Summer Student Lecture

Superconductivity and superconducting magnets for the LHC Upgrade

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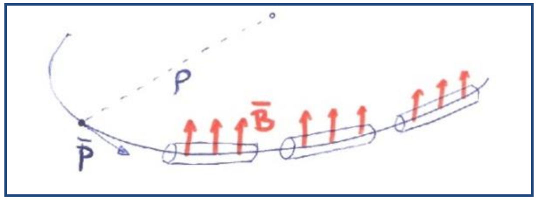
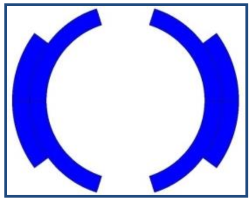
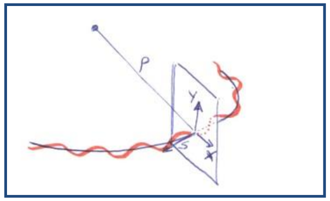
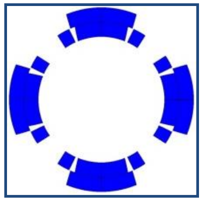
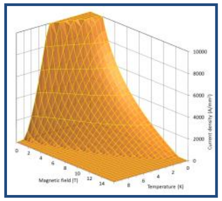
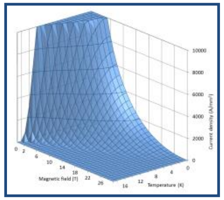
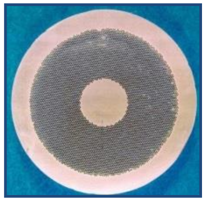
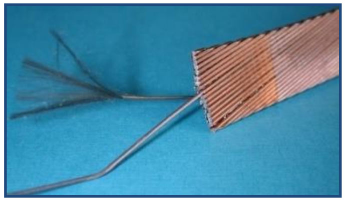
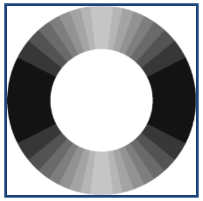
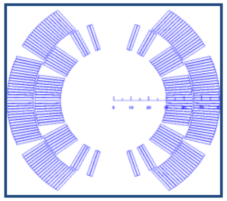
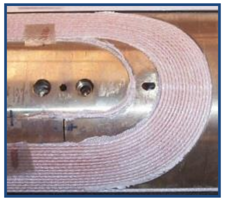
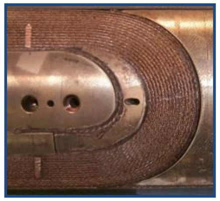
Previous lecture

- **Particle accelerators and superconductors**

- **Magnetic design and coils**


Outline

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

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.
  - 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 10,13,14**

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

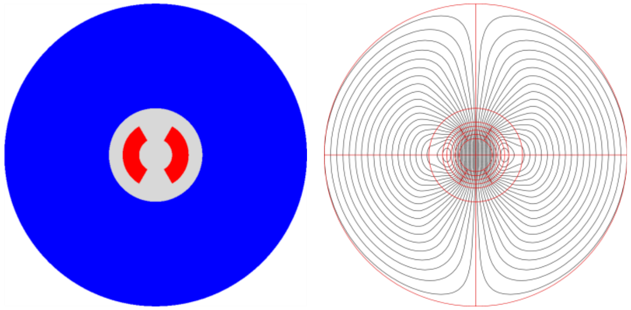
- In the presence of a magnetic field ***B***, an electric charged particle ***q*** in motion with a velocity ***v*** is acted on by a force $\boldsymbol{F_L}$ called electro-magnetic (Lorentz) force [N]:

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

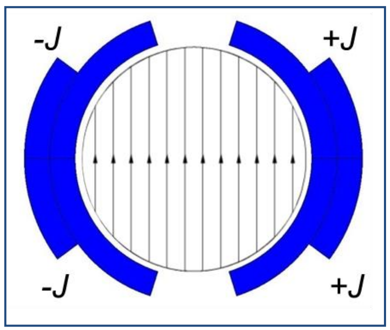
- A conductor element carrying current density *J* (A/mm^2) is subjected to a force density $\boldsymbol{f_L}$ [N/m^3]

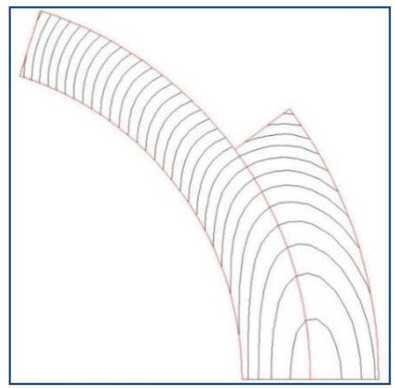
$$\vec{f}_L = \vec{J} \times \vec{B}$$

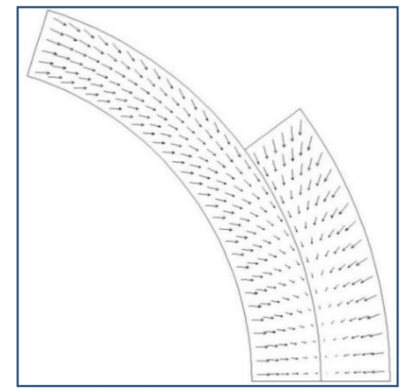
- Superconducing coil in its own field→

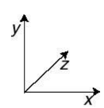


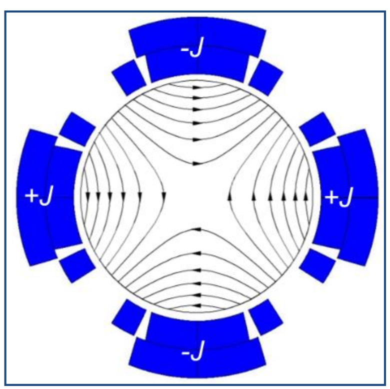
- The e.m. forces in a dipole/quadrupole magnet tend to push the coil
  - Towards the mid plane in the vertical-azimuthal direction (F_y, $F_\theta < 0$)
  - Outwards in the radial-horizontal direction (F_x, $F_r > 0$)

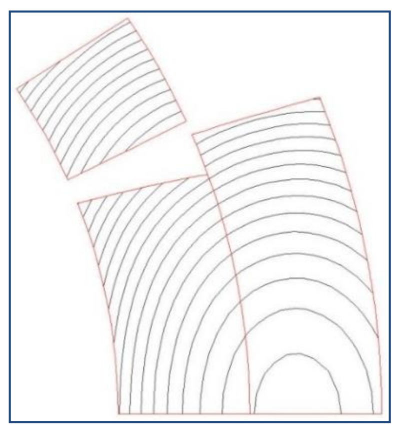


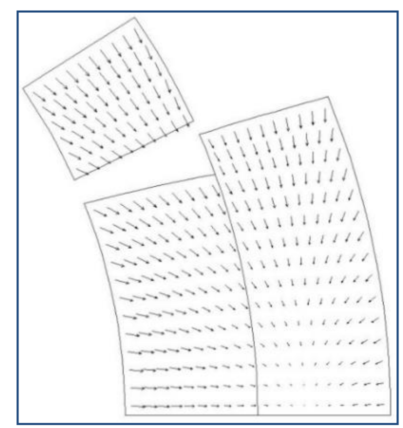






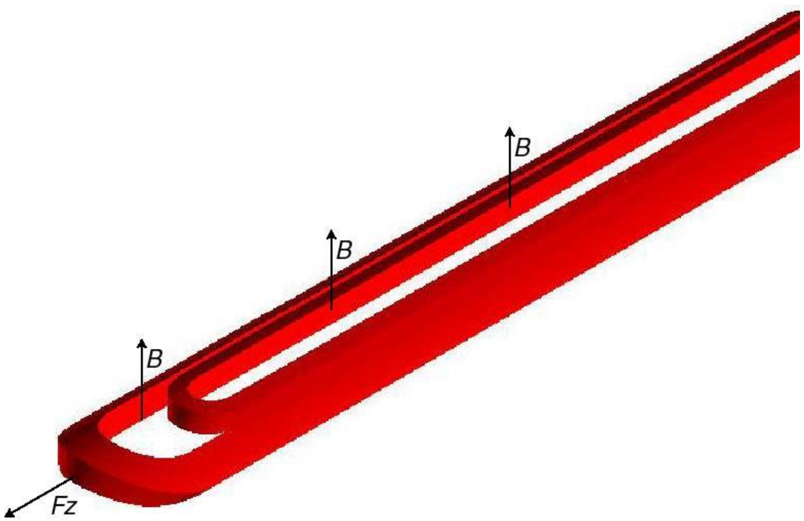


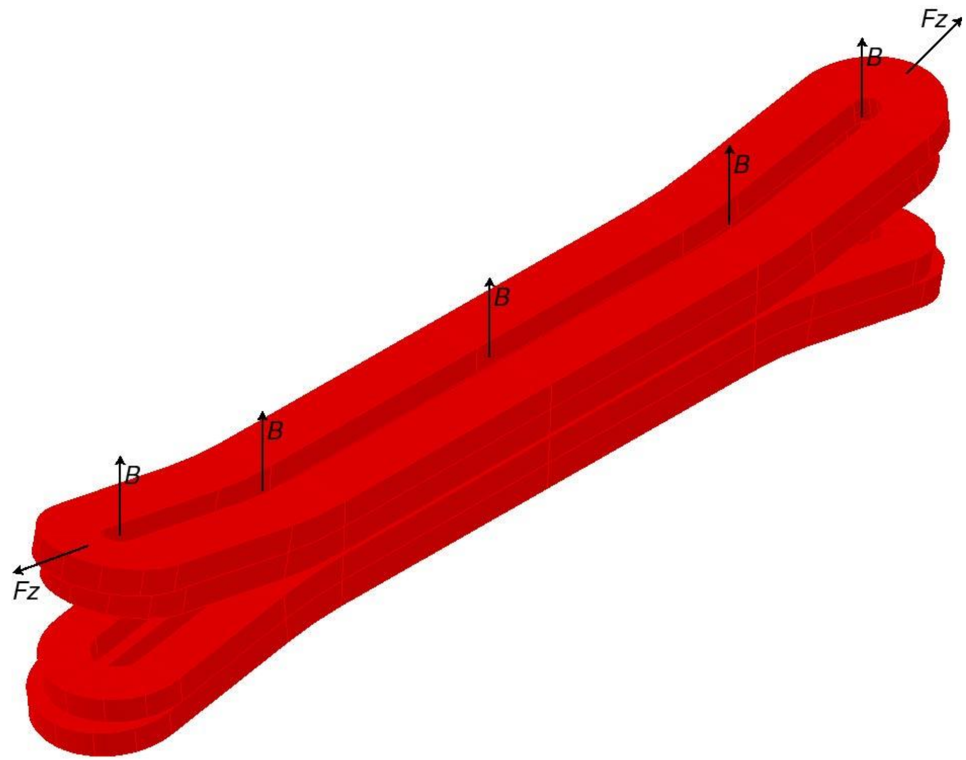




Mechanics of superconducting magnets
Electro-magnetic force

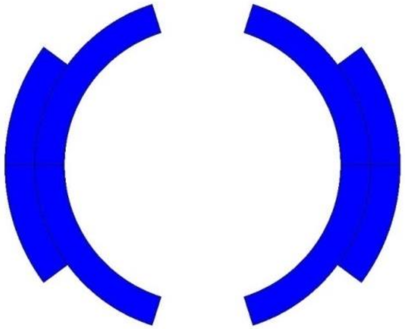
- In the **coil ends** the e.m. forces tend to push the coil
  - **Outwards** in the longitudinal direction ($F_z > 0$)





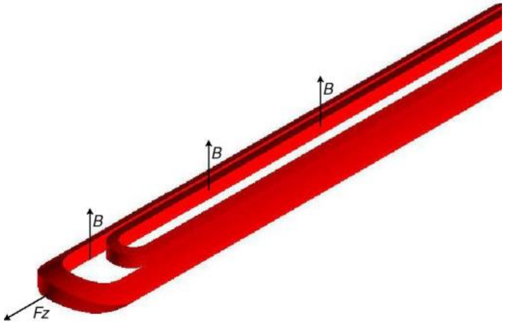
- The e.m. force on a dipole coil varies
  - with the **square** of the bore field
  - **linearly** with the bore radius

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



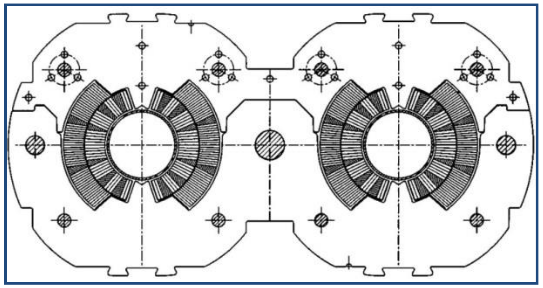
- The axial force on a dipole coil varies
  - with the **square** of the bore field
  - with the **square** of the bore radius

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

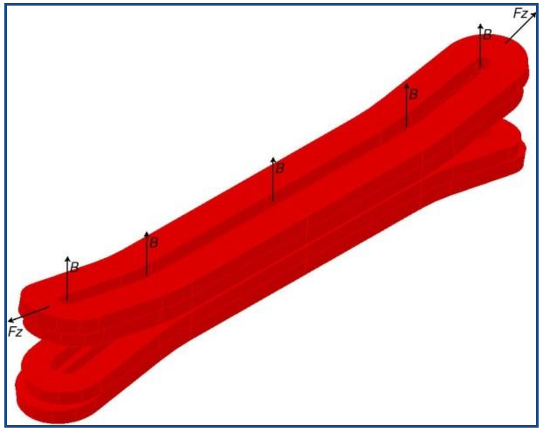


Mechanics of superconducting magnets
Electro-magnetic force

- **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

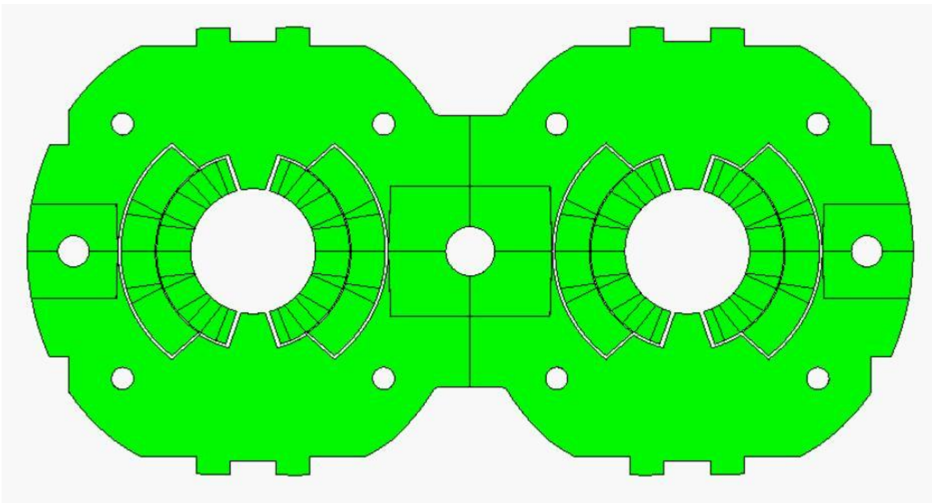


- **Nb_3Sn dipole** (HD2)
  - F_x = **500 t** per meter
  - F_z = **85 t**
  - These forces are applied to an objet with a cross-section of 150x100 mm !!!
    - and by the way, it is brittle

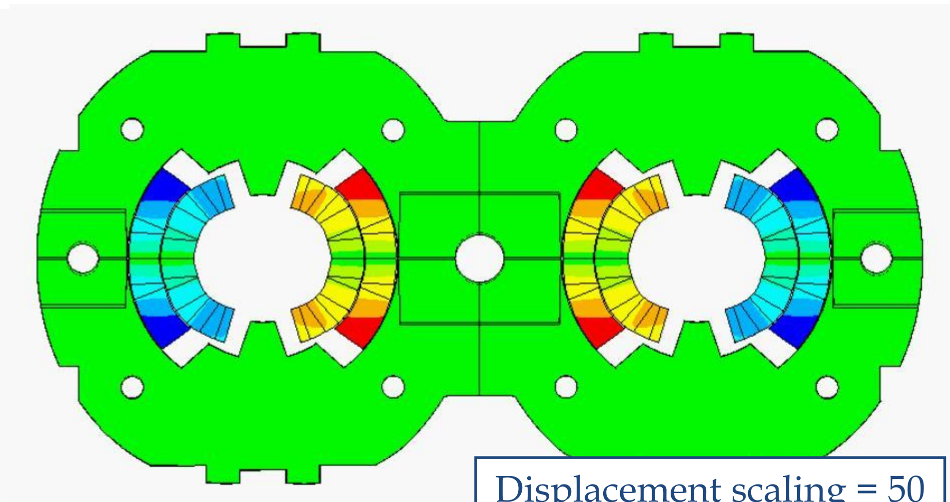


Mechanics of superconducting magnets
Deformation and stress

LHC dipole at 0 T



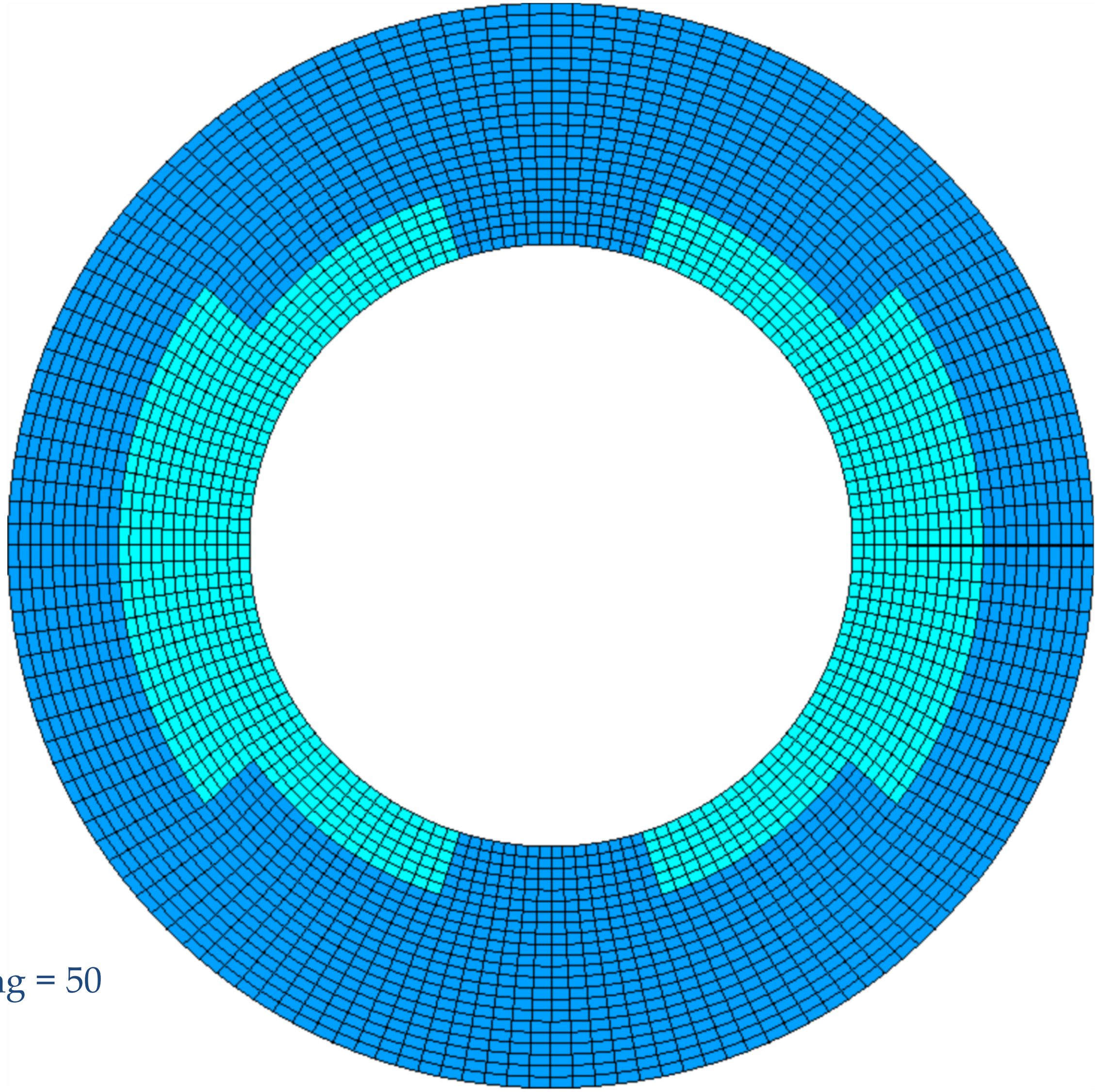
LHC dipole at 9 T



Displacement scaling = 50

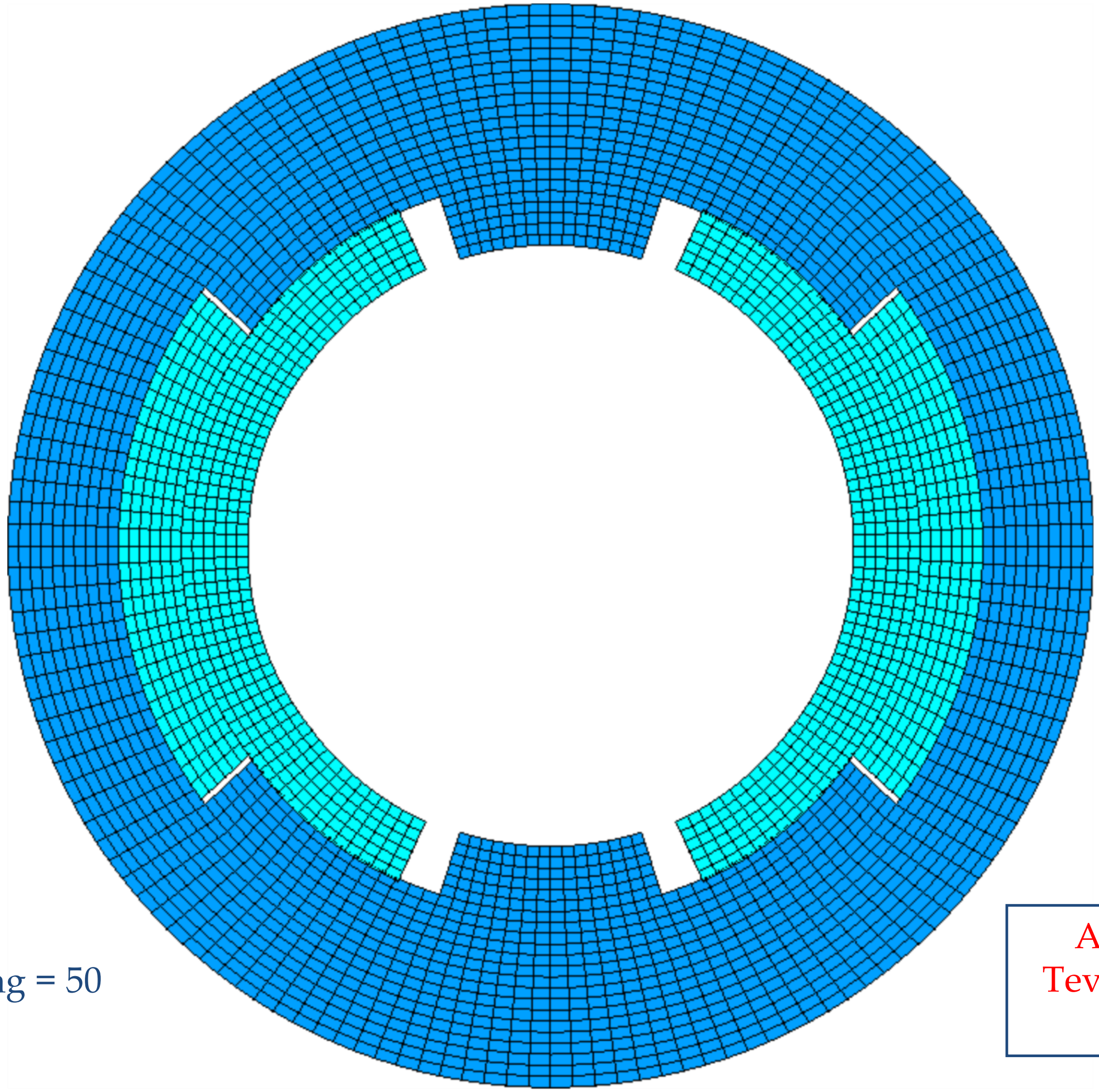
- Effect of e.m forces
  - change in **coil shape** → effect on field quality
  - a **displacement** of the conductor → potential release of frictional energy
  - Nb-Ti magnets: possible **damage** of kapton **insulation** at~150-200 MPa.
  - Nb_3Sn magnets: possible **conductor degradation** at about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

No pre-stress, no e.m. force



Displacement scaling = 50

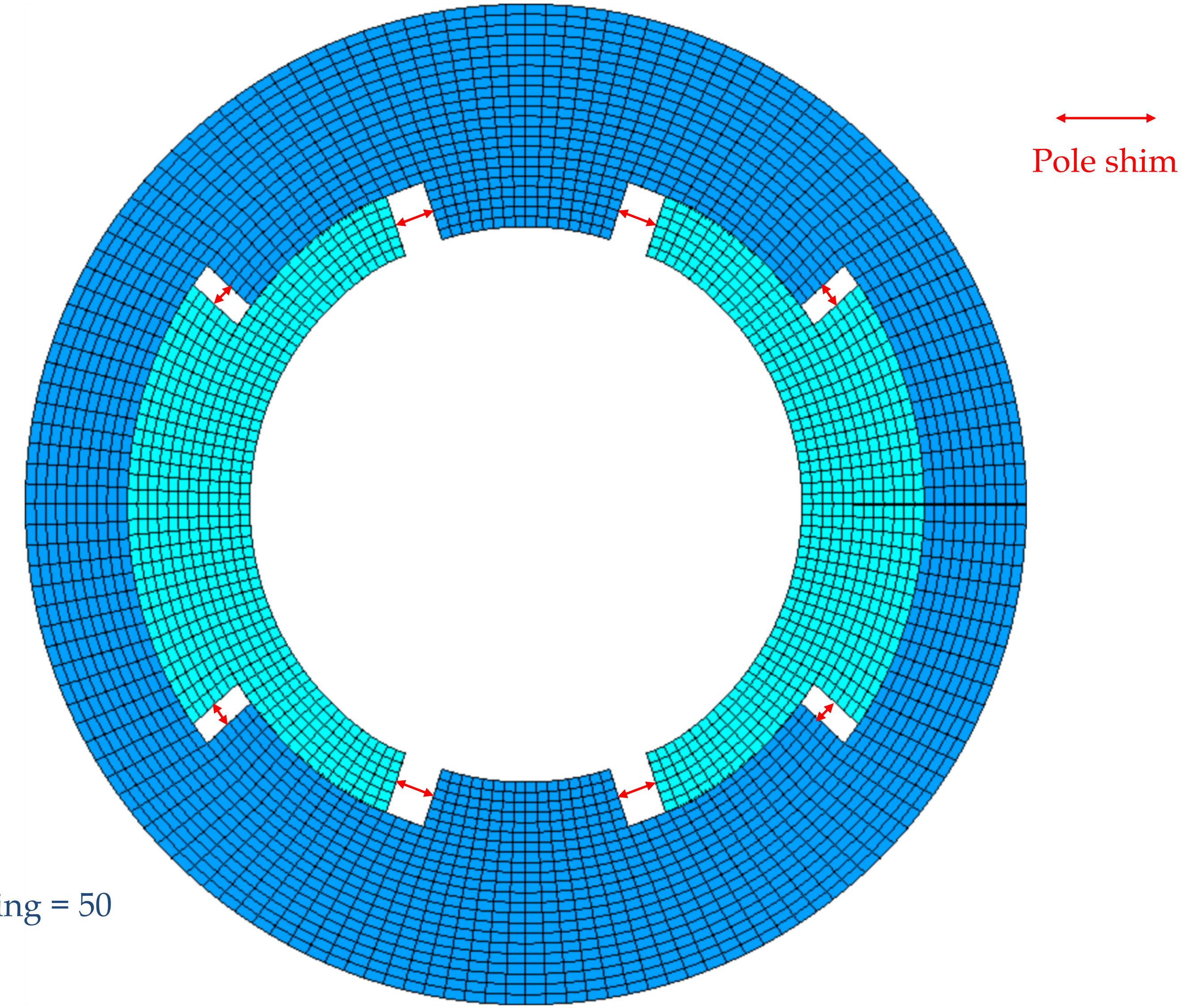
No pre-stress, with e.m. force



Displacement scaling = 50

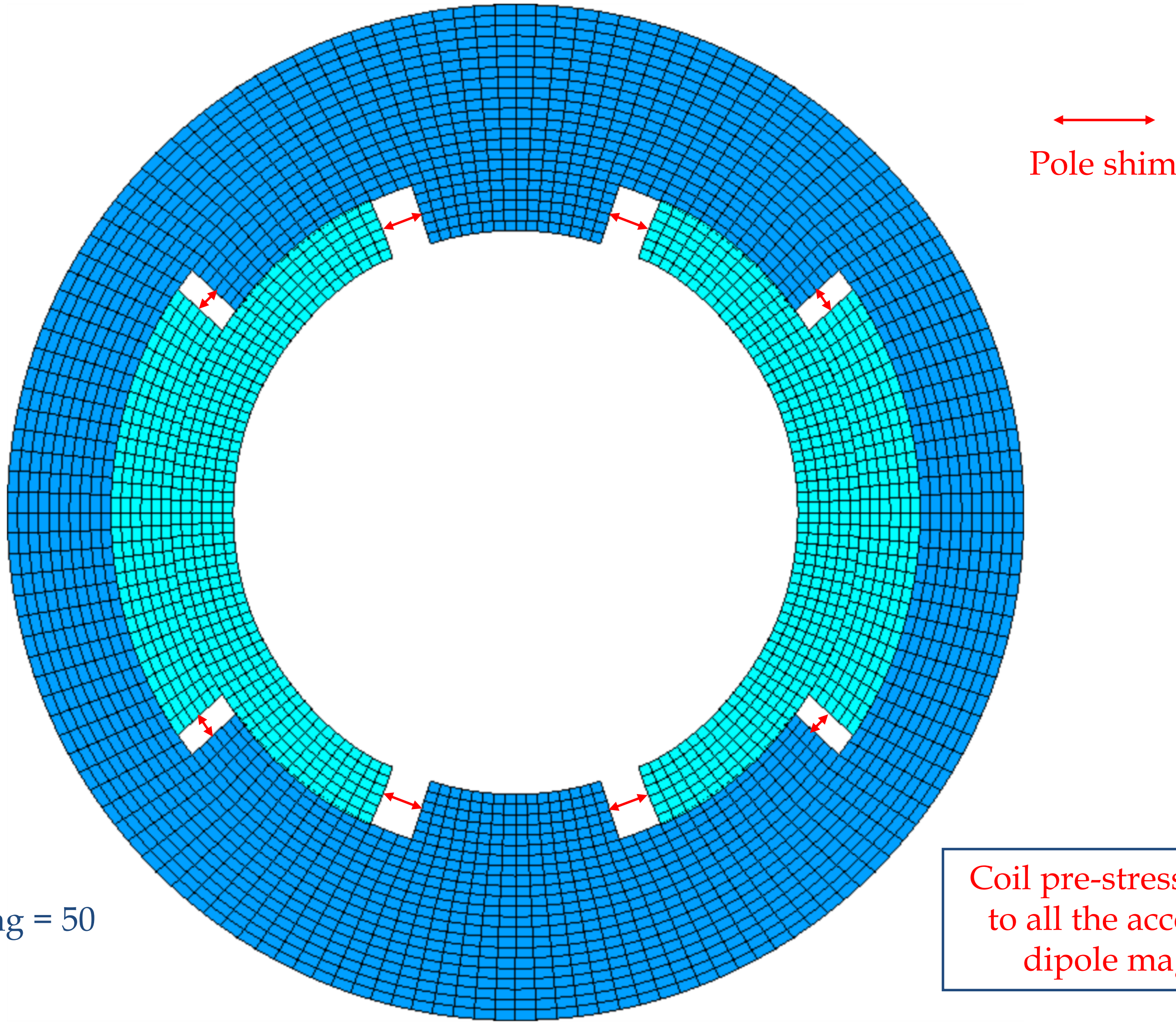
About 100 μm for Tevatron main dipole (B_{nom}= 4.4 T)

Pre-stress, no e.m. force



Displacement scaling = 50

Pre-stress, with e.m. force



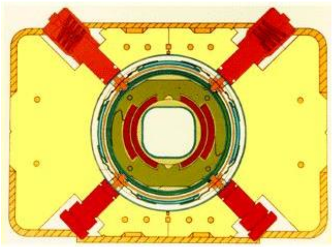
Displacement scaling = 50

Coil pre-stress applied to all the accelerator dipole magnets

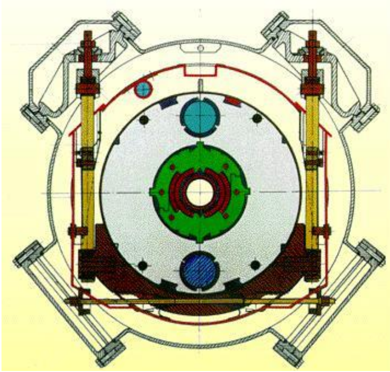
Mechanics of superconducting magnets
Support structures

- 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



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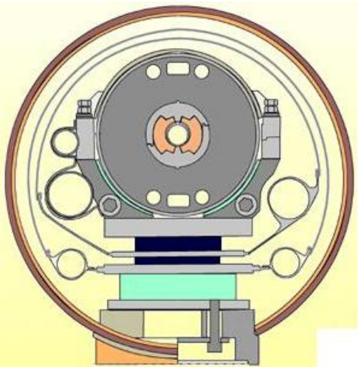
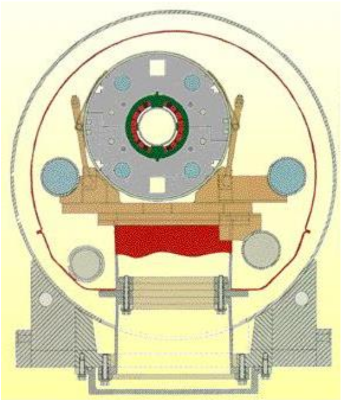
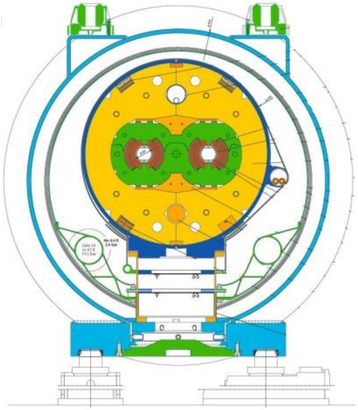


RHIC



LHC

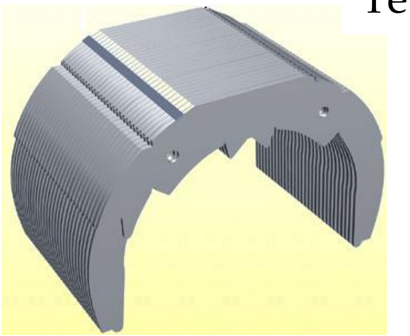
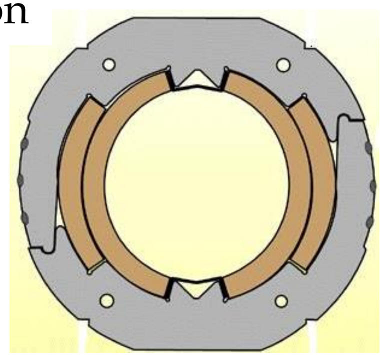


Not in scale

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

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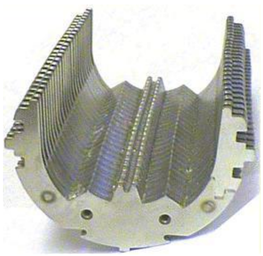
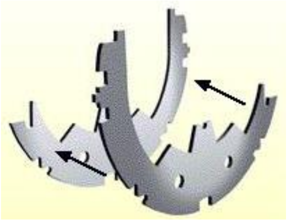
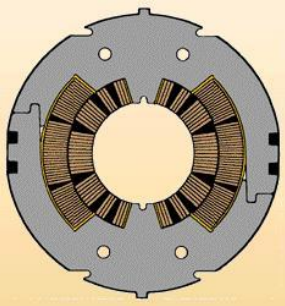

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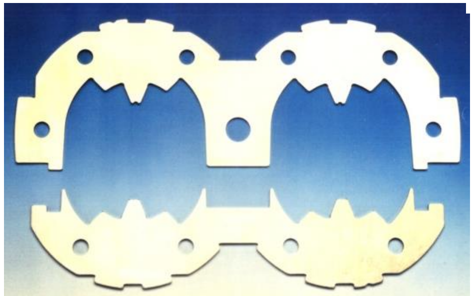
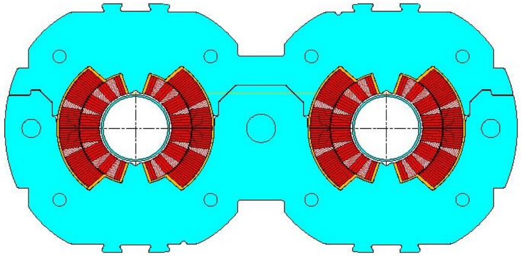
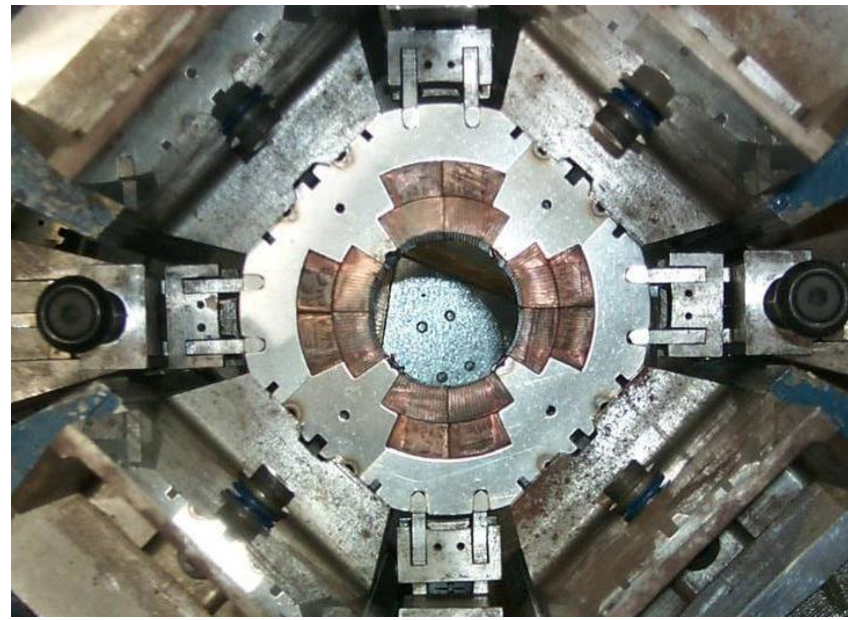



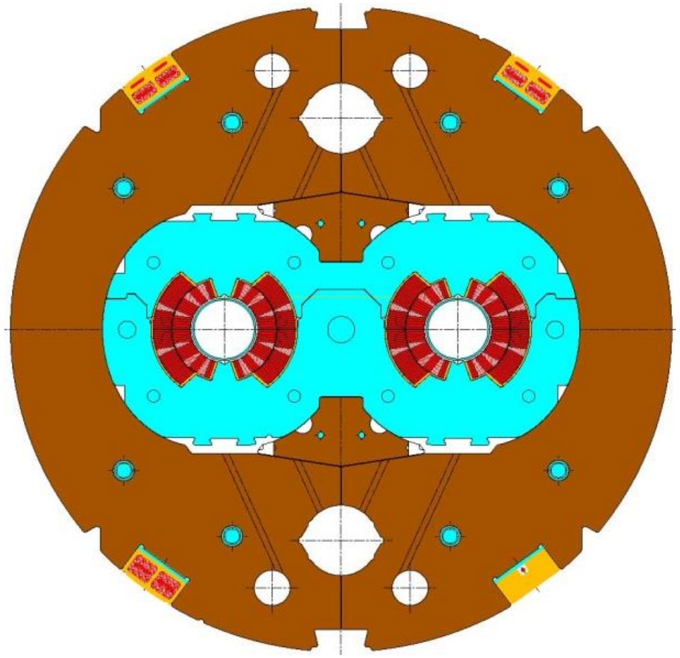
Collaring of a dipole magnet

Collaring of a quadrupole magnet



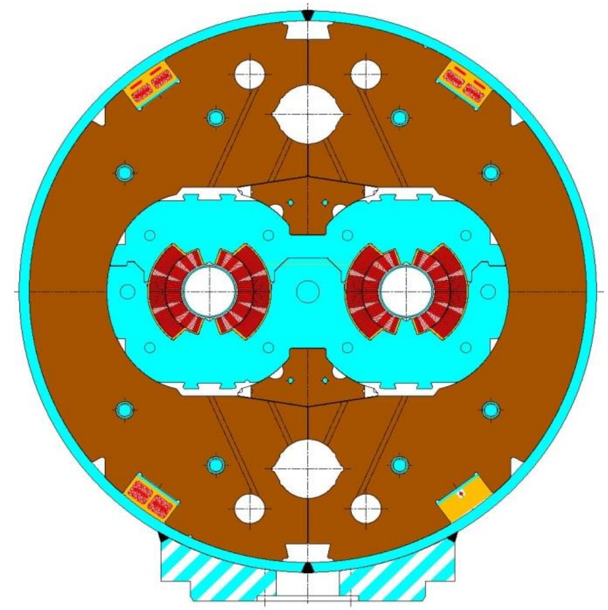
Mechanics of superconducting magnets
Iron yoke

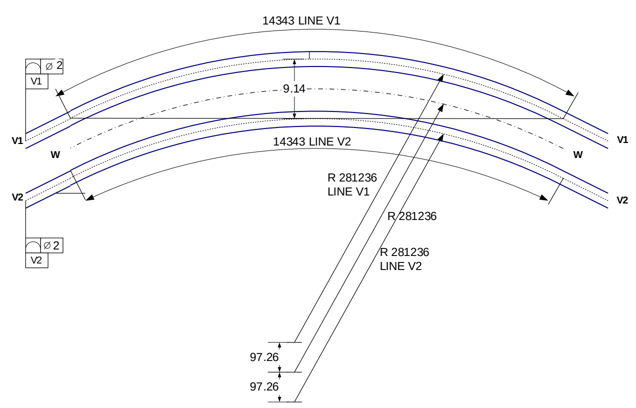
- As the collars, iron yoke are made in **laminations** (several mm thick).
- **Magnetic function**
  - contains and enhances the magnetic field.
- **Structural function**
  - tight contact with the collar
    - it contributes to increase the rigidity of the coil support structure and limit radial displacement.
- Holes are included in the yoke design for
  - Correction of **saturation effect**
  - **Cooling channel**
  - **Assembly features**
  - **Electrical bus**



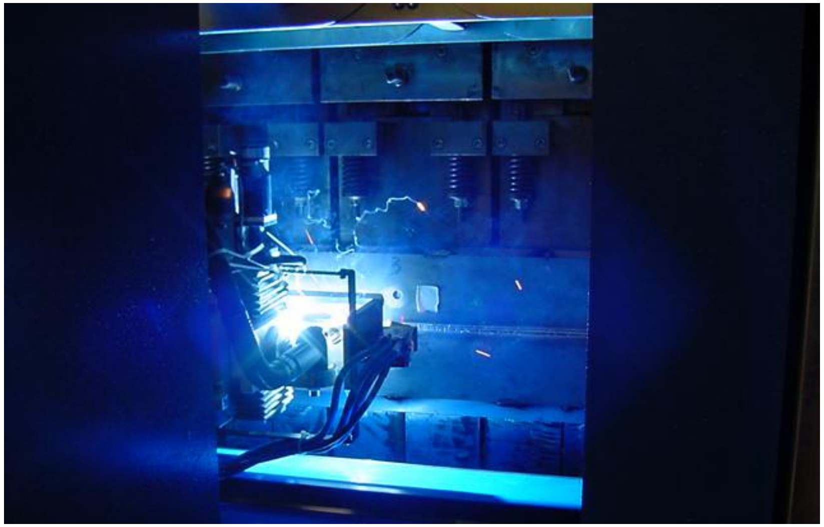
Mechanics of superconducting magnets
Shell

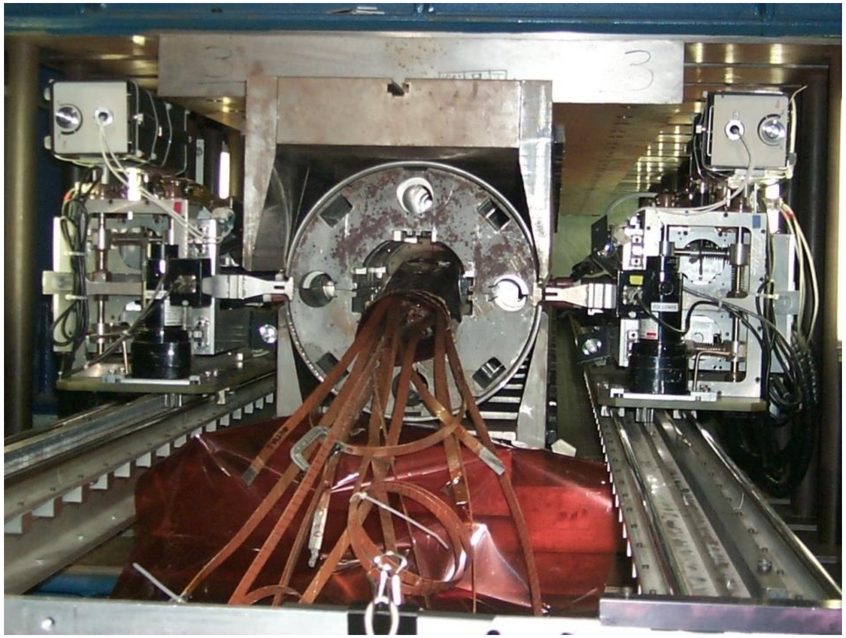
- The cold mass is contained within a shell
- The shell constitutes a **containment structure** for the liquid Helium.
- It is composed by two half shells of stainless steel **welded** around the yoke with high tension (about 150 MPa for the LHC dipole).
  - With the iron yoke, it contributes to create 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**.





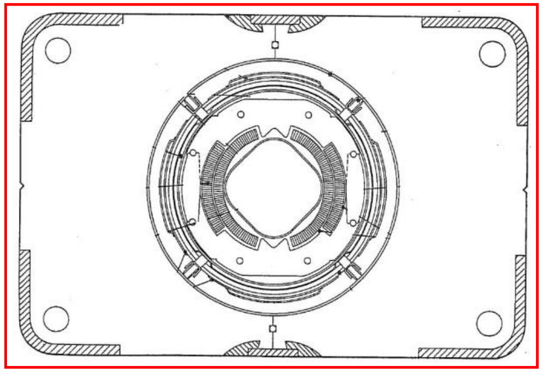
Mechanics of superconducting magnets
Shell





Mechanics of superconducting magnets
Overview

Tevatron



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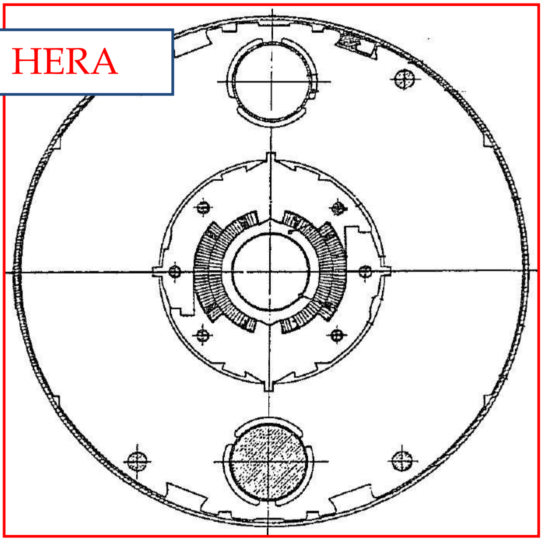

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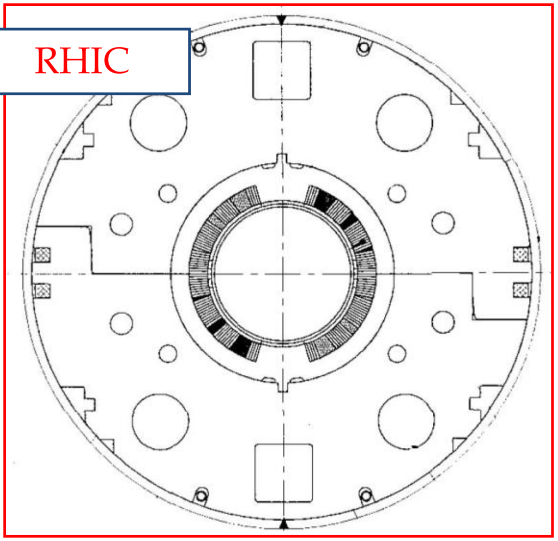

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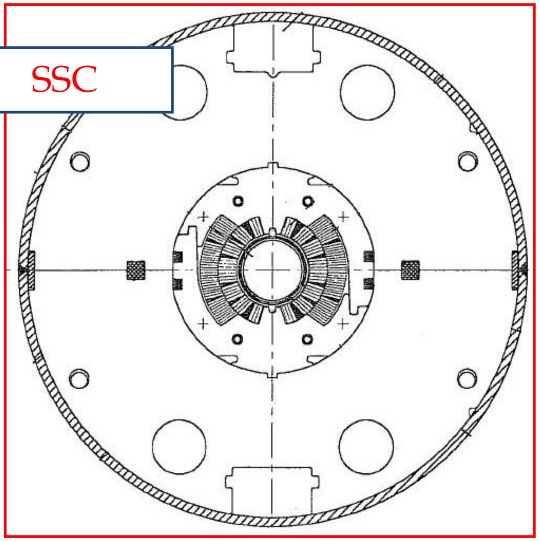
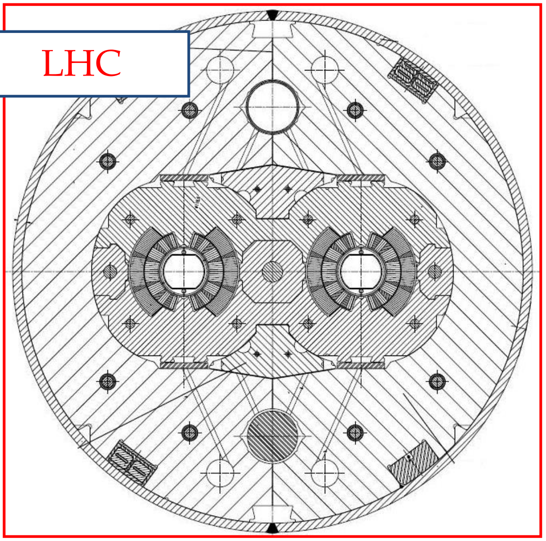
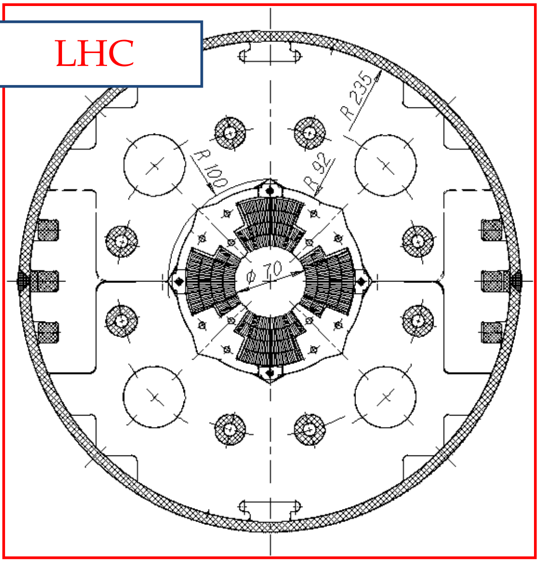


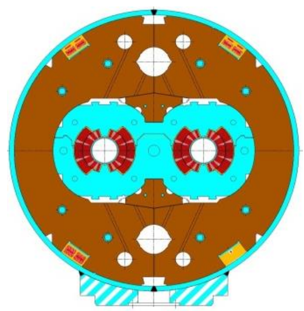
LHC

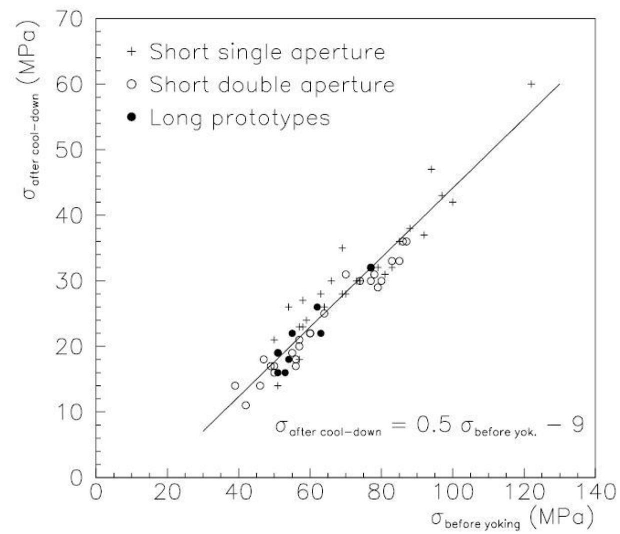


LHC

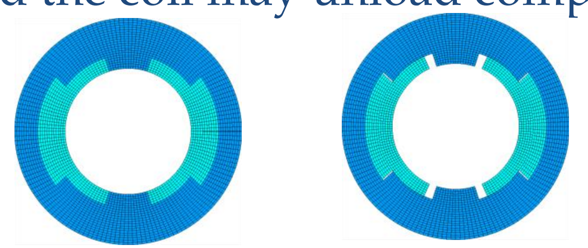


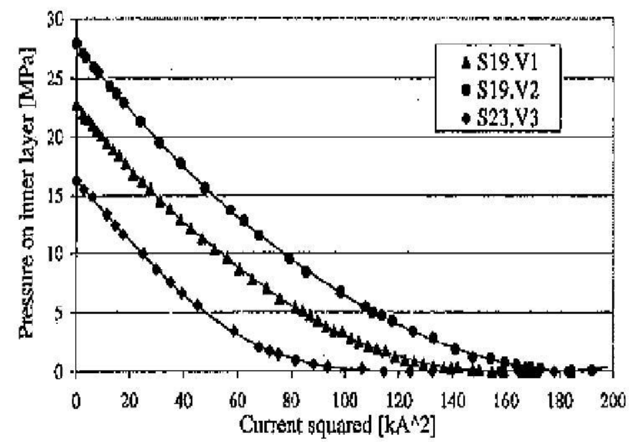
- **During cool-down**
  - Components shrink differently
    - Again, coil positioning within 20-50 μm
  - Significant **variations of coil stress**





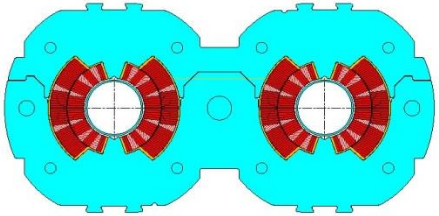
- **During excitation**
  - The pole region of the coil unloads
    - Depending on the pre-stress, at nominal field the coil may unload completely



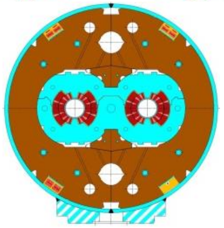


Mechanics of superconducting magnets
Overview of coil stress

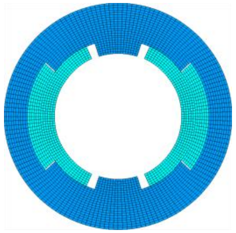
- **Collaring**



- **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).

Outline

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

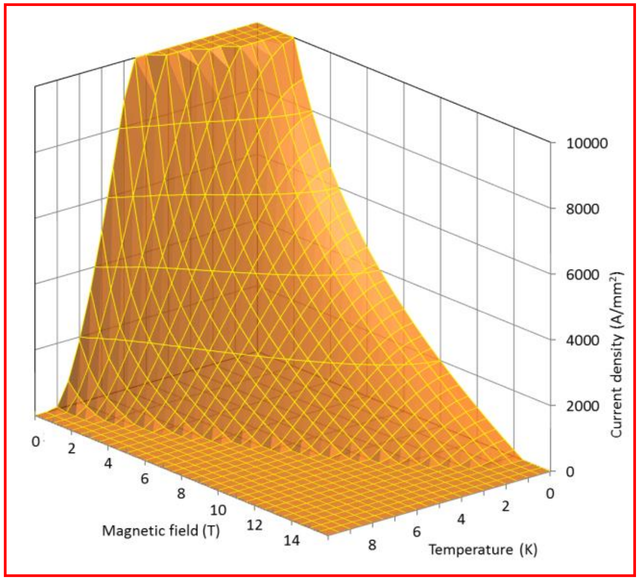
References

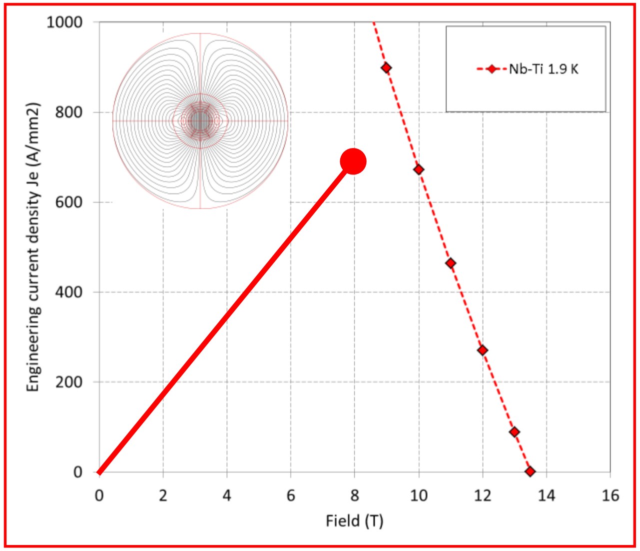
- **Quench and protection**

- 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.

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* ?

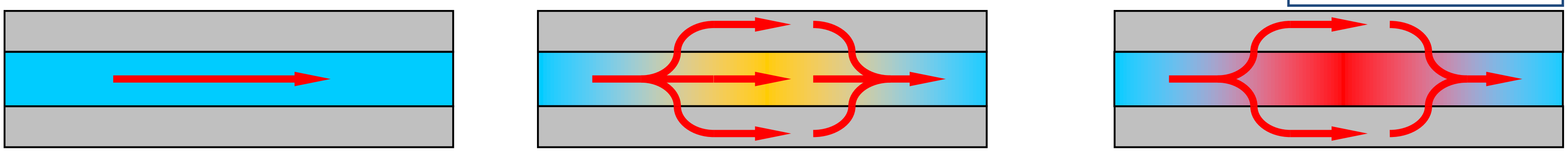




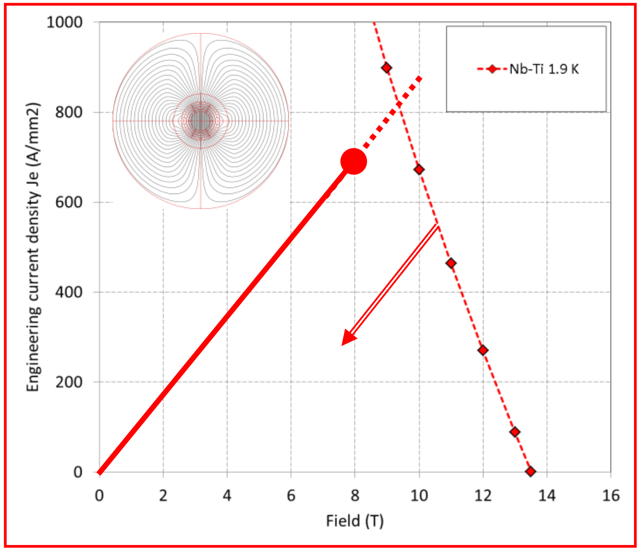
Quench and protection
Quench

- 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

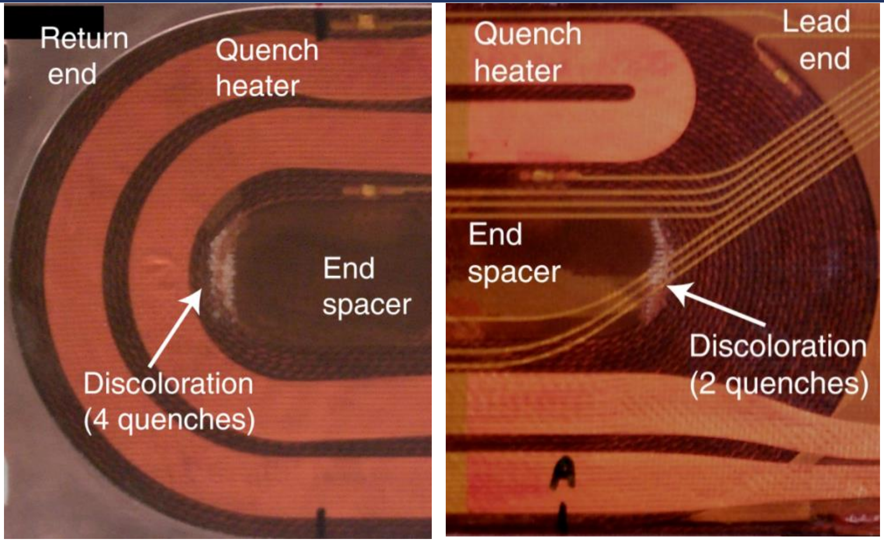


- …but…sometimes
  - Disturbance → release of energy → increases the temperature of the conductor
    - ***energy-deposited*** or ***premature quenches***
- Which are these **disturbances**?



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

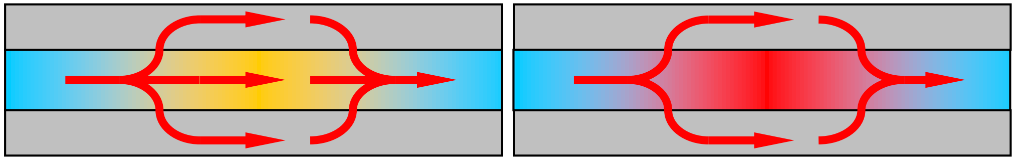


$$C\frac{\partial T}{\partial t} = q'''_{ext} + q'''_{J} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{wh}{A}\left(T - T_{he}\right)$$

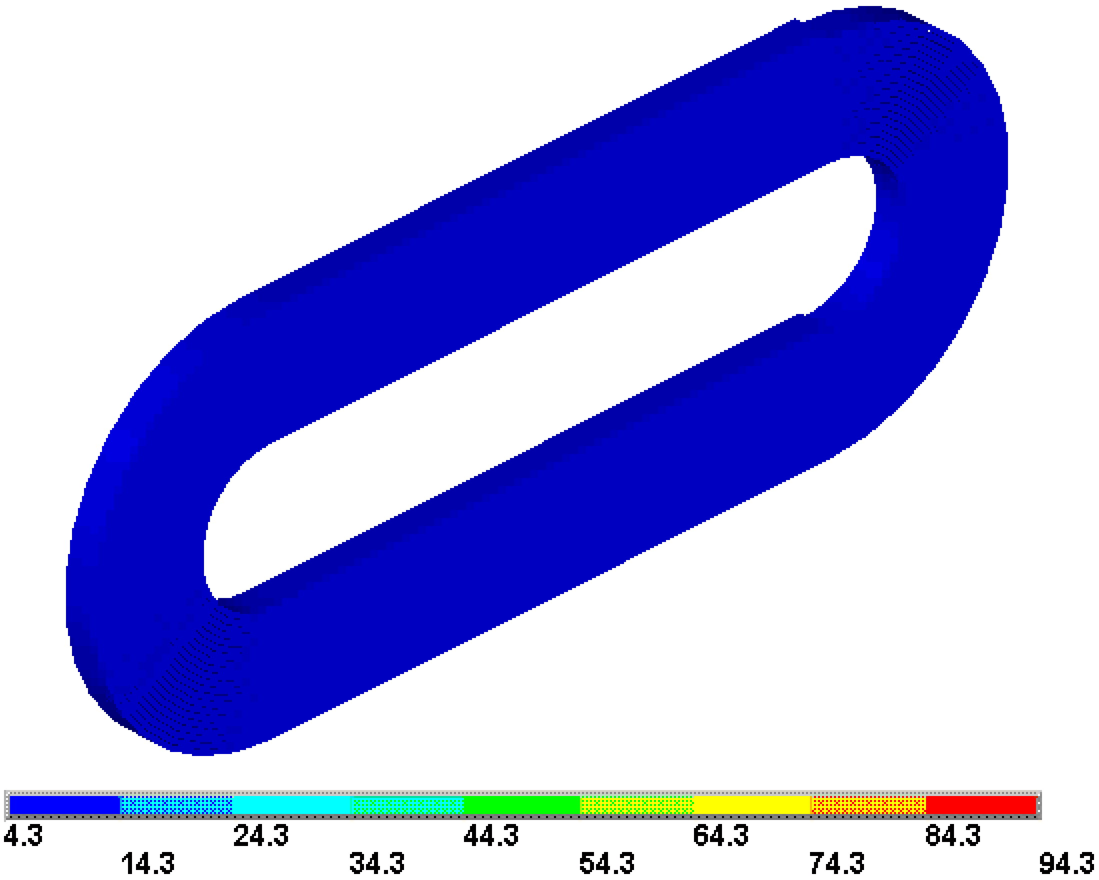
Heat capacity; Heat source; Joule heat (generation); Conduction; Heat transfer (cooling)

by L. Bottura

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



Quench and protection
Propagation



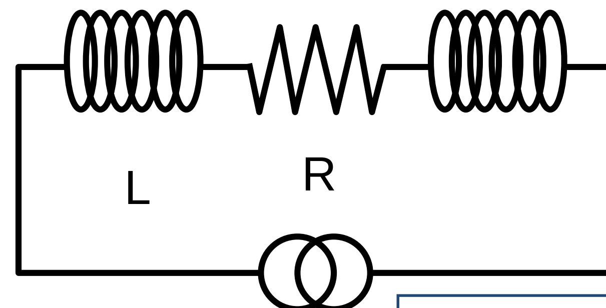
Quench and protection

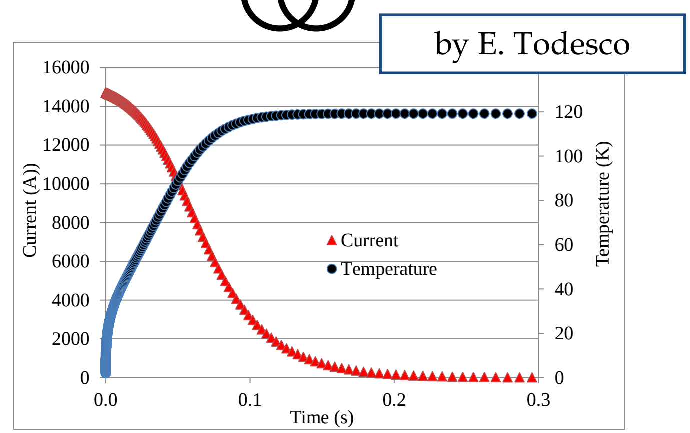
- Quench → dangerous situation
  - Nb-Ti vs. Cu
    - $\rho = 6.5 \times 10^{-7}$ vs. 3×10^{-10} [Ω m]
    - $k = 0.1$ vs. 350 [W m^{-1} K^{-1}]
  - A purely superconductor wire would be impossible to protect
- With Cu a much better
  - Still, we need to **dump the current** rapidly (in ~0.1-0.5 s)
- 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

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

Heat capacity; Heat source; Joule heat; Conduction; cooling; Heat transfer; generation

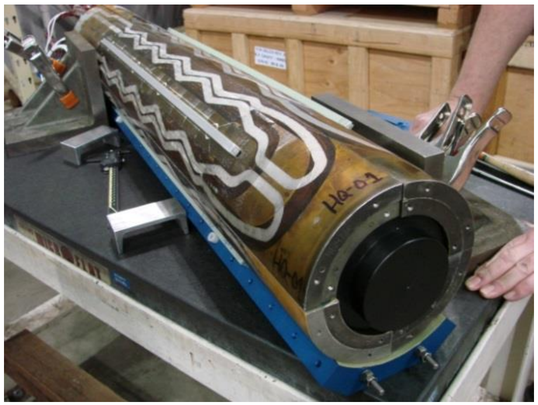
$$\rho(T)[j(t)]^2 dt$$

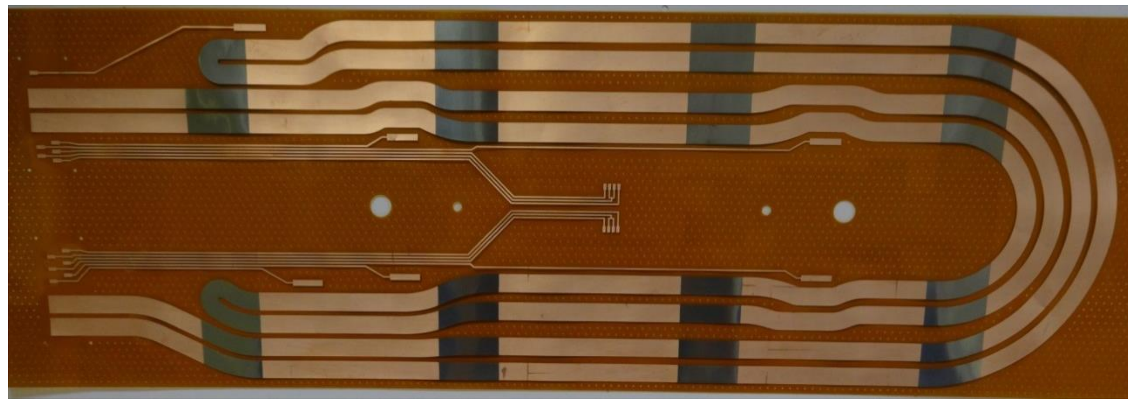




Quench and protection

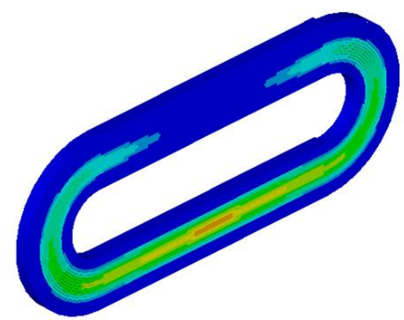
- We should make it quench everywhere
  - **Quench heaters**: strips of stainless steel close to the coil





- 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 Republic of Germany

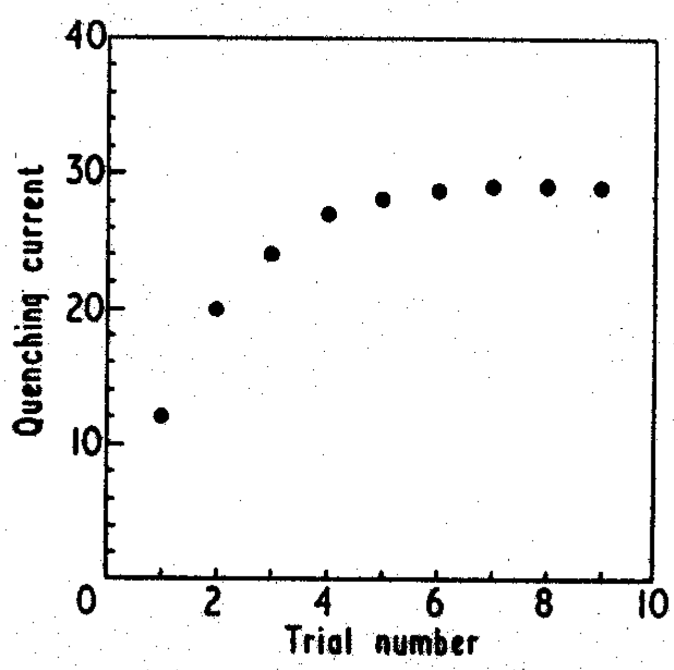
I. INTRODUCTION

In the early 70's interest was centred upon a new phenomenon observed at CERN in two race track shaped epoxy impregnated coils[1]. 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.

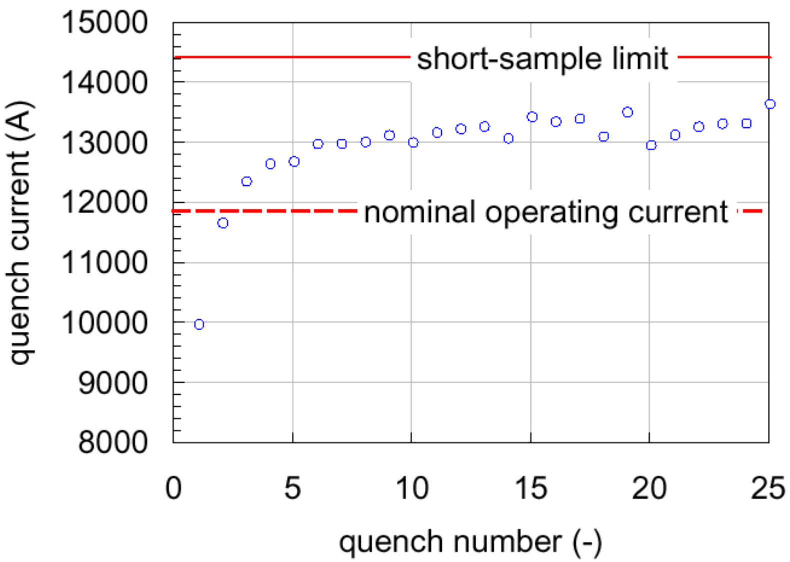
NbZr solenoid
Chester, 1967

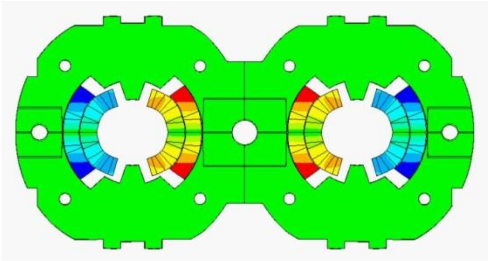


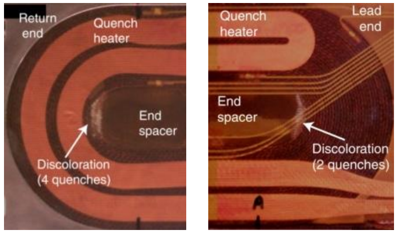
P.F. Chester, Rep. Prog. Phys., **XXX**, II, 561, 1967.

Quench and protection
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



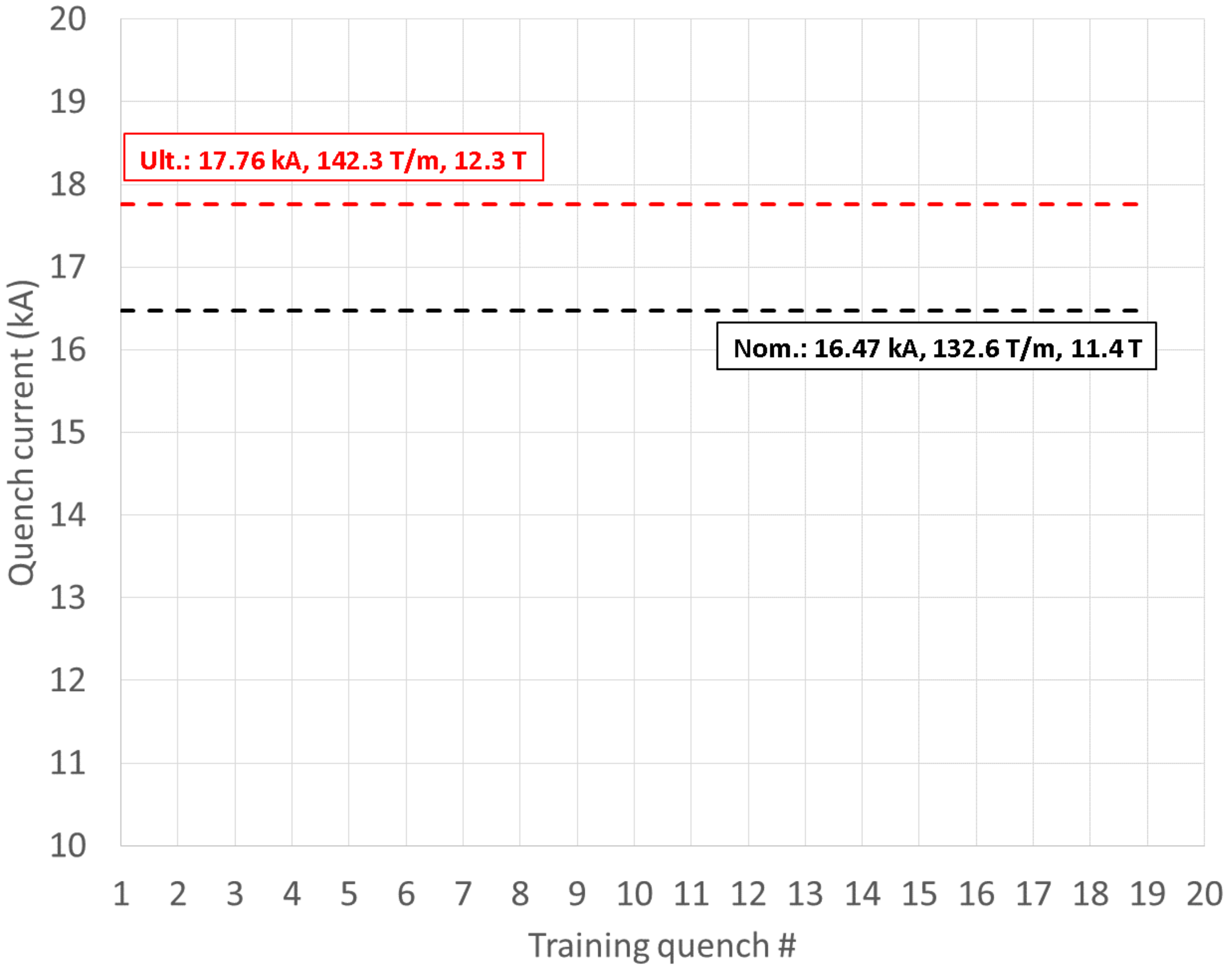




MQXFS01 test
First test of HiLumi Nb_3Sn IR quadrupole

- Test at FNAL in 2016

MQXFS01 test
First test of HiLumi Nb_3Sn IR quadrupole



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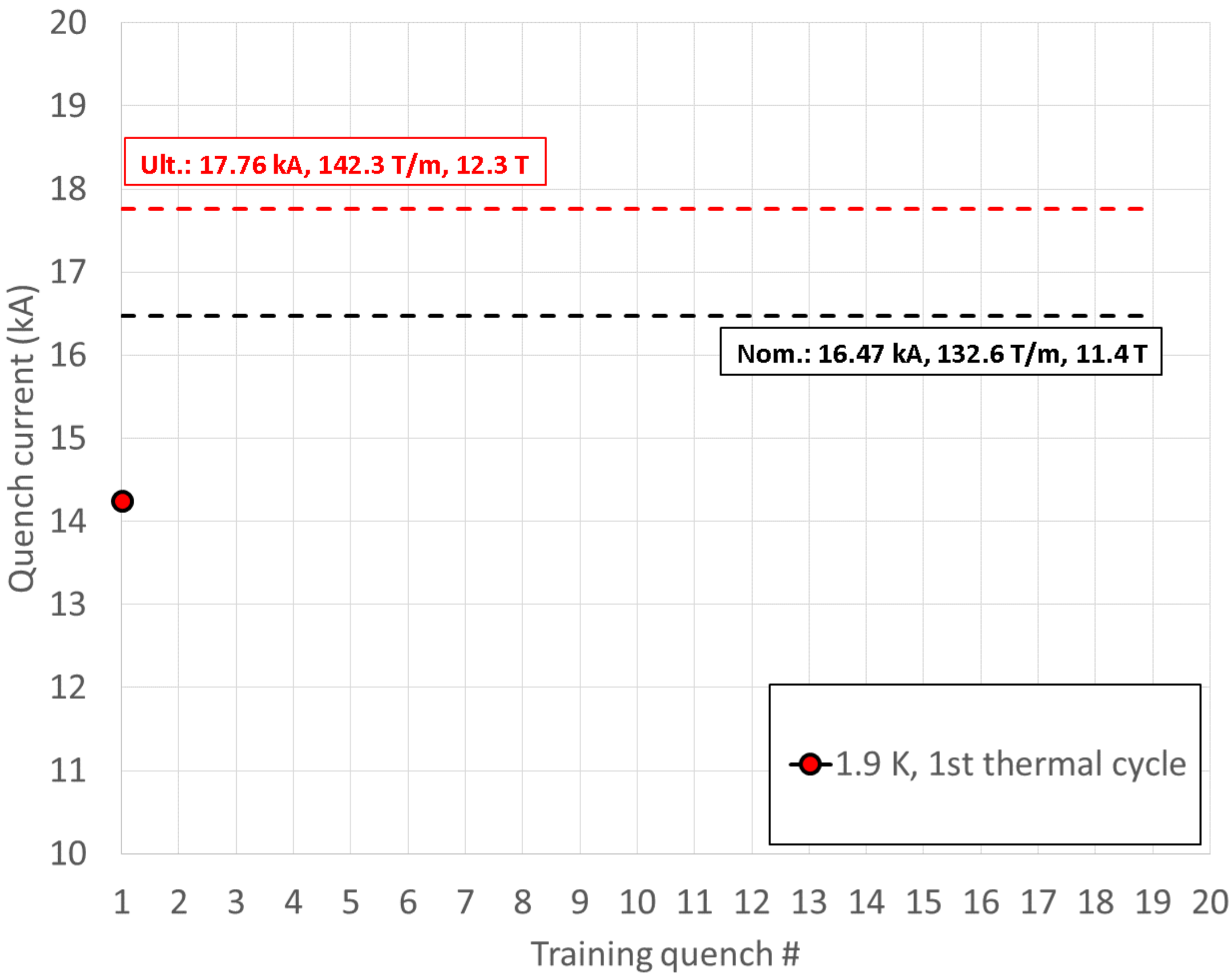

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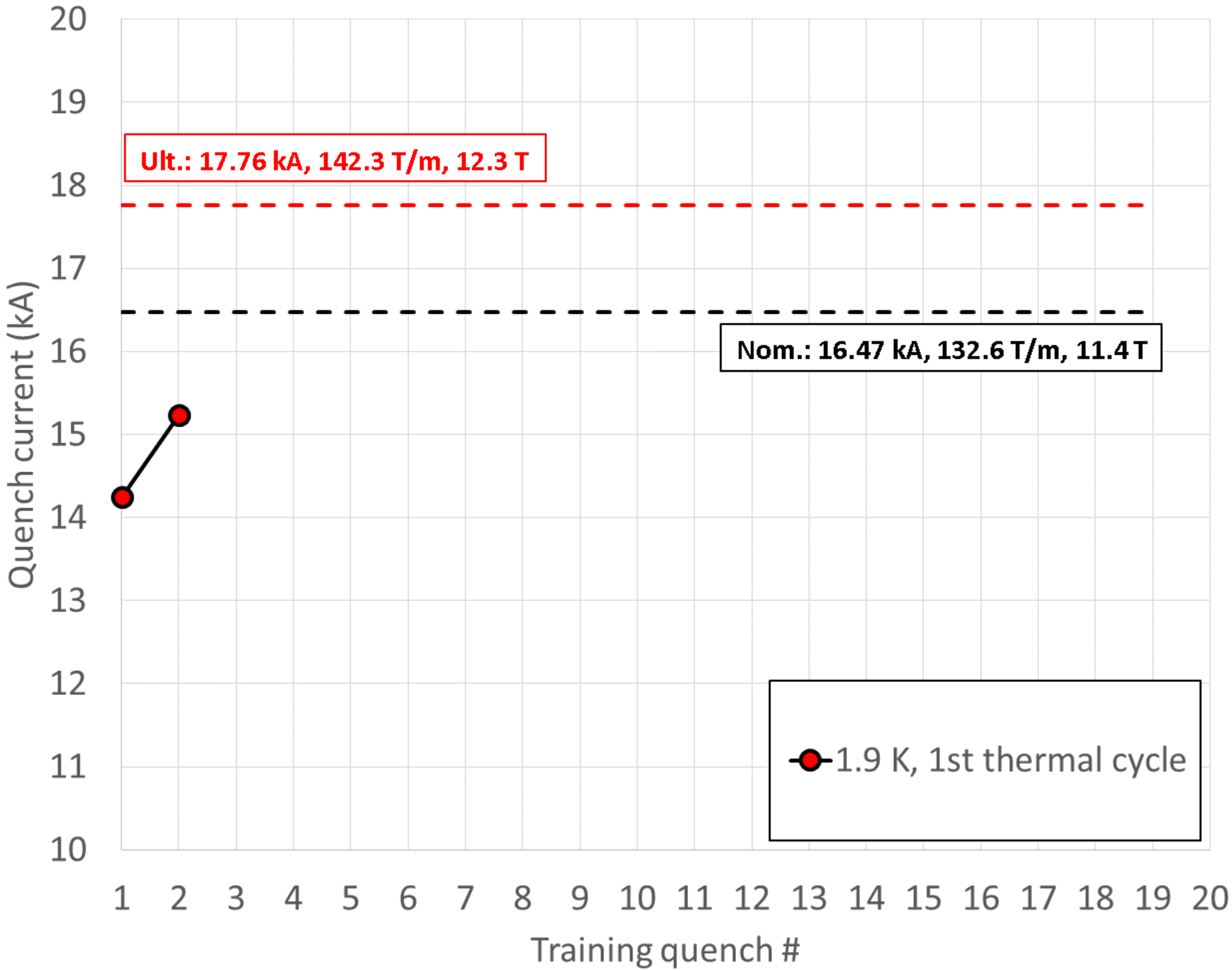

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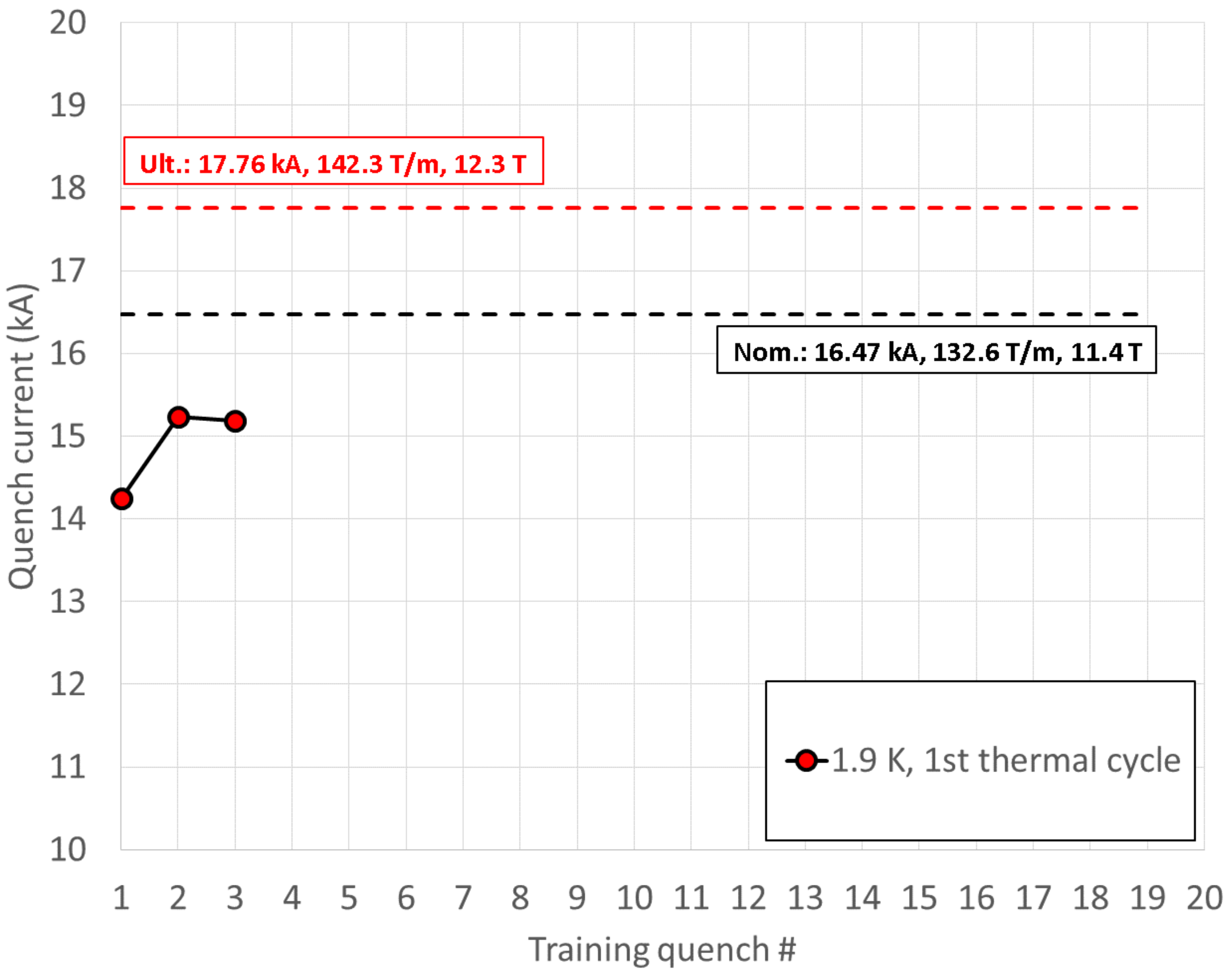

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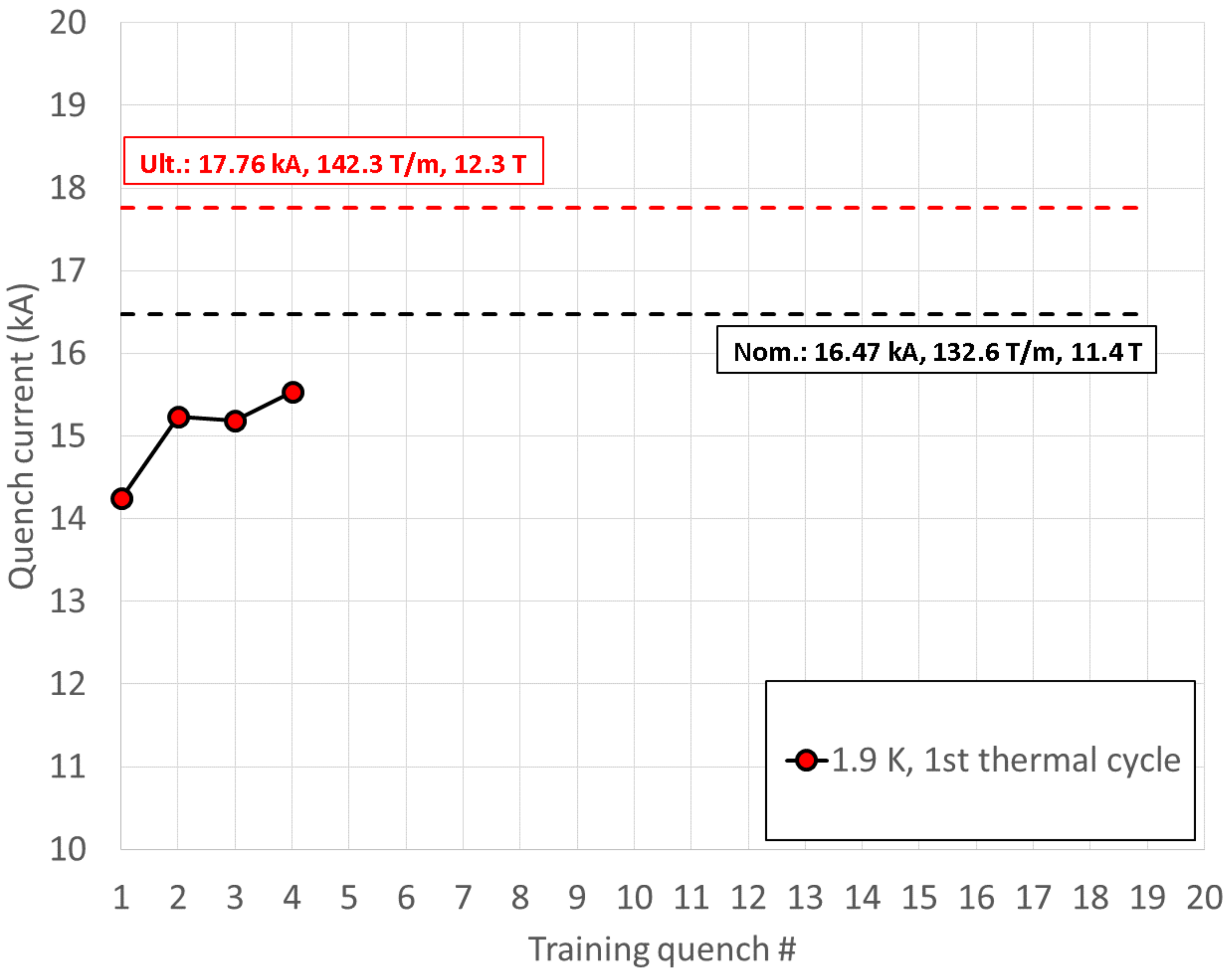

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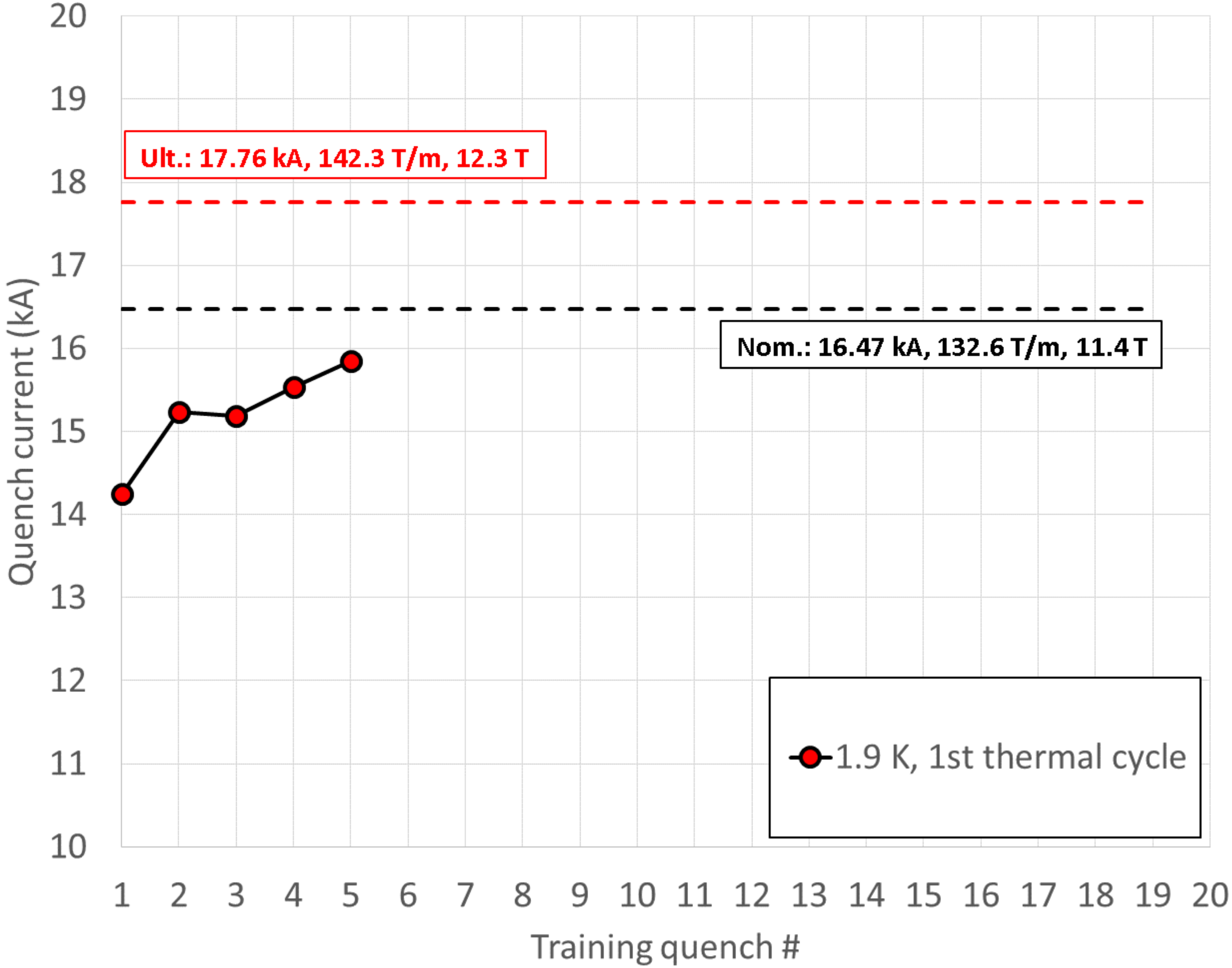

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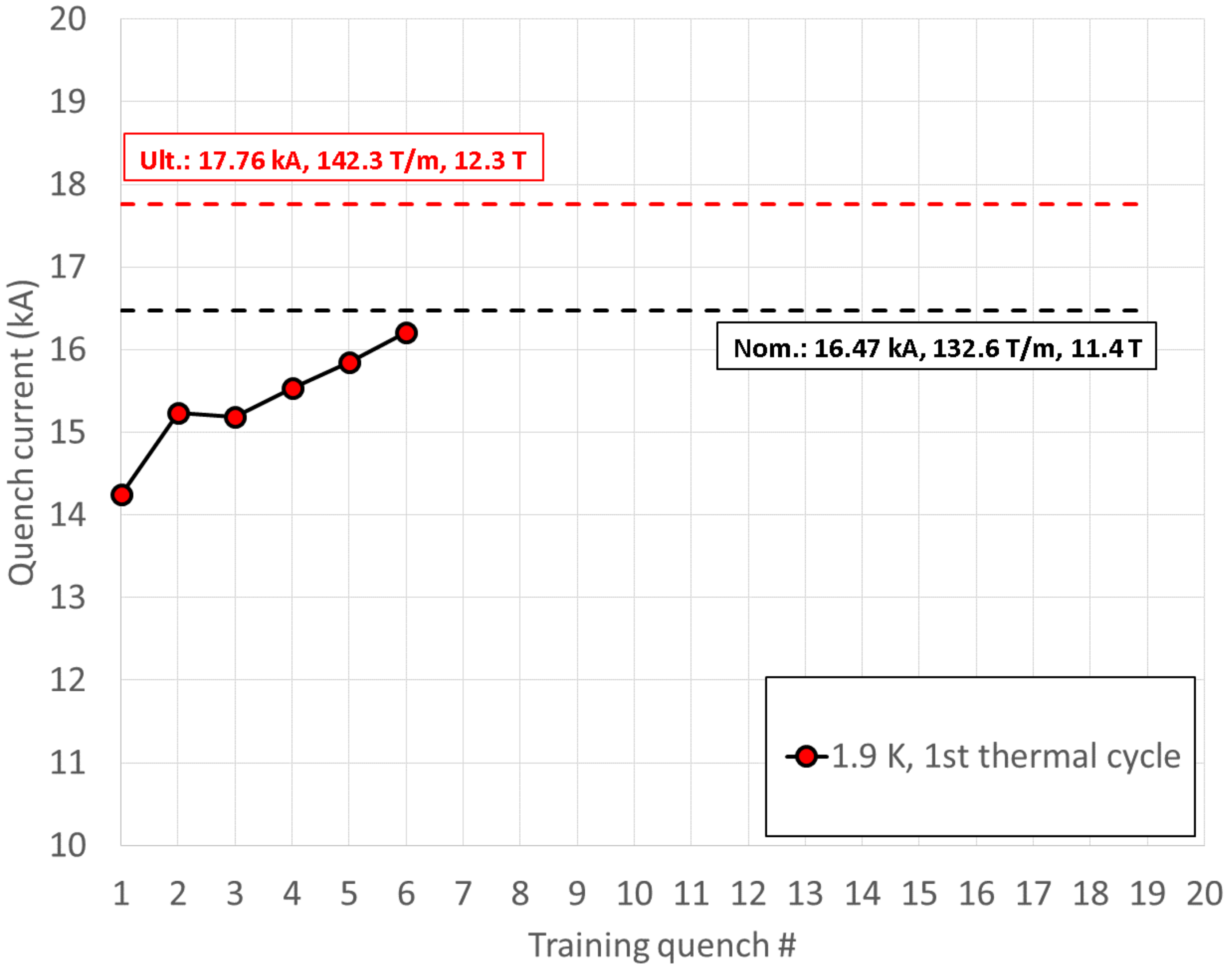

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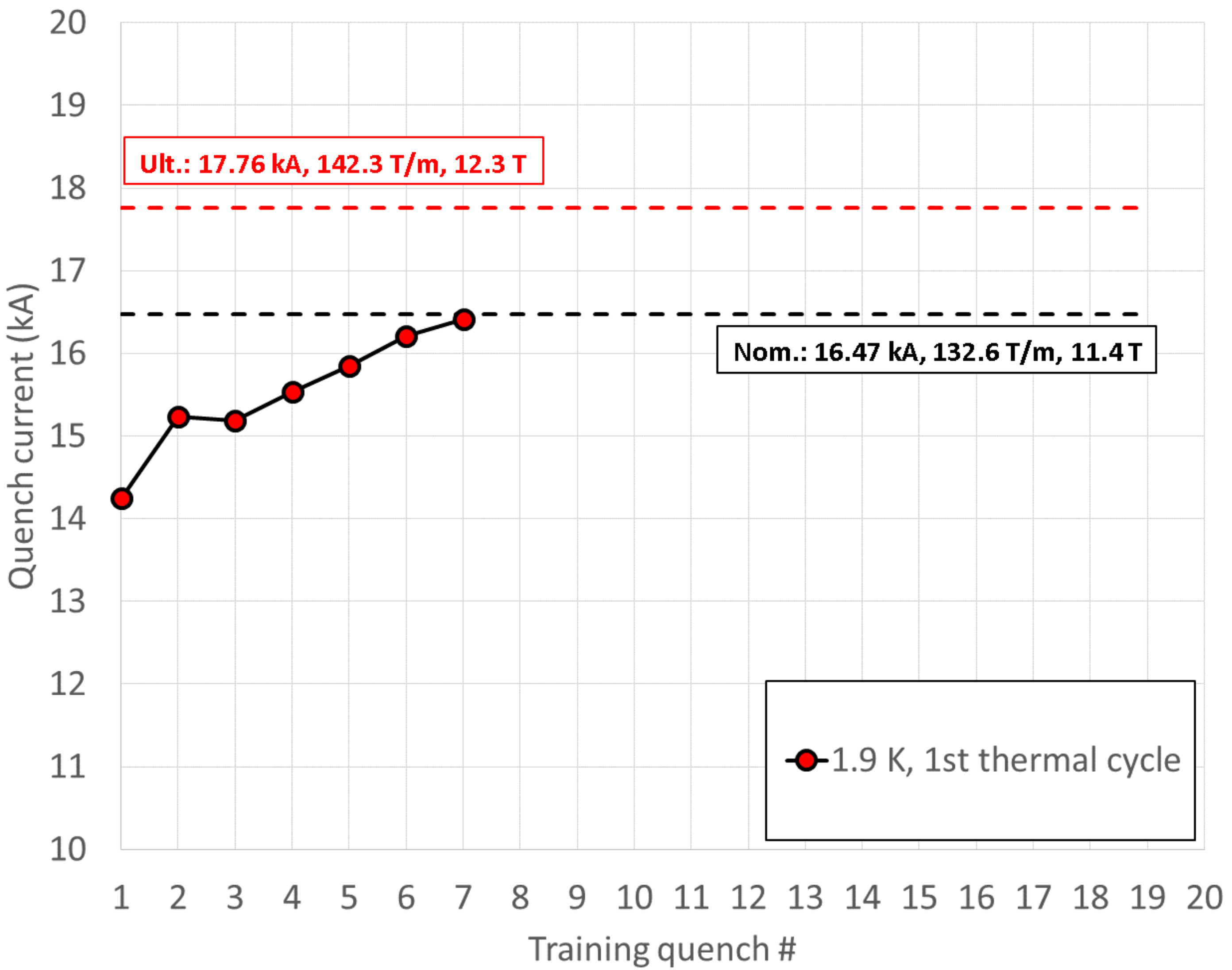

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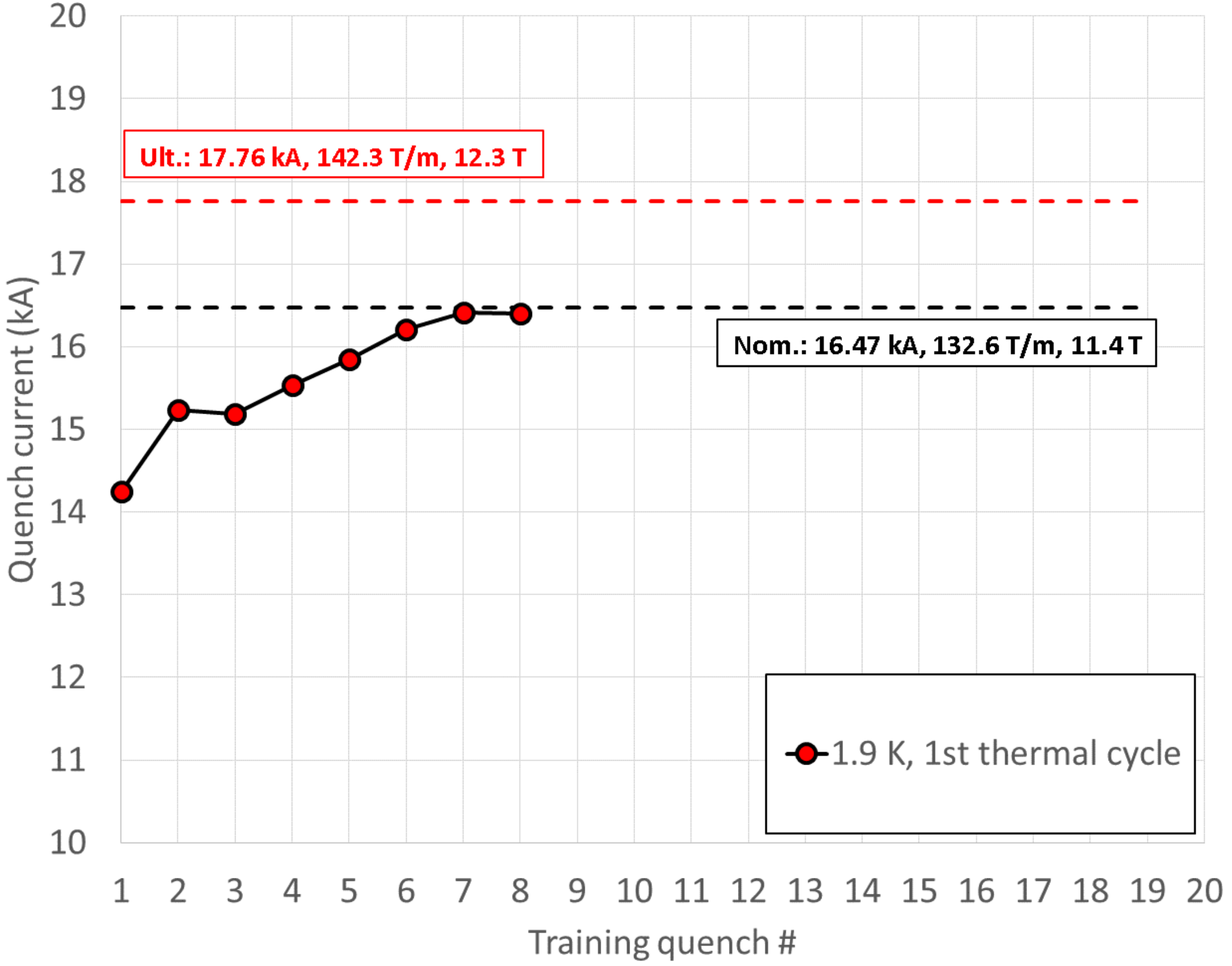

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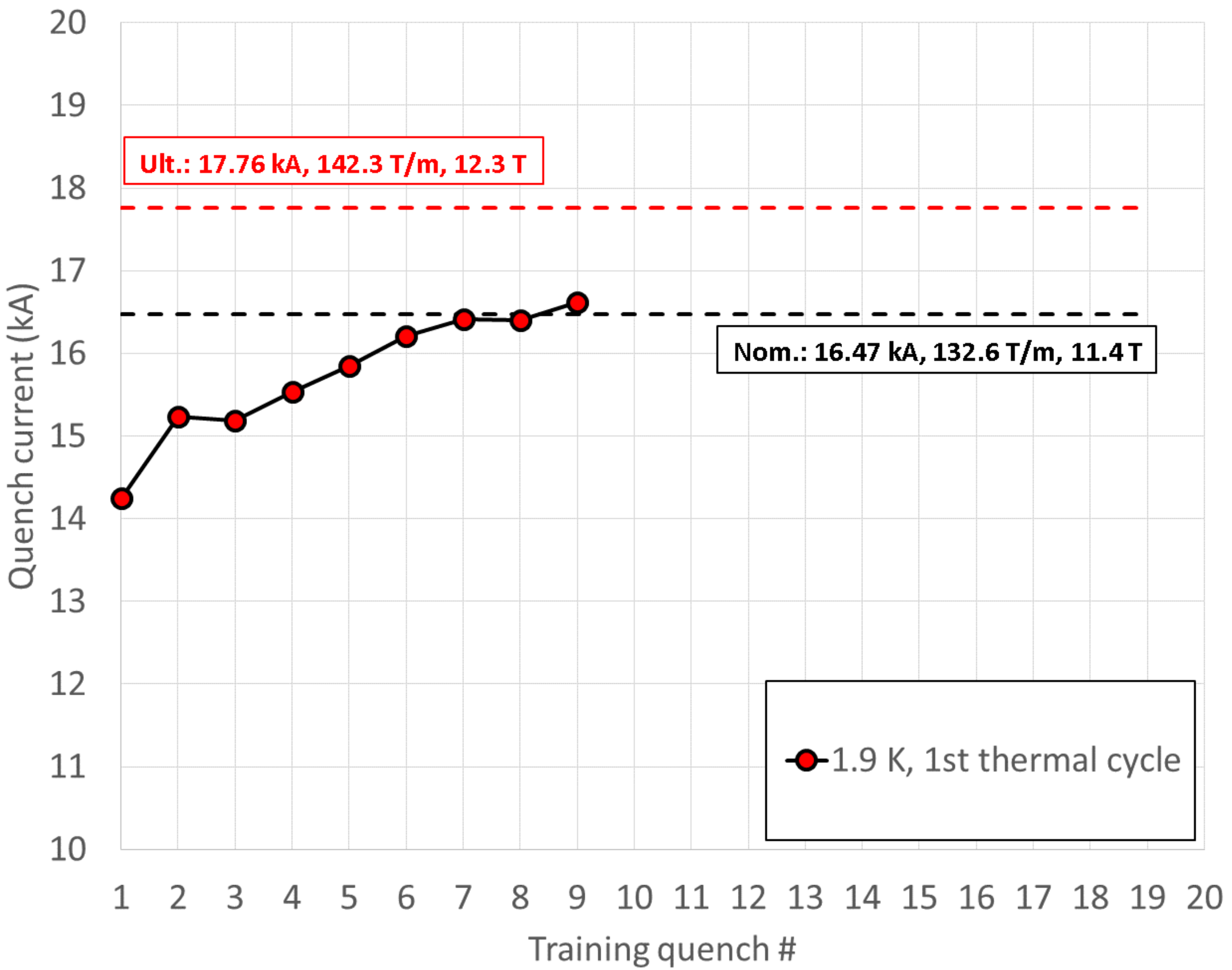

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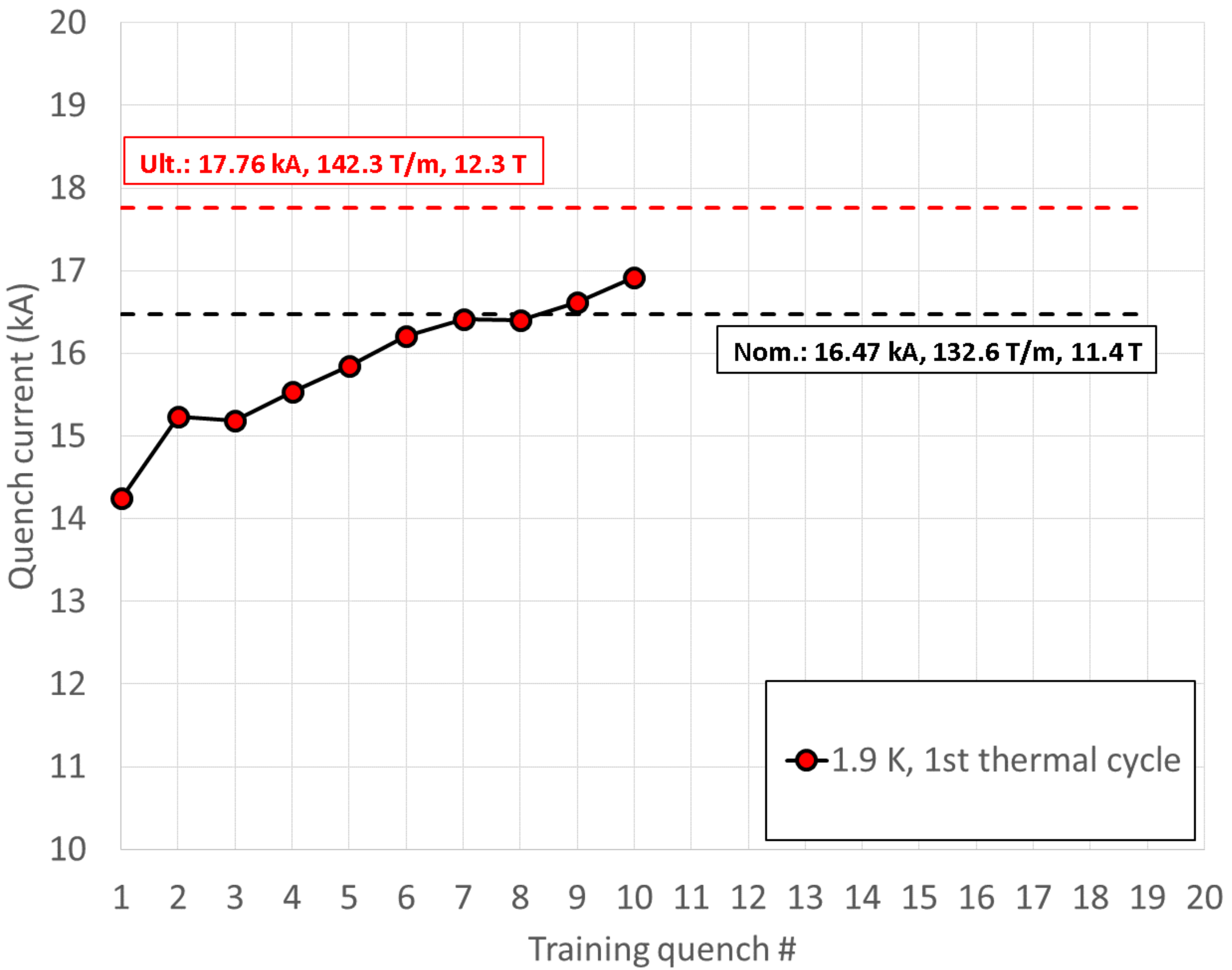

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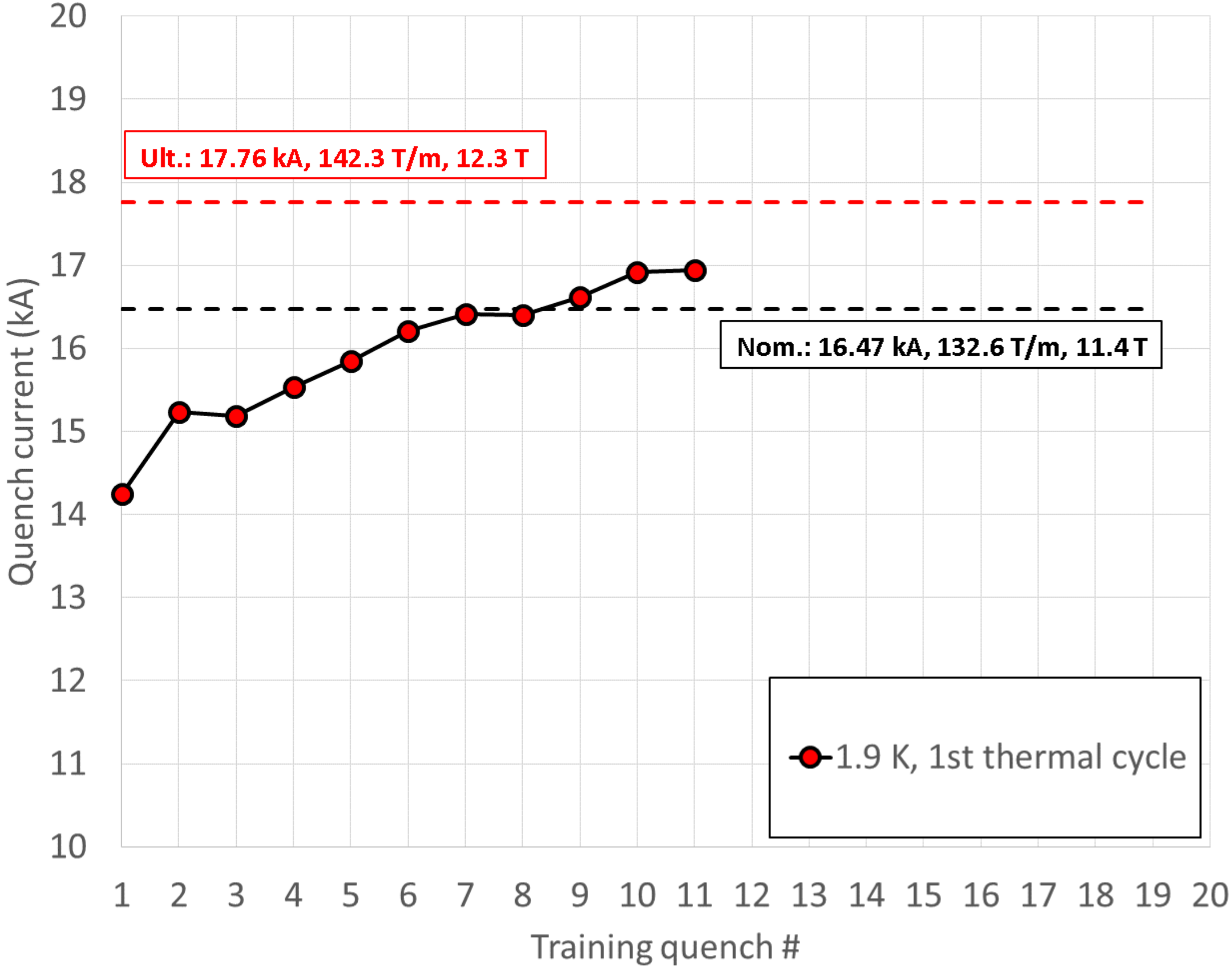

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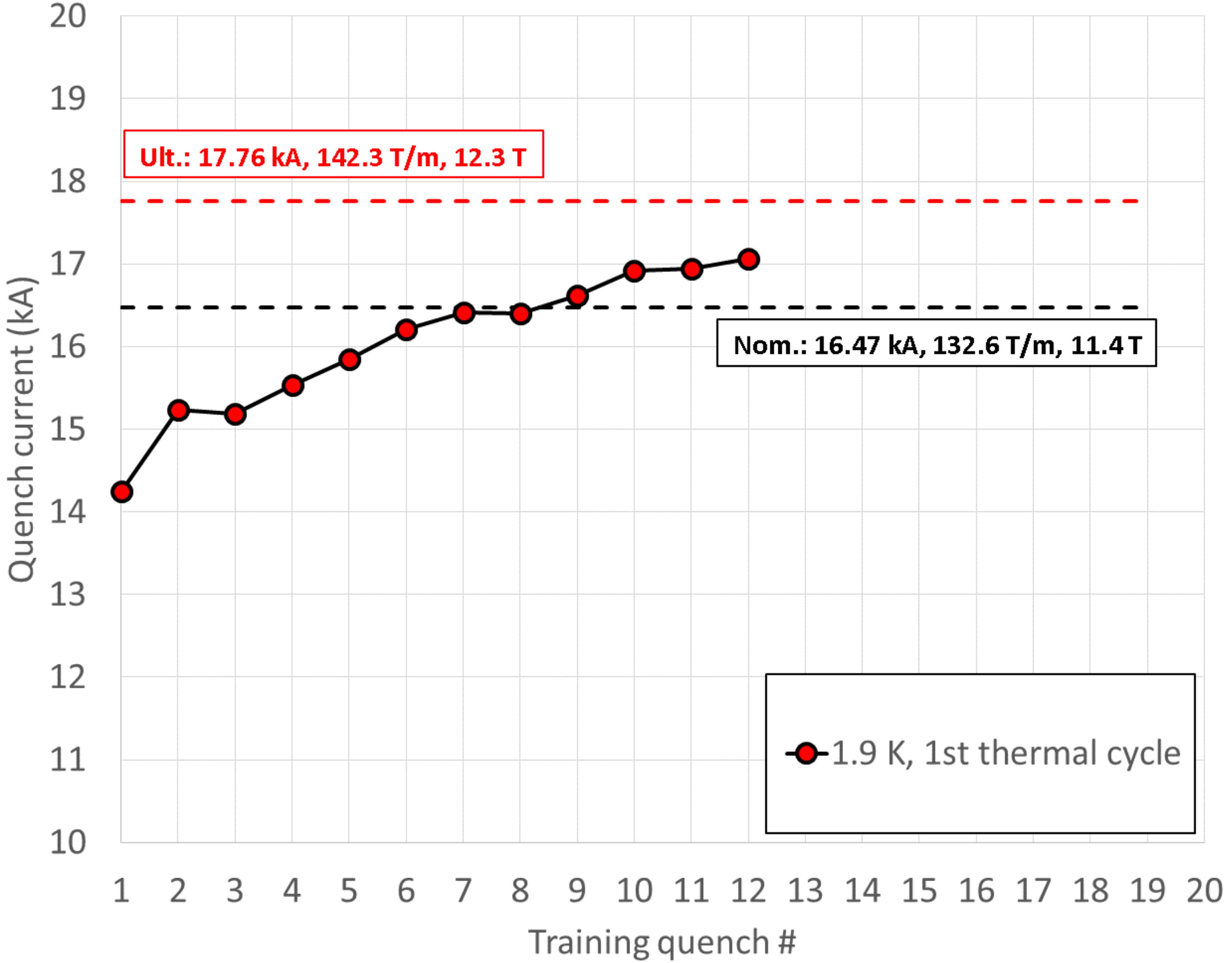

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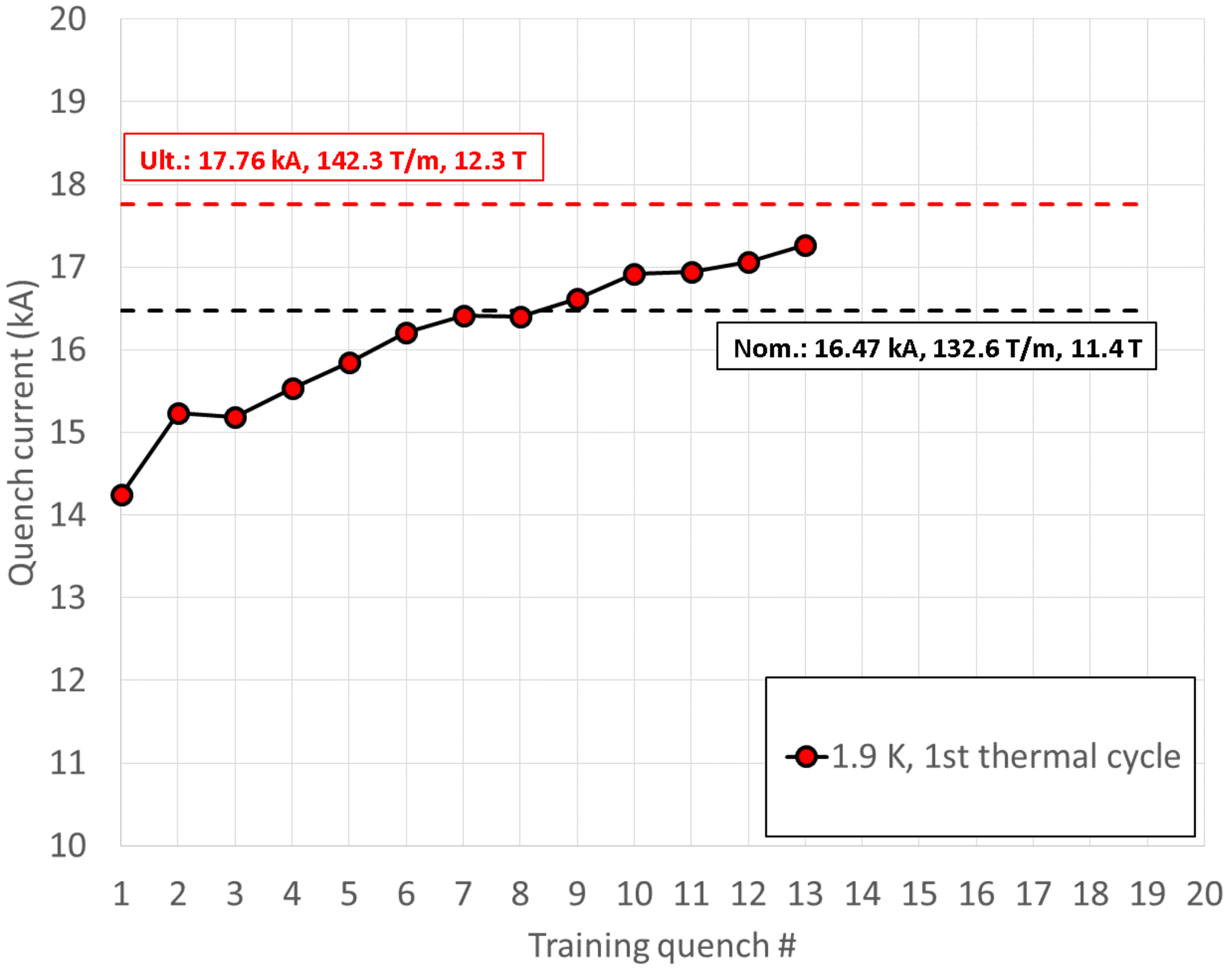

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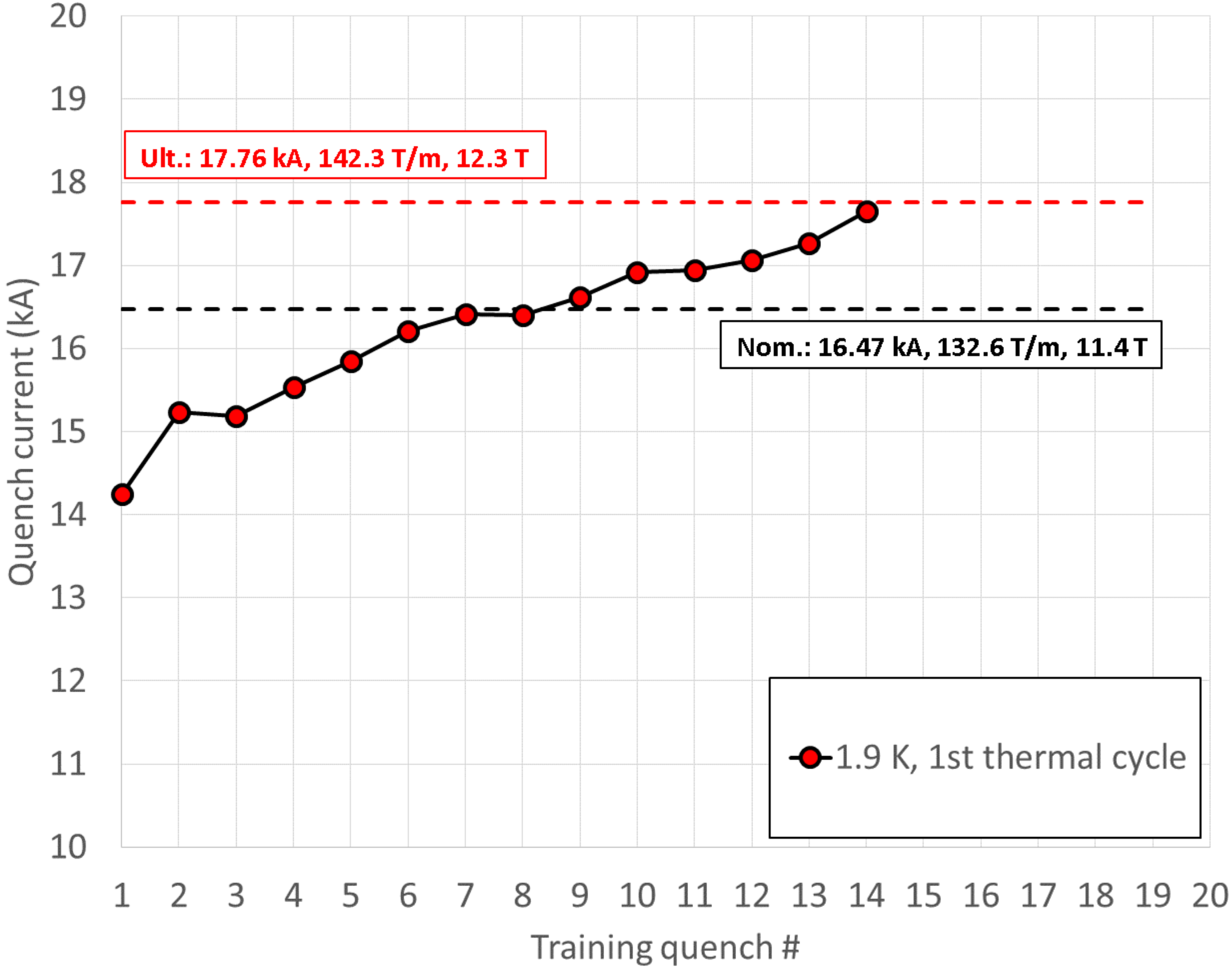

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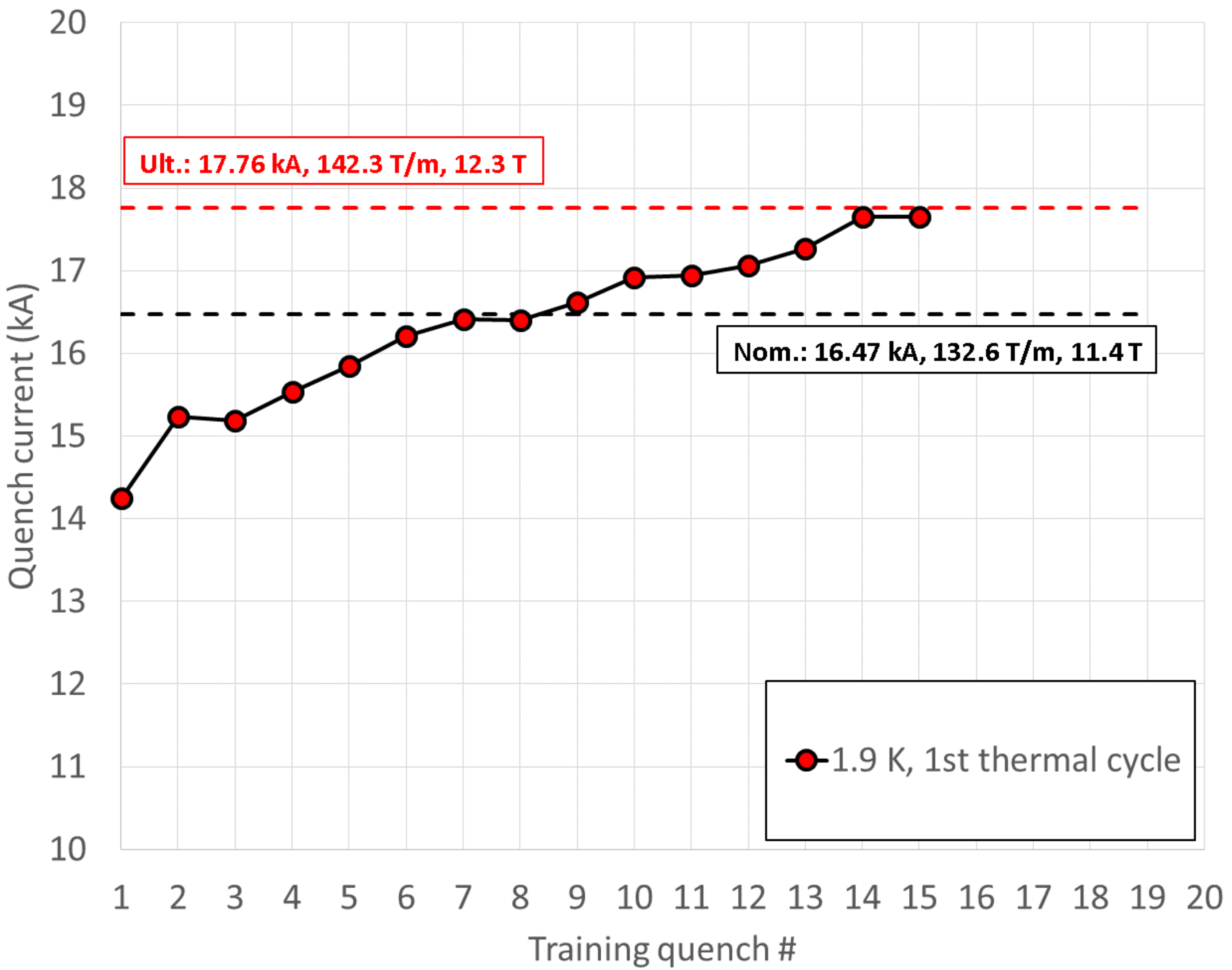

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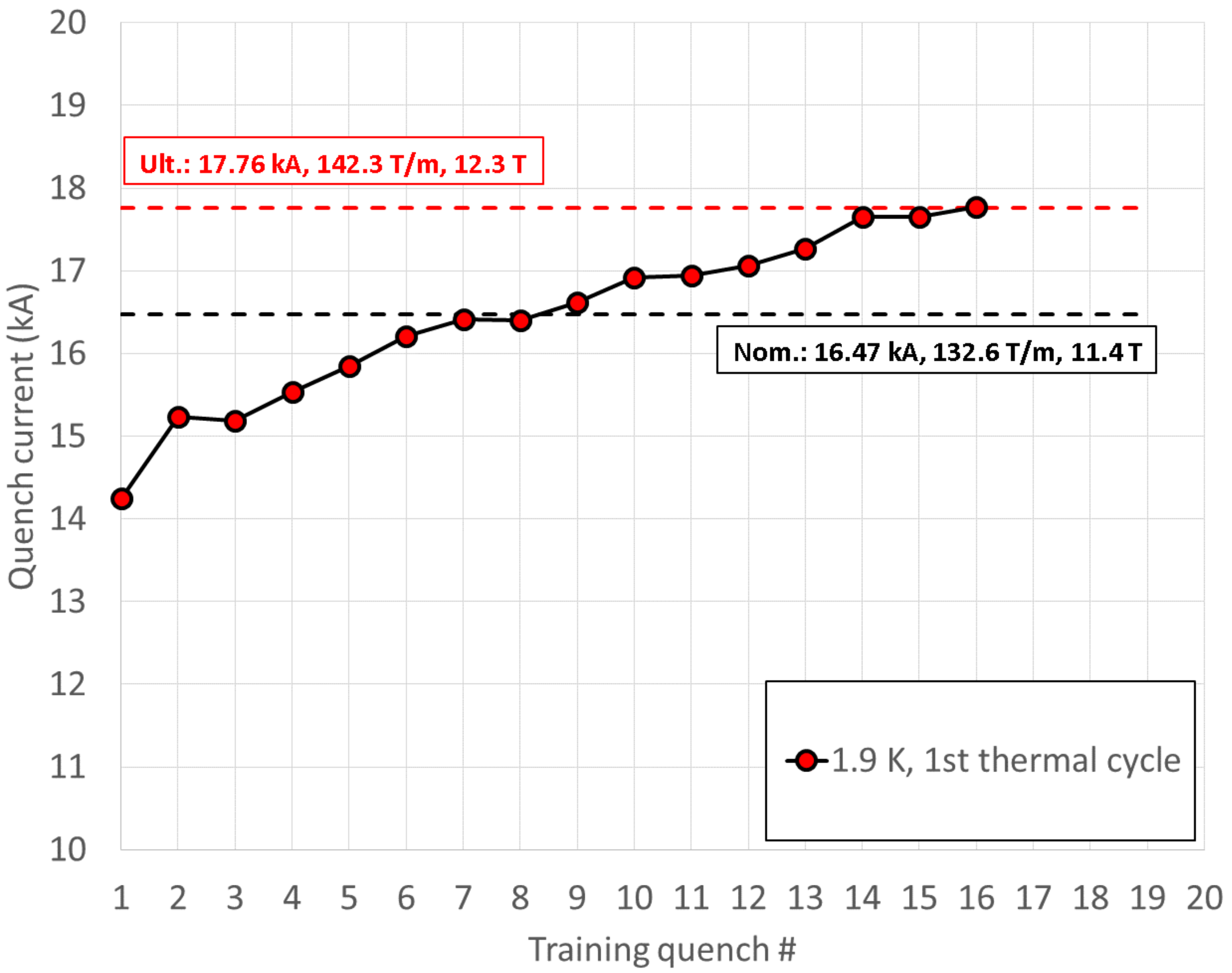

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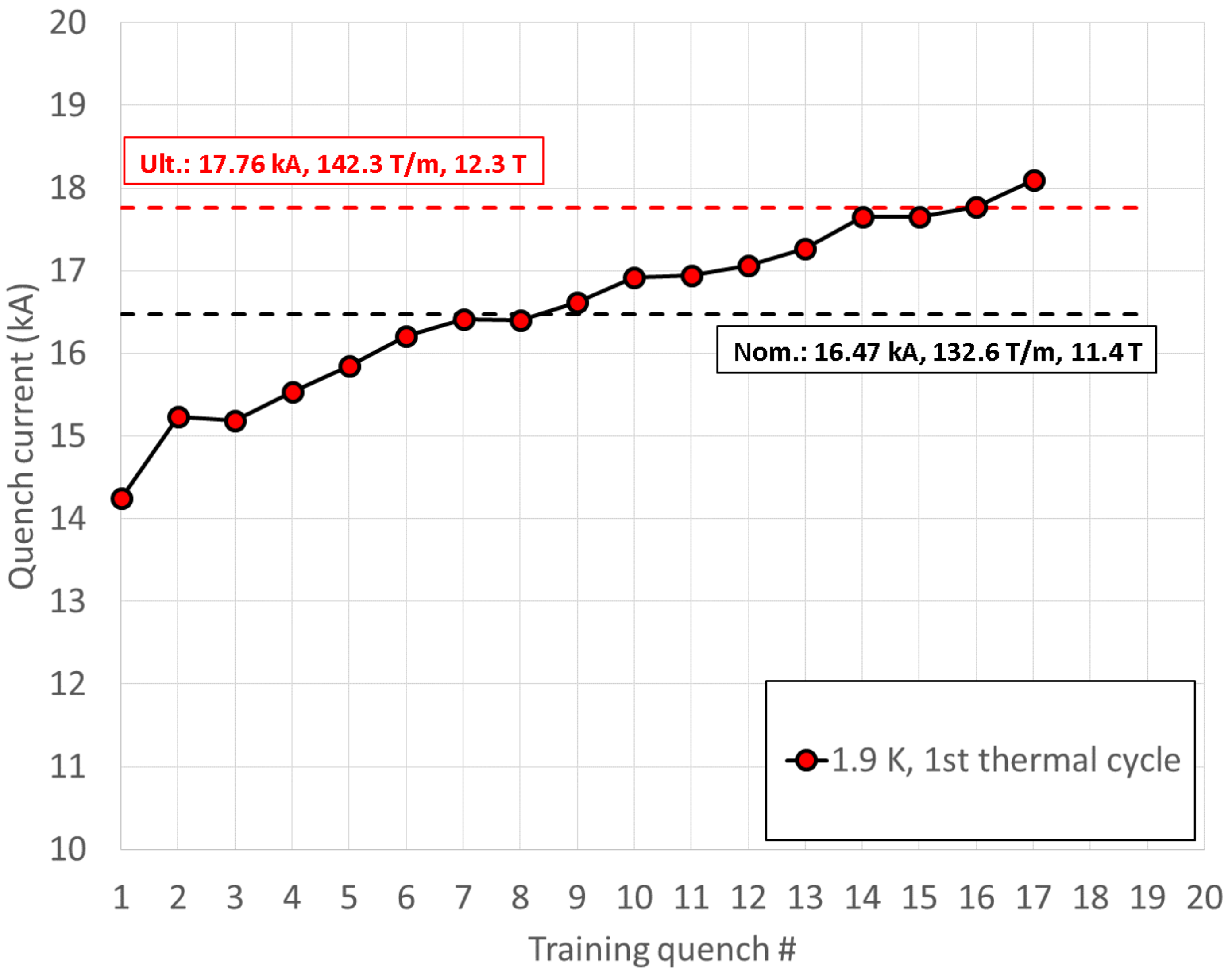

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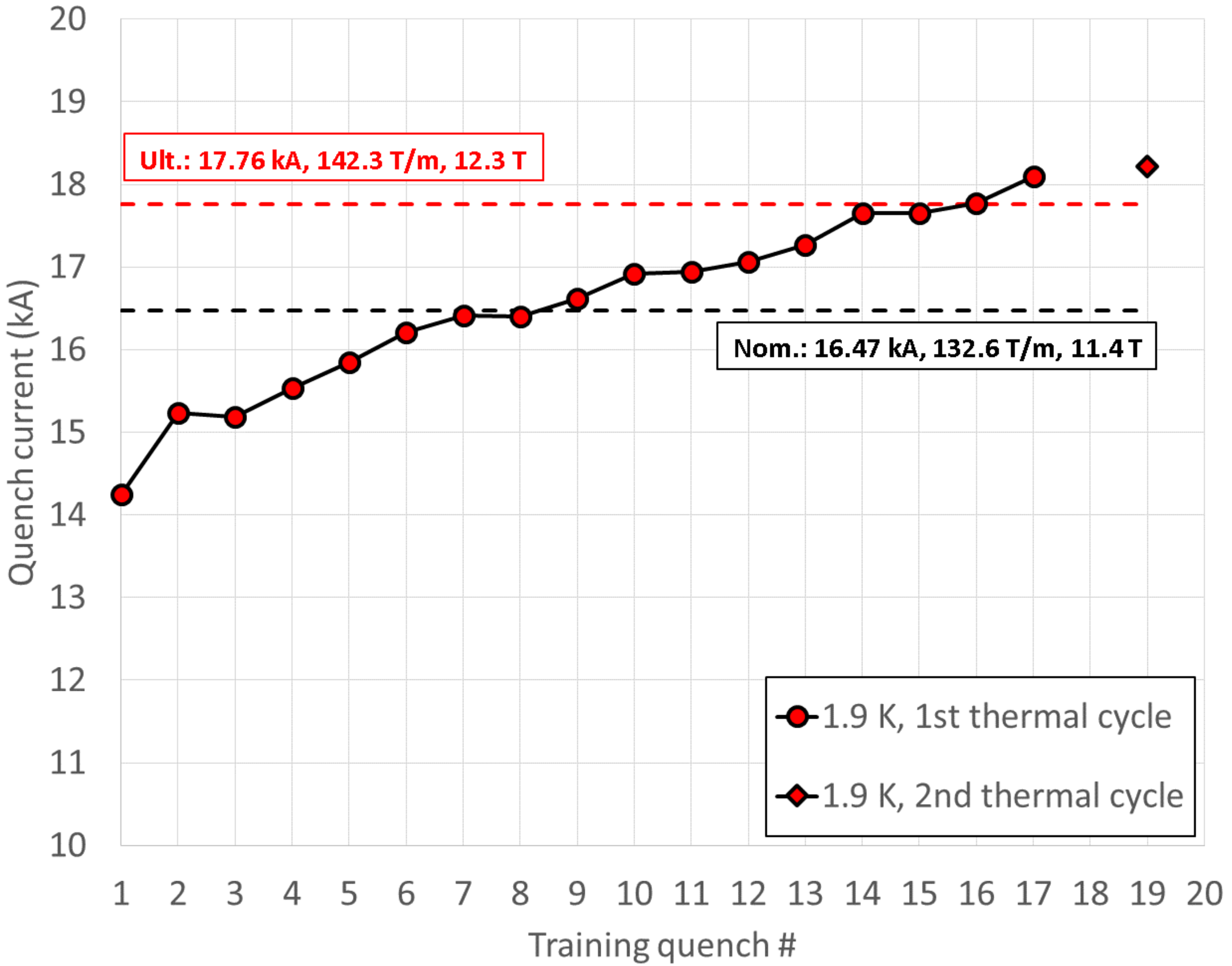
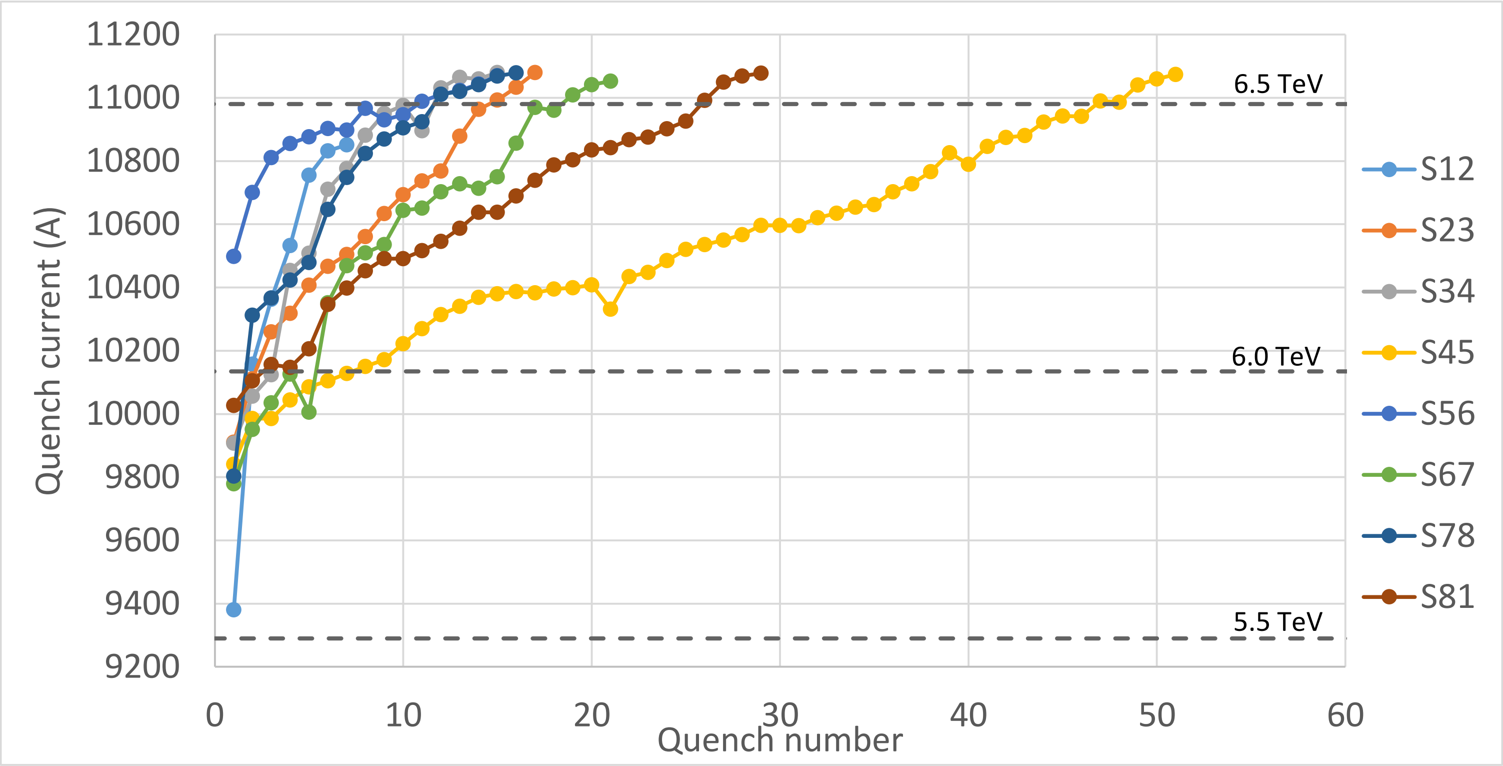


Quench and protection
Training of LHC sectors to 6.5 TeV

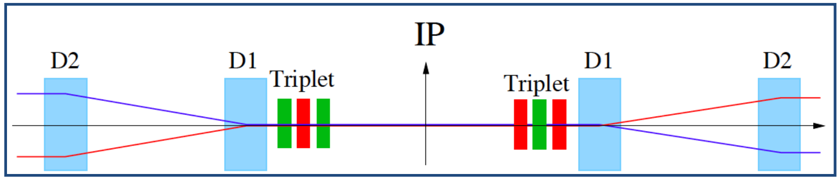


Outline

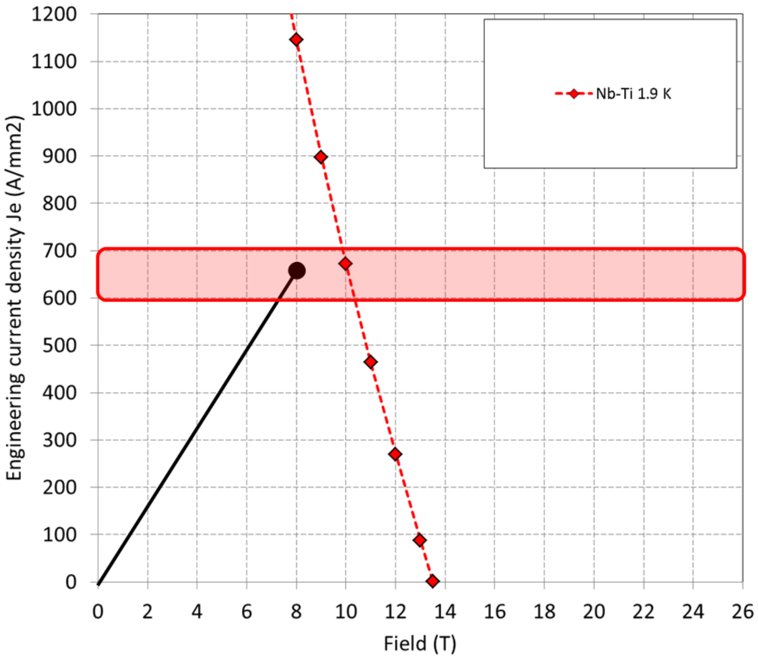
- **Particle accelerators and superconductors**
- **Magnetic design and coils**
- **Mechanics of superconducting magnets**
- **Quench and protection**
- **HiLumi LHC and FCC**

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

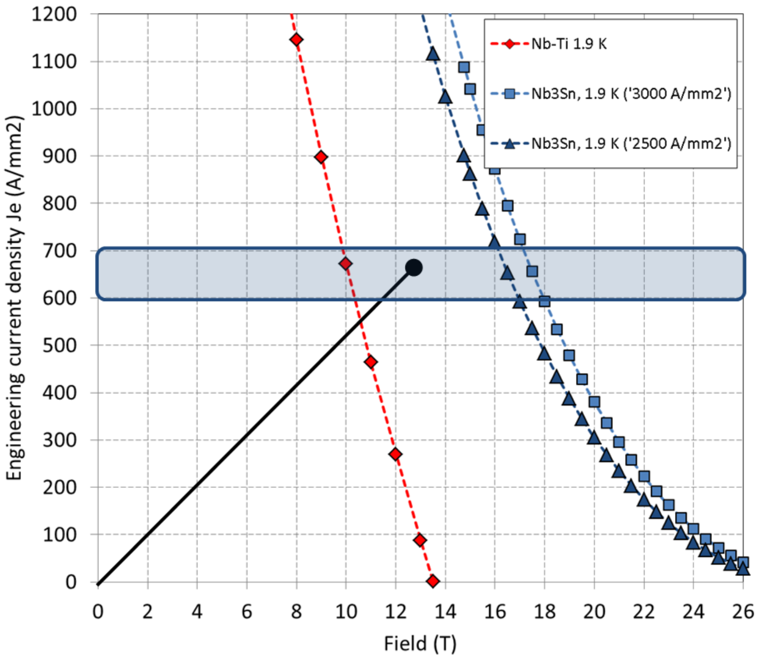
- From **LHC** to **HiLumi LHC**
  - Integrated *L*: ~300 → 3000 fb^{-1}
  - Start in 2025-2035
- Reduce beam size in IR by **factor 2**
- **Nb_3Sn** to be implemented for the first time in an accelerator



Nb-Ti



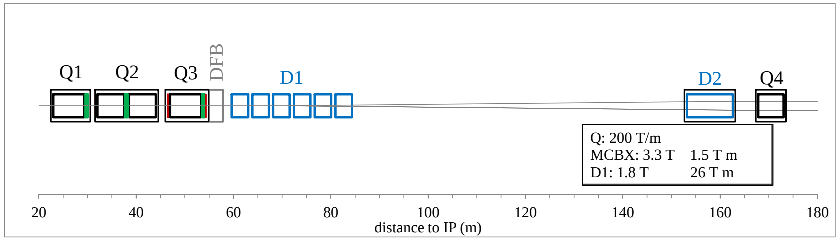
Nb_3Sn



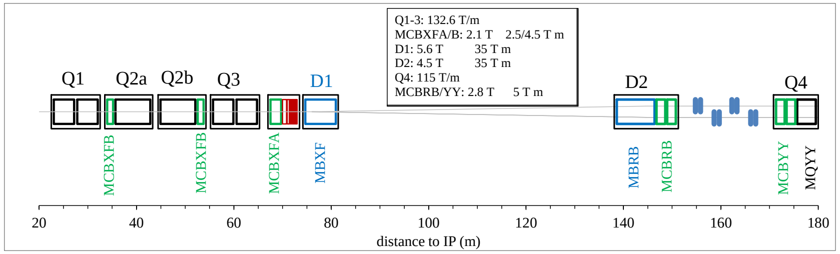
From 8-9 T to 12-13 T
HiLumi LHC

- **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)

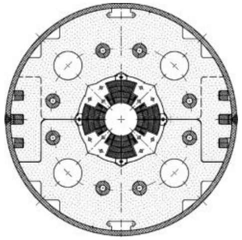
LHC



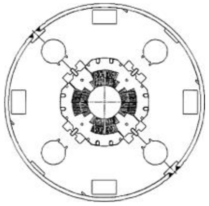
HiLumi LHC



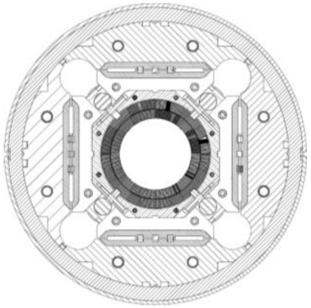
MQXFA



MQXFB

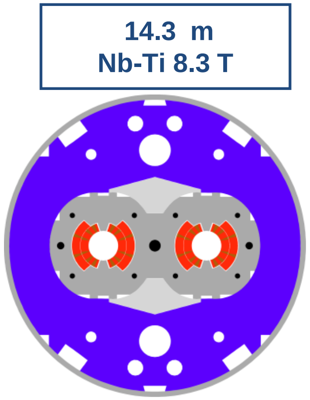


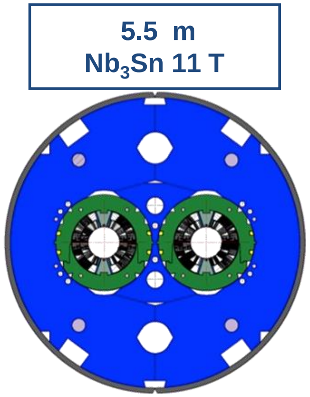
MQXF

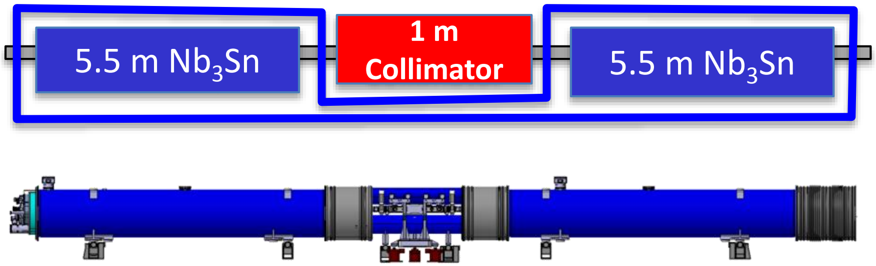


From 8-9 T to 12-13 T
HiLumi LHC

- **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)



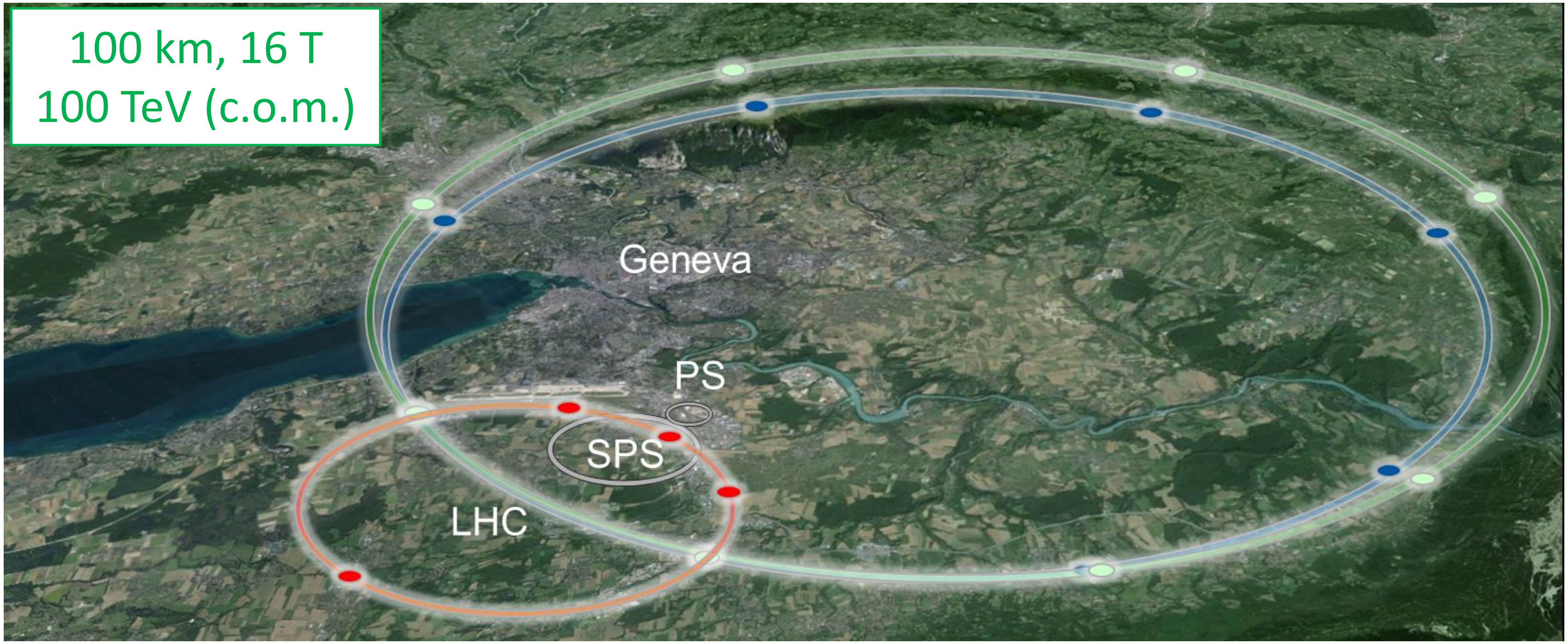




From 12-13 T to 15-16 T
FCC (100 km)

- **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

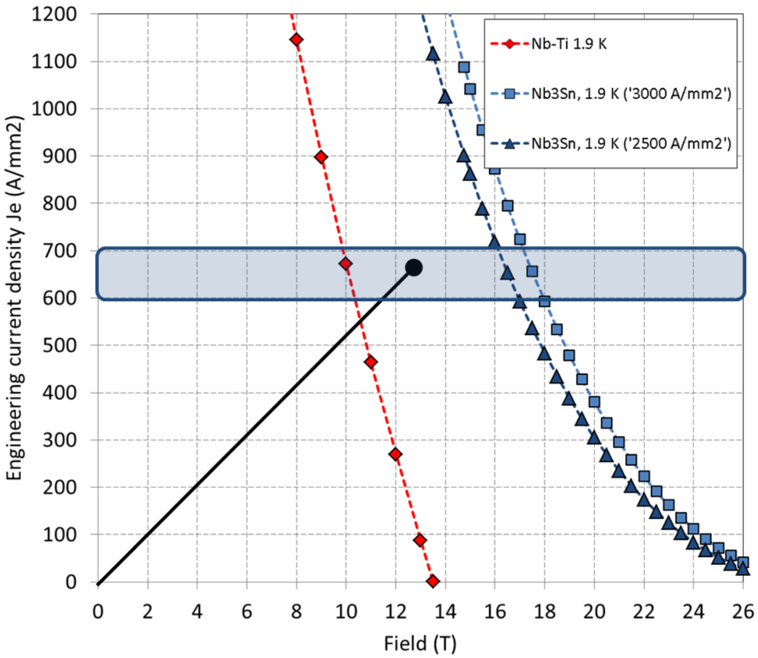
100 km, 16 T
100 TeV (c.o.m.)



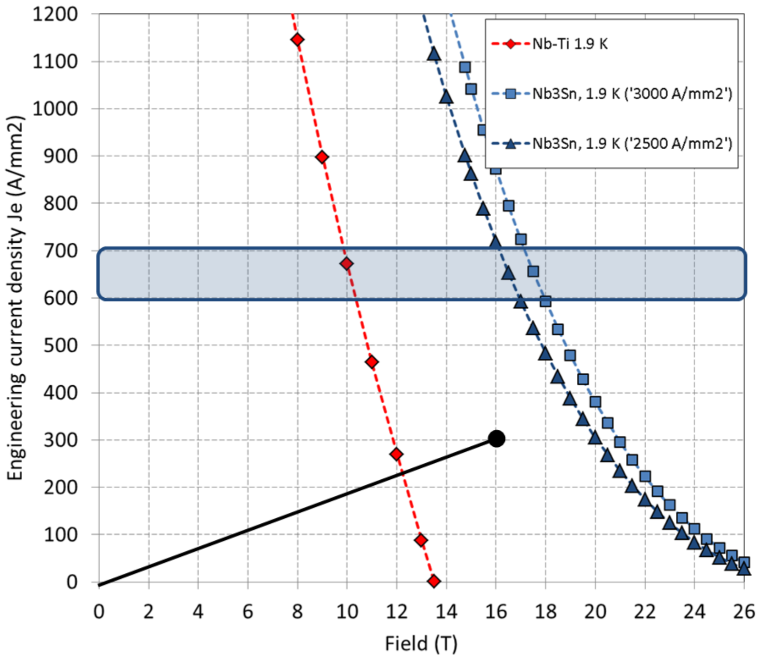
From 12-13 T to 15-16 T
FCC (100 km)

- **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



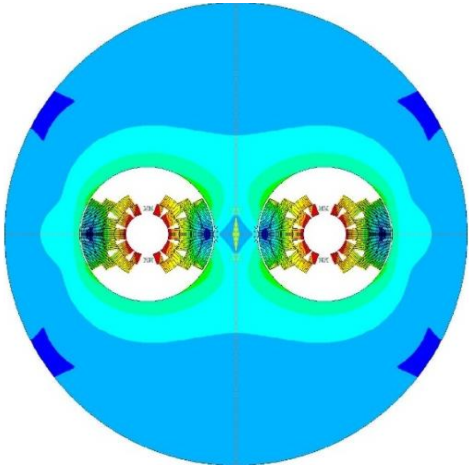
Nb_3Sn 15-16 T



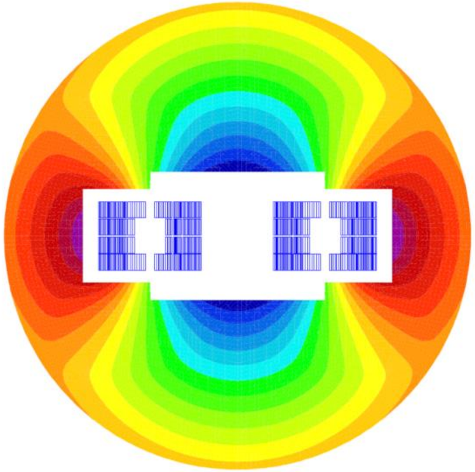
From 12-13 T to 15-16 T
FCC (100 km)

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

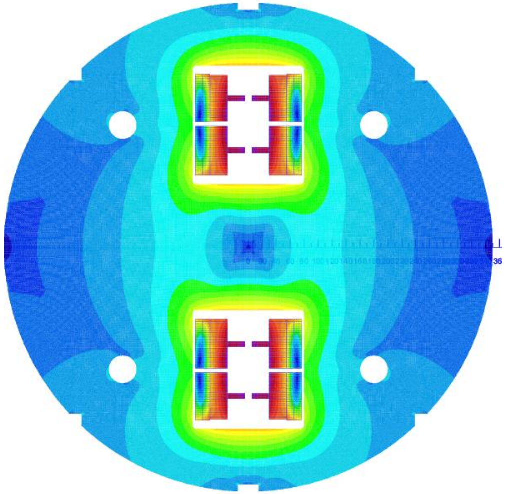
Cos-theta [Zlobin, FNAL]



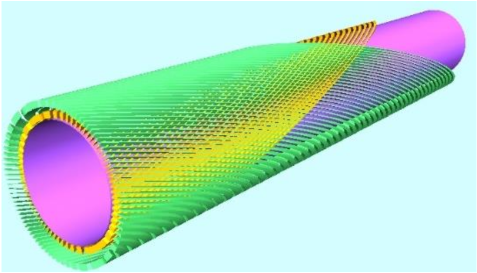
Block [Todesco, CERN]



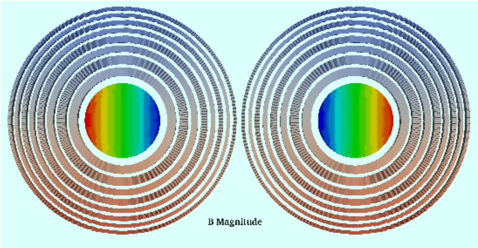
Common coil [Xu, IHEP China]



- Others more "innovative"…

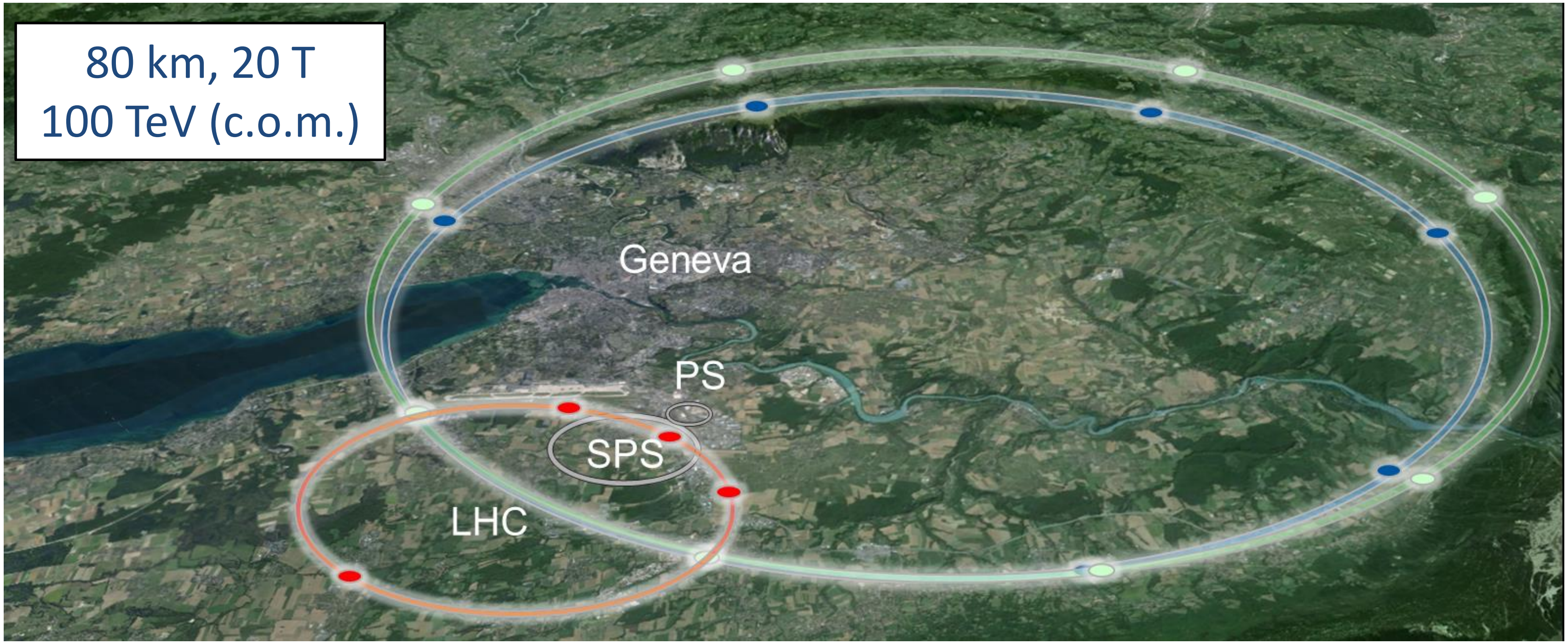


Canted [Caspi, LBNL]



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

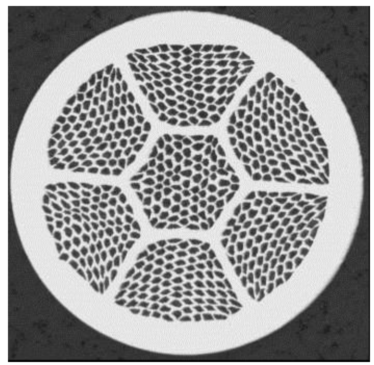
- **FCC project**
  - Magnet R&D focus is on FCC-hh: **100 TeV** pp collider
  - Timeframe: beyond 2035
  - Option: **20 T dipole** magnet in **80 km** machine



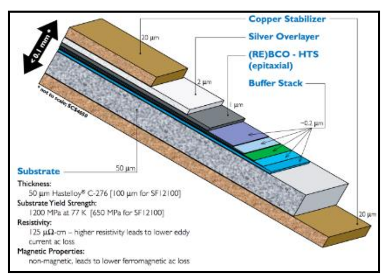
From 15-16 T to 20 T
FCC (80 km)

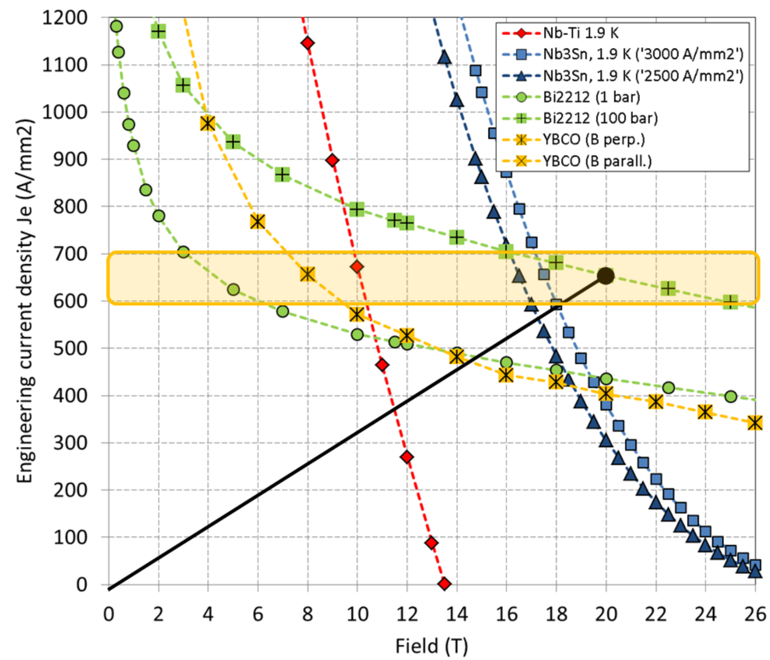
- **New materials** required
  - Coil in Nb_3Sn would be too wide
- High temperature superconductors **(HTS)**

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



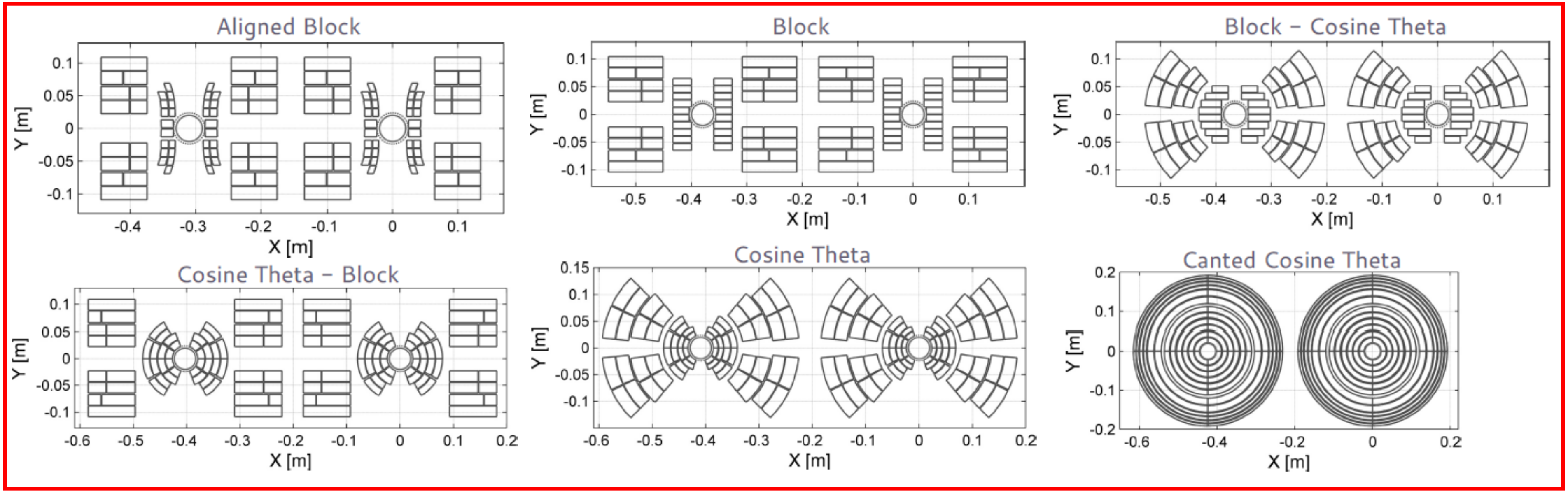
- **YBCO**
  - Tape -> cable?
  - No reaction
  - Resistance to stress
  - Cost ~ 16 x Nb-Ti
  - Strong angle dependance





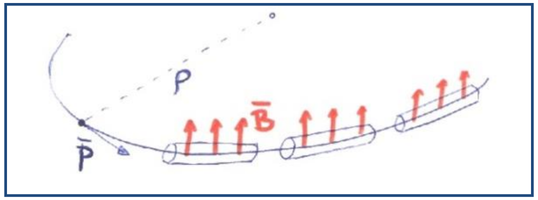
From 15-16 T to 20 T
FCC (80 km)

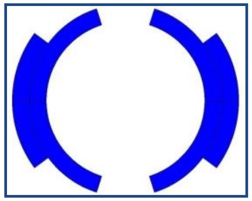
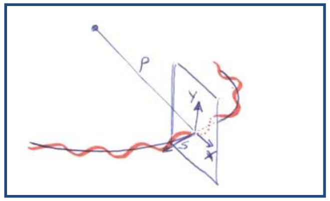
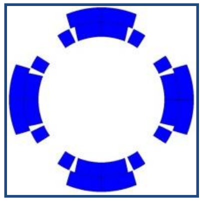
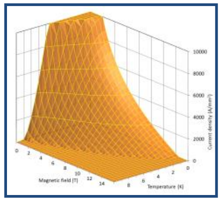
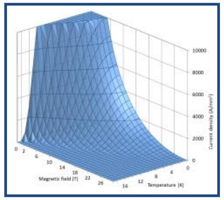
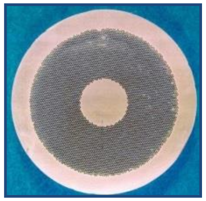
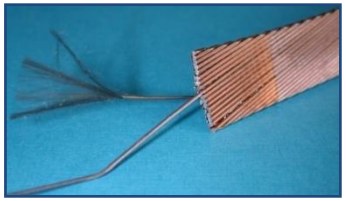
- Again, several designs, under investigation worldwide
  - Very creative moment….



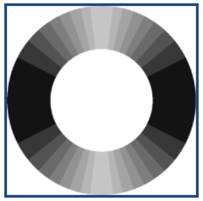
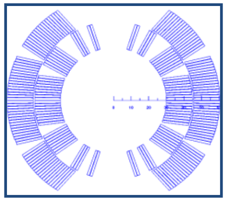
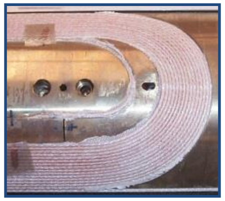
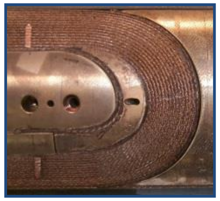
By J. Van Nugteren,
CERN and University of Twente

- **Particle accelerators and superconductors**



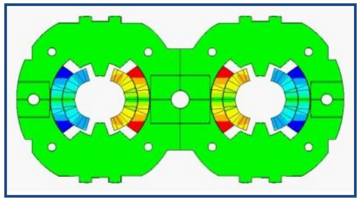








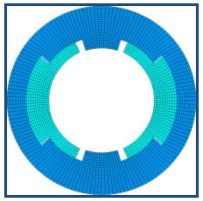
- **Magnetic design and coils**

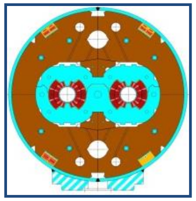






Summary

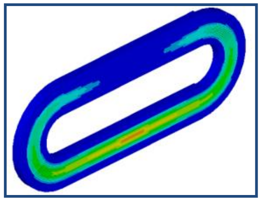
- **Mechanics of superconducting magnets**

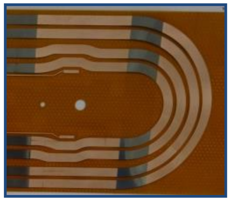


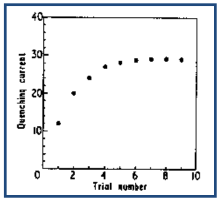




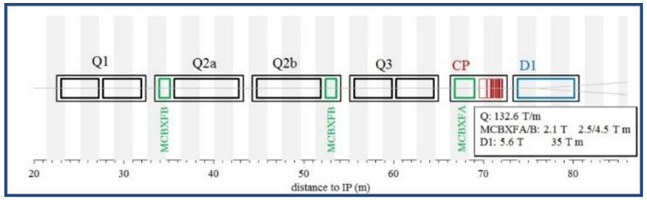
- **Quench and protection**



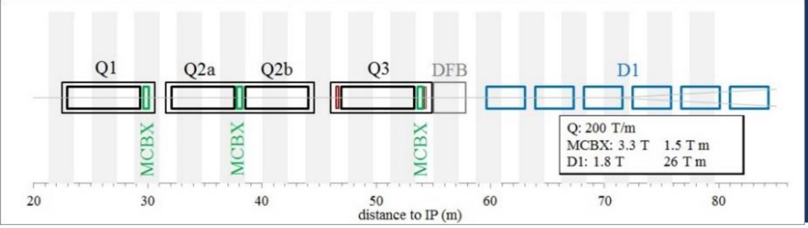


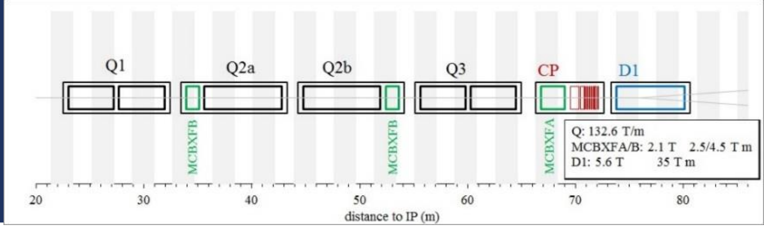


- **HiLumi LHC and FCC**



Appendix





Video by M. Lamont, CERN