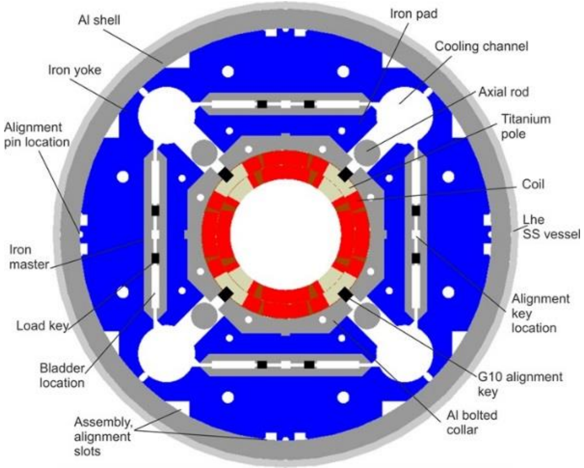
- The main parameters of HL LHC interaction region magnets
- Where are we with the validation of the design
- Conclusions

Where are we ?

- Triplet: 23 (US)+12(CERN)=35 magnets (including 4 prototpyes), 7(US)+3(CERN)=10 completed, 4 (US) + 1 (CERN) tested
  - 6 short models built by CERN+US, 5 tested
- D1: 7 magnets (including 1 prototype), 1 under assembly
  - 3 short models built and tested
- D2: 7 magnets (including 1 prototype), 1 under assembly
  - 1 short model built and tested
- Nested corrector: 20 magnet (including 3 prototypes), 2 completed, 2 tested
- D2 corrector: 15 magnets (including 3 prototypes), 3 completed, 3 tested
- HO correctors: 59 magnets (including 5 prototypes), 23 completed, 7 tested

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
  - 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
    - Allows a full preload of coils
  - First magnet to be operated in a particle accelerator protected by CLIQ
  - Design as a joint venture CERN-US, based on LARP experience

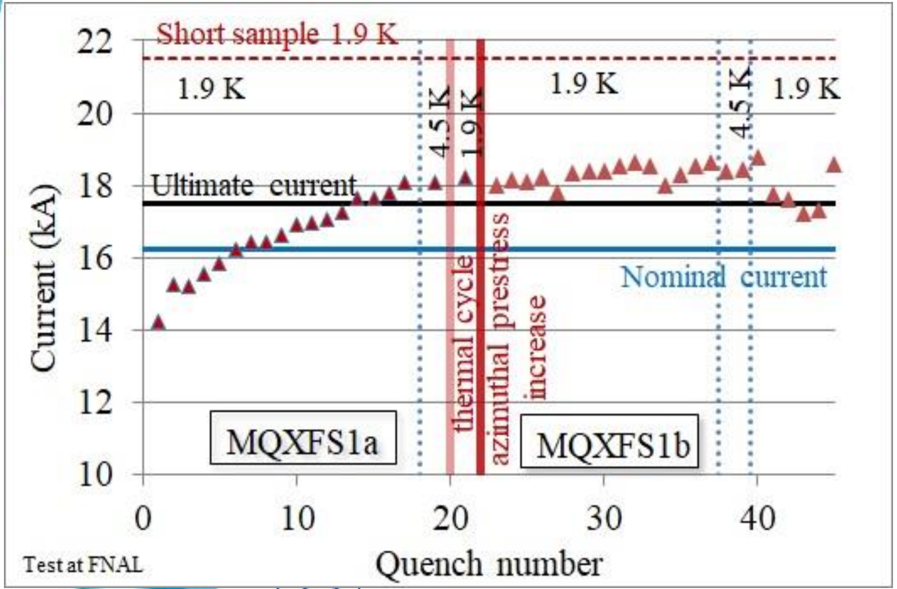


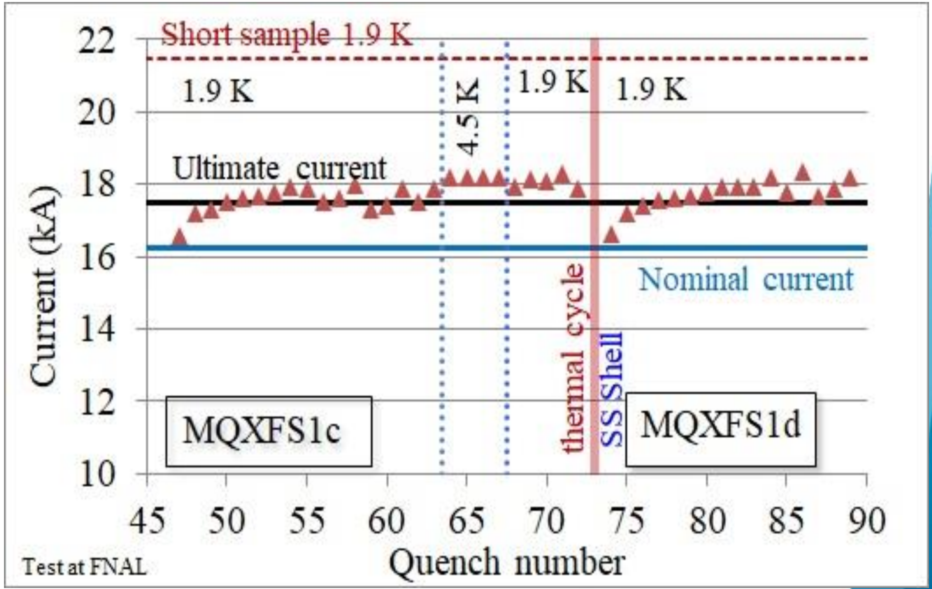
Triplet design

- Conductor is high current density Nb_3Sn
  - 2400 A/mm^2 at 4.22 K, 12 T as a reference value (about 20% less than maximum achieved in LARP)
  - Specification of 1280 A/mm^2 at 4.22 K and 15 T
- One baseline conductor: RRP 108/127 developed by OST
  - Filament size of ~50 μm
- A second conductor has been also used in two short models: PIT 192, developed by Bruker
  - Also showing good performances

Triplet results

- First model reached performance
  - (nominal: needed for 7 Tev ultimate: needed for 7.5 TeV)
  - Several thermal cycles, total of 100 quenches

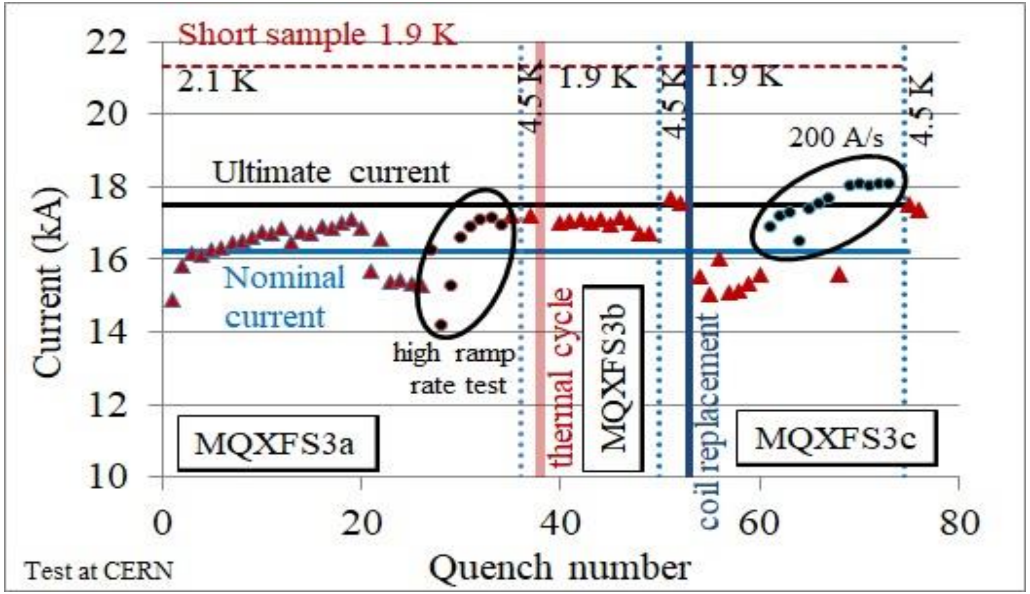




Training of MQXFS1 (G. Ambrosio, S. Stoynev et al.)

Triplet results

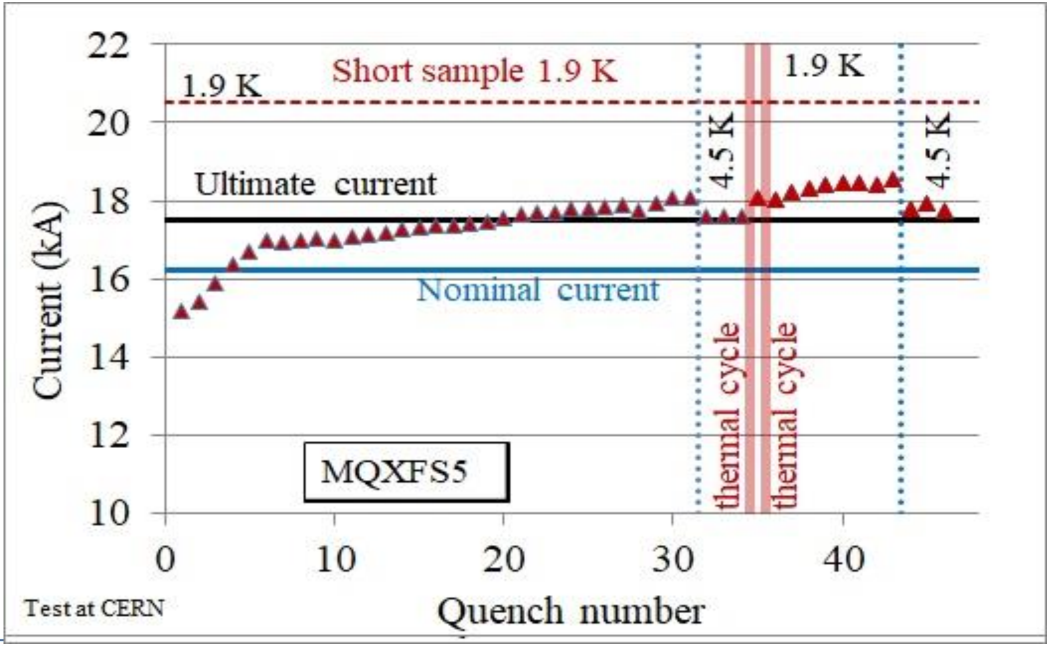
- Second model had reverse behaviour (better performance at higher temperature and at higher ramp rate)
  - Limiting coil was replaced, but same behaviour – not undestood



Training of MQXFS3 (P. Ferracin, S. Izquierdo Bermudez, J. C. Perez, H. Bajas, F. Mangiarotti, et al.)

Triplet results

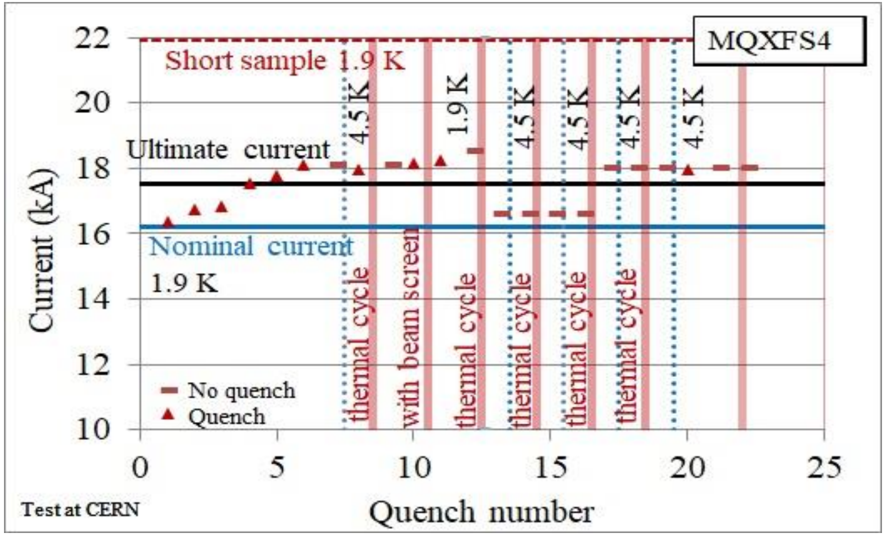
- Third model reached performance
  - It had a different conductor, based on PIT technology



Training of MQXFS5
(P. Ferracin, S. Izquierdo Bermudez, J. C. Perez, F. Mangiarotti, et al.)

Triplet results

- Fourth model reached performance
  - It was not powered above 18 kA to keep a good magnet available
  - It was used to have the test on long term stability with 5 thermal cycles and 1000 powering cycles

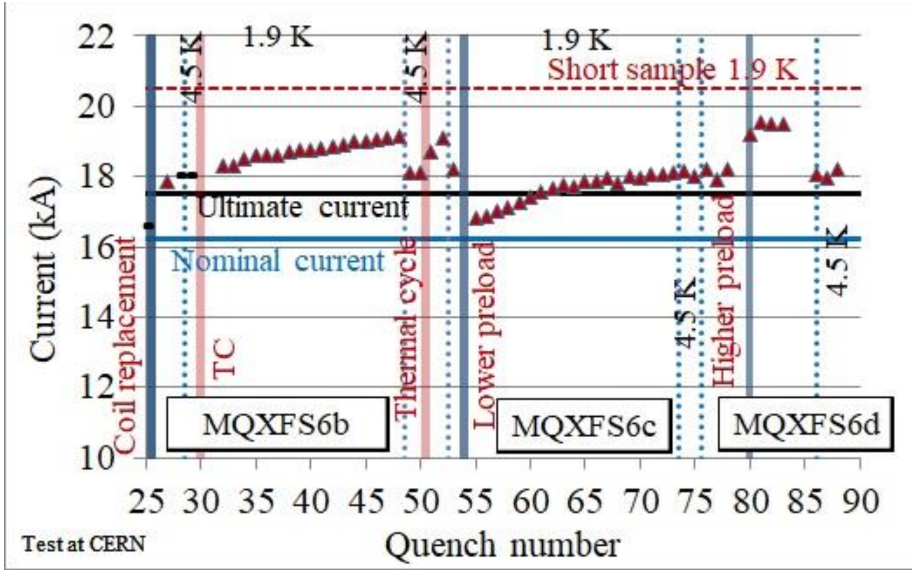


Training of MQXFS4

(P. Ferracin, S. Izquierdo Bermudez, J. C. Perez, F. Mangiarotti, et al.)

Triplet results

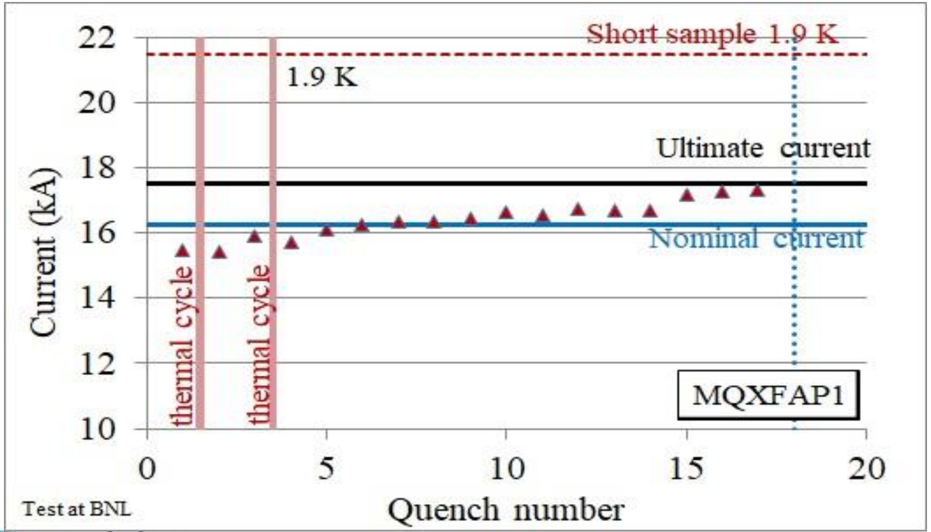
- Fifth model reached performance
  - After a coil replacement – good to check the procedures
  - Reached 13.4 T peak field, and showed that a full preload can give a magnet reaching 1.5 kA more

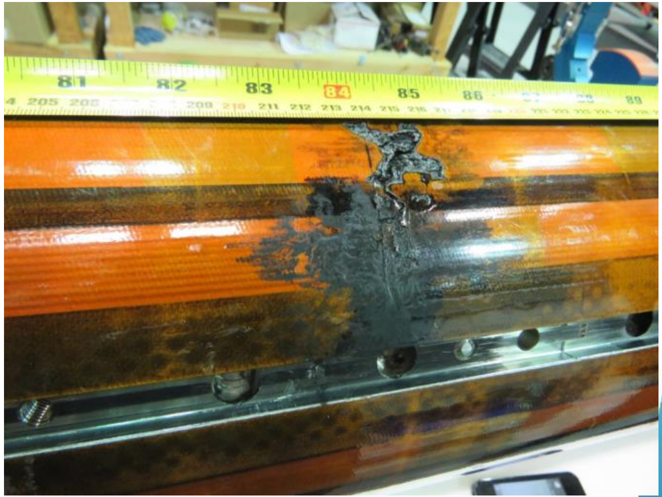


Training of MQXFS6 (P. Ferracin, S. Izquierdo Bermudez, J. C. Perez, S. Ferradas Troitino, et al.)

Triplet results

- First US prototype
  - 4-m-long magnet has similar training of short models
  - Test interrupted by short due to poor impregnation and a non conform component (evil is in details)

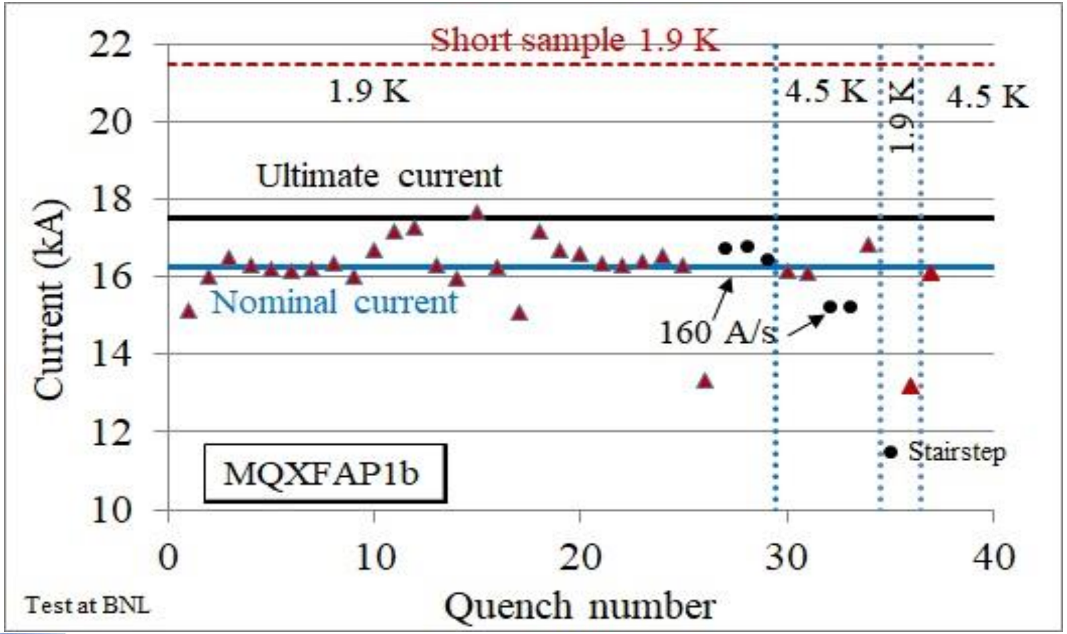




Training of MQXFAP1 (G. Ambrosio, S. Feher, J. Muratore, et al.)

Triplet results

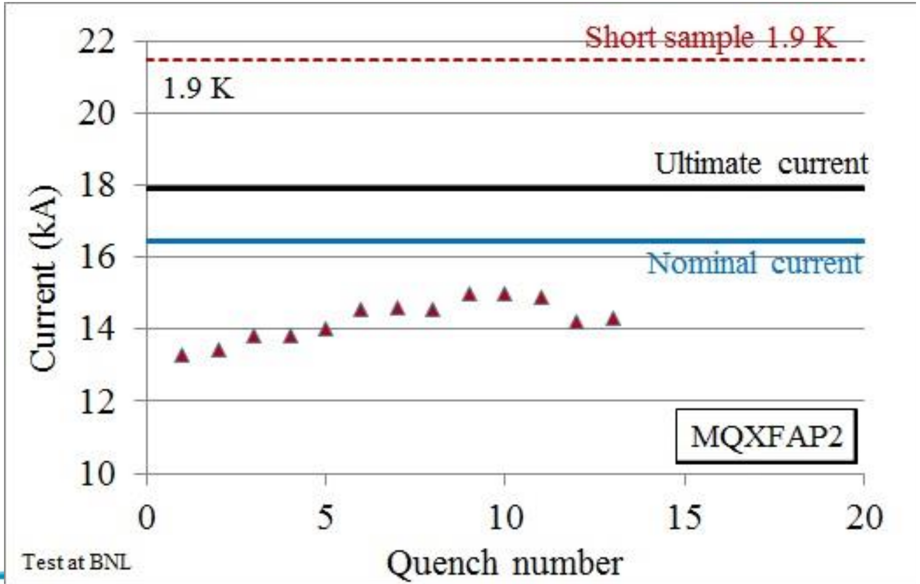
- First US prototype – coil replacement
  - Reverse and erratic behaviour as in MQXFS3 – not conform

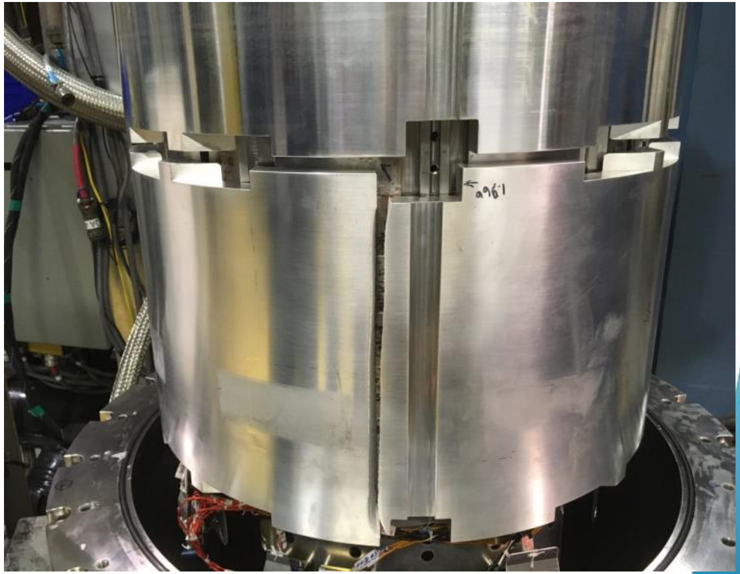


Training of MQXFAP1 (G. Ambrosio, S. Feher, J. Muratore, et al.)

Triplet results

- Second US prototype
  - Blocked at 14 kA, a shell broken during test due to stress in accumulation in too sharp corners
  - Suprised to see that in these conditions 14 kA were reached

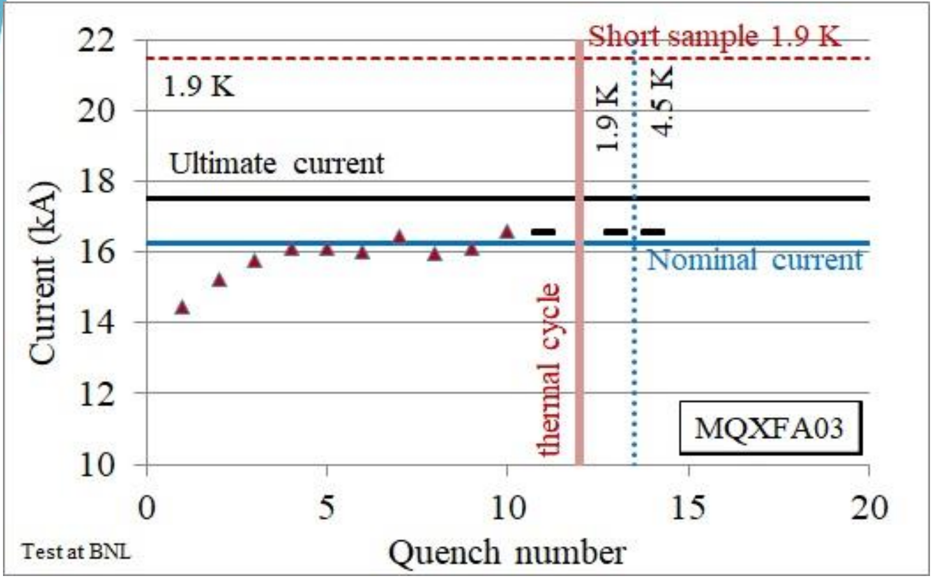


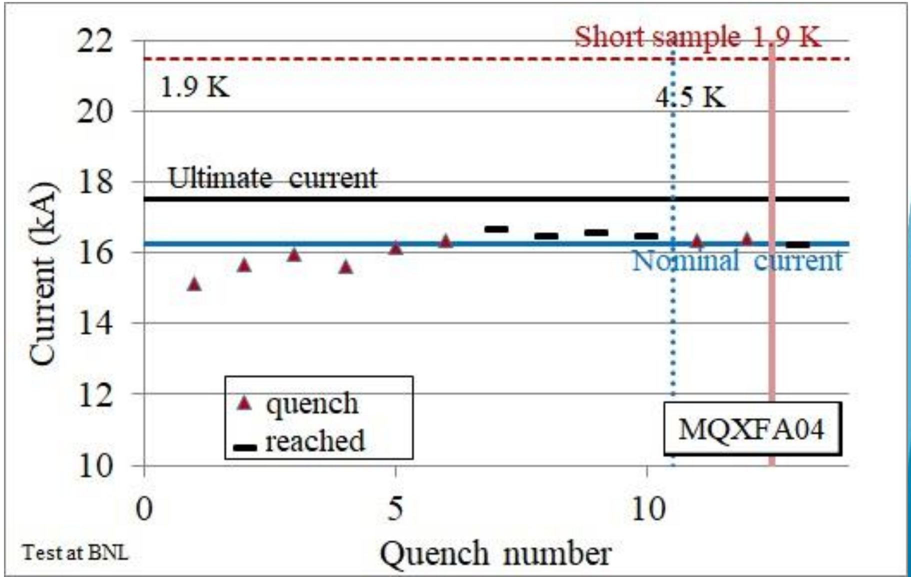


Training of MQXFAP2 (G. Ambrosio, S. Feher, J. Muratore, et al.)

Triplet results

- Preseries
  - Both 03 and 04 magnets reached performance, DOE approved the project
  - MQXFA05 and MQXFA06 are ready for test

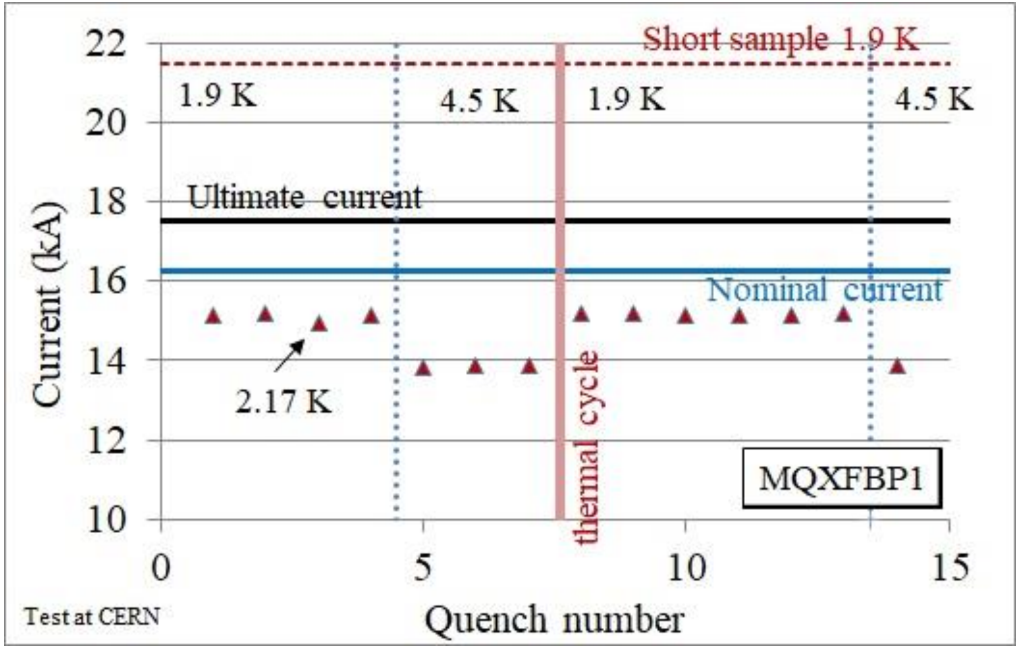




Training of MQXFA03 and MQXFA04 (G. Ambrosio, S. Feher, J. Muratore, et al.)

Triplet results

- First prototype from CERN (7 m long)
  - Blocked at 15 kA, very reproducible limitation, 70% of short sample at 1.9 and 4.5 K – analysis is ongoing



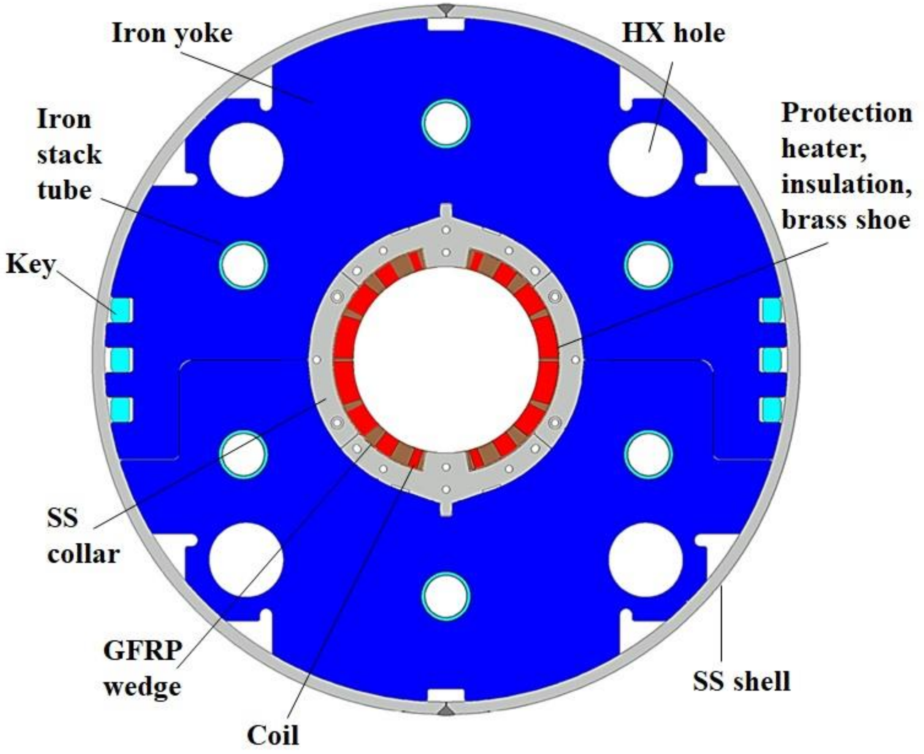
Training of MQXFBP1 (S. Izquierdo Bermudez, F. Mangiarotti, et al.)

Triplet results

- Short model program: 4 reaching performance out of 5
  - Both nominal and ultimate current at reach, with non negligible training in virgin condition
  - No retraining needed at nominal current
  - Nominal current reached also at 4.5 K
  - Long term stability proved on two models
  - One case showing reverse behaviour, not explained
- Long magnets
  - The training does scale with length
  - All main features of the design are confirmed (loading, protection)
  - Reproducibility is not yet there, three setbacks

D1

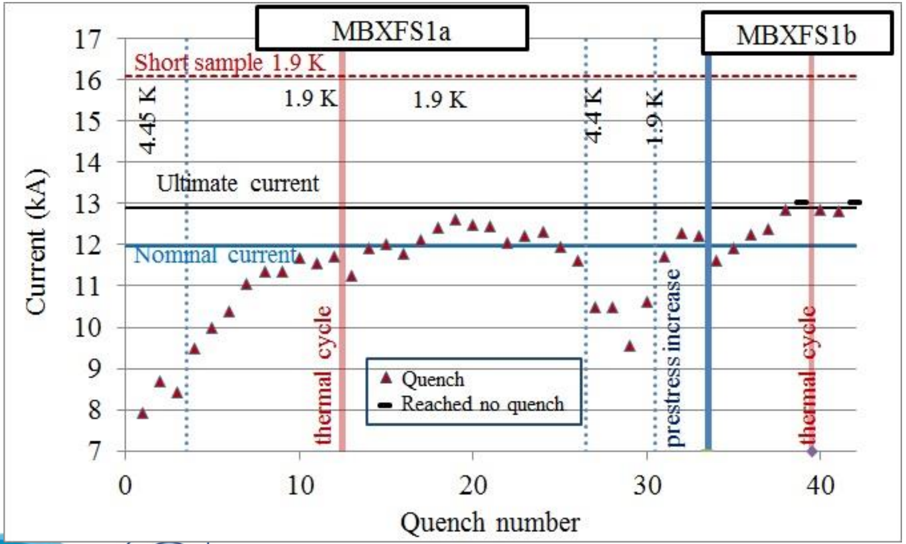
- Bore field: 5.6 T (7.0 TeV)
  - (6.0 T ultimate, corresponding to 7.5 TeV operation)
- Magnetic length: 6.23 m
- Challenges
  - High level of accumulation of pressure in the midplane due to the large aperture and large current density
  - Tight field quality targets in presence of large iron saturation

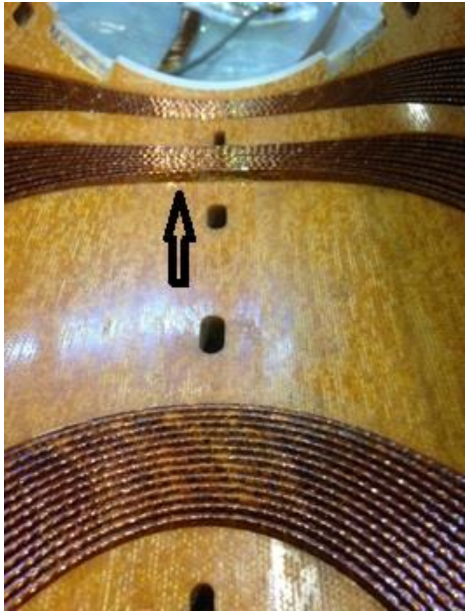


D1 cross-section [T. Nakamoto, M. Sugano, K. Suzuki, et al.]

Status of D1

- Short model program concluded succesfully in 2019, with 3 out of 3 magnets reaching performance, the first one after one iteration on preload
  - Main critical point is the adequate support of coil ends, and the large correction that is being operated in field quality (change of b_3 of 20 units)





Training of first short model (left) and displacement of coil ends in first assembly [T. Nakamoto, M. Sugano, K. Suzuki, et al.]

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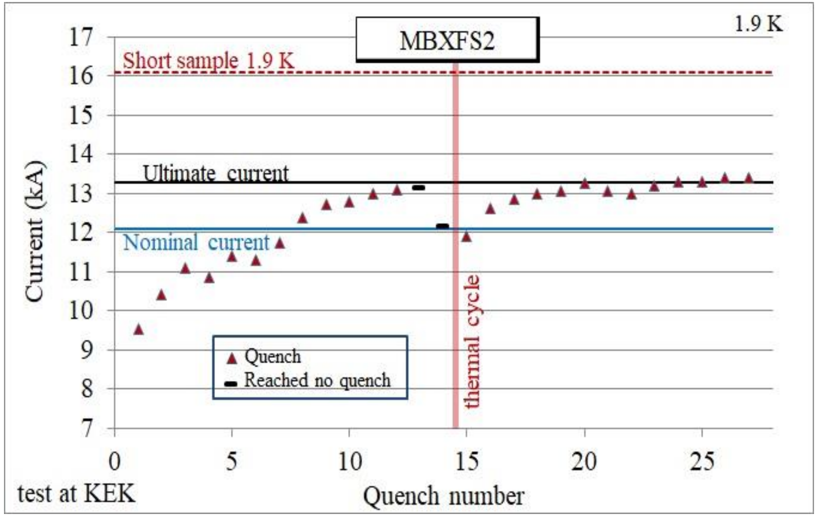
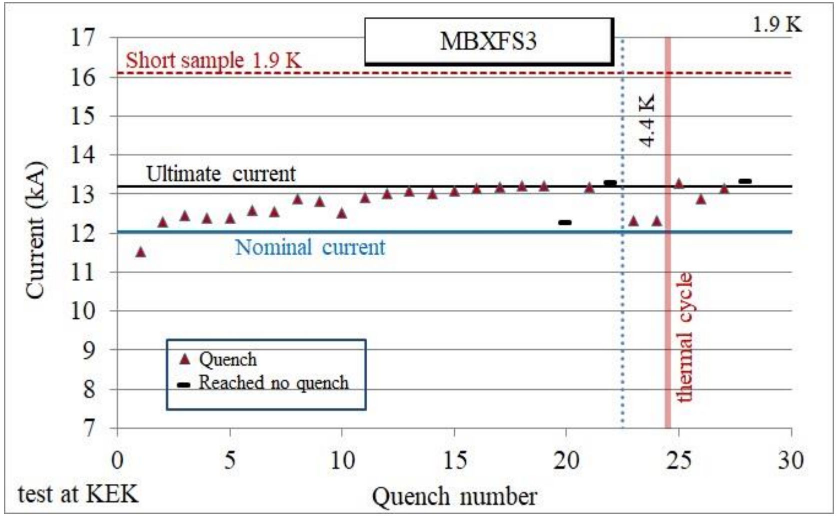




Training of second (left) and third (right) short models [T. Nakamoto, M. Sugano, K. Suzuki, et al.]

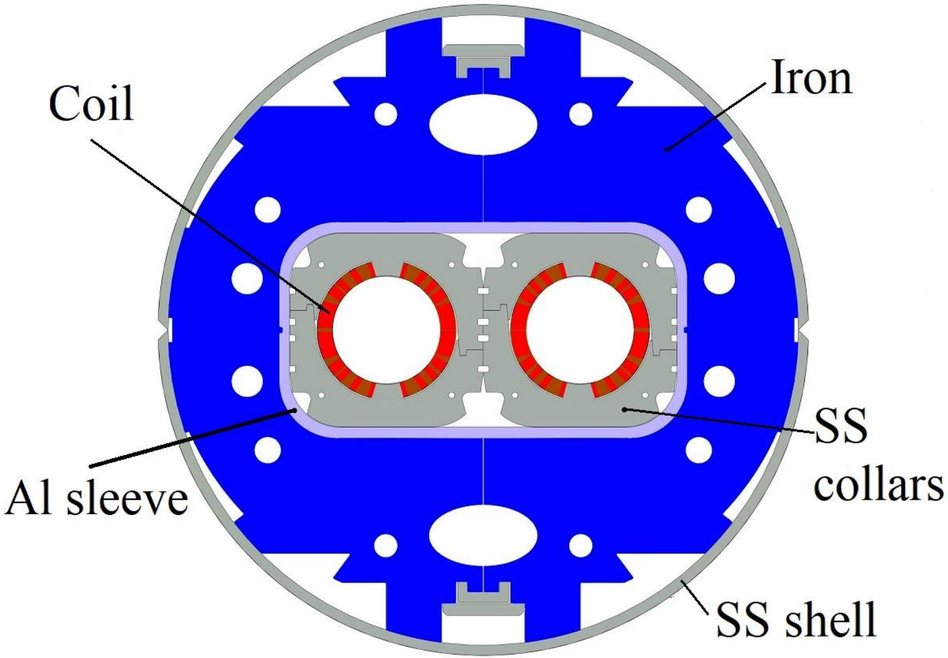
Status of D1

- How’s going at the moment ?
- First coils wound in Hitachi, precollaring ongoing

D1 practice coil for the prototype and precollaring (courtesy of Hitachi and T. Nakamoto)

Challenges of D2

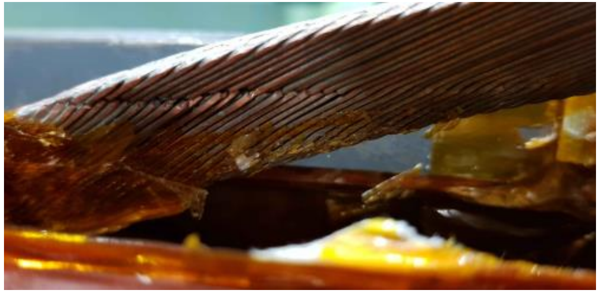
- Bore field: 4.5 T (7.0 TeV)
  - (4.8 T ultimate, corresponding to 7.5 TeV operation)
- Magnetic length: 7.88 m
- Challenges
  - Field quality optimization based on asymmetric coils
  - Novel structure for the two apertures based on Al shells



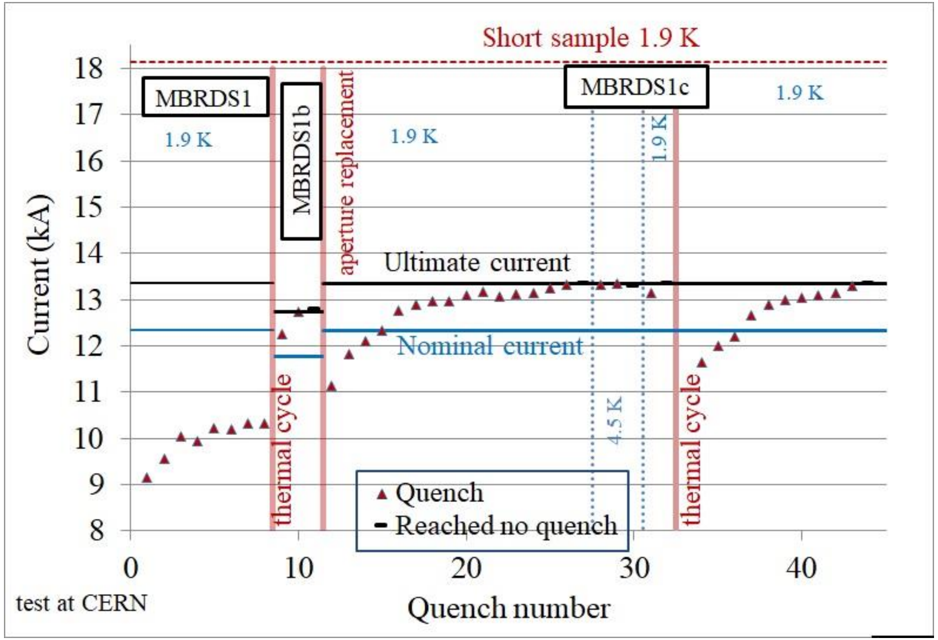
D2 cross-section [P. Fabbricatore, S. Farinon, et al.]

Status of D2

- Short model reached performance
  - One issue with a damaged cable in the first assembly in the delicate location of the leads, coil replaced



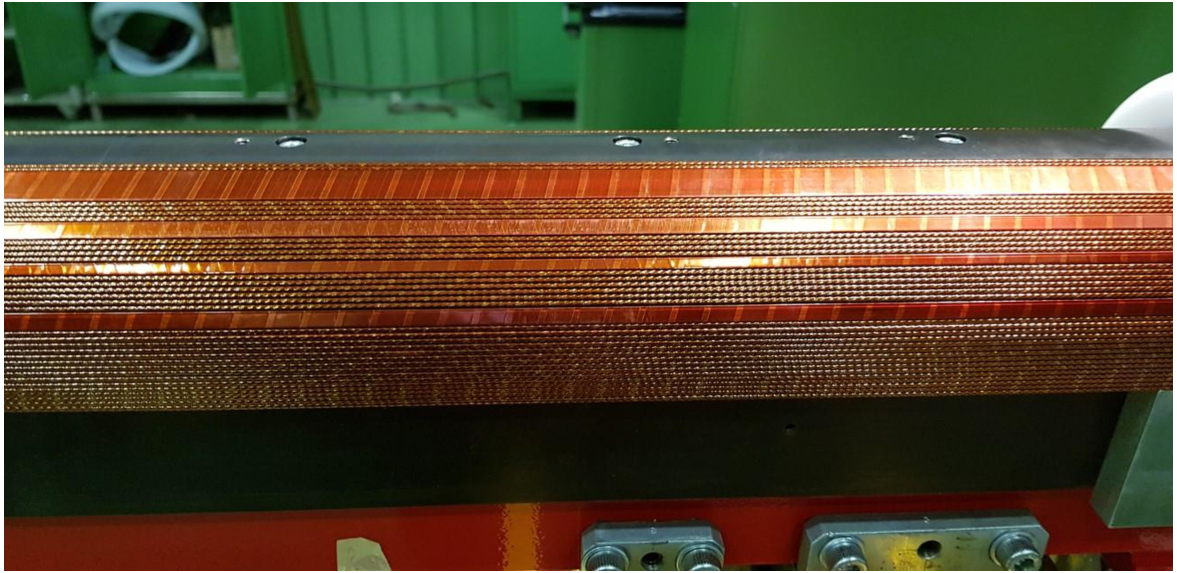
Damaged cable in first assembly

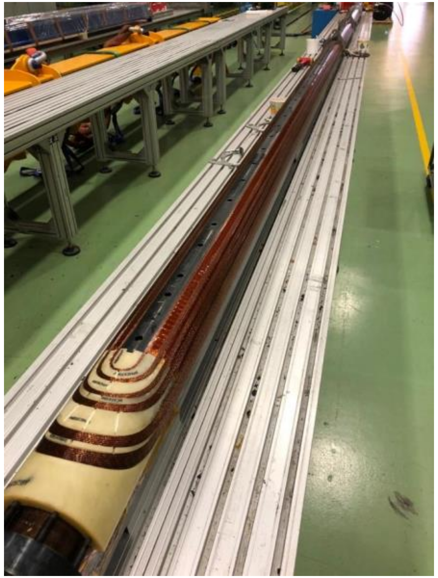


D2 short model training [S. Ferradas Troitino, et al]

Status of D2

- How’s is going now ?
- First coils wound in ASG, collaring of first aperture is ongoing



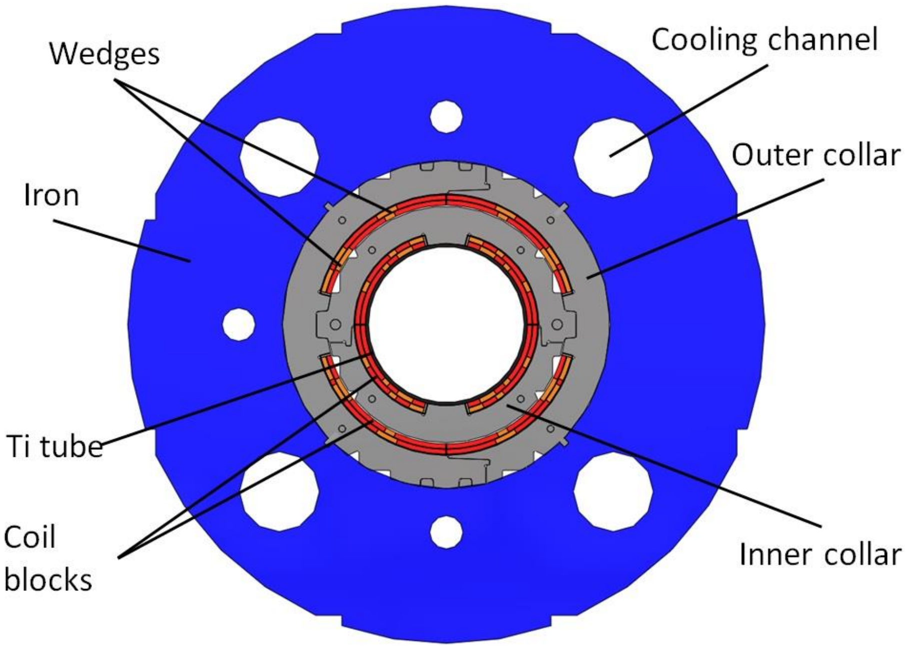


D2 practice coil for the prototype [courtesy of ASG and P. Fabbricatore]

Challenges of MCBXF (nested corrector)

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

- Bore field: 3.4 T in combined mode
  - (3.64 T ultimate)
- Magnetic length: 1.2/2.2 m
- Challenges
  - The double collar structure, a prima in magnet design to steer the torque
  - The torque in the coil heads
  - The force pattern, pushing coils inside the aperture
- This can be considered as a magnet with stress management



MCBXF cross-section

[F Toral, J. Garcia Mateos, J. C. Perez, P. Fessia et al.]

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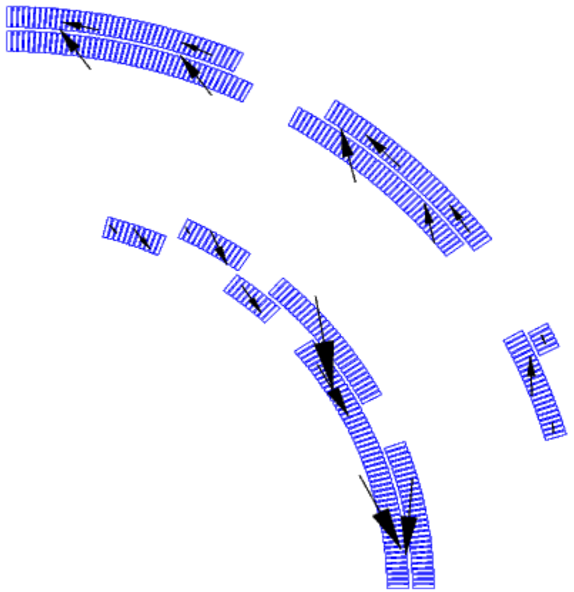
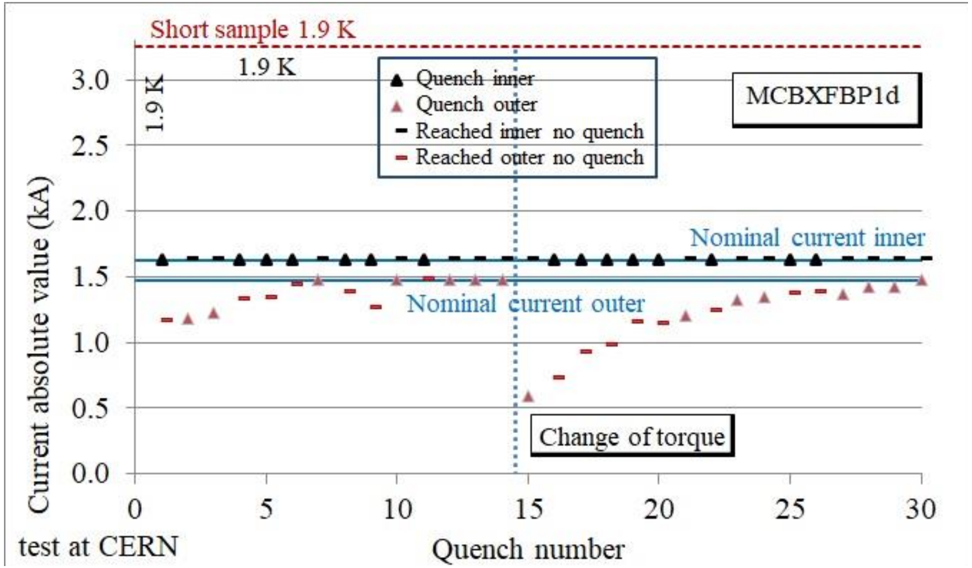


MCBXF force pattern in combined powering

[F Toral, J. Garcia Mateos, J. C. Perez, et al.]

Status of MCBXF (nested corrector)

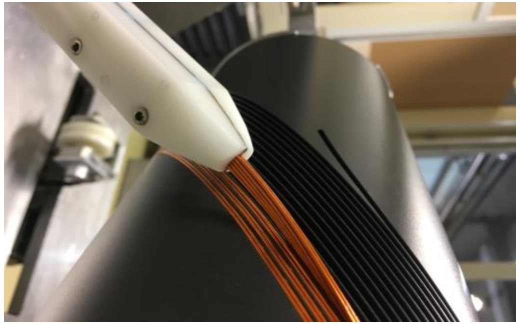
- Two prototypes reached nominal current in combined mode
  - Issue of retraining needed when the torque sign is changed is being addressed

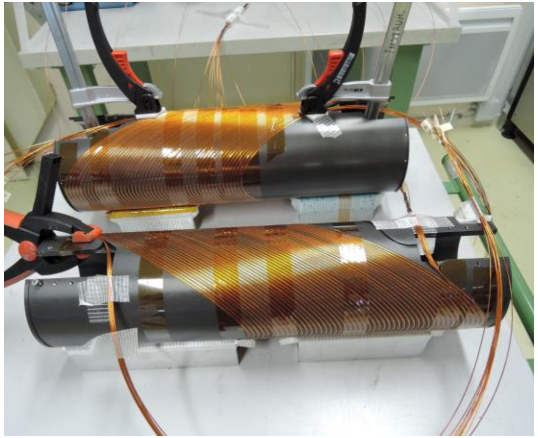


MCBXFP1d training [F. Toral, J. C. Perez, G. Willering et al.,]

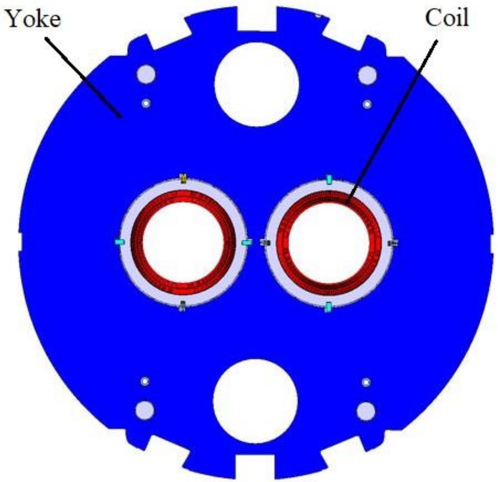
Challenges of MCBRD (CCT, D2 corrector)

- Bore field: 2.6 T
  - (2.8 T ultimate)
- Magnetic length: 1.9 m
  - Canted cos theta technology: first magnet of this type done at CERN
  - Following the experience in LBNL, AML, …
- Challenges
  - Even though a large margin was selected (0.50 on the loadline), the issue of training is present





Short models wound at CERN

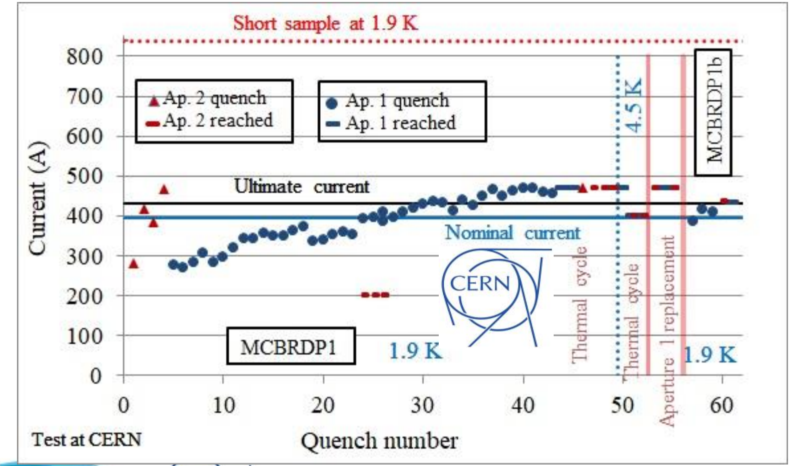


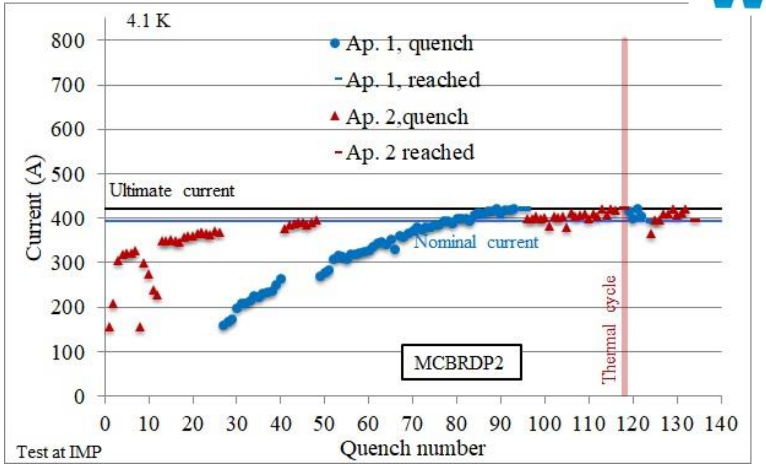
MCBRD cross-section

[G. Kirby, et al.]

Status of D2 corrector (CCT)

- First prototype built in CERN, and second in WST (Xi'an) reached ultimate current in both aperture without need of retraining
  - Long virgin training in Chinese prototype and in one aperture of CERN prototype
  - Issue of long training (below 50% of short sample) not yet understood
  - Critical for





MCBRDP1 training (left) and MCBRDP2 training (right) [F. Mangiarotti et al., Q. Xu, W. Wu et al.]

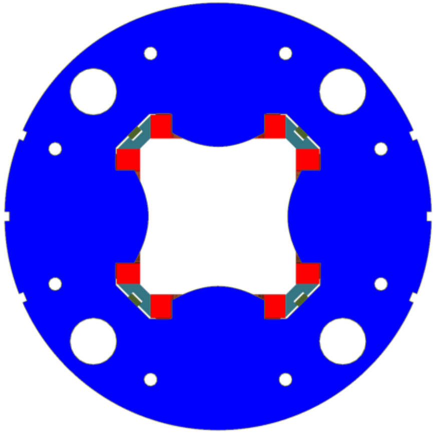
Status of D2 corrector (CCT)

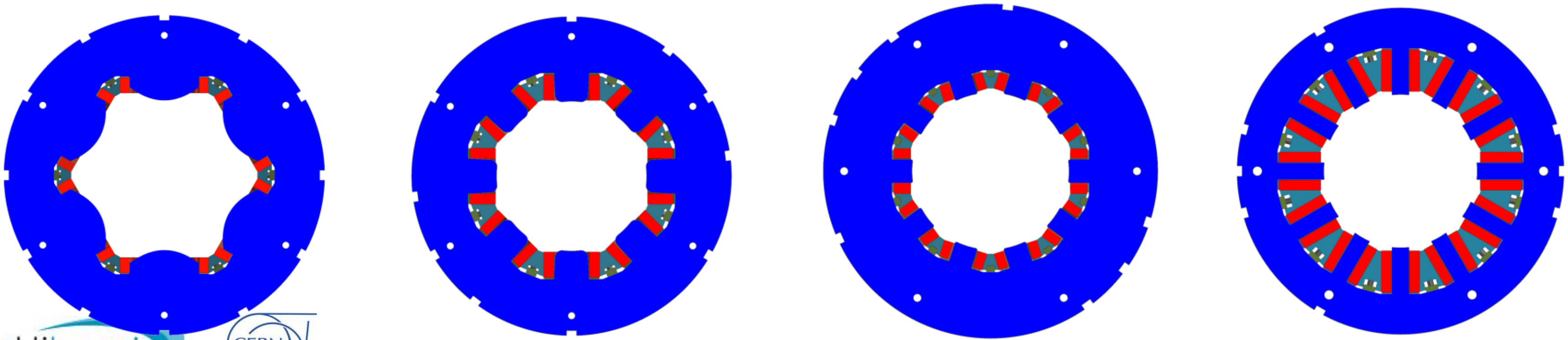
- How's going now ?
- Series production in BAMA started

BAMA premises and winding machine (left) and winding of the first coil (right) [Courtesy of Q. Xu, and BAMA]

Challenges of high order corrector (superferric)

- Field at the pole: between 1.5 and 3.6 T
- This is the most advanced magnet in terms of schedule, main challenge is now going though the beginning of the produciton
  - One (minor) issue with retraining was found in the first skew quadrupole prototype, all other prototype tests were conform

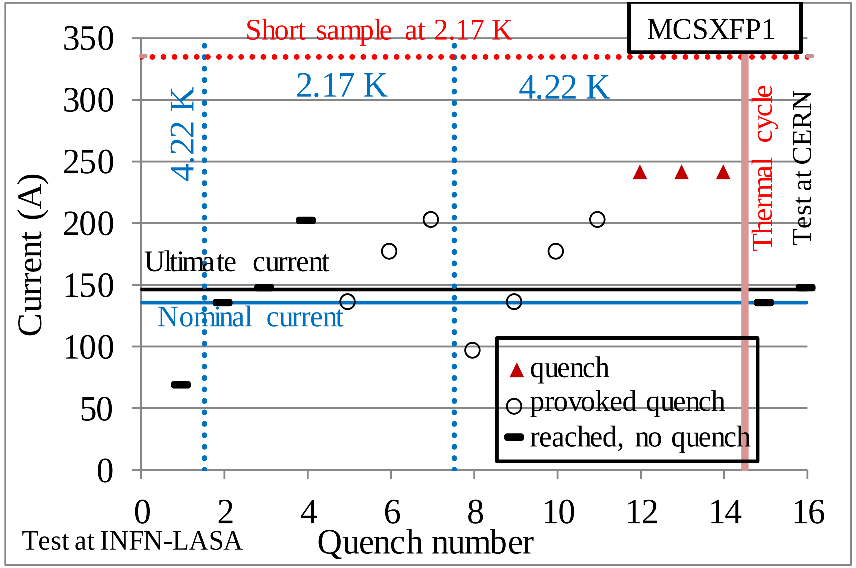


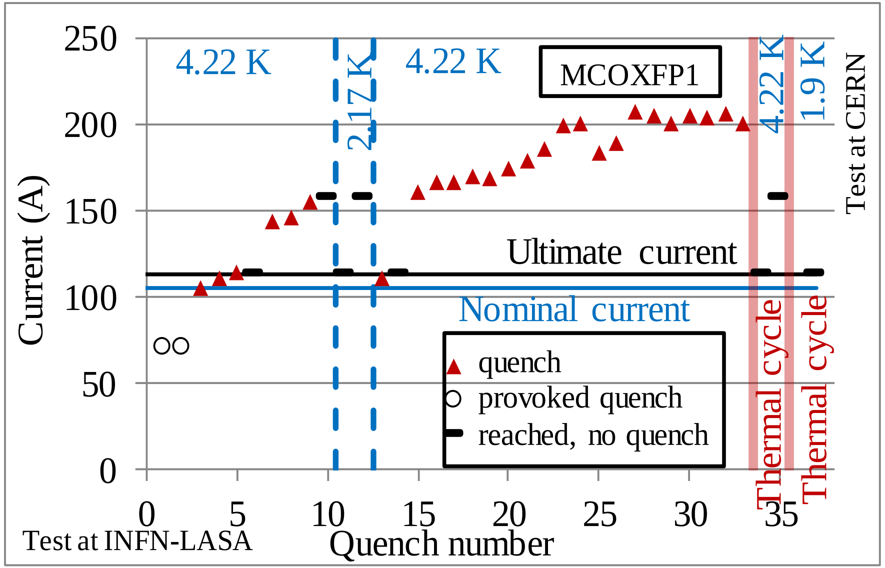


High order correctors cross-sections [G. Volpini, M. Sorbi, M. Statera, et al.]

Status of HO correctors

- All prototypes tested and reaching performance
  - Sextupole and octupole trained well above 50% of short sample

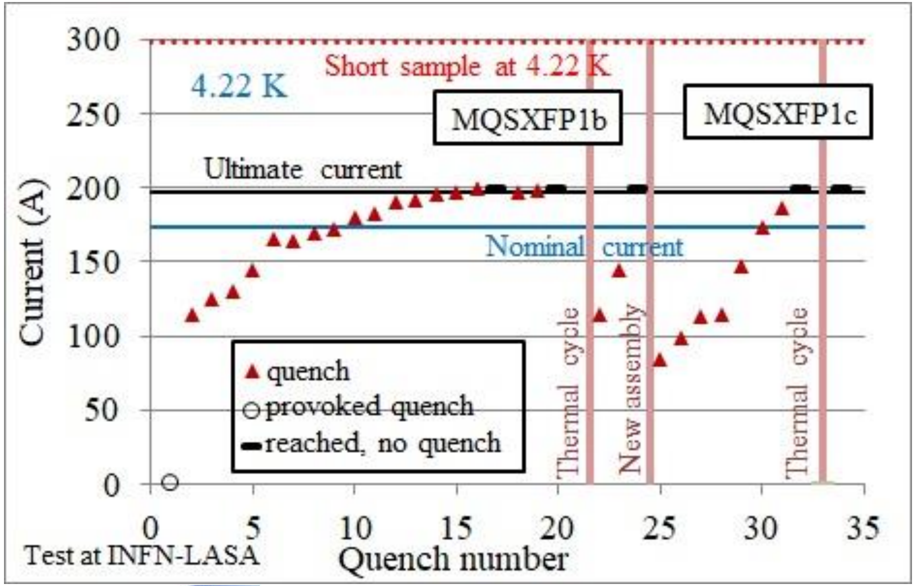




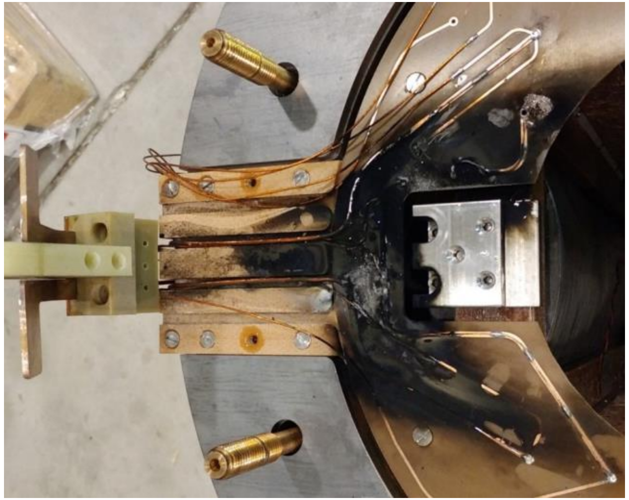
Training of sextupole and octupole [G. Volpini, M. Sorbi et al.]

Status of HO correctors

- All prototypes tested and reaching performance
  - The issue of retraing has been solved thanks to an improvement on the mechanical structure
  - We also had a short circuit during first test, origins clarified and cured



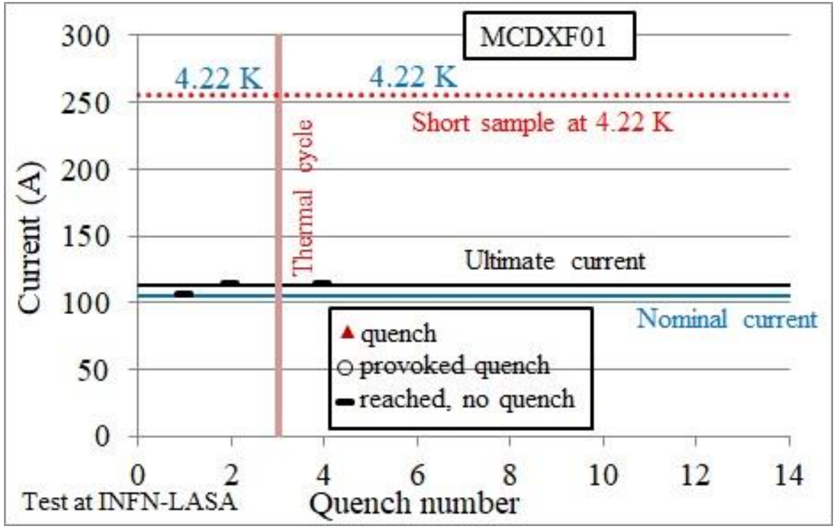
Training of skew quadrupole corrector [M. Statera et al.]

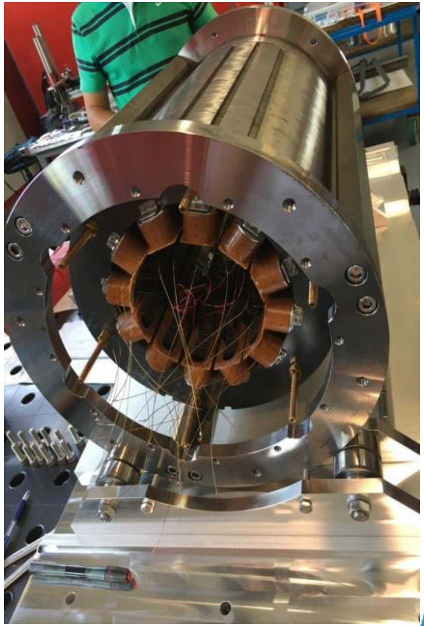


Short circuit in first assembly of the quadrupole

Status of HO correctors

- The series has been started in SEAS-RIAL
  - 1/3 of the coils of the whole production has been completed
  - One magnet tested (decapole), ultimate reached, no training





Training of decapole corrector [M. Statera et al.]

Conclusions

- The interaction region magnets are part of the HL-LHC project, started in 2011/2015 and to be installed in 2025
  - The timeline may appear long, but 12 years from aperture selection to installation of 150 magnets of six different types, with 35 of them of a new technology, is very short
  - As usual in accelerator magnets, many activities have to go in parallel, and one cannot wait the completion of a step before going to the successive: continuos exercise of balance of risk
- All magnet design have been validated on short models (main magnets) or prototypes (correctors)
- For the Nb_3Sn triplet, that is the most advanced piece of technology
  - Two succesful full size pre-series magnets built in US
  - After a thermal cycle a perfect memory is kept (appears to be better than Nb-Ti)
  - A maximum of 13.4 T peak field was reached in one of the short models
  - The same design is used by manufacturing sites in four labs, spanning over 9 time zones: this is the real proof of industrialization of bladder and key technology and of Nb_3Sn accelerator magnets – a total of 35 magnets will be built, for a total length of 200 m

Conclusions

- For every magnet type, issues were found and overcome
  - Two electrical shorts (triplet and skew quadrupole)
  - Insufficient performance due to lack of support (D1, skew quadrupole, first assembly of nested corrector)
  - Broken structure due to sharp edges in the Al shell
- Few issues are still on the table
  - Three cases of triplet magnet not reaching performance, two cases of reverse behaviour
  - Long virgin training for the CCT technology in some cases
  - Retraining needed in the nested corrector when the torque sign is changed
- This is the critical period of transition between prototype and series
  - Here the last iterations on design can be done, only if really necessary

References

- Full list of 100 published papers about the interaction region of the HL-LHC project
  - About 50 papers on the Nb_3Sn triplet
  - This page also contains a list of references on Nb_3Sn accelerator magnets built so far
- The recent review paper about the present status of the IR magnets
  - E. Todesco, et al. « The HL LHC interaction region magnets towards series production » SUST (2021), in press

The 180 team with the second finished MQXFB prototype