Joint Universities Accelerator School

Mini-workshop on Superconductong Magnets

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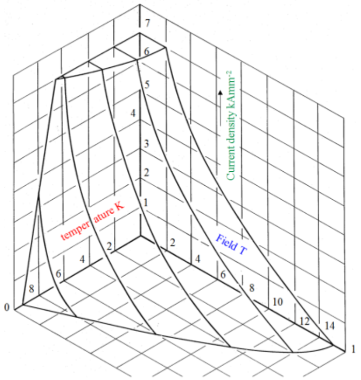
Thanks to Paolo Ferracin and Tiina Salmi

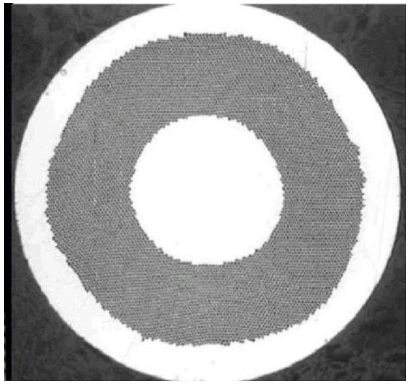
Mini-workshop introduction

- 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 (3 *credits*), deadline: 13th March 2017, 9:00 am, to be submitted to: daniel.schoerling@cern.ch

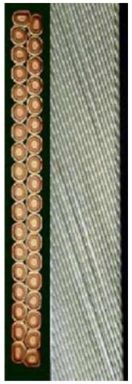
Superconducting material



Superconducting strand

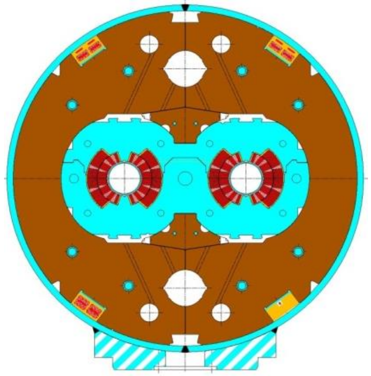


Superconducting cable



Superconducting coil

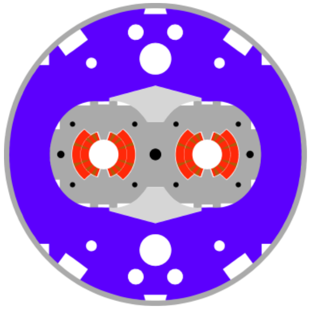
Superconducting magnet



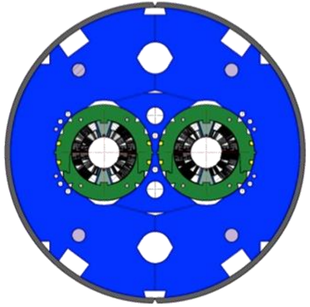
Case study

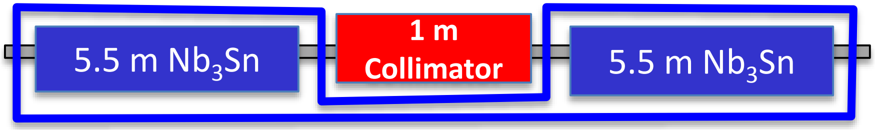
- 11 T Nb_3Sn dipole for the LHC collimation upgrade

14.3 m
Nb-Ti 8.3 T

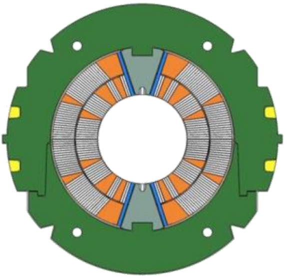


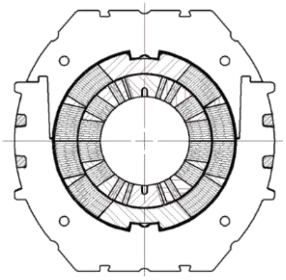
5.5 m
Nb_3Sn 11 T




5.5 m Nb_3Sn
1 m
Collimator
5.5 m Nb_3Sn

- Second long shutdown: increase of collimation efficiency
  - New collimation units
  - Some 8.3 T Nb-Ti dipoles replaced by **11 T Nb_3Sn dipoles**
  - FNAL/CERN collaboration





Case study

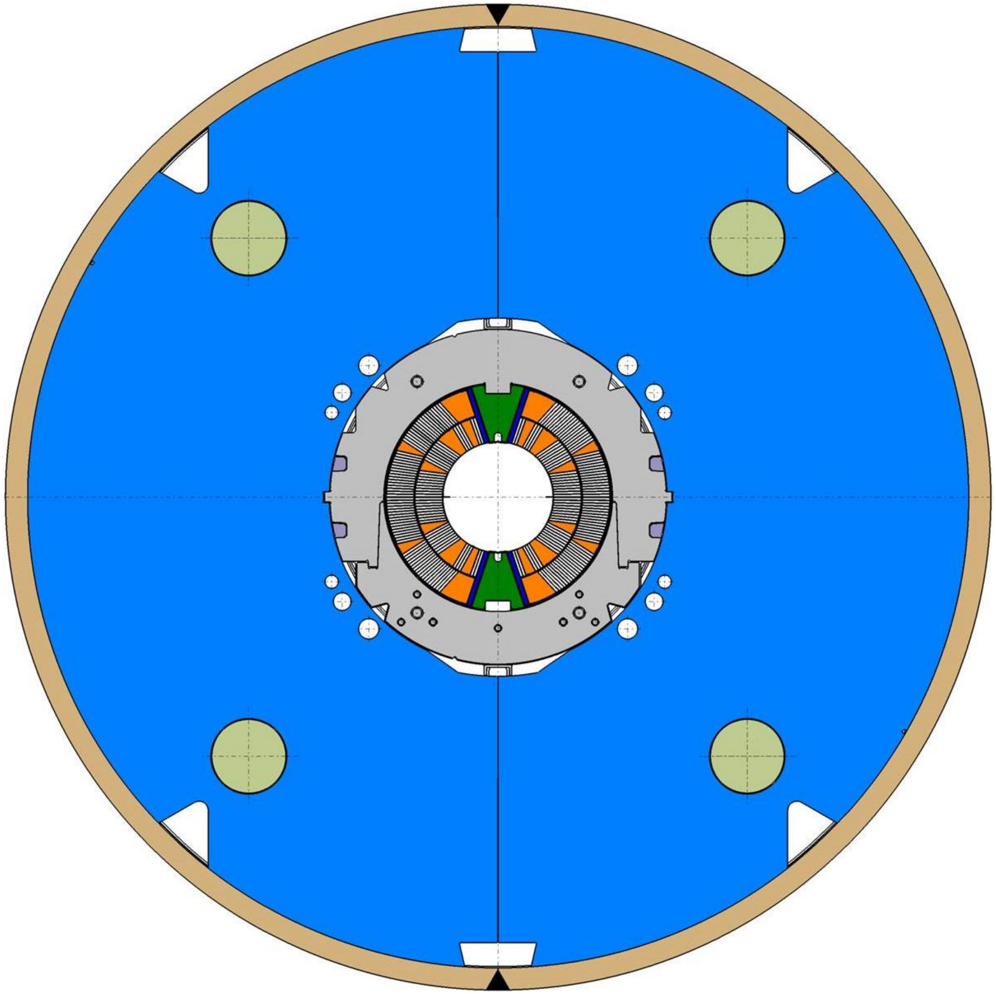
- 11 T Nb_3Sn dipole for the LHC collimation upgrade

  - **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 around points 2, 3, and 7.
    - 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 ($J_{\text{non-Cu}}$ vs. B) for Nb_3Sn and Nb-Ti at 1.9 K
    2. Determine the Cu/Non-Cu ratio to allow for protection of a short model with extraction resistor
    3. Determine coil filling factor λ (J_0 / $J_{\text{non-Cu}}$ ratio or $A_{\text{non-Cu\_cable}}/A_{\text{insulated\_cable}}$)
    4. Compute load-line ($J_{\text{non-Cu}}$ vs. B) for a
       1. Thick shell with $\cos\theta$ current density distribution
       2. Sector coil (60°) with constant current density
    5. Determine coil size, operational (80% of I_{ss}), conditions, "short-sample" conditions, and margins for both approximations
       1. w
       2. $J_{\text{non-Cu\_ss}}$, $J_{\text{o\_ss}}$, $B_{\text{bore\_ss}}$, $B_{\text{peak\_ss}}$
       3. $J_{\text{non-Cu\_op}}$, $J_{\text{o\_op}}$, $B_{\text{bore\_op}}$, $B_{\text{peak\_op}}$
       4. T, $J_{\text{non-Cu}}$, B_{peak} margins
    6. Determine e.m forces F_x and F_y and the accumulated stress on the coil mid-plane in the operational conditions with both the thick shell and sector coil approximation
    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

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  - **Question**
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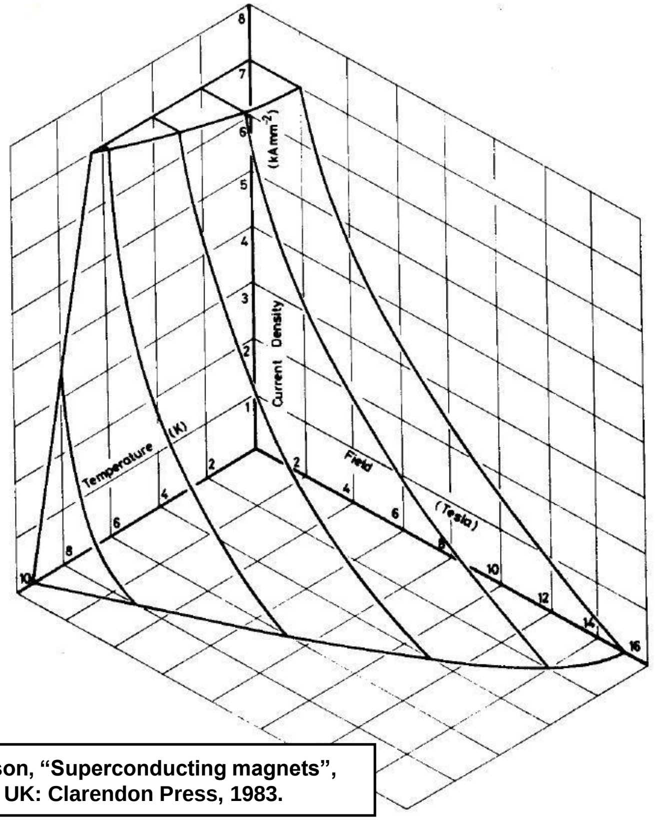
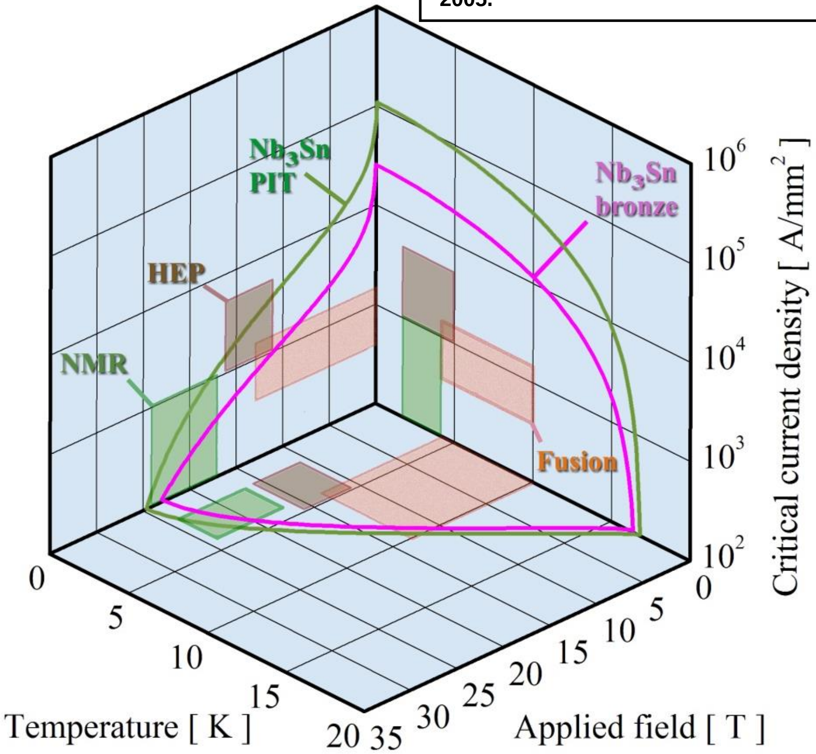
Nb-Ti and Nb_3Sn Critical surfaces

- 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

$$\frac{J_c(B,T)}{J_{c,\mathrm{ref}}} = \frac{C_{\mathrm{Nb\text{-}Ti}}}{B}\left[\frac{B}{B_{c2}(T)}\right]^{\alpha_{\mathrm{Nb\text{-}Ti}}}\left[1-\frac{B}{B_{c2}(T)}\right]^{\beta_{\mathrm{Nb\text{-}Ti}}}\left[1-\left(\frac{T}{T_{c0}}\right)^{1.7}\right]^{\gamma_{\mathrm{Nb\text{-}Ti}}}$$

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

Nb_3Sn parameterization curve (typical values for HEP magnets)

- Nb_3Sn parameterization (B. Bordini):

$$B_{c2}(T) = B_{c20} \cdot (1 - t^{1.52})$$

$$J_C = \frac{C(t)}{B} \cdot b^{0.5} \cdot (1 - b)^2$$

$$C(t) = C_0 \cdot (1 - t^{1.52})^{\alpha} \cdot (1 - t^2)^{\alpha}$$

- Where $t = \frac{T}{T_{c0}}$; $b = \frac{B}{B_{c2}(t)}$, with B as peak field on the conductor.
- T_{c0}, B_{c20}, a, C_0 are fitting parameters computed from the analysis of measurements on the conductor.
- For a reasonable estimate of the critical current density of a round wire, magnet designers can assume the following parameters: T_{c0} = 16 K, B_{c20} =29.38 T, a = 0.96, C_0 = 213000 A/mm^2 T. Self-field is included.
- The target for future HEP projects is ~25% larger.

Parameterization curves

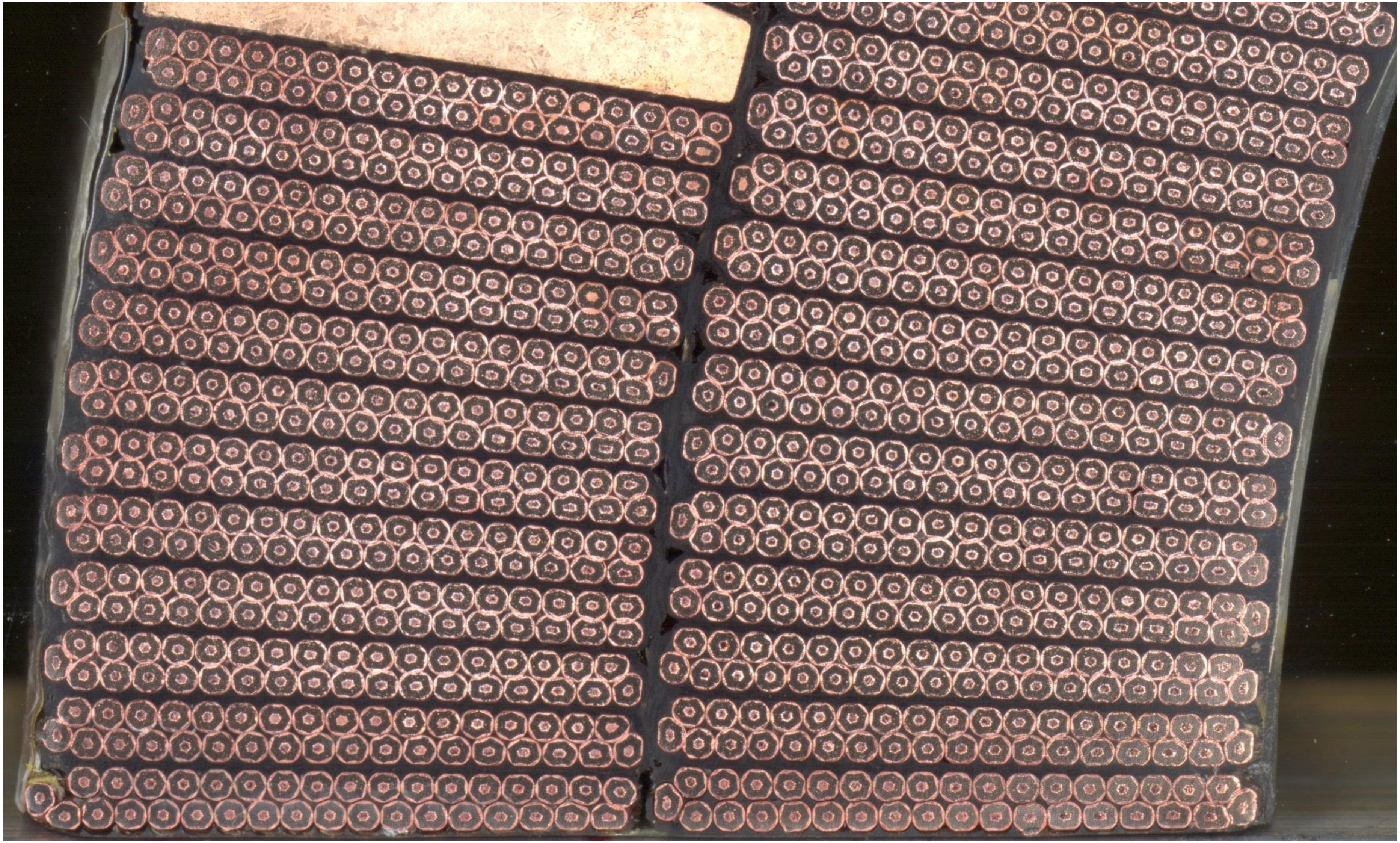
- References

  - 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.
  - B. Bordini, personal communication.

Case study

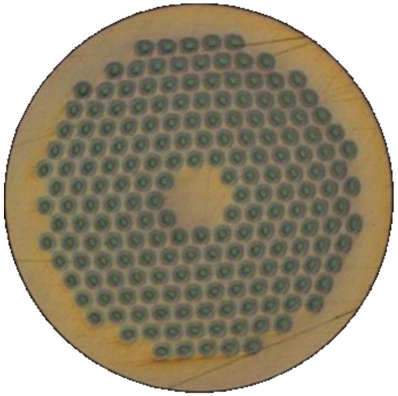
- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Question**
    - Determine the Cu/Non-Cu ratio to allow for protection of a short model (L = 2 m) with extraction resistor
    - Determine coil filling factor λ ($J_0 / J_{\text{non-Cu}}$ ratio or $A_{\text{non-Cu\_cable}} / A_{\text{insulated\_cable}}$)

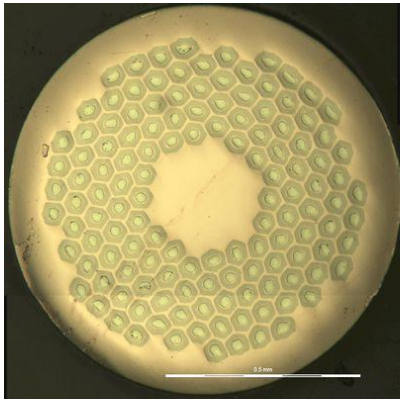
Superconducting cables and coils

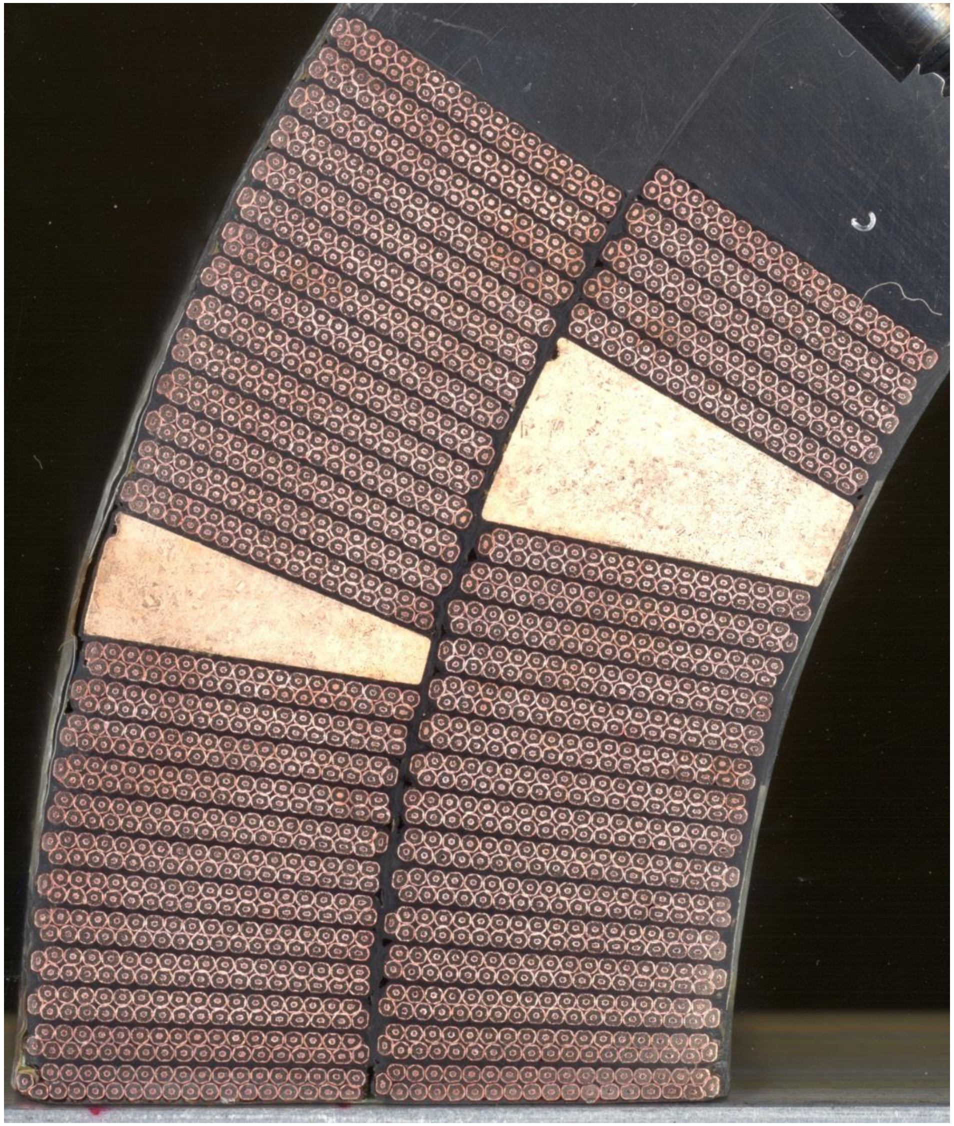


$J_0 / J_{\text{non-Cu}}$ ratio

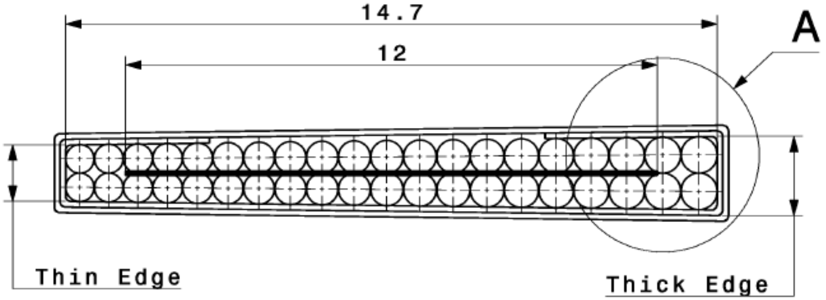
- The cable design parameters are:
  - Number of wires N_{wire}
  - Wire diameter d_{wire}
  - Cable mid-thickness t_{cable}
  - Cable width w_{cable}
  - (Cu/non-Cu) ratio
  - Insulation thickness
  - Pitch angle
    - To be neglected in this comp.



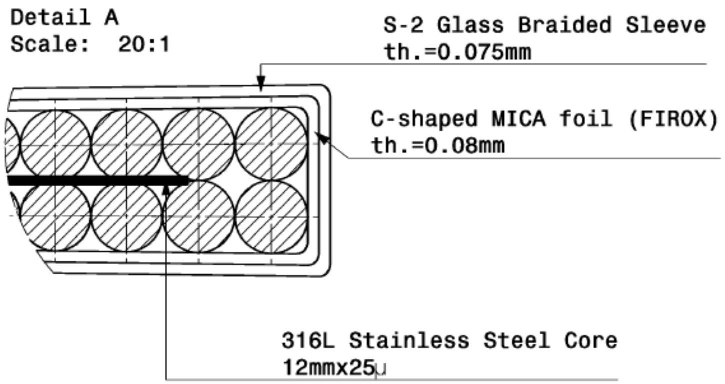


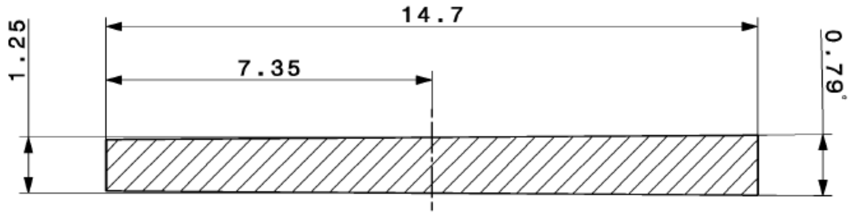


J_0 vs. $J_{\text{non-Cu}}$



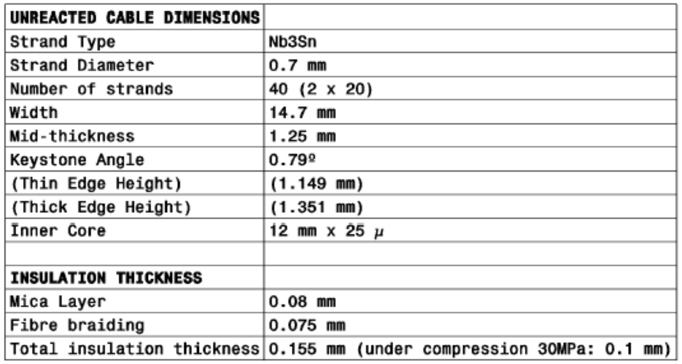
Enlarged and not to scale,
for illustration purposes only





DIMENSION FOR
CONDUCTOR WITHOUT INSULATION
Scale:10:1

$$\text{Keystone Angle} = \operatorname{atan}\left(\frac{\text{Thick Edge} - \text{Thin Edge}}{\text{Width}}\right)$$

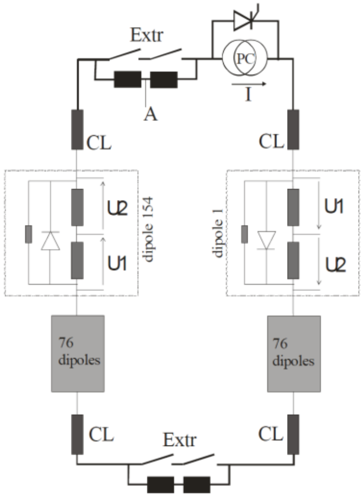


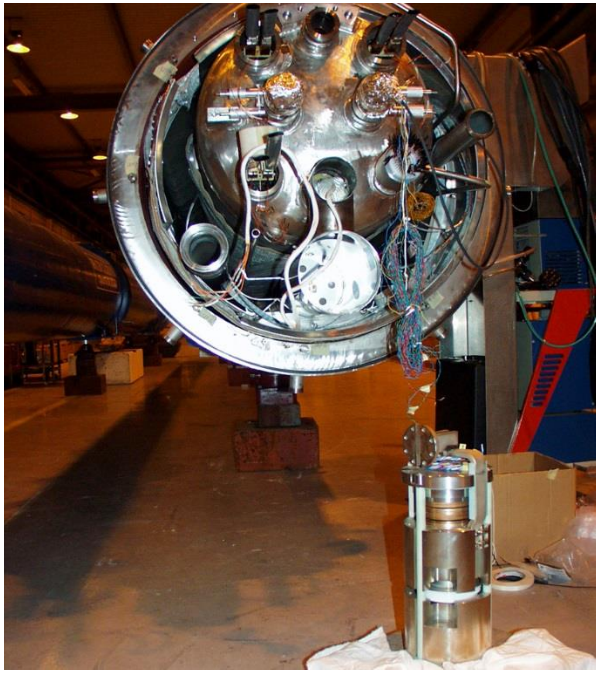
UNREACTED CABLE DIMENSIONS	
Strand Type	Nb3Sn
Strand Diameter	0.7 mm
Number of strands	40 (2 x 20)
Width	14.7 mm
Mid-thickness	1.25 mm
Keystone Angle	0.79º
(Thin Edge Height)	(1.149 mm)
(Thick Edge Height)	(1.351 mm)
Inner Core	12 mm x 25 μ
INSULATION THICKNESS	
Mica Layer	0.08 mm
Fibre braiding	0.075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

- Cu to non-Cu ratio: ?

Magnet protection

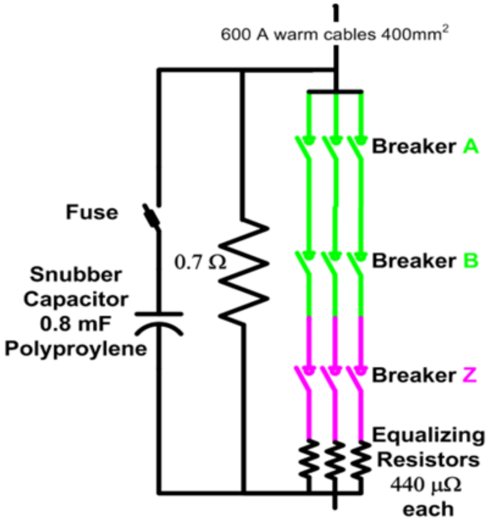
- Electrical network of a quenching magnet in a string:
  - Inductance of circuit *L* is large (LHC dipole circuit L = 15.4 H, τ = 95 s, 8 circuits)
  - Maximum allowed voltage to ground *U* is limited (LHC dipoles U = 1.9 kV)
  - Magnet is quenched with quench heaters and current is by-passed with a diode

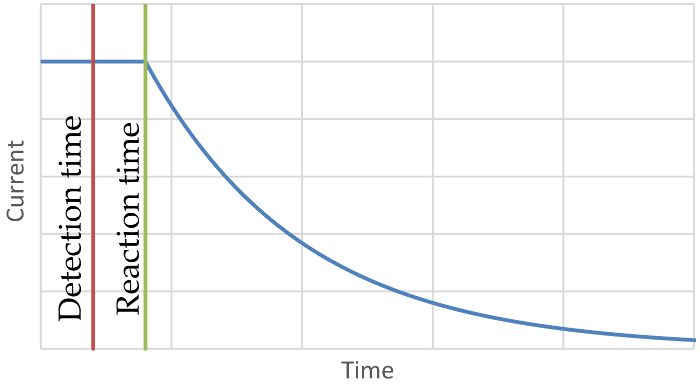




Magnet protection

- Stand-alone SC magnet (energy is extracted with a resistor):
  - Adiabatic, one dimensional approximation: $\frac{I^2(t)\rho}{A}\mathrm{d}t = A \cdot d \cdot C(T)\mathrm{d}T$
  - Circuit and material properties can be separated: $\int_0^{t_0} I^2 \mathrm{d}t = A^2 d \int_{T_0}^{T_1} \frac{C(T)}{\rho(T)} \mathrm{d}T$
  - Left side of equation: $Z = \int_0^{t_1} I^2 \mathrm{d}t = I_0^2 \left(\Delta t + \right.$

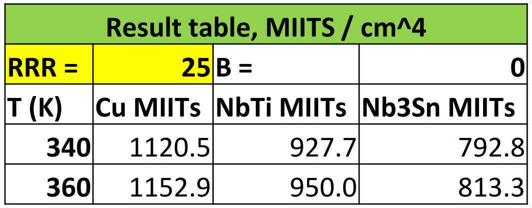




Magnet protection

- Calculate Cu/non-Cu ratio for 350 K maximum allowed temperature increase at 11 T and RRR 100
- η = Cu/Non-Cu; $\zeta_i = Z_i / A_{\mathrm{Cu}}^2$ (see table, *i* = Cu, Nb-Ti, Nb_3Sn)
- Quench load: $Z = A_{\mathrm{Cu}}^2 \left[\zeta_{\mathrm{Cu}} + \frac{\zeta_{\mathrm{N-Cu}}}{\eta} \right] = A_{\mathrm{cable}}^2 \left(\frac{\eta}{1+\eta} \right)^2 \left[\zeta_{\mathrm{Cu}} + \frac{\zeta_{\mathrm{N-Cu}}}{\eta} \right]$

B (T)	RRR
0	100
11	26



Result table, MIITS / cm^4			
RRR =	25	B =	0
T (K)	Cu MIITs	NbTi MIITs	Nb3Sn MIITs
340	1120.5	927.7	792.8
360	1152.9	950.0	813.3

$$\zeta_i = \frac{d_i \cdot \int_{T_0}^{T_1} \frac{C_i(T)}{\rho_{\mathrm{Cu}}(T)} \mathrm{d}T}{A_{\mathrm{Cu}}^2}$$

Magnet protection

$$\frac{d_i \cdot \int_{T_0}^{T_1} \frac{C_i(T)}{\rho_{\mathrm{Cu}}(T)}\,\mathrm{d}T}{A_{\mathrm{Cu}}^2}$$

B (T)	RRR
0	100
1	83
2	70
3	59
4	51
5	45
6	40
7	36
8	33
9	31
10	28
11	26
12	25
13	23
14	22
15	21
16	20
17	19
18	18
19	17
20	16

Result table, MIITS / cm^4			
RRR =	**100**	**B =**	**0**
T (K)	**Cu MIITs**	**NbTi MIITs**	**Nb3Sn MIITs**
10	1.2	4.0	5.5
20	17.9	39.9	38.9
30	84.4	155.5	129.6
40	202.6	334.7	257.3
50	331.6	486.7	375.6
60	449.0	602.6	470.9
70	550.7	692.3	546.7
80	637.7	763.7	607.7
90	712.6	822.5	658.2
100	778.1	872.7	701.2
120	888.9	955.7	772.4
140	981.0	1023.6	830.9
160	1060.4	1081.3	881.2
180	1130.5	1131.5	925.5
200	1193.5	1175.6	965.1
220	1250.8	1214.9	1001.1
240	1303.4	1250.3	1033.9
260	1351.9	1282.5	1064.1
280	1396.8	1312.4	1092.0
300	1438.4	1340.6	1117.9
320	1477.0	1367.2	1142.0
340	1512.9	1391.9	1164.6
360	1546.4	1415.0	1185.9
380	1577.9	1436.7	1206.0
400	1607.5	1457.1	1225.0

Result table, MIITS / cm^4			
RRR =	**50**	**B =**	**0**
T (K)	**Cu MIITs**	**NbTi MIITs**	**Nb3Sn MIITs**
10	0.6	2.0	2.3
20	9.1	20.2	19.2
30	45.5	83.5	68.7
40	119.9	195.8	148.9
50	213.5	305.9	234.6
60	307.7	398.8	311.1
70	394.8	475.6	375.9
80	472.3	539.2	430.3
90	541.0	593.1	476.6
100	602.0	639.9	516.6
120	707.0	718.5	584.1
140	795.4	783.7	640.2
160	872.1	839.5	688.8
180	940.3	888.2	731.9
200	1001.8	931.3	770.6
220	1057.8	969.7	805.7
240	1109.4	1004.4	837.9
260	1157.0	1036.1	867.6
280	1201.2	1065.5	895.0
300	1242.2	1093.3	920.5
320	1280.3	1119.5	944.3
340	1315.7	1143.9	966.7
360	1348.8	1166.8	987.7
380	1380.0	1188.2	1007.5
400	1409.3	1208.4	1026.4

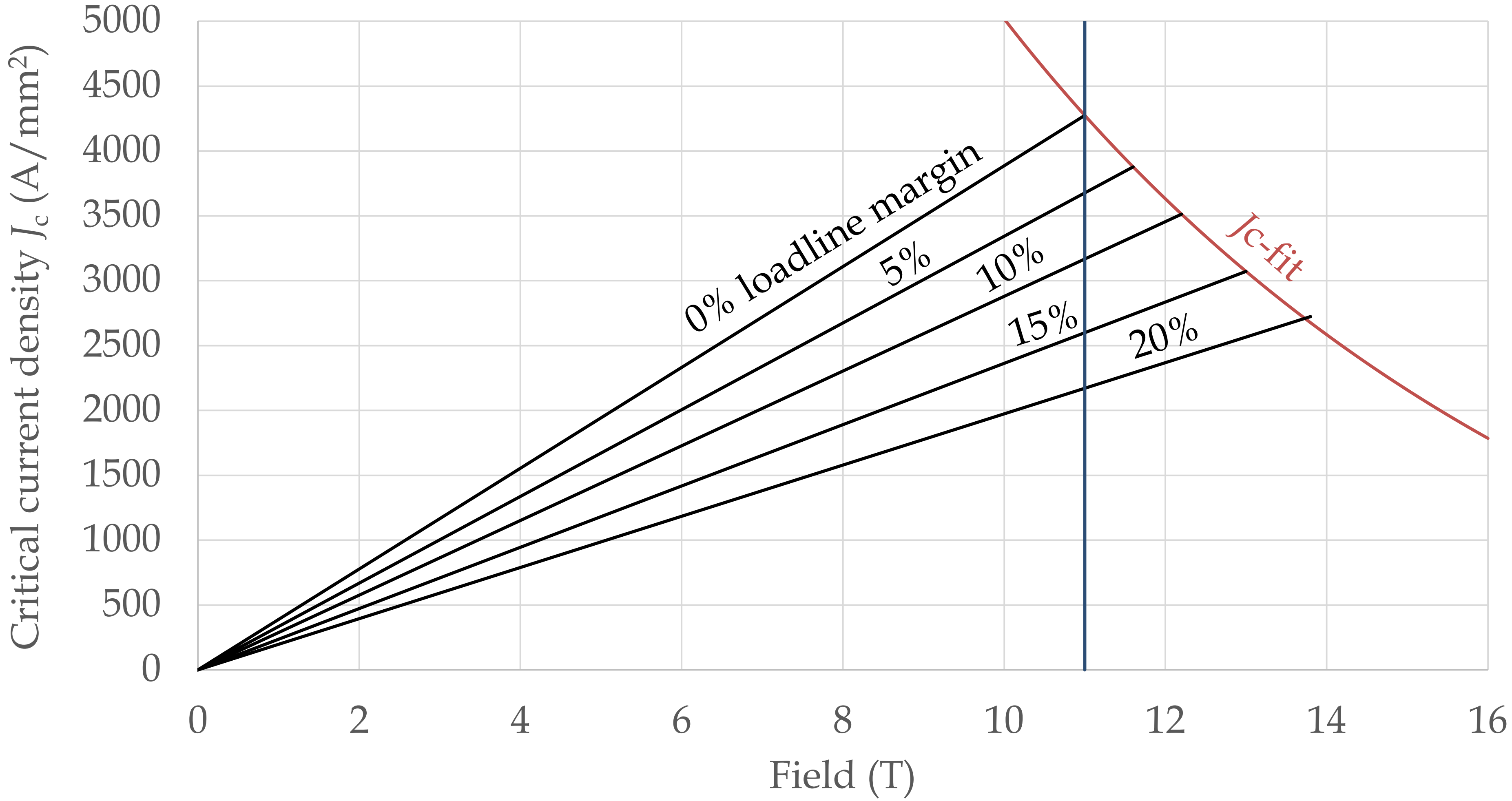
Result table, MIITS / cm^4			
RRR =	**25**	**B =**	**0**
T (K)	**Cu MIITs**	**NbTi MIITs**	**Nb3Sn MIITs**
10	0.3	1.0	1.1
20	4.6	10.2	9.7
30	23.7	43.4	35.7
40	67.0	108.6	82.2
50	128.9	181.3	138.8
60	198.0	249.3	194.9
70	266.7	309.8	246.0
80	331.1	362.7	291.2
90	390.2	409.2	331.0
100	444.3	450.5	366.5
120	539.5	521.8	427.7
140	621.4	582.2	479.7
160	693.5	634.7	525.3
180	758.1	680.9	566.1
200	816.8	722.0	603.1
220	870.5	758.8	636.8
240	920.2	792.2	667.8
260	966.2	822.8	696.5
280	1009.0	851.3	723.1
300	1048.9	878.3	747.8
320	1085.9	903.9	771.0
340	1120.5	927.7	792.8
360	1152.9	950.0	813.3
380	1183.3	971.0	832.7
400	1212.0	990.7	851.2

Case study

- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Question**
    - Compute load-line ($J_{\text{non-Cu}}$ vs. B) for a
      - Thick shell with $\cos\theta$ current density distribution
      - Sector coil (60°) with constant current density
    - Determine coil size, operational (80% of I_{ss}), conditions, “short-sample” conditions, and margins for both approximations
      - w
      - $J_{\text{non-Cu\_ss}}$, $J_{\text{o\_ss}}$, $B_{\text{bore\_ss}}$, $B_{\text{peak\_ss}}$
      - $J_{\text{non-Cu\_op}}$, $J_{\text{o\_op}}$, $B_{\text{bore\_op}}$, $B_{\text{peak\_op}}$
      - T, $J_{\text{non-Cu}}$, B_{peak}; current and temperature margins

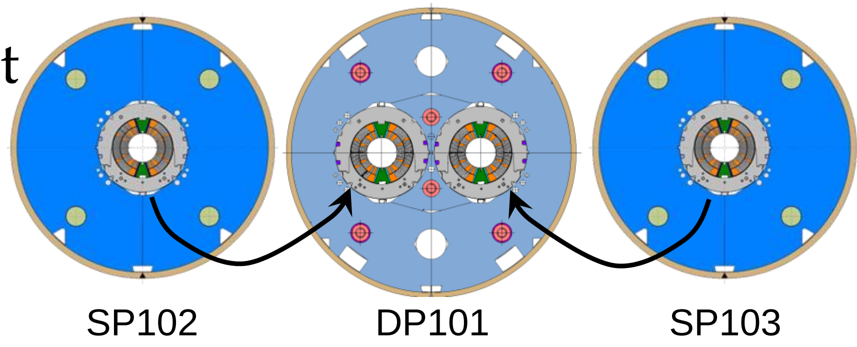
Load line concept

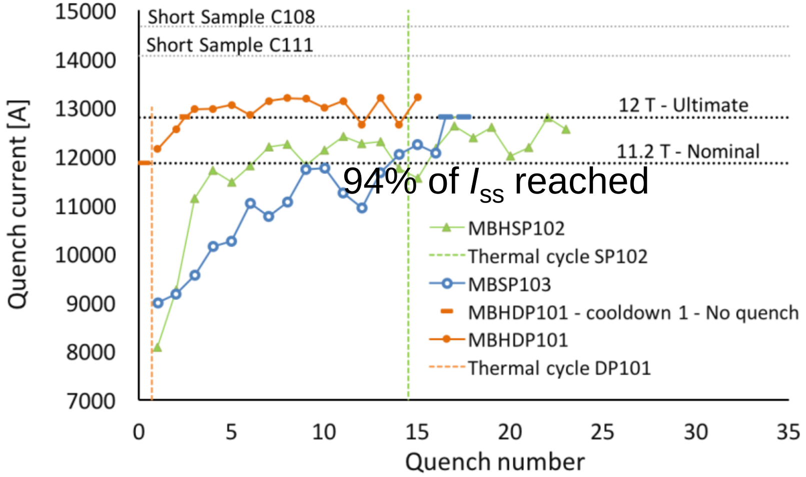
- What is a load line and a load line margin?



Short sample and operational current

- Loadline margin is most widely used because of its simplicity and possibility of easily compare different designs to each other
- Two strategies could be selected:
  - Select a loadline margin such that the first quench is above nominal current (no training)
  - Select a loadline margin such that after training and thermal cycle the next quench is above the nominal current
- Regular re-training in the machine is not an option for a large number of magnets powered in series
- We select 80% loadline margin

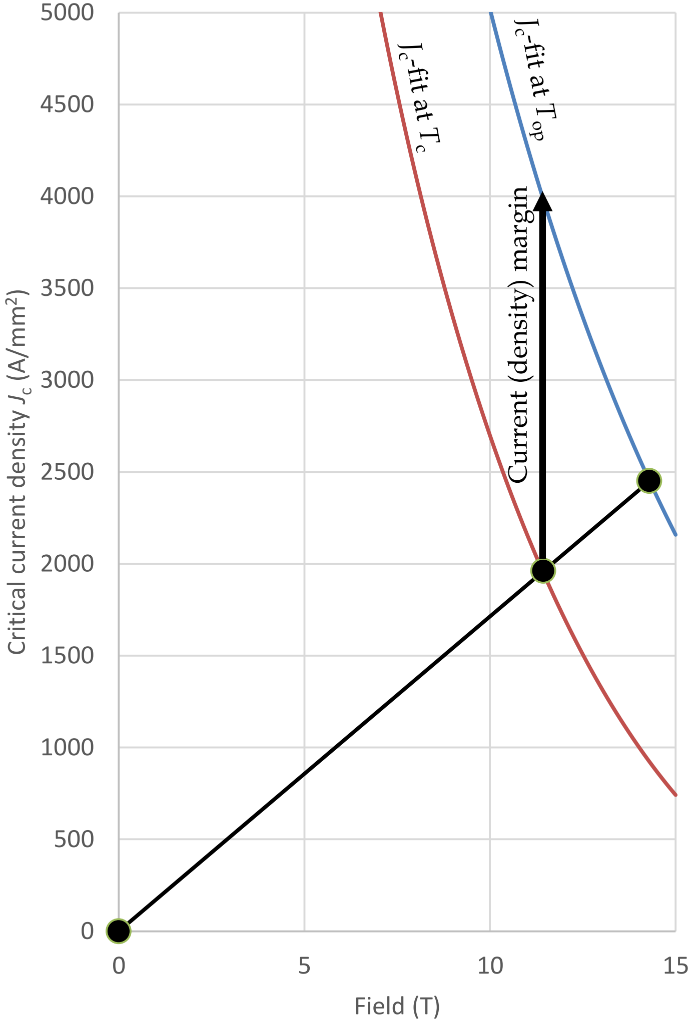




94% of I_{ss} reached

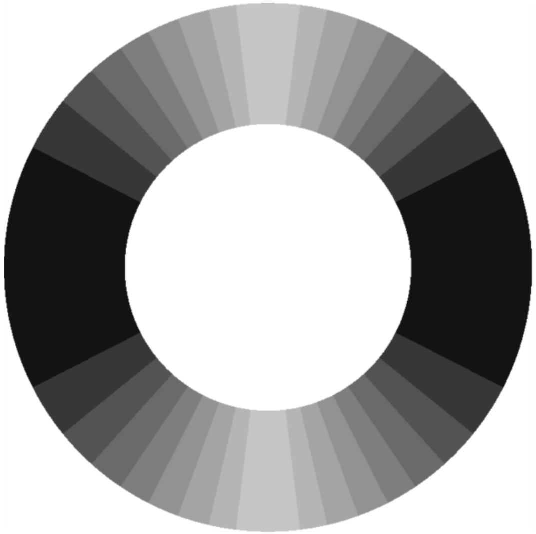
Physical margins

- Current density margin ($J_c(B_{op}, T_{op})$-$J_{\text{non-Cu\_op}}$):
  - current (re-)distribution in the cable
  - variation in the strand production
  - local strain
  - performance variations
- Temperature margin $T_c(B_{op}, B_{op}/B_{ss} \cdot J_c(B_{ss}, T_{op})) - T_{op}$:
  - continuous losses (in conjunction with mechanism of heat extraction)
  - instantaneous losses (e.g., coil movements; enthalpy margin: $\int_{T_{\mathrm{op}}}^{Tc} \rho c_p(T)\mathrm{d}T$)

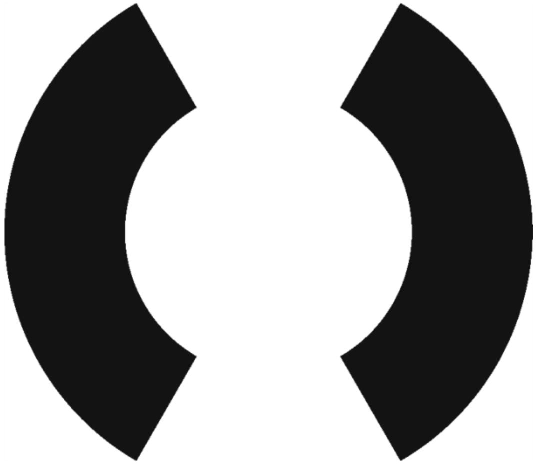


Computation of the load line
Approximations of practical winding cross-sections

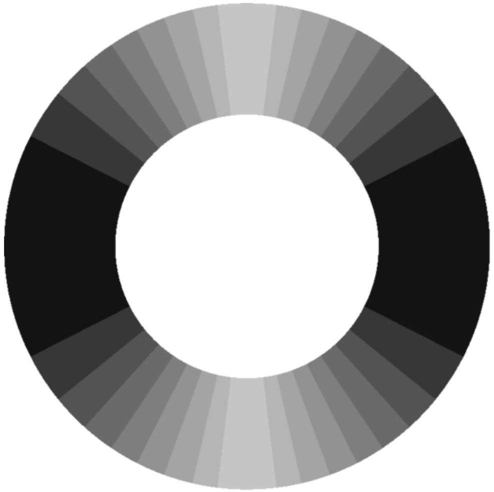
- Thick shell
  - Current density $J = J_0 \cos\theta$ (A per unit area) on a shell with a finite thickness

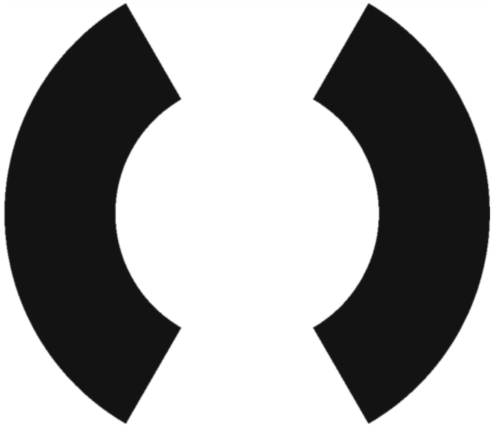


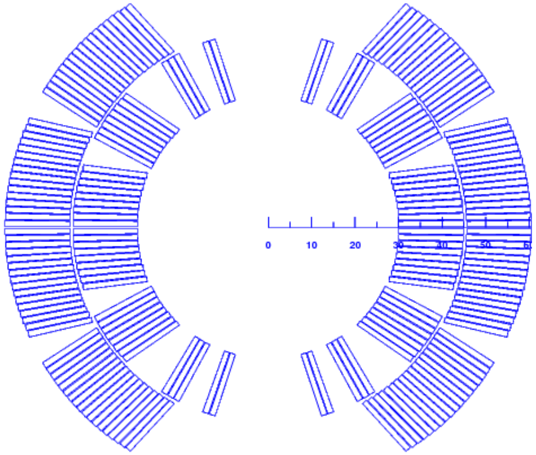
- Sector coil
  - Current density $J = J_0$ (A per unit area) on a a sector with a maximum angle $\theta = 60^{\circ}$ for a dipole



Approximations of practical winding cross-sections





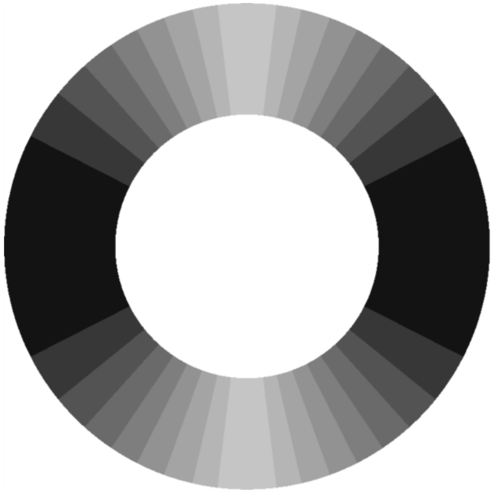


Computation of the load line
Approximations of practical winding cross-sections

- Thick shell
  - Current density $J = J_0 \cos\theta$ on a shell with a finite thickness

$$B_{\mathrm{bore}} = -\frac{J_0 \mu_0}{2} w$$

  - Where, B_{bore} is the bore field, J_0 is overall current density and w is the coil width
  - Ideal case
    - ***Conductor peak field*** $B_{peak} = B_{bore}$
    - Perfect field quality
      - No field errors
        - $b_3 = b_5 = b_7 = \ldots = 0$



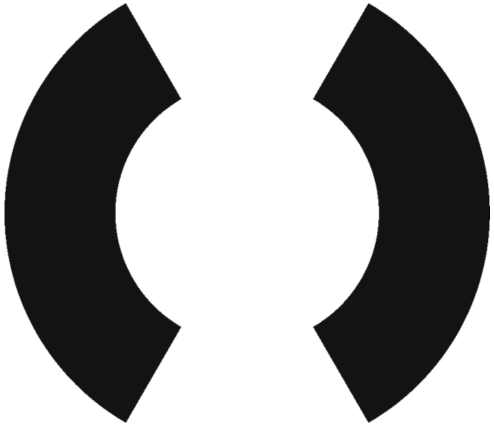
- Comparison:
  - For solenoid
    - $B_1 = -J_0 \mu_0 w$
    - Twice more efficient than a dipole

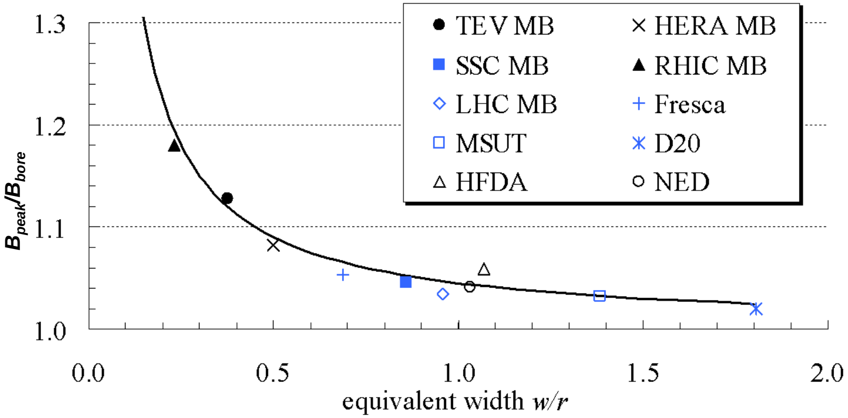
Computation of the load line
Approximations of practical winding cross-sections

- 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

$$B_{\text{bore}} = -\frac{2J_0\mu_0}{\pi} w\sin(60)$$

  - Where, B_{bore} is the bore field, J_0 is overall current density and w is the coil width
  - "Less ideal" case
    - $B_{\text{peak}} = B_{\text{bore}} \cdot \sim 1.04$
    - "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.

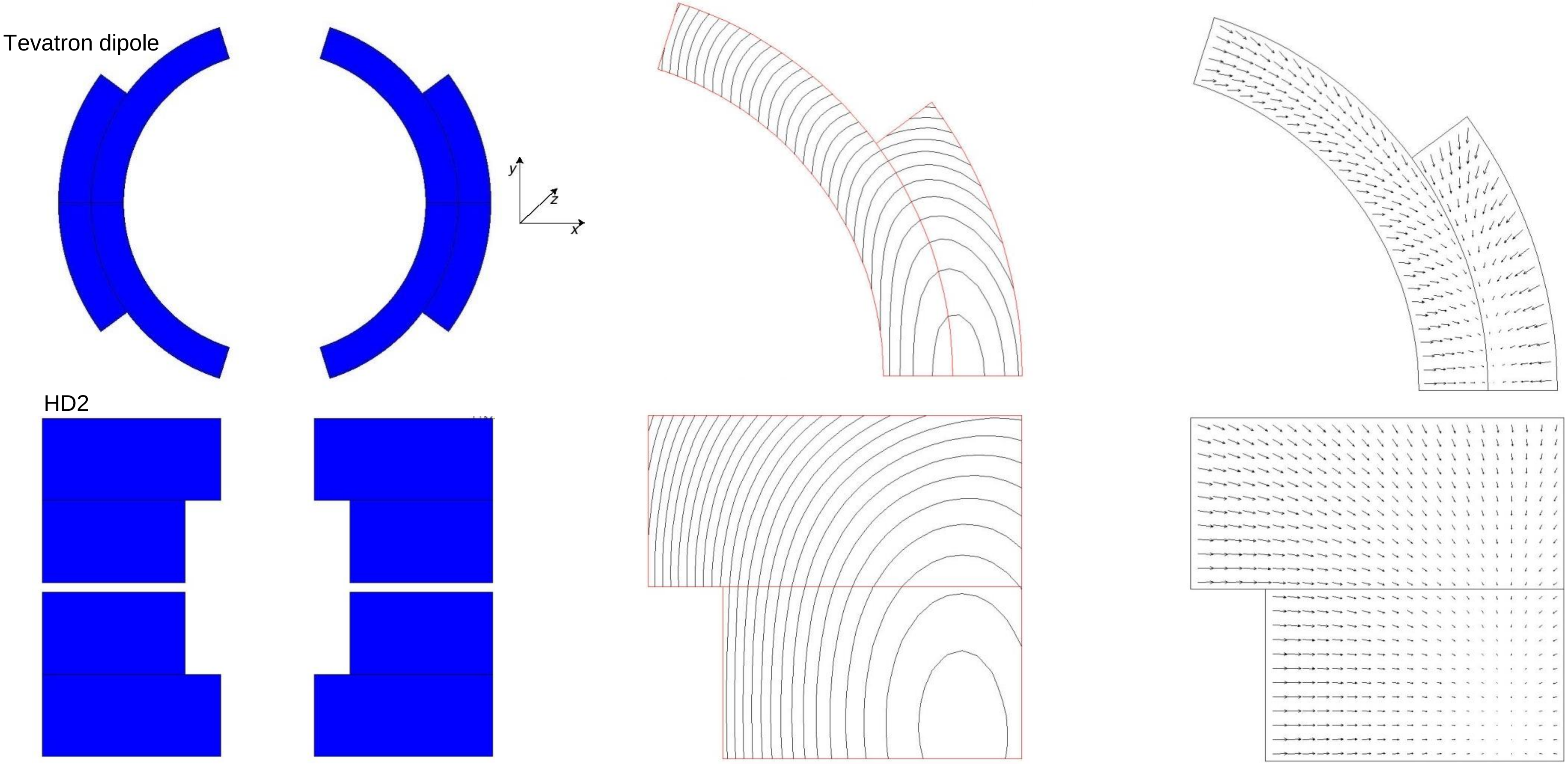
- With a w/r of 30/30 = 1 ➔1.04

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 both the thick shell and sector coil approximation

E.m. forces and stresses

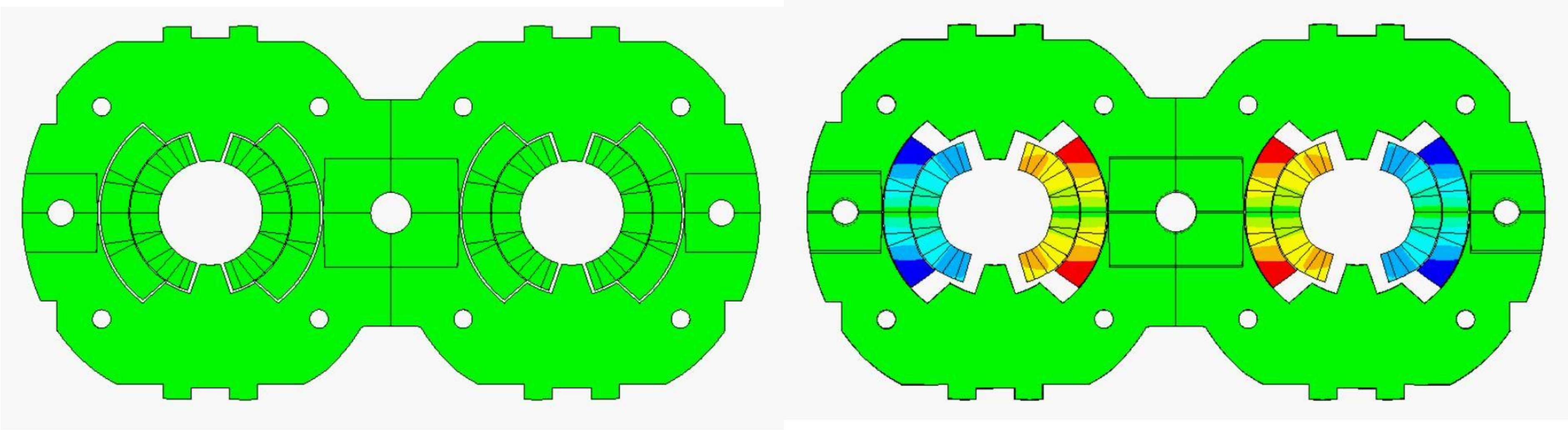
- The e.m. forces in a dipole magnet tend to push the coil
  - Towards the mid plane in the vertical-azimuthal direction (F_y, $F_\theta < 0$)
  - Outwards in the radial-horizontal direction (F_x, $F_r > 0$)



E.m. forces and stresses

LHC dipole at 0 T

LHC dipole at 9 T

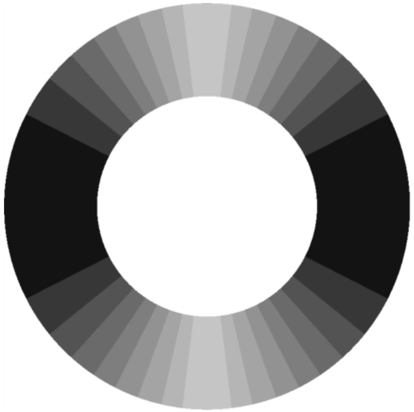


Displacement scaling = 50

- 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
Thick shell approximation

- For a thick shell, with an inner radius a_1, an outer radius a_2 and an overall current density $J = J_0 \cos\theta$, each block (quadrant) see
  - Horizontal force outwards



$$F_x = \frac{\mu_0 J_0^2}{2}\left[\frac{7}{54}a_2^3 + \frac{1}{9}\left(\ln\frac{a_2}{a_1} + \frac{10}{3}\right)a_1^3 - \frac{1}{2}a_2 a_1^2\right]$$

  - Vertical force towards the mid-plan

$$F_y = -\frac{\mu_0 J_0^2}{2}\left[\frac{2}{27}a_2^3 + \frac{2}{9}\left(\ln\frac{a_1}{a_2} - \frac{1}{3}\right)a_1^3\right]$$

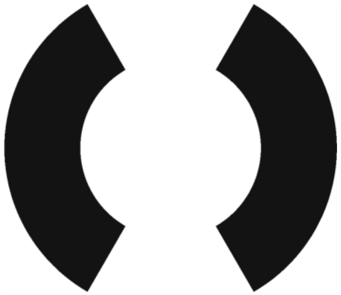
  - In case of frictionless and "free-motion" conditions, no shear, and infinitely rigid radial support, the forces accumulated on the mid-plane produce a stress of

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

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

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



  - 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

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

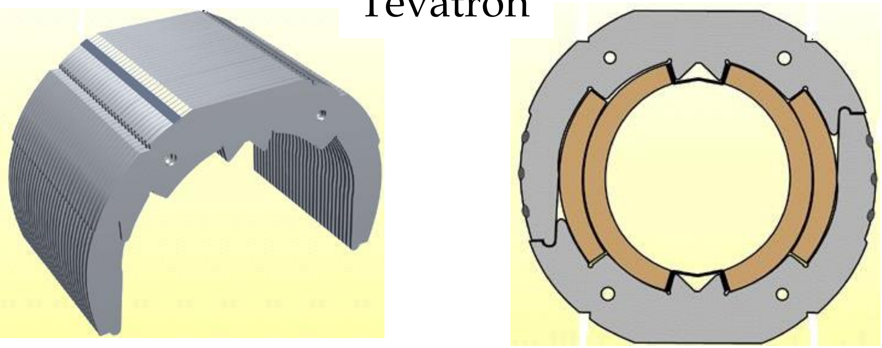
Case study

- 11 T Nb_3Sn dipole for the LHC collimation upgrade
  - **Question**
    - Evaluate dimension of collars (thickness 30 mm), iron yoke, and shrinking cylinder, assuming that the support structure is designed to reach 90% of I_{ss}

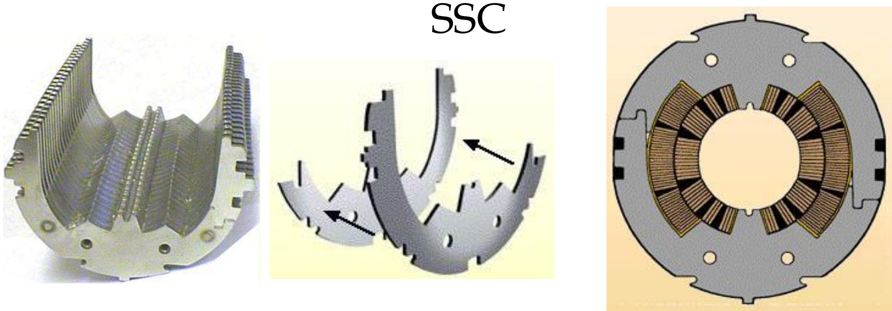
Support structure
Collars

- 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

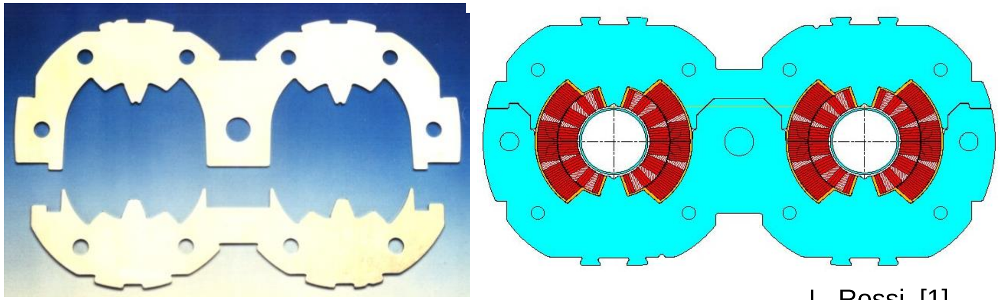


SSC



MJB Plus, Inc., [2]

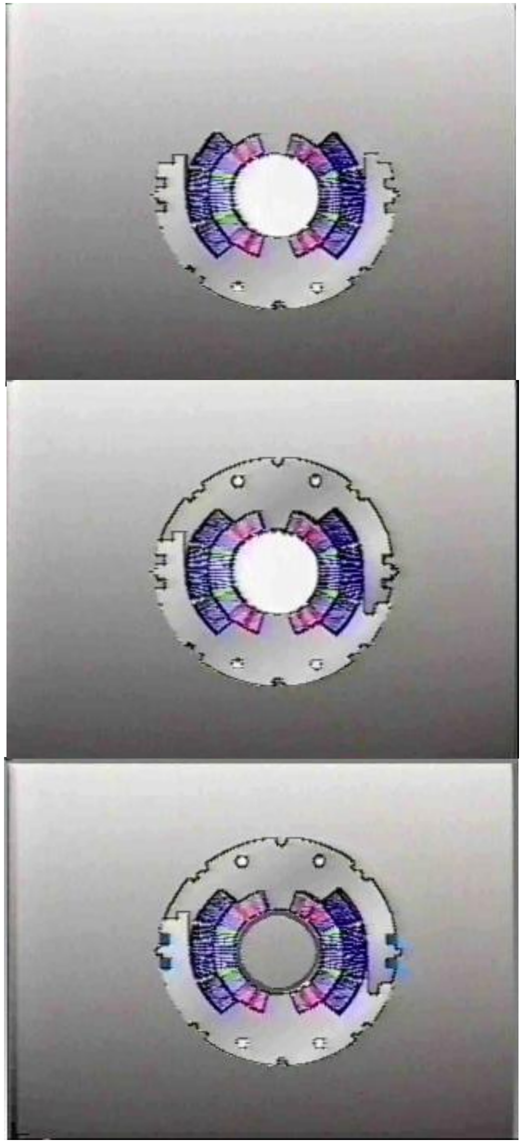
LHC



L. Rossi, [1]

Support structure
Collars

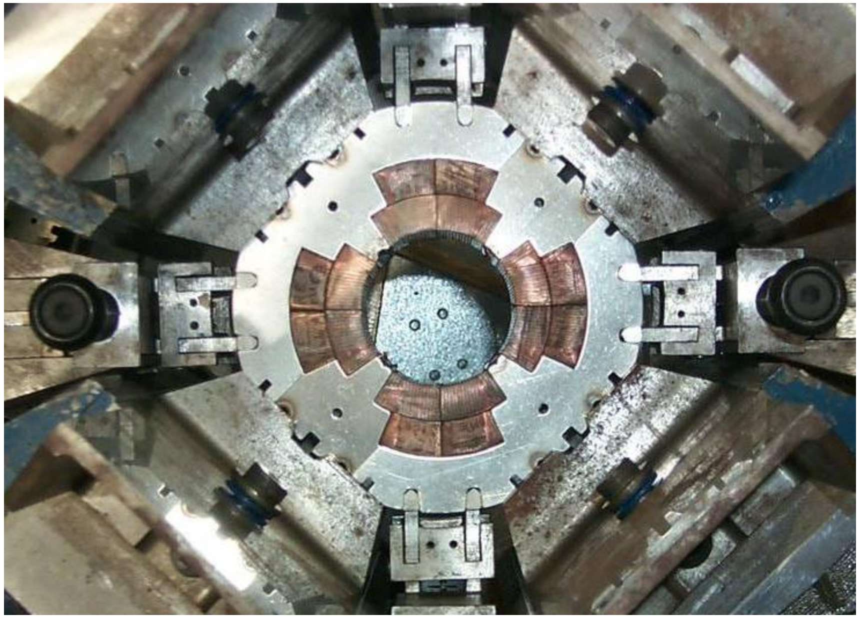
- Collaring procedure
  - Collars are pre-assembled in packs (several cm long) and placed around the coil.
    - The collar laminations are divided in "short" and "long".
  - Since the uncompressed coil is oversized with respect to the collar cavity dimension, at the beginning of the collaring procedure 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

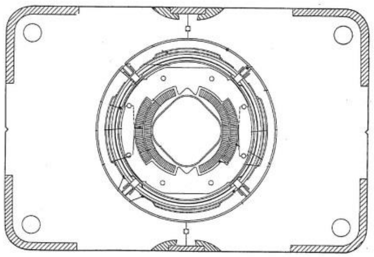
Collaring of a quadrupole magnet



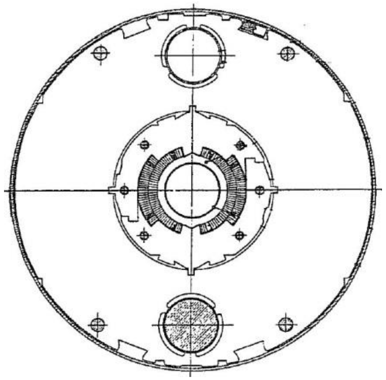
Dimension of the support structure
Collars

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

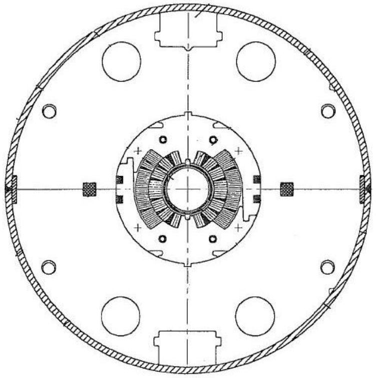
Tevatron



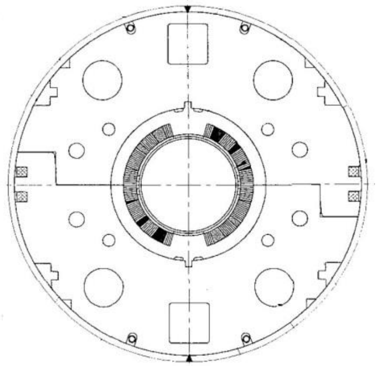
HERA



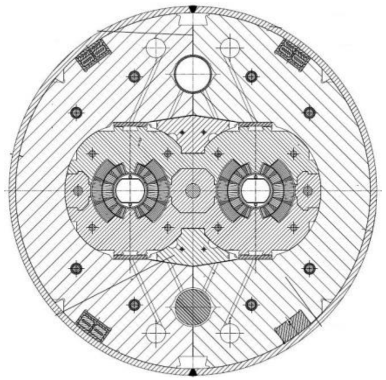
SSC



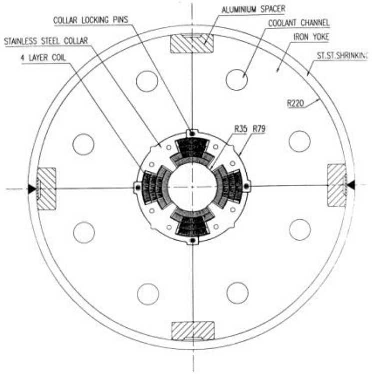
RHIC



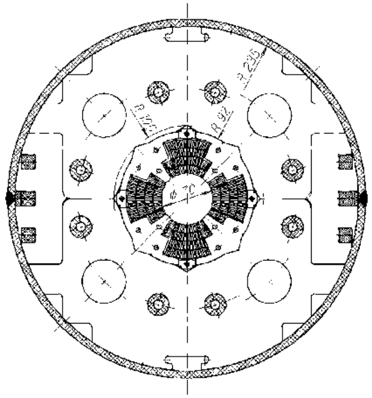
LHC



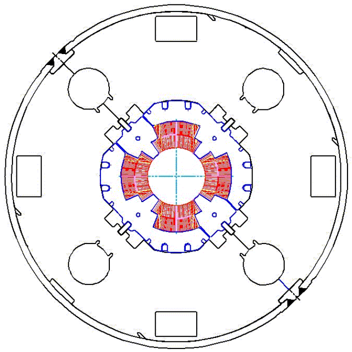
LHC-IR



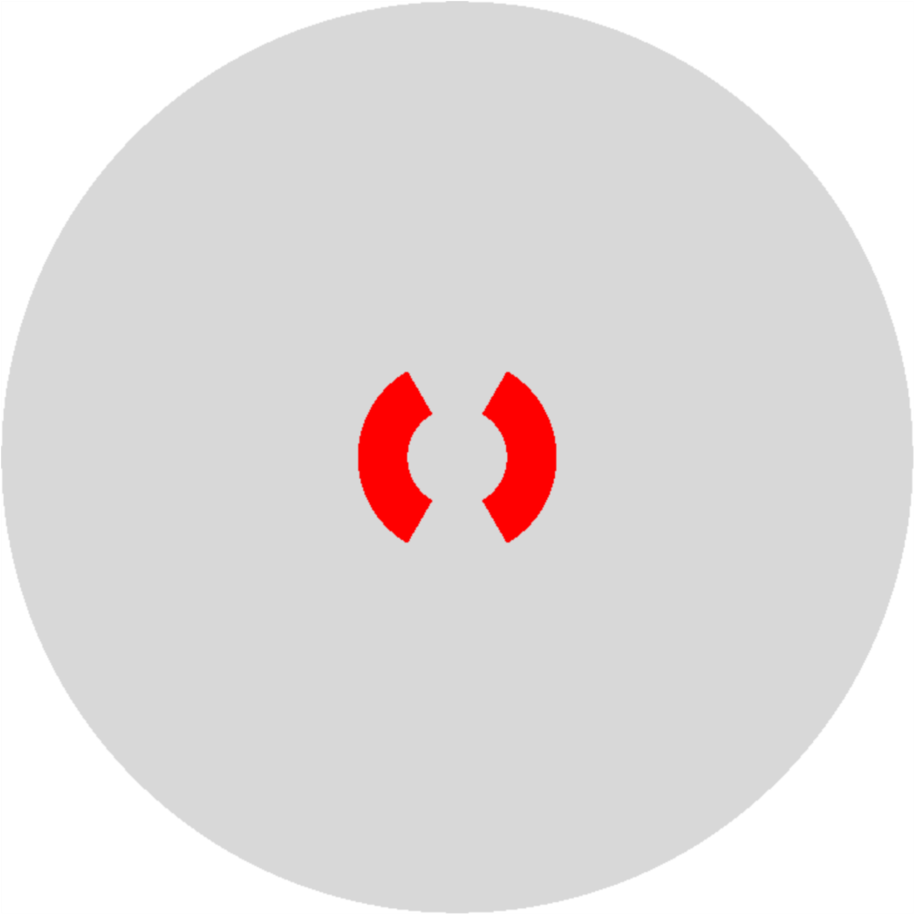
LHC-IR

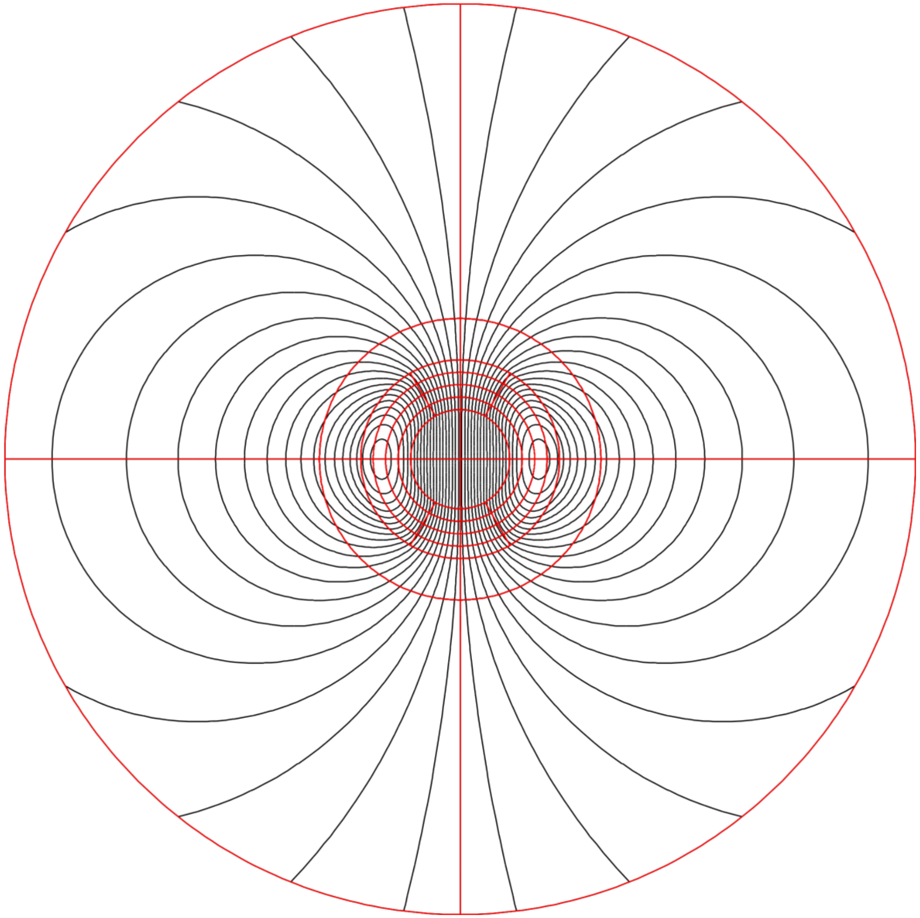


LHC-MQ

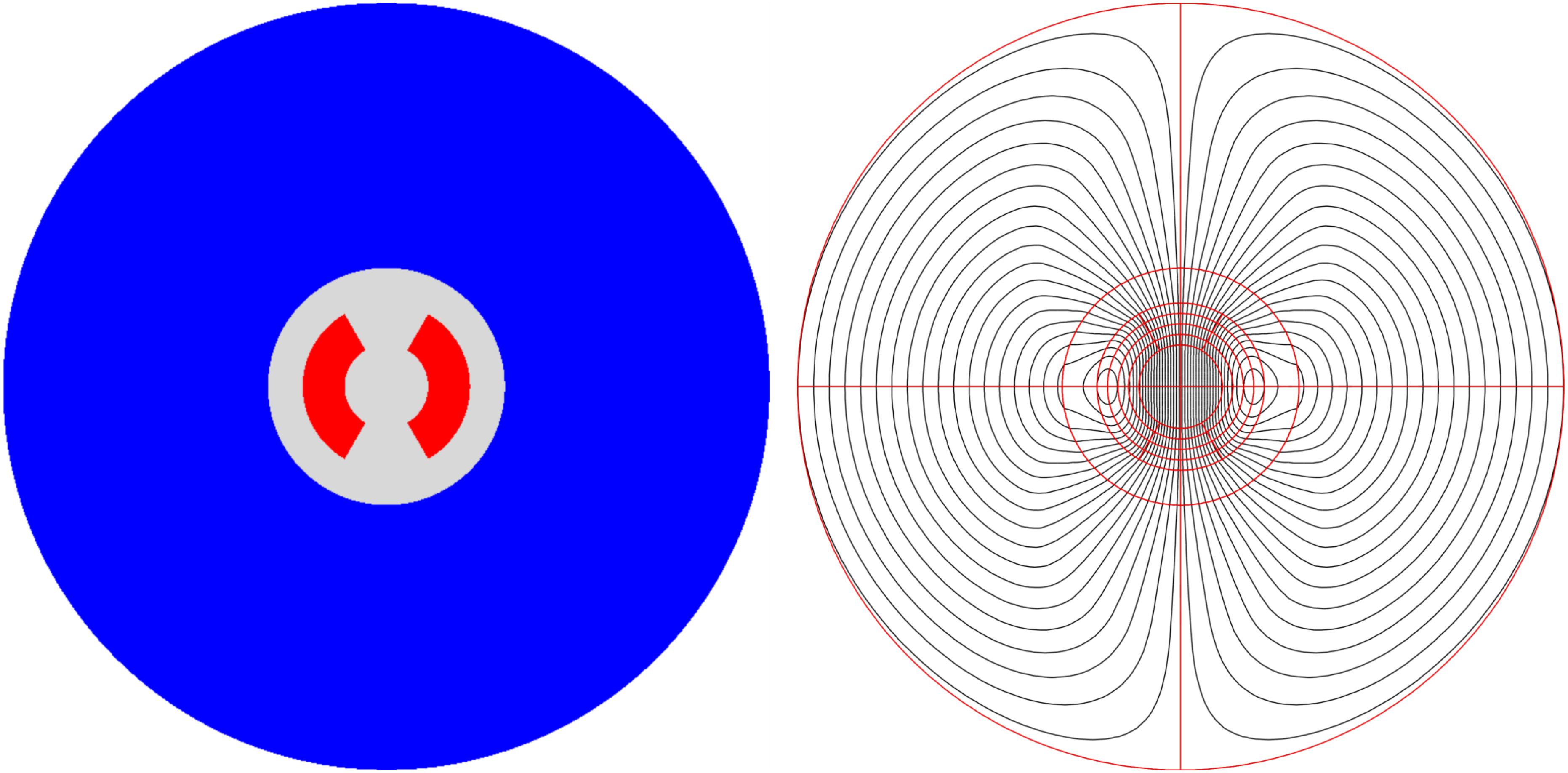


Without iron yoke





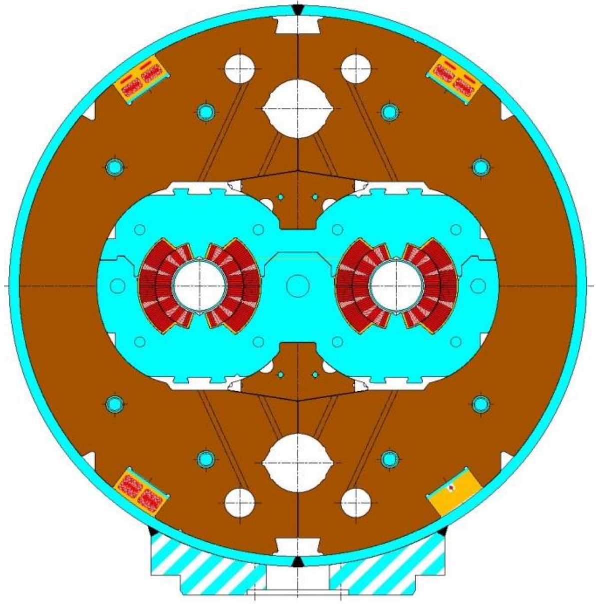
With iron yoke

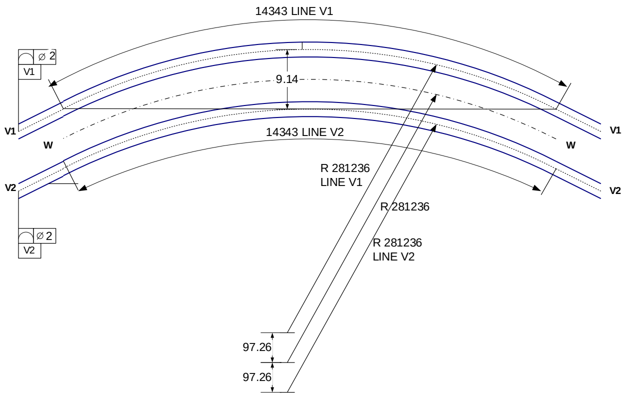


- The iron yoke thickness can be estimated with $rB \sim t_{\text{iron}} B_{\text{sat}}$

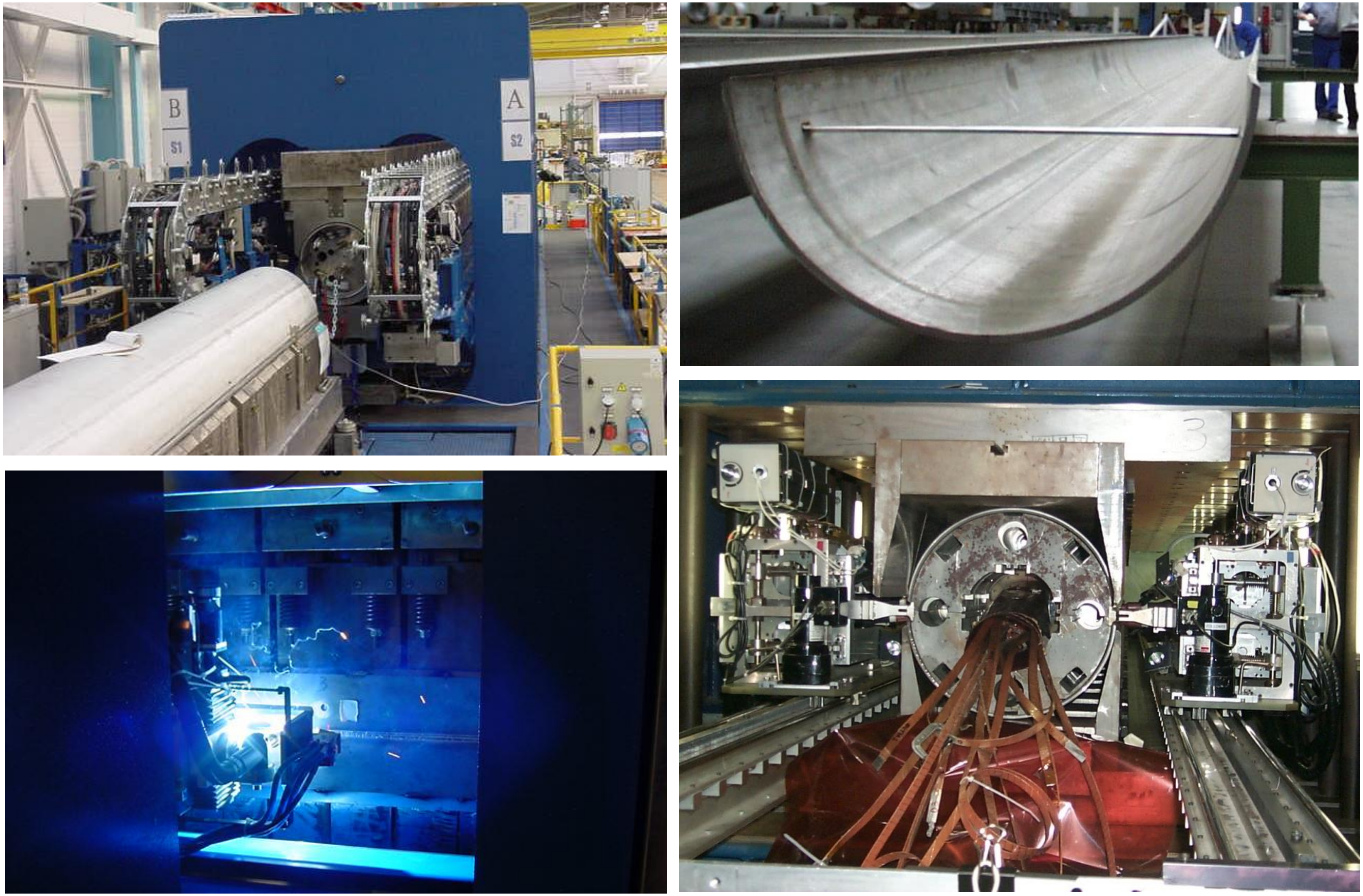
Support structure
Shell (or shrinking cylinder)

- 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 (1- cos $\theta/2$)r is of 9.14 mm.



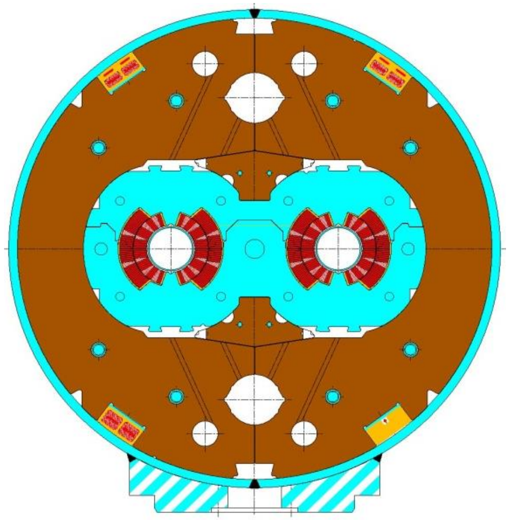


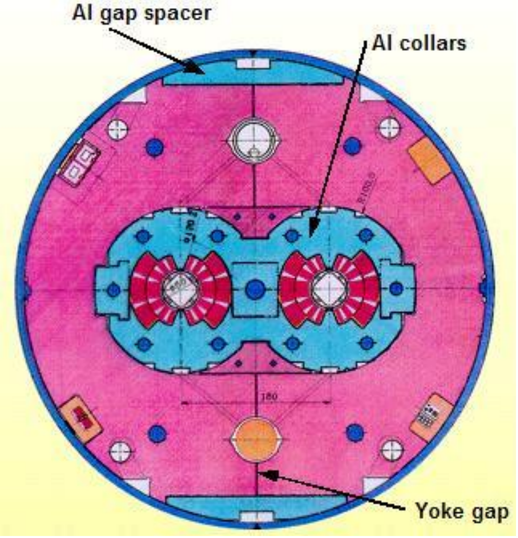
Support structure
Shell (or shrinking cylinder)



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) is kept between the two halves.
  - After welding, the shell tension closes the gap, and contact is provided between yoke and collar.
  - The collared coil has a larger thermal contraction coefficient as the iron yoke. The gap remains nevertheless closed, because of the higher rigidity of the yoke and remains 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
  - $\sigma_{\text{shell}} =$ 200 MPa