HFM
High Field Magnets

Nb_3Sn magnet Technology Development Program (TDP) - CERN

Diego Perini on behalf of the CERN-HFM Nb_3Sn magnet team

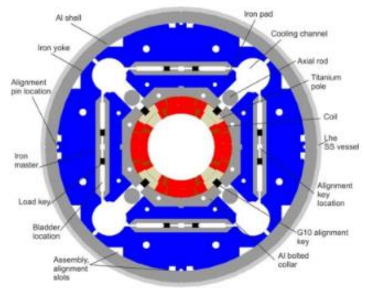
01.11.2023

Table of contents

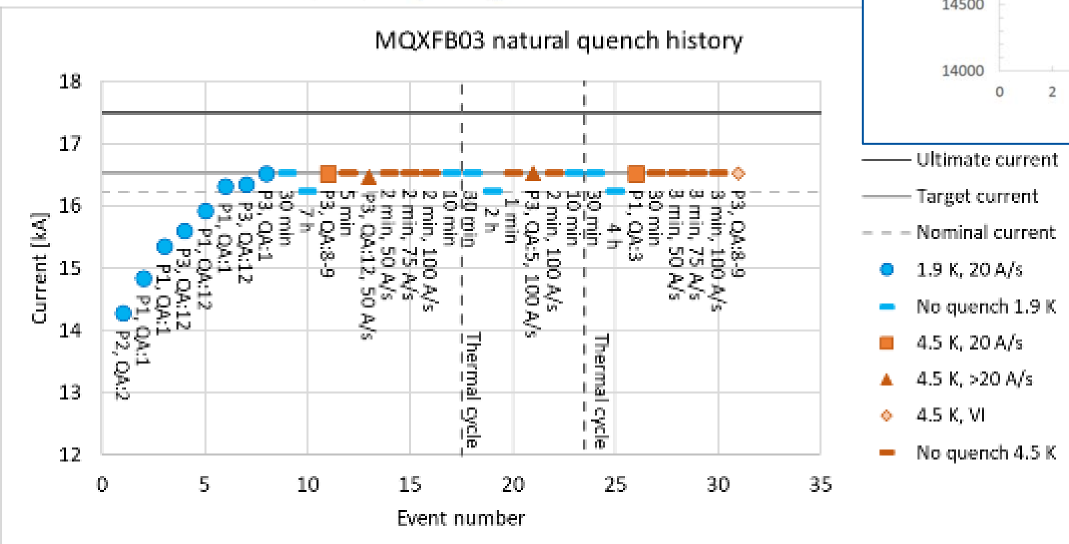
- Strategy of Nb_3Sn magnet development and scope of the Work Package. Recall of the milestones and deliverables
- Ongoing activities and first results of TDP

This work engages CERN and four main collaborations in Europe (CEA, CIEMAT, INFN, PSI) and discussions with American partners (BNL, FNAL, LBNL).

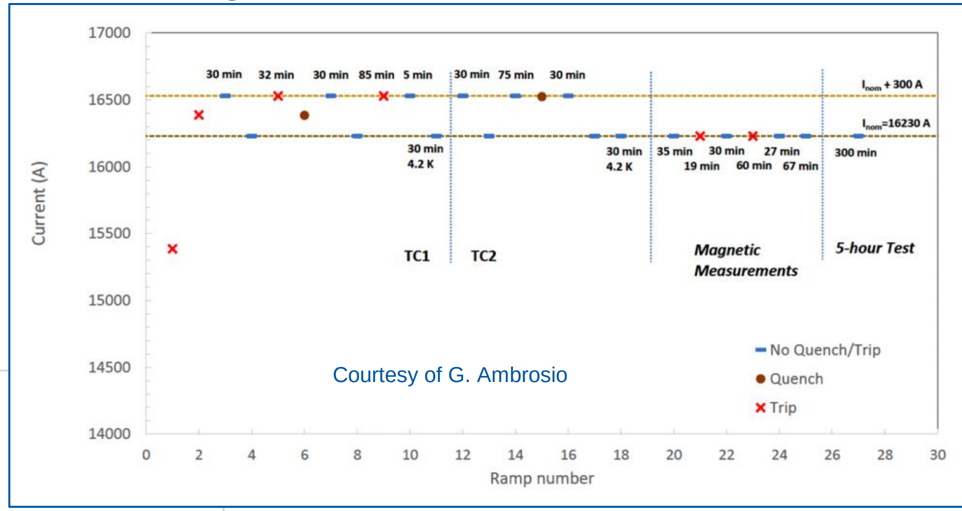
Lesson learned (1/2)



MQXF Quadrupole Magnet X-Section



LQXFA/B-01 Horizontal Test



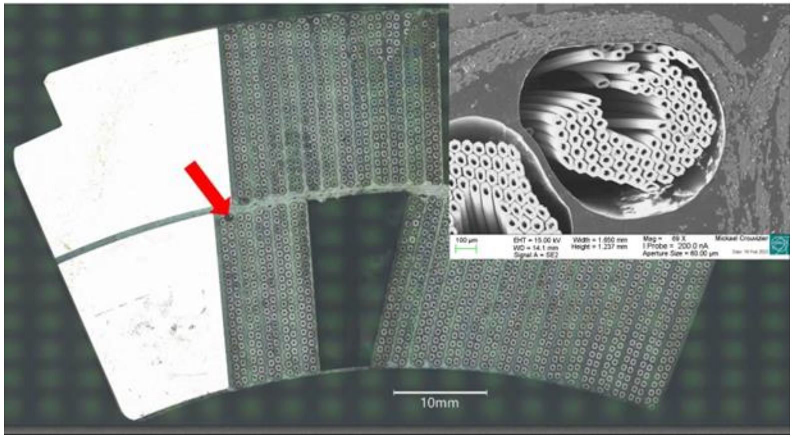
2 x 4.2 m long

7.2 m long

So, it is possible, and it works.

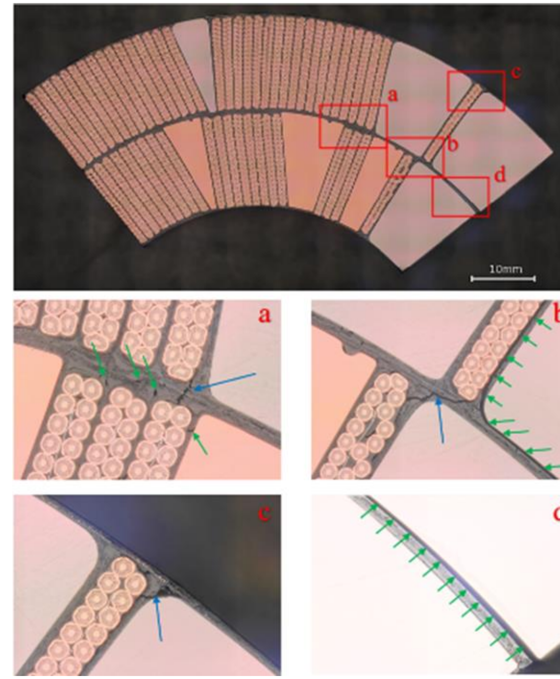
The force, deformations, and stress distribution in a dipole and in a quadrupole are fundamentally different

Lesson learned (2/2)



MQXF damaged coil

Courtesy of S. Sgobba, M. Crouvizier (CERN/EN-MME)



Cracks in a 11 T, 5-m coil

Uncontrolled or excessive loads can cause local peak stresses and cable irreversible damages.

We need:

- **Robust, intrinsically safe structures.**
- **Knowledge of coil material properties.**
- **Rigorous procedures and suitable assembly tools.**

This does not mean complication. We need good engineering practices

Guiding Principles for CERN High-Field Magnet Development (1/3)

- **Humble approach** relying on **lessons learned from previous Nb_3Sn programmes** around the world (*e.g.* Elin-Cern-LHC dipole, MSUT at Twente University, NED Joint Research Activity in Europe, LARP in USA, HL-LHC 11 T and HL-LHC MQXF)
  - Consolidate **engineering good practices;**
  - Improve **weak points** and/or **procedures.**

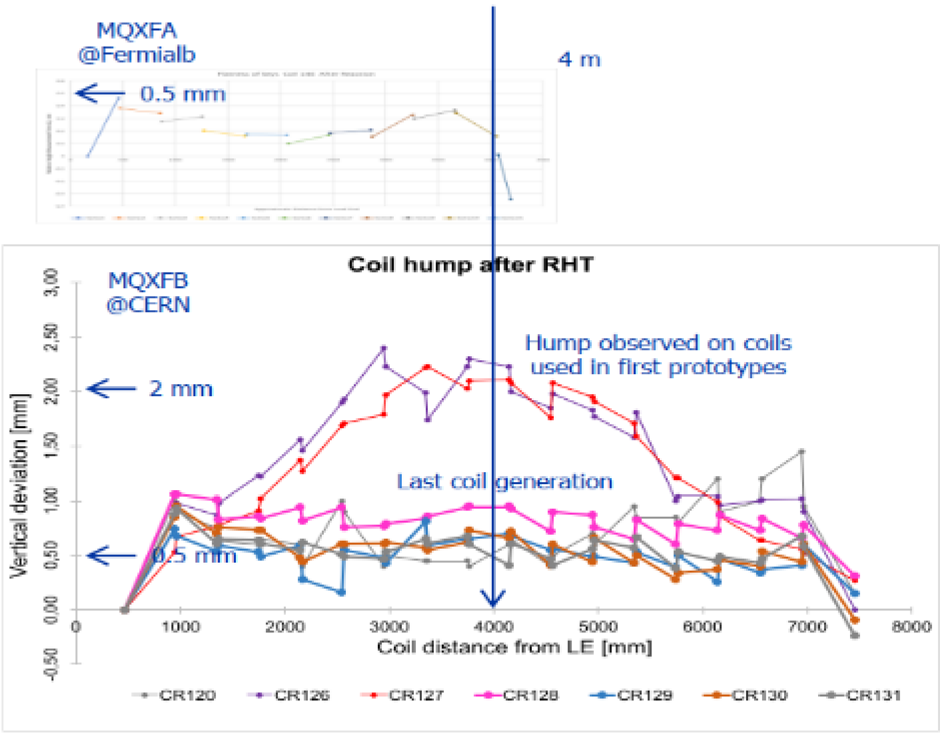
- **Nb_3Sn is a brittle material;** it calls for
  - tight control of **manufacturing and assembly procedures;**
  - Manufacture of **high-quality coils;** importance of **winding tests** to optimize components and parameters, **minimizing coil handling**, size and rigidity **measurements of the coils. These points are part of the TDP programme.**
  - Design of **intrinsically safe structures;** tolerances, misalignments of assembly tools, and accidental loads must not originate unwanted, deleterious **extra stresses on the coils. See Lucie's presentation (12 T VE).**

- **Step-by-step approach**; **validation of coil** design and manufacture before going to **final dipole configuration and production ('mirror test' in the TDP programme).**

- **A robust insulation system and good impregnation resin. See Roland's talk**..

Guiding Principles for CERN High-Field Magnet Development (2/3)

All solutions tested in the short model programme must be scalable and applicable to long (~ 15 m), twin- aperture, accelerator-fit, dipoles magnets.



Evidence of **scalability issue** between 4.2-m-long MQXFA coils at Fermilab and 7.2-m-long MQXFB coils at CERN, manufactured with supposedly identical tooling design and processes: first MQXFB coils exhibited a large **"hump"** towards longitudinal centre after opening of heat treatment mould that was the likely **root-cause of performance limitation** of prototypes.

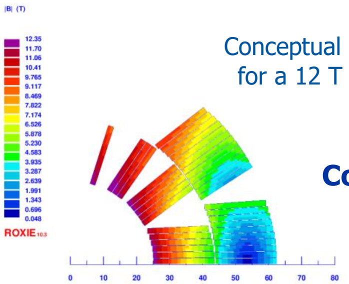
Guiding Principles for CERN High-Field Magnet Development (3/3)

- In order to **focus the programme** and enable **greater chances of success** in a limited time (aiming at a significant demonstration of objectives by 2026), a number of **strategic choices** have been made.

– **12-T, value-engineered dipole magnet:**

2-layers, cosθ design, relying on **MQXF cables.**

Synergies with INFN (FalconD)

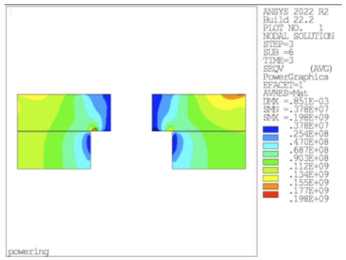


Conceptual cosθ coil design for a 12 T dipole magnet

Courtesy of L. Fiscarelli (CERN/TE-MSC)

– **Exploring the limits of Nb_3Sn technology: 14+T, block-coil design,** relying on **rectangular cables**; strands for prototype phase to be taken from existing CERN inventory, final strands to be selected/optimized.

Synergies with CEA (R2D2). And possibly Ciemat and PSI.



Conceptual block coil design for a 14+ T dipole magnet

The TDP programme is a transverse activity and aims to develop the necessary technologies for these projects in synergy with collaborators whenever possible

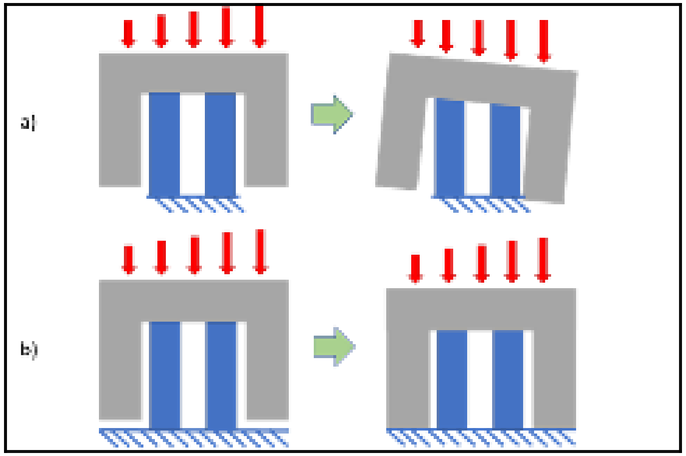
Methodology

- **rejuvenated SMT team** to prepare the future, under training through **transfer knowledge from elder**;
- each new engineer is in charge of at least one project and one organic responsibility ("pole") within the section. **The PE is the responsible for his/her project** but There are open and constructive discussions with the colleagues in the section and outside. **Team approach**.
- large effort to **upgrade infrastructure and workshop layout in 927** (inherited from LHC times…);
- setting up of **transverse project teams with support from other sections** (e.g., MSC-LSC, MSC-LMF, MSC-TM) or from other groups within TE (e.g., TE-CRG, TE-MPE) or outside TE (e.g., EN-MME). No duplications – no delegation of responsibility – just correct use of available resources.
- project plans to incorporate intermediate milestones (e.g., mock-ups, mirror tests) to assess progress;
- reliance on internal and/or external peer reviews (e.g., design review of 12 T in July 2023).

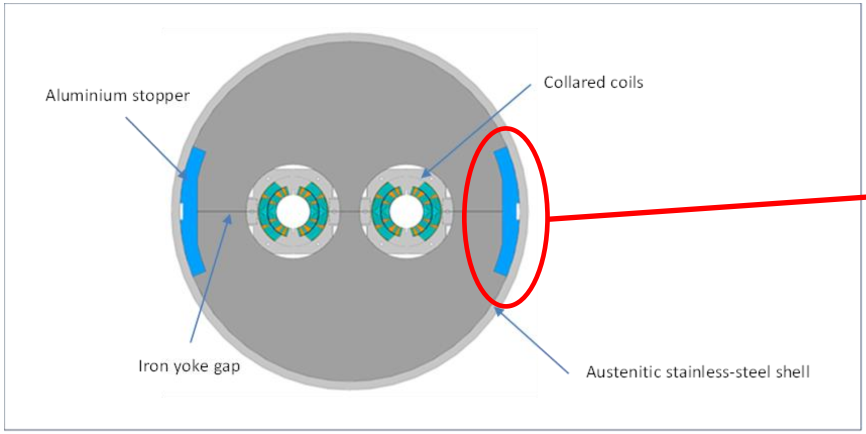
Some of these points require changes. Change management – flexibility.

12-T, Value-Engineered Dipole Magnet Development (1/2)

- **Minimize coil compression** at all stages of magnet lifecycle;
- **Minimize retaining structure deformations** as these can generate extra coil compression in the horizontal midplane;
- Protect the coils against **risk of overstress** due to **accidental loads**;
- Decrease the degree of **redundancy in the structure** to enable better control of **contact force distribution between parts;**
- Increase the **reproducibility of coil fabrication** procedures;
- Decrease influence of **manufacturing tolerances** on **magnet performances.**



The closed cavity concept

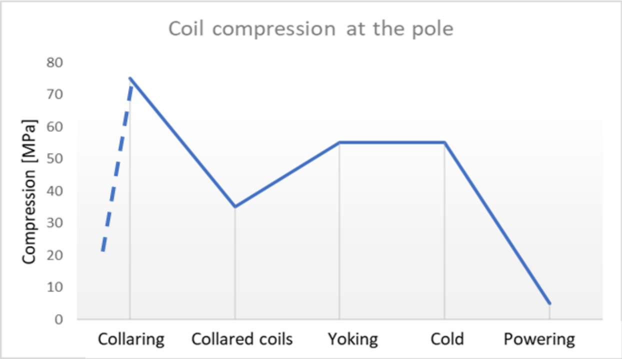


Conceptual design of 12-T Value-Engineered Dipole Magnet Design at CERN

- **Reduced number of pieces** in magnet cross section
  Less pieces ⇒ less tolerances
- The **aluminium stoppers at room temperature** and the **closed iron gap at cold** protect the coils from **extra or accidental stresses;** coils are kept in a closed cavity.
  See Lucie's talk
- **Conceptual Design Review** at CERN on 5 July 2023**.**

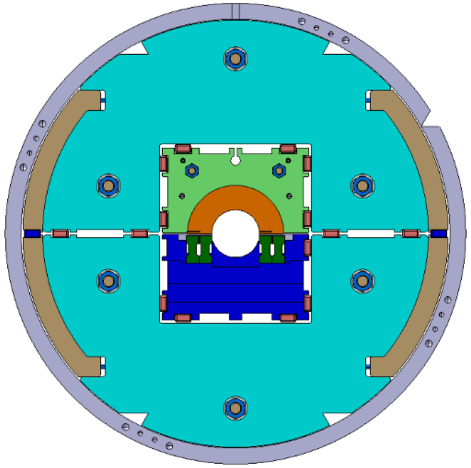
12-T, Value-Engineered Dipole Magnet Development (2/2)

- Advantages of a **horizontal iron yoke gap structure**
  - **Collaring at relatively low prestress** at room temperature;
  - **Structure kinematics** can be designed to enable **coil pre-compression increase during cool down** as in MQXFB (while a vertical gap necessarily results in pre-compression decreases due to thermal shrinkage differentials);
  - **Peaks of coil compression** can be contained to values lower than **110 MPa at room temperature** and **120 MPa at cold** during powering.



Average coil prestress at the contact with the collar pole during the assembly and energization.

- **Support from Technology Development Program**
  - **Collaring mock-up** tests (using 11 T dipole coil sections): **Q1-2 2024**
  - **Mirror coil test** to validate first coil production**: Q4 2024 – Q1 2025**
  - **Single-aperture dipole magnet model** in previous structure: **Q3 2025**



Cross section of coil test structure in a mirror configuration

To arrive to a twin-aperture dipole magnet model: 2026.

14+ T Dipole Manet Development (1/2)

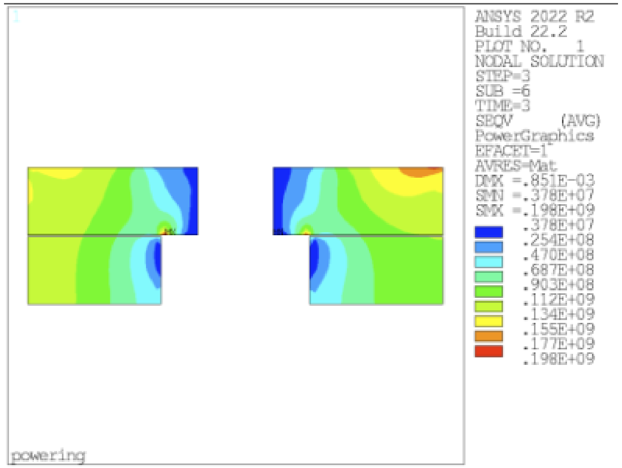
See Juan's talk

- **Ongoing work**

  – Review of **past block-coil magnet programmes** (design and performances);

  – Preliminary studies to assess influence **of different magnetic and mechanical parameters on dipole magnet performances;**

  – Assessment of available **strands and cables characteristics.** Choice of parameters for early stage of program to accommodate available conductor-rectangular cable, with ~1 mm strands (**see Thierry's talk**). Possibility of future developments.



Conceptual Design of 14+ T Block Coil Design at CERN

- SMC and RMM programs integrated into HFM

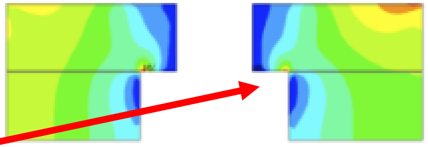
14+ T Dipole Manet Development (2/2)

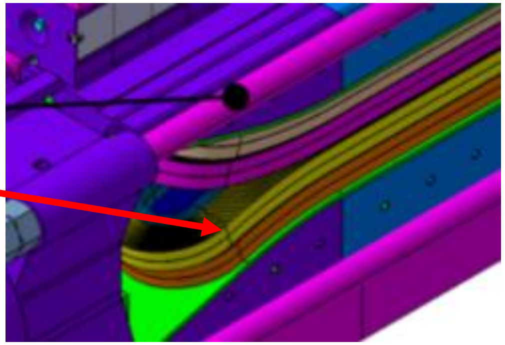
It should be noted that **a twin-aperture dipole magnet, with Nb_3Sn block coils has never been built;** it is a very challenging configuration.

Important points to be developed (single and double aterture)

- 2D issue at the coil corner
- 3D issue in the flared ends
- Need of diagnostic for quench localization

TDP mock-ups





CEA - Future Flared-ends Dipole Demonstrator (F2D2) et Flared Dipole (FD)

- **Step-by-step approach**

– Produce and validate **block coils with flared ends: 2024 – new winding machine in bld. 927;**

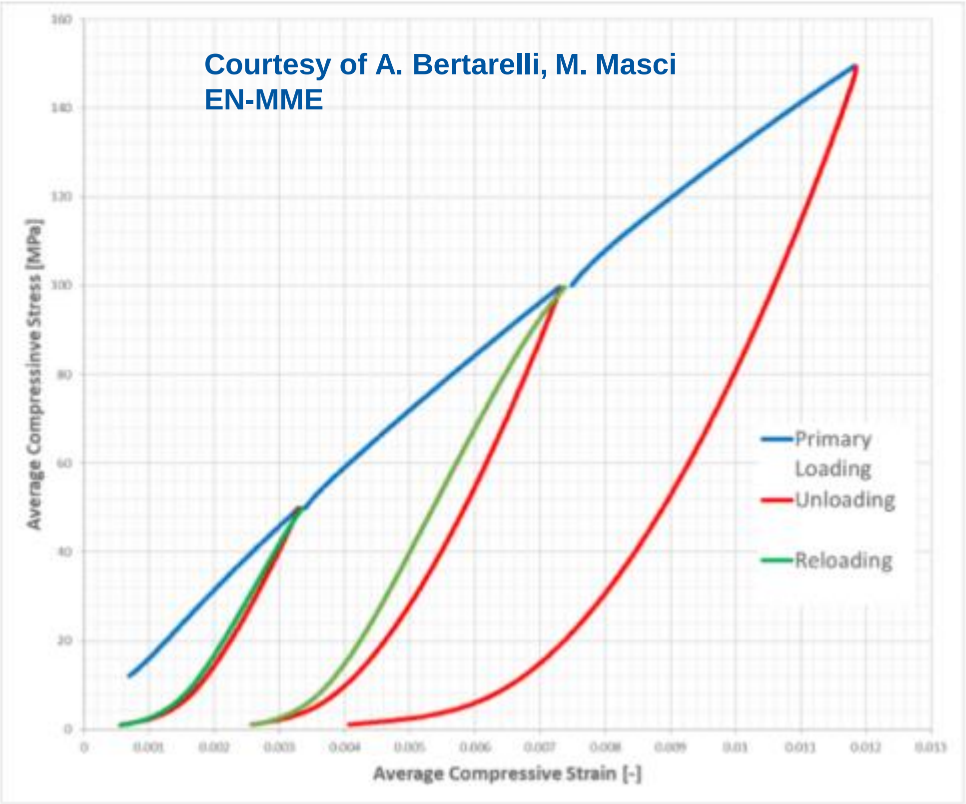
– Design and manufacture of a **single aperture, 2-m long dipole magnet model: 2025-2026;**

– Design and manufacture a **twin aperture, 2-m long dipole magnet model: 2026-2027.**

Recent results and ongoing activities

Nb3Sn coil characteristics – Non-linear E

- Review of data in literature
- Tests and measurements (so far on 11 T coils and collars)
- Systematic tests for 12 T programmed (and starting soon)



All FEM mechanical simulations are now carried out using this curve (or bi-linear approximation).

Systematic winding tests based on quantifiable parameters

- Torque (T)
- Soft bending (SB)
- Hard bending (HB)

} Parameters defined and computed in Roxie

- Cable and strand characteristics

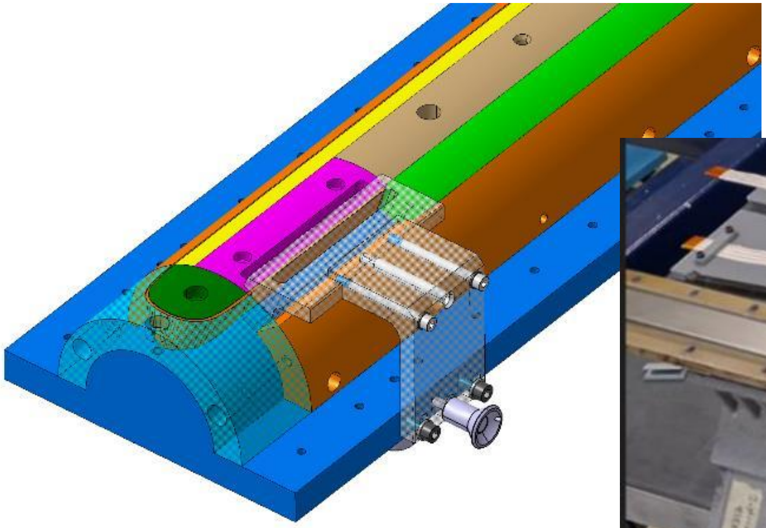
- 3D rapid prototyping allows us a quick and low-cost way to compute and test end spacers. **Variants characterized by parameters (T, SB, HB).**
- Tests for both HFM magnets and other projects using NbTi cables as well.
- Construction of a **documented and traceable database. Feedback to design code(s).**

Thanks to S. Russenschuck, L. Fiscarelli, A. Haziot. M. Liebsch

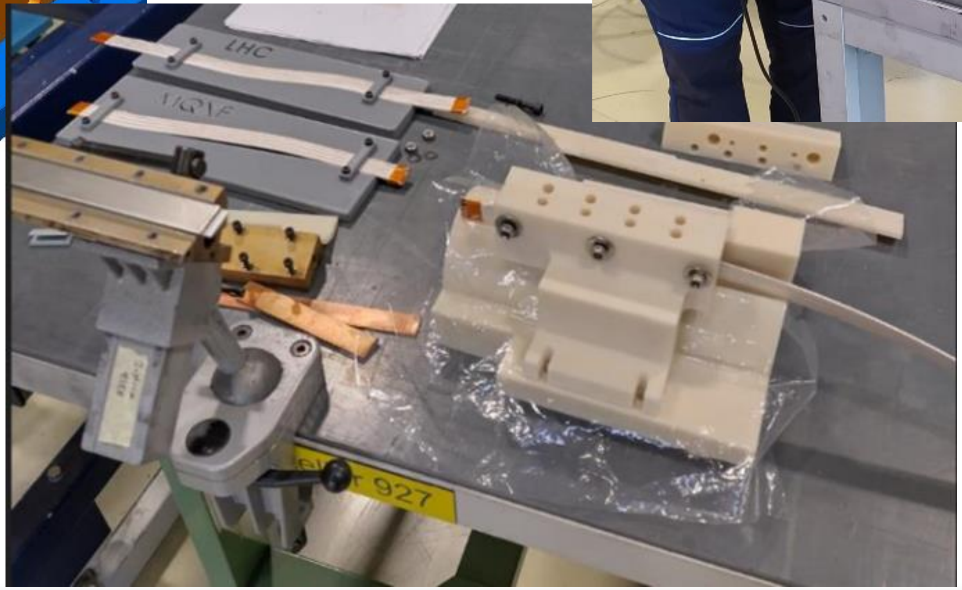
Internal splice development

- Design of the splicing mould completed. Fabrication of metallic components is starting. First iteration with 3D printed plastic parts.

- First soldering tests done. Results under analysis

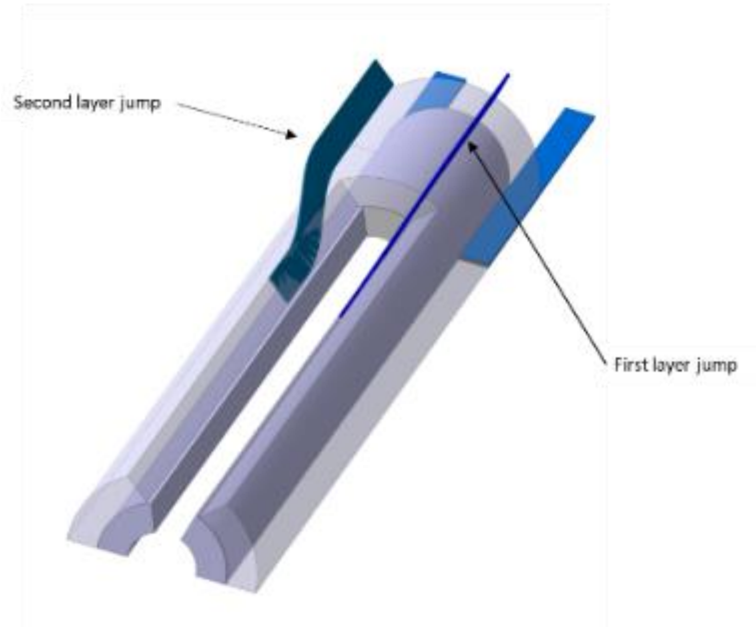


Mould for the internal splice



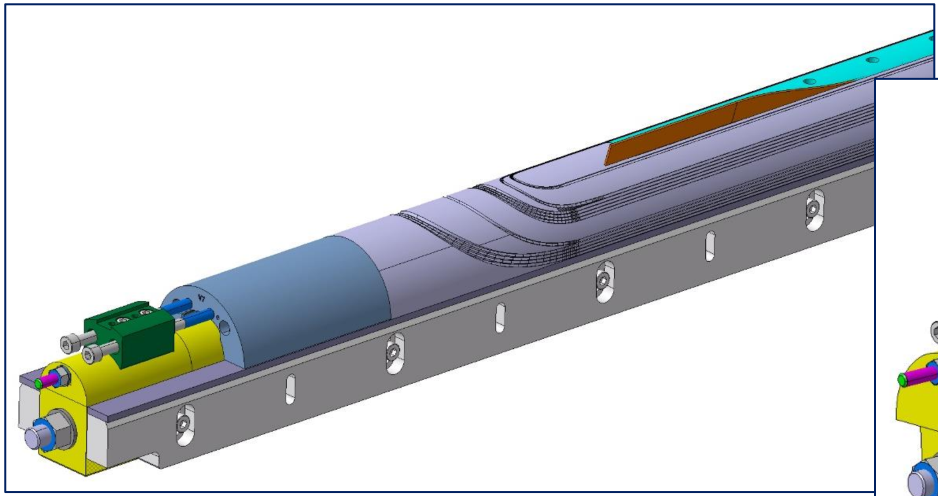
Plan B - External splice development

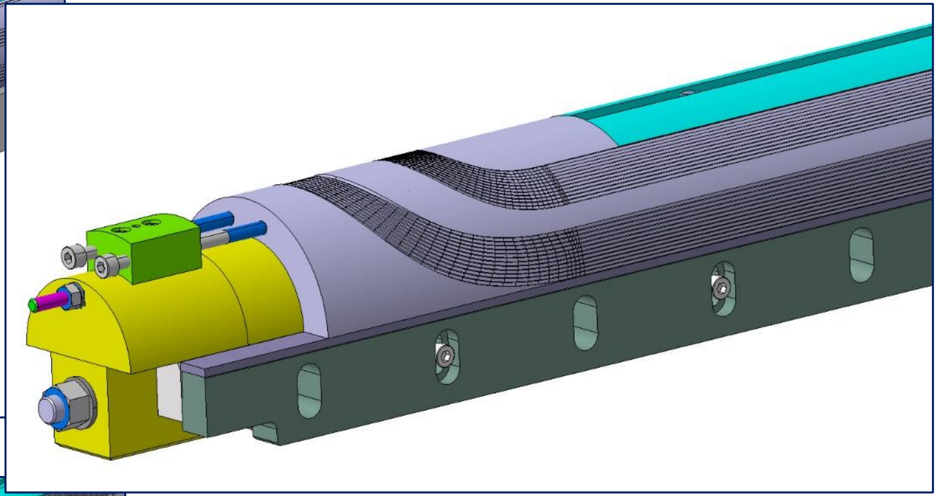
- FEM computations to assess the special collars in the splice area

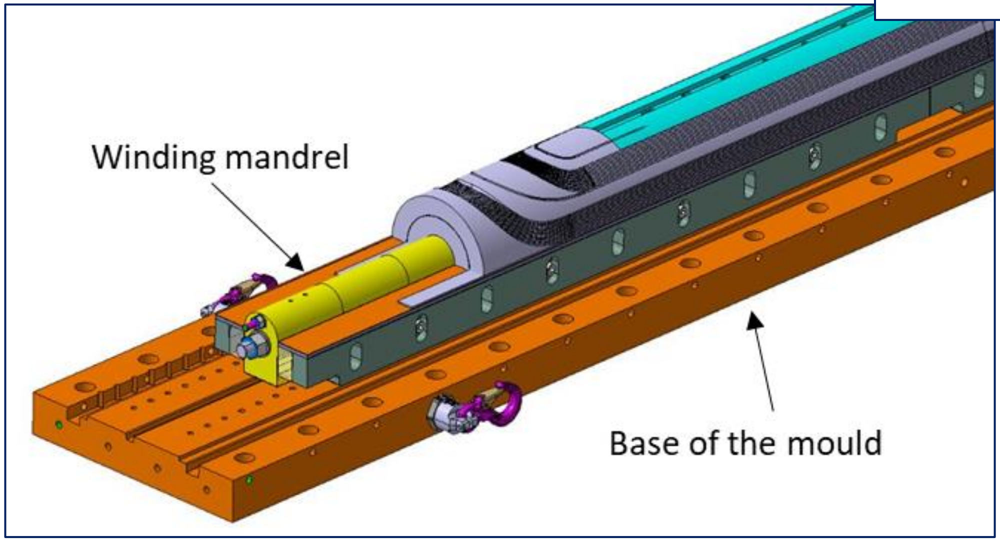


Modular coil moulds to realize the two different splices, internal and external (or an 11 T type coil - which is not our baseline).

Development of tools to minimize coil handling from winding to HT and impregnation





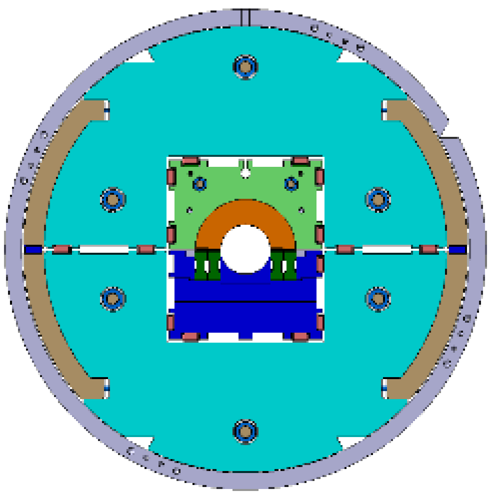


- Pre-design for two moulds done.
- **Implemented in FalconD – INFN.**
- Under final design for 12 T VE.
- Studies and tests for a single mould (HT and impregnation) on going.

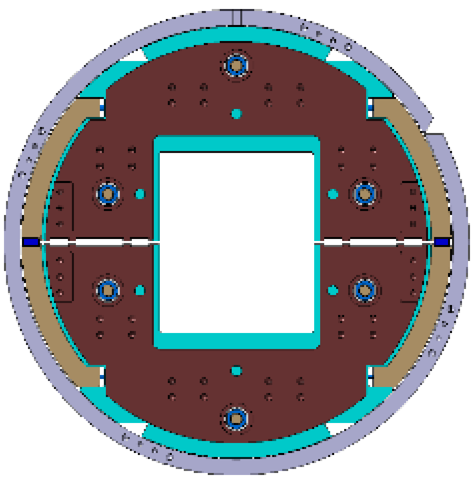
Test coil structure 'mirror' under production

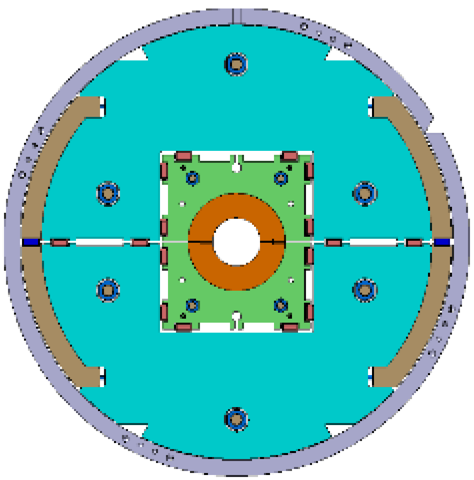
- **Design completed for the version 11 T coil. Design well advanced for version 12 T coils (to test different configurations and/or different resins - See Roland's talk). Can be used for FalconD coils as well.**
- **Assembly tools under study (re-use or refurbishing of many existing tools in bld. 927)**
- **Components for external structure under procurement**

External structure for all cases – assembled once

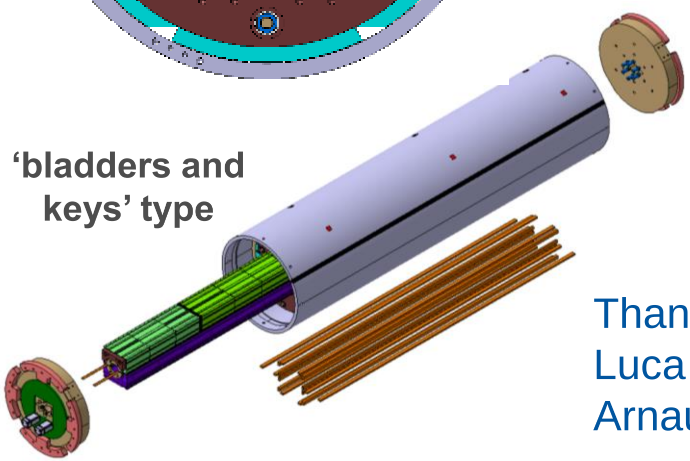


Single aperture half (mirrored)



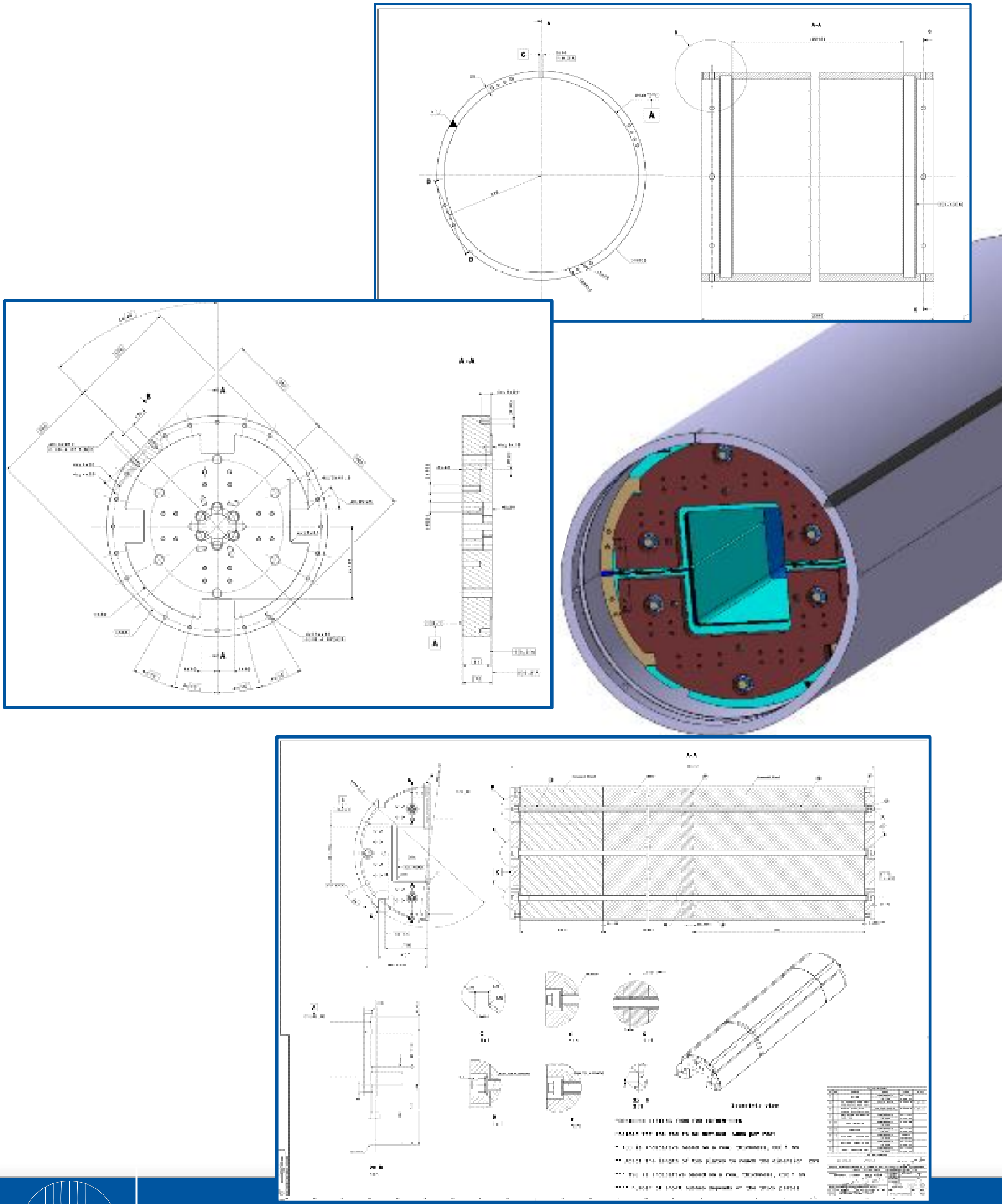


Single aperture full



'bladders and keys' type

Thanks to Nikolina Vejnovic, Luca Dassa, Lucie Baudin, Arnaud Foussat.



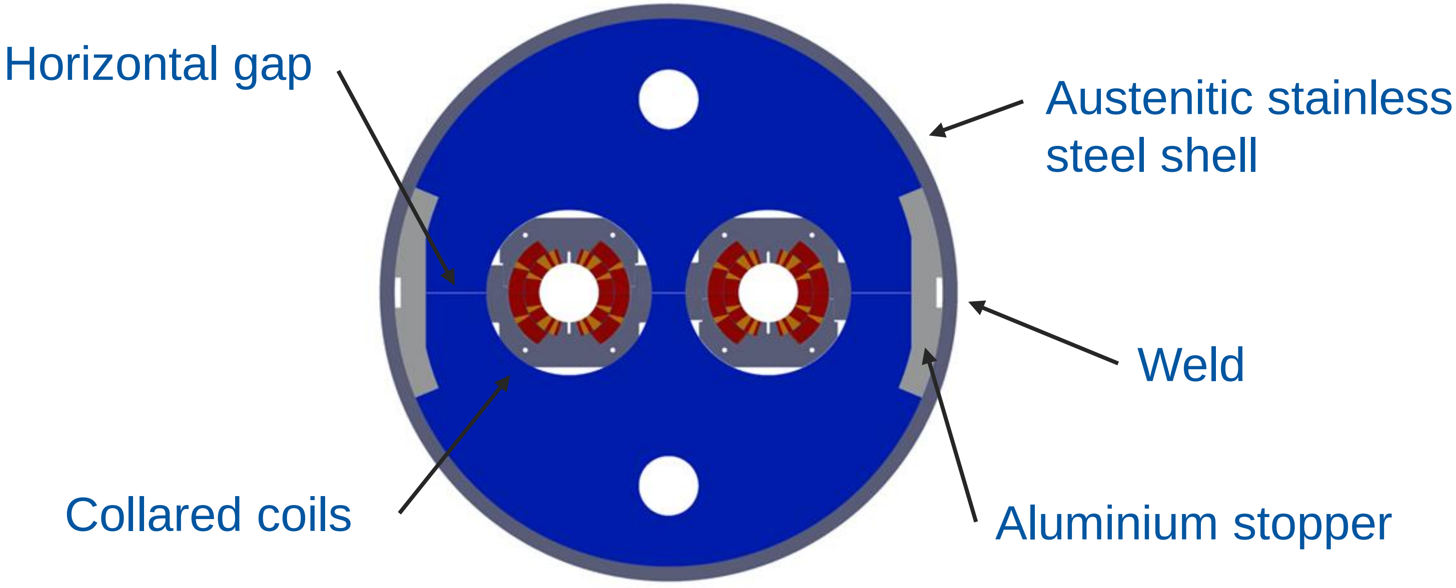
Thanks to MME design office and workshop.

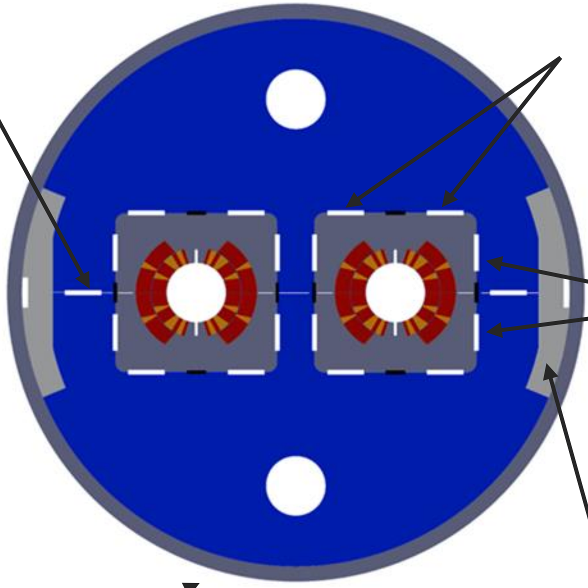
Thank you for your attention

HFM

High Field Magnets

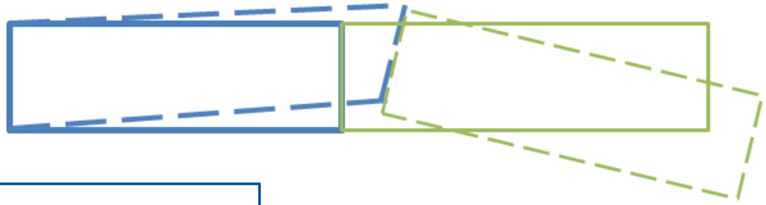
Spare slides


Horizontal gap
Austenitic stainless steel shell
Weld
Collared coils
Aluminium stopper

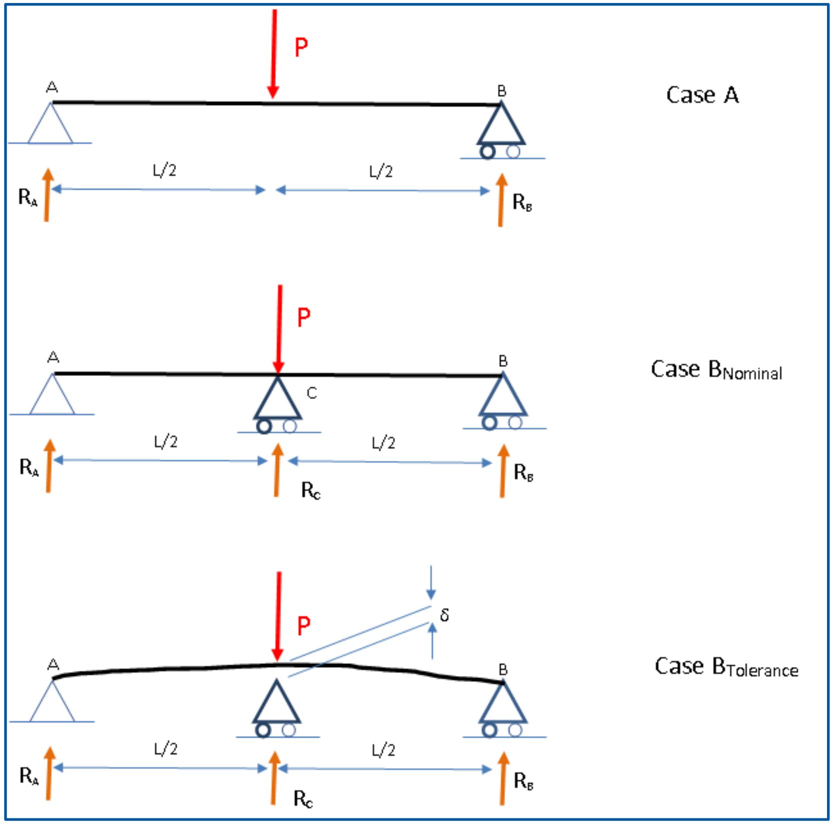

Horizontal gap
Position for
horizontal bladders
Weld
Position for
vertical bladders
Austenitic stainless
steel shell
Aluminium stopper

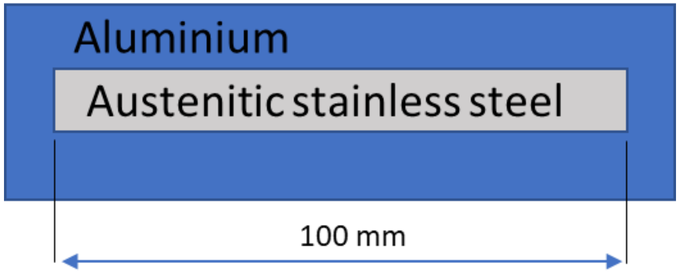
Tolerances and statically indeterminate conditions

Some simple examples



Tolerances of size and shape (lever arm effects).





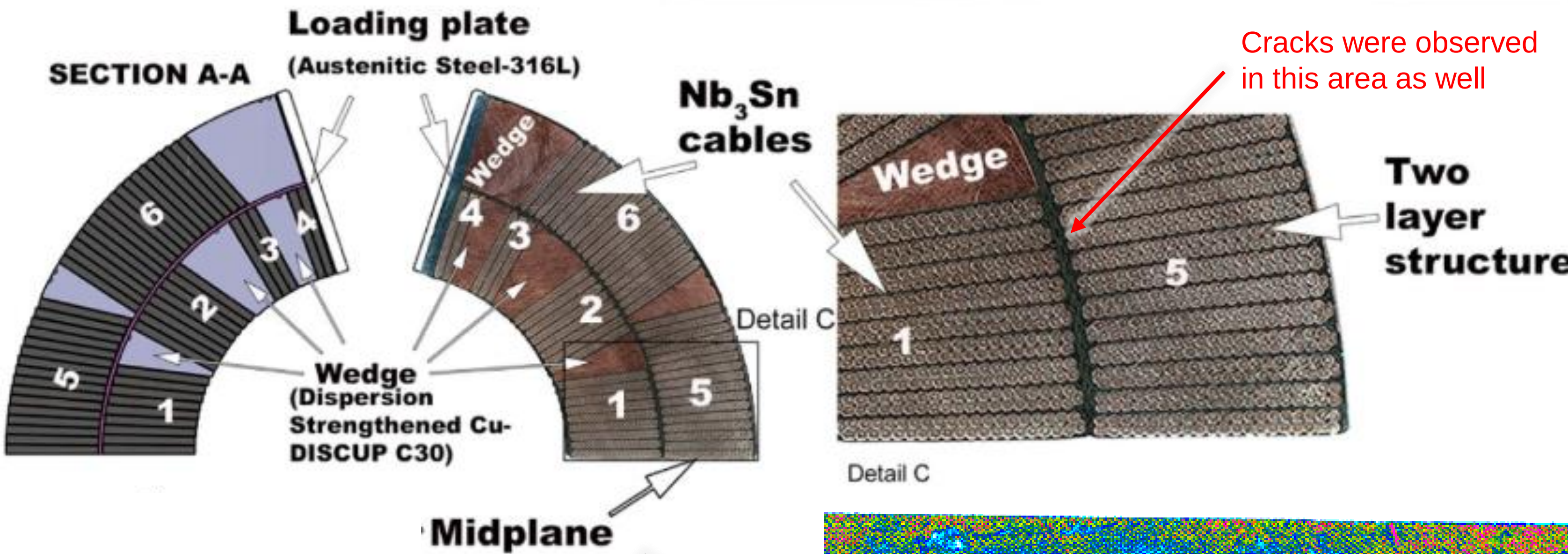
Aluminium slot: 100 ± 0.05 mm
Steel slot: 100 ± 0.05 mm

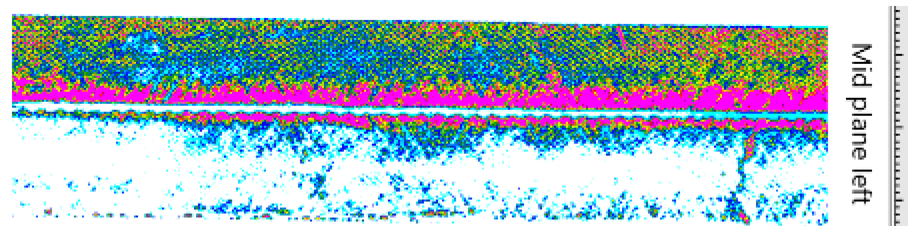
Thermal contraction from 300 K to 2 K

- Aluminium: - 0.4 mm
- Steel: - 0.3 mm

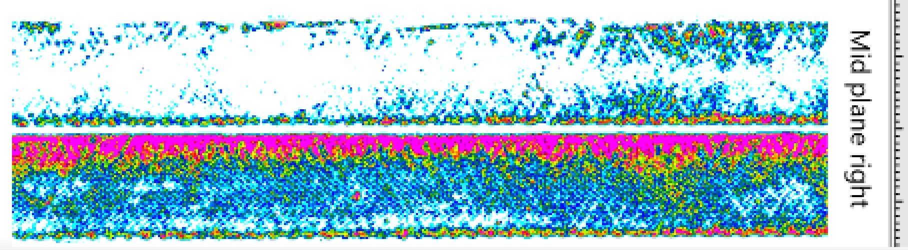
Isostatic structures are easier to control

11 T coils



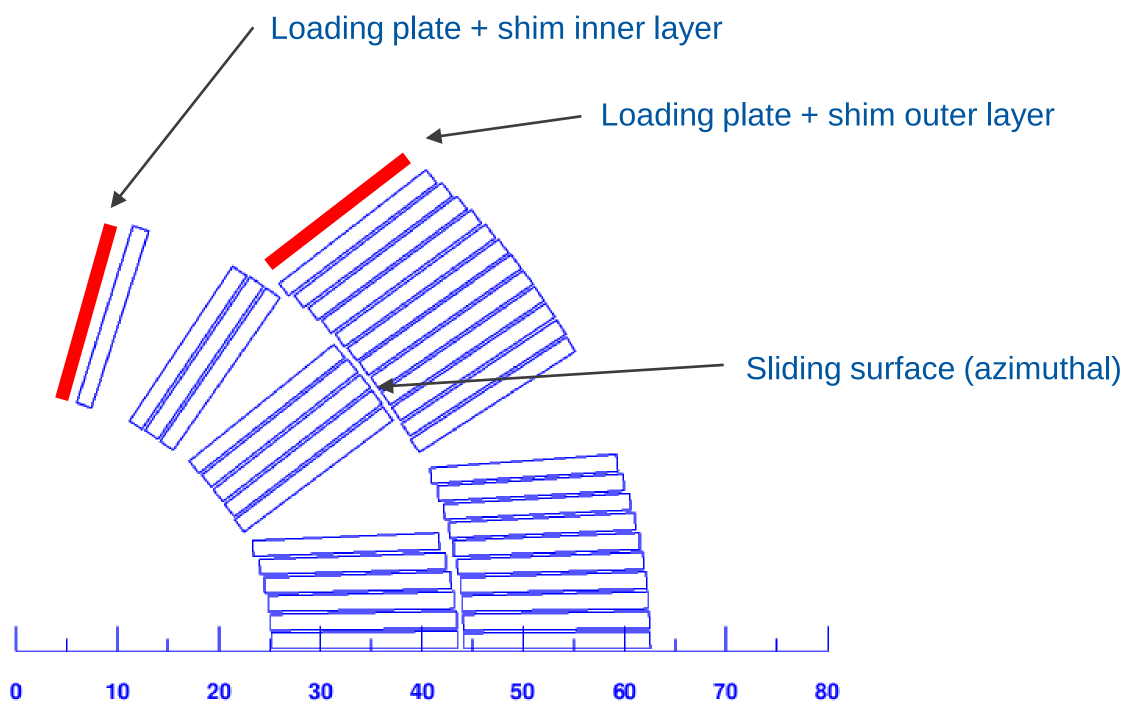


- **More compression in the outer layer**
- **Gradients**
- **No control of the stress distribution**



Impossible inspection of the external surface of the first layer. Gaps!

12 T coils



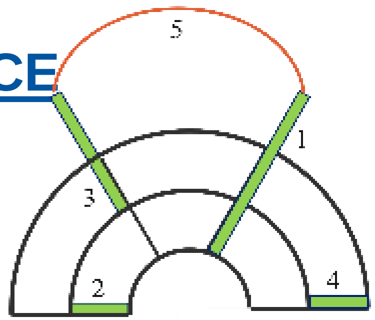
But this requires the development of a splice system …

Splice conceptual designs

Courtesy V. Ilardi

Nb_3Sn – Nb-Ti splice   Nb-Ti – Nb-Ti splice Nb_3Sn – Nb_3Sn splice

EXTERNAL SPLICE

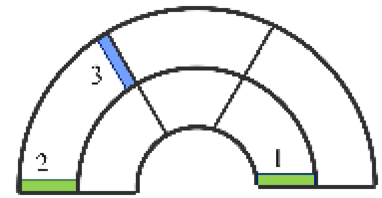


The cable ends are spliced to Nb-Ti outside the coil, before impregnation.

The two layers are then spliced through a Nb-Ti – Nb-Ti joint, during the magnet assembly.

- **Support the brittle Nb_3Sn cable**
- **Two layer-jumps** of different shapes to be accommodated into the coil pack
- **Double-layer jump** for the inner layer cable

INTERNAL SPLICE



A Nb_3Sn – Nb_3Sn joint connects the two layers within the coil at the pole turn level. It is performed after impregnation.

- **Support the brittle Nb_3Sn cable**
- Splicing in the **limited space** of the pole region
- Splice in the **high field region**