CERN, 30th July 201
Summer student lectures

Superconducting magnets

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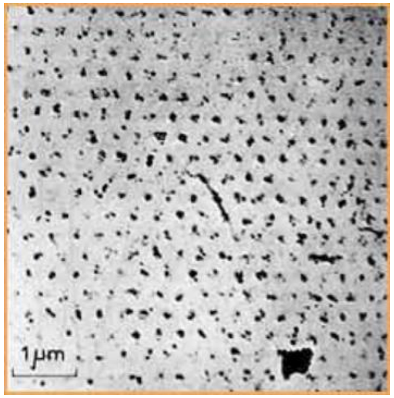
FOREWORD

- The science 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
  - Classical electrodynamics: magnet design
  - Mechanical engineering: support structures
  - Electrical engineering: powering of the magnets and their protection
  - Cryogenics: keep them cool …

- The cost optimization also plays a relevant role
  - 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



Quantized fluxoids penetrating a superconductor used in accelerator magnets

A 15m 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 the formation of a (young) physicist or engineer

FOREWORD

- The size of our objects
  - Length of an high energy physics accelerator: ~Km

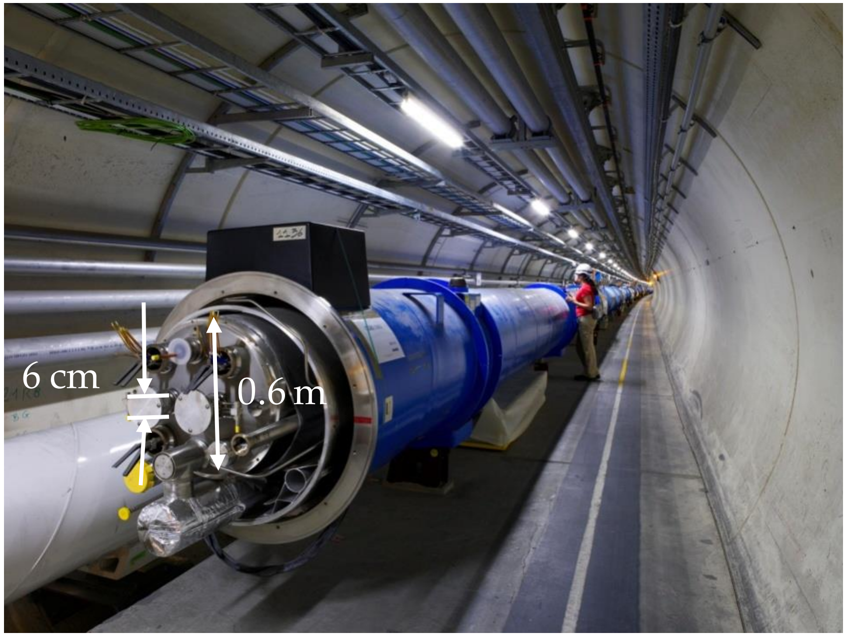
RHIC ring at BNL, Long Island, US

Main ring at Fermilab, Chicago, US

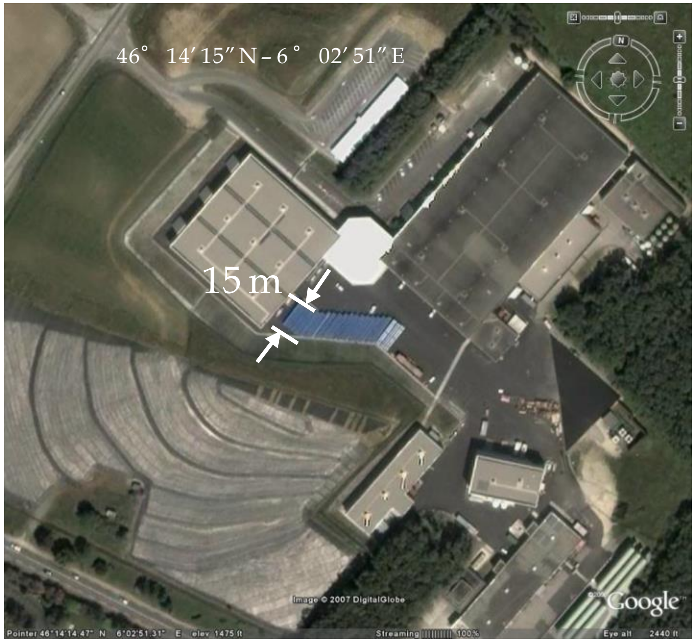
FOREWORD

- The size of our objects
  - Length of an accelerator magnet: ~10 m
  - Diameter of an accelerator magnet: ~m
  - Beam pipe size of an accelerator magnet: ~cm

Unloading a 27 tons dipole



Dipoles in the LHC tunnel, Geneva, CH



A stack of LHC dipoles, CERN, Geneva, CH

CONTENTS

Reminder: the synchrotron and its magnets

How to generate magnetic fields

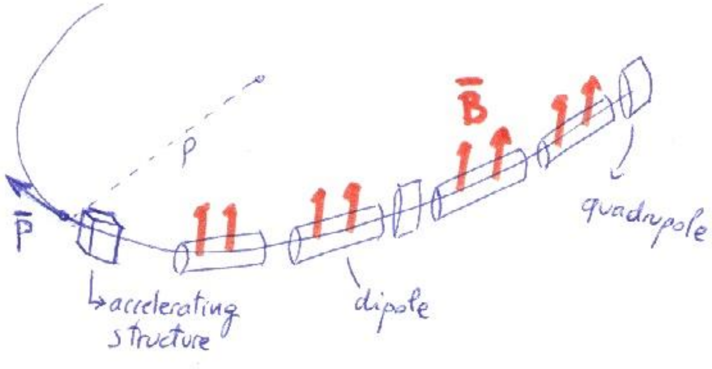
What superconductivity gives

Limits of Nb-Ti magnets

REMINDER: THE SYNCHROTRON AND ITS MAGNETS

- Electro-magnetic field accelerates particles
- Magnetic field steers the particles in a closed (~circular) orbit

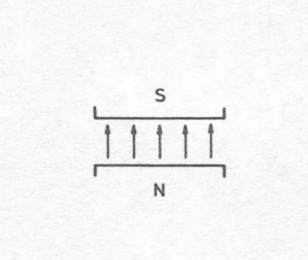
  to drive particles through the same accelerating structure several times

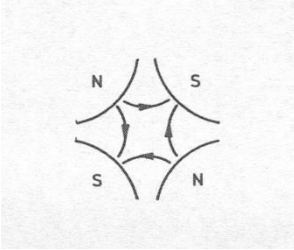


  - Most of the accelerator bends, a small part increases the energy [RF, see E. Jensen talk]
  - As the particle is accelerated, its energy increases and the magnetic field is increased ("synchro") to keep the particles on the same orbit
- What are the limitations to increase the energy ?
  - Proton machines: the maximum field of the dipoles (LHC, Tevatron, SPS …)
  - Electron machines: the synchrotron radiation due to bending trajectories (LEP)

REMINDER: THE SYNCHROTRON AND ITS MAGNETS

- The arcs: bending the beam → energy

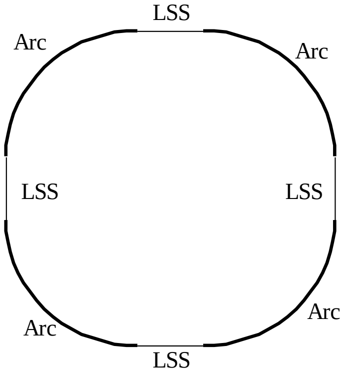




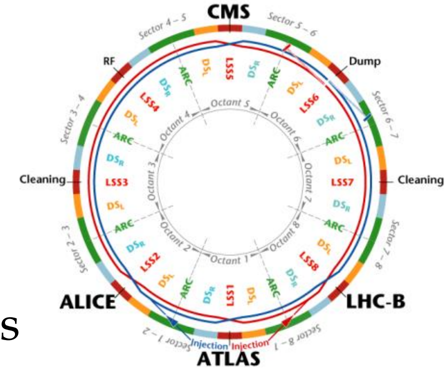
Dipoles for bending   Quadrupoles for focusing

Sextupoles, octupoles … for correcting

[see talk about accelerator physics by B. Holzer]



A schematic view of a synchrotron



The lay-out of the LHC

- Long straight sections (LSS) → luminosity
  - Interaction regions (IR) housing the experiments
    - Solenoids (detector magnets) acting as spectrometers
    - Quadrupole triplet to squeeze the beams in collision
  - Regions for other services
    - Beam injection and dump (dipole kickers)
    - Accelerating structure (RF cavities) and beam cleaning (collimators)

REMINDER: THE SYNCHROTRON AND ITS MAGNETS

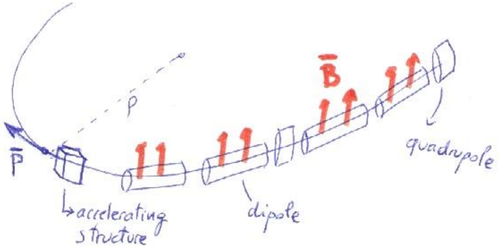
- Why do we need many km to get a few TeV?
  - Dynamics ruled by Lorentz force

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

$$\vec{p} = m\gamma\vec{v}$$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$\left|\frac{d\vec{v}}{dt}\right| = \frac{v^2}{\rho}$$



$$F = evB$$

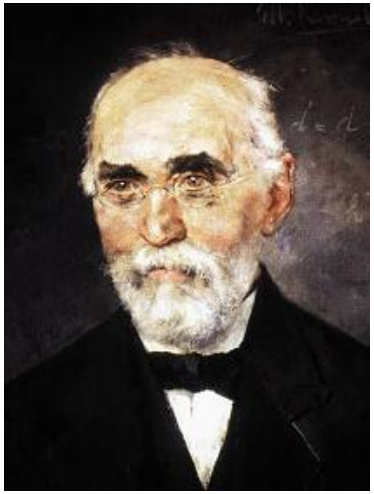
$$\vec{F} = \frac{d}{dt}p = m\frac{d}{dt}(\gamma v) \sim m\gamma\frac{d}{dt}v$$

$$eB = m\gamma\frac{v}{\rho} = \frac{p}{\rho}$$

$$F = m\gamma\left|\frac{d\vec{v}}{dt}\right| = m\gamma\frac{v^2}{\rho}$$

$$p = eB\rho$$

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



Hendrik Antoon Lorentz, Dutch

(18 July 1853 – 4 February 1928), painted by Menso Kamerlingh Onnes, brother of Heinke, who discovered superconductivity

TERMINATOR-3 INTERLUDE

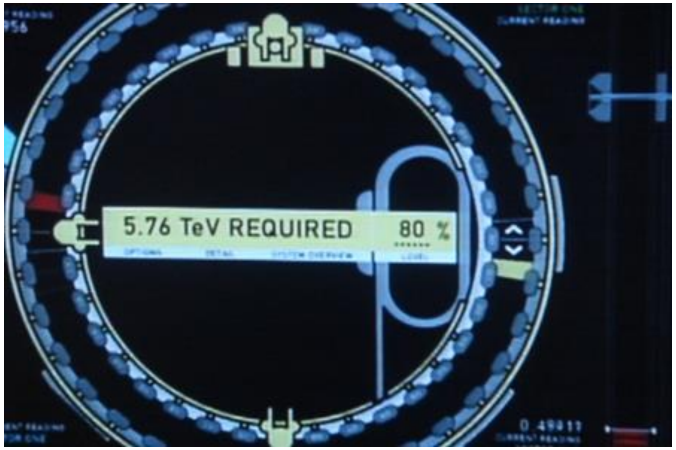
We analyse the accelerator shown in Terminator-3 [Warner Bros., Columbia Pictures, 2003]

- Estimation of the magnetic field

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

  - Energy = 5760 GeV
  - Radius ~30 m
  - Field = 5760/0.3/30 ~ 640 T (a lot !)

- Is it possible to have 640 T magnets ??
  - Or is it science-fiction?

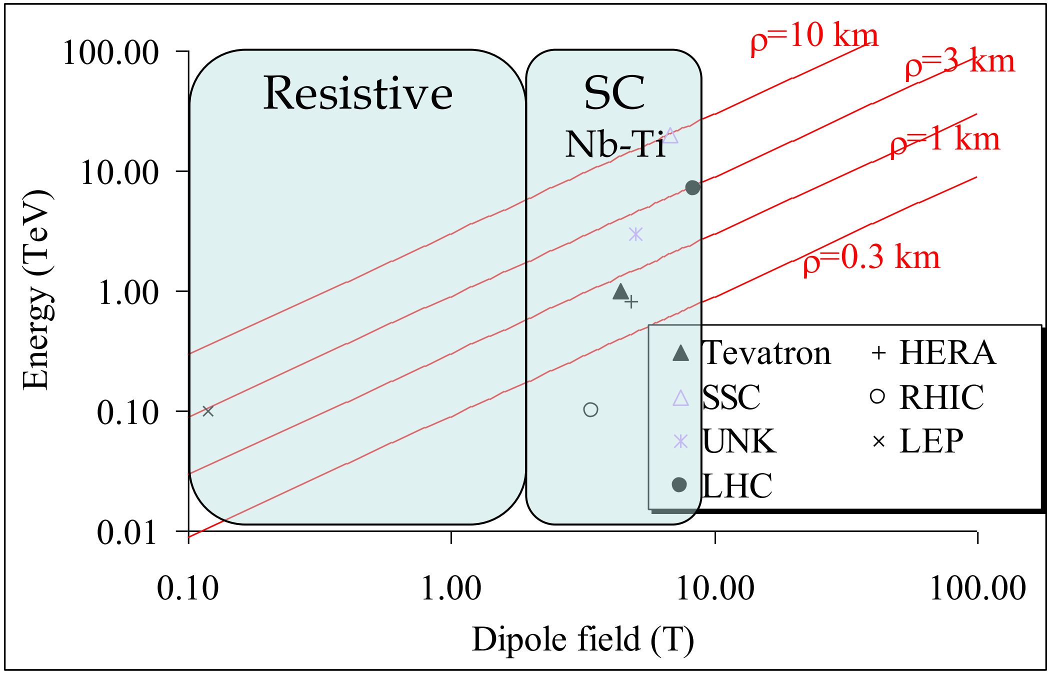


5.76 TeV nominal energy

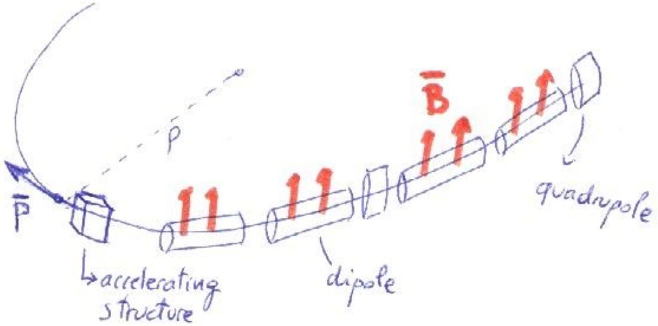
A 200 m ring ?

REMINDER: THE SYNCHROTRON AND ITS MAGNETS

- Relation momentum-magnetic field-orbit radius
  - Having 8 T magnets, we need 3 Km curvature radius to have 7 TeV
  - If we would have 800 T magnets, 30 m would be enough …
  - We will show why 8 T is the present limit for accelerator magnets



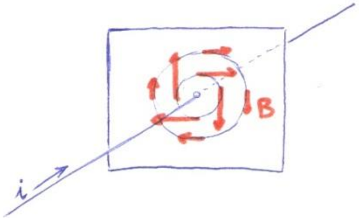
$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$



CONTENTS

GENERATION OF MAGNETIC FIELDS: BIOT-SAVART LAW

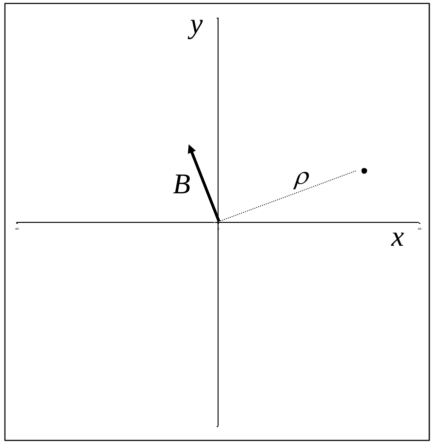
- A magnetic field is generated by two mechanisms
  - An electrical charge in movement (macroscopic current)
  - Coherent alignment of atomic magnetic momentum (ferromagnetic domains)



- Biot-Savart law: magnetic field generated by a current line is

$$|B| = \frac{I\mu_0}{2\pi\rho}$$

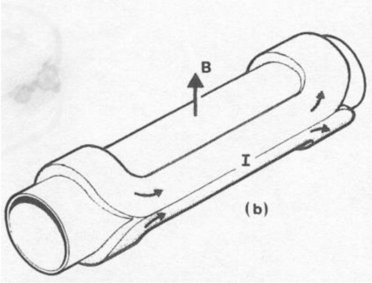
  - Proportional to current
  - Inversely proportional to distance
  - Perpendicular to current direction and distance



Félix Savart, French
(June 30, 1791-March 16, 1841)

Jean-Baptiste Biot, French
(April 21, 1774 – February 3, 1862)

GENERATION OF MAGETIC FIELDS: FIELD OF A WINDING

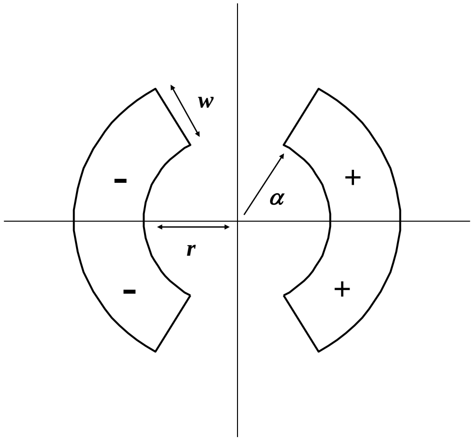


- Magnetic field generated by a winding
  - We compute the central field given by a sector dipole with uniform current density *j*

$$|B| = \frac{I\mu_0}{2\pi\rho} \qquad I \to j\rho d\rho d\theta$$

$$B = -4\frac{j\mu_0}{2\pi}\int_0^{\alpha}\int_r^{r+w}\frac{\cos\theta}{\rho}\rho d\rho d\theta = -\frac{2j\mu_0}{\pi}w\sin\alpha$$

    - Setting α=60° one gets a more uniform field



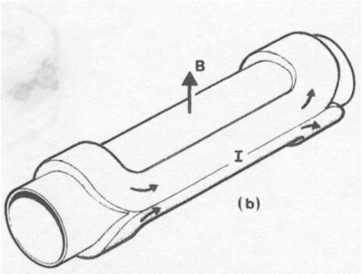
  - $B \propto$ current density (obvious)
  - $B \propto$ coil width w (less obvious)
  - B is independent of the aperture r (much less obvious)

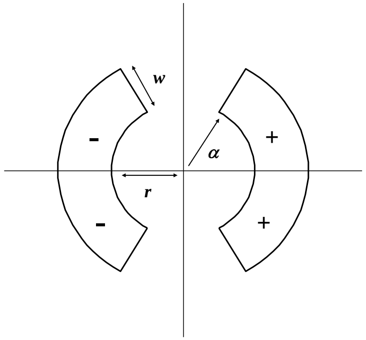
$$B[T] \approx 7\times 10^{-4}\, j[\text{A/mm}^2]\, w[\text{mm}]$$

GENERATION OF MAGETIC FIELDS: SUPERCONDUCTORS VERSUS NORMAL CONDUCTORS

- Magnetic field generated by a winding of width *w*

$$B[T] \approx 7\times 10^{-4}\, j[\mathrm{A/mm}^2]\, w[\mathrm{mm}]$$



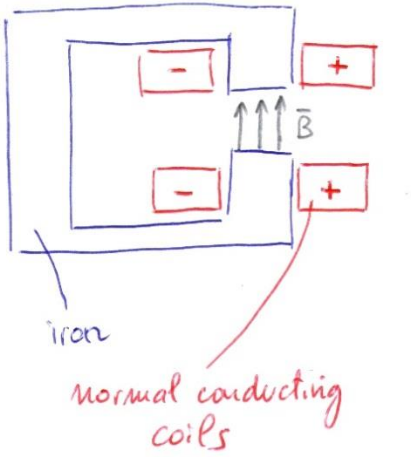


  - The current density in copper for typical wires used in transmission lines is ~ 5 [A/mm^2]
  - Using special techniques for cooling one can arrive up to ~ 100 [A/mm^2]

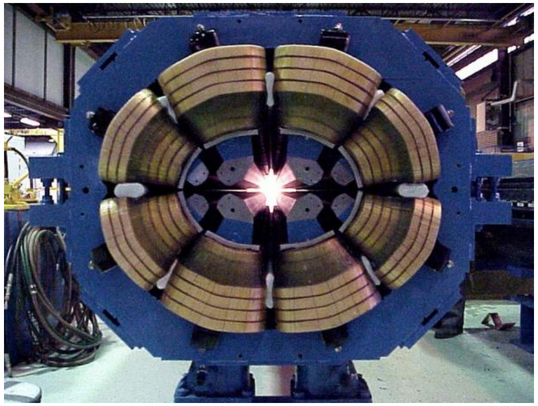
  - Superconductors allow current densities in the sc material of ~1000 [A/mm^2]
    - Example: LHC dipoles have j_{sc}=1500 A/mm^2 j=360 A/mm^2 , (~ ¼ of the cable made by sc !) Coil width *w*~30 mm, B~8 T

  - There is still a factor 10, and moreover the normal conducting consumes a lot of power …

GENERATION OF MAGETIC FIELDS: IRON DOMINATED ELECTROMAGNETS



- Normal conducting magnets for accelerators are made with a copper winding around a ferromagnetic core that greatly enhances the field
  - This is a very effective and cheap design
- The shape of the pole gives the field homogeneity
  - The limit is given by the iron saturation, i.e. 2 T
  - This limit is due to the atomic properties, i.e. it looks like a hard limit
- Therefore, superconducting magnets today give a factor ~4 larger field than normal conducting – not so bad anyway …
  - LHC with 2 T magnets would be 100 Km long, and it would not fit between the lake and the Jura …



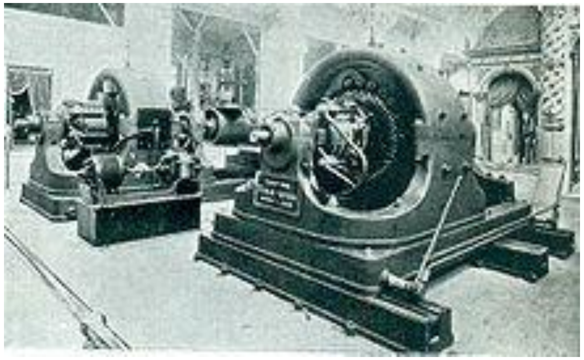
TESLA INTERLUDE

Nikolai Tesla (10 July 1856 - 7 January 1943)

- Born at midnight during an electrical storm in Smiljan near Gospić (now Croatia)
- Son of an orthodox priest
- A national hero in Serbia – but also in the other republics of ex-Yugoslavia

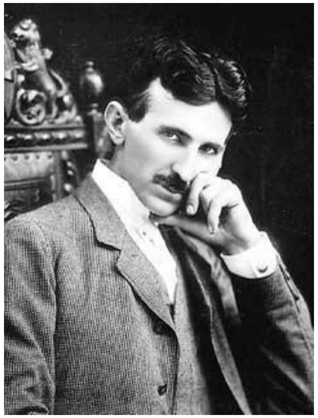
Career

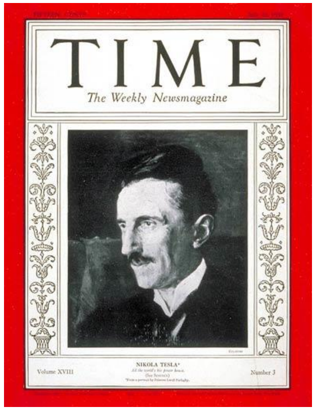
- Polytechnic in Gratz (Austria) and Prague
- Emigrated in the States in 1884
- Electrical engineer
- Inventor of the alternating current induction motor (1887)
- Author of 250 patents



A rather strange character, a lot of legends on him …

Check on the web ! (wikipedia, etc …)





CONTENTS

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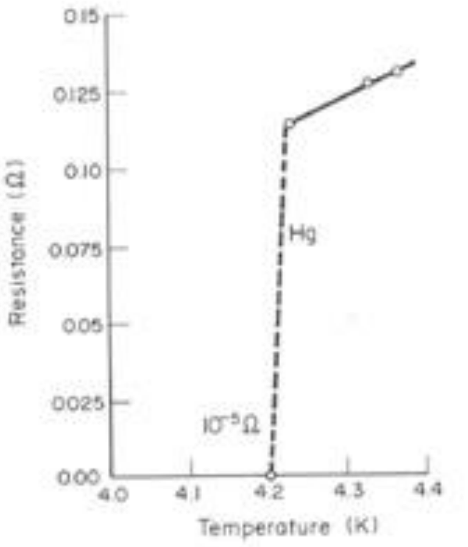
SUPERCONDUCTIVITY

- 101 years ago, in 1911, Kamerlingh Onnes discovers the superconductivity of mercury
  - Below 4.2 K, mercury has a non measurable electric resistance – not very small, but zero !
  - This discovery has been made possible thanks to his efforts to liquifying Helium, a major technological advancement needed for the discovery
  - 4.2 K is called the critical temperature: below it the material is superconductor

Heinke Kamerlingh Onnes

(18 July 1853 – 4 February 1928)

Nobel prize 1913



- Superconductivity has been discovered in other elements, with critical temperatures ranging from a few K (low temp. sc) to up to 150 K (high temperature sc)

- The behaviour has been modeled later in terms of quantum mechanics
  - Electron form pairs (Cooper pairs) that act as a boson, and “freely” move in the superconductor without resistance
  - Several Nobel prizes have been awarded in this field …

SUPERCONDUCTIVITY

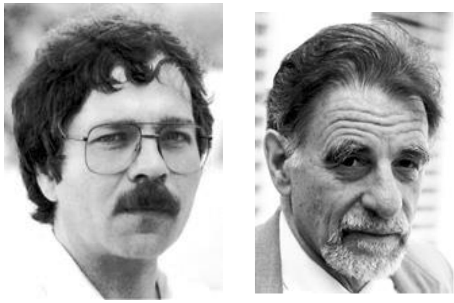
- 1950: Ginzburg and Landau propose a macroscopic theory (GL) for superconductivity
  - Nobel prize in 2003 to Ginzburg, Abrikosov, Leggett

Ginzburg and Landau (circa 1947)

- 1957: Bardeen, Cooper, and Schrieffer publish microscopic theory (BCS) of Cooper-pair formation in low-temperature superconductors
  - Nobel prize in 1972

Bardeen, Cooper and Schrieffer

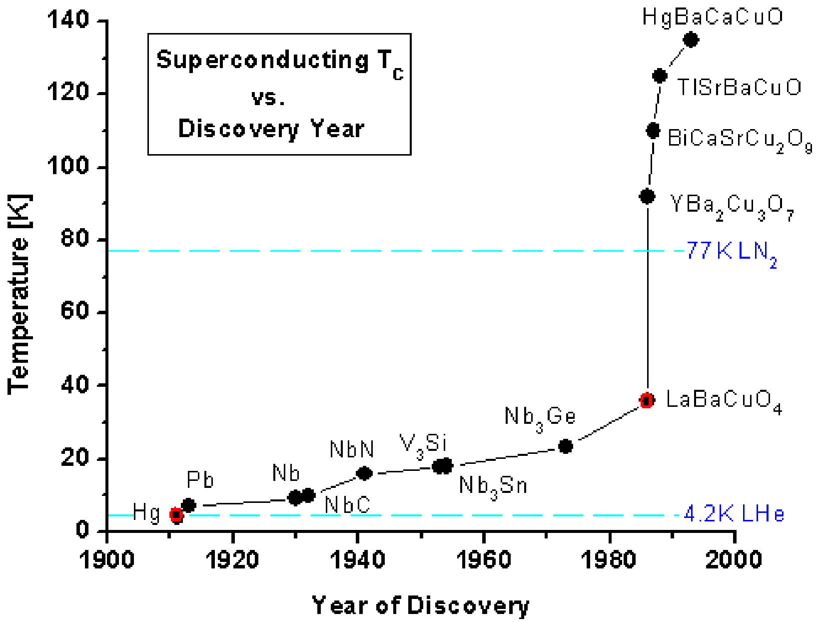
- 1986: Bednorz and Muller discover superconductivity at high temperatures in layered materials having copper oxide planes
  - Nobel prize in 1986 (a fast one …)

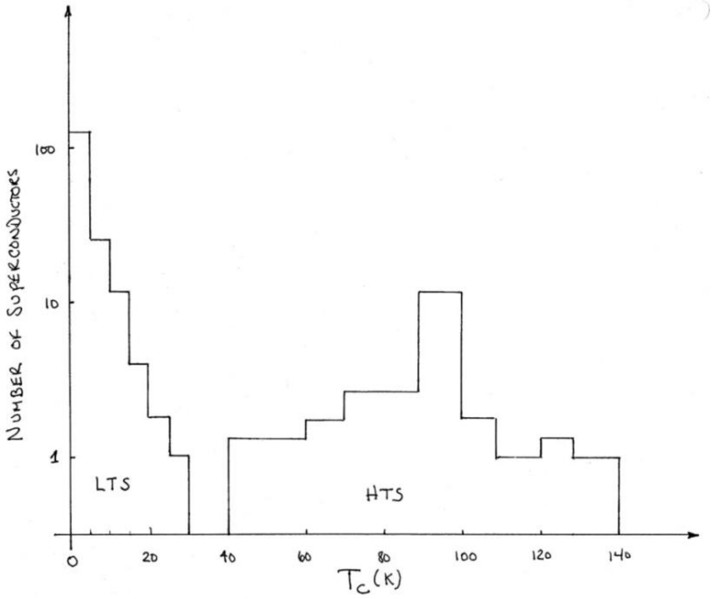


George Bednorz and Alexander Muller

SUPERCONDUCTIVITY

- The quest for the Holy Graal of superconductivity at higher temperatures
  - LTS: Low Temperature Superconductors (below 30 K)
  - HTS: High Temperature Superconductors (above 30 K)
- Two main application: power lines and magnets – radically different
  - Power lines: no field or absent field, possibly high T to simplify cooling
  - Magnets: have “enough” current density able to stay in large field, working at low T is not a problem





Courtesy from J. Schwartz, CERN academic training 2012

https://indico.cern.ch/conferenceDisplay.py?confId=158073

SUPERCONDUCTIVITY

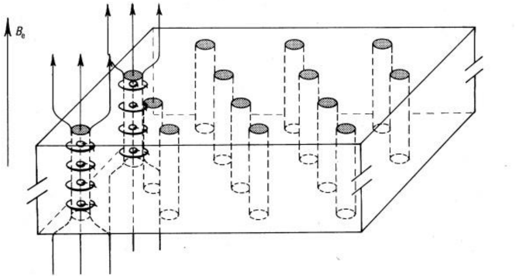
For making magnets, our Holy Graal is having ability to survive magnetic fields

- Type I superconductors: they expel magnetic field (example: Hg)
  - They cannot be used for building magnets

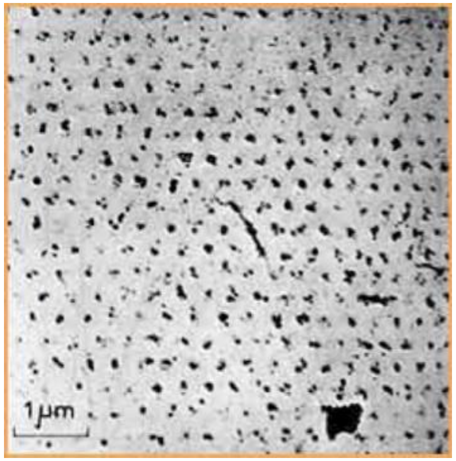
- Type II superconductors: they do not expel magnetic field (example: Nb-Ti)
  - The magnetic field penetrates locally in very tiny quantized vortex

$$\phi_0 = \frac{h}{2e}$$

  - The current acts on the fluxoids with a Lorentz force that must be balanced, otherwise they start to move, dissipate, and the superconductivity is lost
  - The more current density, the less magnetic field, and viceversa → concept of critical surface



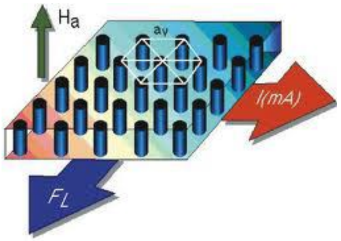
Artist view of flux penetration in a type II superconductor



First image of flux penetration, U. Essmann and H. Trauble Max-Planck Institute, Stuttgart Physics Letters 24A, 526 (1967)

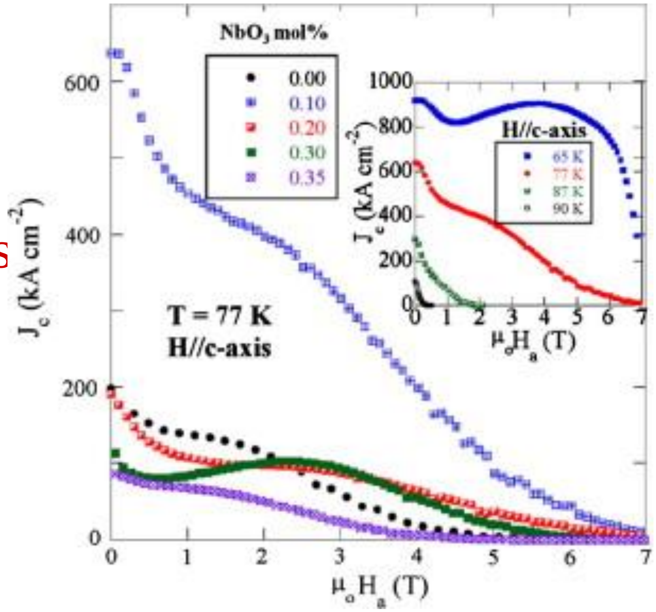
SUPERCONDUCTIVITY

  - The magnetic field penetrates locally in very tiny quantized vortex
  - The current acts on the fluxoids with a Lorentz force that must be balanced, otherwise they start to move, dissipate, and the superconductivity is lost



Artist view of flux penetration in a type II superconductor and resulting Lorentz force

- The sc material is built to have a strong pinning force to counteract fluxoid motion
  - Pinning centers are generated with imperfections in the lattice
  - This is sometimes done with doping
  - It is a very delicate and fascinating cooking …

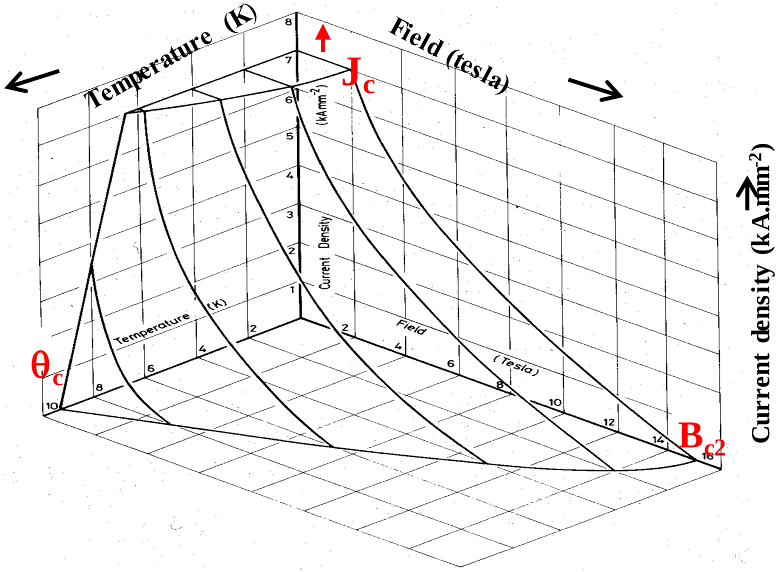


Optimal doping of HTS with NbO_3 to improve critical current [B. Li, et al., Physica D (2012) in press]

SUPERCONDUCTIVITY

- The material is superconductor as long as *B*, *j*, and temperature stay below the critical surface
  - The maximum current density ~ 10 000 A/mm^2, but this at zero field and zero temperature
  - In a magnet, the winding has a current density to create a magnetic field → the magnetic field is also in the winding → this reduces the current density
- Operational temperature
  - The lowest the better … but not at 0 K !
    - Specific heats go to zero
  - Many machines run at 4.2 K (liquid He)
  - LHC has been the first accelerator to operate at 1.9 K (after Tore Supra tokamak)

    ☺ Superfluid helium ! (second purely quantum effect on which LHC technology relies daily)

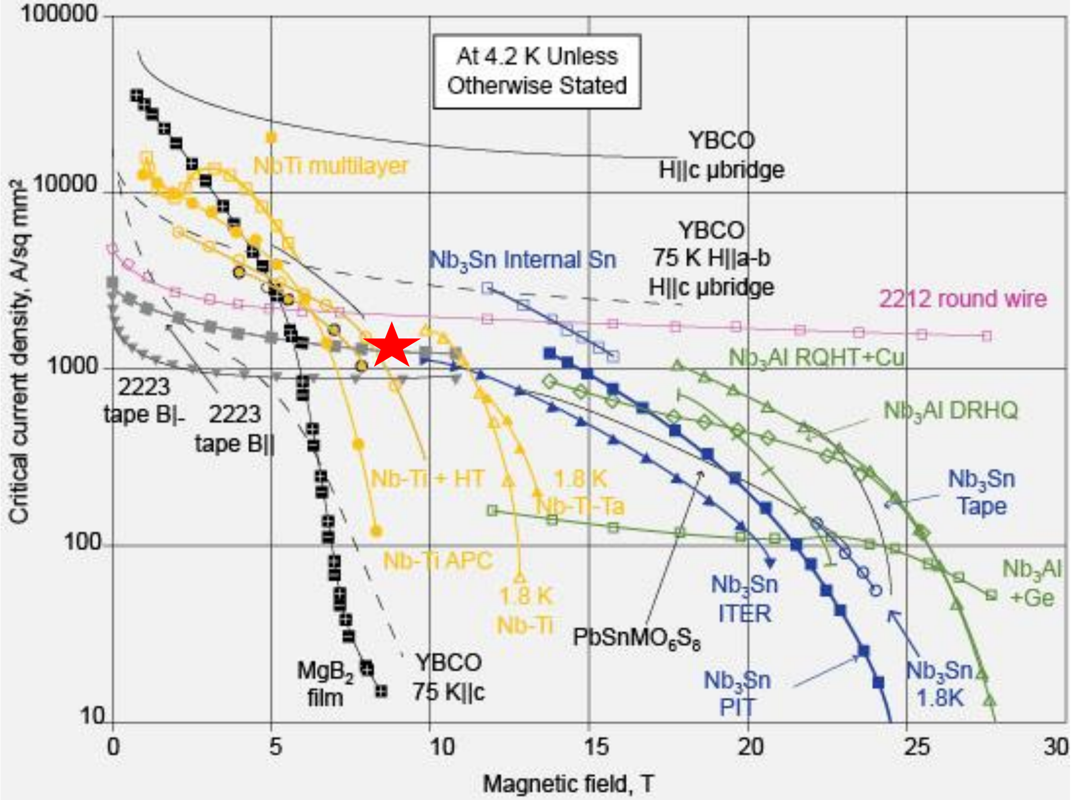


Critical surface for Nb-Ti

Tore Supra Tokamak

SUPERCONDUCTIVITY

- Critical current density vs. field for different materials (semilog scale) at 4.2 K
  - To remember: more critical current density, less field

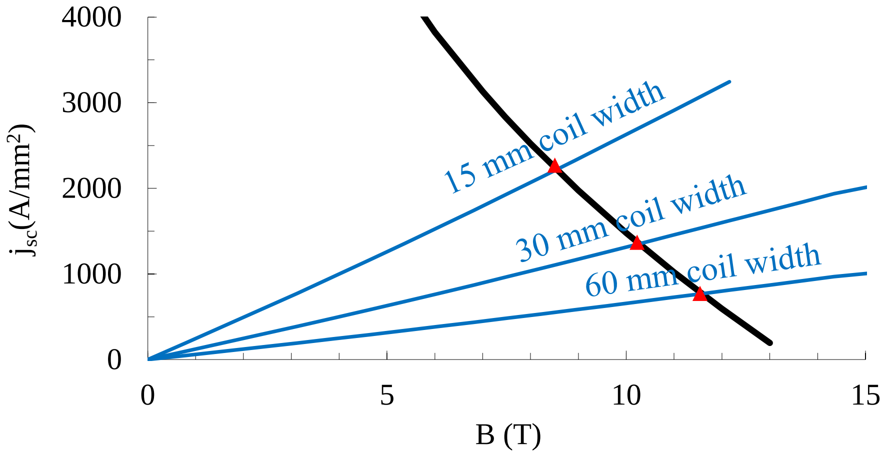


Critical current density in the superconductor versus field for different materials at 4.2 K [P. J. Lee, et al]

CONTENTS

LIMITS IN NB-TI MAGNETS

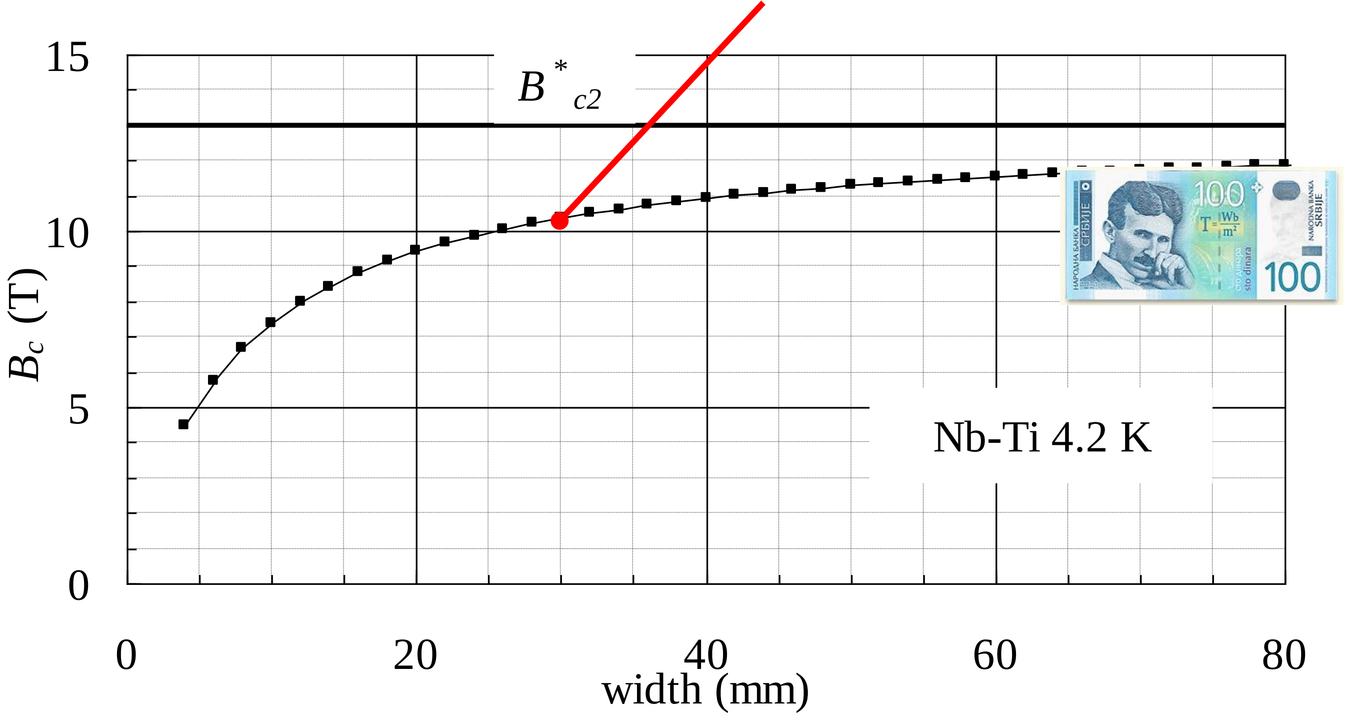
- Nb-Ti loses superconductivity at 13 T, 1.9 K – why 8 T is the limit ?
  - Cost
  - Stability
- We start with cost
  - Field is proportional to current density – so called loadline
    - At a certain point (B(j),j) crosses the critical surface – this is the limit
  - How to have more field ? Put more coil, and lower the loadline
  - But this is an expensive game !



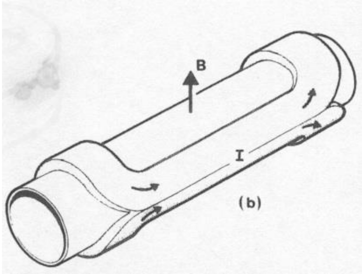
Critical surface for Nb-Ti: j versus B and magnet loadline

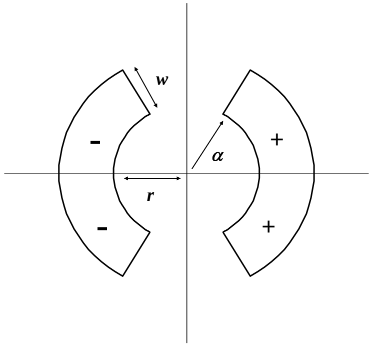
SUPERCONDUCTING MAGNET DESIGN

- We have computed what field can be reached for a sector coil of width *w* for Nb-Ti – goes as ~*w/(1+w)*
  - There is a slow saturation towards 13 T
  - The last Tesla are very expensive in terms of coil, so we could go to 13 T, but we do not go: not for lack of physics but for lack of $$$
  - LHC dipole has been set on 30 mm coil width, giving ~10 T



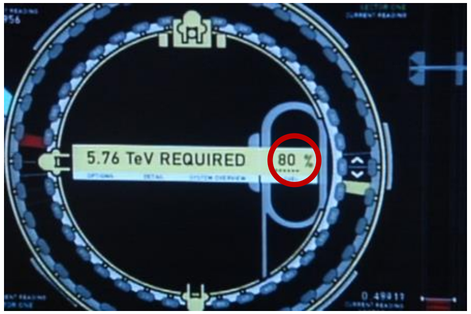
Field versus coil thickness for Nb-Ti at 1.9 K





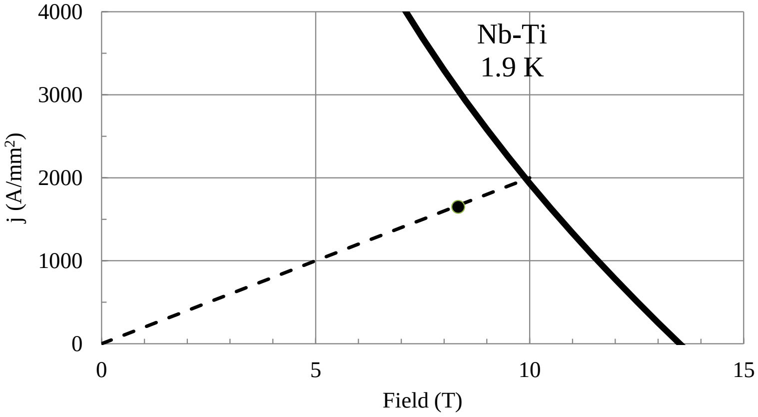
SUPERCONDUCTING MAGNET DESIGN

- Stability: one cannot work on the critical surface
  - Any disturbance producing energy (beam loss, coil movements under Lorentz forces) increases the temperature and the superconductivity is lost
  - A margin of ~20% is usually taken
    - So magnet work at 80% of loadline
    - LHC dipoles are giving the maximum field 10 T given by a reasonable amount of coil (30 mm) for Nb-Ti at 1.9 K
    - With a 20% operational margin one gets ~ 8 T which is the baseline value
    - This corresponds to 2 K of margin



Margin of the main dipoles in four accelerators

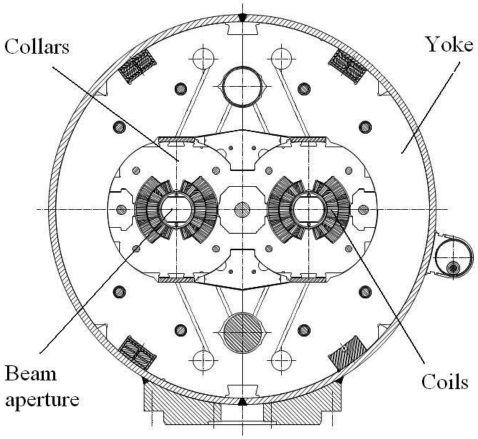
	Nominal			Actual		
	Temp. (K)	Field (T)	Margin	Temp. (K)	Field (T)	Margin
Tevatron	4.6	4.3	4%	4.6	4.2	6%
Hera	4.6	4.7	23%	3.9	5.3	23%
RHIC	4.5	3.5	30%	4.5	3.5	30%
LHC	1.9	8.3	14%	1.9	*7.8**	*19%*



SUPERCONDUCTING MAGNET DESIGN

- Final estimate of the transverse size of LHC main dipoles
  - Magnet aperture radius: 30 mm for the beam
  - Coil width: 30 mm to get 8 T
  - Collars
    - Lorentz forces need a mechanical structure
  - Yoke
    - This is needed to shield : iron takes 2 T max, we have 8 T in 30 mm so we need 30/2*8=120 mm of iron
  - Total about 500 mm diameter

  - For the Terminator-3 accelerator, we have 640 T in 30 mm, we would need 30/2*640~10 m of iron → no space in their tunnel



What can happen if you do not shield your magnet

SUMMARY

- Principles of magnets
  - Why superconducting magnets are very effective
  - The mechanisms behind superconductivity
- Superconductivity is based on couples and relies on defects
  - And gives many Nobel prizes …
- Some features of the design
  - Why 8 T is the present limit for Nb-Ti
  - Why Ms. Terminator sticks on the T3 accelerator dipoles
- Coming soon
  - Going to larger fields: other materials
  - Luminosity in the LHC: how to improve
  - The High Energy LHC: a 16.5+16.5 TeV hadron collider with 20 T dipoles

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  - A. Devred, “Practical low temperature superconductors for electromagnets”, CERN Yellow report 2004-006.
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- Warner Bros. and Columbia Pictures for some images of Terminator-3: the rise of machines, by J. Mostow