2017 Joint Universities Accelerator School

Superconducting Magnets

Section II

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Outline

- **Section I**
    - Particle accelerators and magnets
    - Superconductivity and practical superconductors
    - Magnetic design

- **Section II**
    - Coil fabrication
    - Forces, stress, pre-stress
    - Support structures

- **Section III**
    - Quench, training, protection

References

- Coil fabrication
- Forces, stress, pre-stress
- Support structures

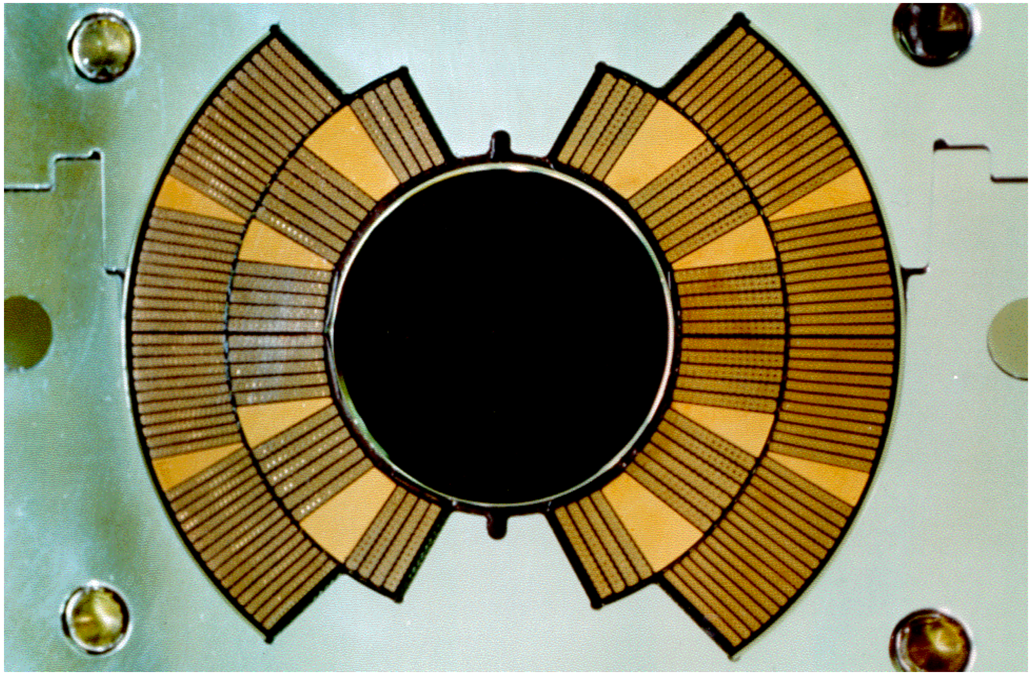
- K.-H. Mess, P. Schmuser, S. Wolff, "*Superconducting accelerator magnets*", Singapore: World Scientific, 1996.
- Martin N. Wilson, "*Superconducting Magnets*", 1983.
- Fred M. Asner, "*High Field Superconducting Magnets*", 1999.

- P. Ferracin, E. Todesco, S. Prestemon, "*Superconducting accelerator magnets*", US Particle Accelerator School, www.uspas.fnal.gov.
    - **Units 10,13,14**

- "*LHC design report v.1: the main LHC ring*", CERN-2004-003-v-1, 2004.

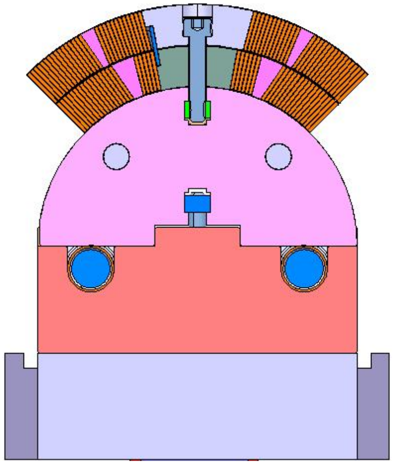
Coil fabrication
Winding and curing

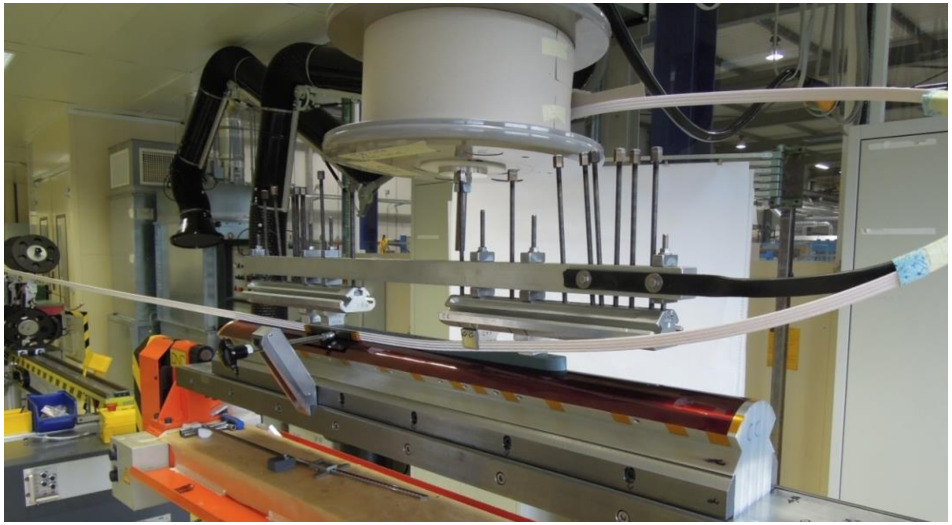
- The coil: most **critical component** of a superconducting magnet
- **Cross-sectional accuracy** of few hundredths of millimeters (few mils) over up to 15 m length
- **Laminated tooling**



Coil fabrication
Winding and curing

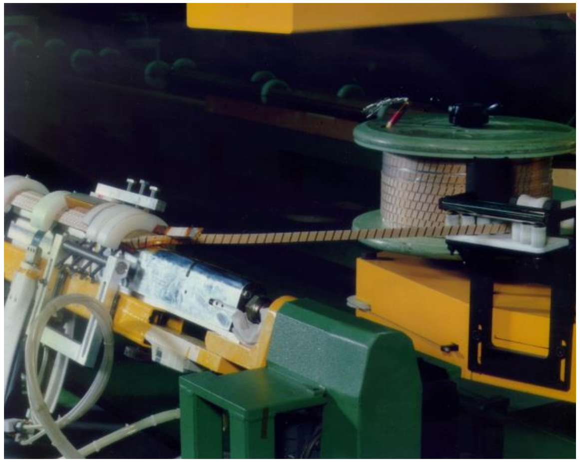
- The cable is wound around a **pole** mounted on a steel mandrel.
    - The mandrel is made of laminations
- Winding starts from the **pole turn** of the inner layer after preparing the coil ramp for the outer layer.
- Cable maintained in **tension** (200 N)





Coil fabrication
Winding and curing

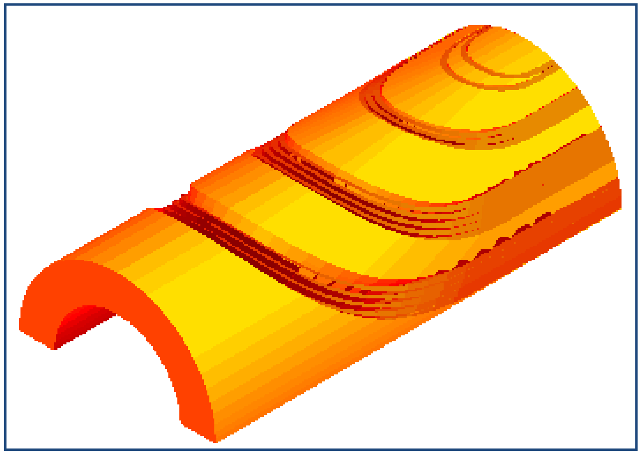
- For large production of long coils, coil winding done with automated **winding machines**
- The cable spool, mounted on a **motor driven wagon**, moves around the mandrel.

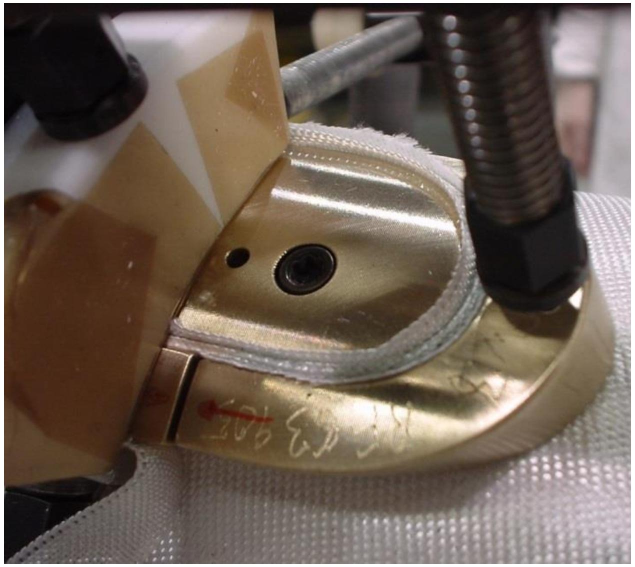


- As an alternative, the **mandrel moves** back and forth with respect a spool fixed to a frame

Coil fabrication
Winding and curing

- In the **end region**, more difficult to constrain the turns
  - bent over the narrow edge
- To improve the mechanical stability and to reduce the peak field → **end spacers**
  - **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 resins
- In Nb_3Sn magnets, end spacers are made of **aluminum bronze** or **stainless steel**.

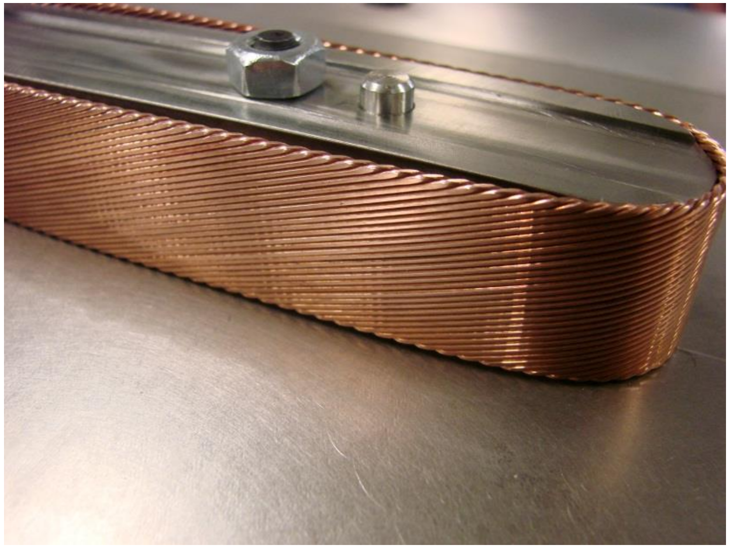


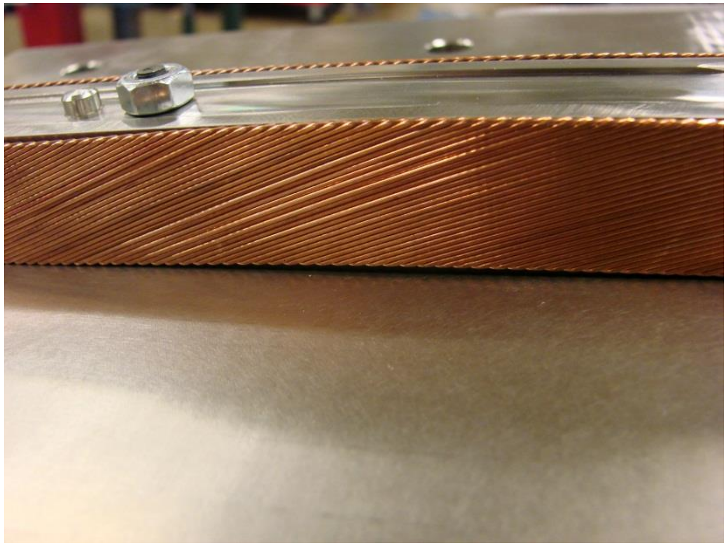


Coil fabrication
Winding and curing

- 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.

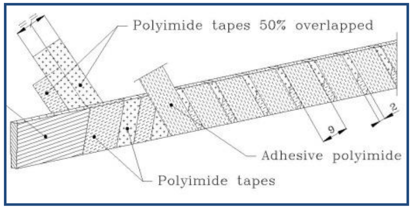
- If the bending radius is too small
  - **De-cabling** during winding;
  - Strands "**pop-out**".



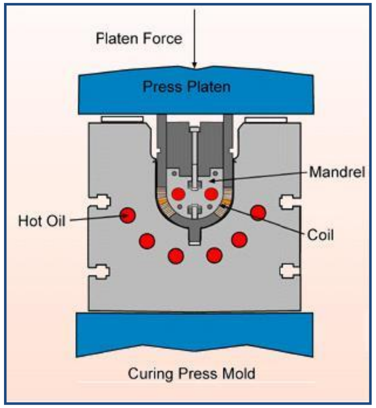


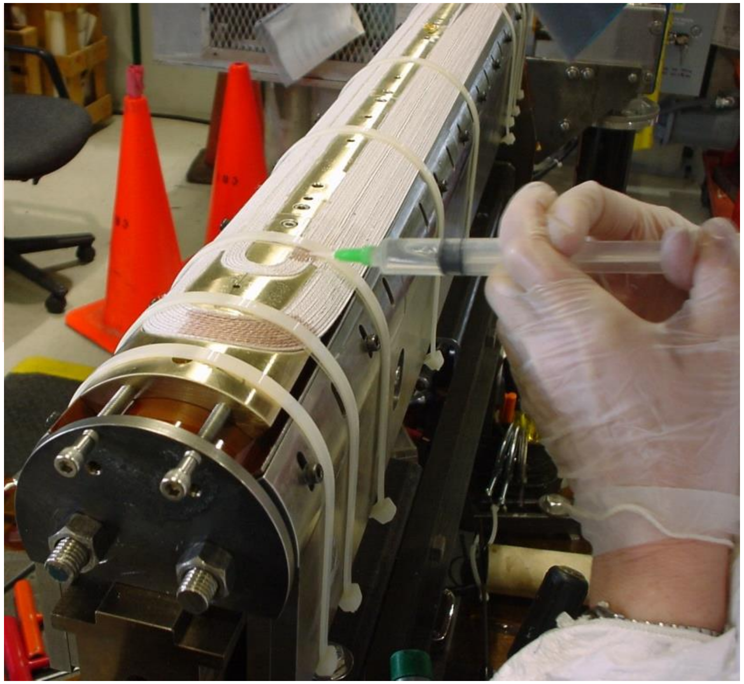
Coil fabrication
Winding and curing

- The goal of curing
  - Glue the turns together
    - Facilitate **coil handling** and define **coil dimensions**
- While still on the mandrels, coils are placed in the **curing mould** equipped with a **heating** system, and **compressed** in curing press
- Nb-Ti coils cured up to 190±3 °C at 80-90 MPa (LHC) to **activate resin**

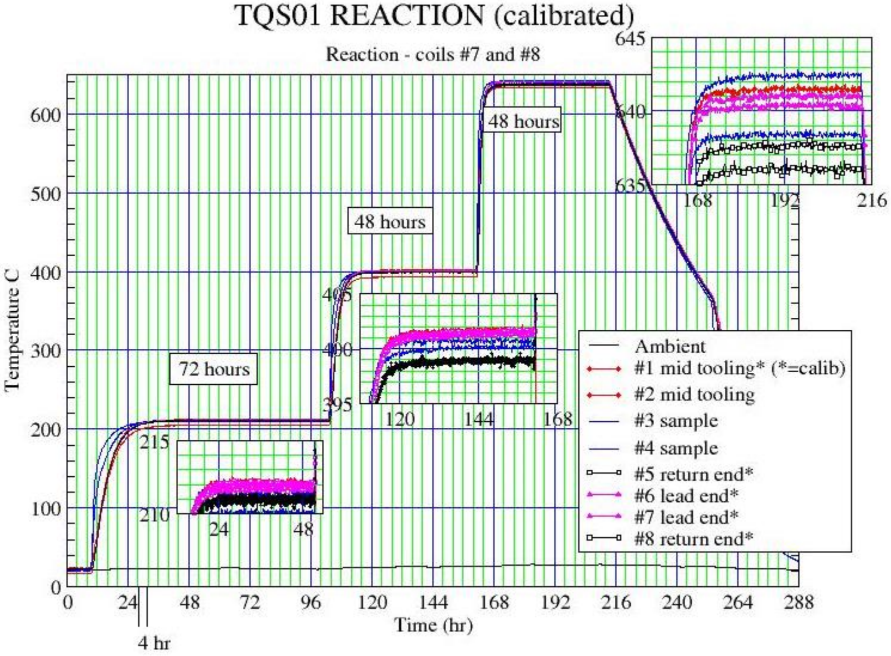


- In Nb_3Sn coils, cable insulation is injected with **ceramic binder**
  - Cured at 150° C and at ~10-30 MPa



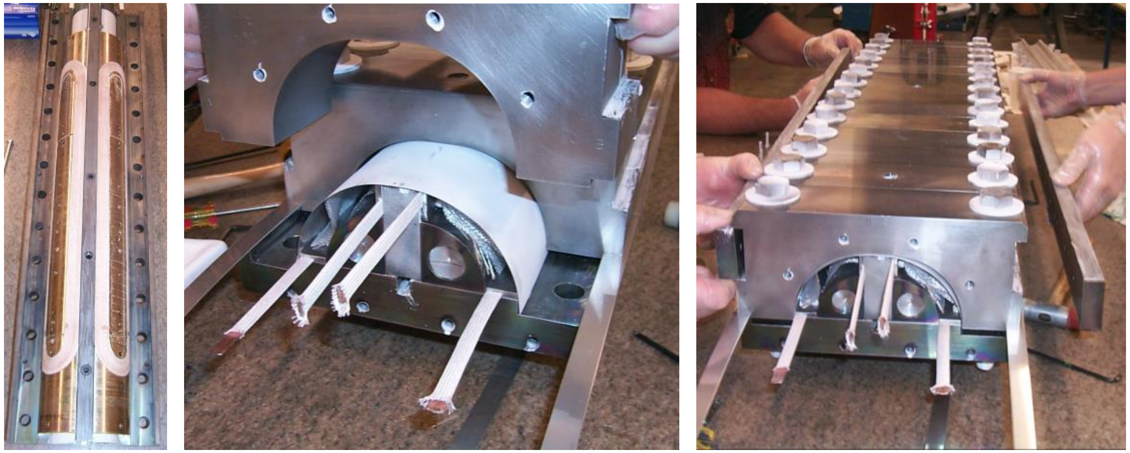


Coil fabrication
Reaction of Nb_3Sn coils



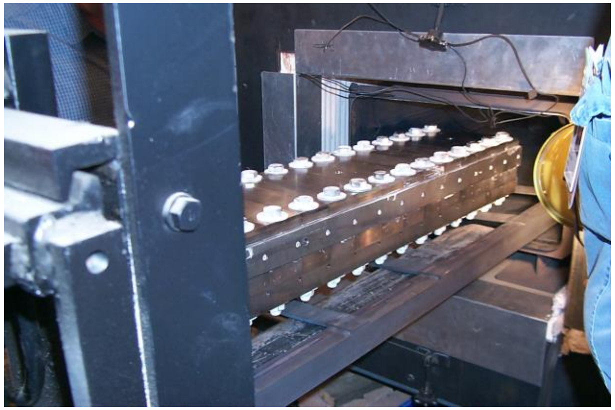
- **Heat treatment**
  - CuSn and Nb are heated to 650-700 C in vacuum or inert gas (argon) atmosphere
  - Sn diffuses in Nb and reacts to form Nb_3Sn.
- The cable becomes **brittle**
- The reaction is characterized by **three temperature steps**
  - homogeneity is of about ± 3 °C

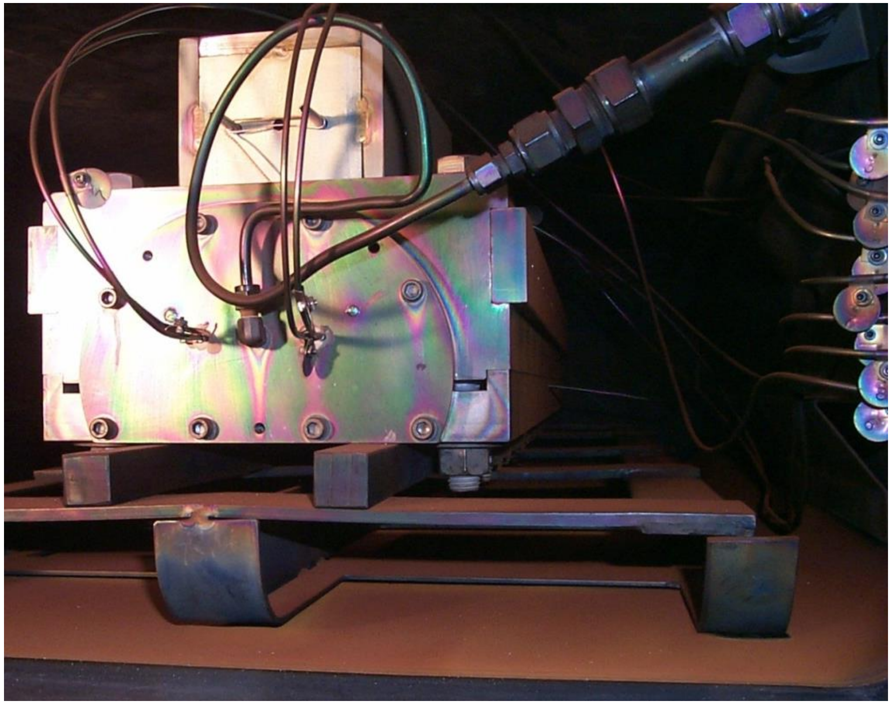
- Coils clamped in a **reaction fixture** made of stainless steel mold blocks.
  - "Minimum" pressure to avoid damaging the turns



Coil fabrication
Reaction of Nb_3Sn coils

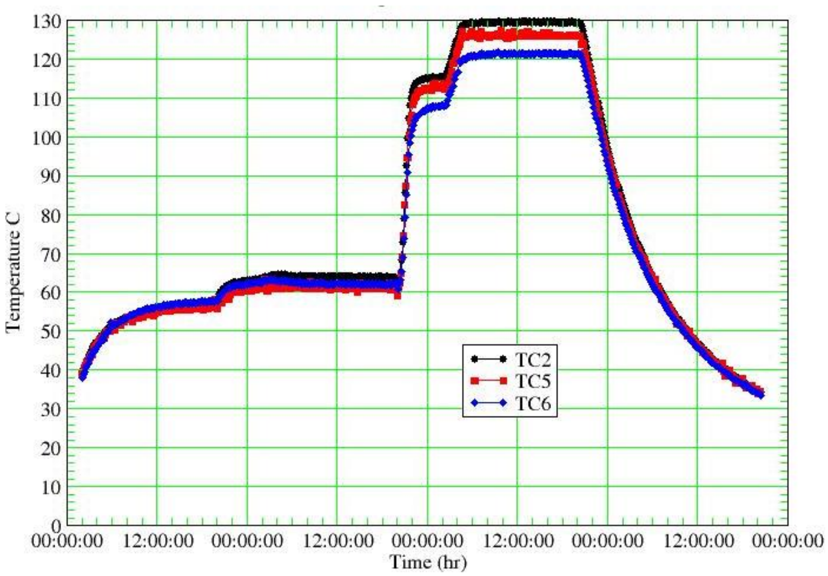
- Reaction fixture is placed in the oven and argon gas flow connected
  - **Minimize oxygen content** and Cu oxydation
- The **argon flows** in the reaction fixture in contact with the conductor and fills the oven (leak tight)

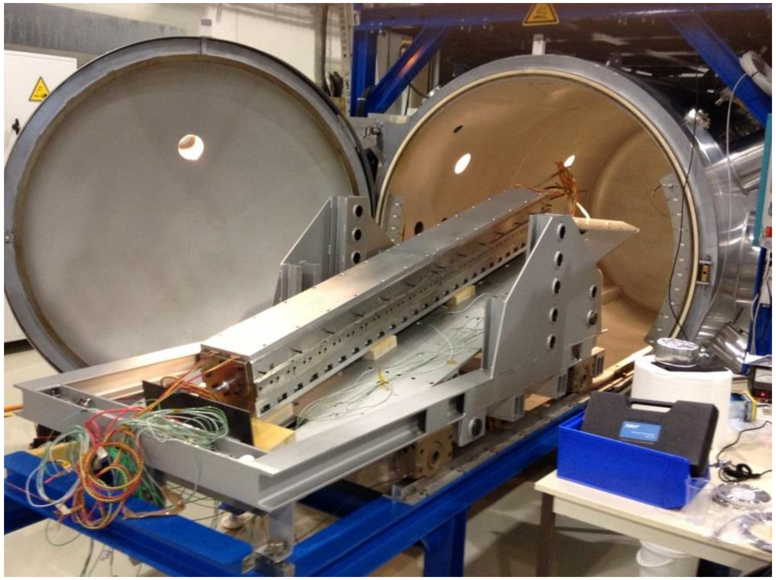


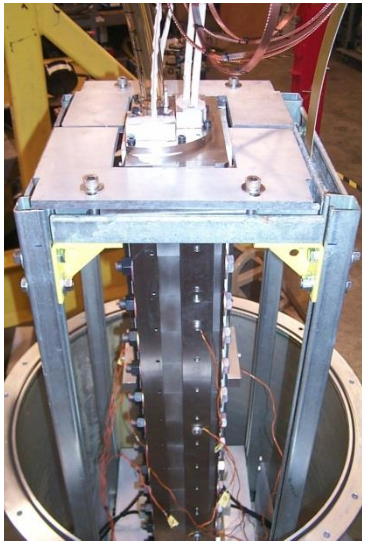


Coil fabrication
Vacuum impregnation of Nb_3Sn coils

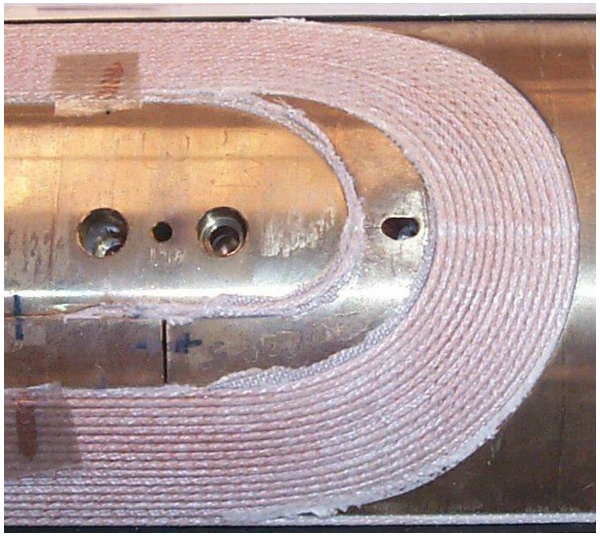
- After reaction, coil placed in a **impregnation fixture**
  - The fixture is inserted in a vacuum tank, evacuated → **epoxy injected**
  - Epoxy has
    - high viscosity at room temperature
    - low viscosity at ~60 °C
  - Then, curing at ~150 °C → **solid block**



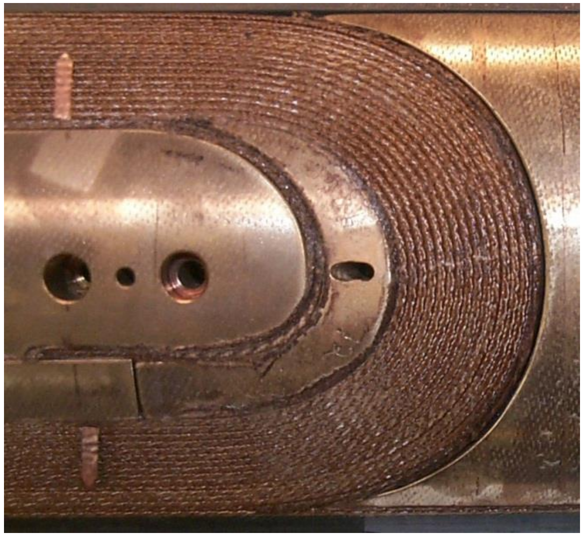




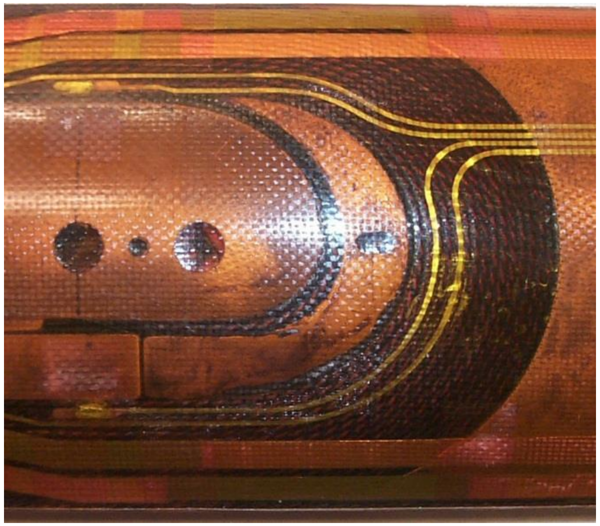
Overview of Nb_3Sn coil fabrication stages



After winding/curing

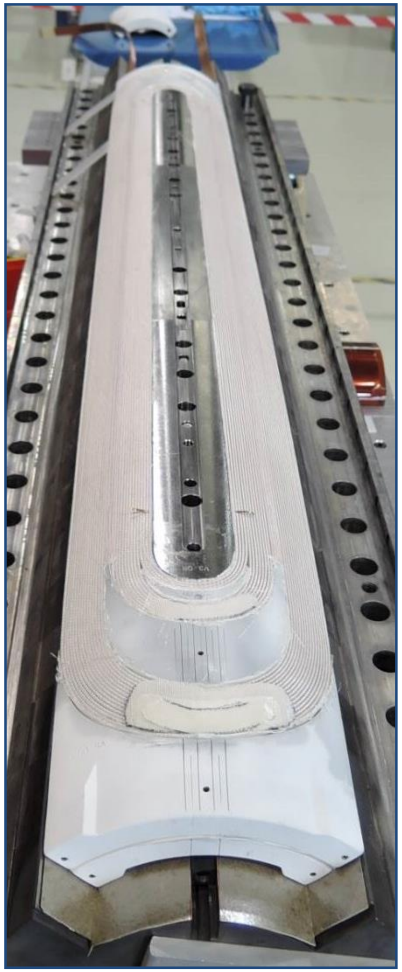


After reaction



After impregnation

Overview of Nb_3Sn coil fabrication stages



After winding/curing

After reaction

After impregnation

Outline

- **Section I**
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Introduction

- Superconducting accelerator magnets are characterized by high fields and high current densities.
- As a results, the coil is subjected to strong electro-magnetic forces, which tend to move the conductor and deform the winding.
- A good knowledge of the magnitude and direction of the electro-magnetic forces, as well as of the stress of the coil, is mandatory for the mechanical design of a superconducting magnet.

Mechanics of superconducting magnets
Electro-magnetic force

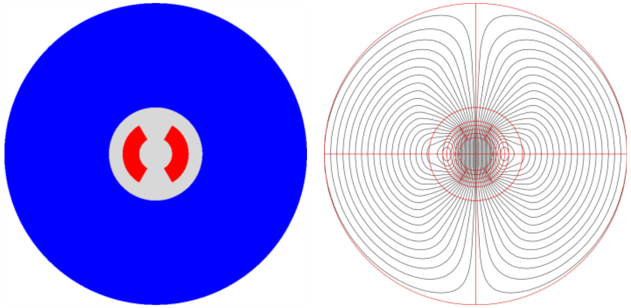
- In the presence of a magnetic field ***B***, an electric charged particle ***q*** in motion with a velocity ***v*** is acted on by a force $\boldsymbol{F_L}$ called electro-magnetic (Lorentz) force [N]:

$$\vec{F}_L = q\vec{v} \times \vec{B}$$

- A conductor element carrying current density *J* (A/mm^2) is subjected to a force density $\boldsymbol{f_L}$ [N/m^3]

$$\vec{f}_L = \vec{J} \times \vec{B}$$

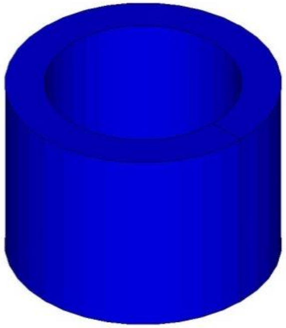
- Superconducing coil in its own field→



Magnetic pressure and forces

- *B* acts on the coil as a **pressurized gas** on its container.
- Infinitely long **“thin-walled” solenoid**, with thickness *d*, radius *a*, and current density J_θ .
  - The field outside the solenoid is zero. The field inside the solenoid B_0
  - We can define a magnetic pressure p_m acting on the winding

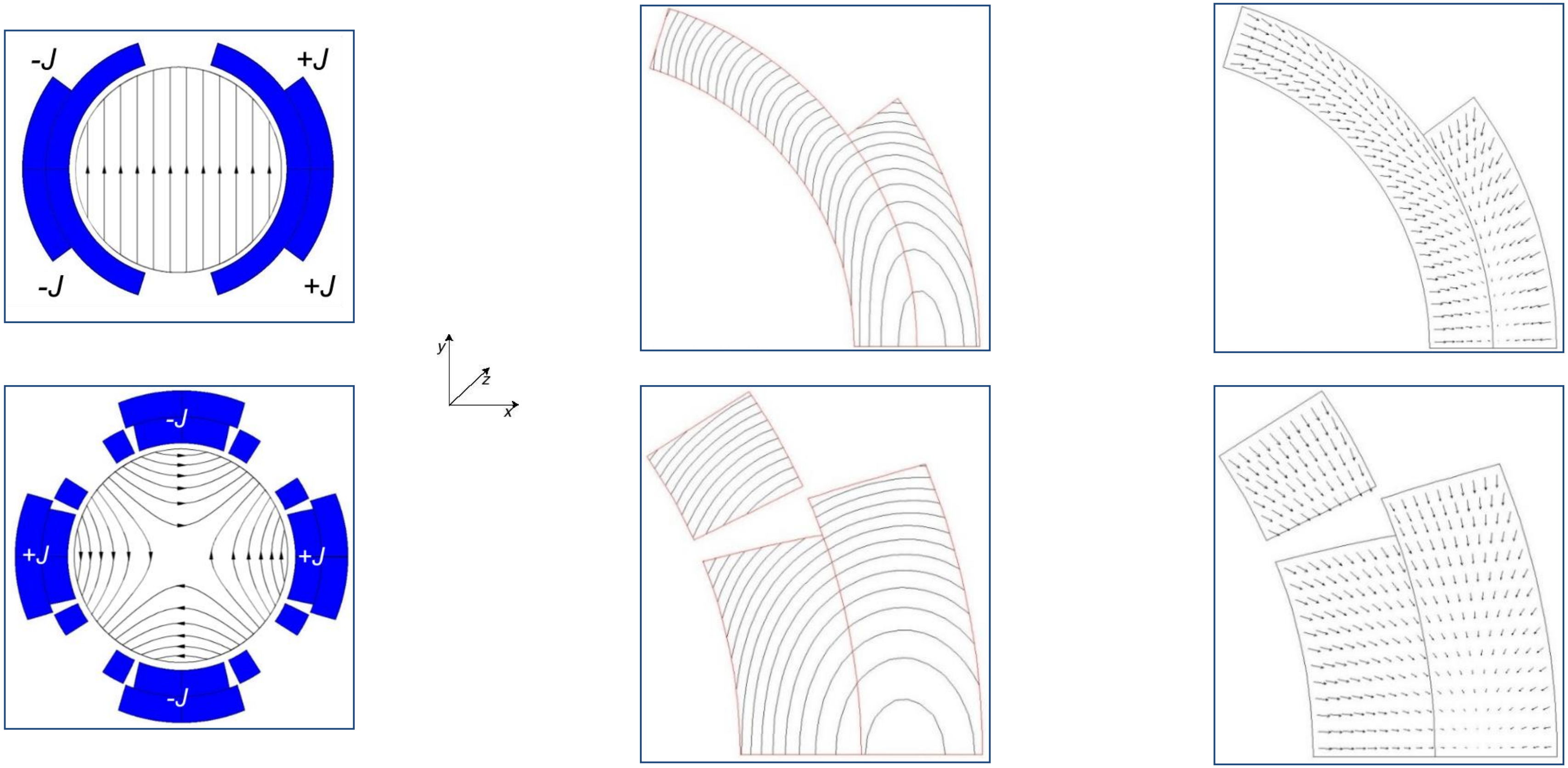
$$p_m = \frac{B_0^2}{2\mu_0}$$



- So, with a **10 T magnet**, the windings undergo a pressure $p_m = (10^2)/(2 \cdot 4\,\pi \times 10^{-7}) = 4 \times 10^7$ Pa = **390 atm**.
- The force pressure increase with the square of the field.
- A pressure [N/m^2] is equivalent to an energy density [J/m^3].

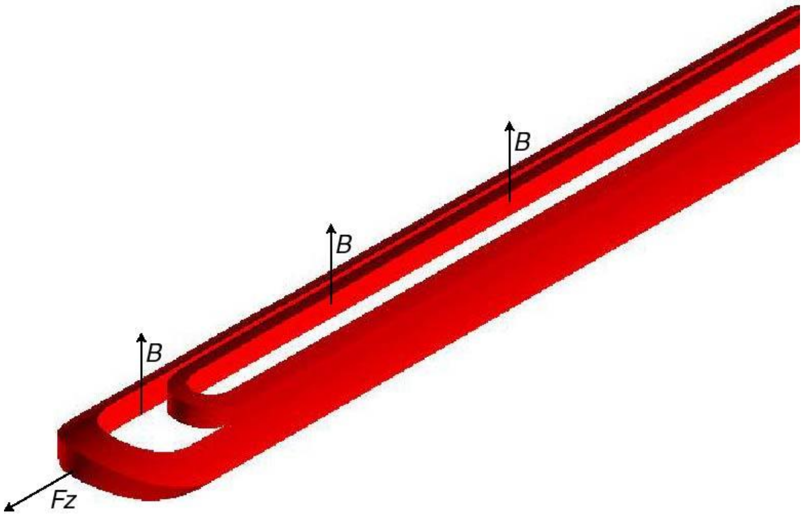
Mechanics of superconducting magnets
Electro-magnetic force

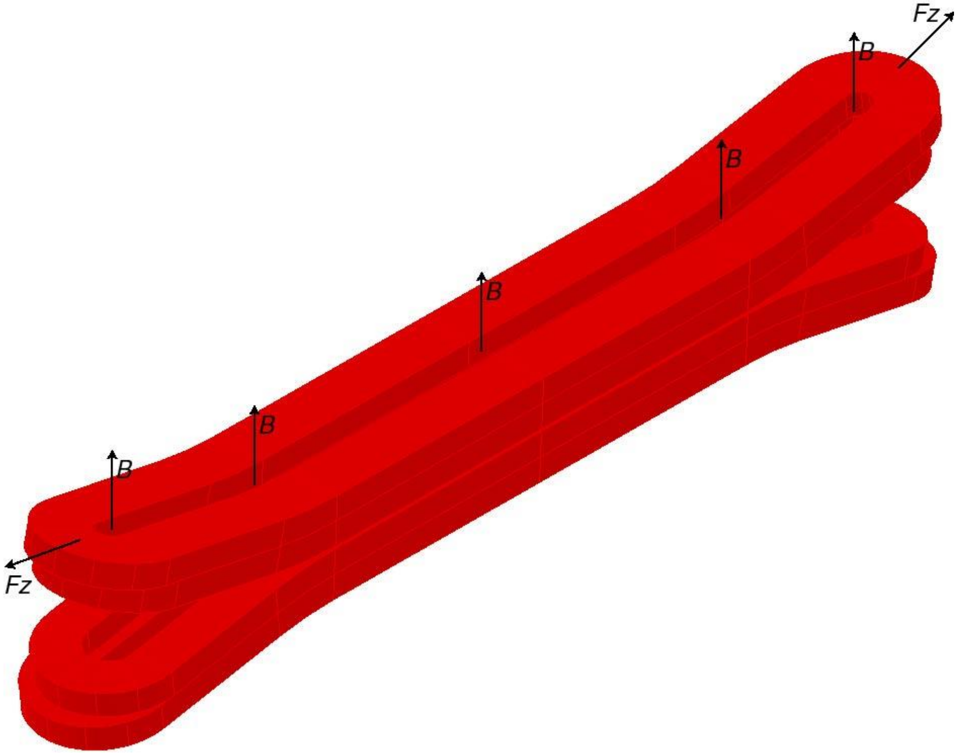
- The e.m. forces in a dipole/quadrupole magnet tend to push the coil
  - Towards the mid plane in the vertical-azimuthal direction (F_y, $F_\theta < 0$)
  - Outwards in the radial-horizontal direction (F_x, $F_r > 0$)



Mechanics of superconducting magnets
Electro-magnetic force

- In the **coil ends** the e.m. forces tend to push the coil
  - **Outwards** in the longitudinal direction ($F_z > 0$)

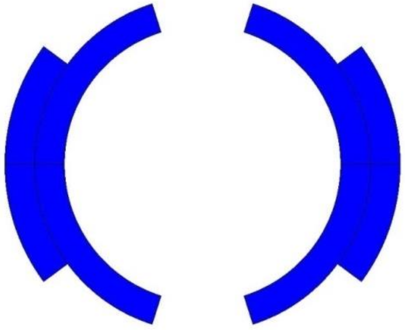




Electro-magnetic force
Infinitely thin shell approximation

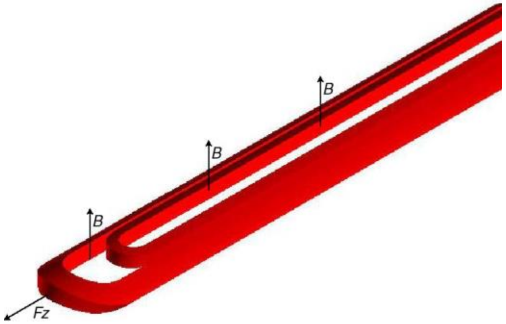
- The e.m. force on a dipole coil varies
  - with the **square** of the bore field
  - **linearly** with the bore radius

$$F_x = \frac{B_y^2}{2\mu_0}\frac{4}{3}a \qquad F_y = -\frac{B_y^2}{2\mu_0}\frac{4}{3}a$$



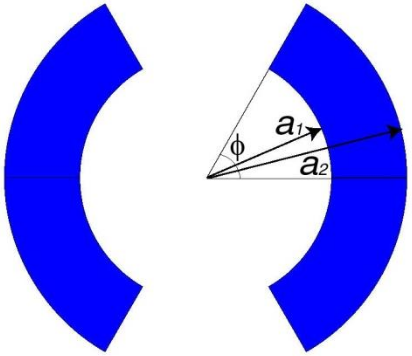
- The axial force on a dipole coil varies
  - with the **square** of the bore field
  - with the **square** of the bore radius

$$F_z = \frac{B_y^2}{2\mu_0}2\pi a^2$$



Electro-magnetic force
Sector coil

- We assume
  - $J=J_0$
  - Inner (outer) radius of the coils = *a1 (a2)*
  - Angle ϕ = 60° (third harmonic term is null)
  - No iron



- The field inside the aperture

$$B_r = -\frac{2\mu_0 J_0}{\pi}\left[(a_2 - a_1)\sin\phi\sin\theta + \sum_{n=1}^{\infty}\frac{r^{2n}}{(2n+1)(2n-1)}\left(\frac{1}{a_1^{n-1}} - \frac{1}{a_2^{n-1}}\right)\sin(2n+1)\phi\sin(2n+1)\theta\right]$$

$$B_\theta = -\frac{2\mu_0 J_0}{\pi}\left[(a_2 - a_1)\sin\phi\cos\theta + \sum_{n=1}^{\infty}\frac{r^{2n}}{(2n+1)(2n-1)}\left(\frac{1}{a_1^{n-1}} - \frac{1}{a_2^{n-1}}\right)\sin(2n+1)\phi\cos(2n+1)\theta\right]$$

- The field in the coil is

$$B_r = -\frac{2\mu_0 J_0}{\pi}\left\{(a_2 - r)\sin\phi\sin\theta + \sum_{n=1}^{\infty}\left[1 - \left(\frac{a_1}{r}\right)^{2n+1}\right]\frac{r}{(2n+1)(2n-1)}\sin(2n-1)\phi\sin(2n-1)\theta\right\}$$

$$B_\theta = -\frac{2\mu_0 J_0}{\pi}\left\{(a_2 - r)\sin\phi\cos\theta - \sum_{n=1}^{\infty}\left[1 - \left(\frac{a_1}{r}\right)^{2n+1}\right]\frac{r}{(2n+1)(2n-1)}\sin(2n-1)\phi\cos(2n-1)\theta\right\}$$

Electro-magnetic force
Sector coil

- The Lorentz force acting on the coil [N/m^3], considering the basic term, is

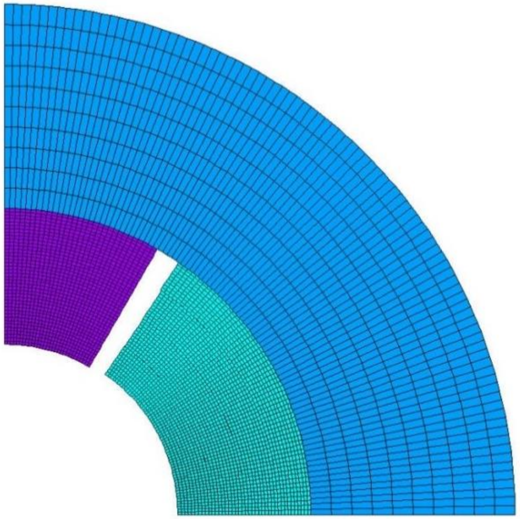
$$f_r = -B_\theta J = +\frac{2\mu_0 J_0^2}{\pi}\sin\phi\left[(a_2 - r) - \frac{r^3 - a_1^3}{3r^2}\right]\cos\theta \qquad f_x = f_r\cos\theta - f_\theta\sin\theta$$

$$f_\theta = B_r J = -\frac{2\mu_0 J_0^2}{\pi}\sin\phi\left[(a_2 - r) + \frac{r^3 - a_1^3}{3r^2}\right]\sin\theta \qquad f_y = f_r\sin\theta + f_\theta\cos\theta$$

- The total force acting on the coil [N/m] is

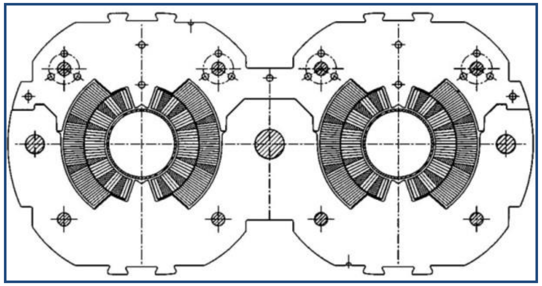
$$\boxed{F_x = +\frac{2\mu_0 J_0^2}{\pi}\frac{\sqrt{3}}{2}\left[\frac{2\pi - \sqrt{3}}{36}a_2^3 + \frac{\sqrt{3}}{12}\ln\frac{a_2}{a_1}a_1^3 + \frac{4\pi + \sqrt{3}}{36}a_1^3 - \frac{\pi}{6}a_2 a_1^2\right]}$$

$$\boxed{F_y = -\frac{2\mu_0 J_0^2}{\pi}\frac{\sqrt{3}}{2}\left[\frac{1}{12}a_2^3 + \frac{1}{4}\ln\frac{a_1}{a_2}a_1^3 - \frac{1}{12}a_1^3\right]}$$

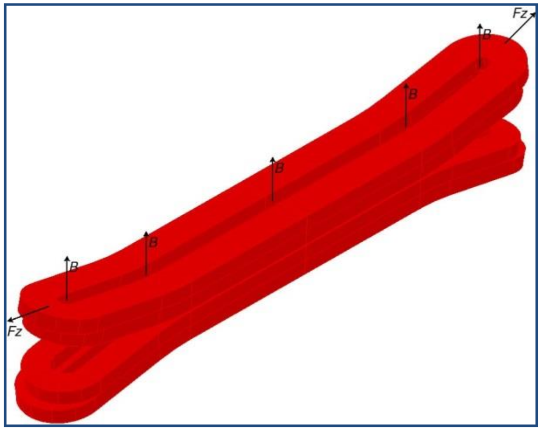


Mechanics of superconducting magnets
Electro-magnetic force

- **Nb-Ti LHC** MB
  - values per aperture
  - F_x = **340 t** per meter
    - ~300 compact cars
    - Precision of coil positioning: 20-50 μm
  - F_z = **27 t**
    - ~weight of the cold mass

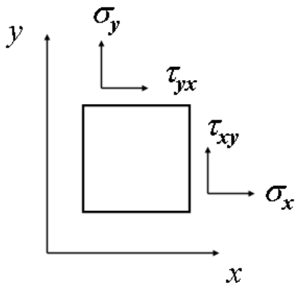


- **Nb_3Sn dipole** (HD2)
  - F_x = **500 t** per meter
  - F_z = **85 t**
  - These forces are applied to an objet with a cross-section of 150x100 mm !!!
    - and by the way, it is brittle



Stress and strain
Definitions

- A **stress σ or τ** [Pa] is an internal distribution of force [N] per unit area [m^2].
  - When the forces are perpendicular to the plane the stress is called normal stress (σ) ; when the forces are parallel to the plane the stress is called shear stress (τ).
  - Stresses can be seen as way of a body to resist the action (compression, tension, sliding) of an external force.



- A **strain ε** ($\delta l/l_0$) is a forced change dimension δl of a body whose initial dimension is l_0.
  - A stretch or a shortening are respectively a tensile or compressive strain; an angular distortion is a shear strain.

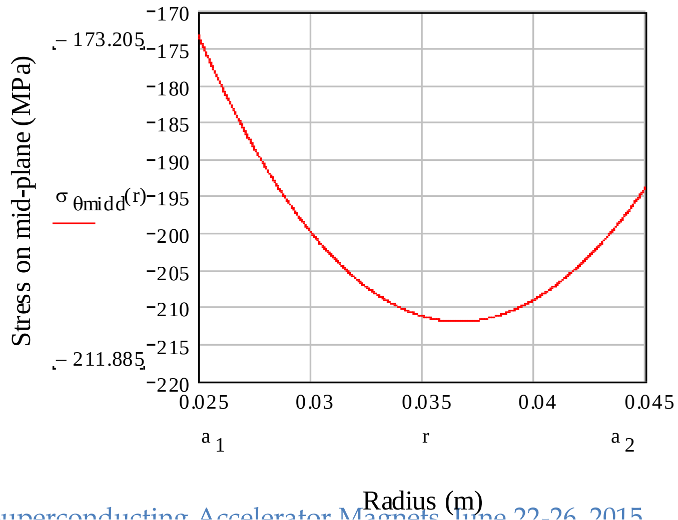
Stress in sector coil

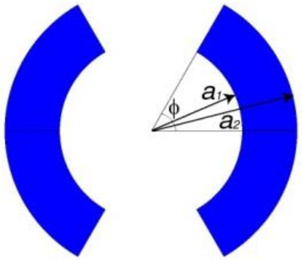
- For a dipole,

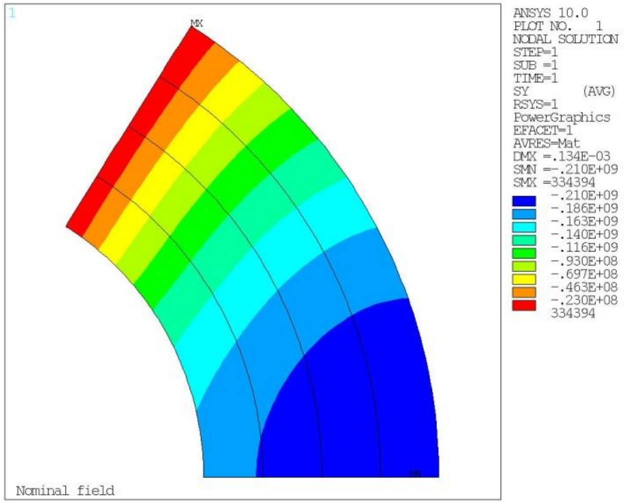
No shear

$$\sigma_{\theta\_mid-plane}=\int_0^{\pi/3} f_\theta r d\theta = -\frac{2\mu_0 J_0^2}{\pi}\frac{\sqrt{3}}{4} r\left[(a_2-r)+\frac{r^3-a_1^3}{3r^2}\right]$$

$$\sigma_{\theta\_mid-plane\_av}=-\frac{2\mu_0 J_0^2}{\pi}\frac{3}{4}\left[\frac{5}{36}a_2^3+\frac{1}{6}\left(\ln\frac{a_1}{a_2}+\frac{2}{3}\right)a_1^3-\frac{1}{4}a_2 a_1^2\right]\frac{1}{a_2-a_1}$$

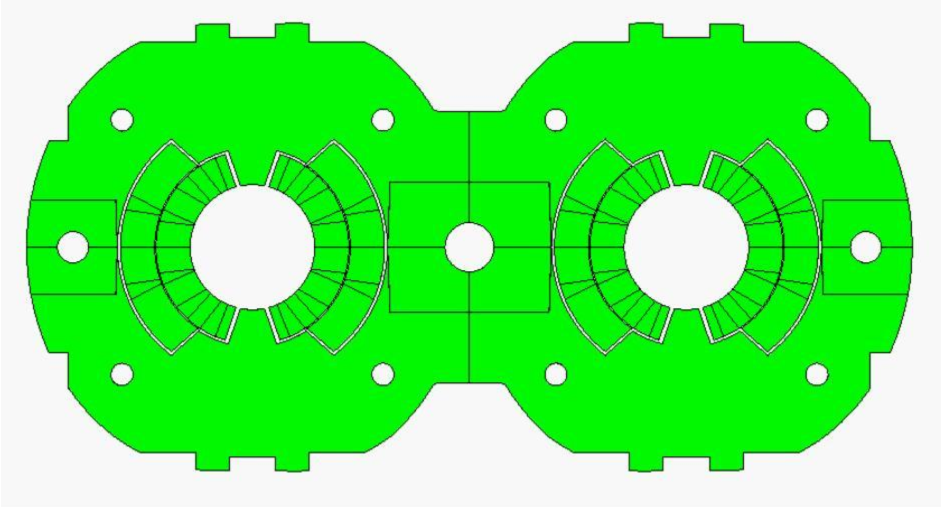




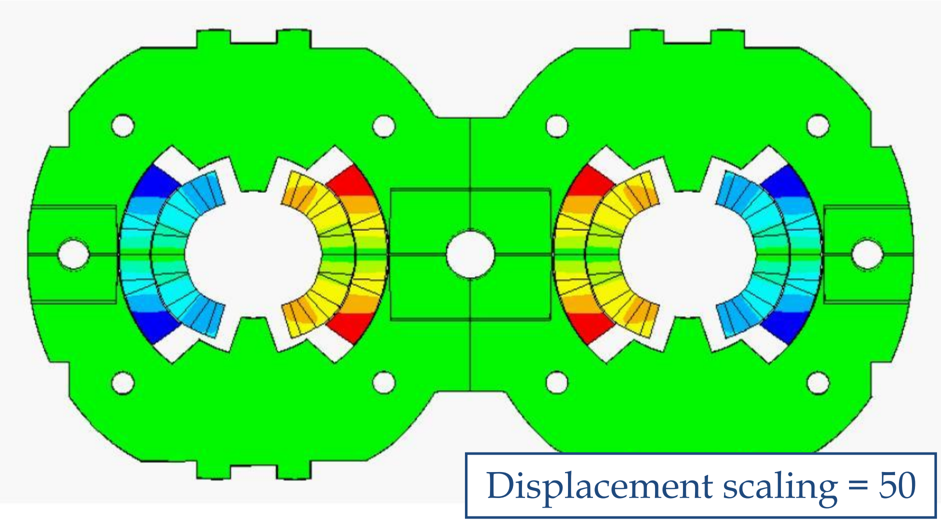


Mechanics of superconducting magnets
Deformation and stress

LHC dipole at 0 T



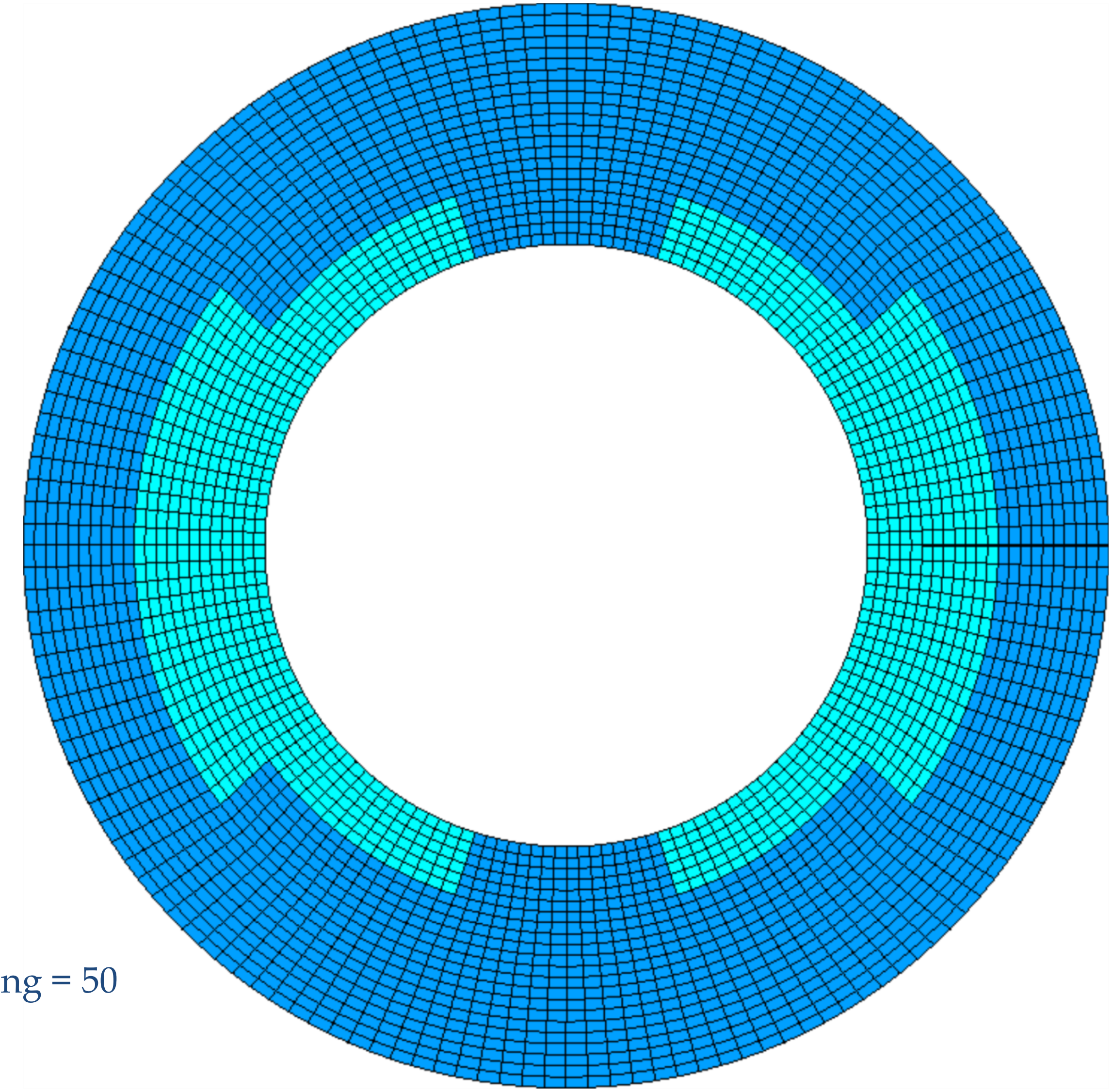
LHC dipole at 9 T



Displacement scaling = 50

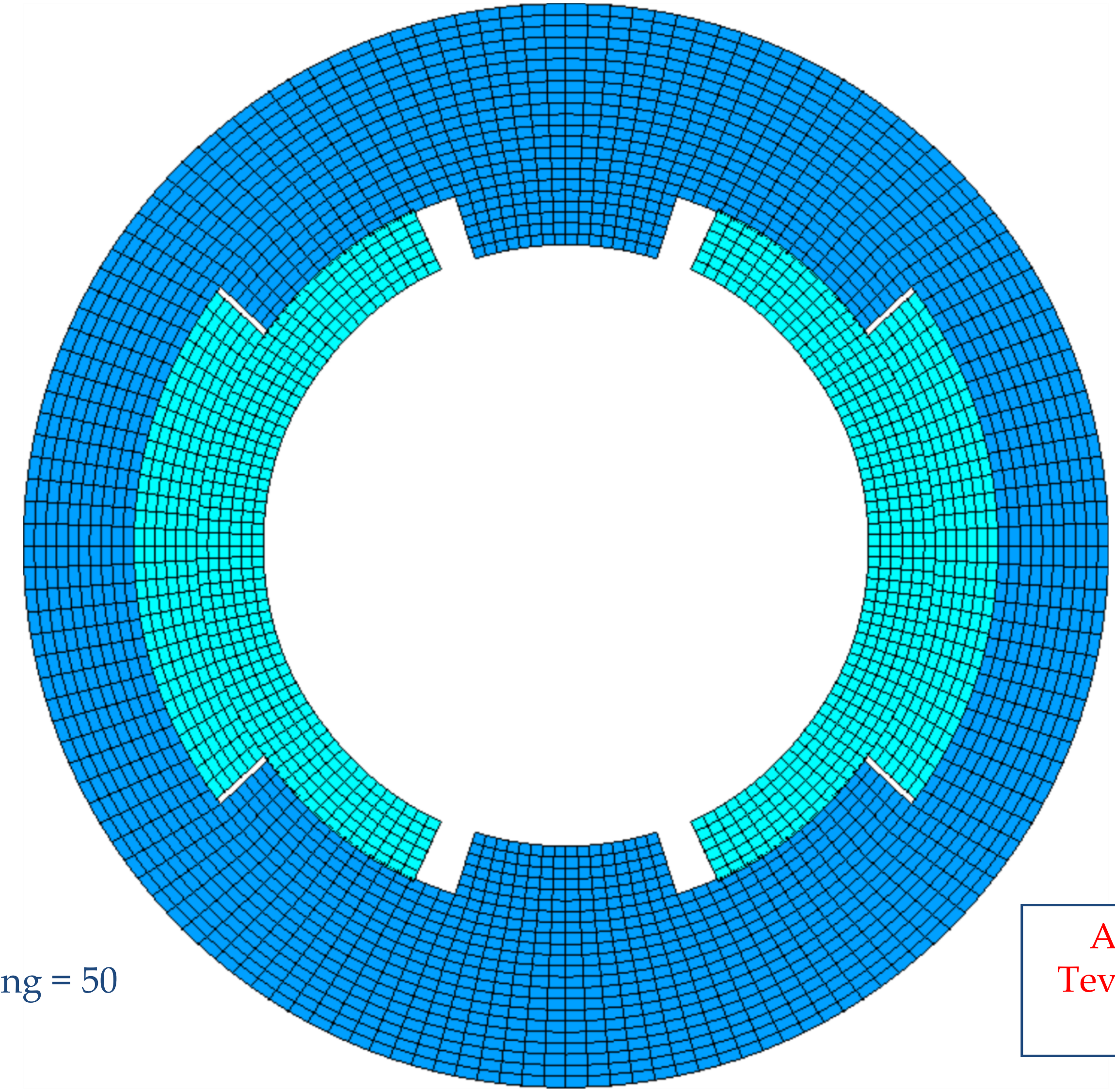
- Effect of e.m forces
  - change in **coil shape** → effect on field quality
  - a **displacement** of the conductor → potential release of frictional energy
  - Nb-Ti magnets: possible **damage** of kapton **insulation** at~150-200 MPa.
  - Nb_3Sn magnets: possible **conductor degradation** at about 150-200 MPa.
- All the components must be below stress limits.

No pre-stress, no e.m. force



Displacement scaling = 50

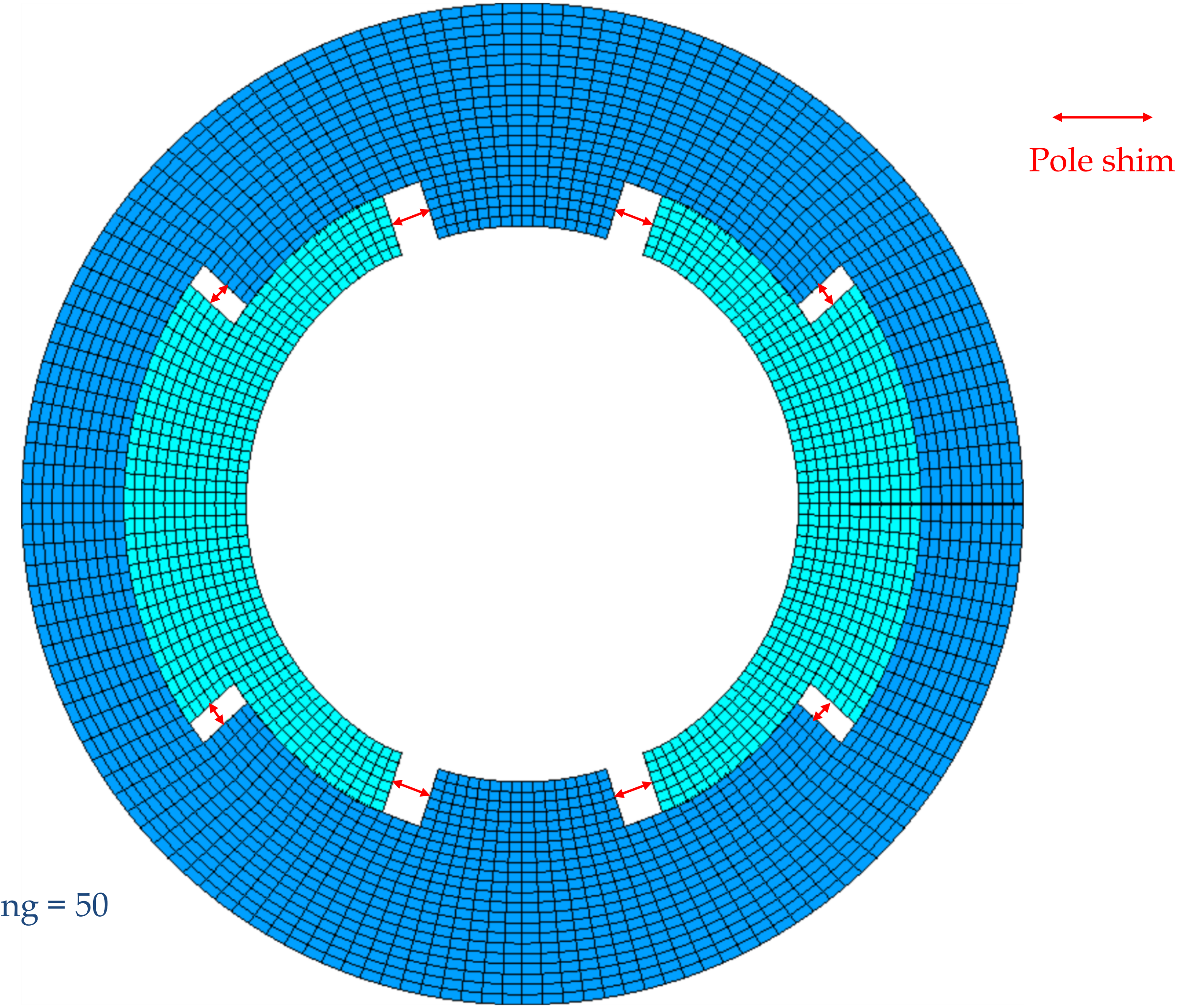
No pre-stress, with e.m. force



Displacement scaling = 50

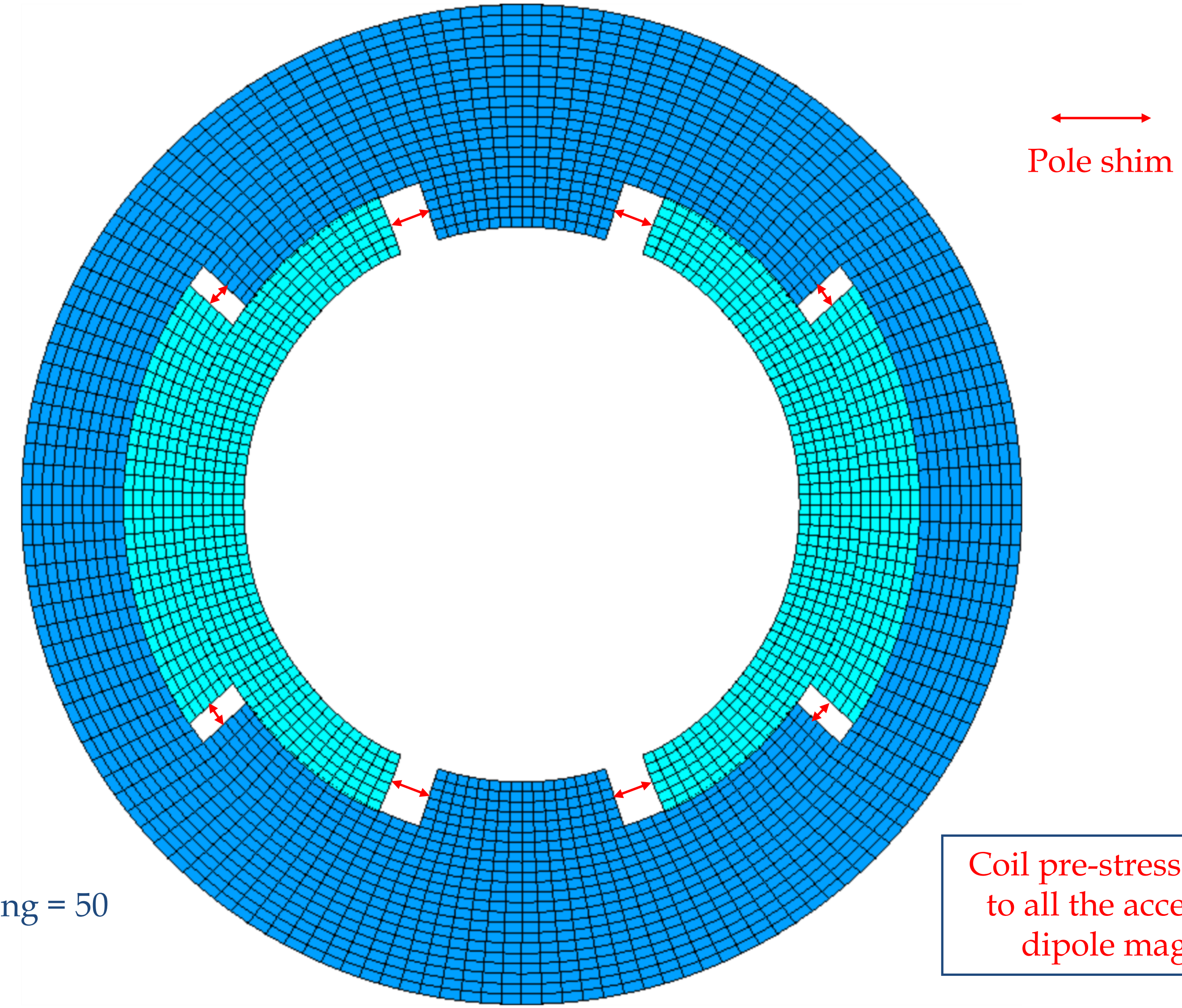
About 100 μm for Tevatron main dipole (B_{nom}= 4.4 T)

Pre-stress, no e.m. force



Displacement scaling = 50

Pre-stress, with e.m. force

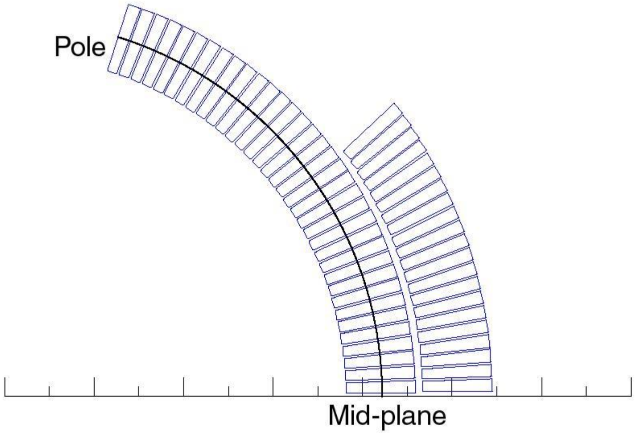


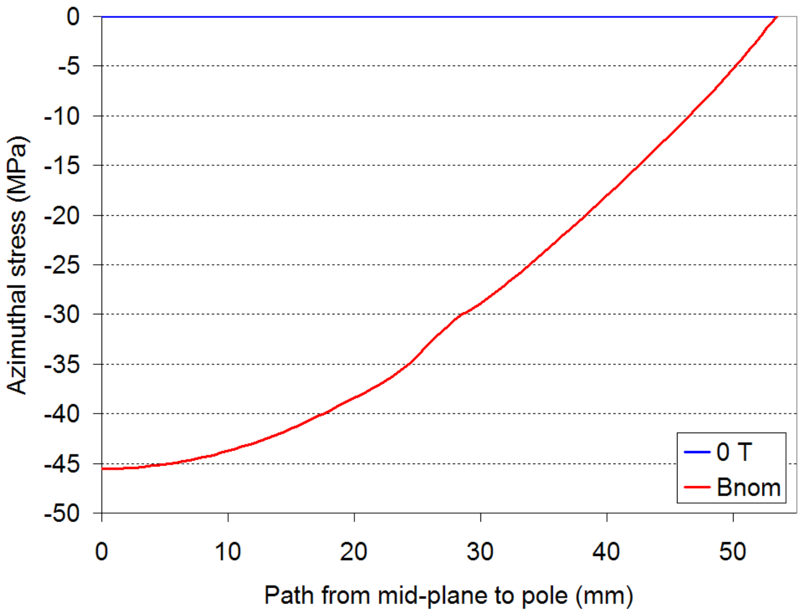
Displacement scaling = 50

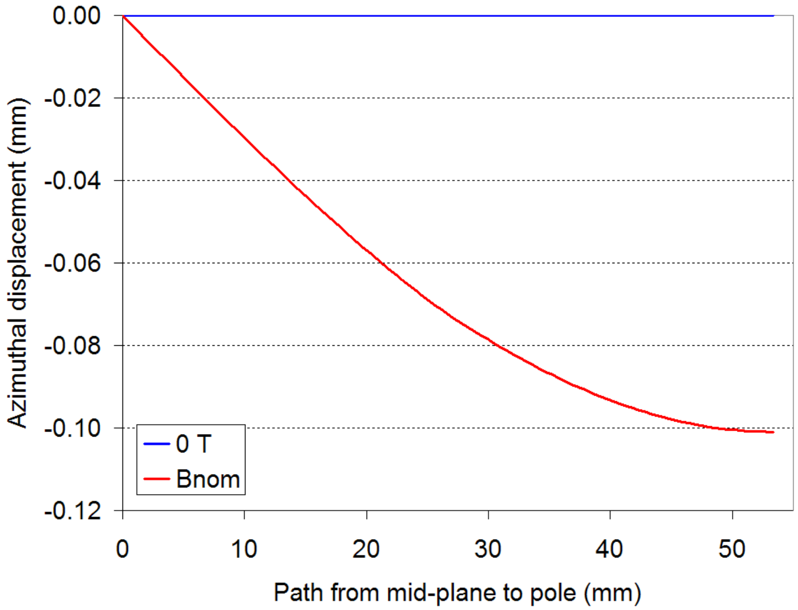
Coil pre-stress applied to all the accelerator dipole magnets

Pre-stress
Tevatron main dipole

- We can plot the **displacement** and the **stress** along a path moving from the mid-plane to the pole.
- In the case of no pre-stress, the displacement of the pole during excitation is about **-100 μm**.

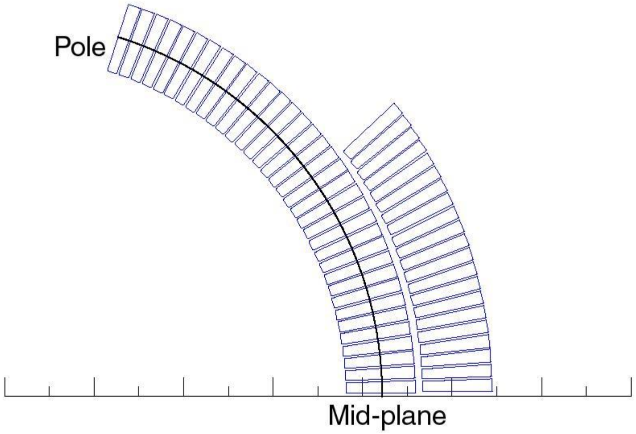


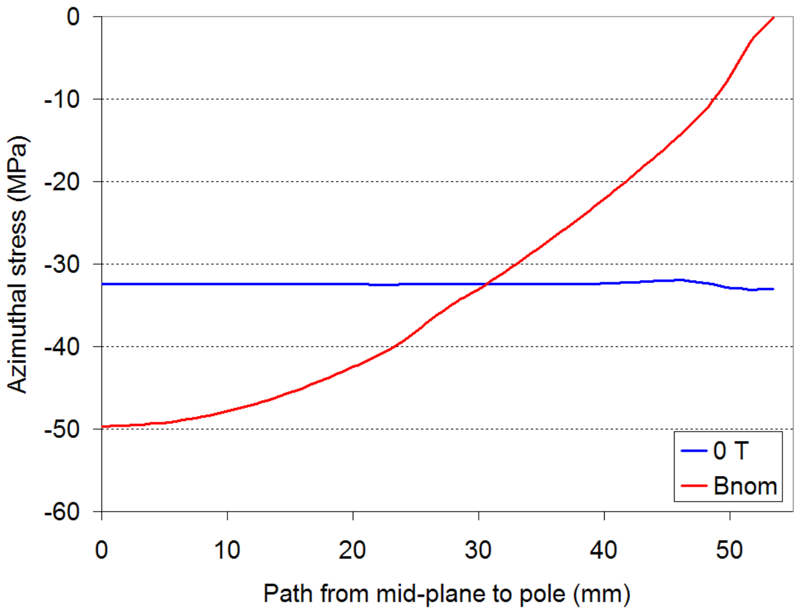


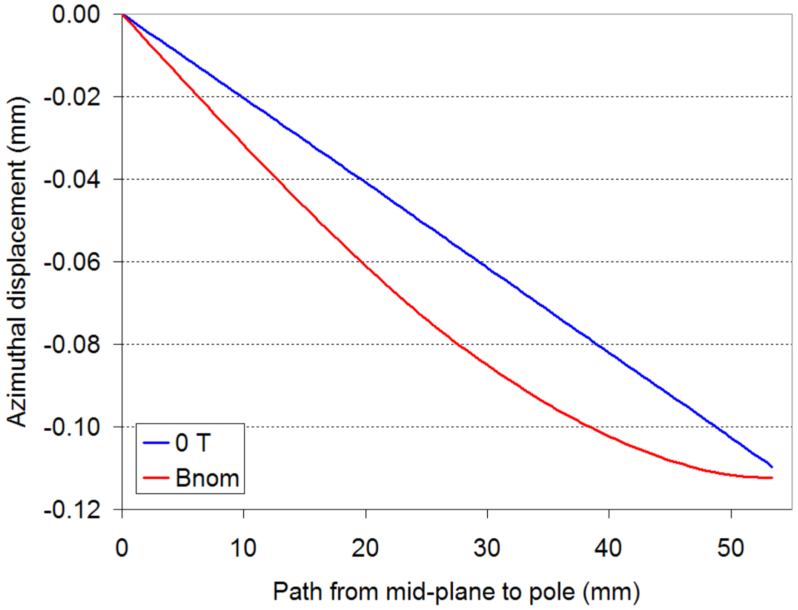


Pre-stress
Tevatron main dipole

- We now apply to the coil a **pre-stress** of about **-33 MPa**, so that no separation occurs at the pole region.
- The displacement at the pole during excitation is now **negligible**, and, within the coil, the conductors move at most of **-20 µm**.

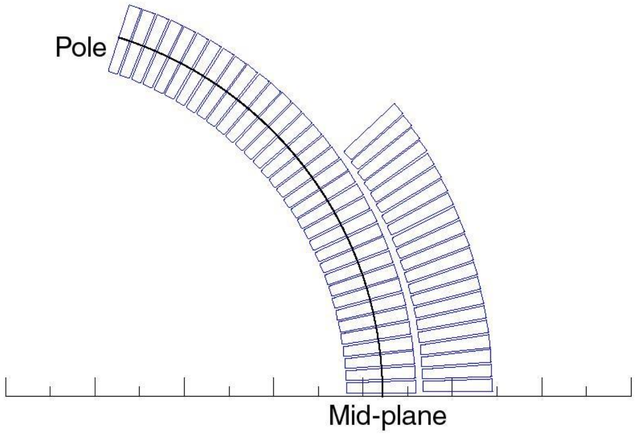


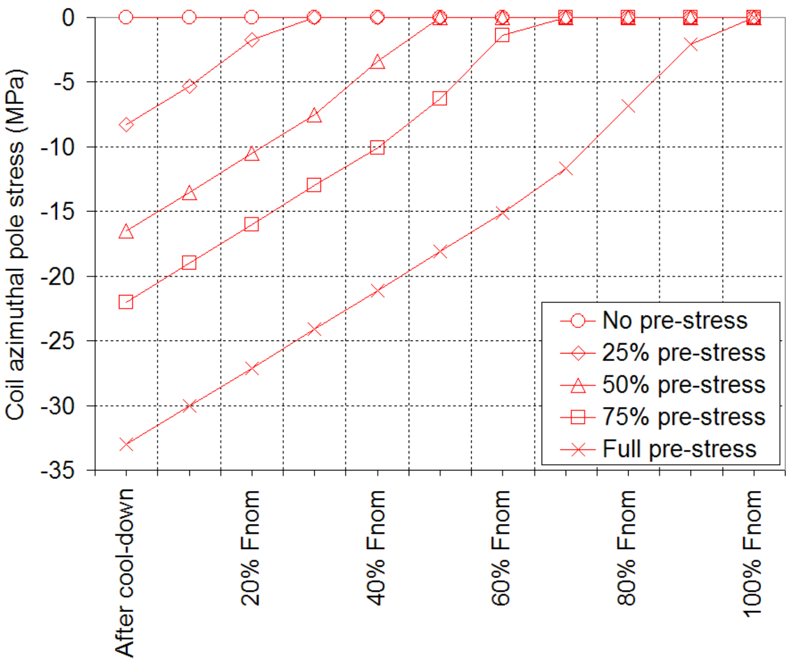


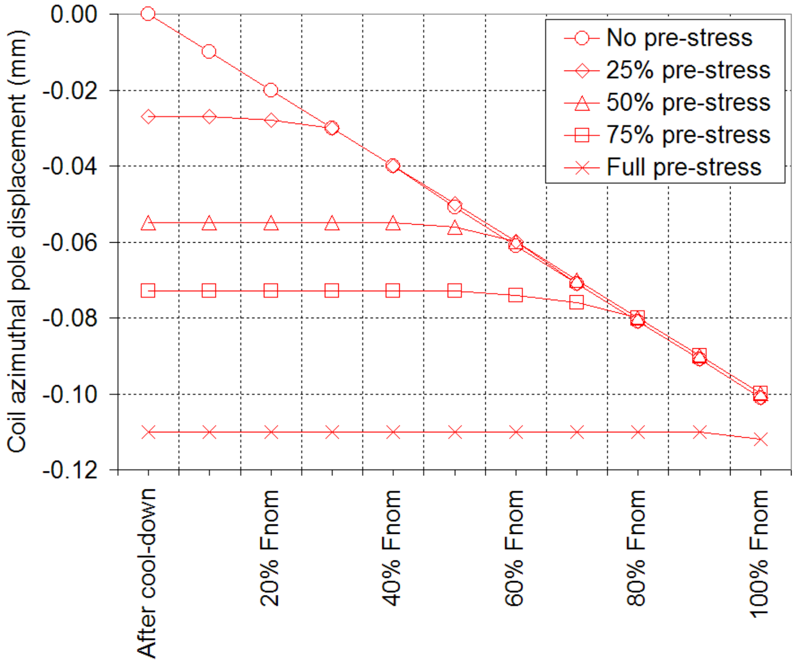


Pre-stress
Tevatron main dipole

- We focus now on the stress and displacement of the pole turn (high field region) in **different pre-stress conditions**.
- The total displacement of the pole turn is **proportional to the pre-stress**.
  - A full pre-stress condition minimizes the displacements.

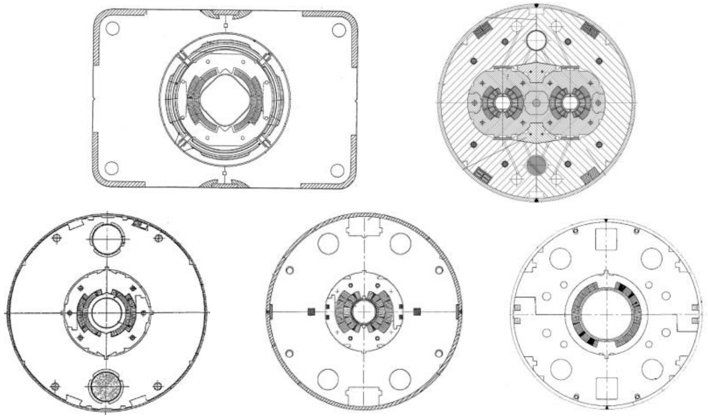


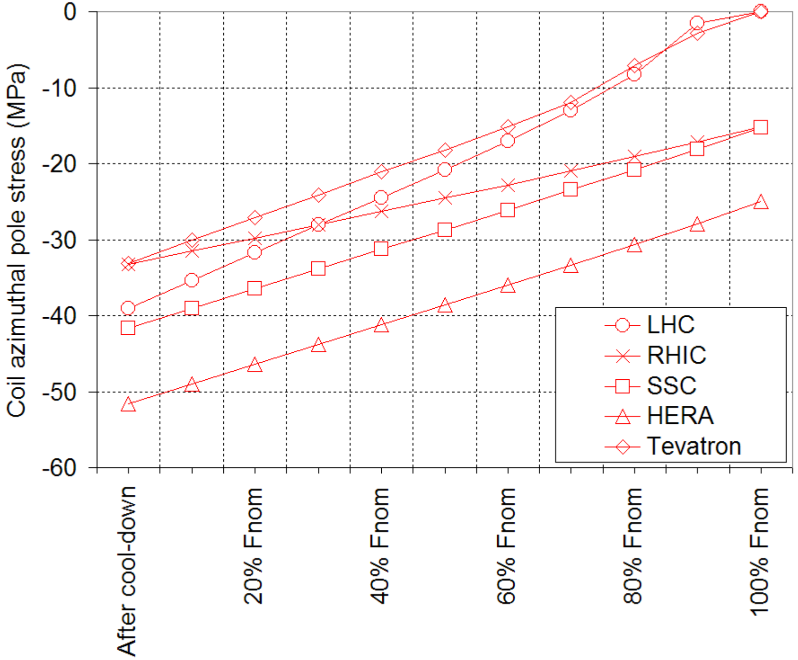




Pre-stress
Overview of accelerator dipole magnets

- The practice of pre-stressing the coil has been applied to **all the accelerator dipole magnets**
  - Tevatron
  - HERA
  - SSC
  - RHIC
  - LHC
- The pre-stress is chosen in such a way that the coil remains in contact with the pole at nominal field, sometime with a “mechanical margin” of more than 20 MPa.

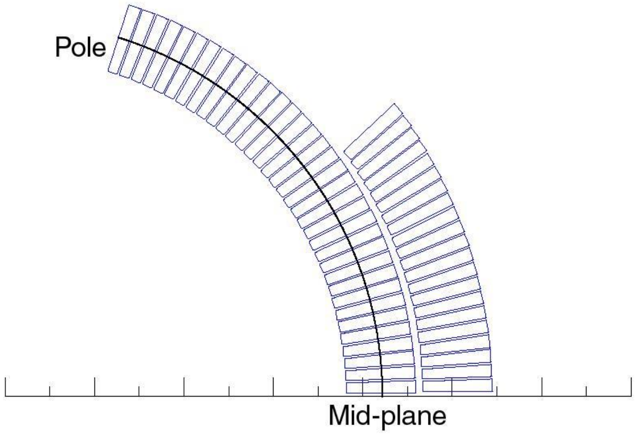


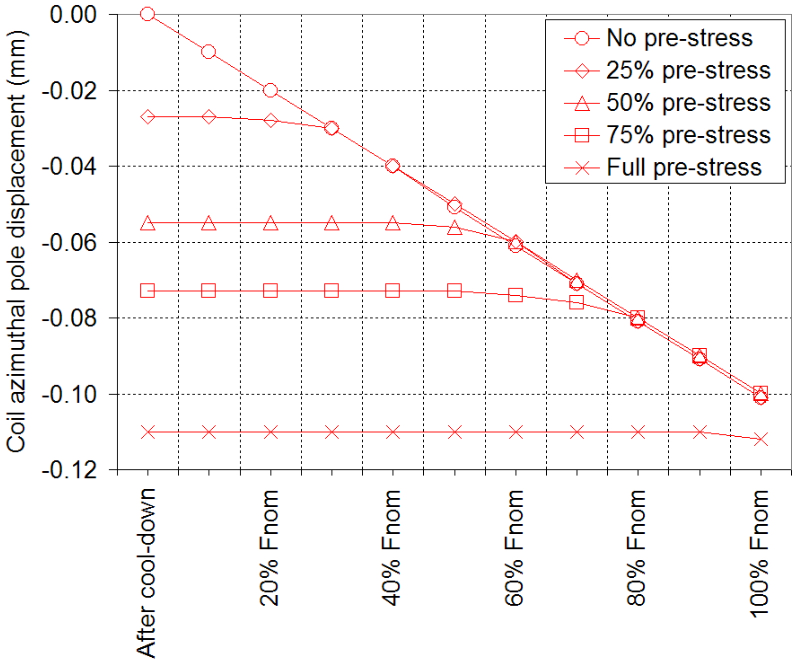


Pre-stress
General considerations

- As we pointed out, the pre-stress reduces the **coil motion** during excitation.

- What about the **effect** of pre-stress on **quench performance**?
  - In principle less motion means **less frictional energy** dissipation or resin fracture.
  - Nevertheless the impact of pre-stress on quench initiation remains **controversial**





Outline

- **Section I**
  - Particle accelerators and magnets
  - Superconductivity and practical superconductors
  - Magnetic design

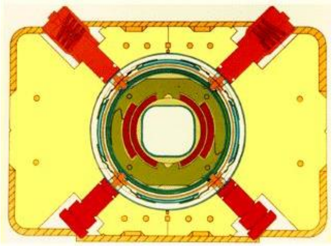
- **Section II**
  - Coil fabrication
  - Forces, stress, pre-stress
  - Support structures

- **Section III**
  - Quench, training, protection

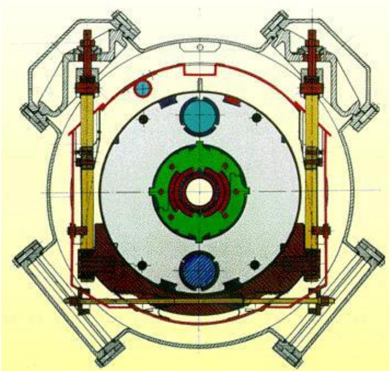
Mechanics of superconducting magnets
Support structures

- 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**.

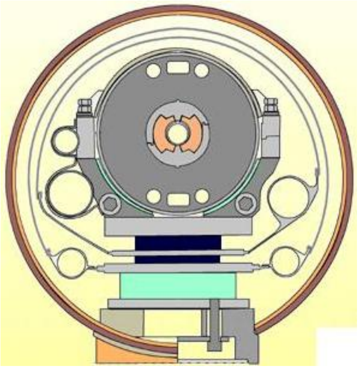
Tevatron



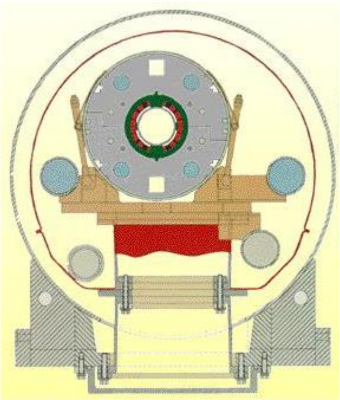
HERA



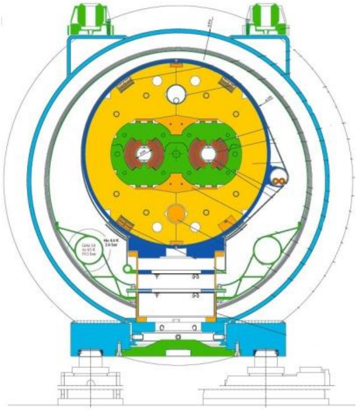
SSC



RHIC



LHC

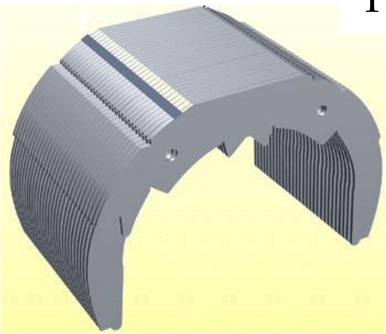


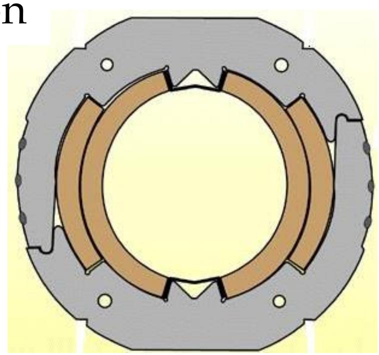
Not in scale

Mechanics of superconducting magnets
Collars

- Implemented for the first time in Tevatron
  - Since then, almost always used
- Composed by **stainless-steel or aluminum laminations** few mm thick.
- By clamping the coils, the collars provide
  - coil **pre-stressing**;
  - **rigid support** against e.m. forces
  - **precise cavity**

Tevatron





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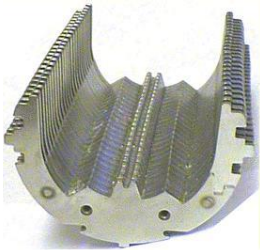
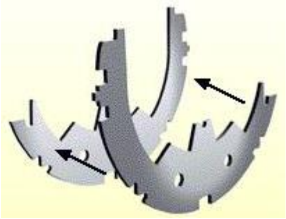
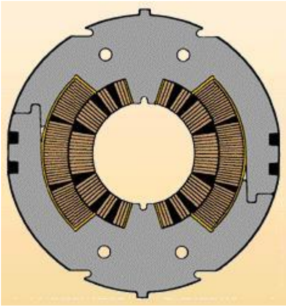
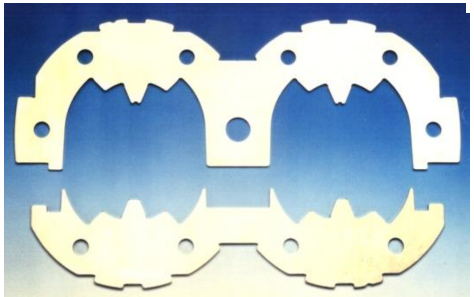
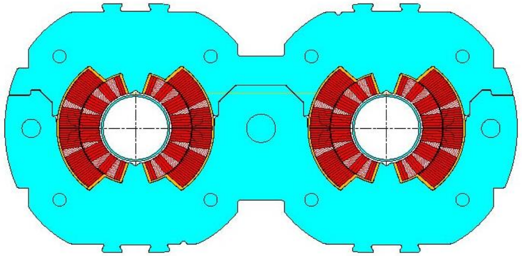






LHC

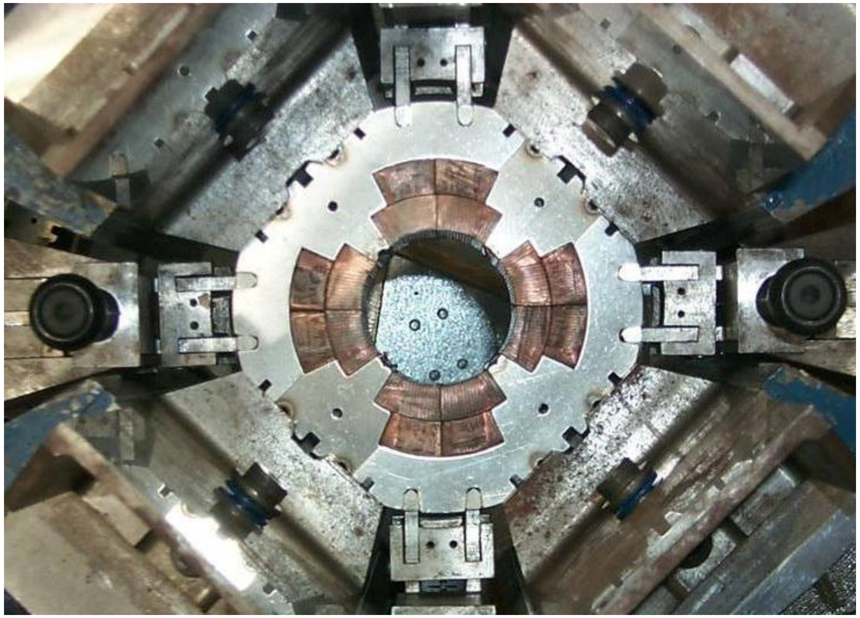




Mechanics of superconducting magnets
Collars

Collaring of a dipole magnet

Collaring of a quadrupole magnet



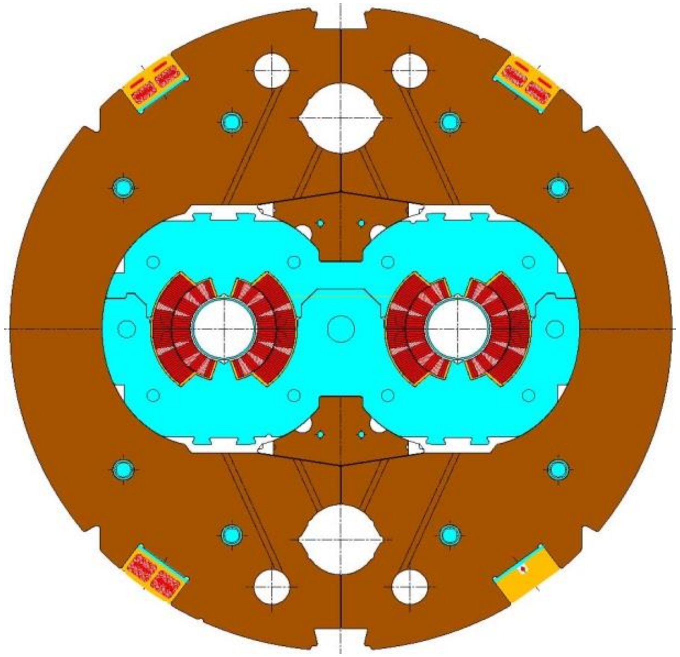
Mechanics of superconducting magnets
Iron yoke

- As the collars, iron yoke are made in **laminations** (several mm thick).

- **Magnetic function**
  - contains and enhances the magnetic field.

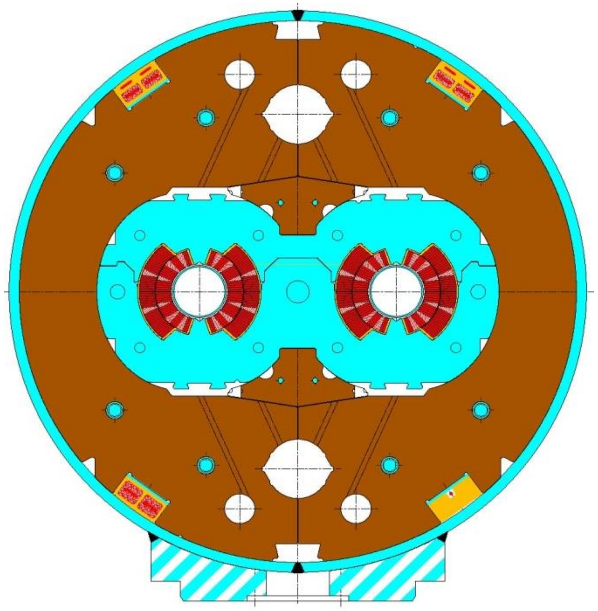
- **Structural function**
  - tight contact with the collar
    - it contributes to increase the rigidity of the coil support structure and limit radial displacement.

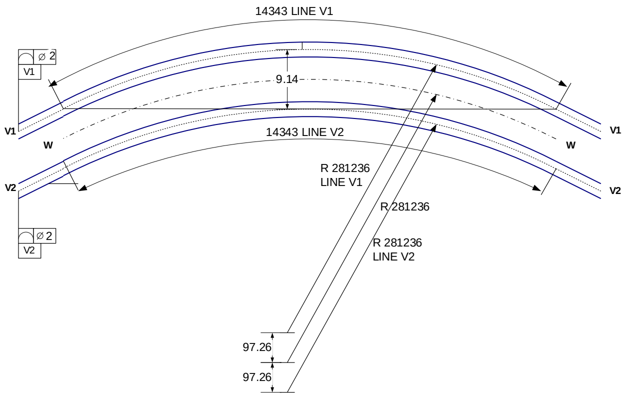
- Holes are included in the yoke design for
  - Correction of **saturation effect**
  - **Cooling channel**
  - **Assembly features**
  - **Electrical bus**



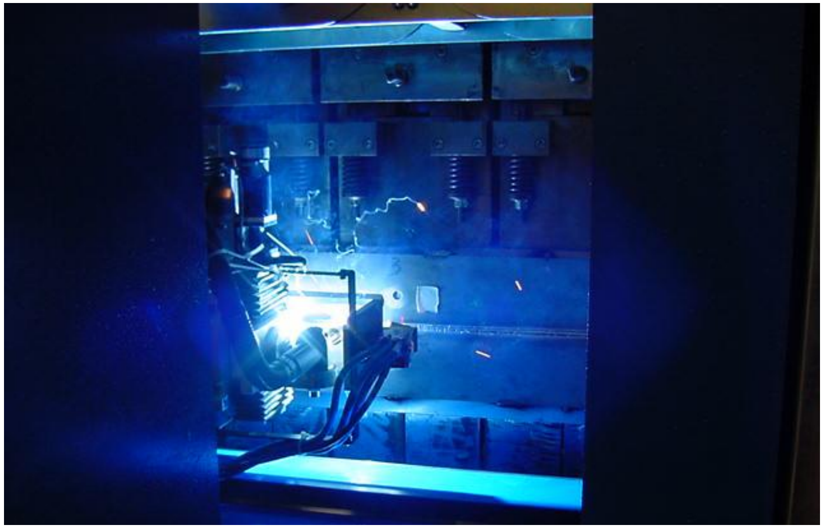
Mechanics of superconducting magnets
Shell

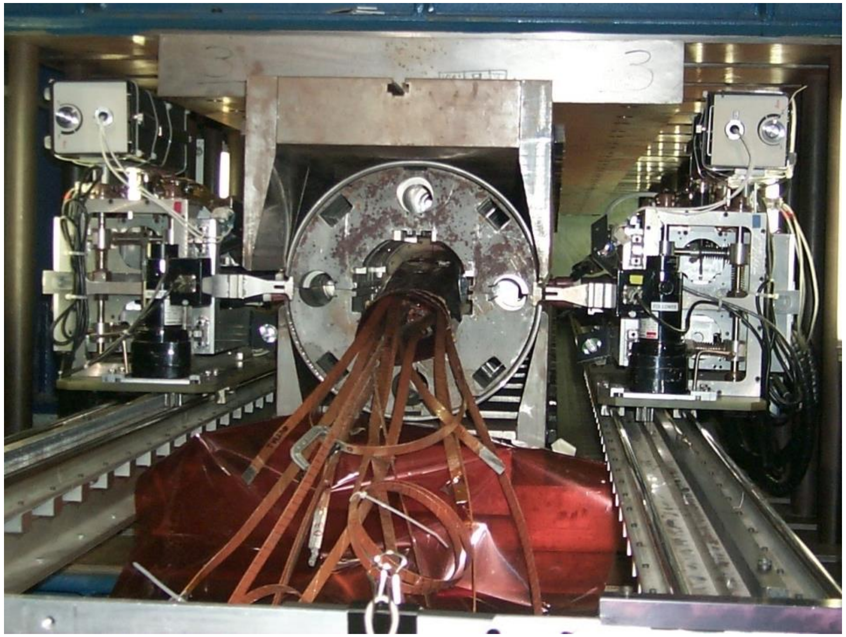
- The cold mass is contained within a shell
- The shell constitutes a **containment structure** for the liquid Helium.
- It is composed by two half shells of stainless steel **welded** around the yoke with high tension (about 150 MPa for the LHC dipole).
  - With the iron yoke, it contributes to create 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**.





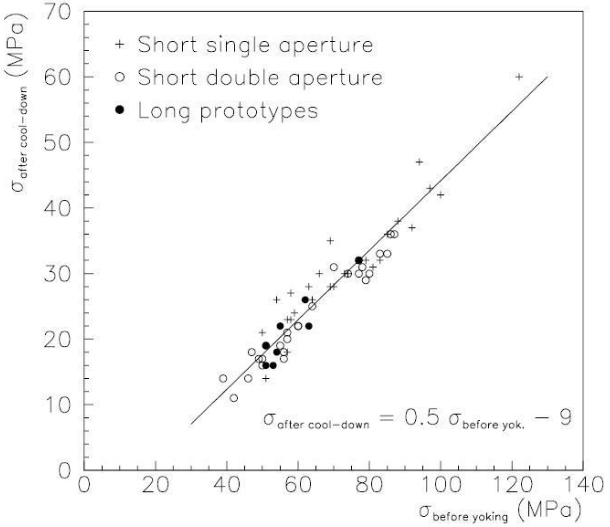
Mechanics of superconducting magnets
Shell

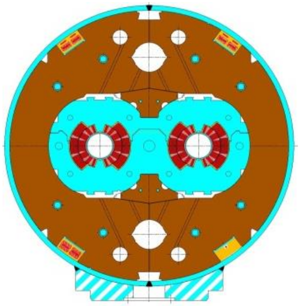




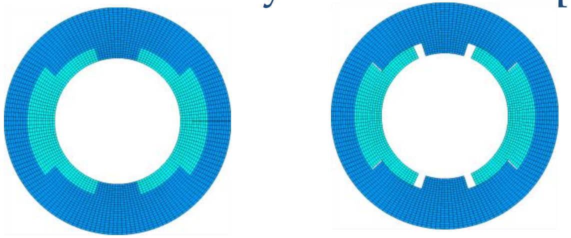
Mechanics of superconducting magnets
Cool-down and excitation

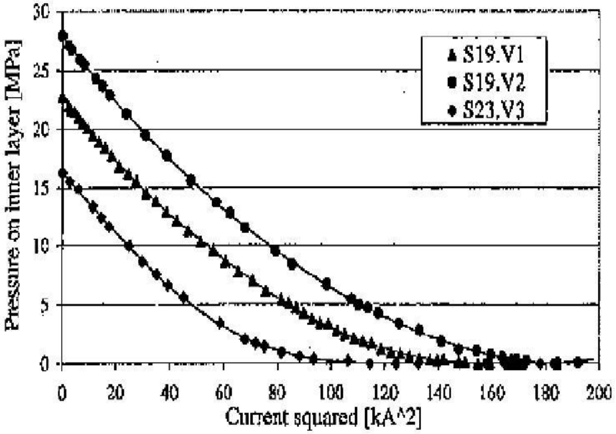
- **During cool-down**
  - Components shrink differently
    - Again, coil positioning within 20-50 μm
  - Significant **variations of coil stress**



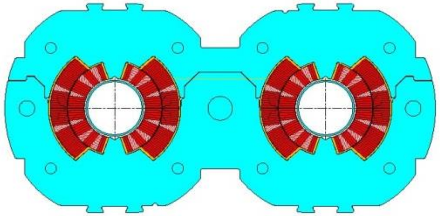


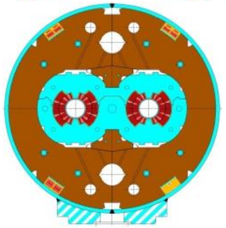
- **During excitation**
  - The pole region of the coil unloads
    - Depending on the pre-stress, at nominal field the coil may unload completely

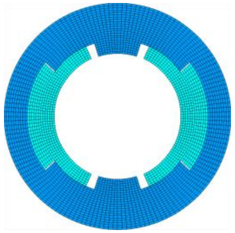




Mechanics of superconducting magnets
Overview of coil stress



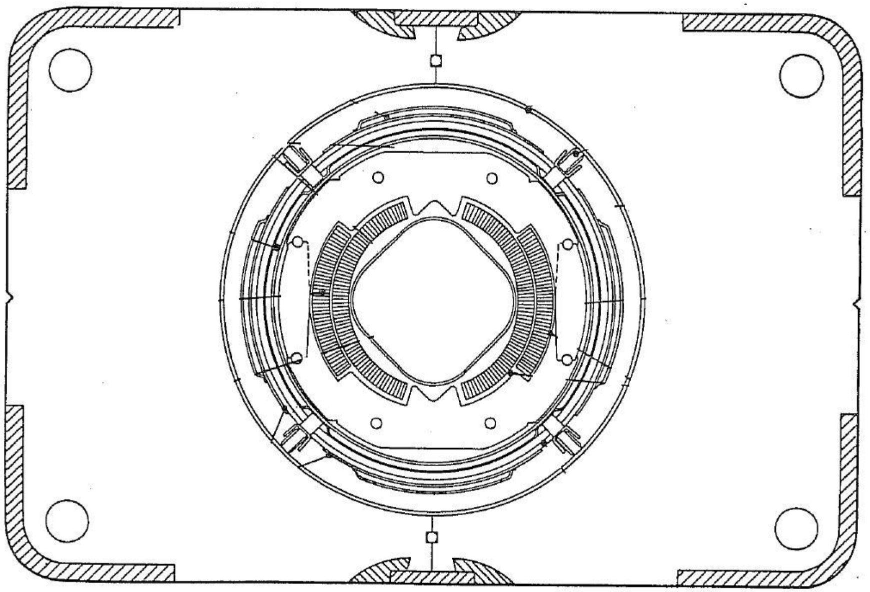


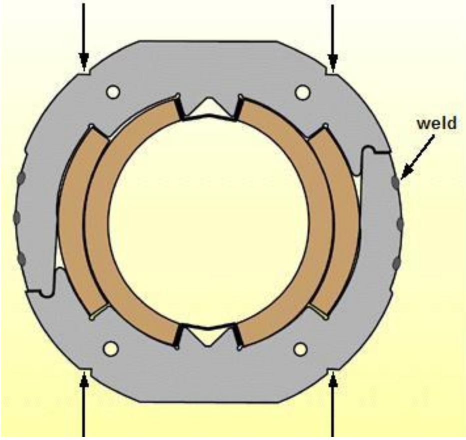


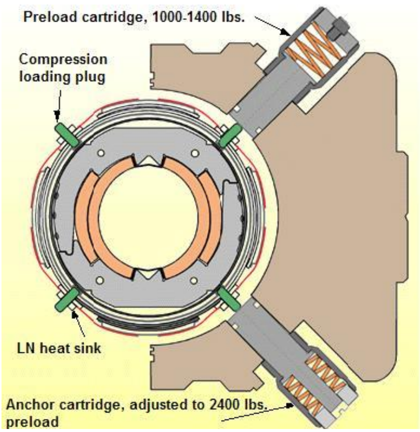
- **Collaring**
- **Yoking and shell welding**
- **Cool-down**
- **Excitation**
- All these contributions taken into account in the **mechanical design**
  - Minimize **coil motion** (pre-stress)
  - Minimize **cost and dimension** of the structure
  - Maintain the maximum stress of the component **below the plasticity limits**
  - …and for (especially) Nb_3Sn coils, **limit coil stress** (150-200 MPa).

Practical examples of accelerator magnets
Tevatron main dipole

- The stainless steel collars are **welded** in three locations per side at the end of the collaring procedure.
    - The stress provided by the collaring press is retained (minimum spring-back)
- **Warm iron** design
    - The cold mass is composed by the collared coil; the iron is maintained at room temperature.
- The **compact cryostat** contains a liquid helium shield and a liquid nitrogen shield.
- The cold mass and cryostat are supported by **four cartridges**, which also contribute to the alignment of the magnet.

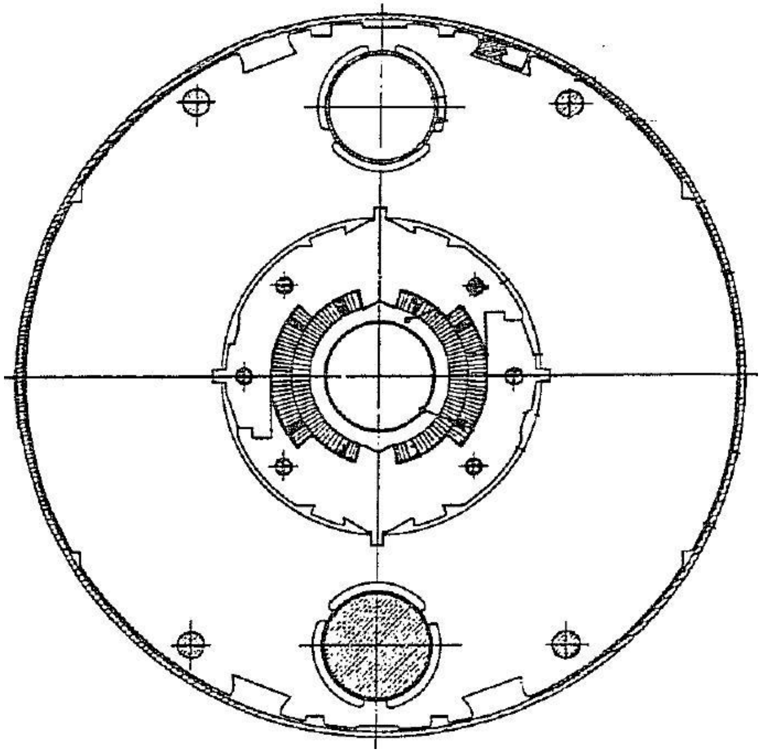


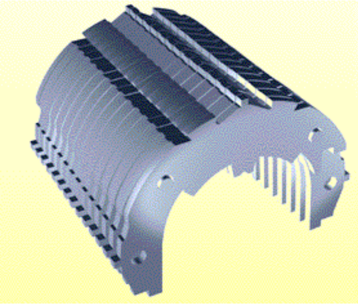


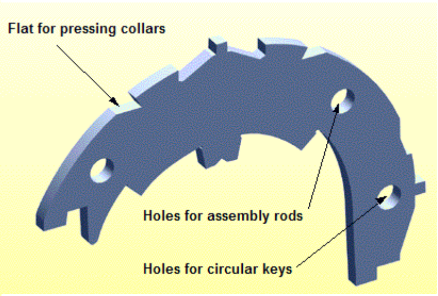


Practical examples of accelerator magnets
HERA main dipole

- **Collars** are made of **aluminum** and are self supporting
    - No contact between collars and yoke.
- Collared coil is locked by keys.
- The **iron yoke is cooled** to liquid He temperature
    - Cold iron design.
- **Alignment** is achieved through keys between the collars and the yoke.
- The He containment is provided by **two half shells** welded together.
- The welding process provides also the **sagitta** (17 mm over 9 m length).

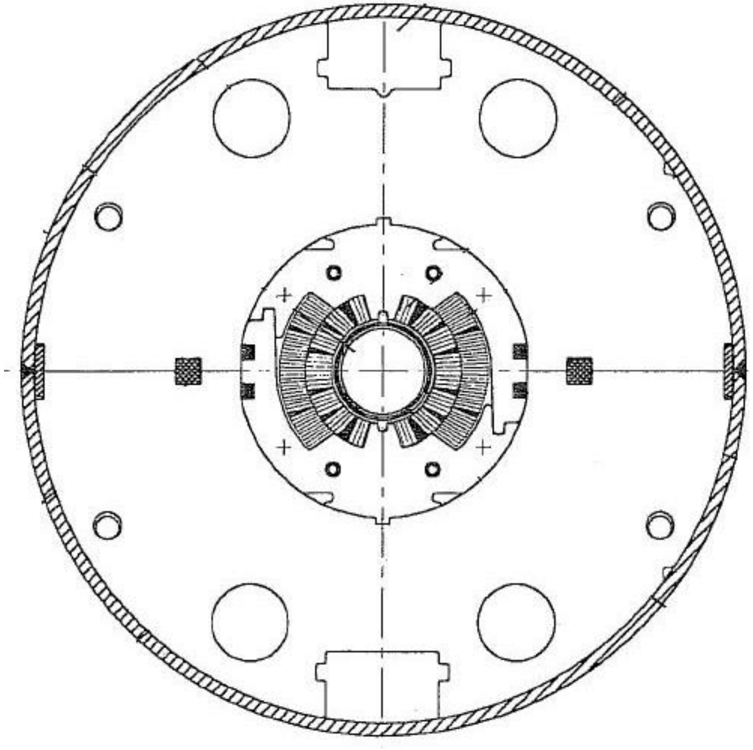


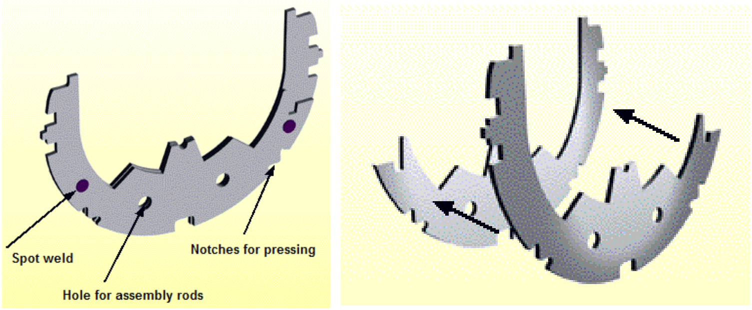




Practical examples of accelerator magnets
SSC main dipole

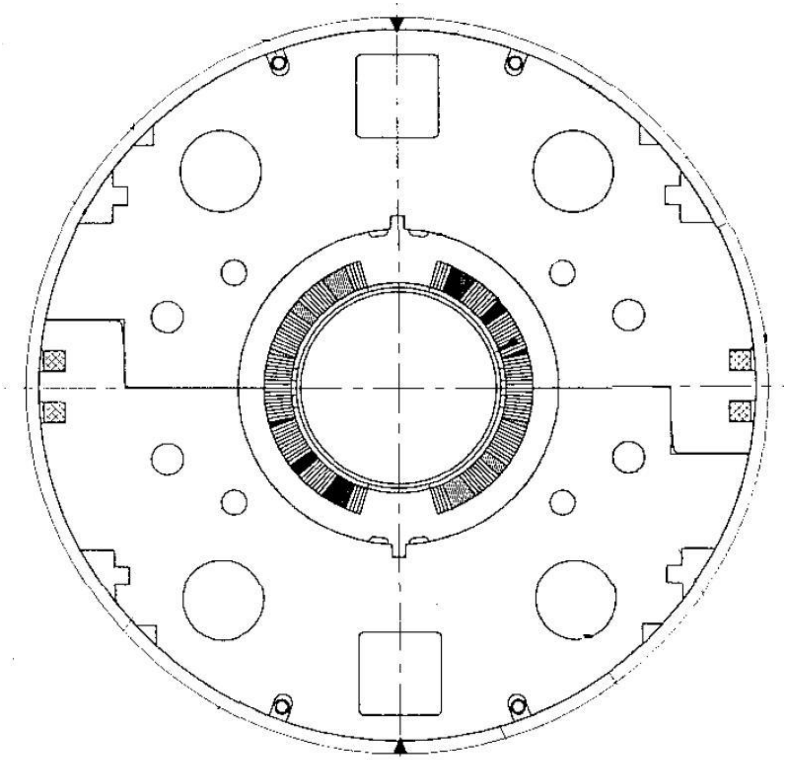
- **Stainless steel collars** are assembled into packs from spot welded pairs.
- The collared-coil assembly is contained by the iron yoke and the welded a stainless steel outer shell.
- Interference is provided between collars and yoke (**line-to-line fit**).
- Two different designs
  - In the BNL design, the yoke is **split horizontally**
    - Tight contact results from a collar-yoke interference along the vertical diameter.
  - In the FNAL design, the yoke is **split vertically**
    - Tight contact results from a collar-yoke interference along the horizontal diameter.

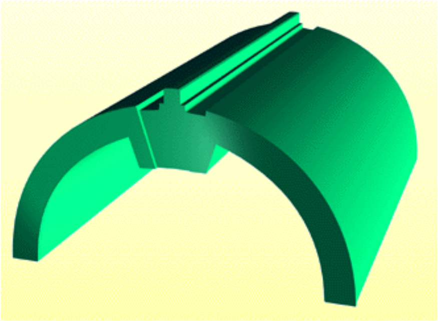


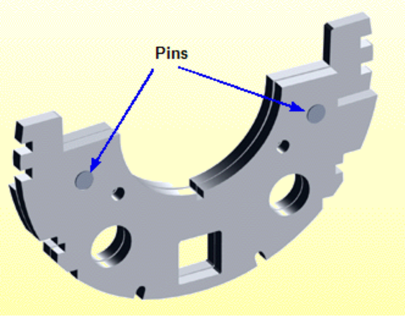


Practical examples of accelerator magnets
RHIC main dipole

- 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.

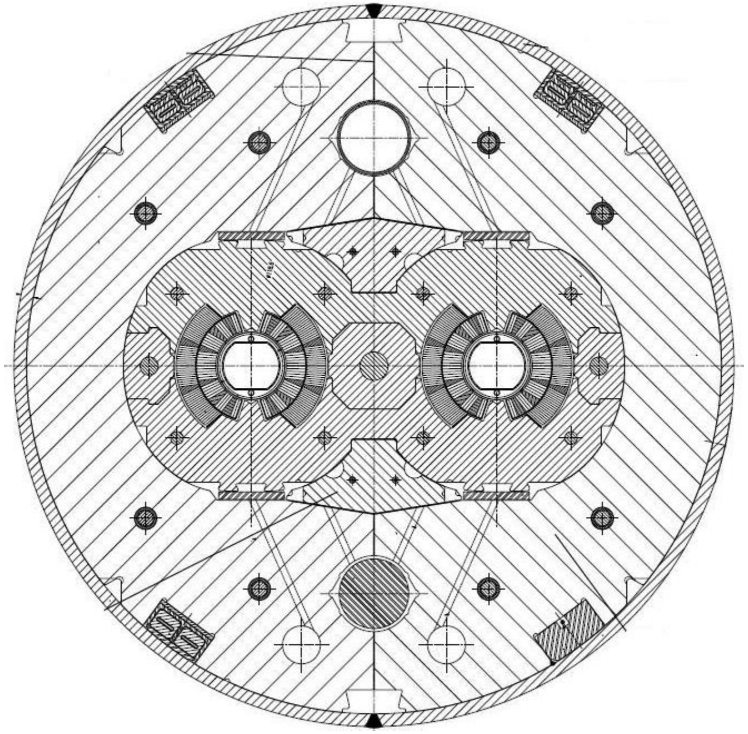


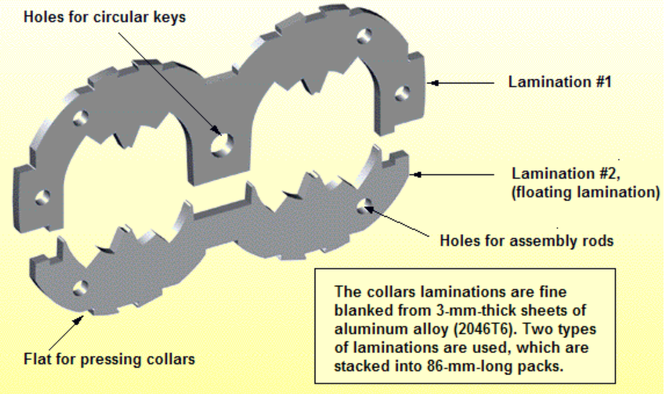




Practical examples of accelerator magnets
LHC main dipole

- **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.



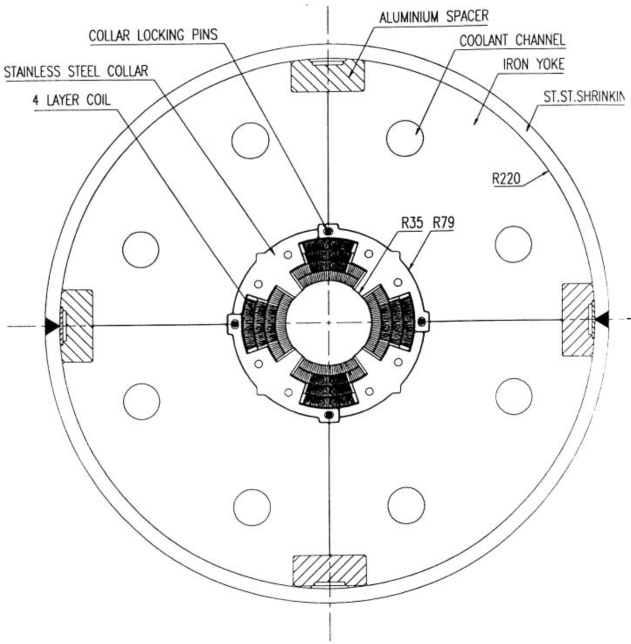


The collars laminations are fine blanked from 3-mm-thick sheets of aluminum alloy (2046T6). Two types of laminations are used, which are stacked into 86-mm-long packs.

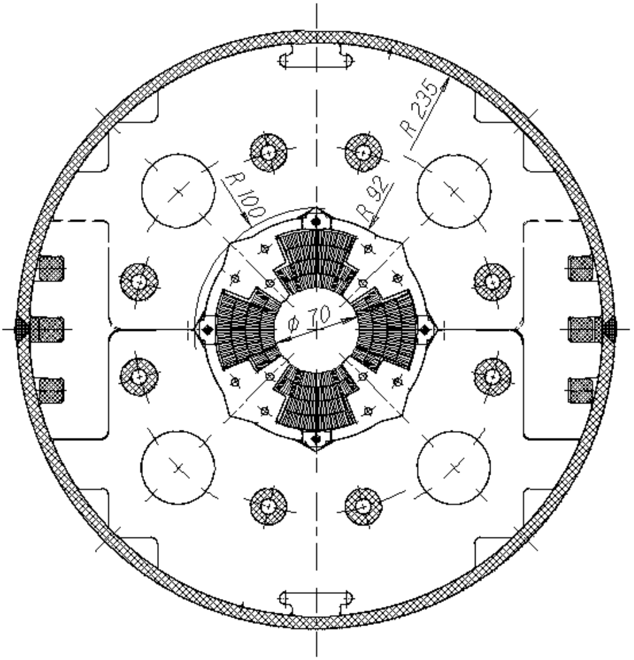
Practical examples of accelerator magnets
LHC IR quadrupole

- Support structure based on collars and welded stainless steel shell are also used for quadrupole magnets.
- During the collaring operation, 4 keys/rods are inserted at the four mid-planes.

CERN-Oxford Inst.
(MQY)



KEK
(MQXA)



Fermilab
(MQXB)