

The HL-LHC project: high field magnets

E. Todesco, G. Ambrosio, P. Ferracin, F. Savary on behalf of WP3 (IR magnets) and WP11 (11 T dipoles) done in MSC group (L. Bottura) for HL-LHC project (L. Rossi)













THE TEAM

WP3 (Interaction region magnets)

- MQXF-CERN: P. Ferracin, S. Izquierdo Bermudez, J. Carlos Perez, G. Vallone, B. Bordini, A Ballarino, J. Fleiter, D. Duarte Ramos, V. Parma, P. Hagen, H. Prin, F. Savary, F. Lackner, L. Fiscarelli, C. Petrone, O. Dunkel, H. Bajas, M. Bajko, P. Moyret, A. Dallocchio, A. Verweij, F. Rodriguez-Mateos
- MQXF-US: G. Ambrosio, R. Bossert, G. Chlachidze, L. Cooley, E. Holik, S. Krave, F. Nobrega, I. Novitsky, C. Santini, S. Stoynev, T. Strauss, M. Yu, D. Cheng, D.R. Dietderich, R. Hafalia, M. Marchevsky, H. Pan, I. Pong, S. Prestemon, E. Ravaioli, G. Sabbi, X. Wang, J. Di Marco, M. Mackiewski, S. Stoynev, M. Anerella, A. Ghosh, P. Joshi, J. Muratore, J. Schmalzle, P. Wanderer
- D1 (KEK): T. Nakamoto, M. Sugano, S. Enomoto, N. Higashi, M. Iida, Y. Ikemoto, H. Kawamata, N. Kimura, T. Ogitsu, H. Ohata, N. Okada, R. Okada, K. Sasaki, K. Suzuki, N. Takahashi, K. Tanaka + A. Musso (CERN PE)
- D2 (INFN-Ge): P. Fabbricatore, S. Farinon, A. Bersani + A. Foussat (CERN PE)
- MCBXF (CIEMAT): F. Toral, J. Garcia Matos, P. Abramian, J. Calero, P. Gómez, J. L. Gutierrez, L. García-Tabarés, D. López, J. Munilla + J. Carlos Perez (CERN PE)
- High order correctors (INFN LASA): M. Sorbi, M. Statera, F. Alessandria, G. Bellomo, F. Broggi, A. Leone, V. Marinozzi, S. Mariotto, A. Paccalini, D. Pedrini, M. Quadrio, M. Todero, C. Uva + A. Musso (CERN PE)
- D2 correctors-CERN: G. Kirby, G.de Rijk, J. Van Nutgeren, L. Gentini, J. Mazet, M. Mentink, F. Mangiarotti, J. Murtomäki, F. Pincot, N. Bourcey, J. C. Perez
- MQYY (CEA): H. Felice, D. Simon, J. M. Rifflet, M. Segreti, J. M. Gheller, D. Bouziat, A. Madur + A. Foussat (CERN PE) plus QUACO: F. Toral, P. Krawcyzk, I. Bejar Alonso, H. Garcia Gavela, M. Losasso

WP11 (Dispersion suppressor dipole)

11 T: F. Savary, J. Carlos Perez, M. Daly, L. Grand-Clement, M. Semeraro, J. L. Rudeiros Fernandez, F. Lackner, C. Loeffler, A. Foussat, F. Lackner, H. Prin, D. Duarte Ramos, V. Parma, D. Smekens, L. Fiscarelli, S. Izquierdo Bermudez, B. Bordini, A Ballarino, J. Fleiter, R. Principe



SUMMARY

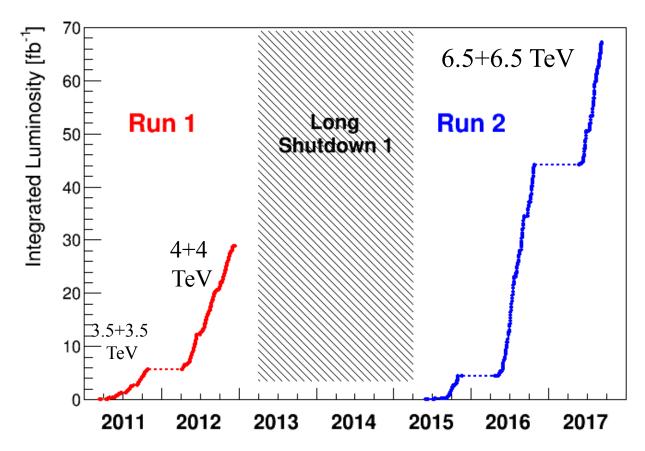
- Why HL-LHC
- Layout and performance
 - The "other magnets" of HL-LHC
- The 12 T challenge





LHC RESULTS

- LHC is operating at 6.5 TeV energy since 2015, delivering 70 fb⁻¹
 - 1 fb⁻¹ is a high energy physics unit meaning for the LHC proton run ~10¹⁴ proton collisions
 - Target for LHC is delivering 300 fb⁻¹

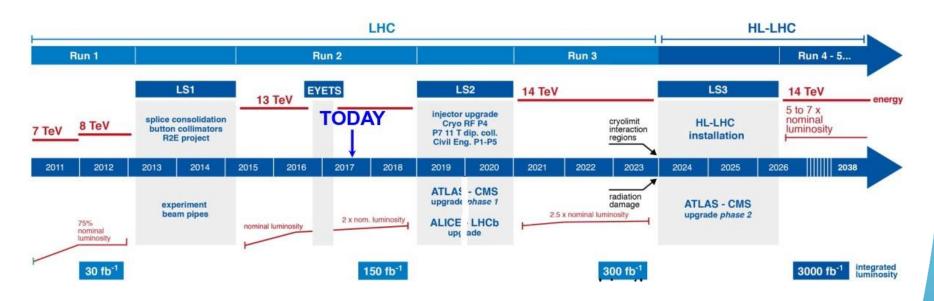






HL-LHC TIMELINE

- Substantial upgrade to be able to deliver 10 times more luminosity from 2026
 - Total target of 3000 fb⁻¹



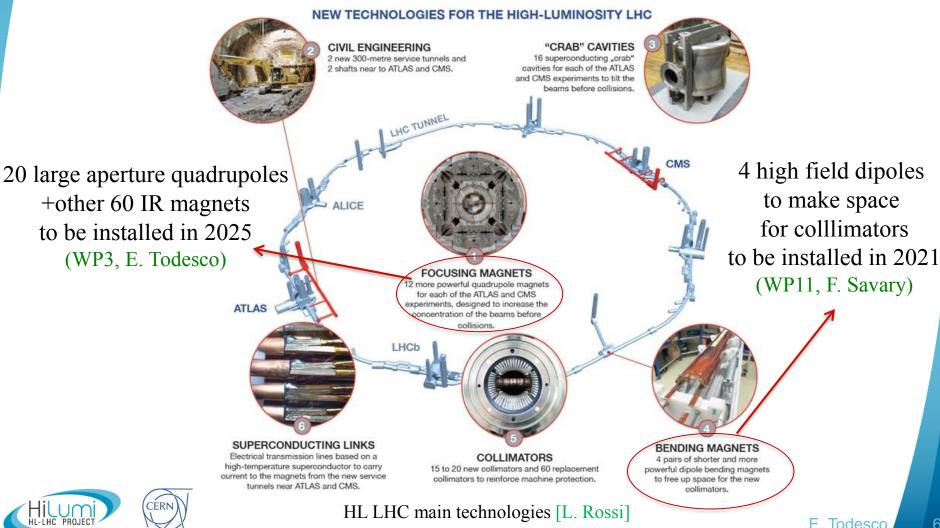
Timeline of LHC and HL-LHC [L. Rossi, F. Bordry]





LHC UPGRADE

Upgrade relying on several technological pillars

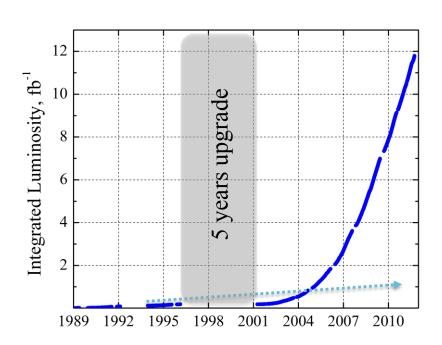






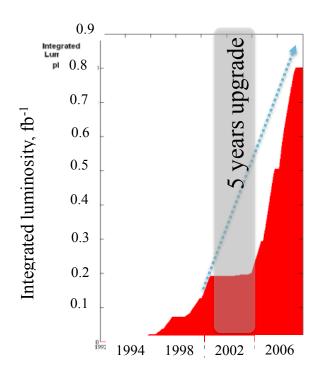
LHC UPGRADE

- In the philosophy of the upgrade, one has to be fast and ambitious
 - Luminosity increase must compensate the loss due to time needed to install equipment, and commissioning



Tevatron integrated luminosity







and Goals for Accelerators in the XXI Century",

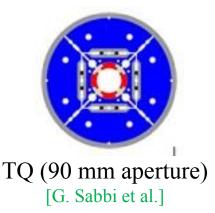
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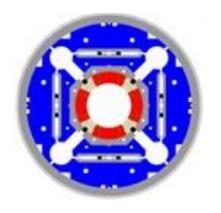


APERTURE AND PREVIOUS STUDIES

- Rate of collisions ∞ (aperture of the triplet)²
- 2000: first studies on LHC upgrades [F. Ruggiero, O. Bruning, et al., LHC Project Report 626]
 - This also launched US-LARP
 - TQ: moderate increase of triplet aperture (from 70 to 90 mm) to increase rqate of collisions by a factor 2
 - HQ: going to 120 mm aperture
 - Final decision of HL-LHC in 2013 is more ambitious: MQXF aperture at 150 mm, rate of collisions up by a factor 4









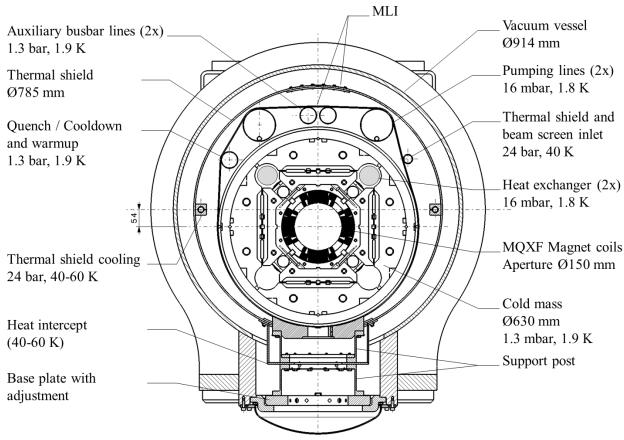


MQXF (150 mm aperture)
[P. Ferracin, G. Ambrosio et al.]

E. Todesco

APERTURE, CRYOSTAT, TUNNEL SIZE

- With 2013 decision of 150 mm aperture, we are at the limit of what is doable
 - We are hitting the size of the cryostat and tunnel

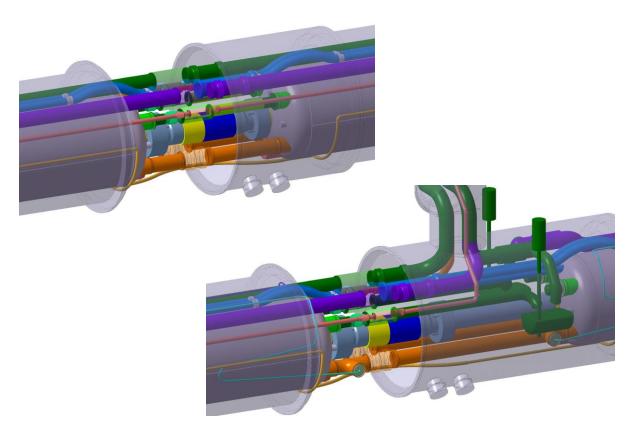


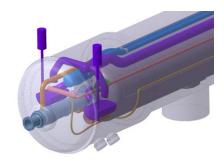




APERTURE, CRYOSTAT, TUNNEL SIZE

 A detail of crowded interconnections (H. Prin and D. Duarte Ramos)









TIME AND SCHEDULE

- Our projects have ~25 years timeline
 - LHC
 - First design report 1984
 - Project approved 1995 (t+11)
 - Commissioning 2008 (t+24)
 - Nominal reached 2015 (t+31)
 - HL-LHC
 - First ideas and report 2000
 - Project approved 2016 (t+16)
 - Foreseen commissioning 2026 (t+26)
 - Foreseen nominal reached 2028 (t+28)
 - FCC
 - First studies 2014
 - Foreseen commissioning ~2040 (t+26)
- Looking from Euler point of view, very exciting period: one running accelerator towards performance, one project in the prototype phase, one study of future machine
- Paradox: notwithstanding long timelines, we are constantly running against time
 - Fabrication has to continue in parallel with tests
 - 2 years time feedback loop





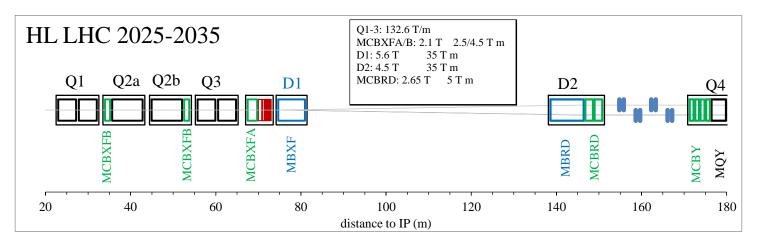
SUMMARY

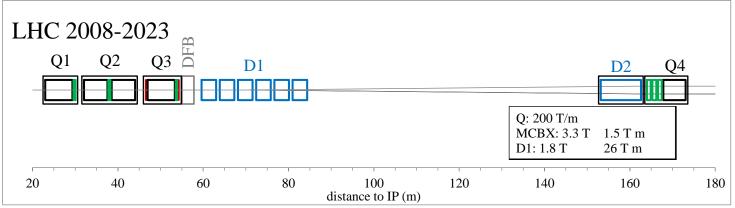
- Why HL-LHC
- Layout and performance: the "other magnets" of HL LHC
- The 12 T challenge





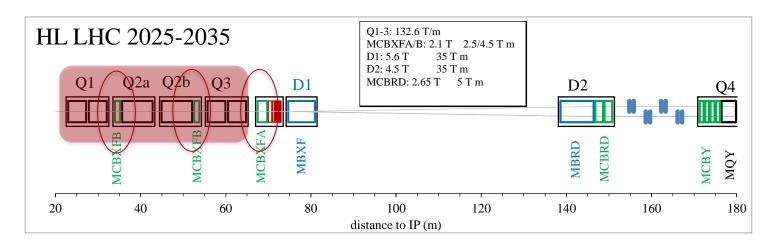
 Replacement of Q1-Q3, D1 and D2 plus correctors in IP1 and IP5 with larger aperture magnets (~twice)





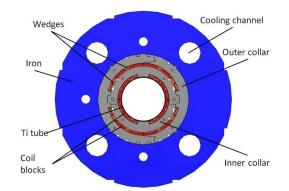


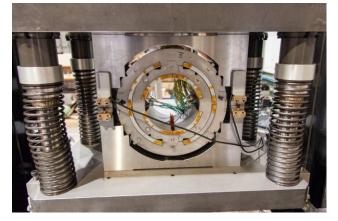




- In the first zone, space is essential
 - Nested horizontal-vertical correctors
 - Peak field of 3.4 T, two layers Rutherford cable
 - Test in 2018

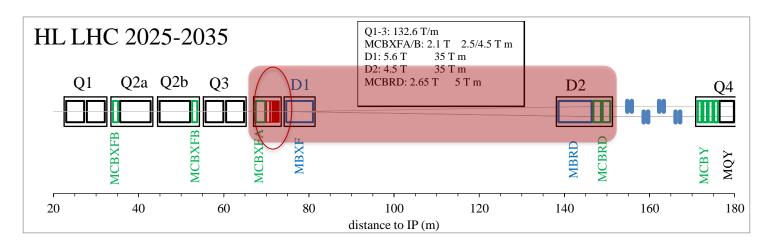






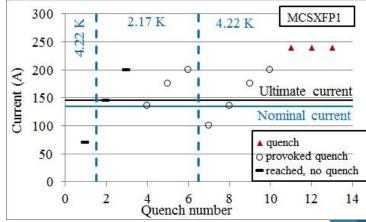






- In the second zone, space is relevant but not essential
 - Non nested high order correctors up to dodecapole [M. Statera 4LP1-16]
 - 2-3 T peak field, superferric technology, Nb-Ti wire
 - Sextupole and octupole successfully tested





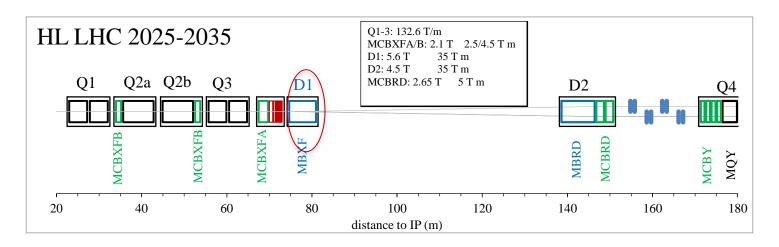


INFN

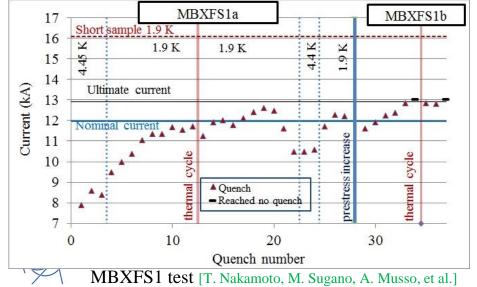


Istituto Nazionale

di Fisica Nucleare



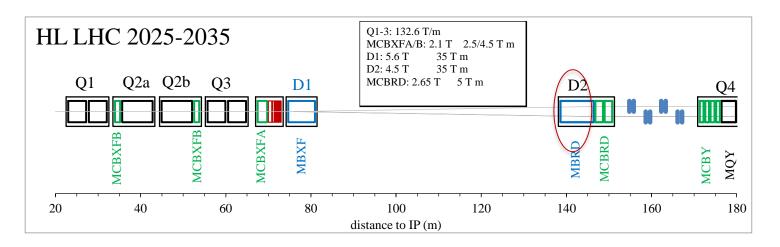
- D1 and D2 are Nb-Ti dipoles in the 5 T range
 - D1 model tested successfully (after an iteration on prestress)







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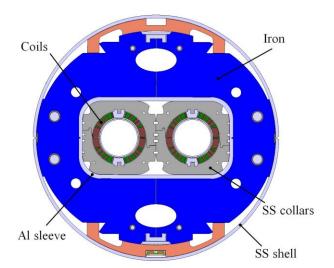


- D1 and D2 are Nb-Ti dipoles in the 5 T range
 - D2 model construction ongoing in industry

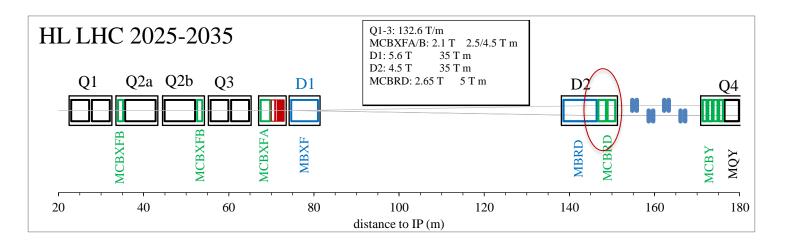






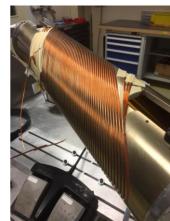


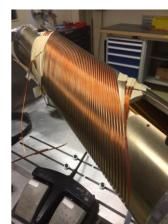




D2 orbit correctors are in the 3 T range

- Canted cos theta design (tilted solenoid)
- First model succesfully tested









E. Todesco

CONTENTS

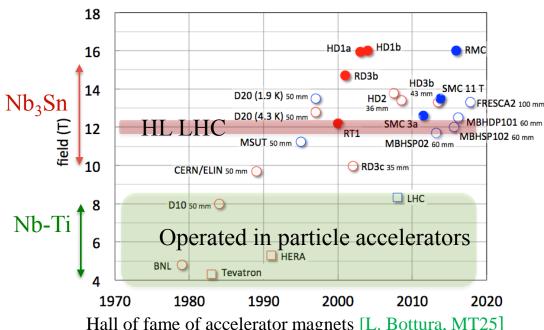
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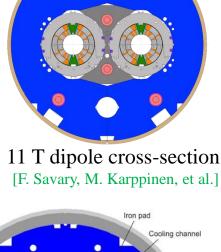
THE 12 T CHALLENGE

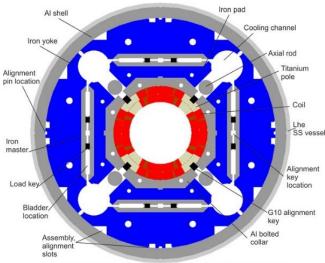
HL-LHC developes magnets in the 12 T peak field range in Nb₃Sn



Hall of fame of accelerator magnets [L. Bottura, MT25]

- The challenges
 - Thermal contraction and lengths
 - Current density
 - Prestress control
 - For strand, see [L. Cooley, 2MO1-01]
 - For protection, see [S. Izquierdo Bermudez, 3LO3-01]











THE 12 T CHALLENGE: THERMAL CONTRACTION AND MAGNET LENGTH

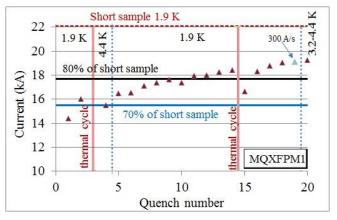
- Nb₃Sn requires heating at 650 C and operating at -271 C
 - All components must tolerate nearly 900 degrees of temperature gradients, with significantly different thermal contraction properties
- Technology proved for 1-m-long models accelerator magnets since the 80s
 - CERN Elin, MSUT
- LARP pushed the magnet length up to 3.4 m
 - With a significant iteration on the mechanical structure
- HL-LHC will explore the 7 m range
 - 11 T magnet of 11 m split in two units 5.5-m-long
 - US MQXF decided to split the 8.4 m, in two 4.2-m-long coils
 - CERN MQXF will be 7.15 m long
 - Final target is to demonstrate 15 m long magnets (as for FCC)



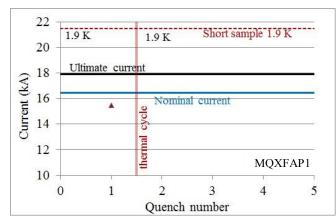


THE 12 T CHALLENGE: THERMAL CONTRACTION AND MAGNET LENGTH

- First results: MQXF in US
 - Good performance for a 4-m-long coil in mirror configuration
 - First 4-m-long prototype had good level of first quench (under test at the moment)
 - New world record of accelerator coil length



Training of first 4-m-long MQXF mirror



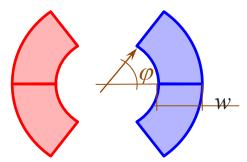
Training of first 4-m-long MQXF (test ongoing)

- CERN plans
 - First long coils manufactured for 11 T and MQXF, first tests in 2018



THE 12 T CHALLENGE: COIL WIDTH AND CURRENT DENSITY

- In an electromagnet field proportional to ampere turns $B_1 \propto NI$
 - For superconducting magnets it is more convenient to write in terms of current density *J* and coil width *w*



$$B = \frac{2m_0}{\rho} J w \sin(j)$$

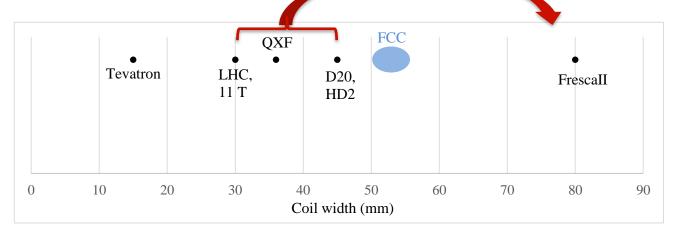
- Two ways to increase field:
 - Increase coil width w (less difficult option)
 - Increase current density *J* (more difficult option)
- 11 T: same w of LHC (30 mm) and we increase *J*: no space

MQXF: larger coil width of 36 mm





THE 12 T CHALLENGE: COIL WIDTH AND CURRENT DENSITY



- 45 mm coil width were explored in the past: D20, HD2
- Frescall, with 80 mm coil width (CERN/CEA project, steered by G. de Rijk)
 - Reached 13 T at 70% of the short sample training will continue soon (P. Ferracin, 4LP1-17)



Fresca2 assembly in 927









THE 12 T CHALLENGE: CURRENT DENSITY

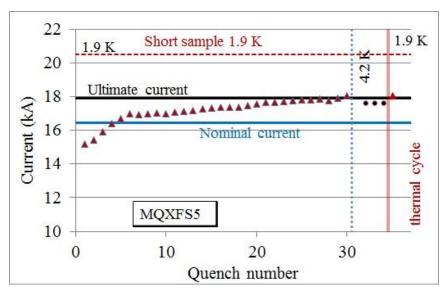
- HL LHC magnet will explore a non trivial jump of 20-30% in current density
- So current density in the strand will increase from 500-600 A/mm² in the LHC dipoles to 720 (MQXF) and 770 (11 T) A/mm²
- This is a non trivial jump for
 - Stress J B [G. Vallone, 1MP107]
 - Protection J² [S. Izquerdo Bermudez, 3LO3-01]
 - Instabilities
 - Magnetization $D_{eff} J$
- Target for FCC is very close: 800 A/mm² [D. Tommasini et al., MT25]

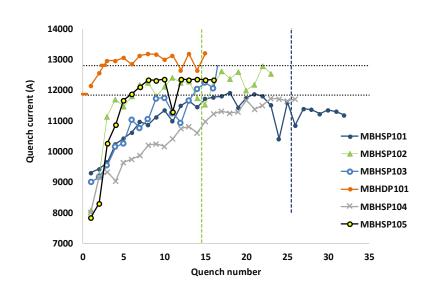




THE 12 T CHALLENGE: CURRENT DENSITY

- Results: both projects had short models reaching performance, proving that the design can achieve these current densities
 - Reproducibility is not yet given
 - MQXF: 3/3 reached nominal, 2/3 reached ultimate
 - 11 T: 4/5 reached nominal, 2/5 ultimate
 - Long training, but memory is very good
 - First double aperture Nb₃Sn magnet reached performance







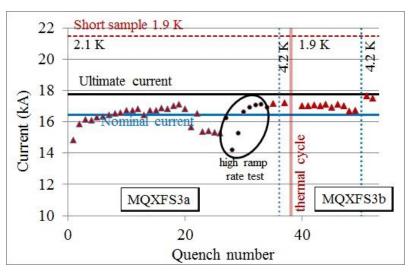
MQXF short model test (#5)

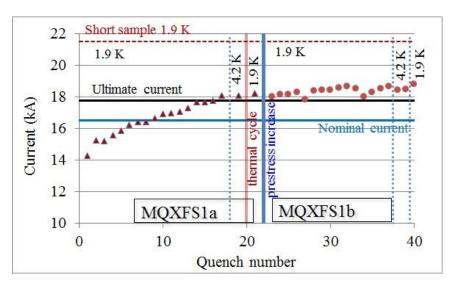
ajas and SM18 team)

11 T short model tests
(G. Willering and SM18 team)

THE 12 T CHALLENGE: CURRENT DENSITY

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MQXF short model test (#3)

(H) Bajas and SM18 team)

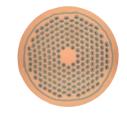
MQXF short model test (#1)
(G. Chlachidze and FNAL team)
E. Todesco

THE 12 T CHALLENGE: STRAND AND CABLE

- All the wire for the 11 T series coils and the MQXF prototype coils has been produced
 - For the whole 11 T project (MQXF project) CERN has received about 1200 km (1000 km) of 0.7 mm (0.85 mm) wire
 - For the MQXF project 600 km expected in the next 8 months; by beginning 2018 final contract for 1100 km

 J_c (12 T), J_c (15 T), $B_{c2}(4.3 \text{ K}), J_c(16 \text{ T}), J_c(18 \text{ T}), Degradation J_c$ **Minimum RRR Sub-Element** (15% rolling) Layout RMS **RMS RMS RMS RMS** (15% rolling) size [A/mm²][A/mm²] [A/mm²] [A/mm²][T] [%] 0.7 mm 2676, 1410, 24.5, 1098, 610, 108/127 46 µm 0 >100 RRP 68 58 0.39 55 47 0.85 mm 2835, 1601, 25.9, 1289, 785, 0 >100 108/127 55 μm **RRP** 44 33 0.19 25 30 0.85 mm 2323, 26.7. **1342**. 1093. 688, 39 µm 5.5 % >150 Bundle 192 83 0.1 49 26 40 **Barrier PIT**

Bundle Barrier PIT 192



RRP 108/127



- Nb₃Sn strand (B. Bordini, A. Ballarino)
- Cable has 40 strands (large aspect ratio)
 - Produced 65 Rutherford cables (about 20 longer than 650 m) no showstoppers, careful iteration on cable parameters at the beginning of the project (J. Fleiter, L.





THE 12 T CHALLENGE: PRESTRESS CONTROL

Coils must be kept under compression during powering to balance electromagnetic forces

- In the LHC we had prestress requirement of 50-70 MPa
- In 11 T and MQXF this doubles to 100-150 MPa
- Strain in Nb₃Sn conductor reduces the performance reduces
 - Degradation starts around 150-200 MPa
- Good control of prestress is a critical point
- The two projects explore two different structures
- In MQXF we impose stress
 - Bladder and key load and Al shell developed in LBNL
 - We partially load at warm with bladders, no tooling, controlling stress (50 MPa)
 - We mainly load at cold: Al ring adds 100 MPa
 - Pole impregnated





THE 12 T CHALLENGE: PRESTRESS CONTROL

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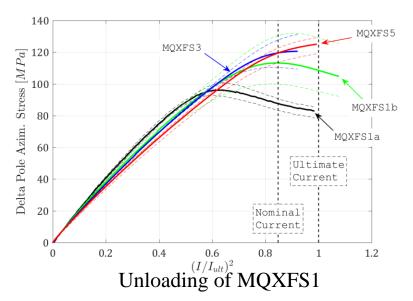
- Classical collar structure
- We totally load at warm with press, controlling displacement (150 MPa)
- Removable pole, adding one degree of freedom for shimming

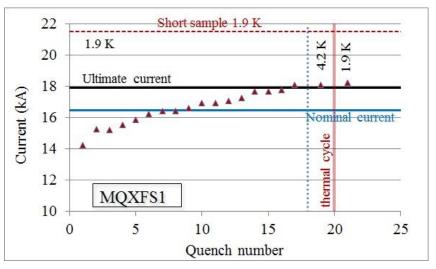




THE 12 T CHALLENGE: PRESTRESS CONTROL

- Results: both in 11 T and in MQXF we have evidence, as in the LHC dipoles, that magnet still trains after coil unloading
 - Very important feature otherwise the loading window becomes very narrow
- On the other hand, we tend to avoid situations of total unloading





MQXF short model test (#1) (HL LHC US AUP)

- In 11 T we see in some magnets signs of degradation due to excessive stress (quences in the midplane)
 - Optimization to reduce the prestress in the coil (C. Loeffner 1LP1-11, 4LP1-04)

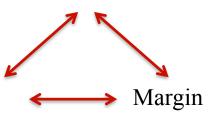




FINE TUNING

Performance

- Since 2011, we made few design fine tuning
 - Pretty small changes, but in our field evil is in details



Cost

- Keystone angle of MQXF cable: reduction from 0.55° to 0.40°
 - To reduce critical current degradation due to cabling this induced a change of cross-section
- Critical current specification at 15 T in MQXF strand: reduction of 10%
 - To include the whole production and reduce cost
 - To recover the loadline margin in MQXF, gradient was reduced by 5% and magnet was made 5% longer - small performance loss
- Increase the magnetic field of D1 from 5.2 to 5.6 T
 - To make the magnet shorter and fit the vertical test station in KEK lower margin but risk considered acceptable
- Go from single to double layer in MCBXF
 - To reduce the operational current below 2 kA more components and complexity
- Adopt CCT design for D2 corrector
- Have the quadrupoles on one main circuit





CONCLUSIONS

- The HL-LHC project is developing accelerator Nb₃Sn magnets in the 12 T range of operational peak field
 - First Nb₃Sn magnets to be installed in a particle accelerator
 - Main challenge is reaching performance
 - Short model program well advanced
 - First prototypes arriving
- The program is complemented by 60 additional large aperture magnets based on Nb-Ti
 - Fields between 2-6 T, different designs
 - Half of them with short models tested, the other half in 2018

www.cern.ch/hilumi/wp3 (Interaction Region magnets)
www.cern.ch/hilumi/wp11 (11 T)



