SC magnet fabrication and testing
based on LHC and HL-LHC magnet production

Susana Izquierdo Bermúdez
susana.izquierdo.bermudez@cern.ch

Additional slides

Strand and cable

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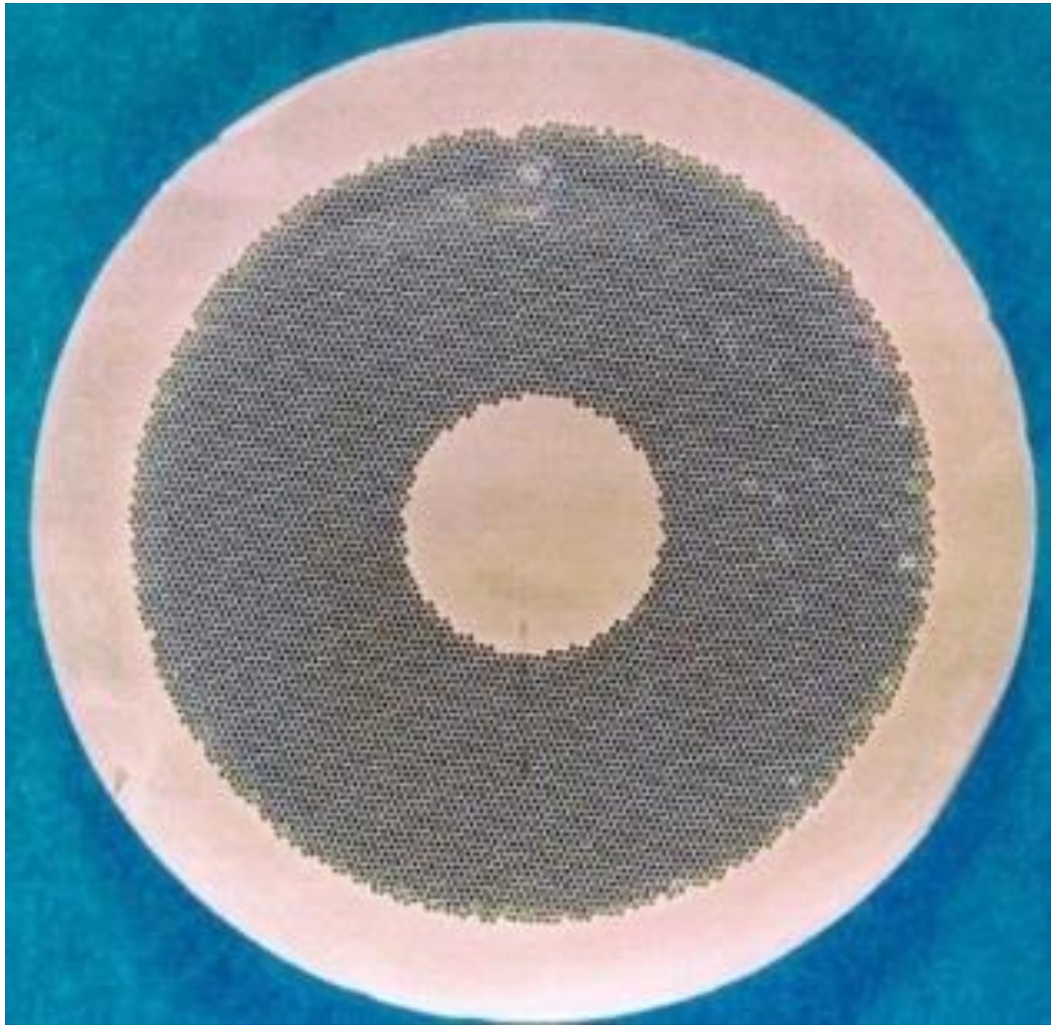
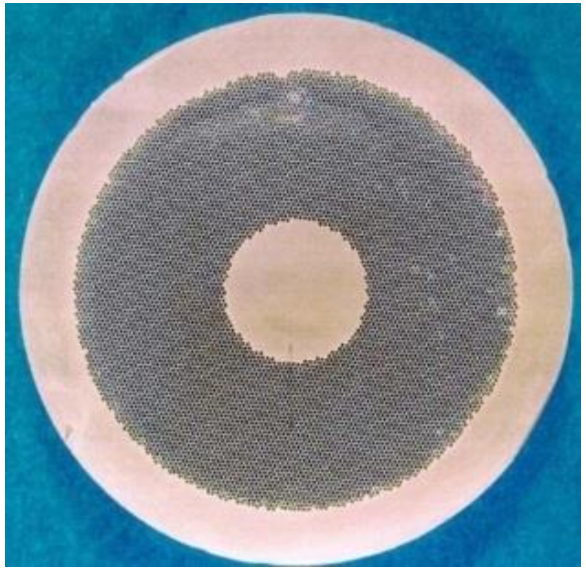
Strand: a multifilament wire



- 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*"
- We small filaments are needed?
  - Stability (flux jumps)
  - Magnetic field quality
    - Persistent currents
    - Inter-filament coupling currents
- Why are they embedded in a copper matrix?
  - Stability (again)
  - Protection, to redistribute the current in case of quench

See lectures on Technical Superconductors (M. Eisterer), Quench protection (E. Todesco) and Hysteresis and dynamic effects (E. Todesco)

Strand manufacturing process (NbTi)

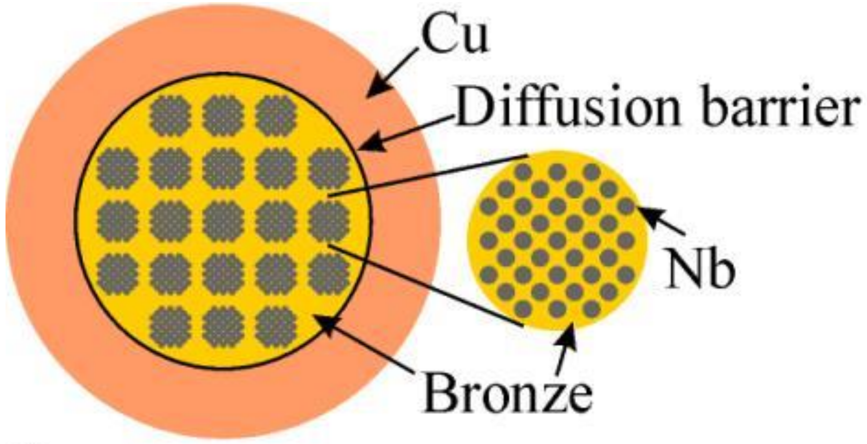


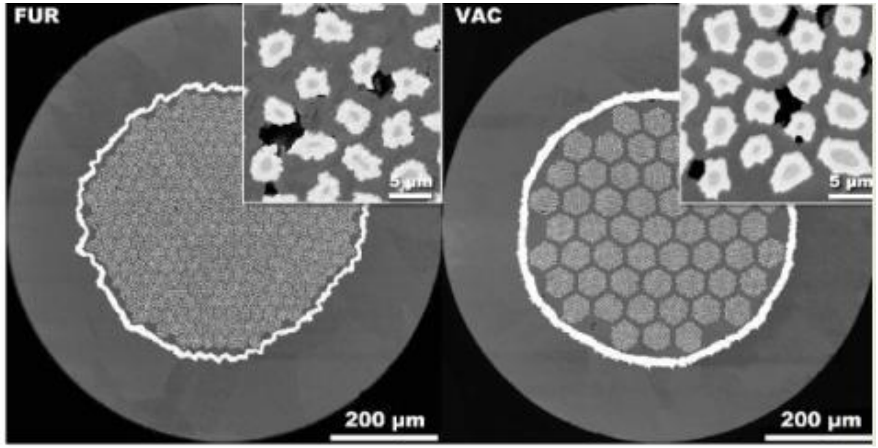
- The **copper to superconductor ratio** is specified for the application to ensure quench protection, without compromising the overall critical current of wire.
- The **filament diameter** is chosen to minimize flux jumps and field errors due to persistent currents, at the same time maintaining the wire processing cost down.
- The **inter-filament spacing** is kept small so that the filaments, harder than copper, support each other during drawing operation. At the same time, the spacing must be large enough to prevent filament couplings.
- A **copper core and sheath** is added to reduce cable degradation.
- The main manufacturing issue is the **piece length**.
  - It is preferable to wind coils with single-piece wire (to avoid welding). LHC required piece length longer than 1 km.

Fabrication of Nb_3Sn multifilament wires

- **Bronze process**
  - Nb rods are inserted in a bronze (CuSn) matrix. Pure copper is put in the periphery and protected with a diffusion barrier (Ta) to avoid contamination.
  - Advantage: small filament size
  - Disadvantage: limited amount of Sn in bronze and annealing steps during wire fabrication to maintain bronze ductility.
  - Non-Cu J_C up to 1000 A/mm^2 at 4.2 K and 12 T.

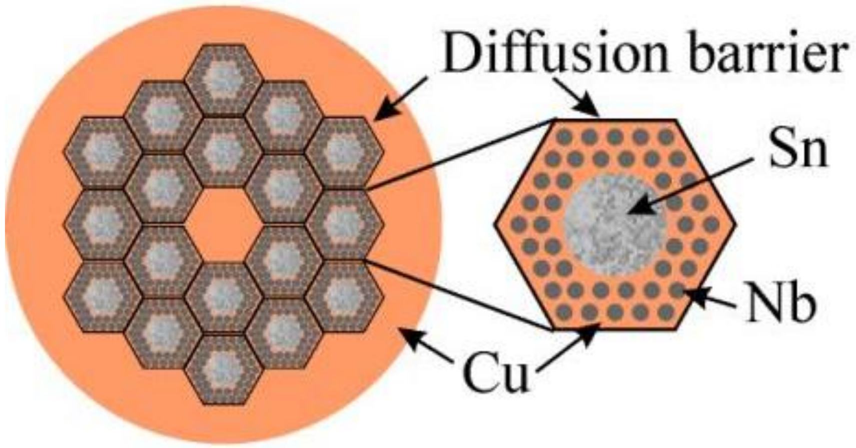
A. Godeke



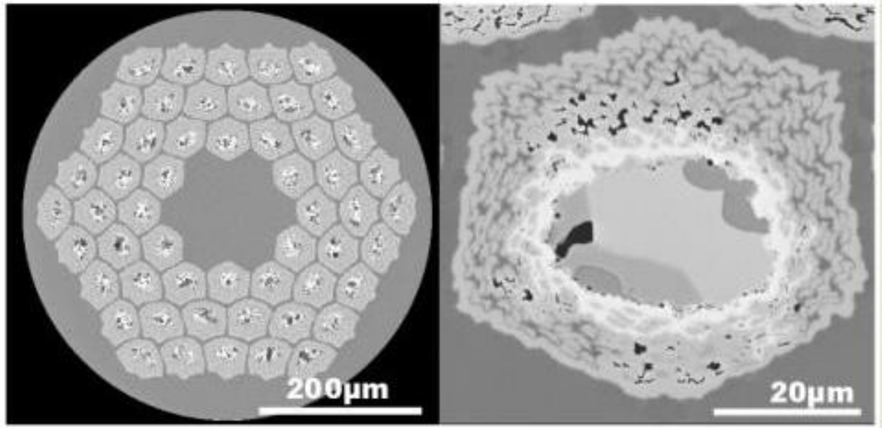


Fabrication of Nb_3Sn multifilament wires

- **Internal tin process**
  - A tin core is surrounded by Nb rods embedded in Cu (Rod Restack Process, RRP) or by layers of Nb and Cu (Modify Jelly Roll, MJR).
  - Each sub-element has a diffusion barrier.
  - Advantage: no annealing steps and not limited amount of Sn
  - Disadvantage: small filament spacing results in large effective filament size (50 μm) and large magnetization effect and instability.
  - Non-Cu J_C up to 3000 A/mm^2 at 4.2 K and 12 T.

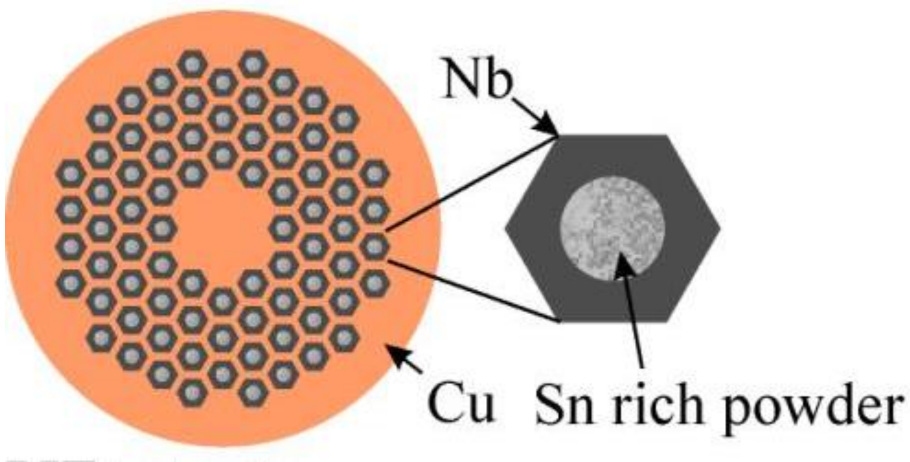


A. Godeke, [2].

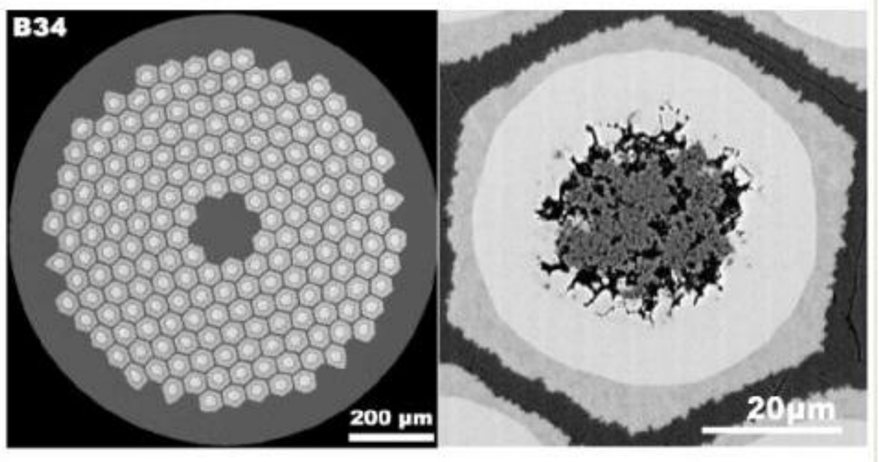


Fabrication of Nb_3Sn multifilament wires

- **Powder in tube (PIT) process**
  - $NbSn_2$ powder is inserted in a Nb tube, put into a copper tube.
  - The un-reacted external part of the Nb tube is the barrier.
  - Advantage: small filament size (30 µm) and short heat treatment (proximity of tin to Nb).
  - Disadvantage: fabrication cost.
  - Non-Cu J_C up to 2400 A/mm^2 at 4.2 K and 12 T.

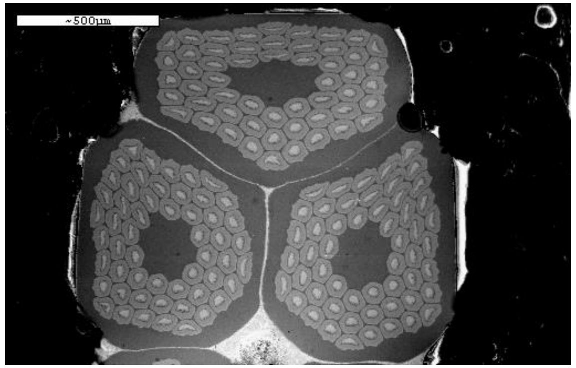


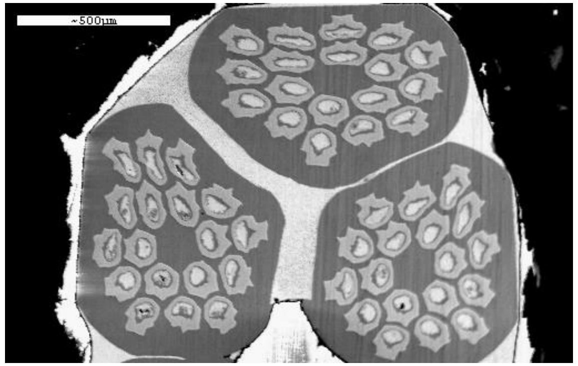
A. Godeke, [2].

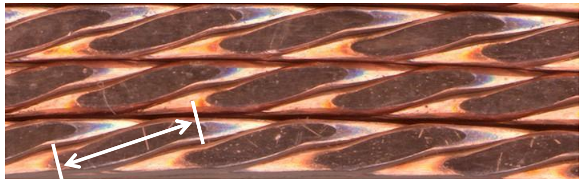


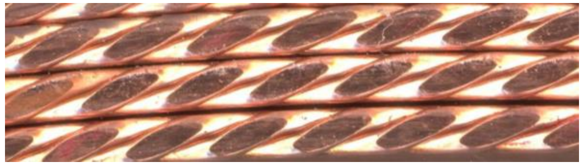
Fabrication of the Rutherford fable

- In the cable sides, the **strands are deformed**; the deformation determines
  - a reduction of the filament cross-sectional area (Nb-Ti) or
  - breakage of reaction barrier with incomplete tin reaction (Nb3Sn).
- In order to avoid degradation
  - The strand cross-section after cabling is investigated
  - Edge facets are measured.General rule: no overlapping of consecutive facets
- Keystone angle is usually limited to 1 or 2°.
- We define as narrow edge packing factor the ratio of the area of two non-deformed strands to that of a rectangle with dimensions of the narrow edge thickness times the wire diameter, that is $\pi d/2t_{in}$.
- Usually, it ranges from 0.95 to 1.03.



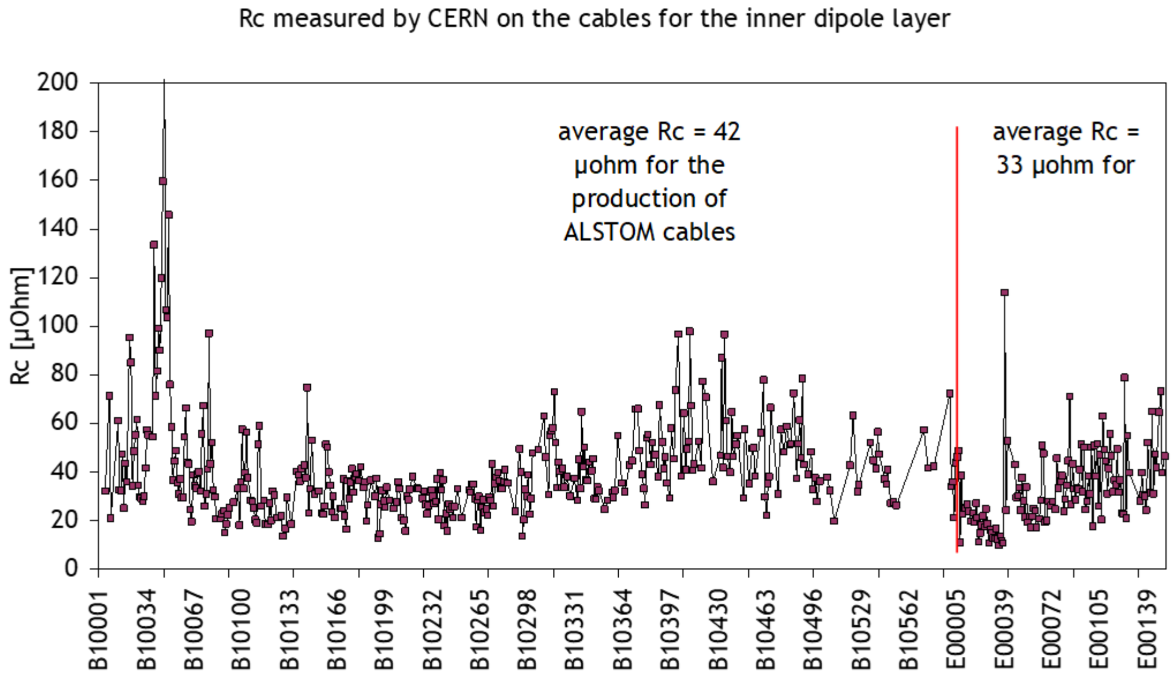


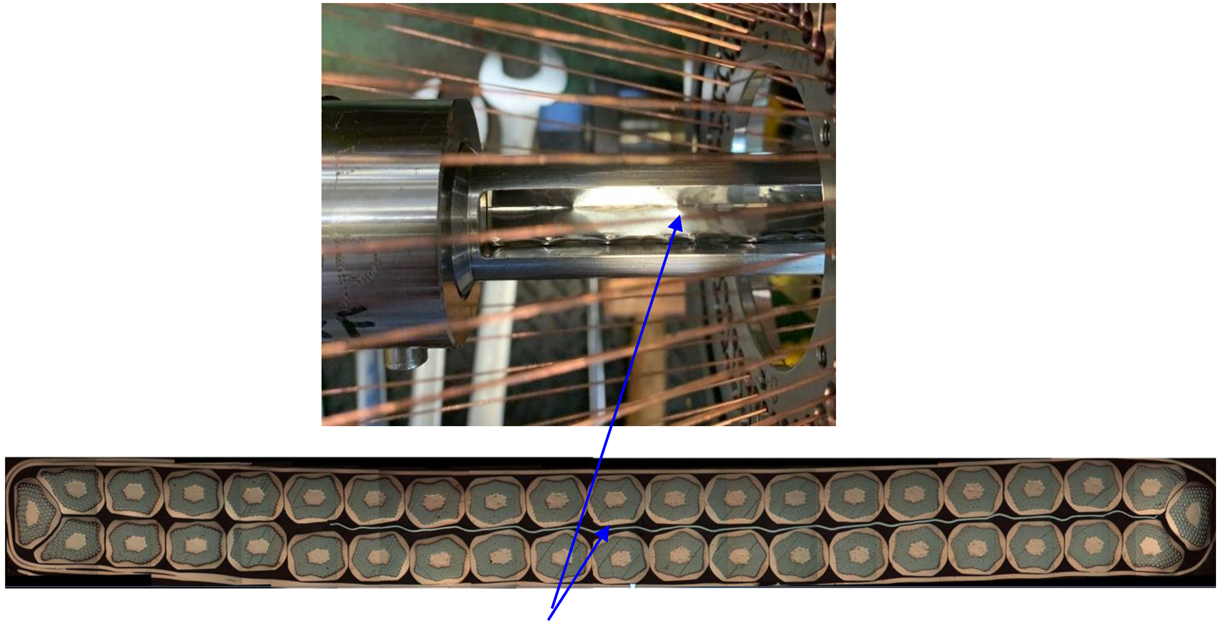




Controlling inter-strand contact resistance

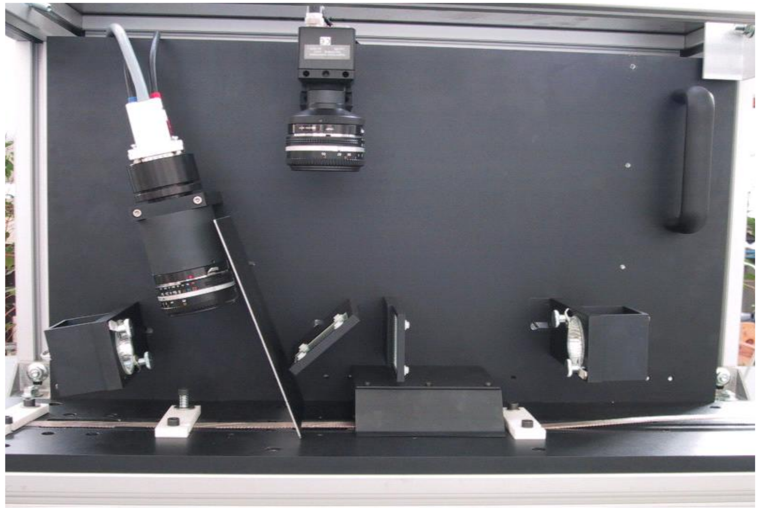
- For the LHC Nb-Ti cables, CERN developed the controlled oxidation method
  - Value too low gives field errors
  - Too high may give instability
- For HL-LHC Nb_3Sn cables, stainless steel 25-µm-thick foil (core) in between strands to control the contact resistance





Cable QA

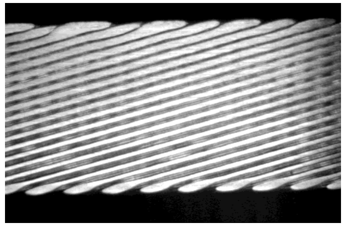
- Continuous monitoring of the thickness (CMM machine) and the quality (camera)
- Experience so far cabling Nb_3Sn rather positive in terms of yield
  - Yield is 96 % for MQXF, with 90 % of the production completed.



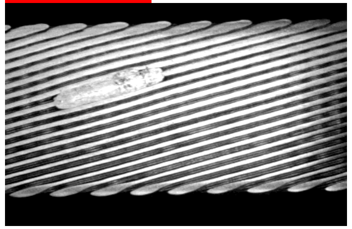
Example defect in LHC NbTi cables

C. I. S.

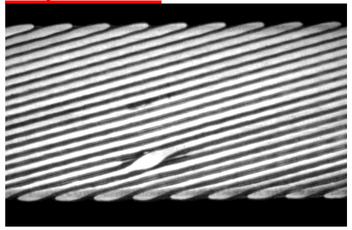
Minor defect



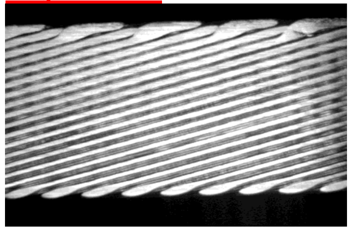
Major defect



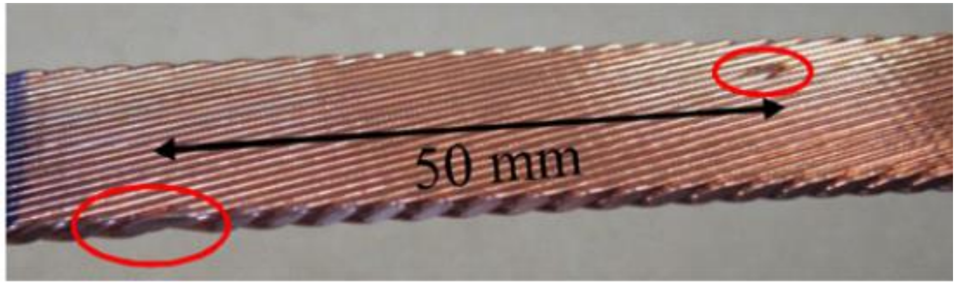
Major defects

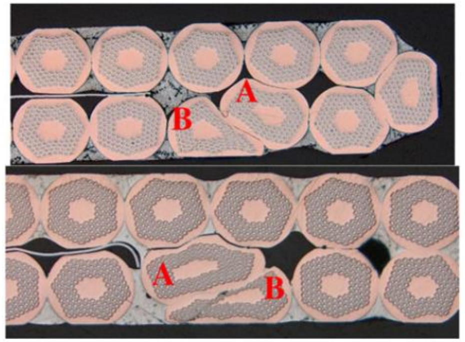


Major defects



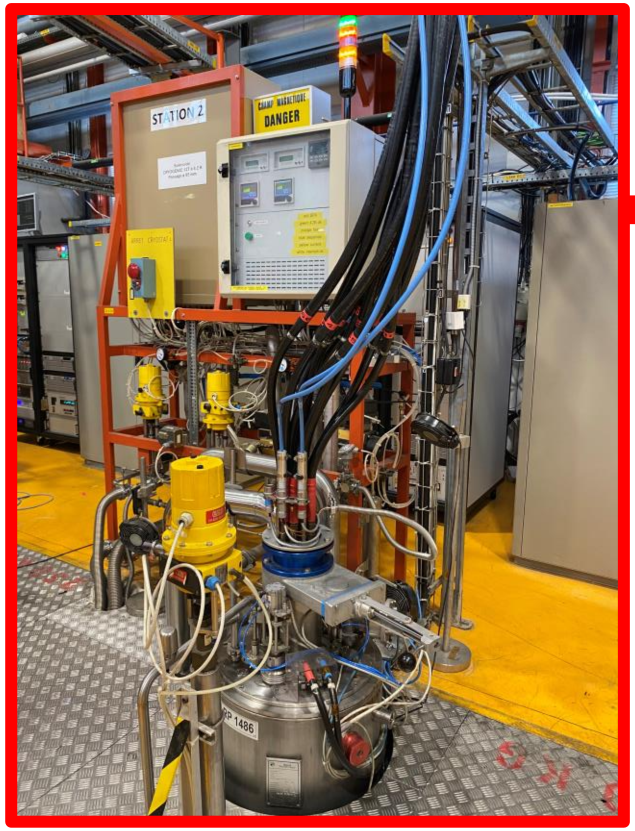
Example of strand cross-over in a MQXFB cable





HL-LHC strand testing infrastructure @ CERN

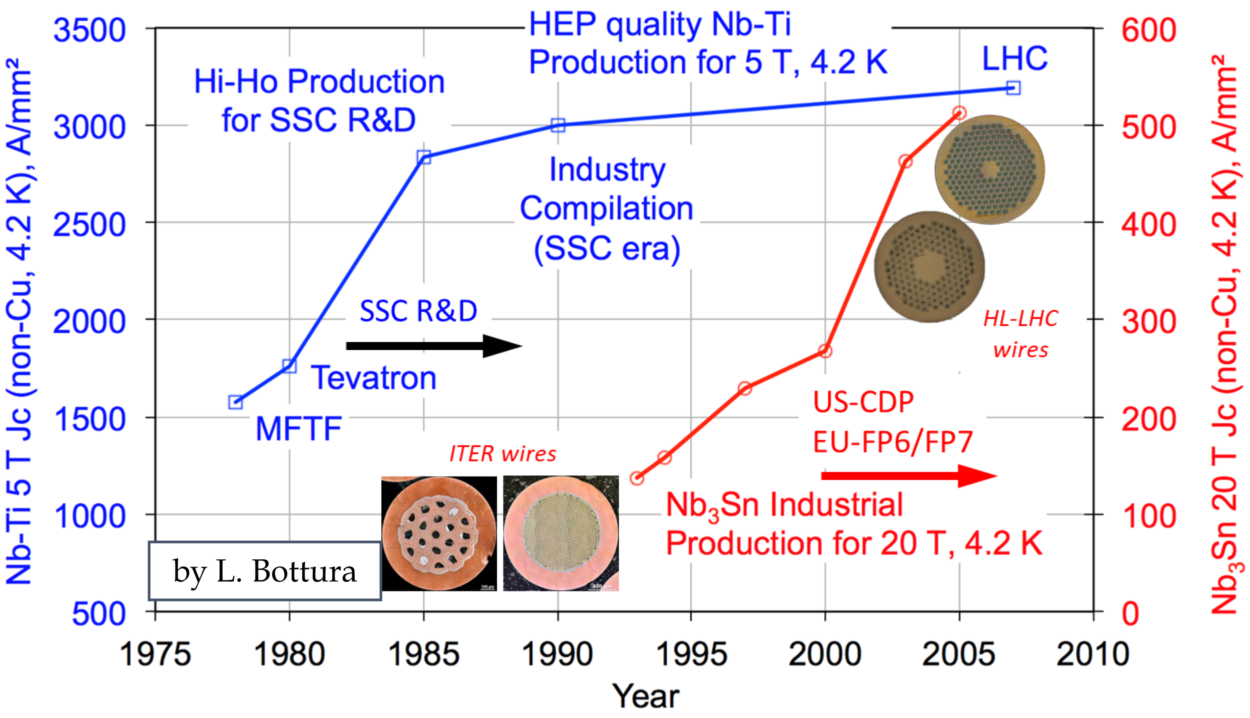
- 7 strand stations running in parallel.
  - 5 stations for Ic measurements
  - 1 station for RRR measurements
  - 1 station for magnetization measurements



Cable testing infrastructure @ CERN

A challenge

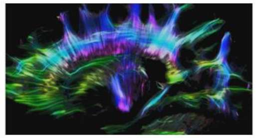
- HEP requires stringent performance requirements
  - Conductor development requires time and $$$$
  - Important to engage industry (i.e., potential market) and keep several vendors
- Other conductors emerging, but cost and production of long unit lengths is still a challenge



L. Cooley et al., https://doi.org/10.48550/arXiv.2208.12379

Table I: Magnet conductors available for procurement in length > 1 km

SC material	Billet or batch mass	Annual production	Relative cost	Comments
Nb-Ti	200-400 kg	Hundreds of tons	1	Driven by MRI industry
Nb_3Sn RRP	45 kg	5–10 tons	5	Driven by general purpose and NMR magnets and by Hi-Lumi LHC
Nb_3Sn PIT	45 kg	< 1 ton	8	Cheaper RRP is also generally more capable
Bi-2212	20 kg	< 1 ton	20–50	See note (1).
REBCO	10 kg	< 1 ton; few tons for fusion	20–50	See note (2).
Bi-2223	20 kg	< 1 ton	20–30	Current leads (3).
MgB_2	20 kg	< 1 ton	2 [5]	Current transfer cables feeding magnets.



≈ 6 BEUR/y business

≈ 0.7 BEUR/y business

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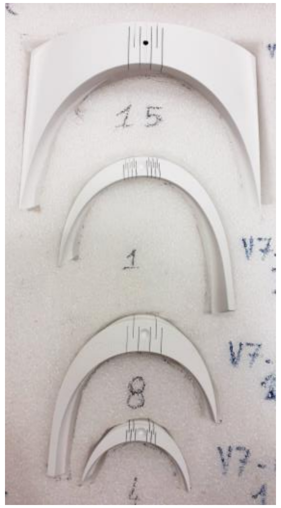
Additional slides

Coil fabrication and magnet assembly

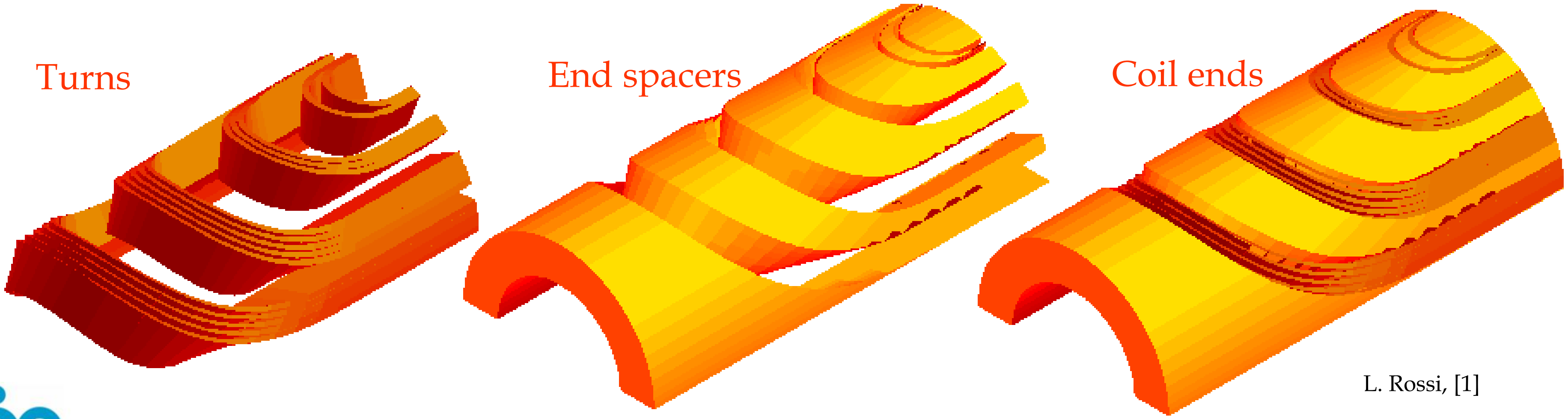
Coil ends

- In the **end region**, it is more difficult to constrain the turn which is bent over the narrow edge while moving around the mandrel.
- To improve the mechanical stability of the ends (and to reduce the peak field), spacers are precisely designed, using the constant **perimeter approach**.
  - The two narrow edges of the turn in the ends follow curves of equal lengths.
- In Nb-Ti magnets, end spacers are produced by 5-axis machining of **epoxy impregnated fiberglass**. Remaining voids are then typically filled by injection of loaded resins.
- In Nb_3Sn magnet, end-spacers are typically in aluminum bronze or stainless steel
  - To easy the winding, the pieces introduce some features to increase flexibility

11 T end spacers, with 'flexible legs'



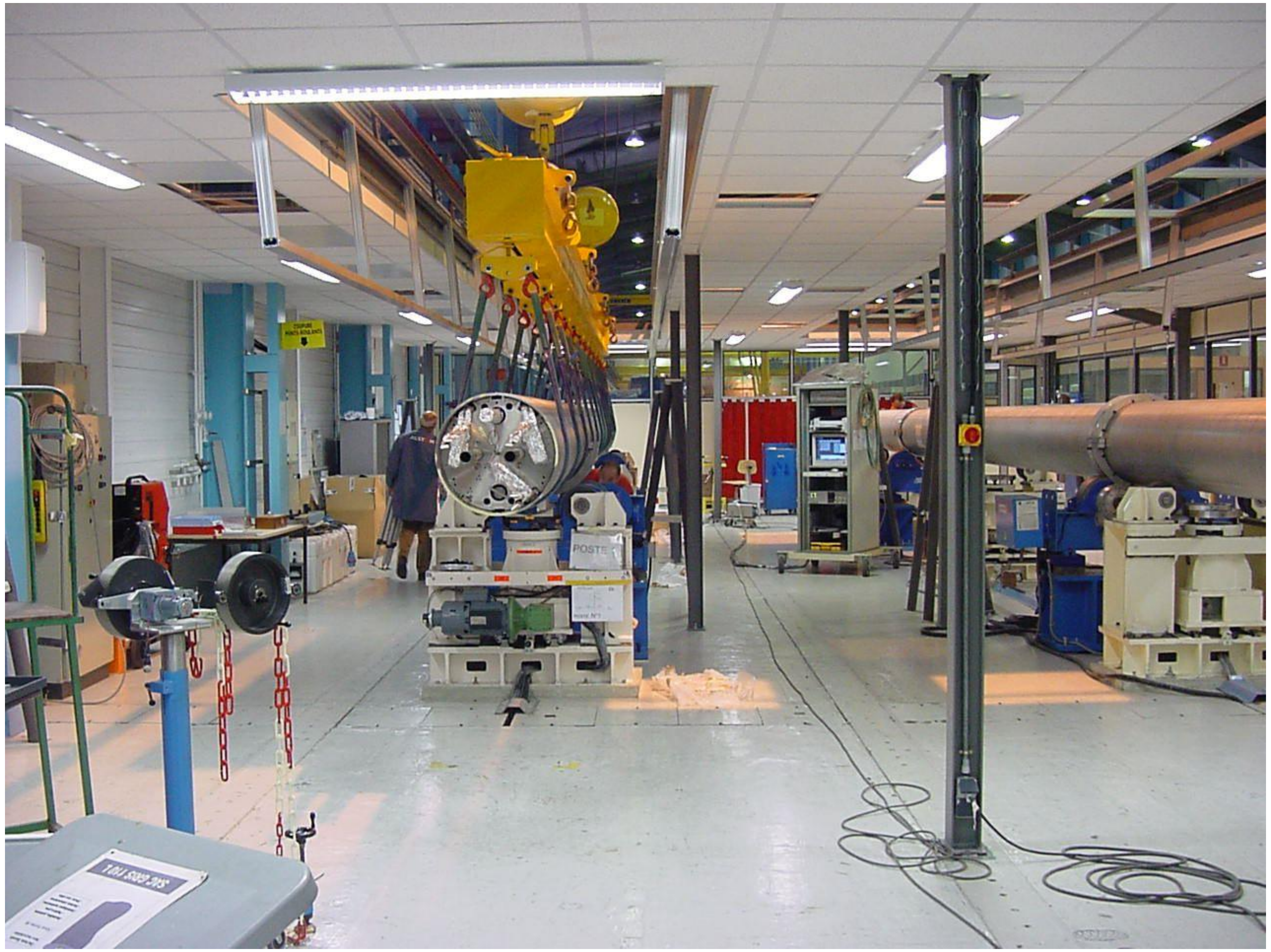
MQXF end spacers, with slits and Alumina coating



L. Rossi, [1]

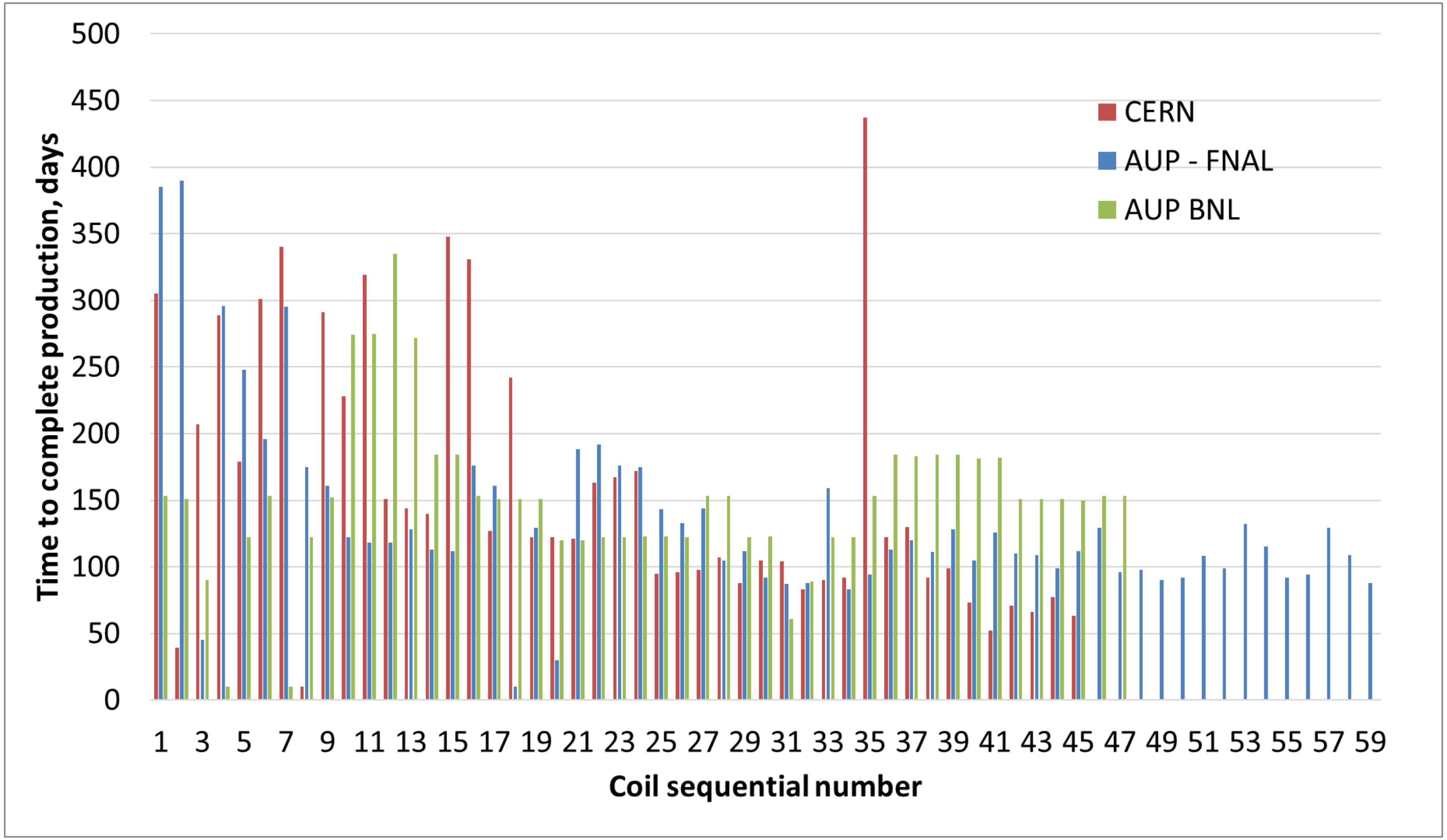
A snapshoot of industry during LHC MB production

A snapshoot of industry during LHC MB production



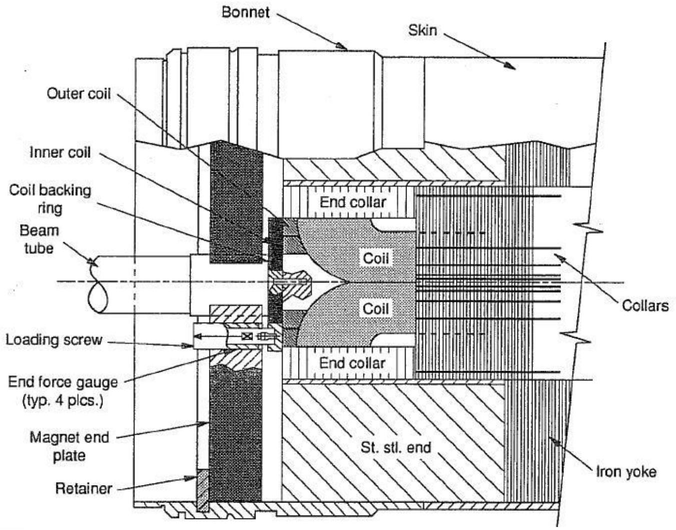
A snapshoot of industry during LHC MB production

MQXF coil production



LHC-MB dipole: end plate

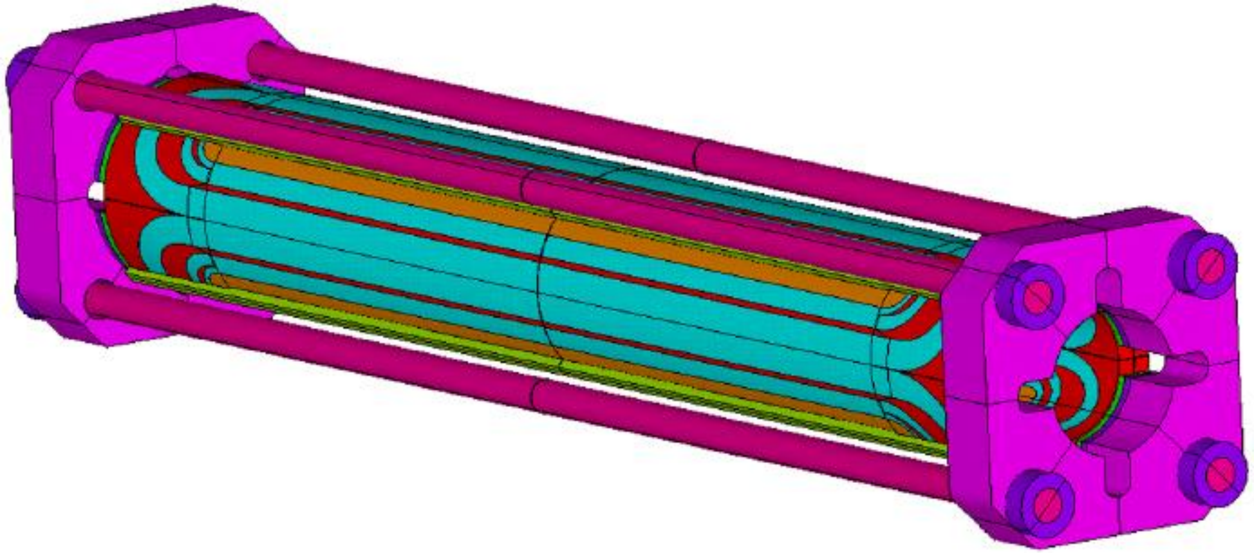
- The axial support is provided by the end-plate, welded to the stainless-steel shell
  - Slight pre-load at room temperature, to guarantee that there is still contact coil to end plate at 1.9 K.
  - Goal: limit the coil displacements providing a rigid axial support

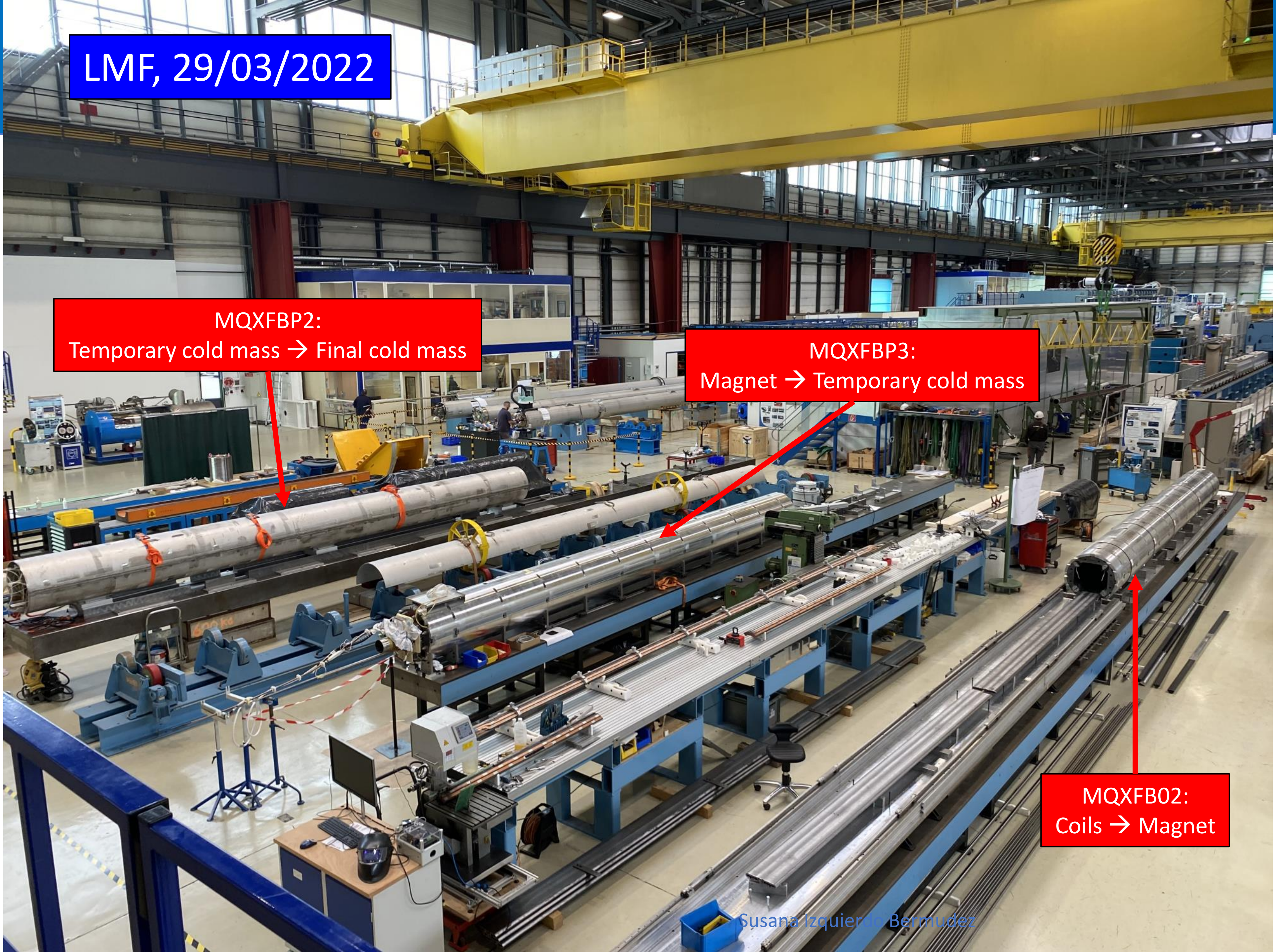


A. Devred

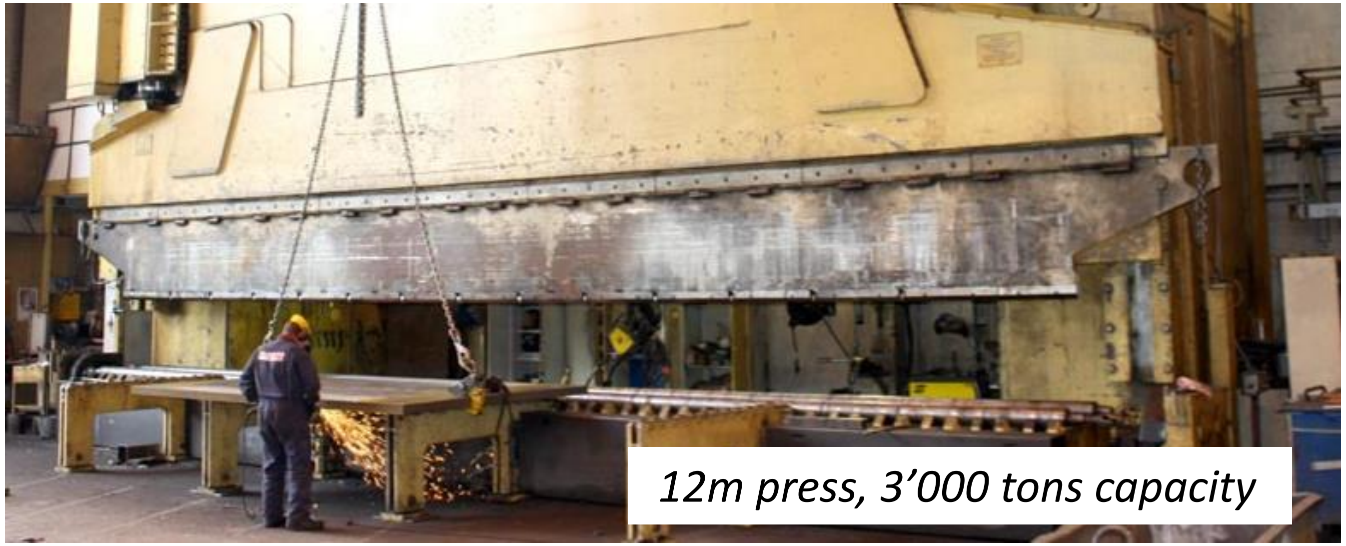
MQXF – axial pre-load

- Axial rods and end plate system for axial support, direct connection between the motion of the rod and the one of the coil ends
- Goal: limit the coil displacements providing a rigid axial support and keep the pole turn under compression during powering.



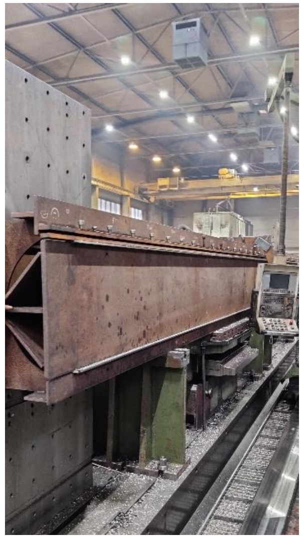

LMF, 29/03/2022
MQXFBP2:
Temporary cold mass → Final cold mass
MQXFBP3:
Magnet → Temporary cold mass
MQXFB02:
Coils → Magnet

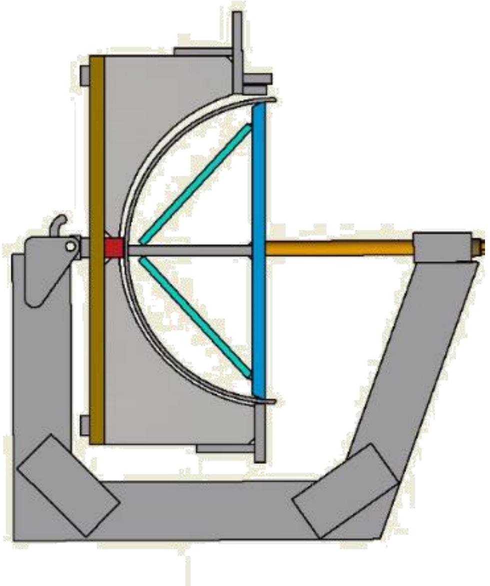
SS shell production



12m press, 3'000 tons capacity

- Forming process in three steps rather than two used previously to improve shaping accuracy.
- Machining of the chamfer after forming, good clamping needed





HL-LHC magnets handling at CERN

MQXFB

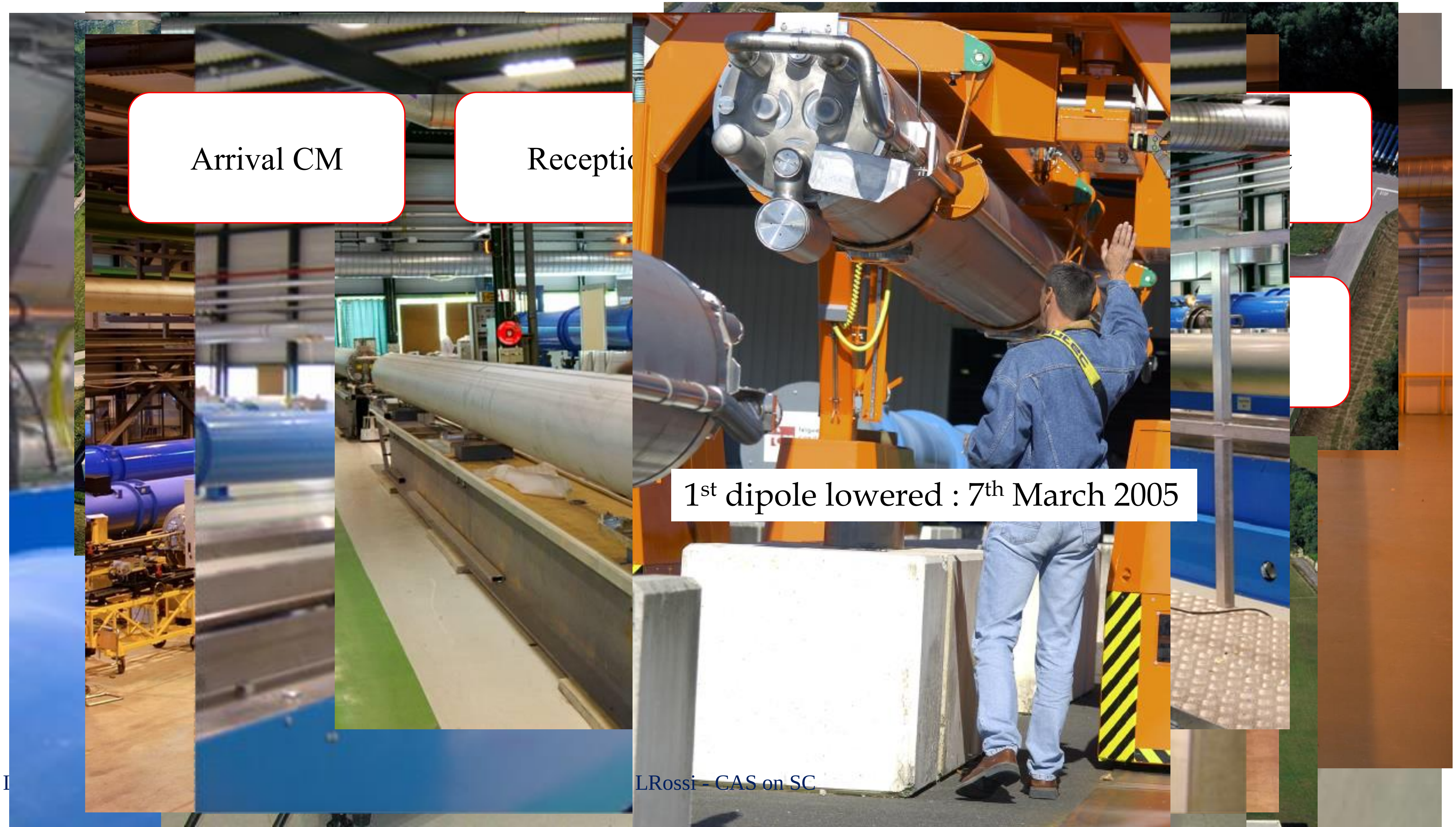
MCBXFA/B

HO corr.

MBRD (D2)

MCBRD (CCT)

Workflow LHC dipoles, by L. Rossi

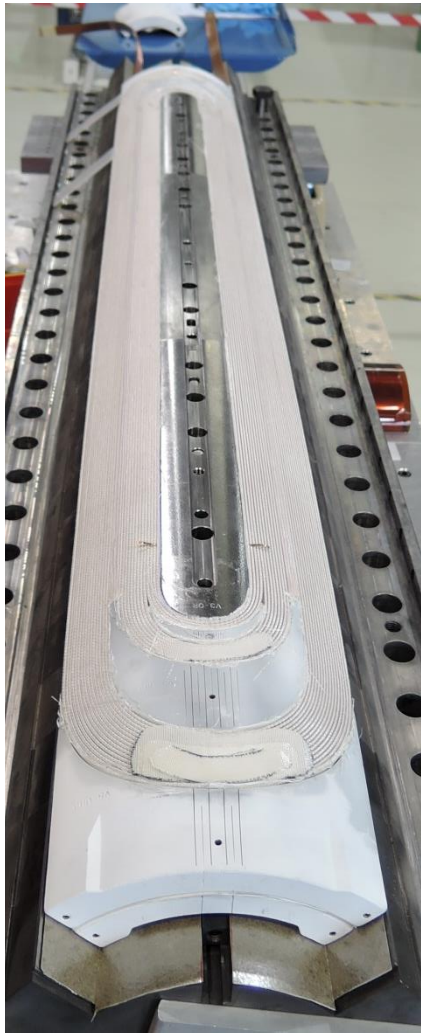


Additional slides

The 12 T challenge

The 12 T challenge – coil fabrication

- Wind and react technology → coil undergo a heat treatment step to ≈ 650 º C to form the superconducting phase
    - 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
- Stringent protection requirements (time margin to reach 350 K T_{hot} is 40 ms instead of 90 ms for the LHC-MB dipoles) call for quench protection heaters placed as close as possible to the coil



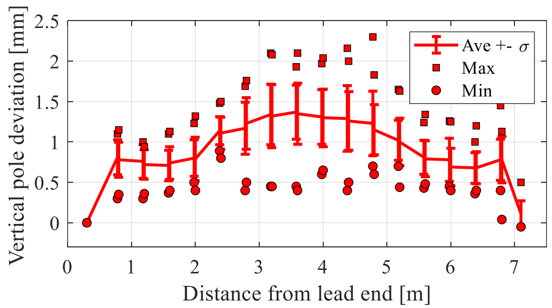
After curing

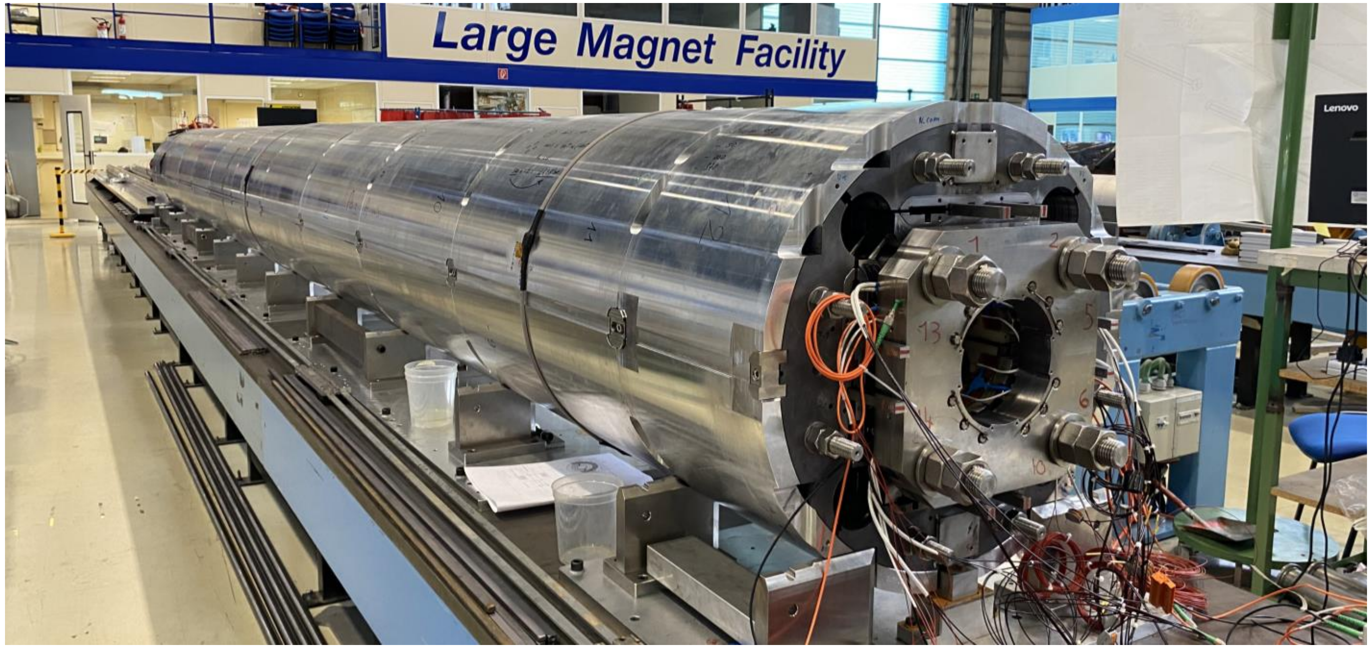
After reaction

After impregnation

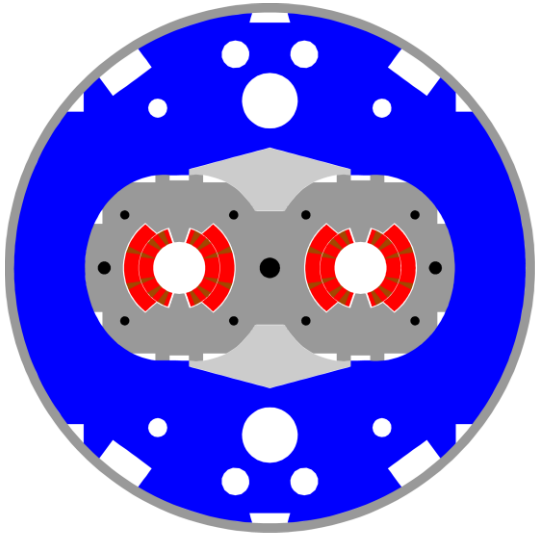
The 12 T challenge – length

- Management of thermal contractions and dilatations (from 1.9 K during magnet operation to 650 º C during coil reaction) of the different components is still one of the main challenges
  - They scale with the magnet length, and need to be properly engineered with particular attention to transitions

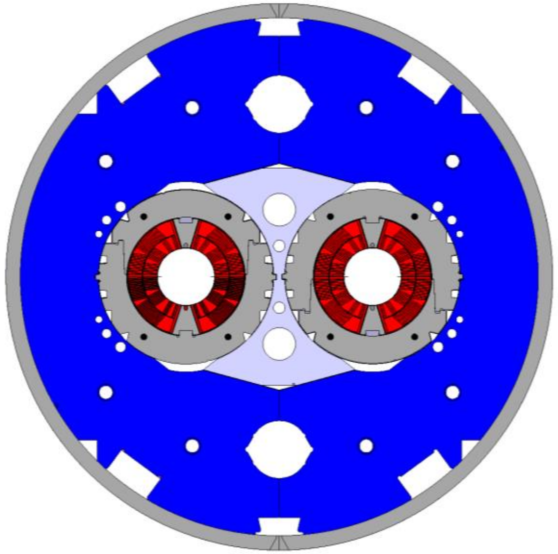




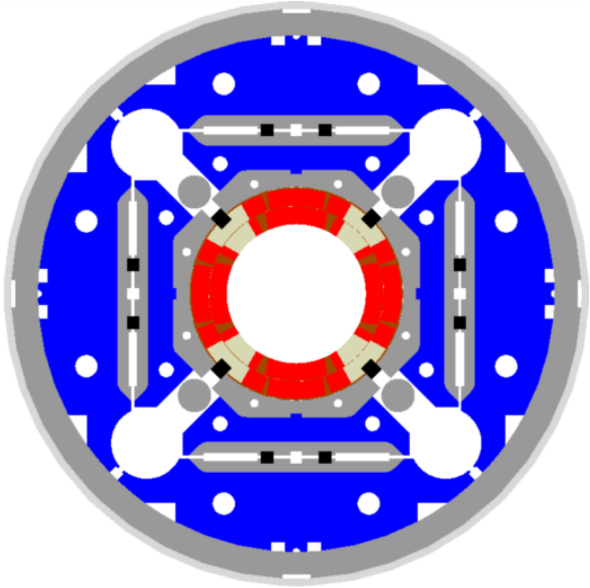
The 12 T challenge – current density



LHC MB
NbTi, B_p = 8.6 T
Eq. coil width: 27 mm
J_{strand} = 475/616 A/mm^2



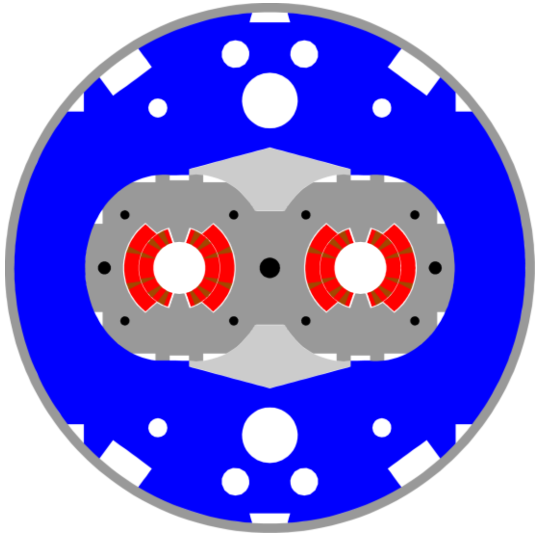
HL-LHC MBH 11 T
Nb_3Sn, B_p = 11.7 T
Eq. coil width: 28 mm
J_{strand} = 770 A/mm^2



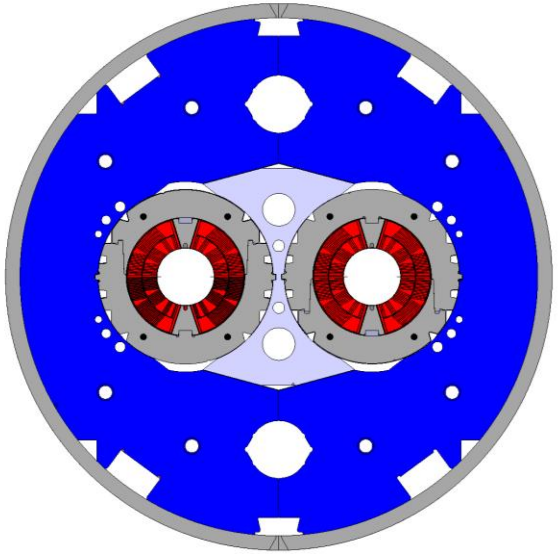
HL-LHC MQXF
Nb_3Sn, B_p = 11.3 T
Eq. coil width: 36 mm
J_{strand} = 715 A/mm^2

The 12 T challenge – e.m. forces

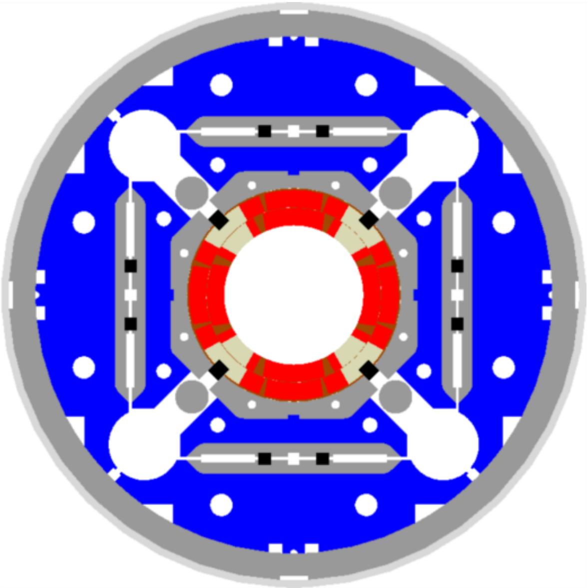
≈ 2 times more force/stress than in the LHC-MB dipoles, in a brittle conductor



LHC MB
NbTi, $B_p = 8.6$ T
$F_x = 3.4$ MN/m
$\sigma_{\theta,em} = 50\text{-}60$ MPa
$F_z = 265$ kN



HL-LHC MBH 11 T
Nb_3Sn, $B_p = 11.7$ T
$F_x = 7.2$ MN/m
$\sigma_{\theta,em} = 100\text{-}110$ MPa
$F_z = 450$ kN

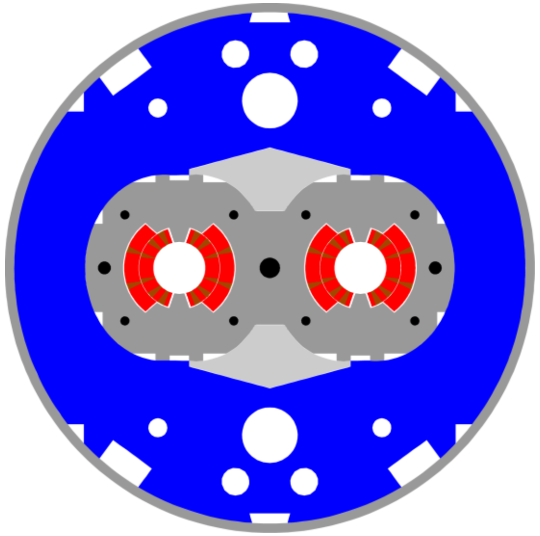


HL-LHC MQXF
Nb_3Sn, $B_p = 11.3$ T
$F_x = 6.8$ MN/m
$\sigma_{\theta,em} = 100\text{-}110$ MPa
$F_z = 1200$ kN

F_x per half magnet; F_z per aperture

The 12 T challenge – protection

$T_{hot} \approx$ 100 K higher than in the LHC-MB dipoles, half the time margin



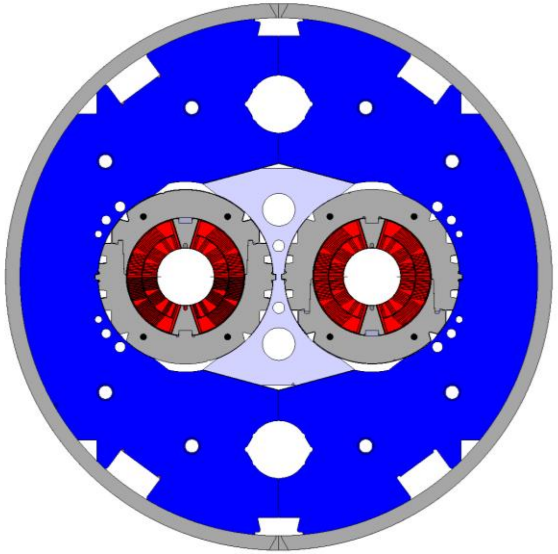
LHC MB

NbTi, B_p = 8.6 T

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

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

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



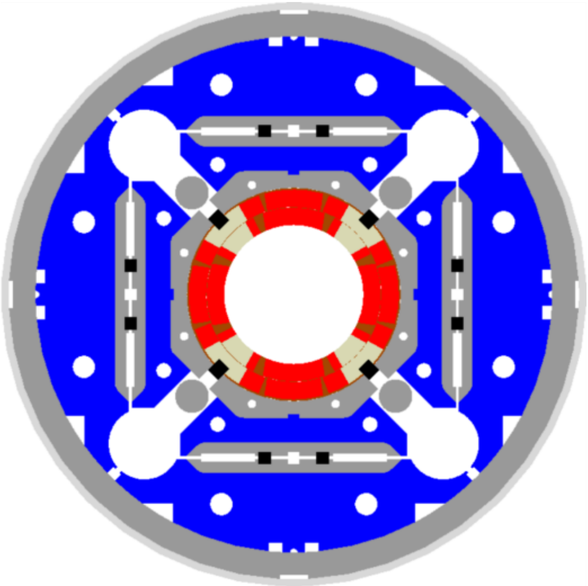
HL-LHC MBH 11 T

Nb_3Sn, B_p = 11.7 T

$J_{overall}(I_{nom})$ = 522 A/mm^2

$J_{cu}(I_{nom})$= 1440 A/mm^2

e_m (I_{nom})= 124 J/cm^2



HL-LHC MQXF

Nb_3Sn, B_p = 11.3 T

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

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

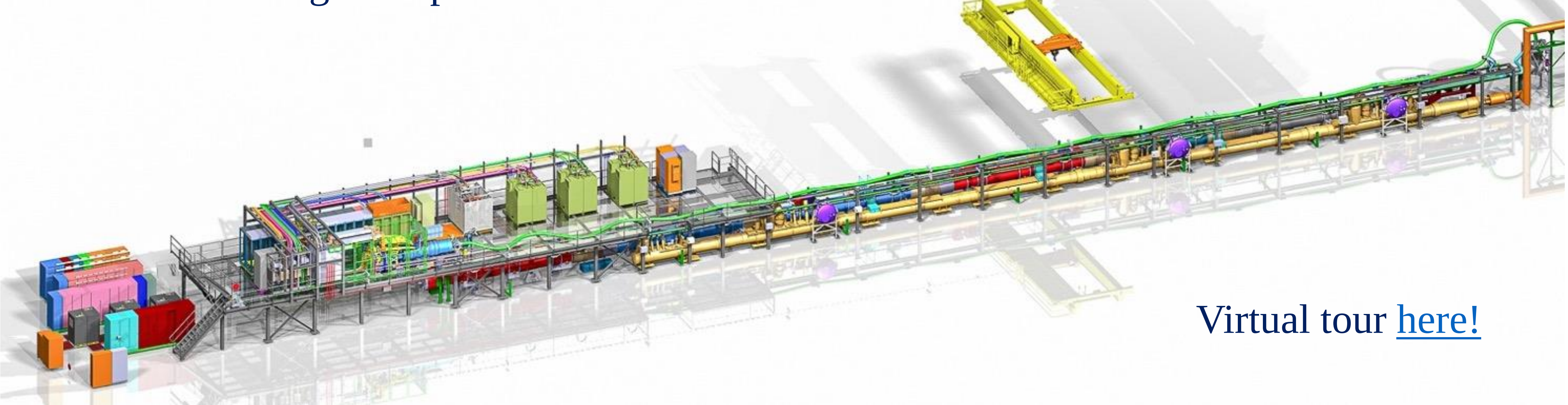
e_m (I_{nom})= 120 J/cm^2

Additional slides

String test

HL-LHC String test

- The HL-LHC IT STRING will 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.
- The HL-LHC IT STRING will validate operational modes and machine protection procedures, as well as the corresponding analysis, in view of the hardware commissioning and operation in the HL-LHC.



Virtual tour here!

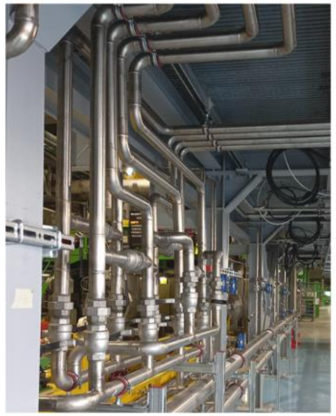
HL-LHC String: Infrastructure & warm powering

by M. Bajko

Power converters

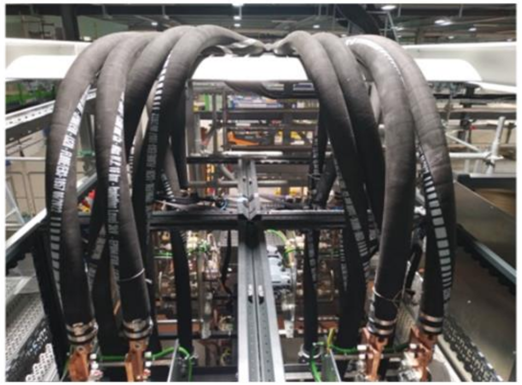
Energy extraction

Demineralized water



Circuit disconnection boxes (CDB)

Water cooled cables



Cryogenic line (SQXL)

HL-LHC String: Cold powering

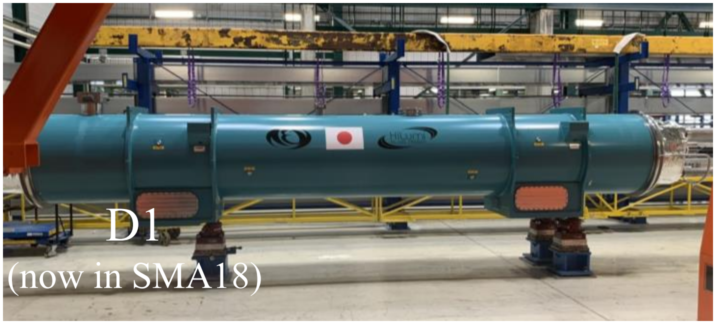
by A. Ballerino

- ≈ 75 m long, ≈ 120 kA DC superconducting link (MgB_2 cables)
- The system will be first individually tested, and then installed in the string

HL-LHC String: Magnets

by E. Todesco

- All magnets needed for the string have been individually tested, and are getting ready for the final cold test, and then the string



- Still a lot of work to develop installation procedures and connections