



Unit 13

Construction methods and support structures

Episode I

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Outline



1. Introduction
2. Coil winding and curing
3. Reaction of Nb_3Sn coils
4. Vacuum impregnation of Nb_3Sn coils
5. “React & Wind” approach
6. Instrumentation and measurements
7. Nb-Ti – Nb-Ti and Nb_3Sn – Nb-Ti splices
8. Final assembly
9. Practical examples
10. Conclusions



References



- [1] L. Rossi, “Superconducting Magnets”, CERN Academic Training, 15-18 May 2000.
- [2] MJB Plus, Inc. “Superconducting Accelerator Magnets”, an interactive tutorial.
- [3] K.-H. Mess, P. Schmuser, S. Wolff, “Superconducting accelerator magnets”, Singapore: World Scientific, 1996.
- [4] “LHC design report v.1: the main LHC ring”, CERN-2004-003-v-1, 2004.
- [5] R. Gupta, *et al.*, “React and wind common coil dipole”, talk at *Applied Superconductivity Conference 2006*, Seattle, WA, Aug. 27 - Sept. 1, 2006.
- [6] Slides from J. C. Perez on coil fabrication process in MDT section at CERN.



1. Introduction



- In this unit we show how the **coils are fabricated**.
 - How do we go from the insulated cable presented in Unit 4 to a full coil ready to be used in a magnet?
 - Which are the fabrication steps for a Nb-Ti coil and Nb₃Sn coil?
 - Which are the differences?



2. Coil winding and curing

- The coil is the **most critical** component of a superconducting magnet.
- Cross-sectional **accuracy** of few hundredths of millimeters (few mils) over up to 15 m length must be reached for field quality requirements (Unit 20).
- 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).
- Coil is fabricated with **laminated tooling**: very accurate laminations can be fabricated at low cost and assembled in long length.



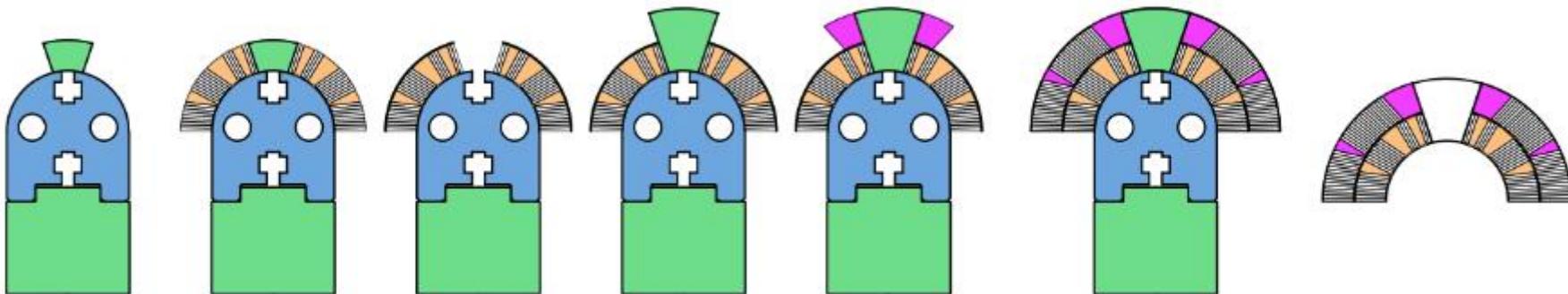
L. Rossi, [1]



2. Coil winding and curing

Winding tooling

- 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**. The mandrel is made of laminations mounted on a beam.
- Winding starts from the pole turn of the inner layer after preparing the coil ramp for the outer layer.
- The cable is maintained in **tension** (200 N)





2. Coil winding and curing Winding machines



- For short models, a **rotating mandrel** is used.

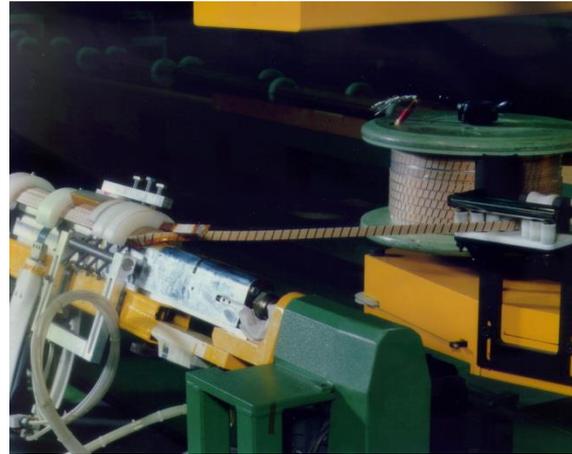




2. Coil winding and curing Winding machines



- 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.



L. Rossi, [1]

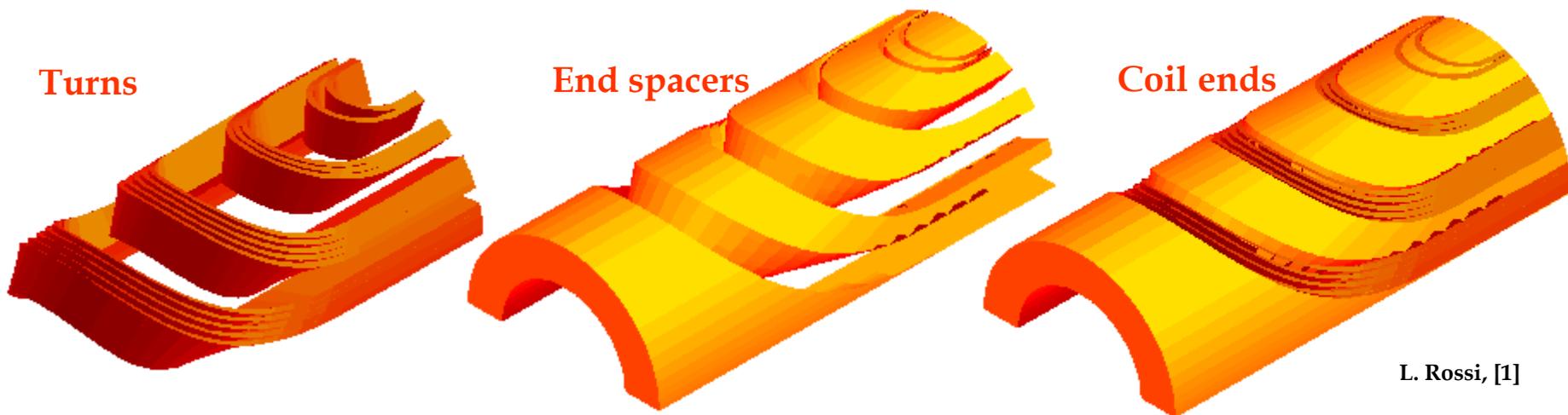




2. Coil winding and curing Ends



- 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 filled by injection of loaded resins.



L. Rossi, [1]



2. Coil winding and curing Ends



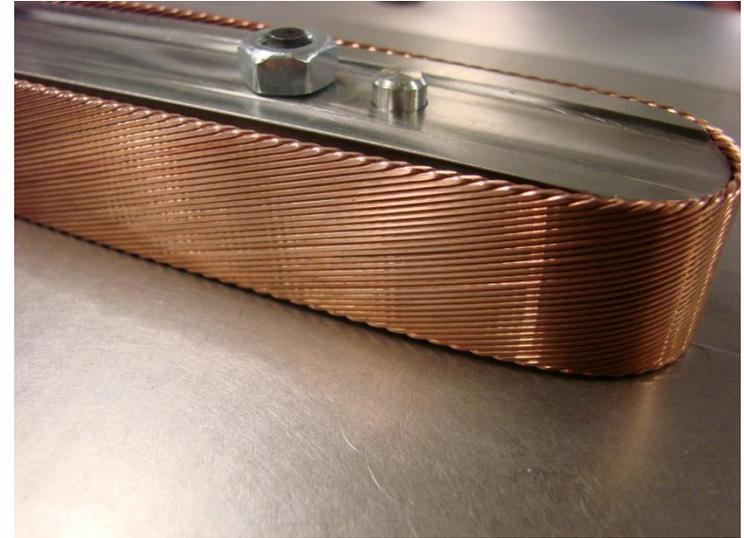
- In Nb_3Sn magnets, end spacers are produced by 5-axis machining of **aluminum bronze or stainless steel**.





2. Coil winding and curing Ends

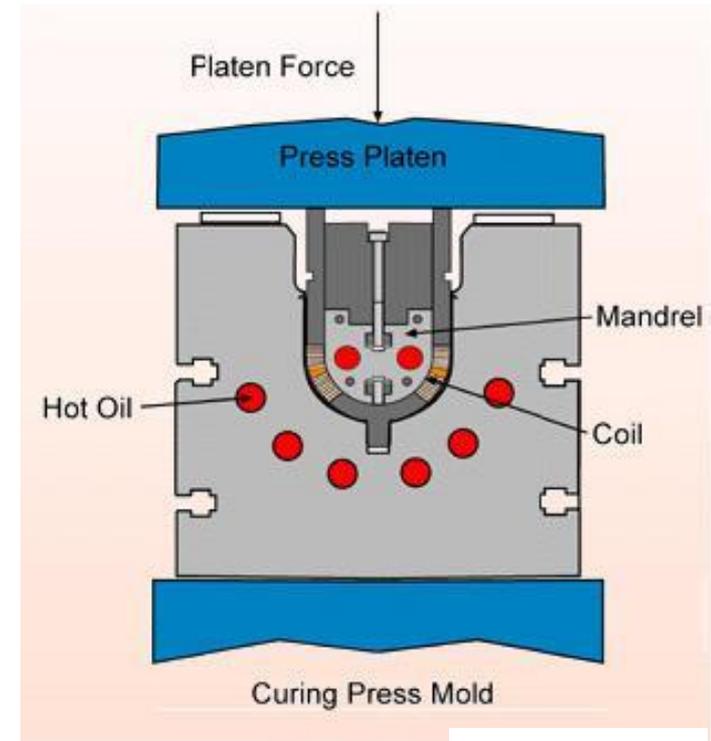
- There is a **minimum bending radius**, which depends on the cable dimensions.
 - Is there a general rule? No, but usually the bending radius is 10-15 times the cable thickness.
 - The cable must be constantly monitored during winding.
- If the bending radius is too small
 - **De-cabling** during winding;
 - Strands **“pop-out”**.
- There is no difference in minimum bending radius between Nb-Ti and Nb₃Sn, if the cable is reacted after winding (“wind-and-react technique”).
- If the cable is reacted before winding (“react-and-wind” technique), a much larger bending radius is required.



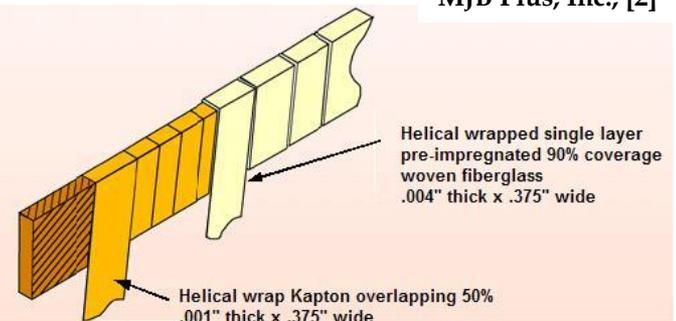


2. Coil winding and curing NbTi coil curing

- 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.
 - For the LHC, coil dimensions must respect a tolerance of ± 0.05 mm, with the average value having ± 0.03 mm.
- 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 3rd insulation layer.



MJB Plus, Inc., [2]

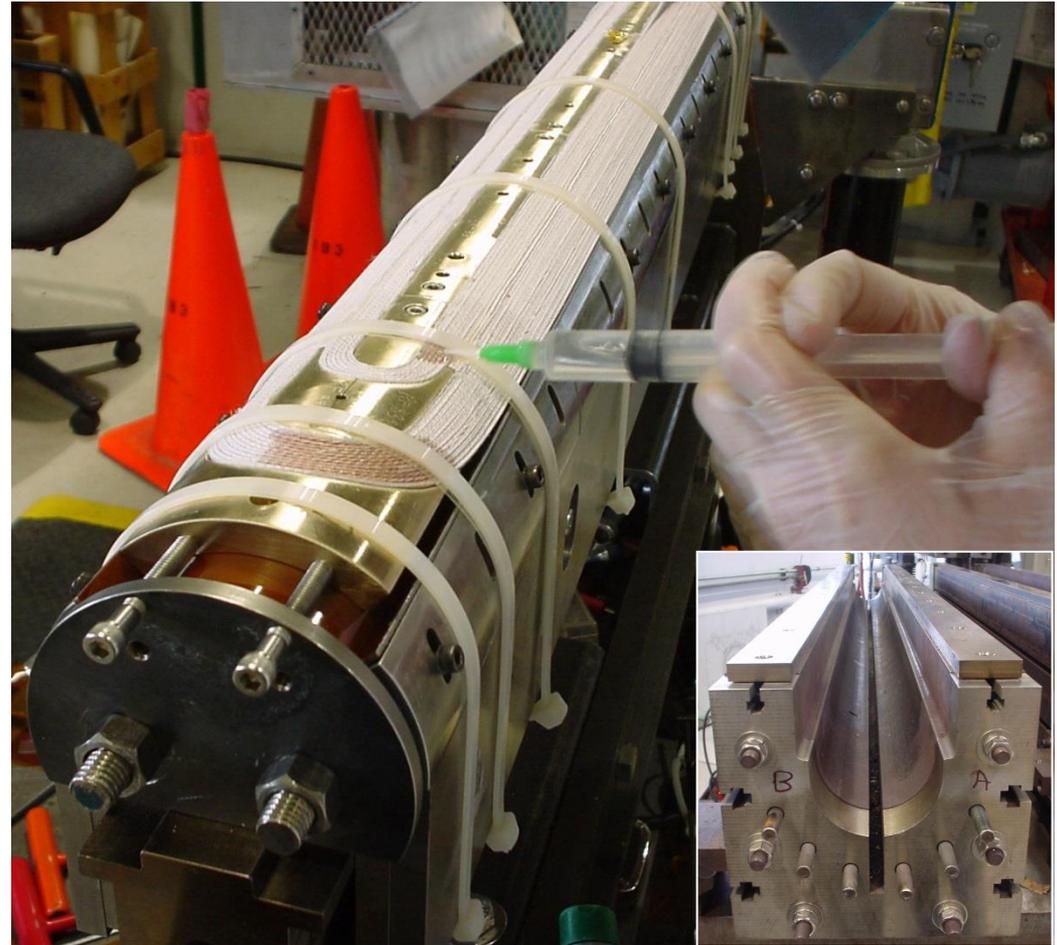




2. Coil winding and curing Nb₃Sn coil curing

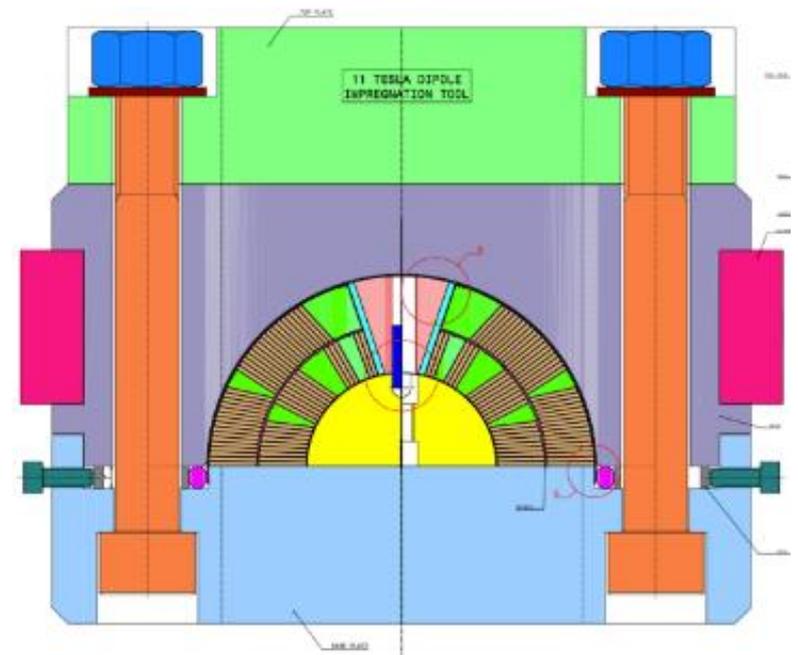


- Similarly to Nb-Ti coils, in **Nb₃Sn coils** curing is done to set the coil size for reaction, as well as allow the coils to be easily handled, facilitating insertion into the reaction fixture without damage.
- After winding, cable insulation is injected with **ceramic binder**. Then coils are cured at 150° C for 30 minutes, subjected to an azimuthal pressure of approximately 5 to 35 MPa.





2. Coil winding and curing Nb₃Sn coil curing





Outline

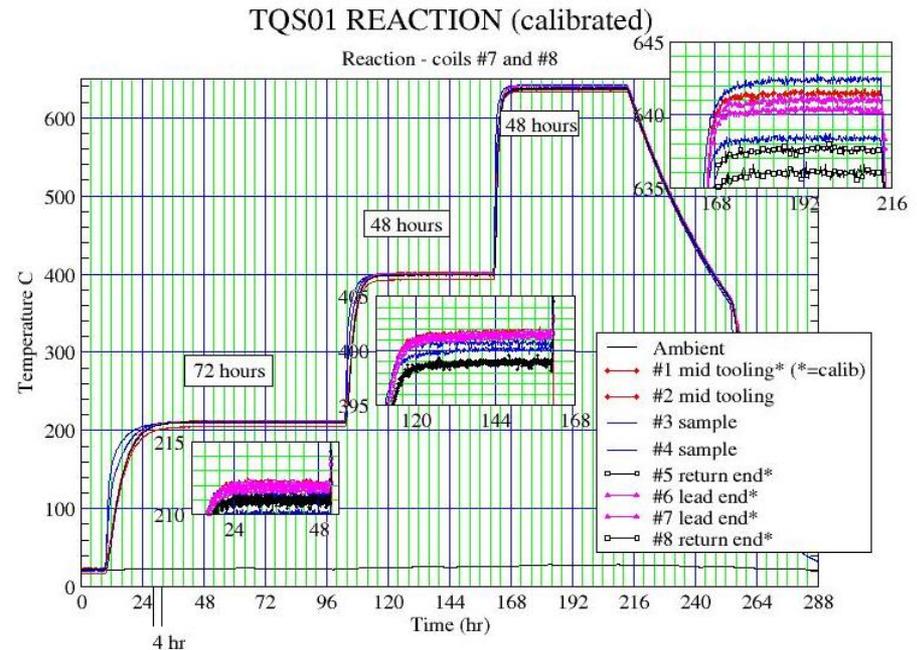


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10. Conclusions



3. Reaction of Nb₃Sn coils

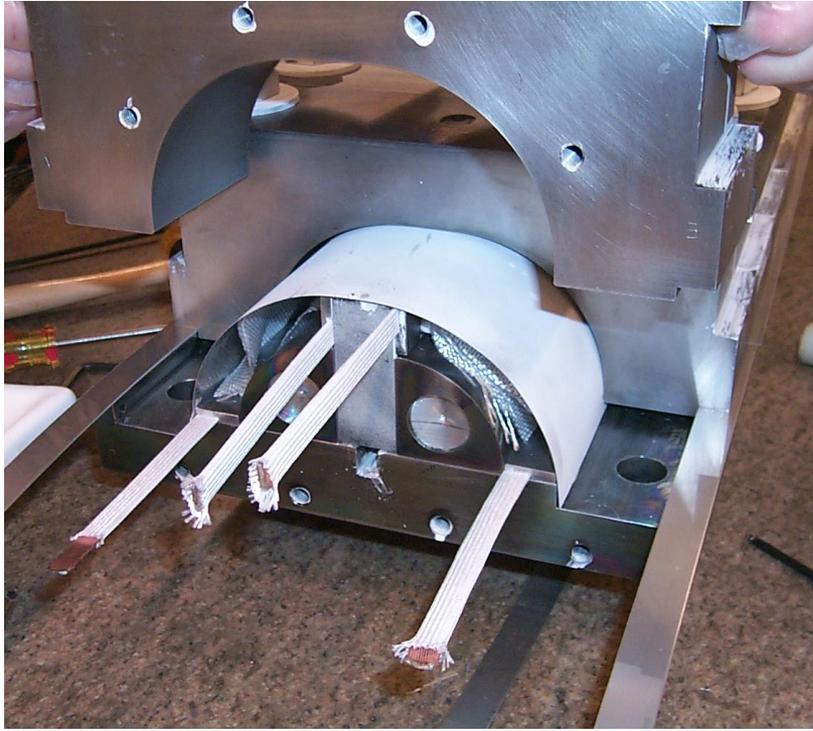
- During the “**reaction**” process, the CuSn and Nb are heated to about 650-700 C in vacuum or inert gas (argon) atmosphere, and the Sn diffuses in Nb and reacts **to form Nb₃Sn**.
- A cable of Nb₃Sn is **brittle**, thus it cannot be bent to a small radius.
- In the “**Wind & React**” approach, the coil is wound unreacted: then the entire coil undergoes the reaction process.
- The reaction is characterized by three temperature steps.
- The required temperature homogeneity is of about ± 3 °C.





3. Reaction of Nb₃Sn coils

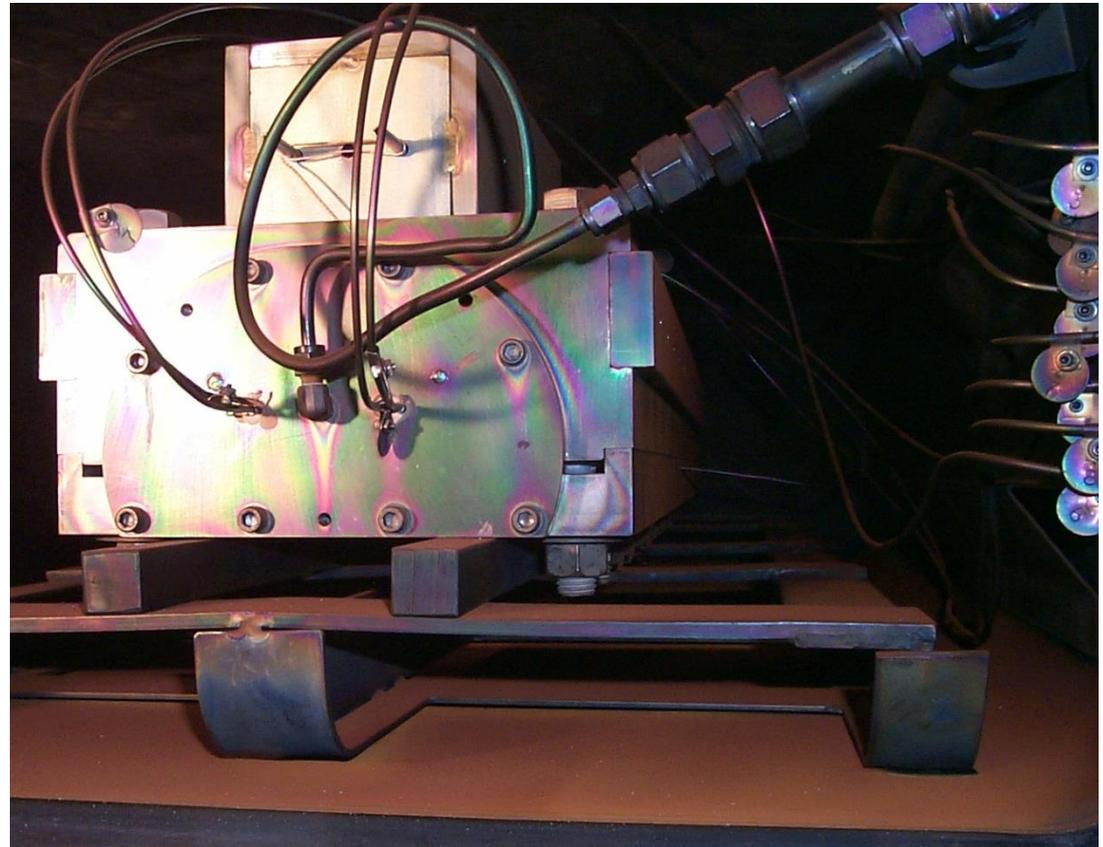
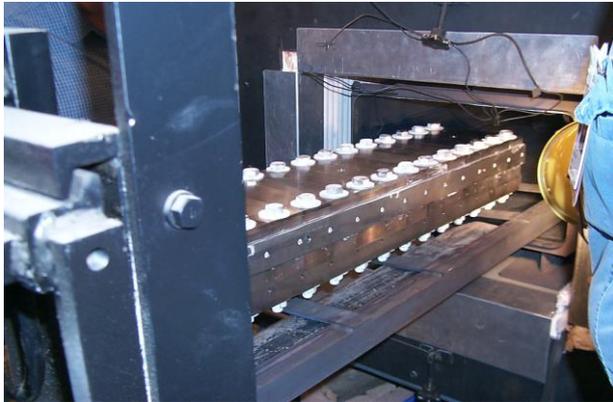
- Coils are clamped in a **reaction fixture** made of stainless steel mold blocks.
 - The pressure on the coil is minimal to reduce risk of degradation.
- Layers of fiberglass, MICA, stainless steel are placed between coil and mold blocks.





3. Reaction of Nb₃Sn coils

- Reaction fixture is placed in the **oven and argon gas flow** connected.
- The argon flows in the reaction fixture in contact with the conductor and fills the oven (welded).





3. Reaction of Nb₃Sn coils





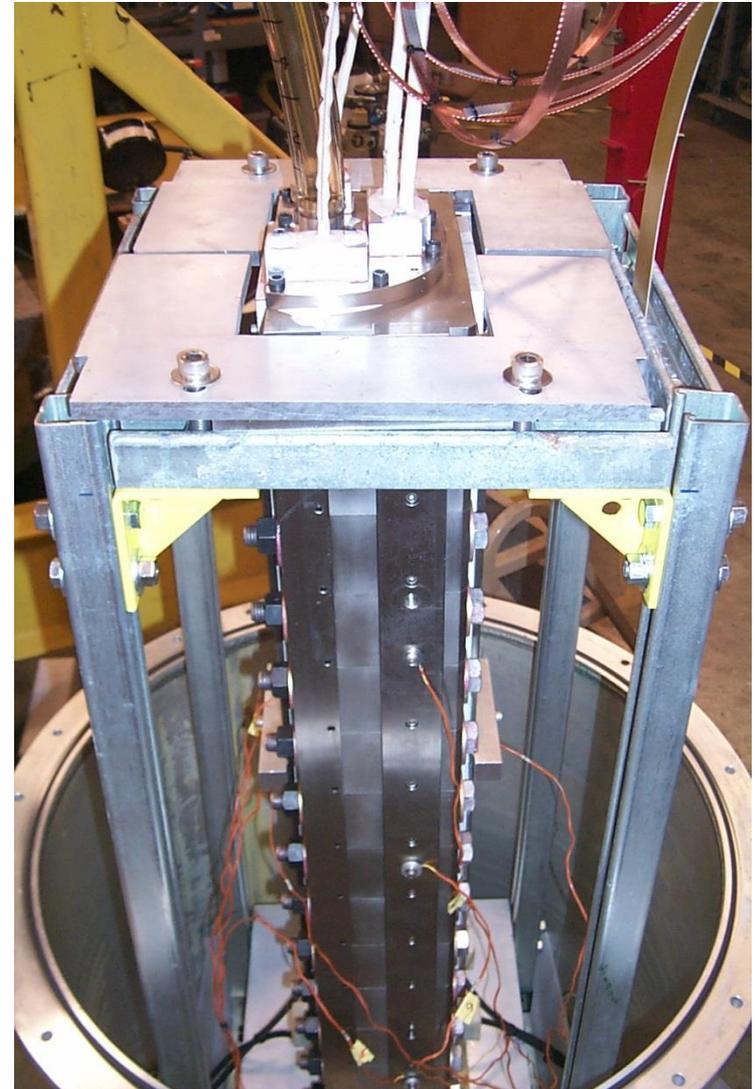
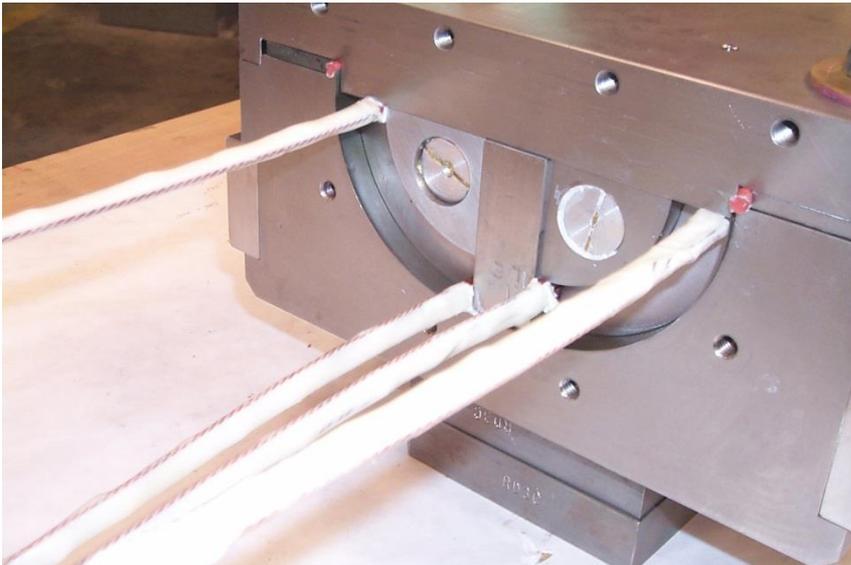
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4. Vacuum impregnation of Nb₃Sn coils

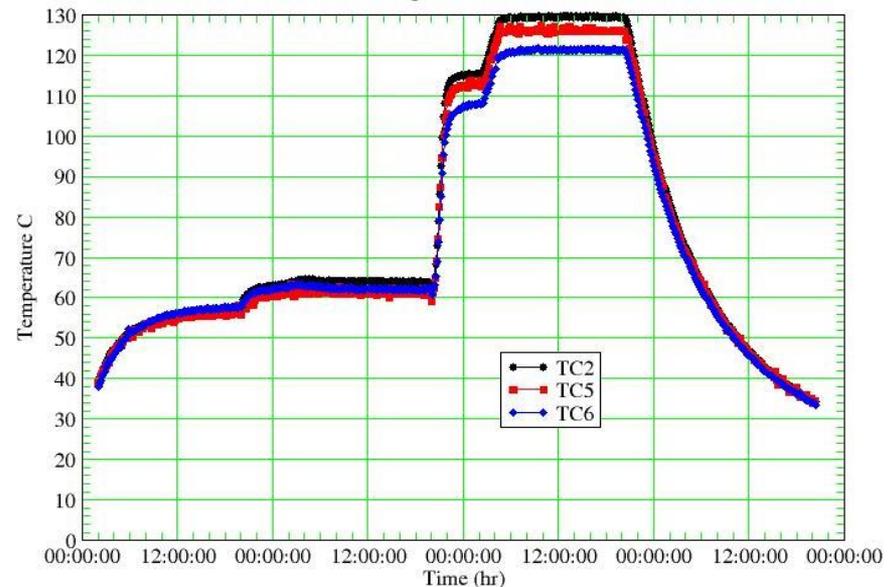
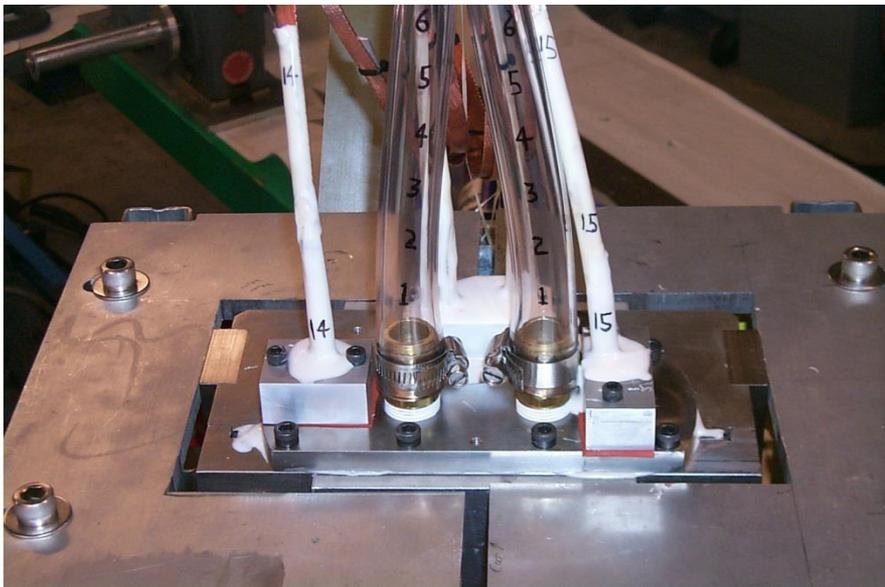
- After reaction, Nb₃Sn coil are **vacuum impregnated** (potted) with epoxy.
 - Resin creates a solid block, thus distributing the stress.
- Coil is placed in a **fixture** (potting fixture) in tight contact with the winding in order to minimize voids.
- The fixture is inserted in a **vacuum tank** and evacuated.





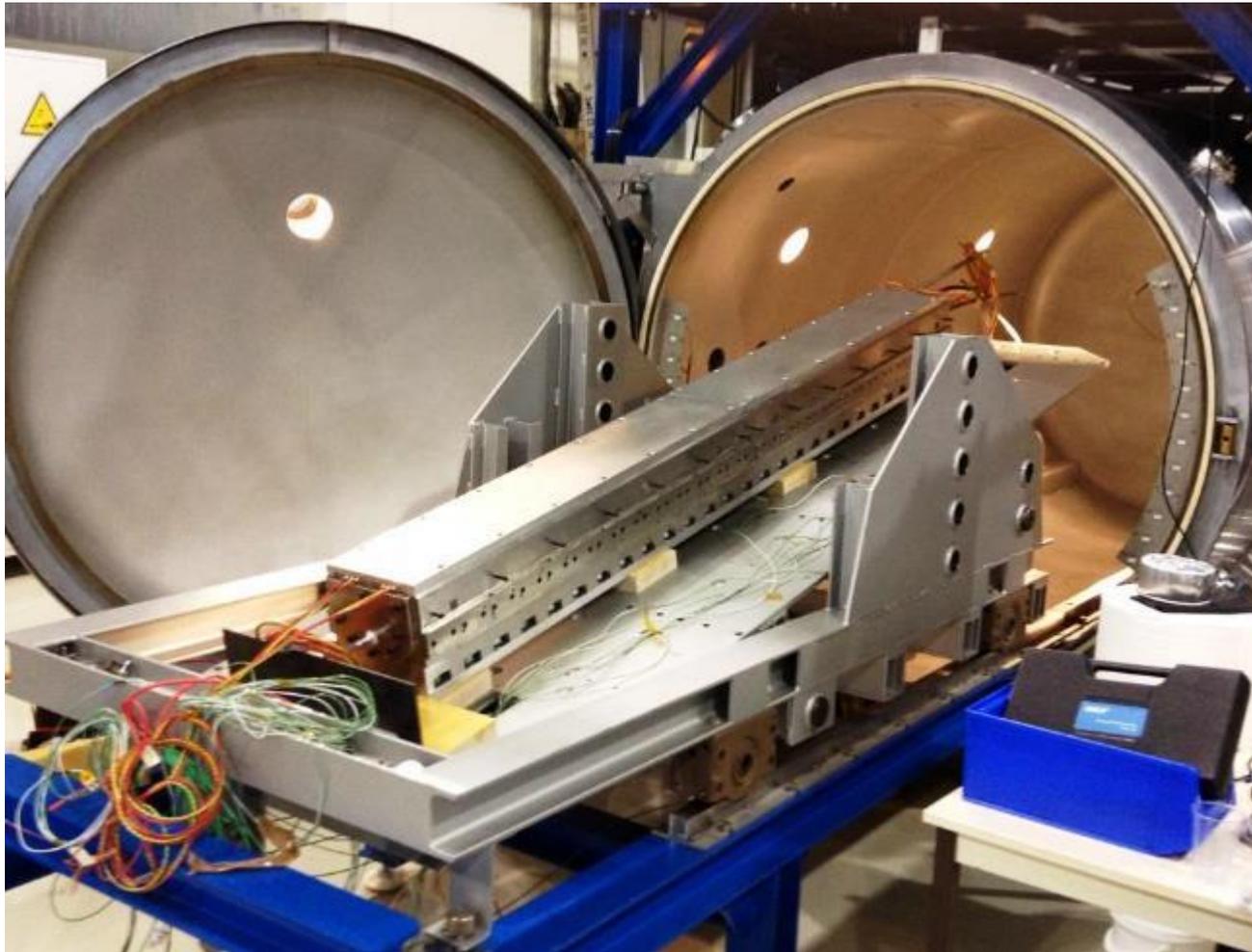
4. Vacuum impregnation of Nb₃Sn coils

- Reservoirs are connected to the fixture.
- Epoxy has high viscosity at room temperature. At about 60 °C, when it has **low viscosity**, atmospheric 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.





4. Vacuum impregnation of Nb₃Sn coils

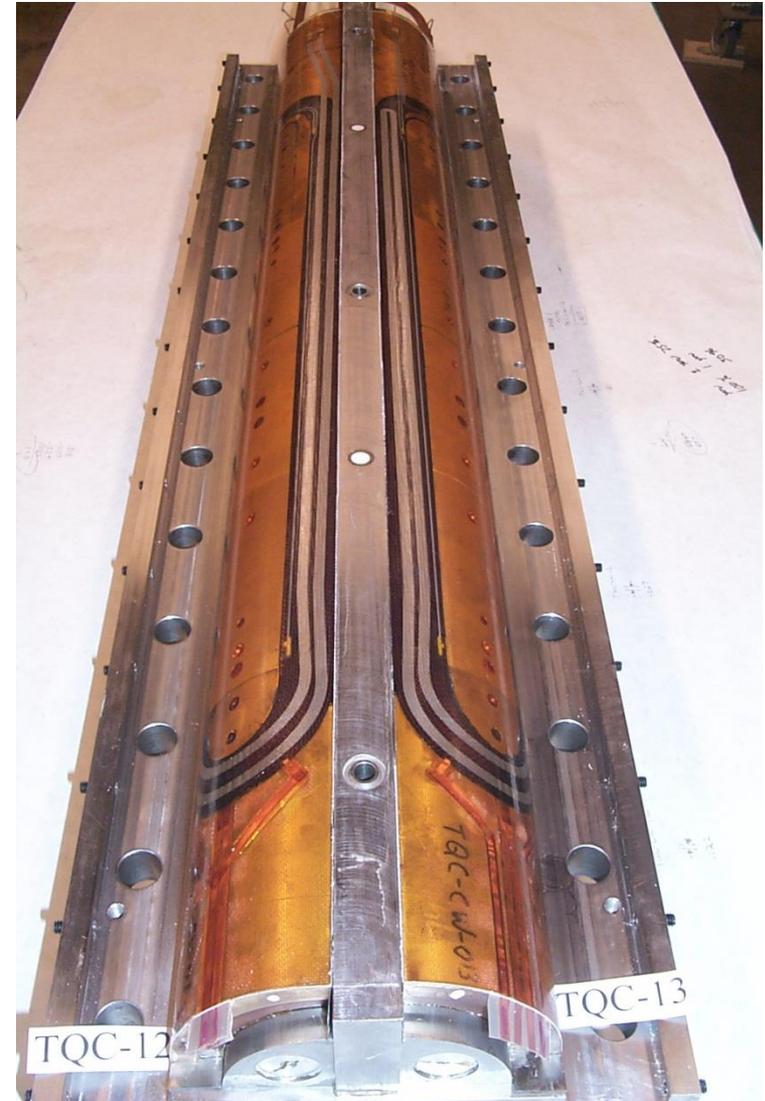




4. Vacuum impregnation of Nb₃Sn coils

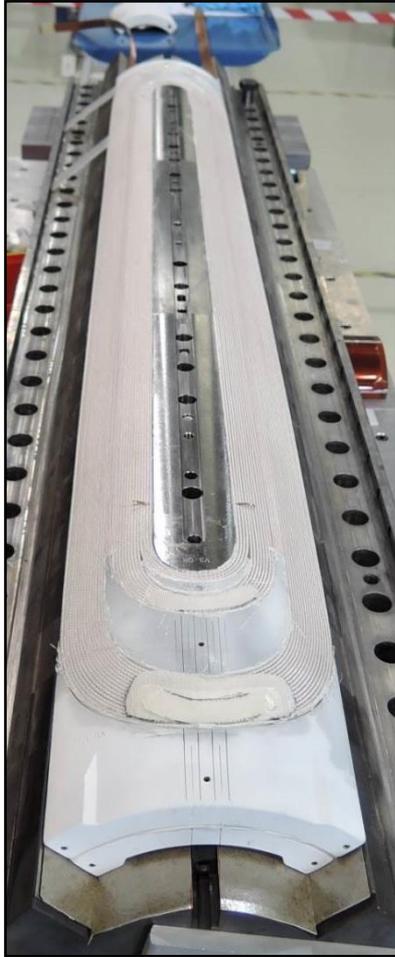


- Once the fixture is brought to room temperature again, the coil can be inspected.
- While for Nb₃Sn coils the impregnation is mandatory due to the brittleness of the superconductor, in most cases NbTi coils are not potted.
- Porous coils, with overlapping polyimide layers, allow the helium to get in contact with the conductor providing higher stabilization.
- Furthermore, because of its high thermal contraction with respect to the strands resin may fracture.
- An energy release is associated to epoxy fracture (see Unit 17).





Overview of Nb₃Sn coil fabrication stages



After winding/curing



After reaction



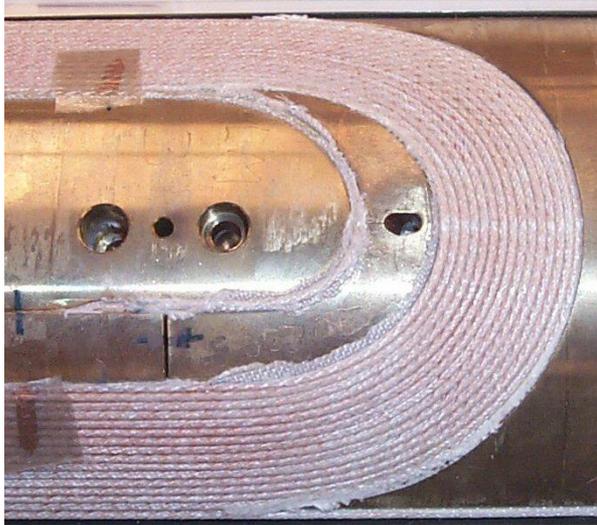
After impregnation



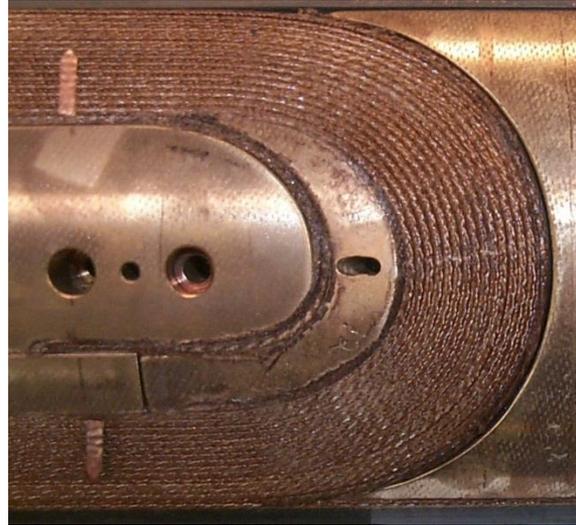
Overview of Nb₃Sn coil fabrication stages



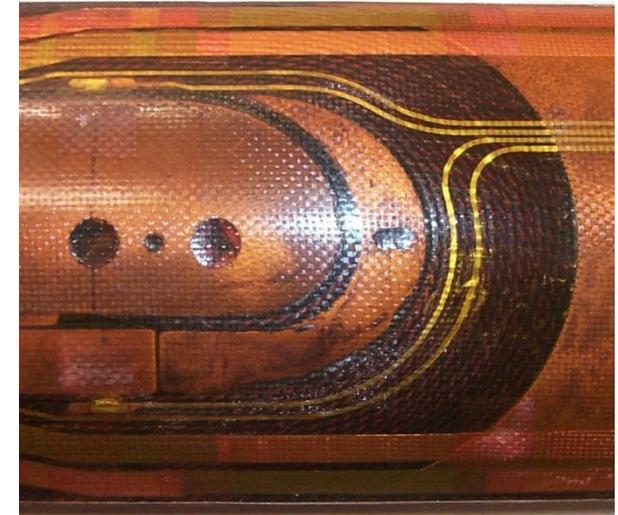
After winding/curing



After reaction



After impregnation





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5. “React & Wind” approach

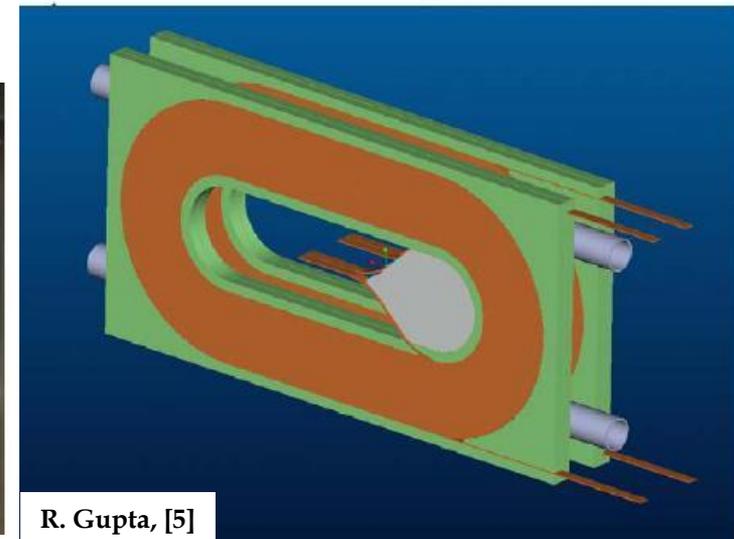
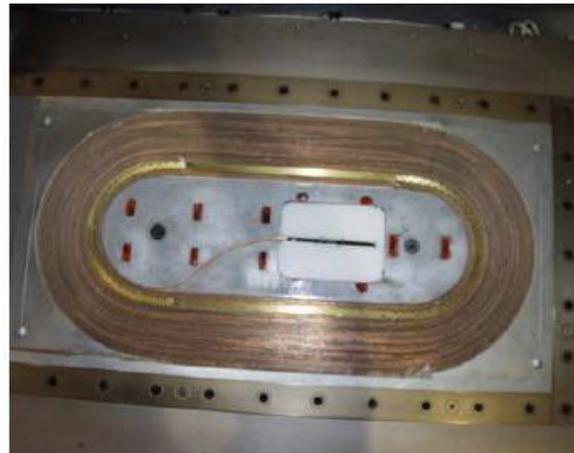
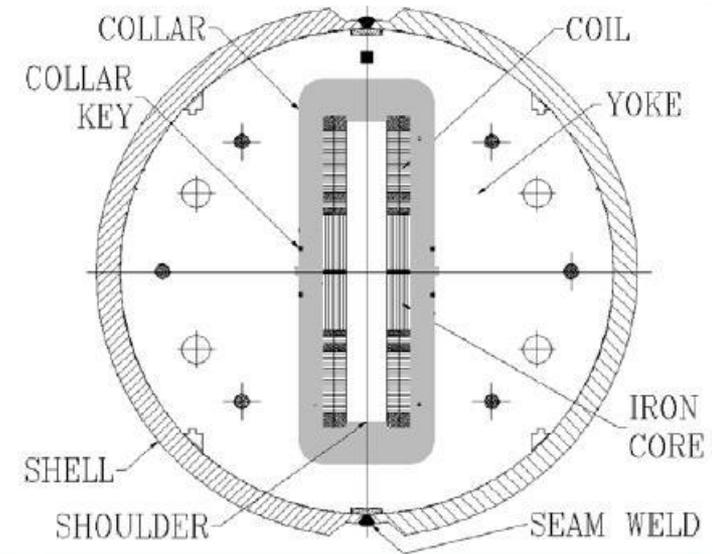


- An alternative construction process for Nb_3Sn coils is the “**React & Wind**”.
 - First react the conductor and second wind the coil
- On the one hand, since the conductor is brittle, small bending radius and complex end geometries (like in $\cos\theta$ magnets) are **not allowed**.
- On the other hand, the process may look attractive for long magnets
 - “In the “Wind & React” approach, the integrated build-up of differential thermal expansion of various materials during the high temperature heat treatment may result in large accumulated strain in the ends of the magnets. Magnets with complex end geometries are more prone to degradation/damage due to this large local strain. Since the integral build-up is proportional to length, this issue becomes more critical in “Wind & React” as magnets get longer” [5].



5. “React & Wind” approach

- Conductor is **reacted on a spool** with large radius.
- Coil geometry must be simple conductor friendly
 - **Common coil design** is a particular suitable design due to the large bending radius in the ends
- Strain is minimized during winding.



R. Gupta, [5]



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6. Instrumentation and measurements



- Quench heaters
 - When a quench occurs, quench heaters **raise the temperature** of the entire coil, bringing it to the normal state. By dissipating the stored energy in the whole coil volume, peak temperature after a quench is minimized

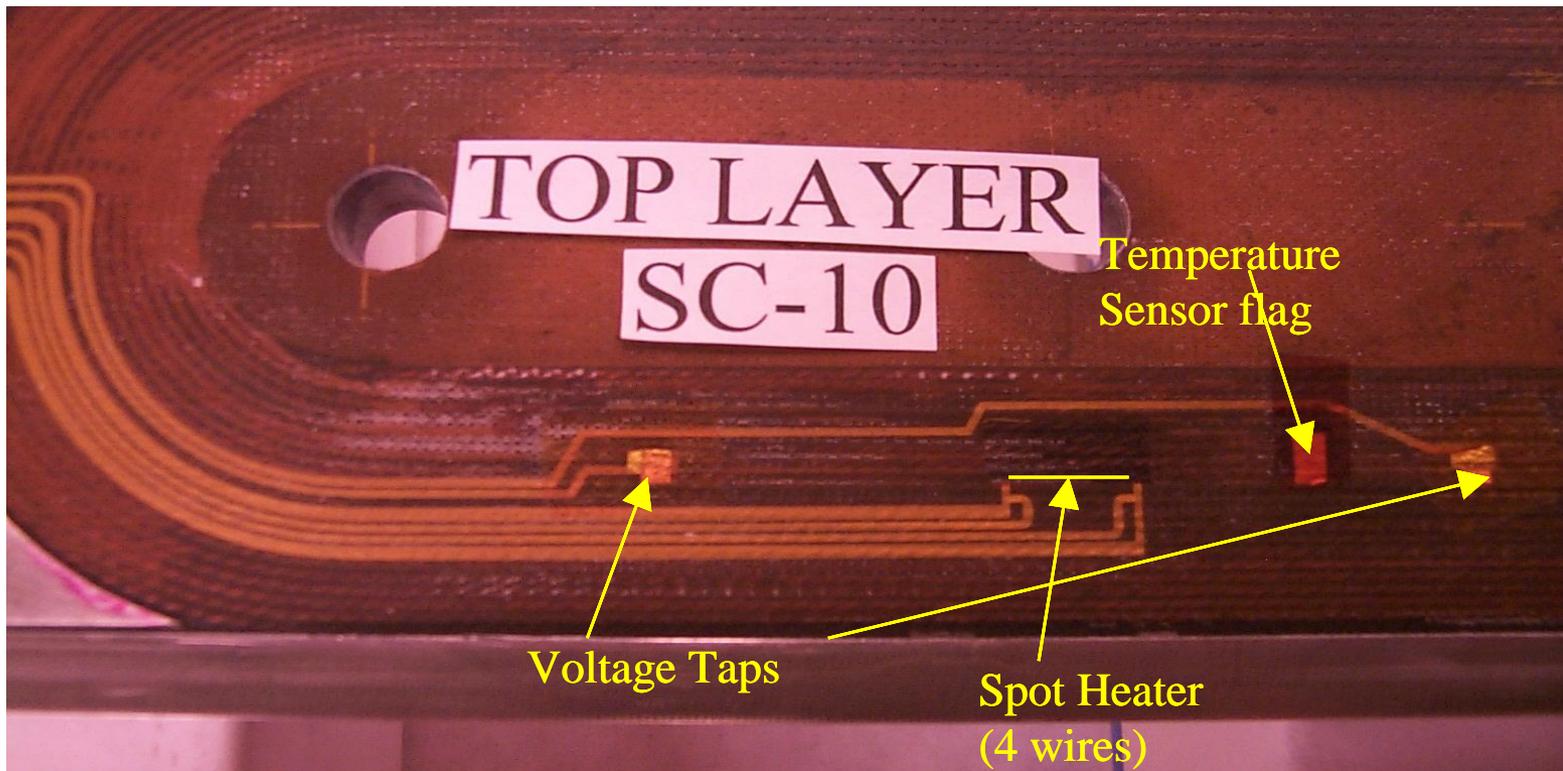




6. Instrumentation and measurements



- Spot heaters
 - By **initiating a quench** in a particular turn/location, they allow investigating quench velocities, peak temperature, and voltages as a function of current and field.

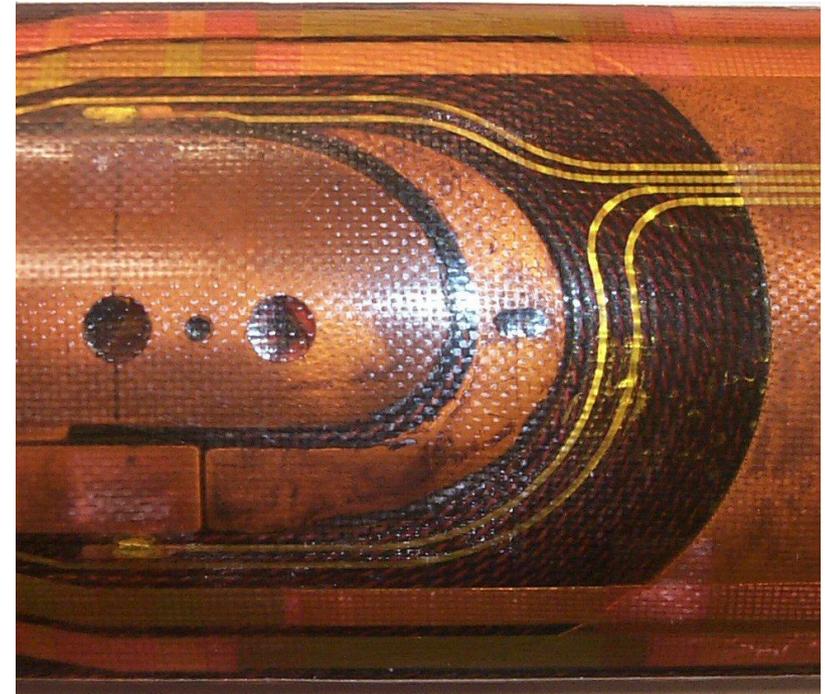
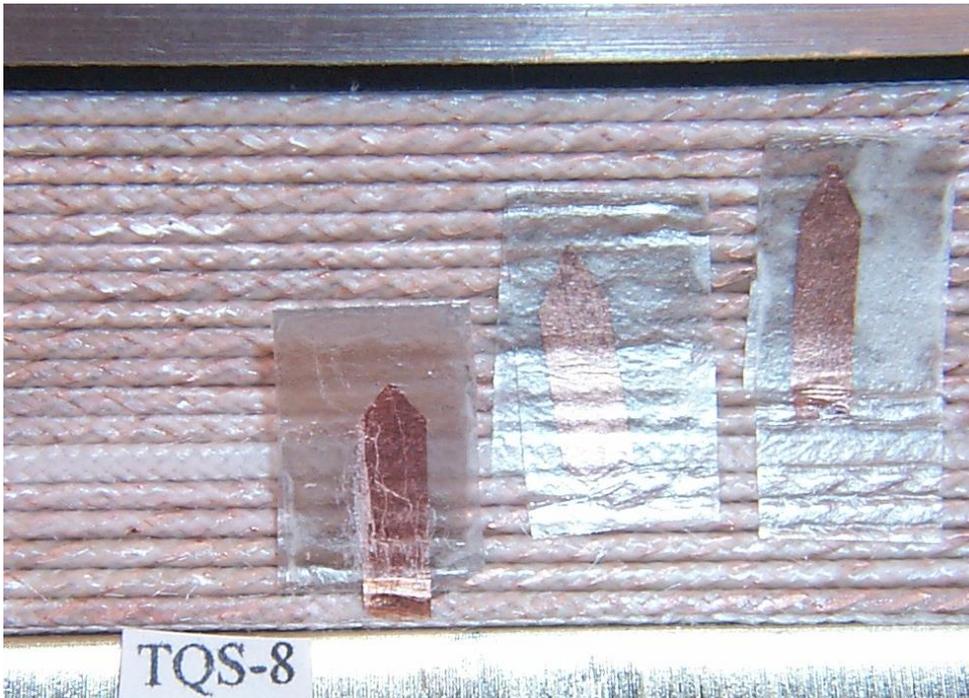




6. Instrumentation and measurements



- Voltage taps
 - By providing a **measurement of the voltage** across a conductor segment, they allow monitoring in which turn/location a quench occurred, and how it propagated along the turn and from turn to turn.





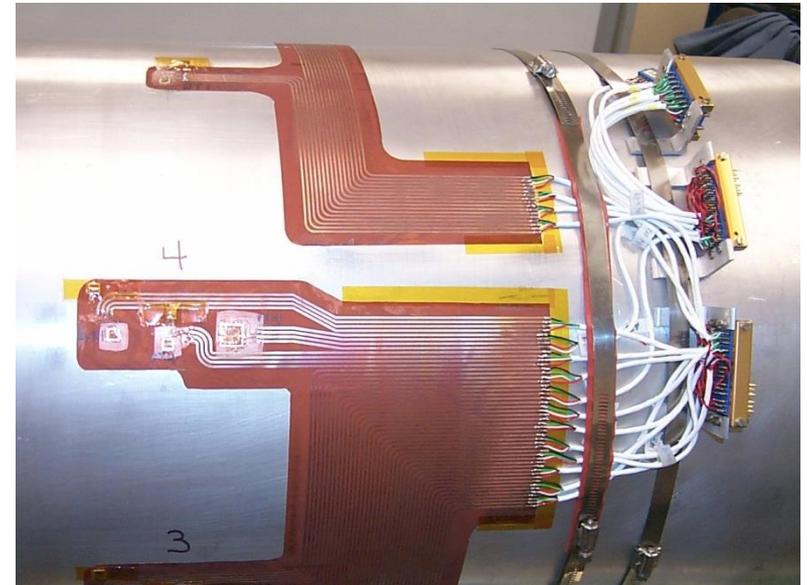
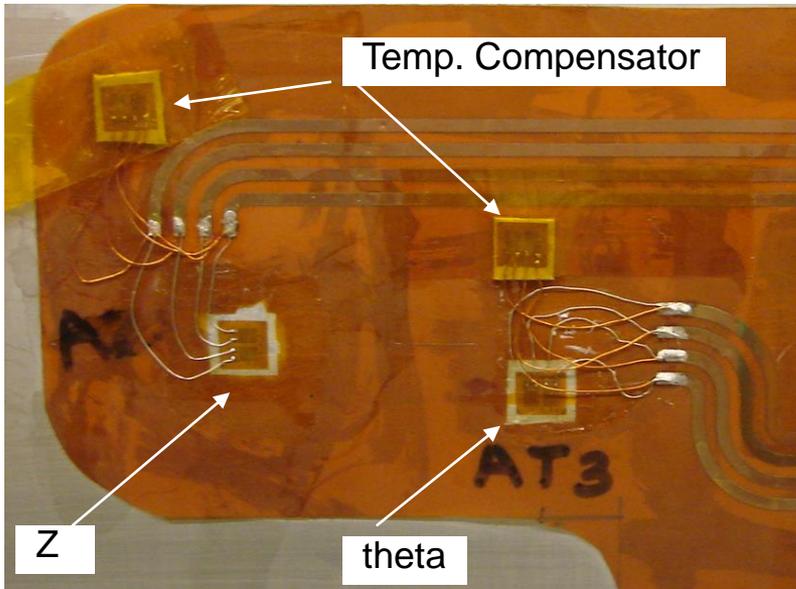
6. Instrumentation and measurements



- Strain gauges
 - By **measuring strain**, they provide information about the stress status of coil and components (see Unit 19).

$$\sigma_x = \frac{E}{1-\nu^2} (\varepsilon_x + \nu\varepsilon_y)$$

$$\sigma_y = \frac{E}{1-\nu^2} (\varepsilon_y + \nu\varepsilon_x)$$

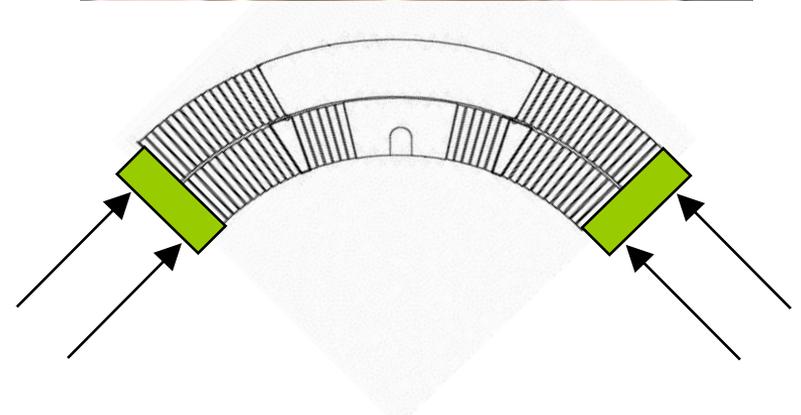
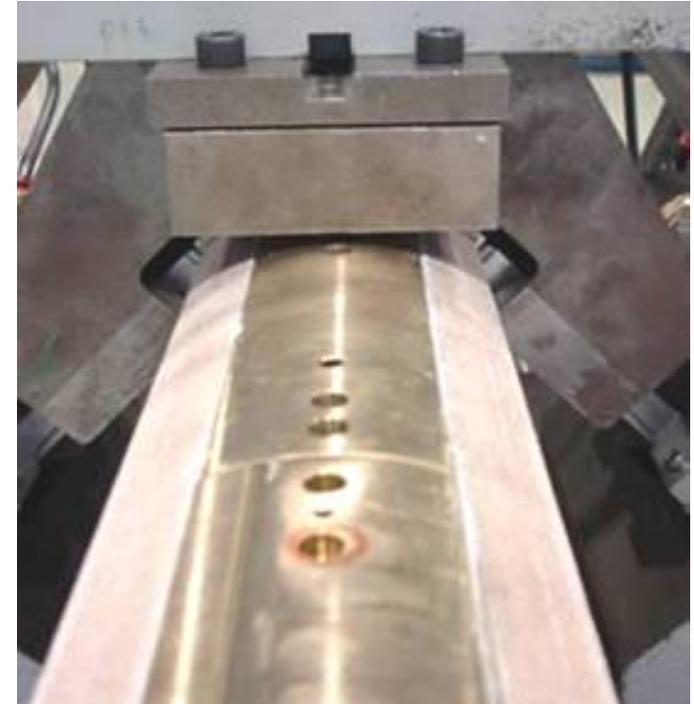




6. Instrumentation and measurements



- **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.





Outline



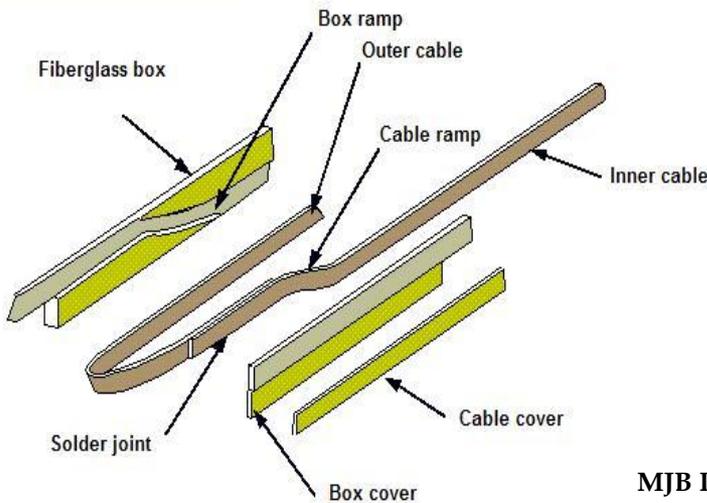
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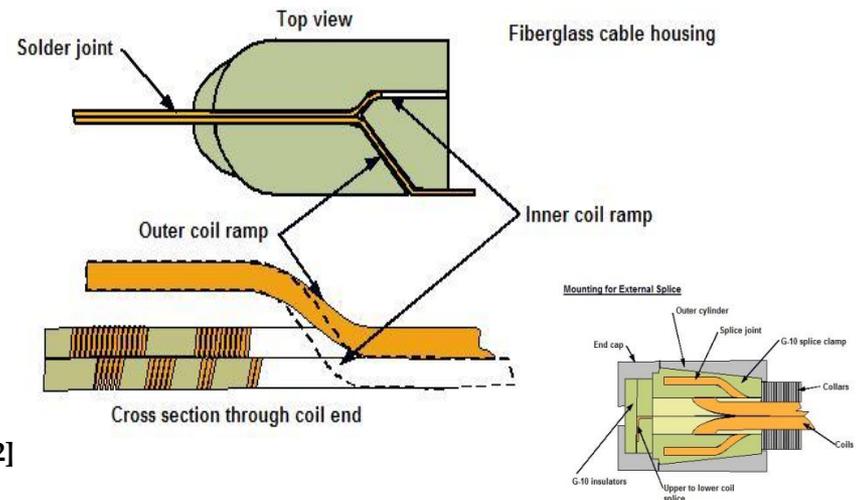
7. Nb-Ti – Nb-Ti splices

- 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.
- 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).
- Solder is usually 40% lead and 60% tin, or silver-tin (5% silver) with a resistivity of less than $2-3 \times 10^{-9} \Omega\text{m}$.
- The temperature rise in the joints is of the order of few mK.

Internal Ramp Splice Design



External Splice



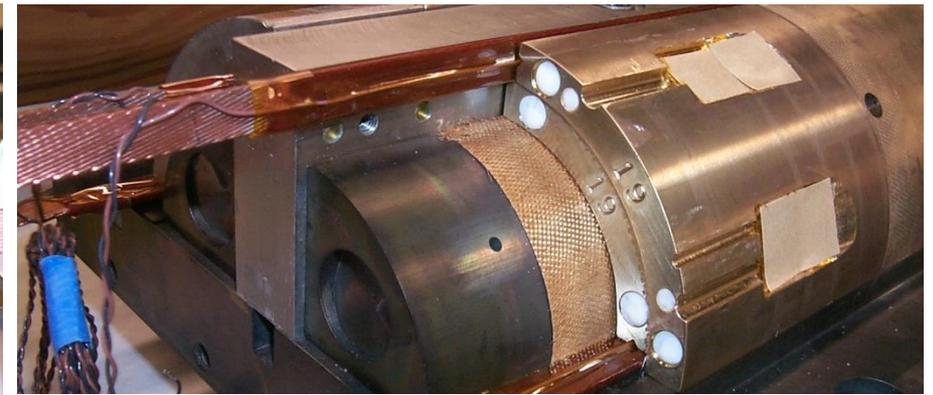
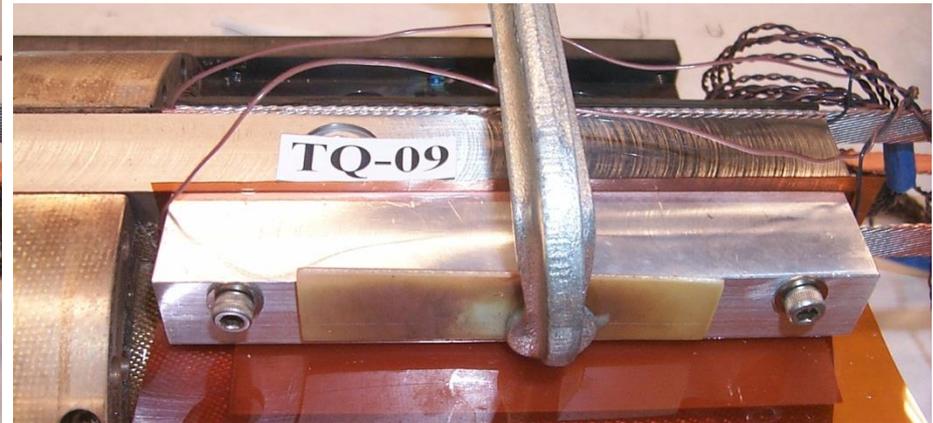
MJB Plus, Inc., [2]



7. Nb₃Sn – Nb -Ti splices



- Nb-Ti leads are compressed against Nb₃Sn cables for a length of about 1-1.5 time the pitch length and soldered.





Outline

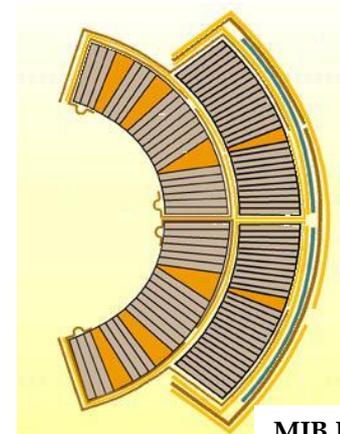
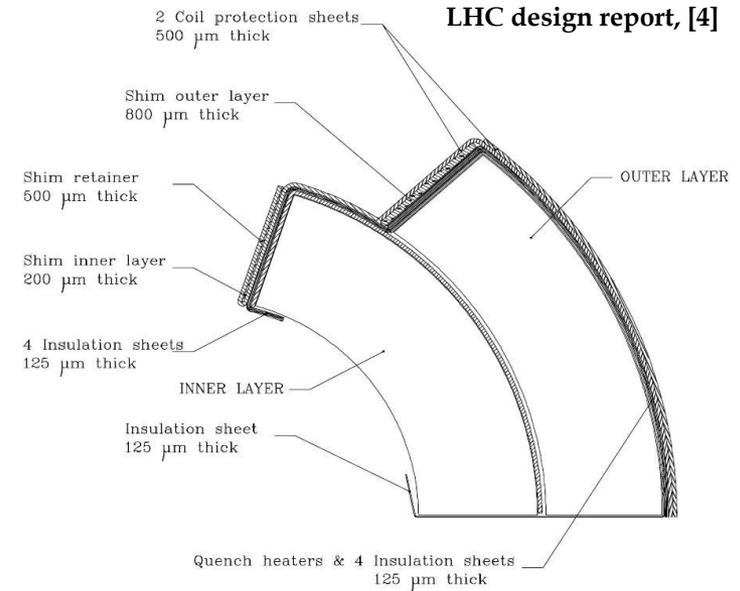


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8. Final assembly

- Additional layers of insulations, usually composed by **polyimide films**, are added around the coils. Besides the electrical function of guaranteeing coil-to-coil and coil-to-ground insulation, they also provide slip surfaces during assembly of the surrounding support structure (collars).
- **Quench protection heaters** are also added to warm the entire coil after a quench. The quench heaters consist stainless steel strips in a sandwich of polyimide insulating foils.
- The conductor must be **protected** from the clamping structure.
 - In the HERA dipoles, 6 layers of kapton 125 mm thick.
 - In the RHIC dipole, glass-phenolic form
 - In the SSC, kapton
 - In the LHC dipoles, coil protection sheets made of stainless steel are used.



MJB Plus, Inc., [2]



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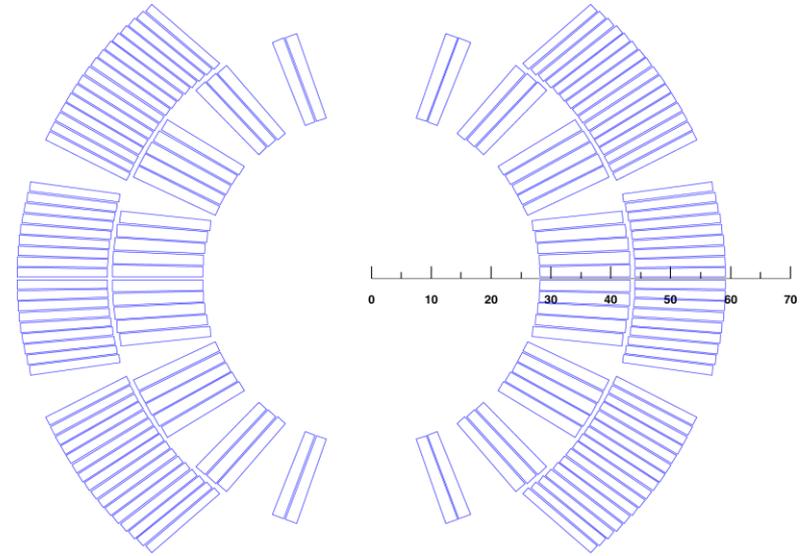


9. Practical examples

LHC dipole coil (Nb-Ti) fabrication steps



- Winding
- Curing
 - Coil at 190 °C under a pressure of 35 MPa
- Surfacing of the heads
 - Voids in the ends are filled with resin
- Measurements of coil azimuthal size
- Superposition of the outer layer onto the inner
- Splicing
- Shimming of the end region
- Assembly of four poles around the bore tube
- Instrumentation (quench heaters) and insulation)

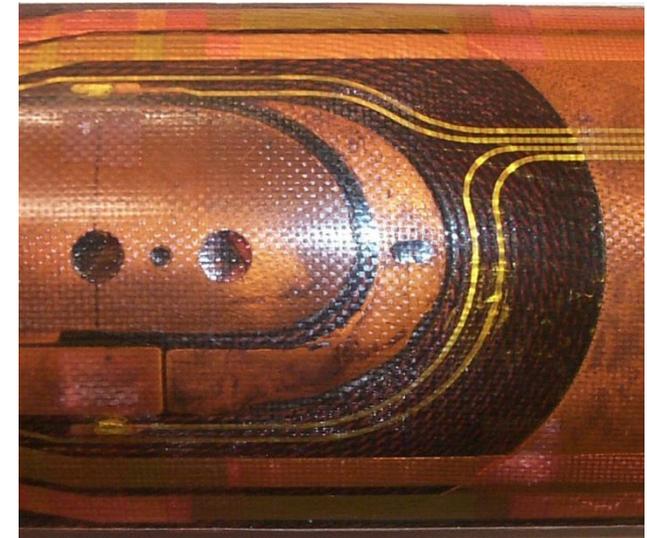
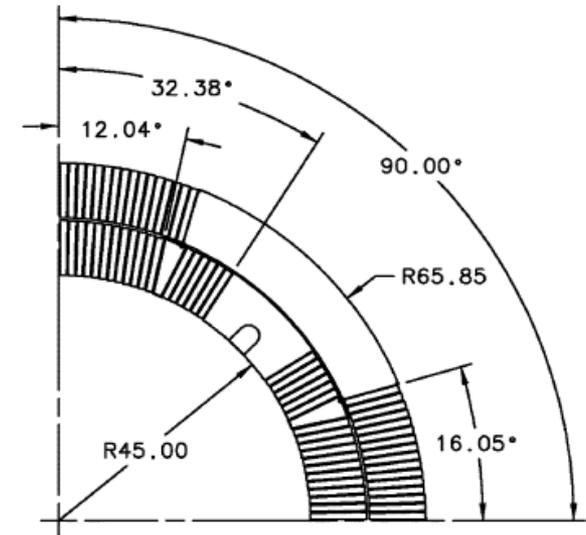




9. Practical examples

TQ quadrupole coil (Nb_3Sn) fabrication steps

- Winding of inner layer
- Curing of inner layer
 - Coil at 150 °C under a pressure of 30 MPa
- Winding of outer layer
- Curing of inner and outer layer
 - Coil at 150 °C under a pressure of 30 MPa
- First instrumentation phase
 - voltage taps
- Reaction
- Splicing
- Second instrumentation phase
 - Voltage taps, strain gauges, quench heaters
- Impregnation





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10. Conclusions



- We described the steps in the fabrication of a superconducting coil
 - **Winding**
 - **Curing**
 - **Reaction**
 - **Impregnation**
- Instrumentation is implemented to monitor the mechanical, electrical and thermal behavior of the coils.