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High-Field Accelerator Magnets

Bernardo Bordini

Thanks to the many colleagues at CERN who provided relevant material for this presentation in particular:
L. Bottura, A. Devred, G. De Rijk, D. Tommasini, A. Ballarino, F. Savary, E. Todesco, M. Bajko, and P. Ferracin

Outline

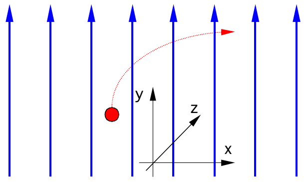
- **Introduction**
  - The Need For High Field
  - What are High Fields for Accelerator Magnets?
- **Status of the Nb_3Sn High Field Accelerator Magnets**
  - High Luminosity Large Hadron Collider (HL-LHC)
  - Future Circular Collider (FCC)
  - The US-Magnet Development Program (US-MDP)
- **Challenges for Nb_3Sn High Field Accelerator Magnets**
  - Mechanics to cope with huge Lorentz forces and to limit the coil stress/strain
  - Increasing the critical current to reduce the cost of the magnets
  - Efficient use of the critical current: I_c vs transversal loads; Conductor Stability; Training

Introduction

The Need For High Fields

- Increase the collision/beam **energy** to possible generate new particles

Dipoles to bend the trajectory of the beam



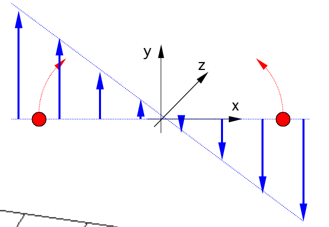
Beam energy — Bending radius

$$E[GeV] = 0.3 \, B[T] \, \rho[m]$$

Dipole field

- Increase the number of particles collisions (**luminosity** at the experiment)

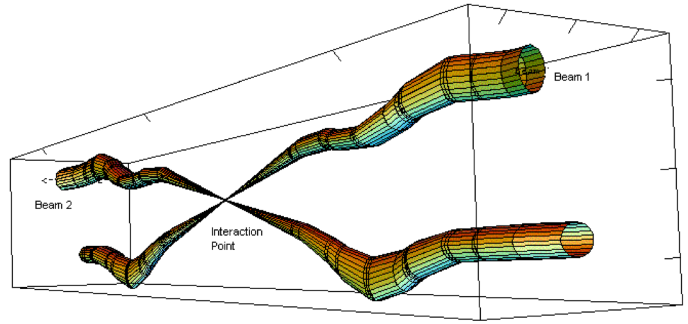
Final focus quadrupoles to reduce the beam dimension at the interaction point



Peak coil field

$$B \ell_q \approx \frac{1}{\sigma^*}$$

Quadrupole length — Beam size at the collision point



Relative beam sizes around IP1 (Atlas) in collision

Introduction

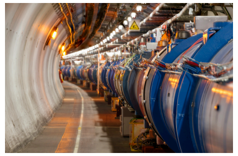
High Fields For Accelerator Magnets

Based on Nb-Ti

RHIC
3.5 T

Tevatron
4.3 T

HERA
4.7 T



LHC
8.33 T

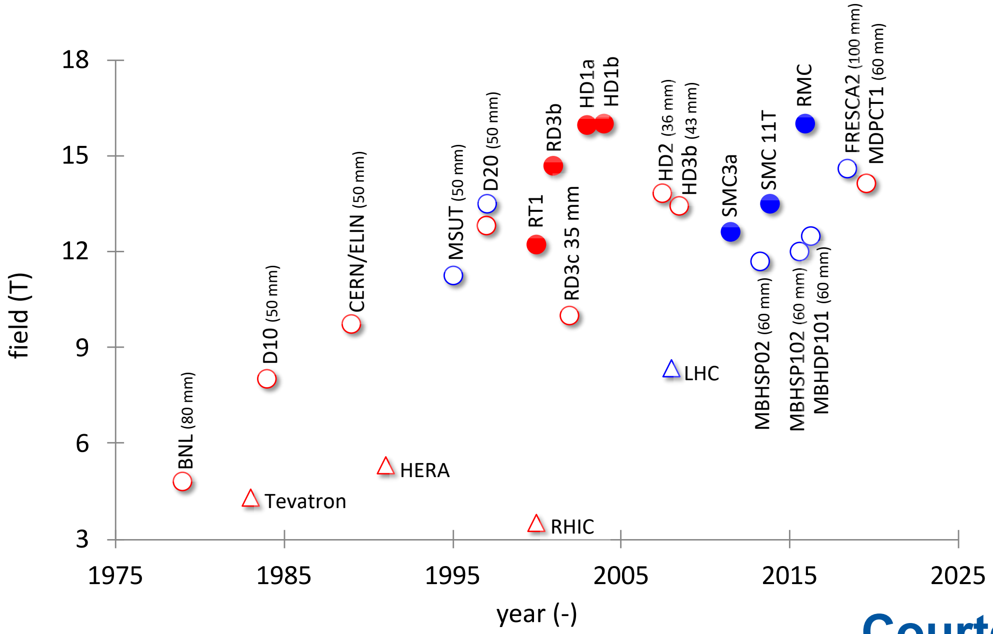
High Field Accelerator Magnets > ~ 10 T

HL-LHC
~ 11 T (Nb_3Sn)

FCC-HH
16 T (Nb_3Sn)

SPPC
12 T → 24 T (IBS)

- At present **Nb_3Sn** is the only **mature** technology for **HF Accelerator Magnets**
- The rest of the presentation will be focused on Nb_3Sn Magnets

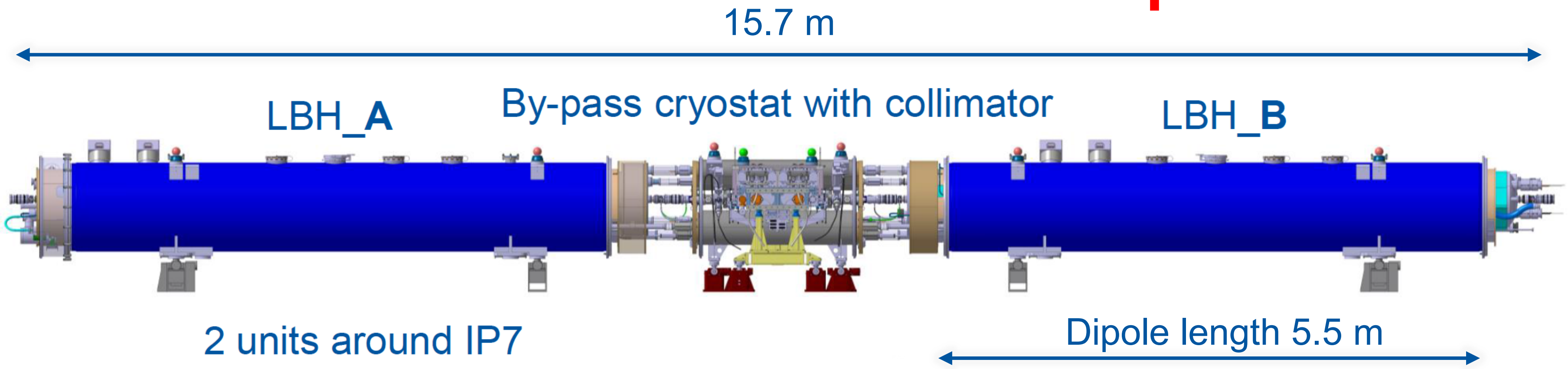


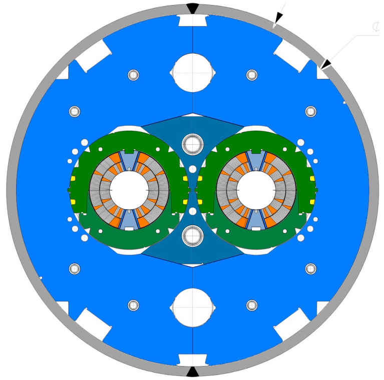
Field in Accelerator Type **Nb_3Sn Dipoles**
vs
Field in the main **Nb-Ti dipoles** in accelerators (triangles)

Courtesy L. Bottura

Status of the HL-LHC High Field Magnets

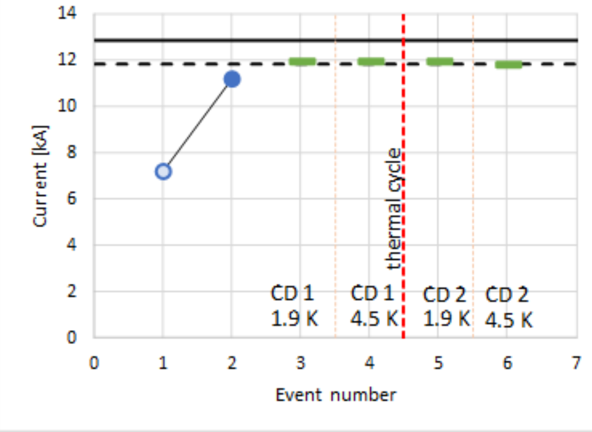
The 11 T Dipole





- CERN is manufacturing 11 T Nb_3Sn dipoles (60 mm aperture) to be installed in the LHC by end 2020
- First Series cold mass **successfully tested** this summer

Quench History of MBHB_002
(Courtesy G. Willering)



MBHB_002 **Qualified** for **installation** in the LHC

Courtesy F. Savary

Status of the HL-LHC High Field Magnets

Low-β quadrupole MQXF - Final focus Quadrupoles

- In collaboration with US HL-LHC AUP, CERN is manufacturing quadrupole to be placed in the LHC interaction regions **by end 2024**

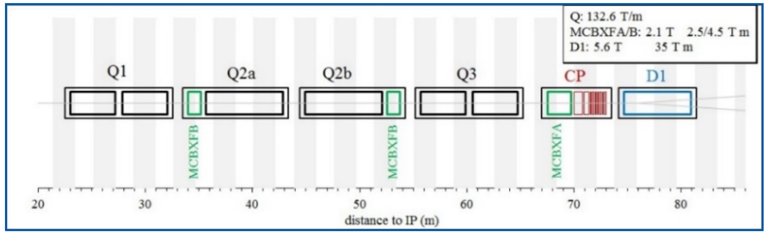
Courtesy of E. Todesco, P. Ferracin, G. Ambrosio

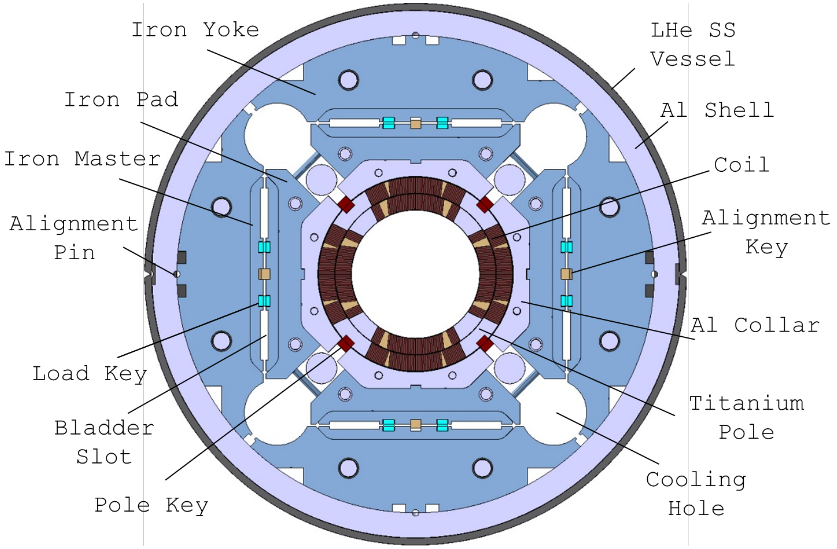
- Target
  - G_{nom}=132.6 T/m, 11.4 T B_{peak_nom}
    - Corresponds to 14 Tev in LHC
  - G_{ult}=143.2 T/m, 12.3 T B_{peak_ult}

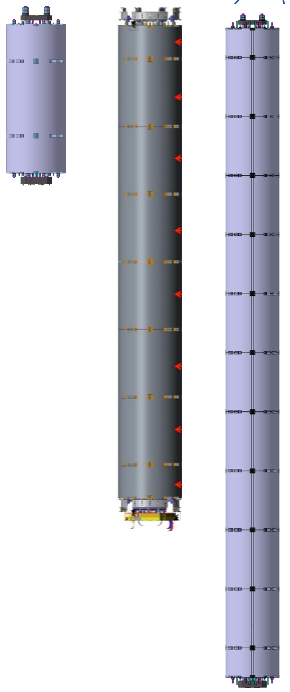
- Q1/Q3 (by AUP)
  - 2 magnets MQXFA with 4.2 m
    - **Series: 20 magnets**

- Q2a/Q2b (by CERN)
  - 1 magnet MQXFB with 7.15 m
    - **Series: 10 magnets**

- Different lengths, same design
  - Identical short models





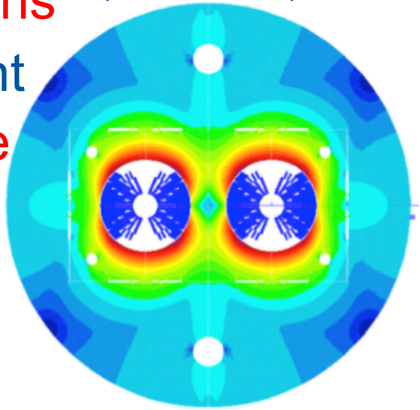


Status of the FCC High Field Magnets

- CERN is presently pursuing several ambitious **collaborations** aimed at developing **4** different **50-mm**-aperture twin-aperture **dipole magnet** designs with **16.0/16.5 T** bore/peak field

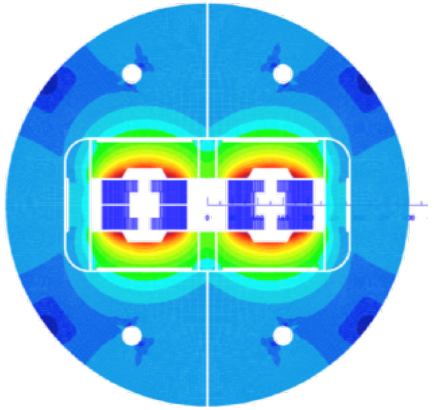
Courtesy D. Tommasini

Cos-Theta Coil (2018-2022)



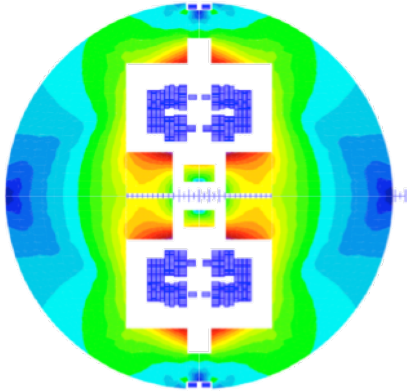
S. Farinon, P. Fabbricatore (INFN)

Block Coil (2017-2021)



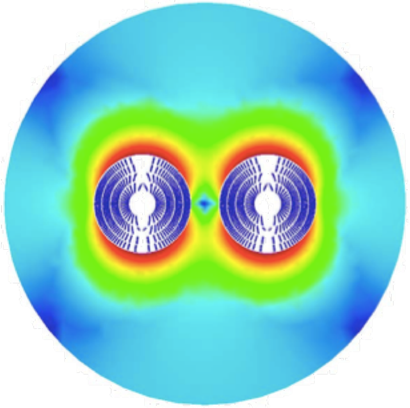
M. Durante, C. Lorin (CEA)

Common Coils (2018-2022)

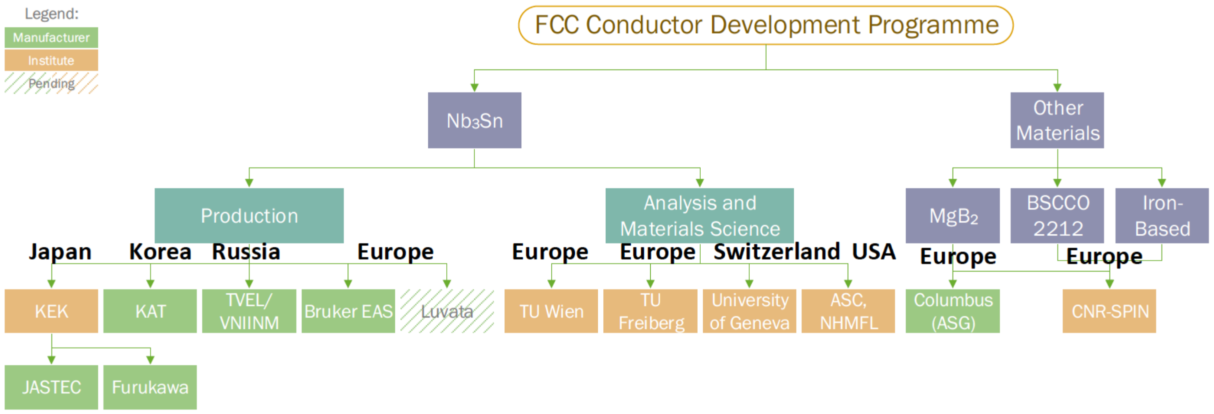


F. Toral (CIEMAT)

CCT (2016-2019)



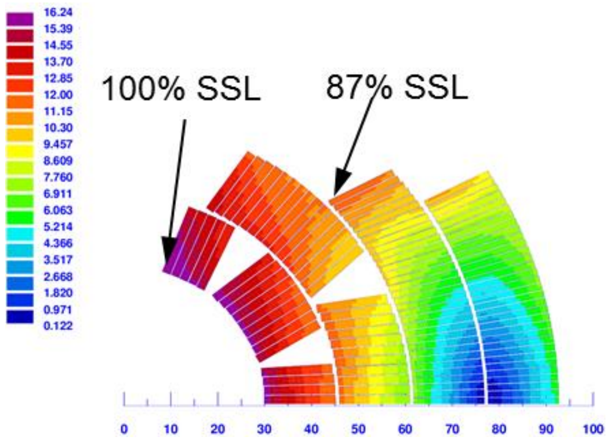
S. Sanfilippo (PSI)
B. Auchmann (CERN)



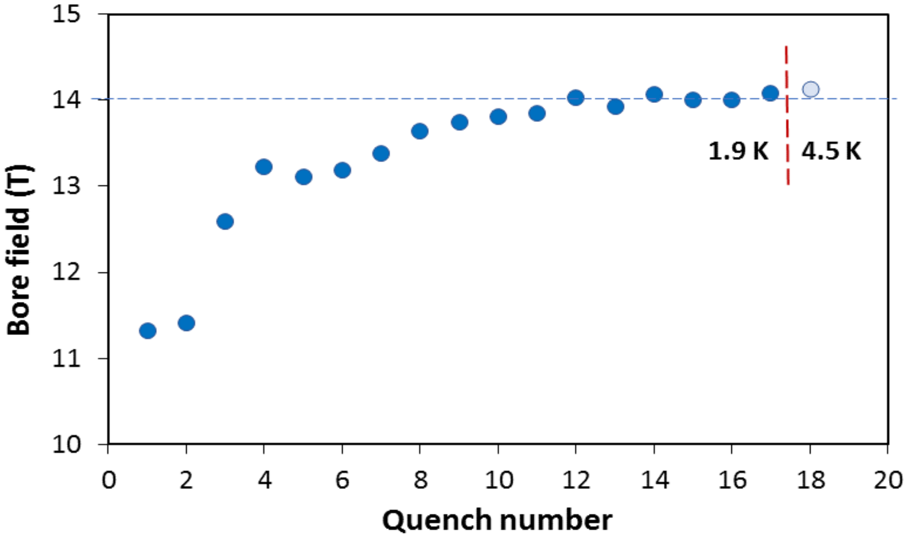
- CERN has launched a **word-wide effort** to increase the performance of state of the art Nb_3Sn conductor

Courtesy A. Ballarino

Status of the US-MDP 15 T Dipole Demonstrator



U.S. MAGNET DEVELOPMENT PROGRAM



Magnet conductor limit for the wire J_c(12T,4.2K)~2.65 kA/mm^2

- **B_{ap}=15.3T @4.5K**
- **B_{ap}=16.7T @1.9K**

60 mm aperture dipole magnet
4-layer graded coils based on RRP Wires
Outer Diameter cold mass < 610 mm

- A 1-m long 15 T dipole model has been developed, fabricated and first tested at Fermilab (June 2019)
- The magnet reached B_{max}=14.1 T at 1.9 K and 4.5 K - extremely encouraging results!

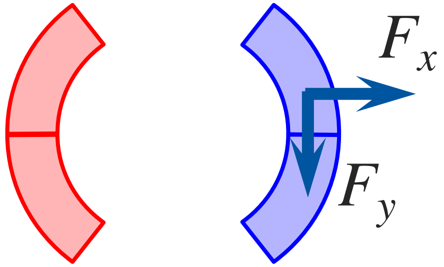
Courtesy of S. Zlobin

Challenges

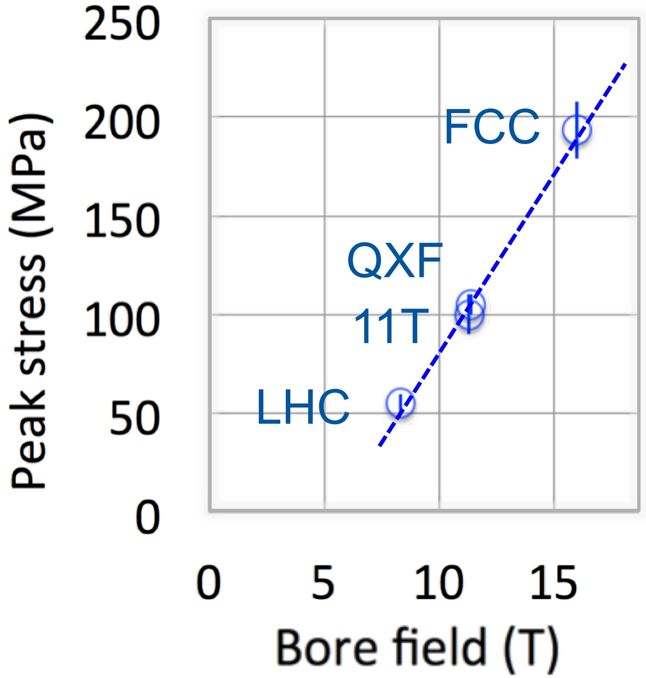
Mechanics & Stress (and Strain)

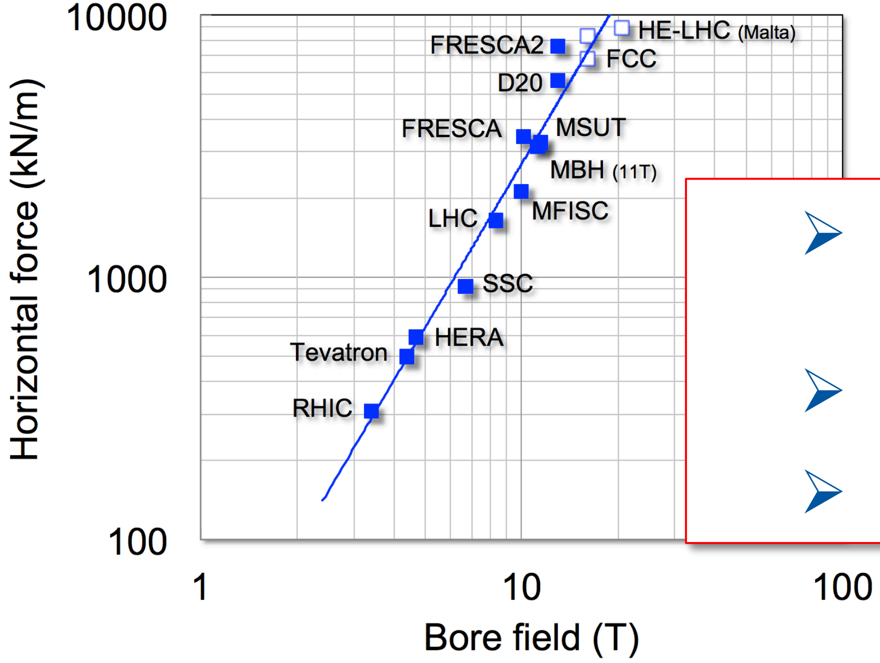
Lorentz forces in the plane of a thin coil of radius R_{in} generating a dipole field B (thin shell approximation), referred to a coil quarter

$$F_x = -F_y \propto B^2$$



$$\sigma \propto J_e B$$





Progression of F_x:

- ➢ Devise an appropriate support concepts for the coil (bladder-and-key, stress management, canted-cosinus-theta, …)
- ➢ Cope with increasing stress on the conductor
- ➢ Limit mechanical energy release (training)

Courtesy L. Bottura

Challenges

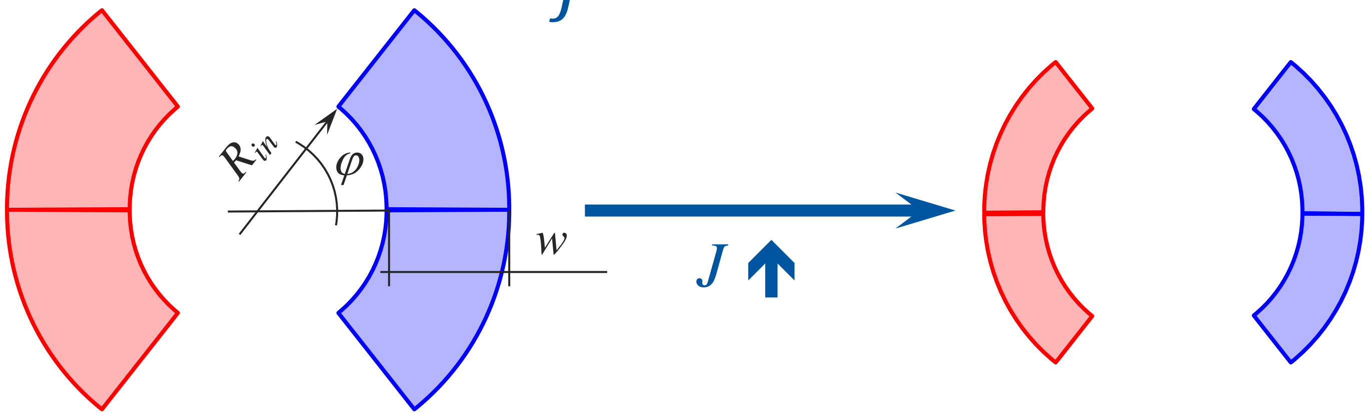
Increase J_c to Reduce magnet costs

Breakthroughs in Nb_3Sn Wire R&D

Dipole field generated by a current distribution with constant current density J over a sector of inner radius R_{in}, outer radius R_{out}, coil width w = R_{out}-R_{in} and opening angle φ

$$w \propto \frac{1}{J} \qquad A_{Coil} \propto \frac{1}{J^n} \qquad n \approx 1\ldots2$$

In the range of typical magnet designs considered n≈1.5

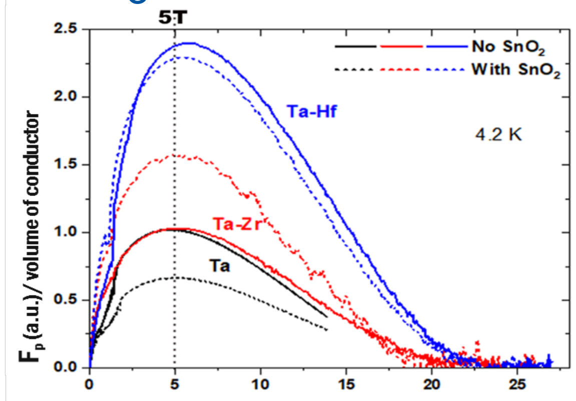


$$A_{Coil} \propto M_{Coil} \propto COST$$

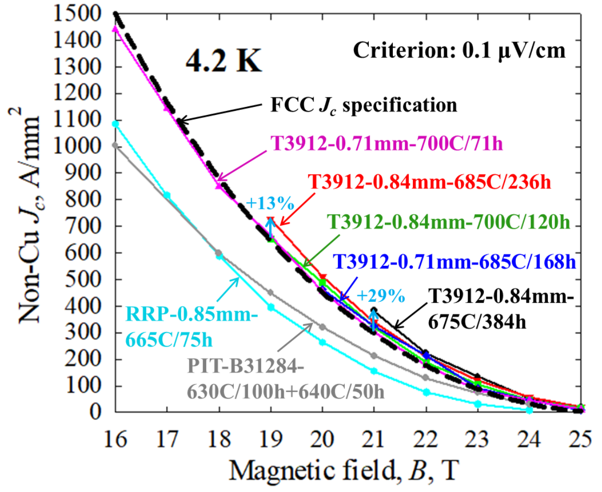
B (T)	16	
J (A/mm²)	300	600
w (mm)	76	38
A_{coil} (mm²)	20,000	7000

Factor 2

Factor 3



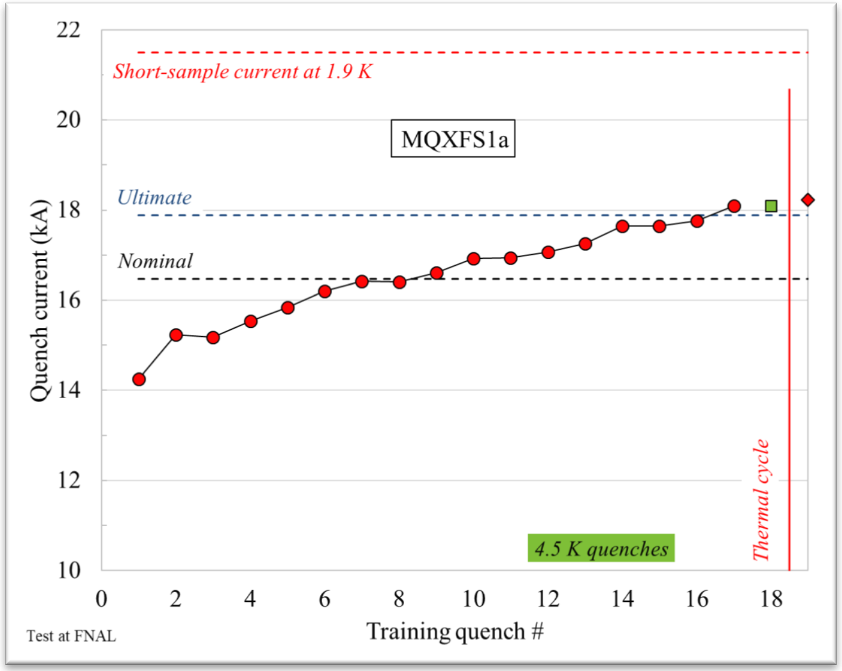
(Courtesy of S. Balachandran, NHMFL-ASC)

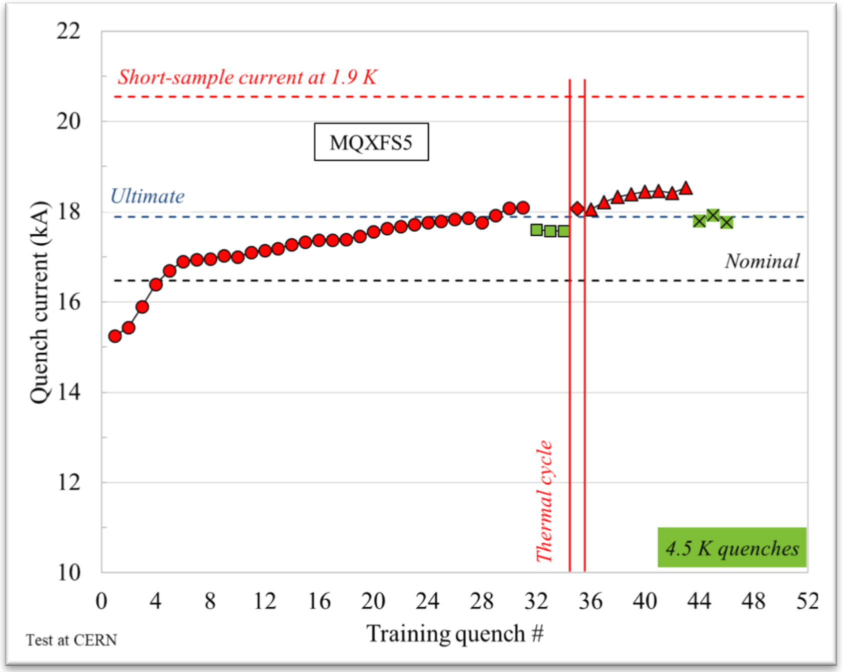


(Courtesy of X. Chu, Fermilab)

Challenges

Efficient Use of J_c – Training & Margin





Training of MQXFS models (at 1.9 K – red markers) – Courtesy of P. Ferracin and H. Bajas

- **Limit training**

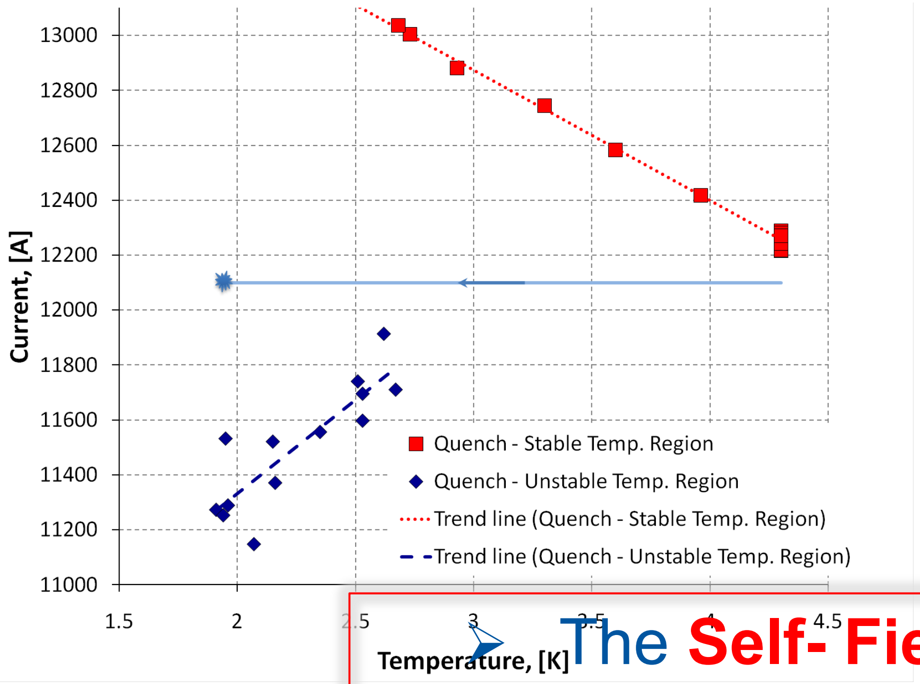
- **Increase** the **ratio** between the **operational** current **density** and the **conductor** J_c (presently at ≈ 40 % for Nb_3Sn at 1.9 K)

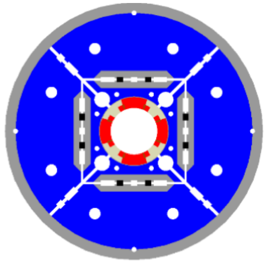
Challenges

Efficient Use of J_c - Stability

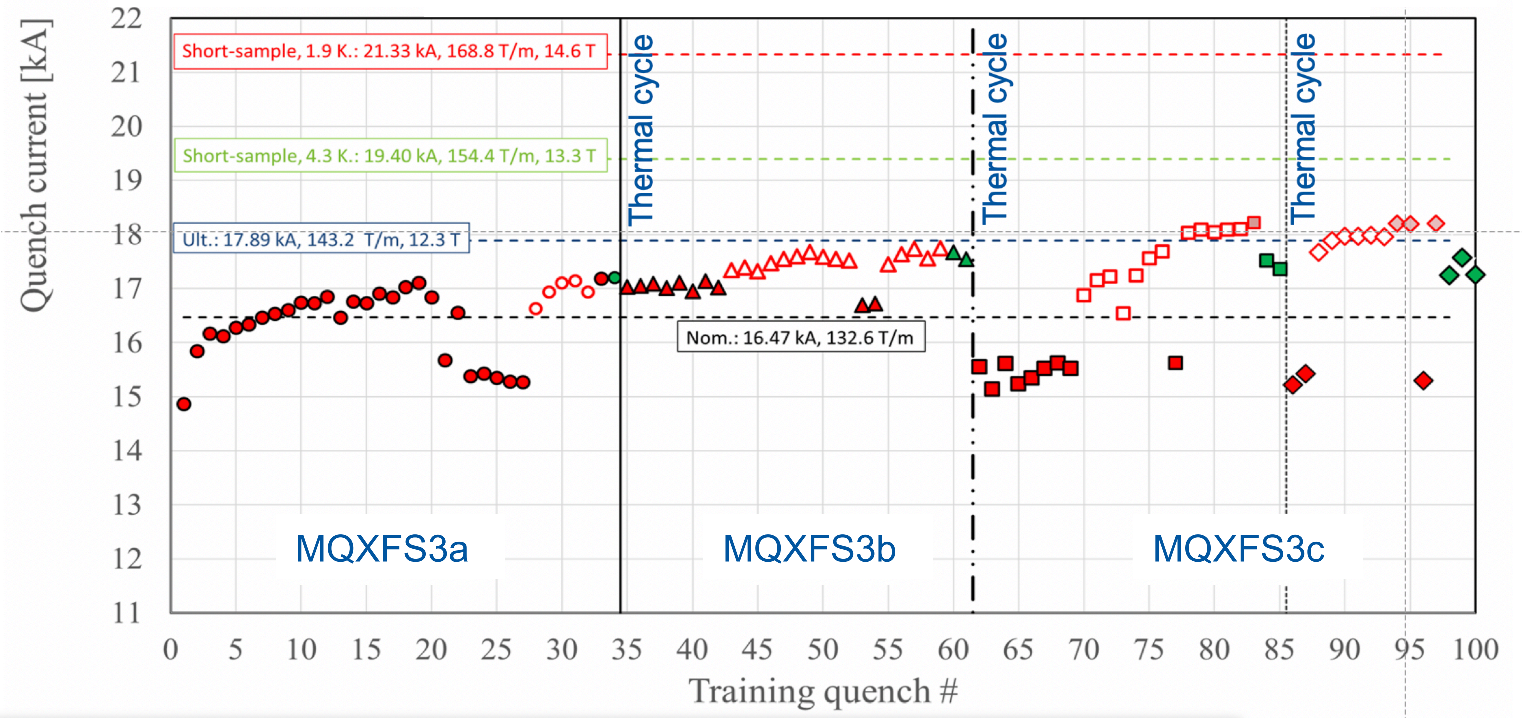
- Because of the self-field instability, the quench current at **1.9 K** can be lower than that one at **4.3 K**

Test at CERN of LARP TQS02C (90 mm bore), the grand-father of the MQXF quadrupole
Quench Current vs Temperature





Quench History of the MQXFS3 model (Courtesy of H. Bajas)
Full marks represent quench currents at the nominal, slow ramp-rate: red 1.9 K, green 4.5 K → **Quench current lower at 1.9 K**



- The **Self- Field stability** has to be properly **guaranteed**

Challenges

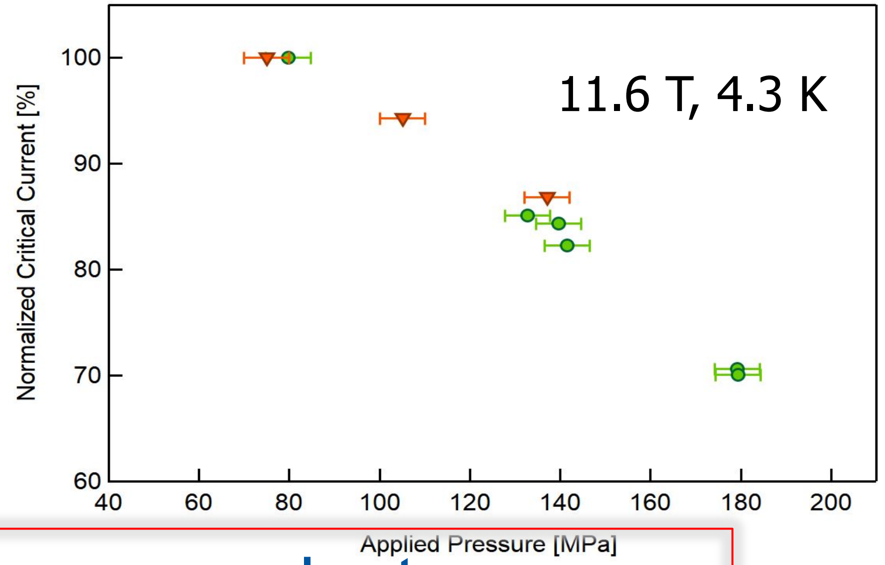
Efficient Use of J_c – Transverse Loads and J_c 1/2

- The critical current I_c of Nb_3Sn Rutherford cable is significantly affected by the transverse load applied on the cable

- **Up to** about **180 MPa** (depending on the wire layout) the I_c reduction is driven by the reduction of the upper critical field B_{c2} and it is **mainly reversible**

- **Above** about **180 MPa** (depending on the wire layout) **cracks** starts to occur in the Nb_3Sn

Effect of the strain, induced by a transverse load, on 18 strands Rutherford cables based: on 1 mm PIT (circle) and 1 mm RRP (triangles) wires*



- make sure that **no cracks** occur in the superconductor
- take in to account the **effect of strain** on the **critical current**

* From Bordini, De Marzi – tomorrow Wed-Af-Or14-06.

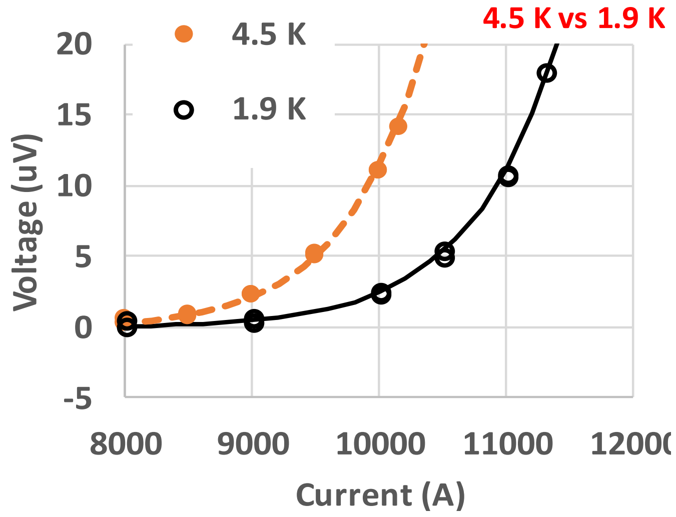
Challenges

Efficient Use of J_c – Transverse Loads and J_c 2/2

- The **understanding** of the transverse **load effects** on the Nb_3Sn J_c and the **handling** of these **loads** have greatly contributed to the **success** of the **11 T HL-LHC dipole**

- Because of large transverse loads, several 11 T magnet models were limited in the dipole mid-plane where a **critical current** much lower than the expected short sample limit was **reached**

Reversible transition measured in the mid-plane of a 11 T Dipole model
Courtesy of G. Willering



- To overcame this problem, a **special attention** was put in
  - guaranteeing a very **accurate precision** in the **coil dimensions** (to prevent stress concentrations);
  - **precisely controlling** the **collaring** forces;
  - **minimizing** the coils **precompression**.

Conclusions

- **High** Magnetic **Fields** (>10 T) are **essential** in accelerator magnets to **contain** the considerable **costs** of next generation **hadron colliders**

- The **Nb_3Sn technology**, although complex, is **mature** for building high field accelerator magnets
  - Thanks to the last **20 years** of **R&D** many difficulties have been overcome and all the **major challenges** have been **identified** (in particular transverse load effects and conductor stability)
  - In the framework of the **HL-LHC** project CERN and US HL-LHC AUP are manufacturing **~ 11 T** Nb_3Sn **accelerator magnets** that will be all installed in the LHC between 2020 and 2024

- We are now **ready** to develop **next generation** high field Nb_3Sn **accelerator magnets**

Thank you for your attention