EASISchool 3

5th October 2020

Superconducting dipoles and quadrupoles for accelerators

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European Organization for Nuclear Research (CERN TE-MSC)
Based on USPAS lecturers from Paolo Ferracin, Soren Prestemon,
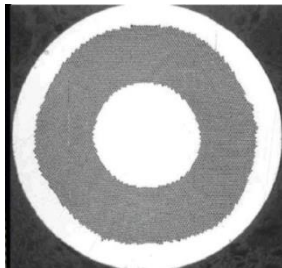Ezio Todesco and Helene Felice

Goal of the course

- Overview of superconducting magnets for particle accelerators (dipoles and quadrupoles)
  - Conductor
  - Magnetic design

    Stefania Farinon
  - **Mechanical design**
  - Quench protection

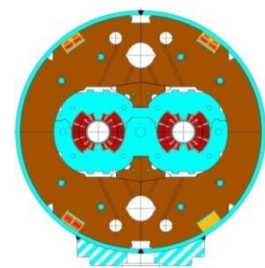   Susana Izquierdo Bermudez

Superconducting strand

Superconducting cable

Superconducting coil

Superconducting magnet

Outline

- Force

- Stress and strain

- Pre-load

- Support structures

  - Structures based on collars

  - Structures based on iron yoke

  - Structures based on aluminum shell

  - Other structures for stress management

  - Structures for axial support

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Mechanical design

- 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 **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 **f_L** [N/m^3]

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

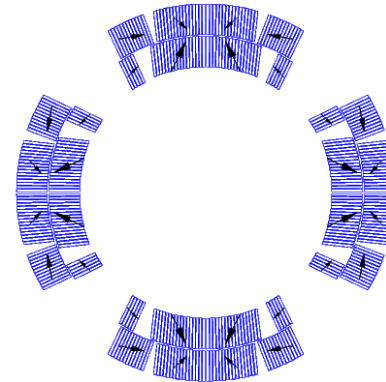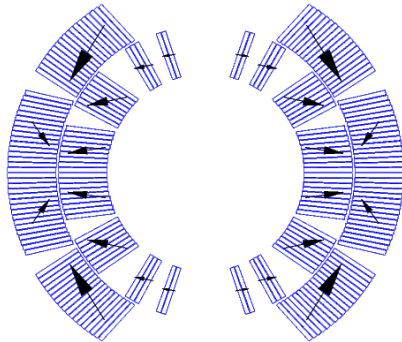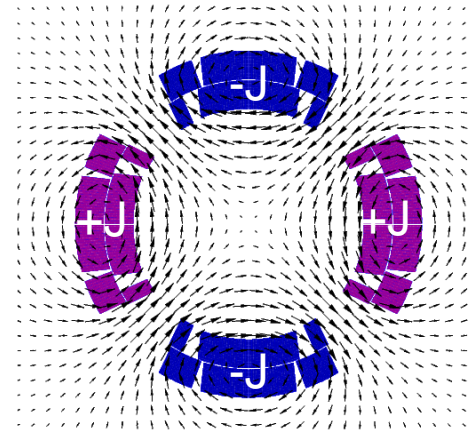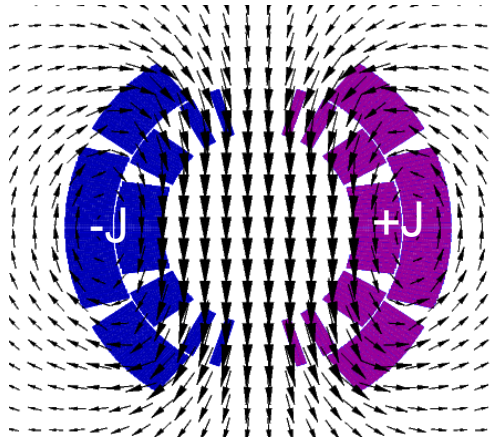Some examples (values per aperture):

Nb-Ti LHC MB (8.3 T)
- F_x = **340 t** per meter
  - ~300 compact cars
- F_z = **27 t**

Nb$_3$Sn DS dipole (11T)
- F_x = **620 t** per meter
- F_z = **47 t**

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Electro-magnetic force

- The e.m forces in a dipole/quadrupole magnet tend to push the coil
  - Towards the mid-plane in the azimuthal direction
  - Outwards on the radial direction.

Electro-magnetic force

- In the coil ends, the electromagnetic forces tend to push the coil outwards in the longitudinal direction ($F_z > 0$)

Fz

Fz

Fz

Fz

11 T dipole for HL-LHC

MQXF quadrupole for HL-LHC

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Electro-magnetic force

- The x/y e.m. force on a dipole coil varies
  - with the square of the bore field
  - Linearly with the bore radius (a)

$$F_x = \frac{B_y^2}{2\mu_0} \frac{4}{3} a \qquad\qquad F_y = -\frac{B_y^2}{2\mu_0} \frac{4}{3} a$$
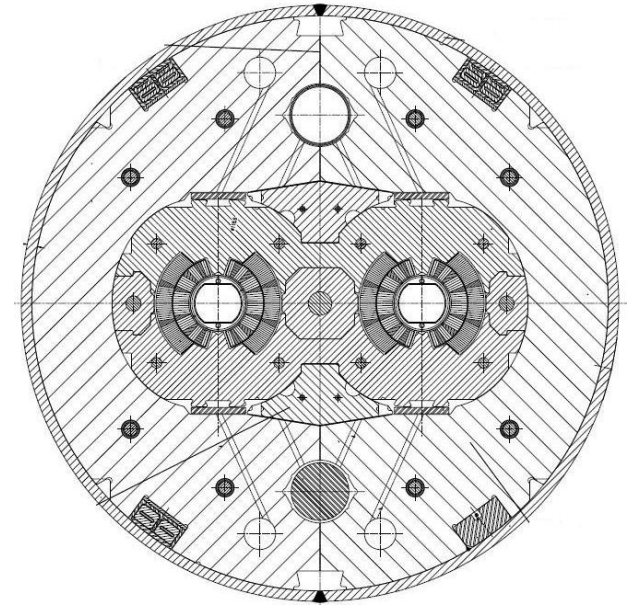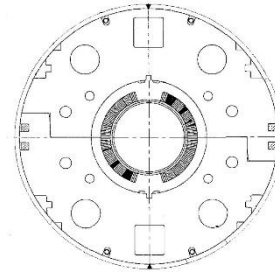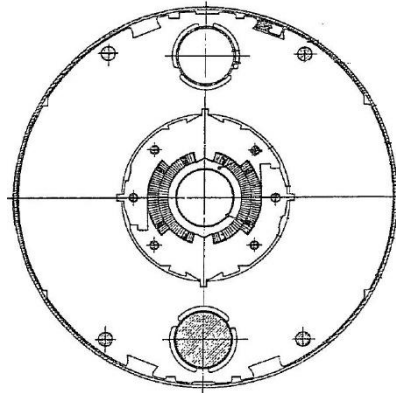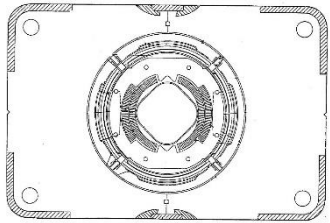
Approximation of thin shell dipole, see how to derive the equations in [2]

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

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

See how to derive the equation in [2]

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Superconducting dipoles (of the past)

Tevatron	**HERA**	**RHIC**	**LHC**
1983-2011	1991-2007	2000-running	2008-running
Bore: 76 mm	Bore: 75 mm	Bore: 80 mm	Bore: 56 mm
Field: 4.3 T	Field: 5.0 T	Field: 3.5 T	Field: 8.3 T
F_x = 0.5 MN/m	F_x = 0.6 MN/m	F_x = 0.3 MN/m	F_x = 1.7 MN/m
F_z = 78 kN	F_z = 87 kN	F_z = 48 kN	F_z = 265 kN

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Superconducting dipoles (past & future)

Lorentz forces in the plane of a thin coil of radius R_{in} generating a dipole field B (thin shell approximation), referred to a coil quarter

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

From L. Bottura
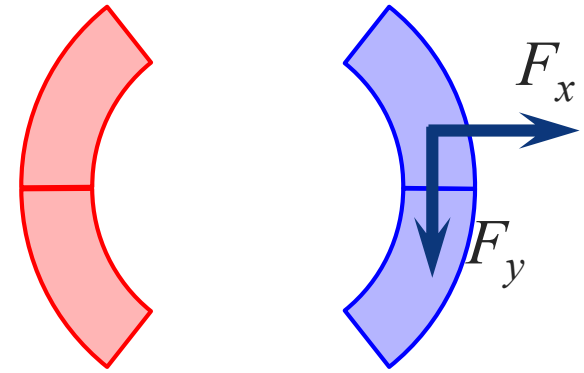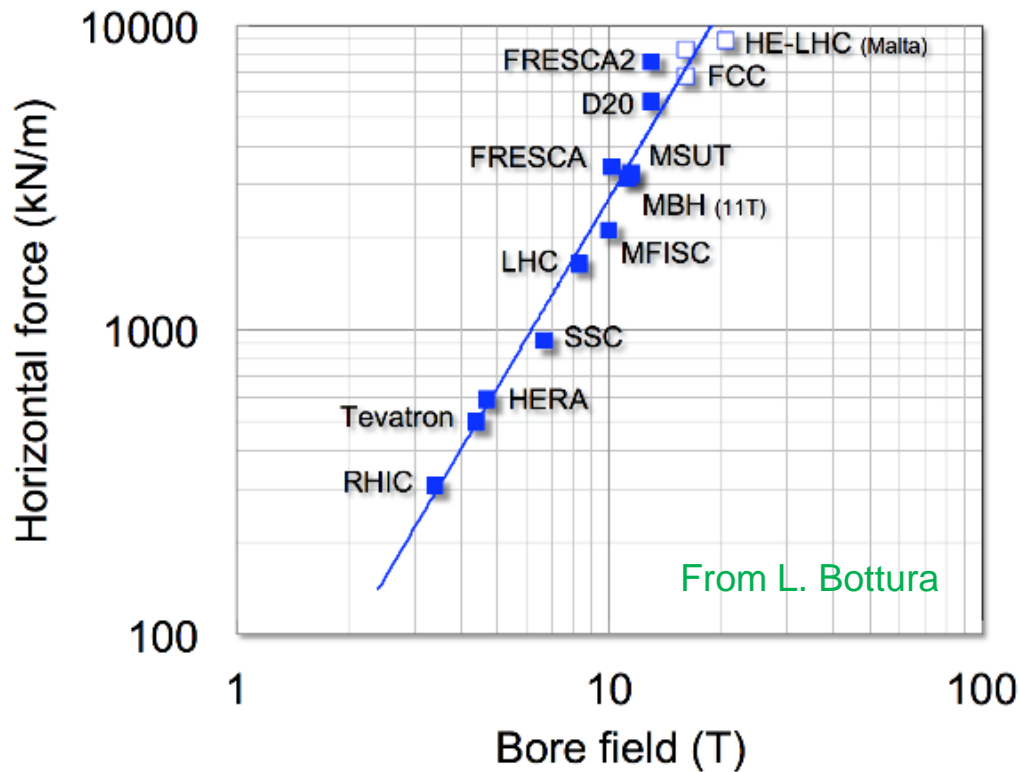
Progression of F_x:
LHC MB(8.33T) ≈ 1.7 MN/m
LHC MBH(11T) ≈ 3.2 MN/m
FRESCA2(13T) ≈ 7.6 MN/m
FCC MB(16T) ≈ 8 MN/m
HE-LHC MB(20T) ≈ 10 MN/m
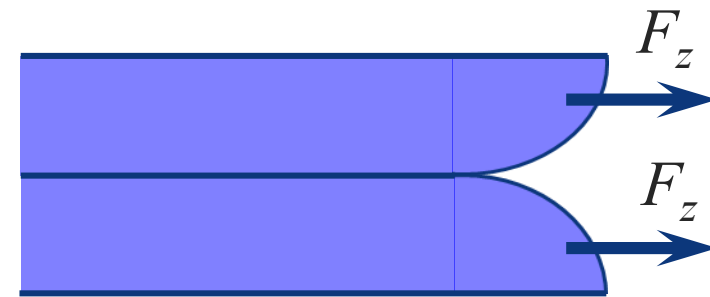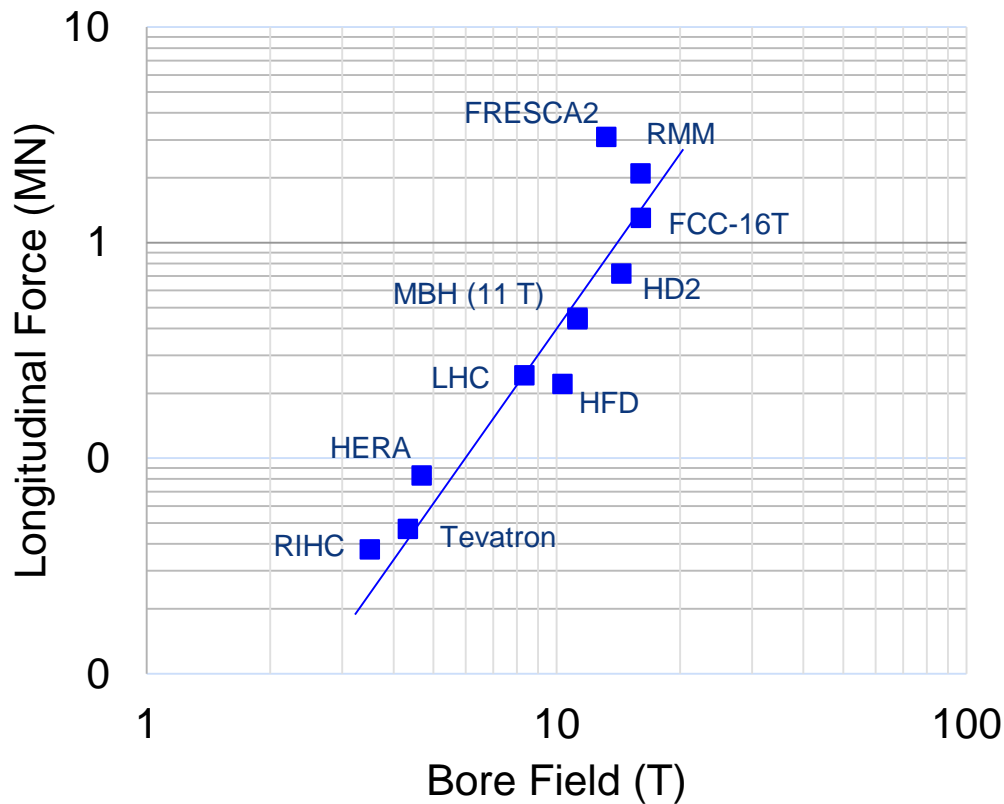
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Superconducting dipoles (past & future)

Lorentz forces in the plane of a thin coil of radius R_{in} generating a dipole field B (thin shell approximation), referred to a coil quarter

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

Progression of F_z:
LHC MB(8.33T) ≈ 0.24 MN
LHC MBH(11T) ≈ 0.45 MN
FRESCA2(13T) ≈ 3.1 MN
FCC MB(16T) ≈ 1.3 MN

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Outline

- Force
- Stress and strain
- Pre-load
- Support structures
  - Structures based on collars
  - Structures based on iron yoke
  - Structures based on aluminum shell
  - Other structures for stress management
  - Structures for axial support

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.
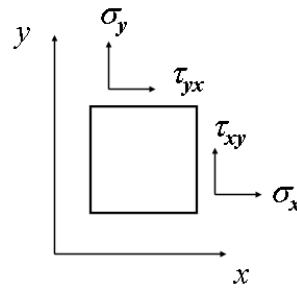
- A strain ε ($\delta l / l_0$) is a forced change dimension δl of a body whose initial dimension is l_0.

  - A stretch or a shortening are respectively a tensile or compressive strain; an angular distortion is a shear strain.

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Stress and strain - definitions

- The *Elastic modulus* (or Young modulus, or modulus of elasticity) E [Pa] is a parameter that defines the stiffness of a given material. It can be expressed as the rate of change in stress with respect to strain (Hook's law):

$$E = \sigma / \varepsilon$$

- The *Poisson's ratio* ν is the ratio between "axial" to "transversal" strain. When a body is compressed in one direction, it tends to elongate in the other direction. Vice versa, when a body is elongated in one direction, it tends to get thinner in the other direction.

$$\nu = -\varepsilon_{trans} / \varepsilon_{axial}$$
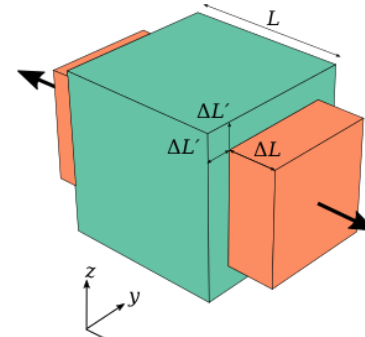
A cube with a Poisson's ratio of 0.5, courtesy of Wikipedia

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Stress and strain - definitions

- By combining the previous definitions, for a biaxial stress state we get

$$\varepsilon_x = \frac{\sigma_x}{E} - \nu\frac{\sigma_y}{E} \qquad\qquad \varepsilon_y = \frac{\sigma_y}{E} - \nu\frac{\sigma_x}{E}$$

and

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

- Compressive stress is negative, tensile stress is positive.
- The Poisson's ration couples the two directions
  - A stress/strain in *x* also has an effect in *y.*
- For a given stress, the higher the elastic modulus, the smaller the strain and displacement.

Deformation and stress

- 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$_3$Sn magnets: possible **conductor degradation** at about 150-200 MPa.
- All the components must be below stress limits.

LHC dipole at 0 T
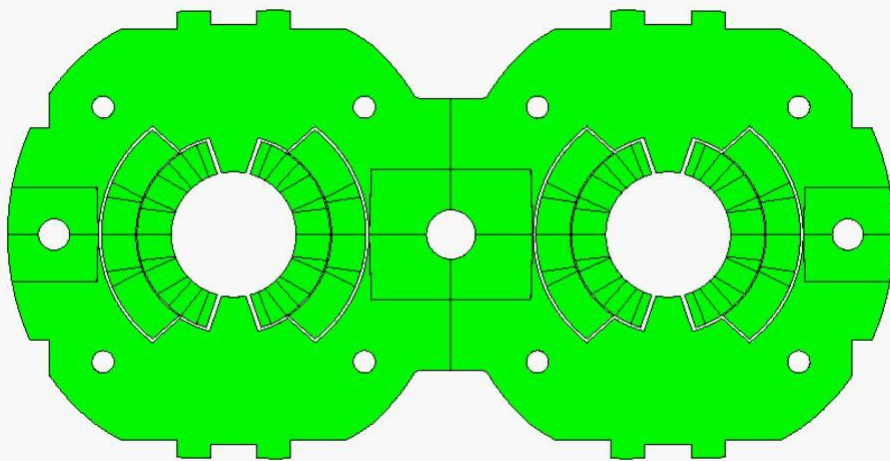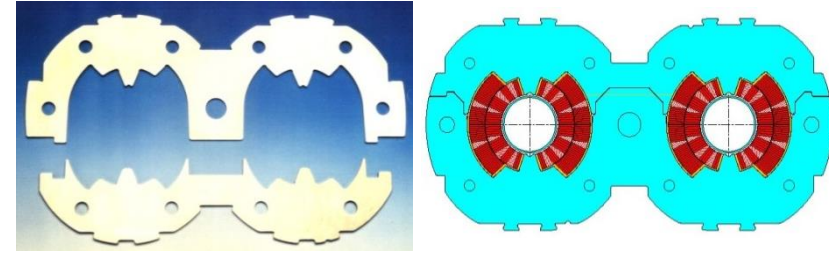
LHC dipole at 9 T
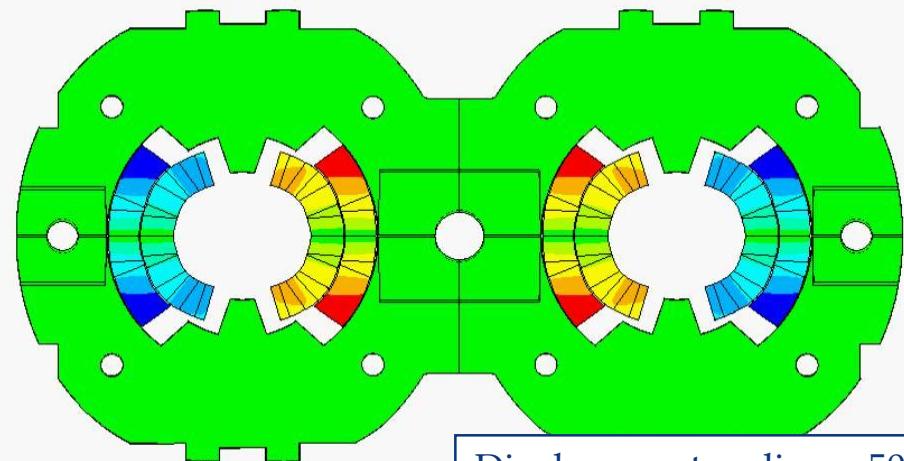
By P. Ferracin

Displacement scaling = 50
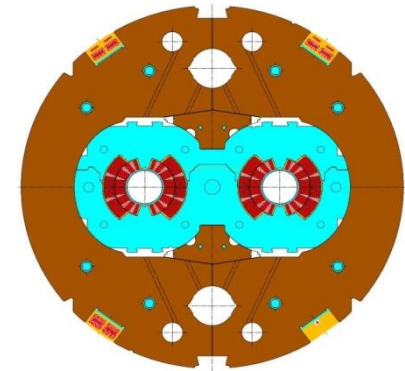
Overview of the coil stress

By P. Ferracin

1. **Collaring**: By clamping the coils, the collars provide
    *   coil **pre-stressing**;
    *   **rigid support** against e.m. forces
   *   **precise cavity**

2. **Yoking:** Ferromagnetic yoke around the collared coil provide
    *   Magnetic function
    *   Mechanical function (increase the rigidity of the coil support structure and limit radial displacement)
    *   Alignment, assembly features…

3. **Shell welding**: two half shells welded around the coil to provide
    *   Helium container
    *   Additional rigidity
    *   If necessary, the welding press can impose the desired curvature on the cold mass

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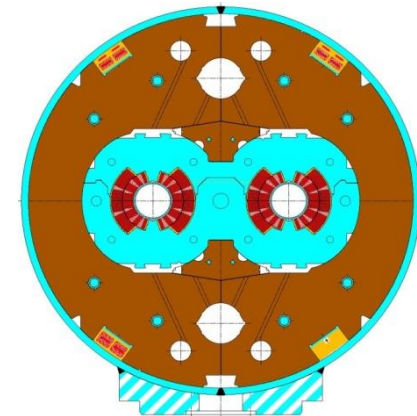
Overview of coil stress

4. Cool-down
- Components shrink differently
  - Again, coil positioning within 20-50 μm
- Significant **variations of coil stress**

5. Excitation
- The pole region of the coil unloads
  - Depending on the pre-stress, at nominal field the coil may unload completely

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).

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Pre-stress

- The prestress paradigm is that coil should never be in tension but always precompressed (as reinforced concrete)
- The initial reasons for this paradigm were field quality concerns: change of b_3 (A. Tollestrup, Ann. Rev. Sci. 1984, father of Tevatron magnets and collared structure)
- Later, it was believed that the detachment provokes training – and this is what many of us think still today

We are now in a position to discuss a difficult problem in magnet construction. If the azimuthal forces of the last section were allowed to act on a coil supported only in the radial direction, the coil would compress itself as it was excited and the angles of the shell would change. If these change symmetrically, a sextupole moment is induced and, if asymmetrically, quadrupole terms appear as well. The field is enormously sensitive to these angles—they must be maintained to an accuracy of ~ 25 μrad for adequate field quality. The forces are so large that, with the elastic modulus available in the insulated coil packages ($E = 10^6$ psi), the compression of the coil would far exceed this limit. As a result, when the coil is constructed, it is preloaded in the azimuthal direction to the extent that the elastic forces are greater than the magnetic forces. This ensures that the boundaries of the coil package will stay in contact with the collars during excitation. The Tevatron coils (18) were assembled in a large press, and the CBA magnets were bolted together with a similar pressure. Elastic motion of the coil relative to its support can still take place but at a much reduced level. (It is similar to fixing two ends of a loaded beam, compared to fixing only one end.) Elastic motion can also be reduced by making the elastic modulus high. The group at LBL has had successes in achieving $E \approx 4 \times 10^6$ psi, which is perhaps four times larger than achieved in the Tevatron magnet; the CBA coils had 2×10^6 psi.

Annu. Rev. Nucl. Part. Sci. 1984.34:247-284.

- The paradigm is always used in design and not always followed in reality
  - Typically, for the first models and prototypes one speaks of "conservative" loading, meaning that the preload is lower than what required to avoid pole unloading in operational conditions
  - The fear is to break something of degrade the conductor

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Pre-stress

This is the example of the MQXF and 11 T, the Nb_3Sn magnets for the HiLumi upgrade.

- Strain gauges placed in the pole in MQXF, in the collar nose in 11 T. They allow seeing the pole unload
- Estimated stress proportional to square of current (forces)
- The end of the linear region implies a pole unloading, i.e. that the coil at the pole is not compressed any more


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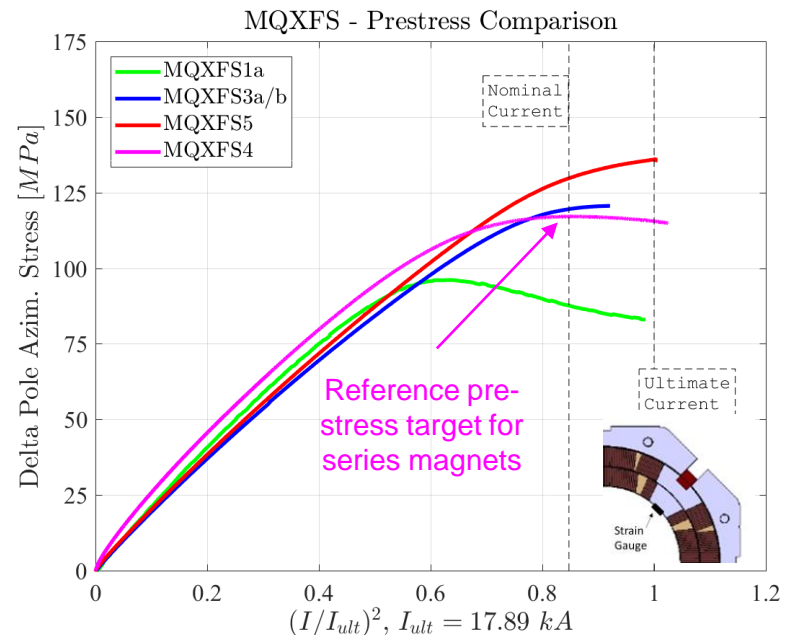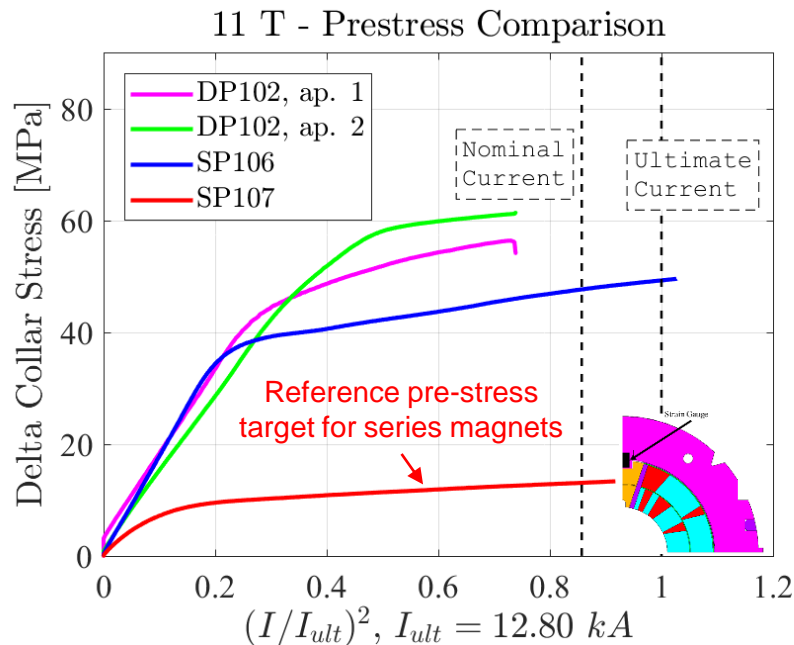
Pre-stress – MQXF example

- MQXFS6b reached the MQXF record of 19.1 kA, 93% of short sample at 1.9 K
  - Reassembled with much lower preload
  - Nominal without training, ultimate reached after retraining, and kept after thermal cycle
  - Very good indication of wide preload window, reproducibility of performance after reassembly and thermal cycle
  - Apparent plateau above ultimate may indicate that larger preload is beneficial to reach 90% of short sample

Training of MQXFS6b&6c
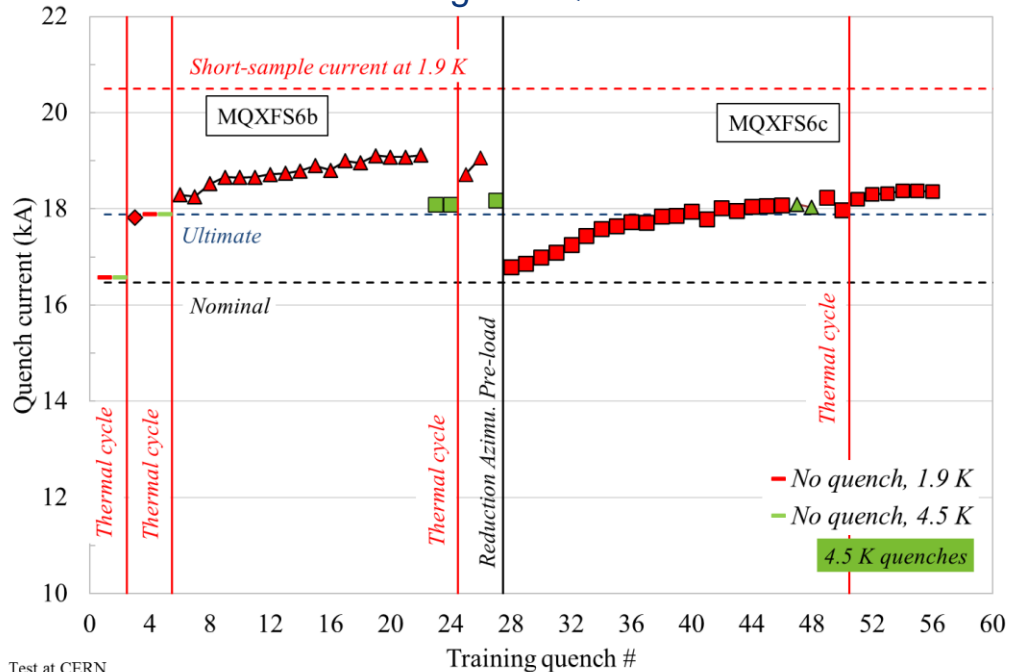
Unloading during powering of MQXFS6b&6c
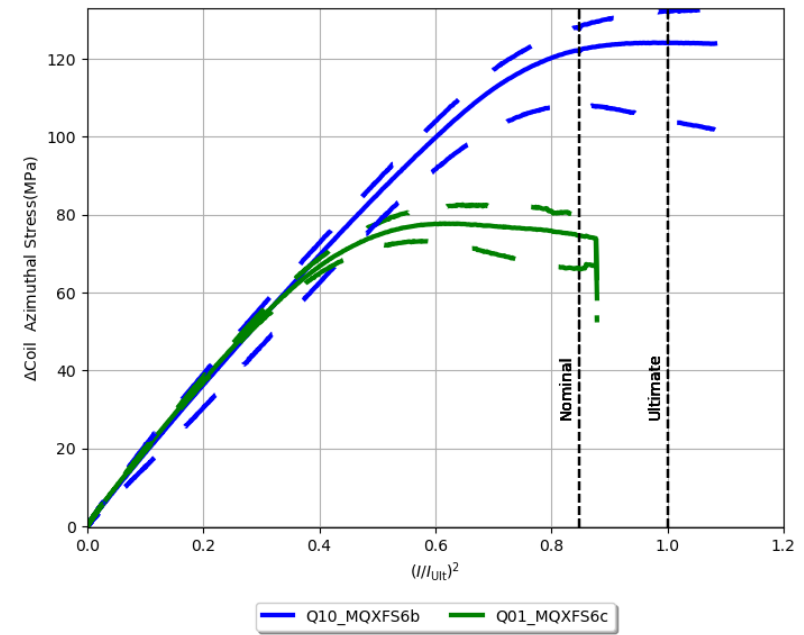

Test at CERN

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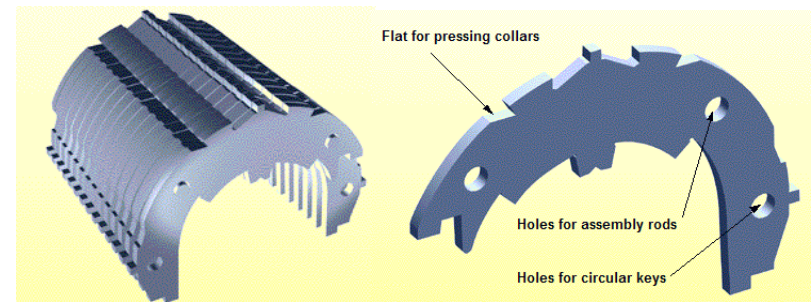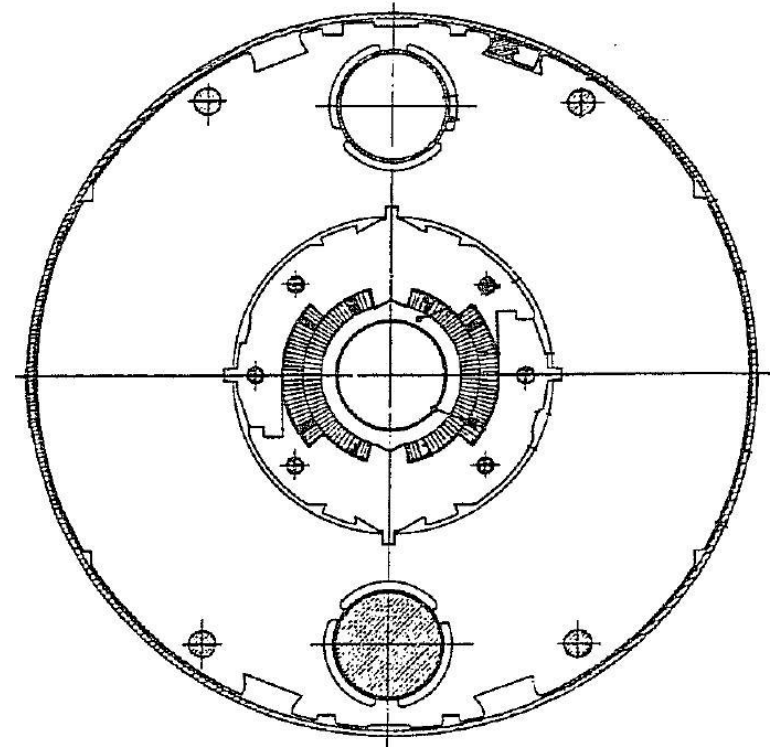 - Structures for axial support

Collars: 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., [1]

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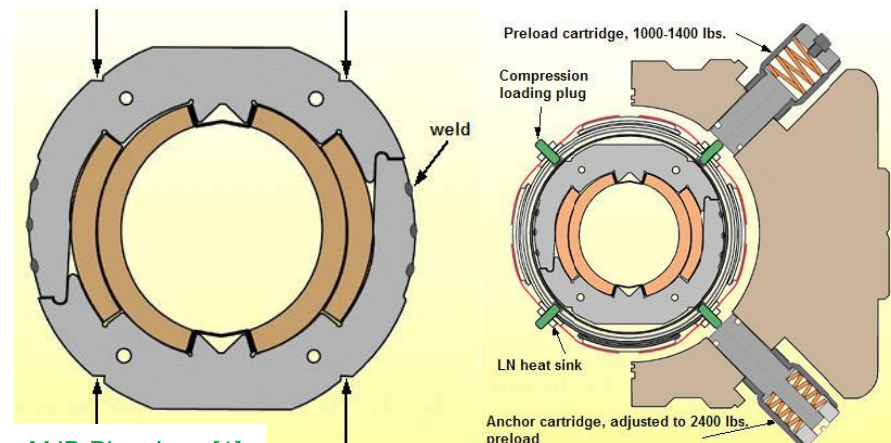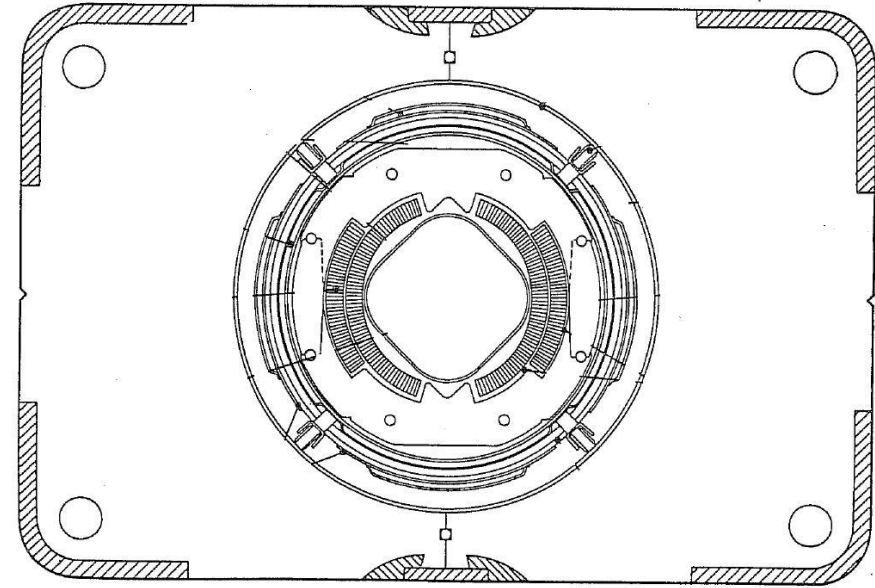
Collars: HERA main dipole

- 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).

Flat for pressing collars

Holes for assembly rods

Holes for circular keys

MJB Plus, Inc., [1]

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Collars: SCC 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.
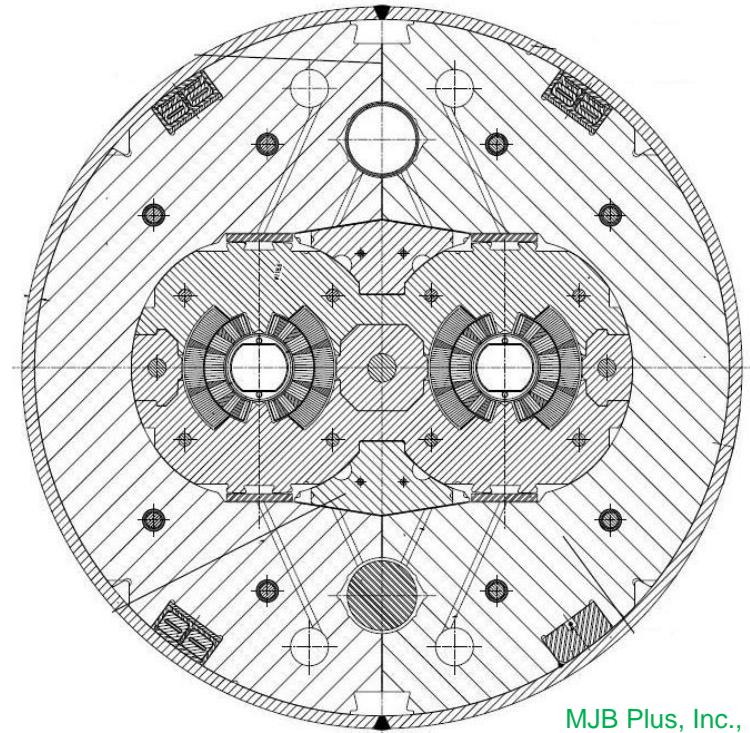

MJB Plus, Inc., [1]

Spot weld

Notches for pressing
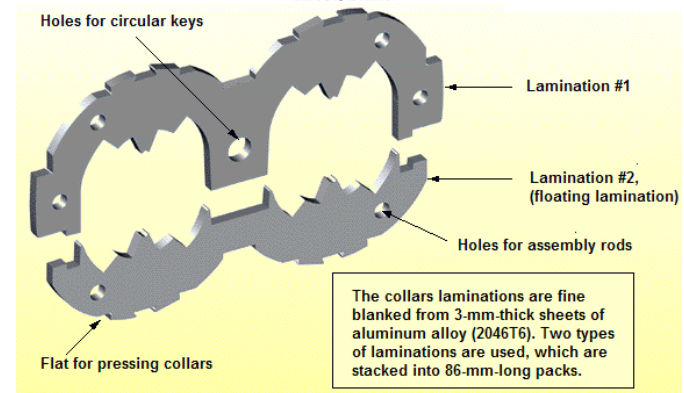
Hole for assembly rods

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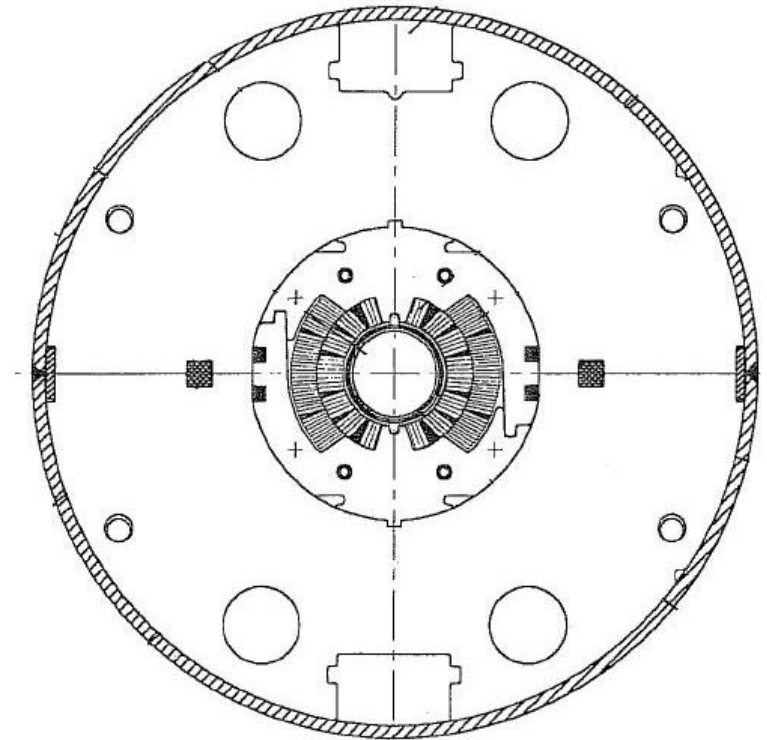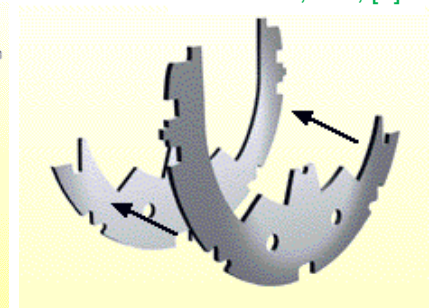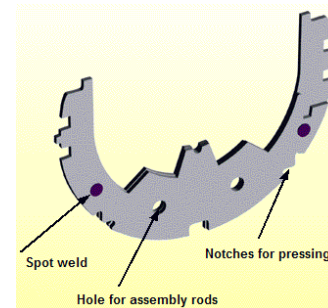
Collars: LHC dipole

- 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.

MJB Plus, Inc., [1]

Holes for circular keys

Lamination #1

Lamination #2, (floating lamination)

Holes for assembly rods

Flat for pressing collars

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.

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Collars: MBH 11 T dipole in HL-LHC

- Two-in-one configuration
  - Both beam pipes are contained within one cold mass
- Stainless steel collars are locked by keys. Pole in titanium, not integrated in the collar.
- Each aperture individually collared.
- Iron yoke vertically split
  - At the end of the welding operation the yoke gap is not fully closed
- Stainless steel shell halves are welded around the yoke to provide He containment, no sagitta, and to increase rigidity.
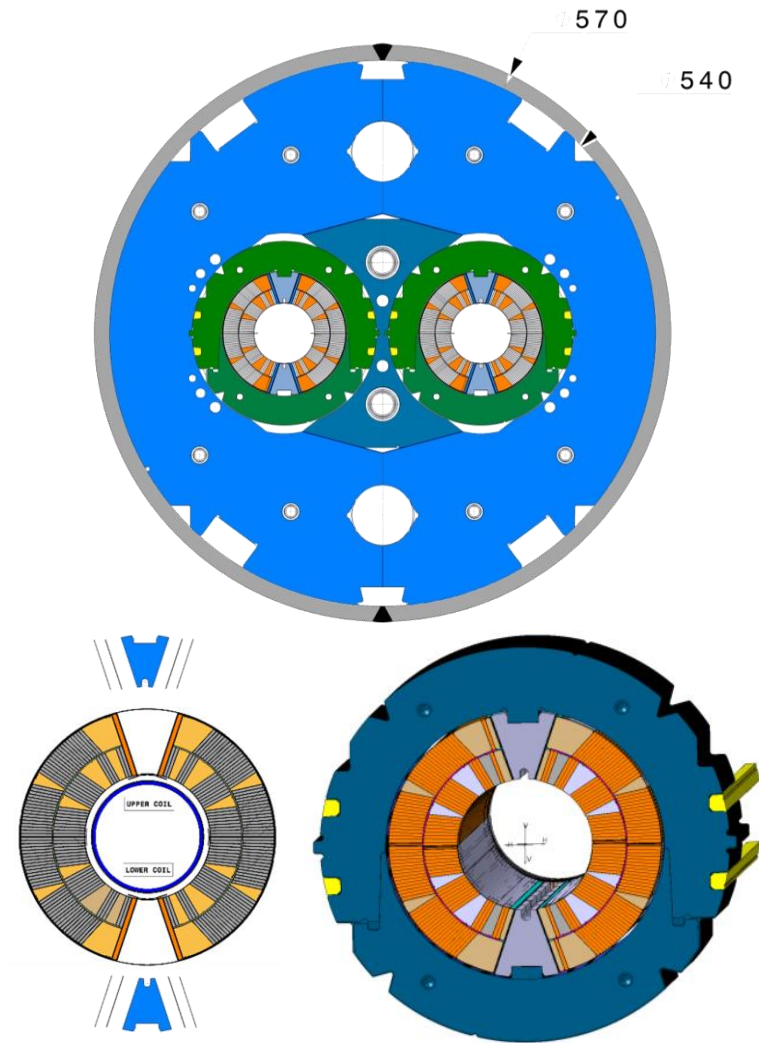
M. Karppinen, F. Savary, et al

Collars: D2 in HL-LHC

- Each aperture is individually collared

  - a pressure is applied to align the holes, the keys are inserted, the pressure is released

- Once collared, the aperture are inserted inside the aluminium sleeves

- Then a pressure is applied to the yokes to close the 1.2 mm gap, the C-clamps are inserted, the pressure is released

Short model   Prototype
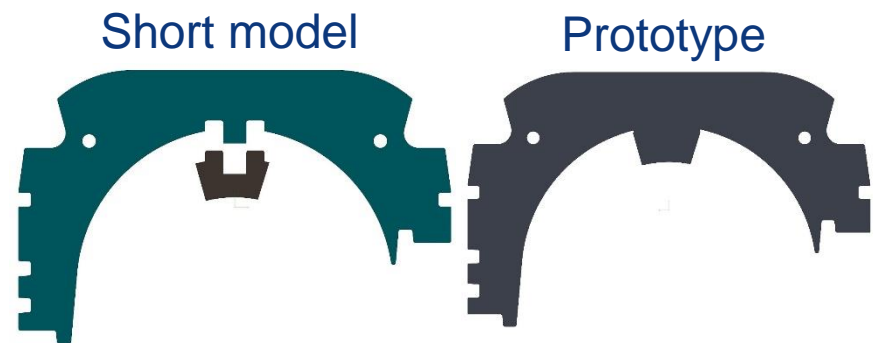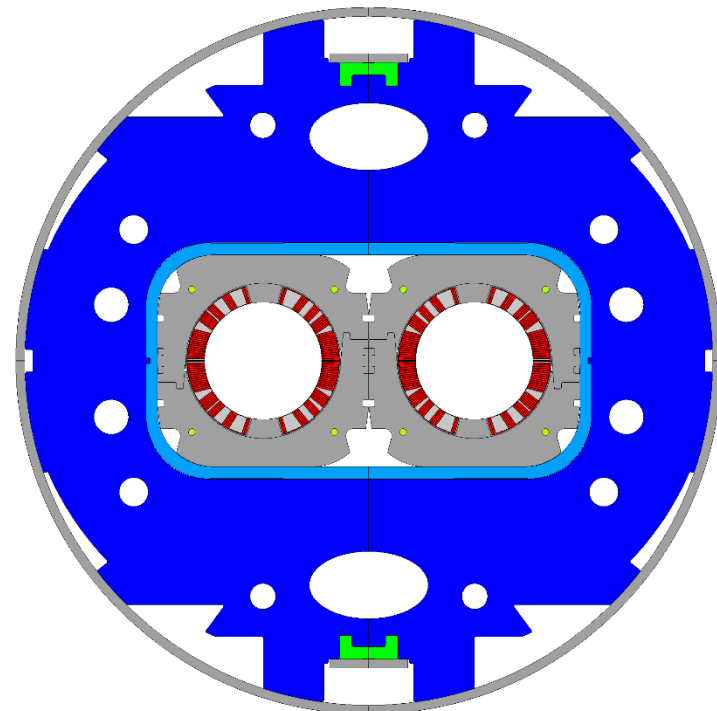
P. Fabbricatore, S. Farinon, et al

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Iron yoke: RHIC 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.
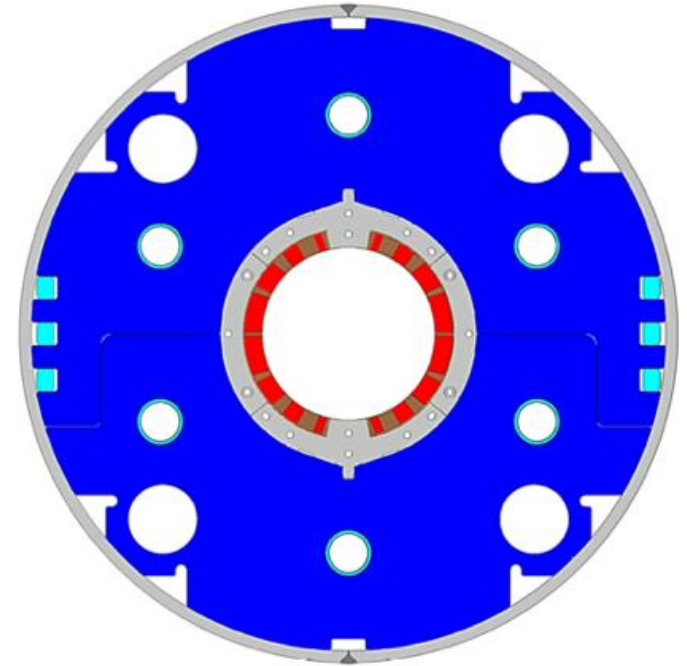

MJB Plus, Inc., [1]

Pins
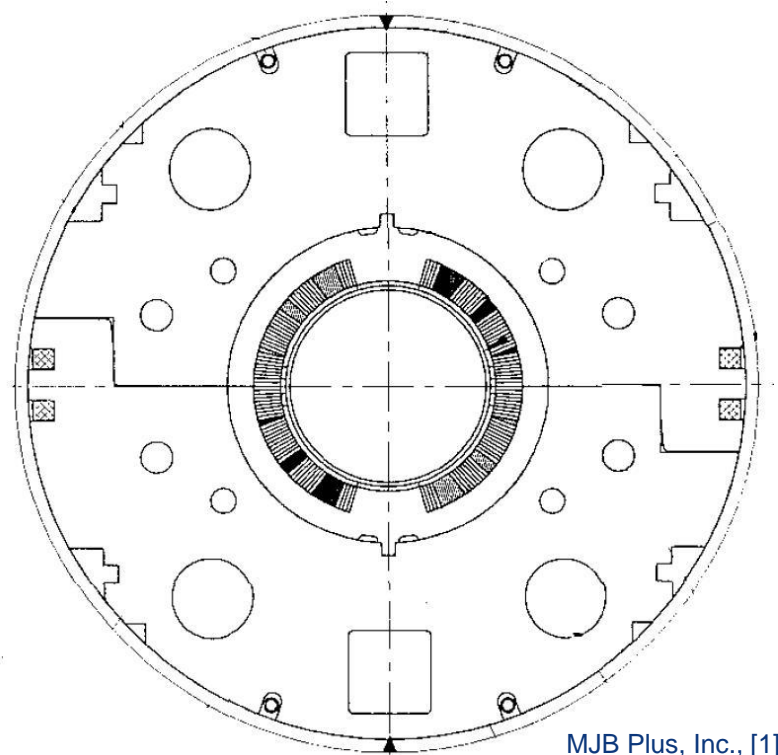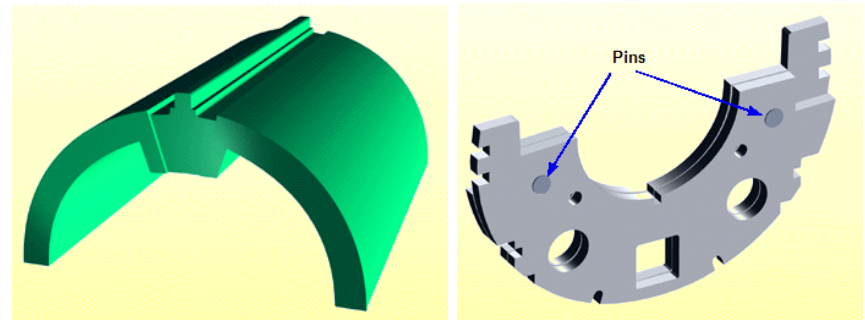
Iron yoke: D1 in-HL LHC

- 4-way split stainless steel collars

- The iron yoke clamps the coil-collar structure, applying a target pre-stress of 115 MPa at warm. About half of the pre-stress is lost during cool down.

- Iron very close to the coil, providing an important 3D contribution to first order harmonics even for a 7 m length magnet.
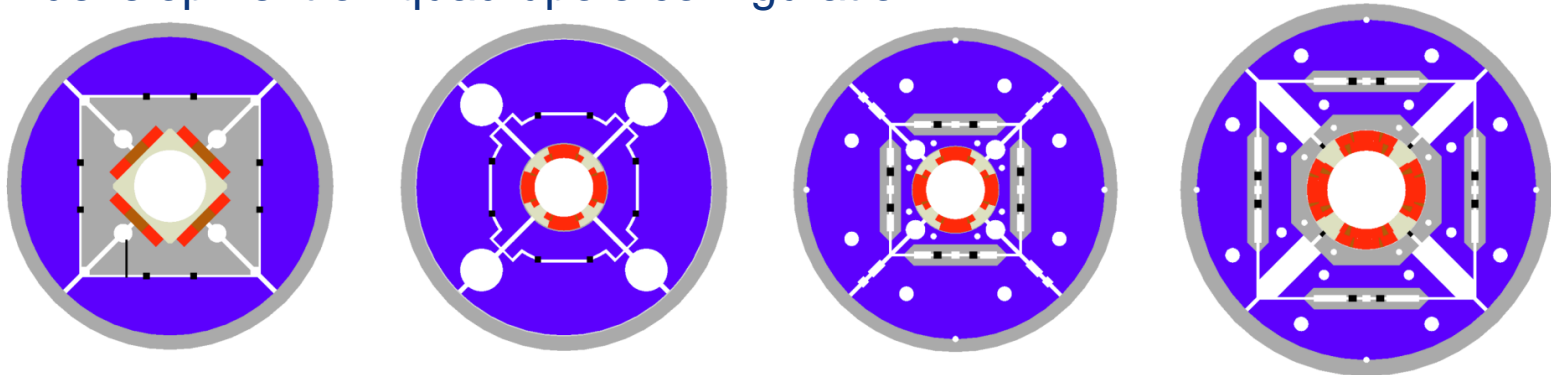
Iron collars for D1 in HL-LHC
(T .Nakamoto, M. Sugano, et al.)

Aluminum shell-based support structures
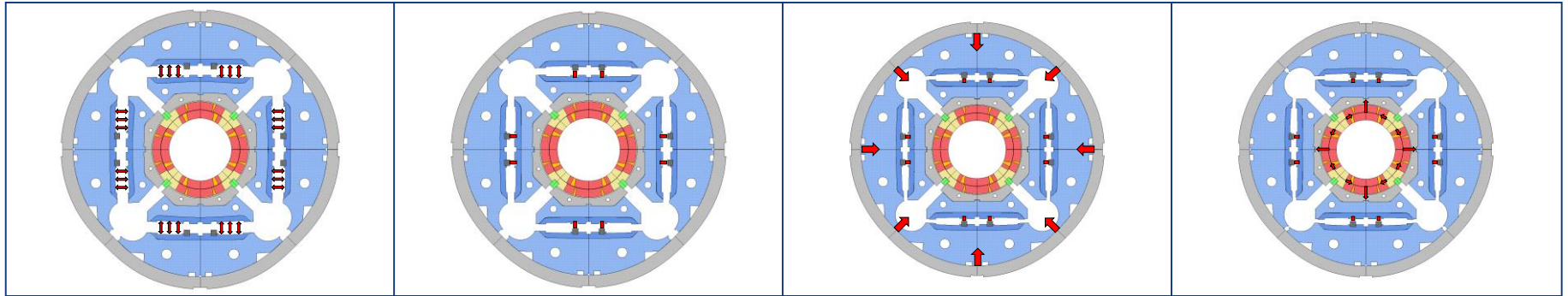
LBNL development on dipole configuration
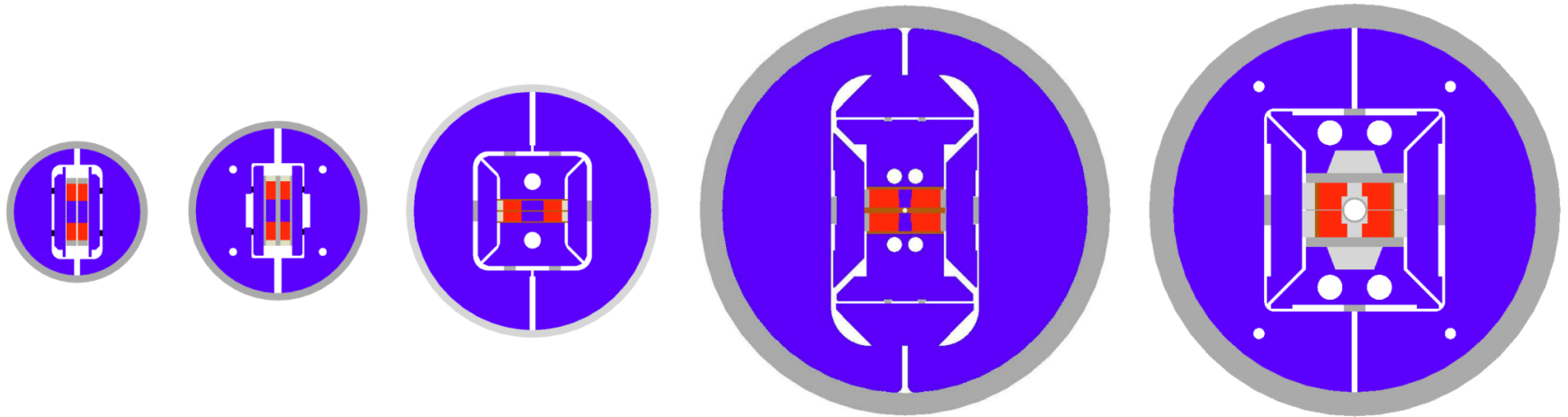
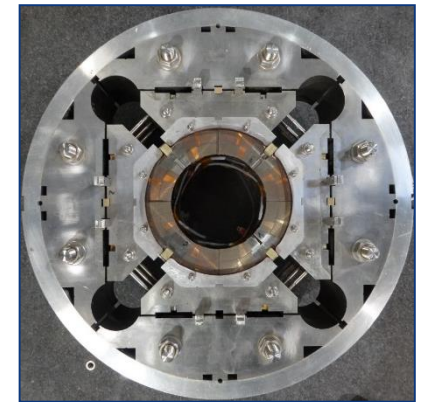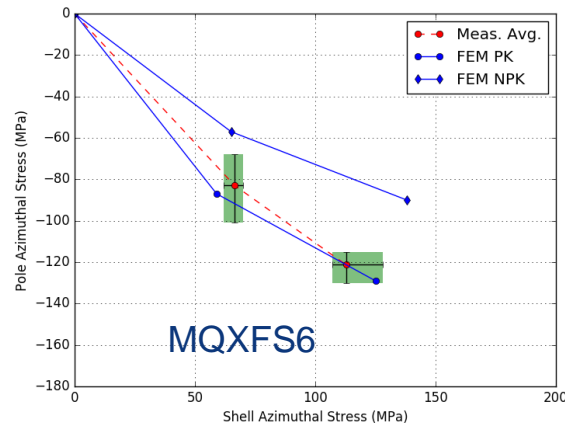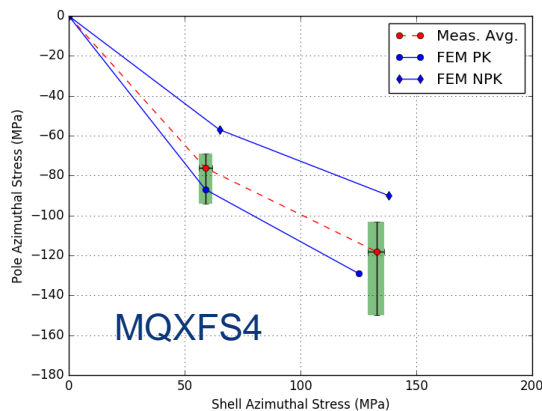LARP development on quadrupole configuration

RD, HD and LARP magnets (G. Sabbi, P. Ferracin, G. Ambrosio, S. Caspi, et many al.)

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Al shell: MQXF in HL-LHC

- Aluminum shell, bladder and key technology, prima for accelerators

- During cool-down increase in coil/shell stress
  - Predictable stress variation → Capability to control final coil and shell stress

MQXFS4

MQXFS6

Other structures for stress management

- The structure gives a dilution of the current density, i.e. a less effective design.
  - But this is a price we are ready to pay to reach higher fields

- Canted cos theta
  - Each turn is individually supported
  - The stress is managed also radially since there is a segmentation in several layers, each one supported
 - No mechanism to provide azimuthal prestress
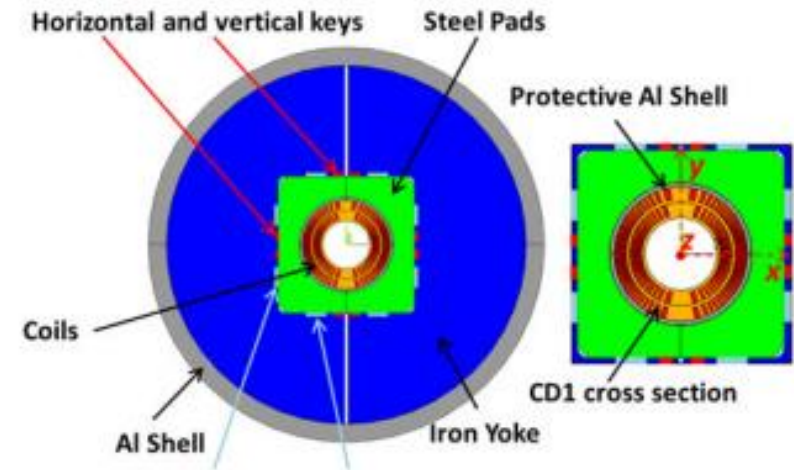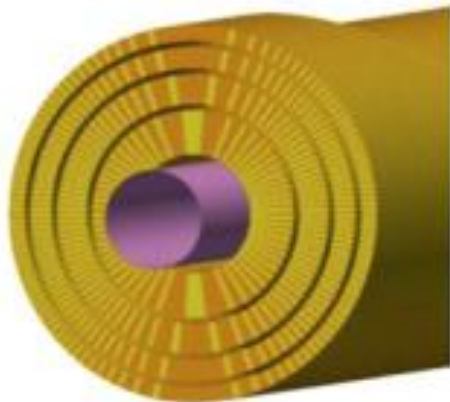
S. Caspi, et al. IEEE TAS 27 (2017) 4001505

B. Auchman, et al., . IEEE TAS 28 (2018) 4002805

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Other structures for stress management

- The structure gives a dilution of the current density, i.e. a less effective design.
  - But this is a price we are ready to pay to reach higher fields

- Cos theta with stress management
  - keep the traditional shell-type structure with the floating wedges and pole blocks for the inner coil (layers 1and 2);
  - maximally unload the inner coil by redistributing turns between the inner and the outer coil;
  - introduce the azimuthal and radial SM in the outer coil (layers 3 and 4) only.
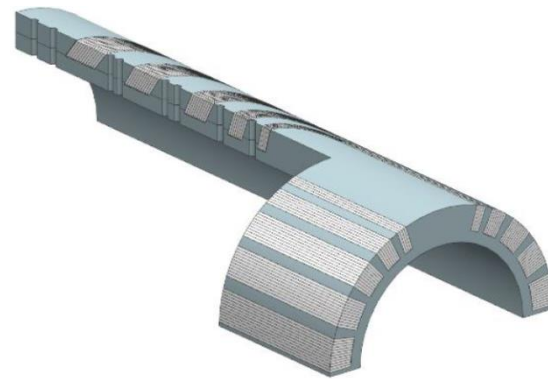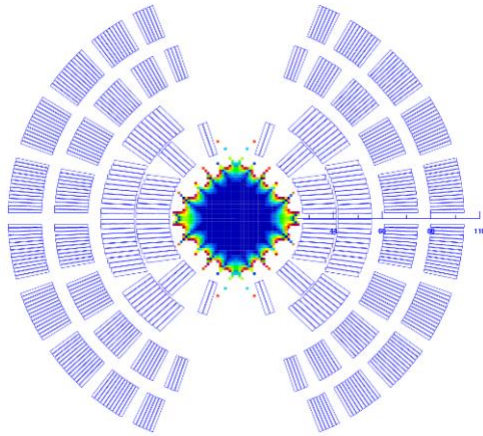
I. Novitski, A. Zlobin, FNAL-CONF-17-340 (2017)

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Other structures for stress management

- For block coils, proposal by Texas A&M
    - 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
- Main difficulty is to have both stress interception and preload
- Several years of research, concept not yet proved
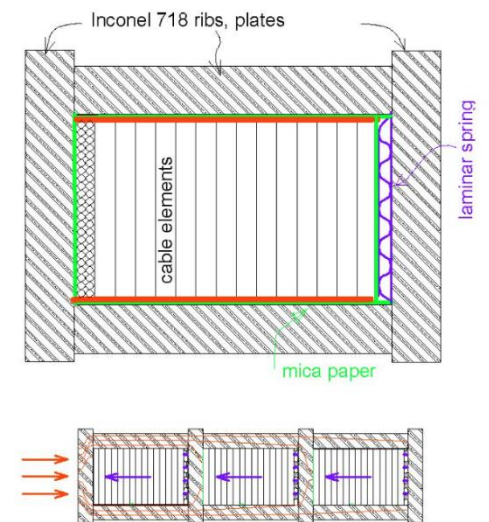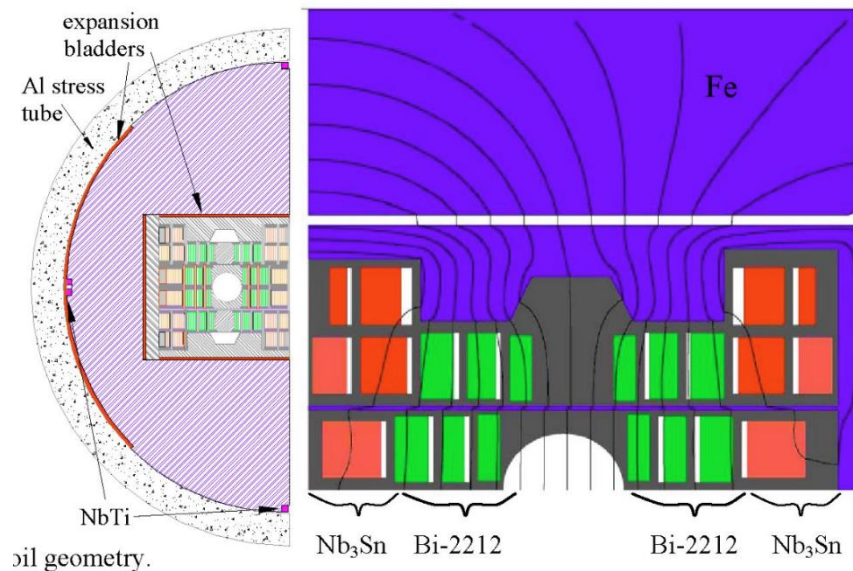
P. Mcintyre, IEEE TAS between 1995 and today

Axial support

- 'Two schools' in terms of longitudinal support, with no consensus on the magnet community:

  - Limit the coil displacements due to electromagnetic forces by having a rigid structure in the longitudinal direction (LHC Dipole, MBH-11 T concept, end-plate welded to the shell)

  - Limit the coil displacements due to electromagnetic forces by having a rigid structure in the longitudinal direction and pre-load coil ends to compensate the axial forces and keep coil end turns under compression (MQXF, FRESCA2, concept,)

Axial support: force or not force?

- Two type of axial displacements:
  - Relative movement of the coil with respect to the structure. It depends on the overall stiffness of the structure, i.e., independent of the level of pre-load in the ends.
  - Relative movement of the coil ends with respect to the pole. It depends of the level of pre-load.

- This was extensively studied in LBNL, developing the rods - plate axial pre-load system we are currently using for MQXF

S. Caspi, P. Ferracin., "Towards integrated design and modeling of high field accelerator magnets," IEEE Trans. Appl. Supercond., vol. 16, no. 2, pp. 1298–1303, June 2006.
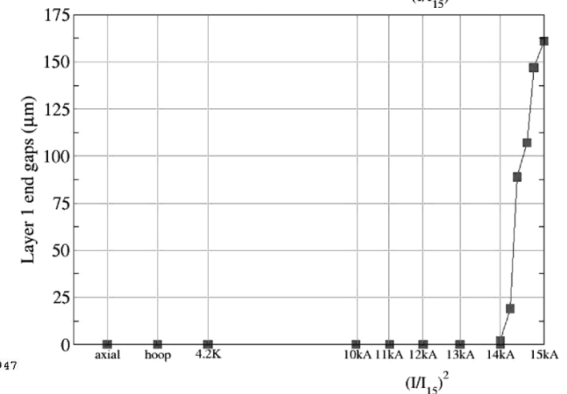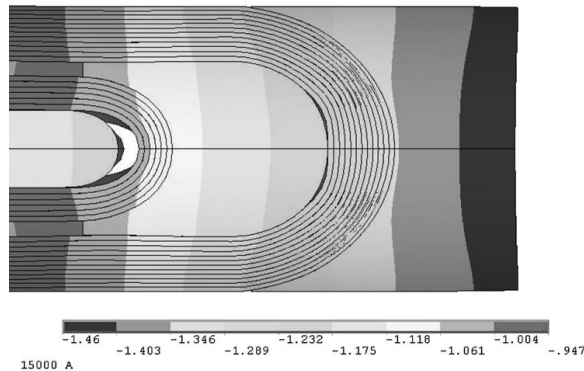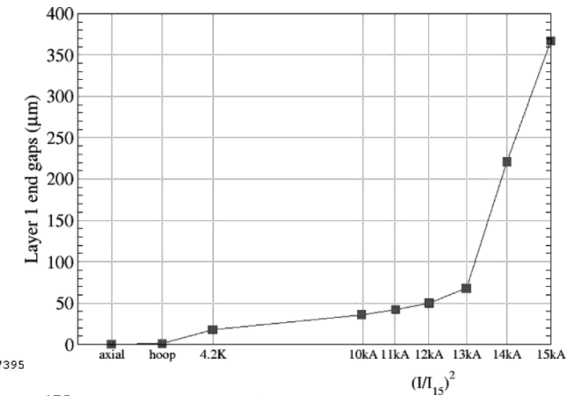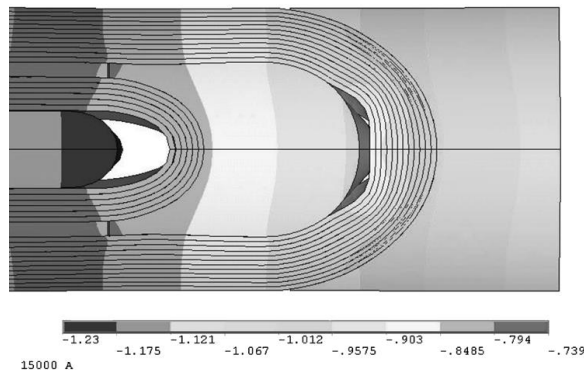
Axial displacements of inner layer's (0.2 friction factor assumed).
Limited axial support (top) and full axial support (bottom).

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# Axial support: welded end plate

- We take as example the 11 T dipole for the HL-LHC
- Slight pre-load at room temperature, to guarantee that there is still contact coil to end plate at 1.9 K.
- Goal: limit the coil displacements providing a rigid lateral support
- 1in1 models:
  - 43 mm thick end-plate, 12 mm stainless steel shell.
- 2in1 models:
  - 75 mm thick end-plate, 15 mm stainless steel shell.
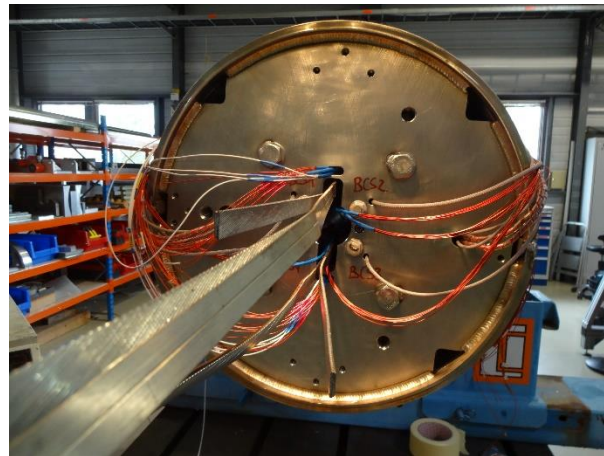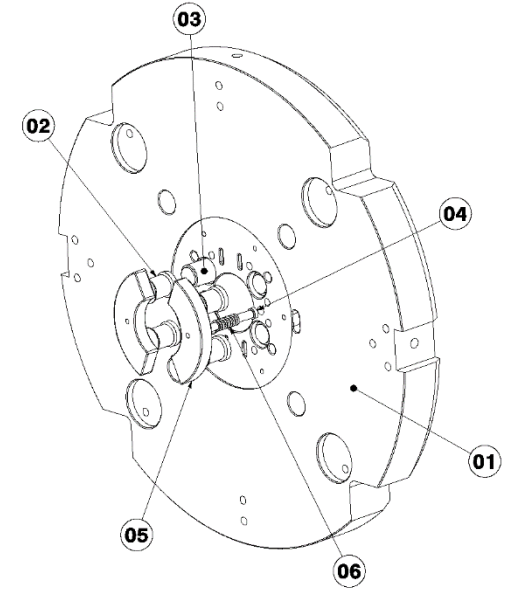
Axial support: rods and end-plate

- We take as example the MQXF quadrupole for the HL-LHC

- Direct connection between the motion of the rod and the one of the coil ends
  - Very nice and clean measurements!

- Goal: keep the pole turn under compression during powering.

- Short models (1.2 m):
  - Aluminum rods, 36 mm diameter
  - Nitronic 50 end plate, 75 mm thick

- MQXFA (4.2 m):
  - Stainless steel rods, 32 mm diameter
  - Nitronic 50 end plate, 75 mm thick

- MQXFB (7.15 m):
  - Stainless steel rods, 35 mm diameter
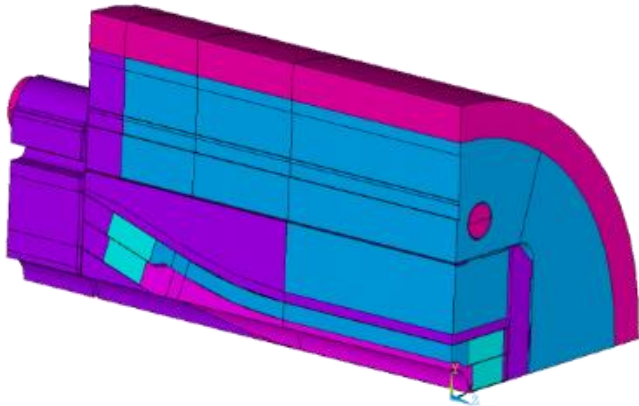 - Nitronic 50 end plate, 75 mm thick
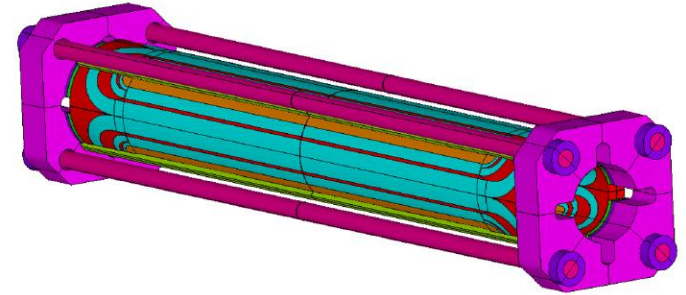
Measured delta in the rods during powering from 0 to I_{nom}

	Rod Strain [με]	Rod Stress [MPa]	Force [MN]	% of F_{em} at I_{nom}	Rod elongation [mm]
MQXFS	75	6	0.02	2	0.12
MQXFA	80	13	0.05	4	0.37
MQXFB	80	16	0.06	5	0.60

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More examples of rods and end-plate

FRESCA2

G. De Rijk, P. Ferracin, et al.

eRMC/RMM

Shell
Yoke
Top pad
Pole
Tie-rod
Spacers
Coil ends
End-shoes
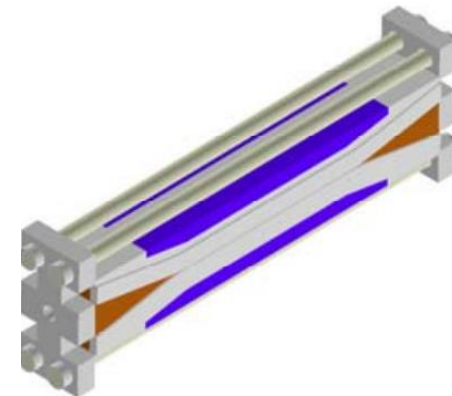End-plate
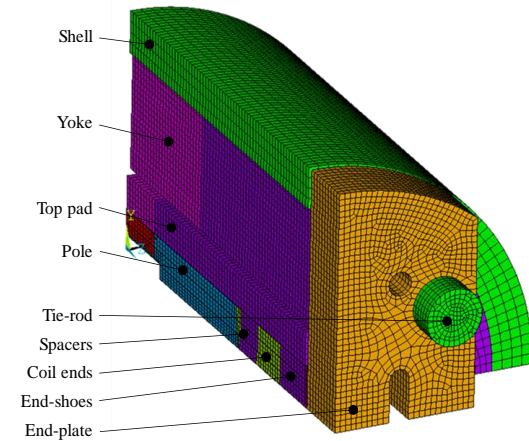
S. Izquierdo Bermudez, J. C. Perez, , et al.

MDPCT1 dipole
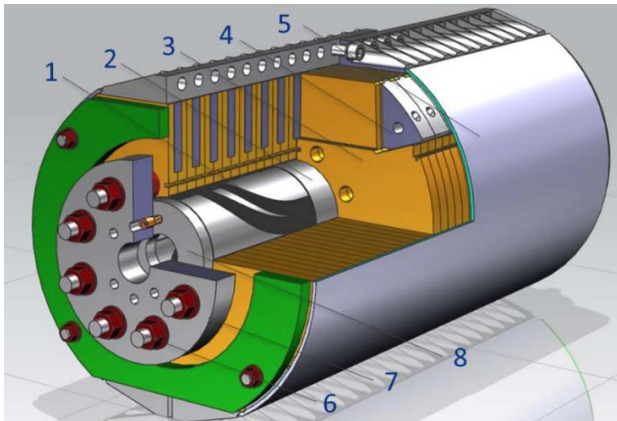
A. Zolbin, I. Novitski et al.

HD2 dipole

G. Sabbi, S. Caspi, et al.

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Summary

- We presented the force profiles in superconducting magnets. In dipole and quadrupole magnets, the forces are directed towards the mid-plane and outwardly.
    - They tend to separate the coil from the pole and compress the mid-plane region
    - Axially they tend to stretch the windings

- The importance of the coil pre-stress has been pointed out, as a technique to minimize the conductor motion during excitation.

- There are several ways of designing a support structure
    - The solution for a given magnet is not unique

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Summary

- Structures based on collars are the workhorse of Nb-Ti magnets
  - Guarantees adequate support to avoid deformation and allows giving azimuthal prestress
- A partial support of the iron yoke has been used in several cases
  - This allows reducing the collar thickness, and having more contribution to the field, and reduction of collar deformation
- A total support of the yoke is also an option
  - Very thin spacers allow to place the iron much closer to the coil, reducing the current density, and therefore stress
  - It a very rigid structure due to the large thickness of the iron
- Aluminum shell structure guarantees that the peak pre-stress is reached in operational conditions
  - Introduced in LNBL, used in several Nb_3Sn magnets where the degradation threat at 150 MPa is present
  - It showed to be suitable to a very precise control of prestress
  - It has been scaled from 1-m-long to 3.4 m long magnets with LARP, and to 7.15 m long magnet in HL LHC MQXFB at CERN

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References

- [1] MJB Plus, Inc. "*Superconducting Accelerator Magnets*", an interactive tutorial.

- [2] Paolo Ferracin, USPAS - Superconducting Magnets for Particle Accelerators, Unit 10, 13 and 14 (available in https://indico.cern.ch/event/440690/)

- [3] Y. Iwasa, "Case studies in superconducting magnets", New York, Plenum Press, 1994.

- [4] M. Wilson, "Superconducting magnets", Oxford UK: Clarendon Press, 1983.

- [5] A.V. Tollestrup, "Superconducting magnet technology for accelerators", Ann. Reo. Nucl. Part. Sci. 1984. 34, 247-84

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