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Istituto Nazionale di Fisica Nucleare

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IPAC23

14th International Particle Accelerator Conference

IPAC '23

7 - 12 May 2023

VENICE, ITALY

Hosting institutions

Elettra Sincrotrone Trieste

Istituto Nazionale di Fisica Nucleare

Paolo Ferracin

Lawrence Berkeley National Laboratory

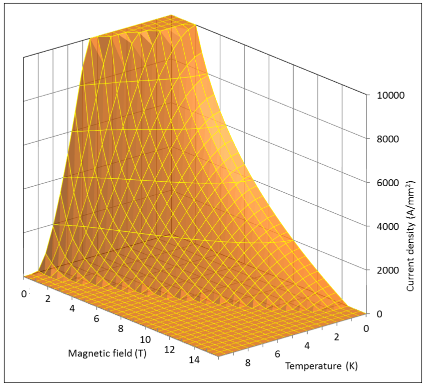
Superconducting magnets for circular accelerators

IPAC '23

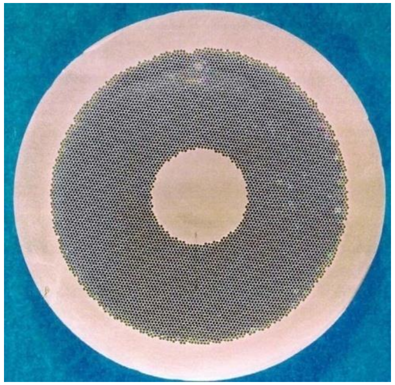
Introduction
Goal of the course

- Overview of **superconducting magnets** for particle accelerators (dipoles and quadrupoles)
    - Description of the components and their function
- From the superconducting material to the full magnet

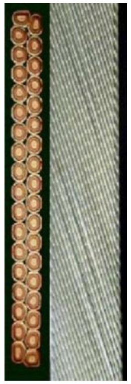
Superconducting material



Superconducting strand

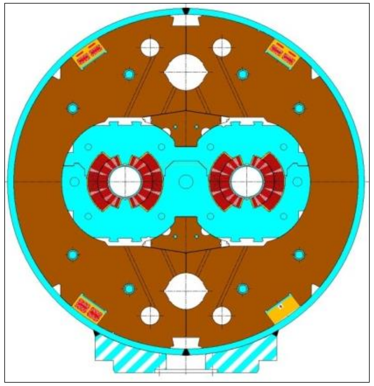


Superconducting cable



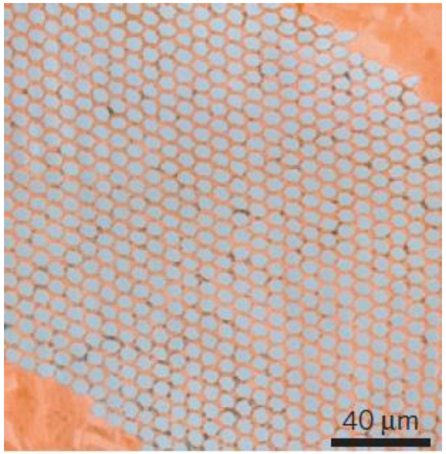
Superconducting coil

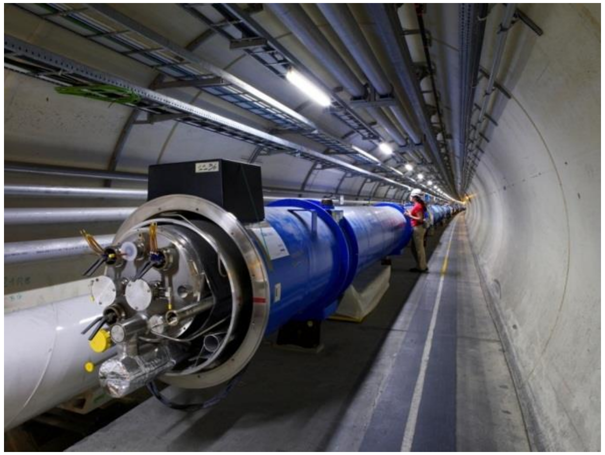
Superconducting magnet



Introduction
Superconducting magnet technology

- Multidisciplinary field: mixture of
  - Chemistry and material science: **superconducting materials**
  - Quantum physics: the key mechanisms of **superconductivity**
  - Classical electrodynamics: **magnet design**
  - Mechanical engineering: **support structures**
  - Electrical engineering: powering of the magnets
  - Cryogenics: keep them **cold** …
- Very different order of magnitudes





Outline

- Particle accelerators and superconductors
- Magnetic design and coils
- Mechanics of superconducting magnets
- Quench and protection

References

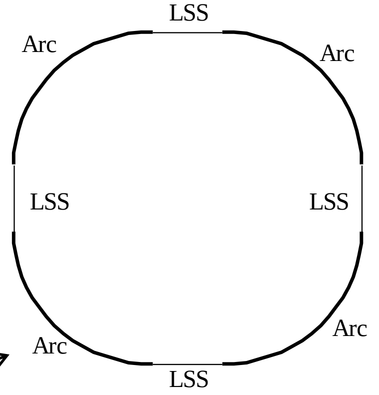
- K.-H. Mess, P. Schmuser, S. Wolff, “Superconducting accelerator magnets”, Singapore: World Scientific, 1996.
- Martin N. Wilson, "Superconducting Magnets", 1983.
- Fred M. Asner, "High Field Superconducting Magnets", 1999.
- P. Ferracin, E. Todesco, S. Prestemon, “Superconducting accelerator magnets”, US Particle Accelerator School, www.uspas.fnal.gov.
- E. Todesco, “Masterclass - Design of superconducting magnets for particle accelerators”, https://indico.cern.ch/category/12408/

Particle accelerators and magnets

by E. Todesco

- Principle of synchrotrons
  - Driving particles in the same accelerating structure several times
- Electro-magnetic field accelerates particles

$$\vec{F} = e\vec{E} \longrightarrow$$



- Magnetic field steers the particles in a ~circular orbit

$$\vec{F} = e\vec{v} \times \vec{B} \longrightarrow$$

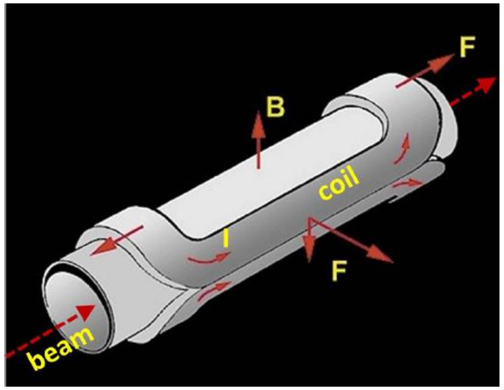
- Particle accelerated → energy increased → magnetic field increased (“synchro”) to keep the particles on the same orbit of curvature ρ

$$\overset{\uparrow}{p} = e\overset{\uparrow}{B}\underset{\searrow}{\rho}$$

Constant

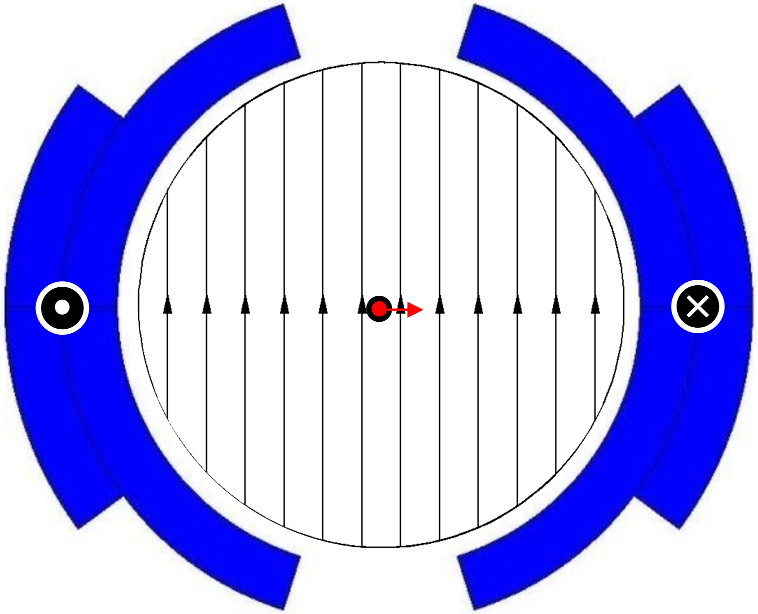
Particle accelerators and magnets
Dipoles

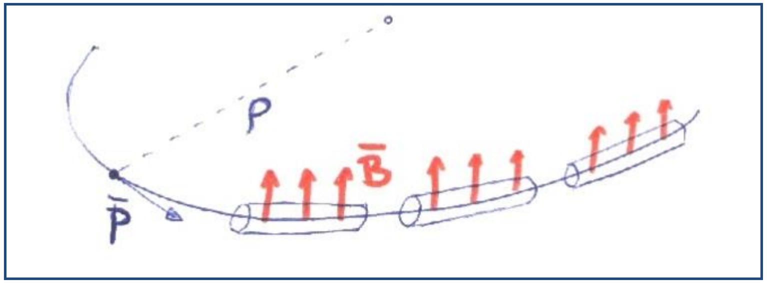
- Main field components is B_y
  - Perpendicular to the axis of the magnet z
- Electro-magnets: field produced by a current (or current density)



$$\boxed{B_y = -\frac{\mu_0 J_0}{2}(r_{out} - r_{in})}$$

- **Magnetic field steers (bends) the particles in a ~circular orbit**



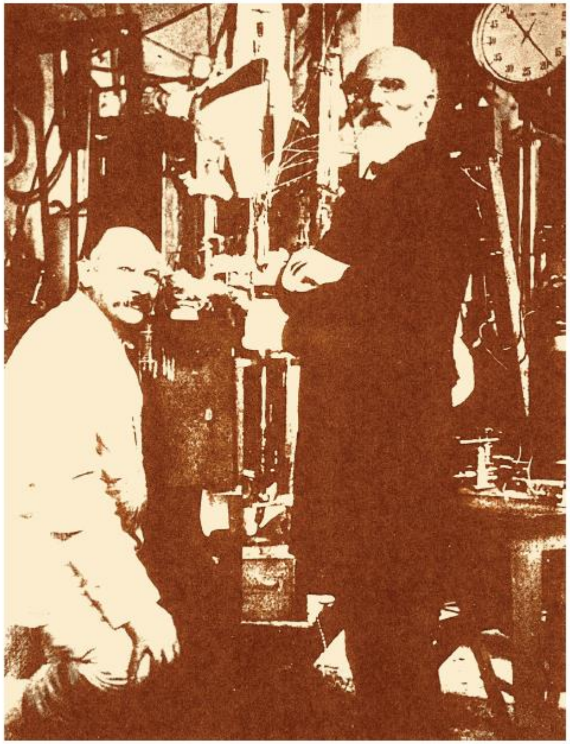


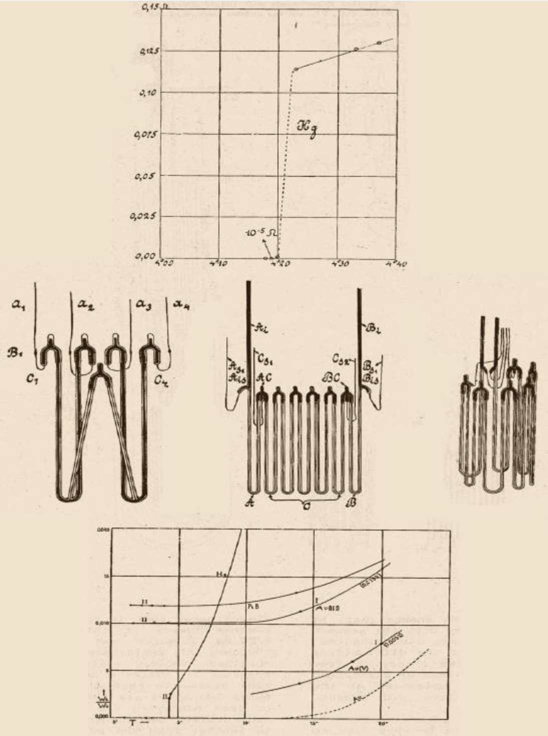
$$\boxed{p = eB\rho}$$

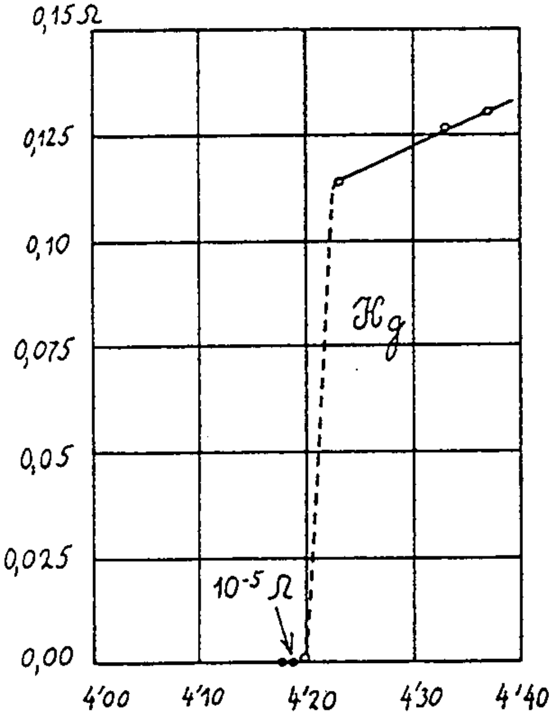
by E. Todesco

Superconductivity
The discovery

- Superconductivity was discovered in 1911 by Kammerling-Onnes who observed that the resistance of a mercury wire disappeared (immeasurably small value) at 4.2 K
  - Not just "little" resistance - truly **ZERO resistance**

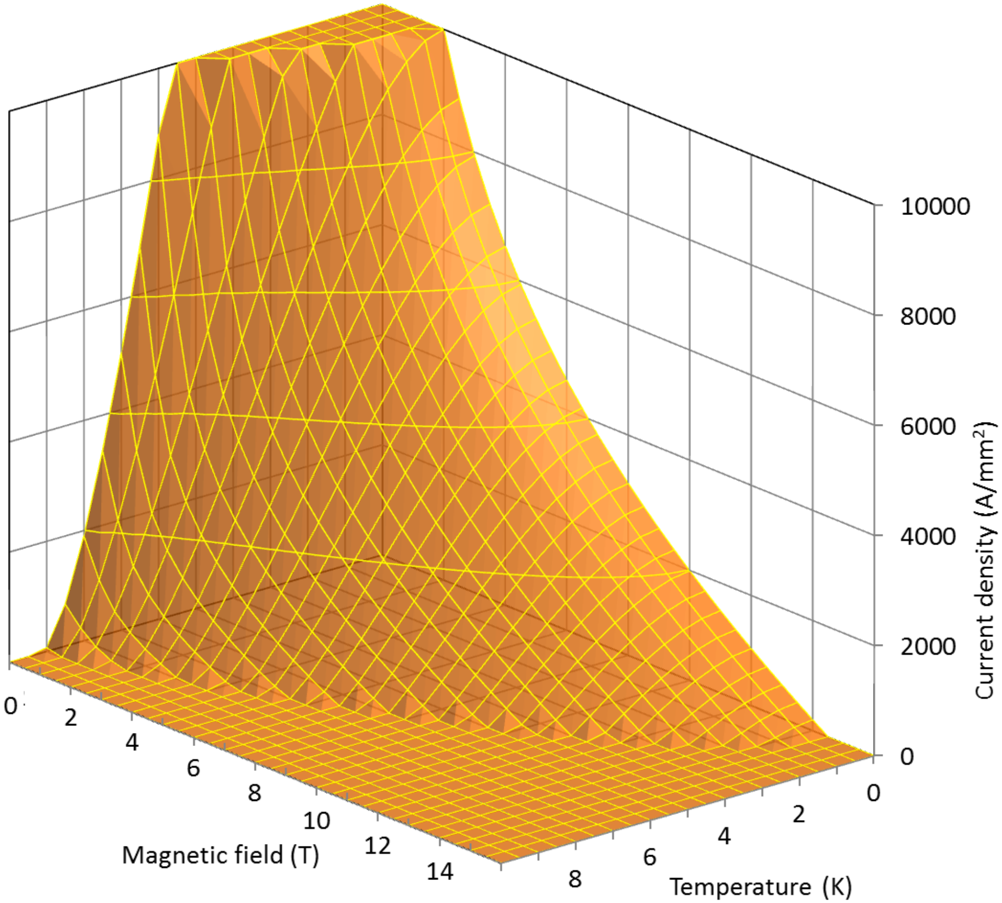






Superconductivity
Critical surface

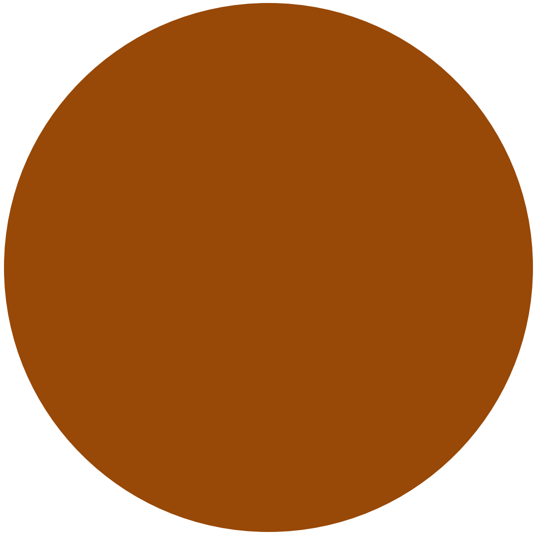
- A superconducting material is superconducting below the **critical surface** defined by
  - Critical temperature ***Tc***
    - Property of the material
  - Upper critical field B_{c2}
    - Property of the material
  - Critical current density J_c
    - Hard work by the producer



Practical superconductors

- Typical operational conditions (0.85 mm diameter strand)

Cu

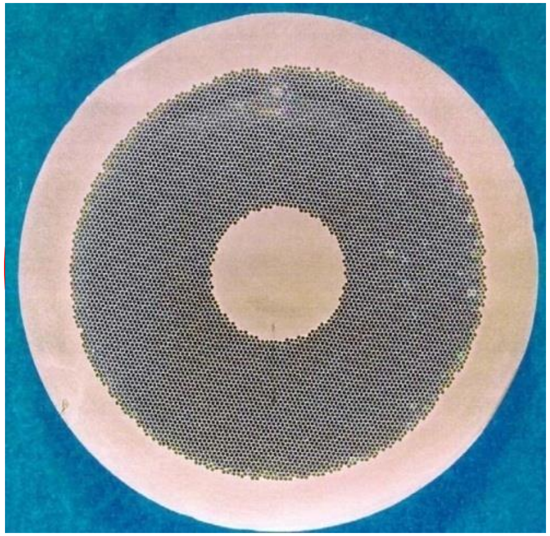


$J_e \sim$ **5 A/mm^2**

$I \sim$ **3 A**

B **= 2 T**

Nb-Ti

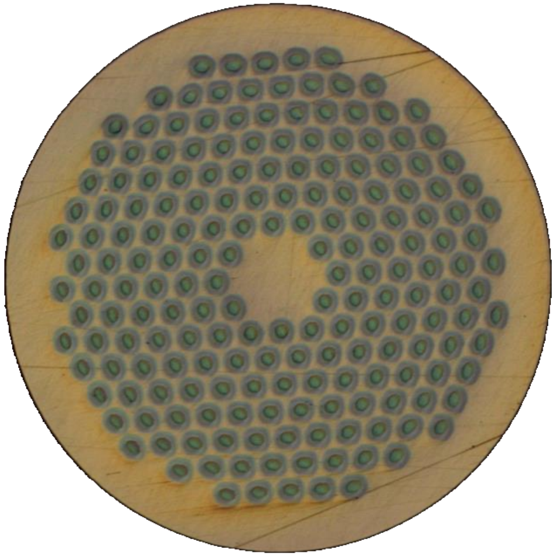


$J_e \sim$ **600-700 A/mm^2**

$I \sim$ **300-400 A**

B **= 8-9 T**

Nb_3Sn



$J_e \sim$ **600-700 A/mm^2**

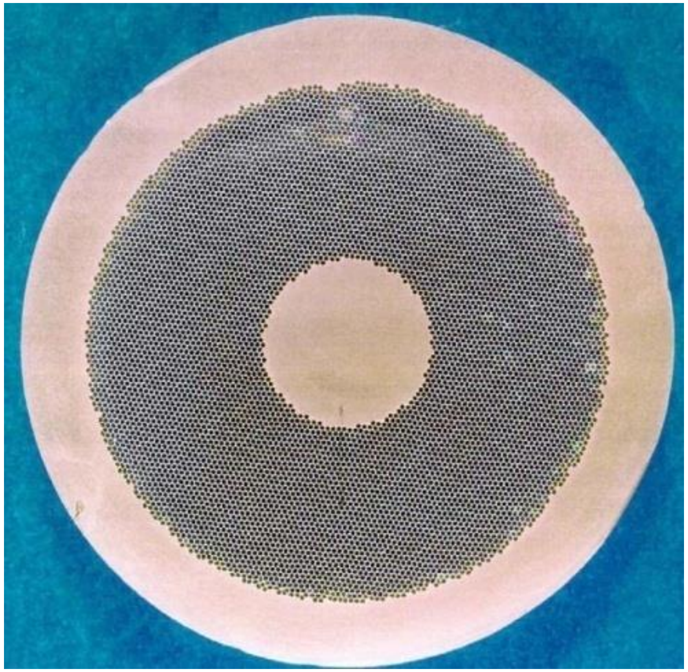
$I \sim$ **300-400 A**

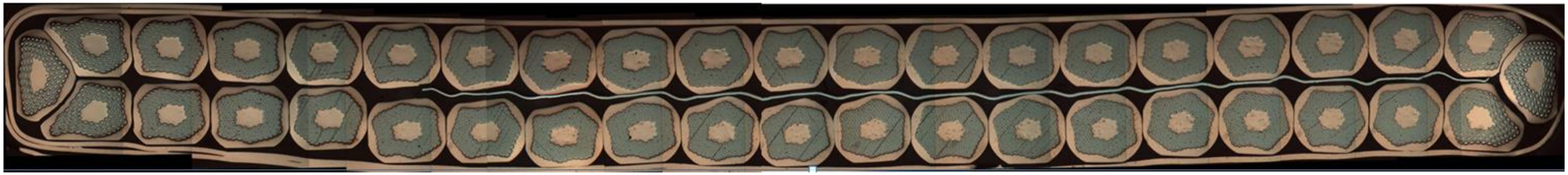
B **= 12-13 T**

Practical superconductors
Introduction

- Superconducting materials are produced in small filaments and surrounded by a stabilizer (typically copper) to form a *multi-filament wire* or *strand*.

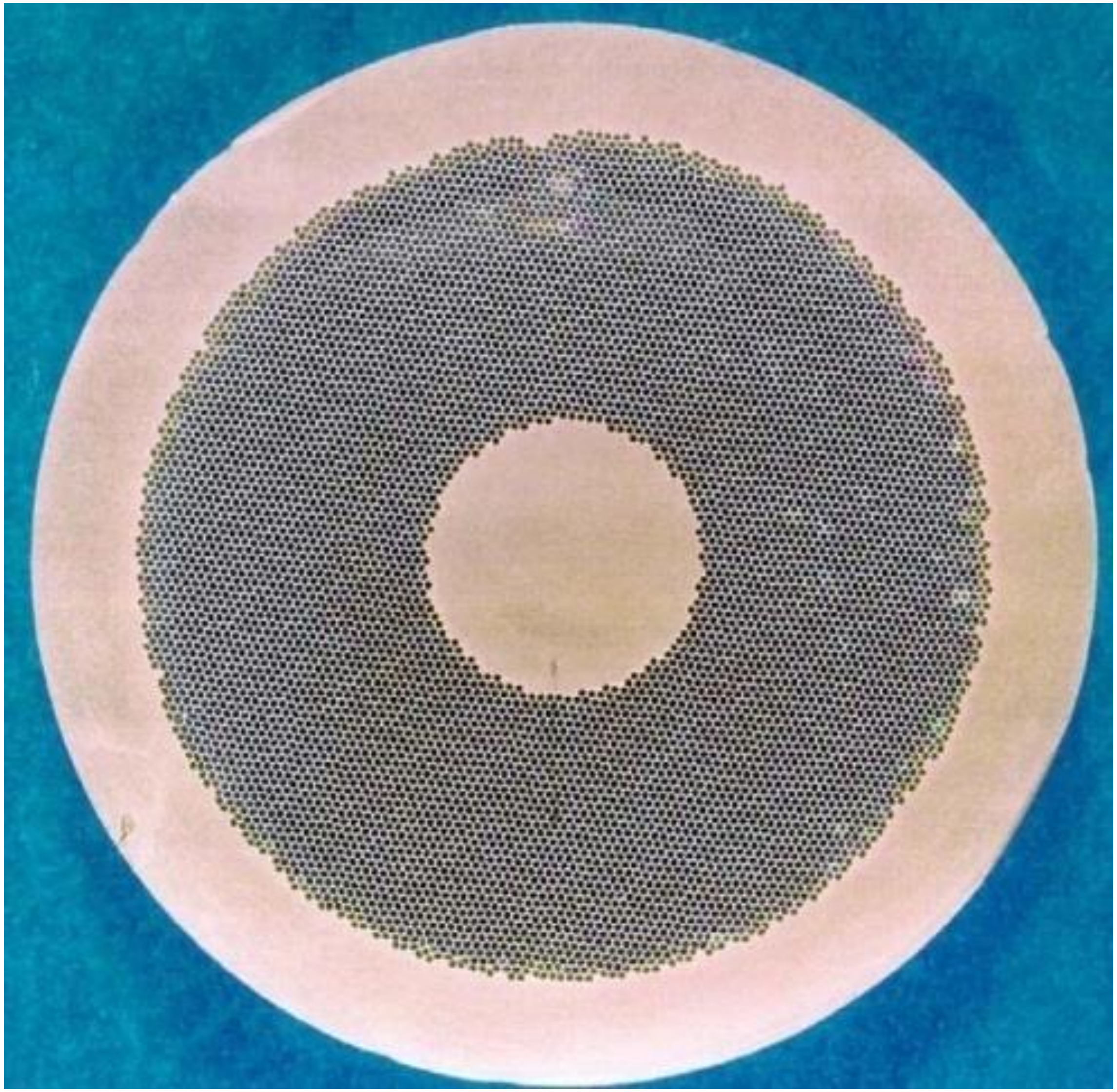
- A superconducting cable is composed by several wires: *multi-strand cable*.





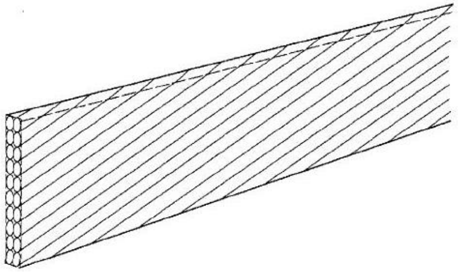
Multifilament wires
Motivations

- Filament size
  - Magneto-thermal instabilities (flux jump)
  - AC losses within filament
  - Field errors (persistent current)
- Filament twisting
  - AC losses
- Strand size
  - Magneto-thermal instabilities (Self field stability)
- Cu matrix
  - Quench protection/stability
  - Flux jump and self-field



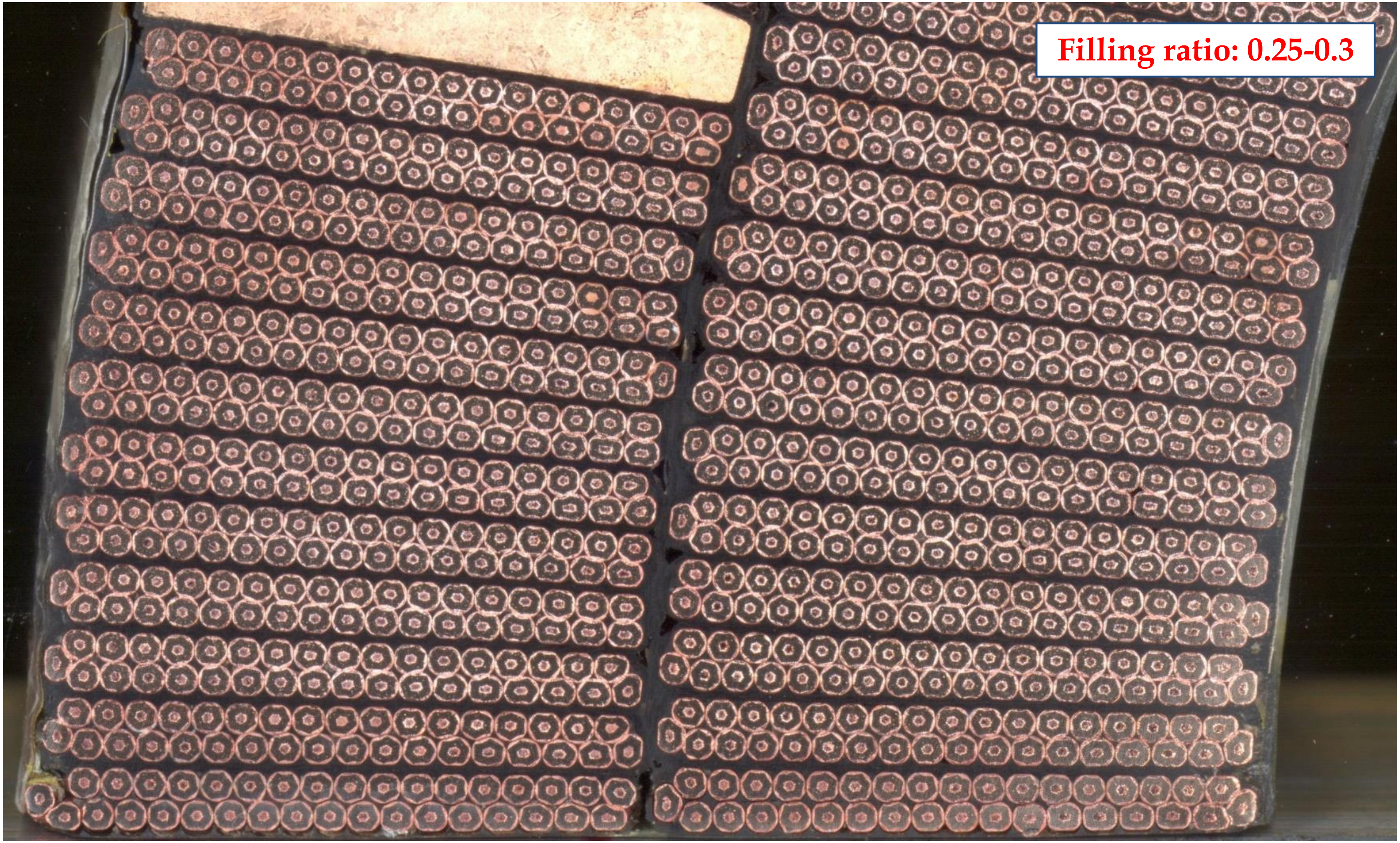
Practical superconductors
Multi-strand cables motivations

- Most of the superconducting coils for particle accelerators are wound from a **multi-strand cable**.
- The advantages of a multi-strand cable are:
  - reduction of the strand piece length;
  - reduction of number of turns
    - easy winding;
    - smaller coil inductance
      - less voltage required for power supply during ramp-up;
      - after a quench, faster current discharge and less coil voltage.
  - current redistribution in case of a defect or a quench in one strand.



- The most commonly used multi-strand cables are the **Rutherford cable** and the cable-in-conduit.

Practical superconductors
Superconducting cables



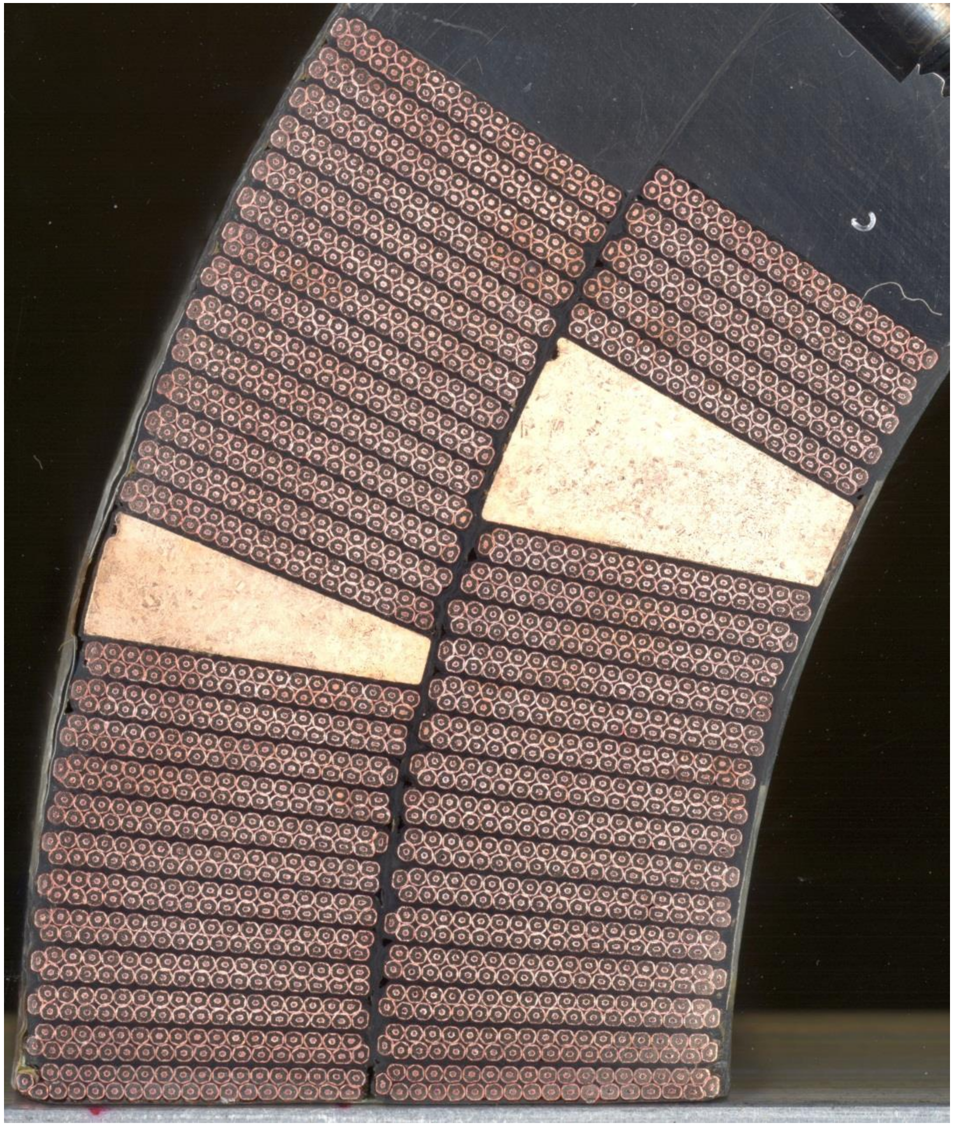
Filling ratio: 0.25-0.3

Outline

- **Particle accelerators and superconductors**
- **Magnetic design and coils**
- **Mechanics of superconducting magnets**
- **Quench and protection**

Magnetic design and coils

- How do we create a **perfect field**?
- How do we **express** field and its "**imperfections**"?
- How do we design a coil to **minimize field errors**?
- How do we **fabricate** a coil?



Perfect dipole field
Intercepting circles (or ellipses)

- Within a cylinder carrying j_0, the field is perpendicular to the radial direction and proportional to the distance to the centre ***r***:

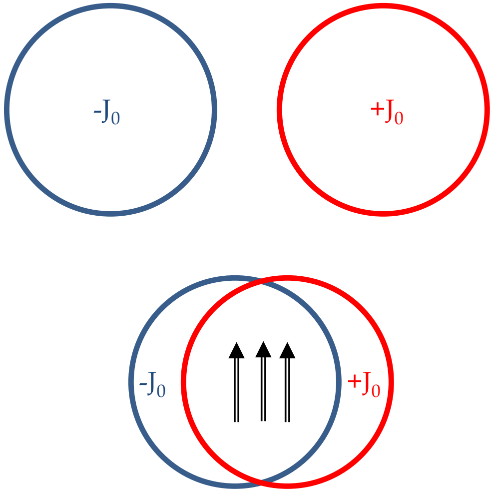
$$B = -\frac{\mu_0 j_0 r}{2}$$

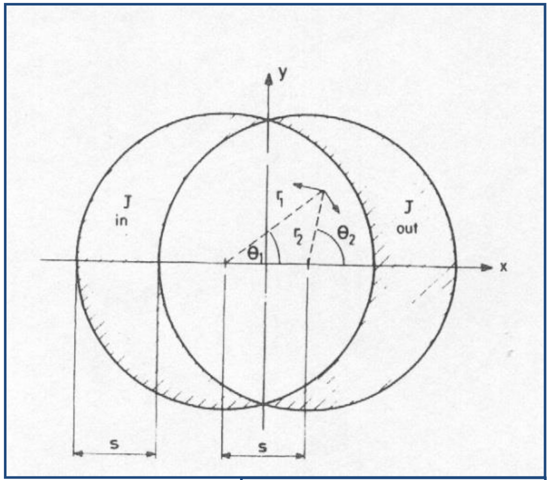
  - Combining the effect of two intersecting cylinders

$$B_x = \frac{\mu_0 j_0 r}{2}\left\{-r_1 \sin\theta_1 + r_2 \sin\theta_2\right\} = 0$$

$$B_y = \frac{\mu_0 j_0 r}{2}\left\{-r_1 \cos\theta_1 + r_2 \cos\theta_2\right\} = -\frac{\mu_0 j_0}{2} s$$

- A uniform current density in the area of two **intersecting circles** produces a pure dipole
  - The aperture is not circular
  - Not easy to simulate with a flat cable
- Similar proof for **intersecting ellipses**





by M. Wilson

Perfect dipole field
Thick shell with $\cos\theta$ current distribution

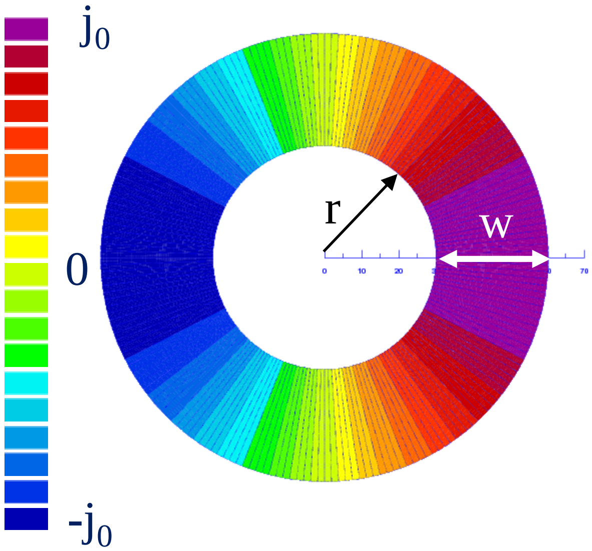
- If we assume
  - $J = J_0 \cos\theta$ where J_0 [A/m^2] is ⊥ to the cross-section plane
  - Width of the coil = w

- The generated field is a **pure dipole**

$$B_y = -\frac{\mu_0 J_0}{2} w$$

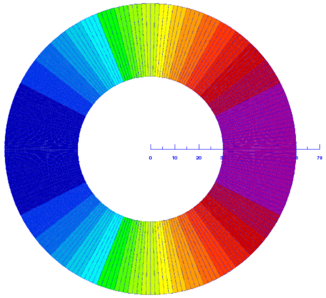
- Linear dependence on **coil width**

- **Easier** to achieve with a Rutherford cable

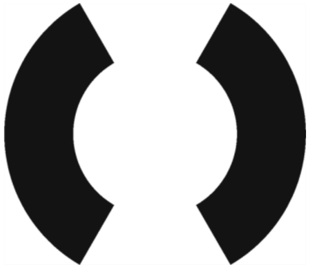


From ideal to practical configuration

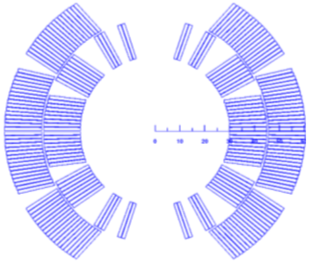
- How can I reproduce **thick shell with a *cosθ*** distribution with a cable?
  - Rectangular cross-section and constant *J*



- First "rough" approximation
  - **Sector dipole**



- Better ones
  - More **layers** and **wedges** to reduce *J* towards 90°



- As a result, the field is **not perfect** anymore
  - How can I express and improve the "imperfect" field inside the aperture?

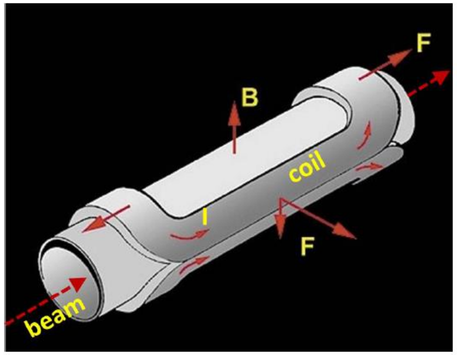
Field representation
Maxwell equations

- **Maxwell equations** for magnetic field

$$\nabla \cdot B = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0 \qquad \nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

- In absence of charge and magnetized material

$$\nabla \times B = \left(\frac{\partial B_y}{\partial z} - \frac{\partial B_z}{\partial y}, \frac{\partial B_z}{\partial x} - \frac{\partial B_x}{\partial z}, \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} \right) = 0$$



- If $\frac{\partial B_z}{\partial z} = 0$ (constant longitudinal field), then

$$\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} = 0 \qquad \frac{\partial B_x}{\partial y} - \frac{\partial B_y}{\partial x} = 0$$

Field representation
Analytic functions

- If $\frac{\partial B_z}{\partial z} = 0$

  Maxwell gives

$$\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} = 0$$

$$\frac{\partial B_y}{\partial y} + \frac{\partial B_x}{\partial x} = 0$$

$$\begin{cases} \frac{\partial f_x}{\partial x} - \frac{\partial f_y}{\partial y} = 0 \\ \frac{\partial f_x}{\partial y} + \frac{\partial f_y}{\partial x} = 0 \end{cases}$$

Cauchy-Riemann conditions

and therefore the function $B_y + iB_x$ is analytic

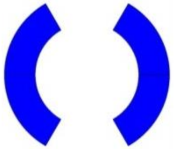
$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1}$$

where C_n are **complex coefficients**

$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1} = \sum_{n=1}^{\infty} (B_n + iA_n)(x+iy)^{n-1}$$

- Advantage: we reduce the description of the field to a (simple) series of complex coefficients

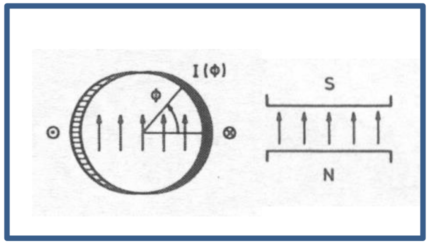
Magnetic design
Harmonics



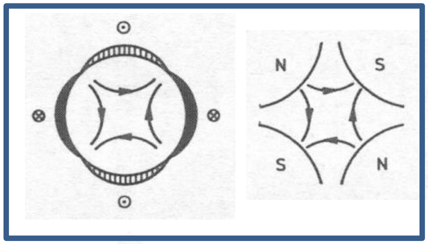
- The field can be expressed as (simple) series of coefficients
- So, each coefficient corresponds to a "pure" multipolar field

$$B_y(x,y)+iB_x(x,y)=\sum_{n=1}^{\infty}C_n(x+iy)^{n-1}=\sum_{n=1}^{\infty}(B_n+iA_n)(x+iy)^{n-1}$$

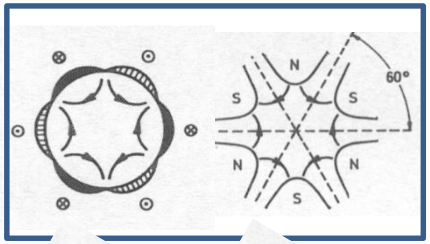
B_1



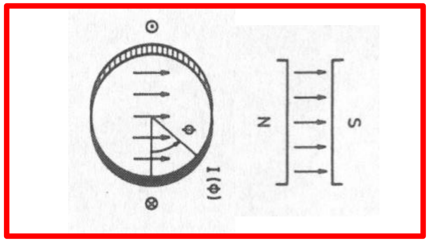
B_2



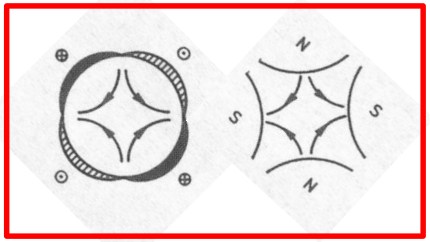
B_3



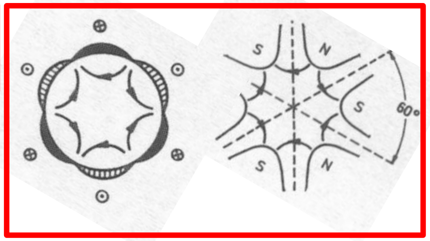
A_1



A_2



A_3



by K.-H. Mess, *et al.*

- The field harmonics are rewritten as

$$B_y+iB_x=10^{-4}B_1\sum_{n=1}^{\infty}(b_n+ia_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

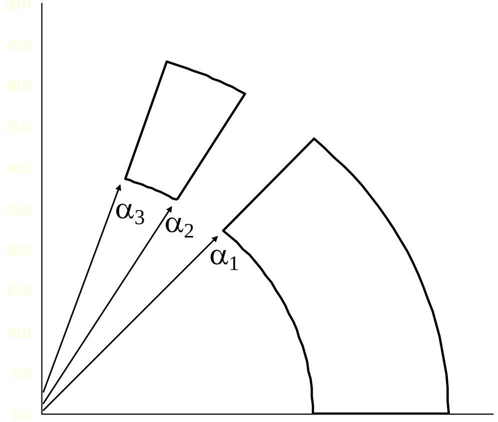
- The coefficients b_n, a_n are called normalized multipoles
  - b_n are the normal, a_n are the skew (adimensional)

A “good” field quality dipole
Sector dipole

by E. Todesco

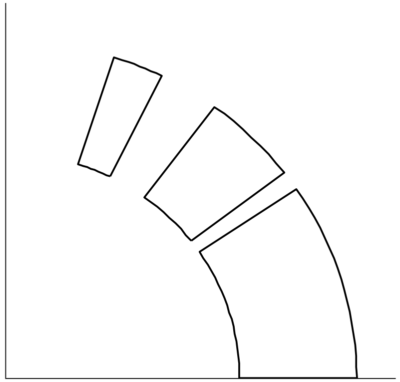
- We compute the central field given by a **sector dipole with 2 blocks**
  - Equations to set to zero **B_3, B_5 and B_7**

$$\begin{cases} \sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) = 0 \\ \sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) = 0 \end{cases}$$



- And the one given by a **3 blocks**
  - Equations to set to zero **B_3, B_5, B_7, B_9 and B_{11}**

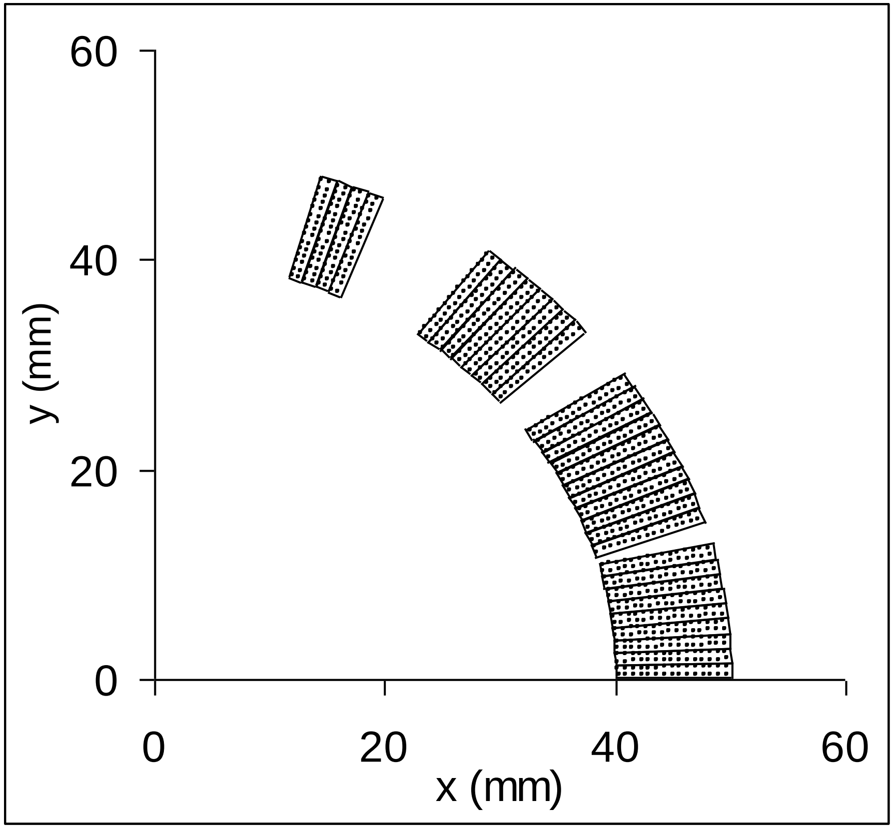
$$\begin{aligned} \sin(3\alpha_5) - \sin(3\alpha_4) + \sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) = 0 \\ \sin(5\alpha_5) - \sin(5\alpha_4) + \sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) = 0 \\ \sin(7\alpha_5) - \sin(7\alpha_4) + \sin(7\alpha_3) - \sin(7\alpha_2) + \sin(7\alpha_1) = 0 \\ \sin(9\alpha_5) - \sin(9\alpha_4) + \sin(9\alpha_3) - \sin(9\alpha_2) + \sin(9\alpha_1) = 0 \\ \sin(11\alpha_5) - \sin(11\alpha_4) + \sin(11\alpha_3) - \sin(11\alpha_2) + \sin(11\alpha_1) = 0 \end{aligned}$$

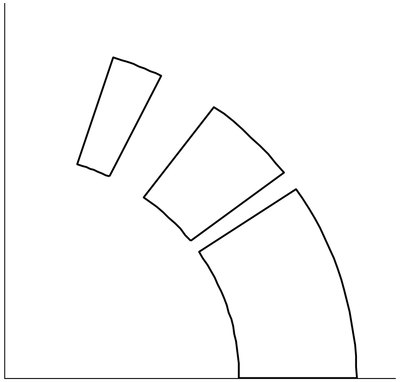


Two wedges, $b_3=b_5=b_7=b_9=b_{11}=0$
[0°-33.3°,37.1°-53.1°,63.4°- 71.8°]

A “good” field quality dipole
Sector dipole

- Let us see two coil lay-outs of real magnets
  - The **RHIC dipole** has **four blocks**





Two wedges, $b_3=b_5=b_7=b_9=b_{11}=0$
[0°-33.3°,37.1°-53.1°,63.4°- 71.8°]

Outline

- Particle accelerators and superconductors
- Magnetic design and coils
- Mechanics of superconducting magnets
- Quench and protection

Mechanics of superconducting magnets
Electro-magnetic force

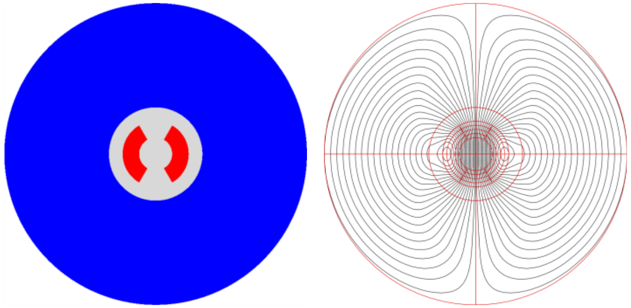
- In the presence of a magnetic field ***B***, an electric charged particle ***q*** in motion with a velocity ***v*** is acted on by a force $\boldsymbol{F_L}$ called electro-magnetic (Lorentz) force [N]:

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

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

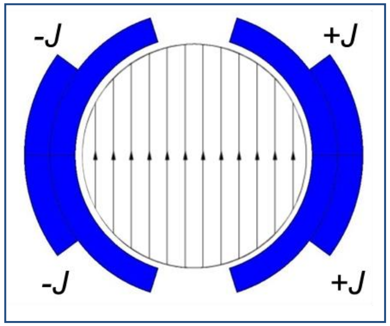
$$\vec{f}_L = \vec{J} \times \vec{B}$$

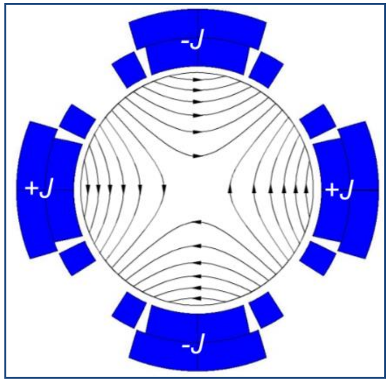
- Superconducing coil in its own field→

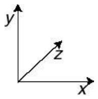


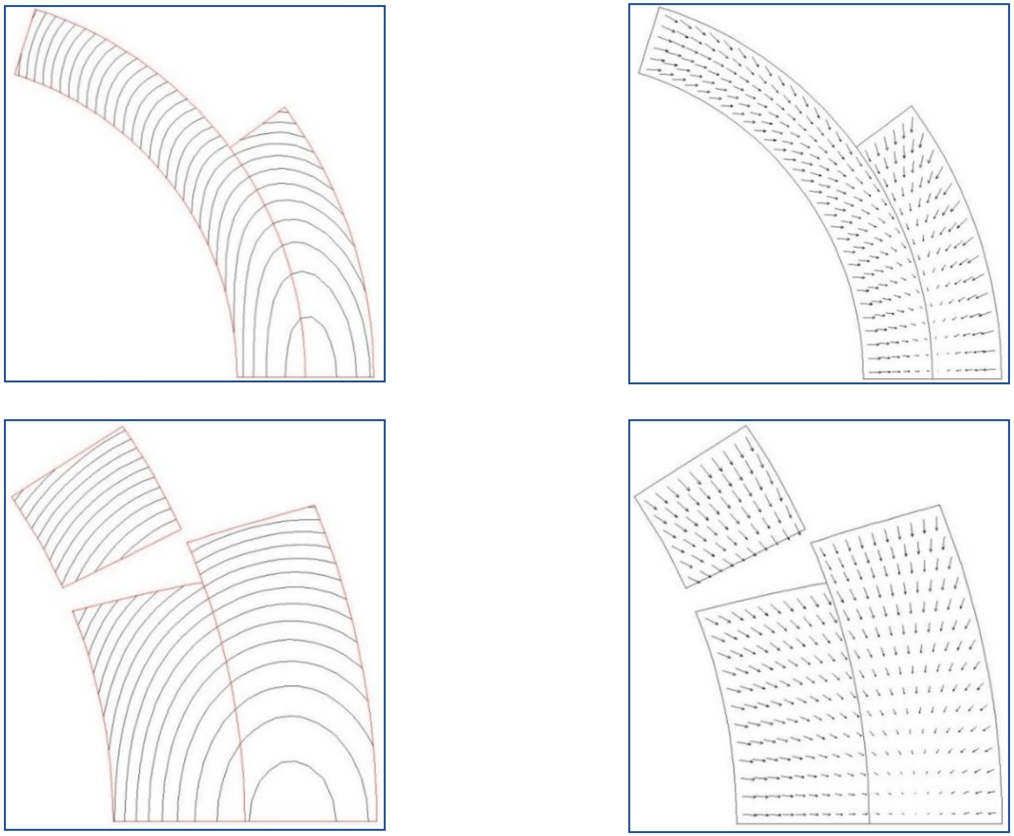
Mechanics of superconducting magnets
Electro-magnetic force

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



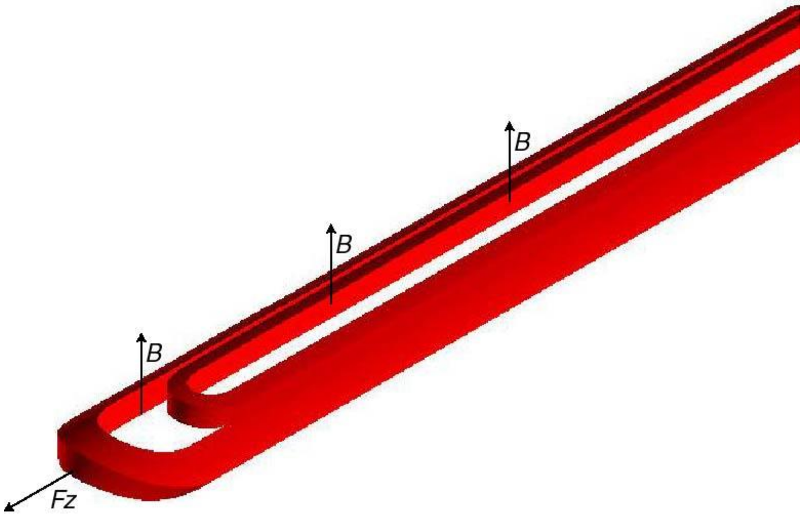


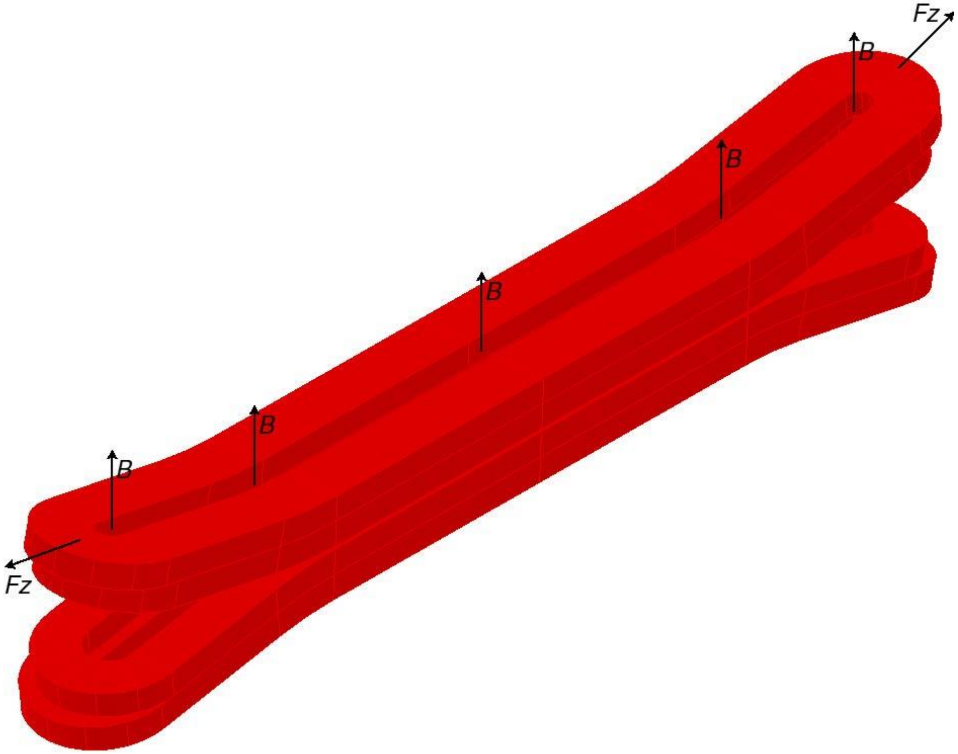




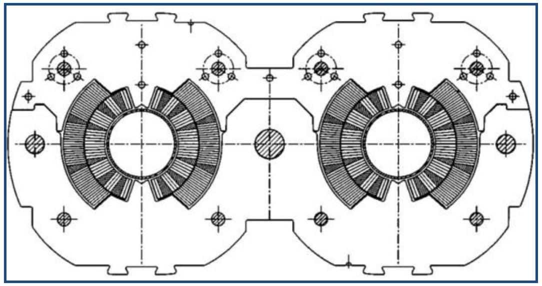
Mechanics of superconducting magnets
Electro-magnetic force

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

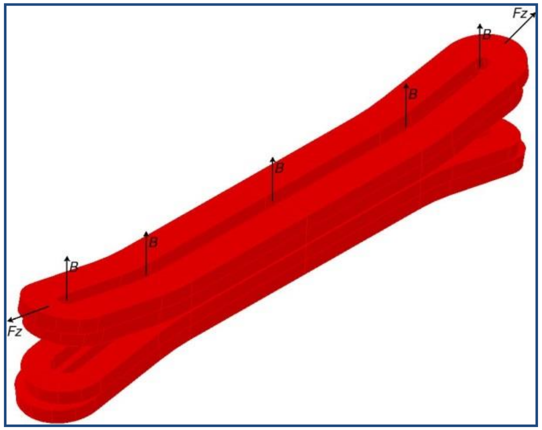




Mechanics of superconducting magnets
Electro-magnetic force



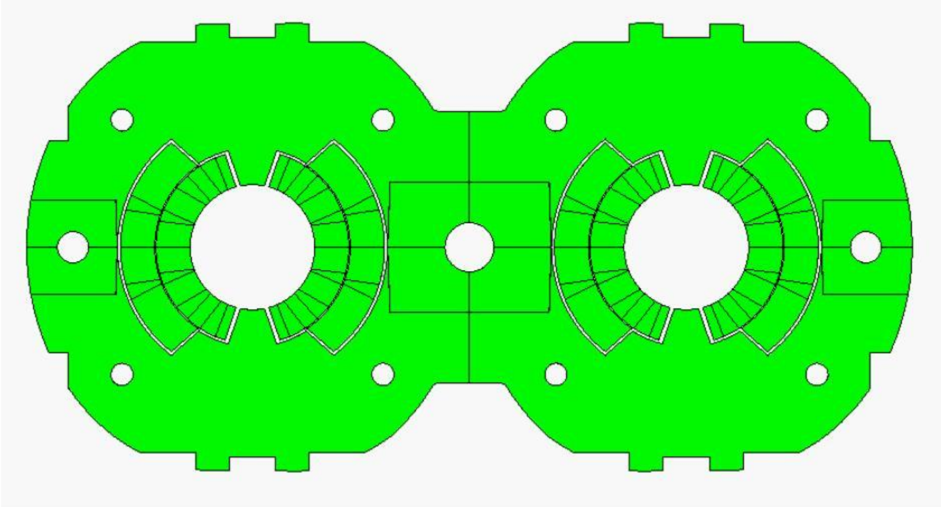
- **Nb-Ti LHC** MB
  - values per aperture
  - F_x = **340 t** per meter
    - ~300 compact cars
    - Precision of coil positioning: 20-50 μm
  - F_z = **27 t**
    - ~weight of the cold mass



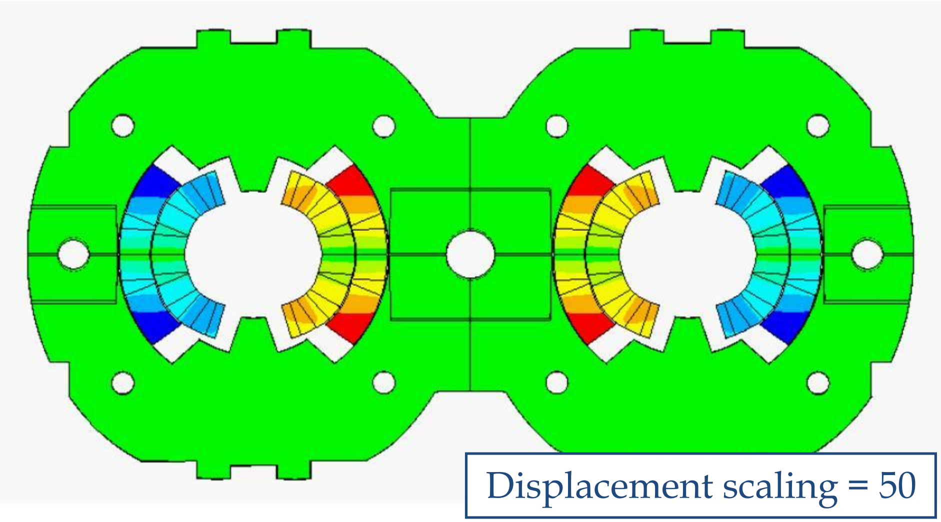
- **Nb_3Sn dipole** (HD2)
  - F_x = **500 t** per meter
  - F_z = **85 t**
  - These forces are applied to an objet with a cross-section of 150x100 mm !!!
    - and by the way, it is brittle

Mechanics of superconducting magnets
Deformation and stress

LHC dipole at 0 T



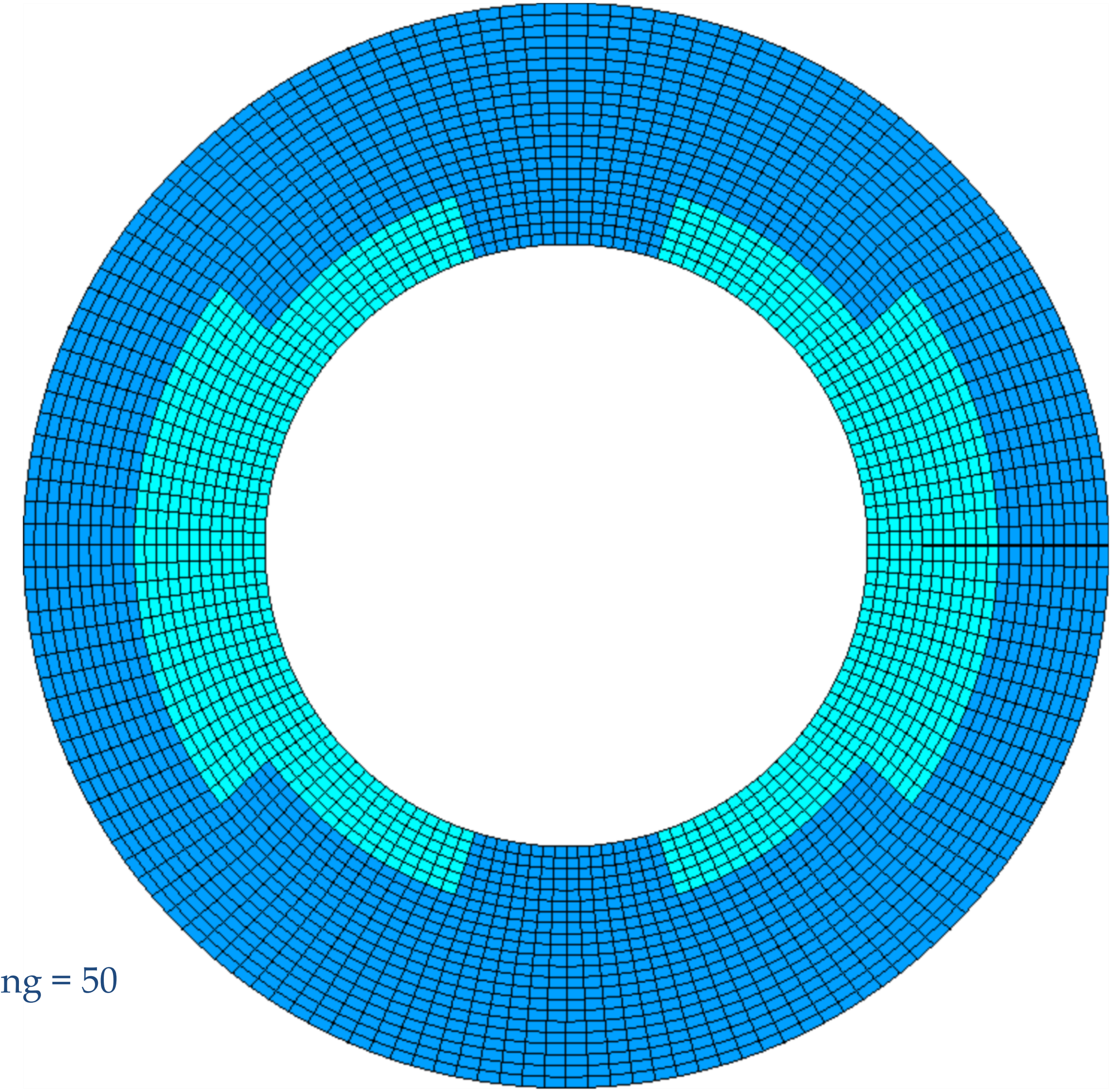
LHC dipole at 9 T



Displacement scaling = 50

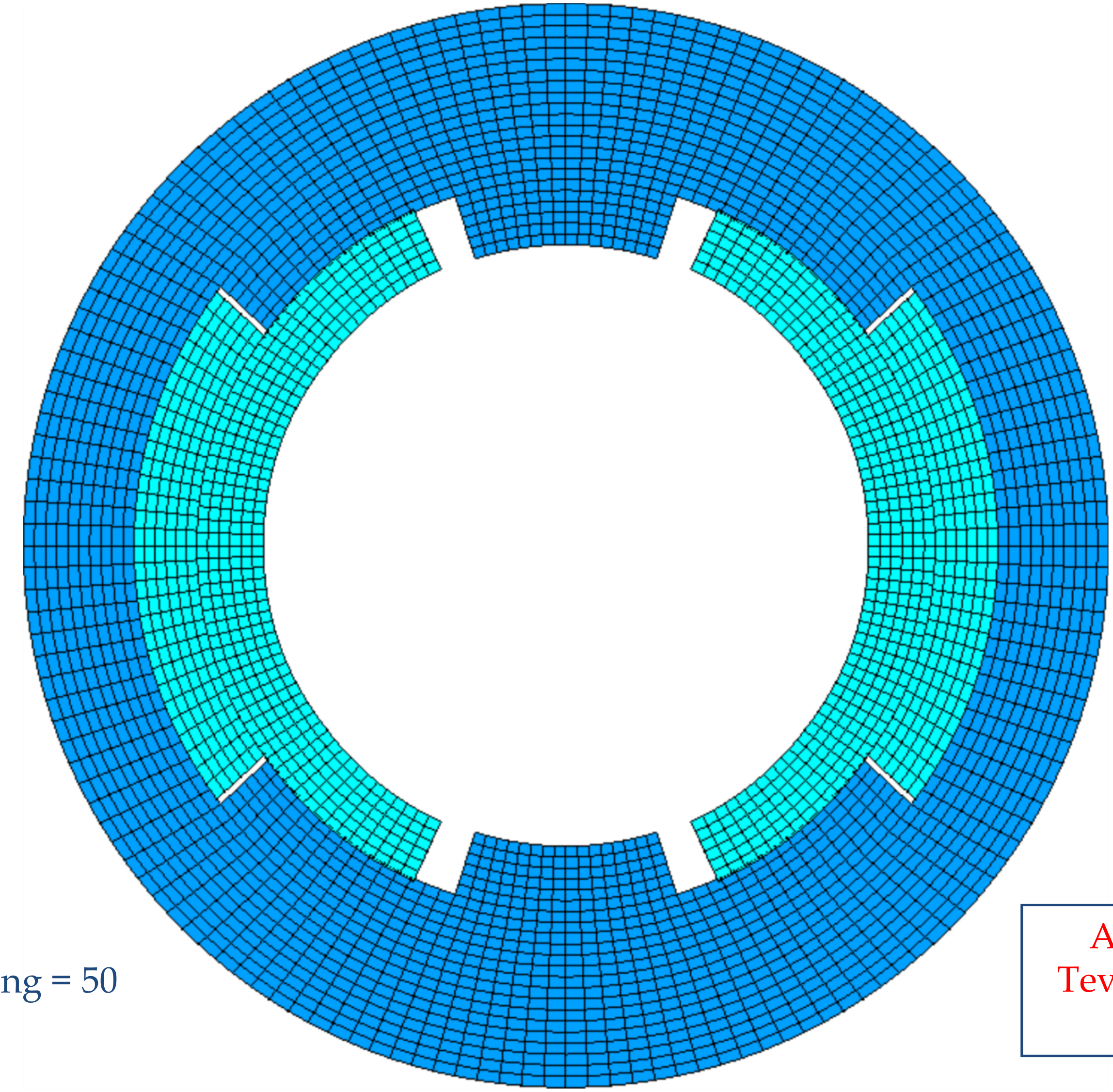
- Effect of e.m forces
  - change in **coil shape** → effect on field quality
  - a **displacement** of the conductor → potential release of frictional energy
  - Nb-Ti magnets: possible **damage** of kapton **insulation** at~150-200 MPa.
  - Nb_3Sn magnets: possible **conductor degradation** at about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

No pre-stress, no e.m. force



Displacement scaling = 50

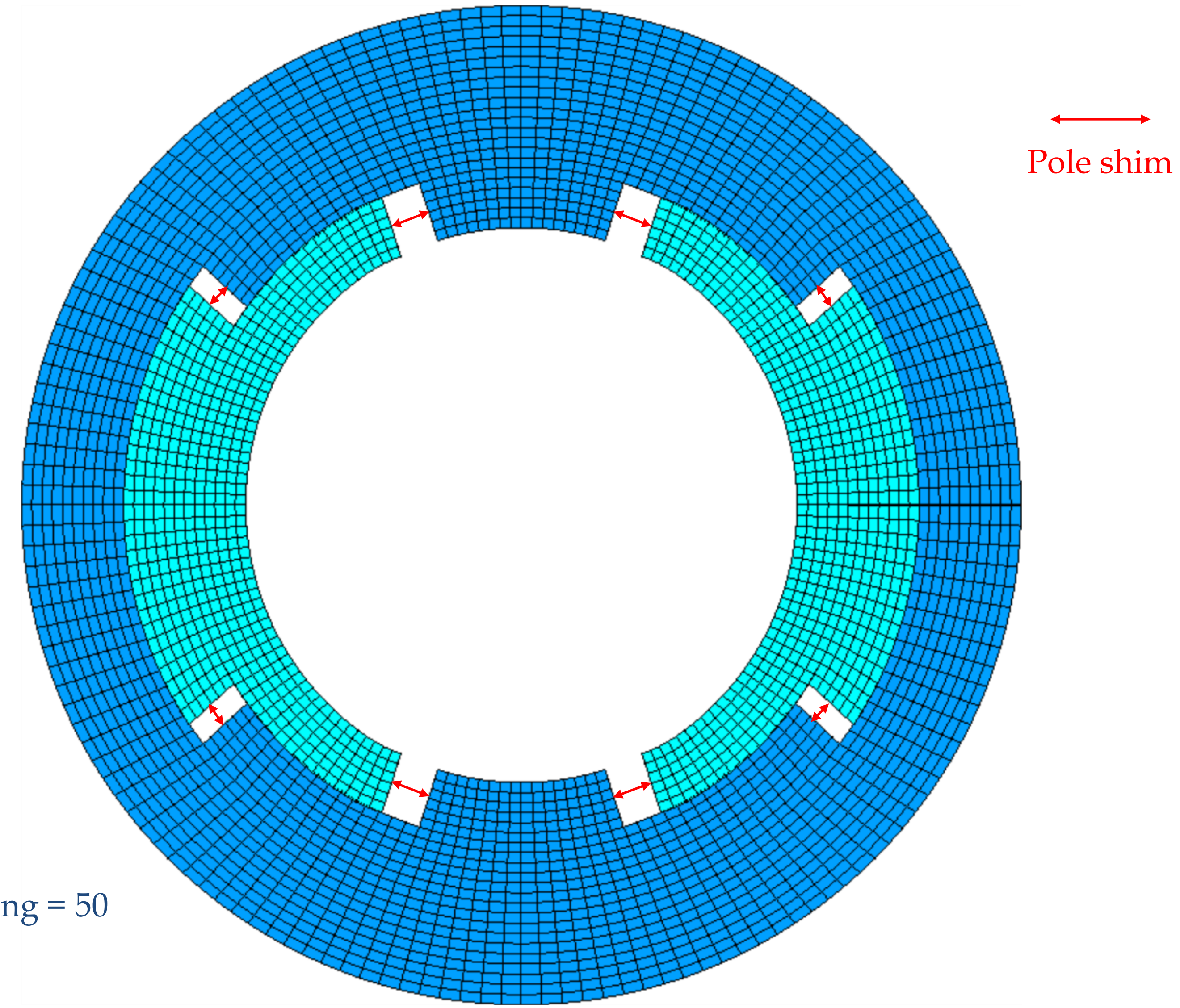
No pre-stress, with e.m. force



Displacement scaling = 50

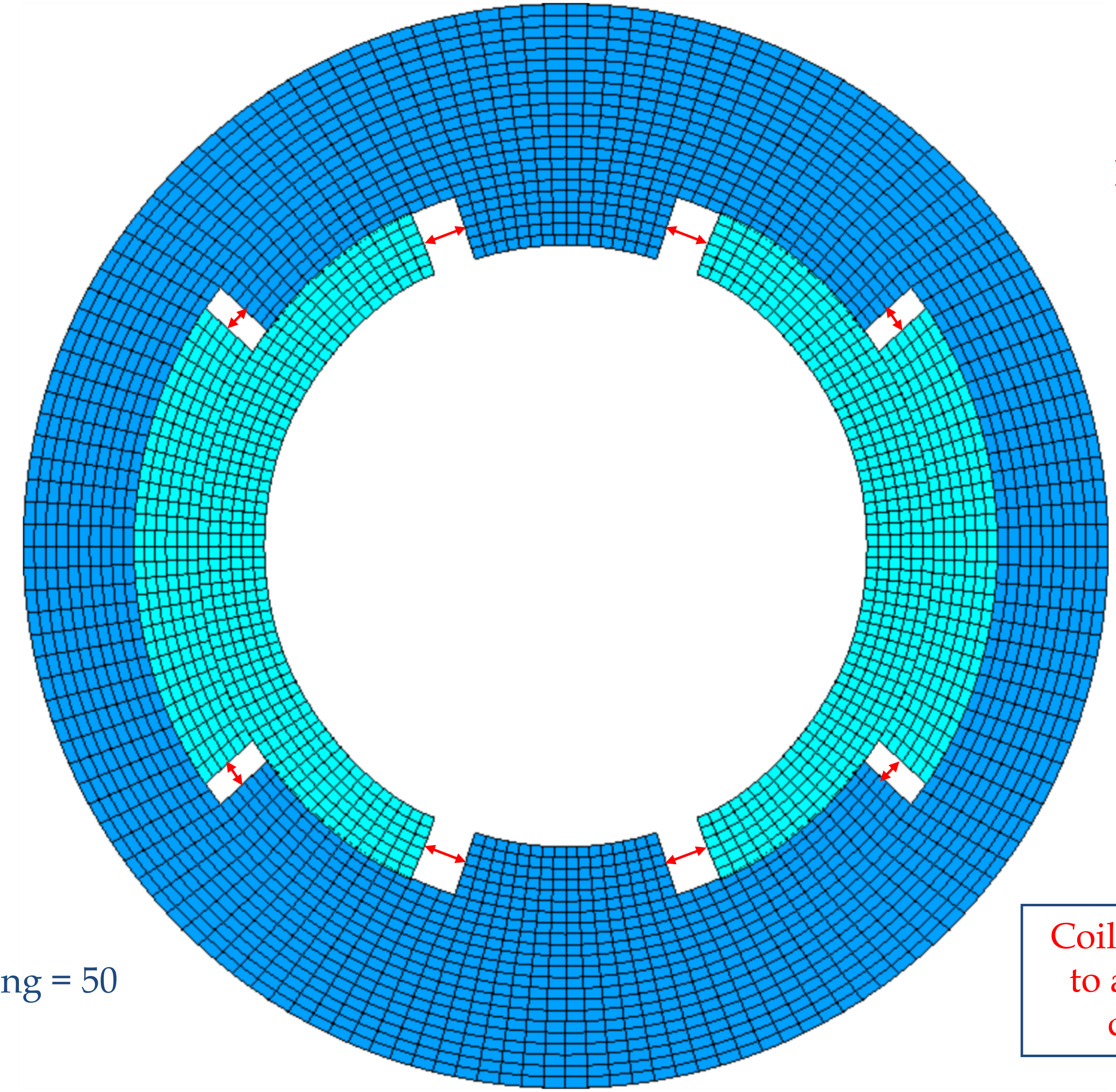
About 100 μm for Tevatron main dipole (B_{nom}= 4.4 T)

Pre-stress, no e.m. force



Displacement scaling = 50

Pre-stress, with e.m. force



↔ Pole shim

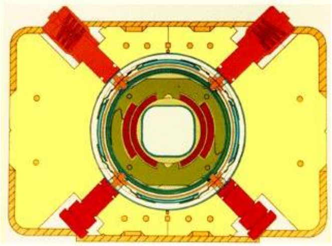
Coil pre-stress applied to all the accelerator dipole magnets

Displacement scaling = 50

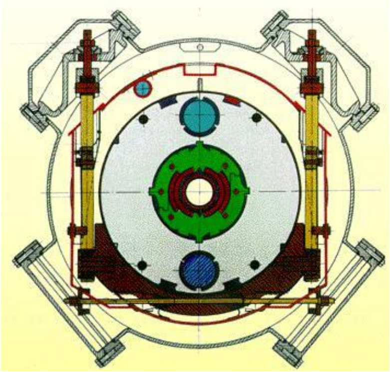
Mechanics of superconducting magnets
Support structures

- The coil is placed inside a **support structure** capable of
  - providing the required **pre-stress** to the coil after cool-down in order to reduce conductor motion;
  - **withstanding** the electro-magnetic forces;
  - providing **Helium containment**.

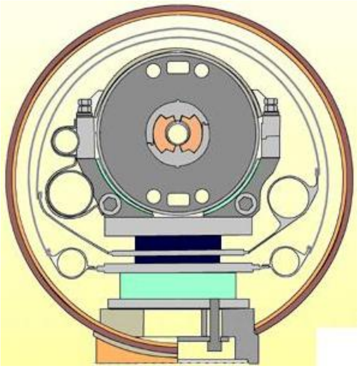
Tevatron



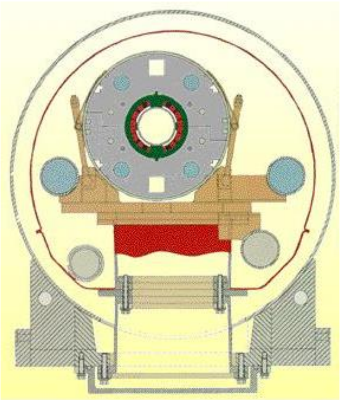
HERA



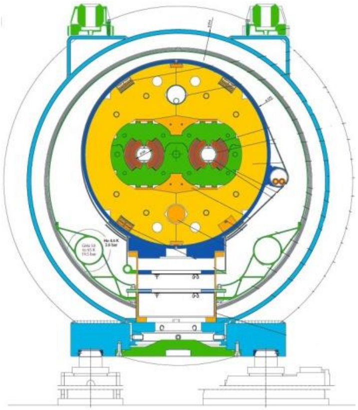
SSC



RHIC



LHC

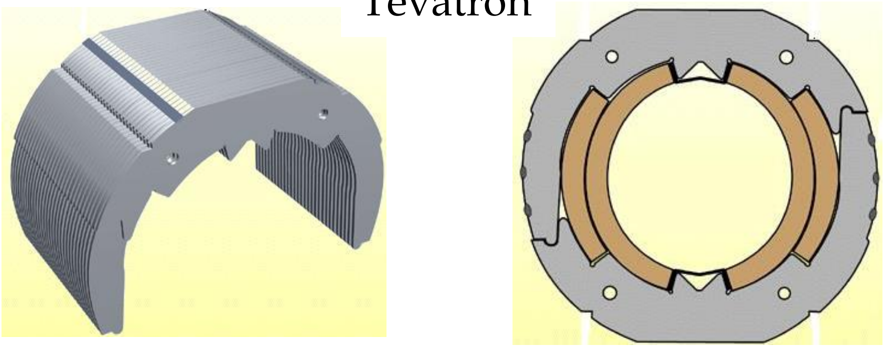


Not in scale

Mechanics of superconducting magnets
Collars

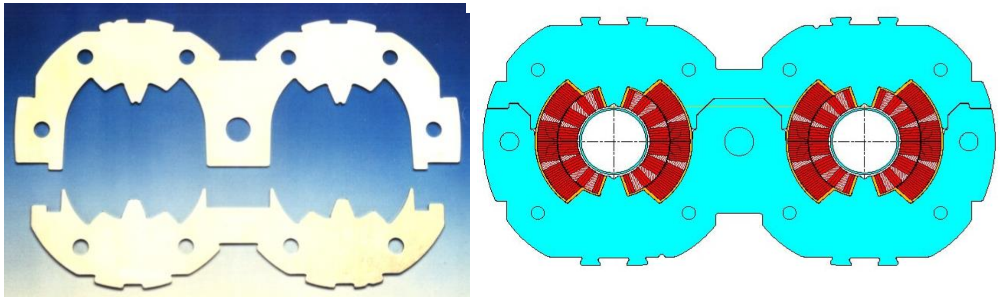
- Implemented for the first time in Tevatron
  - Since then, almost always used
- Composed by **stainless-steel or aluminum laminations** few mm thick.
- By clamping the coils, the collars provide
  - coil **pre-stressing**;
  - **rigid support** against e.m. forces
  - **precise cavity**

Tevatron



SSC

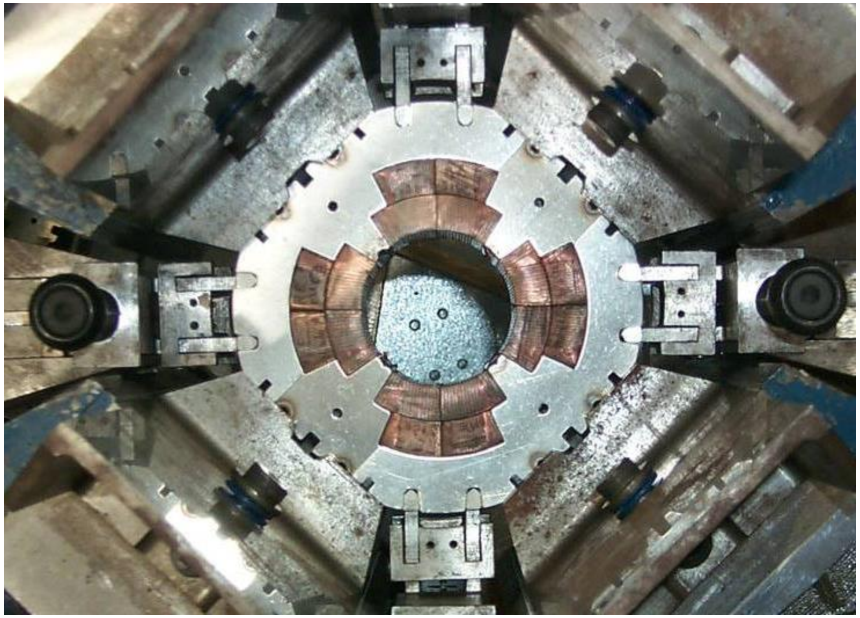
LHC



Mechanics of superconducting magnets
Collars

Collaring of a dipole magnet

Collaring of a quadrupole magnet



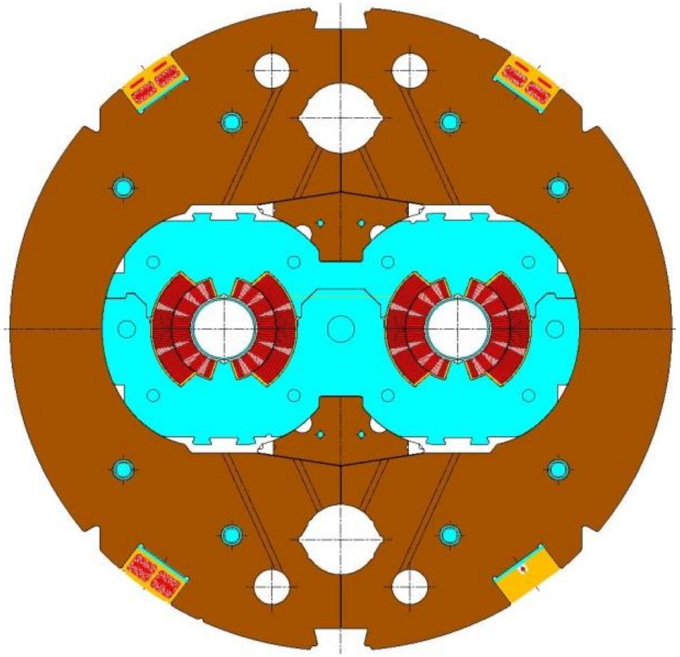
Mechanics of superconducting magnets
Iron yoke

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

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

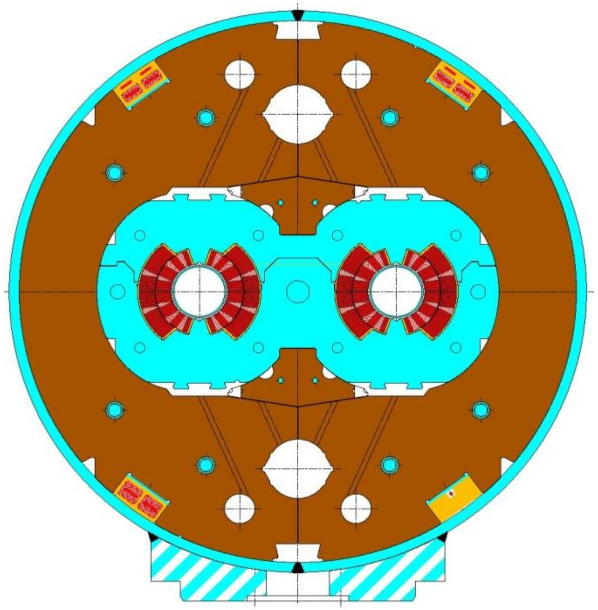
- **Structural function**
  - tight contact with the collar
    - it contributes to increase the rigidity of the coil support structure and limit radial displacement.

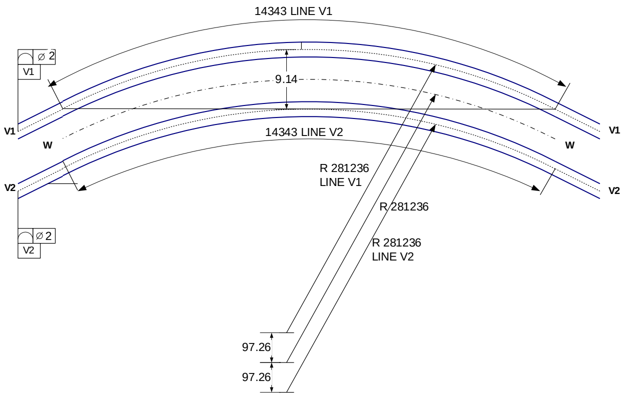
- Holes are included in the yoke design for
  - Correction of **saturation effect**
  - **Cooling channel**
  - **Assembly features**
  - **Electrical bus**



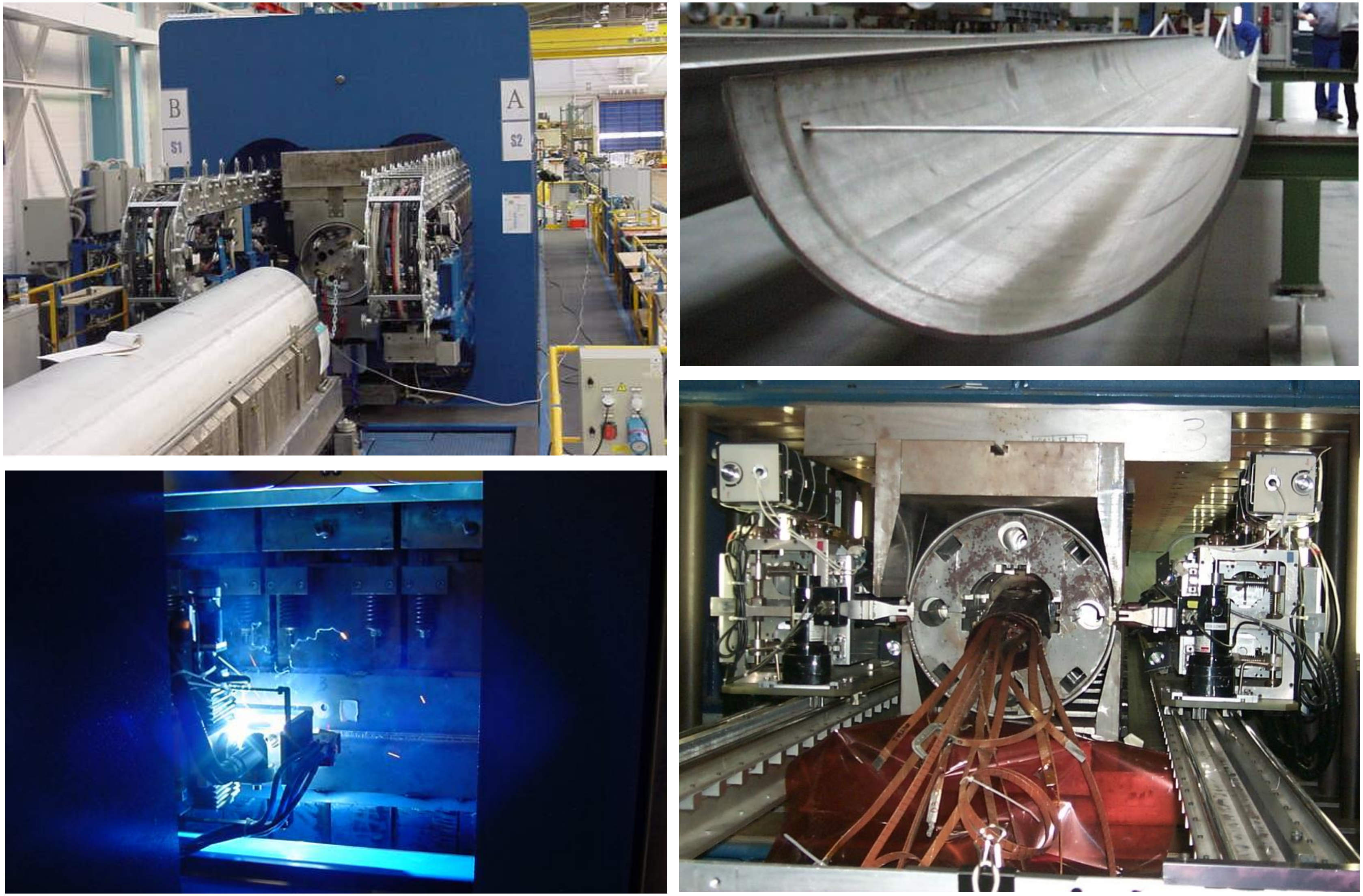
Mechanics of superconducting magnets
Shell

- The cold mass is contained within a shell
- The shell constitutes a **containment structure** for the liquid Helium.
- It is composed by two half shells of stainless steel **welded** around the yoke with high tension (about 150 MPa for the LHC dipole).
  - With the iron yoke, it contributes to create a rigid boundary to the collared coil.
- If necessary, during the welding process, the welding press can impose the desired curvature on the cold mass
  - In the LHC dipole the nominal sagitta is of **9.14 mm**.



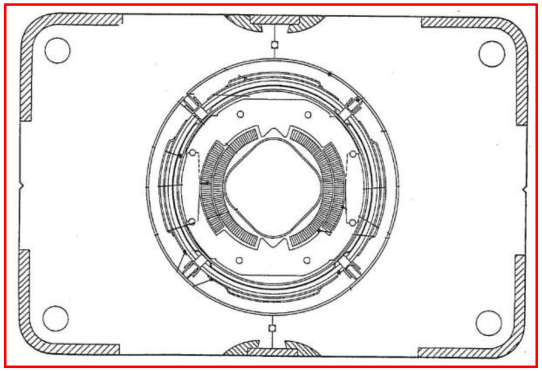


Mechanics of superconducting magnets
Shell

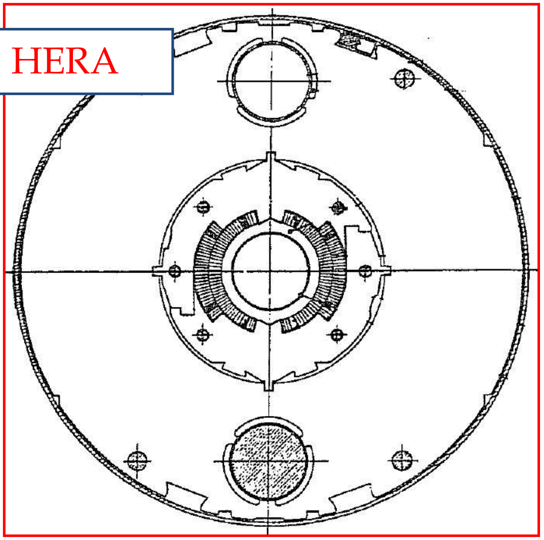


Mechanics of superconducting magnets
Overview

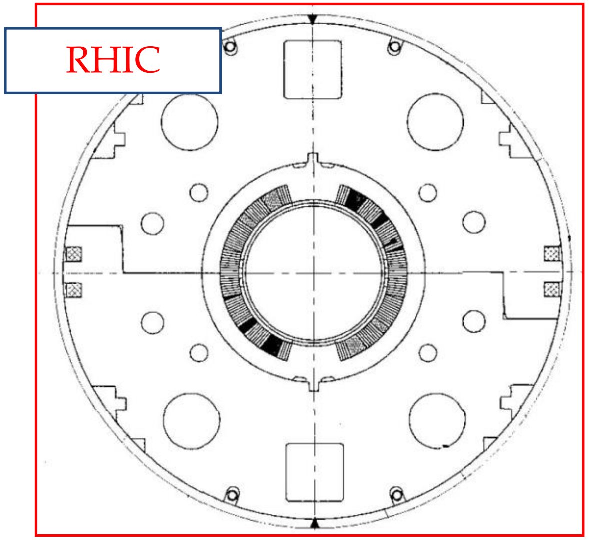
Tevatron



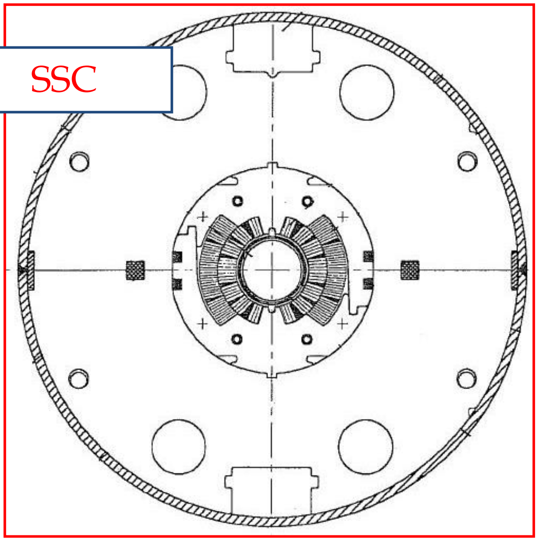
HERA



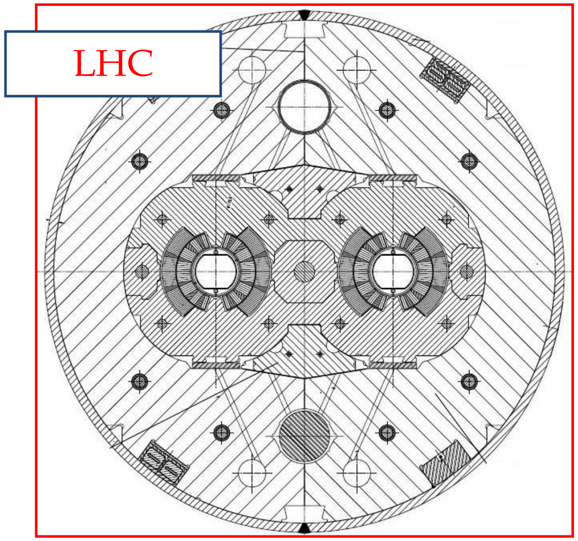
RHIC



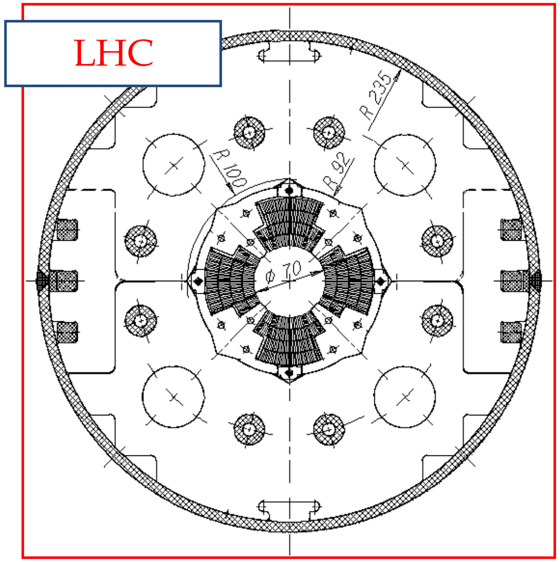
SSC



LHC

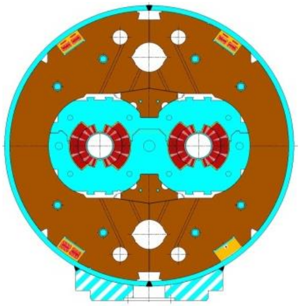


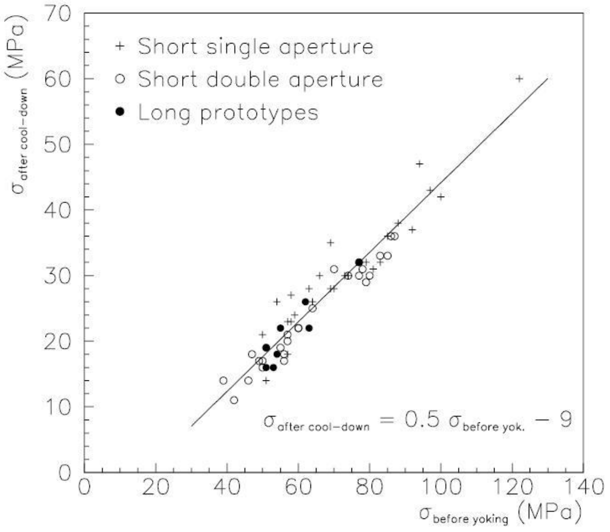
LHC



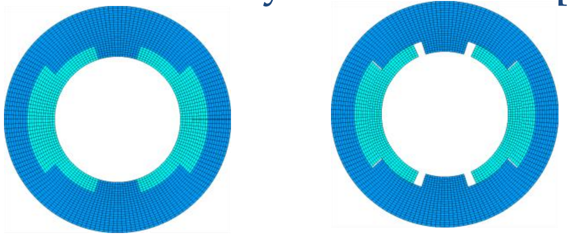
Mechanics of superconducting magnets
Cool-down and excitation

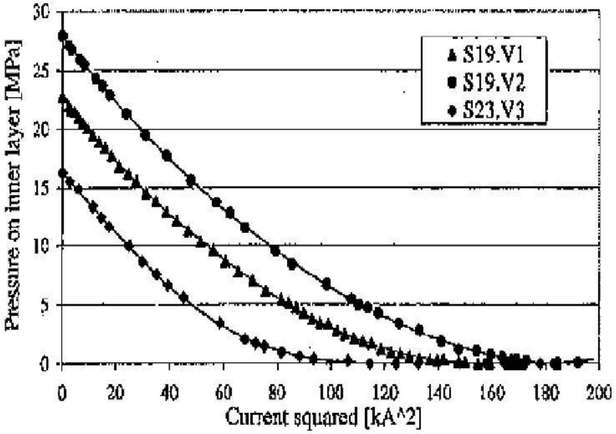
- **During cool-down**
  - Components shrink differently
    - Again, coil positioning within 20-50 μm
  - Significant **variations of coil stress**





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





Outline

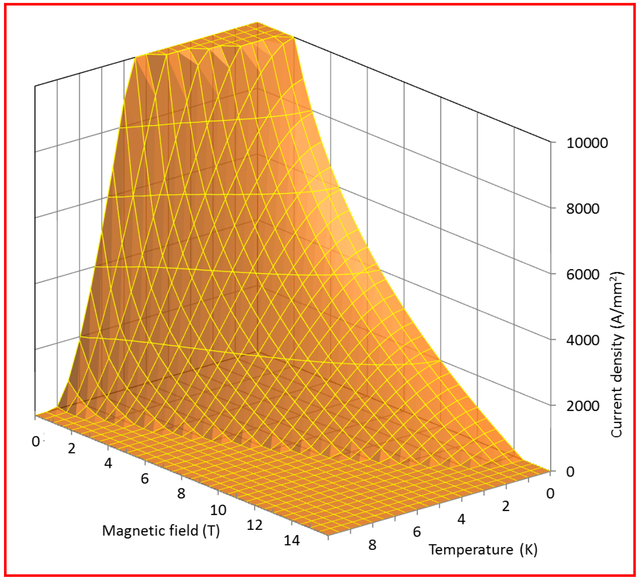
- Particle accelerators and superconductors
- Magnetic design and coils
- Mechanics of superconducting magnets
- Quench and protection

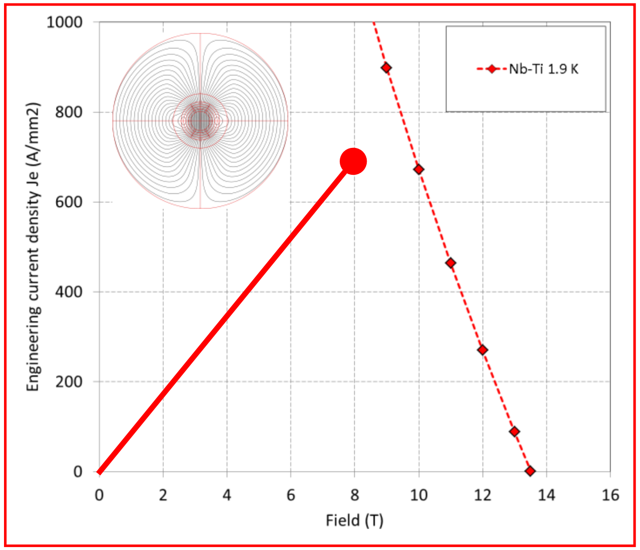
Quench and protection
Magnet ramp-up

- Current **ramp-up** (magnet powering, excitation)
  - Increase of bore and coil/conductor field
    - **Load line**

- **Target**
  - Achieve operational current/field
    - Usually at about **80%** of maximum *I* or **short sample current I_{ss}**
      - i.e. **not too close** to the critical surface

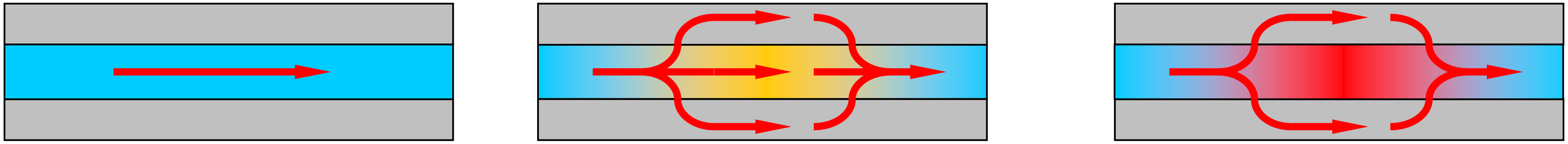
- What if you continue to increase *I* ?





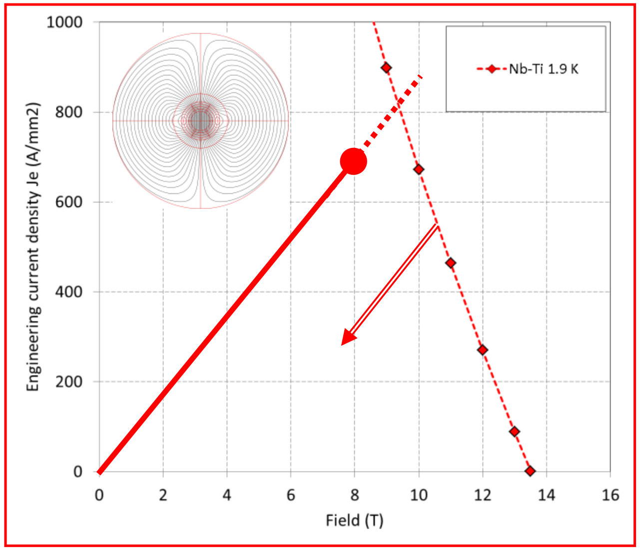
Quench and protection
Quench

- If critical **surfaces/current is passed**
  - Current starts flowing in the stabilizer → **power dissipation**
- If power high enough and cooling low enough
  - Irreversible transition → **quench** → **propagation**
    - ***Conductor-limited quench***



by L. Bottura

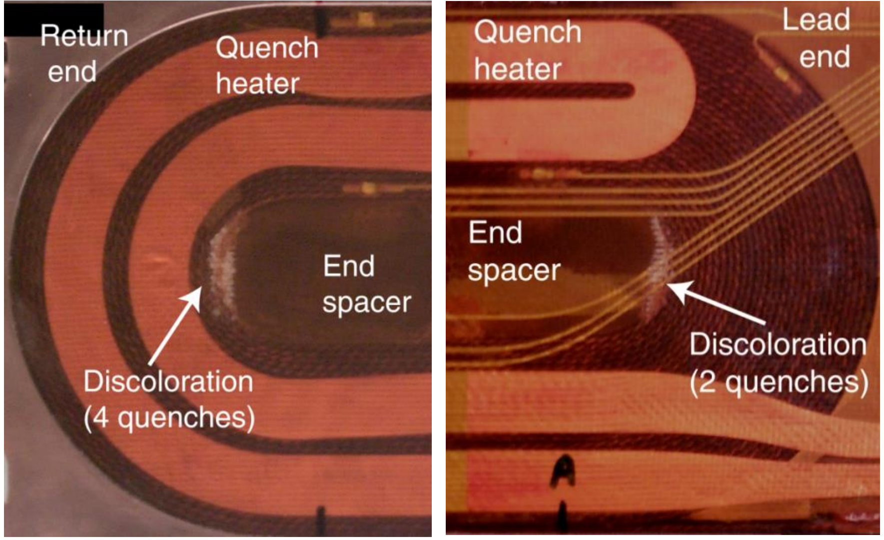
- …but…sometimes
  - Disturbance → release of energy → increases the temperature of the conductor
    - ***energy-deposited*** or ***premature quenches***
- Which are these **disturbances**?

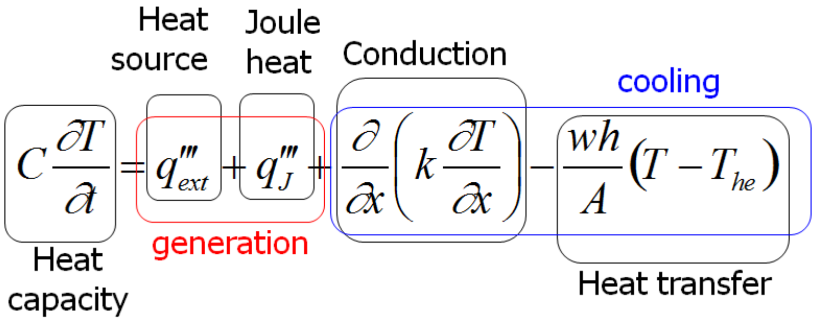


Quench and protection
Disturbances

- Thermal energy released by
  - **Mechanical events**
    - Frictional motion
    - Epoxy cracking
  - **Electromagnetic events**
    - Flux-jumps ,AC loss
  - **Thermal events**
    - Degraded cooling
  - **Nuclear events**
    - Particle showers

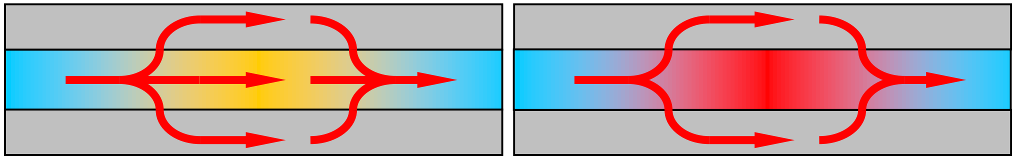
- **Quench**, i.e. irreversible transition to normal state
  - **Heat generation > cooling**





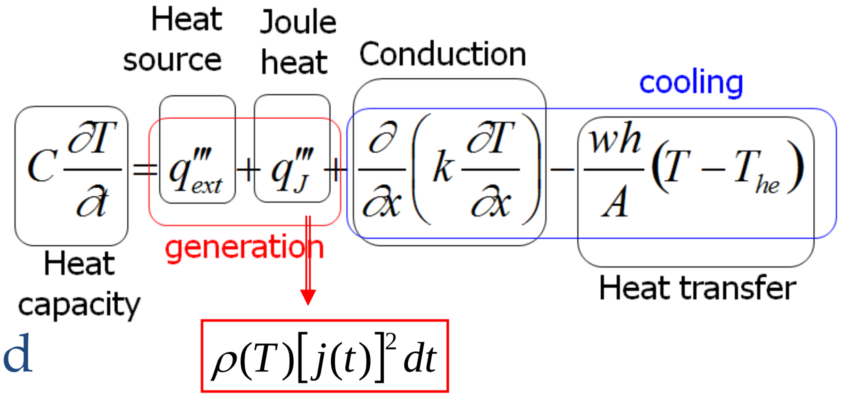
$$C\frac{\partial T}{\partial t} = q'''_{ext} + q'''_{J} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{wh}{A}\left(T - T_{he}\right)$$

by L. Bottura



Quench and protection

- Quench → dangerous situation
  - Nb-Ti vs. Cu
    - $\rho = 6.5 \times 10^{-7}$ vs. 3×10^{-10} [Ω m]
    - $k = 0.1$ vs. 350 [W m^{-1} K^{-1}]
  - A purely superconductor wire would be impossible to protect
- With Cu a much better
  - Still, we need to **dump the current** rapidly (in ~0.1-0.5 s)
- Magnet is a ***RL*** circuit with time constant $\tau = L/R$
  - Where *R* is the magnet resistance
    - We should make it quench everywhere for higher *R* and lower *τ*



Heat source

Joule heat

Conduction

cooling

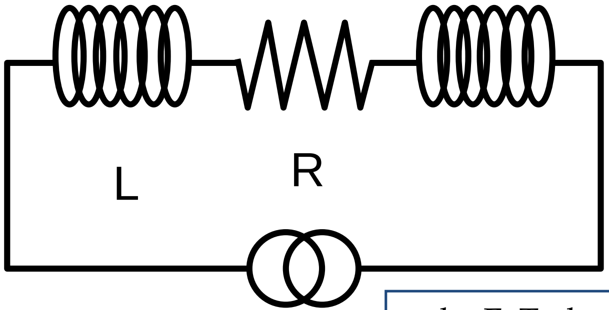
$$C\frac{\partial T}{\partial t} = q'''_{ext} + q'''_{J} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{wh}{A}\left(T - T_{he}\right)$$

Heat capacity

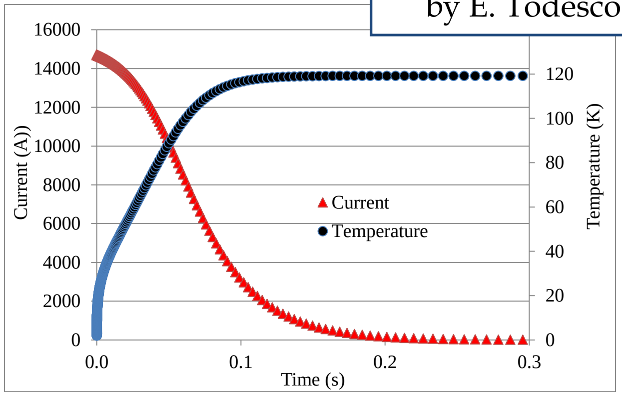
generation

Heat transfer

$$\rho(T)\left[j(t)\right]^2 dt$$

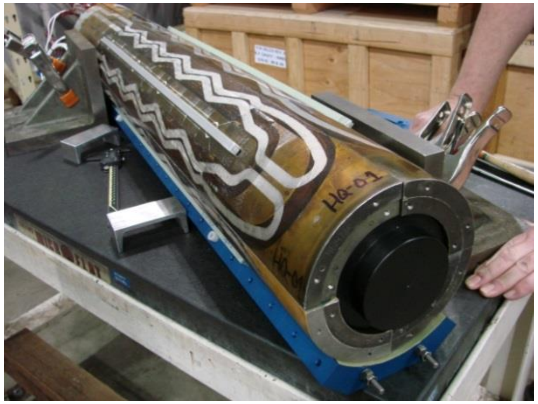


by E. Todesco



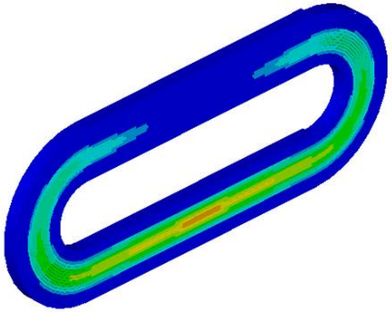
Quench and protection

- We should make it quench everywhere
  - **Quench heaters**: strips of stainless steel close to the coil

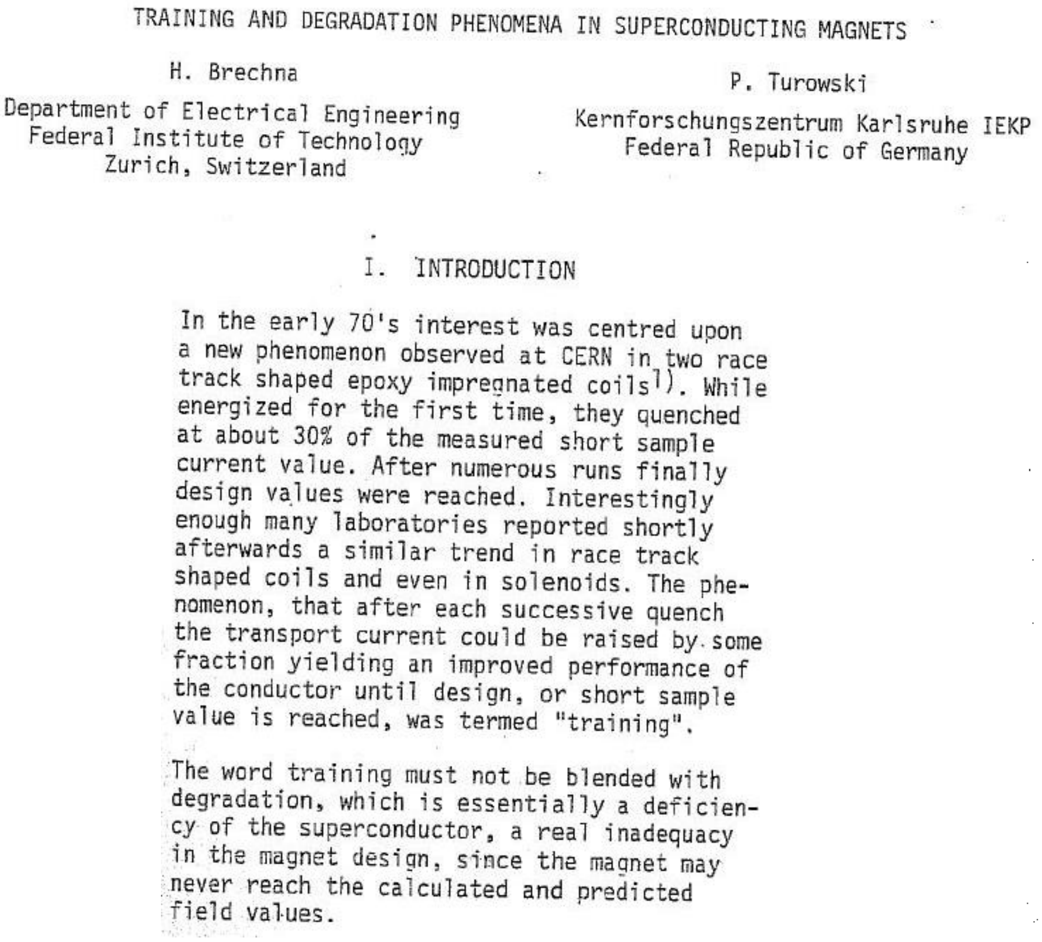


- Another way of looking at it
  - Conversion **magnetic energy - thermal energy**
  - LHC dipole stored energy: 7 MJ
    - Potential energy of a dipole at 25 m of height
  - One has to **redistribute the energy** in the whole coil volume

$$E_m = \int_V \frac{B^2}{2\mu_0} dv = \frac{1}{2} L I^2$$



Quench and protection
Training



TRAINING AND DEGRADATION PHENOMENA IN SUPERCONDUCTING MAGNETS

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Federal Institute of Technology
Zurich, Switzerland

P. Turowski
Kernforschungszentrum Karlsruhe IEKP
Federal Republic of Germany

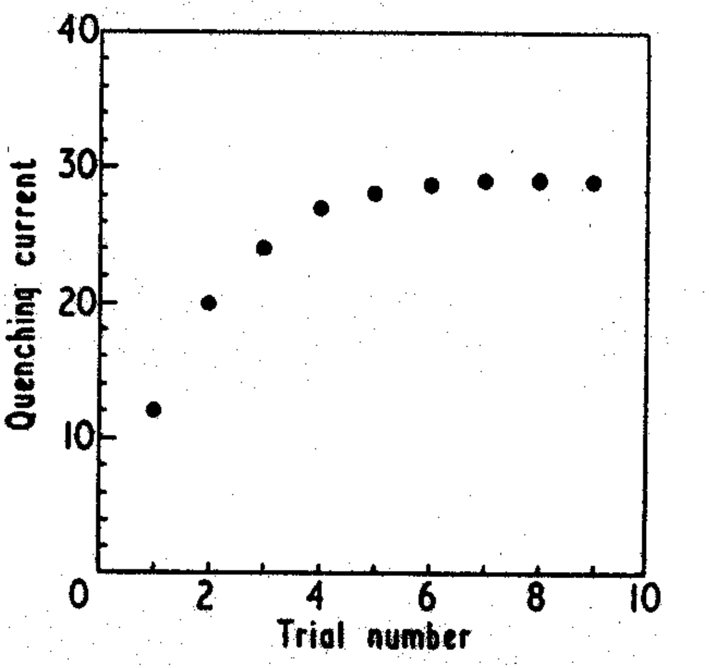
I. INTRODUCTION

In the early 70's interest was centred upon a new phenomenon observed at CERN in two race track shaped epoxy impregnated coils1). While energized for the first time, they quenched at about 30% of the measured short sample current value. After numerous runs finally design values were reached. Interestingly enough many laboratories reported shortly afterwards a similar trend in race track shaped coils and even in solenoids. The phenomenon, that after each successive quench the transport current could be raised by some fraction yielding an improved performance of the conductor until design, or short sample value is reached, was termed "training".

The word training must not be blended with degradation, which is essentially a deficiency of the superconductor, a real inadequacy in the magnet design, since the magnet may never reach the calculated and predicted field values.

Proceedings of the 6th International Conference on Magnet Technology, 1978. p. 597.

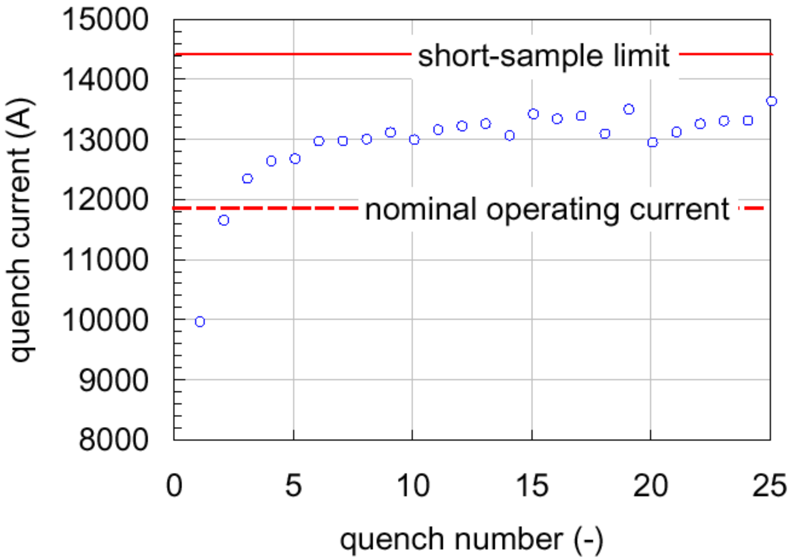
NbZr solenoid
Chester, 1967

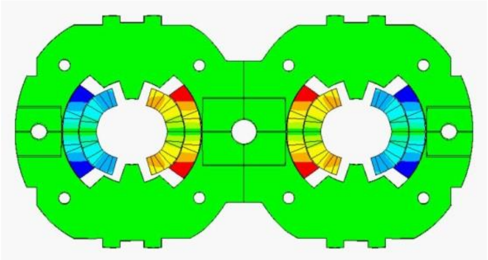


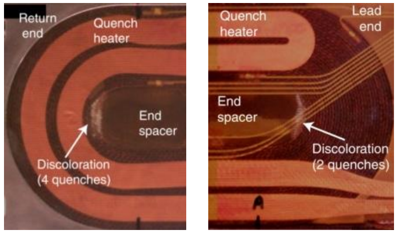
P.F. Chester, Rep. Prog. Phys., **XXX**, II, 561, 1967.

Training

- Characterized by two phenomena
  - The **occurrence** of premature quenches
  - The progressive **increase of quench *I***
- Magnet "***getting better***"
- Main causes
  - **Frictional motion**
    - E.m. forces → motion → quench
    - Coil locked by friction in a secure state
  - **Epoxy failure**
    - E.m. forces → epoxy cracking → quench
    - Once epoxy locally fractured, further cracking appears only when the e.m. stress is increased.
- Magnets operate with margin
  - Nominal *I* reached with few quenches.
- In general, **very emotional** process





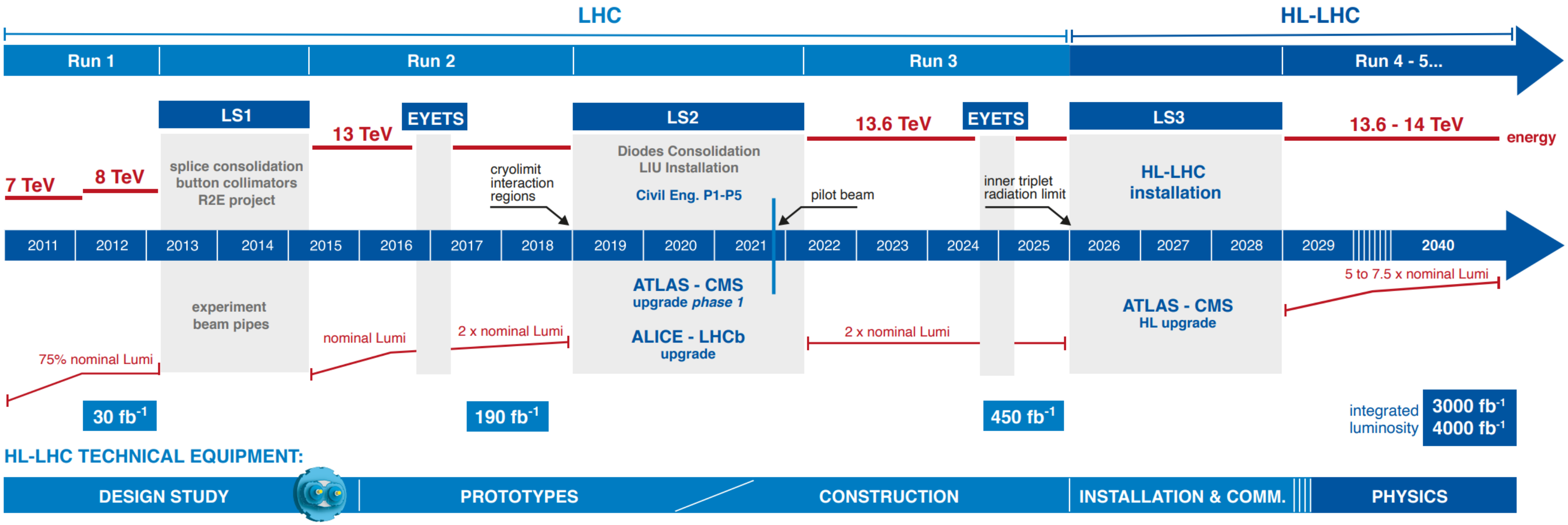


MQXFS01 test
First test of HiLumi Nb_3Sn IR quadrupole

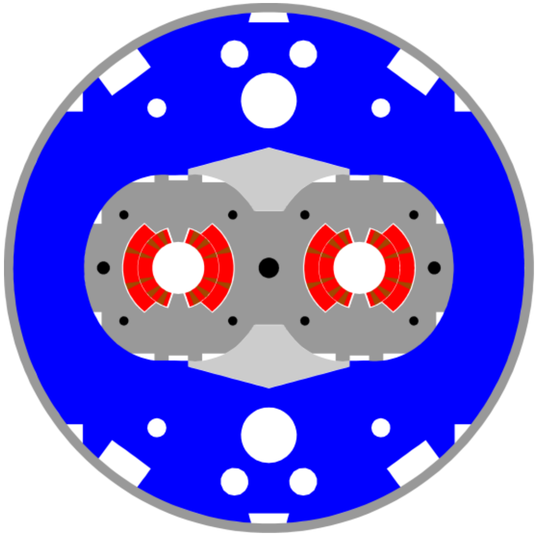
- Test at FNAL in 2016

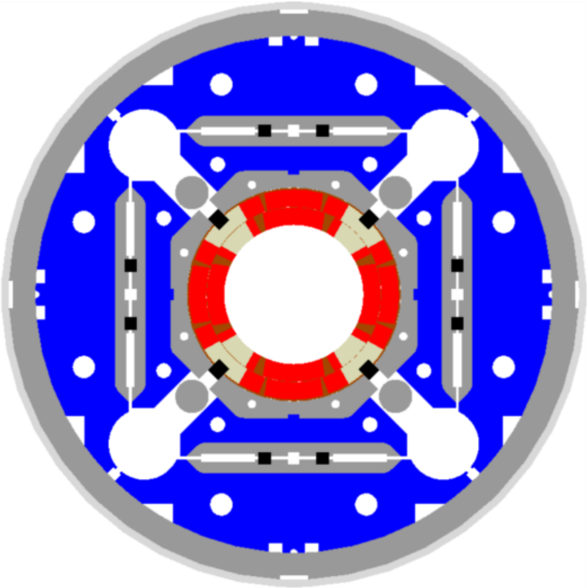
Introduction
From LHC to HL-LHC

- HL-LHC goals
  - 5 to 7.5 x nominal LHC luminosity
  - Integrated luminosity of $3000\ \mathrm{fb}^{-1}$ twelve years after the upgrade
    - More than ten times the luminosity reach of the first 10 years of the LHC lifetime.



Introduction
LHC dipole vs HL-LHC low-β quadrupole

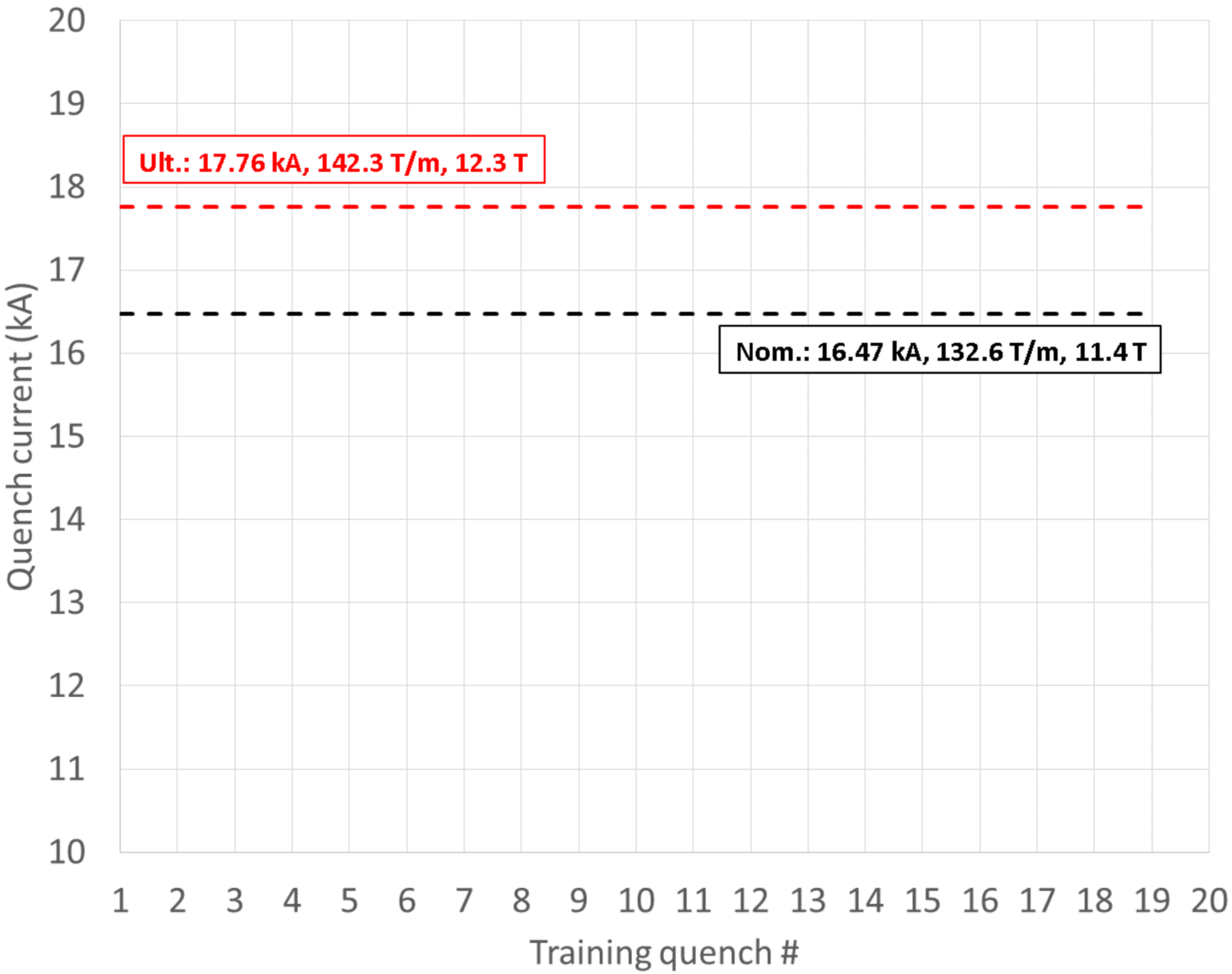




- Nb-Ti
- F_x = 340 t/m
- $\sigma_{\theta\_e.m.}$= 50-60 MPa
- $F_{z\_aperture}$ = 24 t

- Nb_3Sn
- F_x = 680 t/m
- $\sigma_{\theta\_e.m.}$= 100-110 MPa
- $F_{z\_aperture}$ = 120 t

MQXFS01 test
First test of HiLumi Nb_3Sn IR quadrupole



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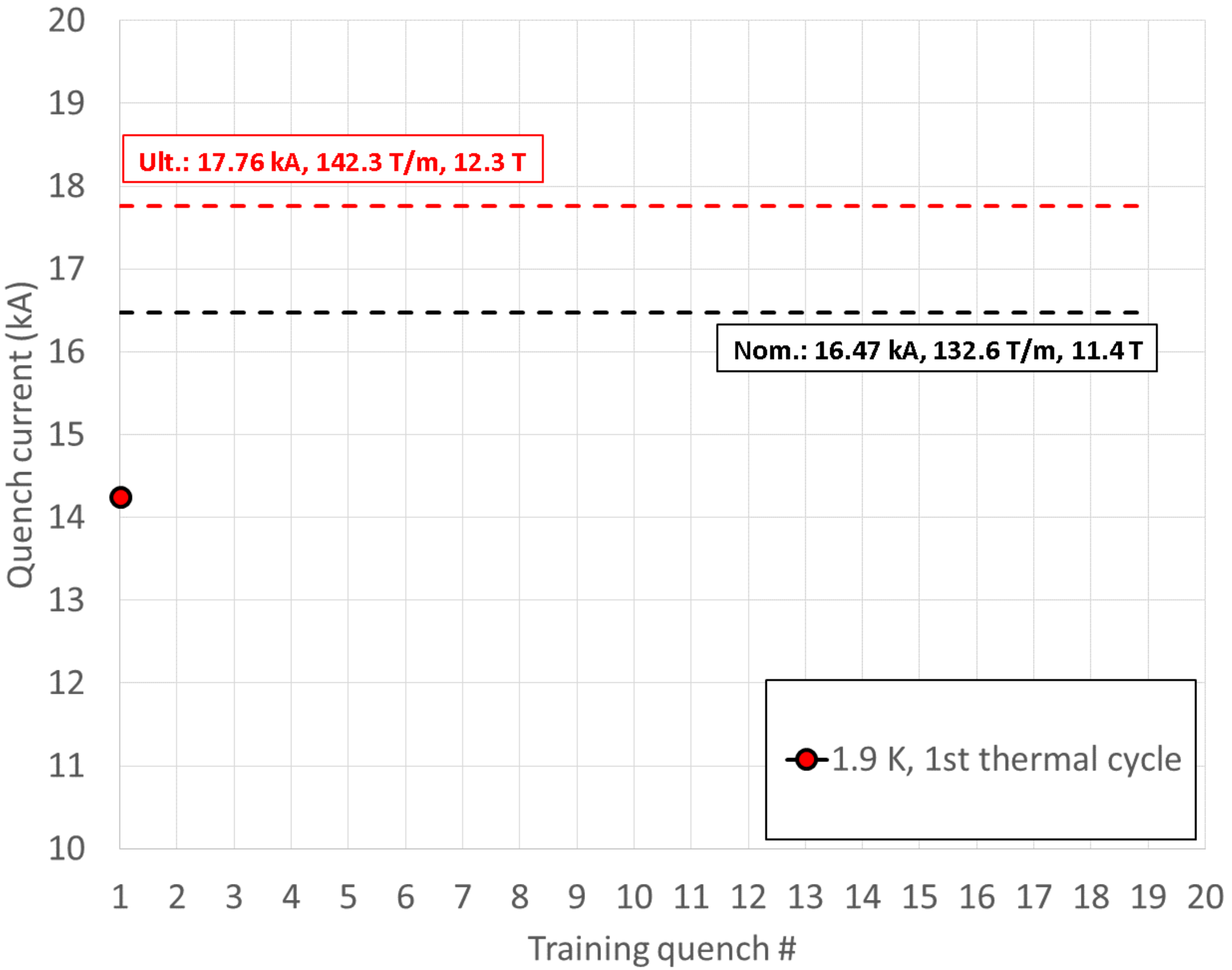

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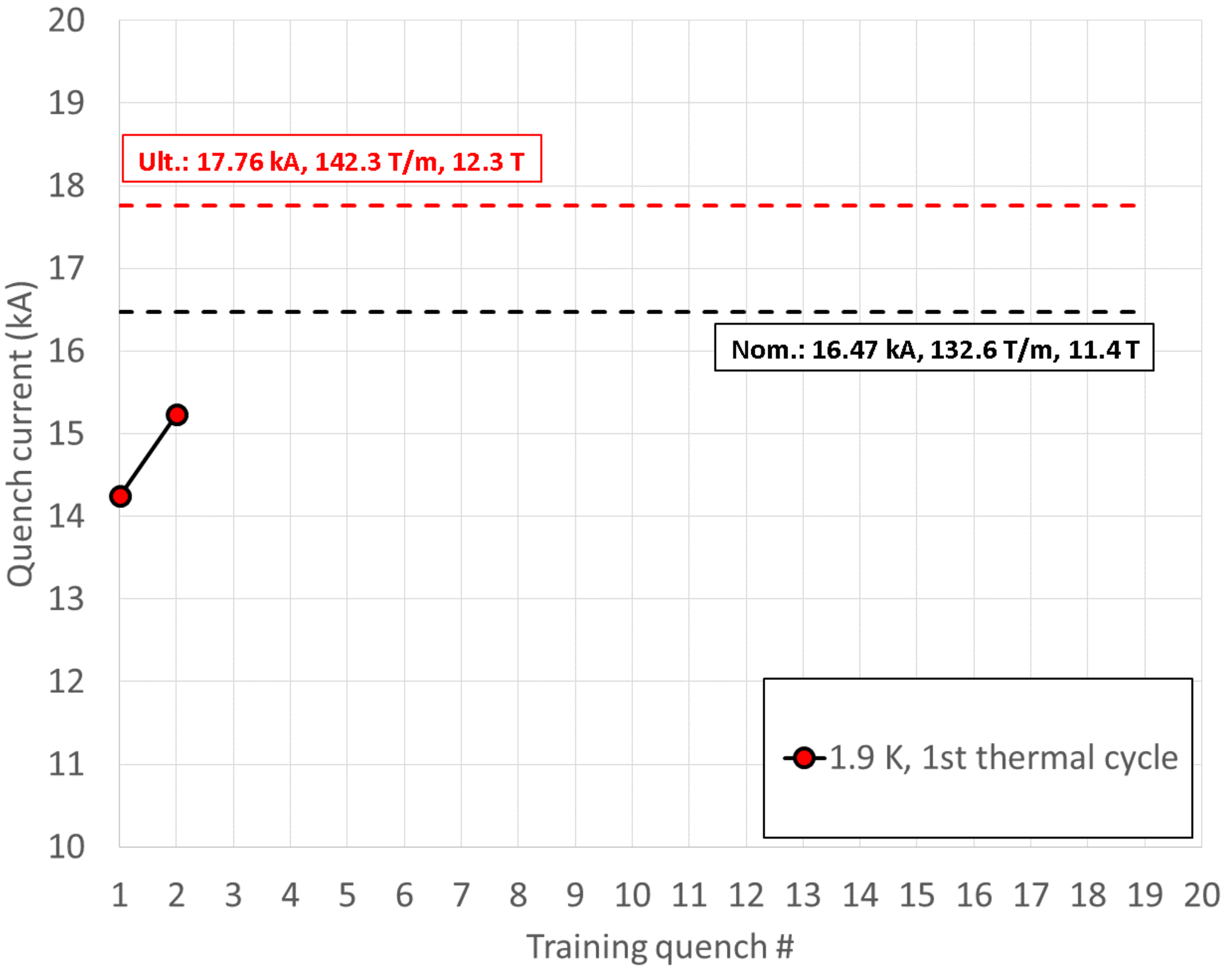

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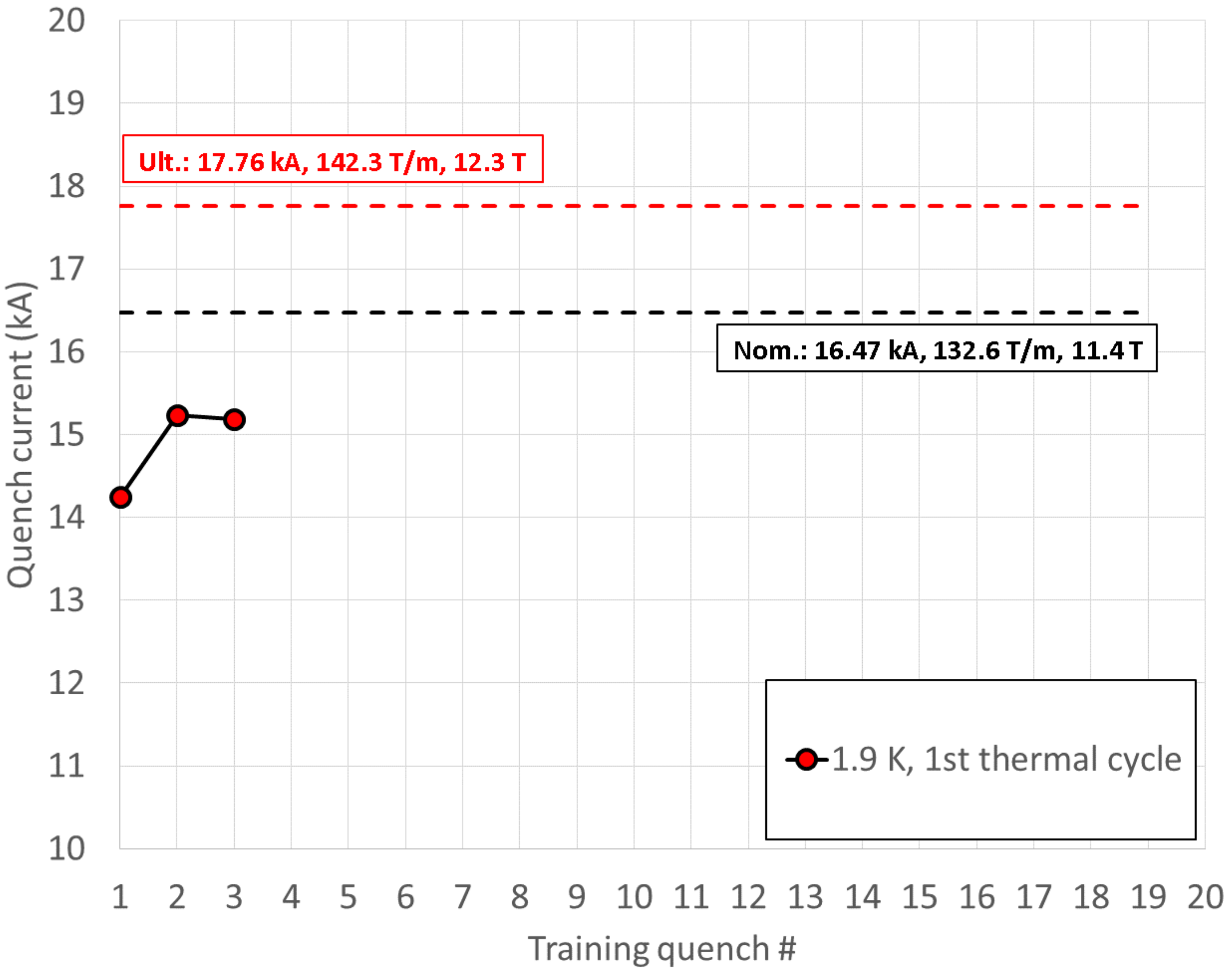

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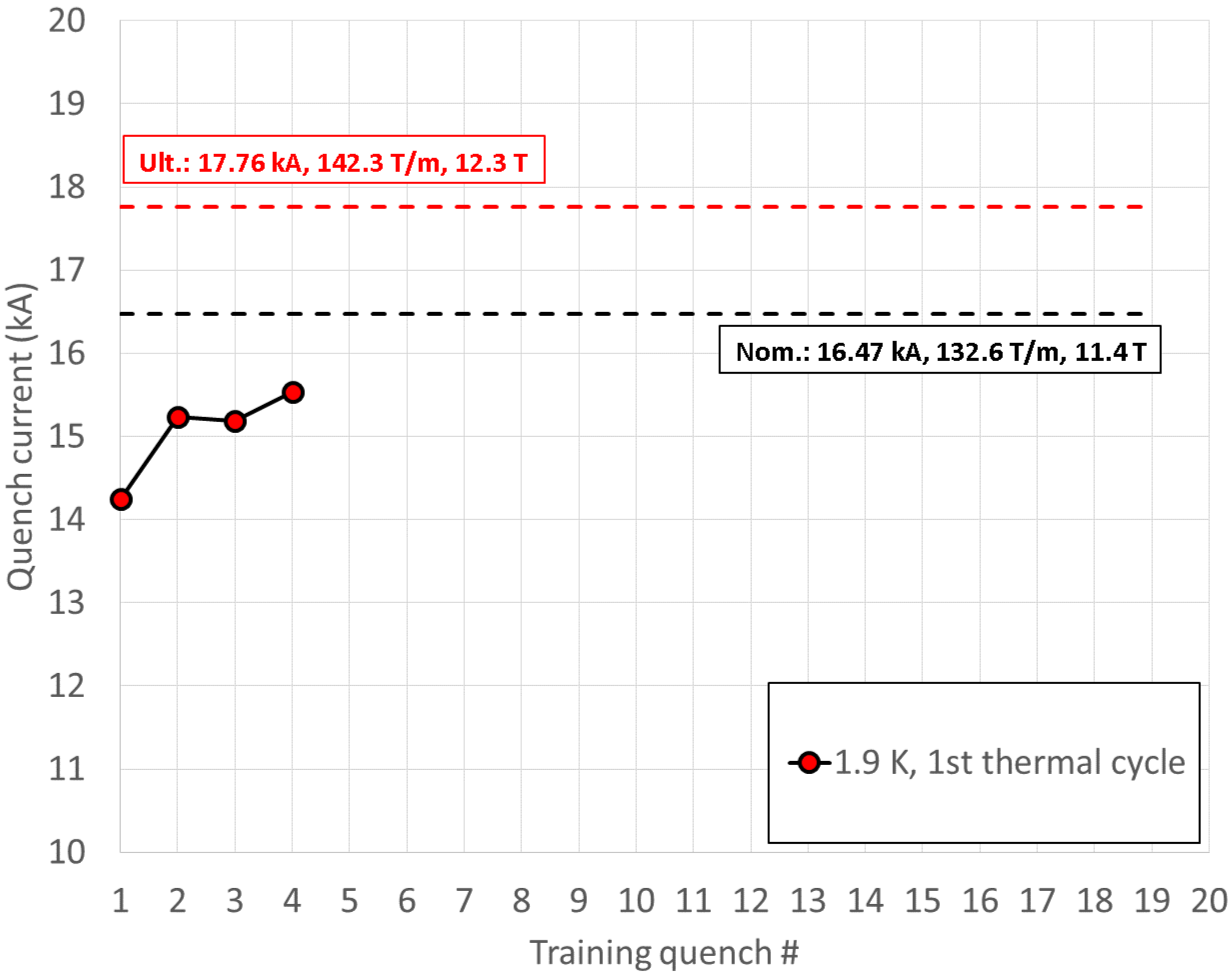

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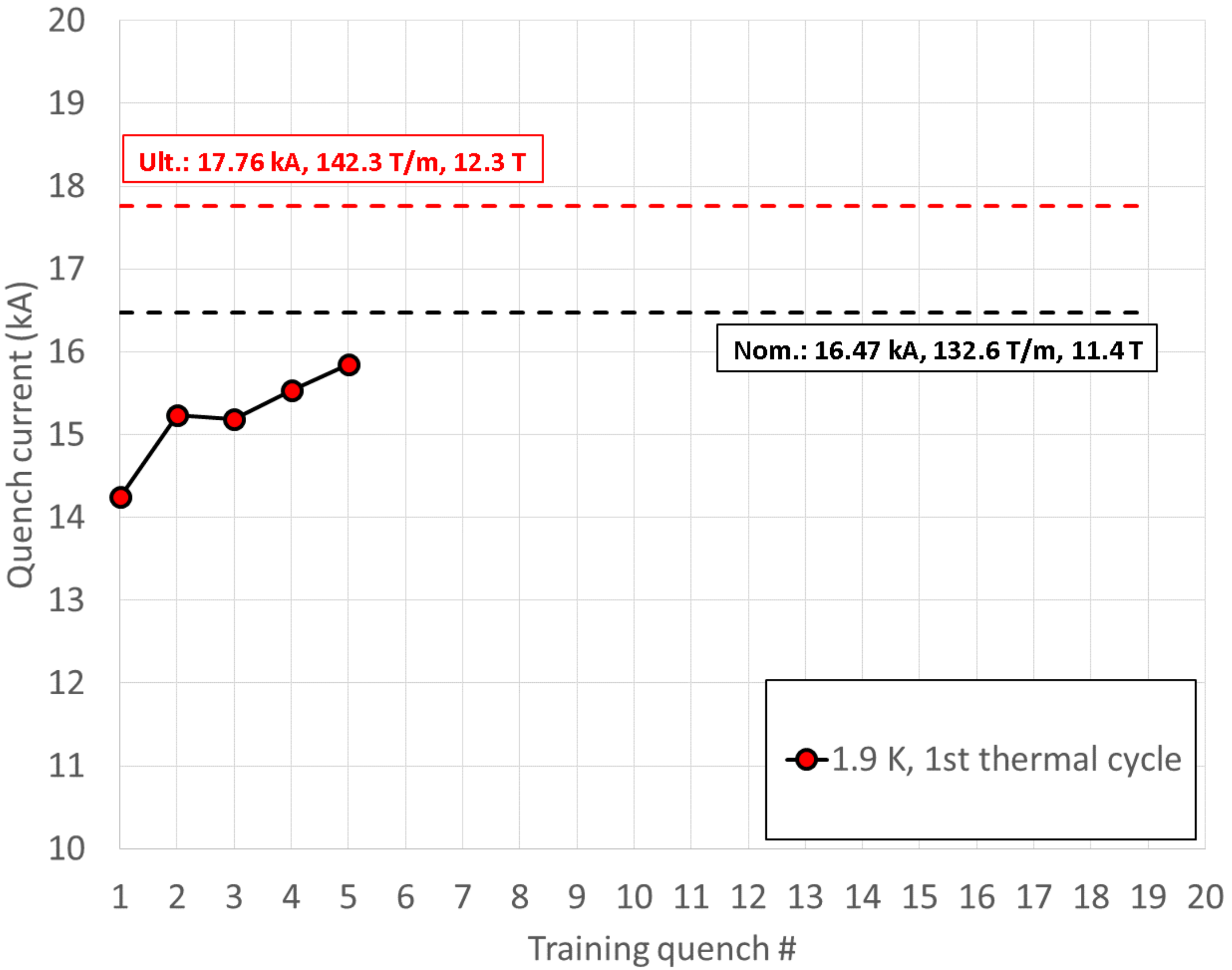

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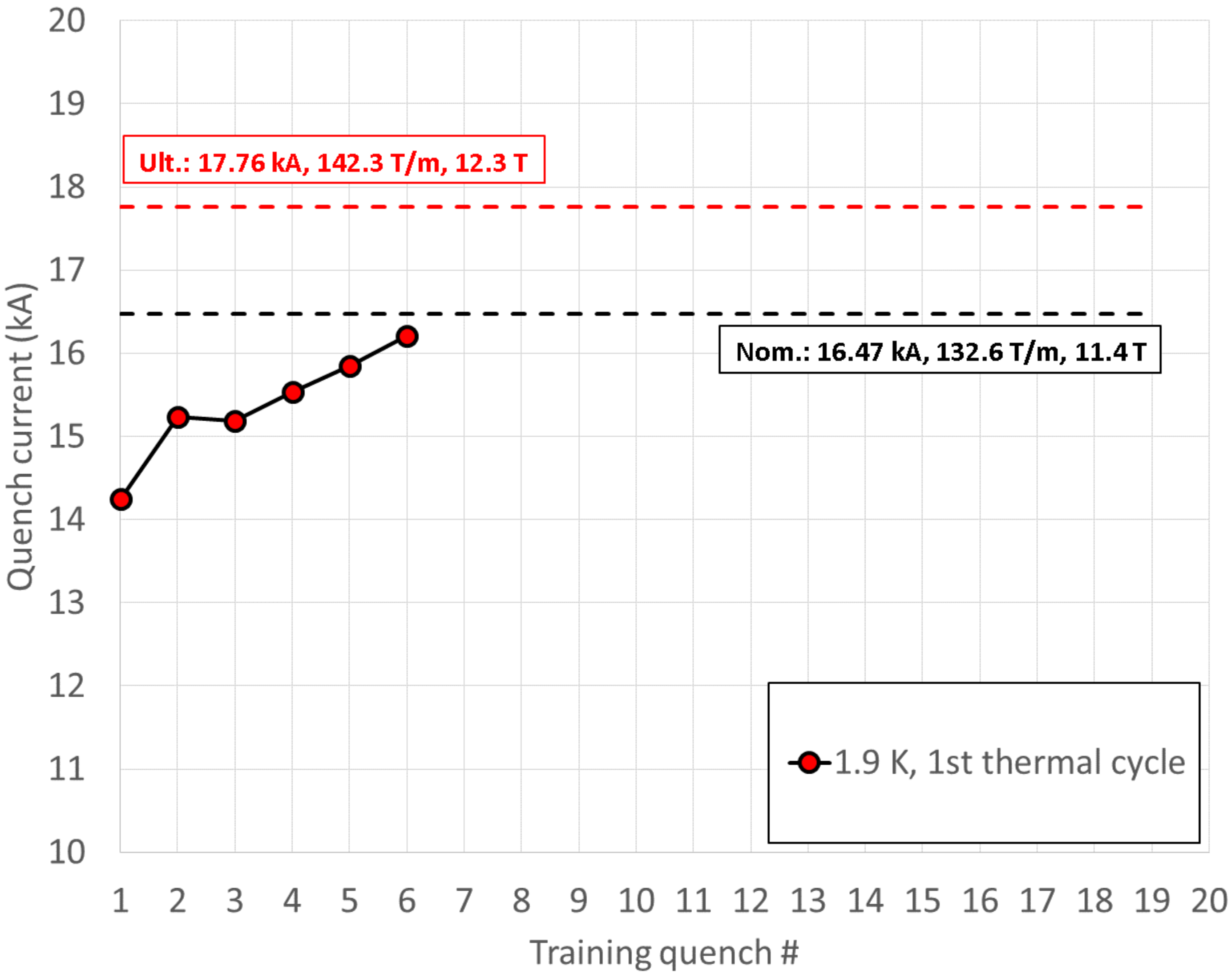

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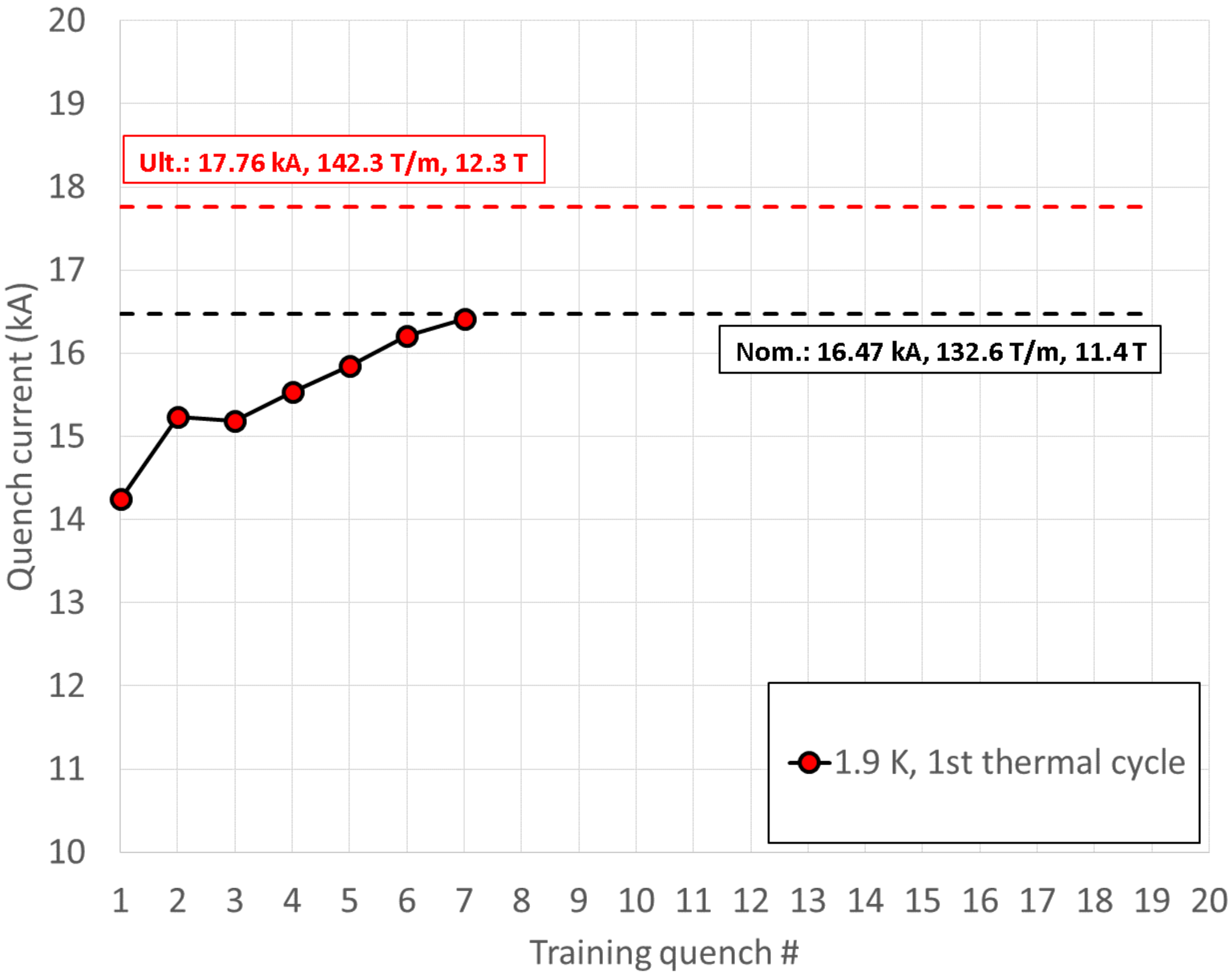

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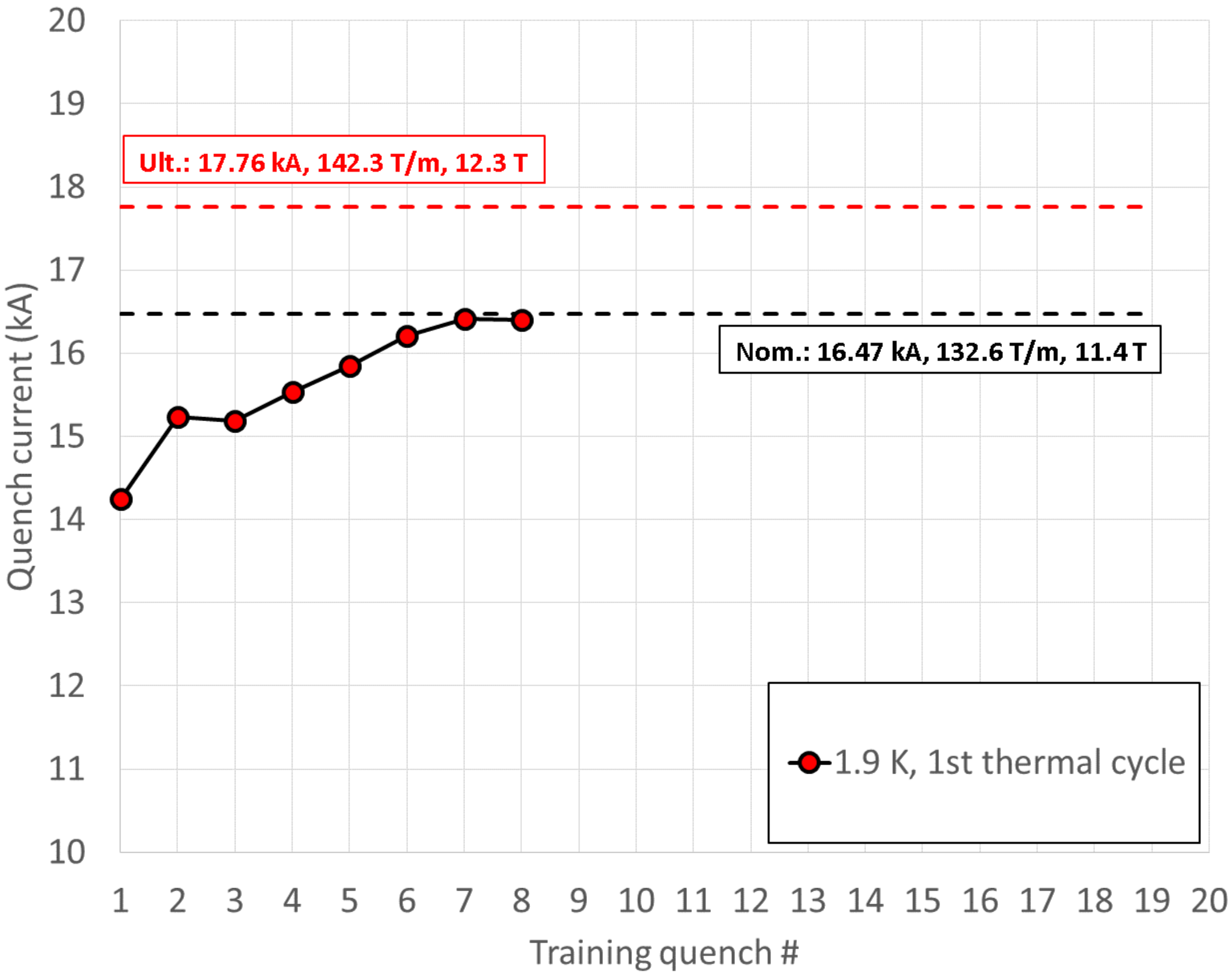

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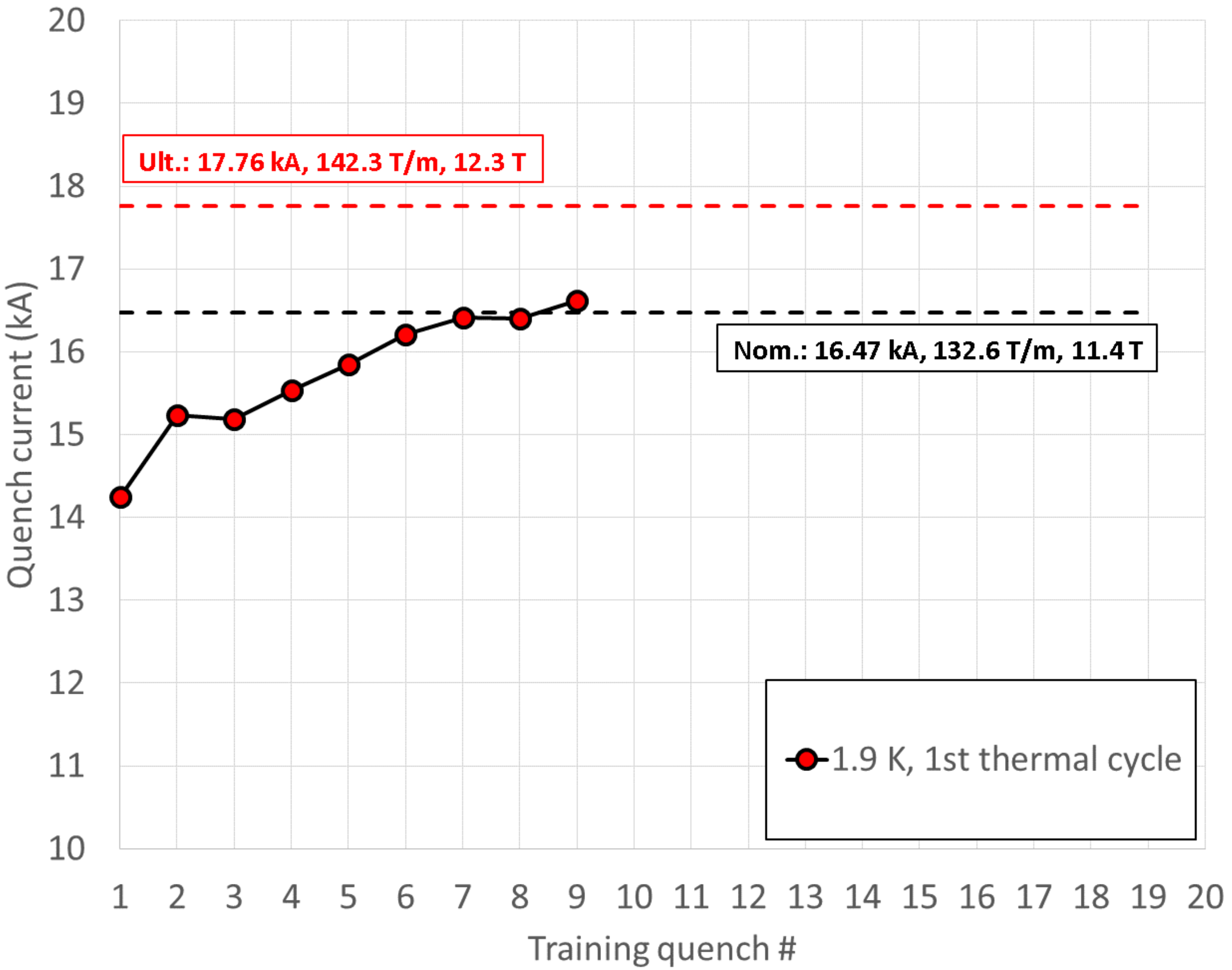

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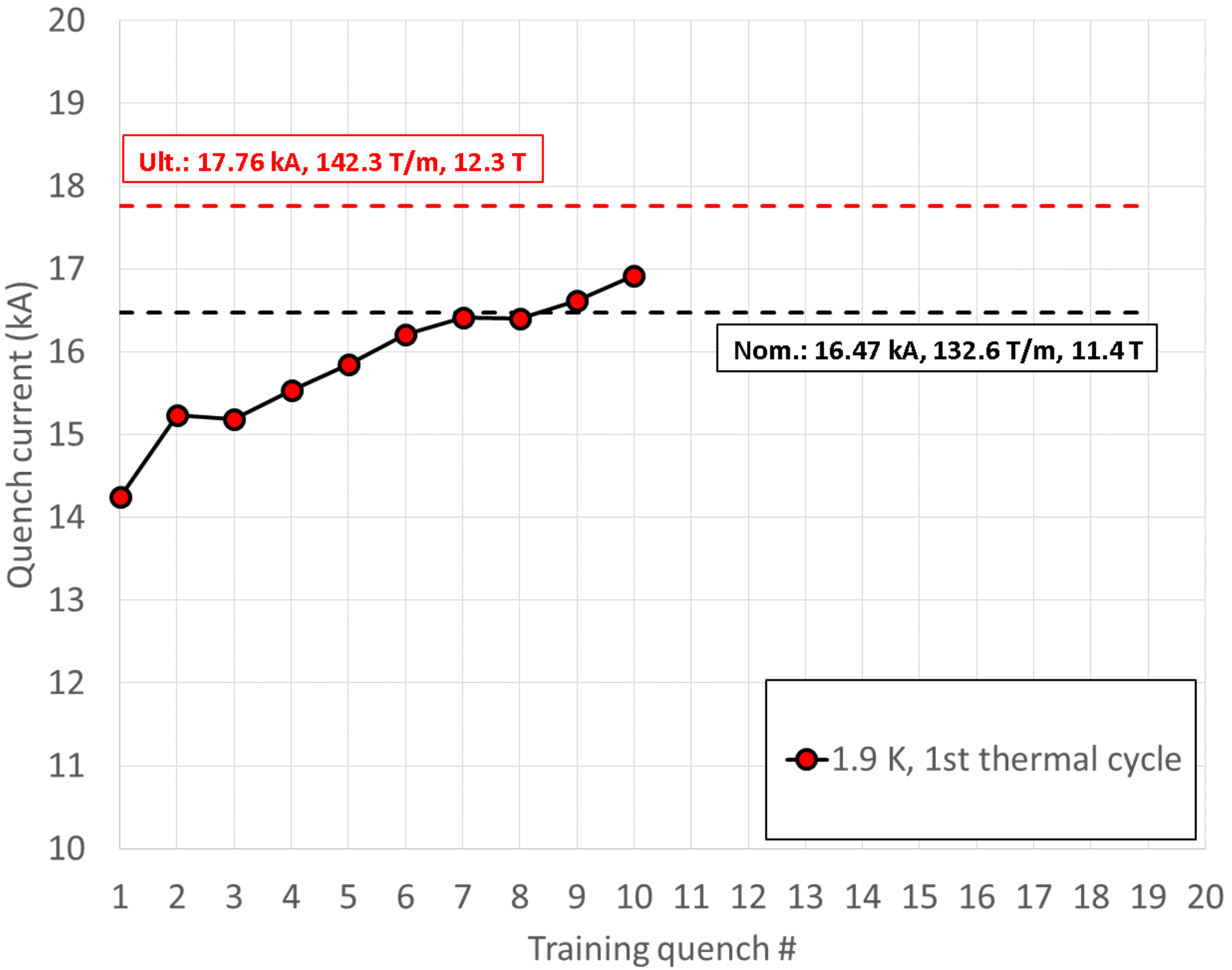

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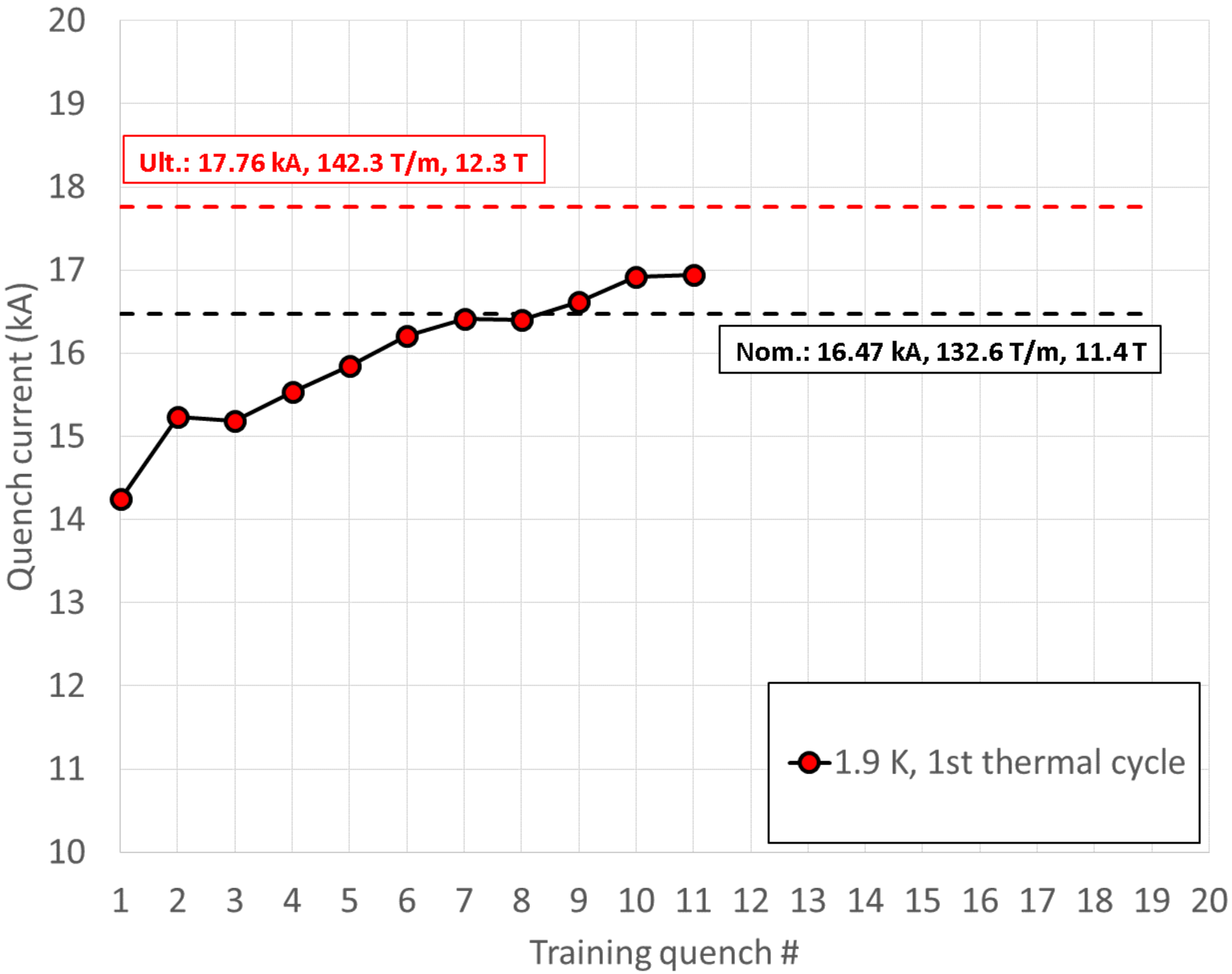

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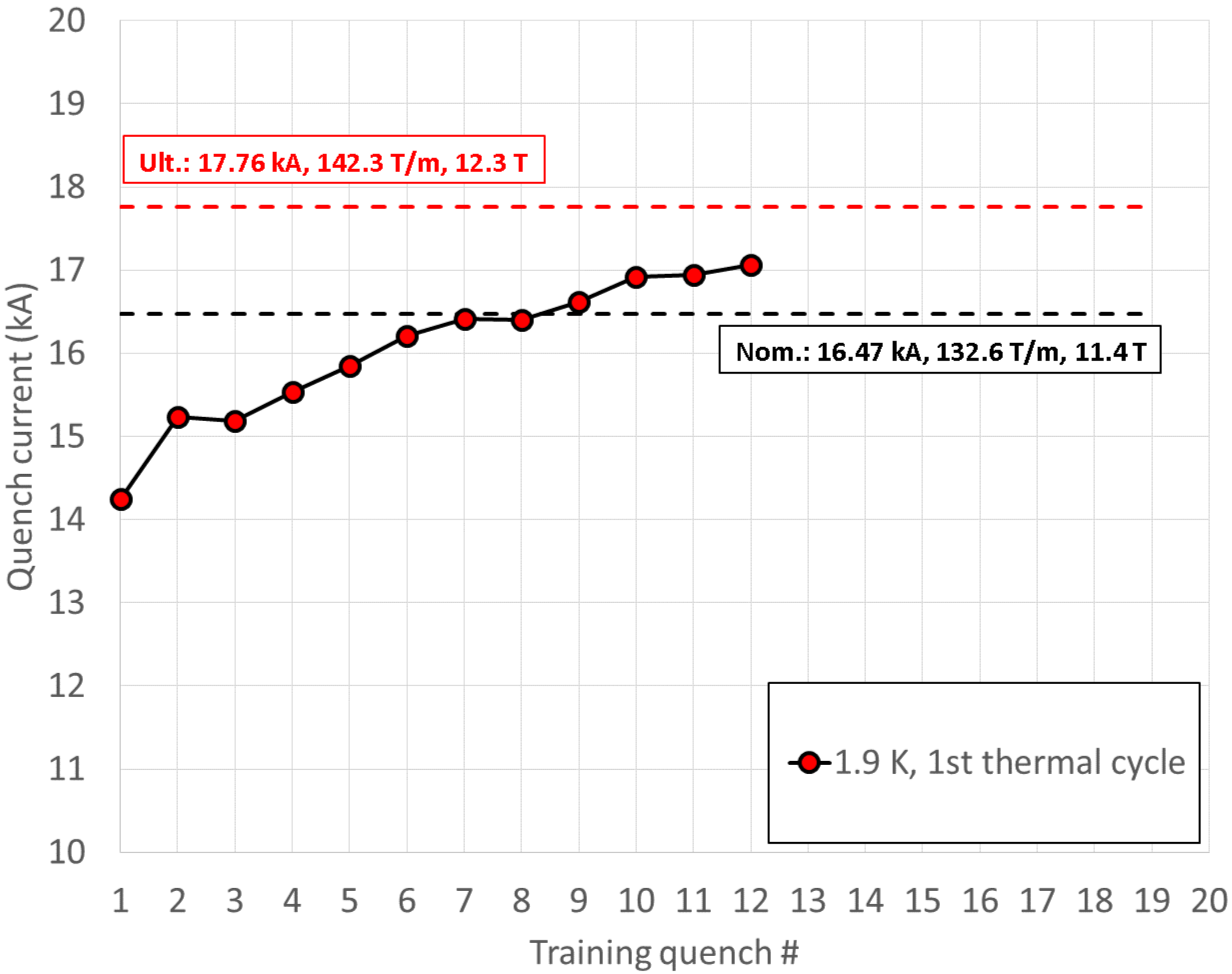

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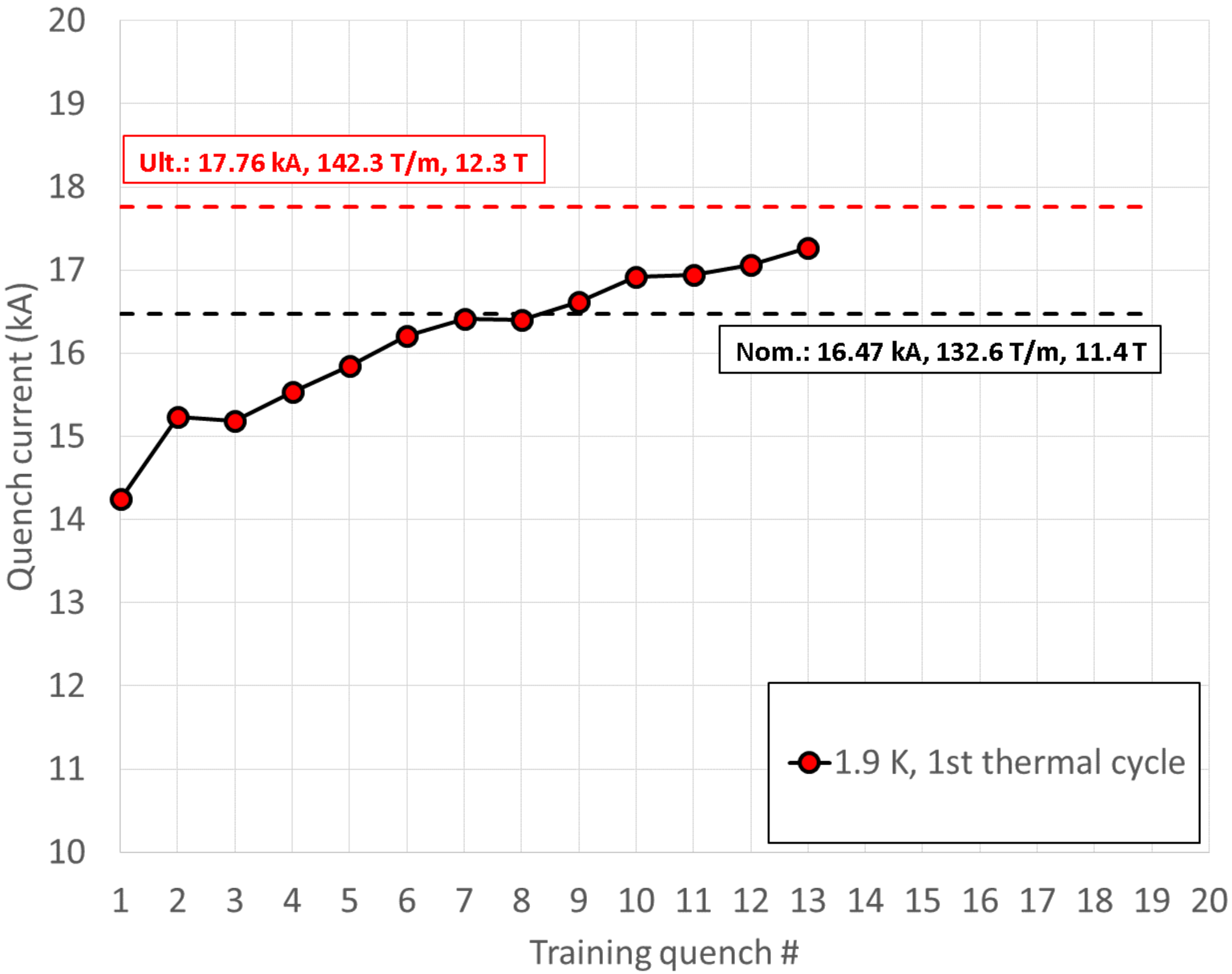

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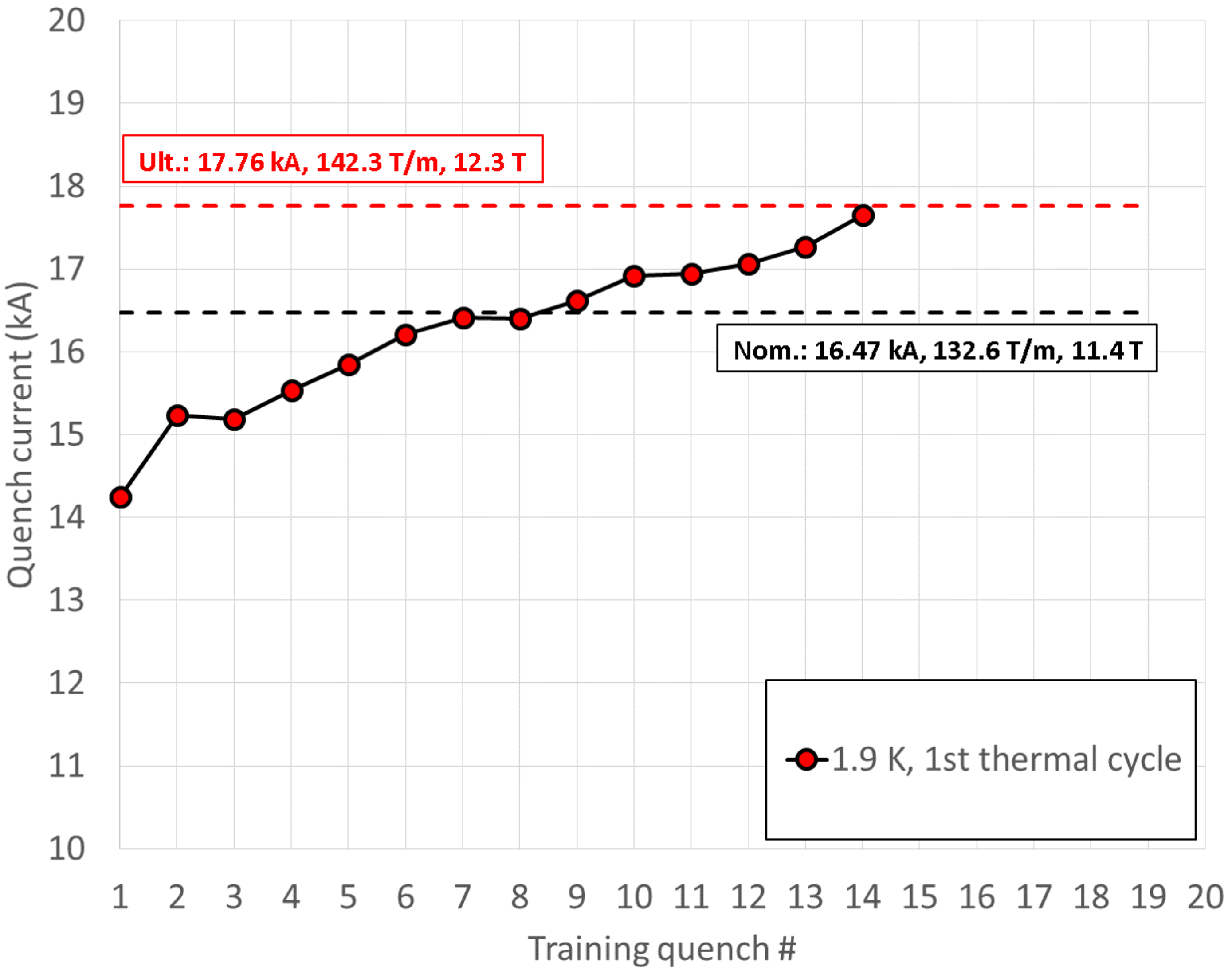

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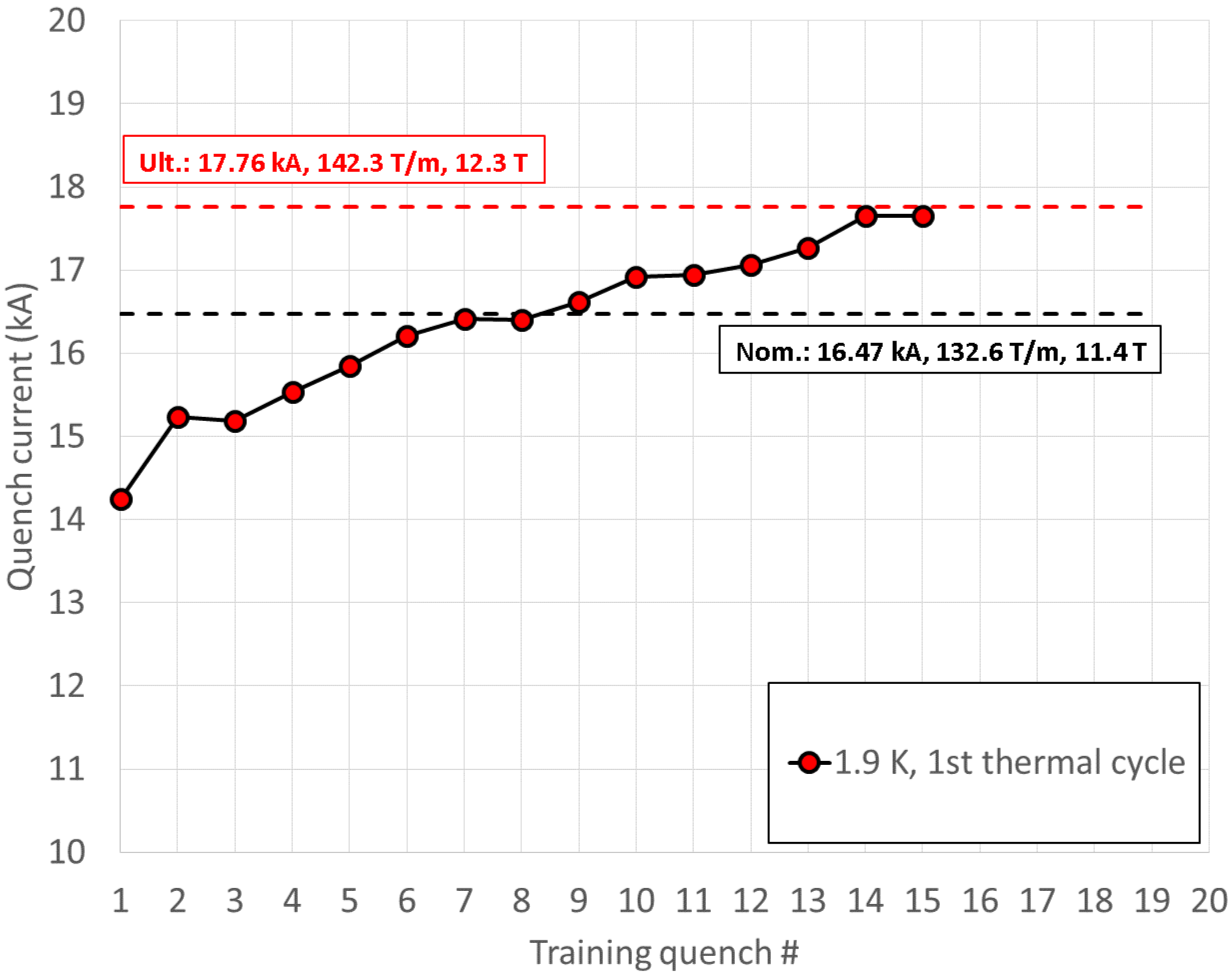

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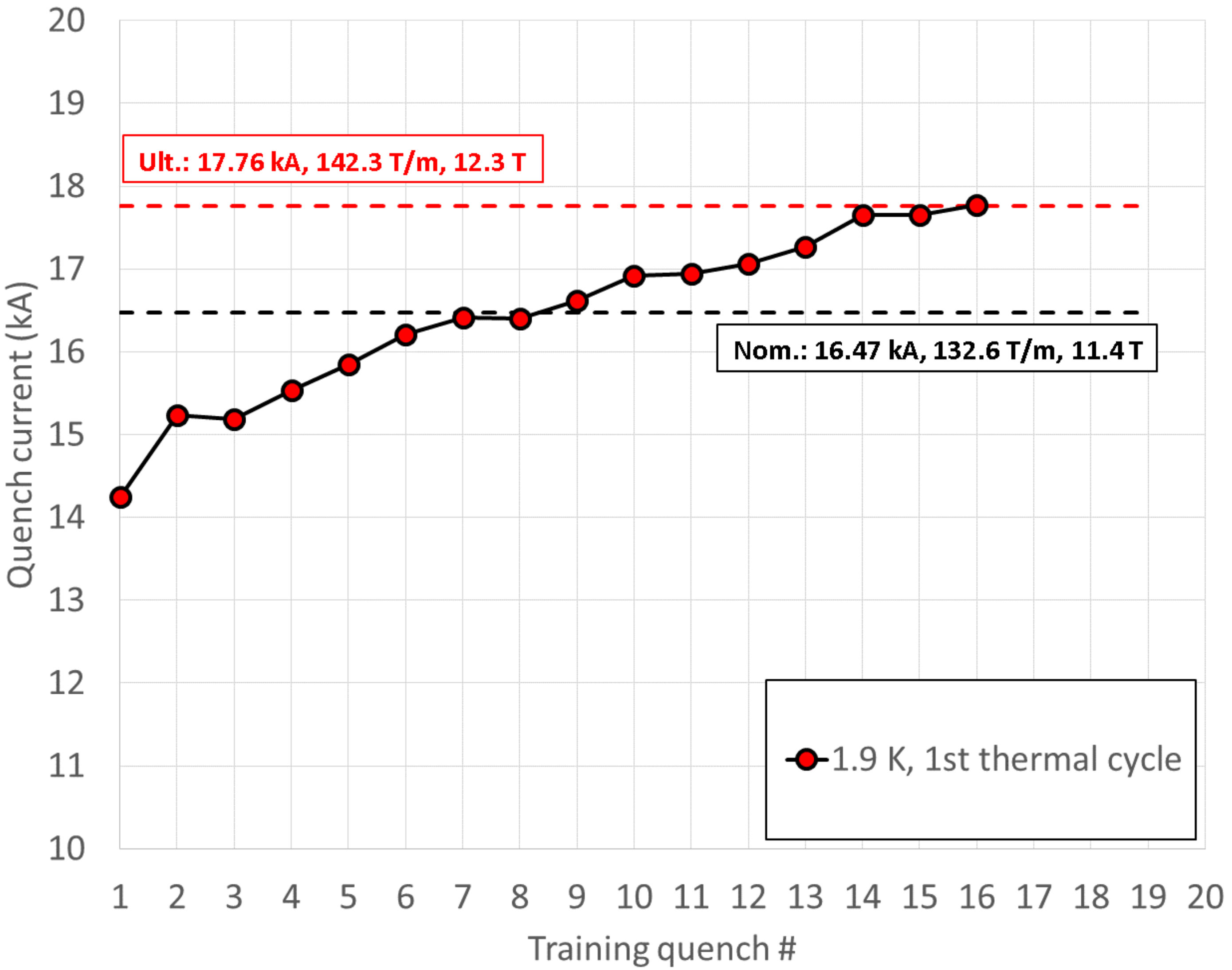

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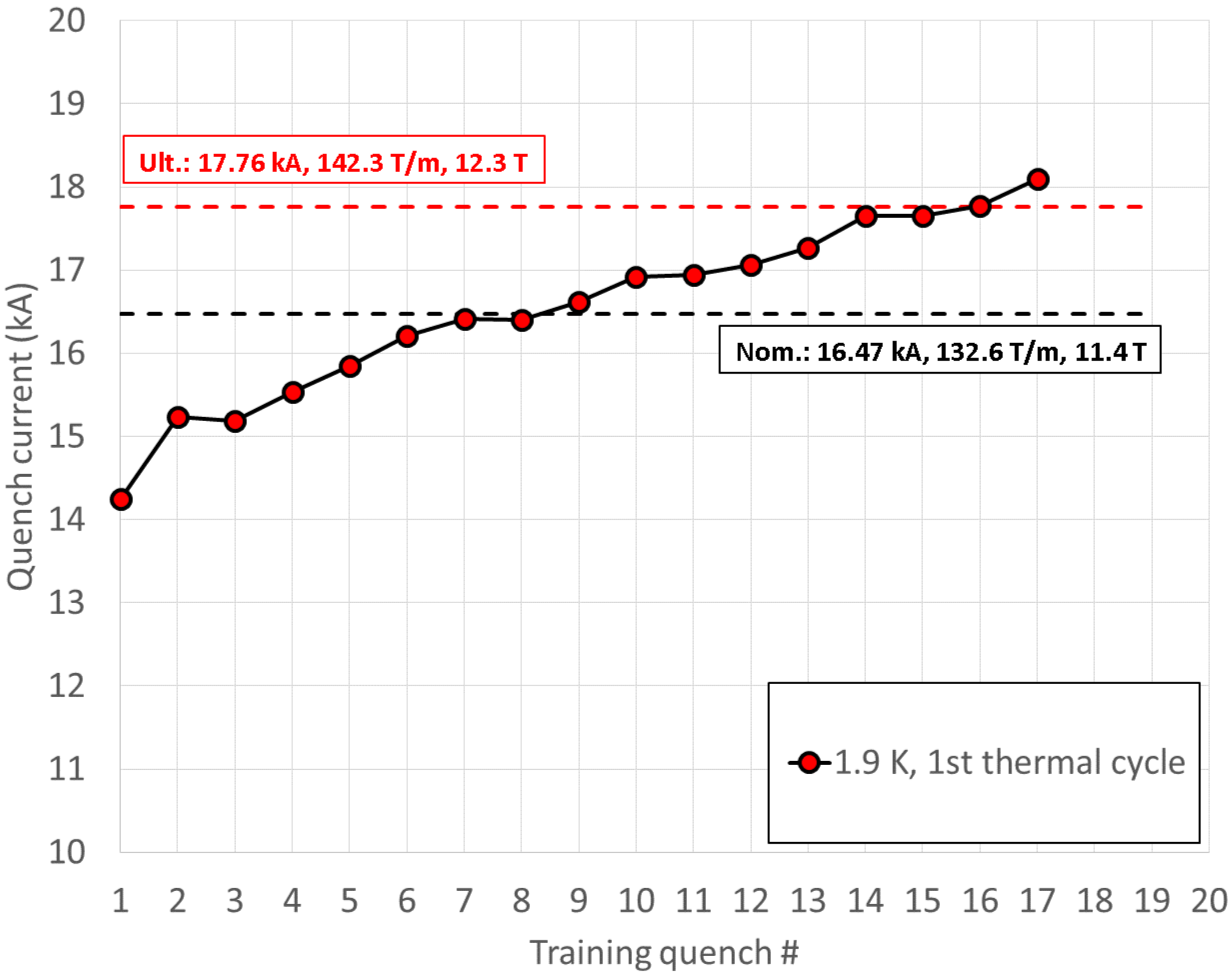

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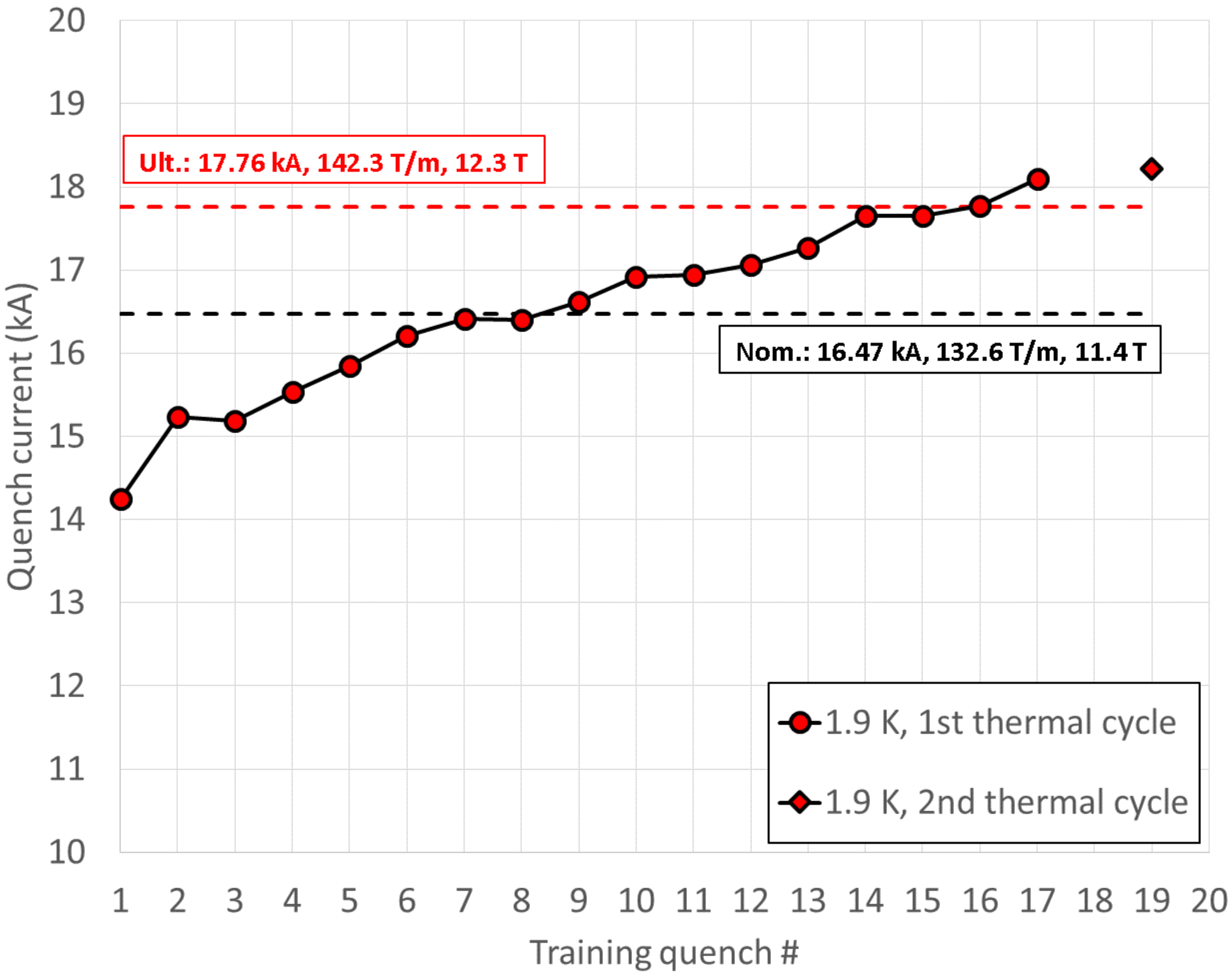
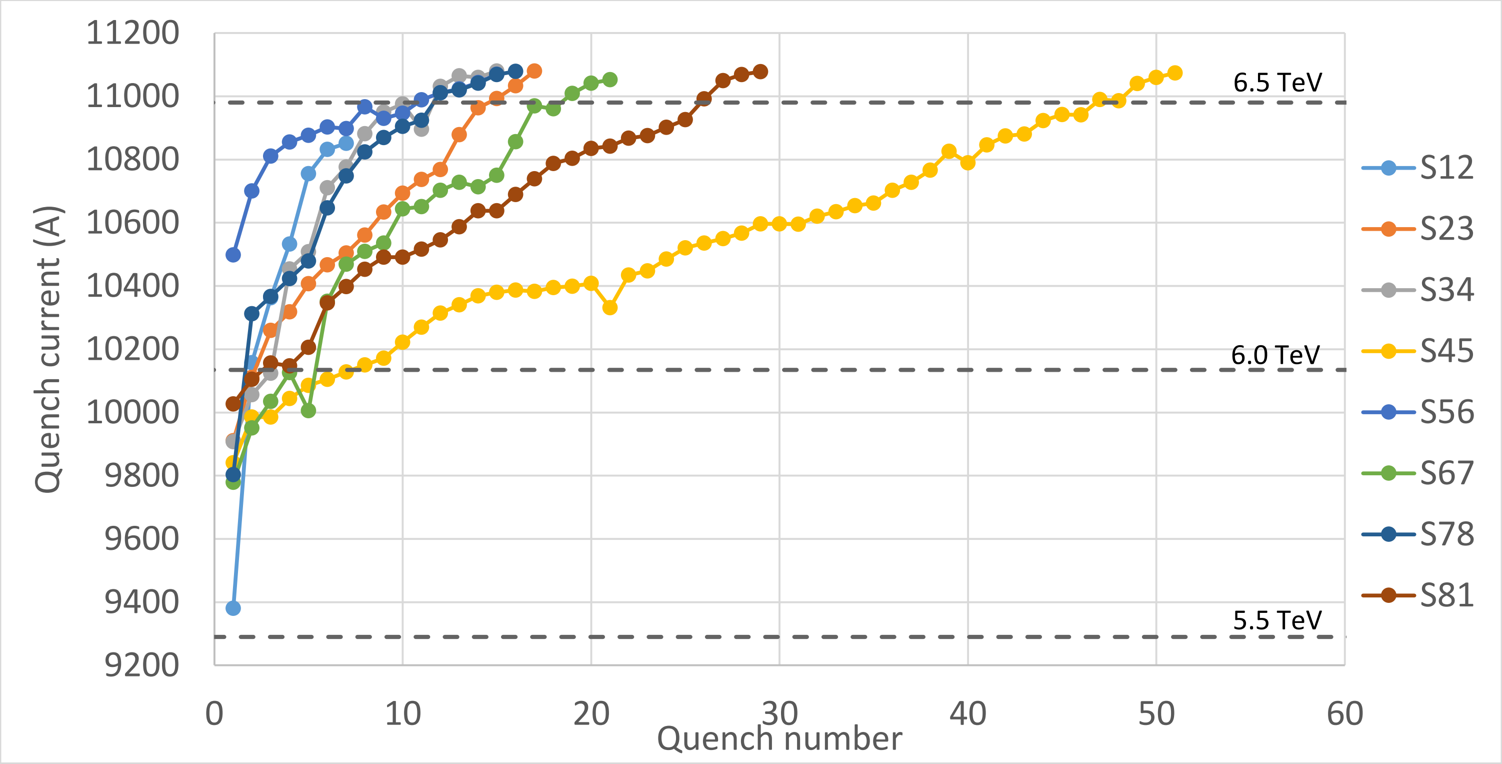
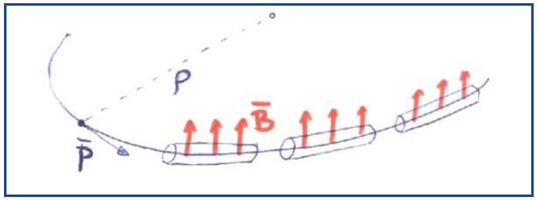


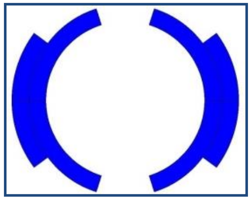
Quench and protection
Training of LHC sectors to 6.5 TeV

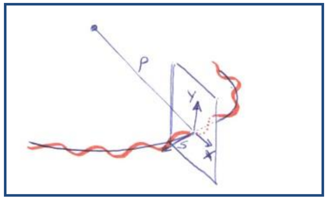


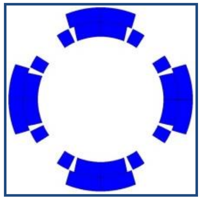
Summary

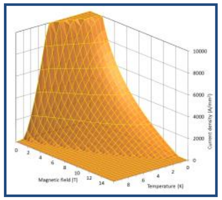
- **Particle accelerators and superconductors**

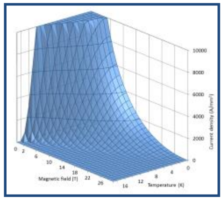


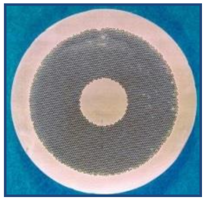


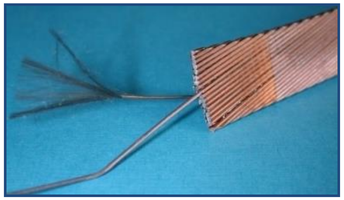




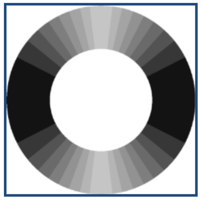


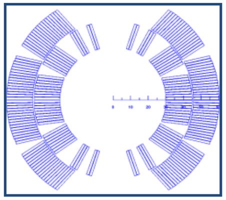


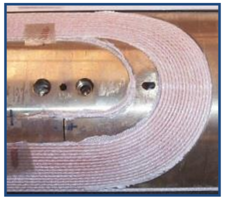


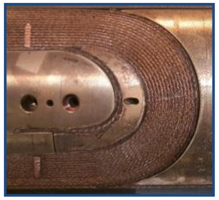


- **Magnetic design and coils**



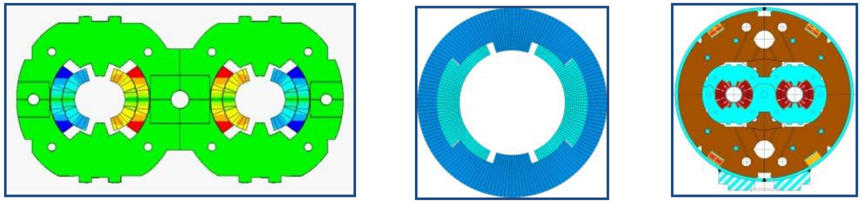




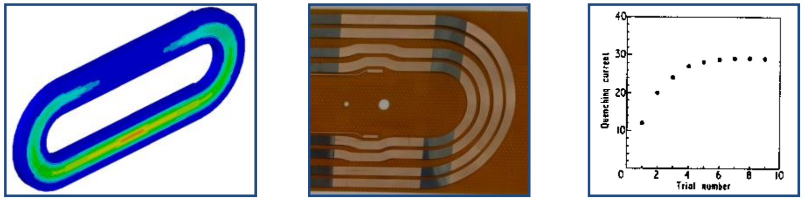


Summary

- **Mechanics of superconducting magnets**



- **Quench and protection**



Appendix

References

- **Particle accelerators and superconductors**
  - K.-H. Mess, P. Schmuser, S. Wolff, "*Superconducting accelerator magnets*", Singapore: World Scientific, 1996.
  - Martin N. Wilson, "*Superconducting Magnets*", 1983.
  - Fred M. Asner, "*High Field Superconducting Magnets*", 1999.
  - P. Ferracin, E. Todesco, S. Prestemon, "*Superconducting accelerator magnets*", US Particle Accelerator School, www.uspas.fnal.gov.
    - **Units 2 by E. Todesco**
  - A. Devred, "*Practical low-temperature superconductors for electromagnets*", CERN-2004-006, 2006.
  - Presentations from Luca Bottura and Martin Wilson

References

- **Magnetic design and coils**
  - K.-H. Mess, P. Schmuser, S. Wolff, “*Superconducting accelerator magnets*”, Singapore: World Scientific, 1996.
  - Martin N. Wilson, "*Superconducting Magnets*", 1983.
  - Fred M. Asner, "*High Field Superconducting Magnets*", 1999.
  - S. Russenschuck, “*Field computation for accelerator magnets*”, J. Wiley & Sons (2010).

  - P. Ferracin, E. Todesco, S. Prestemon, “*Superconducting accelerator magnets*”, US Particle Accelerator School, www.uspas.fnal.gov.
    - **Units 5, 8, 9 by E. Todesco**
  - A. Jain, “*Basic theory of magnets*”, CERN 98-05 (1998) 1-26

  - L. Rossi, E. Todesco, “*Electromagnetic design of superconducting quadrupoles*”, Phys. Rev. ST Accel. Beams 10 (2007) 112401.
  - L. Rossi and Ezio Todesco, “*Electromagnetic design of superconducting dipoles based on sector coils*”, Phys. Rev. ST Accel. Beams 9 (2006) 102401.

References

- **Quench and protection**

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

  - P. Ferracin, E. Todesco, S. Prestemon, “*Superconducting accelerator magnets*”, US Particle Accelerator School, www.uspas.fnal.gov.
    - **Units 16, 17**

  - Presentations from Luca Bottura and Martin Wilson

  - A. Devred, “*Quench origins*”, AIP Conference Proceedings 249, edited by M. Month and M. Dienes, 1992, p. 1309-1372.

References

- **Mechanics of superconducting magnets**

  - K.-H. Mess, P. Schmuser, S. Wolff, *"Superconducting accelerator magnets"*, Singapore: World Scientific, 1996.
  - Martin N. Wilson, "*Superconducting Magnets*", 1983.
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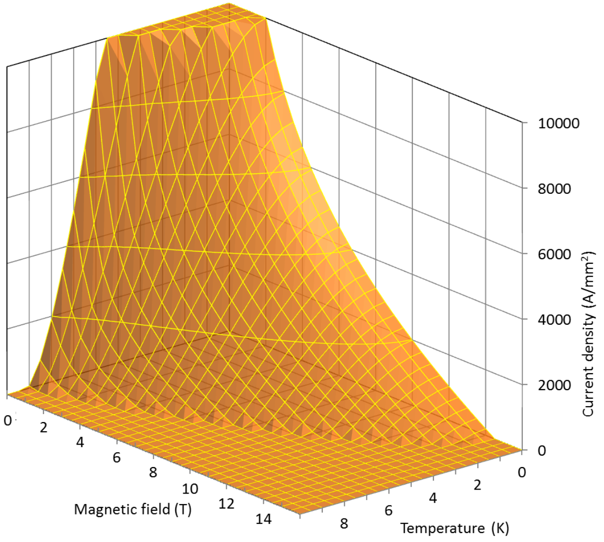
  - P. Ferracin, E. Todesco, S. Prestemon, *"Superconducting accelerator magnets"*, US Particle Accelerator School, www.uspas.fnal.gov.
    - **Units 10,13,14**

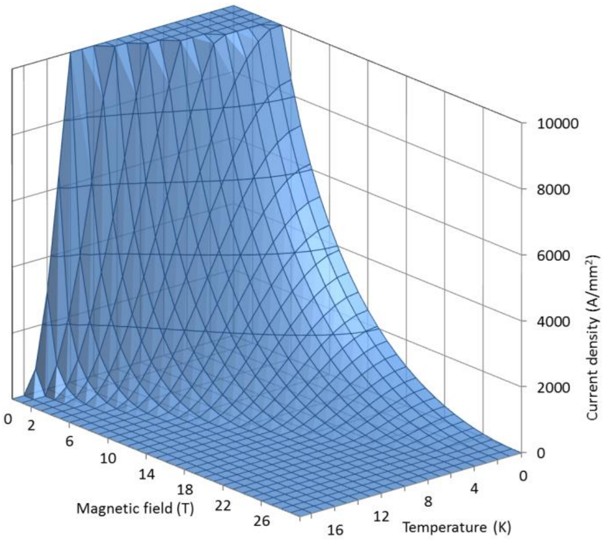
  - *"LHC design report v.1: the main LHC ring"*, CERN-2004-003-v-1, 2004.

Superconductivity Nb-Ti (1961) and Nb_3Sn (1954)

- Nb and Ti → ductile alloy
  - Extrusion + drawing
- **T_c** is ~**9.2 K** at 0 T
- **B_{C2}** is ~**14.5 T** at 0 K
- Firstly in **Tevatron** (80s), then all the other
- ~50-200 US$ per kg of wire (1 euro per m)

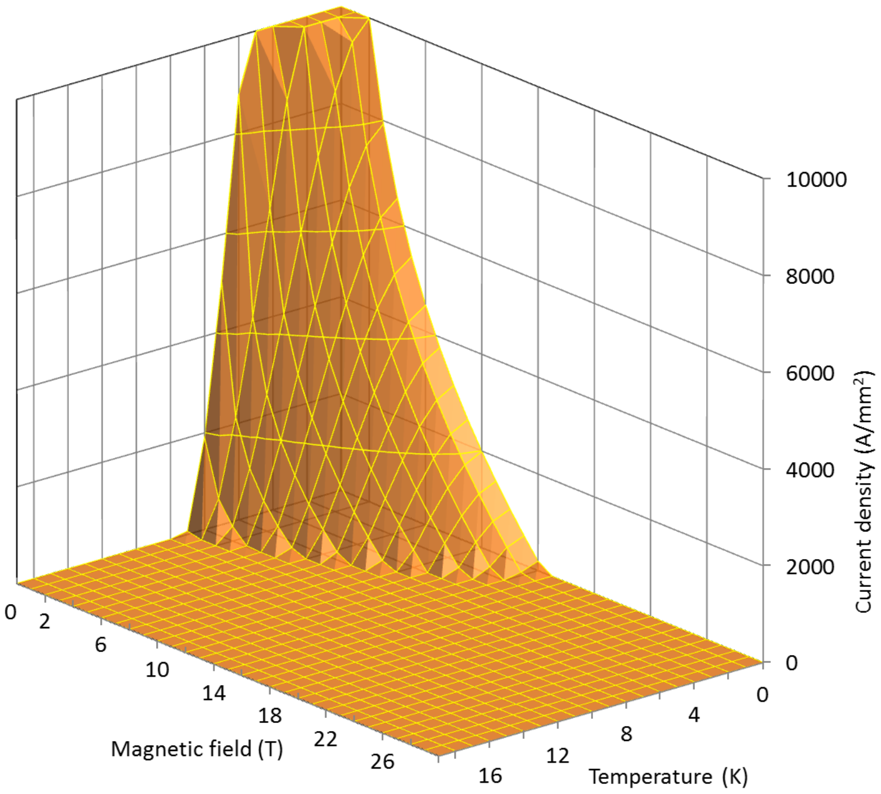


- Nb and Sn → intermetallic compound
  - Brittle, strain sensitive, formed at ~650-700°C
- **T_C** is ~**18 K** at 0 T
- **B_{C2}** is ~**28 T** at 0 K
- Used in **NMR**, **ITER**
- ~700-1500 US$ per kg of wire (5 euro per m)

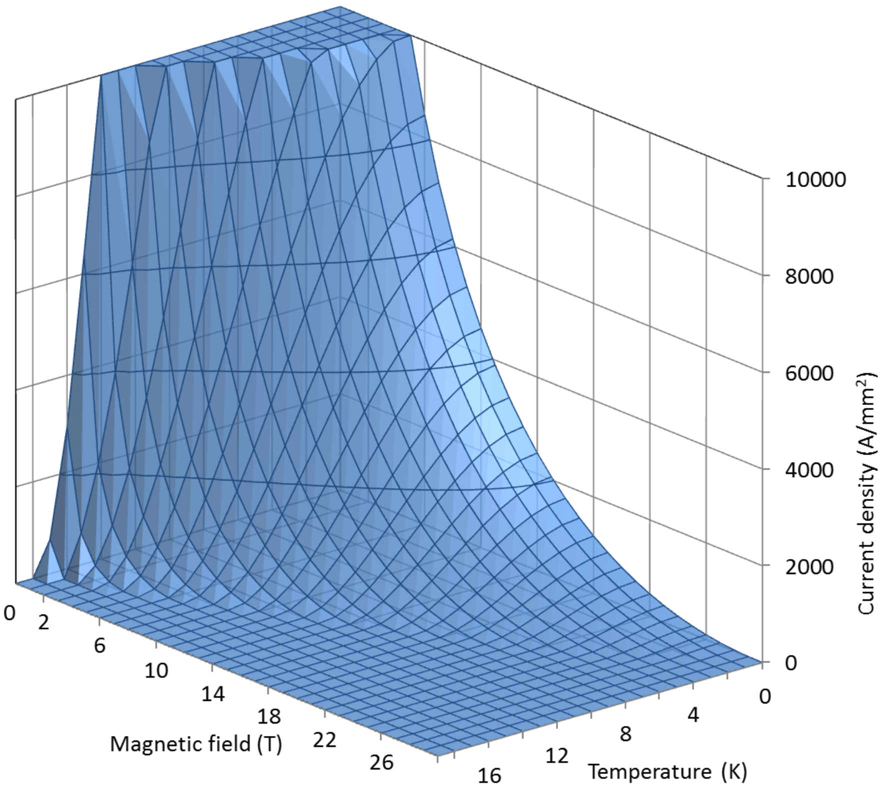


Superconductivity
Nb-Ti vs. Nb_3Sn

Nb-Ti

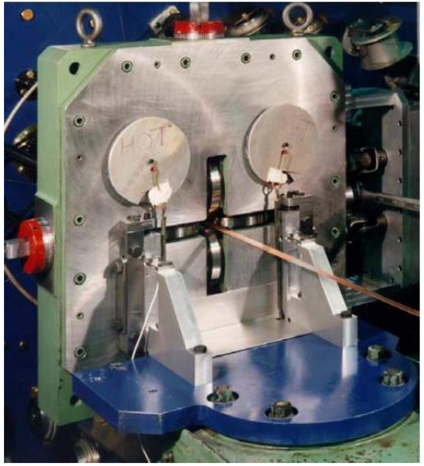


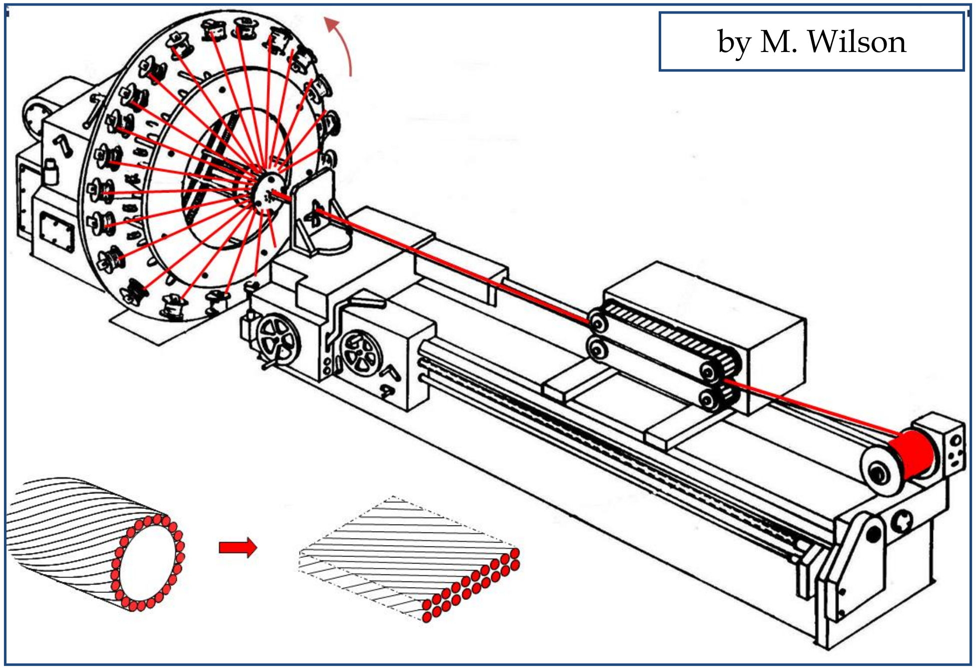
Nb_3Sn

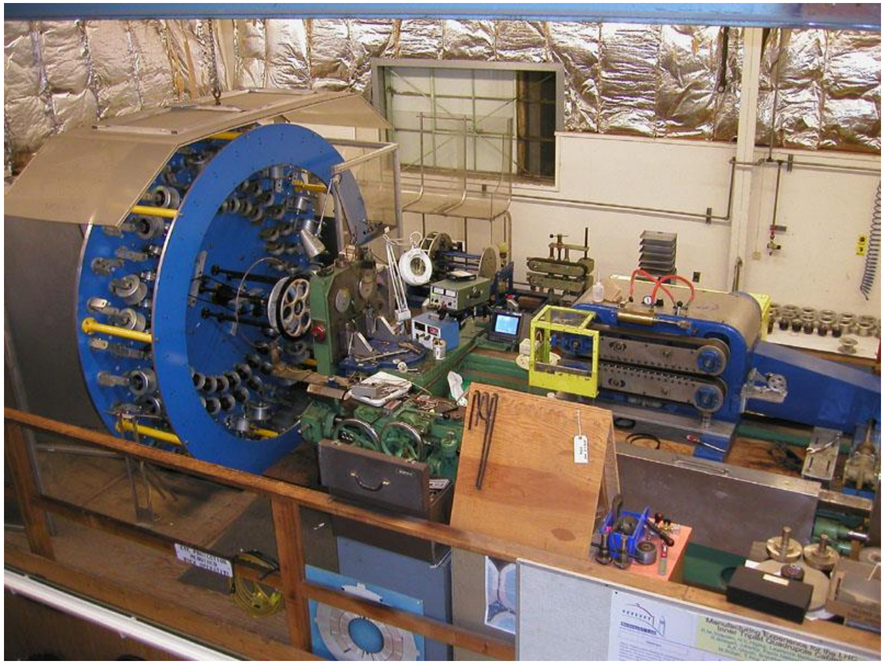


Practical superconductors
Multi-strand cables motivations

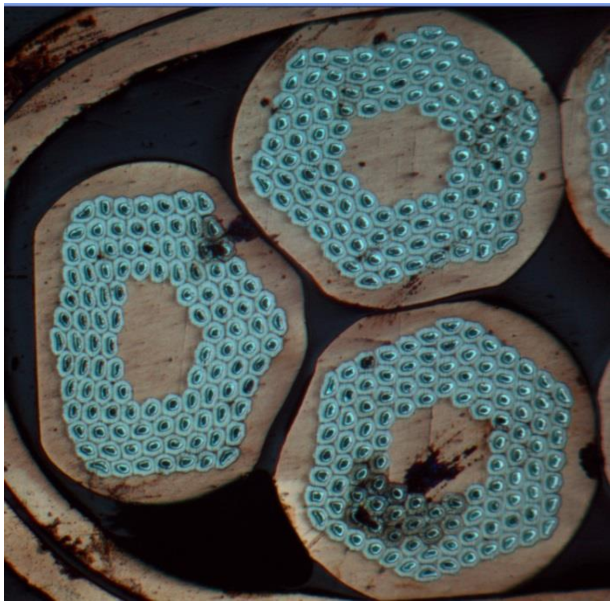
- Rutherford cables fabricated by **cabling machine**
  - Strands wound on spools mounted on a rotating drum
  - Strands twisted around a conical mandrel into rolls (Turk's head)
  - The rolls compact the cable and provide the final shape



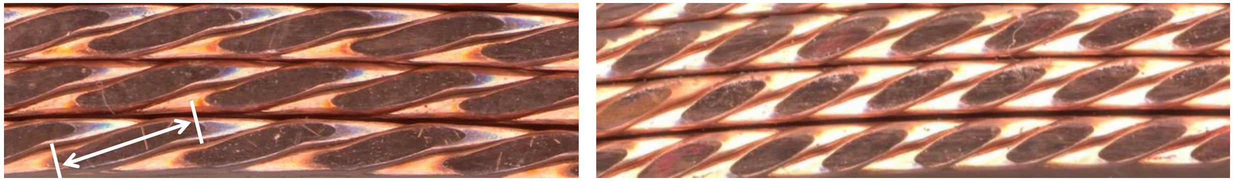

by M. Wilson

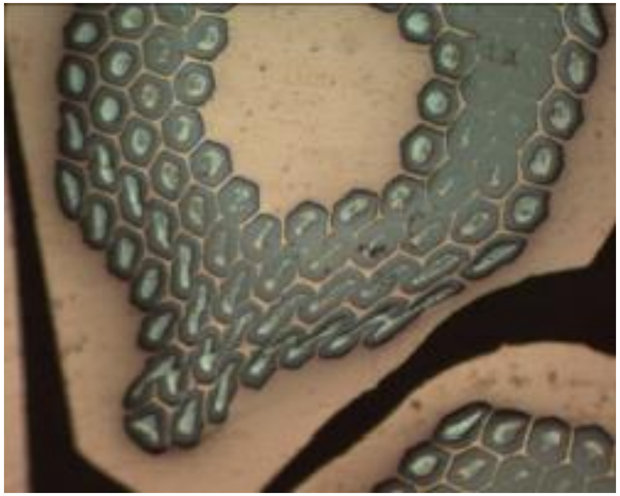


Practical superconductors
Multi-strand cables



- **Edge deformation** may cause
  - reduction of the filament cross-sectional area (Nb-Ti)
  - breakage of reaction barrier with incomplete tin reaction (Nb_3Sn)
- In order to avoid degradation
  - strand cross-section investigated
  - Edge facets are measured
    - General rule: no overlapping of facets

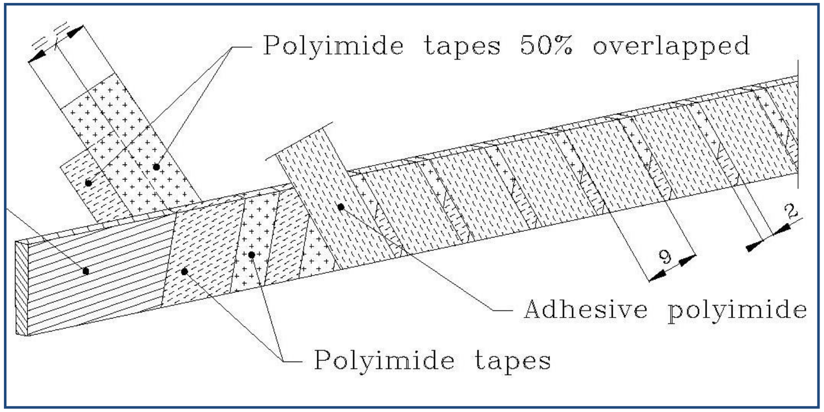




- **Keystone angle** is usually of ~ 1° to 2°

Practical superconductors
Cable insulation

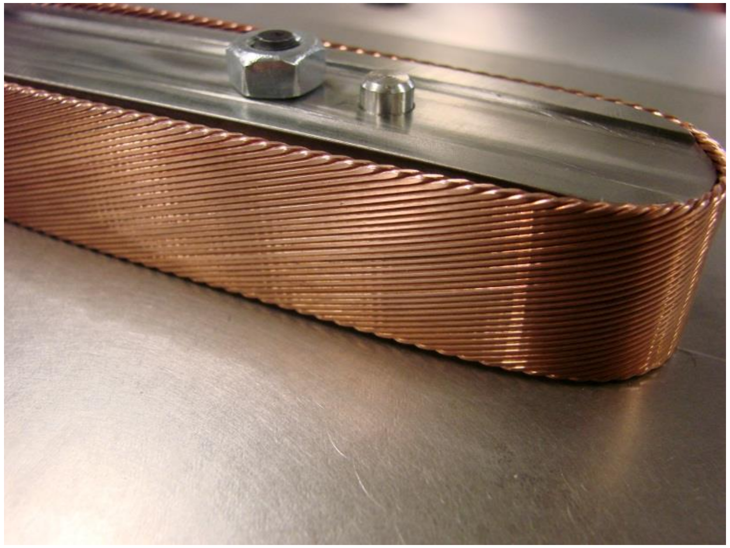
- The cable insulation must feature
  - Good **electrical properties** to withstand turn-to-turn *V* after a quench
  - Good **mechanical properties** to withstand high pressure conditions
  - **Porosity** to allow penetration of helium (or epoxy)
  - **Radiation hardness**
- In Nb-Ti magnets overlapped layers of **polyimide**
- In Nb_3Sn magnets, **fiber-glass** braided or as tape/sleeve.
- Typically the insulation thickness: 100 and 200 μm.

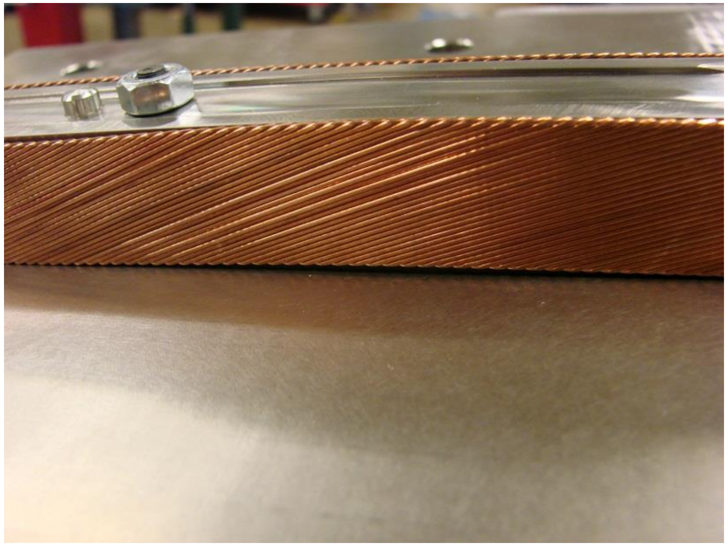


Coil fabrication
Winding and curing

- There is a **minimum bending radius**, which depends on the cable dimensions.
  - Is there a general rule?
    - No, but usually the bending radius is 10-15 times the cable thickness.
  - The cable must be constantly monitored during winding.

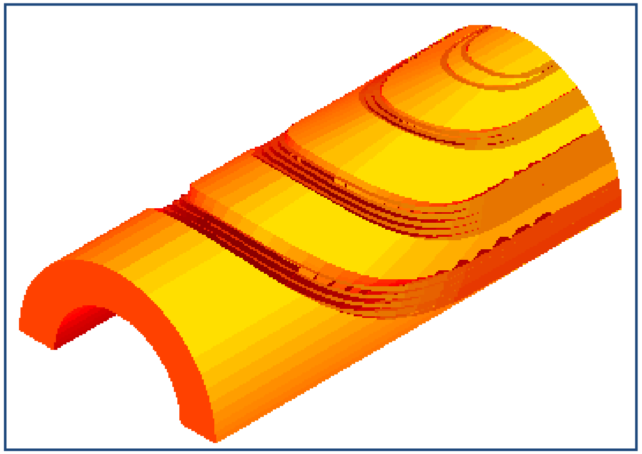
- If the bending radius is too small
  - **De-cabling** during winding;
  - Strands "**pop-out**".

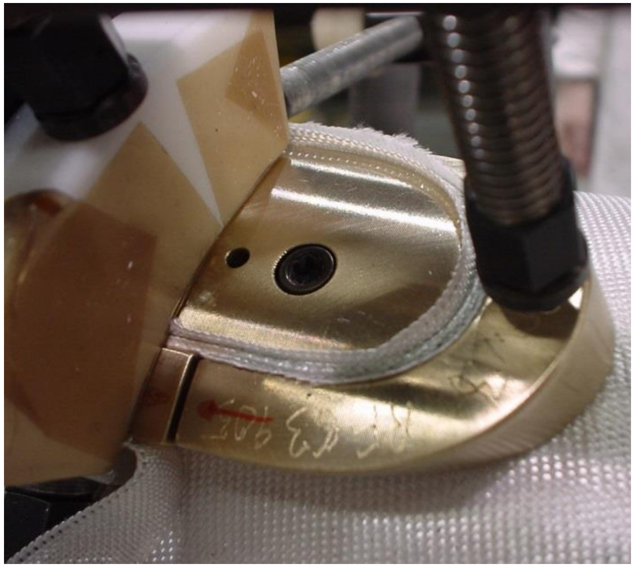




Coil fabrication
Winding and curing

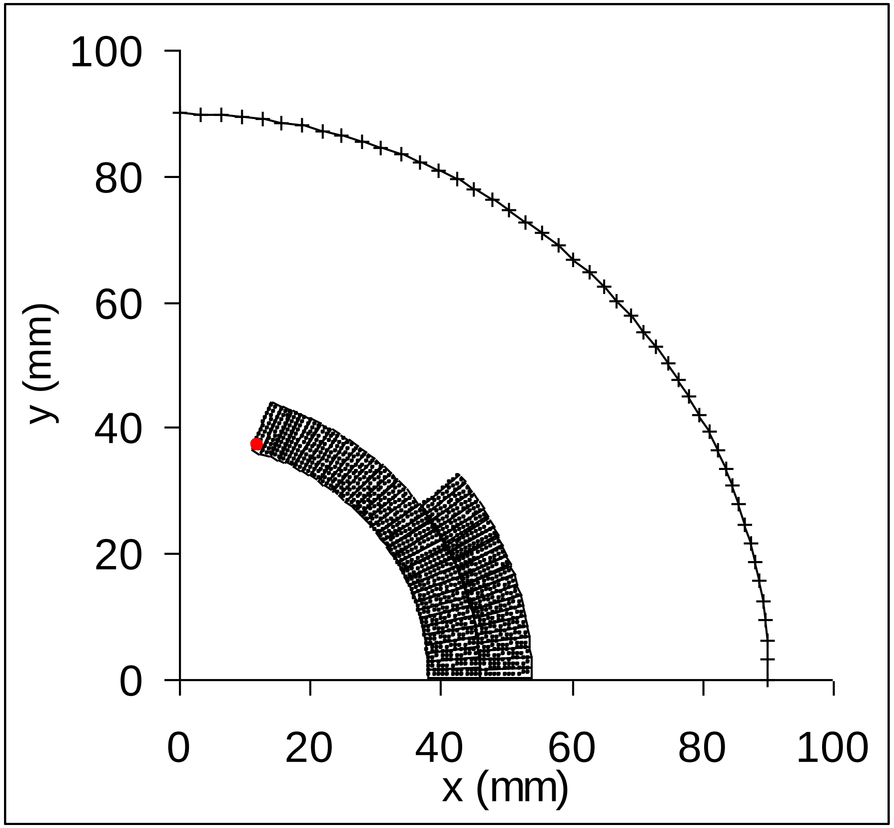
- In the **end region**, more difficult to constrain the turns
  - bent over the narrow edge
- To improve the mechanical stability and to reduce the peak field → **end spacers**
  - **constant perimeter** approach
    - The two narrow edges of the turn in the ends follow curves of equal lengths.
- In Nb-Ti magnets, end spacers are produced by 5-axis machining of epoxy impregnated fiberglass
  - Remaining voids are then filled by resins
- In Nb_3Sn magnets, end spacers are made of aluminum bronze or stainless steel.





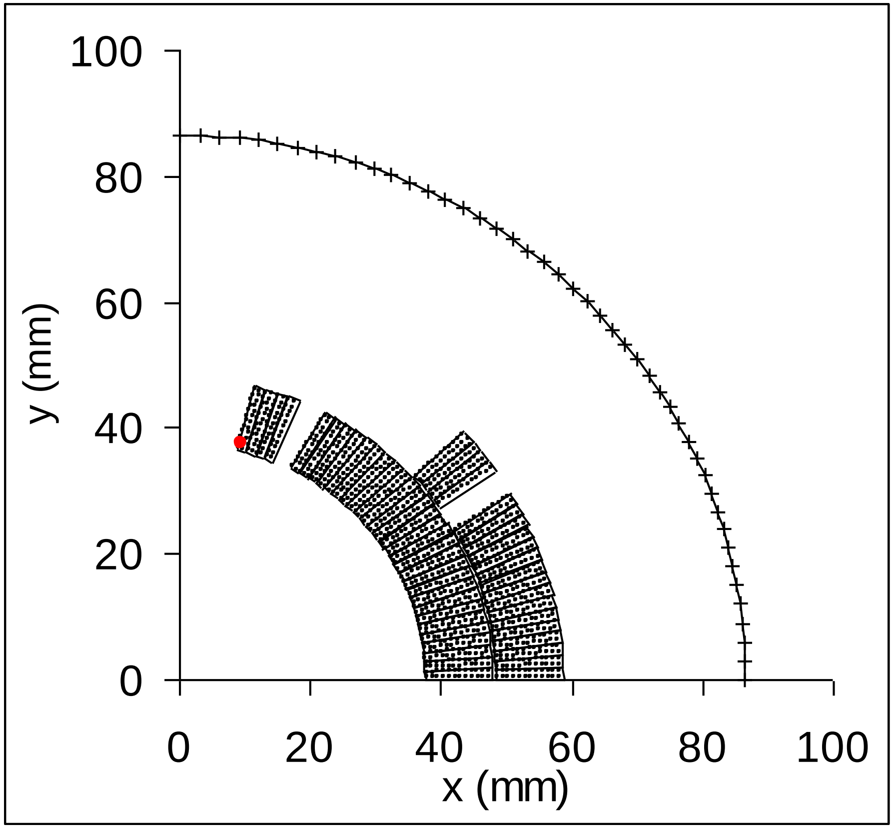
A review of dipole lay-outs

- Tevatron MB



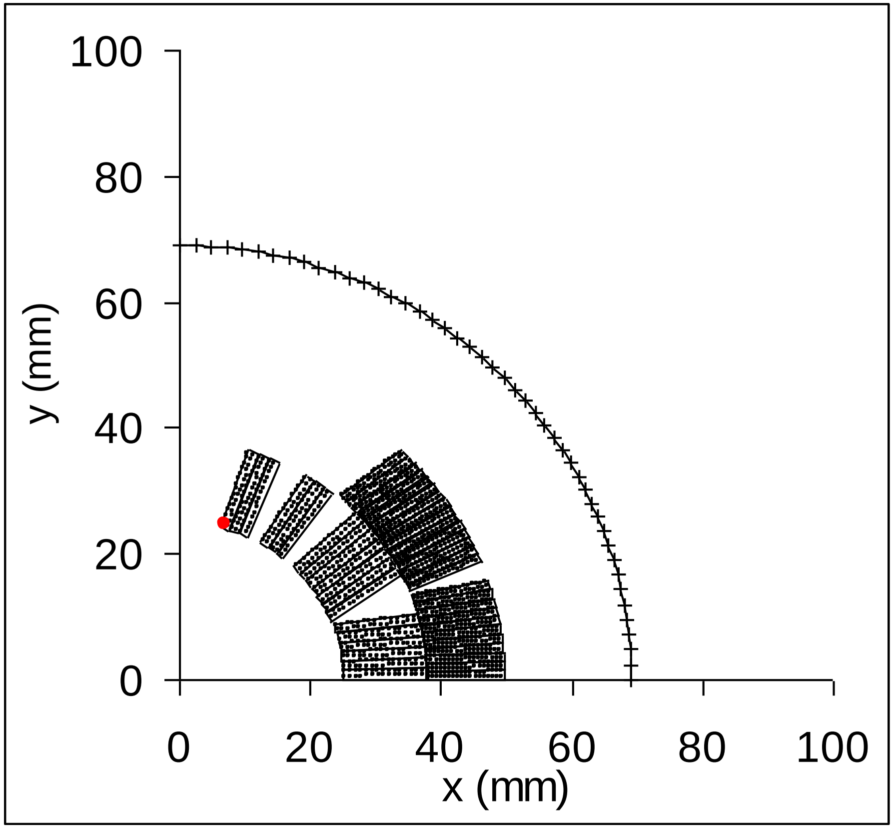
A review of dipole lay-outs

- HERA MB



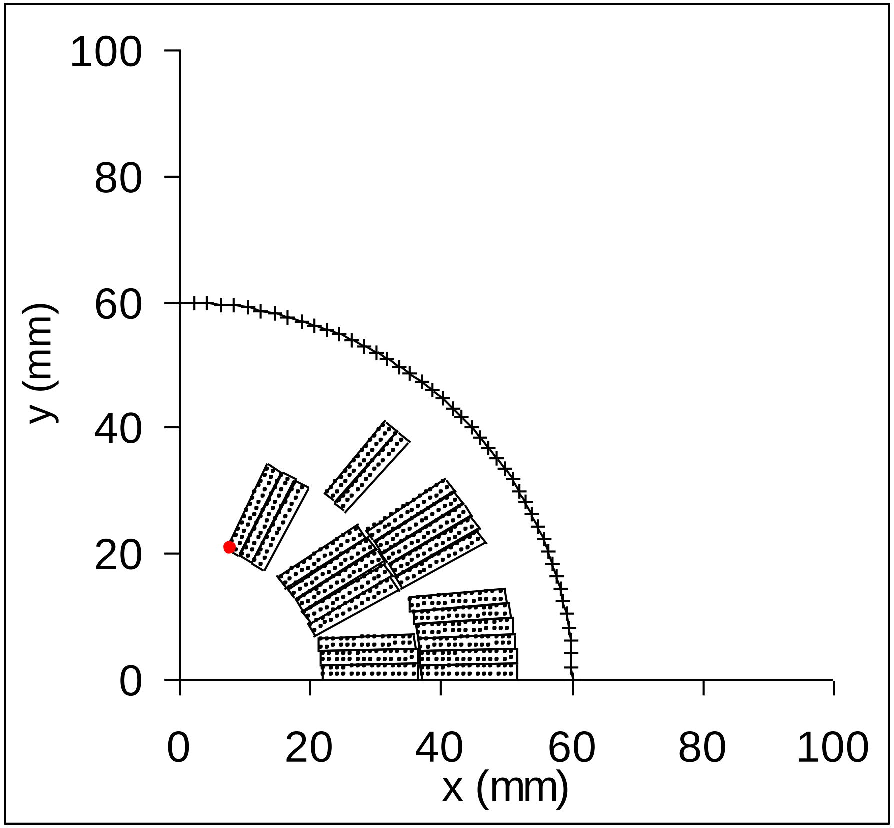
A review of dipole lay-outs

- SSC MB



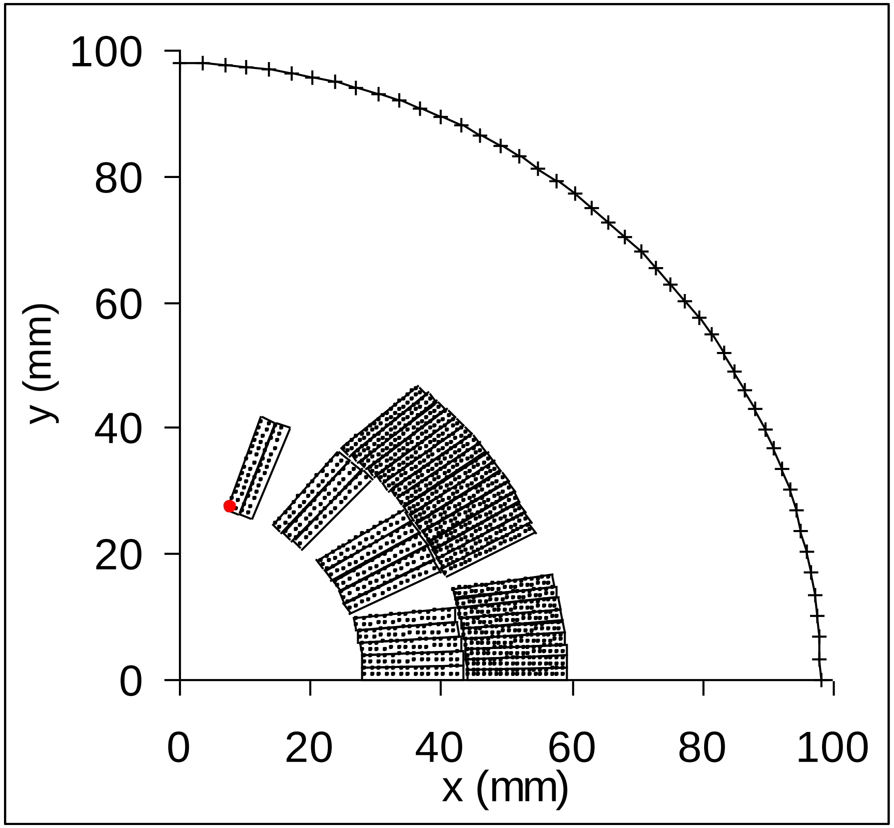
A review of dipole lay-outs

- HFDA dipole



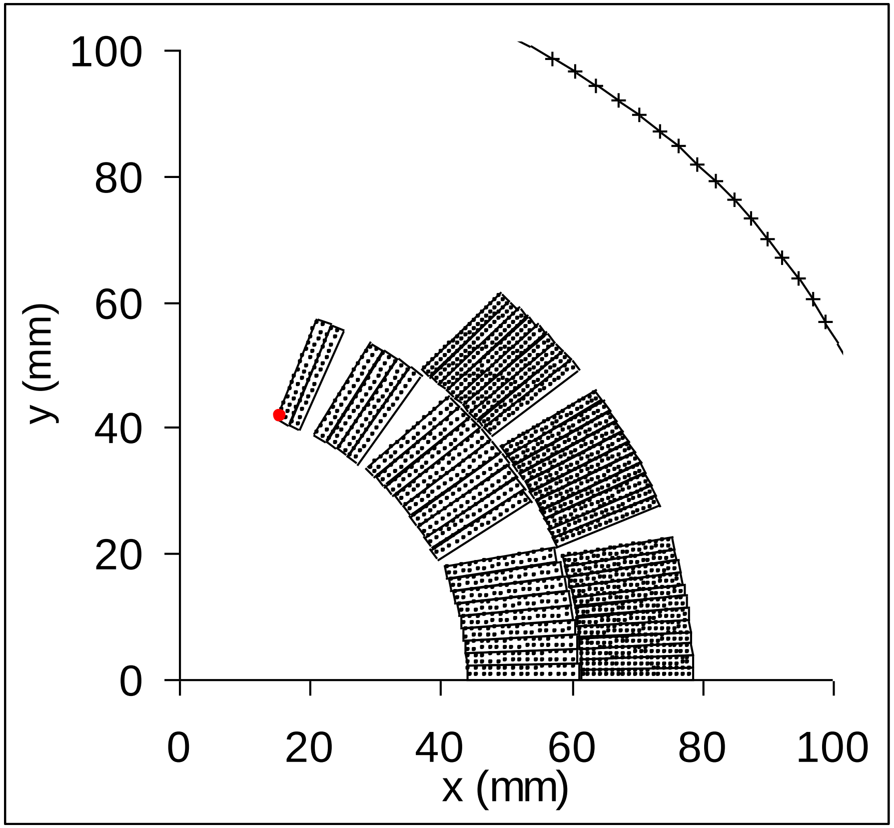
A review of dipole lay-outs

- LHC MB



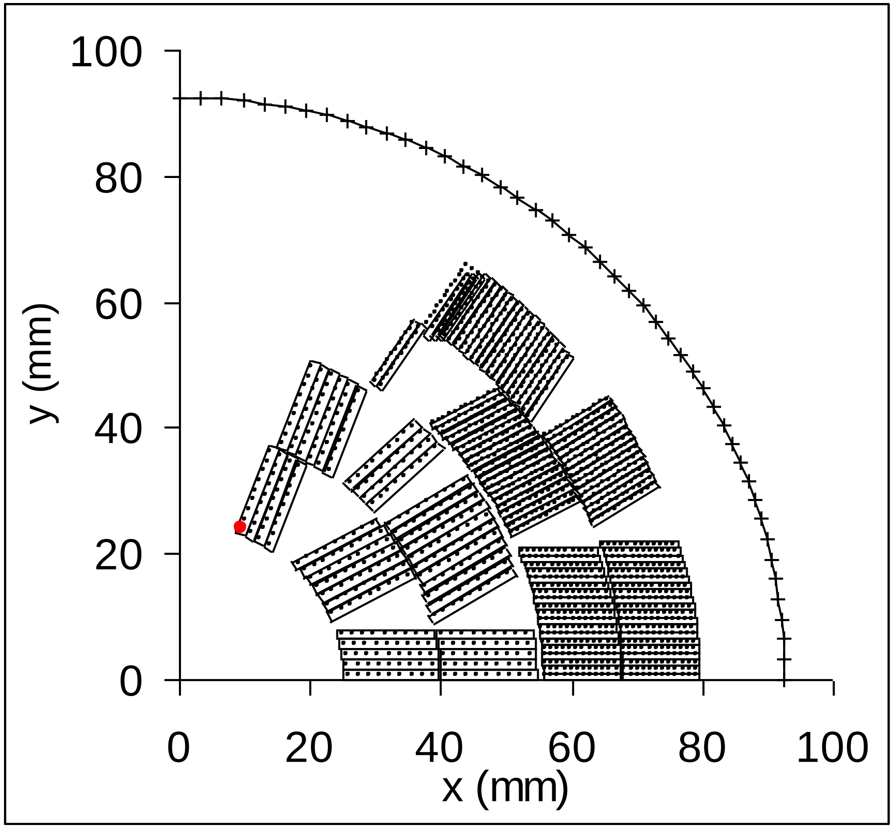
A review of dipole lay-outs

- FRESCA



A review of dipole lay-outs

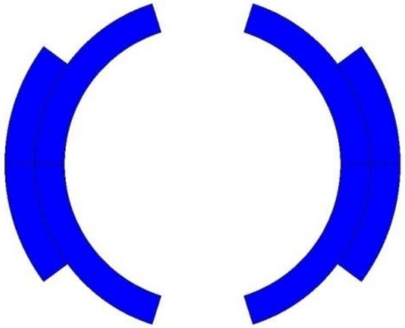
- D20



Mechanics of superconducting magnets
Electro-magnetic force

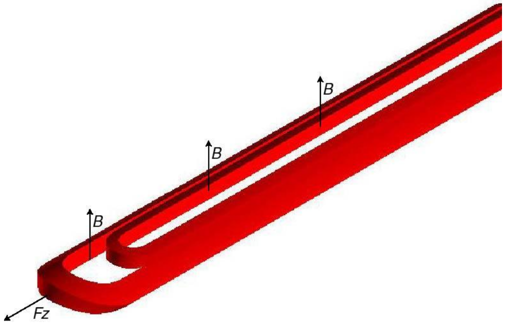
- The e.m. force on a dipole coil varies
  - with the **square** of the bore field
  - **linearly** with the bore radius

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

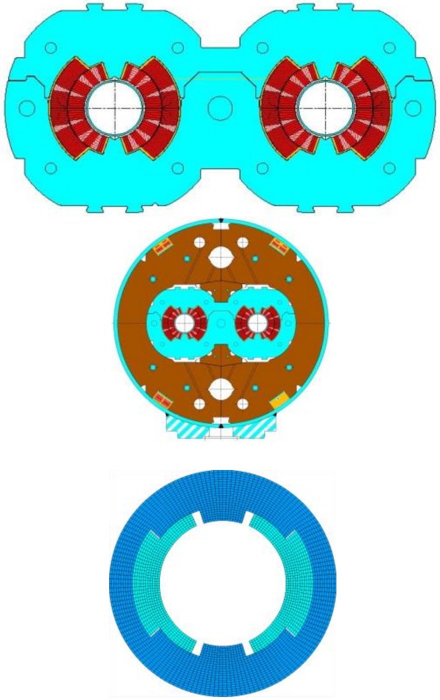


- The axial force on a dipole coil varies
  - with the **square** of the bore field
  - with the **square** of the bore radius

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



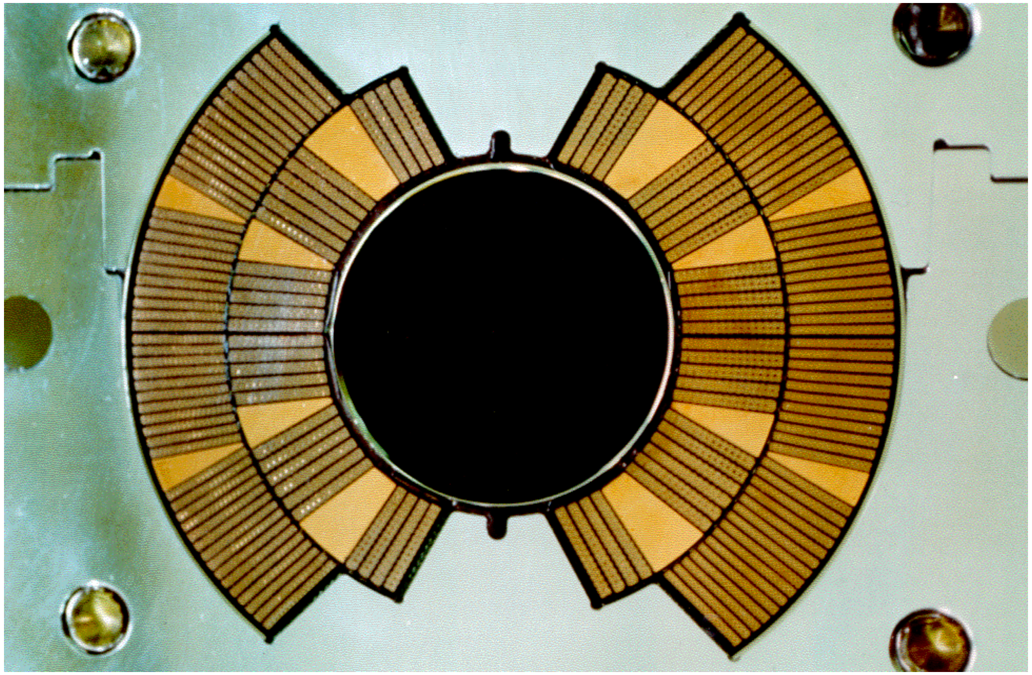
Mechanics of superconducting magnets
Overview of coil stress



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

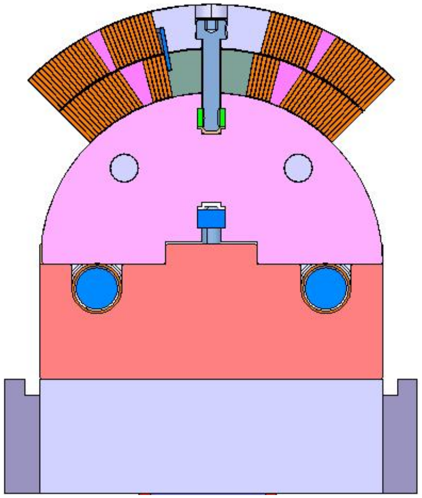
Coil fabrication
Winding

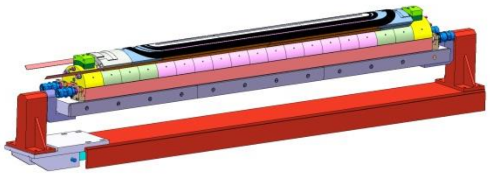
- The coil: most **critical component** of a superconducting magnet
- **Cross-sectional accuracy** of few hundredths of millimeters over ~15 m
- **Laminated tooling**

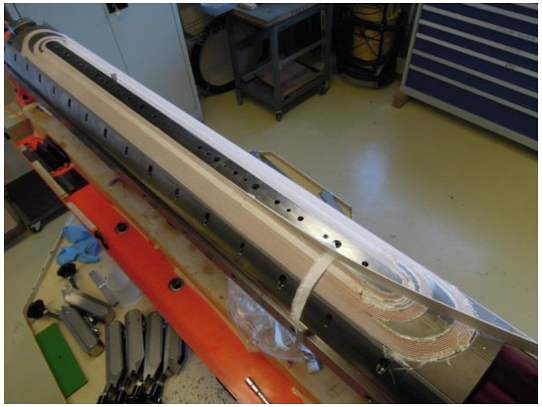


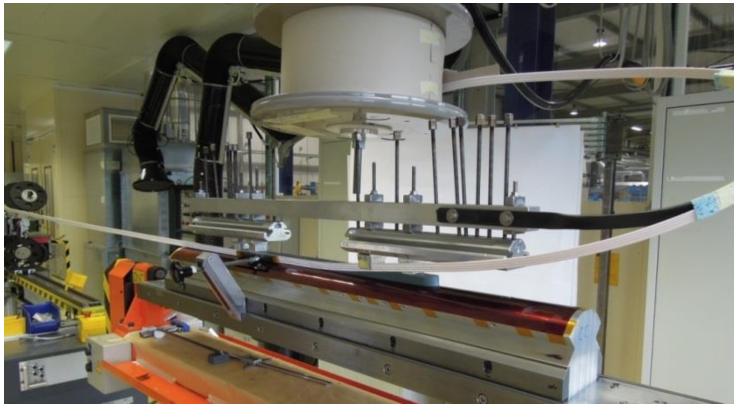
Coil fabrication
Winding

- The cable is wound around a **pole** on a mandrel.
  - The mandrel is made of laminations
- Winding starts from **pole turn** of the inner layer
- Cable maintained in **tension** (200 N)
- For large production→ **automated winding machines**



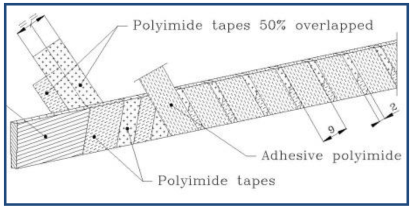




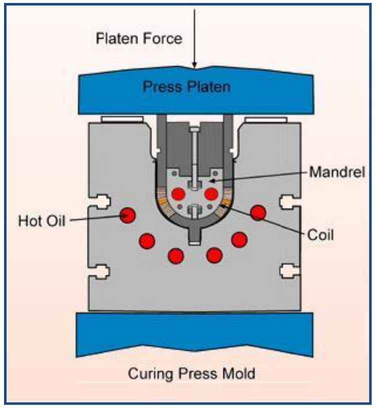


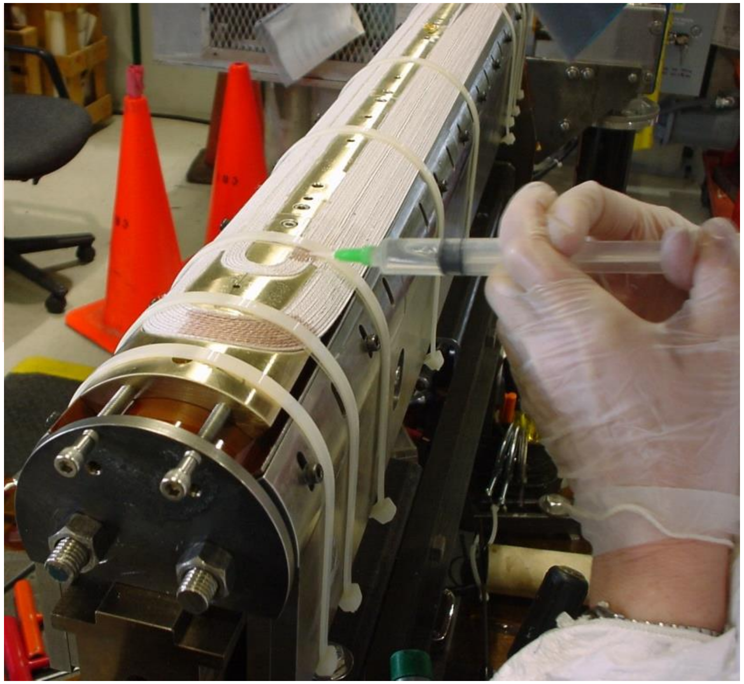
Coil fabrication
Winding and curing

- The goal of curing
  - Glue turns facilitating **handling**
- Coils are placed in the **curing mould** equipped with a **heating** system, and **compressed** in press
- Nb-Ti coils cured up to 190±3 °C at 80-90 MPa (LHC) to **activate resin**

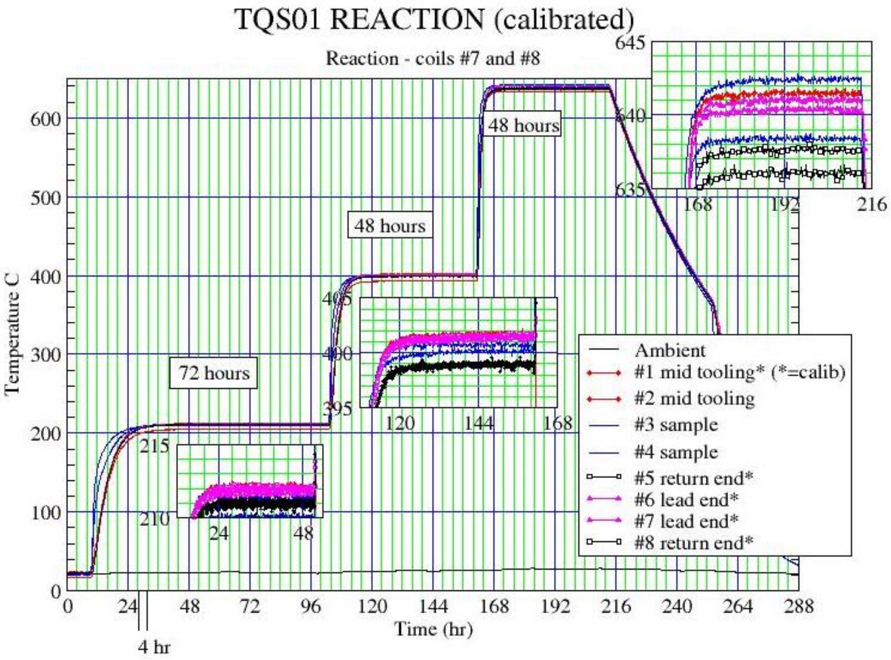


- In Nb_3Sn coils, cable insulation is injected with **ceramic binder**
  - Cured at 150° C and at ~10-30 MPa





Coil fabrication
Reaction of Nb_3Sn coils

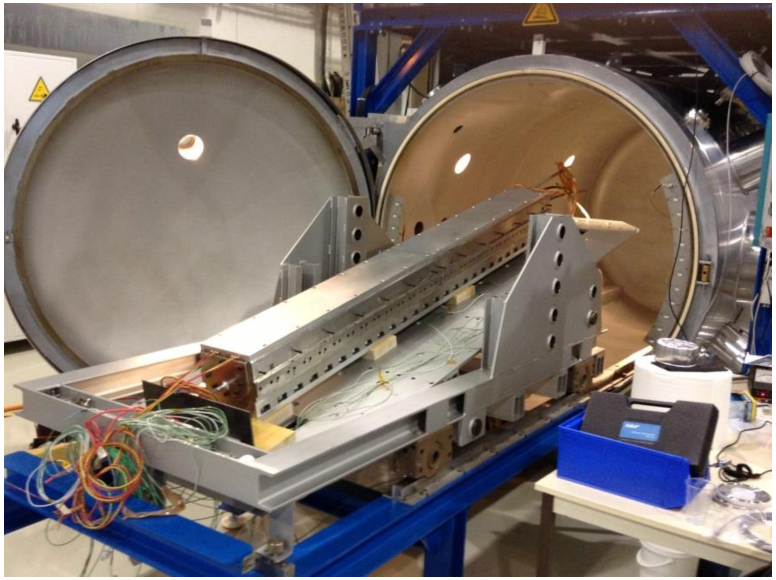


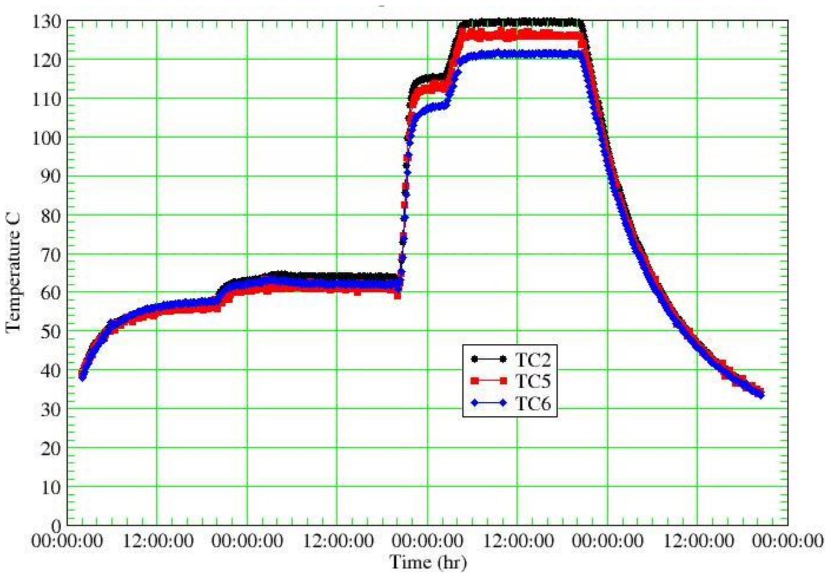
- **Heat treatment**
  - Sn and Nb are heated to 650-700 C in vacuum or inert gas (argon)
    - They reacts to form Nb_3Sn
- The cable becomes **brittle**
- The reaction is characterized by **three temperature steps**
  - Homogeneity is of about ± 3 °C

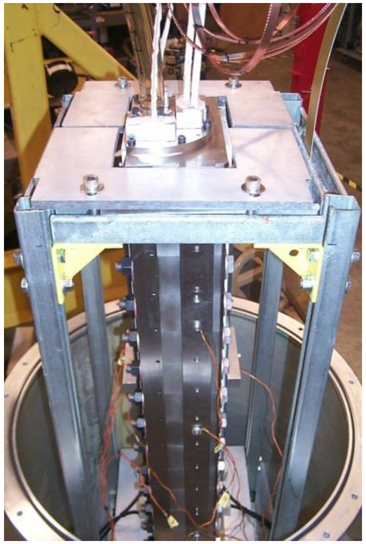
- Reaction oven with argon gas flow
  - **Minimize O_2 content** and Cu oxydation

Coil fabrication
Vacuum impregnation of Nb_3Sn coils

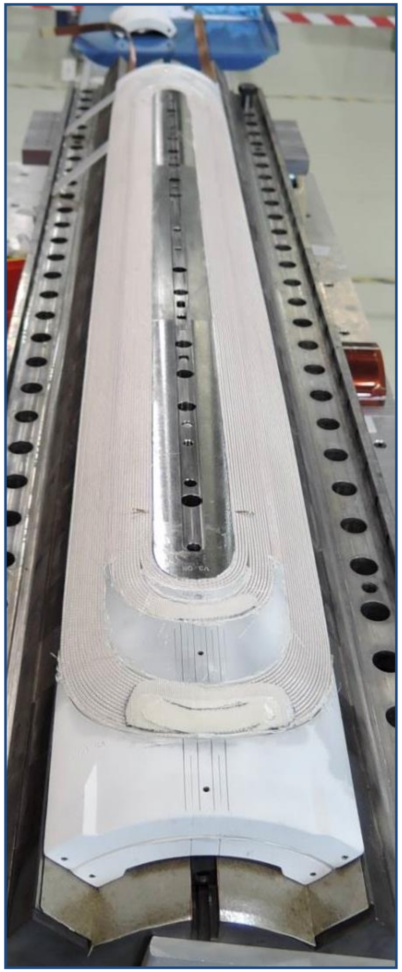
- After reaction, coil placed in a **impregnation fixture**
  - The fixture is inserted in a vacuum tank, evacuated → **epoxy injected**
  - high viscosity at room temperature,
  - low viscosity at ~60 °C
  - Then, **curing** at ~150 °C → solid block







Overview of coil fabrication stages

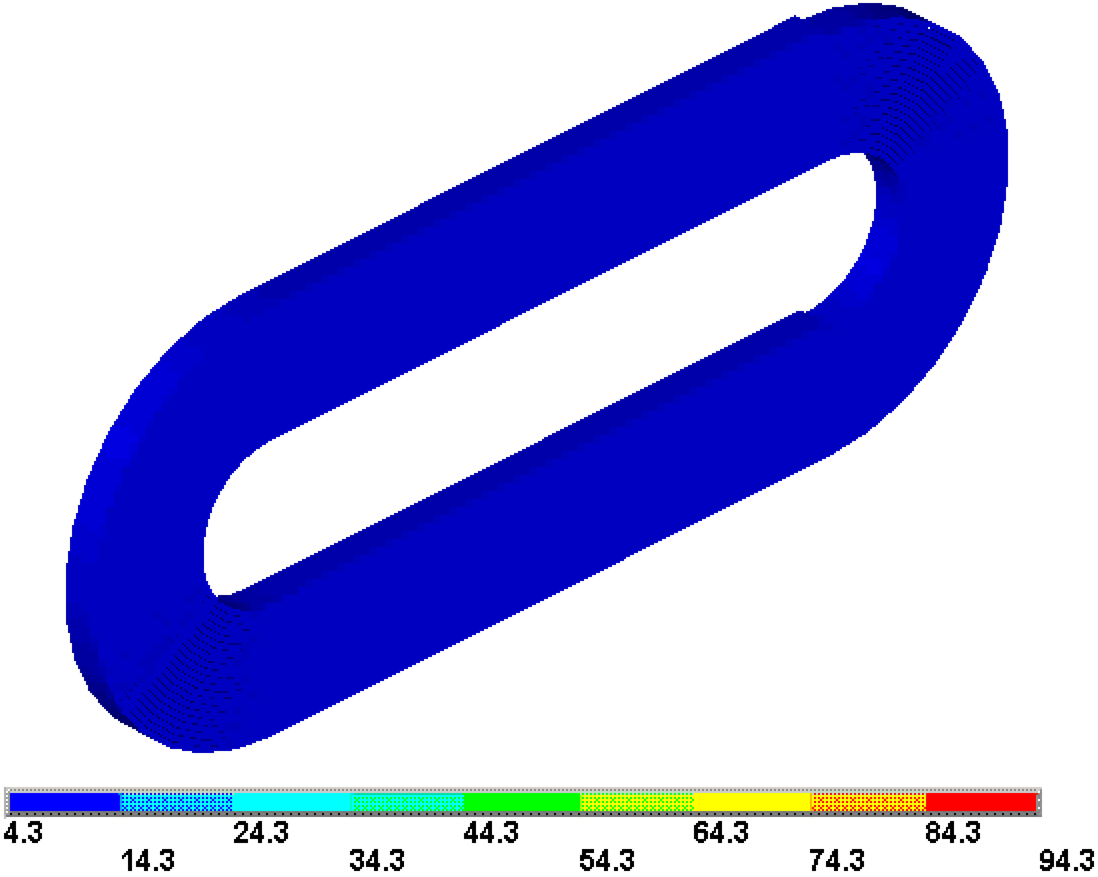


After winding/curing

After reaction

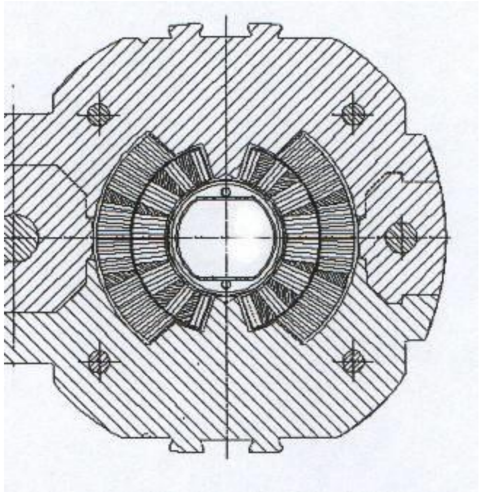
After impregnation

Quench and protection
Propagation

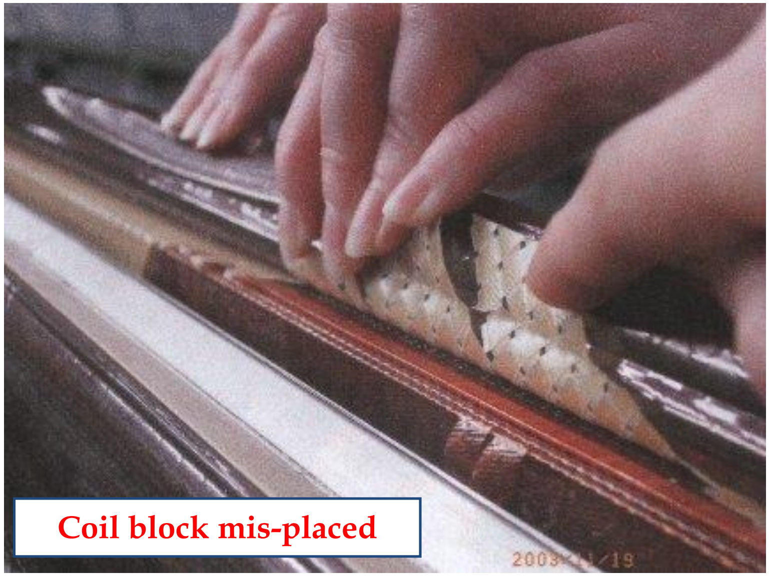


….more on field harmonics

- As we said, we **minimize** harmonics during **design** phase
- After fabrication we can **measure** them
  - Reproducibility of coil positioning is ~20-50 mm (1 σ)
- If an anomaly is observed-→ **inverse problem**
  - Which coil **defect** could cause such an **anomaly**?



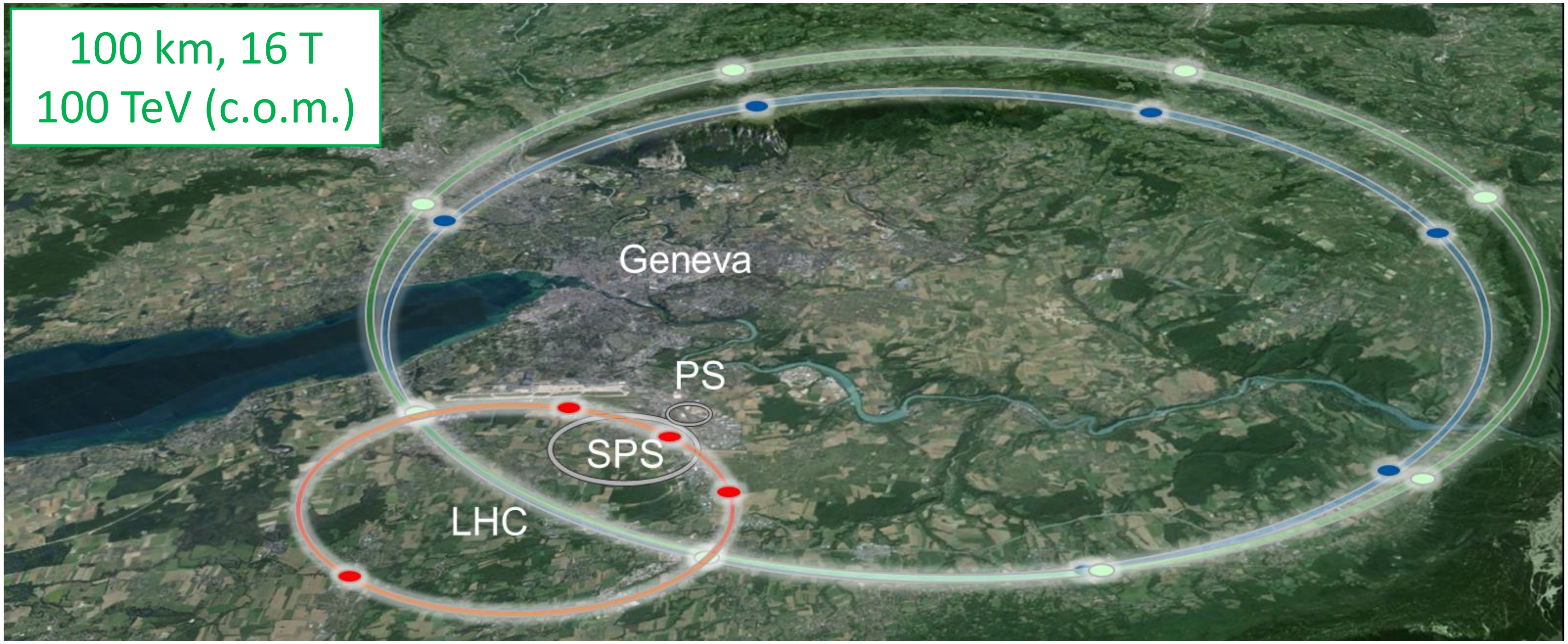
Missing shim



Coil block mis-placed

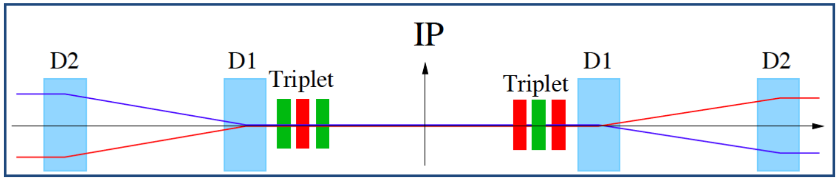
From 12-13 T to 15-16 T
FCC (100 km)

- **FCC project**
  - Magnet R&D focus is on FCC-hh: **100 TeV** pp collider
  - Timeframe: beyond 2035
  - Option: **16 T dipole** magnet in **100 km** machine

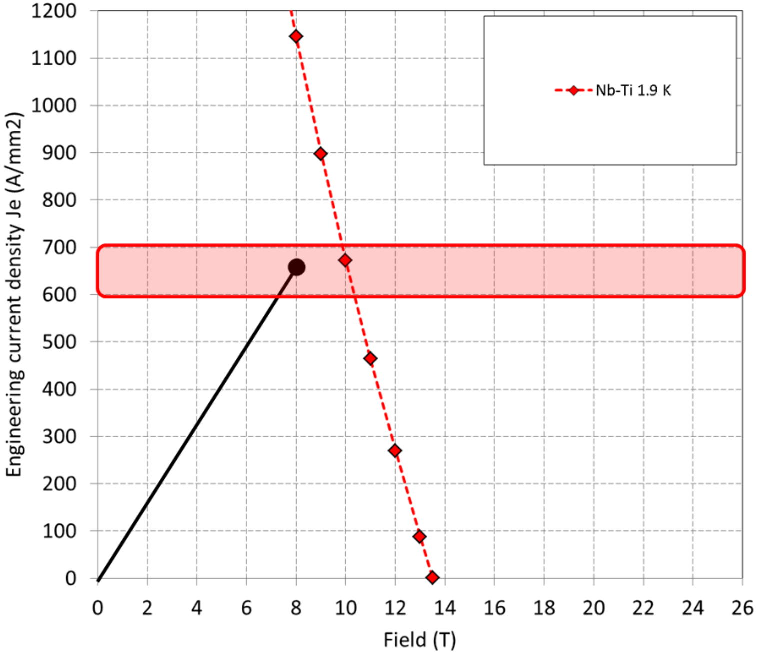


From 8-9 T to 12-13 T
HiLumi LHC

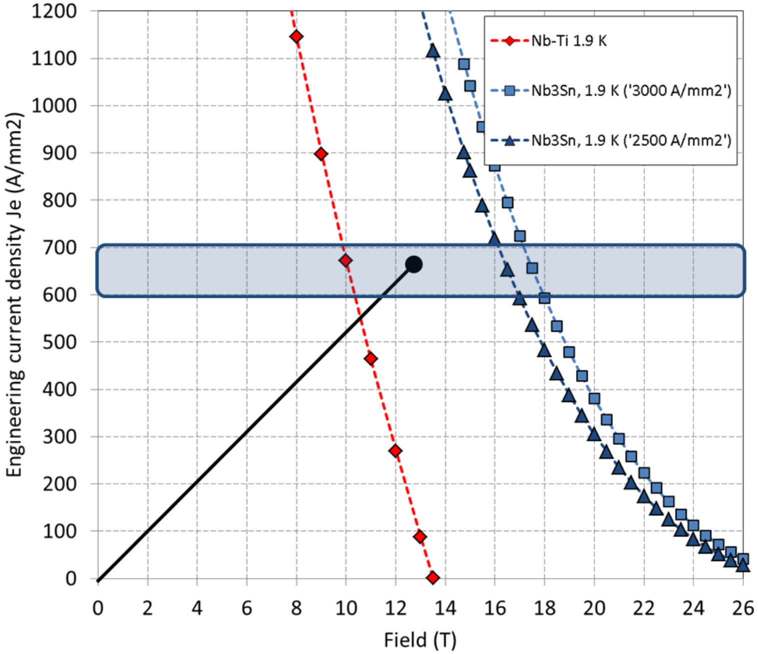
- From **LHC** to **HiLumi LHC**
  - Integrated *L*: ~300 → 3000 fb^{-1}
  - Start in 2025-2035
- Reduce beam size in IR by **factor 2**
- **Nb$_3$Sn** to be implemented for the first time in an accelerator



Nb-Ti



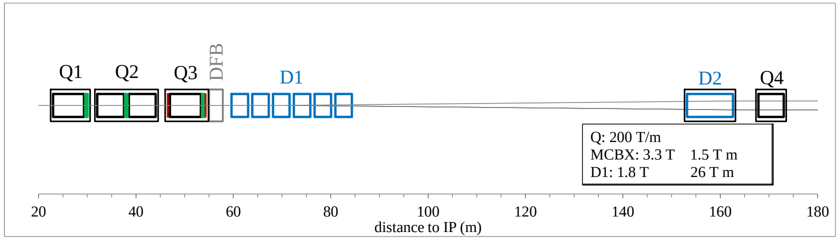
Nb$_3$Sn



From 8-9 T to 12-13 T HiLumi LHC

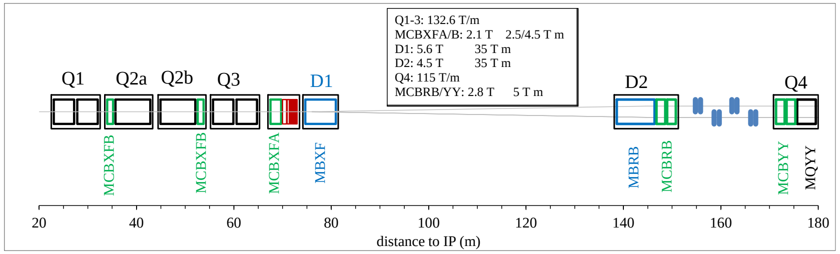
- **MQXF** quadrupole magnet for the inner triplet
  - Aperture doubled (70 mm → 150 mm), e.m. forces increased by factor 4
- **Nb_3Sn** gives **~50% more gradient** for the same aperture
  - More compact triplet (Real estate is always an issue)

LHC



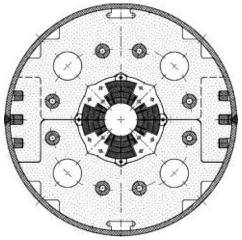
Q: 200 T/m
MCBX: 3.3 T 1.5 T m
D1: 1.8 T 26 T m

HiLumi LHC

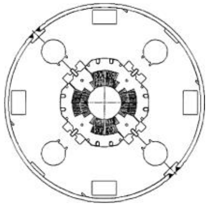


Q1-3: 132.6 T/m
MCBXFA/B: 2.1 T 2.5/4.5 T m
D1: 5.6 T 35 T m
D2: 4.5 T 35 T m
Q4: 115 T/m
MCBRB/YY: 2.8 T 5 T m

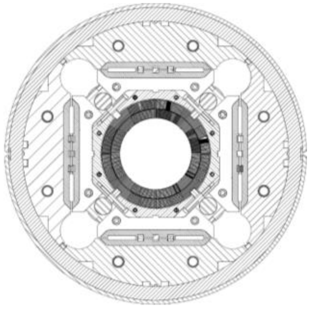
MQXFA



MQXFB

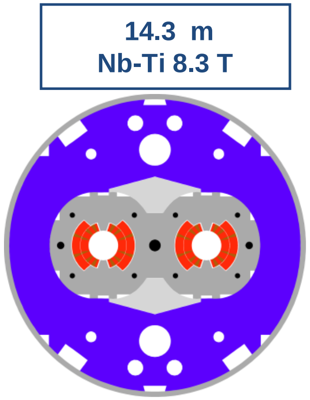


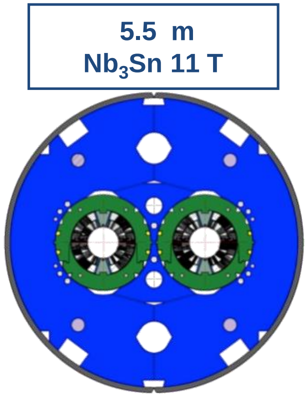
MQXF

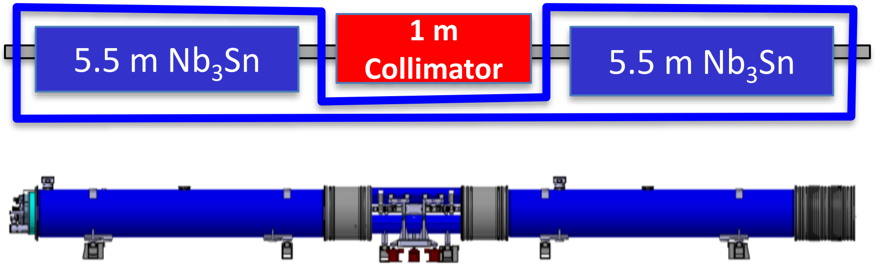


From 8-9 T to 12-13 T
HiLumi LHC

- **11T dipole** project
  - Create space in the LHC to install **additional collimators**
    - Needed to cope with beam intensities larger than nominal, such as in the High Luminosity LHC
- **Nb_3Sn** allows increasing the field from 8.3 T to 11 T
  - Replace standard LHC dipoles (14.3 m) by pairs of 11T dipoles (5.5 m)



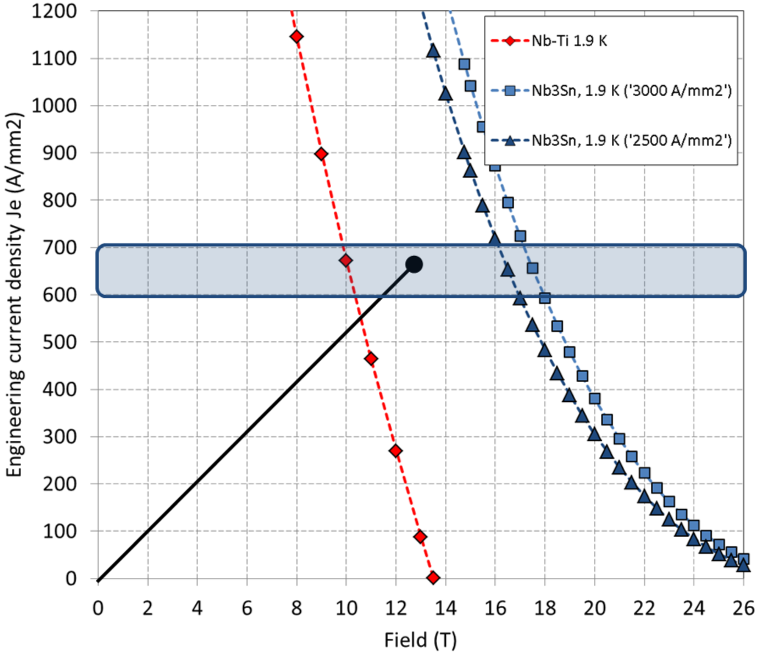




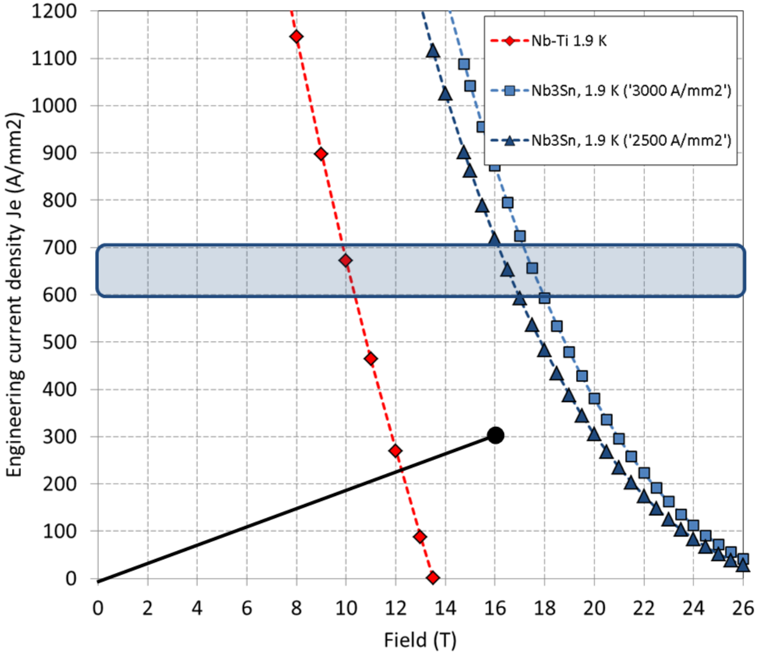
From 12-13 T to 15-16 T FCC (100 km)

- **Nb_3Sn** allows increasing the field from 12-13 to 15-16 T, but
- Larger coil width → lower load-line
  - **Coil width increases** by about factor 2 (from 30 to 60 mm)
- Aperture practically constant (from 56 mm to 50 mm)

Nb_3Sn 12-13 T



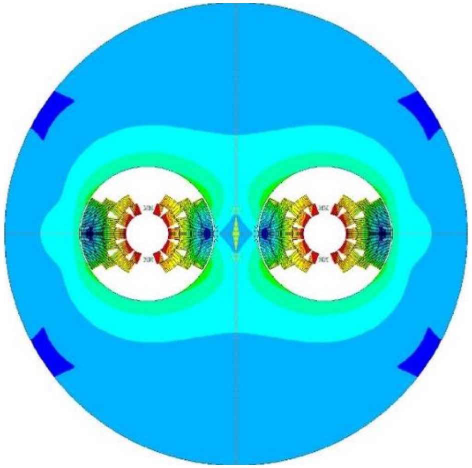
Nb_3Sn 15-16 T



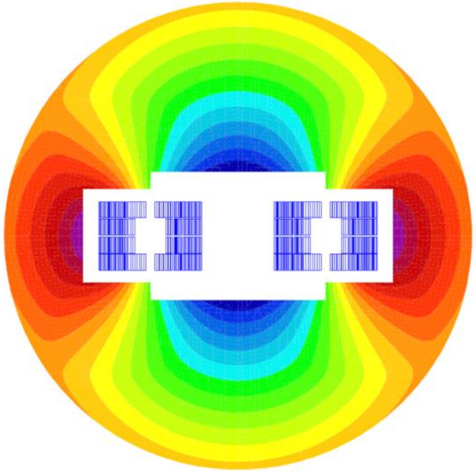
From 12-13 T to 15-16 T
FCC (100 km)

- Several designs, more "traditional", under investigation worldwide

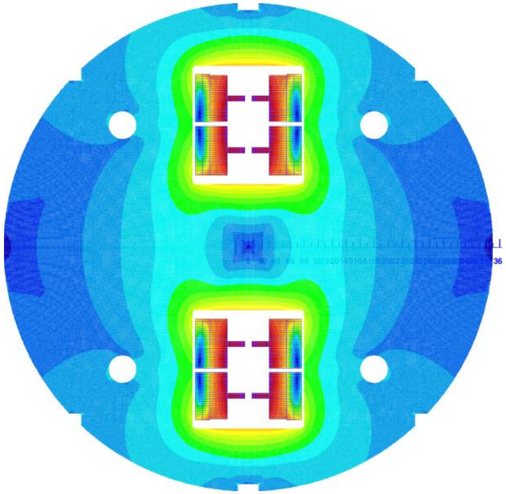
Cos-theta [Zlobin, FNAL]



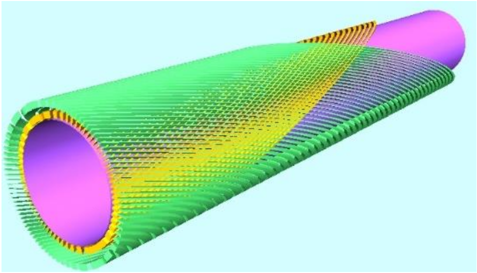
Block [Todesco, CERN]



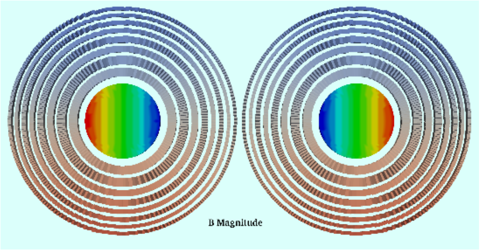
Common coil [Xu, IHEP China]



- Others more "innovative"…

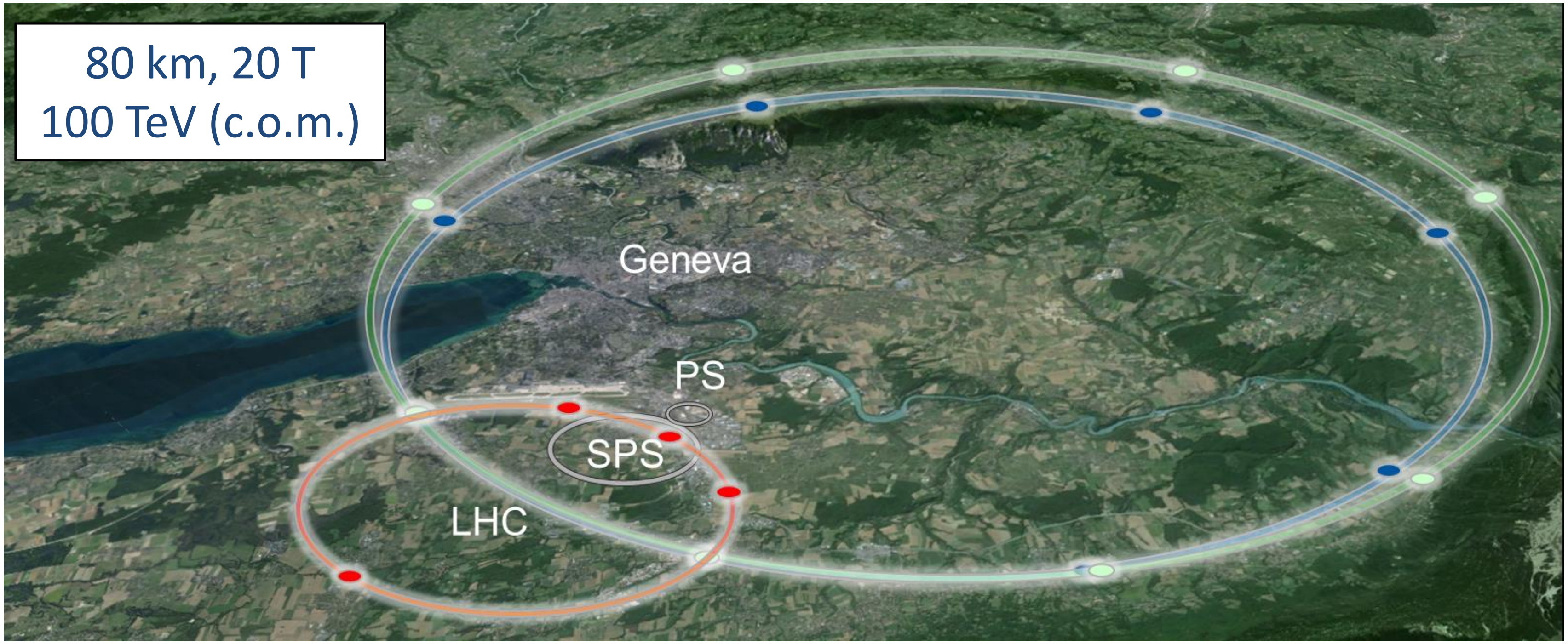


Canted [Caspi, LBNL]



From 15-16 T to 20 T
FCC (80 km)

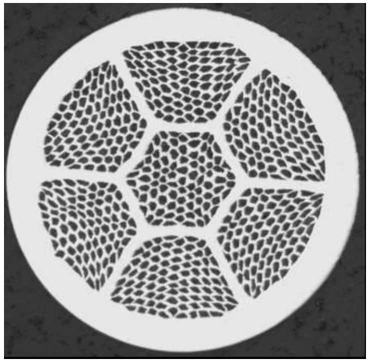
- **FCC project**
  - Magnet R&D focus is on FCC-hh: **100 TeV** pp collider
  - Timeframe: beyond 2035
  - Option: **20 T dipole** magnet in **80 km** machine


80 km, 20 T
100 TeV (c.o.m.)

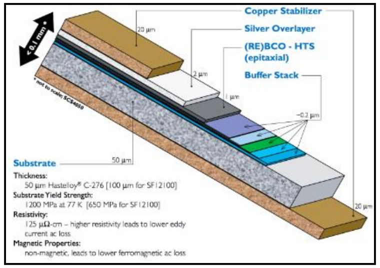
From 15-16 T to 20 T
FCC (80 km)

- **New materials** required
  - Coil in Nb_3Sn would be too wide
- High temperature superconductors **(HTS)**

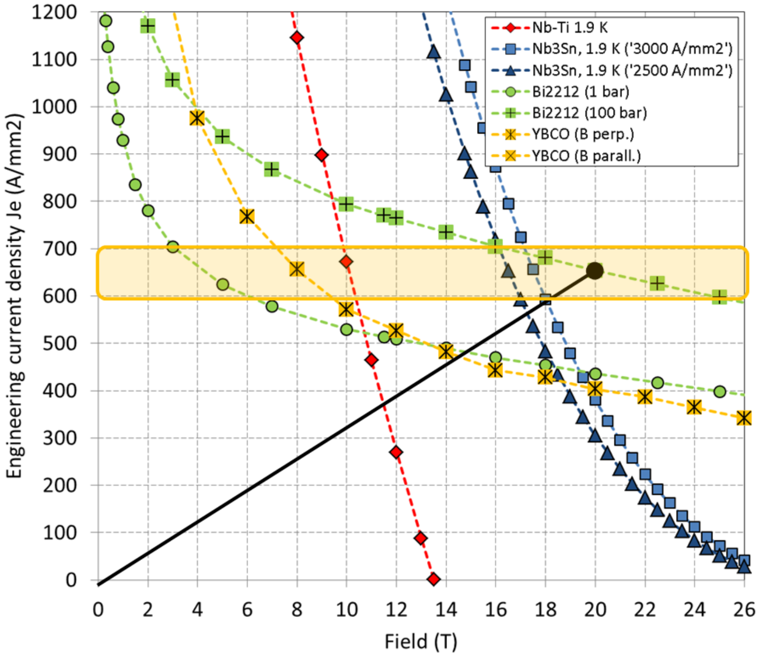
- **Bi2212**
  - Round strand -> cable
  - Reaction to 890 °C
  - Strain sensitive
  - Cost ~ 16 x Nb-Ti



- **YBCO**
  - Tape -> cable?
  - No reaction
  - Resistance to stress
  - Cost ~ 16 x Nb-Ti
  - Strong angle dependance

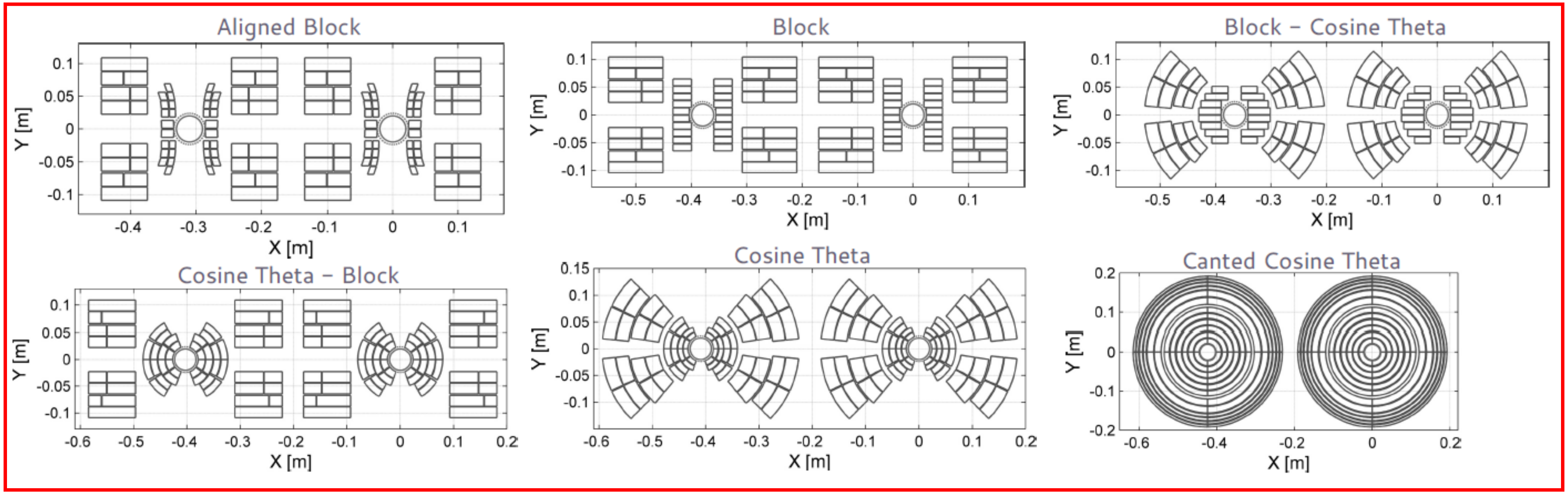


Thickness:
50 µm Hastelloy® C-276 [100 µm for SF12100]
Substrate Yield Strength:
1200 MPa at 77 K [650 MPa for SF12100]
Resistivity:
125 µΩ-cm – higher resistivity leads to lower eddy current ac loss
Magnetic Properties:
non-magnetic, leads to lower ferromagnetic ac loss



From 15-16 T to 20 T
FCC (80 km)

- Again, several designs, under investigation worldwide
  - Very creative moment….



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