SUPERCONDUCTING MAGNETS

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Based on USPAS lectures with P. Ferracin and H. Felice, and S. Prestemon 2005,2008, 2012
and on Milano-Bicocca PhD. Lectures 2017-2019
and on the virtual lectures during the first CoVid-19 wave
https://indico.cern.ch/category/12408/

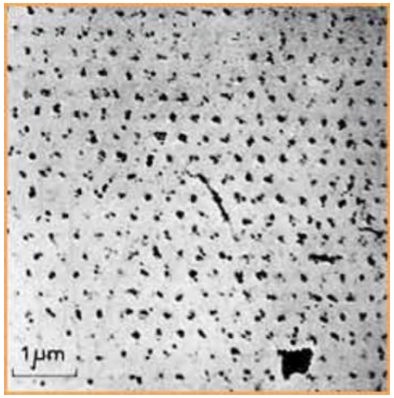
All the units will use International System (meter, kilo, second, ampere) u

FOREWORD

- The science (or the art …) of superconducting magnets is a exciting, fancy and dirty mixture of physics, engineering, and chemistry
  - Chemistry and material science: the quest for superconducting materials with better performances
  - Quantum physics: the key mechanisms of superconductivity and superfluidity
  - Classical electrodynamics: magnet design
  - Mechanical engineering: support structures
  - Electrical engineering: powering of the magnets and their protection
  - Cryogenics: keep them cool …
- The cost optimization is a key element
  - Keep them cheap …

FOREWORD

- An example of the variety of the issues to be taken into account
  - The field of the LHC dipoles (8.3 T) is related to the critical field of Niobium-Titanium (Nb-Ti), which is determined by the microscopic quantum properties of the material, plus aspects related to superconducting magnet design (margins, instabilities, …)



Quantized fluxoids penetrating a superconductor used in accelerator magnets

A 15 m truck unloading a 27 tons LHC dipole

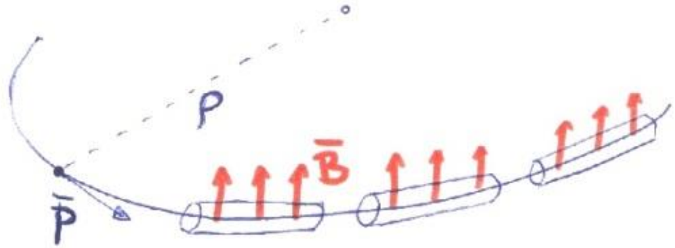
  - The length of the LHC dipoles (15 m) has been determined by the maximal dimensions of (regular) trucks allowed on European roads
- This makes the subject complex, challenging and complete for any physicist or engineer who has the chance of working in this field

CONTENTS

- Requirements on magnets in a circular collider
- Generation of dipolar fields with current lines and the superconducting leap
- Limits: mechanics and protection

- Relation between field, curvature radius and momentum

$$p = eBr$$



- In ultrarelativistic regime $pc >> mc^2$

$$E = \sqrt{p^2c^2 + m^2c^4} \approx pc$$

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

- LHC example: curvature radius is 2800 km, field is 8.3 T, energy is 7000 GeV (i.e. 7 TeV)

$$E[GeV] = 0.3 \times 8.3 \times 2800 = 7000$$

REQUIREMENTS IN A NUTSHELL

- Aperture requirement is given by the beam size

$$\phi = 2n\sqrt{\frac{\varepsilon_i \beta_{\max}}{\gamma_r}} + \phi_0$$

  - γ_r: relativistic gamma factor (at injection)
  - n: number of sigma of the beam (order of 10-15)
  - Maximum beta function β_{max}: given by the sequence of magnets
  - Emittance ε_i: size of the beam provided by the injectors
- LHC arc example:

$$\phi = 30\sqrt{\frac{3.7 \times 10^{-6} \times 170}{490}} + \phi_0 \approx 30 \times 0.001 + 0.015 = 48 \text{ mm}$$

- Beta functions are proportional to the cell semilength L (spacing between quadrupoles)
  - For a 90 degrees phase advance cell
  - LHC example: L=50 m, β_{max}= 170 m

$$\beta = \left(2 \pm \sqrt{2}\right) L$$

REQUIREMENTS IN A NUTSHELL

- Quadrupole integrated strength for a 90 degrees phase advance cell

$$Gl_q = \frac{\sqrt{2}Br}{L}$$

- The longer spacing between quadrupole, the lower the required gradient $1/L$ (but the larger the aperture $\sqrt{L}$)
- LHC quadrupole example:
  - Realized with 210 T/m over 3.15 m

$$Gl_q[\mathrm{T}] = \frac{1.41 \times 8.3 \times 2800}{50} = 650\ \mathrm{T}$$

  - For higher energies, longer spacing between quadrupoles
    - Example: FCC-hh with a double cell lenght L=100 has

$$Gl_q[\mathrm{T}] = \frac{1.41 \times 16 \times 10000}{100} = 2400\ \mathrm{T}$$

- How a sequence of focusing and defocusing can "focus" ?
  - Typical question posed in all lectures about superconducting magnets … see https://indico.cern.ch/event/918320/ for some hints

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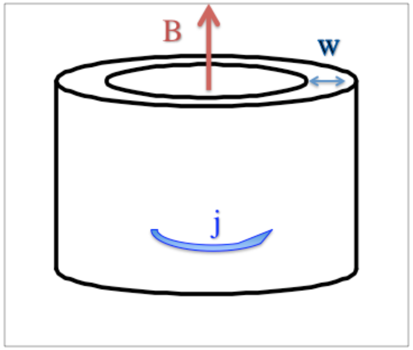
GENERATING DIPOLE FIELDS

- In a solenoid field is given by product of current density and winding width

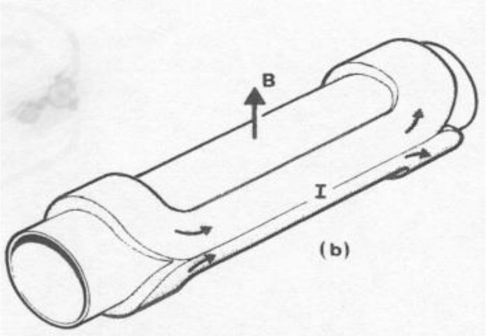
$$B = \mu_0 j w$$

$$B[\mathrm{T}] = 0.00125\, j[\mathrm{A/mm^2}]\, w[\mathrm{mm}]$$



Solenoid

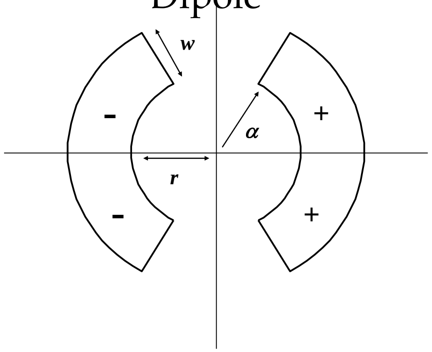
- For a dipole, one has half of this



$$B[\mathrm{T}] \approx 0.00066\, j[\mathrm{A/mm^2}]\, w[\mathrm{mm}]$$

- Example: LHC dipole has ~400 A/mm^2 and 30 mm coil width

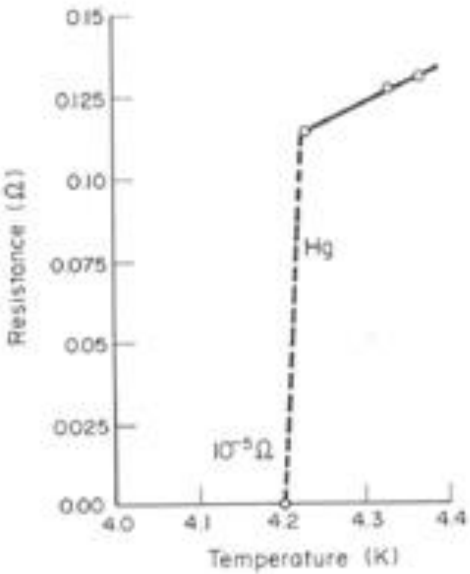
$$B[\mathrm{T}] \approx 0.00066 \times 400 \times 30 = 8 \text{ T}$$



Dipole

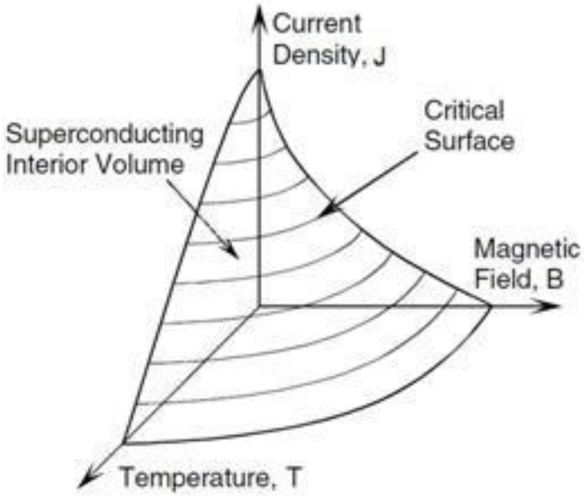
- (see https://indico.cern.ch/event/915752/ for more hints)

- Resistive conductors can operate at 2 to 10 A/mm^2
  - To produce ~ 8 T field, one would need ~1.5 m of coil width ! Huge magnet transverse size also requiring larger tunnel diamater
- Superconductors allow operating at 100 times larger current densities (and without power consumption) – typically at order of ~500 A/mm^2 overall density (current / surface of insulated coil)
  - Discovery in 1911, but took 50 years to apply to build electromagnets! (see https://indico.cern.ch/event/920892/ for more hints)



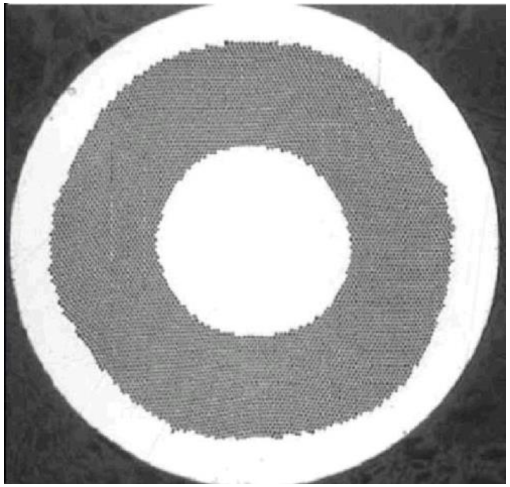
Heinke Kamerlingh Onnes

(1853 –1928) Nobel prize 1913

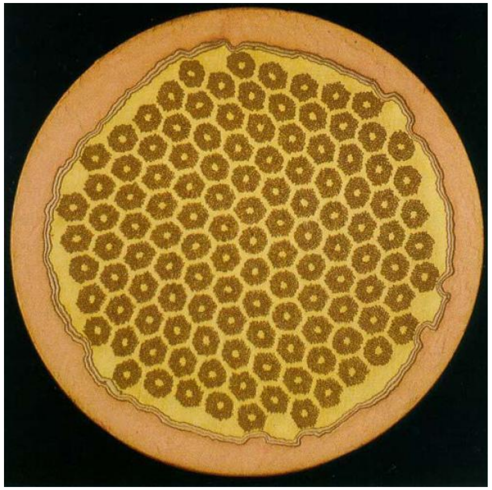


Superconductor critical surface

- A bulk superconductor cannot be used in superconducting magnets (see https://indico.cern.ch/event/920904/ for more hints)
  - About half of the strand must be composed of Cu to allow the longitudinal dissipation of the heat in case of resistive transition – otherwise the heat locally diverges
  - The superconductor magnetization creates instabilities (heat dissipation followed by thermal runaway) – superconductor must be arranged in filaments not larger than ~0.01 to 0.1 mm



Nb-Ti strand used for the LHC dipole
filament size 6-7 μm

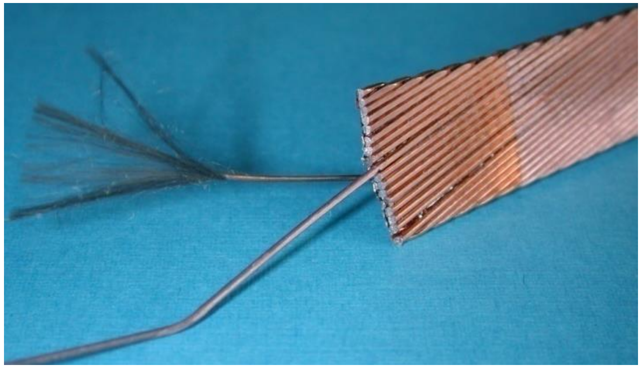


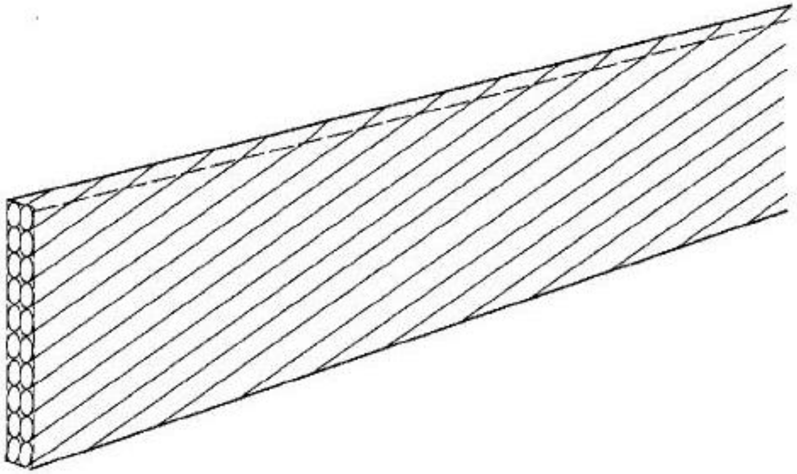
About 1 mm

Nb_3Sn strand used in LARP
filament size ≈50 μm

CABLE ARCHITECTURE AND FILLING FACTOR

- Superconducting strands are assembled in high current cables to allow more effective winding and to lower the magnet inductance
  - Rutherford cable is the typical geometry
  - Cables are insulated with polymide/fiberglass, 0.10-0.15 mm thick
  - (see https://indico.cern.ch/event/925559/ for more hints)
- An insulated cable contains 1/3 to ¼ of superconductor, and therefore typical operational currents in the superconductor are order of ~1500 A/mm^2

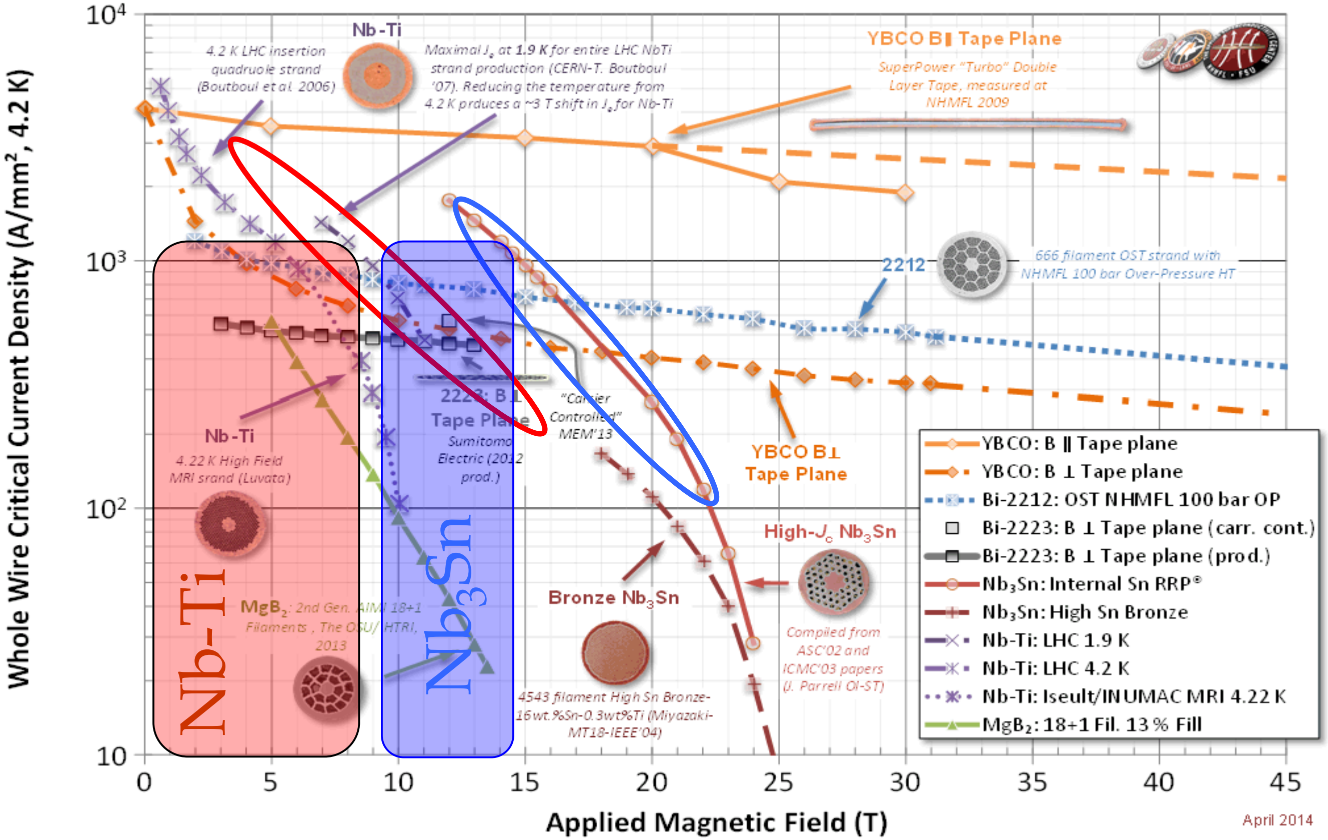




Rutherford cables

PRACTICAL SUPERCONDUCTORS

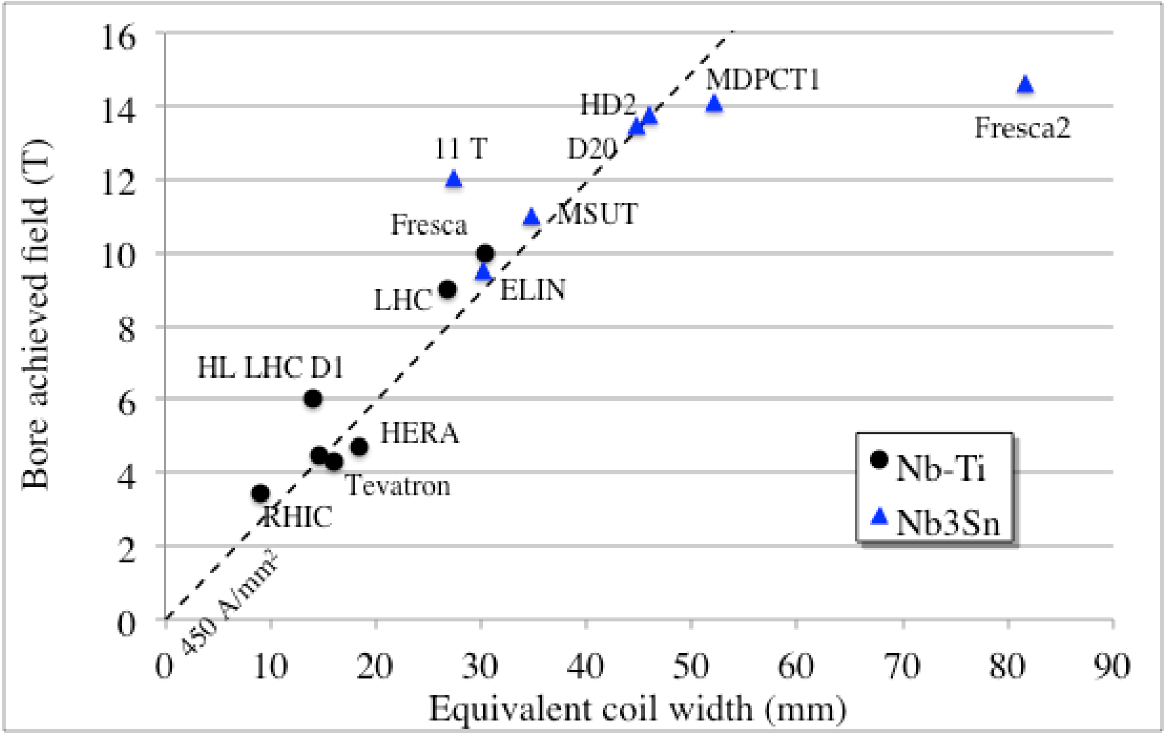
- Superconductive state is destroyed by large temperatures, large current densities, and large magnetic fields
- LTS: low temperature superconductors, operating below 10 K, are used in accelerator magnets



Superconductor critical surfaces at 4.5 K and 1.9 K (P. Lee)

ACHIEVED FIELDS

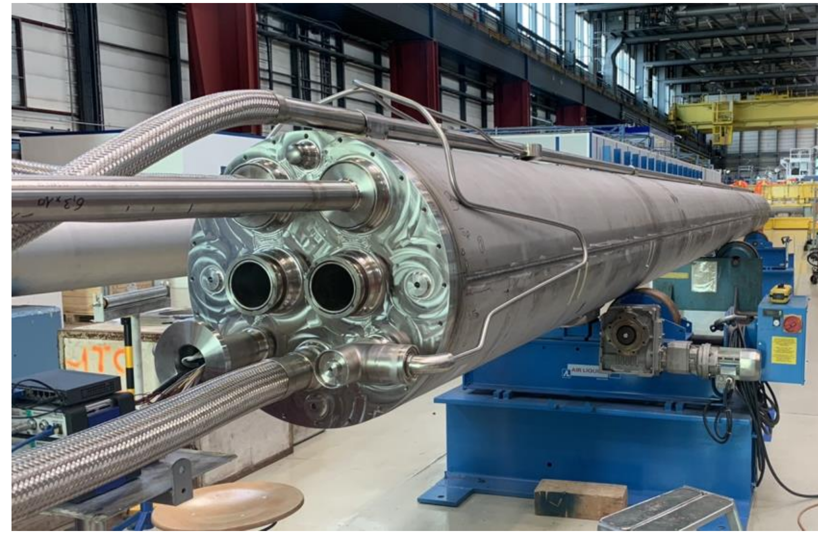
- Nb-Ti can provide up to 8 T (massive production) and up to 10 T (in single magnets)
- Nb_3Sn reached 14-15 T range in short models
  - Coils width up to ~80 to 100 mm were successfully explored, 40 to 50 mm width is what can be envisaged for a large scale production (FCC-hh or HE-LHC)
- HTS can go well above 15 T, but conductor cost is today a major showstopper



Bore field versus coil width for accelerator superconducting magnets

GALLERY

LHC dipole unload at test station



HL-LHC D2 dipole (CERN and INFN collaboration)

MQXF Nb3Sn magnets in FNAL

Nb_3Sn coil of 11 T dipole

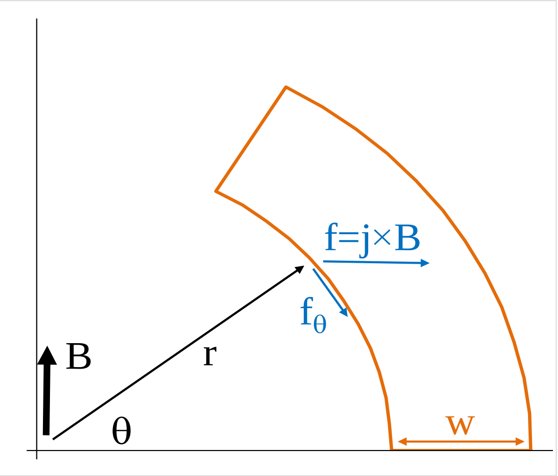
CONTENTS

- Requirements on magnets in a circular collider
- Generation of dipolar fields with current lines and the superconducting leap
- Limits: mechanics and protection

LIMITS: FORCES

- Electromagnetic forces induce a stress accumulation on the midplane that can be estimated (one the edge of the aperture) as

$$\sigma = \frac{jBr}{2}$$



  - Inside the magnet the stress further increases, but we neglect here this complexity

  see https://indico.cern.ch/event/926964/

- In practical units

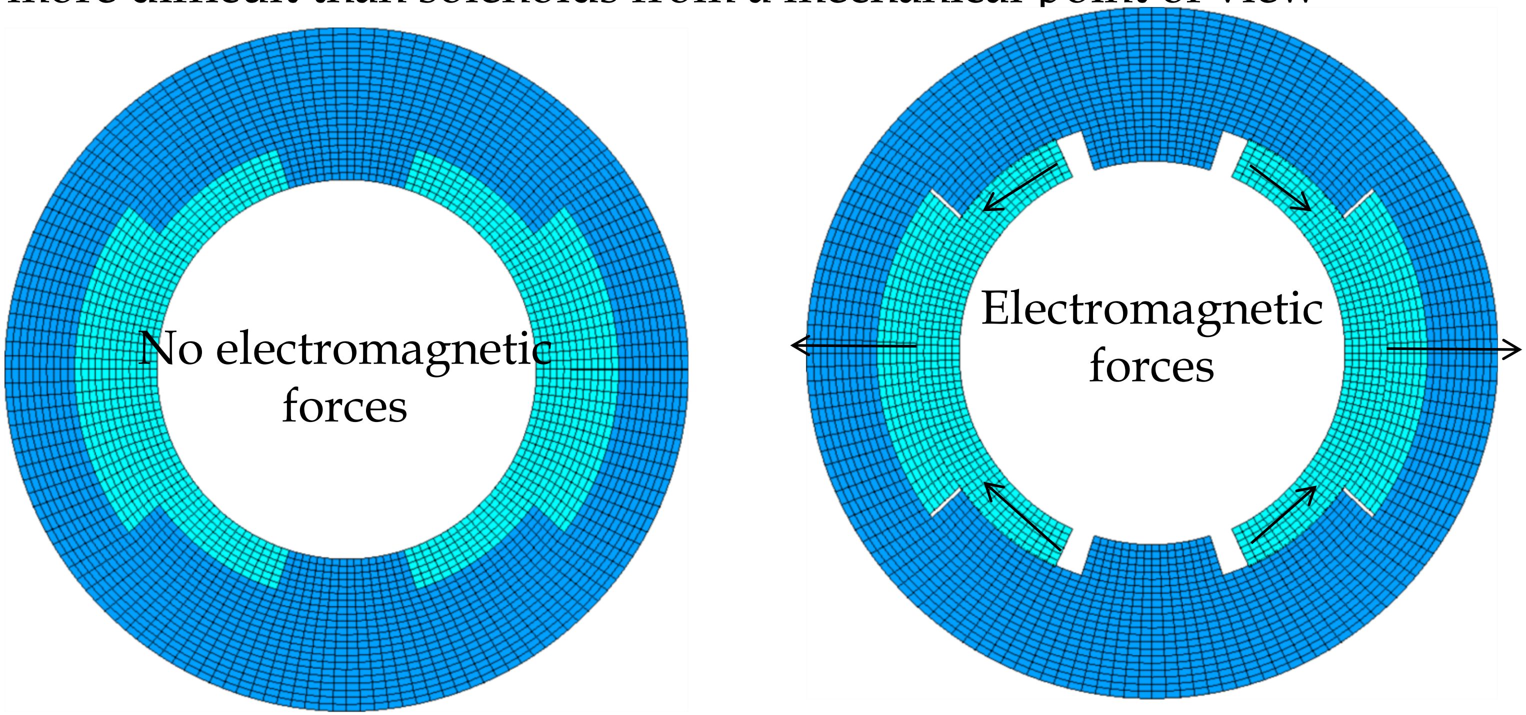
$$\sigma[\mathrm{MPa}] = \frac{j[\mathrm{A/mm^2}]\,B[\mathrm{T}]\,r[\mathrm{mm}]}{2000}$$

- Example: LHC dipole has ~ 400 A/mm^2 and 28 mm aperture radius

$$\sigma[\mathrm{MPa}] = \frac{400 \times 8.3 \times 28}{2000} = 45$$

STRUCTURES TO CONTAIN FORCES

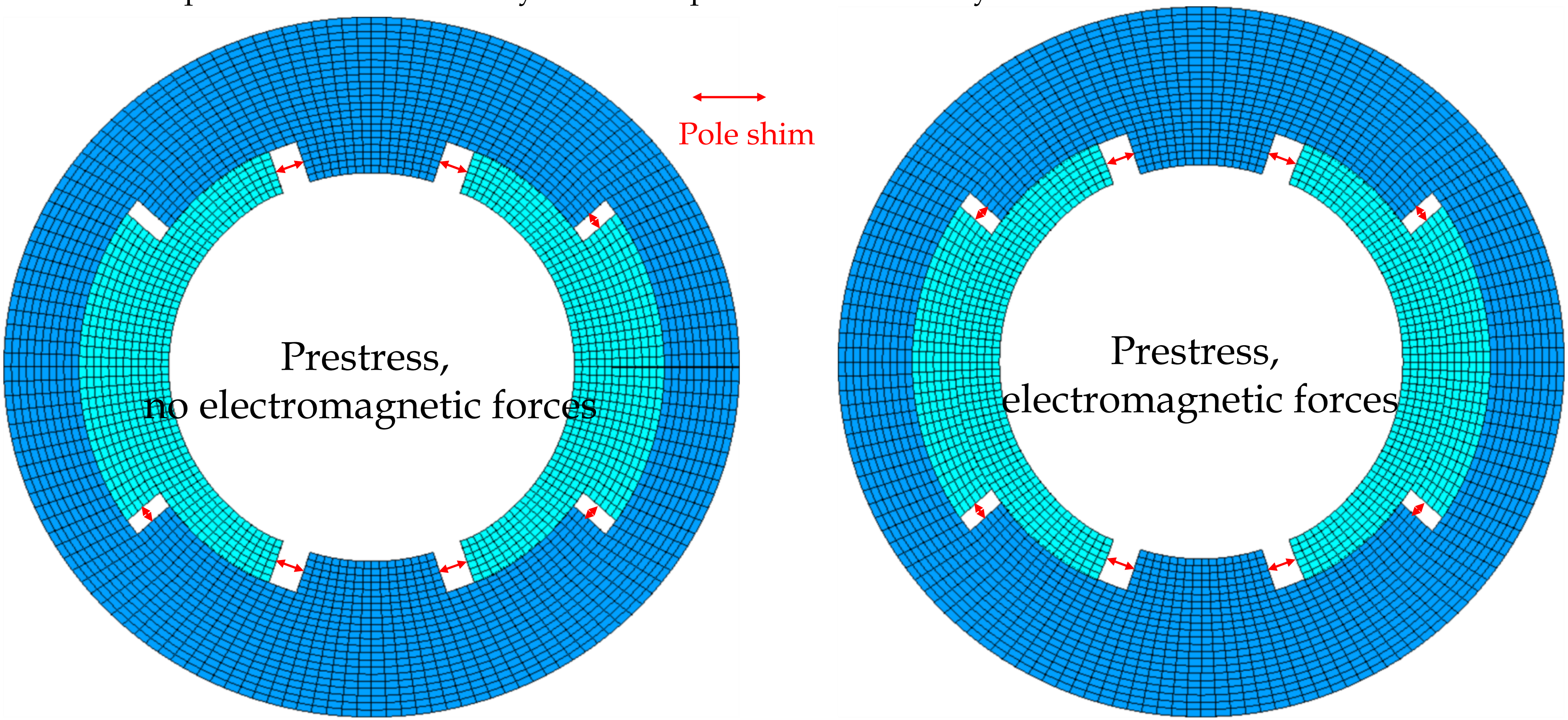
- In a solenoid, forces are orthogonal to the winding
  - Therefore, if the cable is strong enough, it can support the forces all alone
- In a dipole, forces tend to open the winding (and transform it in a solenoid)
  - Therefore a containment structure is needed – this makes the dipoles much more difficult than solenoids from a mechanical point of view



Tevatron dipole coil and collars, without and with electromagnetic forces (courtesy of P. Ferracin)

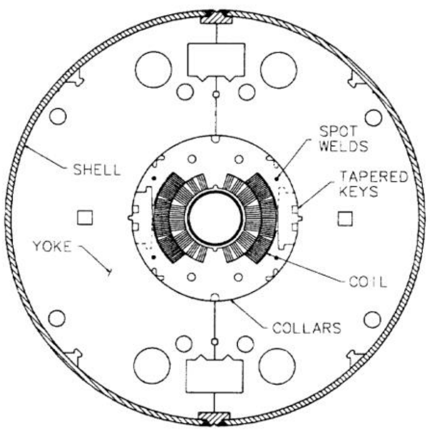
PRESTRESS PARADIGM

- To avoid movements inside the structure, coils are prestressed
  - This avoids "large" (order of 1 mm) movements of conductors during the magnet operation
  - Partial prestress (i.e. accepting a tension state or coil detachment at nominal current) is also possible – this is a widely debated topic in our community

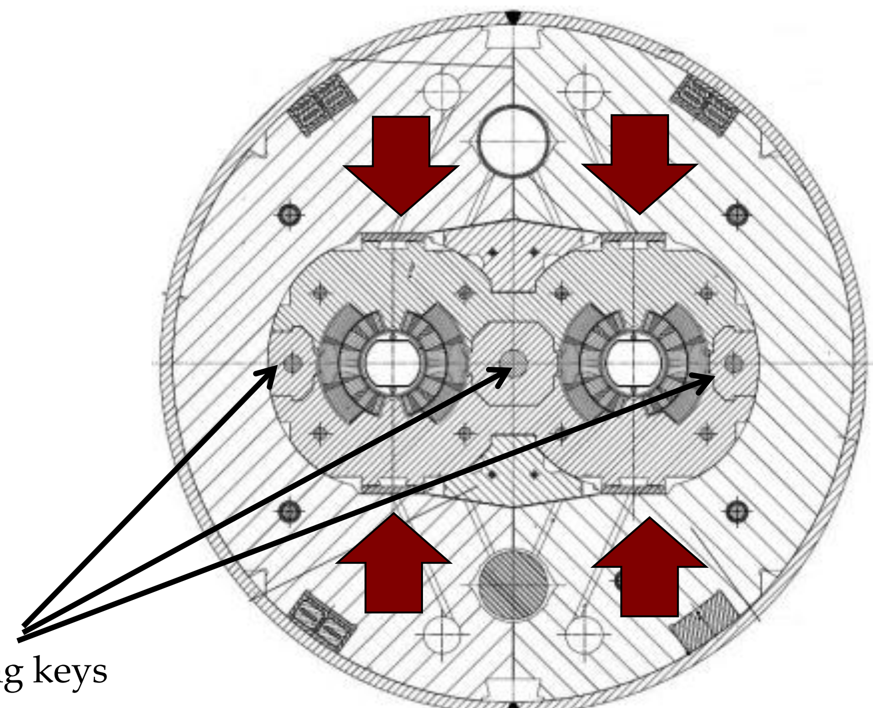


Tevatron dipole coil and collars, without and with electromagnetic forces when prestressed (courtesy of P. Ferracin)

- Structures based on self-standing stainless steel collars
  - Used in massive production (Tevatron, LHC), difficult to achieve large preloads at 1.9 K (more than 50 MPa) due to the large preload loss during cool-down – can partially profit of iron support
  - Example: SSC dipoles, LHC dipoles, 11 T Nb_3Sn dipole



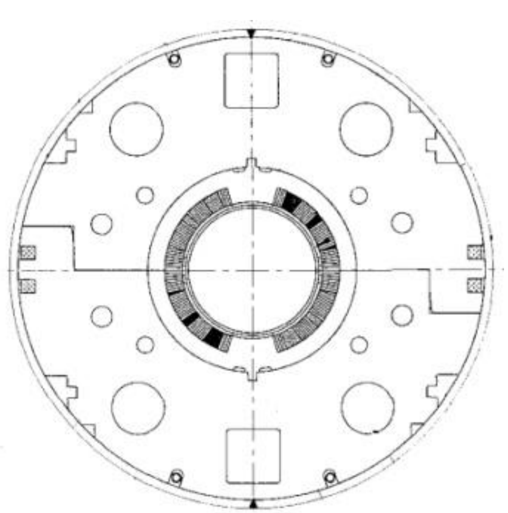
SSC dipole (6 T)



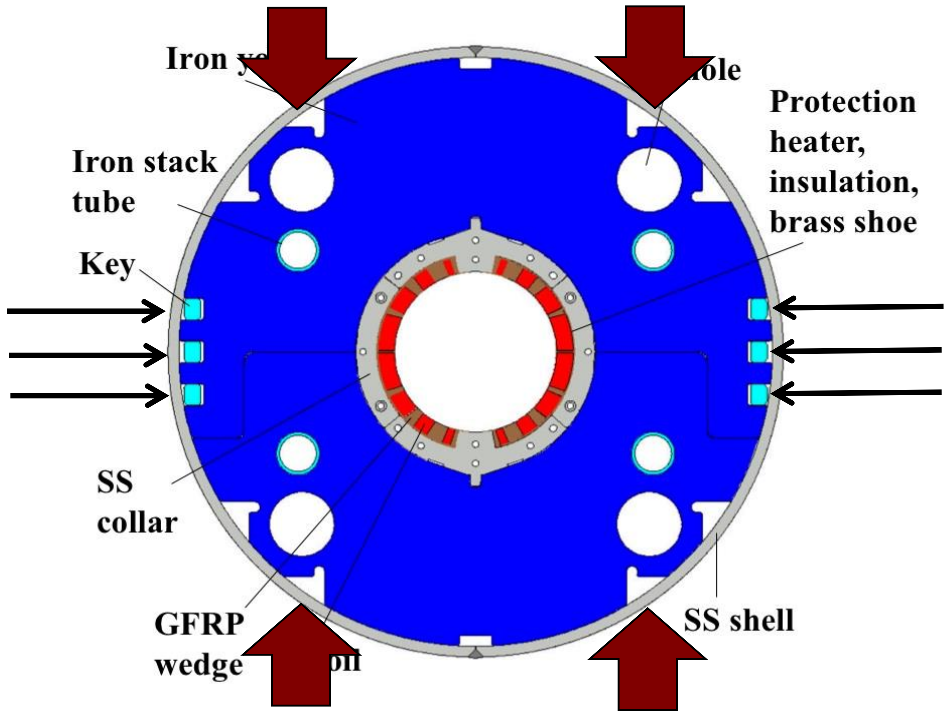
Collaring keys

LHC main dipole (MB, 8 T), with assembly forces (red arrows) and keys (black arrows)

- Structures based on the iron yoke
  - Used in massive productions (RHIC), more interfaces but larger preloads 1.9 K are possible (order of 100 MPa)
  - Example: RHIC dipoles or HL-LHC D1 dipoles



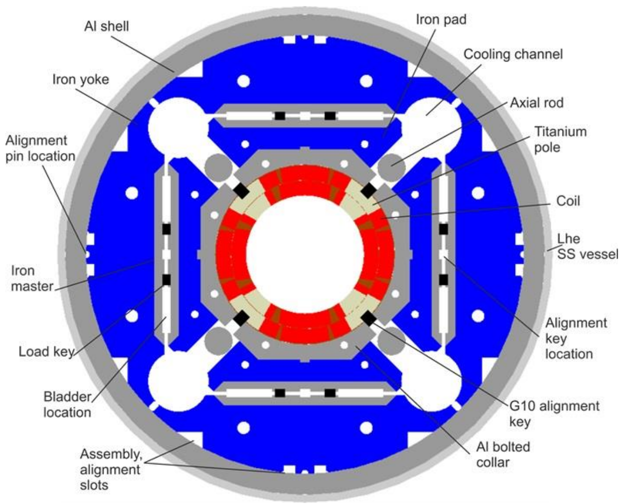
RHIC dipole (3.5 T)



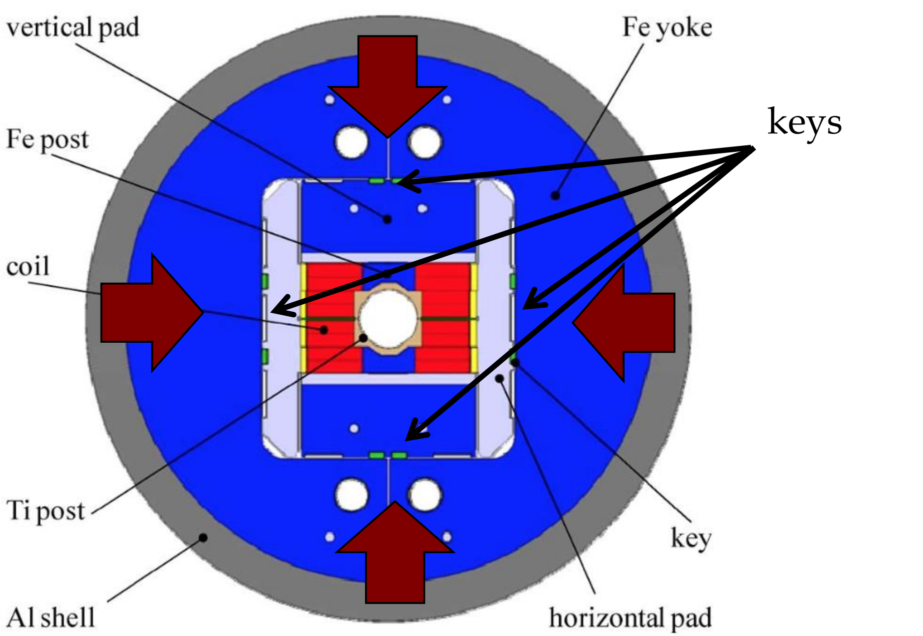
HL-LHC D1 dipole (6 T),
with assembly forces (red arrows) and keys (black arrows)

THREE FAMILIES OF STRUCTURES: THIRD

- Structures based on Al shells
  - Developed for R&D magnets, the highest preloads are possible (up to 150 MPa, and are achieved at 1.9 K thanks to Al thermal contraction)
  - Example: LARP quadrupoles, HD2, Nb_3Sn HL-LHC triplet



MQXF quadrupole (11.5 T peak field, >13 T reached)



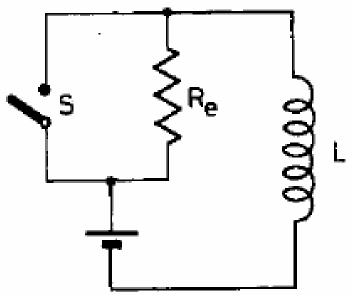
HD2 dipole (13.4 T bore field reached)
with assembly forces at 1.9 K (red arrows) and keys (black arrows)

LIMITS DUE TO FORCES

- If we had a much better superconductor, able to carry, for instance, ten times more current density (~15000 A/mm^2), this would be difficult to use above 10 T and for typical apertures of main dipoles of colliders (aperture radius *r* 25 to 50 mm) since stress would become ~500 MPa
- This would pose issues to different aspects
  - Superconductor: in particular Nb_3Sn has a degradation limit in the >150 MPa range
  - Insulation used in cables withstands order of 200 MPa (one could go for thicker insulation, but then current density would be much more diluted and what counts is the overall current density (over insulated coil)
  - Materials used in the structure to keep the coils can reach the yield limit

LIMITS: PROTECTION

- When the magnet goes through a transition to normal state, the energy stored in the magnet has to be removed or distributed in the magnet to avoid that the coil locally goes above room temperature
  - Energy extraction can be done inserting a dump resistor in series to the magnet – circuit becomes a LR, with time constant $\tau = L/R$
  - Large dump resistor can reduce the time constant, i.e. the total heating induced by Joule effect – but it induces a voltage $V=RI$ that cannot exceed the limits given by insulation (typically 1 kV)



- Example: LHC U=7 MJ, I_0= 12 kA, R_d=50 mΩ, V_d=600 V, L=100 mH, τ= 2 s, only a very small fraction of the energy can be extracted
- The only alternative for long magnet is to dissipate all the energy inside the winding by inducing a resistive transition everywhere in the coil (via heating)

HOW ENERGY CAN BE RELATIVE

- A typical argument used to show how large is the stored energy in the magnetic field of the LHC dipoles (7 MJ) is to compare to the kinetic energy of a 20 tons lorry at 100 km/h
  - U=mv²/2 = 20 000 × 28² / 2 = 7.7 MJ
  - m=20 tons
  - v=100 km/h = 28 m/s

A 7 MJ lorry (S. Spielberg, "Duel" Universal Pictures, 1971)

HOW ENERGY CAN BE RELATIVE

- On the other hand I can also convince you that the stored energy is small …
  - A glass of gasoline
  - Gasoline has stored energy of about 50 MJ/kg
  - That's why it is so difficult to get rid of fossil fuels …

- So protecting the LHC dipole is equivalent to burn a glass of gasoline at 1.9 K and avoid that any part of the magnet goes above 300 K

- How many dipoles can you eat?
  - BigMac has 550 cal
  - Please note that this means 550 kcal

- 1 cal = 4.18 J
  - 1 Big Mac = 2 MJ
  - 3 Big Mac + 1 French fries = 1 LHC dipole

- The idea of quench heaters is to heat the coil to bring the superconductor above the critical surface
    - All the coil becomes resisitive, large resistance reduces τ, and energy is distributed over the whole mass of the coil
- Quench heaters are strips of stainless steel where an impulse of current is put as soon as the quench is detected
    - Capacitor discharge
- Strips heat thanks to Joule heating, and give heat power to the coil
- The reaction time that can be obtained is of the order of 10-50 ms

Quench heaters in HQ magnet (courtesy of H. Felice and LARP teams)

LIMITS: PROTECTION

- What is the limit to this approach? The energy density in the coil should not be larger than the integral of the specific heat of the coil from 2 K to 300 K
  - Typically, the integral of the specific heat of a coil is order of 0.5 J/mm^3
  - The energy density in the coil of typical Nb-Ti magnets is 0.05 J/mm^3, i.e. 10 times smaller – this leaves about 0.1 s to the protection system to react
  - For Nb_3Sn a double density is possible, but this represents a hard limit, since this barely allows the time (order of 50 ms) to the protection system to react
  - More hints on protection in https://indico.cern.ch/event/926967/ and https://indico.cern.ch/event/940961/

- A conclusion about limits posed by protection: you cannot exceed the enthalpy limit of the coil - 0.5 J/mm^3
  - Even though we had a conductor able to carry 5000 A/mm^2, we could not use it since the energy density in the coil would overcome the enthalpy limit

SUMMARY

- Superconductivity allows not only to have «ecological» electromagnets (no dissipation by Joule effect) …
- … but also to build very compact devices, since it allows much larger current densities
- How large ? 500 A/mm^2 overall (over the insulated coil)
  - This allowed to build Nb-Ti 8 T magnets with a 3 cm thick coil !
  - Nb_3Sn gives the possibility of reaching the 10-15 T range
- Mechanics and protection are two relevant aspects that can be mastered for this range of current densities
  - But in both cases we are close to the limits, and therefore imagining superconducting magnets working with much higher current densities appears not feasible

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- M. N. Wilson «Superconducting magnets» Clarendon Press (Oxford, 1983)
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- CAS proceedings
  - Several courses dedicated to superconductivity
- USPAS (uspas.fnal.gov)
  - Superconducting accelerator magnets, every 2-3 years
- E. Todesco lectures given in 2020 during the first Covid-19 wave https://indico.cern.ch/category/12408/
  - Analytical methods to design superconducting accelerator magnets
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