CERN Summer Student Lecture - 2023

Accelerator Technology Challenges: Part 1
Superconducting magnets

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Outline

- Part I
  - Particle accelerators, magnets and the need of superconductors
  - Magnetic design and coil fabrication
- Part II
  - Mechanical design and assembly
  - Quench, training and protection
  - Outlook, what brings the future

Mechanical design

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

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

- Some examples (values per aperture):

Nb-Ti LHC MB (8.3 T)

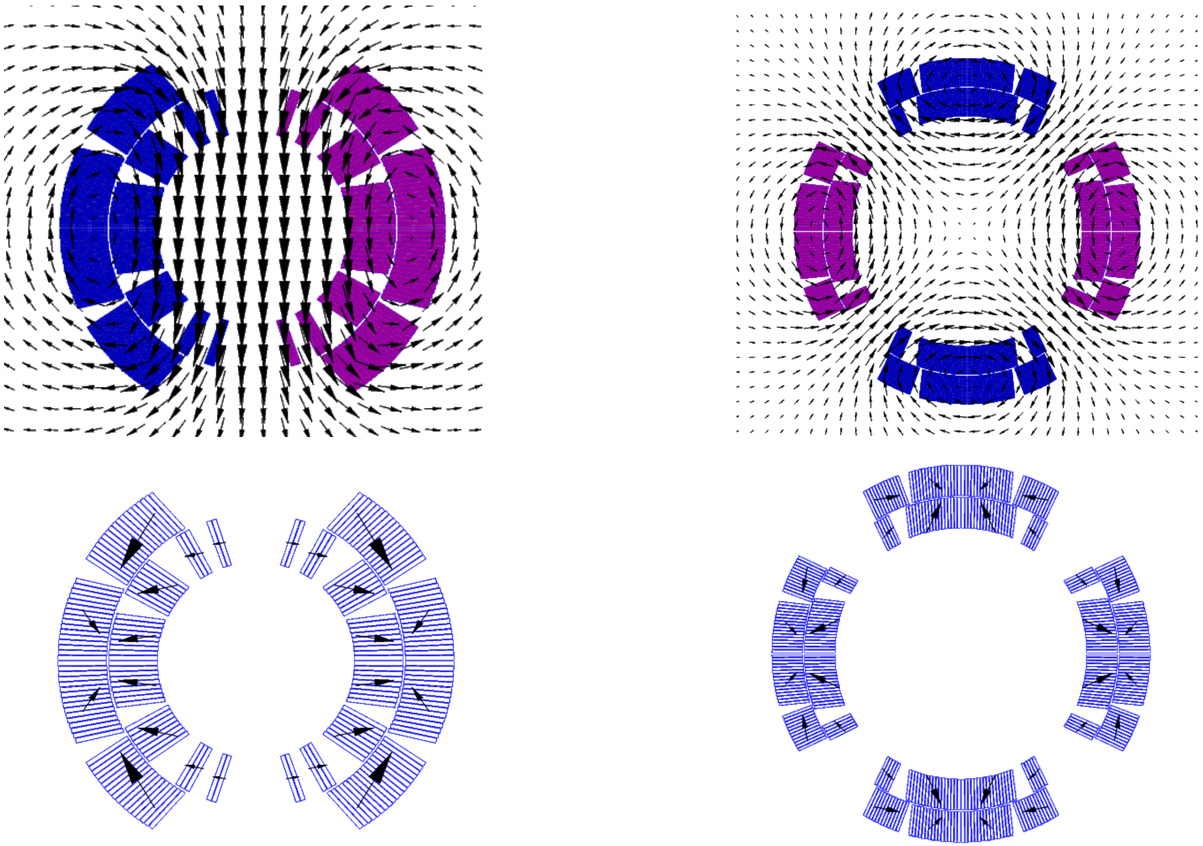
- F_x = **340 t** per meter
- F_z = **27 t**

Nb_3Sn DS dipole (11T)

- F_x = **620 t** per meter
- F_z = **47 t**

Electro-magnetic force

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



Electro-magnetic force

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

11 T dipole for HL-LHC

MQXF quadrupole for HL-LHC

Electro-magnetic force

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

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

Approximation of thin shell dipole, see how to derive the equations in [2]

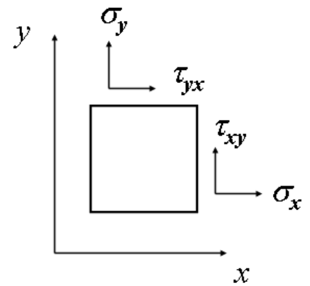
- The axial e.m. force on a dipole coil varies
  - with the square of the bore field
  - with the square of the bore radius

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

See how to derive the equation in [2]

Stress and strain - definitions

- A stress σ or τ [Pa] is an internal distribution of force [N] per unit area [m^2].
  - When the forces are perpendicular to the plane the stress is called normal stress (σ) ; when the forces are parallel to the plane the stress is called shear stress (τ).
  - Stresses can be seen as way of a body to resist the action (compression, tension, sliding) of an external force.



- A strain ε ($\delta l/l_0$) is a forced change dimension δl of a body whose initial dimension is l_0.
  - A stretch or a shortening are respectively a tensile or compressive strain; an angular distortion is a shear strain.

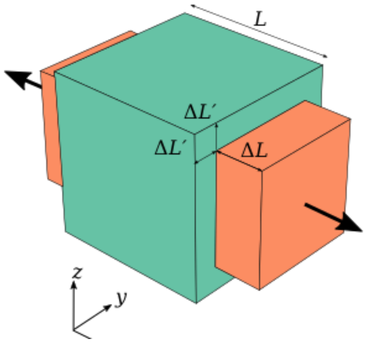
Stress and strain - definitions

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

$$E = \sigma / \varepsilon$$

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

$$\nu = -\varepsilon_{trans} / \varepsilon_{axial}$$



A cube with a Poisson's ratio of 0.5, courtesy of Wikipedia

Pre-stress

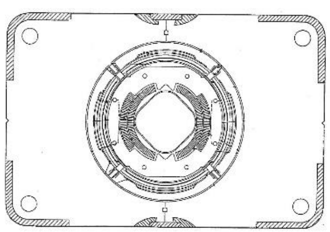
- The prestress paradigm is that coil should never be in tension but always precompressed (as reinforced concrete)
- The initial reasons for this paradigm were field quality concerns: change of b_3 (A. Tollestrup, Ann. Rev. Sci. 1984, father of Tevatron magnets and collared structure)
- Later, it was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

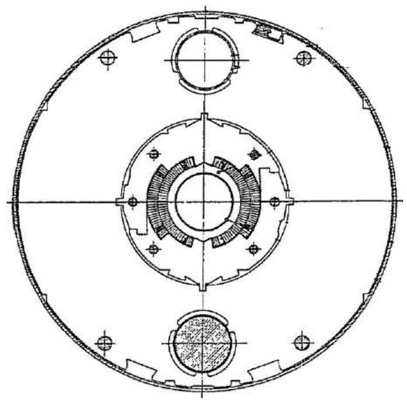
Annu. Rev. Nucl. Part. Sci. 1984.34:247-284.

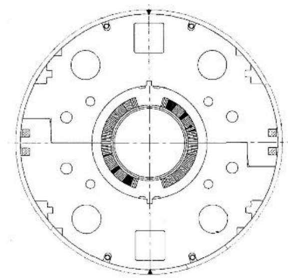
We are now in a position to discuss a difficult problem in magnet construction. If the azimuthal forces of the last section were allowed to act on a coil supported only in the radial direction, the coil would compress itself as it was excited and the angles of the shell would change. If these change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

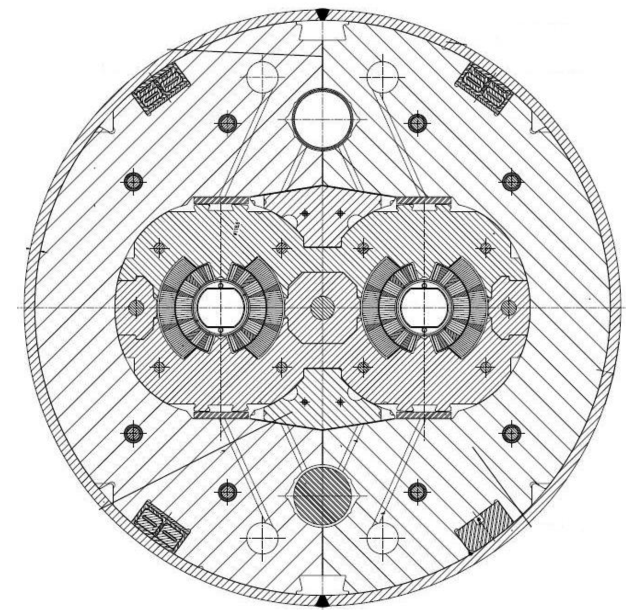
- The paradigm is always used in design and not always followed in reality
  - Typically, for the first models and prototypes one speaks of “conservative” loading, meaning that the preload is lower than what required to avoid pole unloading in operational conditions
  - The fear is to break something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

Superconducting dipoles (NbTi)









Tevatron
1983-2011
Bore: 76 mm
Field: 4.3 T
F_x = 0.5 MN/m
F_z = 78 kN

HERA
1991-2007
Bore: 75 mm
Field: 5.0 T
F_x = 0.6 MN/m
F_z = 87 kN

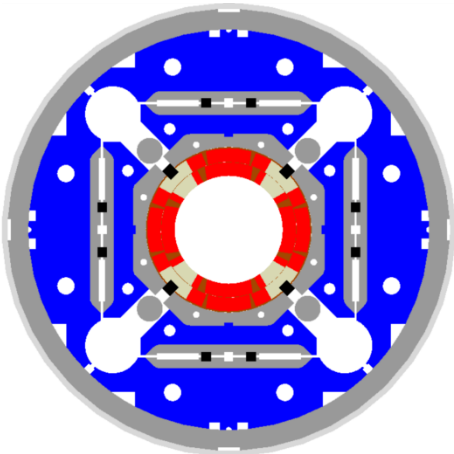
RHIC
2000-running
Bore: 80 mm
Field: 3.5 T
F_x = 0.3 MN/m
F_z = 48 kN

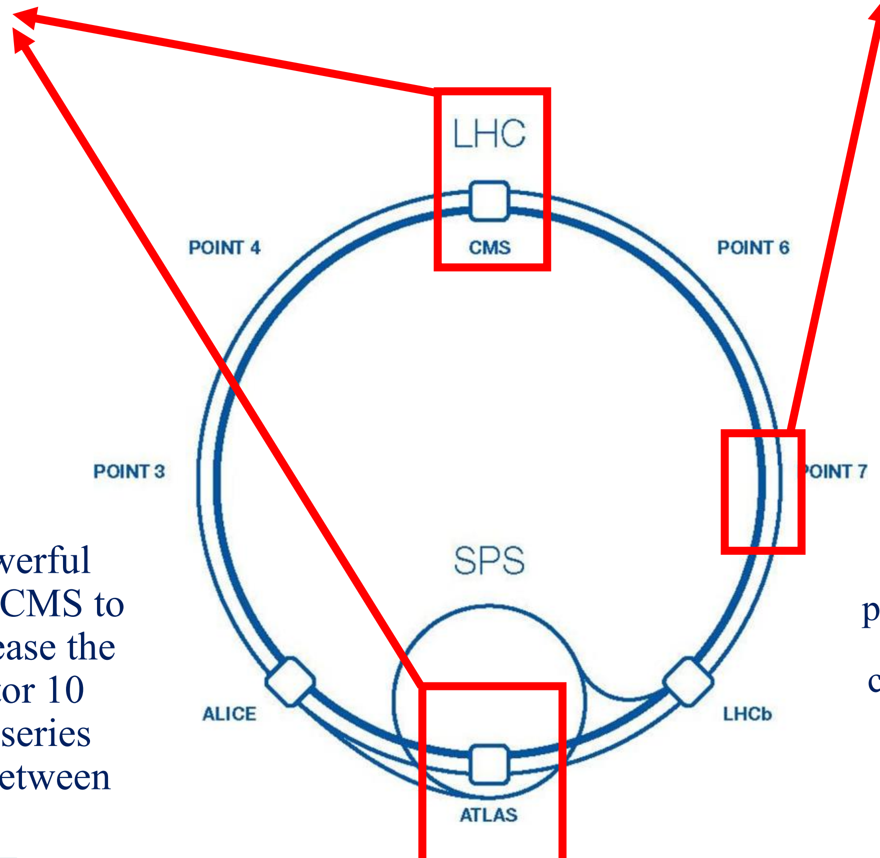
LHC
2008-running
Bore: 56 mm
Field: 8.3 T
F_x = 1.7 MN/m
F_z = 265 kN

F_x per quadrant/F_z per aperture

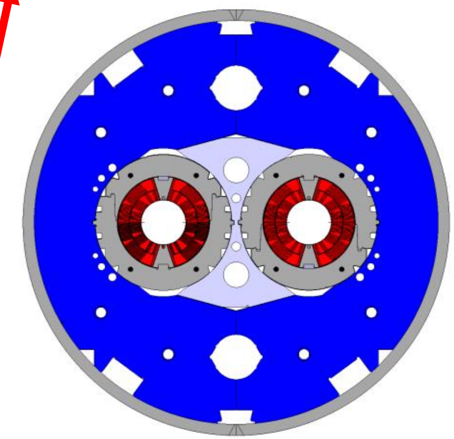
The HL-LHC Nb_3Sn magnets

MQXF

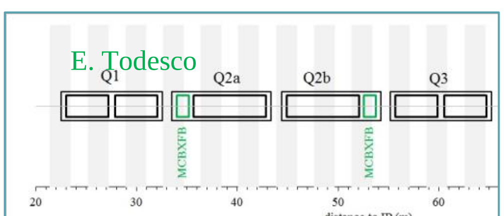




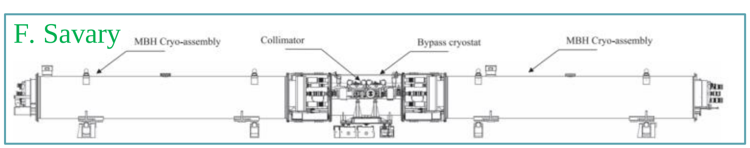
HL-LHC MBH 11 T



30 large aperture and more powerful quadrupoles around ATLAS and CMS to decrease the beam size and increase the integrated luminosity by a factor 10
Construction of pre-series and series magnets on-going, joint effort between CERN and US-AUP

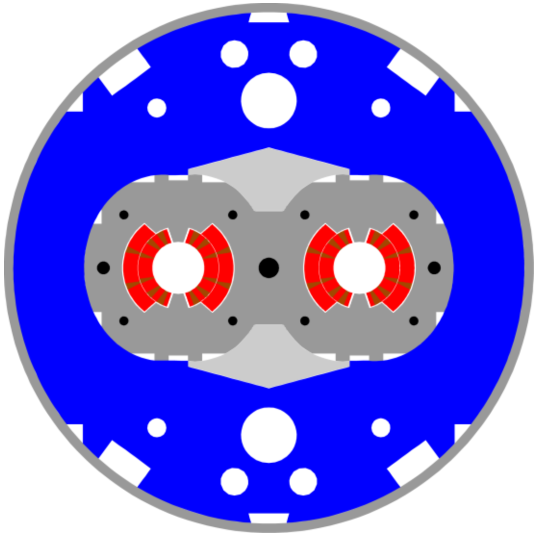


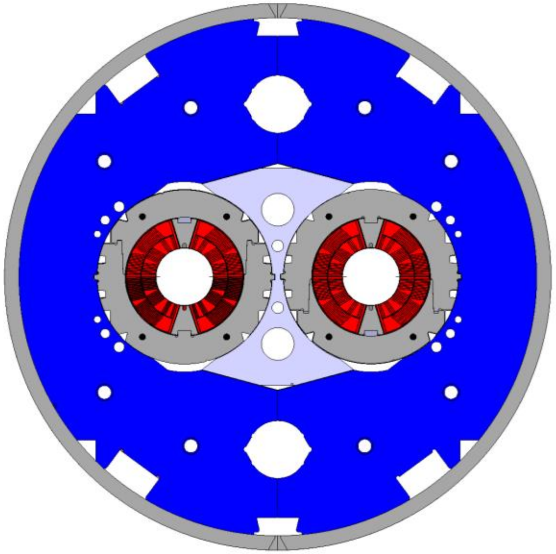
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators (2x5.5 m length 11 T dipoles to replace 14.3-m-long LHC MB dipole)
Initially planned for 2020, now delayed

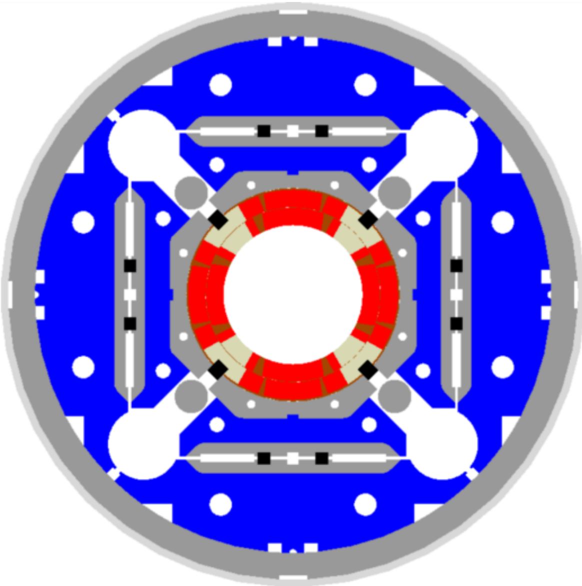


The 12 T challenge – e. m. force

≈ 2 times more force/stress than in the LHC-MB dipoles, in a brittle conductor







LHC MB
NbTi, $B_p = 8.6$ T
$F_x = 3.4$ MN/m
$\sigma_{\theta,em} = 50\text{-}60$ MPa
$F_z = 265$ kN

HL-LHC MBH 11 T
Nb_3Sn, $B_p = 11.7$ T
$F_x = 7.2$ MN/m
$\sigma_{\theta,em} = 100\text{-}110$ MPa
$F_z = 450$ kN

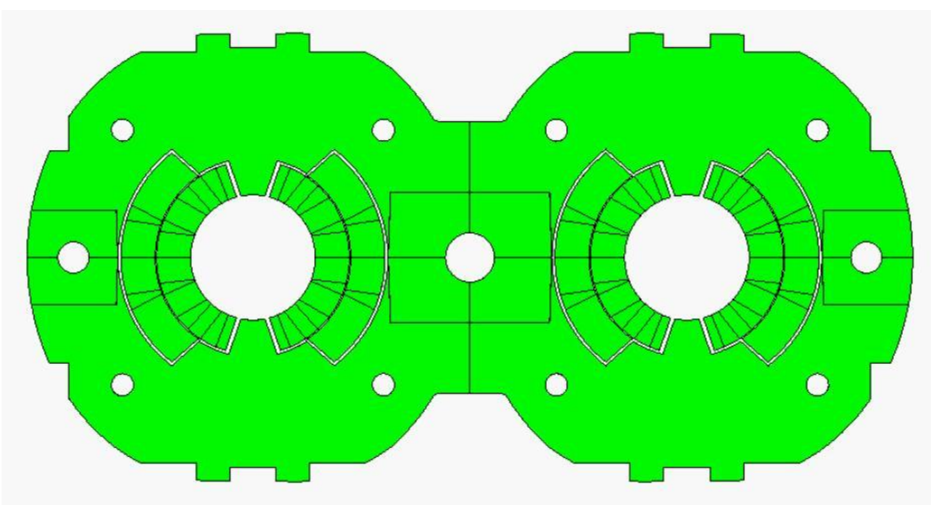
HL-LHC MQXF
Nb_3Sn, $B_p = 11.3$ T
$F_x = 6.8$ MN/m
$\sigma_{\theta,em} = 100\text{-}110$ MPa
$F_z = 1200$ kN

F_x per half magnet; F_z per aperture

Deformation and stress

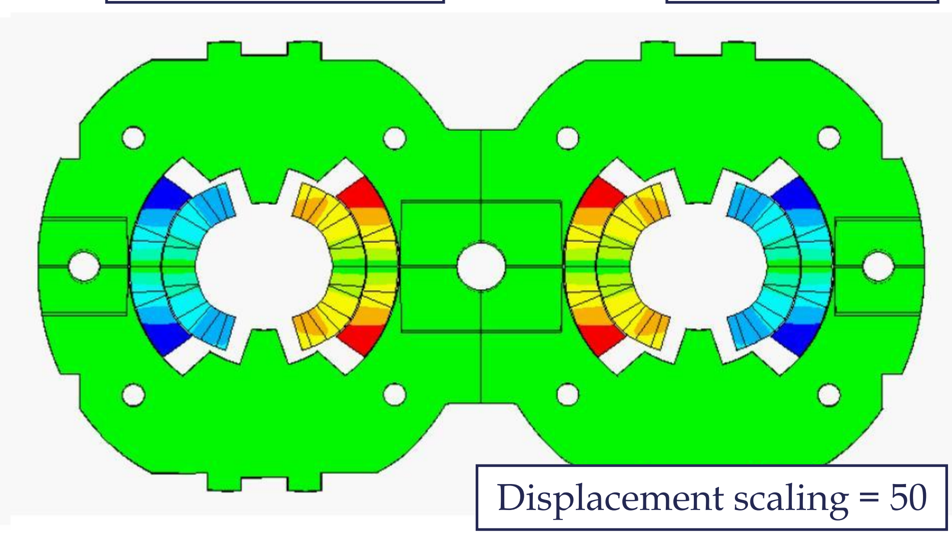
- Effect of e.m forces
  - change in **coil shape** → effect on field quality
  - a **displacement** of the conductor → potential release of frictional energy
  - Nb-Ti magnets: possible **damage** of **insulation** at~150-200 MPa.
  - Nb_3Sn magnets: possible **conductor degradation** at about 150-200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

LHC dipole at 0 T



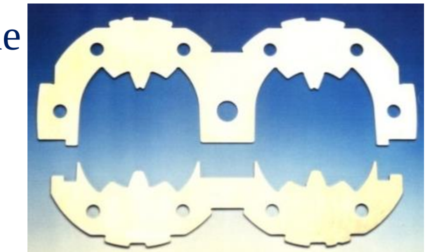
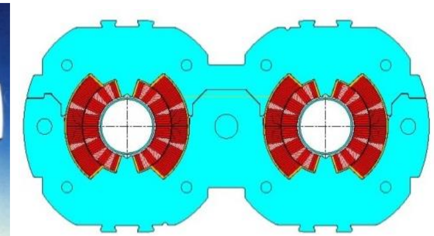
LHC dipole at 9 T

By P. Ferracin



Overview of the coil stress

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

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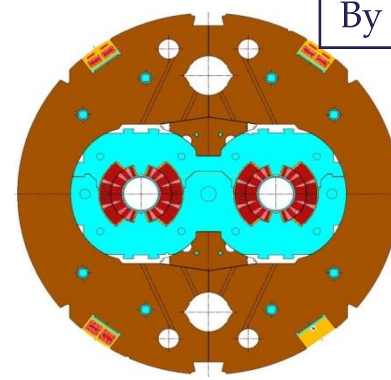
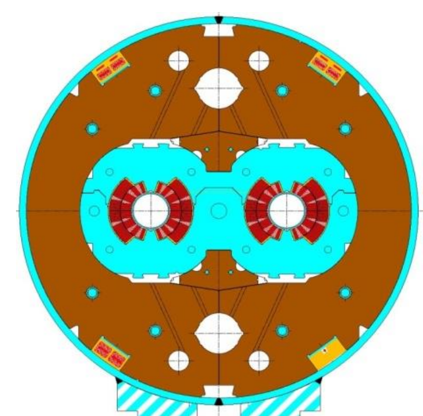


2. **Yoking:** Ferromagnetic yoke around the collared coil provide
   - Magnetic function
   - Mechanical function (increase the rigidity of the coil support structure and limit radial displacement)
   - Alignment, assembly features…

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



Overview of coil stress

4. Cool-down

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

5. Excitation

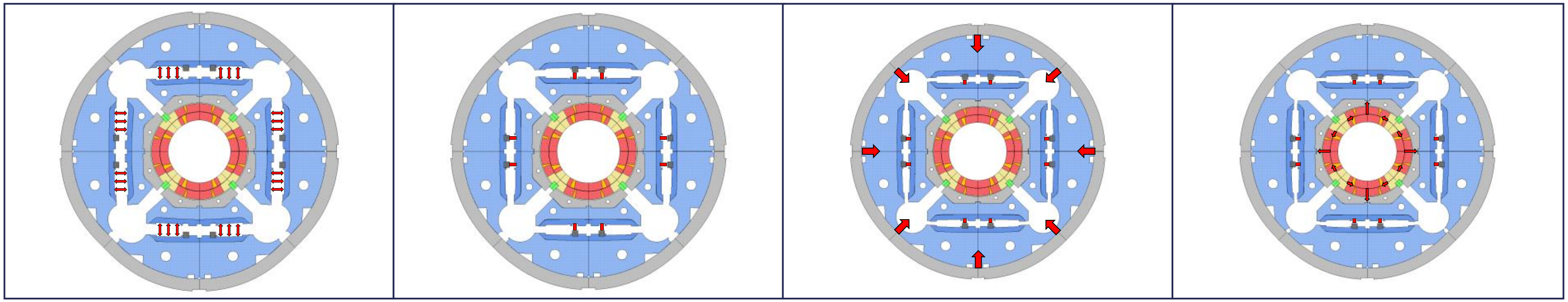
- The pole region of the coil unloads
  - Depending on the pre-stress, at nominal field the coil may unload completely

All these contributions taken into account in the **mechanical design:**

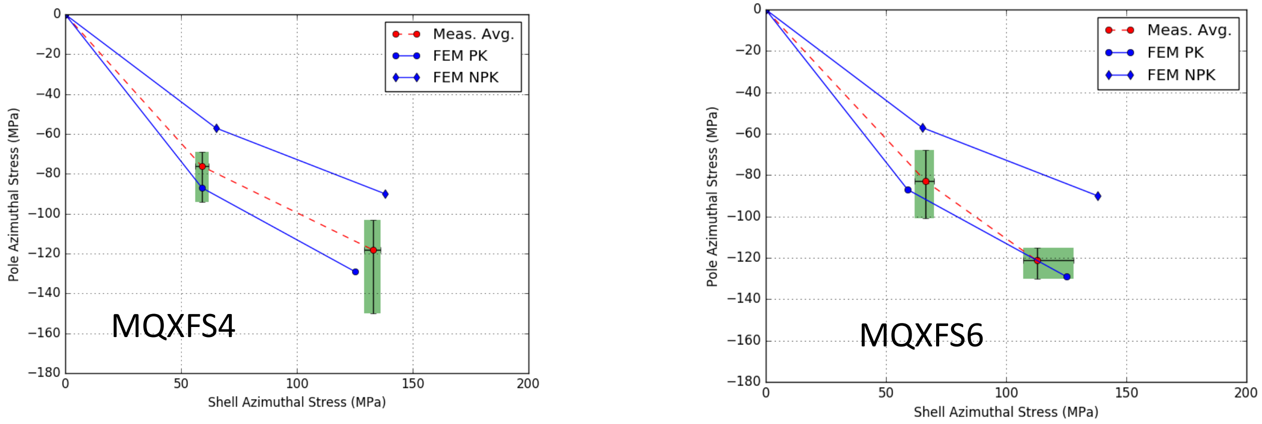
- Minimize **coil motion** (pre-stress)
- Minimize **cost and dimension** of the structure
- Maintain the maximum stress of the component **below the plasticity limits**
- …and for (especially) Nb_3Sn coils, **limit coil stress** (150-200 MPa).

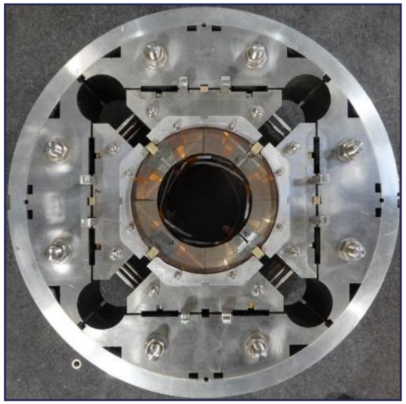
Al shell: MQXF in HL-LHC

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



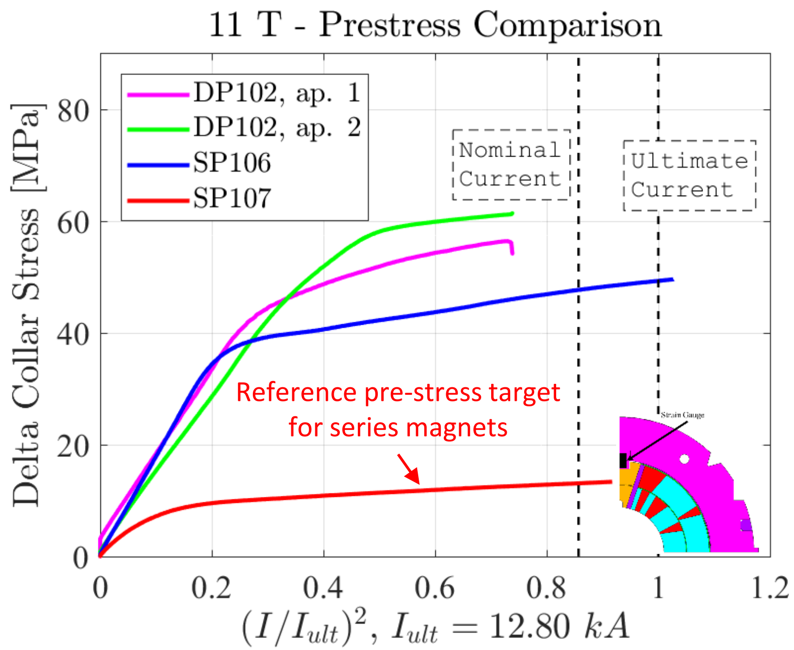
- During cool-down increase in coil/shell stress
  - Predictable stress variation → Capability to control final coil and shell stress

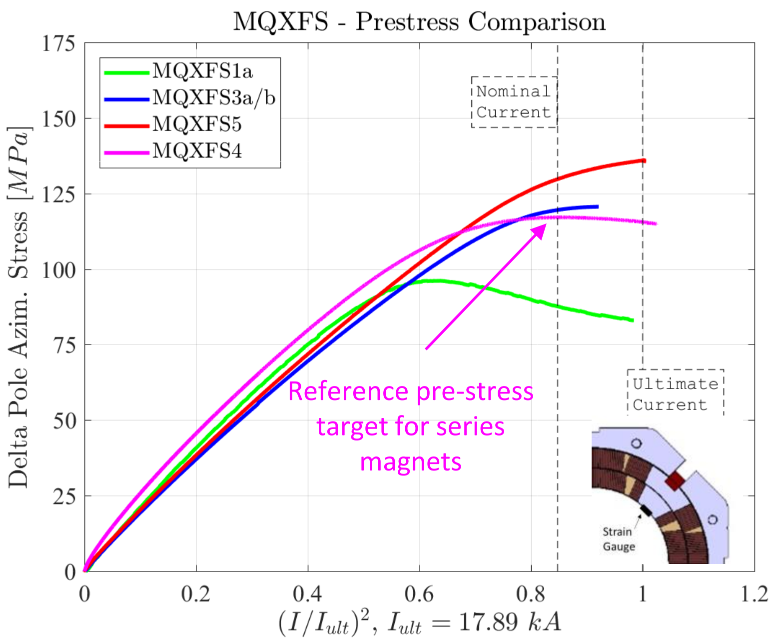




Pre-stress: HL-LHC Nb_3Sn magnets

- This is the example of the MQXF and 11 T, the Nb_3Sn magnets for the HiLumi upgrade.
  - Strain gauges placed in the pole in MQXF, in the collar nose in 11 T. They allow seeing the pole unload
  - Estimated stress proportional to square of current (forces)
  - The end of the linear region implies a pole unloading, i.e. that the coil at the pole is not compressed any more

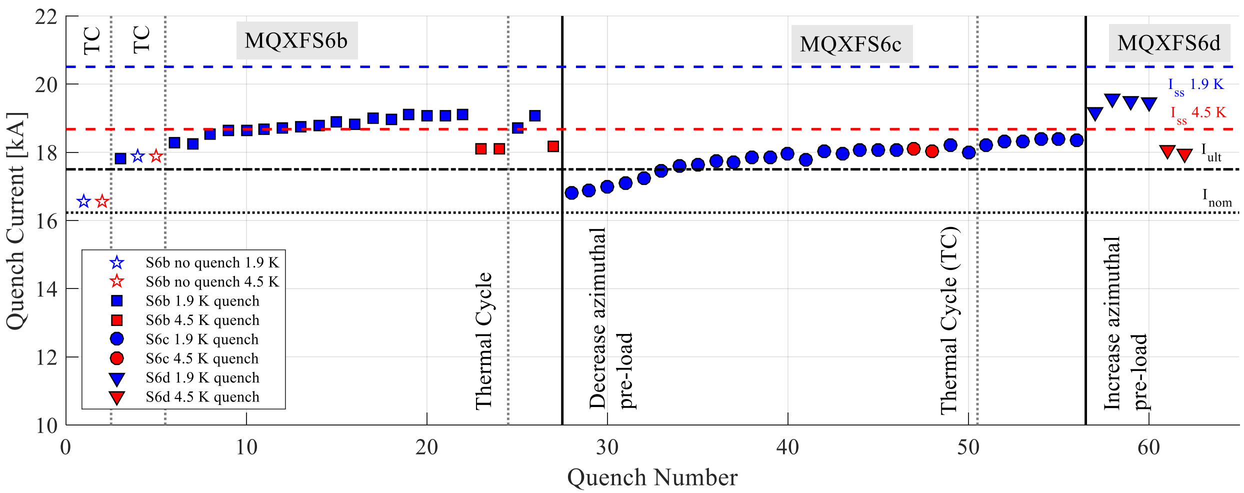




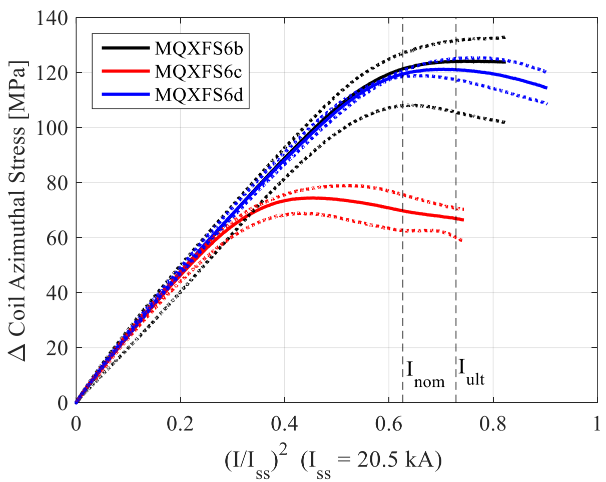
Pre-stress – MQXF example

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

Training of MQXFS6b&6c



Unloading during powering of MQXFS6b&6c



Axial support

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

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

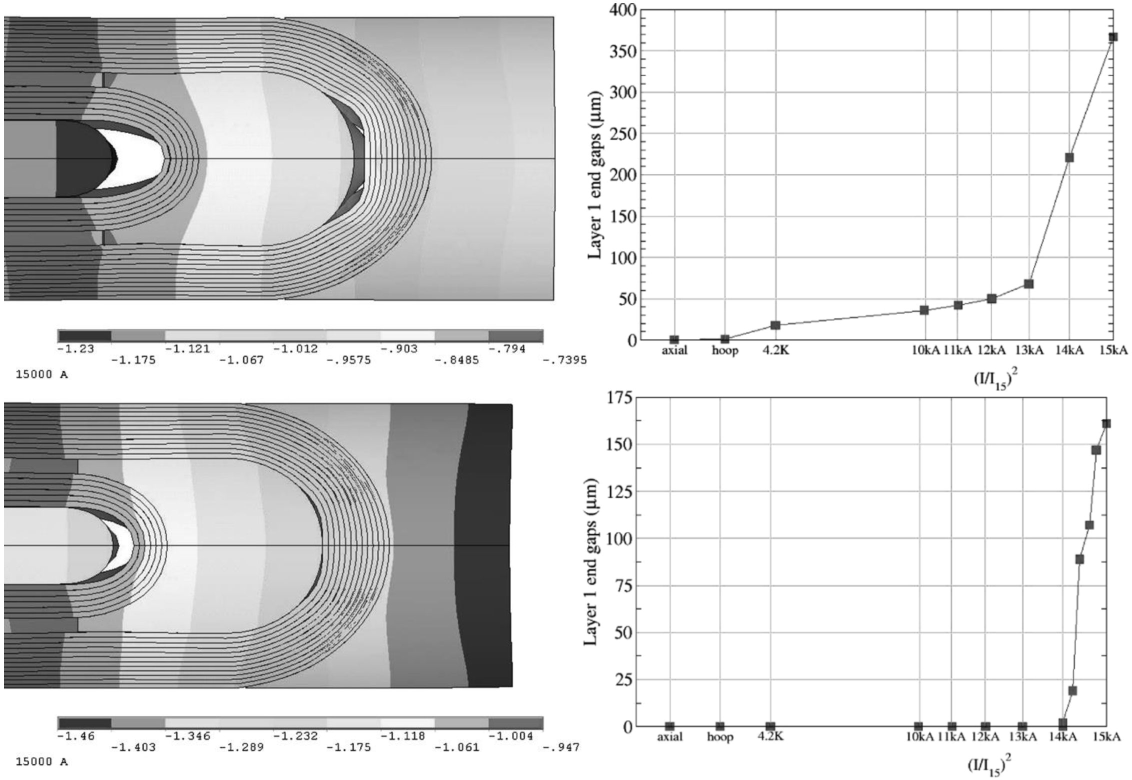
  - Limit the coil displacements due to electromagnetic forces by having a rigid structure in the longitudinal direction and pre-load coil ends to compensate the axial forces and keep coil end turns under compression (MQXF, FRESCA2, concept,)

Axial support: force or not force?

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

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

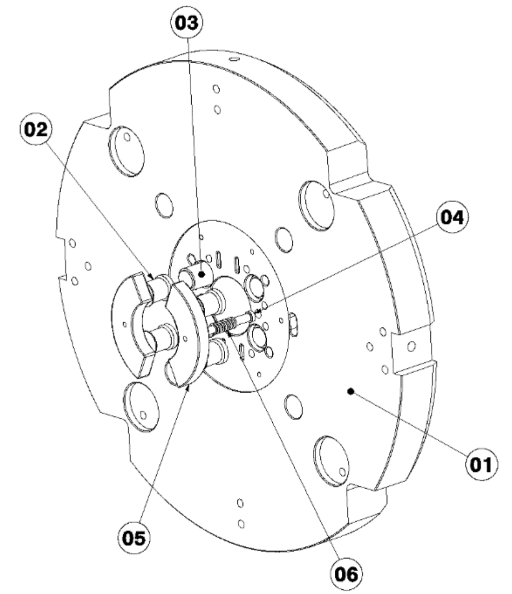
S. Caspi, P. Ferracin., "Towards integrated design and modeling of high field accelerator magnets," IEEE Trans. Appl. Supercond., vol. 16, no. 2, pp. 1298–1303, June 2006.

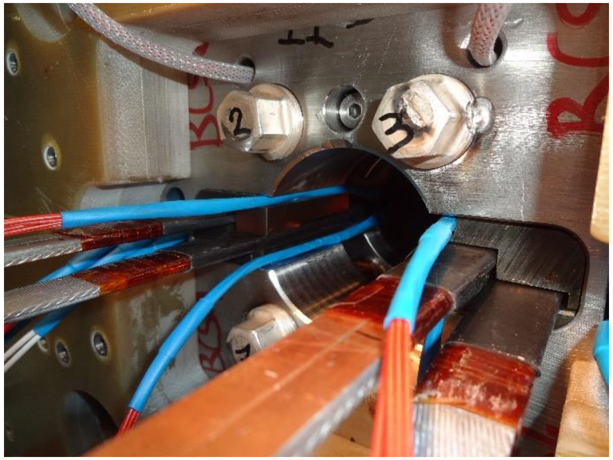


Axial displacements of inner layer's (0.2 friction factor assumed).
Limited axial support (top) and full axial support (bottom).

Axial support: welded end plate

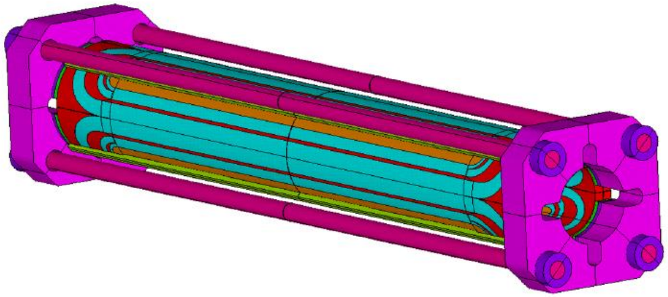
- We take as example the 11 T dipole for the HL-LHC
- Slight pre-load at room temperature, to guarantee that there is still contact coil to end plate at 1.9 K.
- Goal: limit the coil displacements providing a rigid lateral support
- 1in1 models:
  - 43 mm thick end-plate, 12 mm stainless steel shell.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





Axial support: rods and end-plate

- We take as example the MQXF quadrupole for the HL-LHC
- Direct connection between the motion of the rod and the one of the coil ends
  - Very nice and clean measurements!
- Goal: keep the pole turn under compression during powering.
- Short models (1.2 m):
  - Aluminum rods, 36 mm diameter
  - Nitronic 50 end plate, 75 mm thick
- MQXFA (4.2 m):
  - Stainless steel rods, 32 mm diameter
  - Nitronic 50 end plate, 75 mm thick
- MQXFB (7.15 m):
  - Stainless steel rods, 35 mm diameter
  - Nitronic 50 end plate, 75 mm thick



Measured delta in the rods during powering from 0 to I_{nom}

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

Summary

- We presented the force profiles in superconducting magnets. In dipole and quadrupole magnets, the forces are directed towards the mid-plane and outwardly.
    - They tend to separate the coil from the pole and compress the mid-plane region
    - Axially they tend to stretch the windings
- The importance of the coil pre-stress has been pointed out, as a technique to minimize the conductor motion during excitation.
- There are several ways of designing a support structure
    - The solution for a given magnet is not unique
- Structures based on collars are the workhorse of Nb-Ti magnets
    - Guarantees adequate support to avoid deformation and allows giving azimuthal prestress
- Aluminum shell structure guarantees that the peak pre-stress is reached in operational conditions
    - Introduced in LNBL, used in several Nb_3Sn. It has been scaled from 1-m-long to 3.4 m long magnets with LARP, and to 7.2 m long magnet in HL LHC MQXFB at CERN

References

- [1] MJB Plus, Inc. "*Superconducting Accelerator Magnets*", an interactive tutorial.
- [2] Paolo Ferracin, USPAS - Superconducting Magnets for Particle Accelerators, Unit 10, 13 and 14 (available in https://indico.cern.ch/event/440690/)
- [3] Y. Iwasa, "Case studies in superconducting magnets", New York, Plenum Press, 1994.
- [4] M. Wilson, "Superconducting magnets", Oxford UK: Clarendon Press, 1983.
- [5] A.V. Tollestrup, "Superconducting magnet technology for accelerators", Ann. Reo. Nucl. Part. Sci. 1984. 34, 247-84

Outline

- Part I
  - Particle accelerators, magnets and the need of superconductors
  - Magnetic design and coil fabrication
- Part II
  - Mechanical design and assembly
  - Quench, training and protection
  - Outlook, what brings the future

Quench definition

Quench = irreversible transition to normal state

- **Heat generation > cooling**

Why do magnets quench?

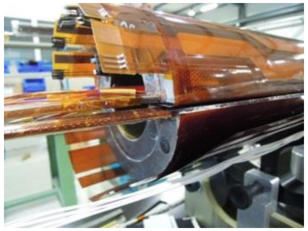
Thermal energy released by

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

What do we do when a magnet quenches?

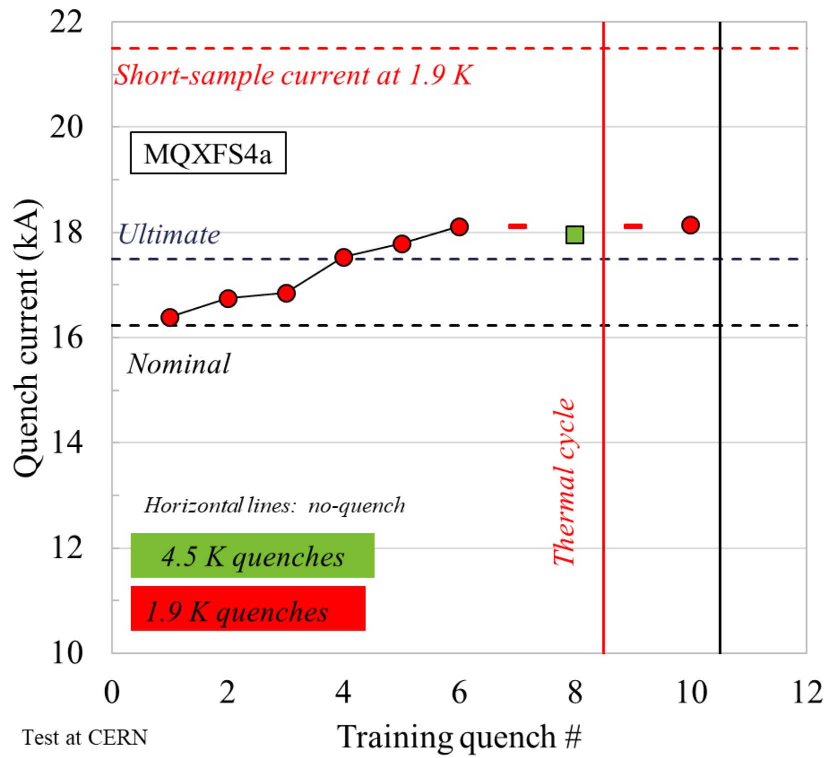
Conversion **magnetic energy** ⟶ **thermal energy** (redistribute the energy in the whole coil volume, joule heating)

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



Training

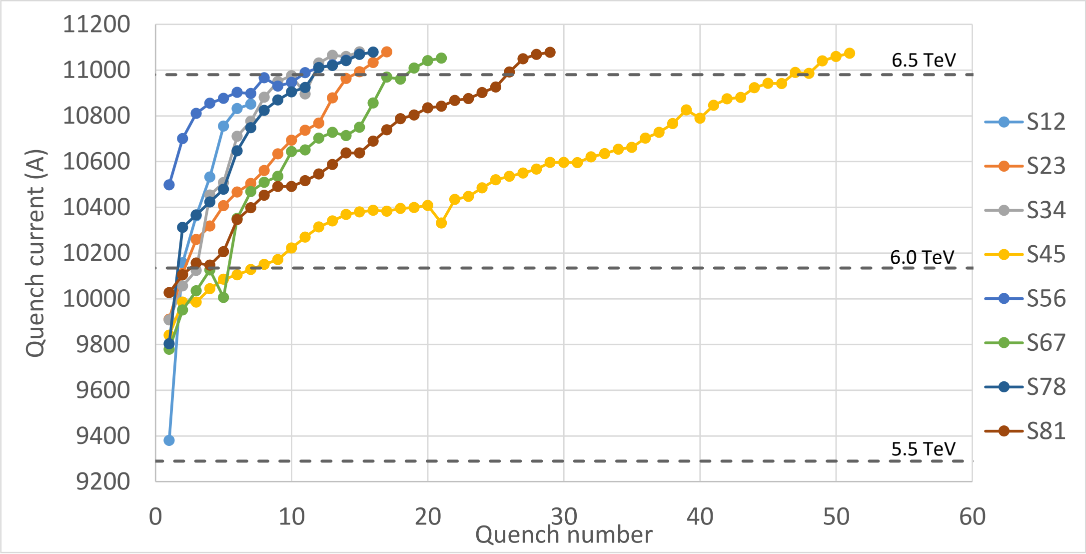
- Superconducting magnets typically quench before reaching their nominal performance, the so-called training
- **Training is characterized by two phenomena:**
  - The occurrence of premature quenches (below short sample limit)
  - The progressive increase of quench current, ramp after ramp
- The magnet «improves» ramp after ramp to reach the nominal performance = operating point with margin
- **Main identified causes :**
  - Frictional motion
    - E.m. forces → motion → quench
    - Coil progressively 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.



Training in the LHC

- The LHC dipoles were assembled by three manufactures
- All magnets tested at 1.9 K in SM18 before installation in the tunnel
  - All powered above nominal (11850 A, 7 TeV)
  - About 50 % powered to ultimate (8 % more than nominal, 12850 A)
  - Less than 10 % went through thermal cycle (biased sample)
    - Magnet not reaching 12850 A with 9 quenches were tested after thermal cycle
  - Bonus strategy: magnets reaching ‘rapidly’ ultimate were given a bonus
- Memory after cycle is important to avoid training in the accelerator (time consuming, i.e., $$$$)
  - In general, memory is better in Nb3Sn than in NbTi

Training of LHC sectors to 6.5 TeV



Quench: why it can be a problem ?

- Quench is the result of the resistive transition, leading to appearance of voltage, temperature increase, thermal and electro-magnetic forces, and cryogen expulsion
- If the process does not happen uniformly: as little as 1 % of the magnet mass may absorb the total energy – large damage potential !

Result of the chain of events triggered by a quench in an LHC bus-bar

Result of degradation due to local heating in a NbTi coil

Result of electrical short circuit quench heater to coil in a Nb_3Sn coil

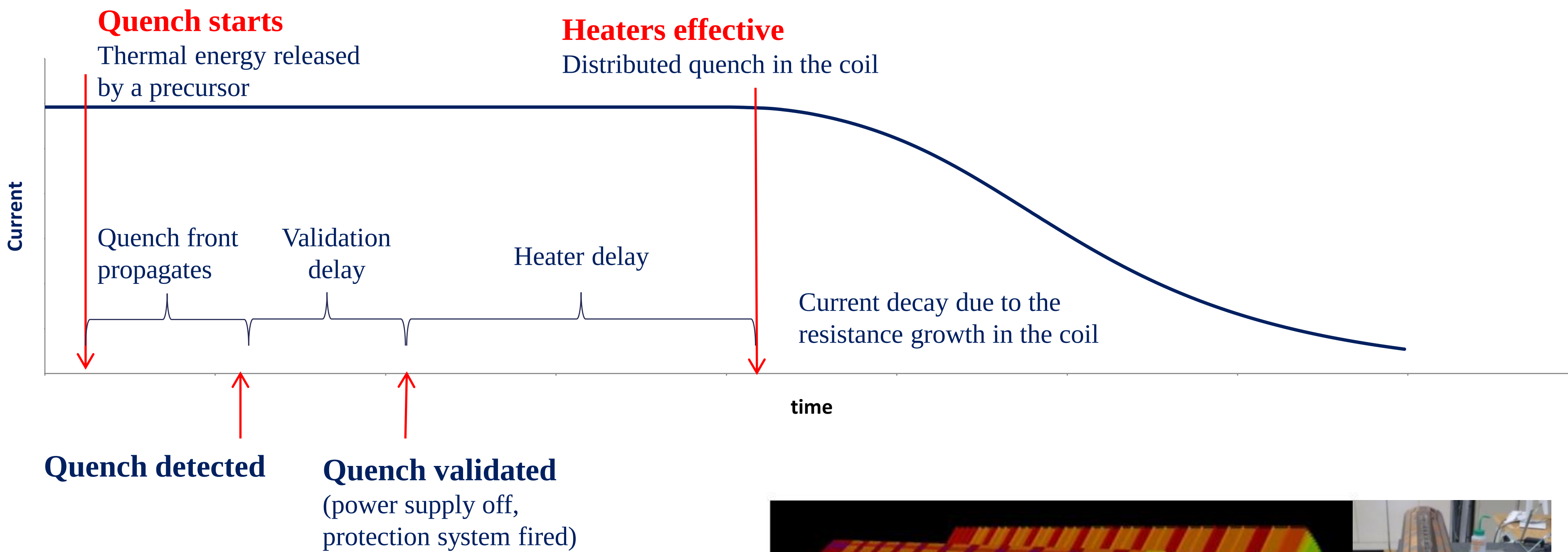
Protection strategies

- Two limiting cases in terms of magnet protection strategy:
  1. **External-dump**: The magnet is dumped externally on a large resistance (R_{dump} >> R_{quench}) as soon as the quench is detected (e.g. ITER)

  2. **Self-dump:** The circuit is on a short circuit and is dumped on its internal resistance ($R_{dump} = 0$) (e.g. LHC). Actually, external dump is not an option for a chain of accelerator magnets.
     - Typical $J_{Cu} \approx 1000\ldots1250$ (A/mm^2)
       - Meaning $dT/dt \approx 1000\ldots2000$ (K/s)
       - We need to dump quickly! $\tau(300\text{ K}) \approx 0.15\ldots0.3$ (s)
     - $I_{op} \approx 15$ (kA)
     - $E/l \approx 1000$ (kJ/m)

$$\frac{\mathbf{V}}{\mathbf{l}} \approx \frac{\mathbf{2E}/\mathbf{l}}{\boldsymbol{\tau}\mathbf{I_{op}}} = \mathbf{500 \ldots 1000\ V/m}$$

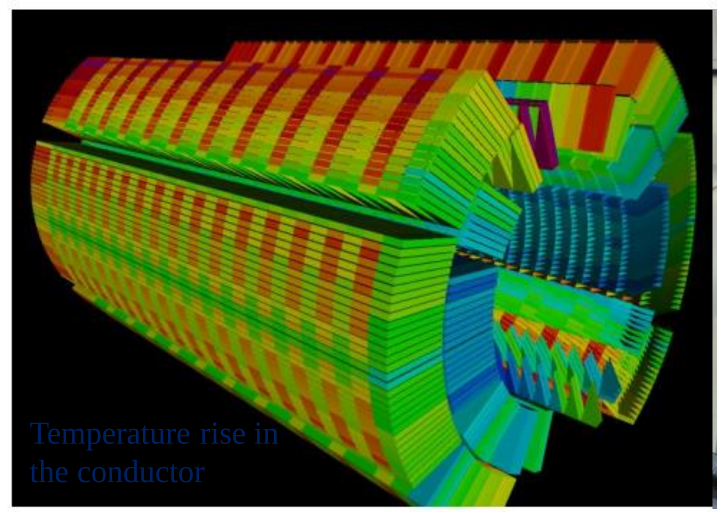
The quench event: summary



Typical time scale:

- From quench start to quench detected ~ 5 ms
- Validation delay ~ 10 ms
- Heater delay ~ 20 ms
- Current decay ~ 100-200 ms

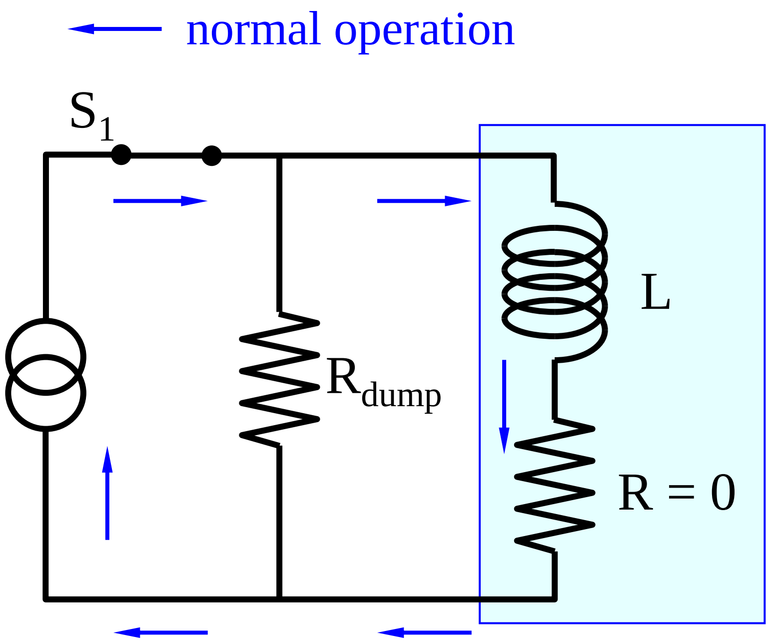
Maximum acceptable temperature: **350K**

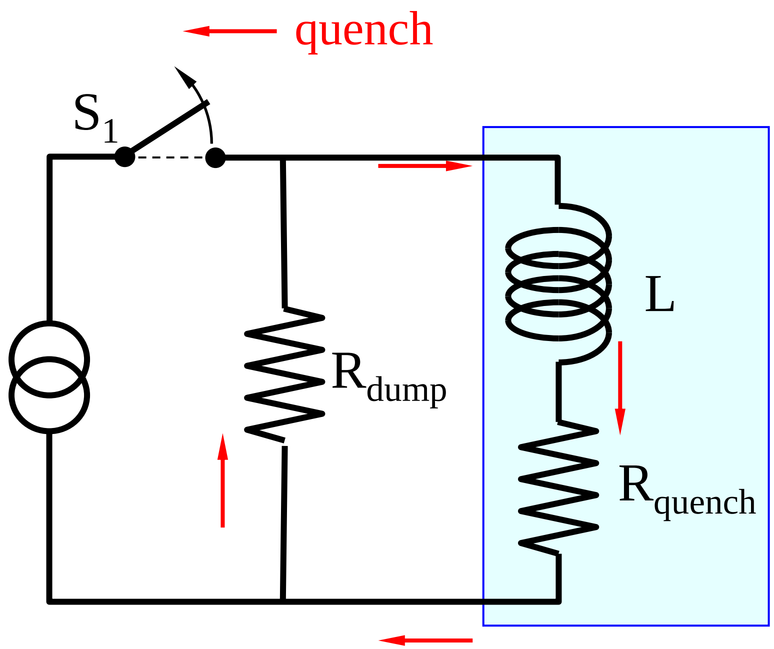


Protection strategy – External dump

- The magnetic energy is extracted from the magnet and dissipated in an external resistor:

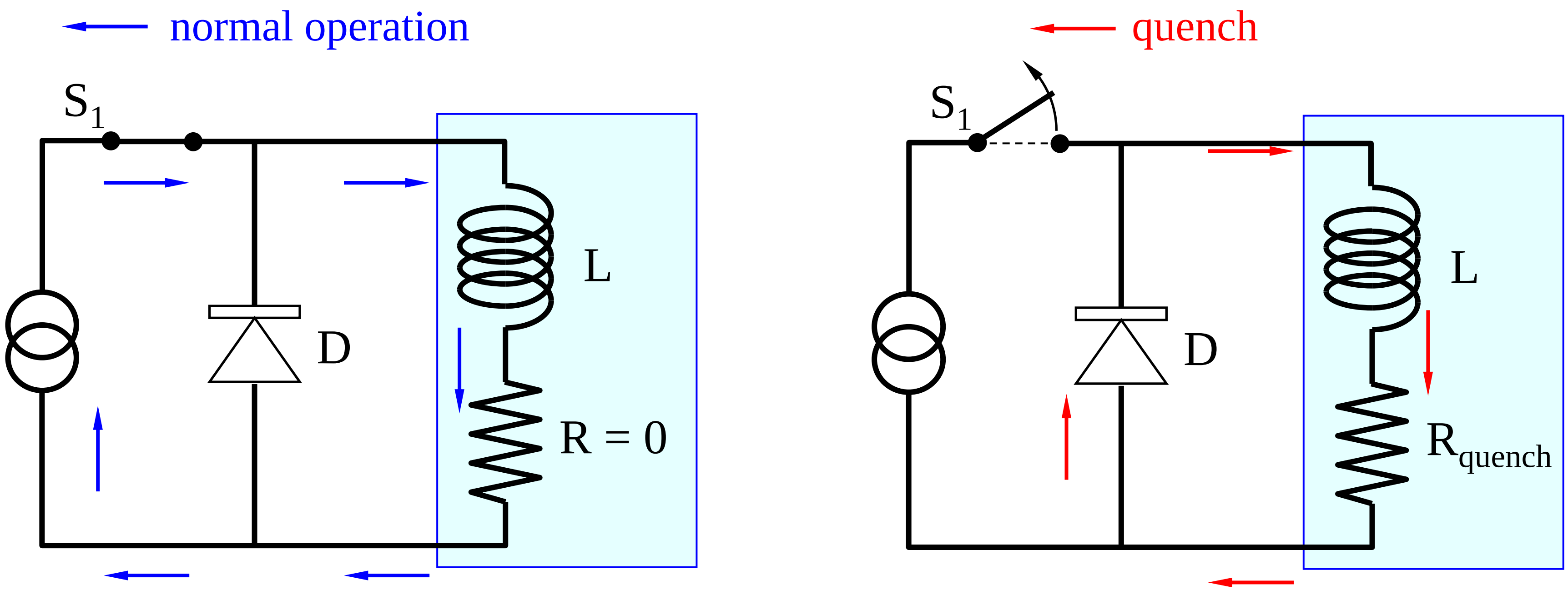
$$I(t) = I_0 \exp\left(-\frac{t}{L}R(t)\right) \approx I_0 \exp\left(-\frac{tR_d}{L}\right)$$





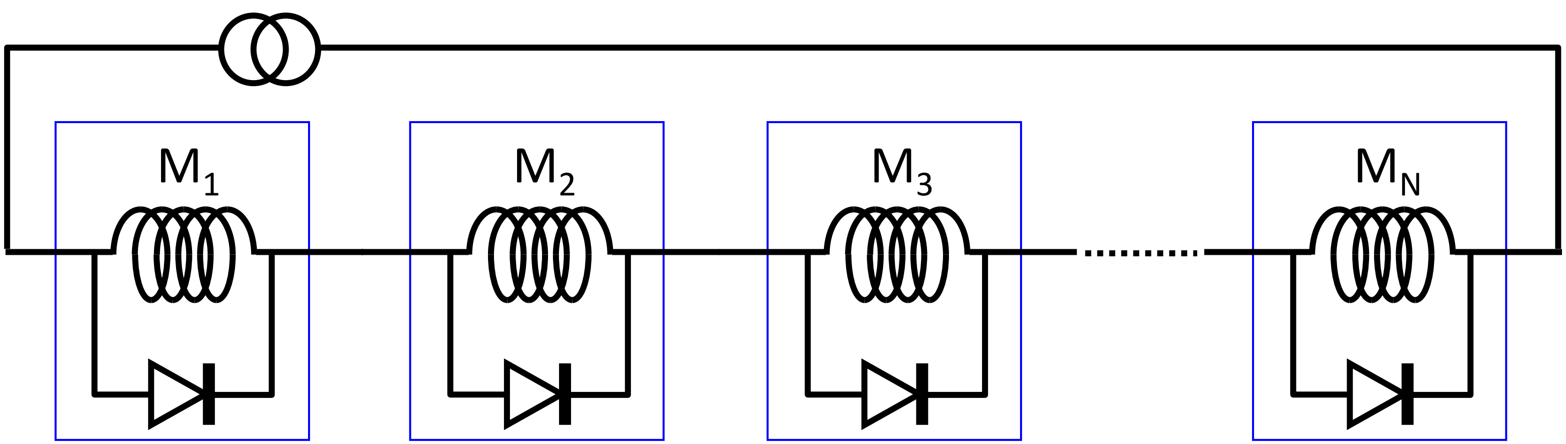
Protection strategy – Self dump

- In the case of the LHC, the magnetic energy is completely dissipated in the internal resistance, which depends on the temperature and volume of the normal zone
  - (when increasing the temperature, the material becomes resistive→ resistance increase→ current decrease (fix voltage))



Protecting a magnet string

- Magnet strings (e.g. accelerator magnets, fusion magnetic systems) have exceedingly large stored energy (10's of GJ):
  - energy dump takes very long time (10…100 s)
  - the magnet string is *subdivided* and each magnet is by-passed by a diode (or thyristor)
  - the diode acts as a shunt during the discharge



Adiabatic heat balance

- The simplest (and conservative) approximation for the evolution of the maximum temperature during a quench is to assume adiabatic behavior at the location of the hot-spot:

$$A\overline{C}\frac{\partial T_{cond}}{\partial t} = Aq''_{joule} \rightarrow \overline{C}\frac{\partial T_{cond}}{\partial t} = \eta_{Cu}J^2$$

Average heat capacity: $\overline{C}(T) = \sum_i f_i \rho_i c_i$

Electrical resistivity of the stabilizer (Cu): $\eta_{Cu}(B, RRR, T)$

- The circuit is a RL circuit
  - with the magnet inductance L
  - and a highly variable resistance R(t), growing with time
  - the higher the resistance, the faster the current dump, the lower hotspot

$$L\frac{\partial I}{\partial t} + RI = 0$$

35

Hot spot temperature

- Adiabatic conditions at the hot spot:

$$\overline{C}\frac{\partial T_{cond}}{\partial t} = \eta_{Cu} J^2$$

- Can be integrated

$$\int_{T_{op}}^{T_{max}} \frac{\overline{C}}{\eta_{Cu}} dT = \int_0^{\infty} J^2 dt$$

Ability of the cable of « taking » the current (combination of enthalpy and resistivity): **Quench capital (Γ)**

Load due to the current decay, that should be made as fast as possible and is an observable: **Quench tax**

Protection limit

- Ideal case: all magnet is quenched at the quench start

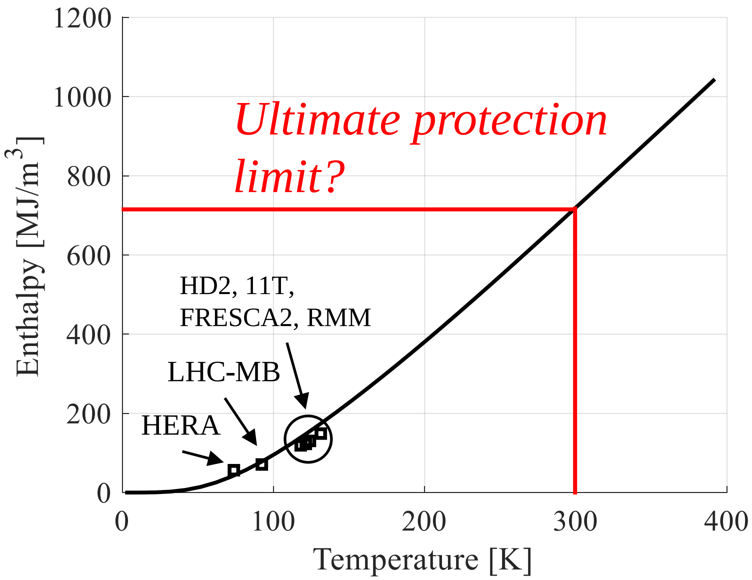
Assuming adiabatic conditions

$$\frac{E}{V} = \int_{T_{op}}^{T} \overline{C}(T)dT$$

$\frac{E}{V}$ Magnet stored energy per unit volume.

$\overline{C}(T) = \sum_i f_i \rho_i c_i$ Volumetric heat capacity of the cable

i = copper, superconductor and insulation.



Enthalpy of the strand volume (neglecting the insulation)

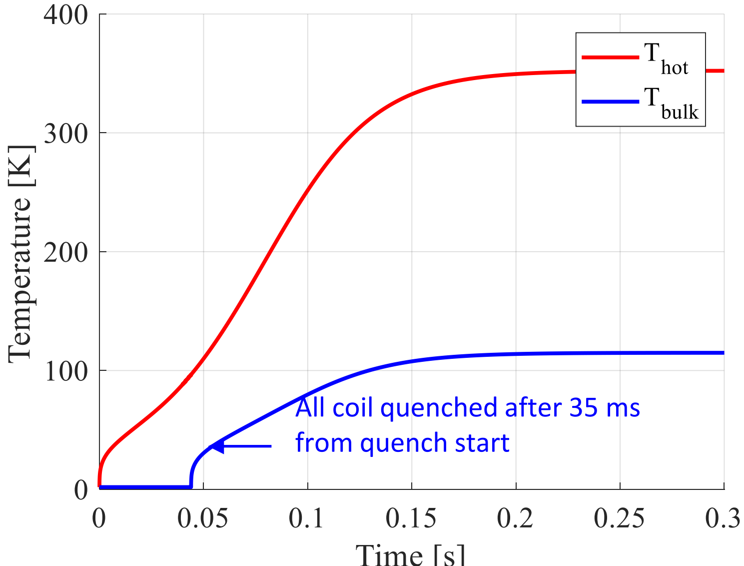
- Reality: we need time to detect, validate and quench the magnet.

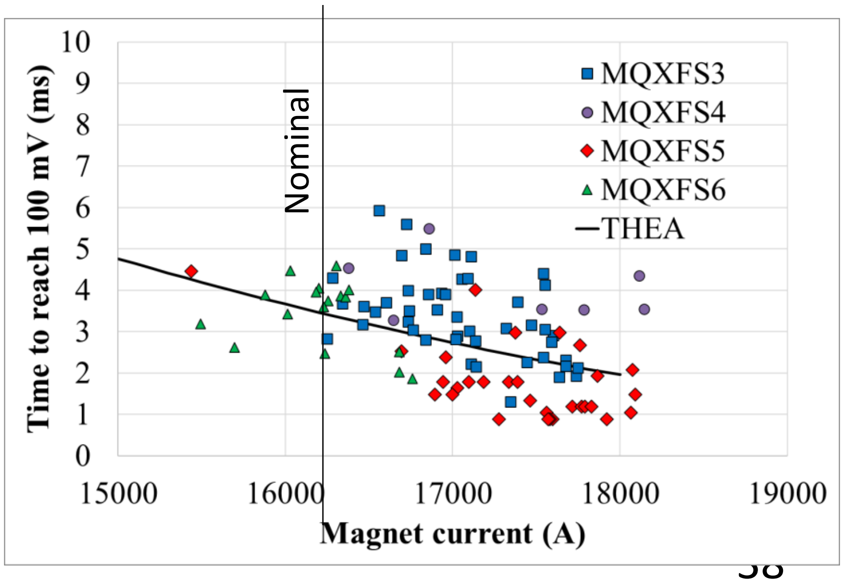
Detection and validation

- The time needed to detect and validate a quench is very expensive in terms of temperature rise. And here is where current density become critical!
- The detection threshold are defined through two parameters:
  - A voltage level (above the noise level) – typically 100 mV → 3-5 ms at nominal
  - A validation time (to reject spurious spikes in voltages) – typically 10 ms
- Voltages staying above voltage level for a time longer than validation time are interpreted as a magnet quench, and activate the protection system
  - Therefore on the time needed to detect the voltage, one has to add the validation time ~ 15 ms

$$\frac{dT_{hot}}{dt} = \frac{I^2}{(A_{Cu} + A_{SC} + A_{ins}) \cdot A_{Cu} \cdot \Gamma(T,B)}$$

$$\Gamma(T,B) = \frac{\overline{C}(T)}{\eta_{Cu}(T,B)}$$



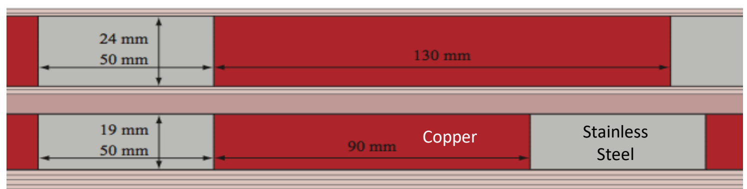


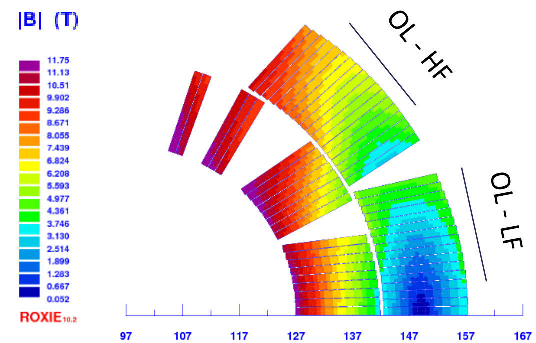
Quench initiation: quench heaters

- Principle: temperature rise in the conductor through the heating of metal strips attached to the coil.
- They are typically installed in the outer surface of the coil
- Time required to induce a quench at nominal ~ 10 ms

11 T Heater Lay-Out (only outer layer heaters)

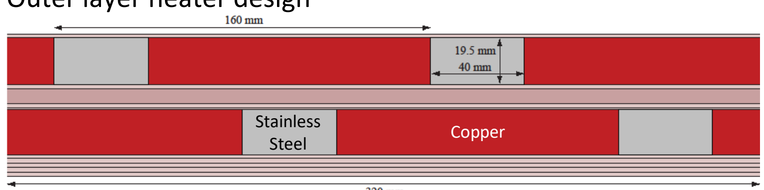
Outer layer heater design



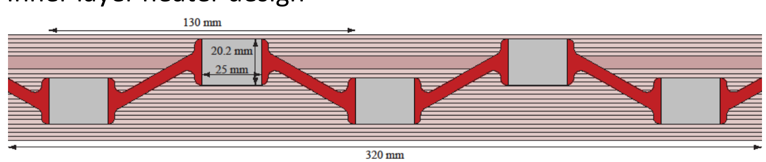


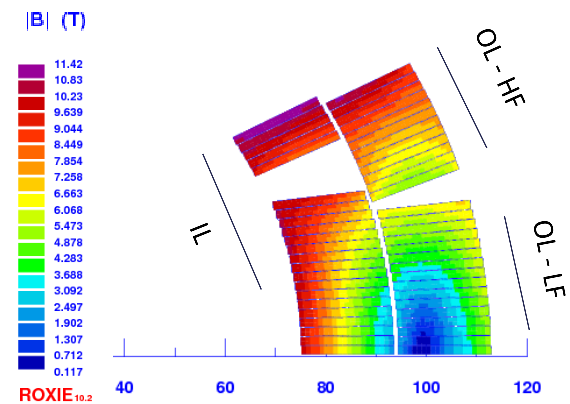
MQXF Heater Lay-Out (heater in the inner and outer layers)

Outer layer heater design



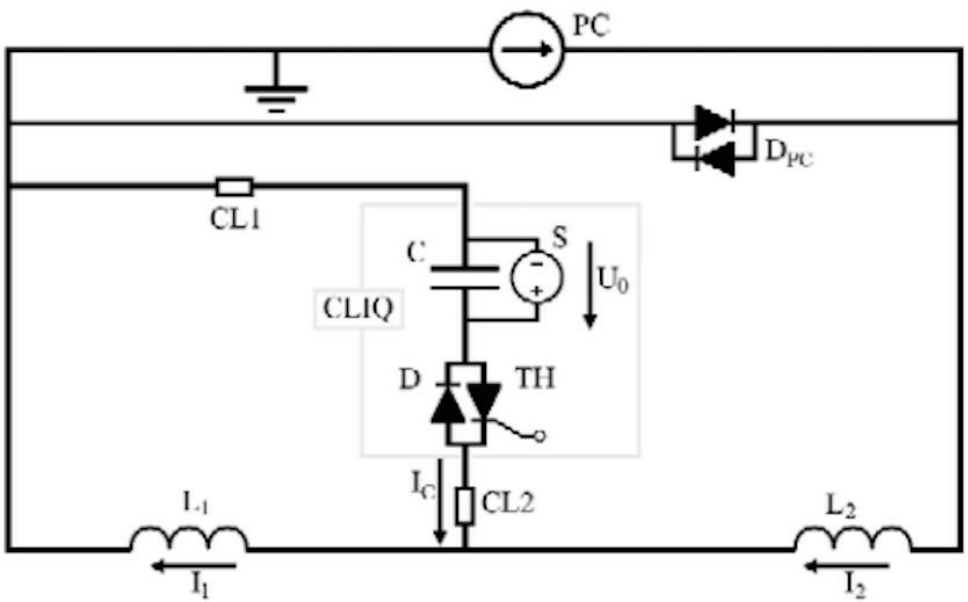
Inner layer heater design





Quench initiation: CLIQ

- CLIQ (Coupling Losses Induced Quench)
  - This system is based on injecting in the magnet coils two opposite impulses of current via a capacitor
  - The mechanism is the heating due to interfilament coupling losses induced by the variation of the field
    - It has been developed at CERN and patented in 2014 (EP13174323.9)

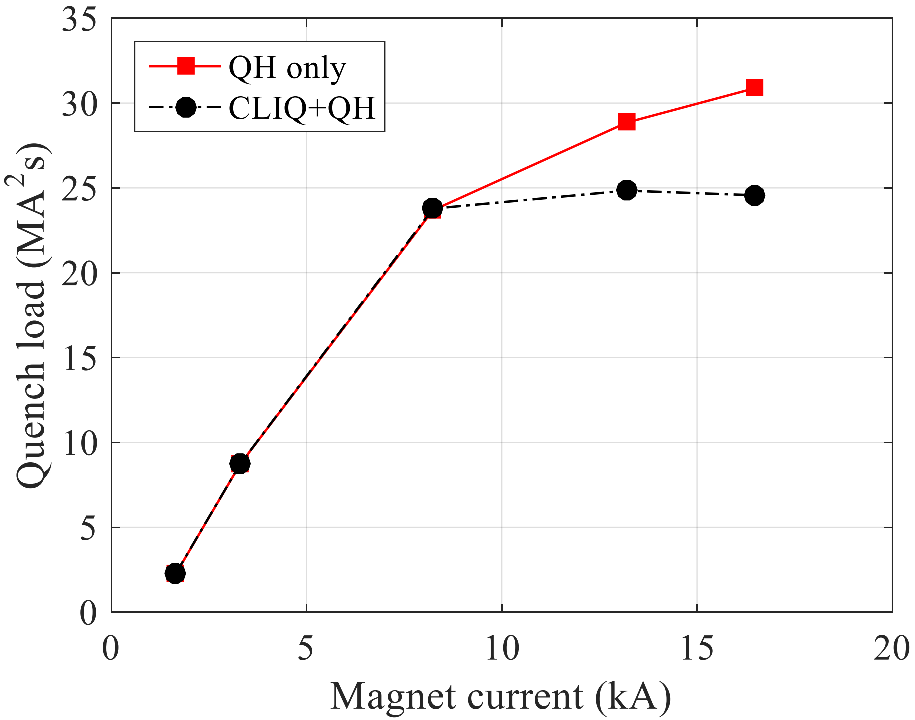


Electrical scheme of CLIQ implementation in a dipole
G. Kirby, V. Datskov, E. Ravaioli et al. IEEE TAS 24 (2014) 0500905

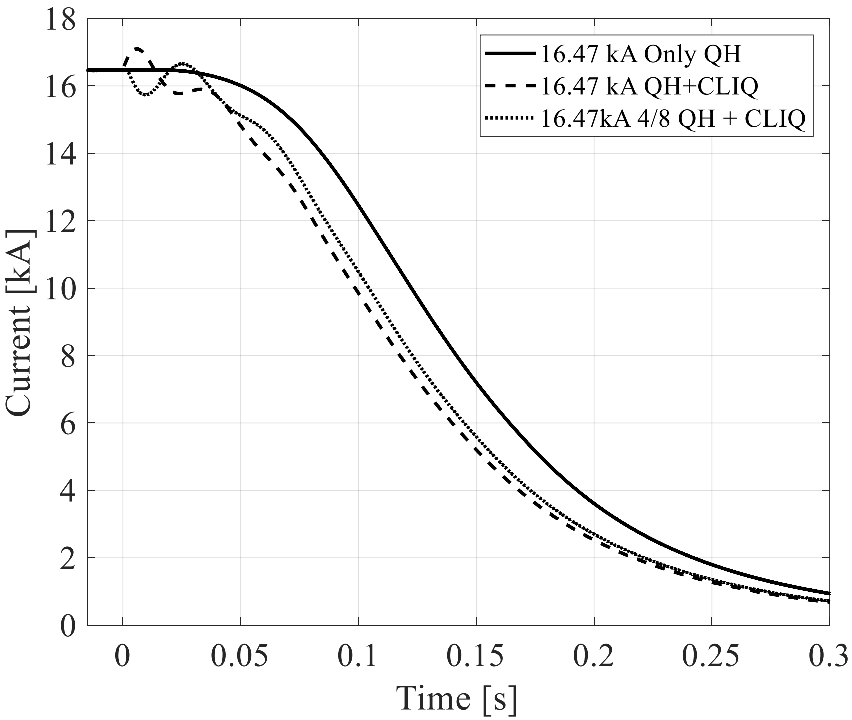
The case of MQXF

- The baseline protection scheme of the HL-LHC MQXF quadrupole relays on CLIQ + QH, a prima for accelerator magnets.
- CLIQ + QH, provides a redundant protection system. In the case of MQXF, it reduces the quench load by 20 % at high current, decreasing the hot spot temperature by~ 100 K (~350 K QH only, ~250 K QH+CLIQ).

Comparison of quench load in MQXF magnets when protected only with QH and QH+CLIQ



Current decay in MQXF for CLIQ + QH or QH only protection



Summary

- Magnet protection concerns two different phenomena: increase of temperature (joule heating) and increase of voltage (transition to resistive state).
- The two key parameters for the protection of a magnet are:
  - Current density in the copper (heating rate)
  - Energy density in the coil (needs to be dissipated in the coil enthalpy)
- A resistor in series with the magnet allows to dump part of the energy, but it is not effective for long magnets or magnets in a string due to the voltage limitation.
- For long and high current density, the protection relies on the induction of a rapid transition to resistive state in the full coil.
  - In the LHC-MB NbTi magnets, the time margin is ≈ 100 ms.
  - In the HL-LHC Nb_3Sn magnets, the time margin is ≈ 40 ms.
- Two systems to induce a resistive transition in the full coil:
  - Quench heaters: temperature rise in the conductor through the heating of metal strips attached to the coil.
  - CLIQ: temperature rise in the conductor through the inter-filament coupling losses induced by the variation of the field.

References

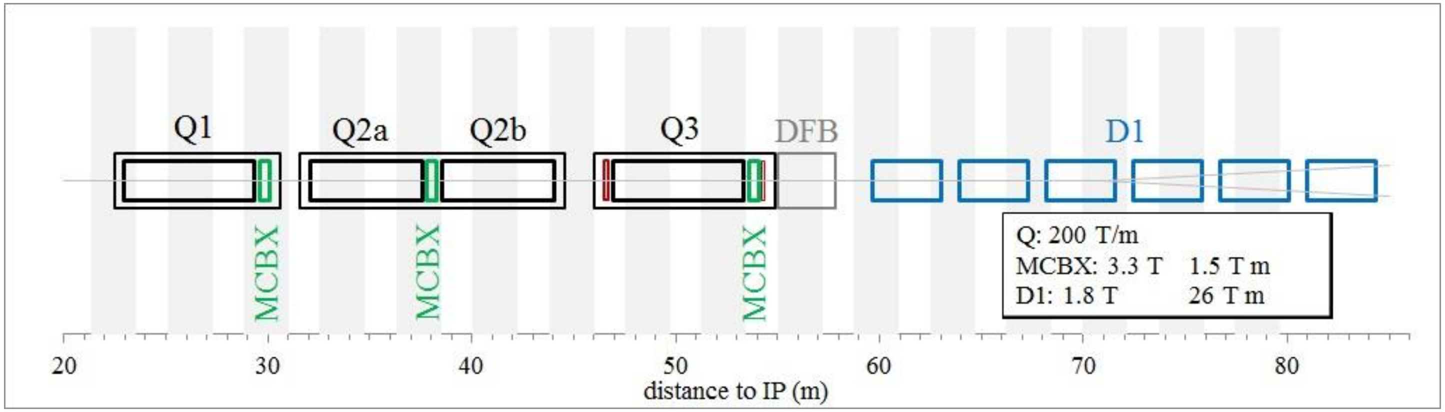
- General principles and equations:
  - M.K. Wilson, Superconducting Magnets, Oxford, Clarendon Press, 1983.
- More on quench propagation and scaling :
  - A. Devred, General Formulas for the adiabatic propagation velocity of the normal zone, IEEE Trans on Magnetics, Vol. 25, No. 2, March 1989
  - E. Todesco, "Quench limits in the next generation of magnets" CERN Yellow Report 2013-006 10-16
  - S. Izquierdo Bermudez, et al., Analytical method for the prediction of quench initiation and development in accelerator magnets, Cryogenics, Volume 95, October 2018, Pages 102-109
- U.S. Particle Accelerator School, lectures from Ezio Todesco, http://etodesco.web.cern.ch/etodesco/
- Wide literature on specific results on magnets and outlook for future magnets, for instance
  - H. Felice, et al., "Instrumentation and quench protection for LARP Nb3Sn magnets" IEEE Trans. Appl. Supercond. 19 (2009) 2458-2462
  - S. Izquierdo Bermudez, et al., "Overview of the quench heater performance for MQXF, the Nb_3Sn low-beta quadrupole for the high-luminosity LHC" IEEE Trans. Appl. Supercond. 28 (2018) 4008406
  - T. Salmi, et al., "Quench protection analysis integrated in the design of dipoles for the Future Circular Collider" Phys. Rev. STAB 20 (2017)

Outline

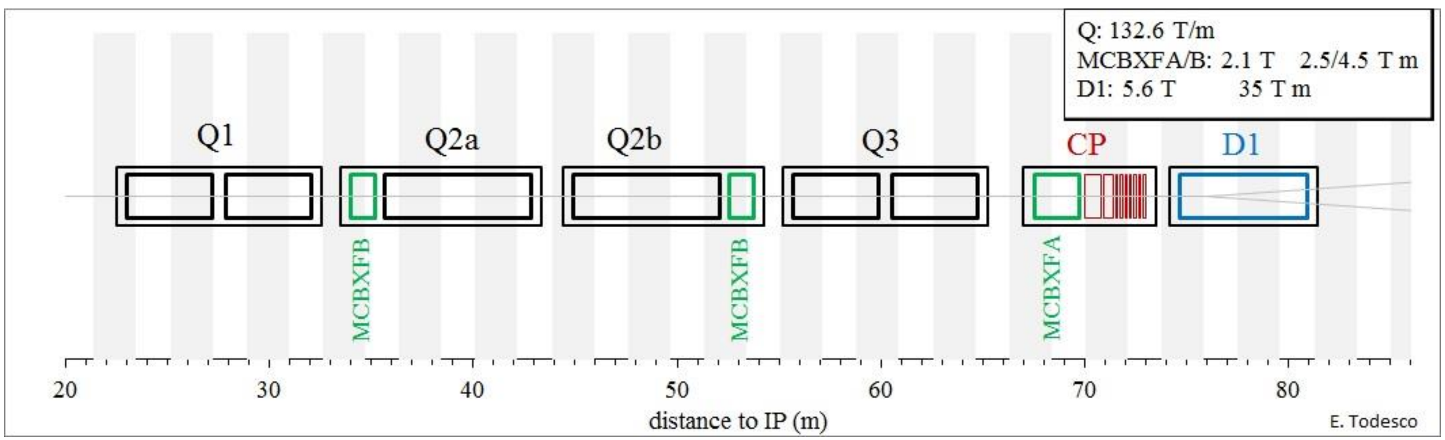
- Part I
  - Particle accelerators, magnets and the need of superconductors
  - Magnetic design and coil fabrication
- Part II
  - Mechanical design and assembly
  - Quench, training and protection
  - Future outlook

HL-LHC

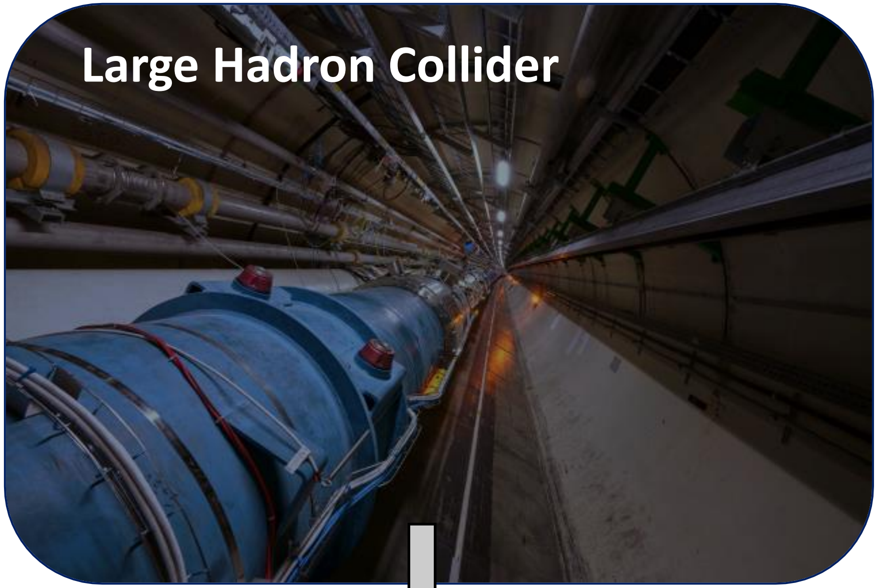
- The IR LHC today:



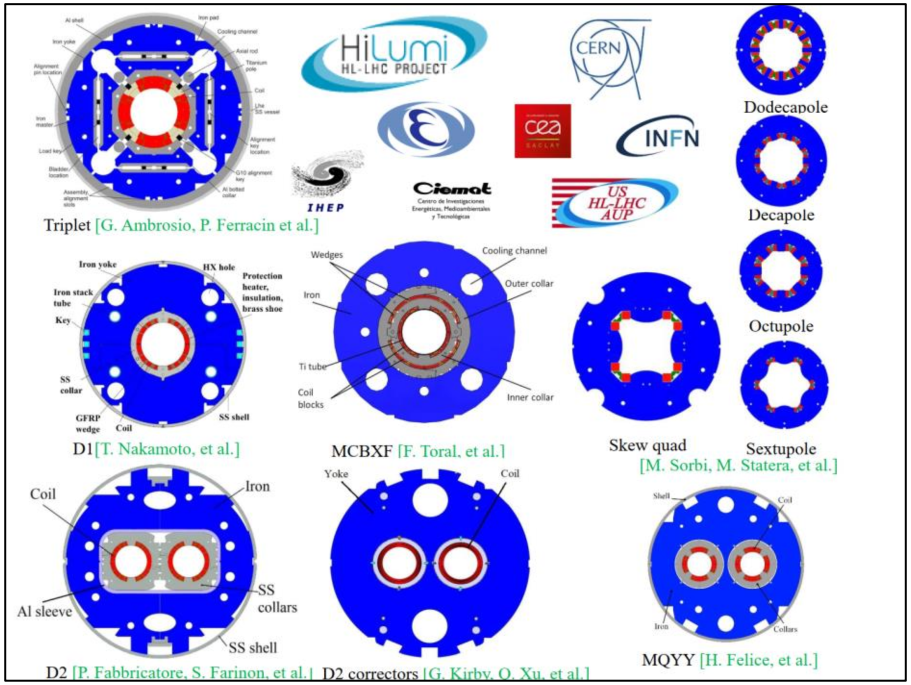
- The HL-LHC IR:



HL-LHC

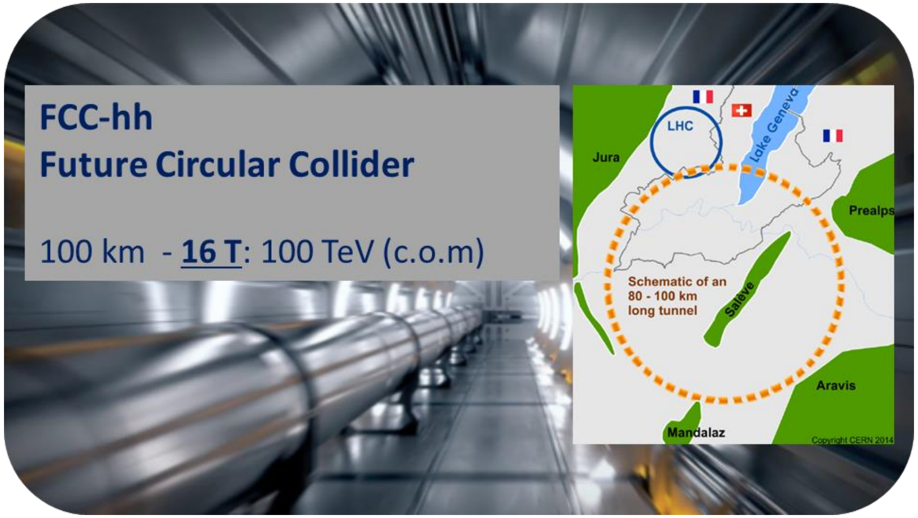


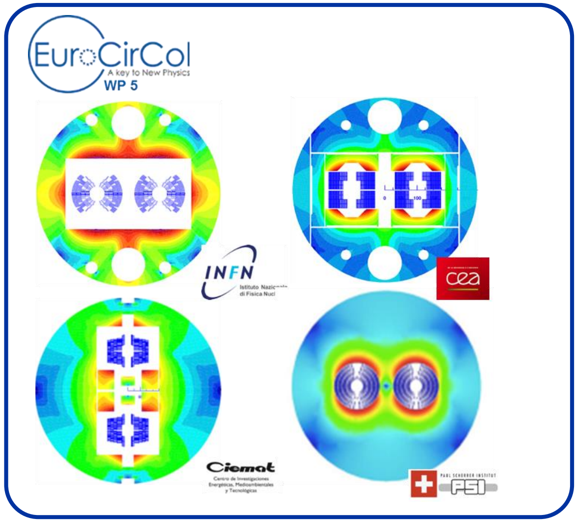
- A large variety of (fun) magnets
- Challenge associated with the production of the first Nb_3Sn accelerator-ready magnets

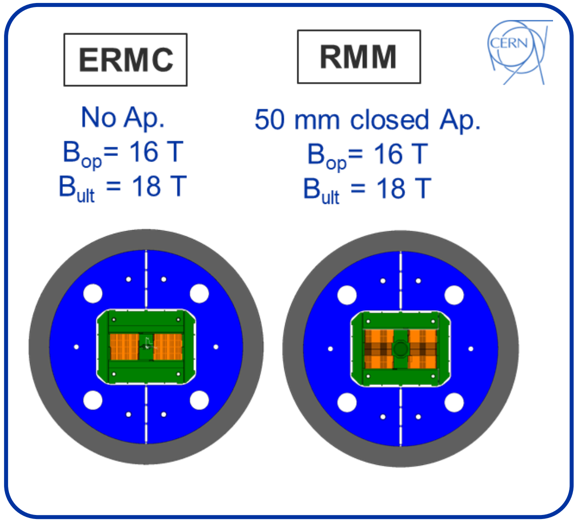


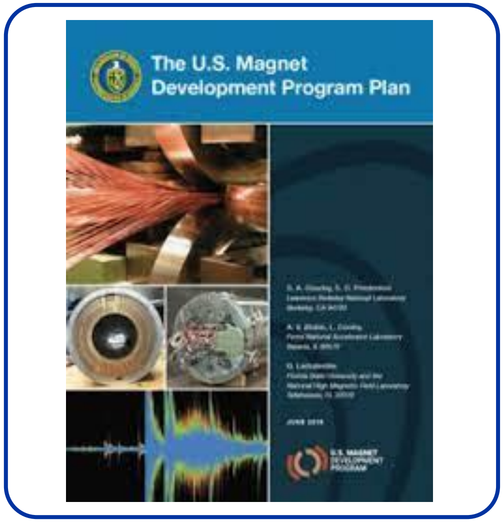
What is next?

- From a magnet perspective,
  - explore the limits of Nb_3Sn and industrialize the technology.
  - develop high temperature superconductors (HTS)
- High Field Magnet (HFM) program coordinates these efforts in Europe
  - Collaboration agreements between CERN and EU institutes to build demonstrators
  - CERN also working on small scale demonstrators to explore the limits
- US Magnet Development Program (MDP), pushing magnets beyond the present state of the art (https://usmdp.lbl.gov/)



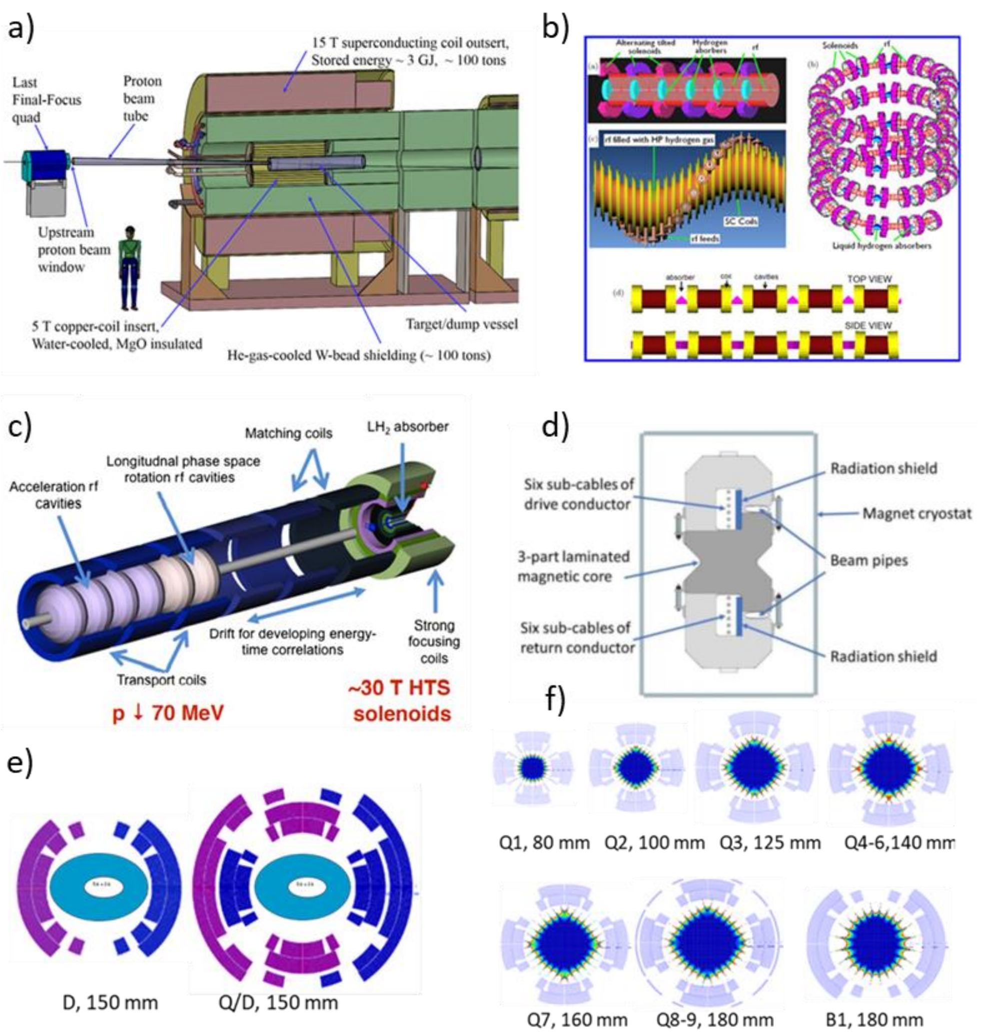


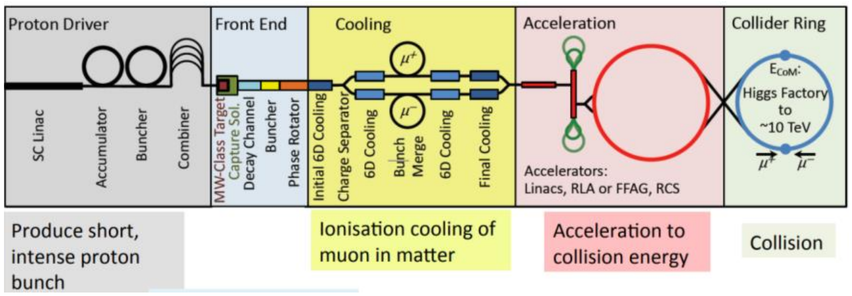




What is next?

- Other machines that also offer a great variety of challenges for magnet builders are also being explored, such as the muon collider
  - a) production solenoid;
  - b) 6D muon cooling solenoids:
  - c) final muon cooling system;
  - d) fust-cycling muon acceleration magnet;
  - e) collider ring magnets;
  - f) IR magnets.
- See https://muoncollider.web.cern.ch/

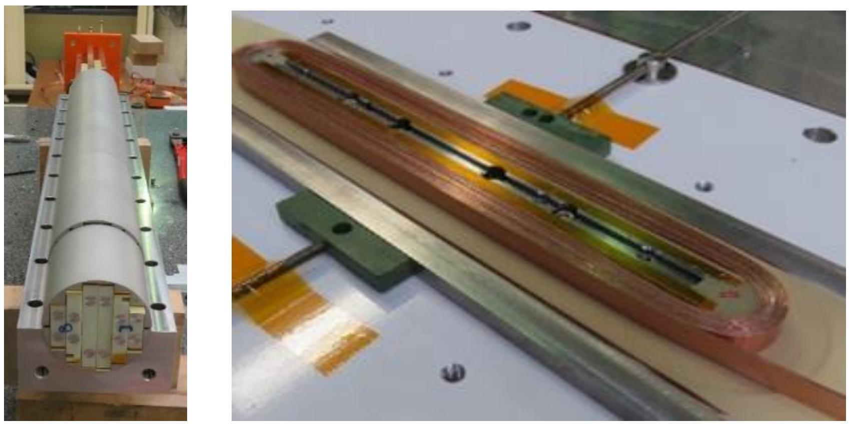




Beyond LTS: the broad world of HTS

- The broad world of HTS, opens the door to fields > 16 T
- So far, most of the developments focused on HTS inside outsert coils made of Nb_3Sn or NbTi

EUCARD REBCO HST insert

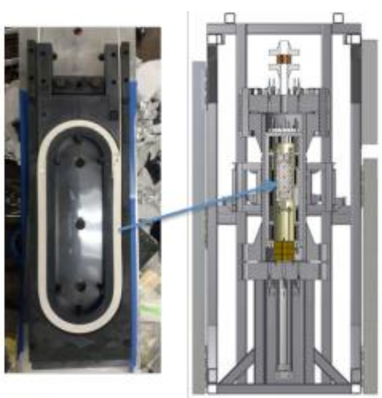


CEA + CRNS Grenoble, J.M. Rey, F. Borgnolutti, M. Durante, CEA-Saclay

FEATHER2 REBCO HST insert

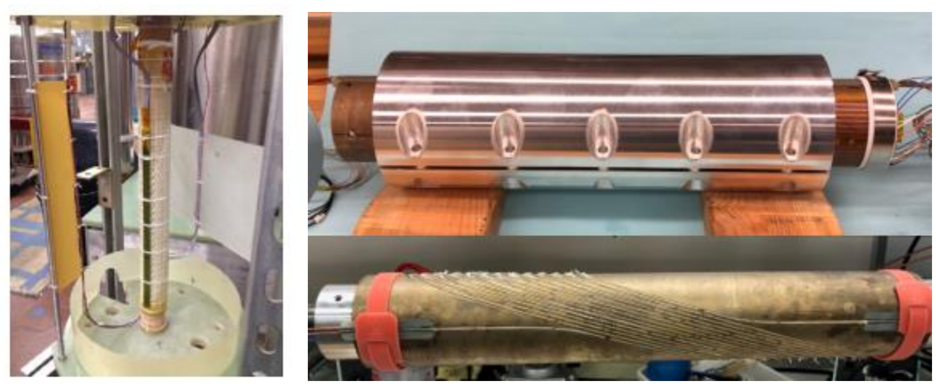
CERN, Gijs the Rijk, Glyn Kirby

Bi-2212 racetracks



MDP, US

Bi-2212 CCT



MDP, US

In conclusion

- Magnet technology is a complex, but very exciting, business: are you convinced?
- There is no magic technology, some are more mature than others.
- There are remaining challenges to go to high field in a robust and reproducible manner.
- The High Field Magnets Program is being launched to tackle these issues.
- The magnet community will need to be creative and pragmatic.
- We need bright minds!

Thank you

For questions, don’t hesitate!

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