Superconducting magnets for particle accelerators

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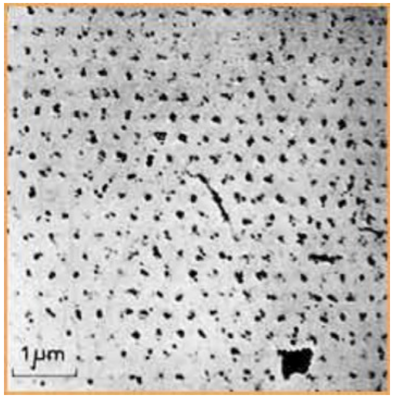
FOREWORD

- The science of particle accelerators and superconducting magnets is a exciting, fancy and dirty mixture of physics, engineering, and chemistry
  - Dynamics of the beam: classical electrodynamics with nonlinear effects, stability, chaos …
  - 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

CONTENTS

- Introduction
  - How to accelerate
  - Phase stability and bunched beams
  - Linear accelerators
- Principles of synchrotron
  - Bending and acceleration
  - Lorentz force: relation radius-energy-field
  - Some examples
  - Why quadrupoles?
- Magnets
  - How to make a magnetic field
  - Electromagnets – iron
  - Electromagnets – coil dominated

INTRODUCTION

- The main aim of high energy physics
  - Break the matter into the smallest constituents
  - Thanks to the equivalence of energy-matter, transform kinetic energy in matter (new particles)
- A particle accelerator accelerates (charged) particles
  - Please note: in the LHC we are close to relativistic regime, so we give more and more energy to the particles but the speed increases by very little
  - So, velocity ~ speed of light
  - In LHC speed goes from 299791.8 km/s to 299792.5 km/s

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

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

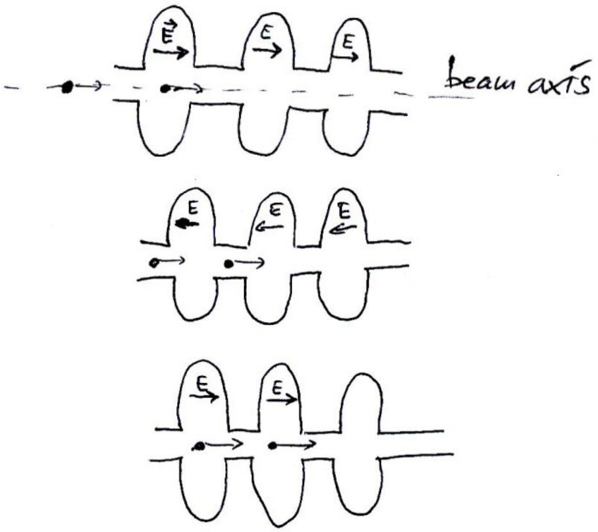
- From an (ecologist) point of view of energy balance
  - A particle accelerator is a concentrator of energy: a lot of energy is put in a few particles
  - We do not produce energy, but we consume energy!

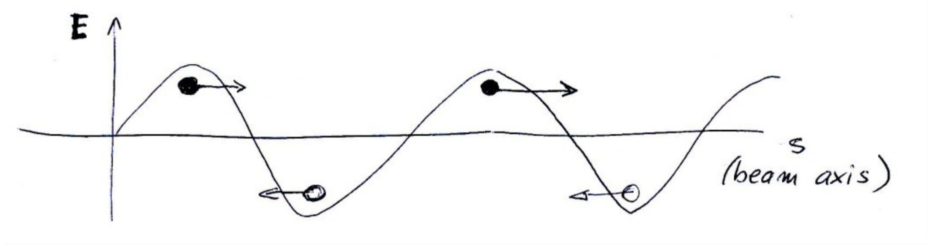
INTRODUCTION

- How to accelerate charged particles?
  - Using electromagnetic force

$$F = eE$$

  - An electric field can be created by a difference in potential or by a current (as in old TV)
  - Using a bunched (discontinuous) beam and a sinusoidal wave one can create long structures
  - The physical object is called RF cavity





INTRODUCTION

- Linear accelerators: a sequence of Rf cavities
  - Energy is proportional to length
  - Today one aims with conventional technology at reaching 35 MV/m (ILC projects)
  - This means that a 10 km give 350 GeV
  - Size becomes a problem …

- Alternative technology (CLIC)
  - Aims at 100 MV/m under study at CERN

Linear accelerator at Stanford, US

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SYCHROTRON PRINCIPLES

- Idea: why not to use a single cavity and then bring back the particles bending through a magnetic field?
  - They did it …

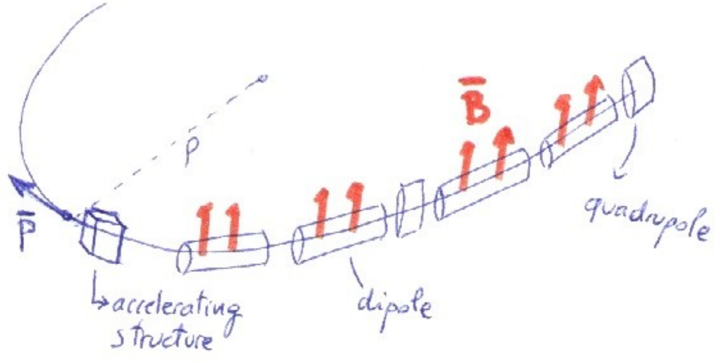
RHIC ring at BNL, Long Island, US

Main ring at Fermilab, Chicago, US
Linear accelerator at Stanford, US

SYNCHROTRON PRINCIPLES

- Electro-magnetic field accelerates particles as before, in a short structure
- Magnetic field steers the particles in a closed (~circular) orbit and brings them back to the accelerating structure

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



  - Most if the accelerator is not increasing the energy but just bending !!
  - As the particle is accelerated, its energy increases and the magnetic field is increased ("synchro") to keep the particles on the same orbit
- Surprise summary of synchrotrons:
  - In the accelerator, particles do not really accelerate!
  - 90% of the accelerator does not provide energy, just bends!

SYNCHROTRON PRINCIPLES

- Kinematics of circular motion
- Relativistic dynamics

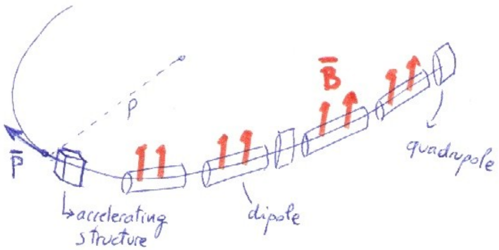
$$\vec{p} = m\gamma\vec{v}$$

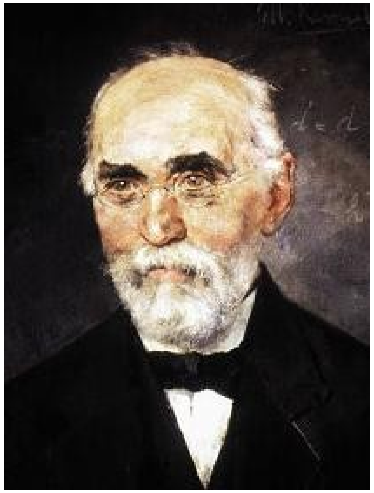
$$\left|\frac{d\vec{v}}{dt}\right| = \frac{v^2}{\rho}$$

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

- Lorentz (?) force

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





Hendrik Antoon Lorentz, Dutch

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

$$F = evB$$

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

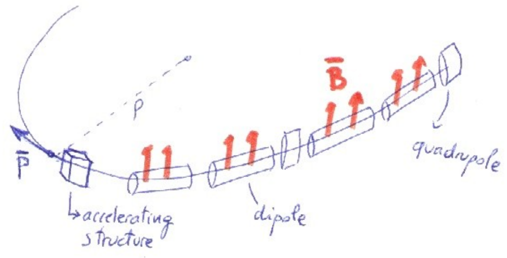
$$F = m\gamma\left|\frac{d\vec{v}}{dt}\right| = m\gamma\frac{v^2}{\rho}$$

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

$$p = eB\rho$$

SYNCHROTRON PRINCIPLES

- Relation momentum-magnetic field-orbit radius $p = eB\rho$
- Preservation of 4-momentum



$$E^2 - p^2c^2 = m^2c^4 \qquad E = \sqrt{m^2c^4 + p^2c^2}$$

- Ultra-relativistic regime $pc >> mc^2$ $\quad E \sim pc$

$$E = ceB\rho$$

- Using practical units for a proton/electron, one has

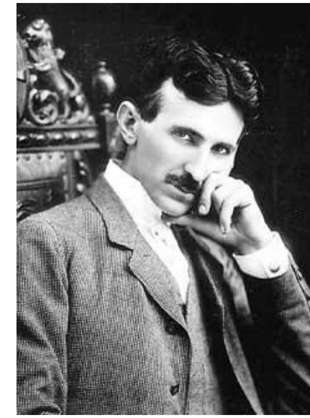
$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

- Remember 1 eV=1.602×10^{-19} J
- Remember 1 e= 1.602×10^{-19} C

The magnetic field is in Tesla …

		r [m]	B [T]	E [TeV]
FNAL	Tevatron	758	4.40	1.000
DESY	HERA	569	4.80	0.820
IHEP	UNK	2000	5.00	3.000
SSCL	SSC	9818	6.79	20.000
BNL	RHIC	98	3.40	0.100
CERN	LHC	2801	8.33	7.000
CERN	LEP	2801	0.12	0.100

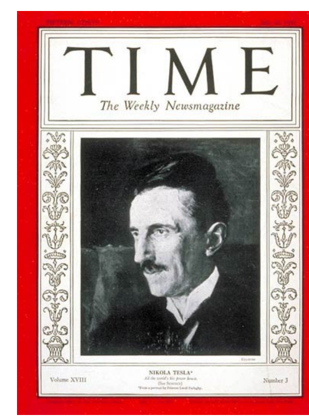
Nikolai Tesla (10 July 1856 - 7 January 1943)



- Born at midnight during an electrical storm in Smiljan near Gospić (now Croatia)
- Son of an orthodox priest
- A national hero in Serbia

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

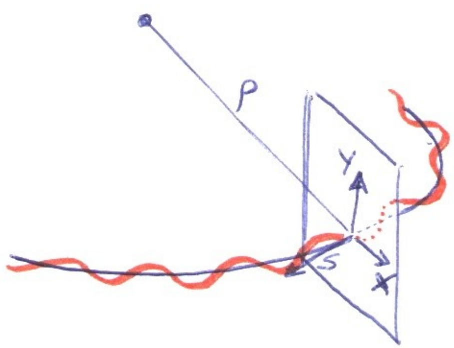


A rather strange character, a lot of legends on him …

http://en.wikipedia.org/wiki/Nikolai_Tesla

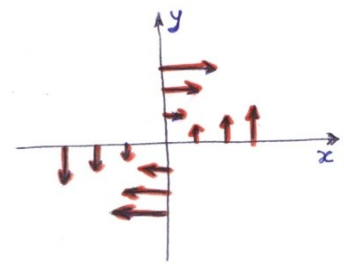
SYNCHROTRON PRINCIPLES

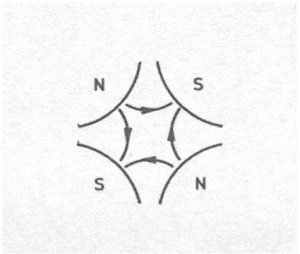
- The force necessary to stabilize linear motion is provided by the quadrupoles
  - Quadrupoles provide a field which is proportional to the transverse deviation from the orbit, acting like a spring



$$F_x = \frac{e}{c}[v \times B]_x = \frac{e}{c}(\dot{y}B_s - \dot{s}B_y) \propto B_y$$

$$\begin{cases} B_y = Gx \\ B_x = Gy \end{cases}$$





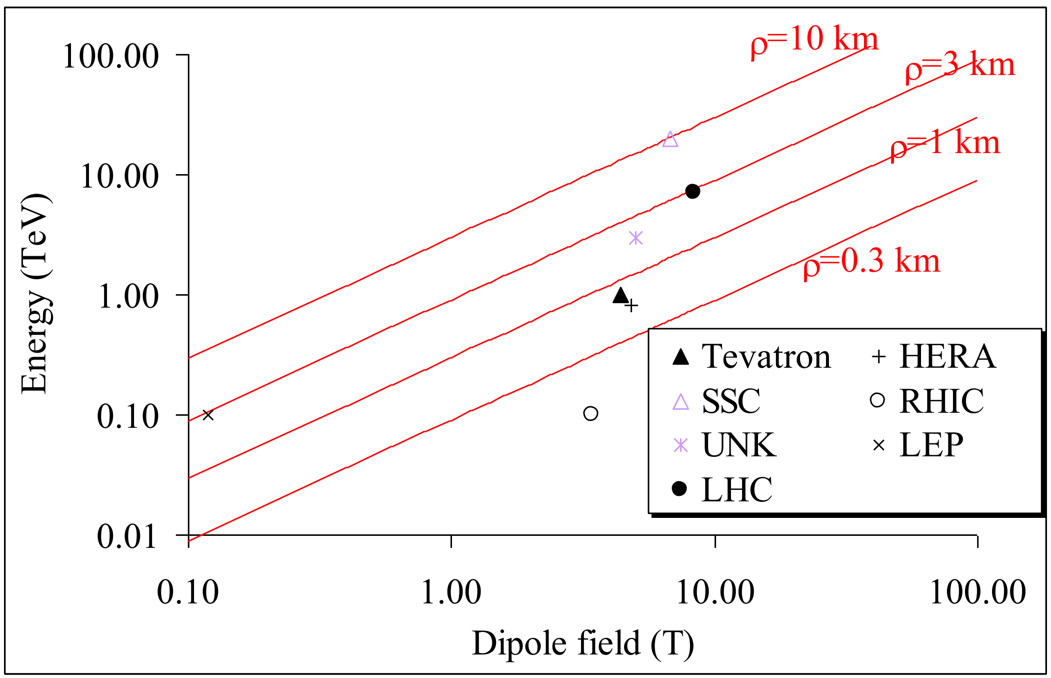
  - One can prove that the motion equation in transverse space (with some approximations) is

$$\frac{d^2x}{ds^2} + K_1(s)x = 0$$

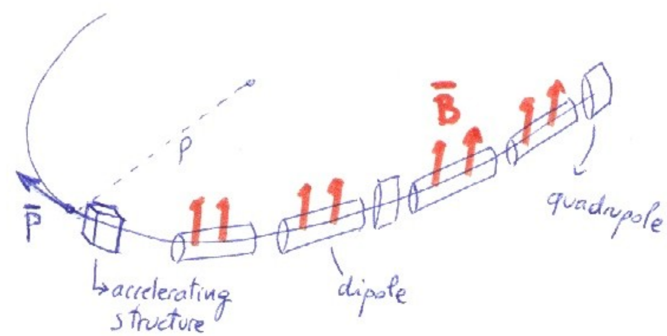
where $K_1 = \frac{1}{B\rho}\frac{\partial B_y}{\partial x} = \frac{G}{B\rho}$

SYNCHROTRON PRINCIPLES

- Now, the limit to the maximum energy is the magnetic field
  - 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 …

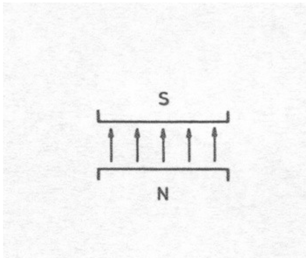


$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

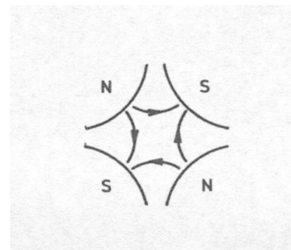


SYNCHROTRON PRINCIPLES

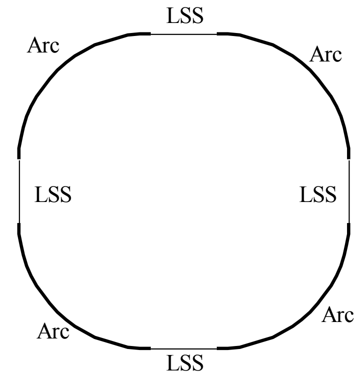
- The arcs: region where the beam is bent



Dipoles for bending

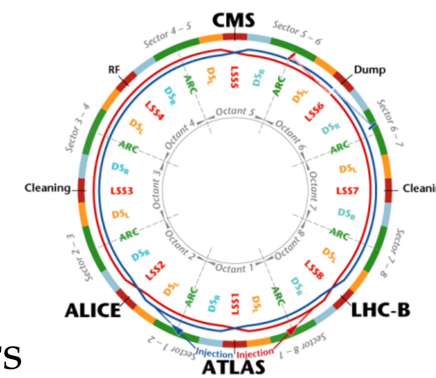


Quadrupoles for focusing



A schematic view of a synchrotron

Sextupoles, octupoles … for correcting



The lay-out of the LHC

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

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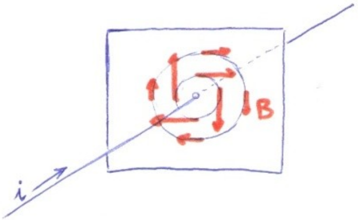
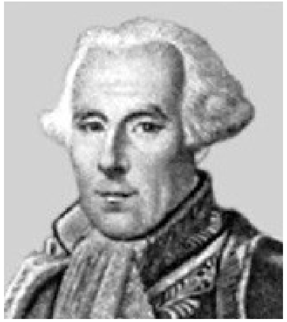
- A magnetic field is generated by two mechanisms
  - An electrical charge in movement (macroscopic current)
  - Coherent alignment of atomic magnetic momentum (ferromagnetic domains)





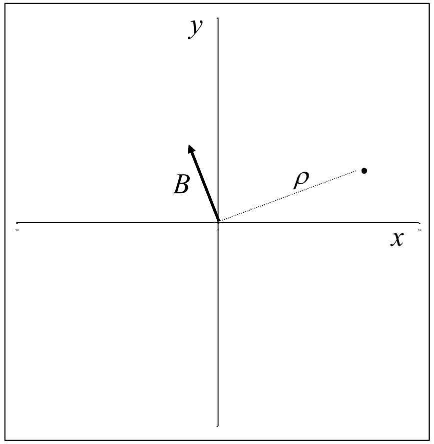
Félix Savart, French
(June 30, 1791-March 16, 1841)

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

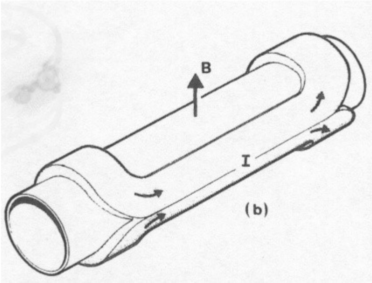
- Biot-Savart law: magnetic field generated by a current line is

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

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

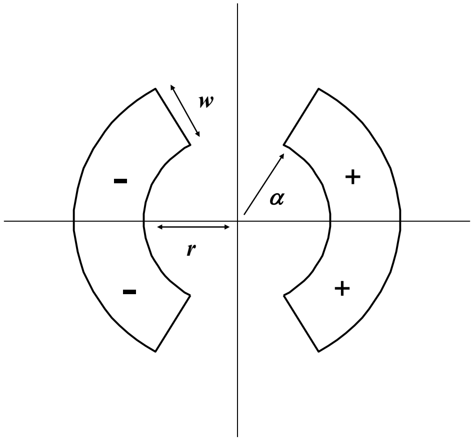


- Magnetic field generated by a winding
  - We compute the central field given by a sector dipole with uniform current density j



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

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



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

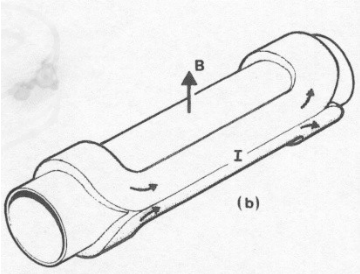
  - $B \propto$ current density (obvious)
  - $B \propto$ coil width w (less obvious)
  - B is independent of the aperture r (much less obvious)

$$B[T] \approx 7\times10^{-4}\, j[\mathrm{A/mm^2}]\, w[\mathrm{mm}]$$

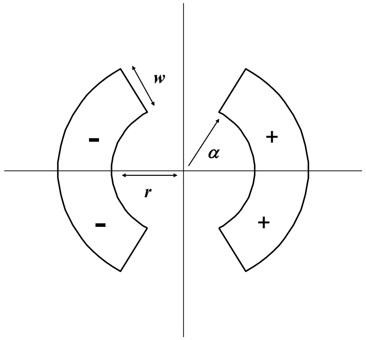
MAGNETS

- 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]



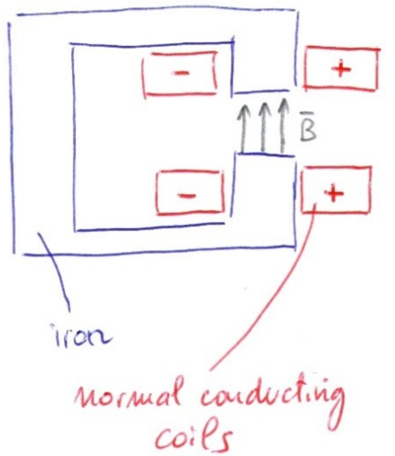
- Using special techniques for cooling one can arrive up to ~ 100 [A/mm^2]

- 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 …

MAGNETS

- 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 …



- But what is the mechanism of superconductivity? And what are its limits?
- In 1911, one century ago 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
- 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 …

Heinke Kamerlingh Onnes
(18 July 1853 – 4 February 1928)
Nobel prize 1913