Unit 14
Construction methods and support structures II

Soren Prestemon and **Steve Gourlay**

Lawrence Berkeley National Laboratory (LBNL)

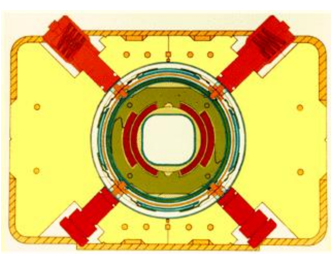
Outline

- Introduction
- Main features of support structures
- Cool-down effect
- Electro-magnetic (Lorentz) force effect
- Practical examples of accelerator magnets
  - Tevatron main dipole
  - Hera main dipole
  - RHIC main dipole
  - SSC main dipole
  - LHC main dipole
  - LHC IR quadrupoles
- Practical examples of R&D magnets
  - TQS
  - TAMU
  - CCT
- Summary

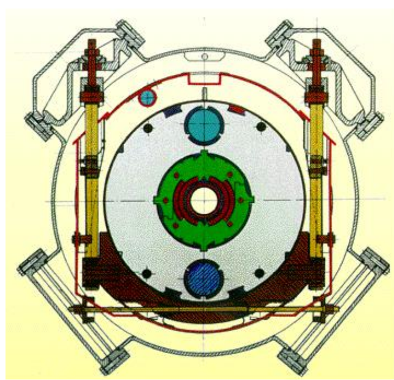
Introduction

- Completed coils are assembled into a support structure
  - Define and maintain precise conductor position for field quality over entire length of the magnet
  - Provide pre-stress to minimize conductor motion under Lorentz forces
  - Helium containment
- Overview of the main features of a magnet support structure (cold mass)
- Assembly process
- And some examples of accelerator and R&D magnets.

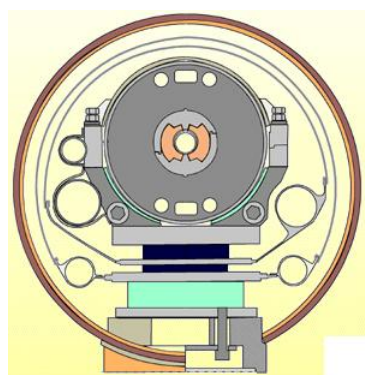
Tevatron



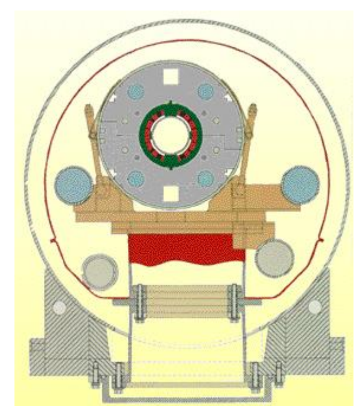
HERA



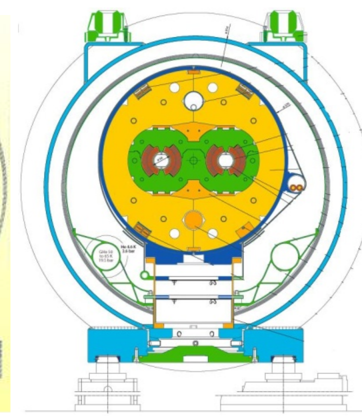
SSC



RHIC



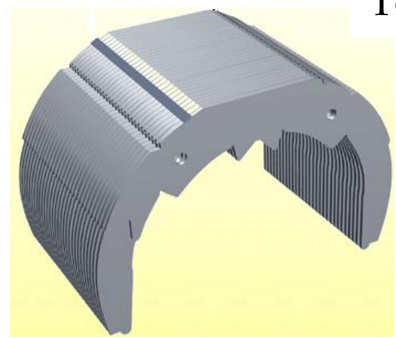
LHC

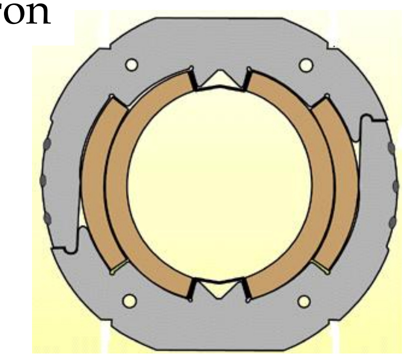


Not to scale

- Collars were implemented for the first time in the Tevatron dipoles.
- Since then, they have been used in all but one (RHIC) accelerator magnet design and in most R&D magnets.
- They are composed of stainless-steel or aluminum laminations a few mm thick.
- By clamping the coils, the collars provide
  - coil pre-stressing;
  - rigid support against e.m. forces (it can be self-supporting or not);
  - precise cavity (tolerance ± 20 μm).

Tevatron





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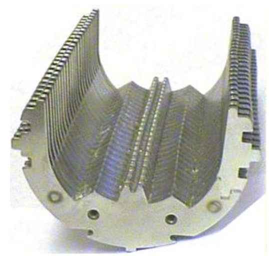
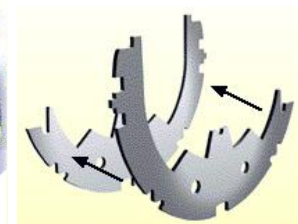
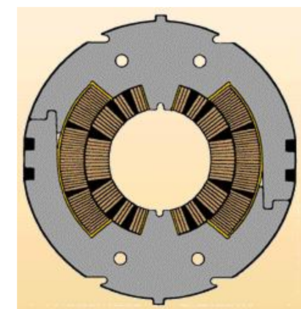
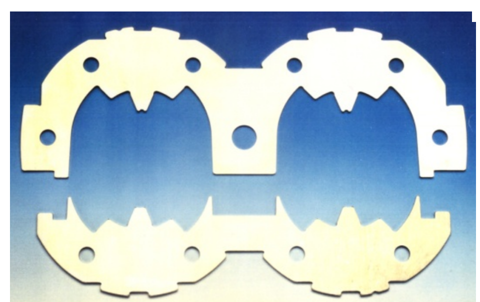


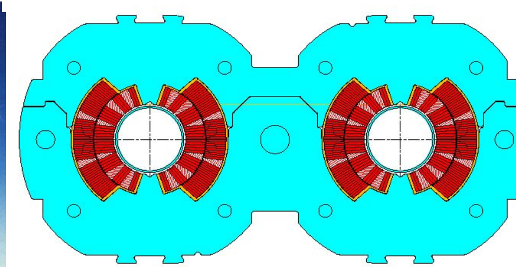




MJB Plus, Inc., [2]

LHC

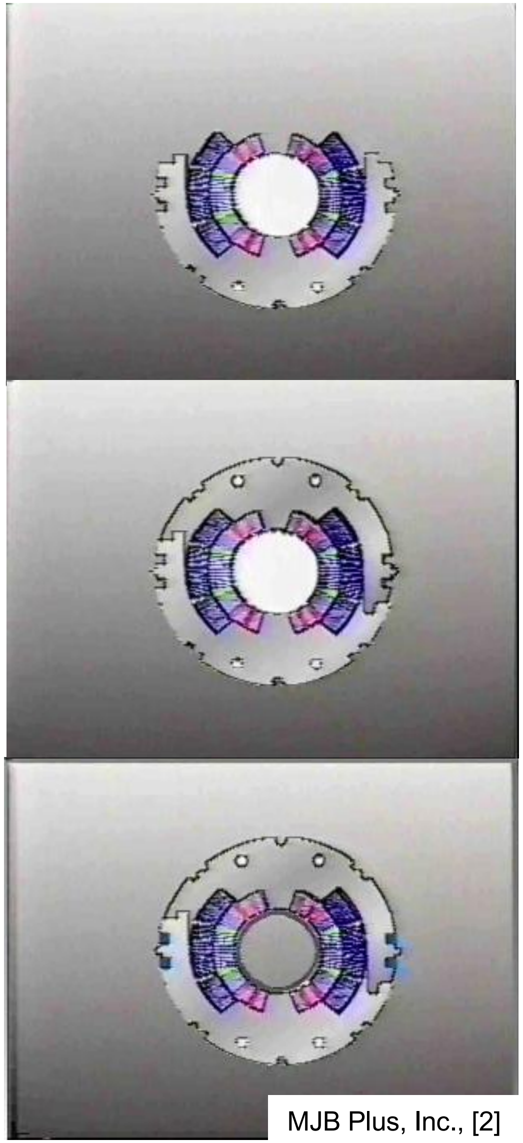




L. Rossi, [1]

Support structure main features
Collars

- Collaring procedure
  - Collars are pre-assembled in packs (several cm long) and placed around the coil.
  - Since the uncompressed coil is oversized with respect to the collar cavity dimension, at the beginning of the collaring procedure the collars are not locked (open).
  - The coil/collar pack is then introduced into a collaring press.
  - The pressure of the press is increased until a nominal value.
  - Collars are locked with keys, rods or welded, and the press released.
  - Once the collaring press is released, the collar experiences a “spring back” due to the clearance of the locking feature and deformation.



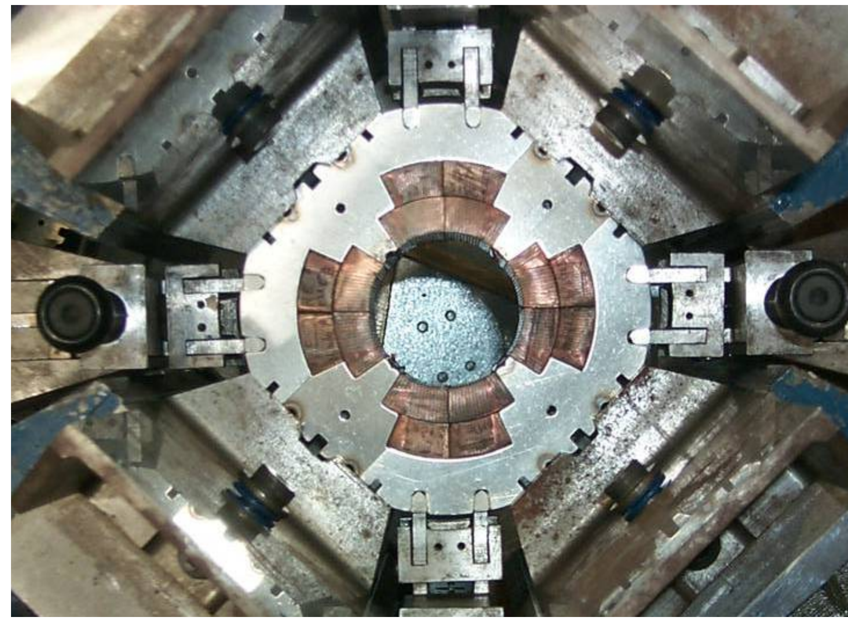
MJB Plus, Inc., [2]

Support structure main features
Collars

Collaring of a dipole magnet

L. Rossi, [4]

Collaring of a quadrupole magnet



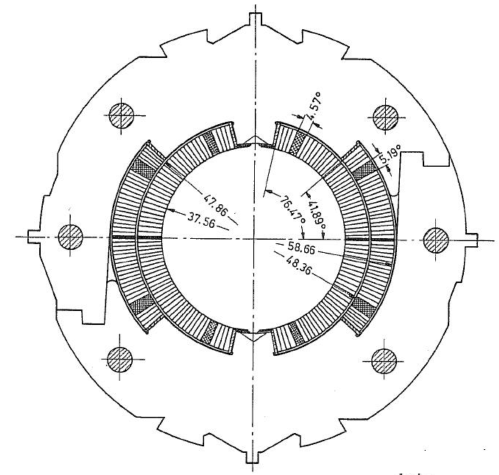
Support structure main features
Collars

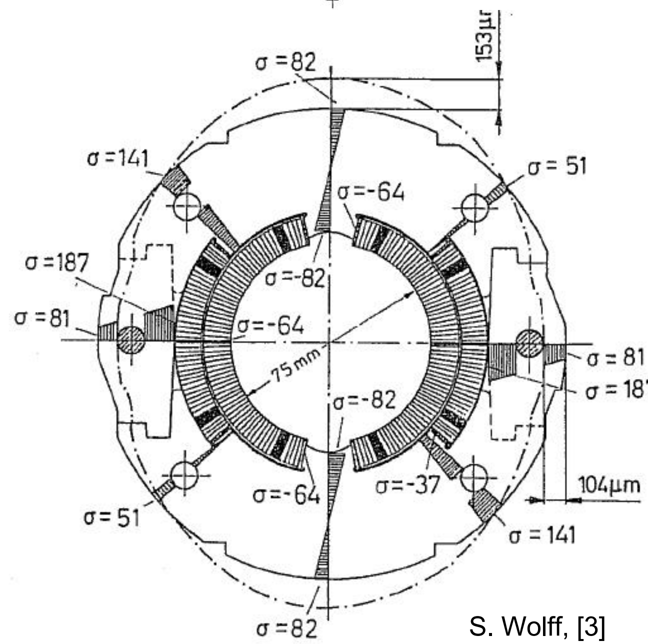
- The purpose of the collar is to pre-compress the coil inside a “rigid” cavity.
  - The collar cavity fixes the dimension of the coil.
  - Coil geometry is given by the collars.
- Coil stress-strain is given by

$$\varepsilon_{\mathrm{coil}}=(l_{coil\_0}-l_{cavity})/l_{coil\_0}$$

$$\sigma_{coil}=E_{coil}\varepsilon$$

- A good knowledge of the coil properties (l_{coil_0} and E) is mandatory to predict final coil status.
- In addition, collar deformation must be taken into account.

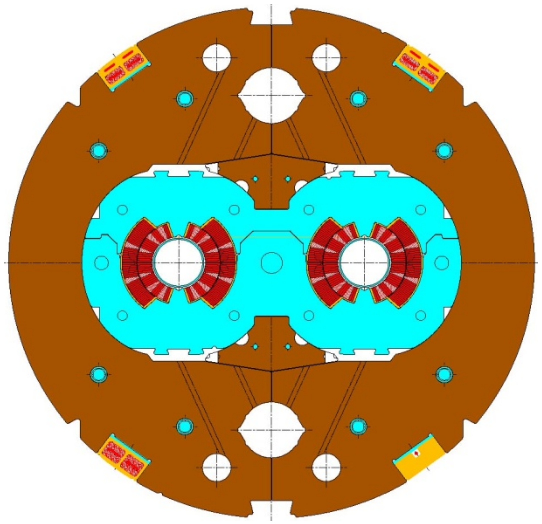




S. Wolff, [3]

Support structure main features
Iron yoke

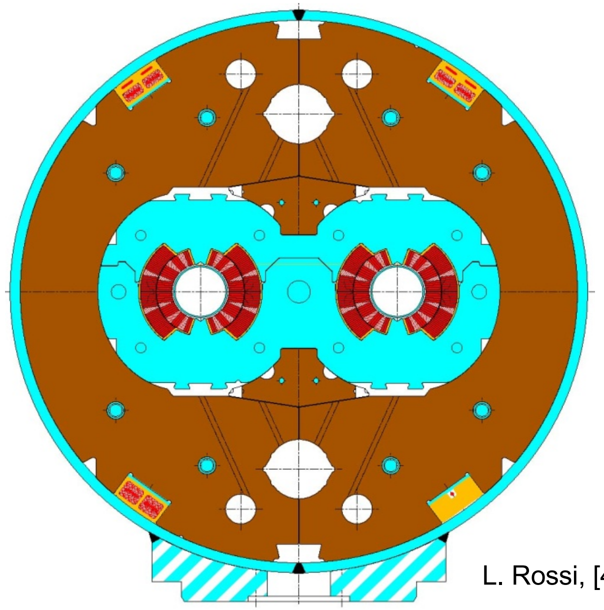
- As the collars, the iron yoke is made from stacked laminations (several mm thick), with a packing factor > 95%.
- Magnetic function
  - The yoke contains and enhances the magnetic field. Contribution to bore field is design dependent.
- Structural function
  - Except for the cases where the collars are self supporting (i.e. like in Tevatron and HERA dipoles), the yoke is in tight contact with the collar. Therefore, it increases the rigidity of the coil support structure and limits radial displacement.
- Holes are included in the yoke design for
  - Correction of saturation effect
  - Cooling channel
  - Assembly features
  - Electrical bus



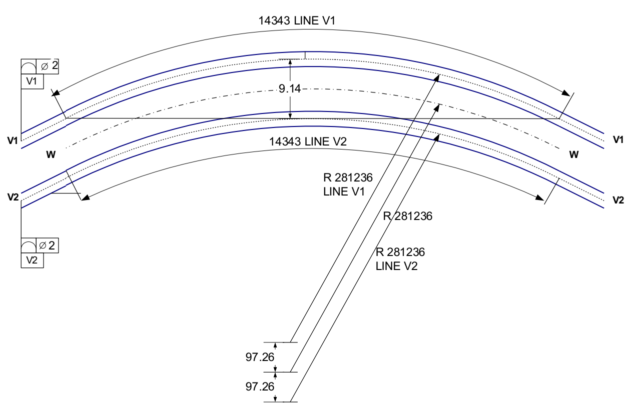
L. Rossi, [4]

Support structure main features
Shell

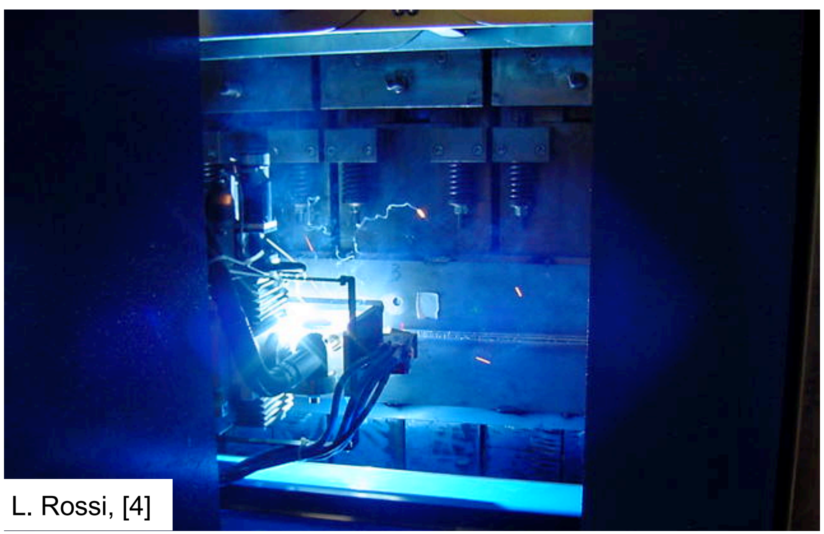
- The cold mass is contained within a shell (or shrinking cylinder).
- The shell constitutes a containment structure for the liquid Helium.
- It is composed of two half shells of stainless steel welded around the yoke with high tension (about 150 MPa for the LHC dipole).
  - With the iron yoke, it creates a rigid boundary for 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 approximately 9.14 mm.



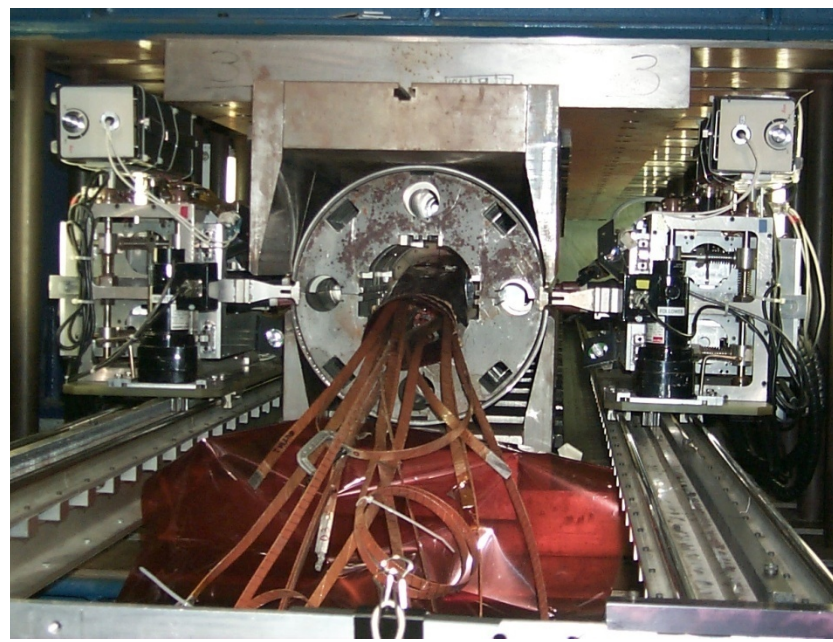
L. Rossi, [4]



Support structure main features
Shell



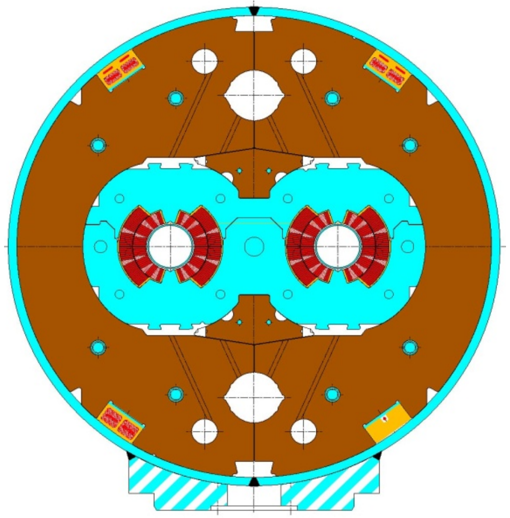
L. Rossi, [4]

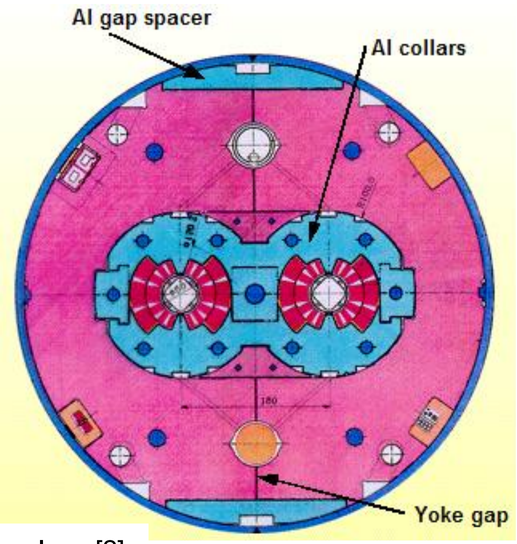


Support structure main features
Shell

- The shell tension provided by the welding may contribute to the overall support of the collared coil. Varies azimuthally and max is weld yield.
- An often (SSC, LHC) implemented approach is the line-to-line fit.
  - When the yoke is put around the collared coil, a gap (vertical or horizontal) remains between the two halves; this gap is due to the collar deformation induced by coil pre-stress.
  - After welding, the shell tension closes the gap, and good contact is provided between yoke and collar.
  - After cool-down, despite the higher thermal contraction of the collared coil with respect to iron, the gap remains closed (high rigidity), and the collared coil is in good contact with the yoke.
- An aluminum spacer may be used to control the yoke gap.

The gap "issue" is very often the subject of much debate

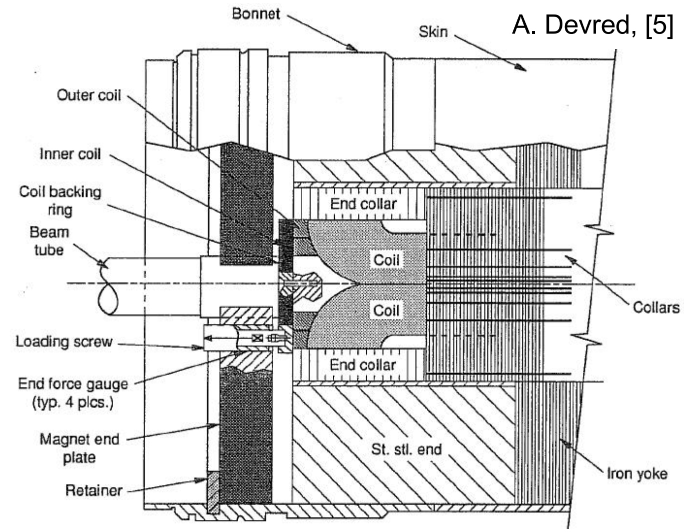




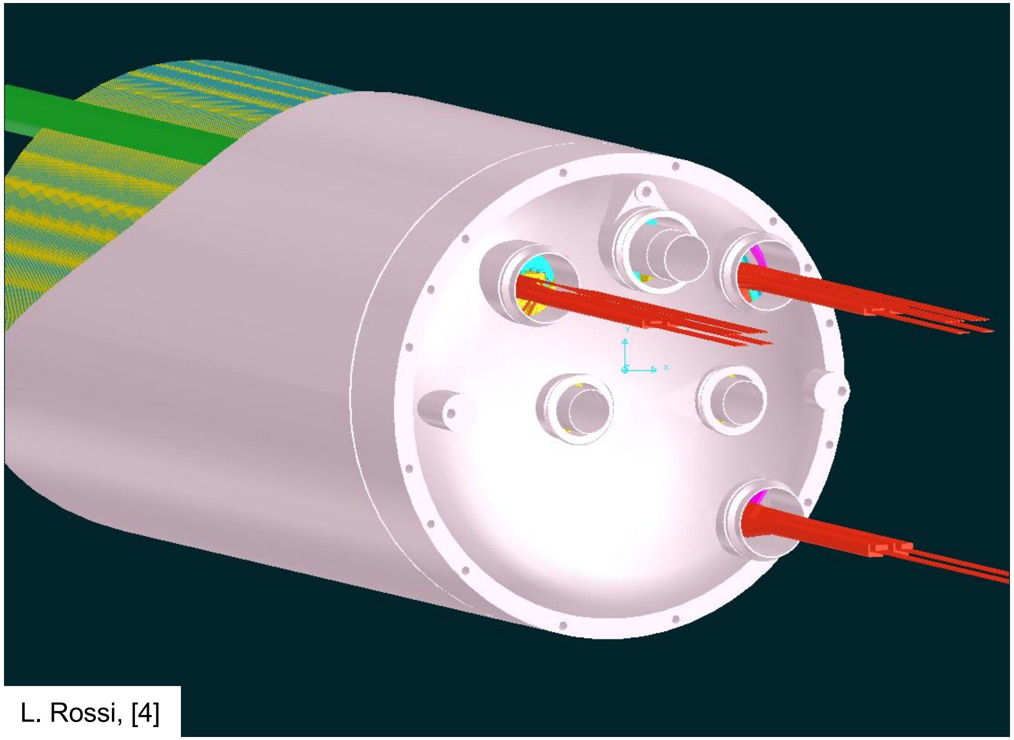
MJB Plus, Inc., [2]

Support structure main features
End plates

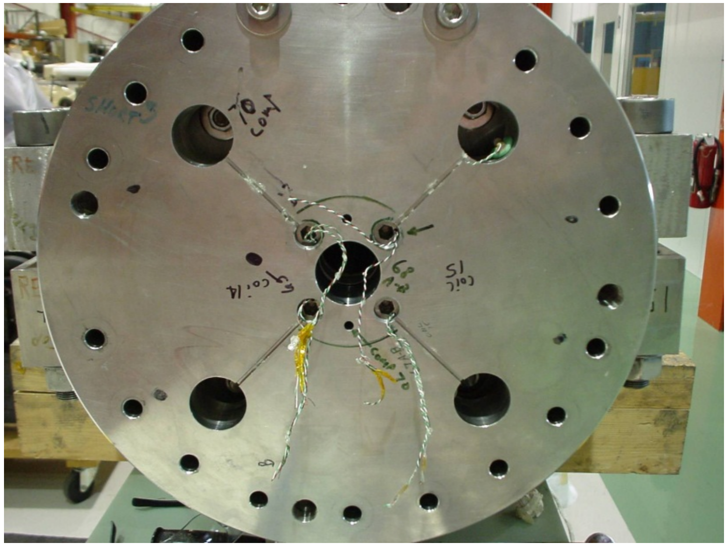
- End plates, applied after shell welding, provide
  - axial support to the coil under the action of the longitudinal e.m. forces
    - Torque may be applied to end bolts;
- End "domes" provide liquid helium containment.



A. Devred, [5]

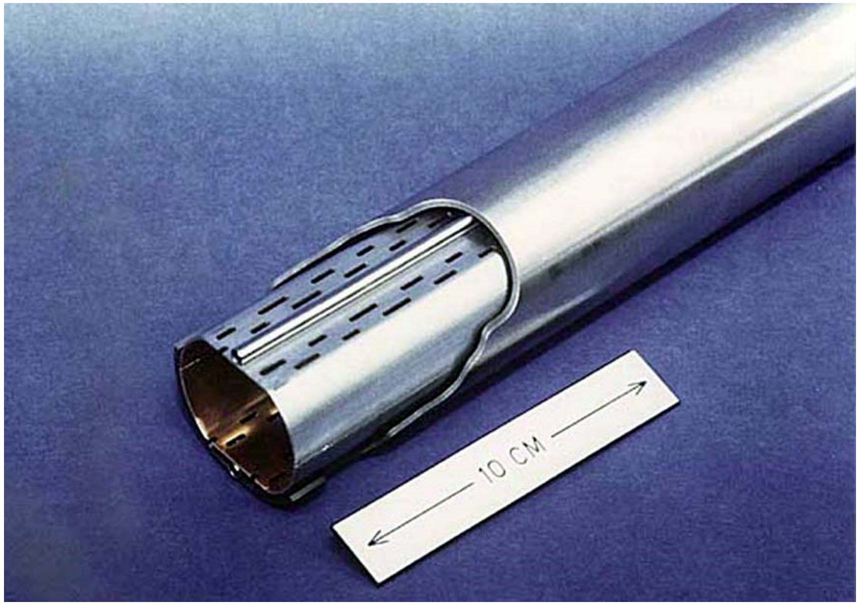


L. Rossi, [4]

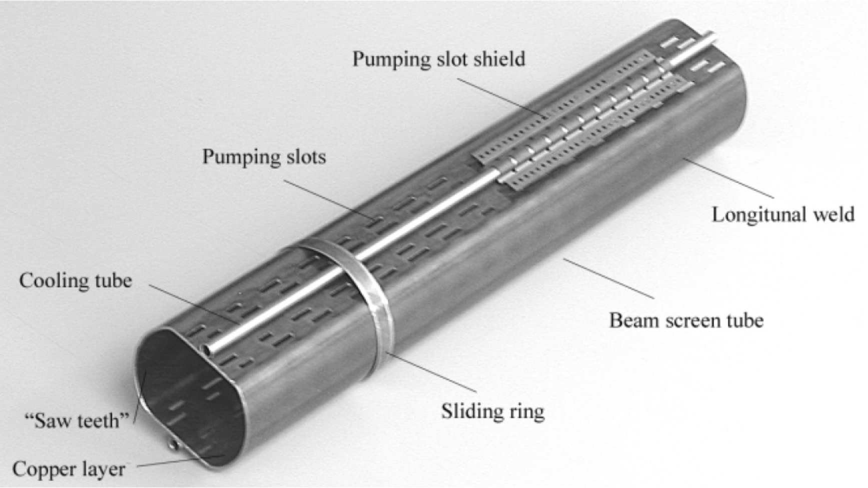


Support structure main features
Cold bore tube and beam screen

- Insulated cold bore tubes are placed in the aperture of the coils and form part of the inner wall of the helium vessel.
  - The tube wall separates the helium volume from the beam vacuum.

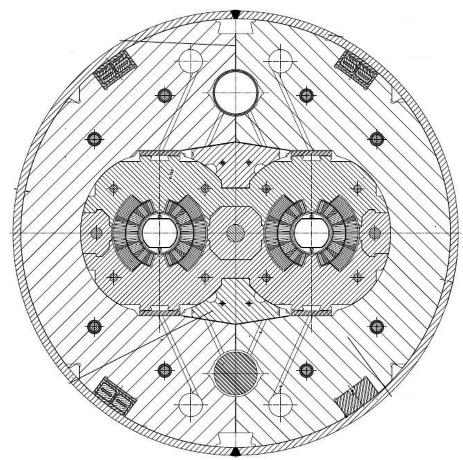


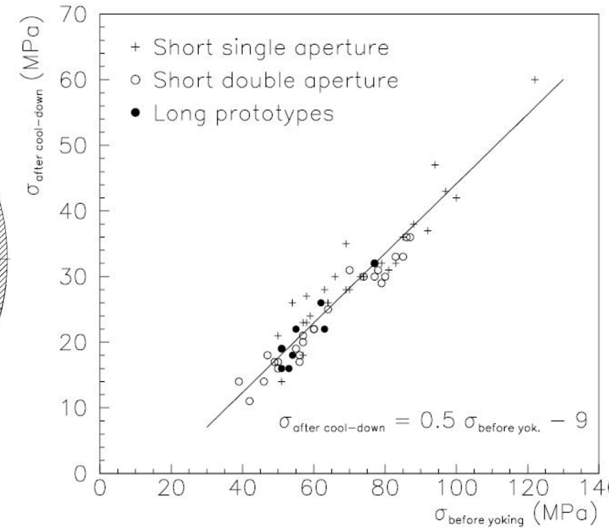
- The beam screen reduces the heat loads from the beam (synchrotron radiation, electron clouds, energy lost by scattering protons, etc).
  - A new feature introduced by LHC
  - Cooled by two stainless steel tubes

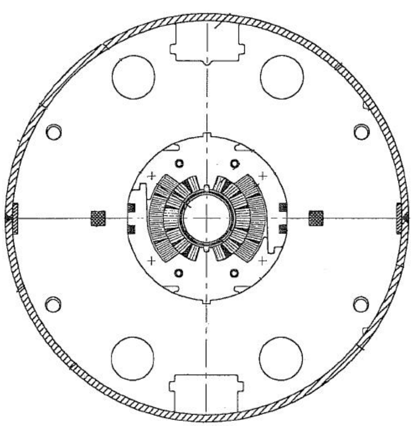


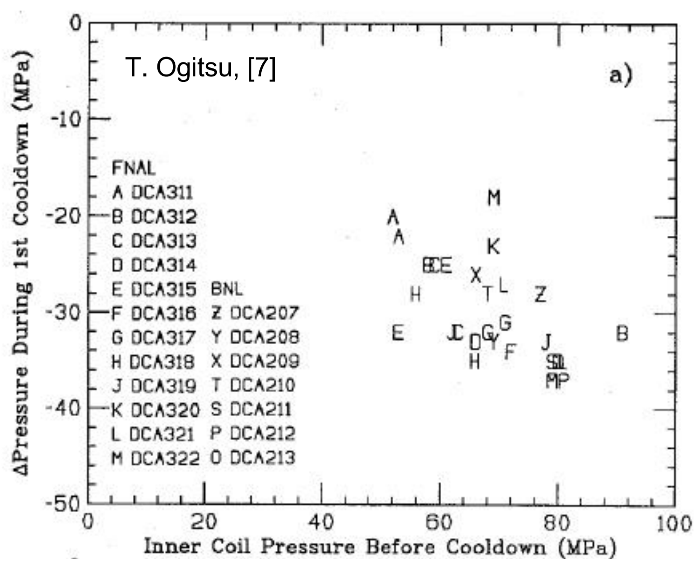
Cool-down effect

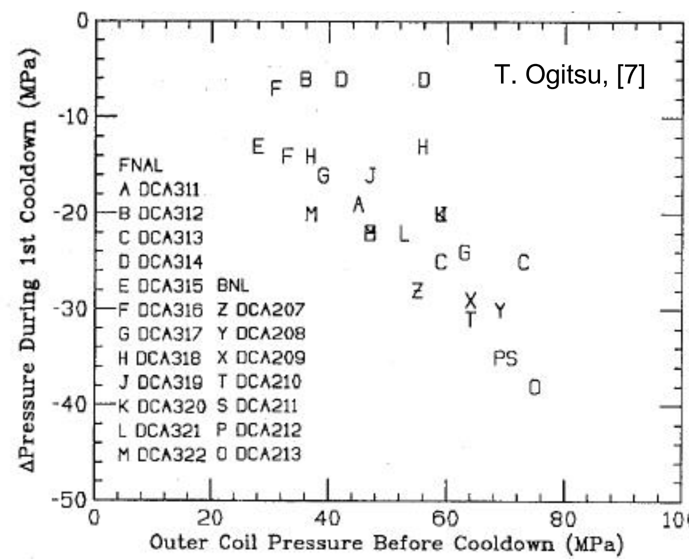
- During cool-down, the shell, the yoke, the collar and the coil shrink differently.
- The integrated thermal contraction from 293 K to 1.9 K varies from $1.9 \cdot 10^{-3}$ for iron to $4.2 \cdot 10^{-3}$ for aluminum.
- Significant variations of coil stress may occur during cool-down.











Cool-down effect

- The cool-down effect (pre-stress loss) can be easily expressed as follows.
- If we assume an infinitely rigid collar (similar to line-to-line fit situation), the variation of coil strain during cool-down (ε_{wc} - ε_{cc}) is given by

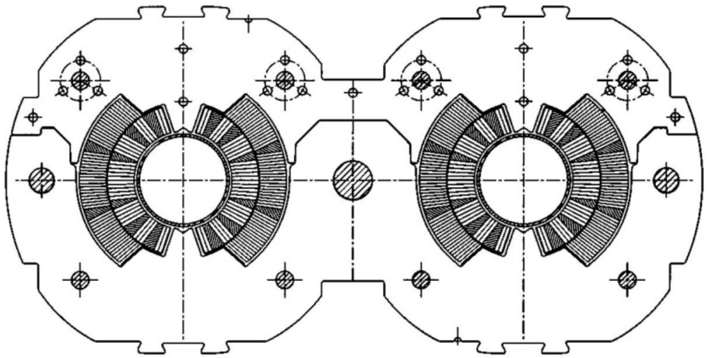
$$\varepsilon_{wc} - \varepsilon_{cc} = \alpha_c - \alpha_s$$

where α_c and α_s are respectively the thermal contraction of the coil and the collar.

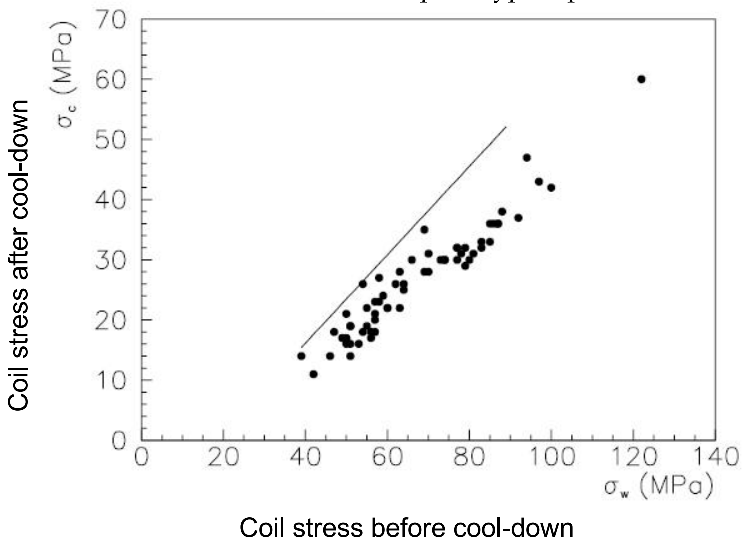
- Therefore, one can write

$$\sigma_{cc} = \frac{E_{cc}}{E_{wc}}\left[\sigma_{wc} - E_{wc}(\alpha_c - \alpha_s)\right]$$

- The loss of pre-stress is proportional to the difference of thermal contraction between coil and collars.

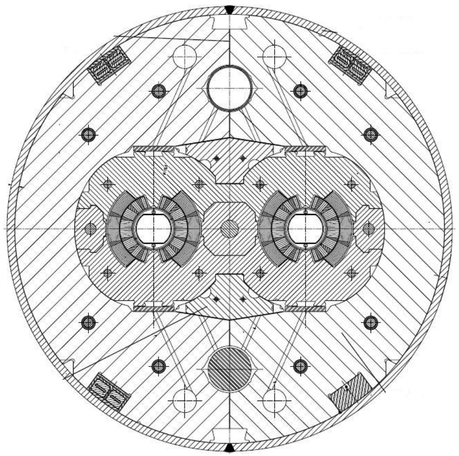


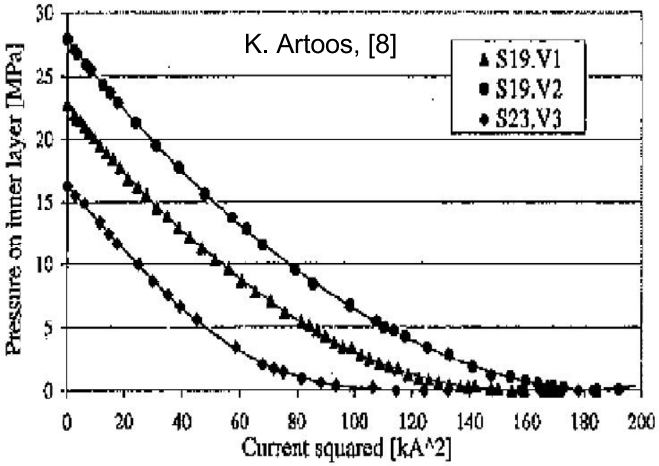
LHC prototype dipole data

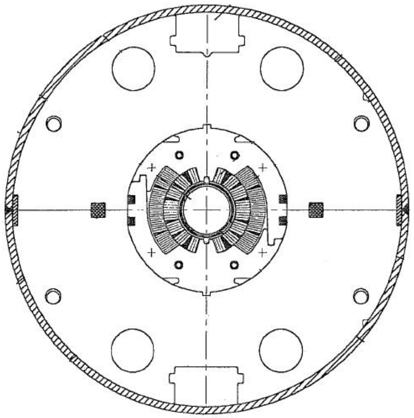


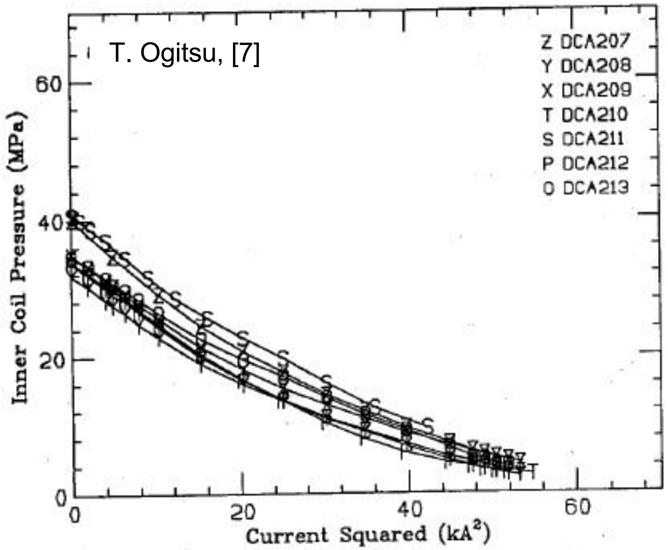
Electro-magnetic force effect

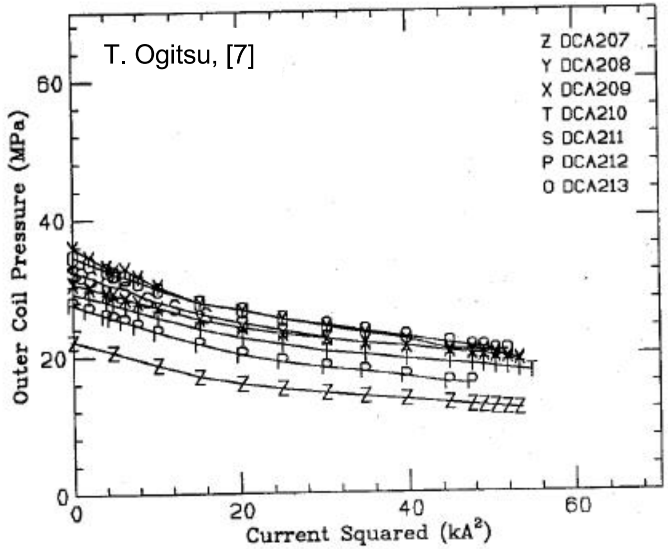
- During excitation, the pole region of the coil unloads because of the e.m. forces.
- Depending on the pre-stress after cool-down, at nominal field the coil may unload completely or maintain a certain compression.









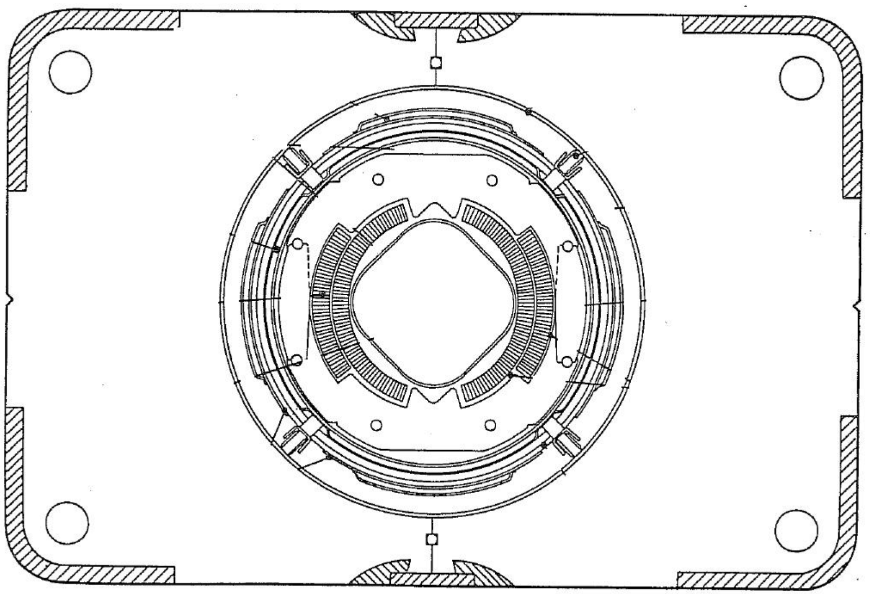


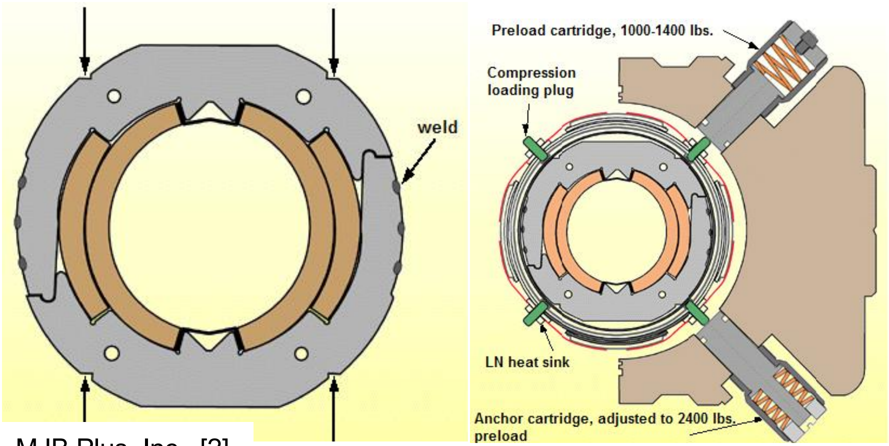
Overview of coil stress

- **Collaring**
  - Azimuthal pre-stress is provided to the coil.
- **Yoking and shell welding**
  - Additional support is added to the collared coil.
- **Cool-down**
  - Coil stress changes depending on the material of the surrounding components.
- **Excitation**
  - The pole unloads, the mid-plane loads, and radially the conductors are pushed against the structure.
- All these contributions must be taken into account in the mechanical design of the structure, with the goal of
  - Minimizing coil motion (pre-stress)
  - Minimizing cost and dimension of the structure
  - Maintaining the maximum stress of the components below plasticity limits
  - …and for (especially) Nb_3Sn coils, limit coil stress (150-200 MPa).

Practical examples of accelerator magnets
Tevatron main dipole

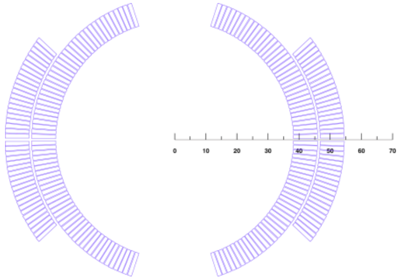
- The stainless steel collars are welded in three locations per side at the end of the collaring procedure.
  - The stress provided by the collaring press is retained (minimum spring-back)
- Warm iron design
  - The cold mass is composed by the collared coil; the iron is maintained at room temperature.
- 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.

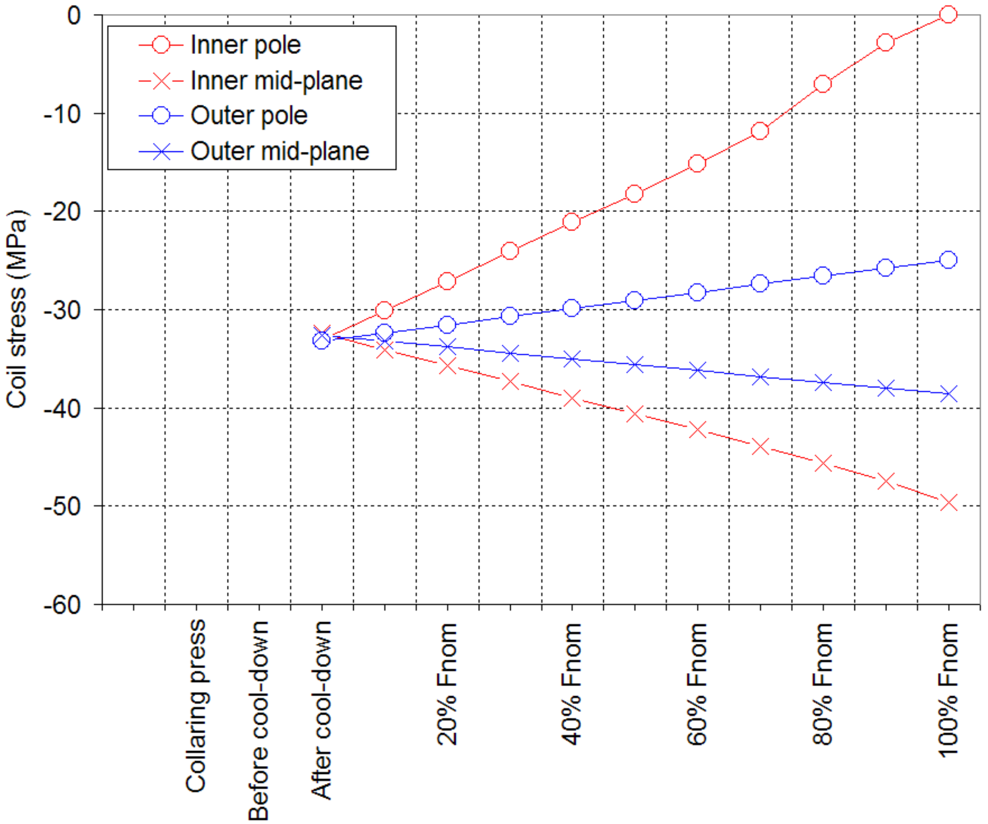




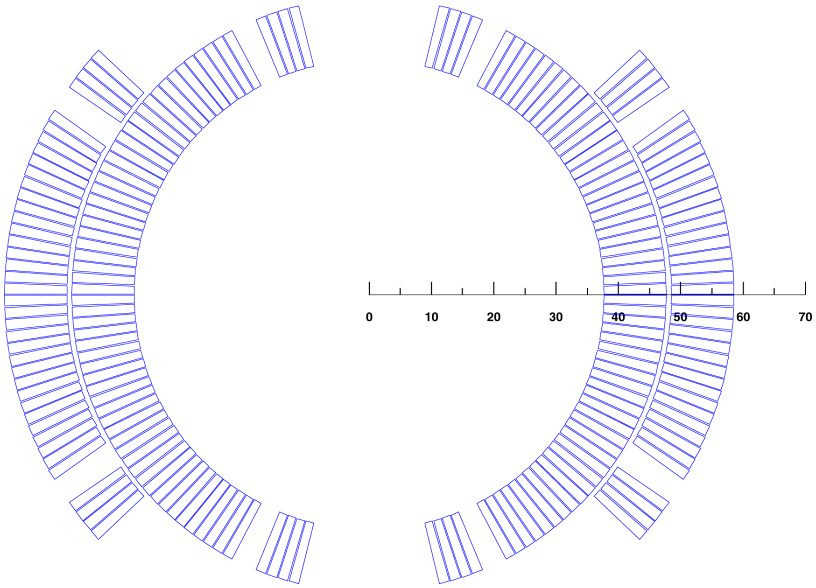
MJB Plus, Inc., [2]

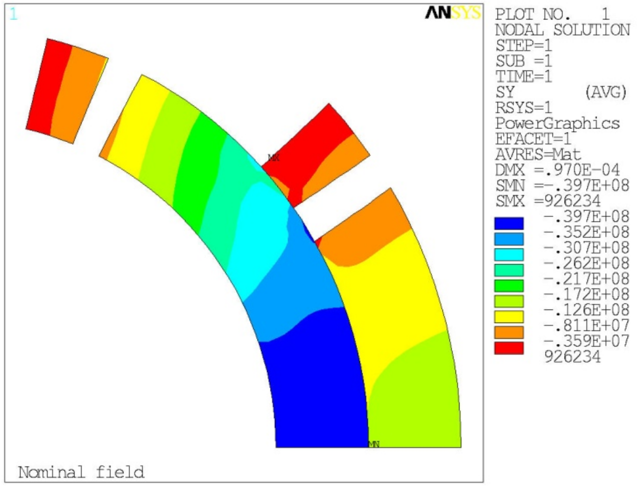
- Coil stress evolution
  - According to [9], “Upon cool-down, at least 4700 PSI (32 MPa) of azimuthal pre-load remains in the inner coil”.
  - By computing the coil response in an infinitely rigid structure, it appears that the coil pole remains always in contact with the collar during excitation.





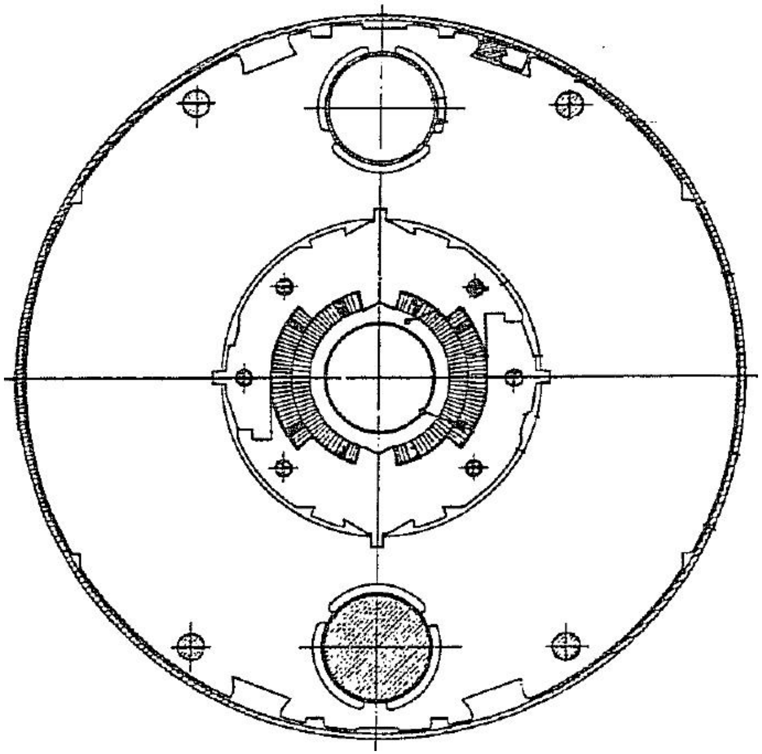
- B_{nom} = 4.68 T
- Force at B_{nom}
  - F_{x_layer1} = + 533 kN
  - F_{x_layer2} = + 45 kN
  - F_{y_layer1} = - 138 kN
  - F_{y_layer2} = - 137 kN
- Stored energy (4 quadrants) at B_{nom}
  - E = 87 kJ/m
- Axial force (4 quadrants) at B_{nom}
  - $F_{z\_}$ = 87 kN
- Average mid-plane stress at B_{nom} (assumptions: infinitely rigid structure and no pre-stress)
  - σ_{θ_layer1} = - 38 MPa
  - σ_{θ_layer2} = - 14 MPa

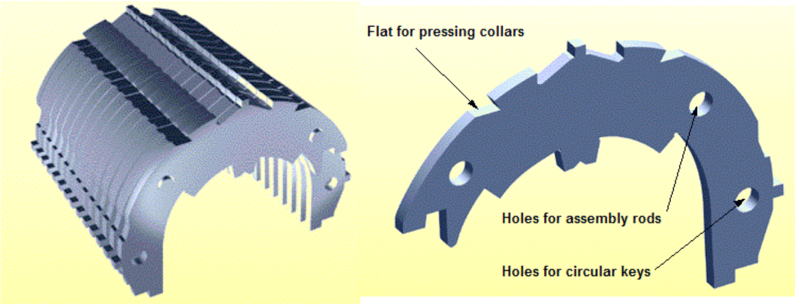




Practical examples of accelerator magnets
HERA main dipole

- 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.
- Collaring press also provides sagitta (17 mm over 9 m length).



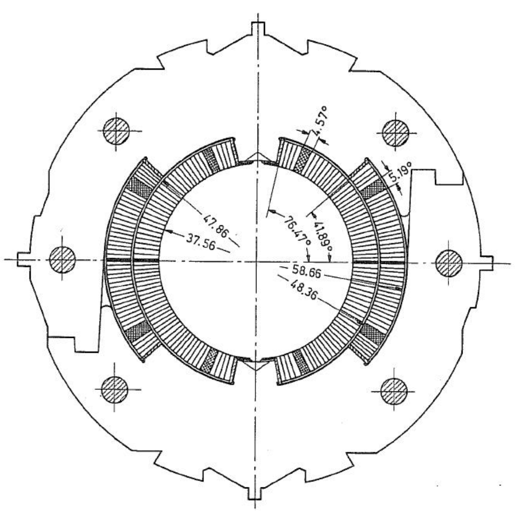


MJB Plus, Inc., [2]

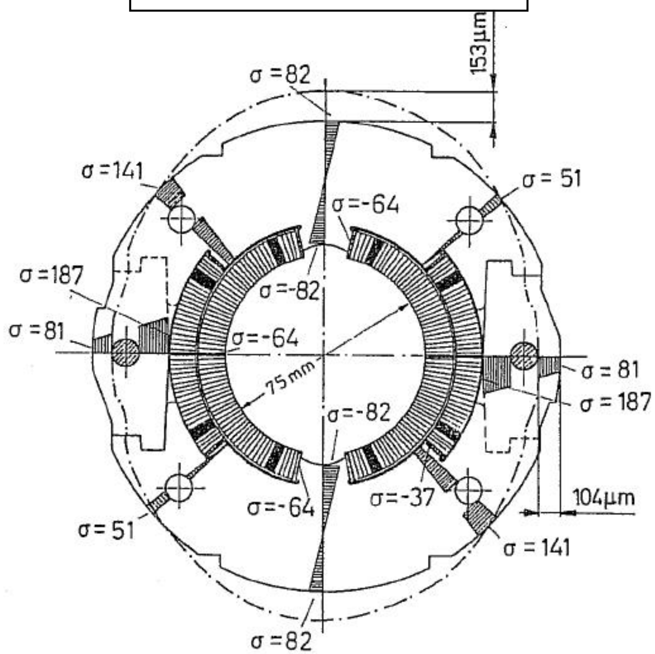
Practical examples of accelerator magnets
HERA main dipole

- Since the collars are not supported by the yoke, they deforms under the action of coil pre-stress and e.m. forces.
  - After cool-down, the collars are vertically ovalized.
  - When e.m. forces are applied, the collars deform horizontally on the mid-plane.

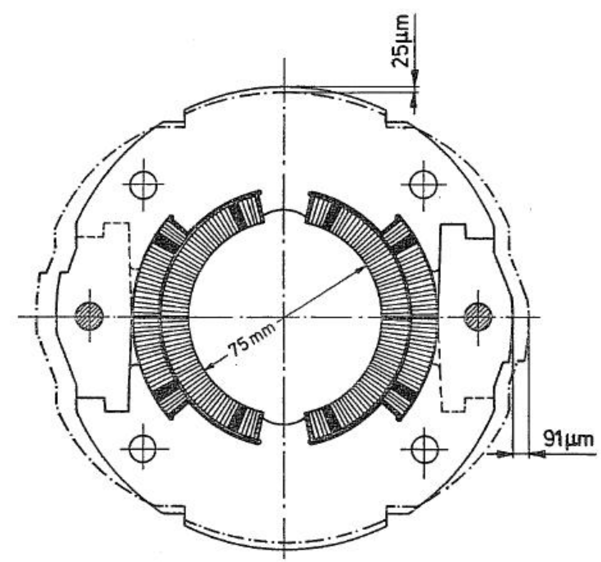
Nominal dimensions



After cool-down

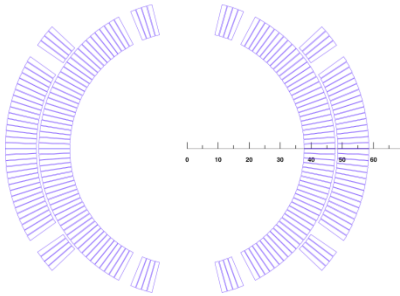


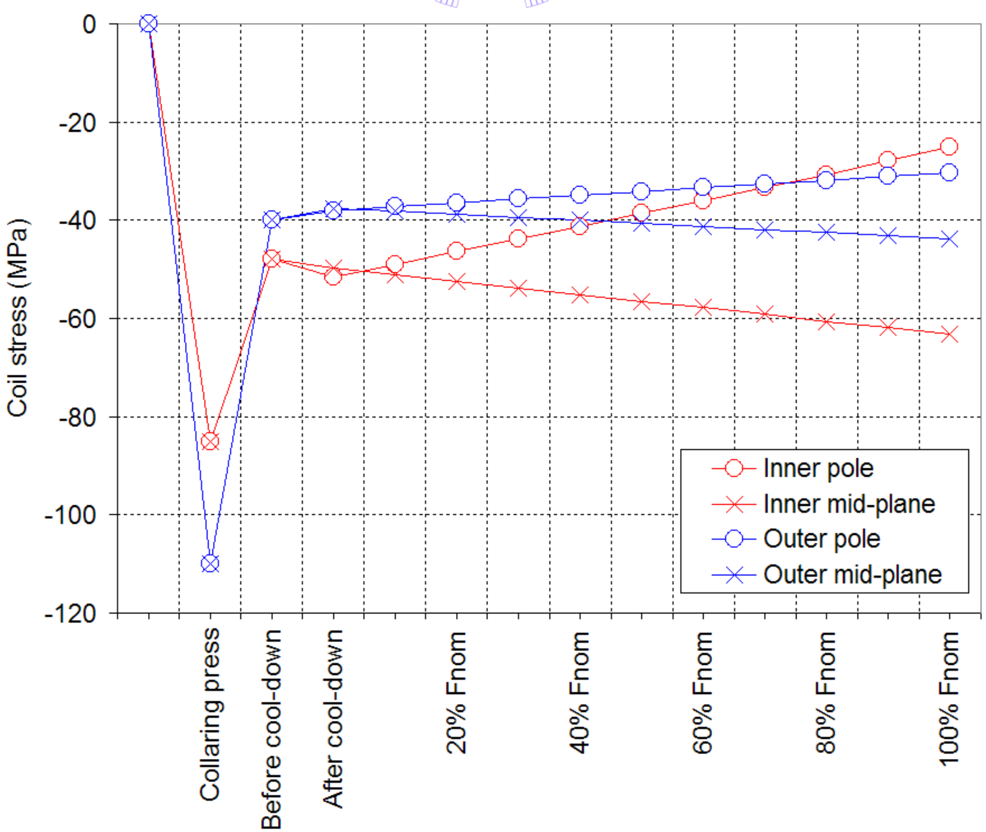
At maximum field



S. Wolff, [3]

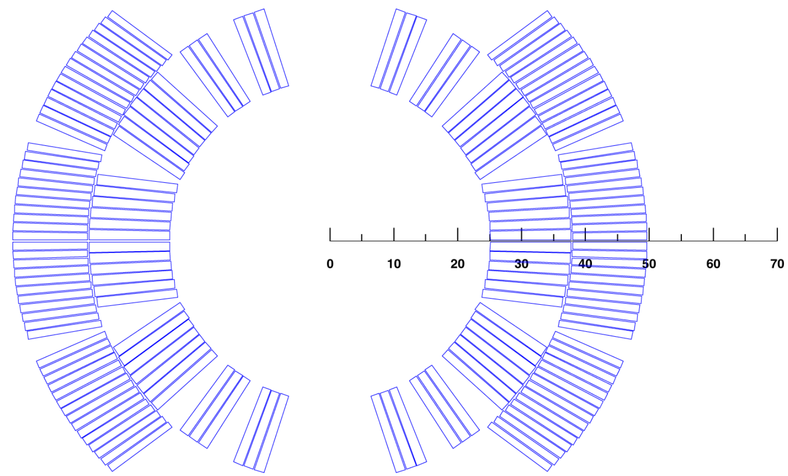
- Coil stress evolution
  - According to [3], after cool-down the coil is pre-compressed to about 50 (40) MPa in the inner (outer) layer.
  - No pre-stress loss occurs during cool-down (aluminum collars).
  - By computing the coil response in a infinitely rigid structure, it appears that the coil pole remains always in contact with the collar during excitation, with a margin of more than 20 MPa in compression.

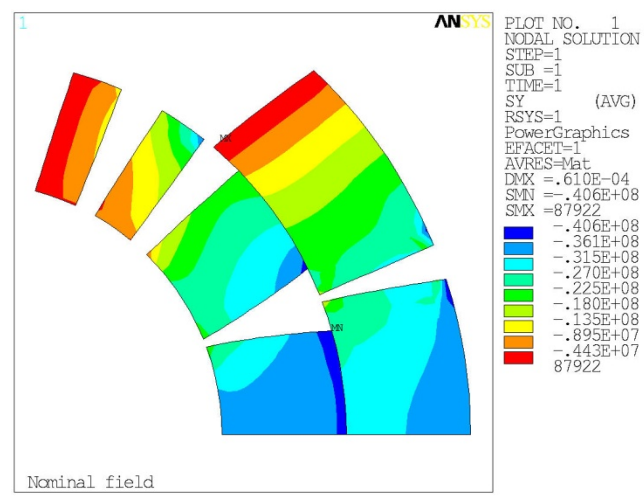




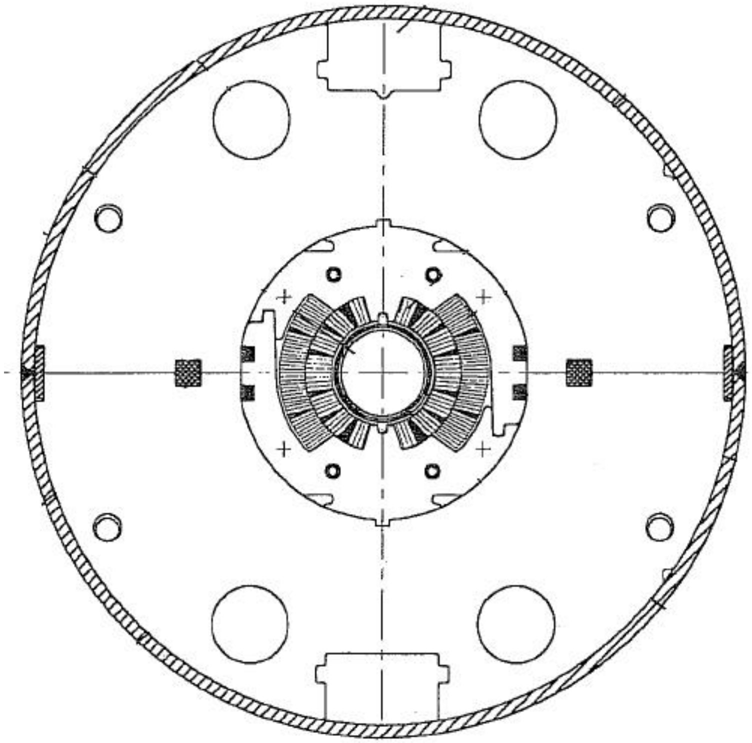
Practical examples of accelerator magnets
SSC main dipole

- B_{nom} = 6.6 T
- Force at B_{nom}
  - F_{x_layer1} = + 634 kN
  - F_{x_layer2} = + 259 kN
  - F_{y_layer1} = - 104 kN
  - F_{y_layer2} = - 304 kN
- Stored energy (4 quadrants) at B_{nom}
  - E = 149 kJ/m
- Axial force (4 quadrants) at B_{nom}
  - $F_{z\_}$ = 149 kN
- Average mid-plane stress at B_{nom} (assumptions: infinitely rigid structure and no pre-stress)
  - σ_{θ_layer1} = - 35 MPa
  - σ_{θ_layer2} = - 32 MPa

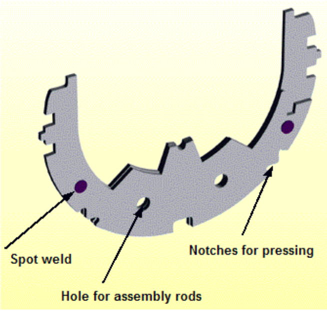


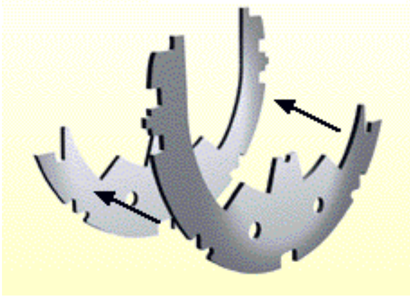


- Stainless steel collars are assembled into packs from spot welded pairs.
- The collared-coil assembly is contained by the iron yoke and the welded a stainless steel outer shell.
- Interference is provided between collars and yoke (line-to-line fit).
- Two different designs
  - In the BNL design, the 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.

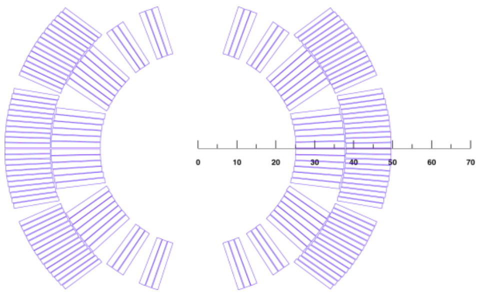


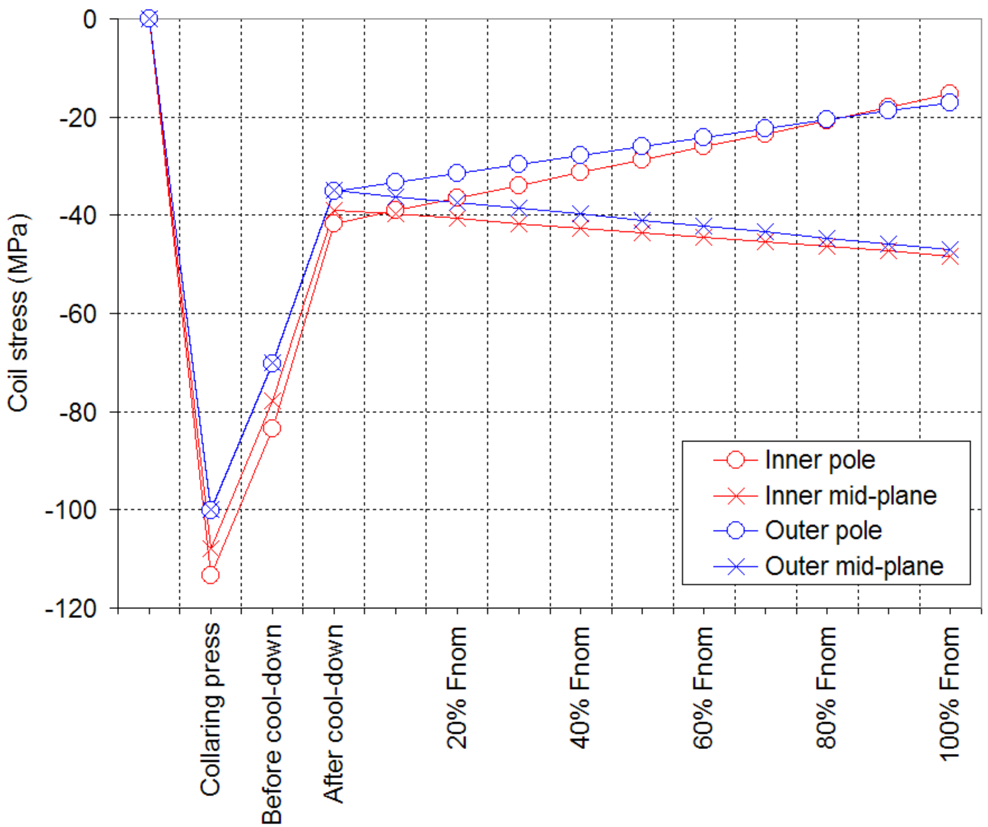
MJB Plus, Inc., [2]





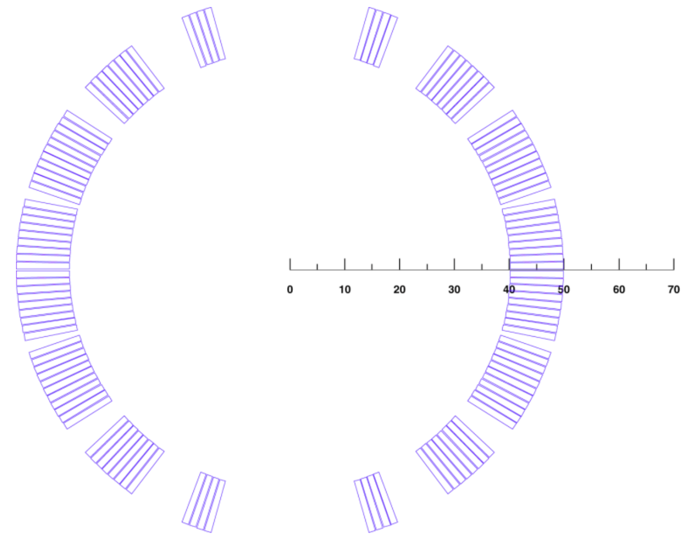
- Coil stress evolution
  - According to [6]-[7], after cool-down the coil is pre-compressed to about 40 (35) MPa in the inner (outer) layer.
  - Pre-stress is lost during assembly and cool-down.
  - By computing the coil response in a infinitely rigid structure, it appears that the coil pole remains always in contact with the collar during excitation, with a margin of more than 15 MPa in compression.

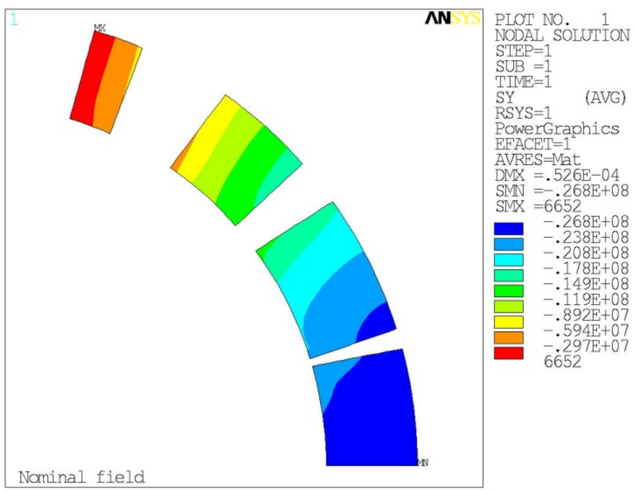




- B_{nom} = 3.46 T
- Force at B_{nom}
  - F_{x_layer1} = + 311 kN
  - F_{y_layer1} = - 110 kN

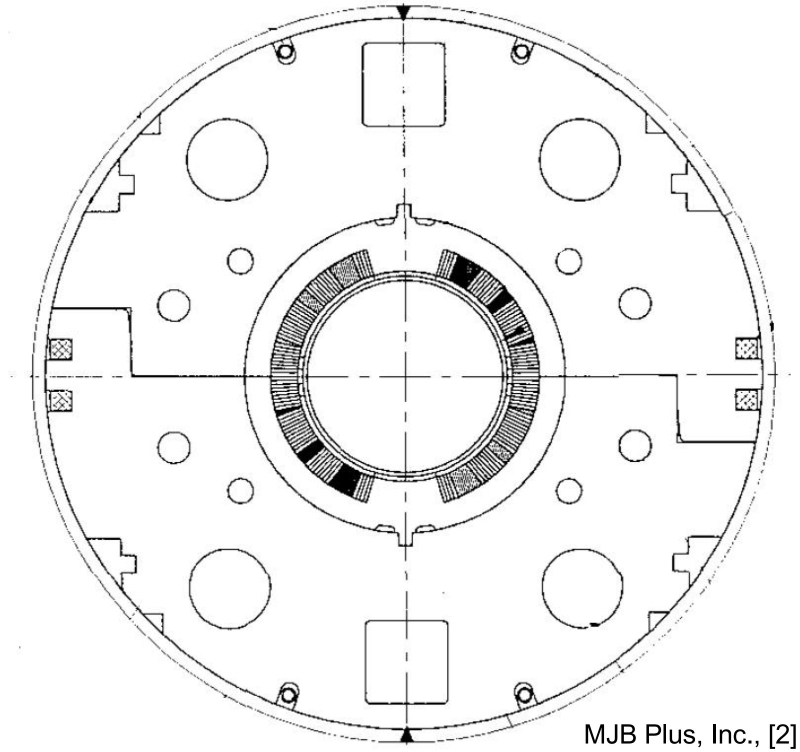
- Stored energy (4 quadrants) at B_{nom}
  - E = 48 kJ/m
- Axial force (4 quadrants) at B_{nom}
  - $F_{z\_}$ = 48 kN
- Average mid-plane stress at B_{nom} (assumptions: infinitely rigid structure and no pre-stress)
  - σ_{θ_layer1} = - 26 MPa



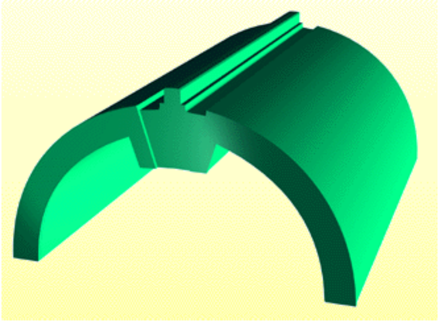


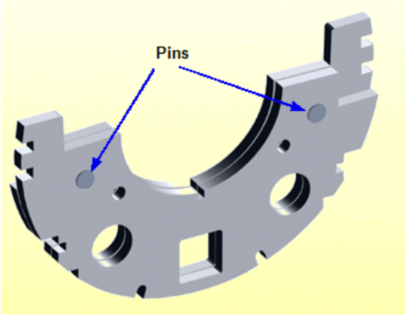
RHIC main dipole

- 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.

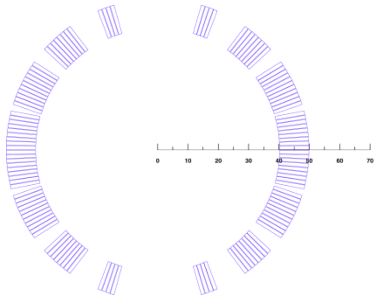


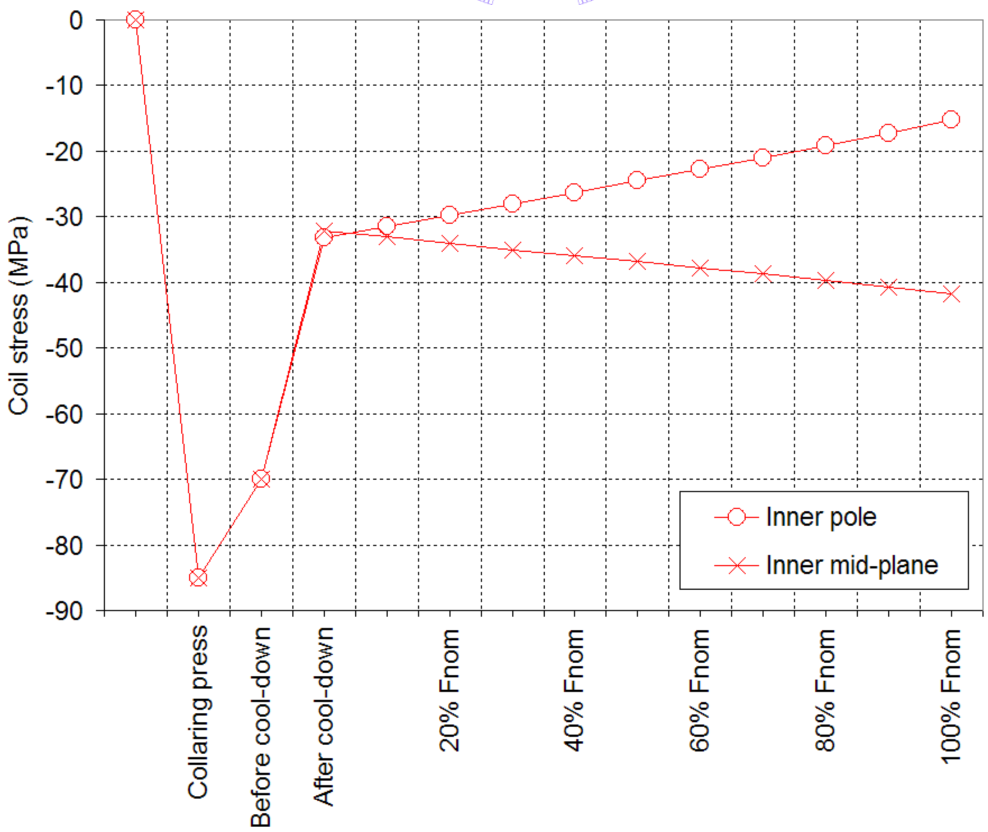
MJB Plus, Inc., [2]





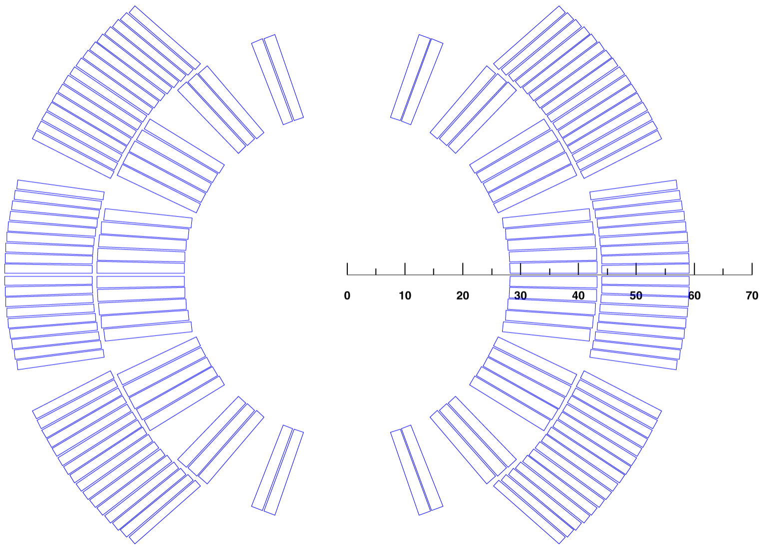
- Coil stress evolution
  - According to [10], after cool-down the coil is pre-compressed to about 35 MPa.
  - Pre-stress is lost during assembly and cool-down.
  - By computing the coil response in a infinitely rigid structure, it appears that the coil pole remains always in contact with the collar during excitation, with a margin of about 15 MPa in compression.

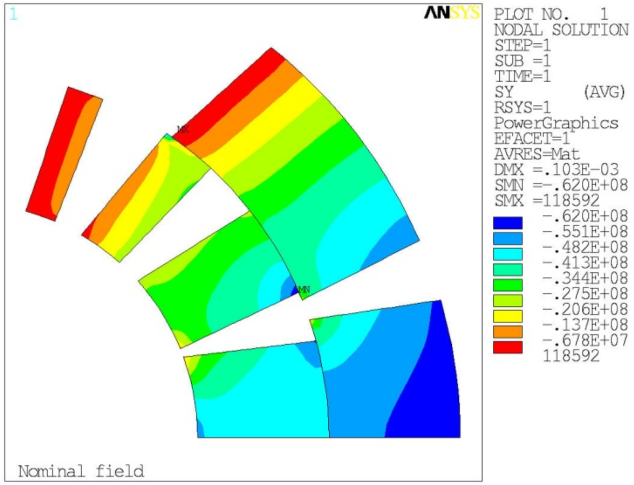




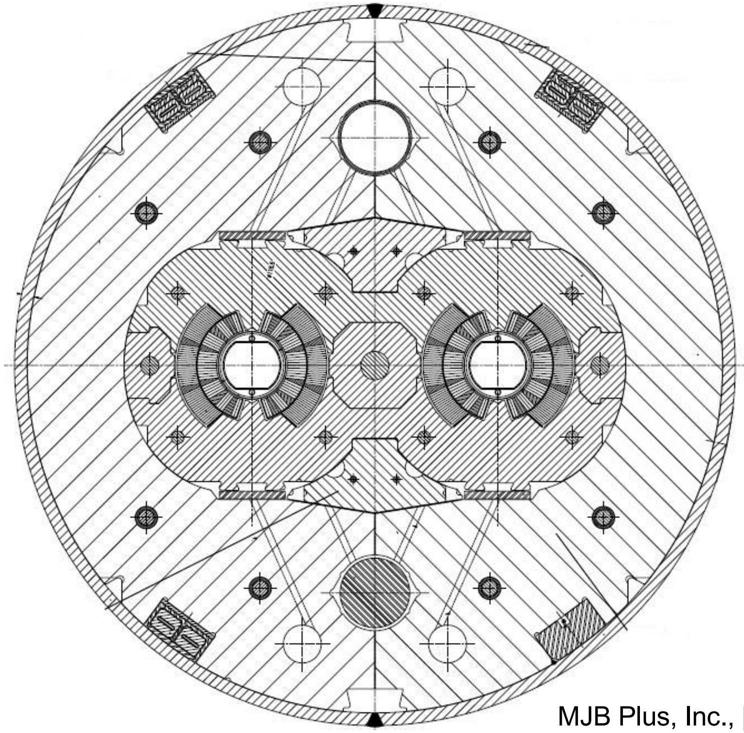
LHC main dipole

- B_{nom} = 8.33 T
- Force at B_{nom}
  - F_{x_layer1} = + 1117 kN
  - F_{x_layer2} = + 532 kN
  - F_{y_layer1} = - 160 kN
  - F_{y_layer2} = - 675 kN
- Stored energy (1 aperture) at B_{nom}
  - E = 265 kJ/m
- Axial force (1 aperture) at B_{nom}
  - $F_{z\_}$ = 265 kN
- Average mid-plane stress at B_{nom} (assumptions: infinitely rigid structure and no pre-stress)
  - σ_{θ_layer1} = - 46 MPa
  - σ_{θ_layer2} = - 57 MPa

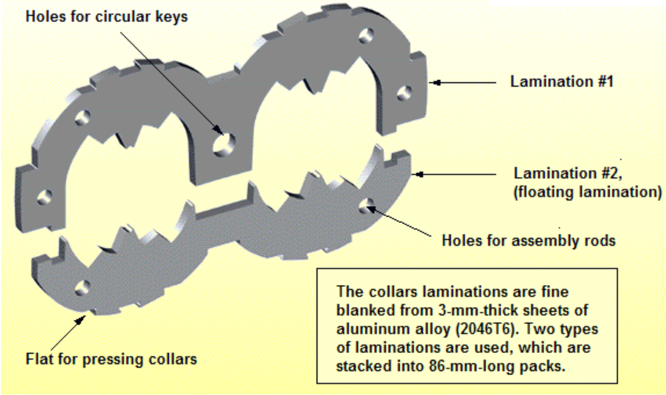




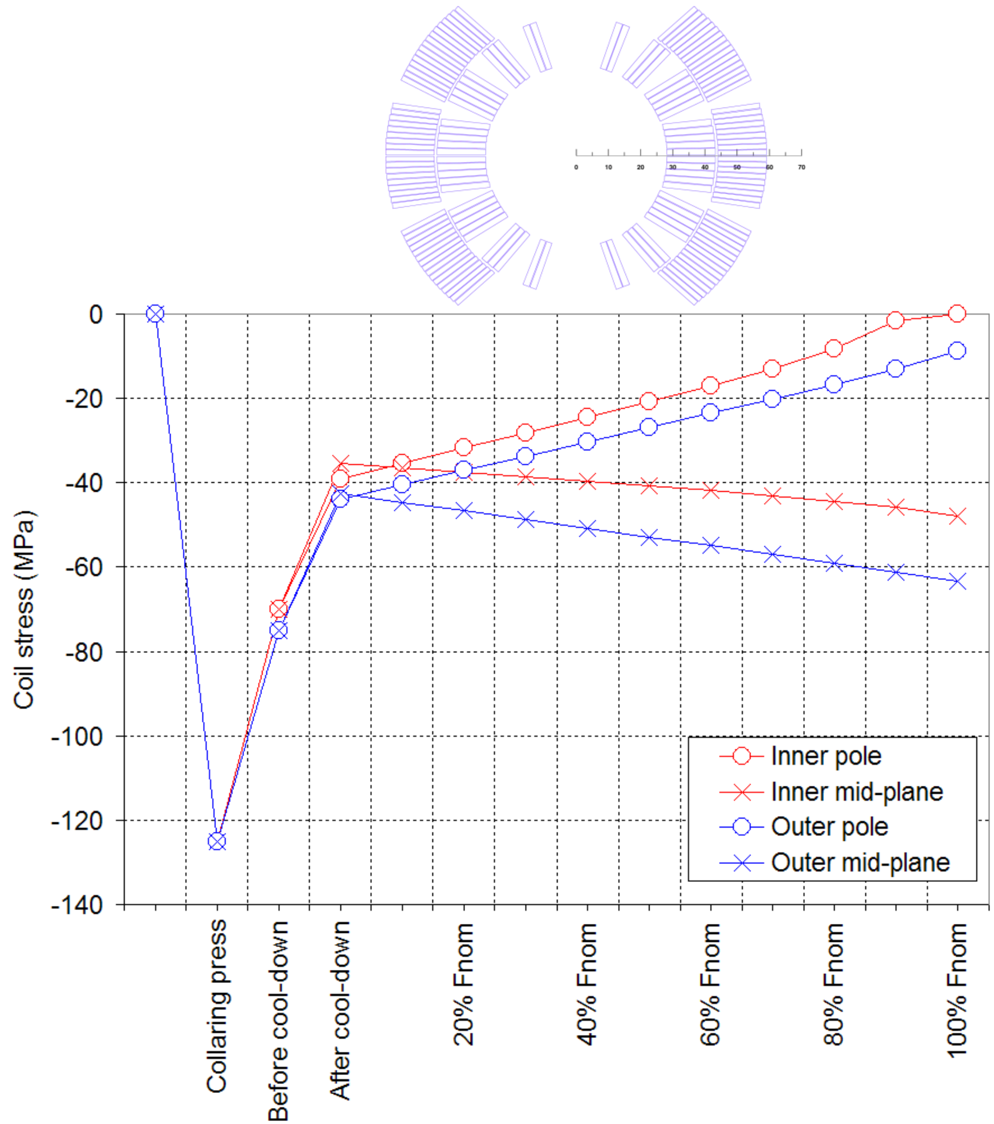
- Two-in-one configuration
  - Both beam pipes are contained within one cold mass
- Stainless steel collars are locked by three full-length rods.
- Magnetic insert
  - It transfers vertical force from the yoke to the collared coils
  - It improves field quality
- Iron yoke vertically split
  - At the 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.



MJB Plus, Inc., [2]

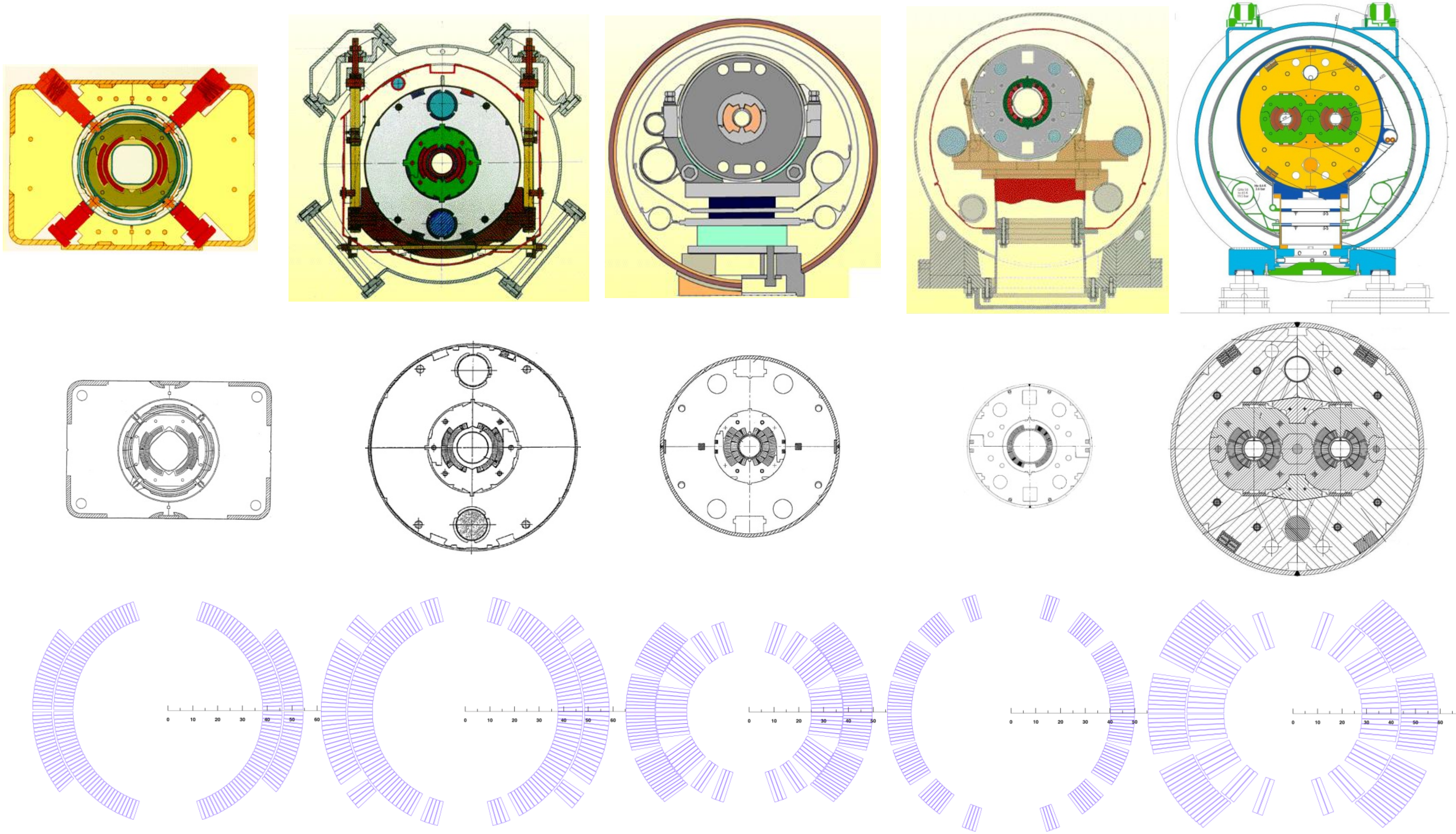


- Coil stress evolution
  - According to [11], after cool-down the coil is pre-compressed to about 40 MPa.
  - Pre-stress is lost during assembly and cool-down.
  - By computing the coil response in a infinitely rigid structure, it appears that the coil pole remains (almost) always in contact with the collar during excitation.



Overview of accelerator dipole magnets

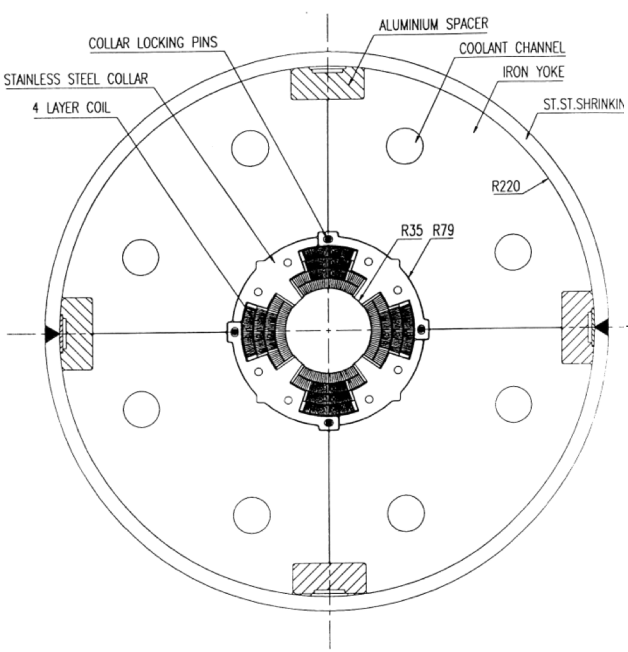
Tevatron HERA SSC RHIC LHC



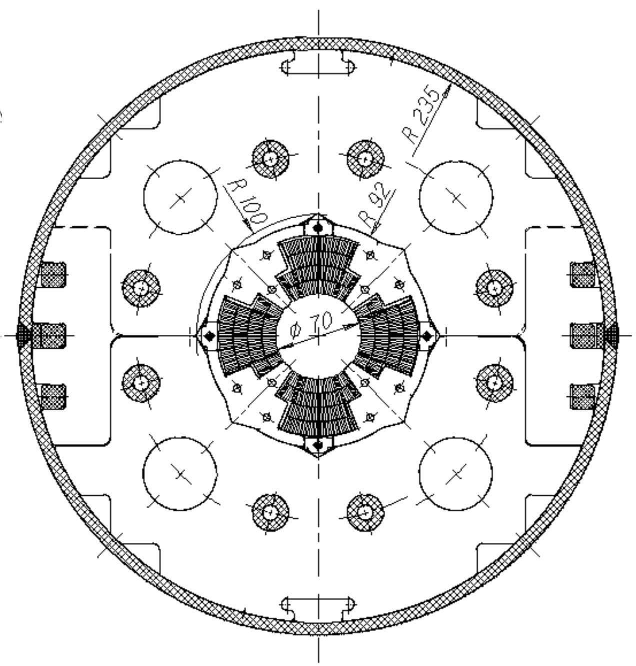
Practical examples of accelerator magnets LHC IR quadrupole

- 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.

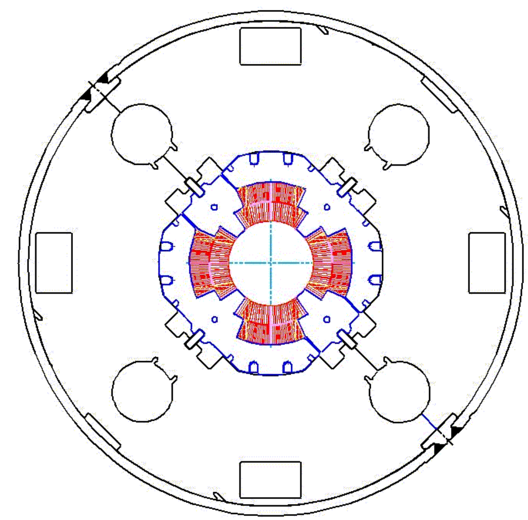
CERN-Oxford Inst. (MQY)



KEK (MQXA)

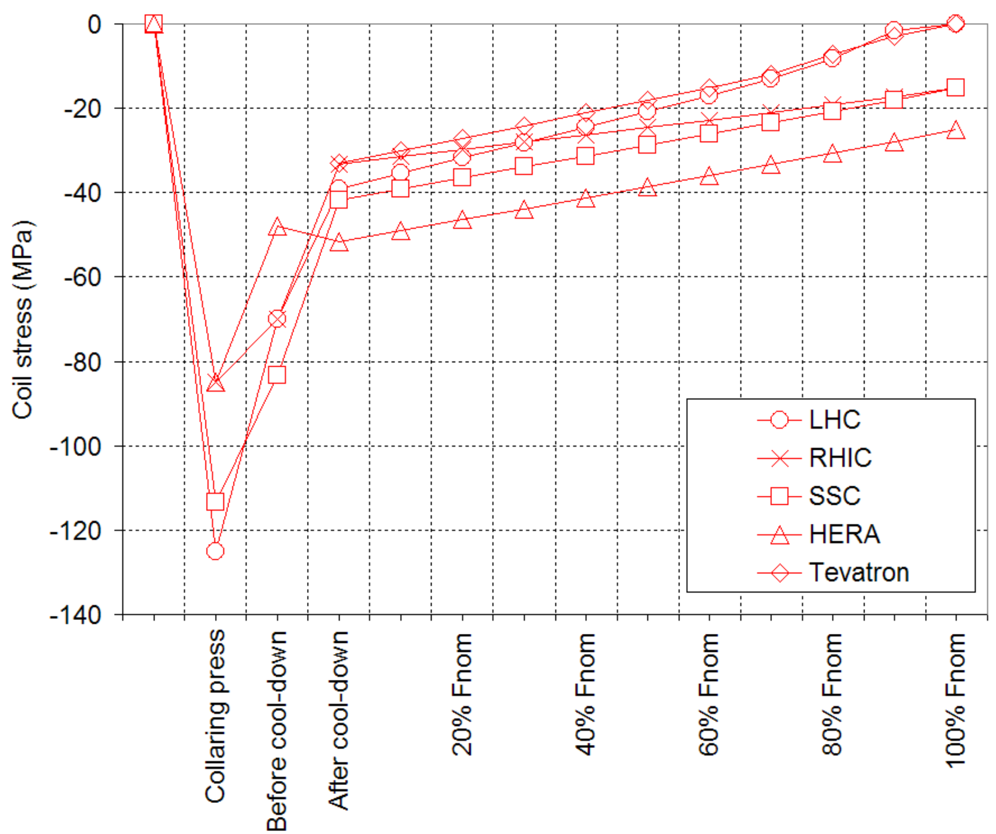


Fermilab (MQXB)



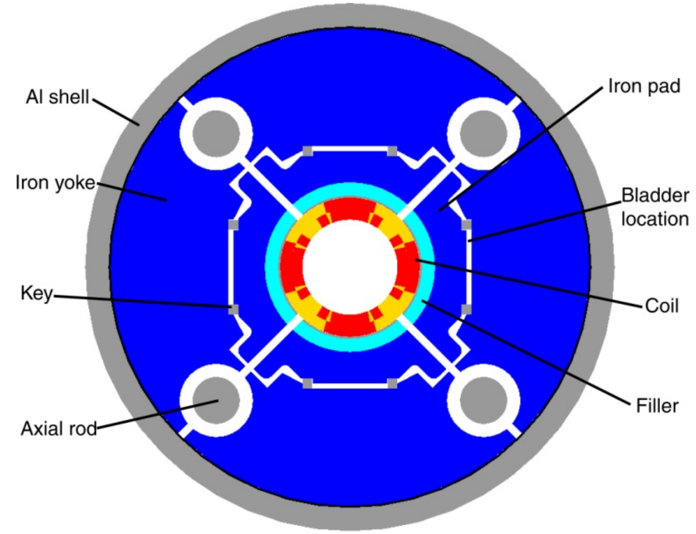
L. Rossi, [1]

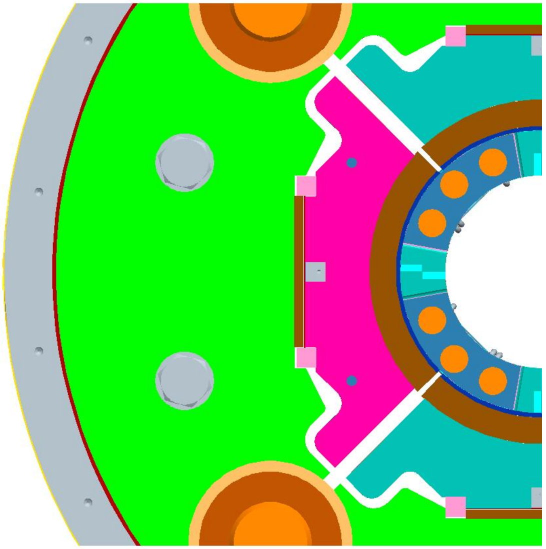
- All the structures presented so far are characterized by significant coil pre-stress losses
  - The coil reaches the maximum compression (about 100 MPa) during the collaring operation.
  - After cool-down the residual pre-stress is of about 30-40 MPa.
- What if the “required” coil pre-stress after cool-down is > 100 MPa?



Practical examples of R&D magnets
TQS

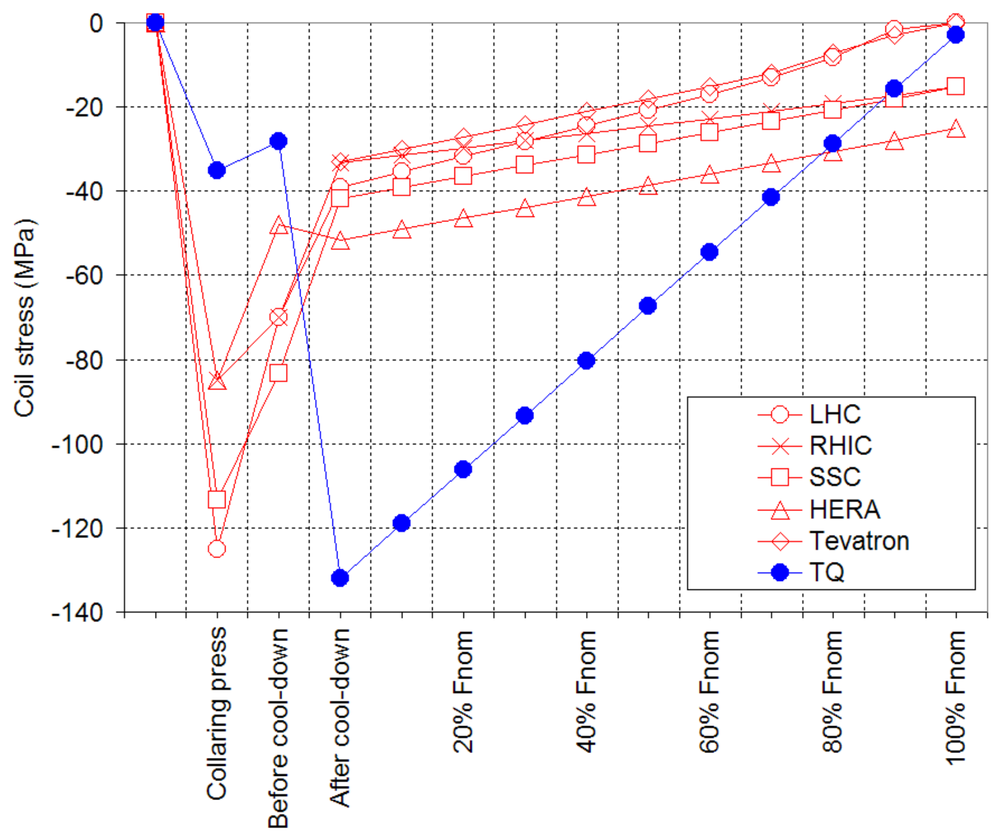
- The coil is surrounded by four pads and four yokes
  - Pad and yoke gaps remain open during all the magnet operations.
- An aluminum shell contains the cold mass.
- Initial pre-compressions is provided by bladders and locked by keys.
- After cool-down the coil pre-stress increases due to the high thermal contraction of the aluminum shell.



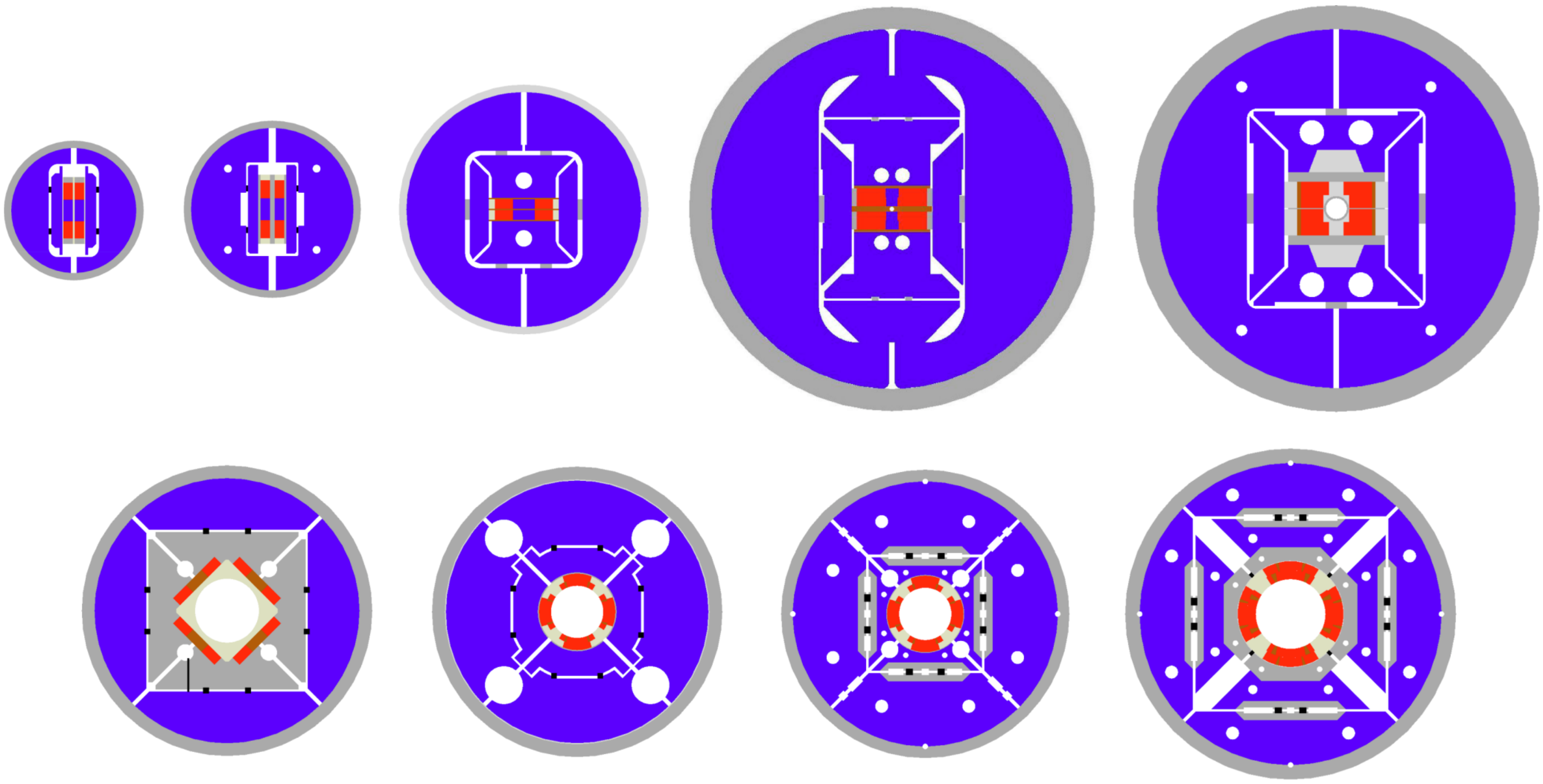


Practical examples of R&D magnets TQS

- In the TQS case, the collaring press operation is substituted by the bladder operation.
- A spring back occurs when bladder pressure is reduced
  - Clearance for key insertion
- The coil pre-stress significantly increases during cool-down.

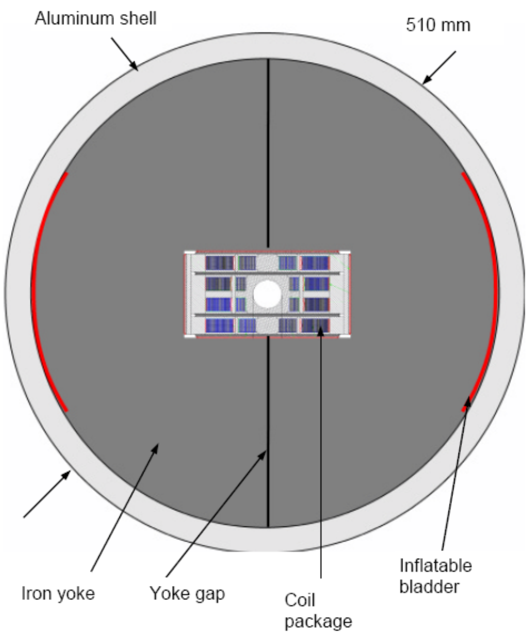


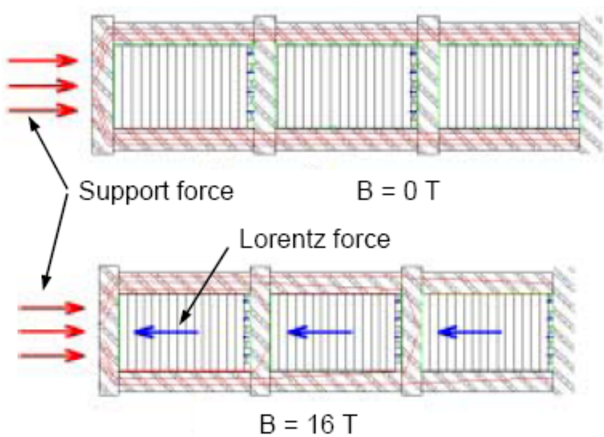
Shell-based support structures

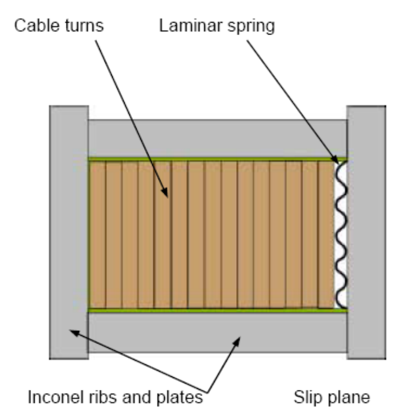


Practical examples of R&D magnets
TAMU (Texas A&M)

- "Stress management" system
  - Each coil block is isolated in its own compartment and supported separately.
  - E.m. force exerted on multiple coil blocks does not accumulate, but it is transmitted to the magnet frame by the Inconel ribs to Inconel plates.
  - A laminar spring is used to preload each block.







C.L. Goodzeit, [11]

Paper by D.I. Meyer and R. Flasck in 1970

(D.I. Meyer, and R. Flasck “A new configuration for a dipole magnet for use in high energy physics application”, Nucl. Instr.and Methods 80, pp. 339-341, 1970.)

A NEW CONFIGURATION FOR A DIPOLE MAGNET FOR USE IN HIGH ENERGY PHYSICS APPLICATIONS*

D. I. MEYER and R. FLASCK

Physics Department, University of Michigan, Ann Arbor, Michigan 48104, U.S.A.

Received 16 December 1969

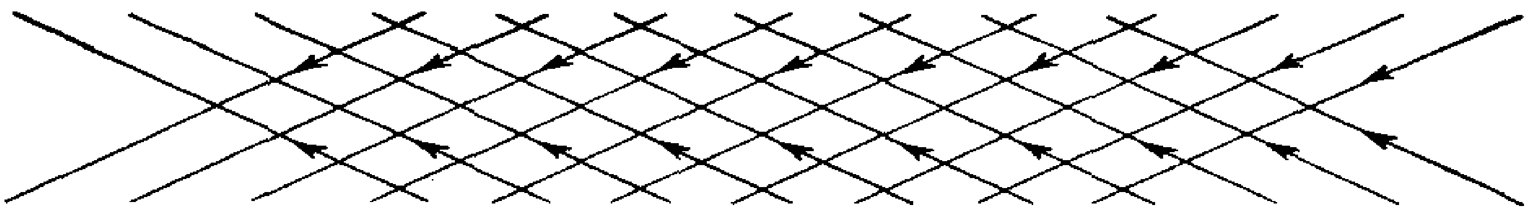
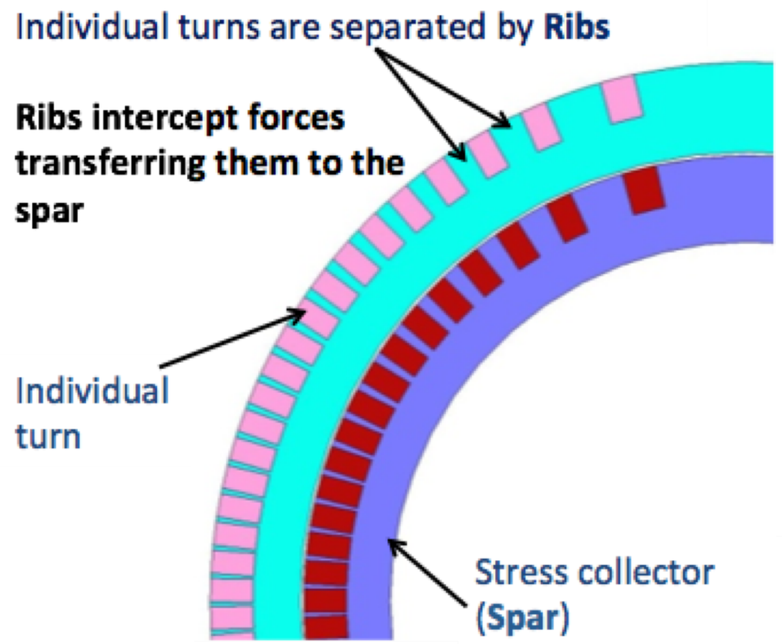


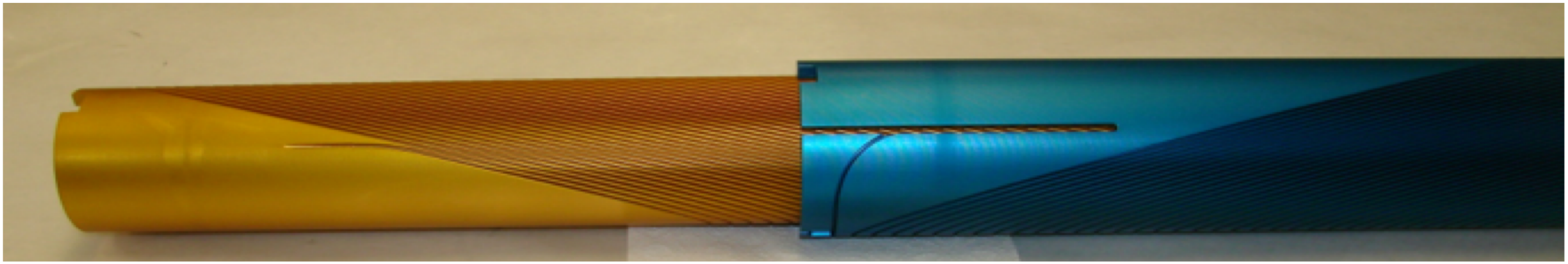
Fig. 2. Two superimposed coils with opposite skew.

Renewed interest during the past decade

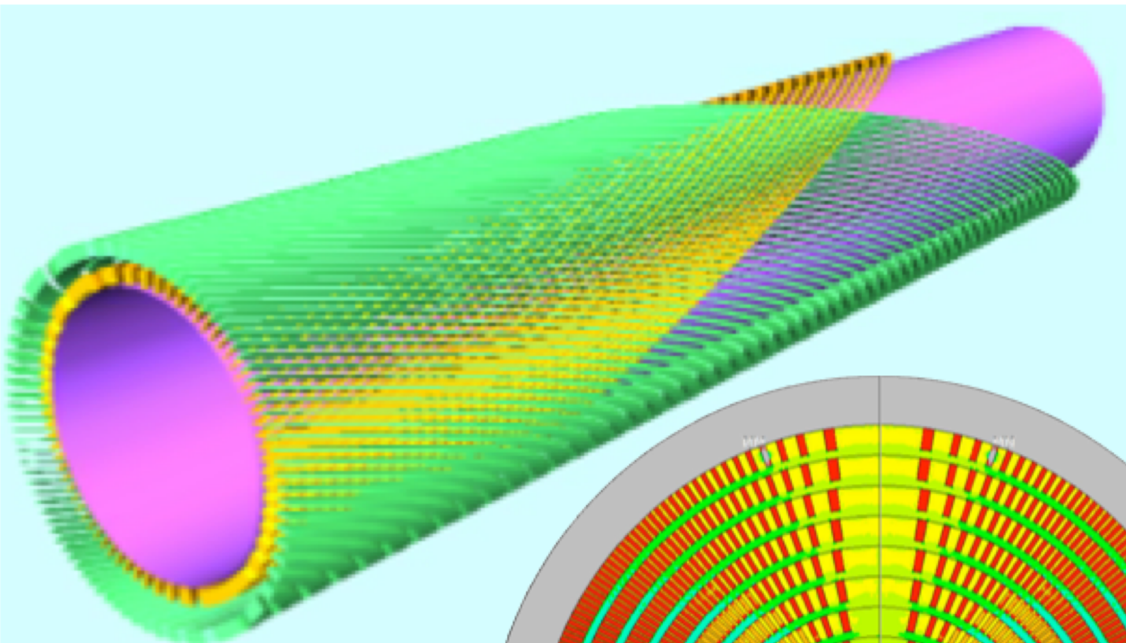
Practical examples of R&D magnets
Canted-Cosine Theta (CCT)

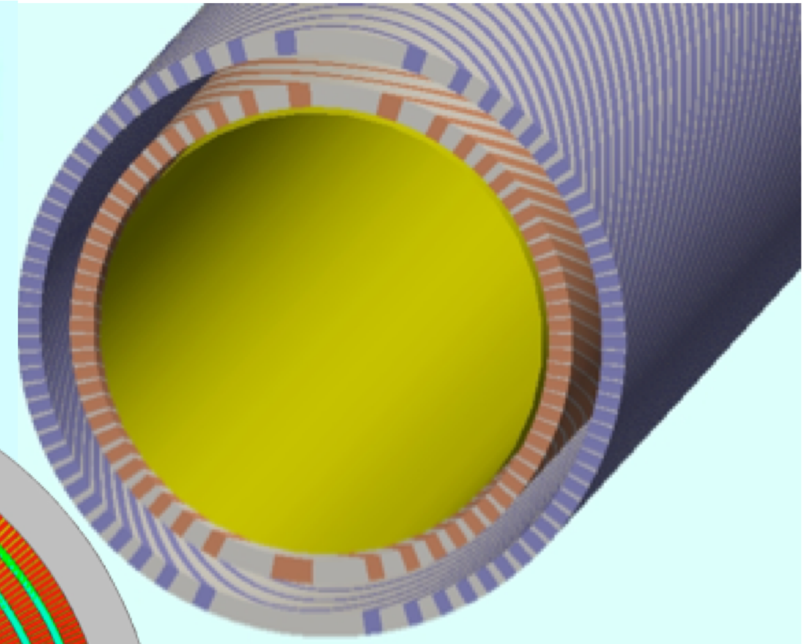
- **Key characteristics we want:**
  - *Remove the stress barrier*
  - *Incorporate grading for efficiency*
  - *Reasonable bore diameter for shielding*
  - *Scalable design allowing industrialization*

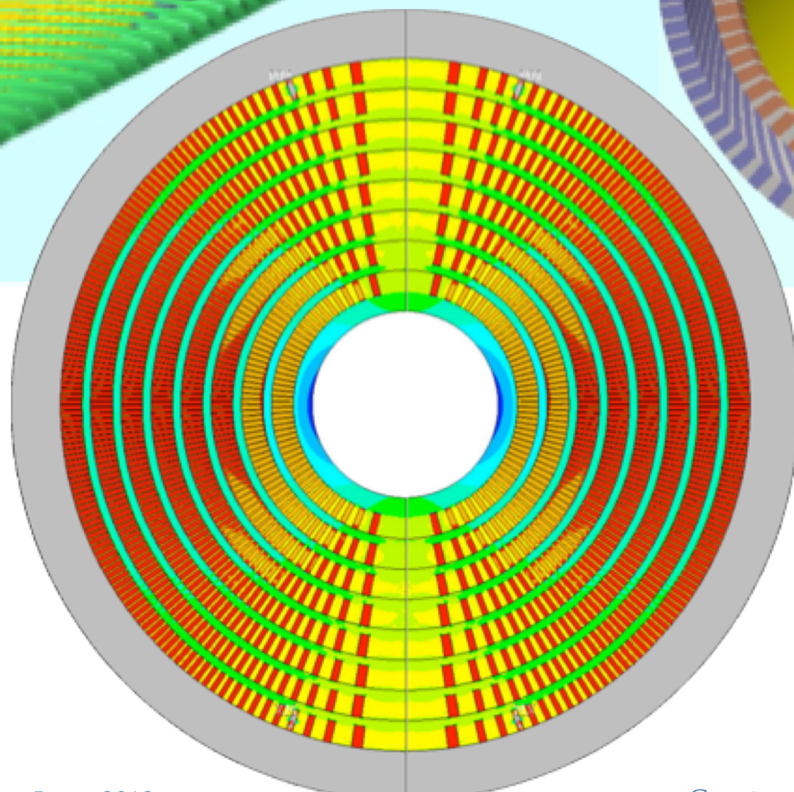




Practical examples of R&D magnets
Canted-Cosine Theta (CCT)





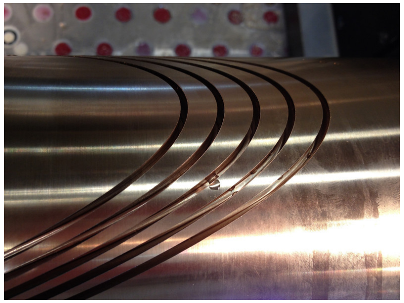


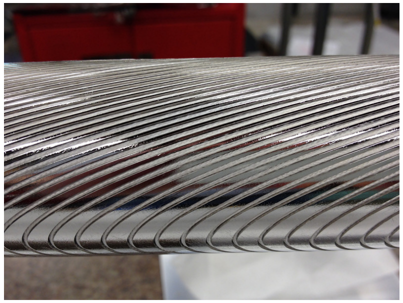
Cos(θ) distribution:
⇒*excellent field quality*
⇒*B_{cond}~B_0*

Stress interception
⇒*avoid force build-up*
⇒*reduce conductor stress*

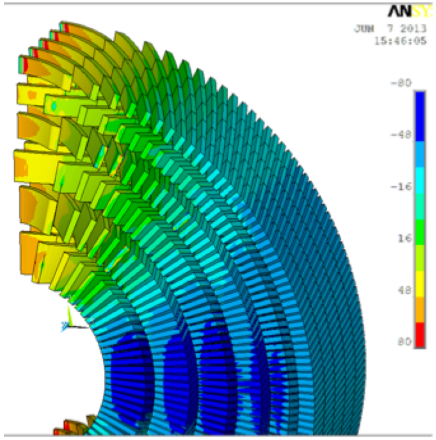
Practical examples of R&D magnets Canted-Cosine Theta (CCT)

- Stress is captured by rib, transferred to mandrel
  - *No accumulation of stress on the mid plane*
  - *No stress issue with larger bore*
- Every layer can use different cable size
  - *Allows near optimal grading for conductor efficiency*
    - *Significant saving in Nb_3Sn over Cos(θ) designs*
- Conductor mass scales with bore radius only
- Excellent field quality ("for free")
- Fabrication:
  - *Minimal external structure*
  - *No spacers, end parts, etc.*
  - *Simple winding ➪ Industrialization*

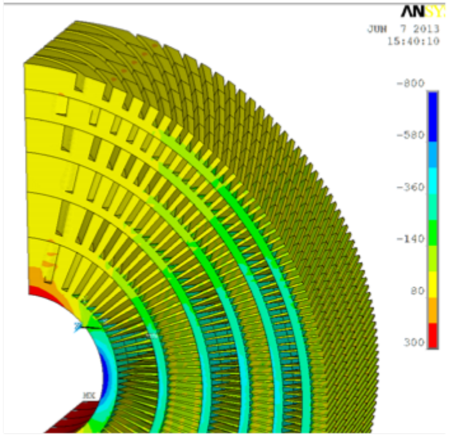




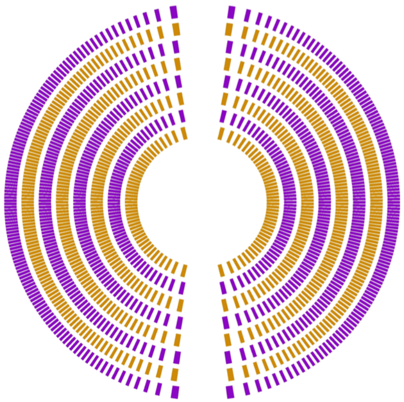
Coil stresses

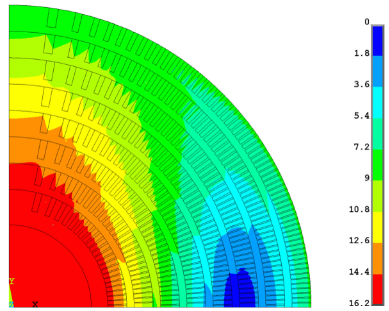


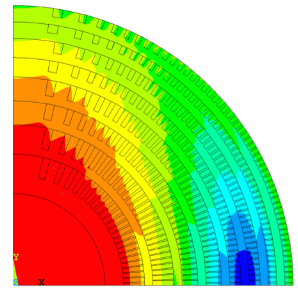
Structure stresses

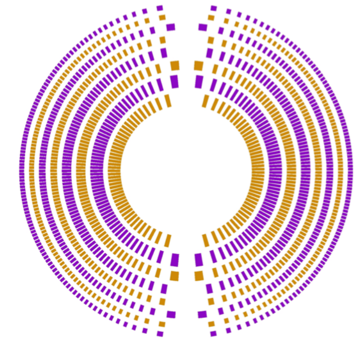


Practical examples of R&D magnets
Canted-Cosine Theta (CCT)

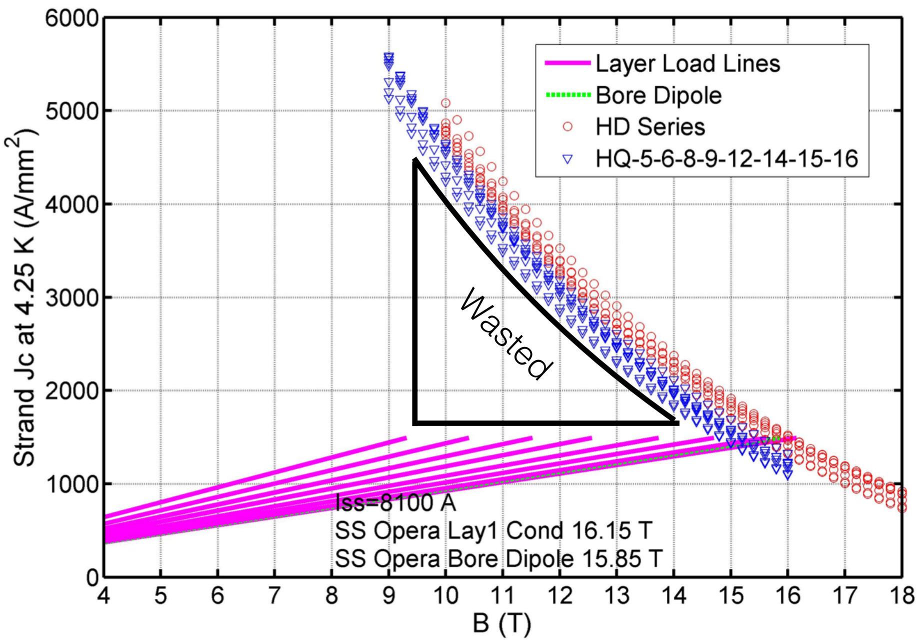


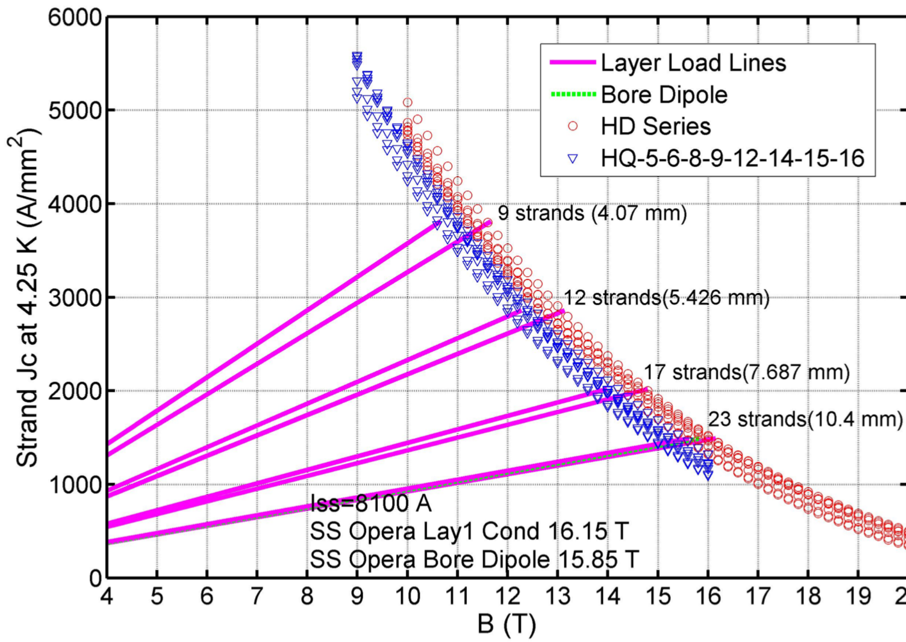






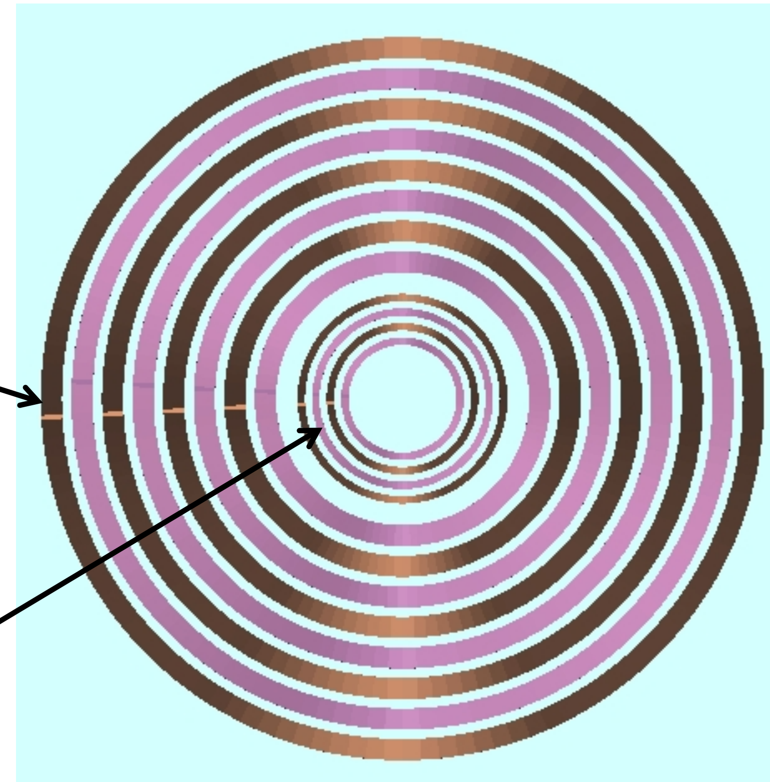
Un-graded Minimize conductor – and cost! *Graded*



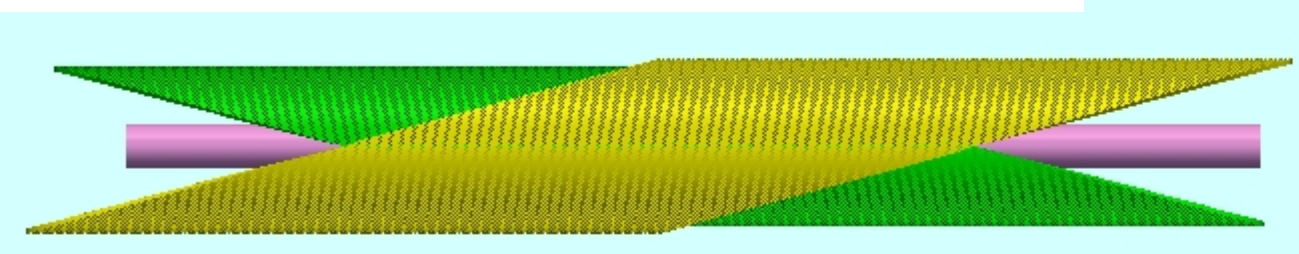


Practical examples of R&D magnets
Canted-Cosine Theta (CCT)

8 layers of Nb_3Sn



4 layers of HTS



Summary

- The main features of magnet support structures was presented
  - Most accelerator magnets are based on collars and a shrinking cylinder
    - This kind of structure guarantees good control of conductor position and coil alignment.
- Coil stress evolution is a critical element of magnet structure design
  - Significant pre-stress losses occur from collaring to excitations, but no separation takes place between coil and collars in the pole region.
- Alternative designs have been presented
  - Bladder and key structure
    - Increase of stress during cool-down
  - Structures that minimize stress accumulation
    - TAMU compartmentalization
    - Canted-Cosine Theta (CCT) structure

Acknowledgement

Thanks (again) to Paolo Ferracin for many of these slides.

References

[1] L. Rossi, "*Superconducting Magnets*", CERN Academic Training, 15-18 May 2000.
[2] MJB Plus, Inc. "*Superconducting Accelerator Magnets*", an interactive tutorial.
[3] S. Wolff, "*Superconducting magnet design*", AIP Conference Proceedings 249, edited by M. Month and M. Dienes, 1992, p. 1160-1197.
[4] L. Rossi, "*The LHC from construction to commisioning*", FNAL seminar, 19 April 2007.
[5] P. Schmuser, "*Superconducting magnets for particle accelerators*", AIP Conference Proceedings 249, edited by M. Month and M. Dienes, 1992, p. 1100-1158.
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