2020 Joint Universities Accelerator School

Mini-workshop on Superconducting Magnets

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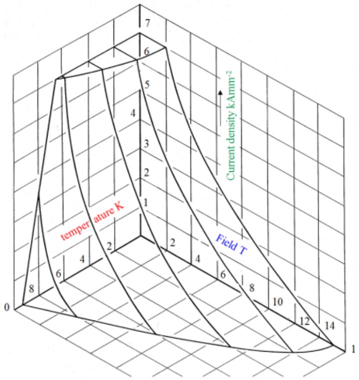
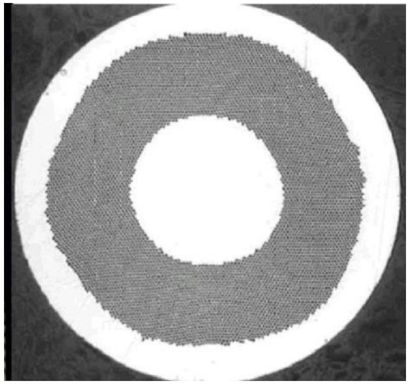
Mini-workshop introduction

- Goal: outline design of a superconducting magnet
  - Apply the theory explained during lectures to a practical case
  - Solve a case study using analytical formulas, "back of the envelope" calculation, plots, data, etc. provided during the presentations
    - From the superconducting material to the full magnet
  - Understand physics and reasoning behind design options
    - General dimensions, orders of magnitude of different parameters
- Provide a short report of the results

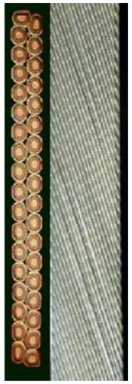
Superconducting material



Superconducting strand

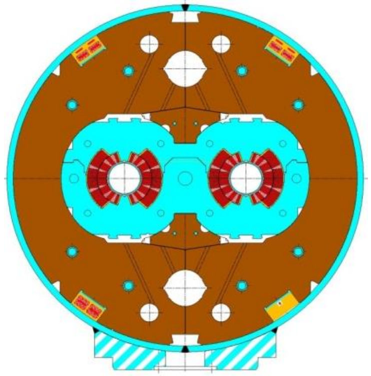


Superconducting cable



Superconducting coil

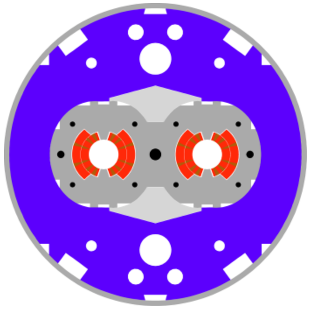
Superconducting magnet



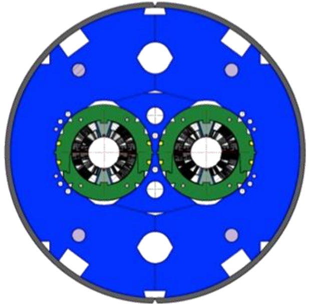
Case study

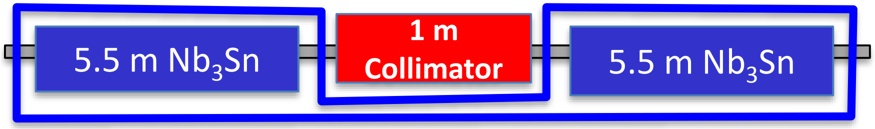
- 11 T Nb$_3$Sn dipole for the LHC collimation upgrade

14.3 m
Nb-Ti 8.3 T

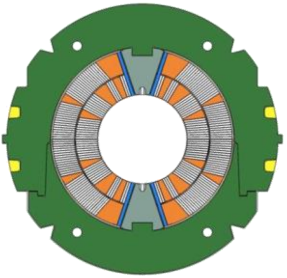


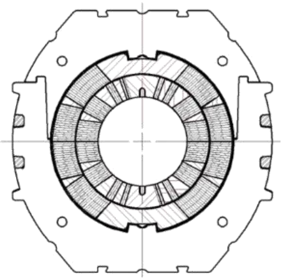
5.5 m
Nb$_3$Sn 11 T





- Second long shutdown: increase of collimation efficiency
  - New collimation units
  - Some 8.3 T Nb-Ti dipoles replaced by **11 T Nb$_3$Sn dipoles**
  - FNAL/CERN collaboration



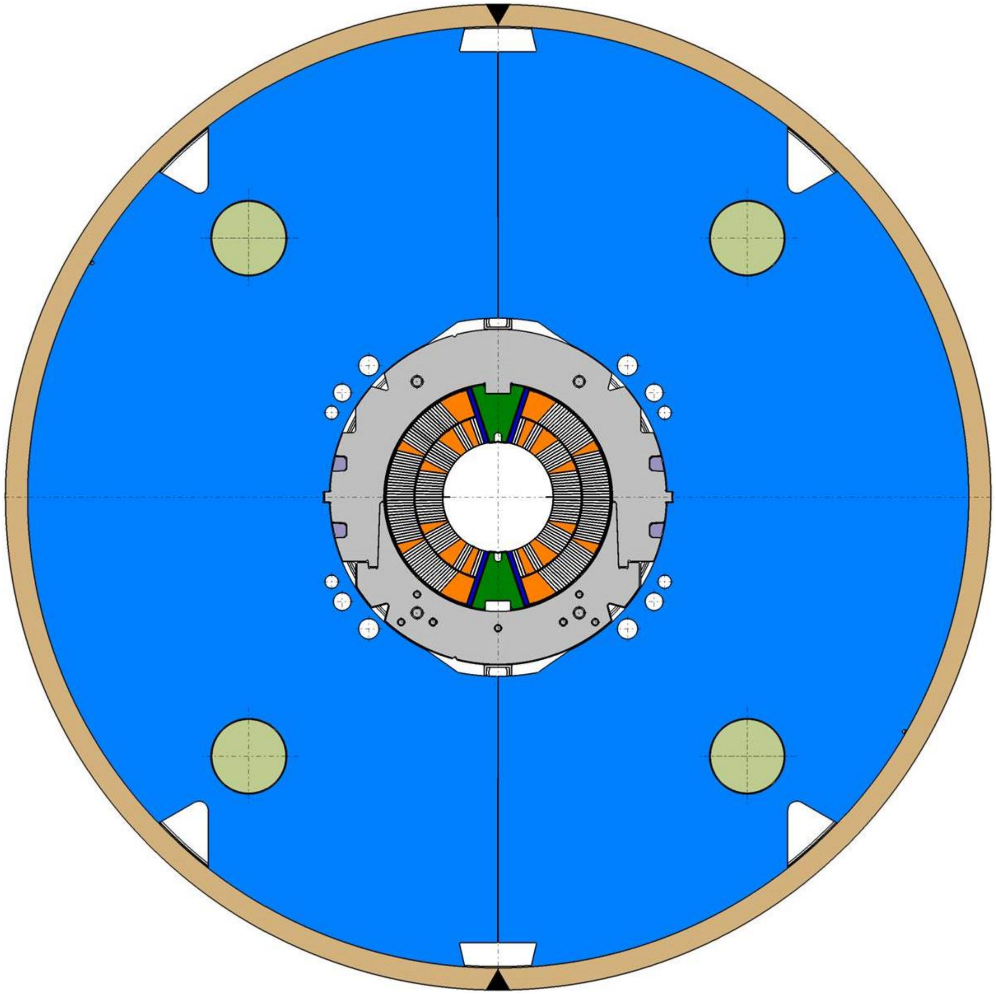


Case study

- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Introduction**
    - The second phase of the LHC collimation upgrade will enable proton and ion beam operation at nominal and ultimate intensities.
    - To improve the collimation efficiency by a factor 15–90, additional collimators are foreseen in the room temperature insertions and in the dispersion suppression (DS) regions.
    - To provide longitudinal space of about 3.5 m for additional collimators, a solution based on the substitution of a pair of 5.5-m-long 11 T dipoles for several 14.3-m-long 8.33 T LHC main dipoles (MB) is being considered.
  - **Goal**
    - Design a **Nb_3Sn** superconducting **dipole** with an **60 mm aperture** and a operational field (80% of the current limit I_{ss}) at **1.9 K** of **11 T**.

Case study

- 11 T Nb_3Sn dipole for the LHC collimation upgrade



Case study

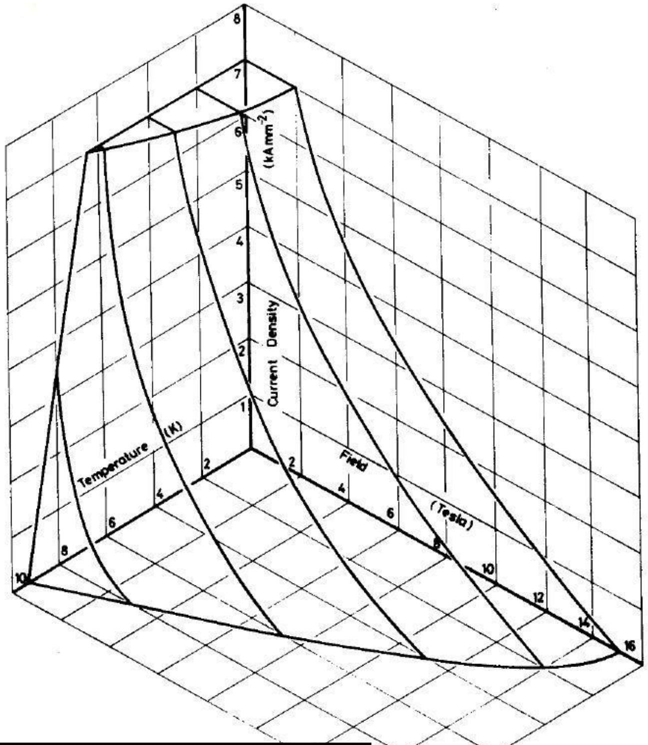
- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Questions**
    1. Determine and plot critical curves (J_{sc} vs. B) for Nb_3Sn and Nb-Ti at 1.9 K
    2. Determine coil filling factor λ (J_0 / J_{sc} ratio or $A_{non\text{-}Cu\_cable} / A_{insulated\_cable}$)
    3. Compute load-line (J_{sc} vs. B) for a
       1. Sector coil (60°) with constant current density
    4. Determine coil size, operational (80% of I_{ss}), conditions, "short-sample" conditions, and margins
       1. w
       2. j_{sc_ss}, j_{o_ss}, B_{bore_ss}, B_{peak_ss}
       3. j_{sc_op}, j_{o_op}, B_{bore_op}, B_{peak_op}
       4. T, j_{sc}, B_{peak} margins
    5. Compare "short sample", "operational" conditions and margins if the same design uses Nb-Ti superconducting technology with the same coil size w
    6. Determine e.m forces F_x and F_y and the accumulated stress on the coil mid-plane in the operational conditions
    7. Evaluate dimension of collars, iron yoke, and shrinking cylinder, assuming that the support structure is designed to reach 90% of I_{ss}

Case study

- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Question**
    - Determine and plot critical curves (J_{sc} vs. B) for Nb_3Sn and Nb-Ti at 1.9 K

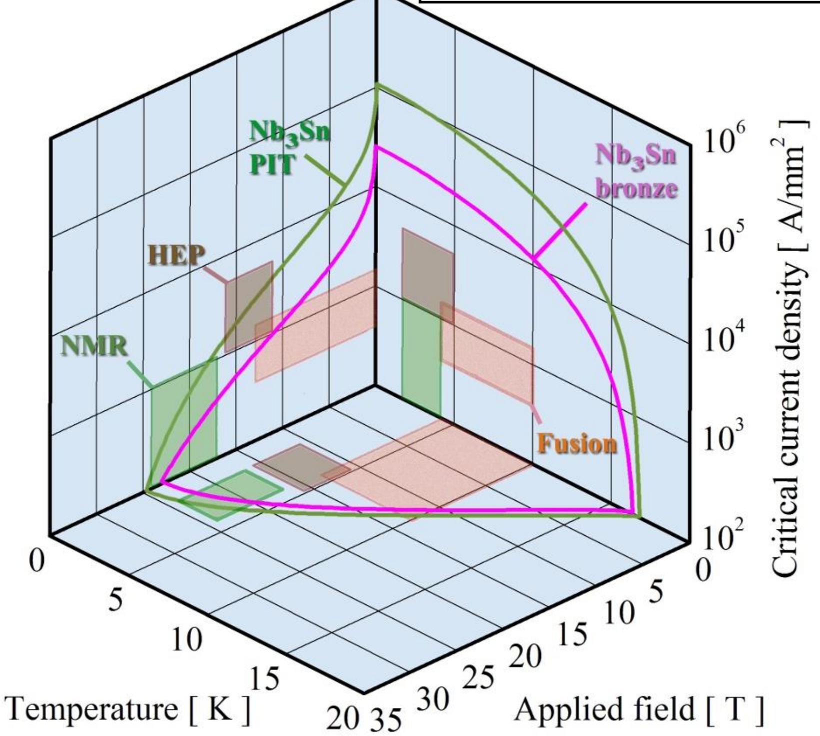
Nb-Ti and Nb_3Sn Critical surfaces

- The critical surface defines the boundaries between superconducting state and normal conducting state in the space defined by temperature, magnetic field, and current densities.
- The surface, determined experimentally, can be fitted with parameterization curves.



M. Wilson, "Superconducting magnets", Oxford UK: Clarendon Press, 1983.

A. Godeke, "Performance boundaries in Nb_3Sn superconductors", PhD thesis, 2005.



Measurements of the conductor critical current

- The critical current of a conductor is measured by winding a sample of the wire around a sample holder.
- To avoid premature quenching induced by Lorentz forces during ramping, the wire must be well supported
  - Stycast glue may be used to constrain the wire around the holder
- In case of Nb_3Sn wires, a sample holder made of titanium is used.
- Once the wire is cooled-down and placed in a given magnetic field, the current is increased until the transition occurs.

Nb-Ti parameterization curve (LHC dipole)

- Nb-Ti parameterization
  - Temperature and field dependence of B_{C2} and T_C are provided by Lubell's formulae:

$$B_{C2}(T) = B_{C20}\left[1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right] \qquad T_C(B)^{1/1.7} = T_{C0}\left[1-\left(\frac{B}{B_{C20}}\right)^{1/1.7}\right]$$

where B_{C20} is the upper critical flux density at zero temperature (14.5 T), and T_{C0} is critical temperature at zero field (9.2 K)

  - Temperature and field dependence of *Jc* is given by Bottura's formula

$$\frac{J_C(B,T)}{J_{C,ref}} = \frac{C_{NbTi}}{B}\left[\frac{B}{B_{C2}(T)}\right]^{\beta_{NbTi}}\left[1-\frac{B}{B_{C2}(T)}\right]^{\beta_{NbTi}}\left[1-\left(\frac{T}{T_{C0}}\right)^{1.7}\right]^{\gamma_{NbTi}}$$

where $J_{C,Ref}$ is critical current density at 4.2 K and 5 T (3000 A/mm^2) and $C_{Nb\text{-}Ti}$ (27 T), $\alpha_{Nb\text{-}Ti}$ (0.63), $\beta_{Nb\text{-}Ti}$ (1.0), and $\gamma_{Nb\text{-}Ti}$ (2.3) are fitting parameters.

Nb_3Sn parameterization curve (typical values for HEP magnets)

- Nb_3Sn parameterization
  - Temperature, field, and strain dependence of *Jc* is given by Summers' formula

$$J_C(B,T,\varepsilon)=\frac{C_{Nb_3Sn}(\varepsilon)}{\sqrt{B}}\left[1-\frac{B}{B_{C2}(T,\varepsilon)}\right]^2\left[1-\left(\frac{T}{T_{C0}(\varepsilon)}\right)^2\right]^2$$

$$\frac{B_{C2}(T,\varepsilon)}{B_{C20}}=\left[1-\left(\frac{T}{T_{C0}(\varepsilon)}\right)^2\right]\left\{1-0.31\left(\frac{T}{T_{C0}(\varepsilon)}\right)^2\left[1-1.77\ln\left(\frac{T}{T_{C0}(\varepsilon)}\right)\right]\right\}$$

$$C_{Nb_3Sn}(\varepsilon)=C_{Nb_3Sn,0}\left(1-\alpha_{Nb_3Sn}|\varepsilon|^{1.7}\right)^{1/2}$$

$$B_{C20}(\varepsilon)=B_{C20m}\left(1-\alpha_{Nb_3Sn}|\varepsilon|^{1.7}\right)$$

$$T_{C0}(\varepsilon)=T_{C0m}\left(1-\alpha_{Nb_3Sn}|\varepsilon|^{1.7}\right)^{1/3}$$

where α_{Nb3Sn} is 900 for $\varepsilon = -0.003$, T_{Com} is 18 K, B_{C20m} is 27.6 T, and $C_{Nb3Sn,0}$ is a fitting parameter equal to 43100000000 $AT^{1/2}mm^{-2}$ for a *Jc*=2900 A/mm^2 at 4.2 K and 12 T.

Assume $\varepsilon = 0.000$

Parameterization curves

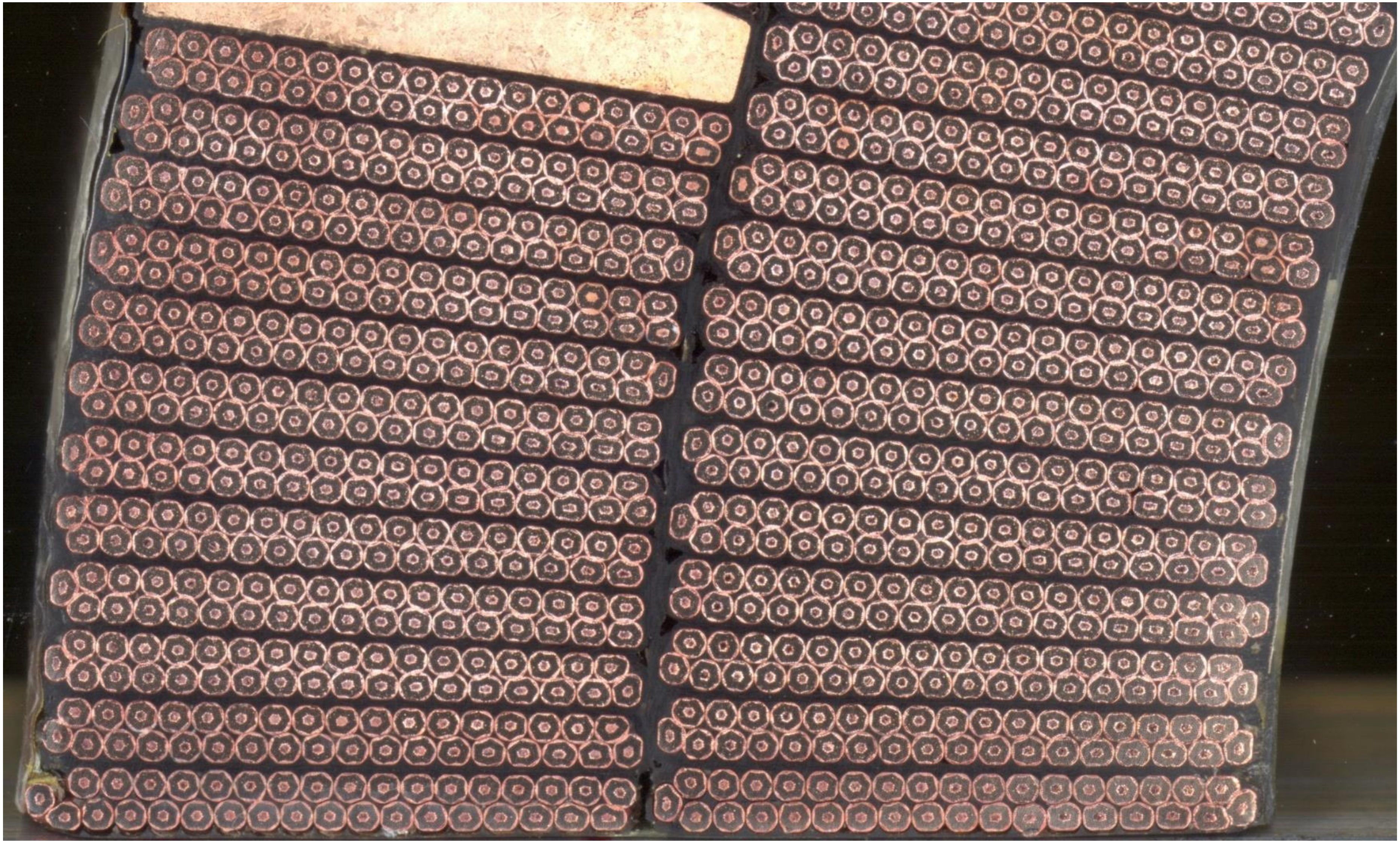
- References

- M.S. Lubell, “Empirical scaling formulas for critical current and critical fields for commercial NbTi,” *IEEE Trans. Magn.*, Vol. MAG-19 No. 3, pp. 754–757, 1983.
- L. Bottura, “A practical fit for the critical surface of NbTi,” *IEEE Trans. Appl. Supercond.*, Vol. 10, No. 1, pp. 1054–1057, 2000.
- L.T. Summers, M.W. Guinan, J.R. Miller and P.A. Hahn, “A model for the prediction of Nb_3Sn critical current as a function of field, temperature, strain and radiation damage,” *IEEE Trans. Magn.*, Vol. 27, No. 2, pp. 2041–2044, 1991.

Case study

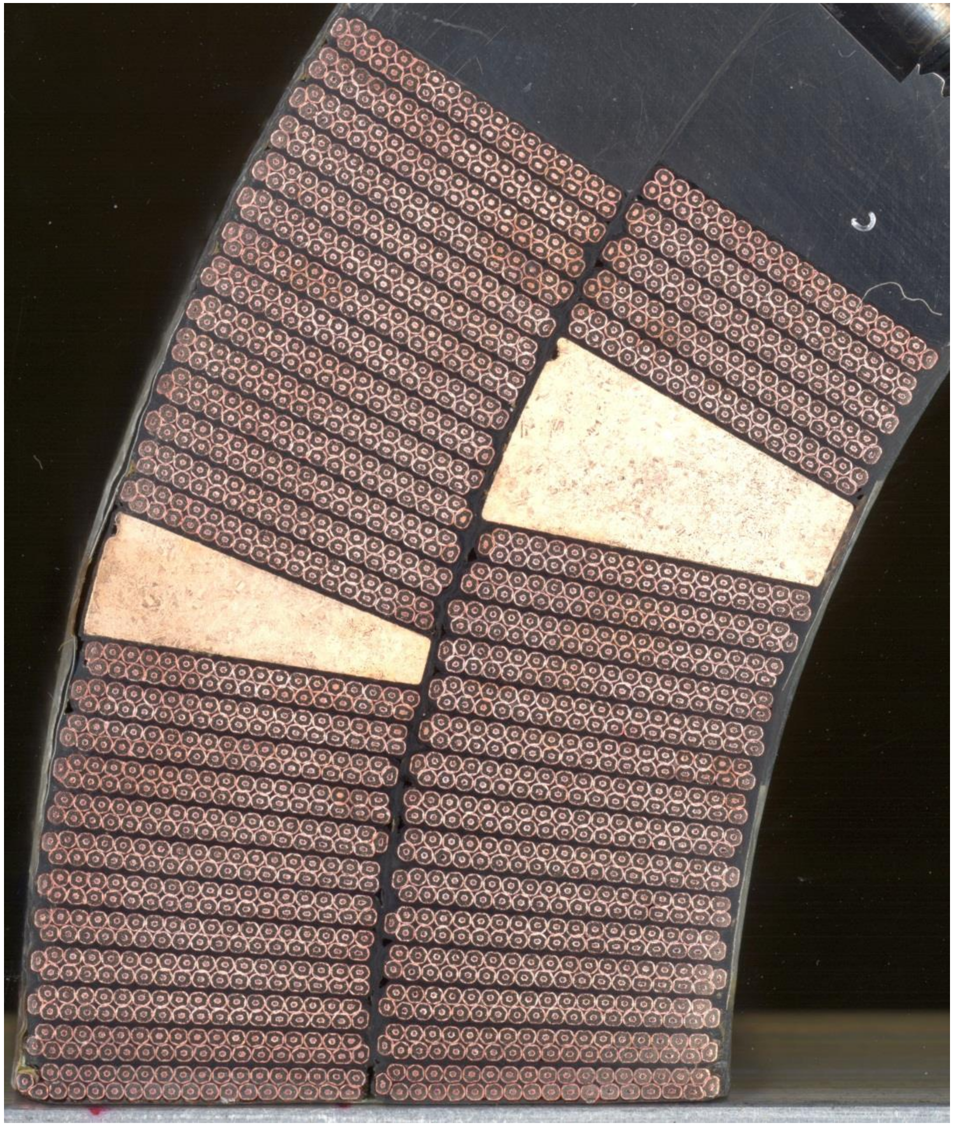
- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Question**
    - Determine coil filling factor λ (J_0 / J_{sc} ratio or $A_{non\text{-}Cu\_cable}$/ $A_{insulated\_cable}$)

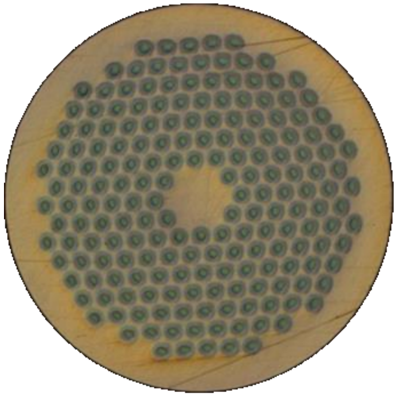
Superconducting cables and coils

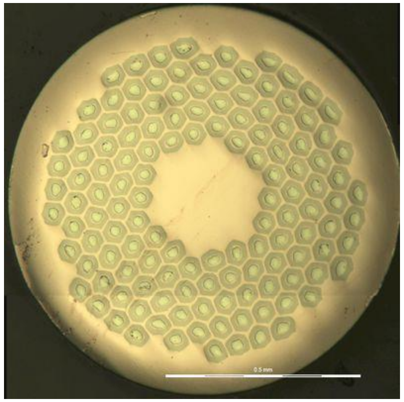


J_0 / J_{sc} ratio

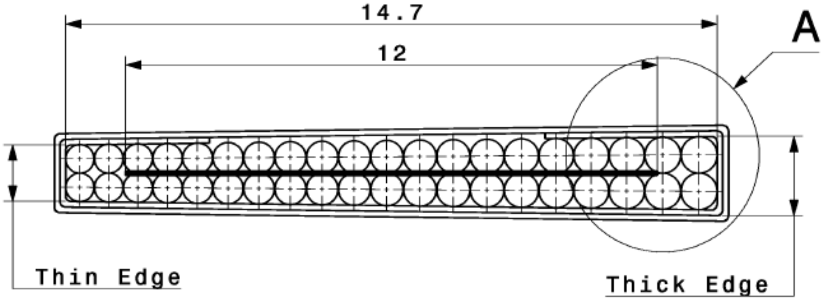
- The cable design parameters are:
  - Number of wires N_{wire}
  - Wire diameter d_{wire}
  - Cable mid-thickness t_{cable}
  - Cable width w_{cable}
  - $(Cu/\text{non-}Cu)$ ratio
  - Insulation thickness
  - Pitch angle
    - To be neglected in this comp.



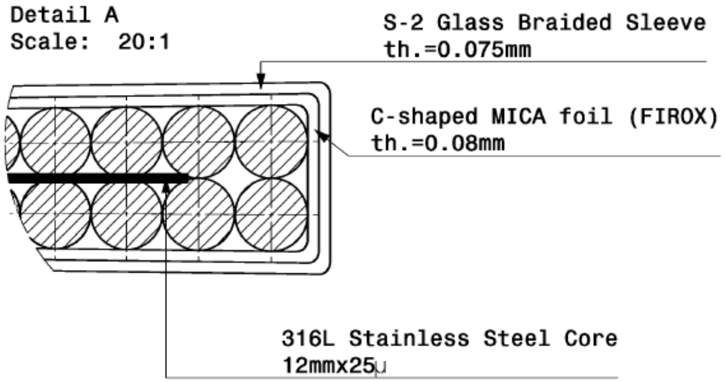


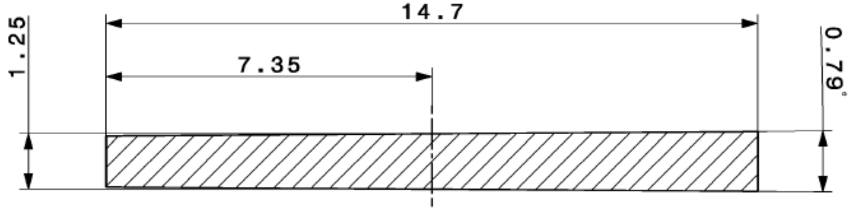


J_0 vs. J_{sc}

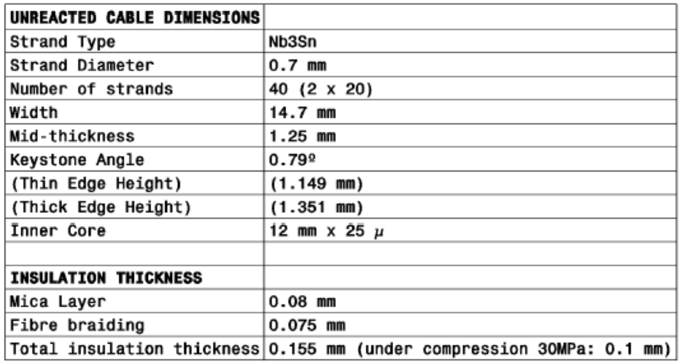


Enlarged and not to scale,
for illustration purposes only





DIMENSION FOR
CONDUCTOR WITHOUT INSULATION
Scale:10:1



UNREACTED CABLE DIMENSIONS	
Strand Type	Nb3Sn
Strand Diameter	0.7 mm
Number of strands	40 (2 x 20)
Width	14.7 mm
Mid-thickness	1.25 mm
Keystone Angle	0.79º
(Thin Edge Height)	(1.149 mm)
(Thick Edge Height)	(1.351 mm)
Inner Core	12 mm x 25 µ
INSULATION THICKNESS	
Mica Layer	0.08 mm
Fibre braiding	0.075 mm
Total insulation thickness	0.155 mm (under compression 30MPa: 0.1 mm)

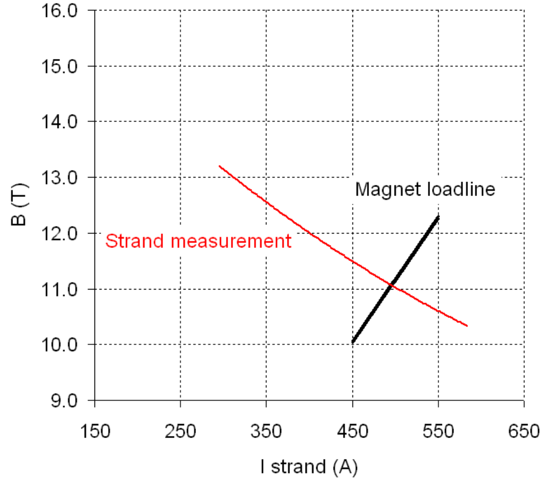
- *Cu to non-Cu ratio: 1.2*

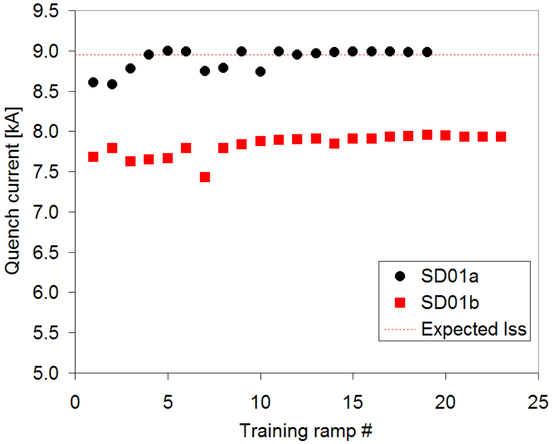
Case study

- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Question**
    - Compute load-line (J_{sc} vs. B) for a
      - Sector coil (60°) with constant current density
    - Determine coil size, operational (80% of I_{ss}), conditions, "short-sample" conditions, and margins
      - w
      - j_{sc_ss}, j_{o_ss}, B_{bore_ss}, B_{peak_ss}
      - j_{sc_op}, j_{o_op}, B_{bore_op}, B_{peak_op}
      - T, j_{sc}, B_{peak} margins
    - Compare "short sample", "operational" conditions and margins if the same design uses Nb-Ti superconducting technology with the same coil size w

Short sample and operational current

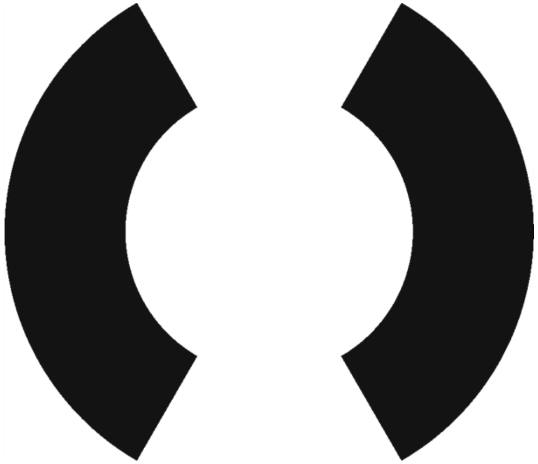
- Short sample current
  - The critical current is measured in few different conditions of temperature and field. By fitting the data with known parameterizations, the entire critical surface can be reconstructed.
- If the magnet reaches the maximum current computed through the intersection of the measured critical surface and the load line, i.e. $I_{max} = I_{ss}$, one can declare victory (at least from the quench performance point of view).
- If the magnet maximum current I_{max} is lower that I_{ss} , the quench performance is expressed in term of fraction of short sample (I_{max}/I_{ss}).
- Usually magnets are designed to operate at $I_{op} = 0.8\ I_{ss}$ or below.



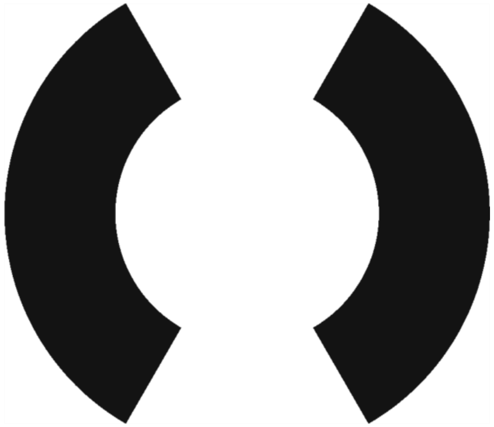


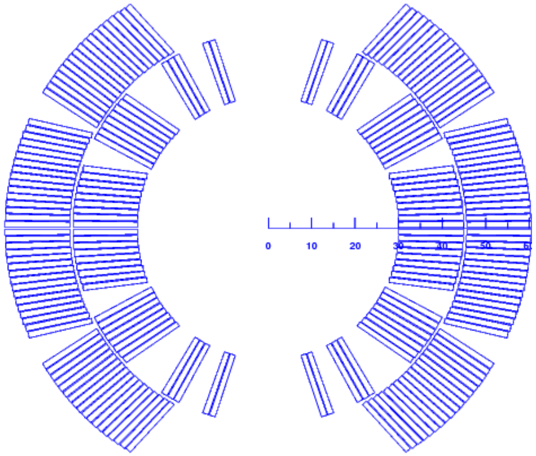
Computation of the load line
Approximations of practical winding cross-sections

- Sector coil
  - Current density $J = J_0$ (A per unit area) on a a sector with a maximum angle $\theta = 60^{\circ}$ for a dipole



Approximations of practical winding cross-sections



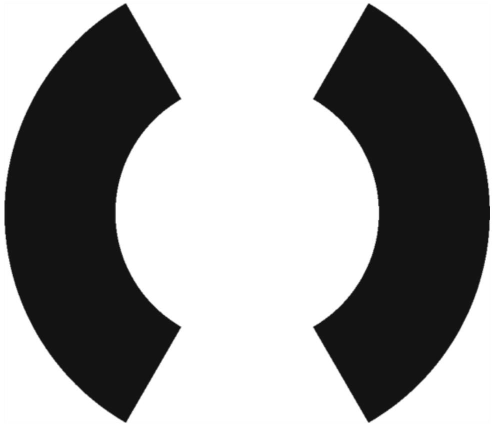


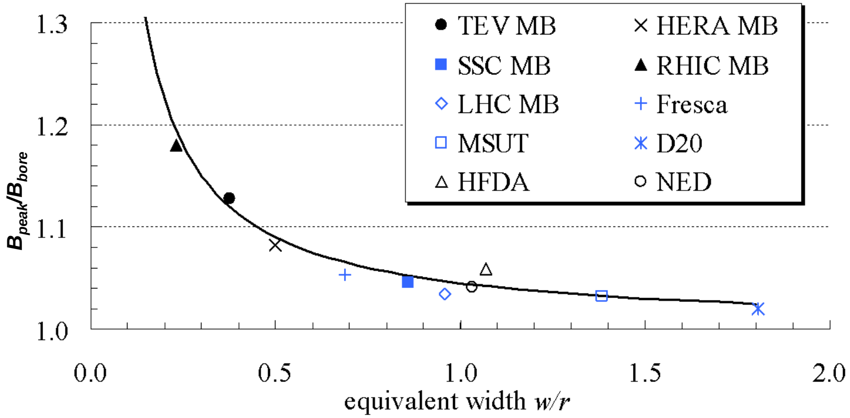
Computation of the load line
Approximations of practical winding cross-sections

- Sector coil
  - Current density $J = J_0$ (A per unit area) on a a sector with a maximum angle $\theta = 60^{\circ}$ for a dipole

$$B_{bore} = -\frac{2 j_0 \mu_0}{\pi} w \sin(60)$$

  - Where, B_{bore} is the bore field, j_0 is overall current density and w is the coil width
  - "Less ideal" case
    - **$B_{peak} = B_{bore} \cdot \sim 1.04$**
    - "Not so perfect" field quality
      - $b_3 = 0$



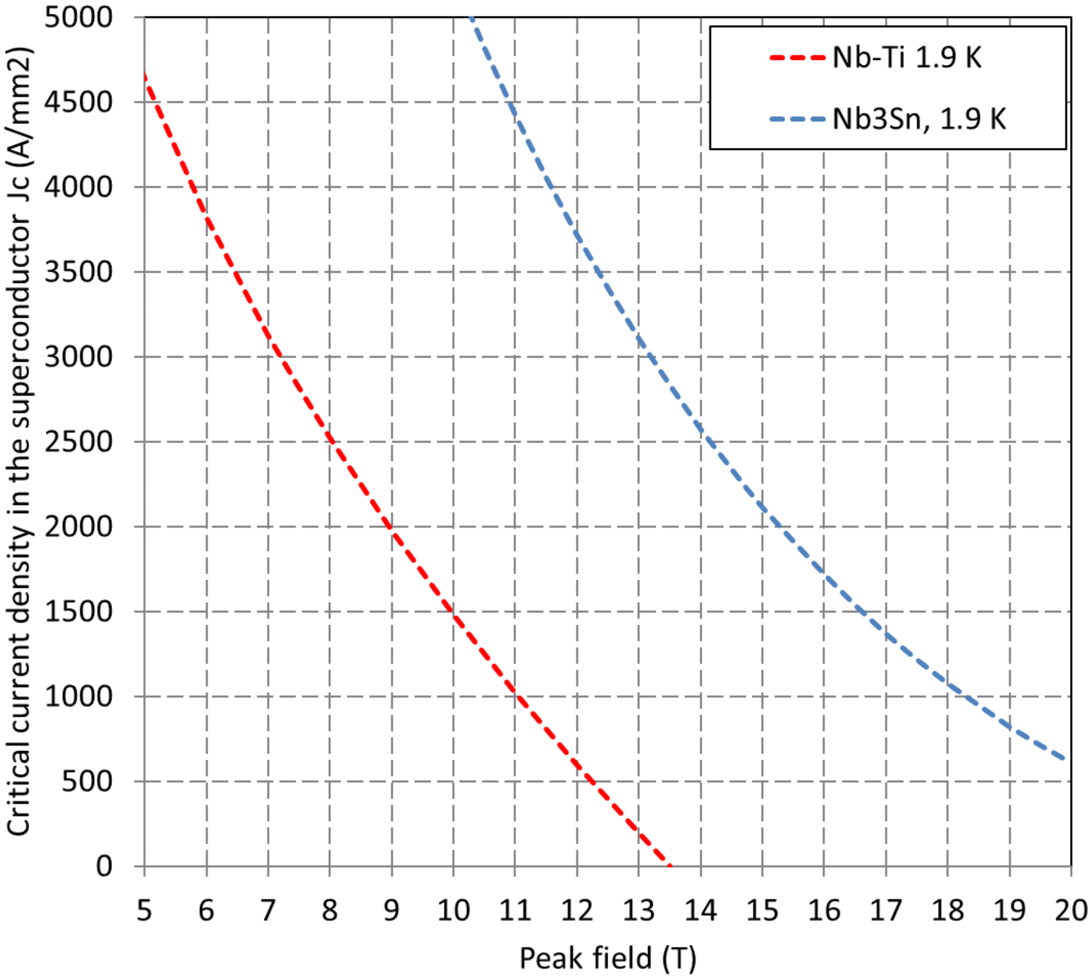


L. Rossi, E. Todesco, "Electromagnetic design of superconducting quadrupoles", Phys. Rev. ST Accel. Beams 9 (2006) 102401.

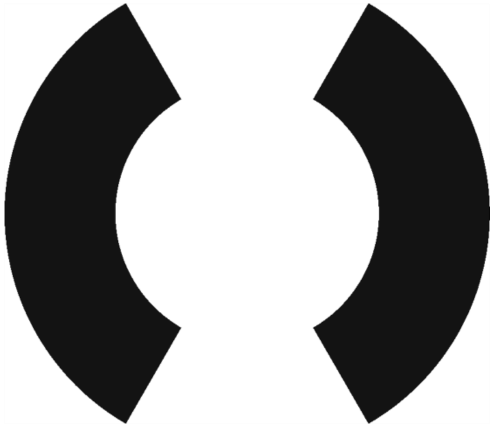
- With a w/r of 30/30 = 1 → 1.04

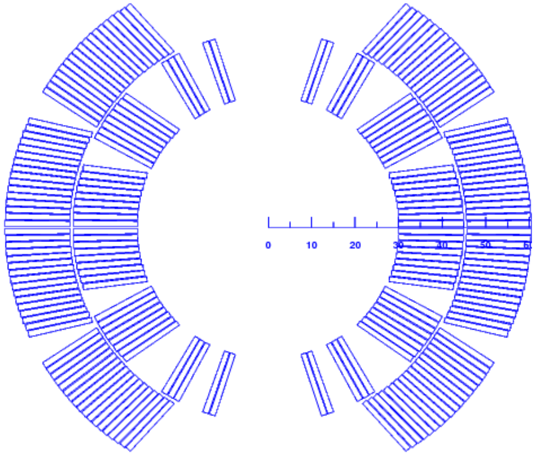
Computation of the load line
Sector coil

- $B_{bore\_op} = 11$ T
- $B_{bore\_ss} = B_{bore\_op} / 0.8 =$ 13.75 T
- $B_{peak\_ss} = B_{bore\_ss} \cdot 1.04 =$ 14.3 T



Comparison





Roxie		
	mu	1.2566E-06
Degree	alpha	
A/m2	J0	796112011
lambda		0.324
A/m2	Jsc	2455676180
A/mm2	Jsc	2456
m	a1	0.03
m	a2	0.0598
m	w	0.0298
T	B1	13.726939
	Bpeak/B1	1.04019549
T	Bpeak	14.2787

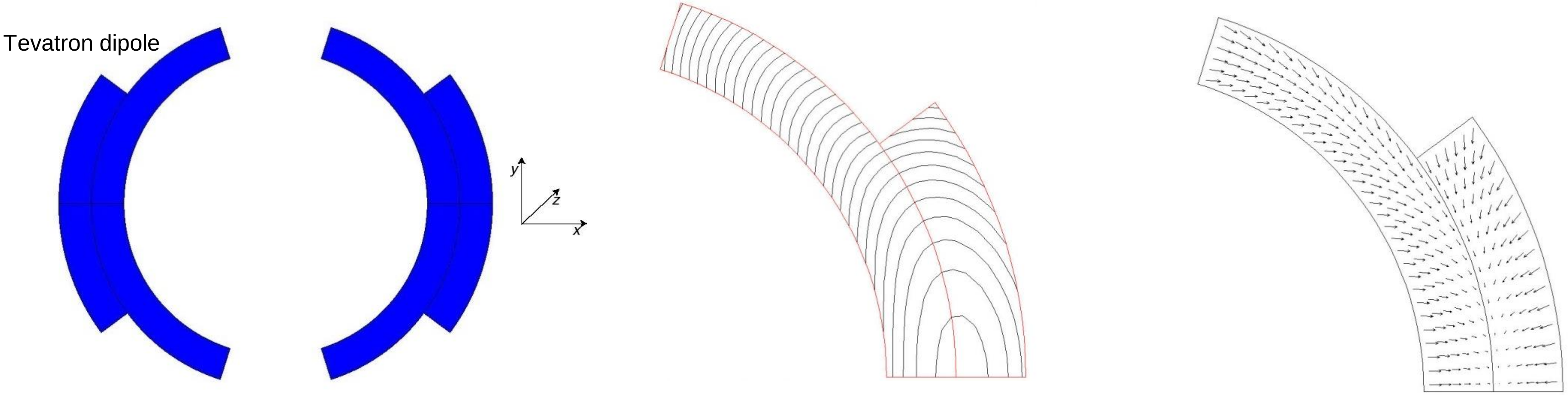
Case study

- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Question**
    - Determine e.m forces F_x and F_y and the accumulated stress on the coil mid-plane in the operational conditions with sector coil approximation

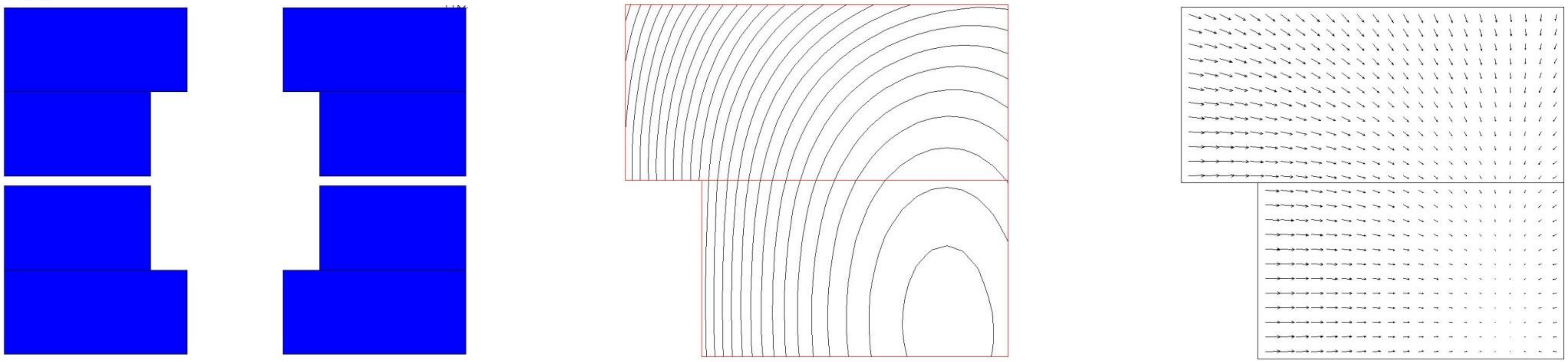
E.m. forces and stresses

- The e.m. forces in a dipole 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, $F_r > 0$)

Tevatron dipole

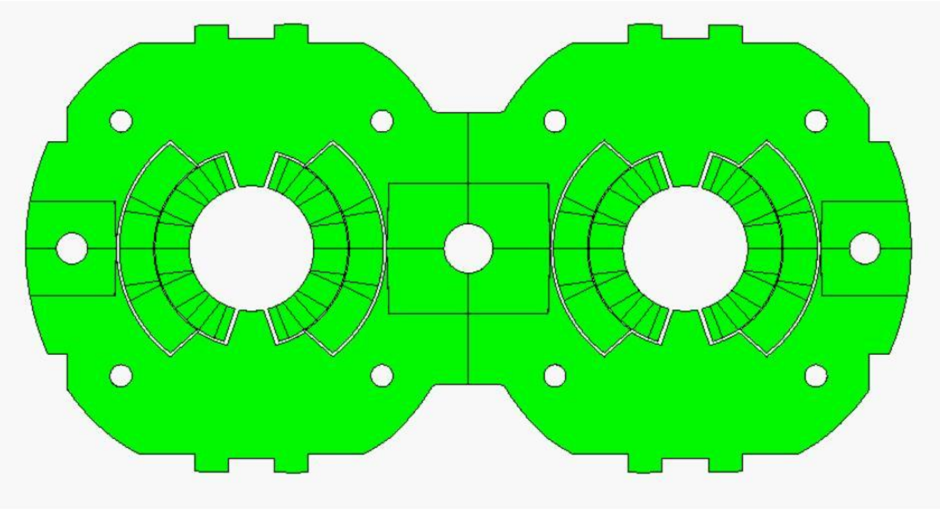


HD2

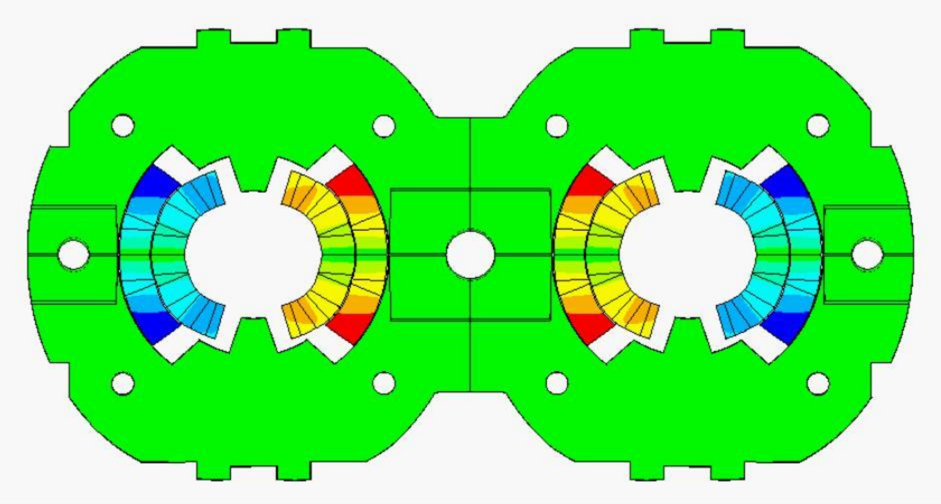


E.m. forces and stresses

LHC dipole at 0 T



LHC dipole at 9 T

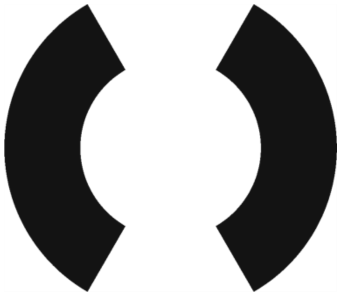


Displacement scaling = 50

- Usually, in a dipole or quadrupole magnet, the highest stresses are reached at the mid-plane, where all the azimuthal e.m. forces accumulate (over a small area).

E.m. forces and stresses
Sector coil approximation

- For a dipole sector coil, with an inner radius a_1, an outer radius a_2 and an overall current density j_o , each block (quadrant) see
  - Horizontal force outwards



$$F_x = +\frac{2\mu_0 J_0^2}{\pi}\frac{\sqrt{3}}{2}\left[\frac{2\pi-\sqrt{3}}{36}a_2^3+\frac{\sqrt{3}}{12}\ln\frac{a_2}{a_1}a_1^3+\frac{4\pi+\sqrt{3}}{36}a_1^3-\frac{\pi}{6}a_2a_1^2\right]$$

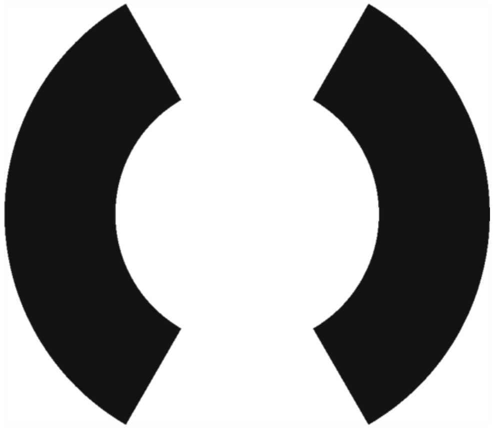
  - Vertical force towards the mid-plan

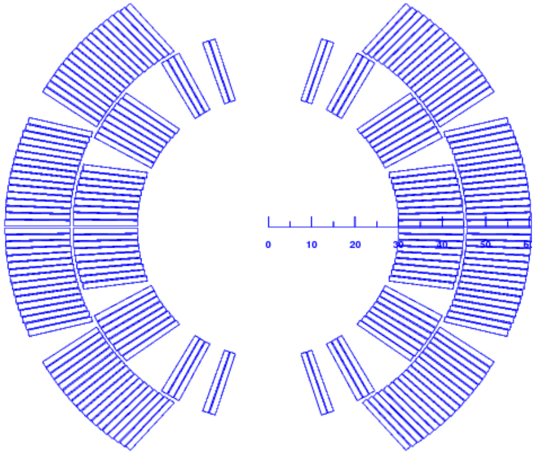
$$F_y = -\frac{2\mu_0 J_0^2}{\pi}\frac{\sqrt{3}}{2}\left[\frac{1}{12}a_2^3+\frac{1}{4}\ln\frac{a_1}{a_2}a_1^3-\frac{1}{12}a_1^3\right]$$

  - In case of frictionless and "free-motion" conditions, no shear, and infinitely rigid radial support, the forces accumulated on the mid-plane produce a stress of

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

Comparison





Roxie		
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Degree	alpha	
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lambda		0.324
A/m2	Jsc	2455676180
A/mm2	Jsc	2456
m	a1	0.03
m	a2	0.0598
m	w	0.0298
T	B1	13.726939
	Bpeak/B1	1.04019549
T	Bpeak	14.2787
N/m	Fx (quad)	4127000
N/m	Fy (quad)	-3294600
N/m	Fx tot	8254000

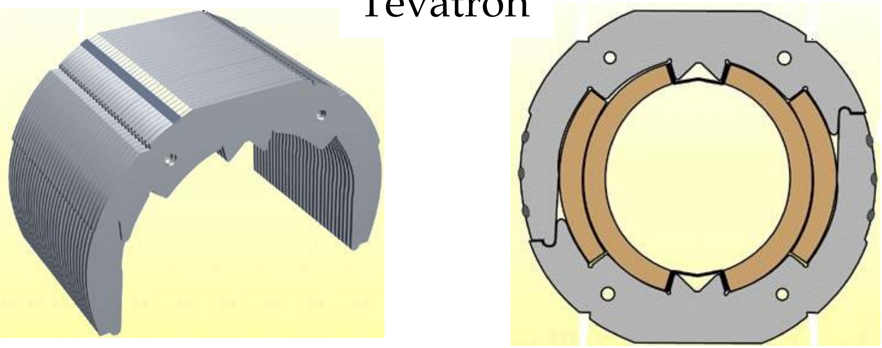
Case study

- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Question**
    - Evaluate dimension of collars, iron yoke, and shrinking cylinder, assuming that the support structure is designed to reach 90% of I_{ss}

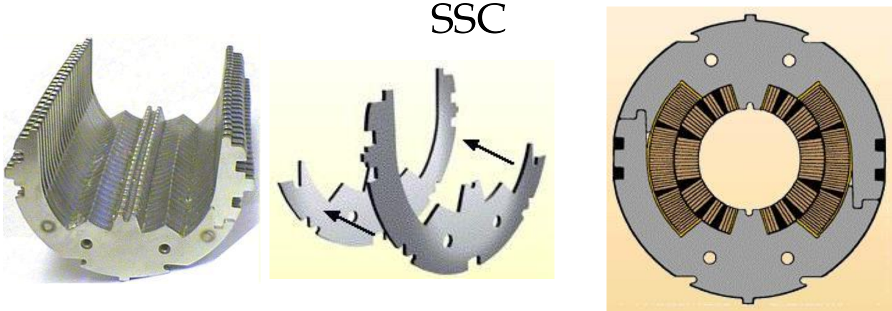
Support structure
Collars

- Collars were implemented for the first time in the Tevatron dipoles.
- Since then, they have been used in all but one (RHIC) the accelerator magnets and in most of the R&D magnets.
- They are 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 (it can be self-supporting or not);
  - precise cavity (tolerance ± 20 μm).

Tevatron

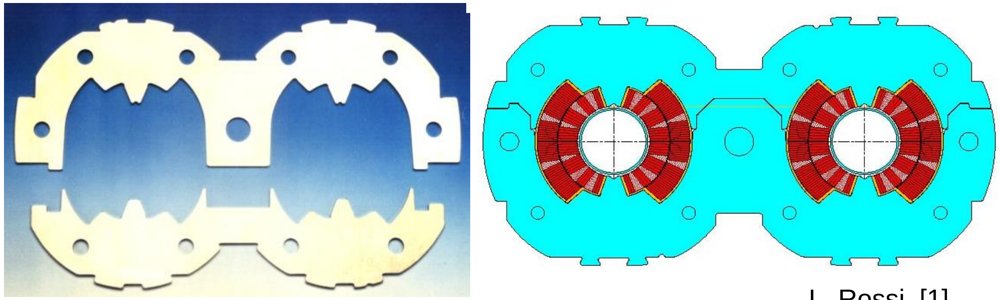


SSC



MJB Plus, Inc., [2]

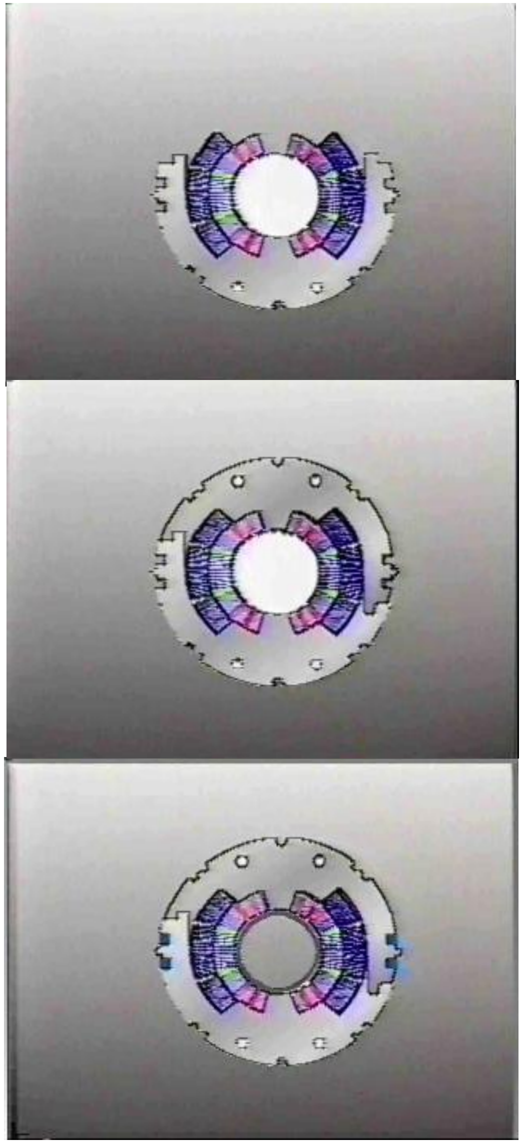
LHC



L. Rossi, [1]

Support structure
Collars

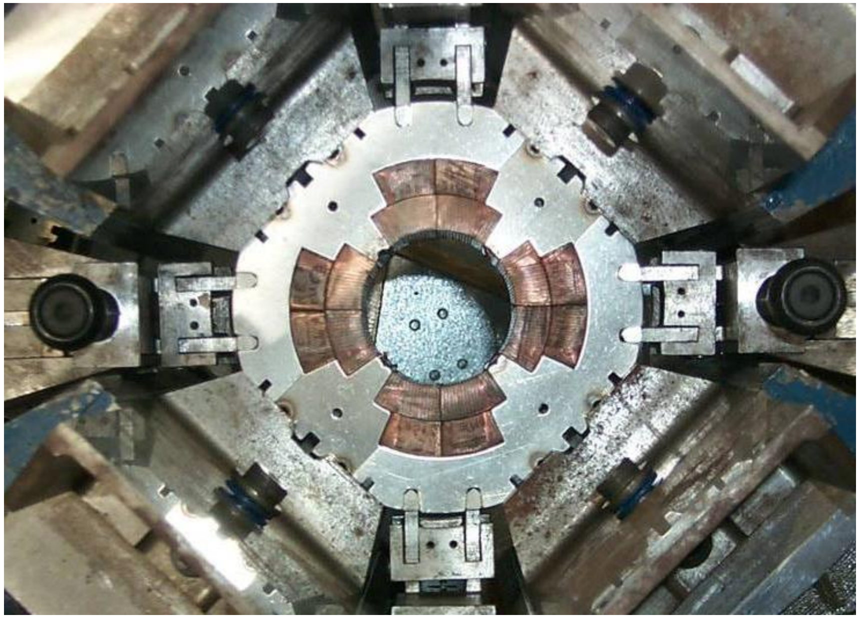
- Collaring procedure
  - Collars are pre-assembled in packs (several cm long) and placed around the coil.
    - The collar laminations are divided in “short” and “long”.
  - Since the uncompressed coil is oversized with respect to the collar cavity dimension, at the beginning of the collaring procedure 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 experience a “spring back” due to the clearance of the locking feature and deformation.



Support structure
Collars

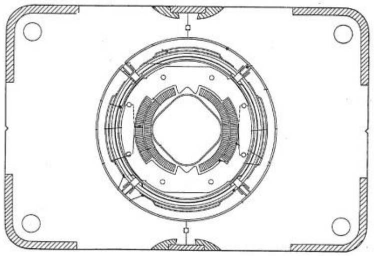
Collaring of a dipole magnet

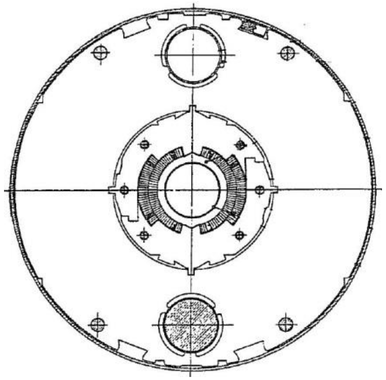
Collaring of a quadrupole magnet

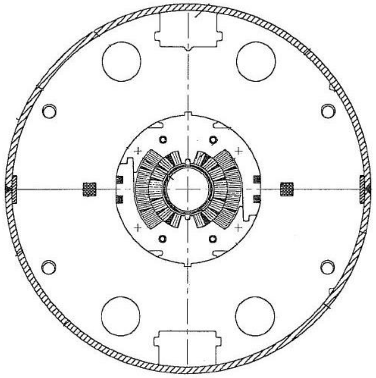


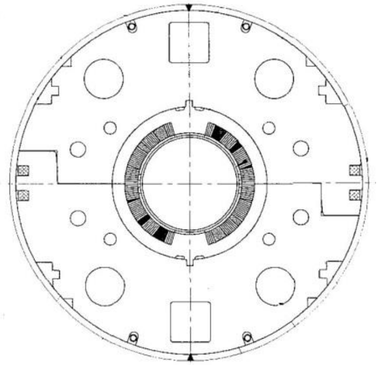
Dimension of the support structure
Collars

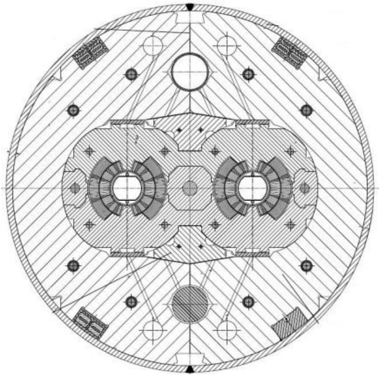
- We assume a 25 mm thick collar
  - Images not in scale

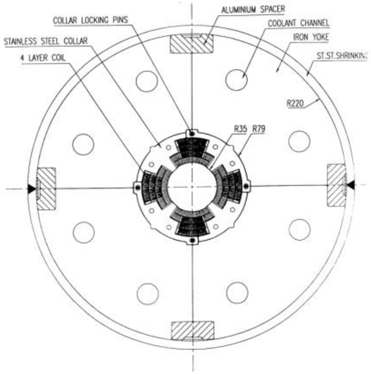


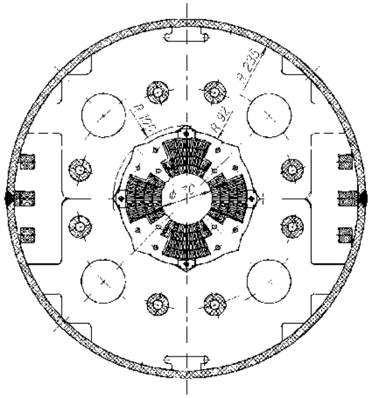


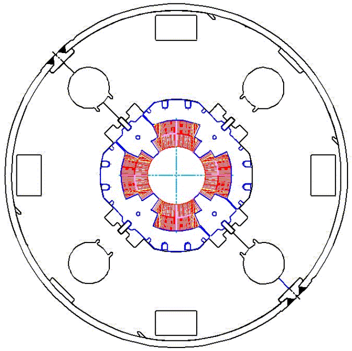




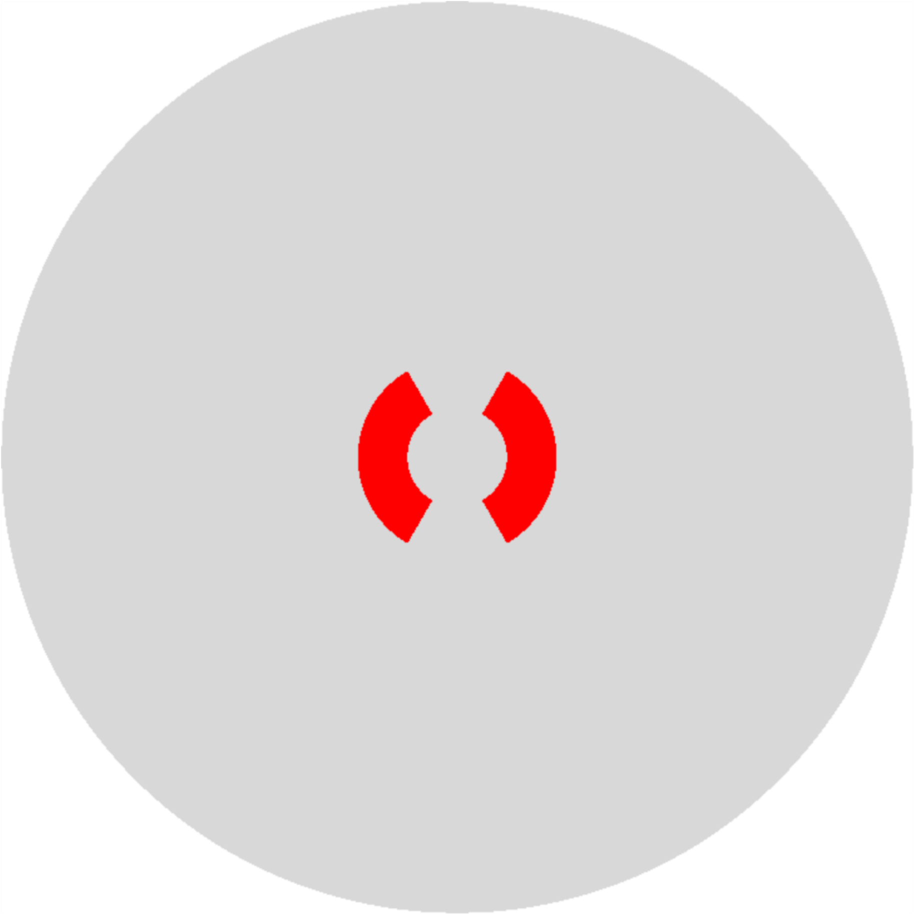


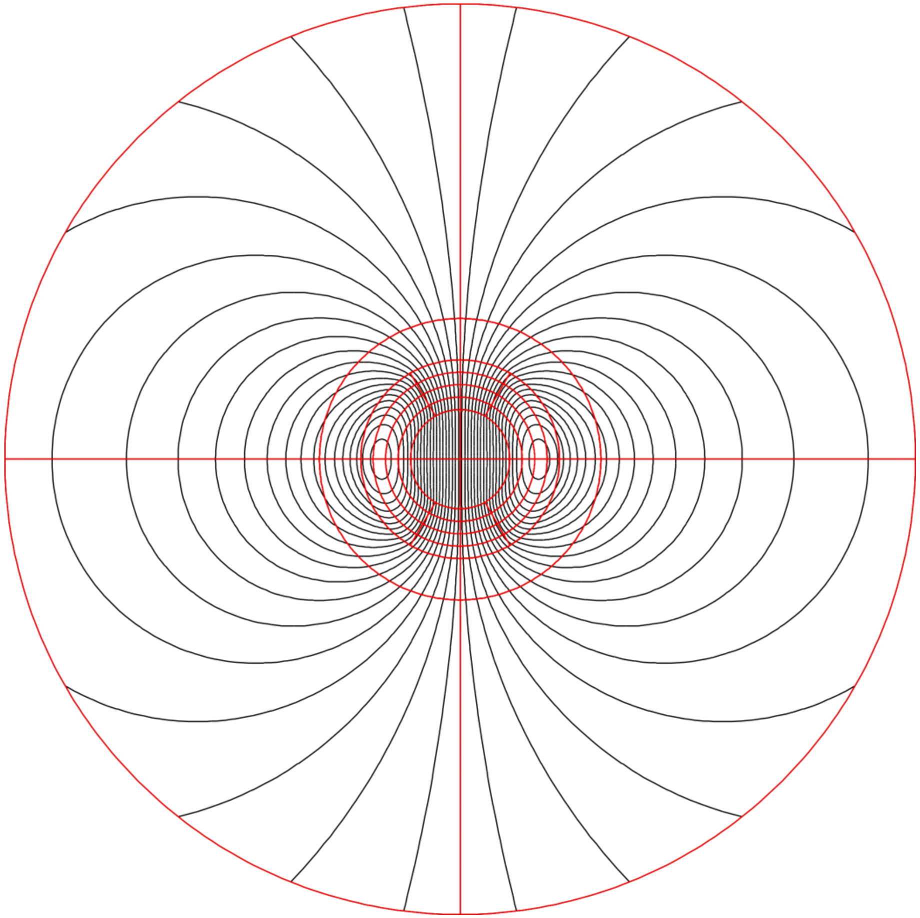




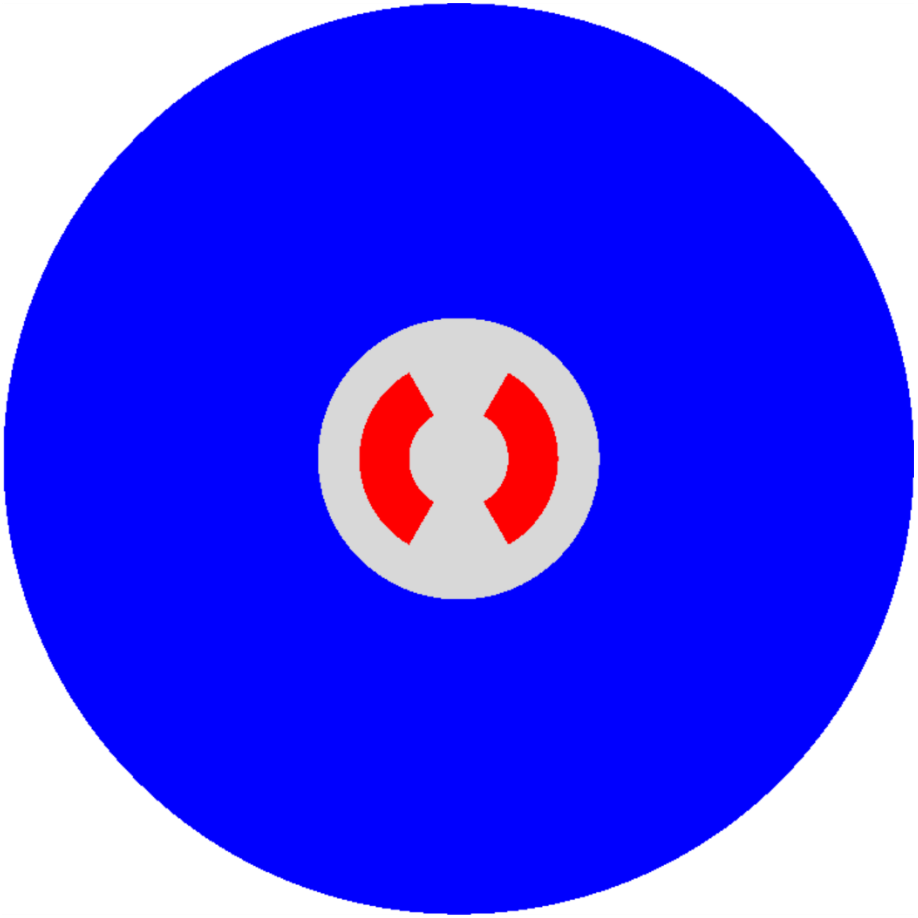


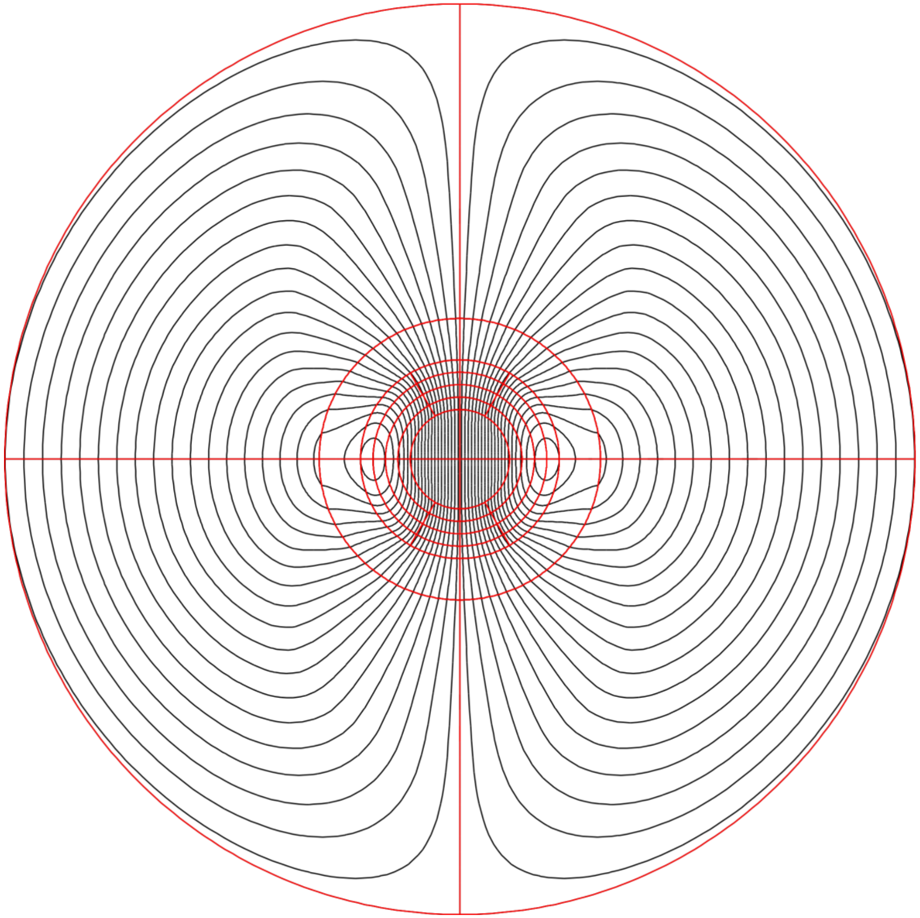
Without iron yoke





With iron yoke

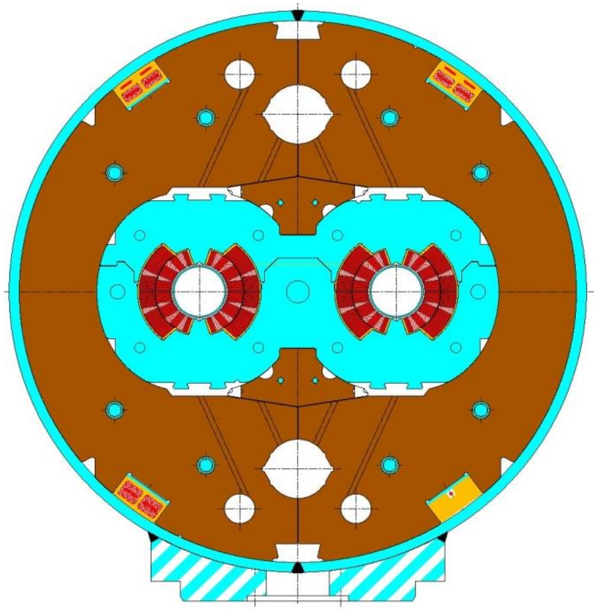


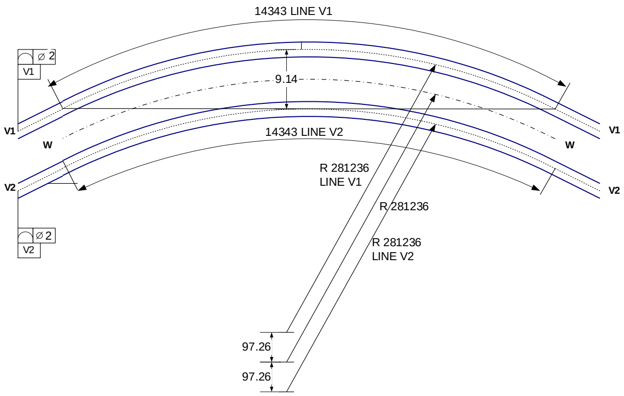


- The iron yoke thickness can be estimated with $rB \sim t_{iron} B_{sat}$

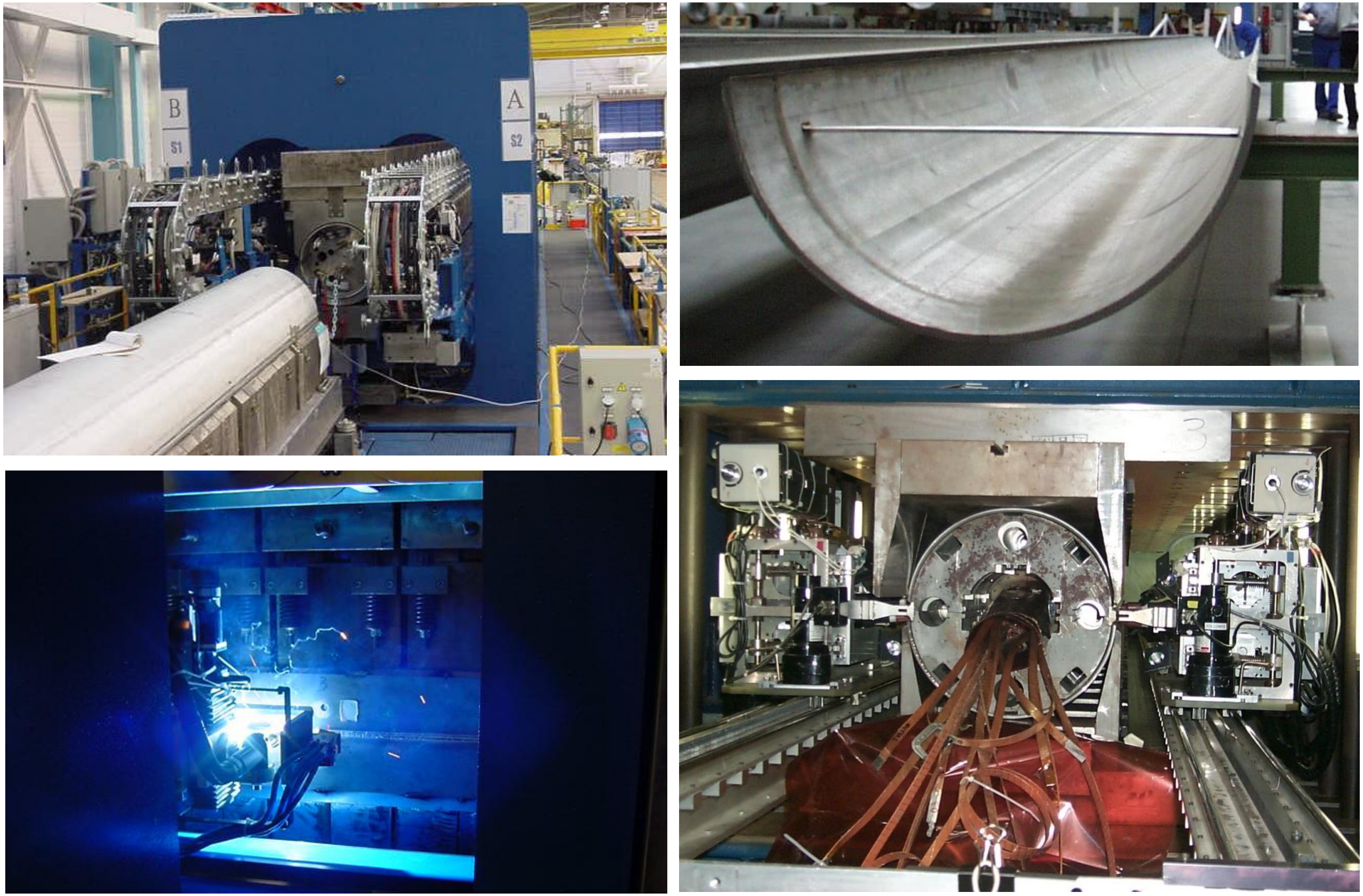
Support structure
Shell (or shrinking cylinder)

- The cold mass is contained within a shell (or shrinking cylinder).
- 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.



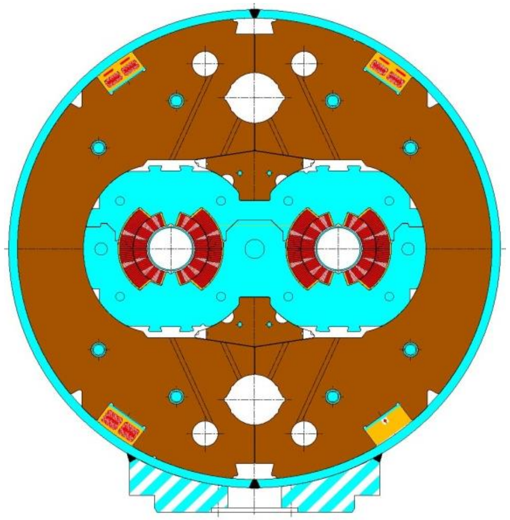


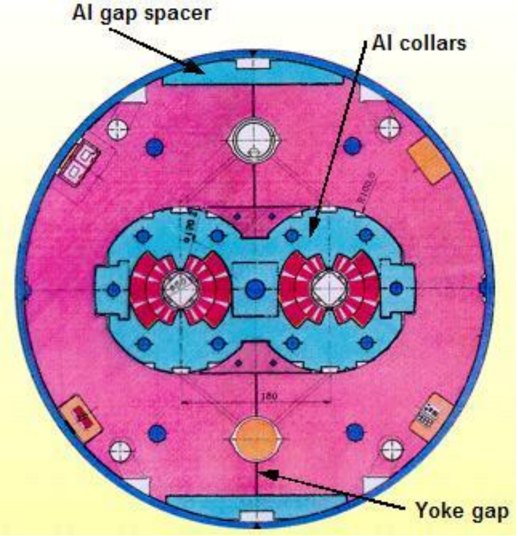
Support structure
Shell (or shrinking cylinder)



Support structure
Shell (or shrinking cylinder)

- The shell tension provided by the welding may contribute to the overall support of the collared coil.
- 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 remain closed (high rigidity), and the collared coil in good contact with the yoke.
- Aluminum spacer may be used to control the yoke gap.





Dimension of the support structure

- We assume that the shell will close the yoke halves with the same force as the total horizontal e.m. force at 90% of I_{ss}
- We assume an azimuthal shell stress after cool-down of
  - σ_{shell} = 200 MPa