Superconducting magnet fabrication and testing

based on LHC and HL-LHC magnet production

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The CERN Accelerator School

Main references

- L. Rossi, “Superconducting Magnets”, CERN Academic Training, 15-18 May 2000.
- L. Rossi, “ Manufacturing and Testing based on LHC SC magnet production”,CAS, Erice 2013 https://cas.web.cern.ch/schools/erice-2013
- USPAS - Superconducting Magnets for Particle Accelerators https://indico.cern.ch/event/440690/
- E. Todesco, “Masterclass – Design of superconducting magnets for particle accelerators” https://indico.cern.ch/category/12408/
- M. Bajko, “Test of large magnets”, EASISchool 3 (2020)
- TIDM^2 x SC magnets (Test, Instrumentation, Diagnostics and Measurement Methods for SC Magnets) https://indico.cern.ch/event/1281454

Outline

- Part I: Magnet fabrication
  - Introduction
  - Strand and cable
  - Coil fabrication
  - Assembly
  - Industrialization
- Part II: Magnet test
  - Why do we test?
  - What do we test?
  - How do we test?
- Conclusions

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- Part I: Magnet fabrication
  - **Introduction**
  - Strand and cable
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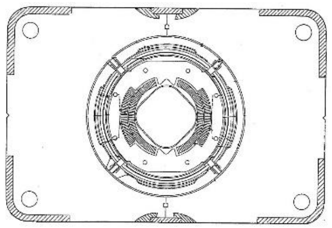
The early days of acc. superconducting magnets

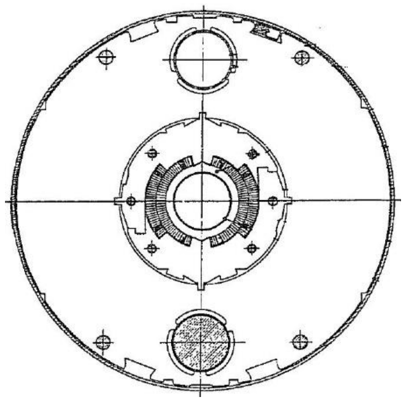
- In 1911, Kammerling-Onnes, discovered superconductivity (ZERO resistance of mercury wire at 4.2 K)
- For 40-50 years, only “Type I” superconductors were known → as soon as Type II superconductors became available (first NbZr and Nb_3Sn, then NbTi which rapidly became the option of preference) researchers and engineers tried to make magnets for proton accelerators (see W. S Gilbert, 1973)
- At the end of the 70s, the first superconducting magnet was installed in an accelerator:
  - Large aperture 1-m-long quadrupoles, about 5 T peak field, placed in the low-β insertion region of the Intercepting Storage Rings (ISR) at CERN (the grandfather of the LHC) [1]
  - 8 units in total, the first SC magnet series industrially manufactured for accelerators!
- Despite the success of the ISR quadrupoles, CERN focused on the development of the resistive Super Proton Synchrotron (SPS) and the Large Electron-Positron Collider (LEP) in the 80s and 90s. The US took the relay for the development of superconducting accelerator magnets with two new large projects:
  - Isabelle, at BNL, a 3.8 km ring based of 4 T dipoles (project was cancelled in 1983) [2]
  - Tevatron, at FNAL, 2 TeV collider in a 6.9 km ring with 4.3 T dipoles. The first large superconducting machine in history! [3]

The ISR quadrupoles, R. Perin et al.

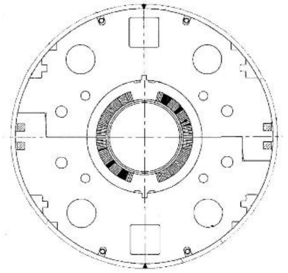
Superconducting dipoles (in accelerators)



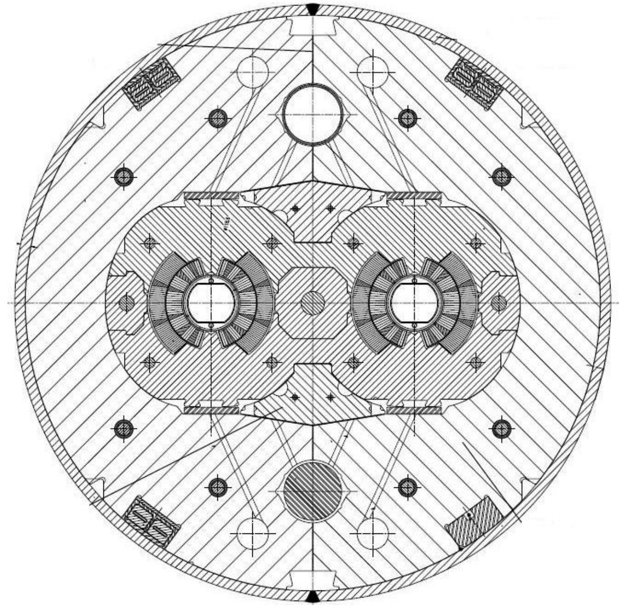
Tevatron
1983-2011
Bore: 76 mm
Field: 4.3 T, NbTi
$J = 375\ A/mm^2$
$F_x = 0.5\ MN/m$
$F_z = 78\ kN$



HERA
1991-2007
Bore: 75 mm
Field: 5.0 T, NbTi
$J = 296\ A/mm^2$
$F_x = 0.6\ MN/m$
$F_z = 87\ kN$



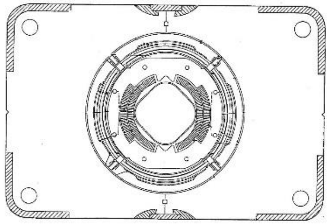
RHIC
2000-running
Bore: 80 mm
Field: 3.5 T, NbTi
$J = 375\ A/mm^2$
$F_x = 0.3\ MN/m$
$F_z = 48\ kN$



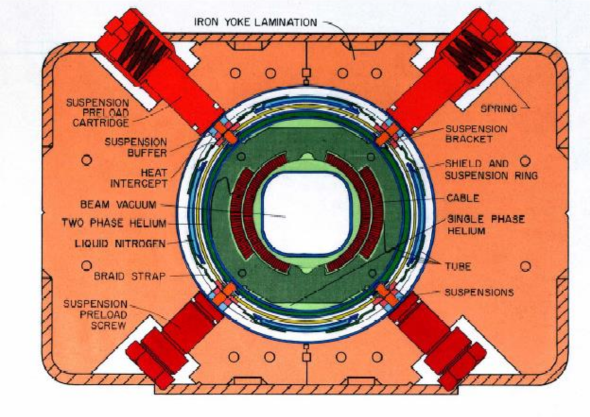
LHC
2008-running
Bore: 56 mm
Field: 8.3 T, NbTi
$J = 349/430\ A/mm^2$
$F_x = 1.7\ MN/m$
$F_z = 265\ kN$

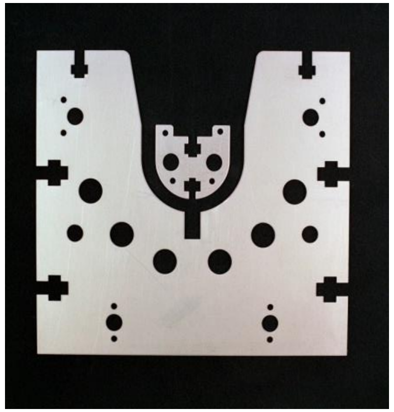
J overall (sc + cu + ins)/F_x per quadrant/F_z per aperture

Tevatron (FNAL)



- 774 x 4.3 T dipoles, 76 mm aperture, 6 m long.
- All in house, R&D, tooling, prototyping, series, construction and testing





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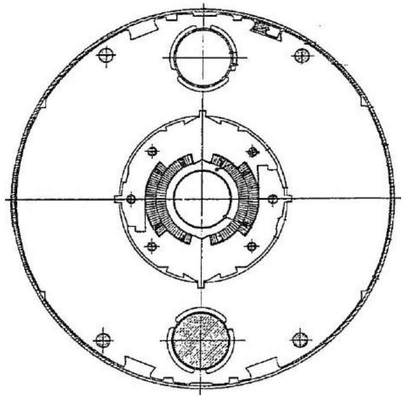
F_x per quadrant/F_z per aperture

HERA (Desy)



- 416 x 5.1 T dipoles, 75 mm aperture, 8.8 m long.
  - Cold iron collared coil (self-supporting aluminium collars)
  - The He containment is provided by two half shells welded together. The welding process provides also the sagitta (17 mm over 9 m length).
- Designed and short prototypes in the laboratory, manufactured all by industry, opening the way for RHIC and LHC

HERA
1991-2007
Bore: 75 mm
Field: 5.0 T, NbTi
$J = 296\ A/mm^2$
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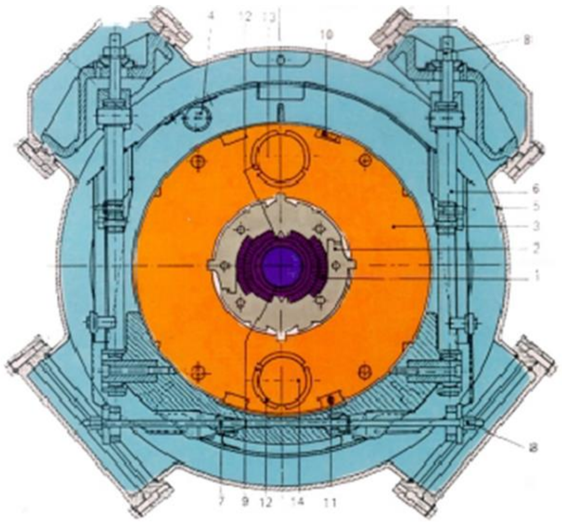
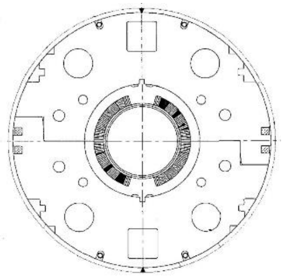
F_x per quadrant/F_z per aperture



HERA

RHIC (BNL)



- 264 x 3.5 T dipoles, 80 mm aperture, 9.5 m long, low cost was a challenge!
  - The coil is surrounded by glass-filled phenolic insulators that provide the alignment, insulation to ground and separation of the coils from the iron to reduce saturation effects.
  - The iron yoke clamps the coil-insulator structure like a collar.
  - Stainless steel shell halves are welded around the yoke to provide He containment, a 48.5 mm sagitta, and to increase rigidity.
- Industry as assembler, saving money by keeping responsibility

RHIC
2000-running
Bore: 80 mm
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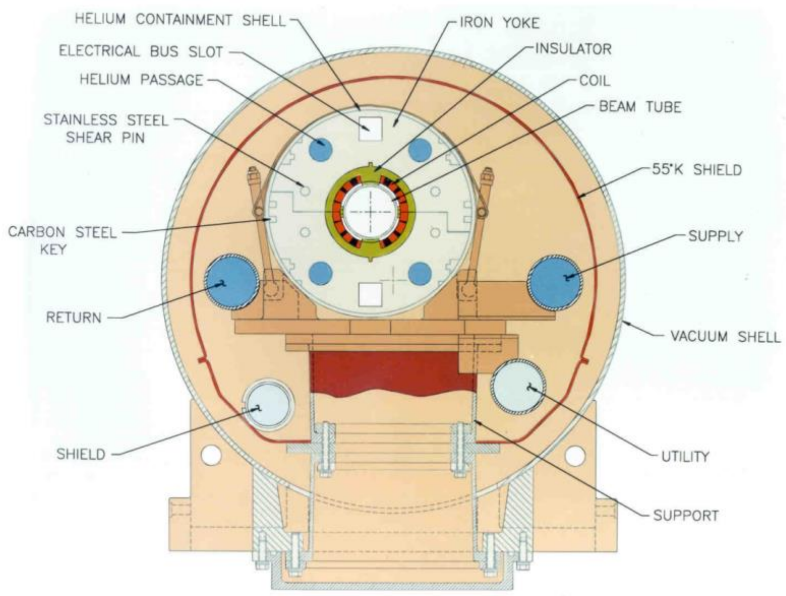
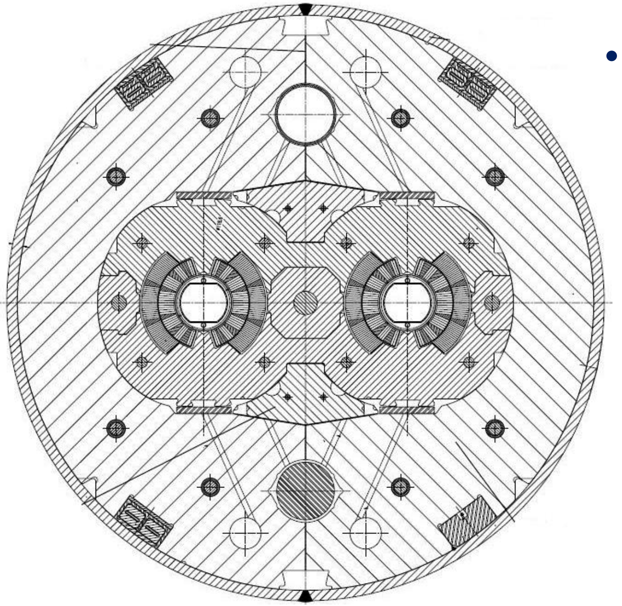
F_x per quadrant/F_z per aperture



LHC MB (CERN)

By L. Rossi

- 27 km machine, 1248 x 8.3 T MB dipoles built, 14.5 m length.
- R&D started in industry. CERN lab for 1 m operative 1991. CERN magnet facility competed only in 2013!



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First ideas Twin Dipoles Hell cooling

R&D for 8-10 T: 13 kA cables, short models, 10 m long prototypes, 1st string test

Final design, industrialization start pre-series

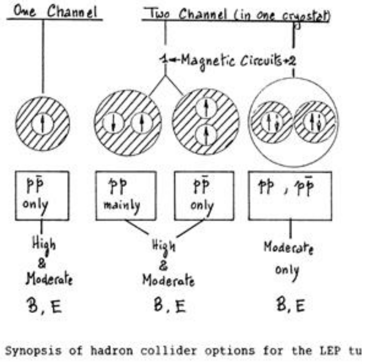
Magnet construction, performance test, tunnel preparation

Installation, LHC start Incident

Re-start 4.2 T

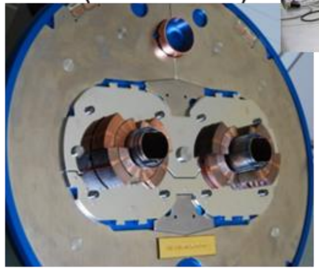
1985 — 1990 — 1995 — 2000 — 2005 — 2010 — 8 T

Magnet designs at first LHC workshop, 1984

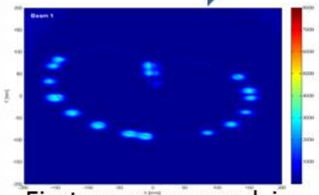


First LHC dipole prototype on the test bench (June1994)

Final dipole cross section (frozen 1999)



Assembly of 15 m long coils in industry, 2003

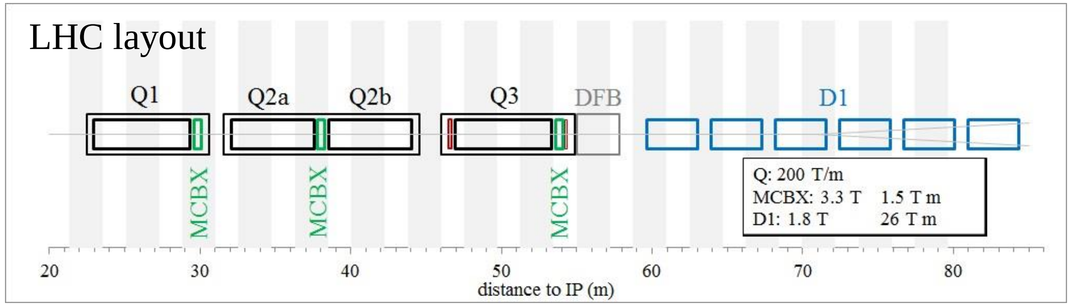


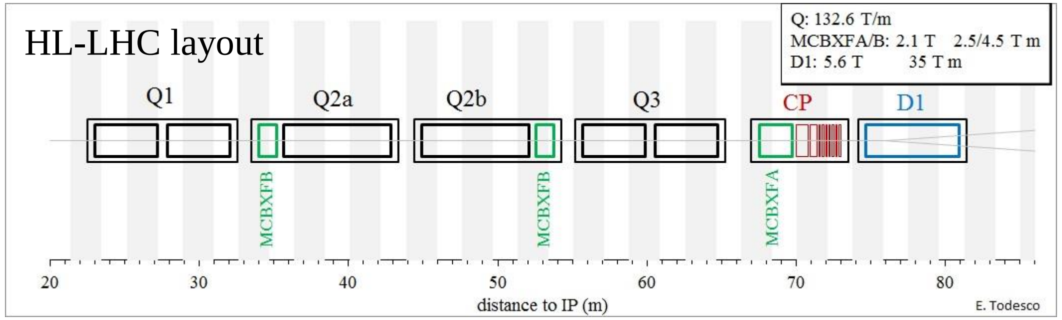
First energy record in the proton beam, December 2009

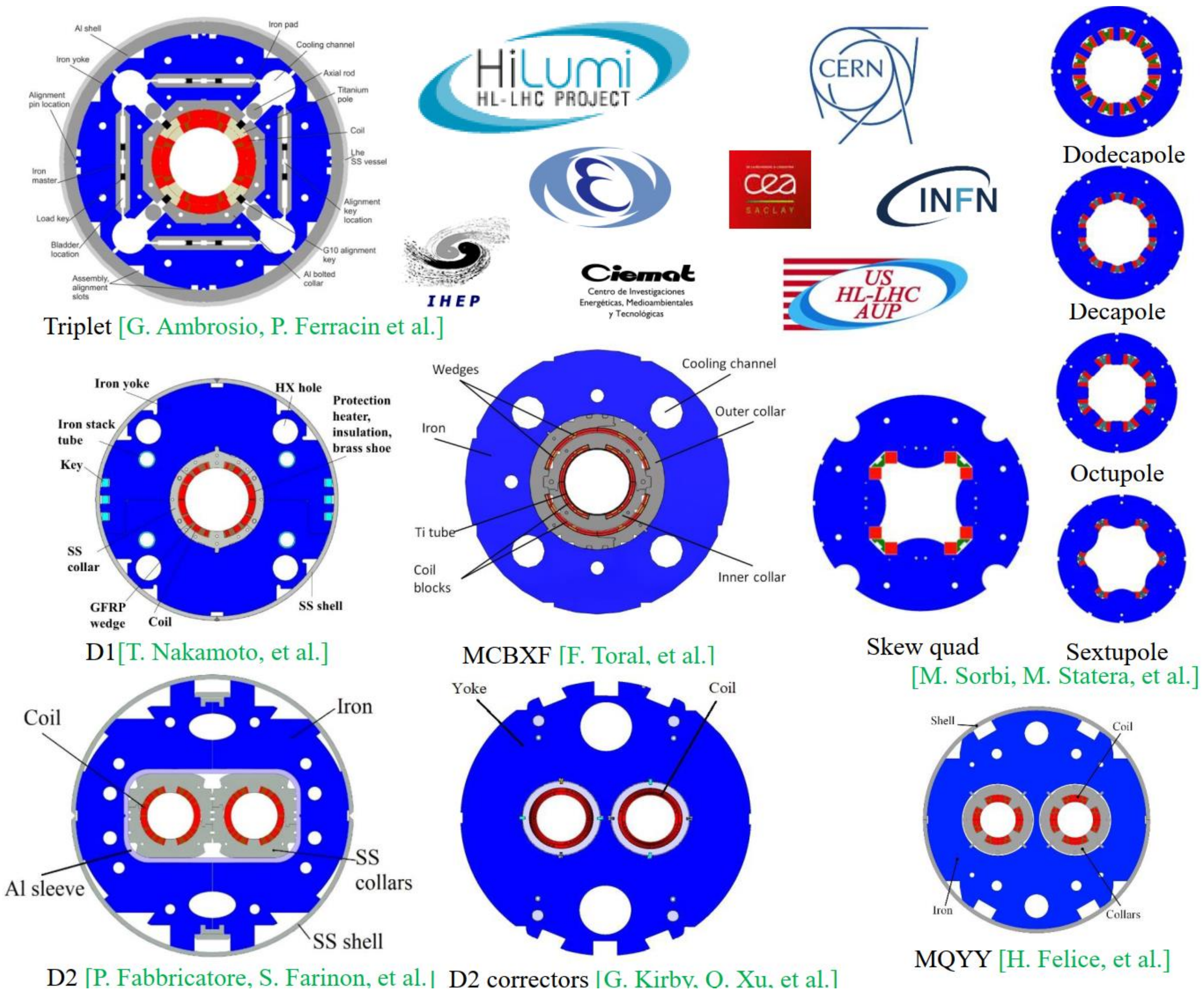
Continuous magnet line installed in the 27 km LHC tunnel, 2006

HL-LHC (CERN)

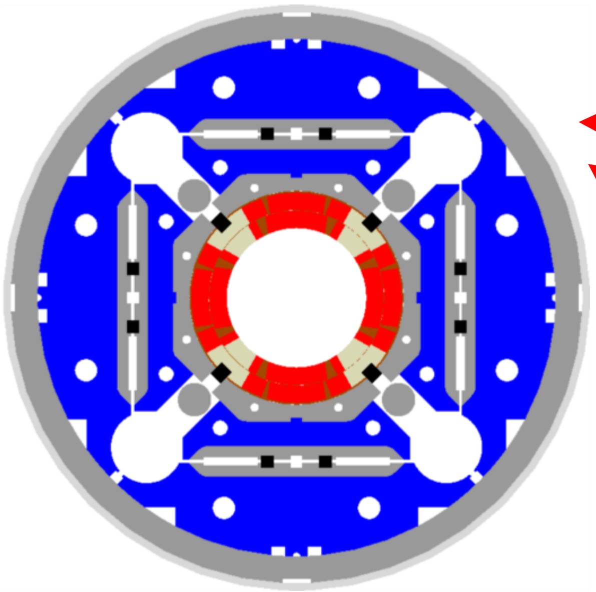
- ≈ 300 m of new magnets under construction, to replace the existing ones around ATLAS and CMS
- A large variety of (fun) magnets
- Challenge associated with the production of the first Nb_3Sn accelerator-ready magnets

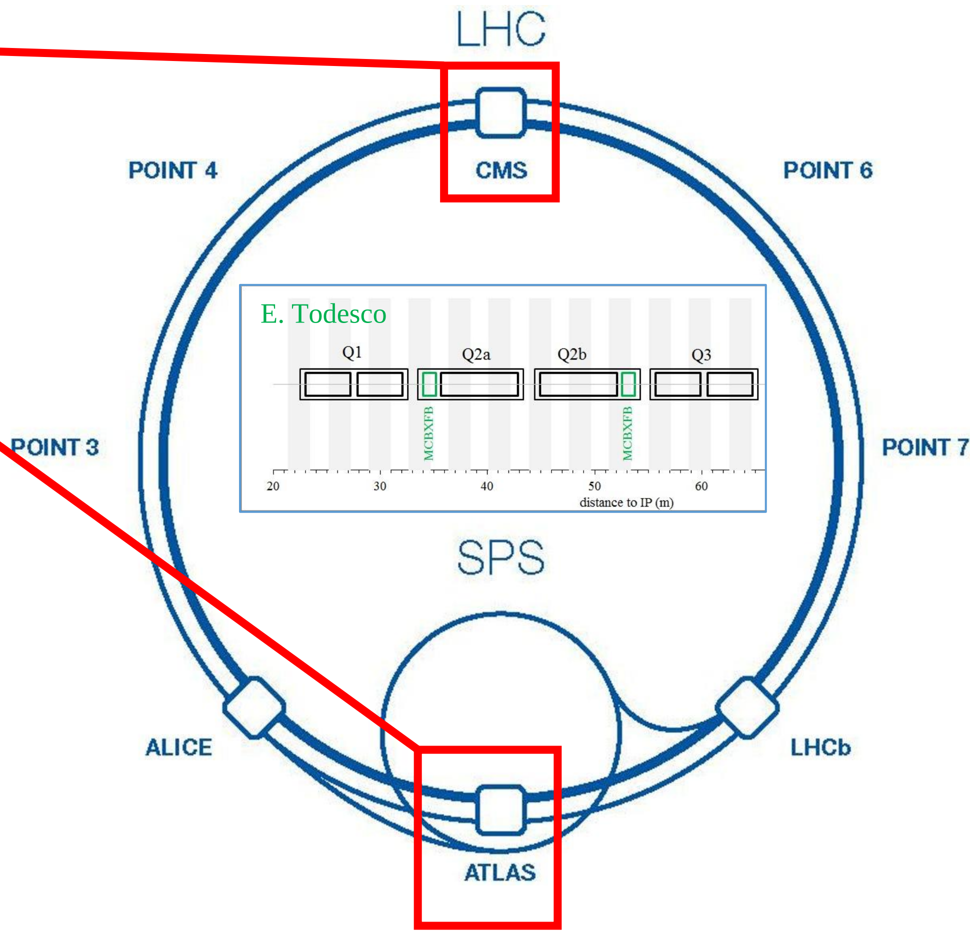






MQXF: the HL-LHC Nb_3Sn magnet



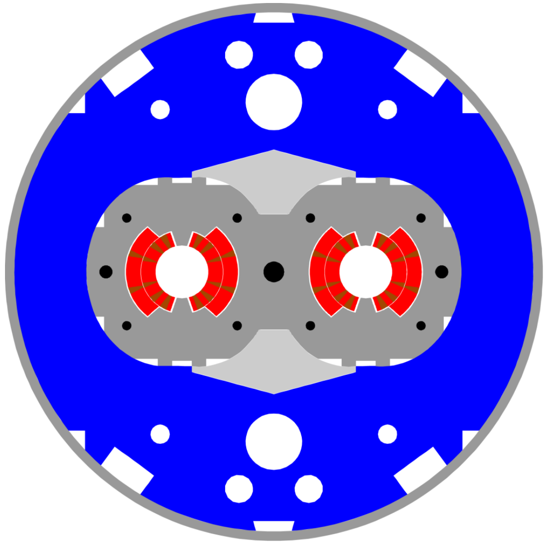


30 large aperture and more powerful quadrupoles around ATLAS and CMS to decrease the beam size and increase the integrated luminosity by a factor 10

Construction of pre-series and series magnets on-going, joint effort between CERN and US-AUP

Objective of the lecture

Provide an overview of the manufacturing steps of a superconducting accelerator magnet (from the strand to the cryostat) using the LHC-MB dipoles and HL-LHC quadrupoles as examples.



LHC MB

NbTi, B_p = 8.6 T

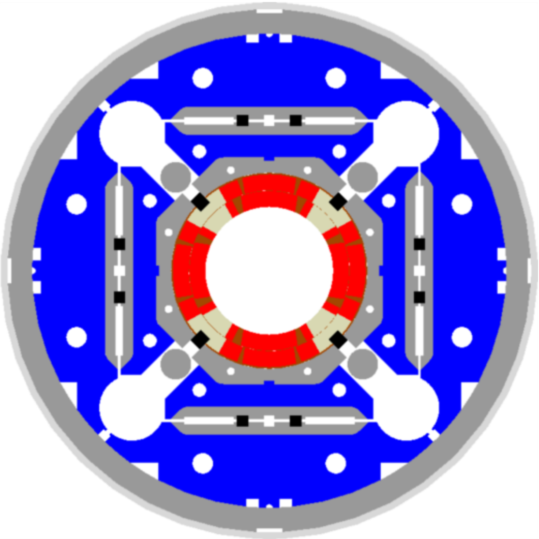
Eq. coil width: 27 mm

$J_{overall}(I_{nom})$ = 356/442 A/mm^2 ;$J_{cu}(I_{nom})$ = 763/932 A/mm^2

e_m (I_{nom}) = 71 J/cm^2

F_x = 3.4 MN/m; $\sigma_{\theta,em}$ = 50-60 MPa

F_z = 265 kN



HL-LHC MQXF

Nb_3Sn, B_p = 11.3 T

Eq. coil width: 36 mm

$J_{overall}(I_{nom})$= 462 A/mm^2; $J_{cu}(I_{nom})$ = 1311 A/mm^2

e_m (I_{nom})= 120 J/cm^2

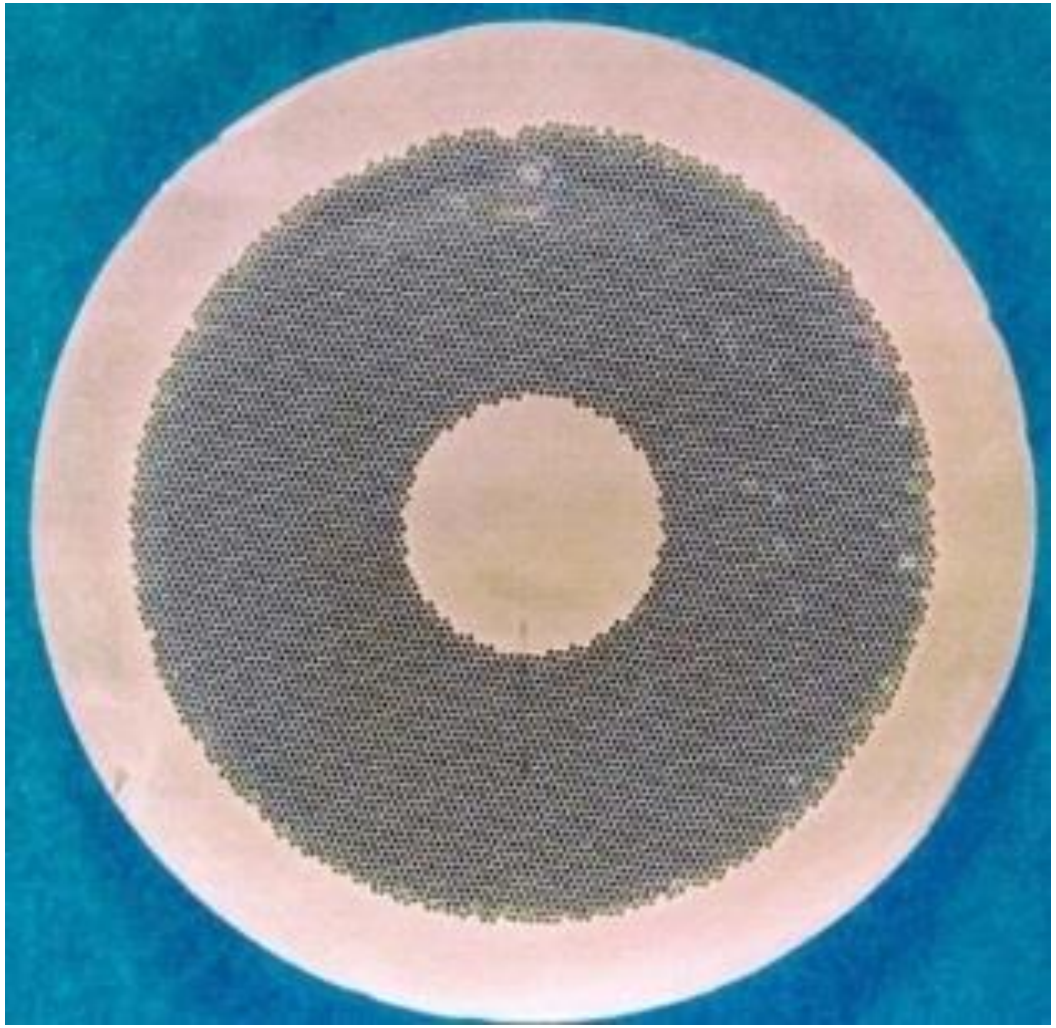
F_x = 6.8 MN/m; $\sigma_{\theta,em}$ = 100-110 MPa

F_z = 1200 kN

Outline

- Part I: Magnet fabrication
  - Introduction
  - **Strand and cable**
  - Coil fabrication
  - Assembly
  - Industrialization
- Part II: Magnet test
- Conclusions

Strand: a multifilament wire



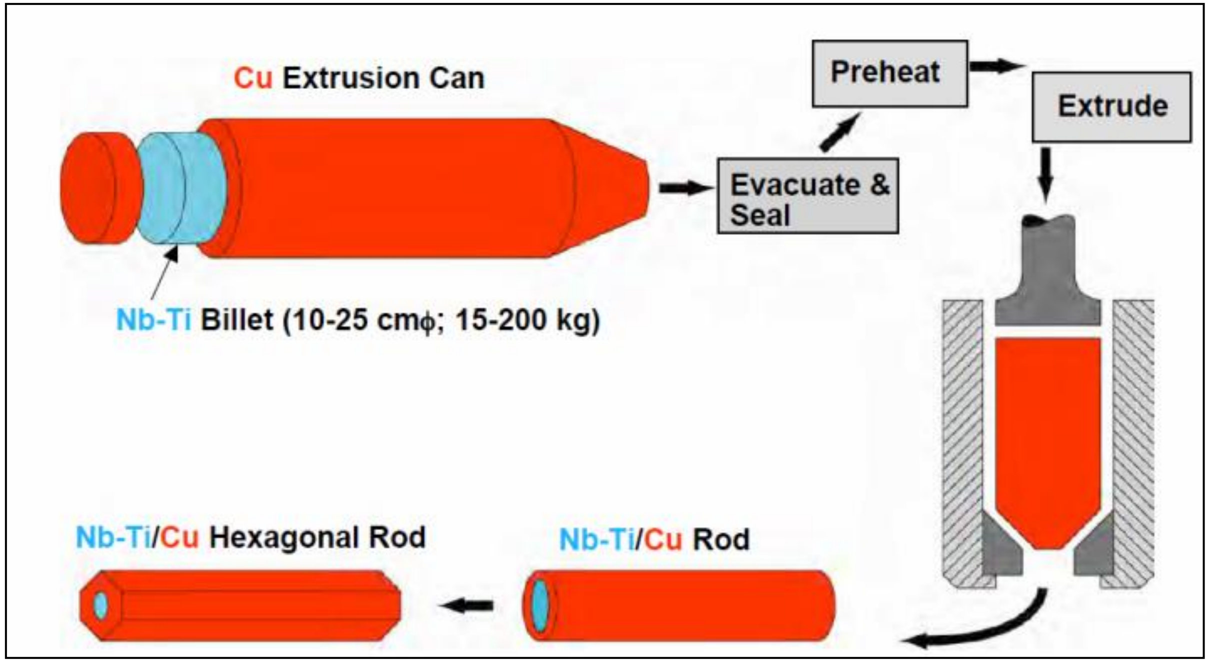
- The two practical superconductors that we have today for accelerator magnets are NbTi and Nb_3Sn
- The superconducting material is produced in small filaments and surrounded by a stabilizer (typically copper) to form a "*multi-filament wire*" o "*strand*"
- The strand is typically produced in industry

See lectures on Technical Superconductors (Michael Eisterer), Quench protection (Ezio Todesco) and Hysteresis and dynamic effects (Ezio Todesco)

Strand manufacturing process (NbTi)

See lecture
Michael Eisterer

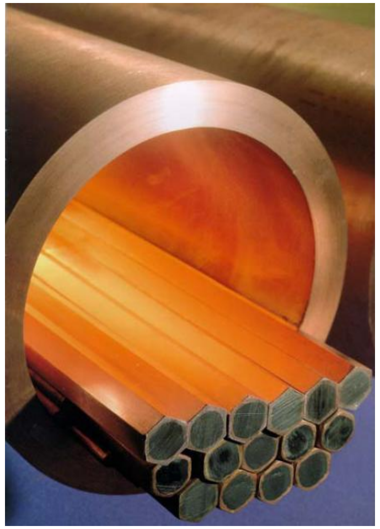
- The fabrication of Nb-Ti wire starts from the production of **Nb-Ti ingots** (with a 200 mm diameter and 750 mm height).
- A monofilament billet is assembled, extruded, and drawn down in small pieces (**monofilament rods**) about 800 mm long and 50 mm in diameter.

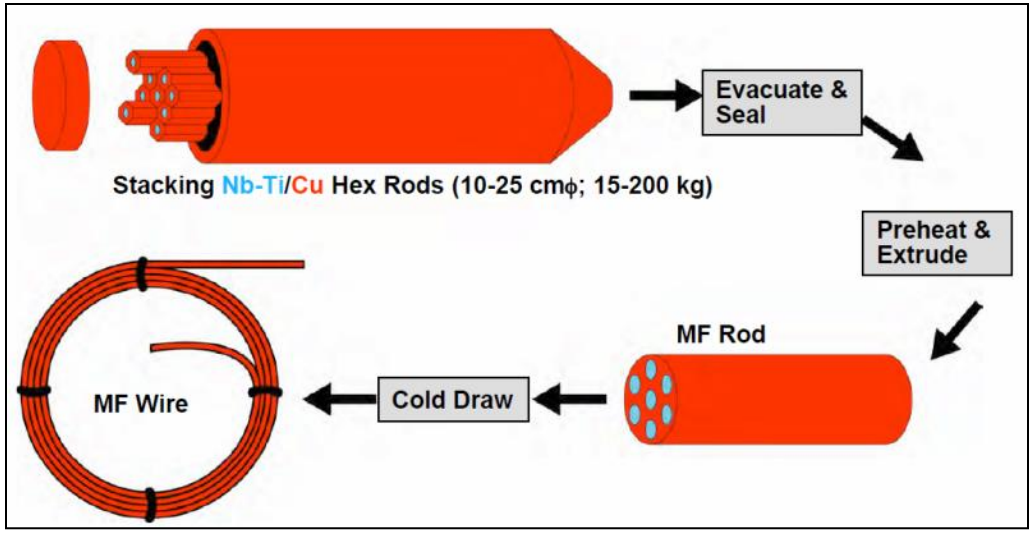


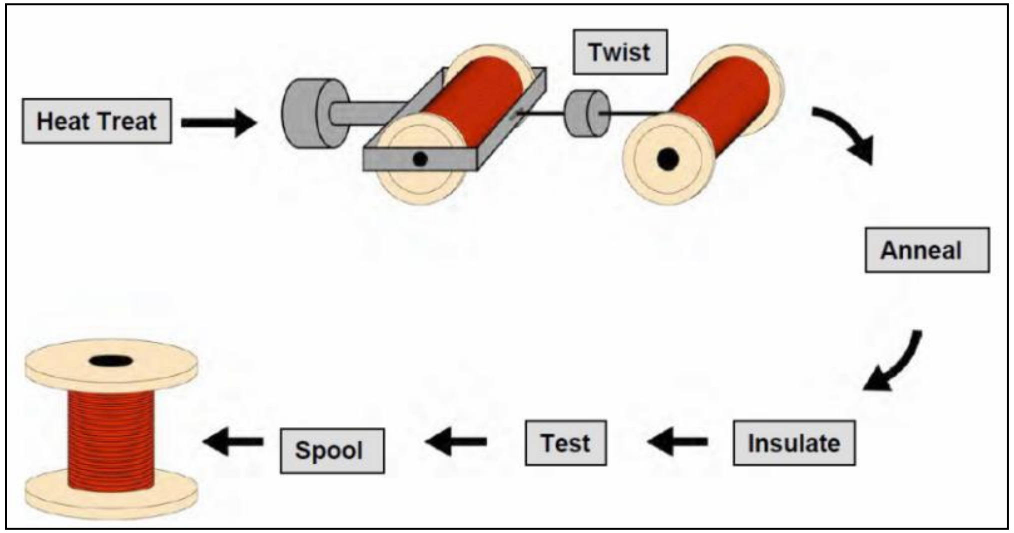
Strand manufacturing process (NbTi)

See lecture
Michael Eisterer

- Monofilament rods are stacked to form a **multifilament billet**, which is then extruded and drawn down.
- Heat treatments are applied to produce **pinning centers** (α-Ti precipitates).
- When the number of filaments is very large, multifilament rods can be **re-stacked** (double stacking process).







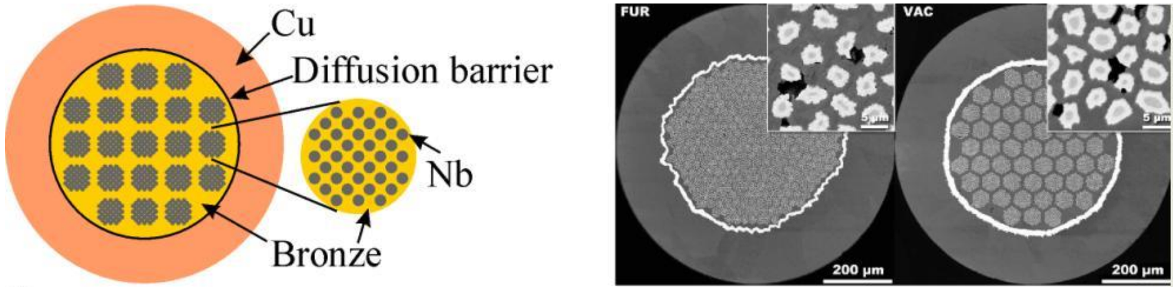
Strand: Manufacturing process (Nb_3Sn)

See lecture
Michael Eisterer

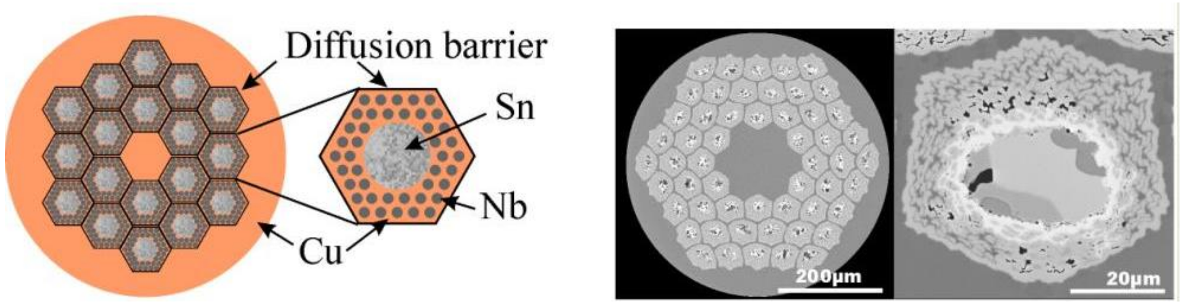
by A. Godeke

- Since Nb_3Sn is brittle
  - It cannot be extruded and drawn like Nb-Ti. It must be formed at the end of the fabrication of the cable (or the coil).
- Process in several steps
  - Fabrication of the wire, assembling multifilament billets from with **Nb and Sn separated**. Different processes tried in industrial scale (bronze process, internal tin process, powder in tube process)
  - Fabrication of the cable
  - Fabrication of the coil. Two different techniques:
    - **Wind & react”** (more common). First coil winding and then formation of Nb_3Sn
    - **“React & wind”.** First formation of Nb_3Sn and then coil winding
  - **Reaction.** Heating to about 600-700 C in vacuum or inert gas (argon) atmosphere, and the Sn diffuses in Nb and reacts to form Nb_3Sn.

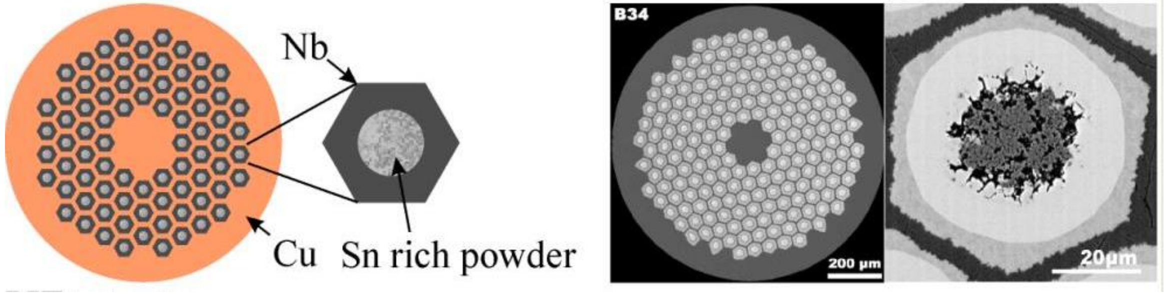
Bronze process



Internal tin process



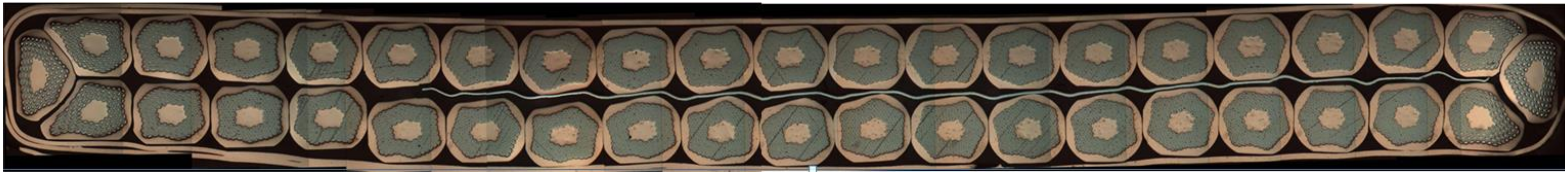
Powder in tube process



The cable

- Most of the superconducting coils for particle accelerators wound from a multi-strand cable (**Rutherford cable**). The strands are **twisted** to
  - Reduce **inter-strand coupling currents**
    - Losses and field distortions.
  - Provide more **mechanical stability**
  - **Current redistribution** (in case a defect in one strand)
  - Reduction the **number of turns** (easier winding, lower inductance)
  - Reduction strand **piece length**

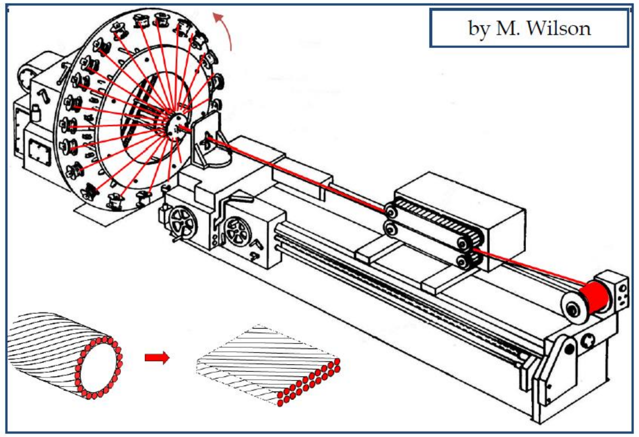
Picture by Charlie Sanabria



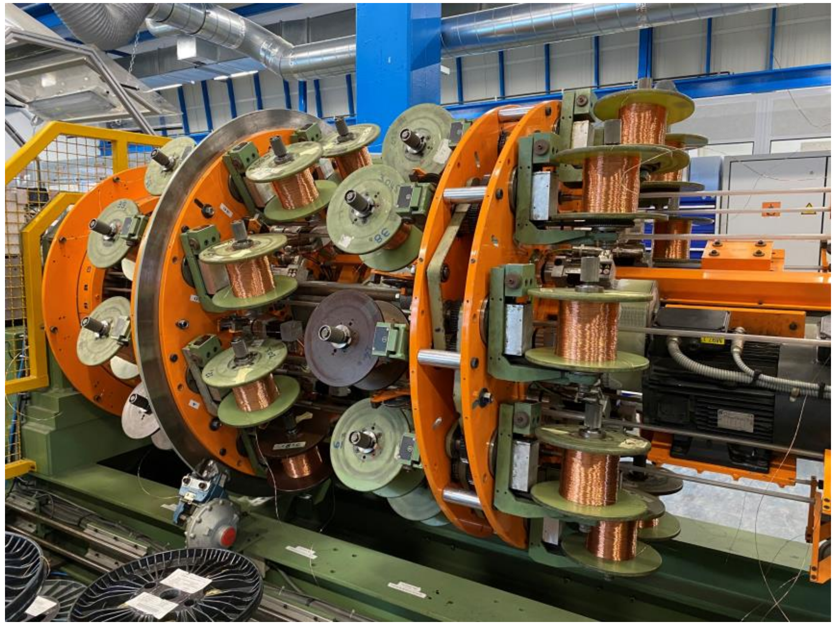
Picture by Jerome Fleiter

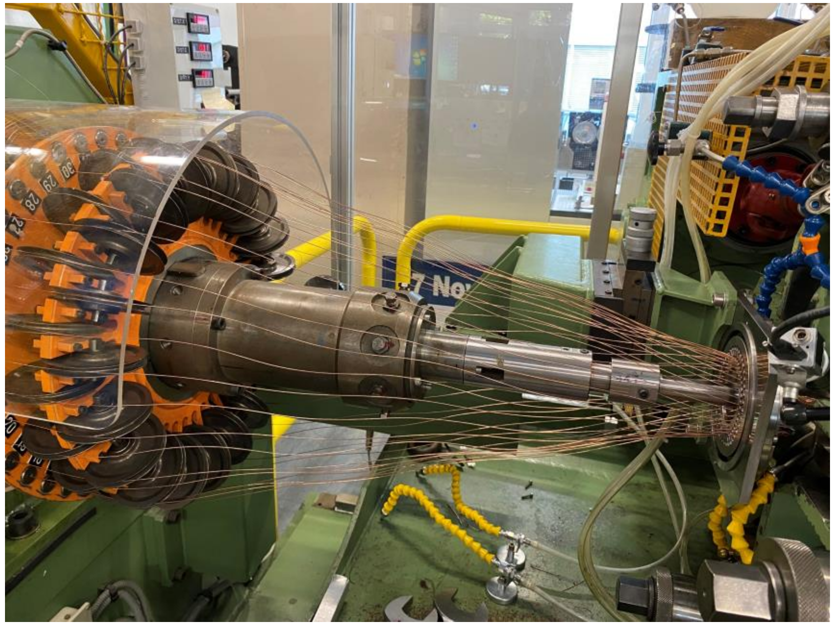
Fabrication of the Rutherford cable

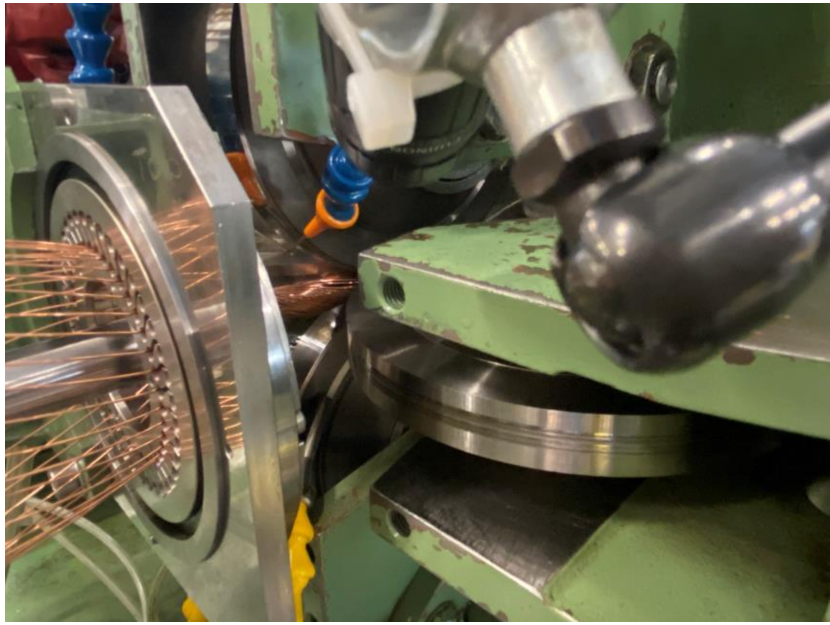
- Fabrication of the Rutherford cable:
  - Strands wound on spools mounted on a rotating drum
  - Strands twisted around a conical mandrel into rolls
  - The rolls compact the cable and provide the final shape



CERN cabling machine

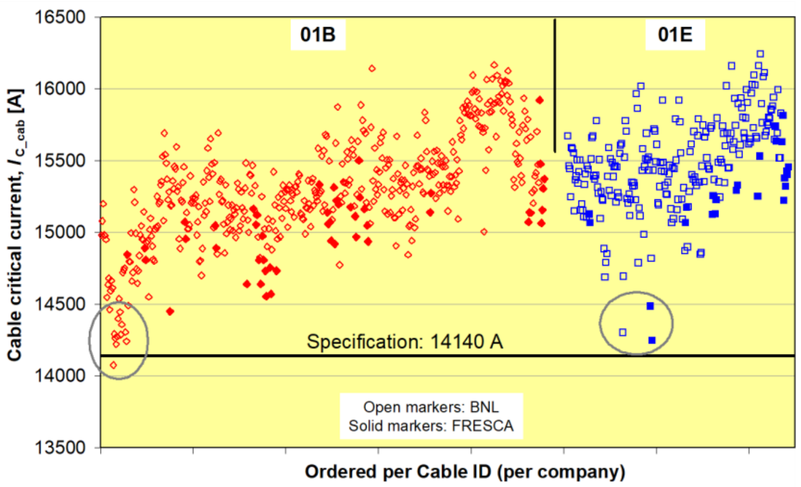


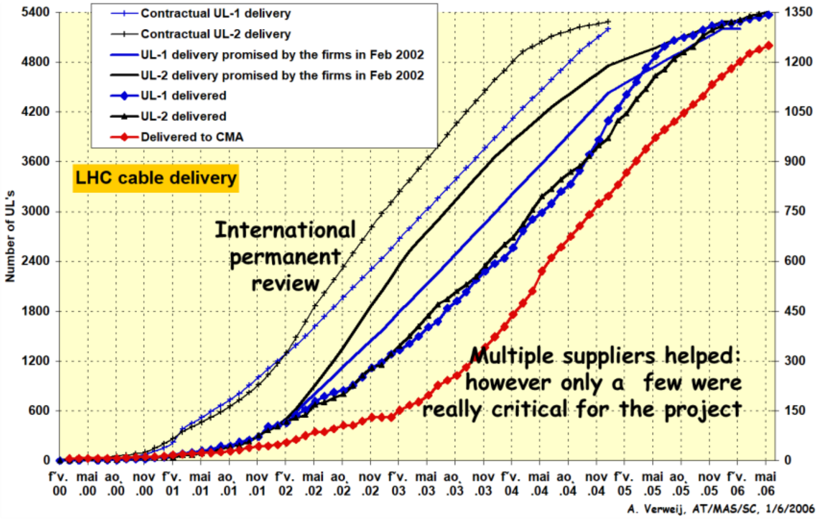




LHC NbTi strand and cable production

- 7000 km Cu/NbTi cable
- Strand and cable manufactured in industry, but stringent QA:
  - Ic measurements on thousands samples (BNL, CERN)





Number of billets approved in 2003 : 1578
Number of UL received in 2003 : 2818

Wire		Cable	
◆ Ic	462 /month	◆ Ic (BNL)	54 /month
◆ RRR	482 /month	◆ Rc	120 /month
◆ Magnetisation	137 / month		
		◆ Bend test	88 /month
◆ Bend test	311 /month	◆ Residuel Twist	83 /month
◆ Spring back	235 /month		
		◆ CMM	88 /month
◆Diameter	251 /month	◆ 10-stack	111 /month
◆ Cu/Sc	850 /month	◆ Sharp edges	93 /month
◆ Coating	454 /month		
◆ Twist pitch	175 /month		

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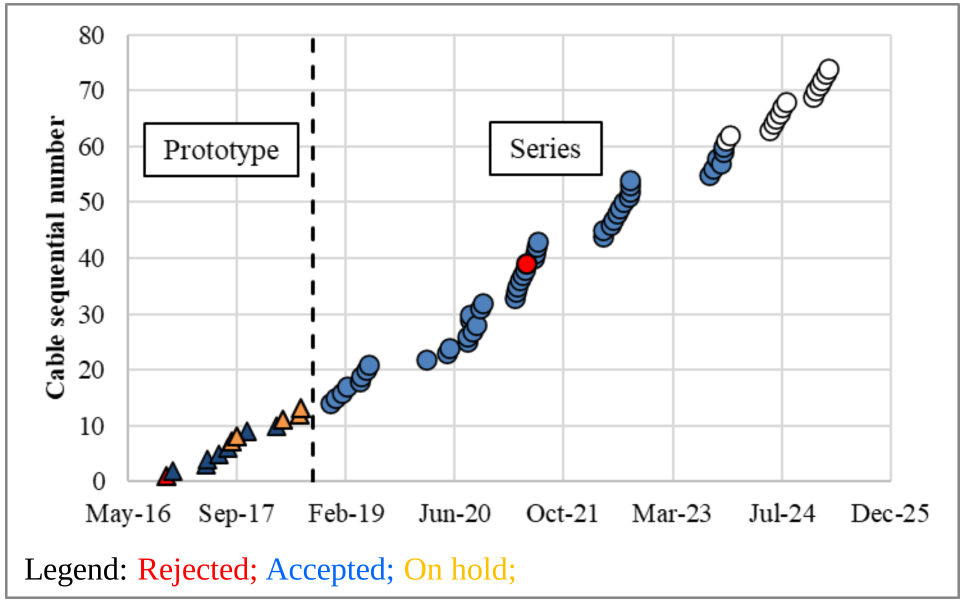
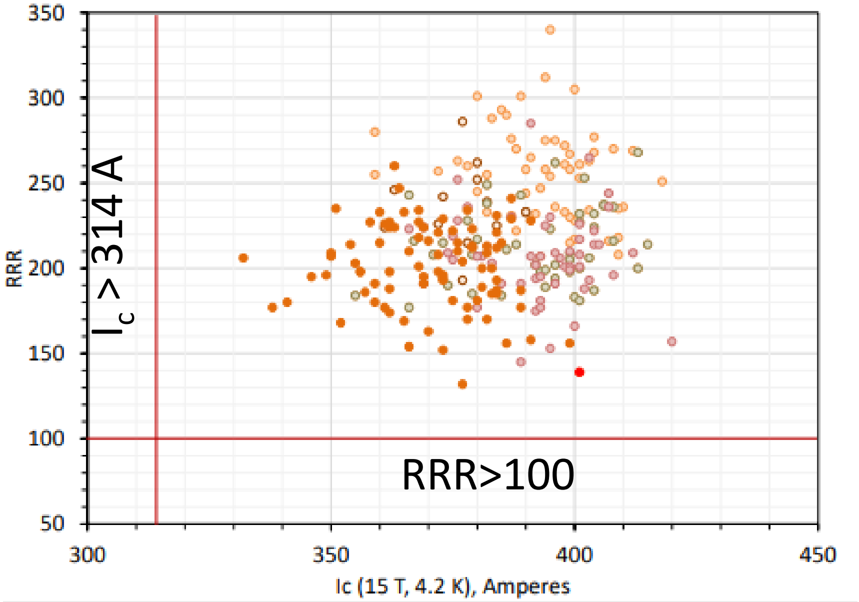
HL-LHC Nb_3Sn strand and cable production

- 110 km of Cu/Nb_3Sn cable, approaching now the end of the production (90 % of the cables are already done).
- Strand produced in industry, cable manufactured in house (LBNL and CERN)
- First big procurement of HEP grade Nb_3Sn, stable production well above minimum required (typically, 10 % more critical current than requested in the specification)

MQXFB cable production dashboard
Courtesy J. Fleiter



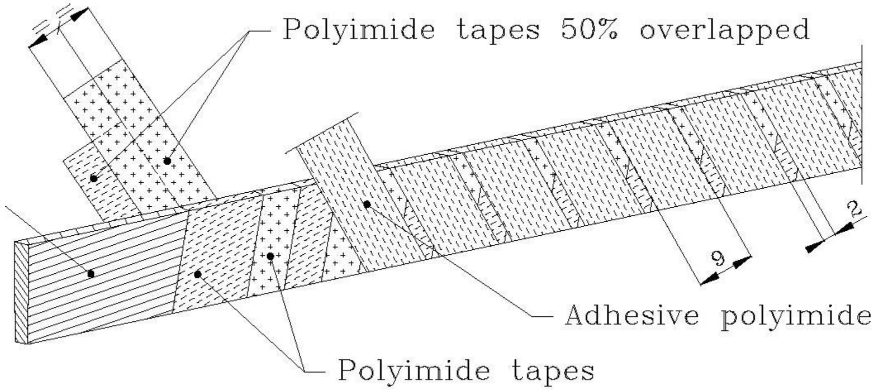
Cumulative data for RRP strand delivered for the US contribution to the HL-LHC (data on 15 % rolled strand)
L. Cooley et al., https://doi.org/10.48550/arXiv.2208.12379



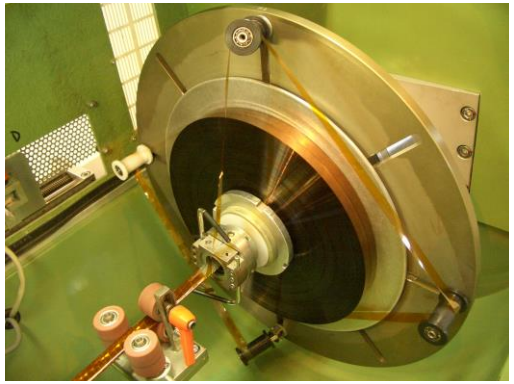
Cable insulation

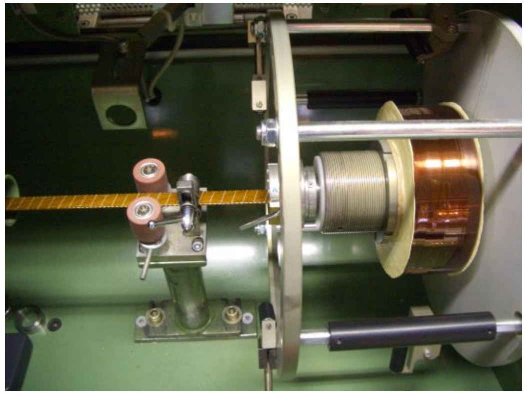
See lecture Roland Piccin

- The cable insulation must feature
  - Good **electrical properties** to withstand turn-to-turn *V* after a quench
  - Good **mechanical properties** to withstand high pressure conditions
  - **Porosity** to allow penetration of helium (for non-impregnated coils)
  - **Radiation hardness** (depending on the location in the machine)
- In Nb-Ti magnets the most common insulation is a series of overlapped layers of polyimide (Kapton®).
- In the LHC case: two polyimide layers 50.8 μm thick wrapped around the cable with a 50% overlap, with another adhesive polyimide tape 68.6 μm thick wrapped with a spacing of 2 mm.




Polyimide insulation for Nb-Ti



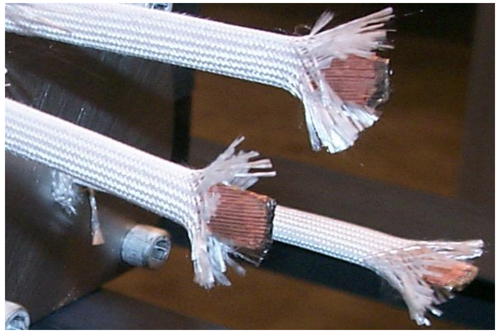


Cable insulation

See lecture Roland Piccin

- In Nb_3Sn magnets, where cable are reacted at 600-700 °C, the most common insulation is fiberglass: tape or sleeve or braided.
    - Braided insulation is done in industry for HL-LHC cables
- Typically, the insulation thickness varies between 100 and 200 µm.

Fiber glass insulation for Nb_3Sn

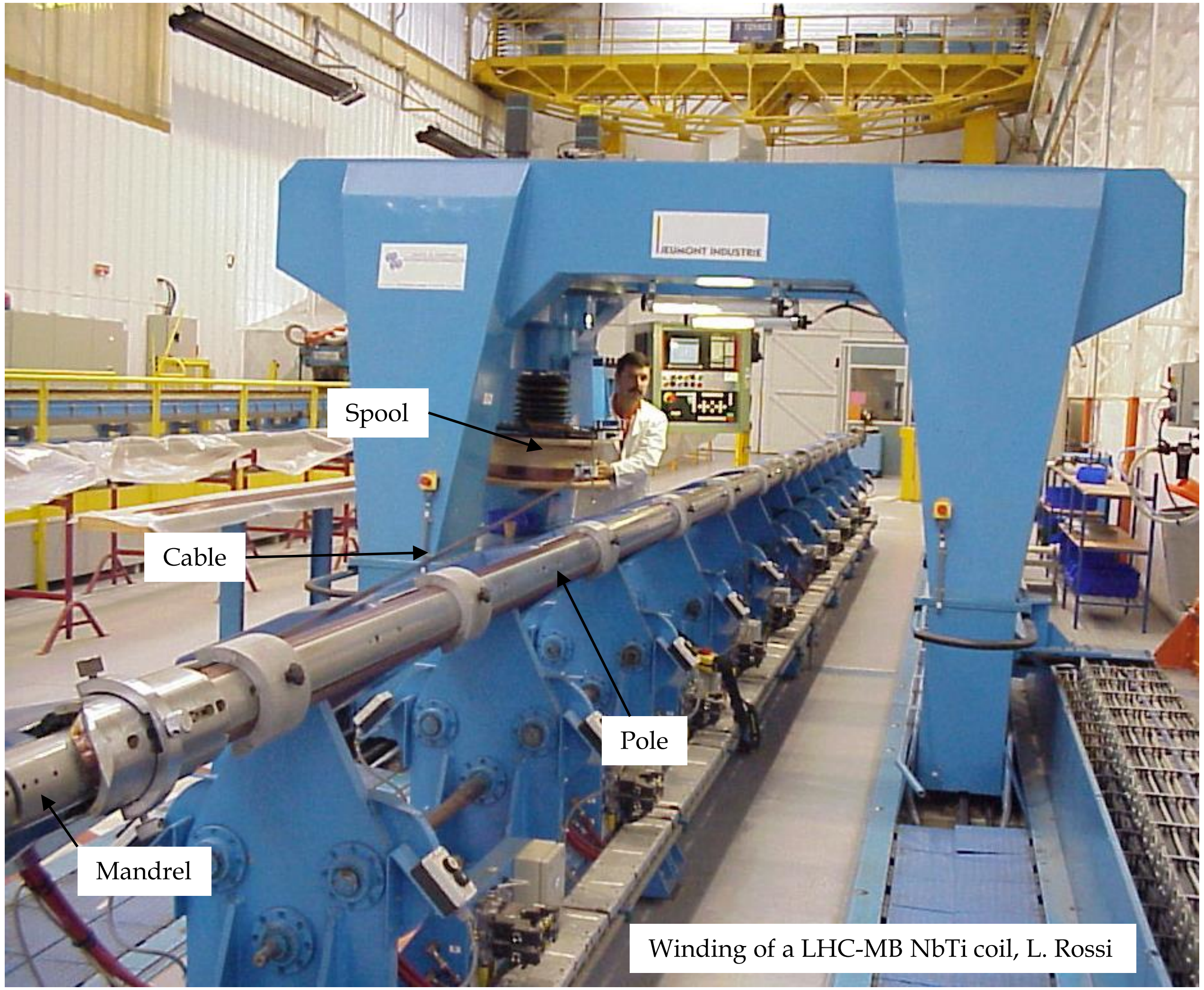


Outline

- Part I: Magnet fabrication
  - Introduction
  - Strand and cable
  - **Coil fabrication**
    - **Winding and curing (NbTi and Nb_3Sn)**
    - **Reaction (Nb_3Sn)**
    - **Impregnation (Nb_3Sn)**
  - Assembly
  - Industrialization
- Part II: Magnet test
- Conclusions

Coil winding and curing

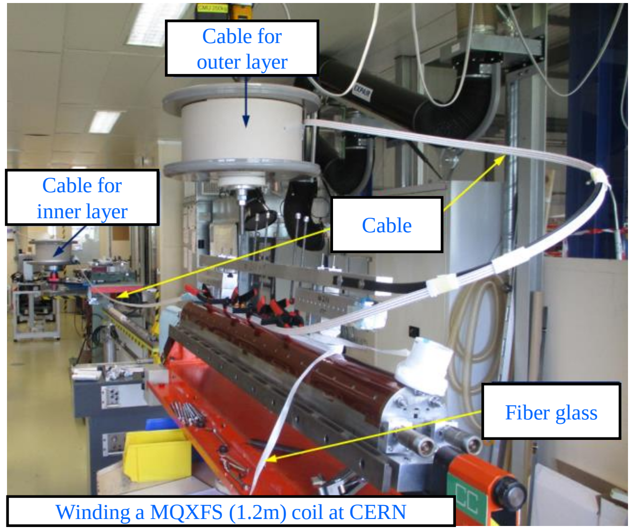
- The coil is the **most critical** component of a superconducting magnet.
- Cross-sectional **accuracy** of few hundredths of millimeters over up to 15 m length must be reached for field quality requirements.
- The coils are manufactured in a clean areas with adequate air circulation and air filtration. The cable must be free of any metallic chips that could damage the conductor or the insulation (shorts).
- A continuous length of insulated cable sufficient for one coil is wound on a **spool**. Then, from the spool, the cable is wound around a **pole** mounted on a steel **mandrel**.



Winding of a LHC-MB NbTi coil, L. Rossi

Winding machines

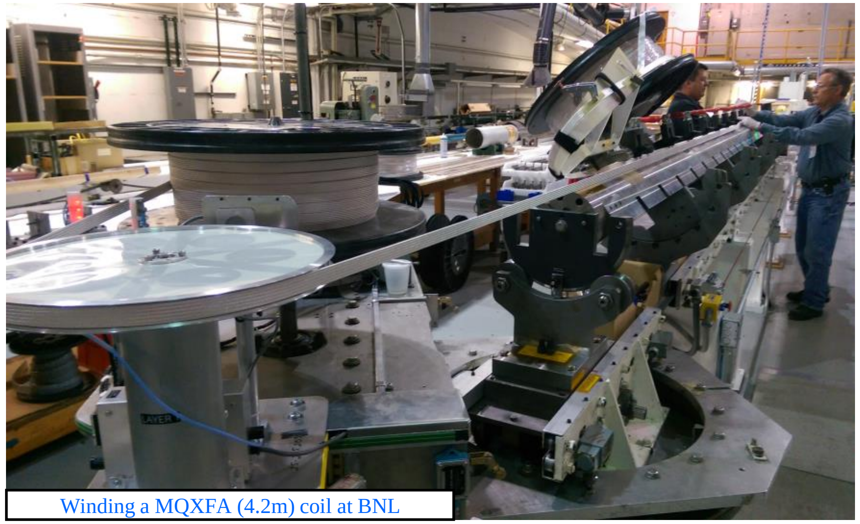
- Short coils are typically wound in a rotating winding machine
- For large production of long coils, coil winding is done with **automated winding machines**.
- The cable spool, mounted on a **motor driven wagon**, moves around the mandrel.
- As an alternative, the mandrel moves back and forth with respect a spool fixed to a frame.
- The conductor must always be **clamped** in the straight parts before winding the ends.



Winding a MQXFS (1.2m) coil at CERN


Winding a MQXFB (7.2m) coil at BNL


Winding a MQXFA (4.2m) coil at FNAL


Winding a MQXFA (4.2m) coil at BNL

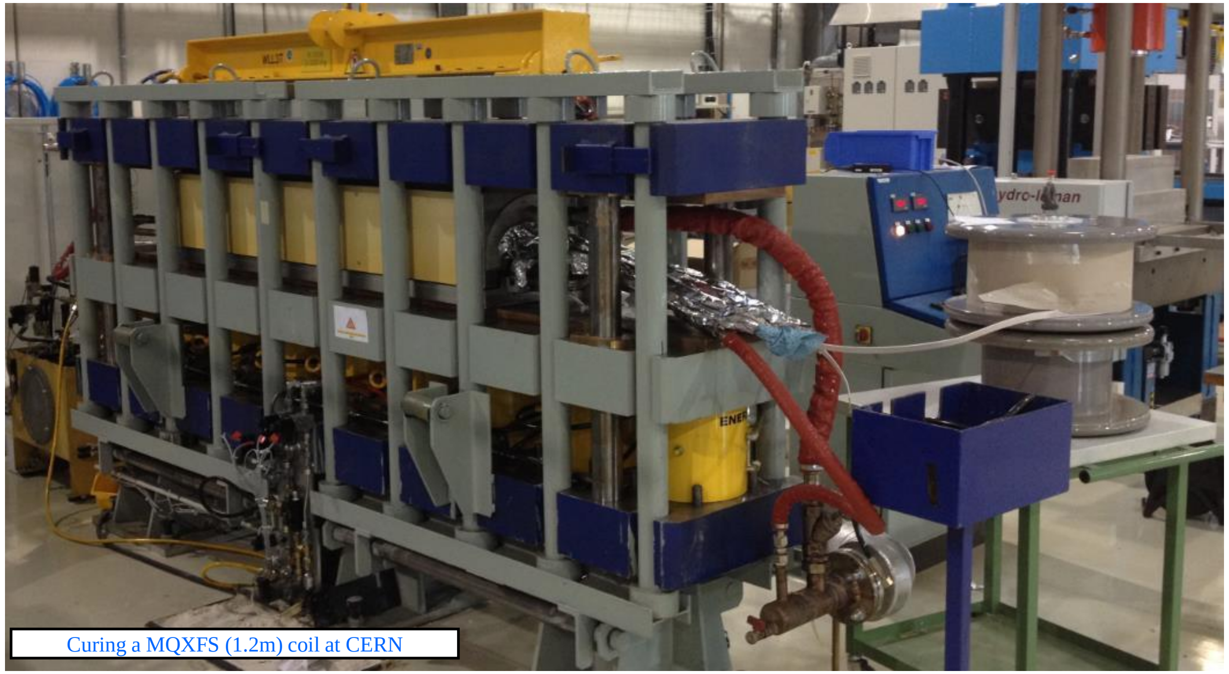
Curing

- The aim of the **curing** operation is to glue the turns together in order to facilitating coil **handling** during magnet assembly and define the mechanical **dimensions** of the coils.

- While still lying on the mandrels, coils are placed in the **curing mold** equipped with a heating system and compressed in curing press.

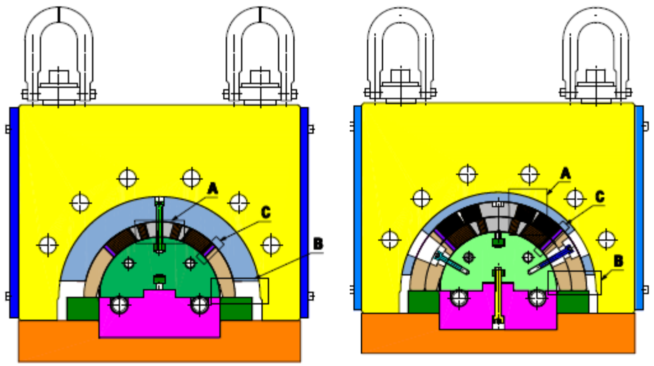
- Nb-Ti coils are cured up to 190 ± 3 °C under a maximum pressure of 80-90 MPa (LHC main dipoles). The high temperature **activates the resin** present on the insulation layer.

- In Nb_3Sn coils, after winding, cable insulation is injected with **ceramic binder**. Then coils are cured at 150° C for 30 minutes, subjected to an azimuthal pressure of approximately 5 to 35 MPa.



Curing a MQXFS (1.2m) coil at CERN

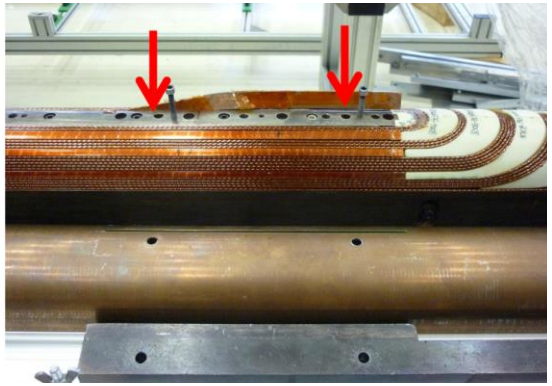
Applying ceramic binder in a MQXFB coil at CERN



Splicing

- If a coil is composed by layers with the same conductor, the outer layer can be wound on the cured inner layer and then cured as well (MQXF case).
- Alternatively, especially in the presence of different cables, the two (or more) layers can be wound and cured separately and then **connected through internal or external splices** (solder joints) (LHC-MB case).
- Solder is usually 40% lead and 60% tin, or silver-tin (5% silver) with a resistivity of less than 2-3 x 10^{-9} Ωm.
  - The temperature rise in the joints during operation is of the order of few mK.

Pre-shaping before winding



Layer jump region after winding IL

Assembly of the OL

Splicing

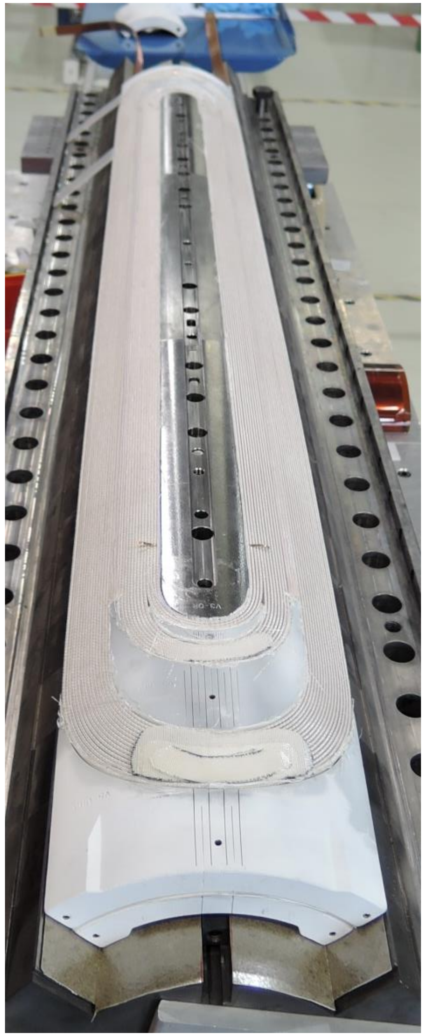
Mechanical stabilization

Reaction and impregnation of Nb_3Sn coils

- A cable of Nb_3Sn is **brittle**, thus it cannot be bent to a small radius. The usual approach is "**Wind & React**": the coil is wound un-reacted: then the entire coil undergoes the reaction process.
  - **Volumetric expansion** of the conductor of ≈ 3 %, tooling must provide enough space to avoid over-compaction, potential cause of degraded performance
  - Limited choice of materials (operation range 1.9 K - 950 K), but must provide good **electrical insulation**

- During the "**reaction**" process, the CuSn and Nb are heated to about 650-700 C in vacuum or inert gas (argon) atmosphere, and the Sn diffuses in Nb and reacts **to form Nb_3Sn**.

- After reaction, Nb_3Sn coil are **vacuum impregnated** (potted) with epoxy. Resin creates a solid block, thus distributing the stress, and improves electrical insulation.



After curing

After reaction

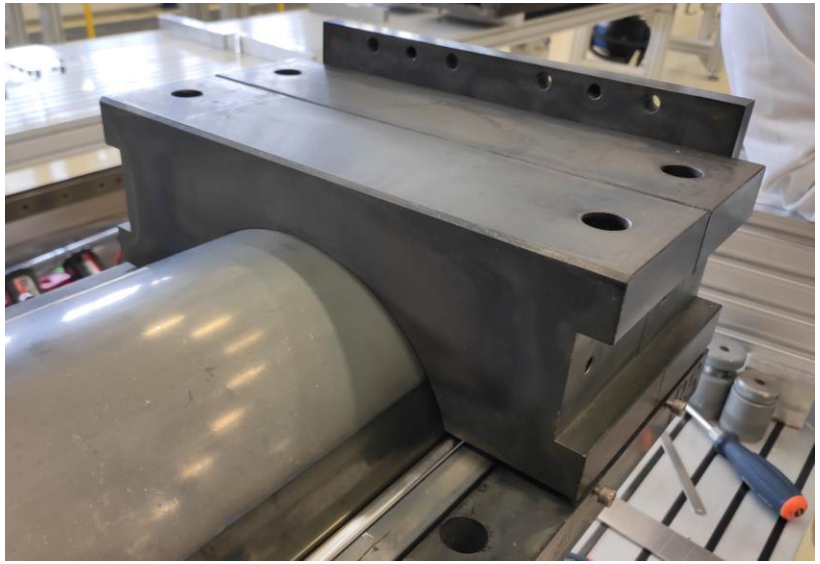
After impregnation

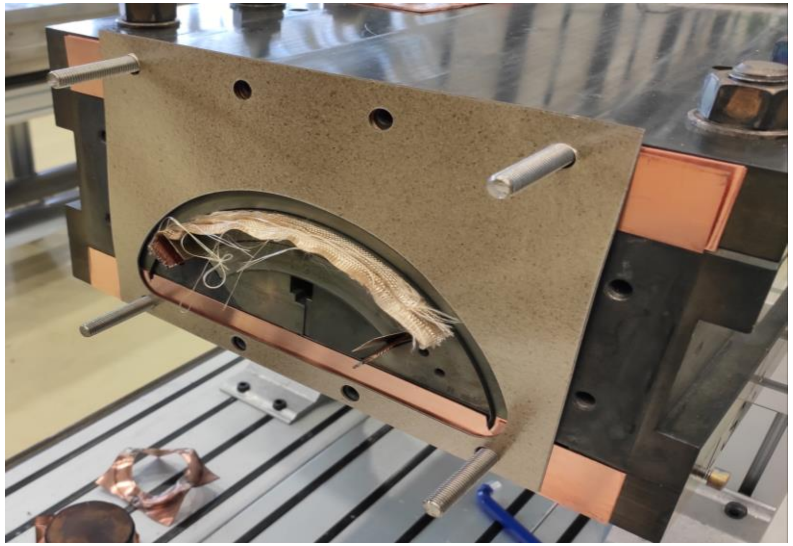
Reaction of Nb_3Sn coils

- Coils are clamped in a **reaction fixture** made of stainless-steel mold blocks.
  - The pressure on the coil is minimal to reduce risk of degradation.

- Layers of fiberglass, MICA, stainless steel are placed between coil and mold blocks.

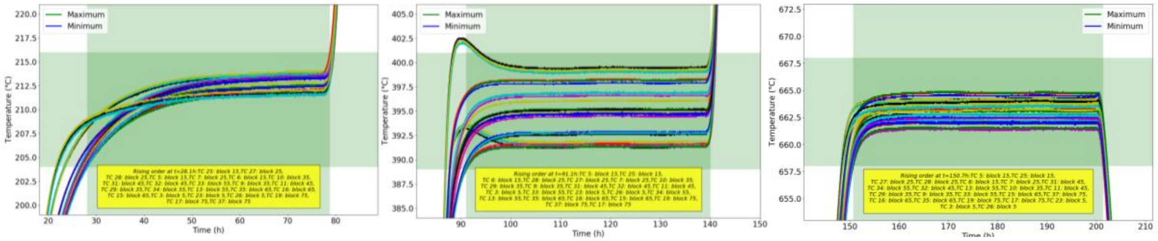
- The fixture needs to be leak-tight, to assure a good argon flow during the reaction and avoid RRR degradation

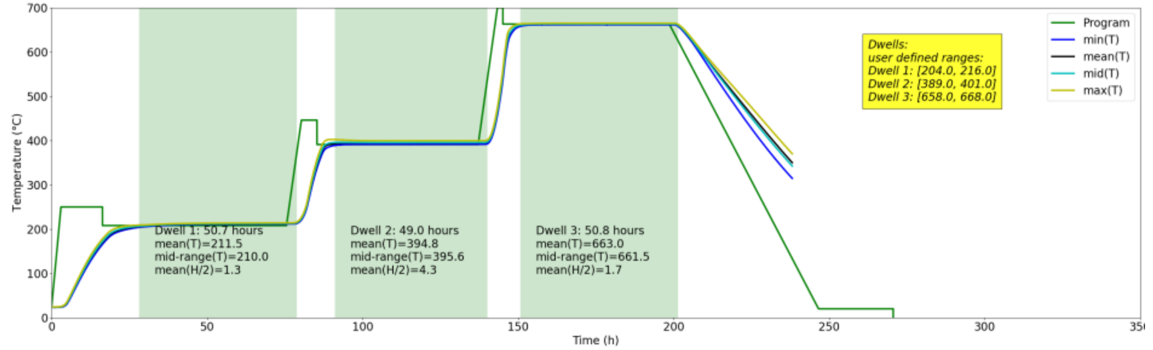


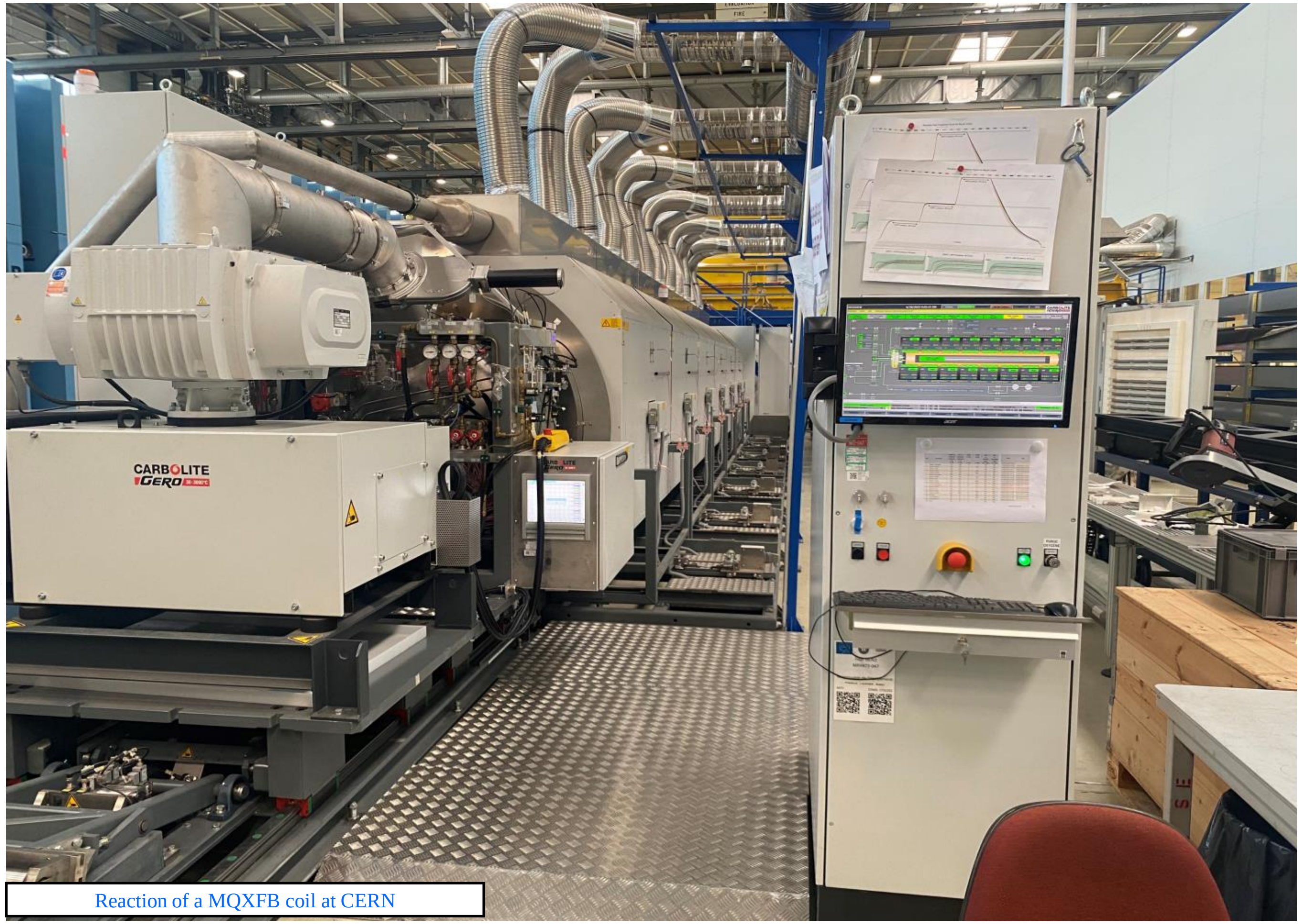


Reaction of Nb_3Sn coils

- Reaction fixture is placed in the **oven and argon gas flow** connected.
- The reaction is characterized by three temperature steps (for MQXF, dwell1 210°C/50h; dwell2 395°C/50h; dwell3 665°C/50h)
- The required temperature homogeneity is of about ± 5 °C.





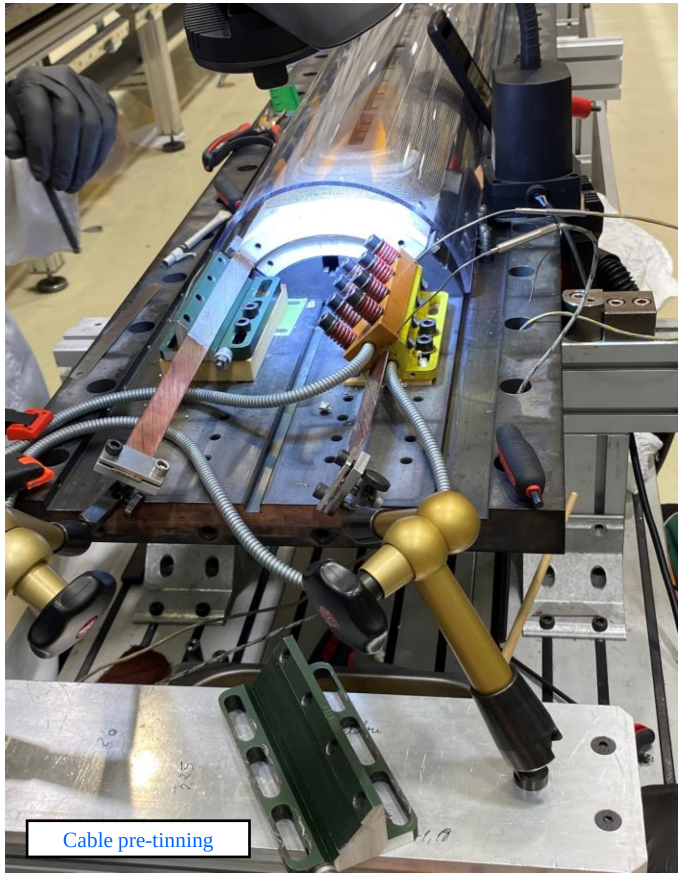


Reaction of a MQXFB coil at CERN

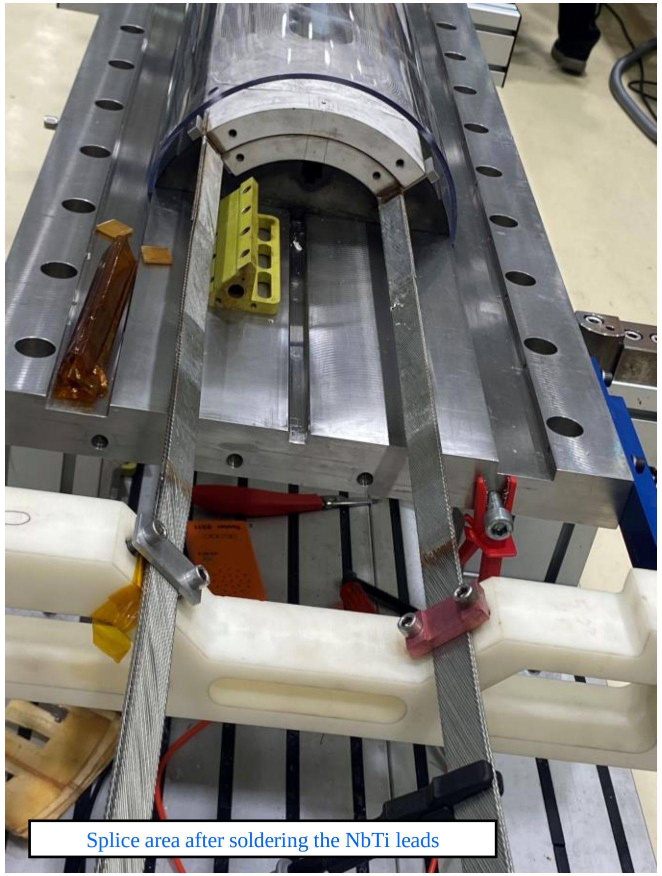
The CERN Accelerator School

NbTi-Nb_3Sn splice

- Nb-Ti leads are compressed against Nb_3Sn cables for a length of about 1-1.5 time the pitch length and soldered.



Cable pre-tinning



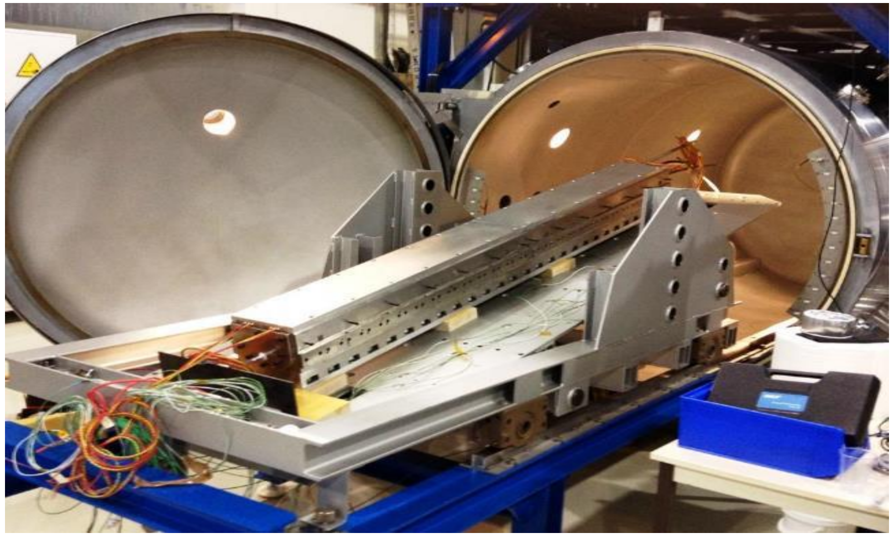
Splice area after soldering the NbTi leads

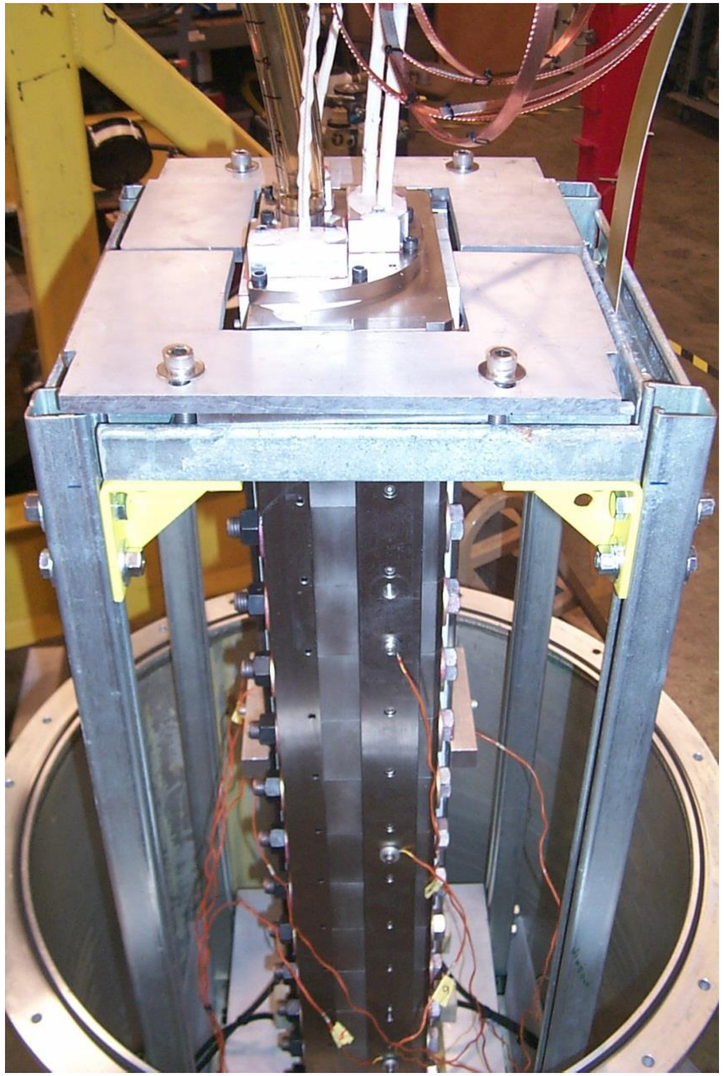
Preparation for impregnation

- After splicing the coil is closed (again) in a stainless-steel fixture. Critical phase for the coil, dealing with a reacted non-impregnated brittle conductor → all handling is done with extreme care
- Mica is removed, accessible layers of glass are replaced with fresh fiber
  - In the case the quench heaters are impregnated with the coils, they are installed at this stage

Impregnation of Nb_3Sn coils

- Nb_3Sn coil are **vacuum impregnated** with epoxy.
  - Resin creates a solid block, thus distributing the stress.
- The fixture is inserted in a **vacuum tank** and evacuated.
  - As for the winding, different layouts: vertical, with an angle, with/without pressure





Impregnation of Nb_3Sn coils

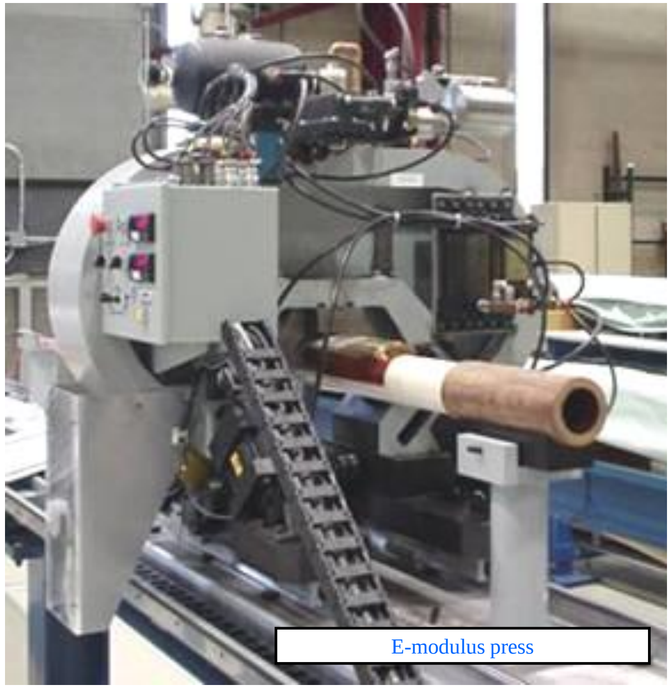
- Reservoirs and heaters are connected to the fixture.
- Epoxy has high viscosity at room temperature. At about 60 °C, when it has **low viscosity**, atmospheric (or higher) pressure is applied to drive the epoxy inside the mould.
  - Fixture must be leak tight
- Then, the further increase of temperature **cures the epoxy** which becomes solid.

Resin mixing and degassing unit at CERN

MQXFB coil inside the impregnation tank CERN

Metrology

- For NbTi, **elastic modulus and arc length** are measured in different locations along the longitudinal direction. A measuring tool moves along the coil applying the pre-loading pressure.
- For Nb_3Sn, typically the **arc length** of the coil in **relax state** is measured, using a portable CMM (see J. Ferradas et al, IEEE vol 28 2018, and J. Rudeiros et al. IEEE vol 29 2019 for a comparison CMM to E-modulus press)



E-modulus press

Faro arm to measure MQXFB coils

Outline

- Part I: Magnet fabrication
  - Introduction
  - Strand and cable
  - Coil fabrication
  - **Assembly**
  - Industrialization
- Part II: Magnet test
- Conclusions

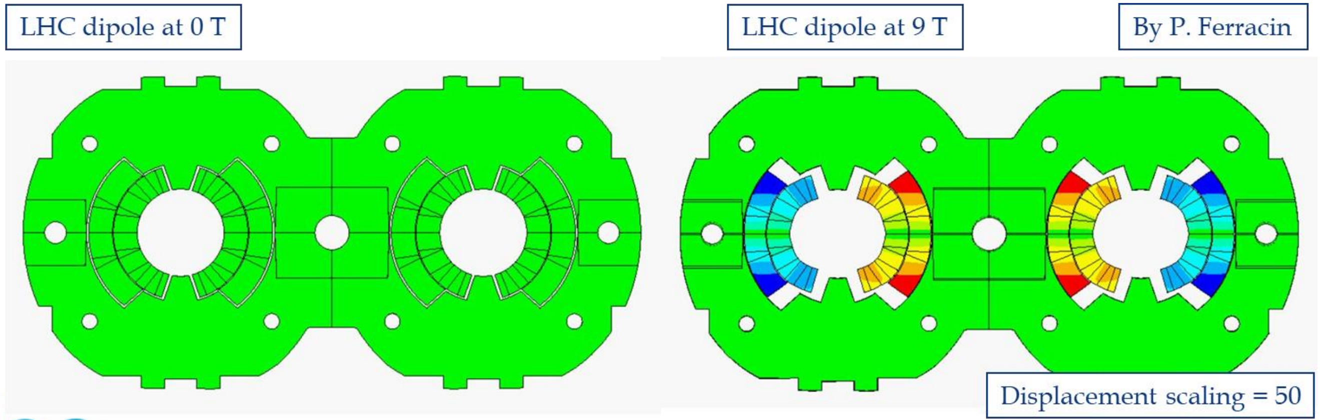
Introduction

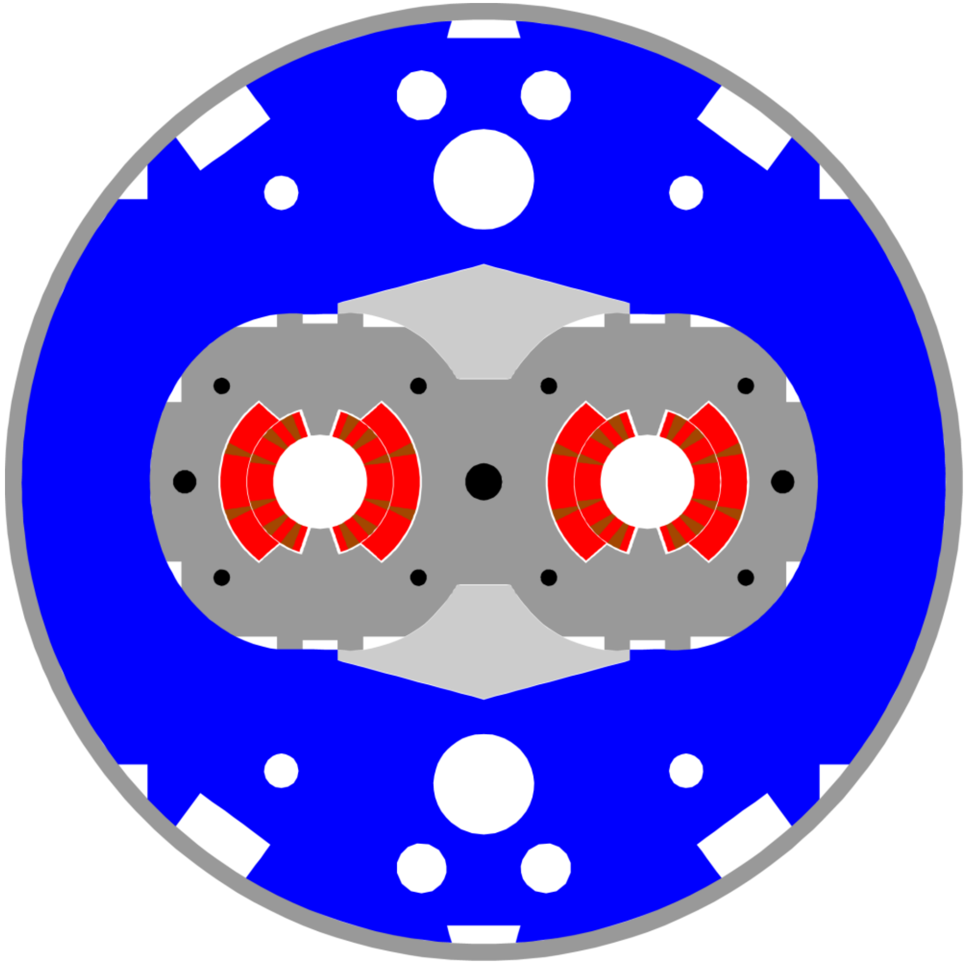
- After winding and curing (reaction and impregnation), the coil is placed inside a support structure capable of
  - providing the required **pre-stress** to the coil after cool-down in order to reduce conductor motion;
  - withstanding the electro-magnetic forces;
  - providing Helium containment.
- Most of the accelerator magnets are based on **collars** and a stainless-steel cylinder. This kind of structure guarantees good control of conductor position and coil alignment. We will use the **LHC-MB dipoles** to explain the main features of this kind of structure
- The Nb_3Sn quadrupoles for the HL-LHC are based on an **aluminium shrinking cylinder pre-loaded with bladders and keys**. We will use **MQXF** to explain the main features of this kind of structure

LHC-MB dipole

See lecture F. Toral

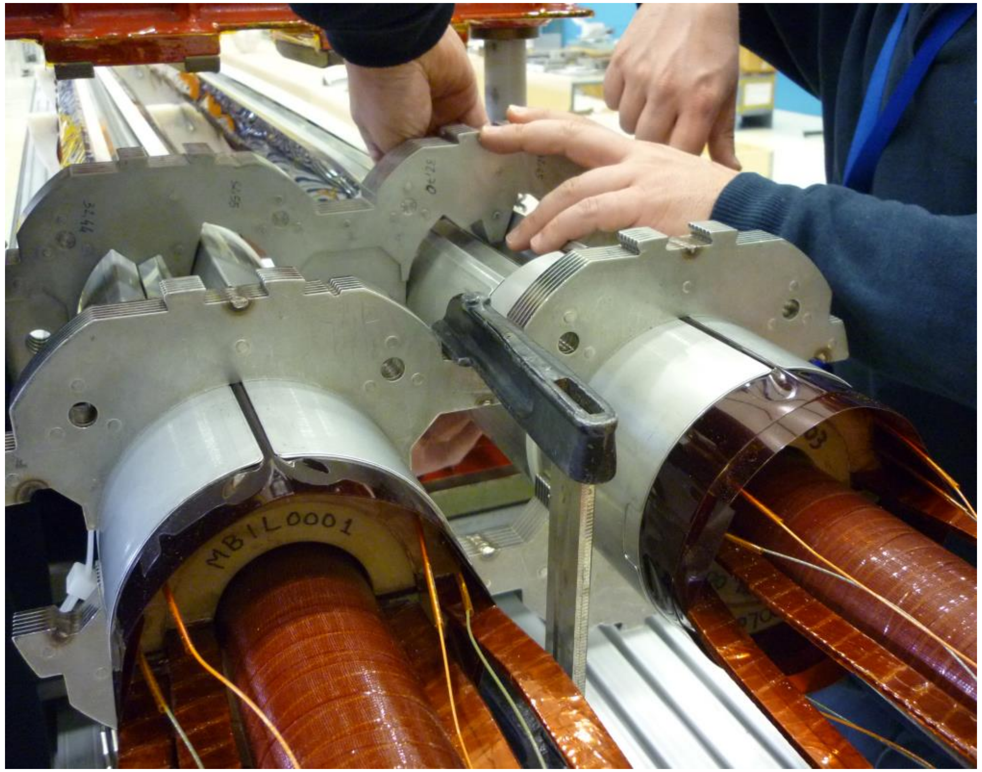
- Two-in-one configuration
  - Both beam pipes are contained within one cold mass
- Stainless steel collars are locked by three full-length rods.
- Magnetic insert
  - It transfers vertical force from the yoke to the collared coils
  - It improves field quality
- Iron yoke vertically split
  - At the end of the welding operation the yoke gap is closed
- Stainless steel shell halves are welded around the yoke to provide He containment, a 9 mm sagitta, and to increase rigidity.





LHC-MB dipole: collaring

- Azimuthal pre-stress is provided to the coil. Collars are composed by stainless-steel or aluminium laminations few mm thick. By clamping the coils, the collars provide
    - coil pre-stressing;
    - rigid support against e.m. forces (it can be self-supporting or not);
    - precise cavity (tolerance ≈20 μm).



by L. Rossi

LHC-MB dipole: MM after collaring

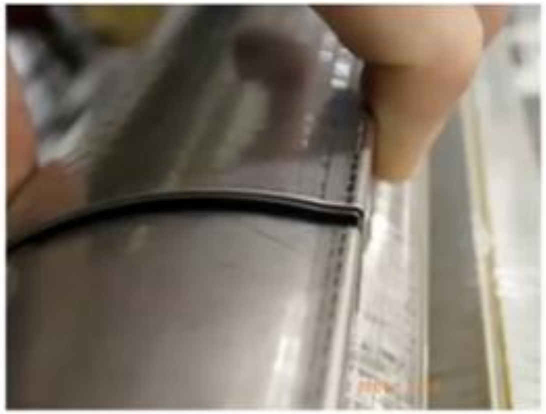
- Magnetic measurements after collaring were used as a tool to monitor production (control the production and identify assembly errors).
- Errors identified with anomalies in warm magnetic measurements for the LHC main dipole production (1276 magnets):
  - Errors identified with anomalies in warm magnetic measurements
    - 15 magnets rescued at the level of collared coils (1.2% of the production). Variety of defects.
    - 18 electrical shorts (1.5%) localized through warm magnetic measurements (see B. Bellesia IEEE TAS vol 16 2006)

by E. Todesco

Block6 inward displacement in the LHC main dipole 2032

Missing shim in the LHC main dipole 1027

Double coil protection sheet



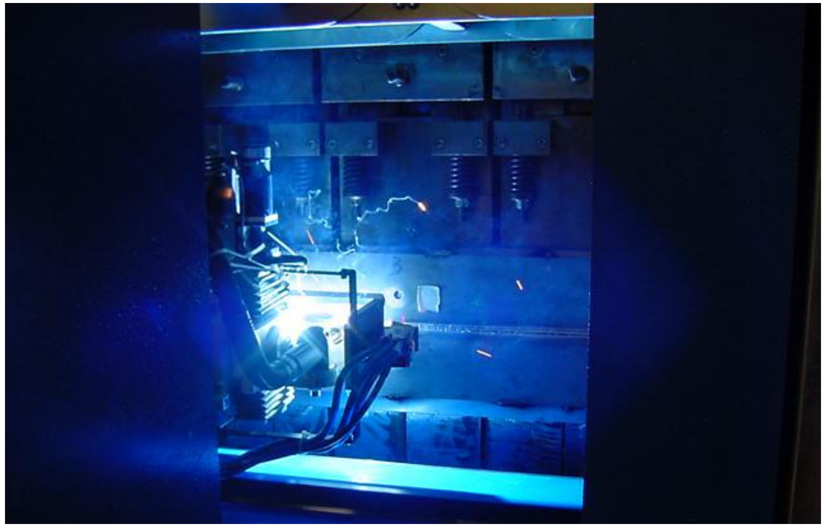
For more details, see lectures M. Buzio and L. Fiscarelli

LHC-MB dipole: iron yoke

- As the collars, iron yoke are made in laminations (several mm thick), with a packing factor > 95%.
- Magnetic function: The yoke contains and enhances the magnetic field.
- Structural function: the yoke is in tight contact with the collar, it contributes to increase the rigidity of the coil support structure and limit radial displacement.
- Holes/slots are included in the yoke design for correction of saturation effect, cooling channel, assembly features, electrical bus

LHC-MB dipole: SS-shell

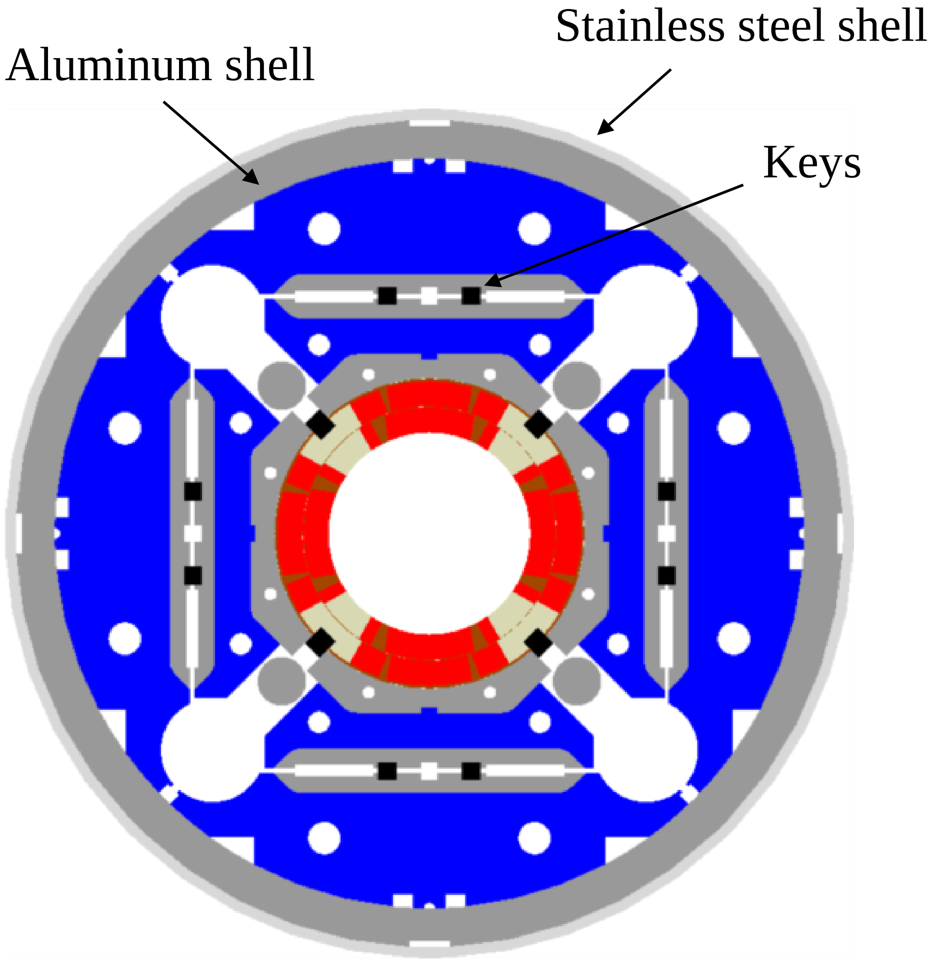
- The cold mass is contained within a shell (or shrinking cylinder).
- The shell constitutes a containment structure for the liquid Helium.
- It is composed by two half shells of stainless steel welded around the yoke with high tension (about 150 MPa for the LHC dipole).
  - With the iron yoke, it contributes to create a rigid boundary to the collared coil.
- If necessary, during the welding process, the welding press can impose the desired curvature on the cold mass.
  - In the LHC dipole the nominal sagitta is of 9.14 mm.

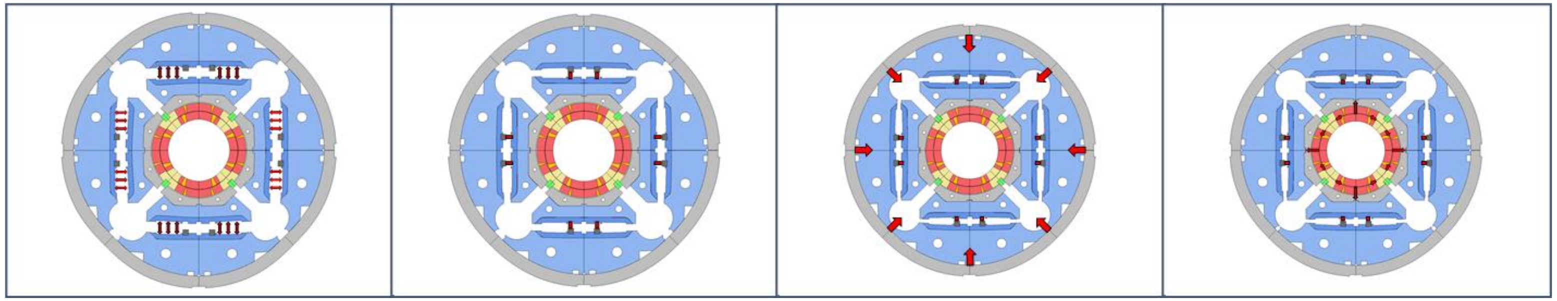


HL-LHC MQXF quadrupole

See lecture F. Toral

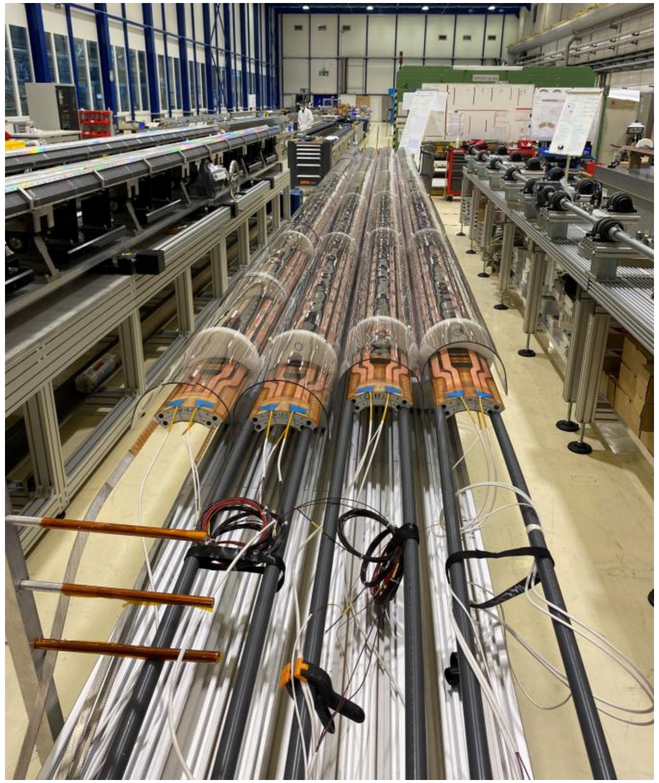
- The coil is surrounded by four collars, pads and four yokes. Collars are just a spacer and do not have a mechanical function
- Pad and yoke gaps remain open during all the magnet operations.
- Initial pre-compressions is provided by bladders and locked by keys.
- After cool-down the coil pre-stress increases due to the high thermal contraction of the aluminum shell.
  - The stainless-steel shell is just an Helium container, it does not have a mechanical function

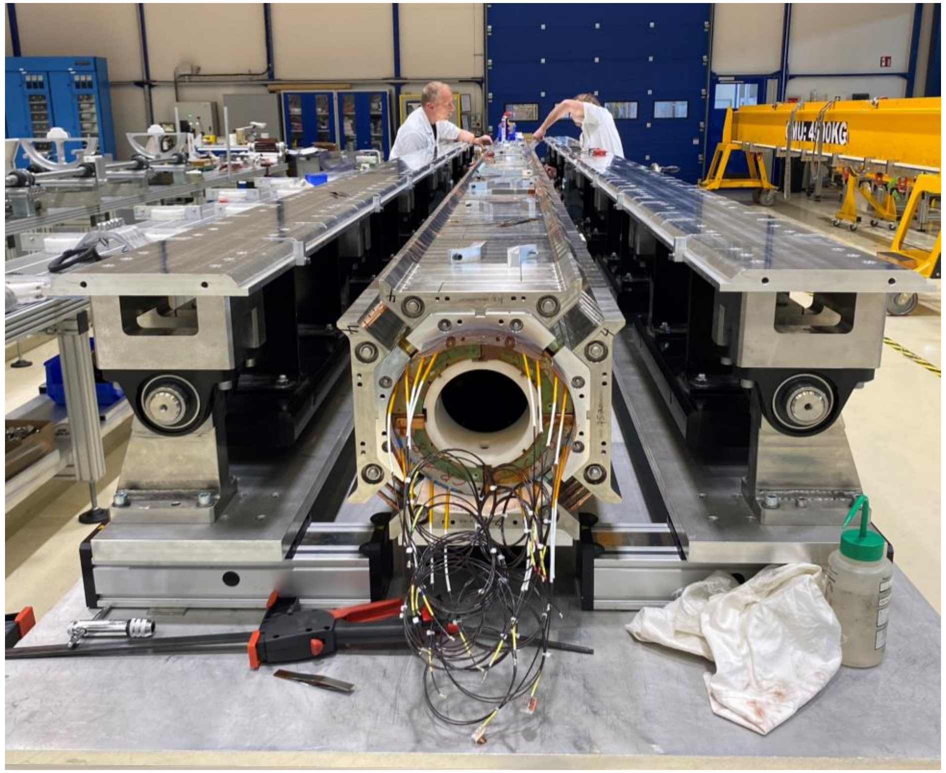




MQXF – coil pack assembly

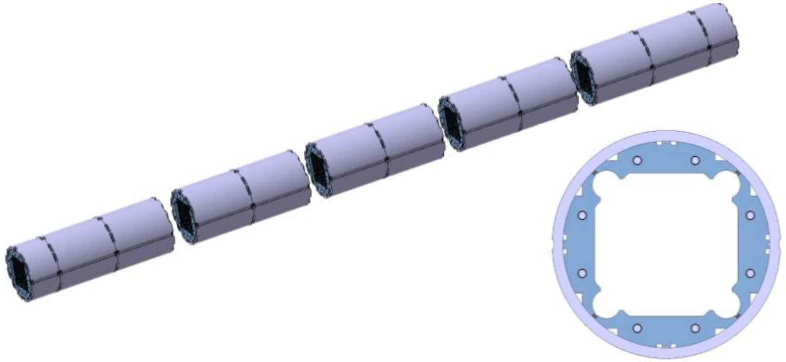
- The four coils are assembled. The difference in size among the coils is compensated with radial and azimuthal shims
- Aluminium collars and iron pads are bolted around the coils
  - The collar does not have a mechanical function, acts as an ‘spacer’





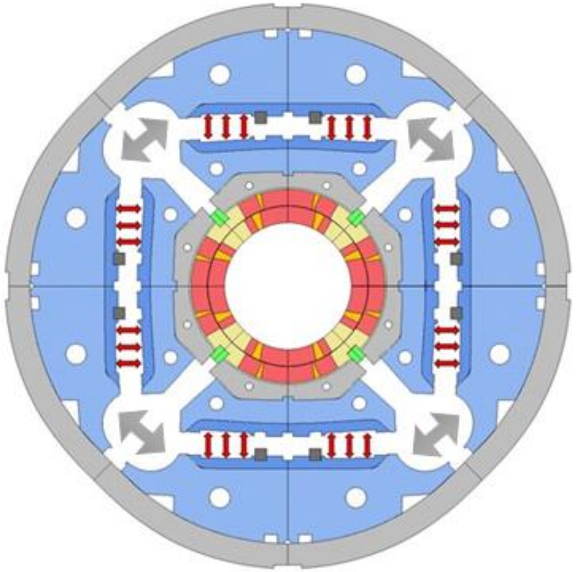
MQXF – yoke-Al shell assembly

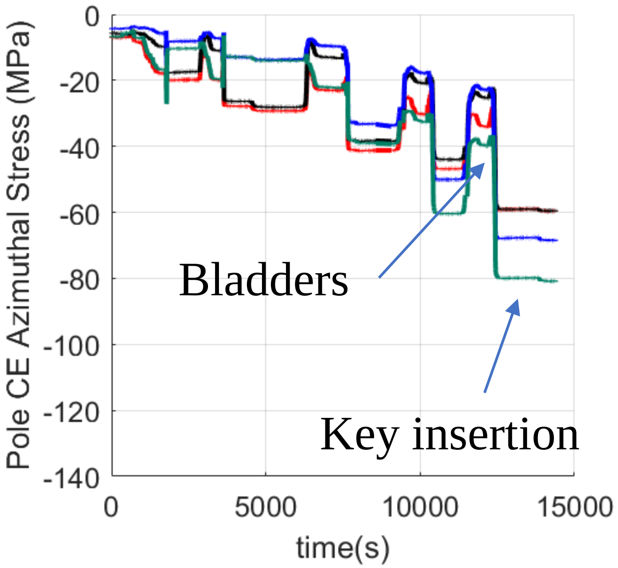
- Yoke-shell subassembly is composed of 5 modules, assembled vertically
- The 5 modules are then assembled horizontally and compressed to have a packing factor ≈ 100 %
- The, the coil pack is inserted in the yoke shell structure
- As in the LHC production, magnetic measurements a after insertion are a powerful took to intercept assembly errors (see S. Izquierdo Bermudez et al., IEEE vol 28 2018)



MQXF - loading

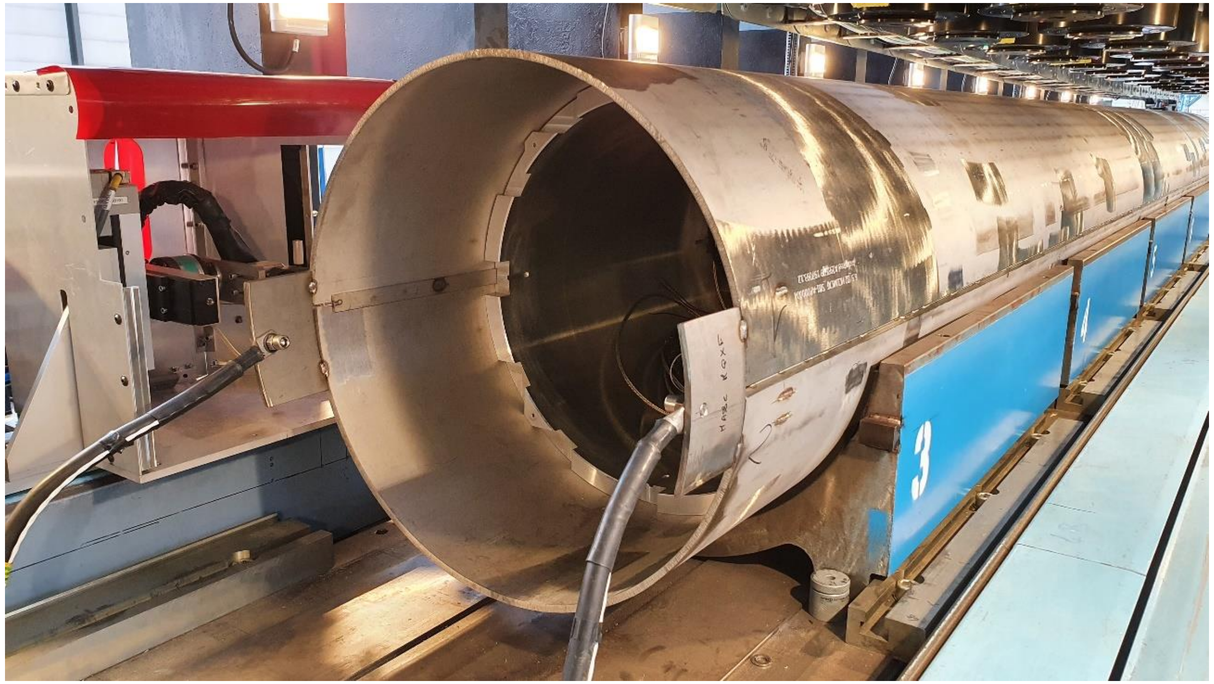
- Initial pre-compressions is provided by bladders (tube that expands when injecting water at high pressure ≈ 400 bars) and locked by keys.
  - The peak stress in the coil is during key insertion





MQXF – stainless steel welding

- No mechanical coupling between SS vessel and magnet. SS vessel serves only as helium container
  - Clearance SS vessel to magnet before welding such that stress in the SS vessel after welding is ≈ 0 MPa



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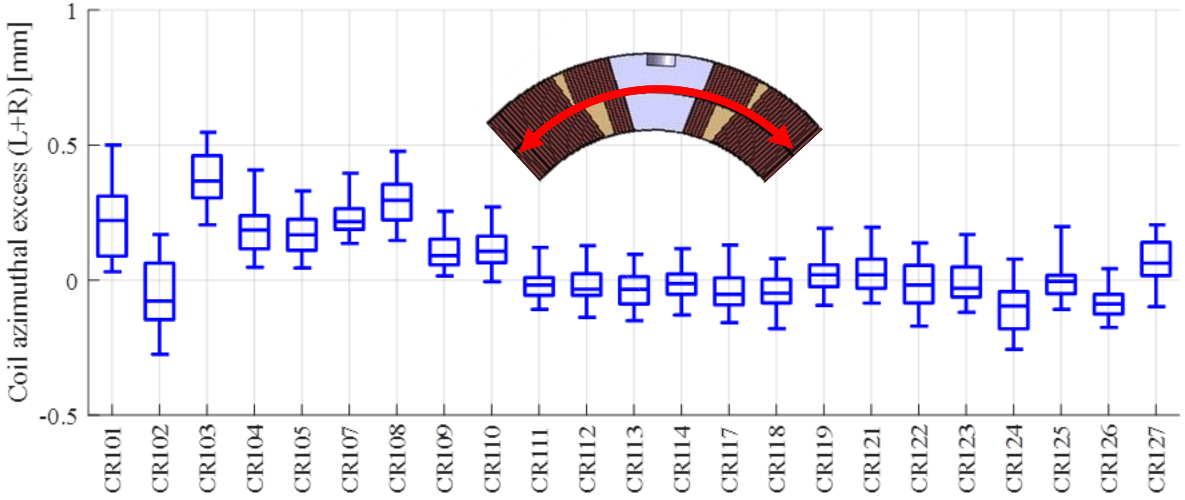
Tolerances - Coil

- Geometrical imperfections (Δl) have different impact on the coil stress, depending on:
  - Coil elastic modulus, E ($\sigma = E \cdot \varepsilon = E \cdot \Delta l / l$)
    - E = 5-10 GPa for non-impregnated NbTi coils; E = 20 – 40 GPa for impregnated Nb_3Sn coils
  - Magnet design
    - If you close the coils in a cavity (as a collared-coil structure), you need to precisely know and control the size of your cavity and coil.
    - If you have an open structure where you impose a force (as Al-shell pre-loaded with bladders and keys), you need to precisely control the force you put in they system.

- The coil is the most critical component, we aim to control the coil azimuthal size with a precision of ≈ 0.1 mm (for MQXF, ± 0.1 mm excess corresponds to ± 13 MPa coil stress)
  - For series production long coils, the average size and variation along the straight section length stabilized to ± 0.125 mm.

Coil azimuthal excess in MQXFB coil production



Tolerances – Magnets components

- Magnet components: From tens to hundreds of mm, depending on the functionality.
- Different manufacturing methods applied depending on the component and the total quantity to be produced

<u>Laminated components (yoke & collars)</u>

Manufacturing method: fine blanking

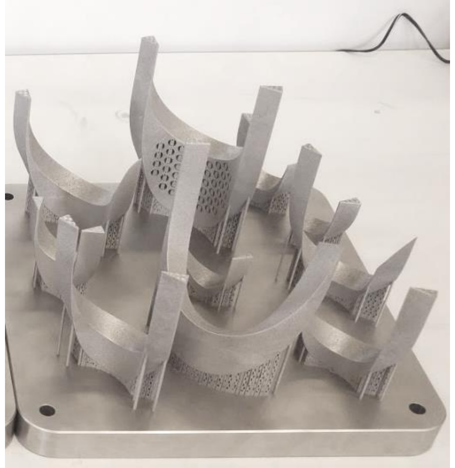
Tight tolerances, repeatability and small dispersion (≈ 0.03 mm)

<u>End spacers</u>

Small production: SLS (3D printing)

Large production: 5 axis machining

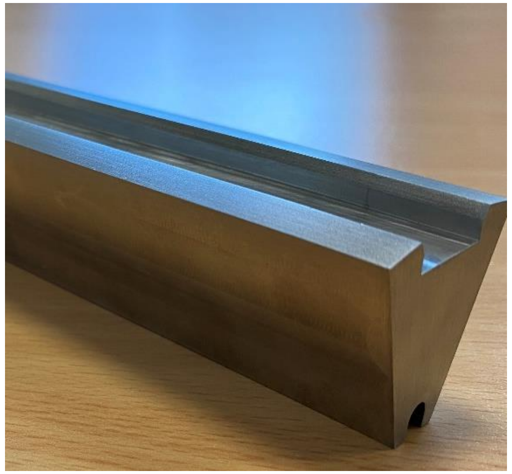
Tolerances: ≈ 0.10 mm



<u>Pole</u>

CNC machining

Tolerances: Hundredths of mm (0.02 is already at the limit…)



<u>Wedges</u>

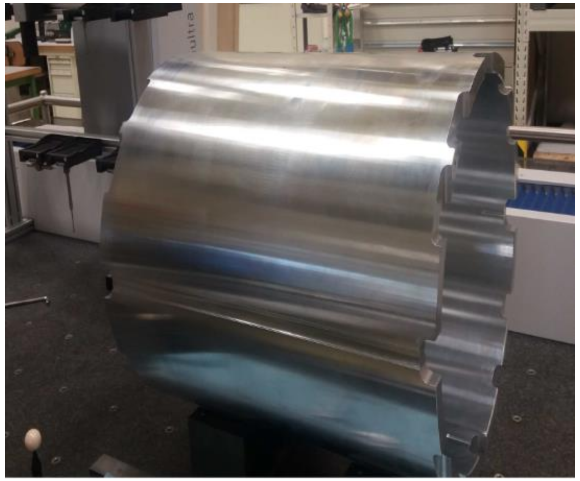
Extrusion and/or drawing

Tolerances: Hundredths of mm (0.03-0.05 mm)

<u>Al-Shell</u>

Manufacturing method: forging – turning – milling

Tolerances: ± 0.05 mm in the inner diameter

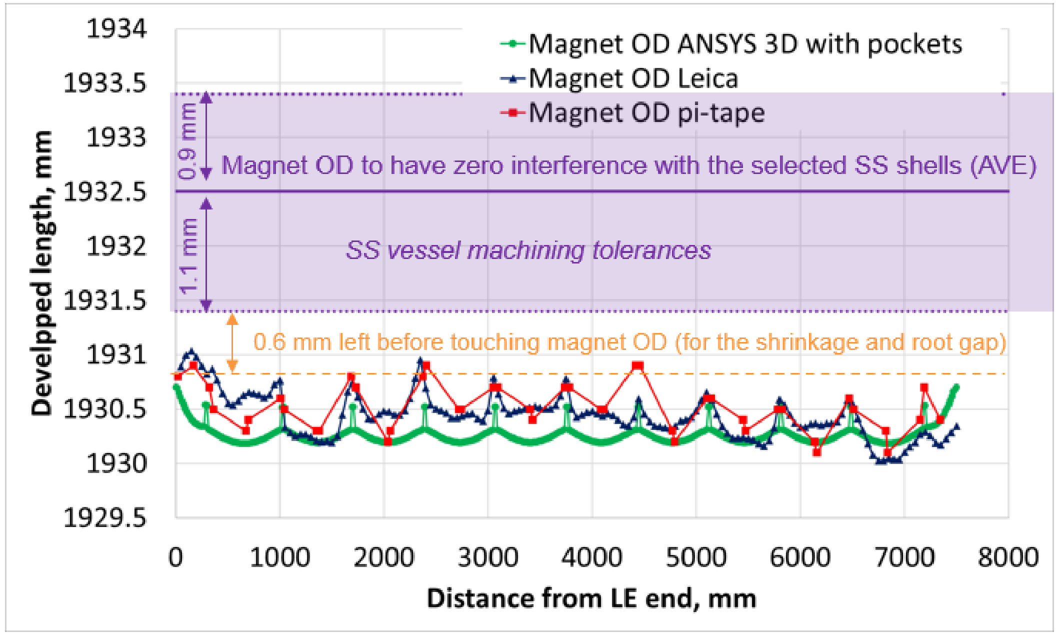


For more details, see Ezio masterclass series, <u>Appendix D – A digression on manufacturing techniques for magnet components</u> (by A. Dallocchio)

Tolerances - Welding

- Stainless steel shells made by forming and machining: when pairing the two shells, ± 1 mm on developed length. In addition, extra tolerance needed for the welding shrinking and root gap. To limit the impact of the welding on the coil stress:
  - The iron yoke closes during the welding, so only part of the force reaches the coil (LHC dipole)
  - The stainless-steel vessel is welded with a ‘clearance’ to the magnet (MQXF quadrupole)

Forming of SS shells
12m press, 3’000 tons capacity



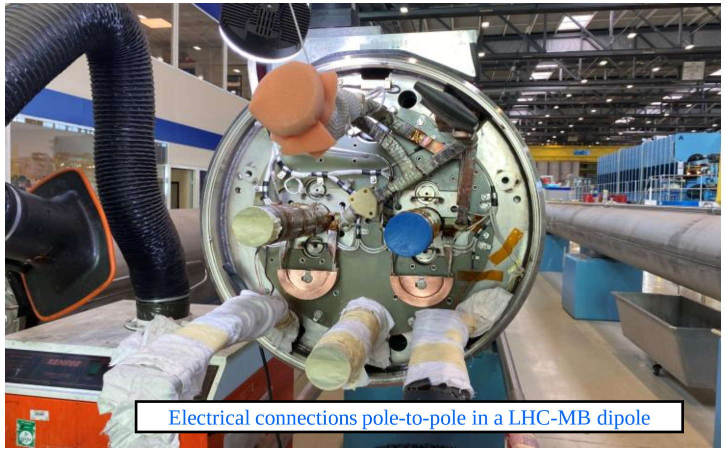
Enough information for one hour?

We continue after the coffee break

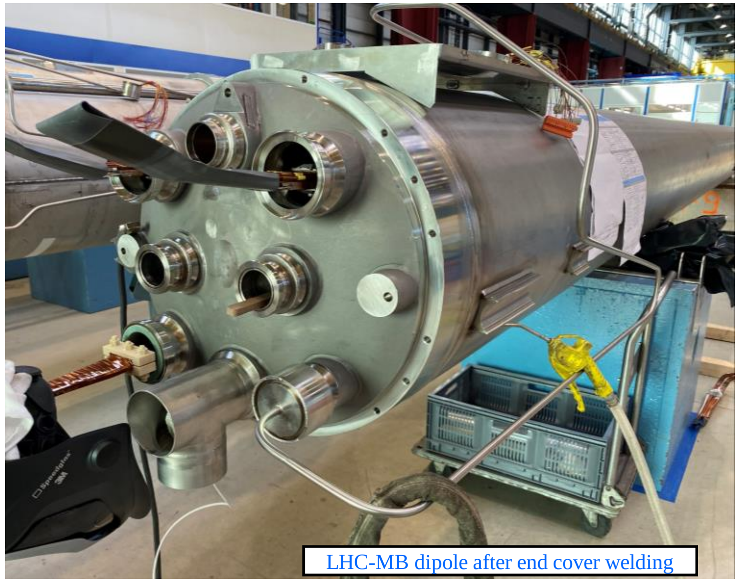
by H. Prin

Cold mass finishing operations

- The cold mass is the leak tight envelope surrounding the superconducting magnet and acts as a helium pressure vessel, providing the mechanical rigidity to align the magnetic elements and interfaces with surrounding systems: powering, protection, cryogenics, beam vacuum, beam instrumentation and vacuum vessel
  - The cold mass contains also busbars, foot, bellows and end lines: everything needs to be integrated.
- Geometrical (laser tracker) and magnetic measurements are combined, for alignment and fiducialization.
- The welding of the end cover welding closes the cold mass (He containment).


Electrical connections pole-to-pole in a LHC-MB dipole


Stretch wire magnetic measurements in MQXFB


LHC-MB dipole after end cover welding


MQXF after end cover welding

Cryostat

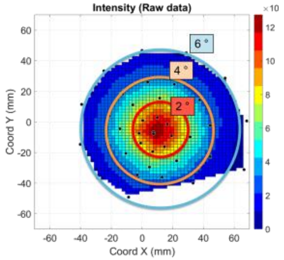
by D. Duarte Ramos

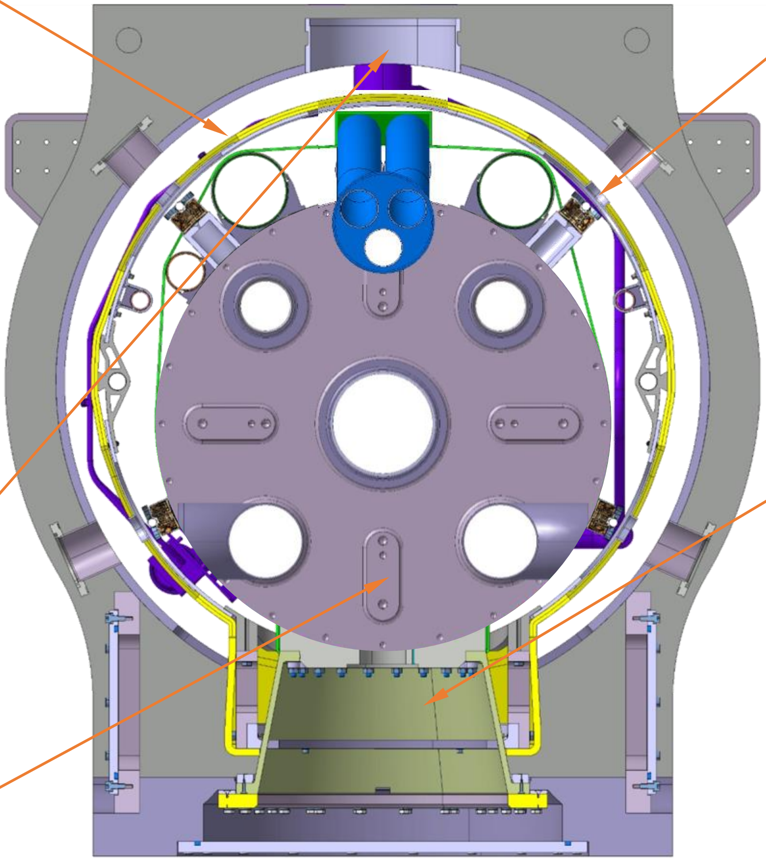
- Function: thermal insulation between the cold mass (1.9 K) and the tunnel (300 K)

MLI and thermal shield (with active cooling)

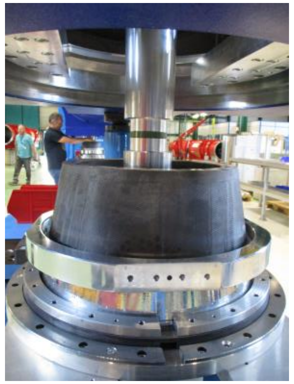
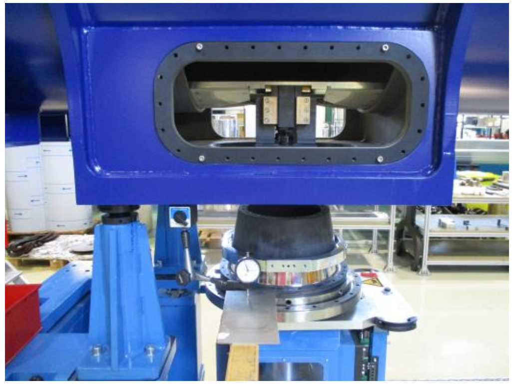

Targets for cold mass position monitoring through frequency scanning interferometry







Cold mass support, made with composite material to reduce heat conduction

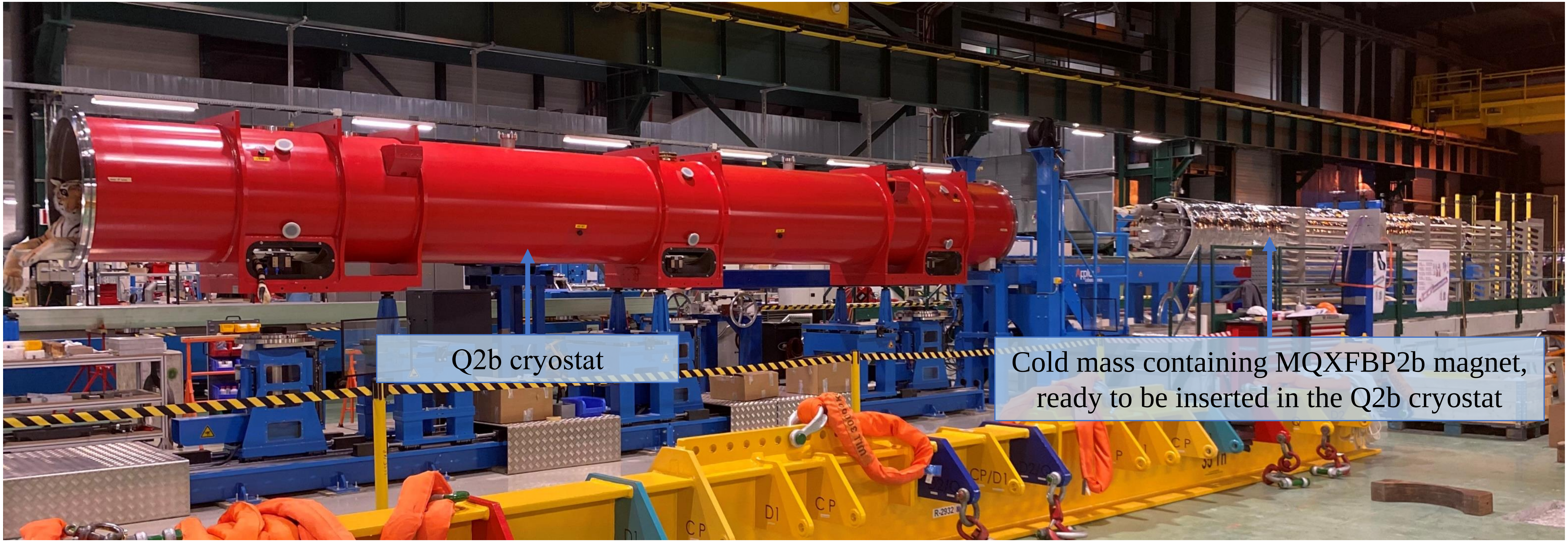
Pressure relief valve on insulation vacuum volume (vacuum level 10^{-6} mbar)

Cold mass alignment references (4x)

by D. Duarte Ramos

Cryostat

Insertion of the first Q2b cold mass in the cryostat



- See https://www.youtube.com/watch?v=Ro9rkQViYxw for an example of an insertion of an LHC-MB cold mass in a cryostat

Cryostat

First Q2b cryo-assembly, ready for connection to the test bench

Outline

- Part I: Magnet fabrication
  - Introduction
  - Strand and cable
  - Coil fabrication
  - Assembly
  - **Industrialization**
- Part II: Magnet test
- Conclusions

The overall picture

	LHC-MB Dipole **L. Rossi 2014 DOI 10.5170/CERN-2014-005.517**	**MQXF**
Technology	NbTi (14.5 m length, B_p = 8.6 T)	Nb_3Sn (MQXFA 4.2 m; MQXFB 7.2 m; B_p = 11.3 T)
Quantity	• 6 prototypes for each of the 3 generations • 3x30 pre-series magnets • Three contracts for the fabrication of 1146 (+30 spares)	• 2 MQXFA prototypes and 2 MQXFB prototypes • 20 MQXFA magnets + 10 MQXFB magnets (includes spares)

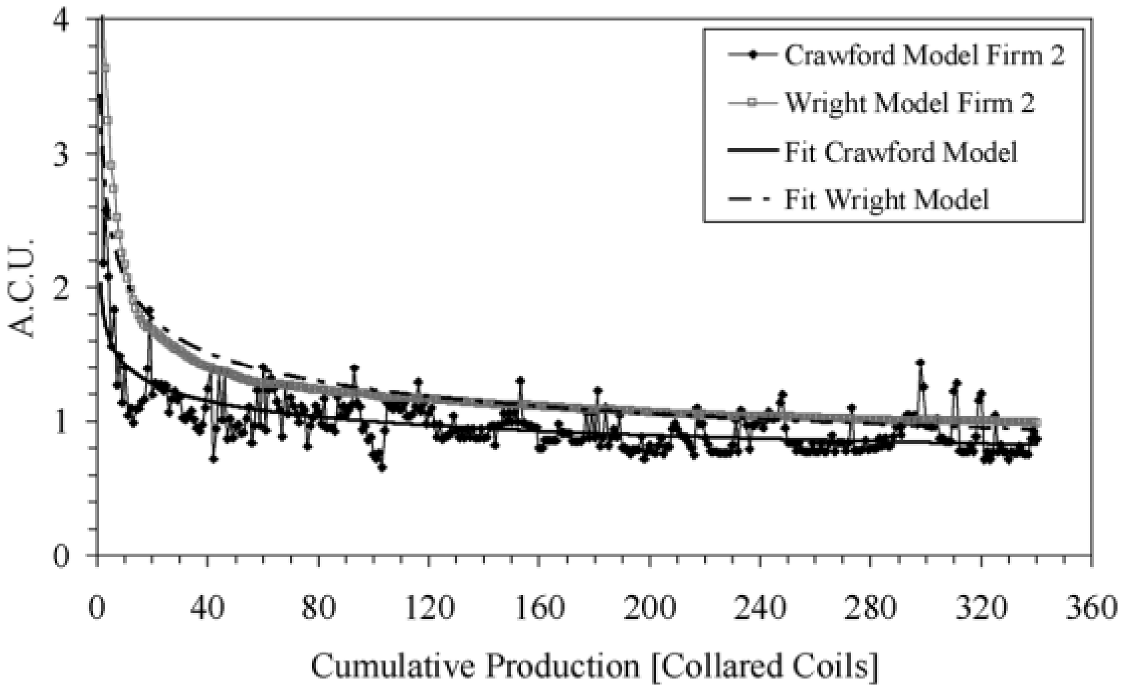
Production time	• ≈ 6 months/cold mass at full production speed P. Fessia, et al., IEEE TAS vol 17 2007	• ≈ 6 months/magnet at full production speed for MQXFA (2 coil manufacturing lines)
		  • + 9 months for the cold mass and cryostating
		• ≈ 9 months/magnet at full production speed for MQXFB (1 coil manufacturing line).
		  • + 5 months for cold mass and cryostating

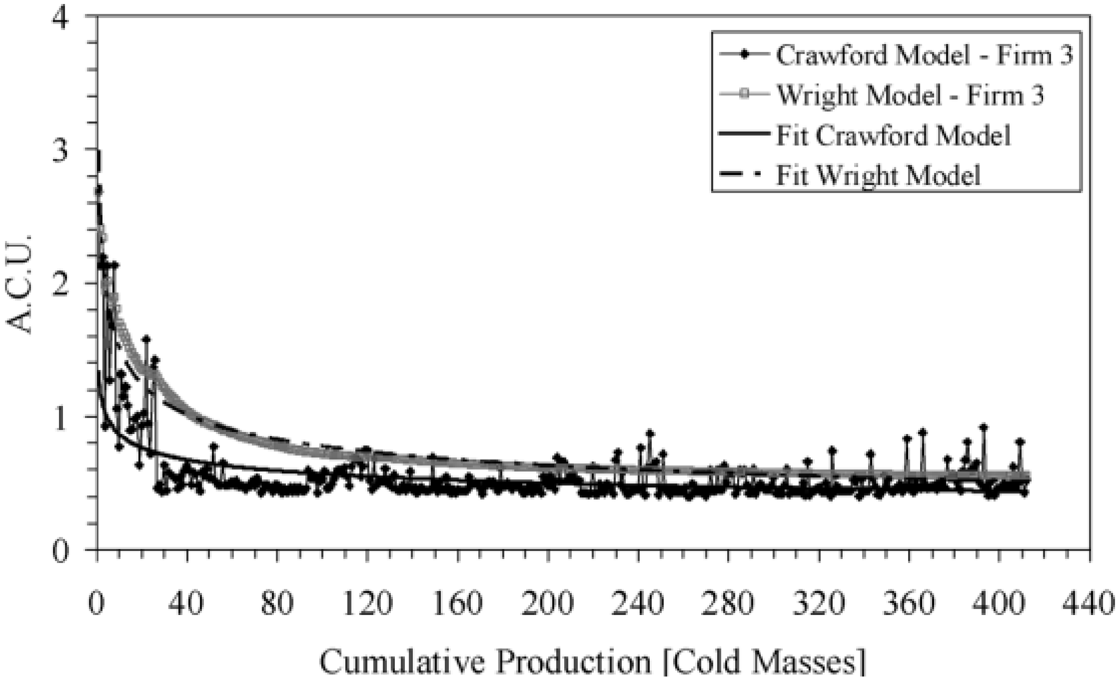
Production strategy	• Three firms, involved from the very beginning (short models and prototypes built in industry/CERN)
	• Procurements of all main components, tooling and set up of particular technologies by CERN (+ flexibility, uniformity and quality; - CERN responsible for everything)
		• Production in the laboratories
		  • MQXFA: cable (LBNL); coil (BNL+FNAL), magnet assembly (LBNL); vertical test (BNL); cold mass and horizontal test (FNAL)
		  • MQXFB: everything at CERN

The learning curve

P. Fessia, et al., IEEE TAS 17 2007

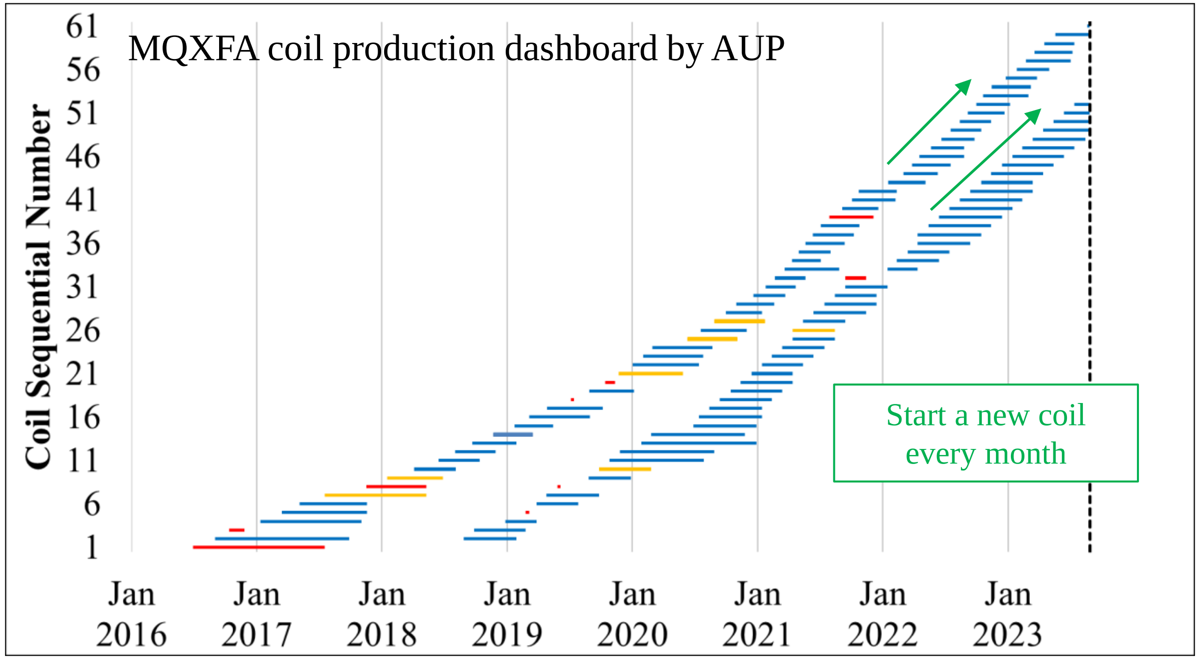
- At full production speed, the time needed to produce an LHC-MB cold mass is ≈ 6 months
- Production stabilizes after the first 30-40 units
- The learning percentage is between 80-85 %

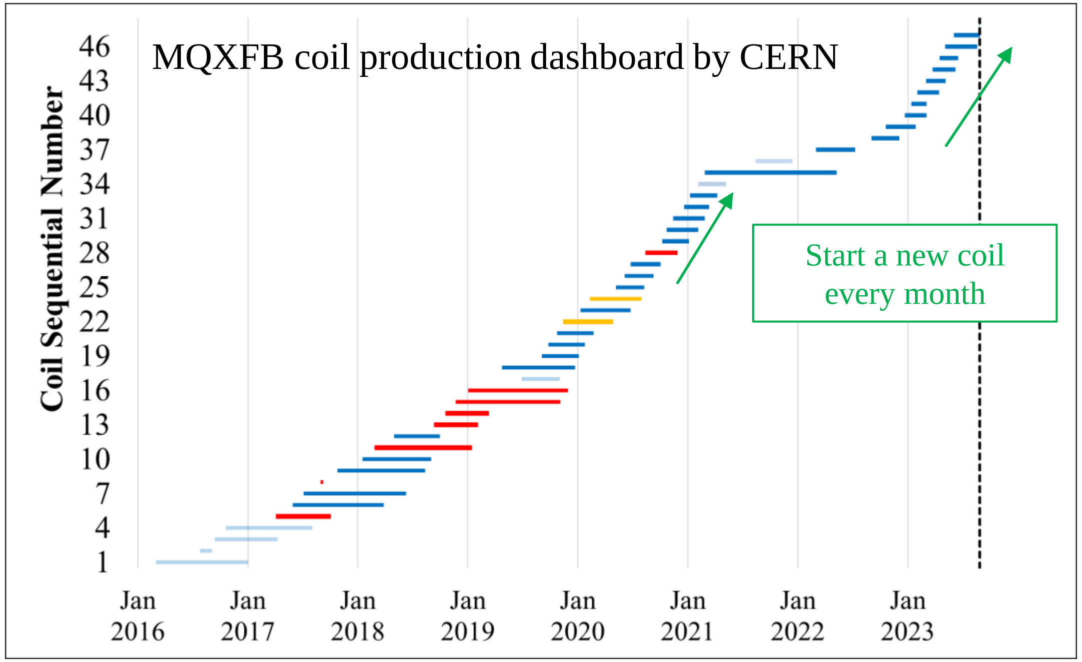




The learning curve

- In Nb_3Sn, for an optimized production process, the clock is given by the production of the coils.
- Similar experience by AUP at CERN:
  - initial phase (≈ 20 coils) with low yield and longer manufacturing times
  - at full production speed, average time required to complete a coil 3 months. Start a new coil every month.





Legend: Rejected; Accepted; On hold; Practice coils

Outline – Part II

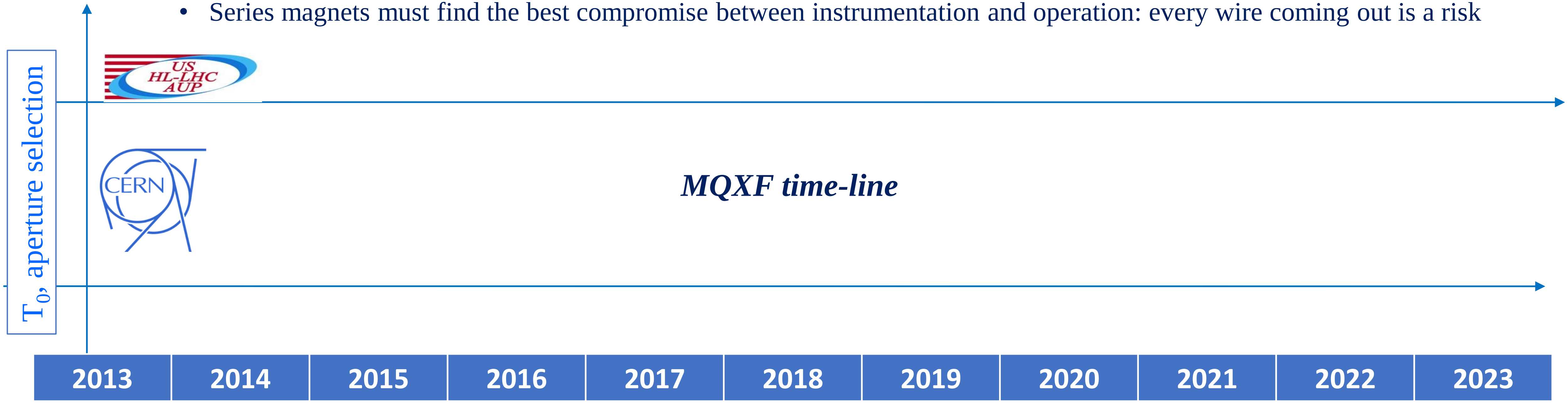
- Part I: Magnet fabrication
- **Part II: Magnet test**
  - **Why do we test?**
  - What do we test?
  - How do we test?
- Conclusions

Why do we test?

- Superconducting magnets are complex systems characterized by challenging features
- Magnet performance has an intrinsic variability that even for mature technologies is not totally understood/controlled
  - This does not prevent us from building reliable accelerators based on superconducting magnets – a challenge in magnet design is finding the good balance between margin/cost/risks. Some examples:
    - RHIC: 14 % of the magnets were tested
    - For the LHC all magnets were tested at 1.9 K
    - For HL-LHC all magnets are/will be tested with thermal cycle (also NbTi)
- Power test at cryogenic temperature is the only way to verify the magnet conformity to the requirements, either before or after installation

Models and proto vs series

- The construction of magnets for accelerators goes through different phases
  - **Model/prototype testing:** understanding design/manufacturing/limits (training, quench protection, etc etc).
    - You can afford to have special instrumentation for a full characterization.
  - **Series testing**: training before installation in the machine & making sure all systems (not just the magnet) work OK: splices, busbars, instrumentation, etc
    - Much cheaper to find non-conformities in the surface during the standalone test than in the tunnel, with 150 other magnets in series cold (~few months for replacement)
    - Series magnets must find the best compromise between instrumentation and operation: every wire coming out is a risk



Grey means not reaching performance requirements

From models to proto and series

✓First validation of the coil fabrication (1.2 m length), testing in a mirror coil configuration (only 1 coil, easier mechanics)

T_0, aperture selection

US HL-LHC AUP

MQXFSM1

$T_0 + 2$

CERN

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

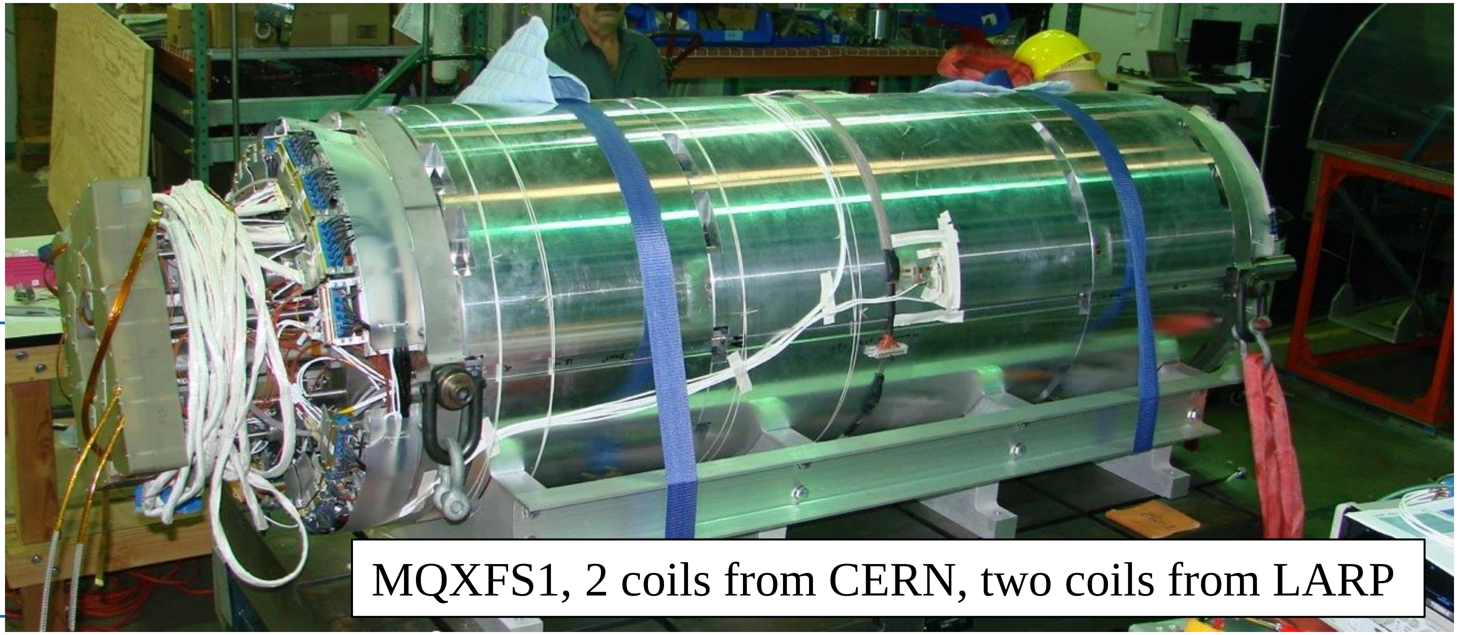
✓*First validation of the magnet design (1.2 m length), 3 years after the selection of the aperture*

T_0, aperture selection

MQXFSM1

MQXFS1

$T_0 + 3$



MQXFS1, 2 coils from CERN, two coils from LARP

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

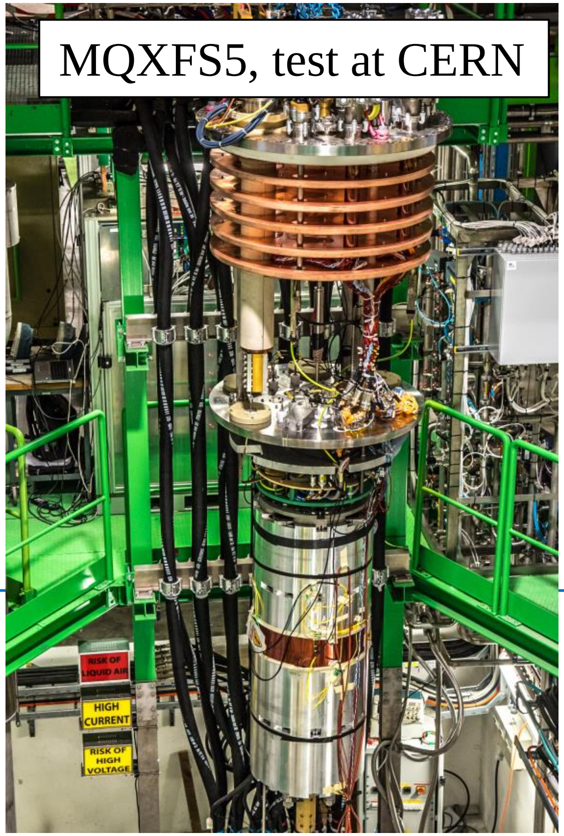
✓MQXFS1 was followed by a series of short models at CERN, to validate design features and margins: today it is still a tool for guiding the construction process

T_0, aperture selection

US HL-LHC AUP: MQXFSM1, MQXFS1

CERN: MQXFS3, MQXFS5, MQXFS6, MQXFS7, MQXFS8

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023


MQXFS5, test at CERN

Grey means not reaching performance requirements

From models to proto and series

✓*MQXFA coil fabrication process validated with the test of a 4 m length coil in mirror structure*

E. Holik et al, IEEE vol 27 2017

T_0, aperture selection

US HL-LHC AUP

MQXFSM1

MQXFAM1

MQXFS1

$T_0 + 4$

CERN

MQXFS3

MQXFS5

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

First 2 MQXFA prototypes did not reach requirements. First magnet fulfilling requirements was MQXFA03 ✓

T_0, aperture selection

US HL-LHC AUP: MQXFSM1, MQXFS1, MQXFAM1, MQXFAP1, MQXFAP2, MQXFA03 (T_0 +6)

CERN: MQXFS3, MQXFS5, MQXFS6, MQXFS7

2013	2014	2015	2016	2017	2018	2019	2020	2021

Grey means not reaching performance requirements

From models to proto and series

A series of magnets followed MQXFA03, not all reaching performance requirements (≈ 3 magnets/year)

T_0, aperture selection


Two MQXFA assembly lines at LBNL

MQXFA03

A04

A05

A06

A07

A08

A10

A11

A08b

A13

MQXFS7

MQXFS8

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

✓*First cold mass tested 10 years after the aperture selection*

T_0, aperture selection

A08b

A10

A13

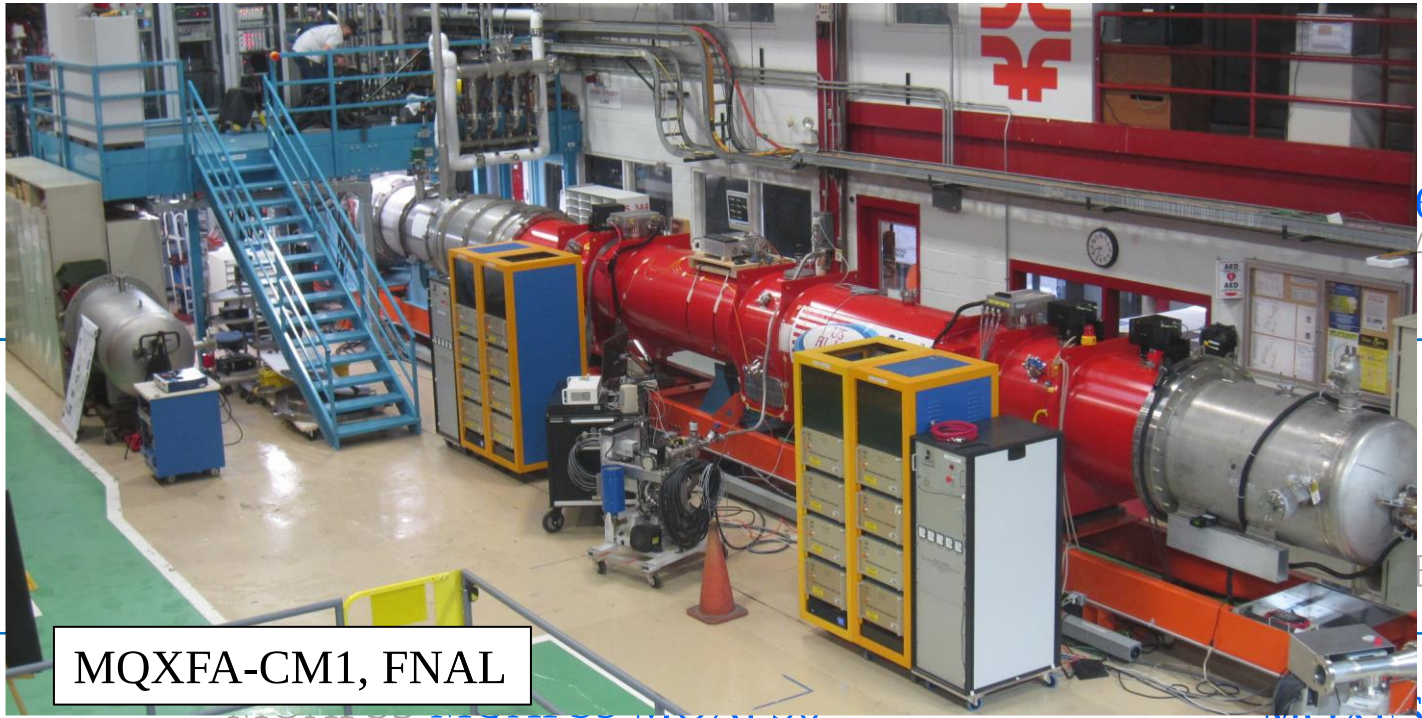
A11

A07

A08

MQXFA-CM1

$T_0 + 10$



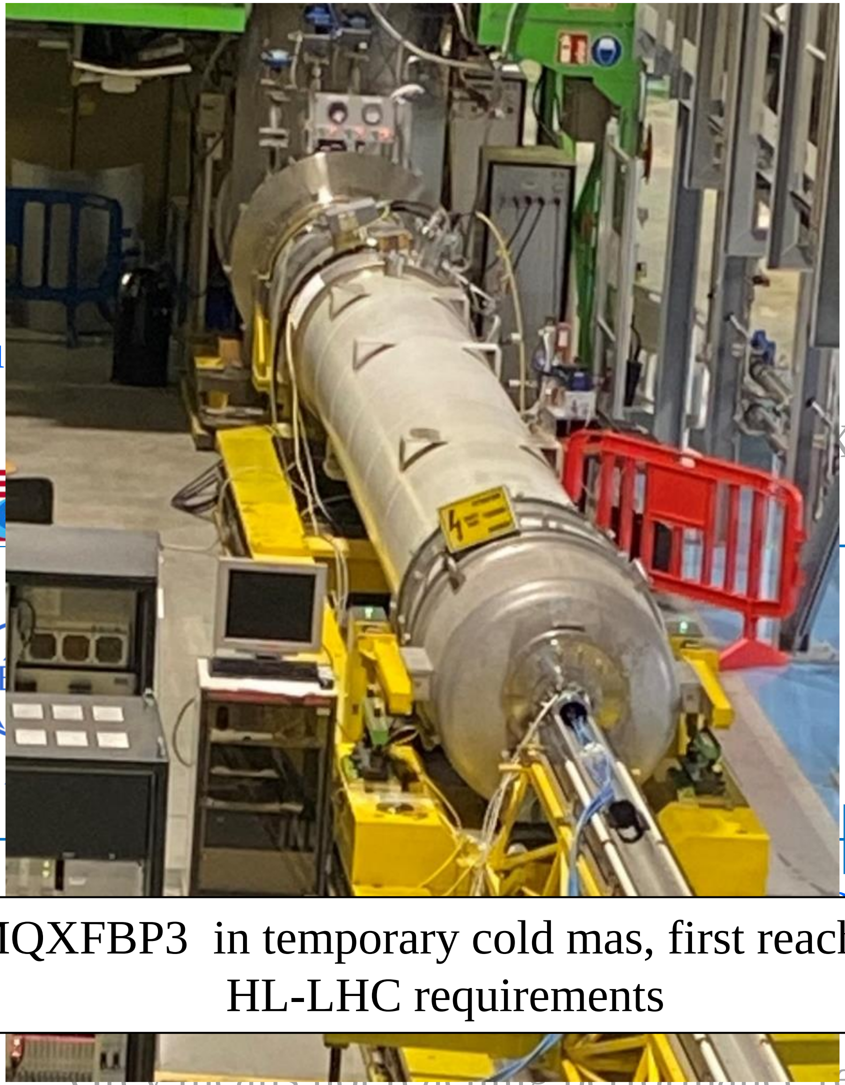
MQXFA-CM1, FNAL

BP2

MQXFS8

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

From models to proto and series



MQXFBP3 in temporary cold mas, first reaching HL-LHC requirements

T_0, apertu

XFAP1

MC

First two long prototype magnets did not reach performance requirements. MQXFBP3 first MQXFB magnet reaching requirements (T_0 +9)

MQXFBP3

MQXFBP1

MQXFBP2

5 MQXFS6

$T_0 + 7$

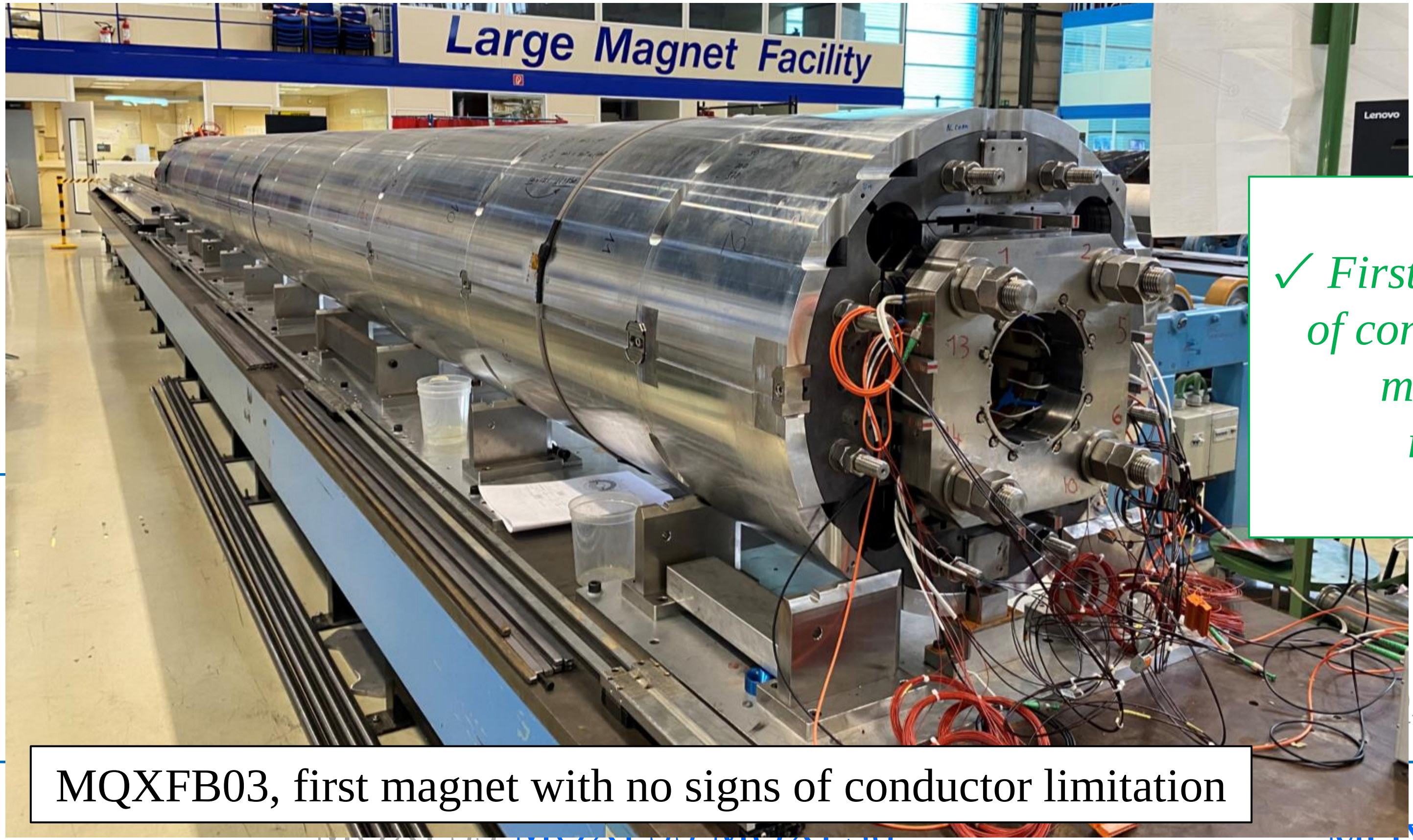
MQXFS7

$T_0 + 9$ MQXFS8

2	2018	2019	2020	2021	2022	2023

requirements

From models to proto and series



MQXFB03, first magnet with no signs of conductor limitation

✓ *First MQXFB magnet with no signs of conductor limitation (T_0 +10). 3 magnets fulfilling HL-LHC requirements (out of 10)*

T_0, aperture selection

US HL-LHC AUP

CERN

MQXFBP3 B03

XFBP2 B02

T_0 + 10

MQXFS7

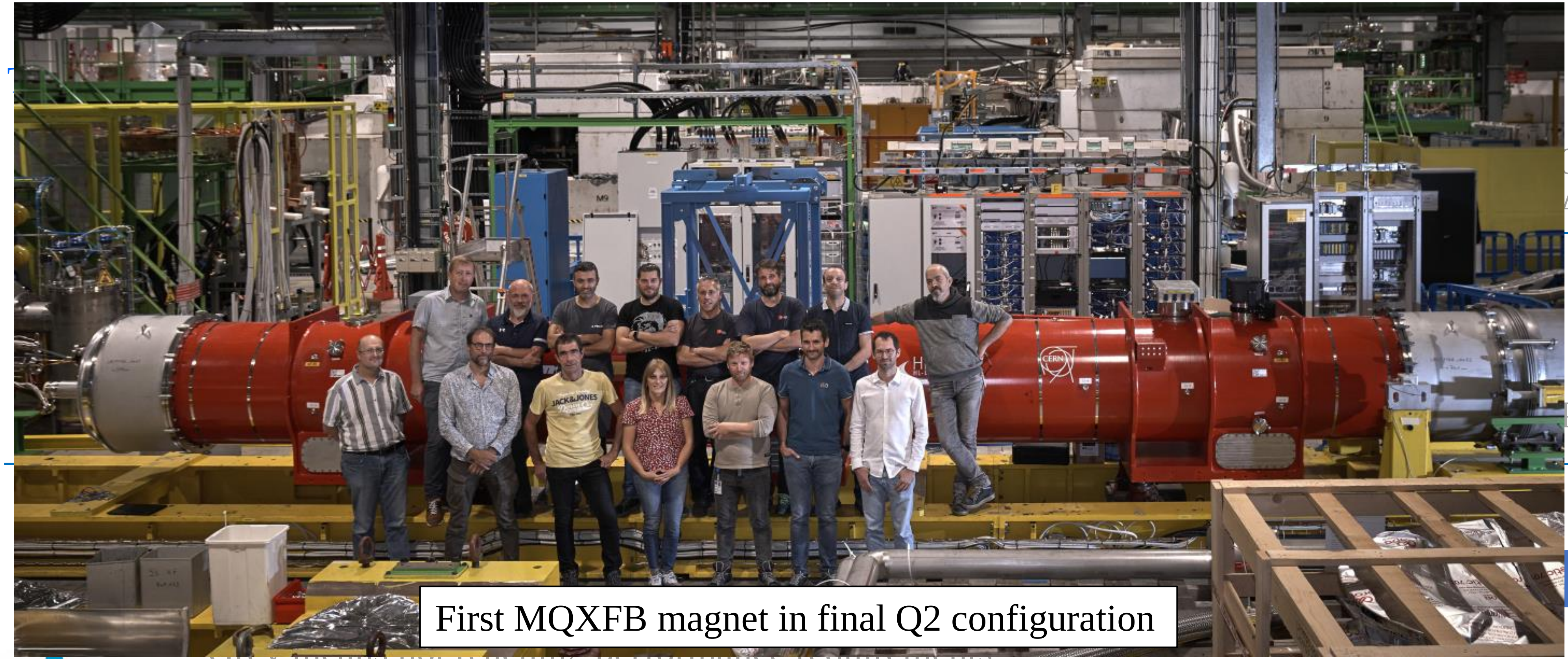
MQXFS8

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

✓*First Q2 final cold mass configuration is being tested now at CERN*



First MQXFB magnet in final Q2 configuration

A08b
A10
A13
A11
07
A08
MQXFA-CM1

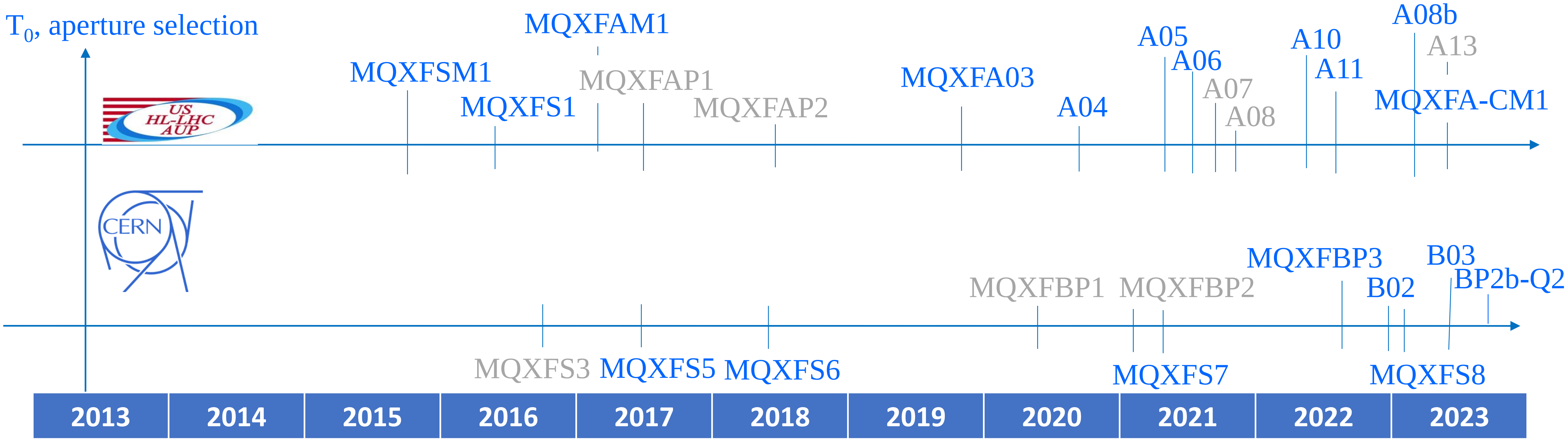
MQXFBP3
B03
P2
B02
BP2b-Q2
$T_0 + 10$
MQXFS8

2022	2023

Grey means not reaching performance requirements

From models to proto and series

Personal note: for new technology such as Nb_3Sn, test as much as and as fast as you can afford, especially in the initial phase of models, prototype and pre-series

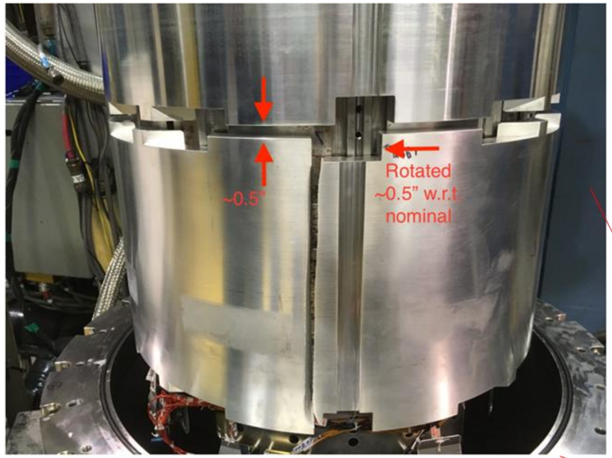


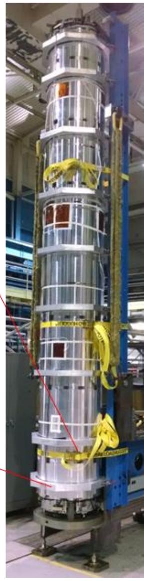
Grey means not reaching performance requirements

The importance of testing in the initial phases

- In some cases, it is easy to find the problem and feedback to the design/manufacturing/testing process can be quickly implemented. In others, it takes a bit longer ☺

Broken Al-support cylinder in MQXFAP2, result of a non-conforming material + not sufficient design margin



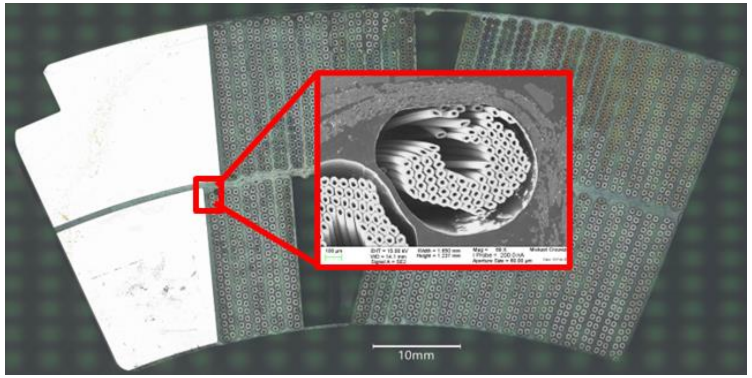


G. Ambrosio et al, IEEE Vol 31, 2021

Electrical short circuit quench heater to coil in a Nb_3Sn coil in MQXFAP1, result of a non-conforming testing procedure

V. Marinozzi et al., IEEE Vol 31 2021

Broken sub-elements in MQXFBP1 coil, systematic coil fabrication problem (longest Nb_3Sn accelerator coils ever built)



S. Izquierdo Bermudez et al, IEEE, vol 33, 2023

Time needed to find the problem

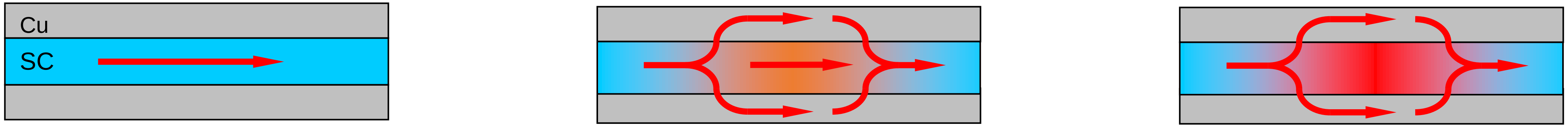
Days → Weeks-Month(s) → ≈ 2 Years

Outline – Part II

- Part I: Magnet fabrication
- Part II: Magnet test
  - Why do we test?
  - **What do we test?**
    - **Quench performance**
    - **Electrical integrity**
    - **Quench protection**
    - **Field quality**
    - **Mechanics**
  - How do we test?
- Conclusions

Quench

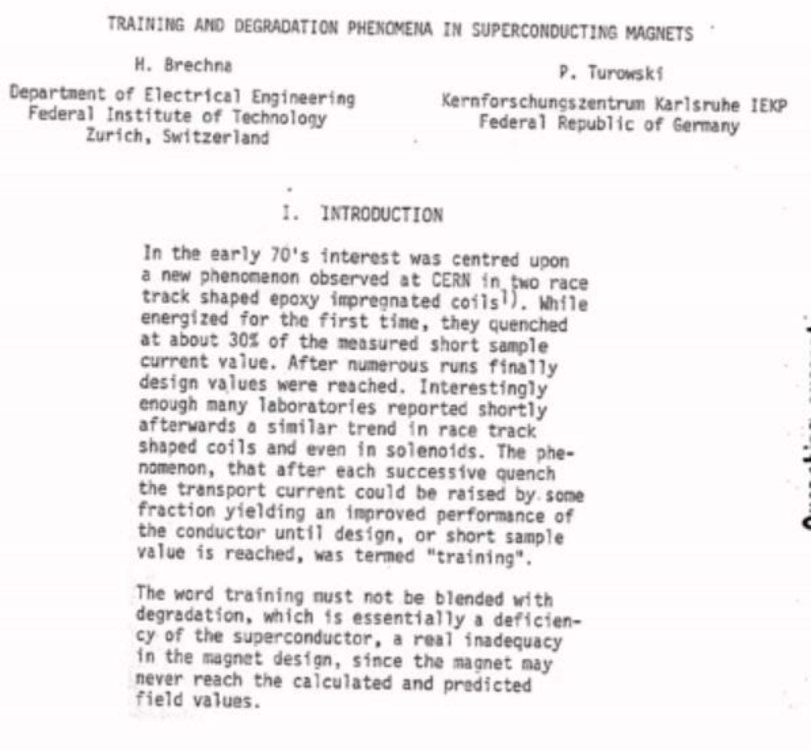
- **Quench** = irreversible transition to normal state. Two scenario:
  - Conductor limited quenches:
    - The superconductor carries its critical current, the rest flow in the stabilizer
    - If power is high enough and cooling low enough, temperature in the superconductor increases → critical current decreases → more current in the stabilizer, less in the superconductor → more dissipation → irreversible transition and quench



  - Energy-deposited or premature quenches:
    - Disturbance → release of energy → increase of temperature of the conductor.
    - If power is high enough and cooling low enough, temperature in the superconductor increases → critical current decreases → more current in the stabilizer, less in the superconductor → more dissipation → irreversible transition and quench
    - Different sources
      - **Mechanical events:** frictional motion, epoxy cracking
      - **Electromagnetic events:** Flux-jumps ,AC loss
      - **Nuclear events:** Particle showers
      - **Thermal events:** Degraded cooling

Training

- Training is characterized by two phenomena:
  - The occurrence of premature quenches
  - The progressive increase of the quench current
    - Irreversible change in the coil's mechanical status
    - Somehow the magnet is 'improving' or getting better quench after quench
  - Mechanical induced quenches are considered the main causes of training in a superconducting magnet (frictional motion & epoxy failure)
- Main features relevant for operation
  - The ability to reach the target current with adequate margin (virgin training)
  - The retraining expected during operation (i.e., memory after thermal cycle)


TRAINING AND DEGRADATION PHENOMENA IN SUPERCONDUCTING MAGNETS

H. Brechna
Department of Electrical Engineering
Federal Institute of Technology
Zurich, Switzerland

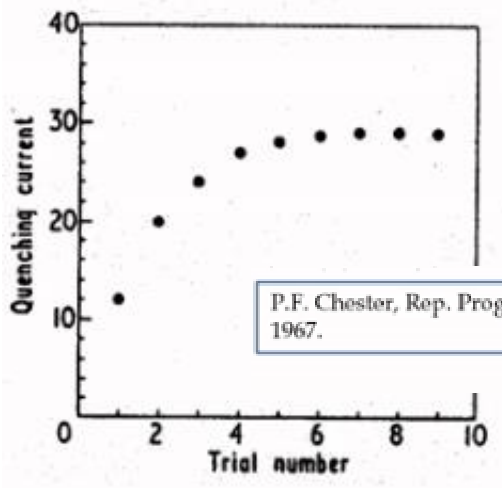
P. Turowski
Kernforschungszentrum Karlsruhe IEKP
Federal Republic of Germany

I. INTRODUCTION

In the early 70's interest was centred upon a new phenomenon observed at CERN in two race track shaped epoxy impregnated coils[1]. While energized for the first time, they quenched at about 30% of the measured short sample current value. After numerous runs finally design values were reached. Interestingly enough many laboratories reported shortly afterwards a similar trend in race track shaped coils and even in solenoids. The phenomenon, that after each successive quench the transport current could be raised by some fraction yielding an improved performance of the conductor until design, or short sample value is reached, was termed "training".

The word training must not be blended with degradation, which is essentially a deficiency of the superconductor, a real inadequacy in the magnet design, since the magnet may never reach the calculated and predicted field values.

Proceedings of the 6th International Conference on Magnet Technology, 1978. p. 597.

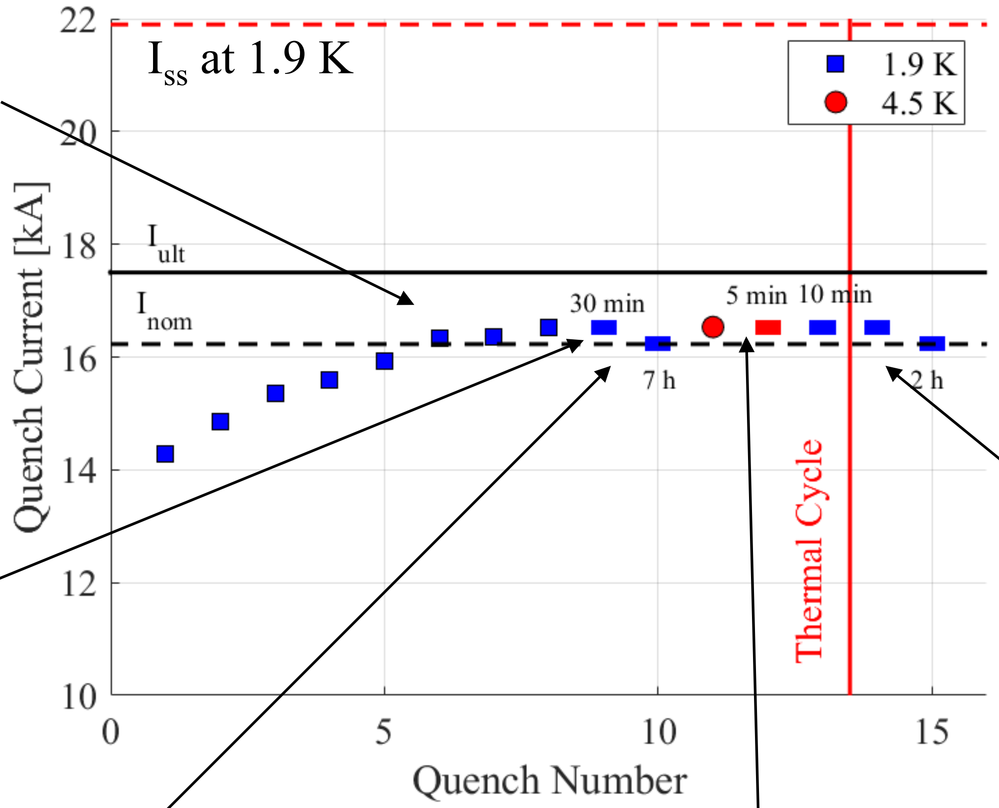


P.F. Chester, Rep. Prog. Phys., XXX, II, 561, 1967.

Example of training

MQXFB03 quench performance

Reached nominal current after 4 quenches



Target current after 8 quenches

Good memory after thermal cycle (i.e., no need to re-train in the machine)

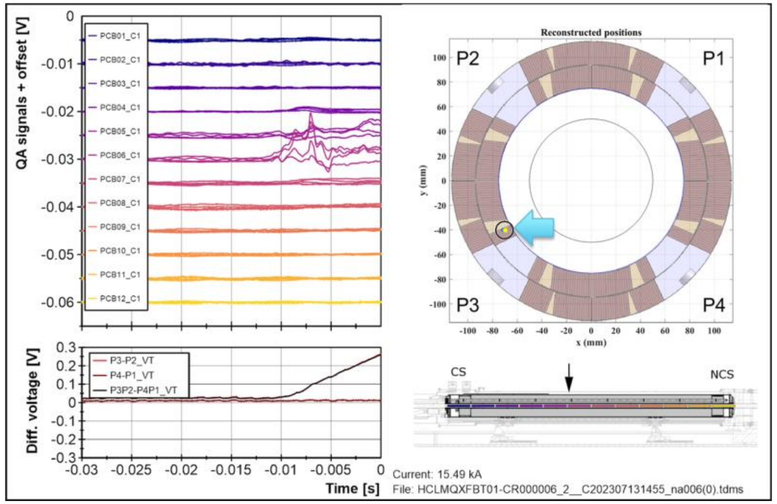
Stable operation at 1.9 K

Reach target current at 4.5 K (i.e., large temperature margin for operation)

Quench performance - diagnosis

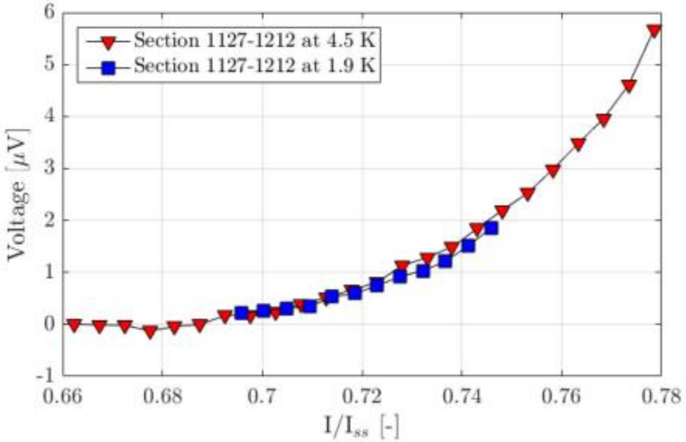
- Important to have good diagnosis tools for quench localization

Quench localization using quench antenna in MQXFB02 [L. Fiscarelli]



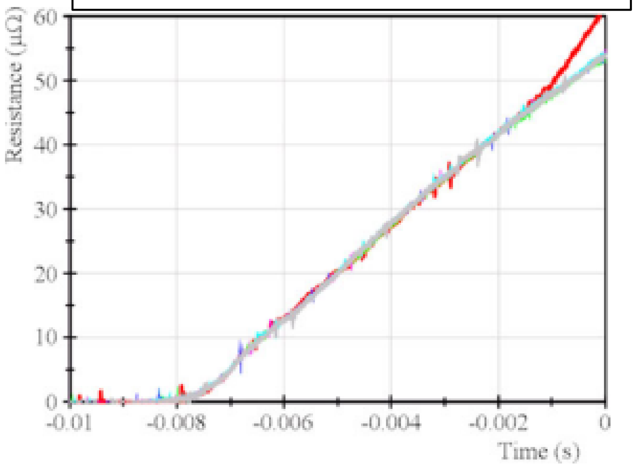
VI measurement in MQXFBP2, indicating conductor limitation in the pole turn segments

[F. Mangiarotti et al, IEEE vol 32 2022]



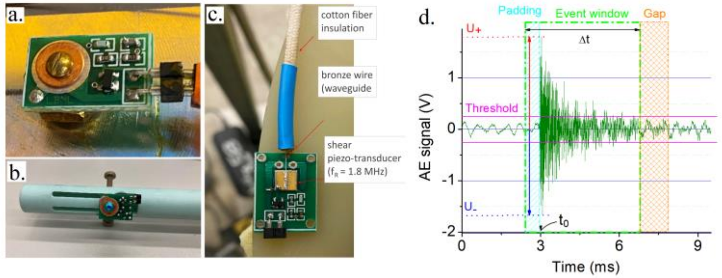
Fast resistance build up in the mid-plane of a 11 T coil, attributed to excessive stress during collaring

[G. Willering et al, IEEE vol 28 2018]

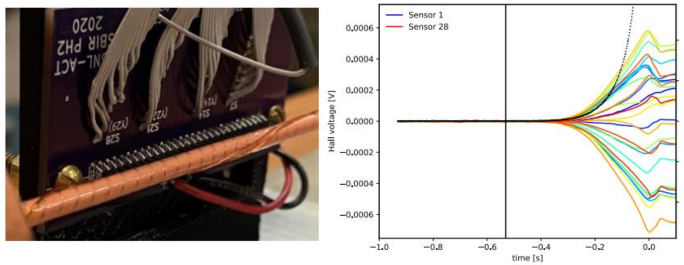


- A field of research with a lot of on-going developments, see M. Marchevsky et al. "Advancing Superconducting Magnet Diagnostics for Future Colliders", [arXiv:2203.08869 [physics.acc-ph] (pdf)].

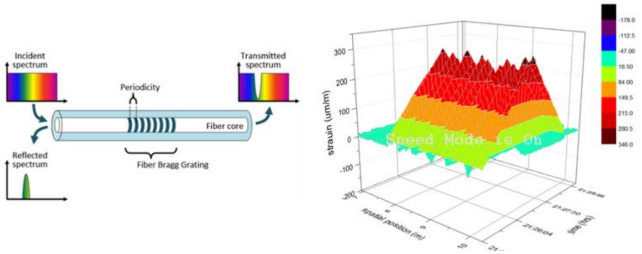
Acoustic emission



Hall sensors array



Fiber optics



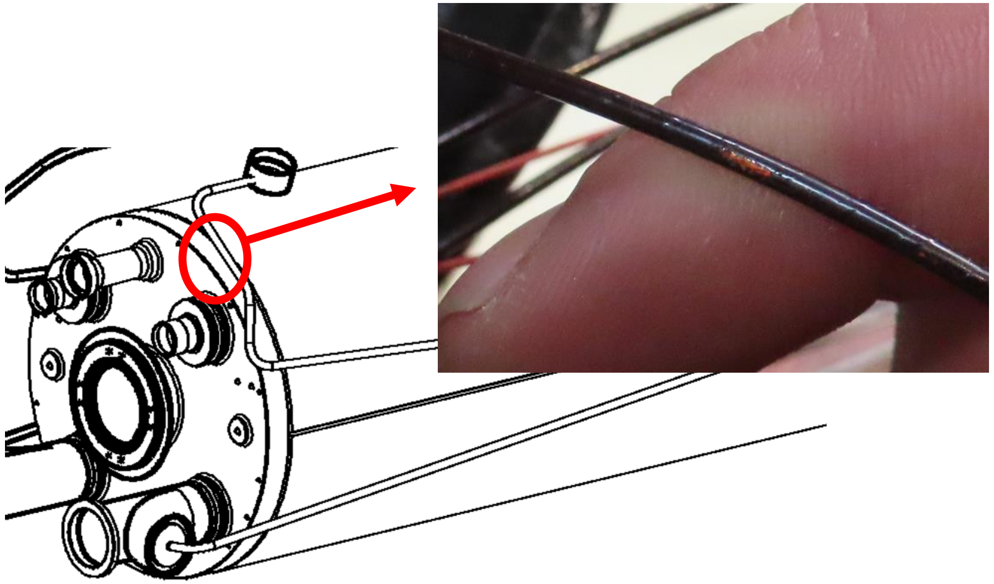
The CERN Accelerator School

Electrical integrity

See lecture R. Piccin

- Electrical integrity:
  - Mandatory for all magnets – at different steps of the fabrication, installation and operation
  - The sooner you intercept faults, the better it is
  - Typical rule:
    - Testing voltage at 1.9 K is twice the maximum voltage expected during operation plus 500 V. Typically is 2.5 – 3.5 kV
    - After test, apply 5 times less voltage at RT (presence of He)

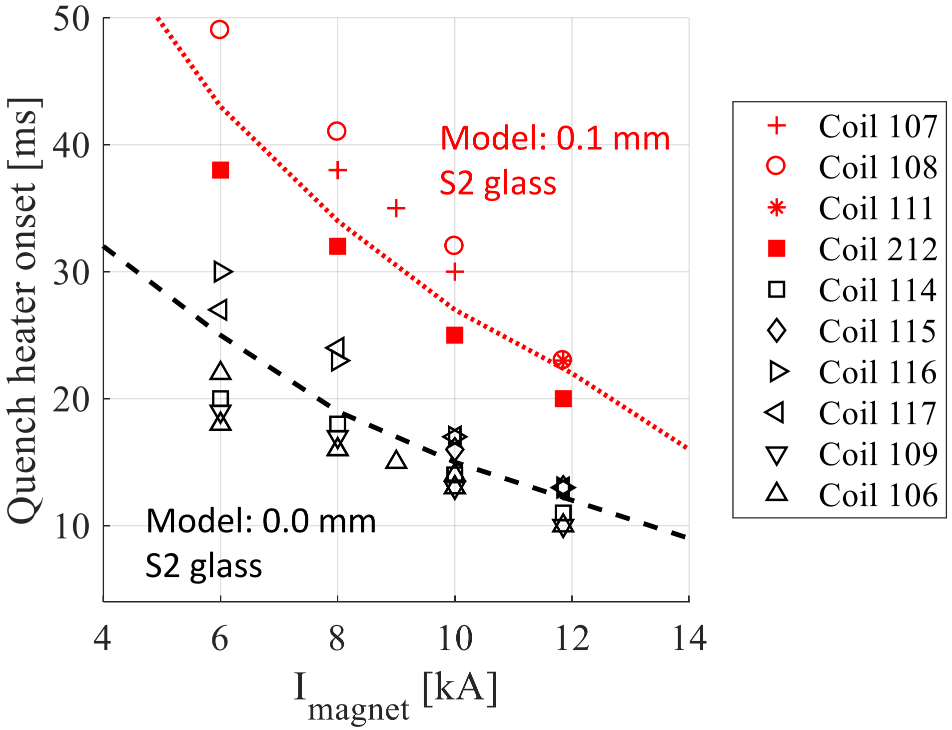
Courtesy of C.A. Cabrera



Quench protection

See lecture E. Todesco

- Several significant observables, to benchmark simulation codes and validate quench protection performance:
  - Quench detection and quench velocity → gives an idea if we are close to the conductor limit or not, validates de protection thresholds
  - MIITs during quench → validates the estimates on Thot
  - Quench heater delay and minimum heater energy → validates the choice of the protection strategy

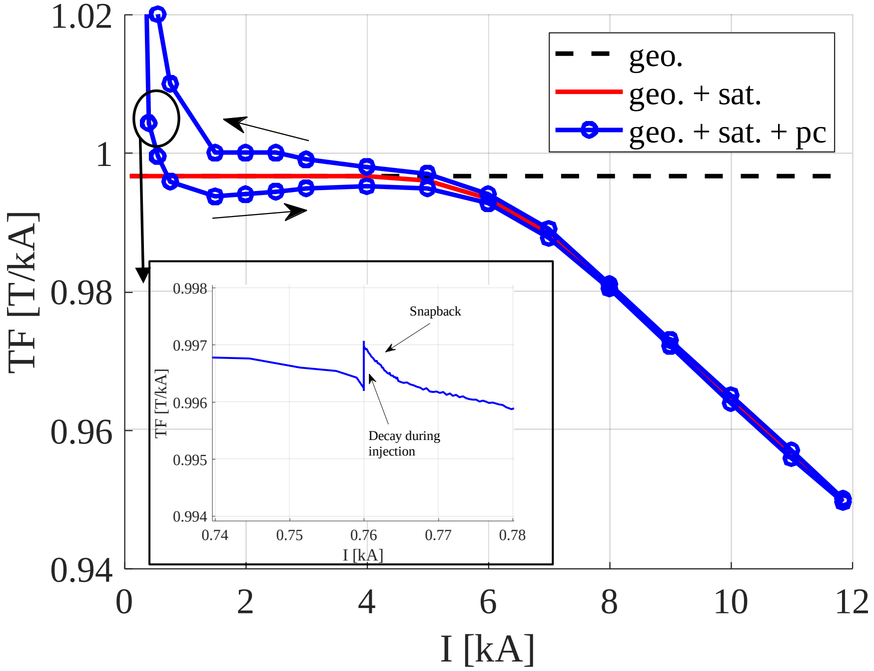


Field quality

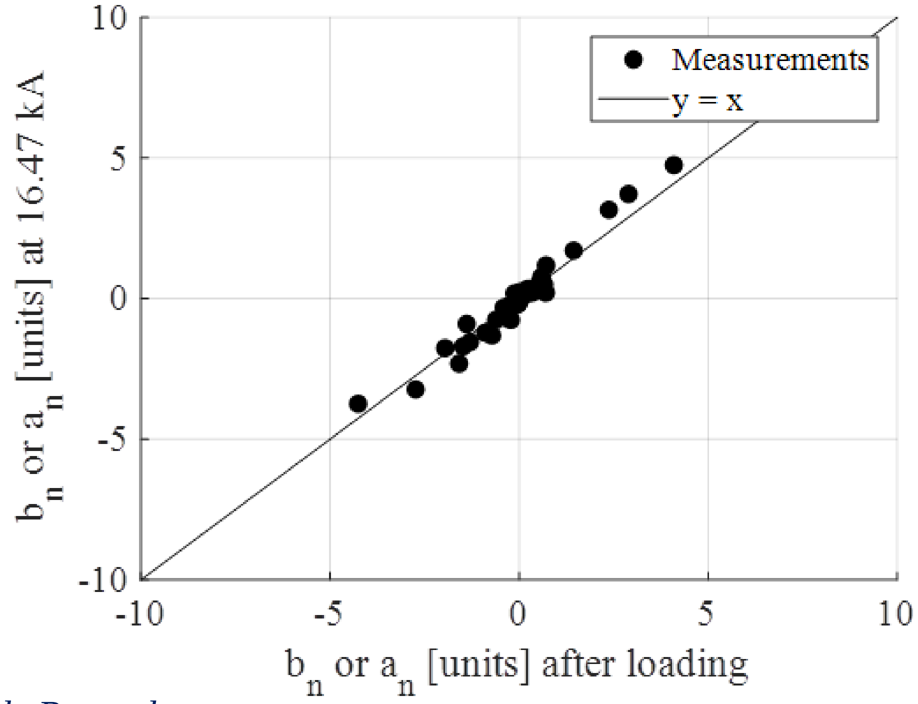
See lecture E. Todesco/M. Buzio/L. Fiscarelli

- Some components can be measured only at 1.9 K/4.5 K (iron saturation, persistent currents, dynamic effects), however, a sampling on a fraction of the magnets (10 %) allows building effective magnetic models (see Fidel).
- Correlations from RT and 1.9 K/4.5 K measurements effective to reduce the testing program at cryogenic temperature.

Transfer function of the MBH-11 T magnet



Cold warm correlation on MQXFS magnets

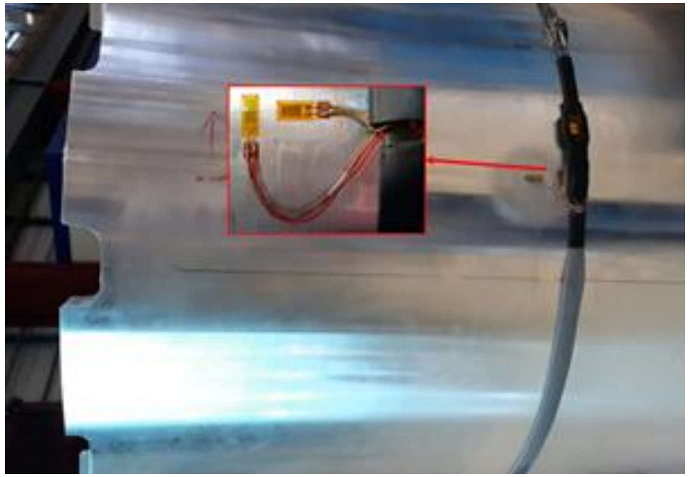


Mechanics

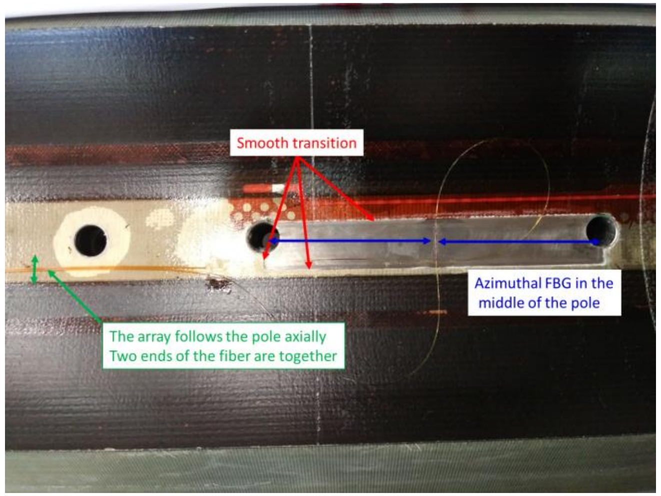
- Allow to have an experimental verification of the mechanical behavior
- It is usually challenging to find a good place to measure, but it is very important to have reliable measurements to understand how your magnet works: start thinking how you are going to measures since the very early state of the design!

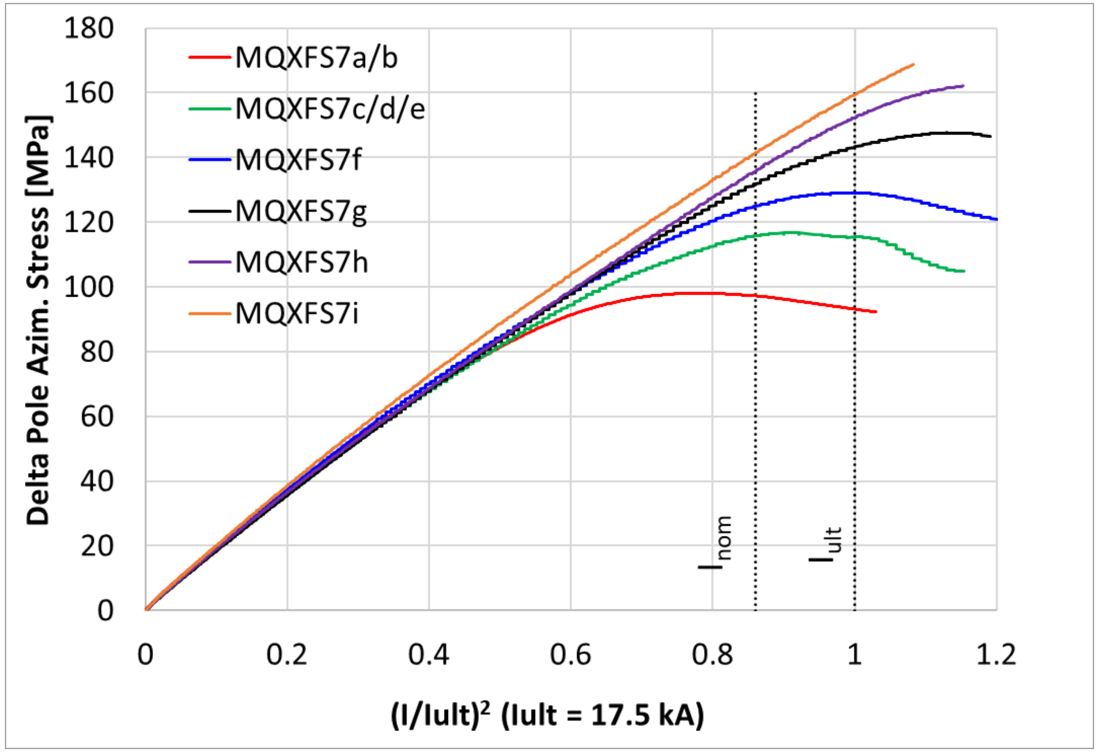
- Strain gauges are the usual way to measure, but new technologies (fiber optics) are emerging

Strain gauges installed in MQXF Al-cylinder



Strain gauges installed in MQXF coils





by M. Guinchard

Outline – Part II

- Part I: Magnet fabrication
- Part II: Magnet test
  - Why do we test?
  - What do we test?
  - **How do we test?**
- Conclusions

How do we test?

- Short to medium length magnets can be tested in a vertical cryostat → magnet can be tested in stand alone configuration (i.e., no need of cold mass and cryostat). Fast turn around time and a lot of flexibility for instrumentation.

- Longer (> 7 m) magnets are tested horizontally, assembled in a cold mass and a cryostat (≈ 6 months of additional work, which is in any case needed for magnets to be installed in an accelerator)

- For complex systems, the test of a series of magnets (string test) can serve as a test bed for matters or conditions that either:
  - cannot be tested within the component's acceptance and characterization program, or
  - depend on the response of the integrated system

- String tests were done for the LHC (ref STRING LHC) and will be done as well for HL-LHC (see M. Bajko, IEEE MT28 special issue, and some more info in the annex)

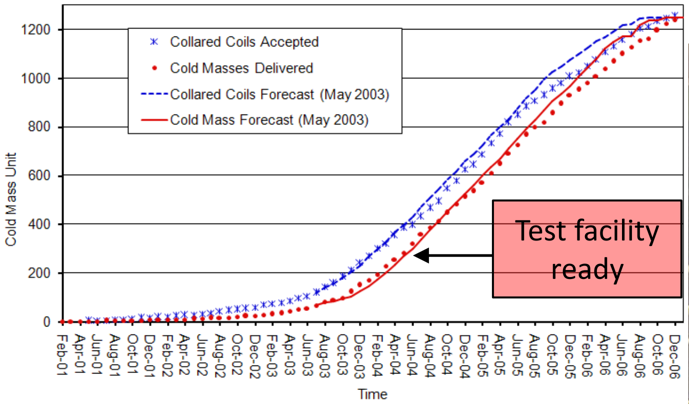
D1 magnet (6.3 m) ready for vertical test in KEK

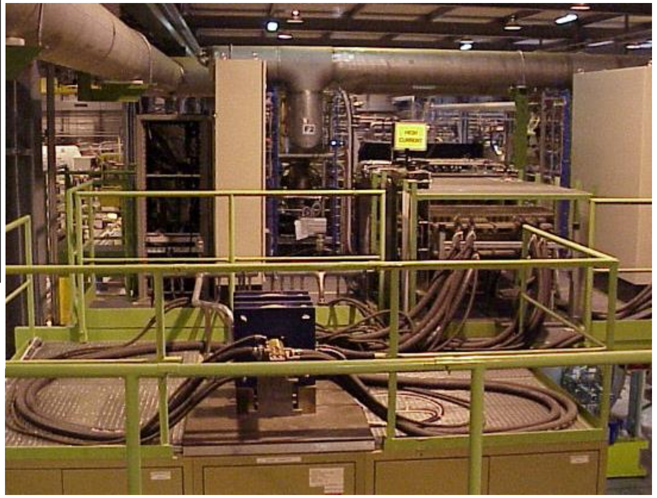
LHC superconducting test facility

- The test facility consists of 12 fully equipped test benches arranged in 6 clusters which can run independently. All test benches are capable to operate, both at 1.9 K and 4.5K
- Cryo-magnets can be equipped with anticryostats & shafts for magnetic measurements and quench localisation
- 1600 magnets to test in 5 years (250 magnets/year), operated round the clock for 11 month per year P. Pugnat, A. Siemko IEEE TAS 17 2007

LHC superconducting test facility

- Facility was completed and fully operational in May 2004
- Testing is part of construction
  - It is never too early to start working in your test station ☺





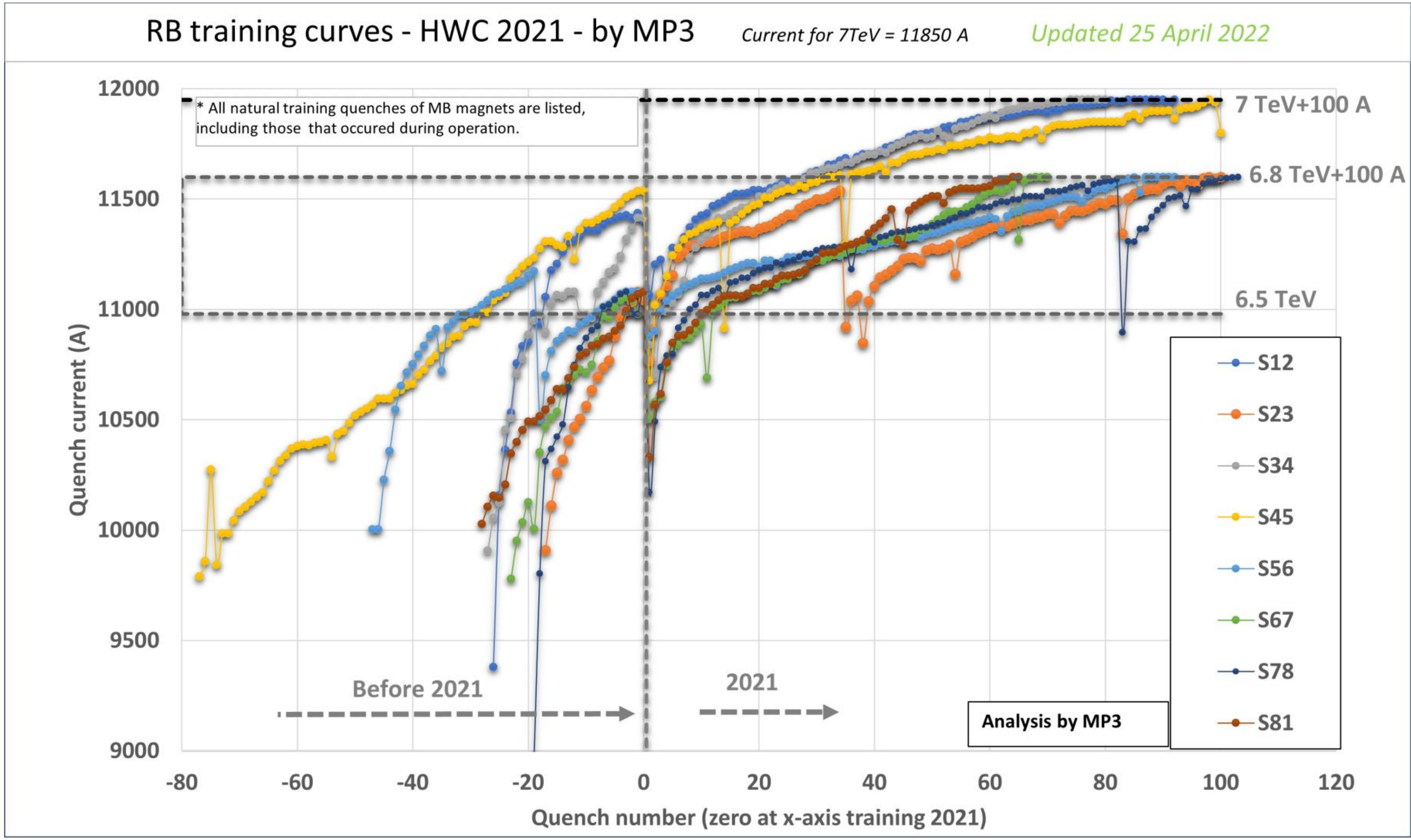
Training in the LHC dipoles

- LHC dipoles assembled by three manufactures (series 1000, 2000 and 3000)
  - Build to print, same procedures with few exceptions
- All magnets individually tested at 1.9 K
  - All powered above nominal (11850 A, 8.3 T, 7 TeV)
  - About 50 % powered to ultimate (8 % more than nominal, 12850 A, 9 T)
    - Requirement: ≤ 2 quenches to nominal, ≤ 7 quenches to ultimate
  - Less than 10 % went through thermal cycle (biased sample)
    - Magnet not reaching 12850 A within 9 quenches were tested after thermal cycle
    - Requirement: no quench to nominal, 3 quenches to ultimate
  - Bonus strategy:
    - Magnets reaching "rapidly" ultimate were given a bonus (1% bonus for magnets going to 9 T with ≤ 3 quenches)

LHC dipoles in the LHC machine

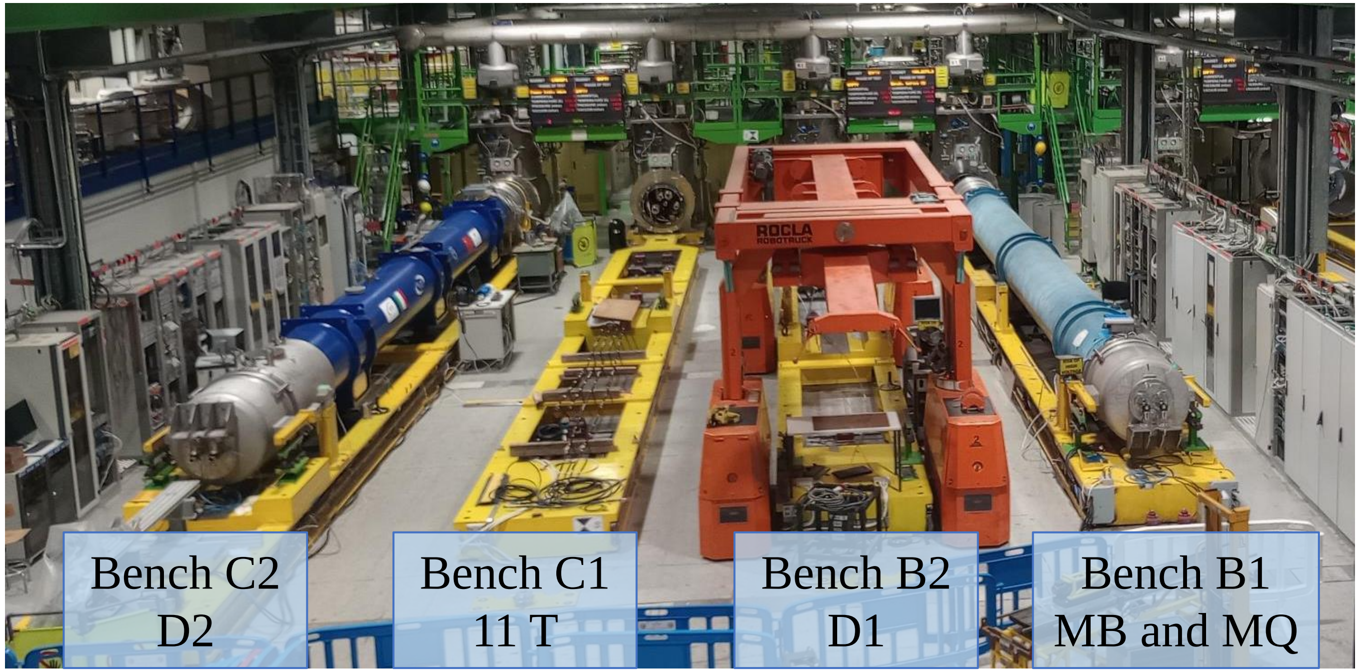
- In the LHC we have 1232 magnets, connected in series in 8 circuits (i.e., 154 magnets per circuit)

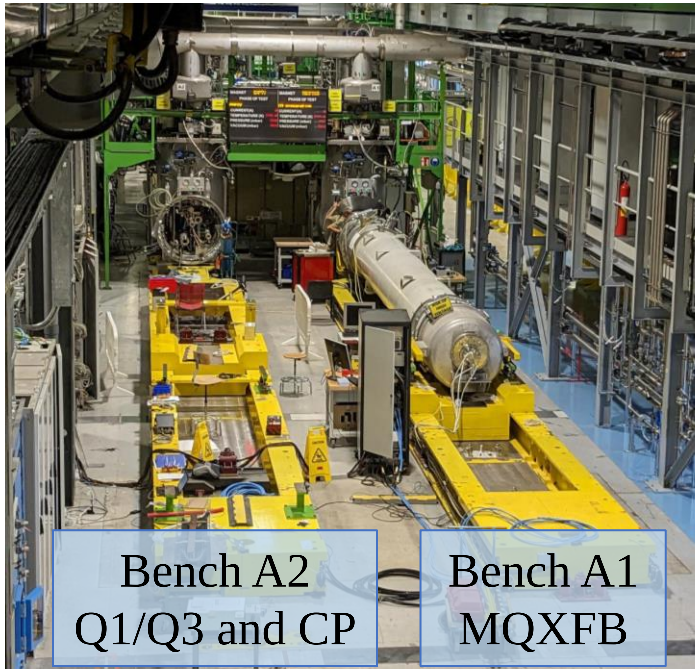
- If every magnet needs to quench once to reach nominal → 154 quenches per sector, and we can do only 2-3 quenches per day → training in the machine is very expensive and that is why memory after thermal cycle is VERY important!

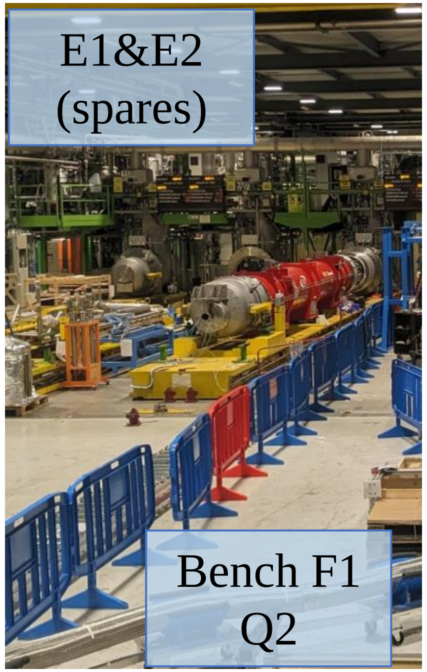


HL-LHC superconducting test facility

- Larger variety, but much less objects to tests. All test benches are capable to operate, both at 1.9 K and 4.5K
- Standardization as much as possible, to limit types of anti-cryostats, shafts for magnetic measurements, and quench antenna.





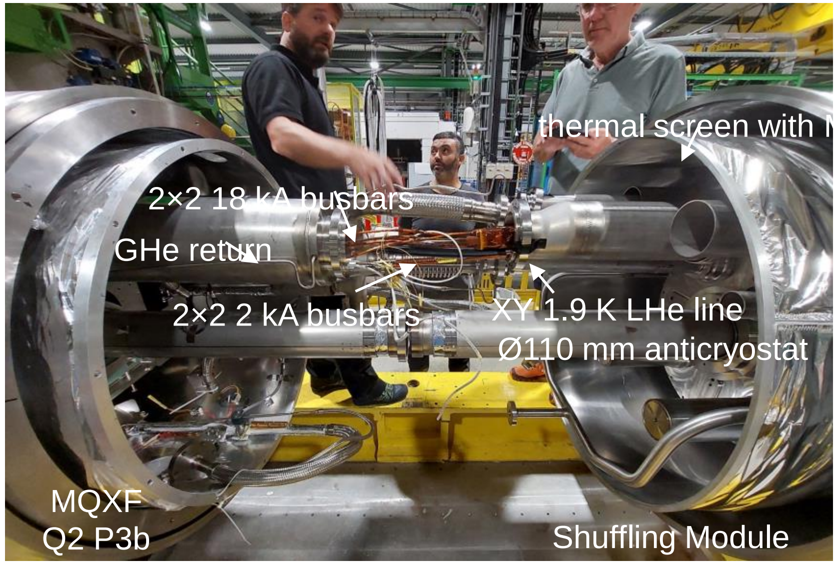


HL-LHC test facility upgrade

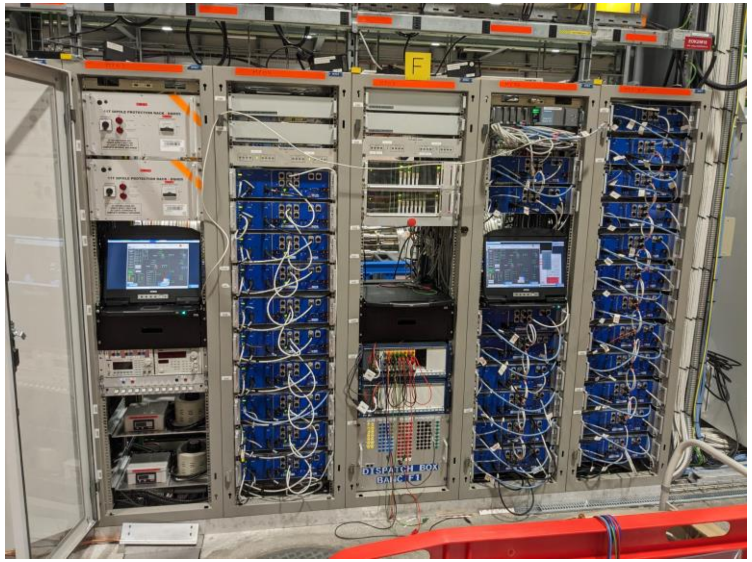
- Upgrade of the test facility needed to adapt to
  - higher current (16.23 kA for MQXF),
  - variety of circuits/configurations, including systematic test at 4.5K
  - and new technology challenges (for example, flux jumps in Nb_3Sn and tight protection settings),

Warm leads

Q2 shuffling module to magnet connection



Protection and data acquisition rack



Training in the HL-LHC magnets

- HL-LHC magnets are built in different places all around the world (China, Italy, Japan, Spain, US). Collaboration agreements between CERN and national laboratories, with the laboratories steering the production of the magnets as in-kind contributions to CERN (except Q2 which is fully produced at CERN).
- All magnets are tested at 1.9 K and 4.5 K. In most of the cases, the magnet is tested first vertically in stand-alone configuration and then assembled & tested in a cold mass.
- Testing strategy:
  - Nb_3Sn magnets are powered to nominal (16230 A, 11.3 T, 7 TeV) at 4.5 K, to nominal + 300 A at 1.9 K.
  - NbTi magnets are powered to ultimate current at 1.9 K (8 % more than nominal)
  - All magnets go through a thermal cycle. The magnets shall be able to reach nominal field after a thermal cycle with a target of ≤ 1 quench and a maximum of ≤ 3 quenches.
- The time needed to test a cold mass horizontally is ≈ 9 weeks (3 weeks are high current tests at cryogenic temperature, the rest (6 weeks) is for preparations, cool down and warm up).

Outline – Part II

- Part I: Magnet fabrication
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Conclusions (1/2)

- A superconducting magnet is a complex system which needs to work in an accelerator: every single detail needs to be engineered
  - It involves many different levels of expertise.
  - There are several ways to design and build a superconducting magnet, the solution is not unique!

- Strand is typically manufactured in industry. For the rest: different solutions for different magnet productions.

- The coil is the most critical component of a superconducting magnet.
  - In Nb_3Sn, since the superconductor is brittle the typical approach is to go for a 'wind and react' technology. Brittle does not mean that does not work; we are building accelerator quality Nb_3Sn magnets to be installed in HL-LHC in few years!

Conclusions (2/2)

- The test of a magnet is the final assessment of its conformity to requirements before installation

- Several aspects: electrical integrity, performance, protection, mechanics, field quality. Each problematic has specific features requiring different approaches

- Testing is a cost, and a challenge in magnet design is finding the good balance between margin/cost/risks
  - *Personal note: for new technology such as Nb_3Sn, test as much as and as fast as you can afford, especially in the initial phase of models, prototype and pre-series*

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