Superconducting magnets

Ezio Todesco
Accelerator Technology Department
European Organization for Nuclear Research (CERN)

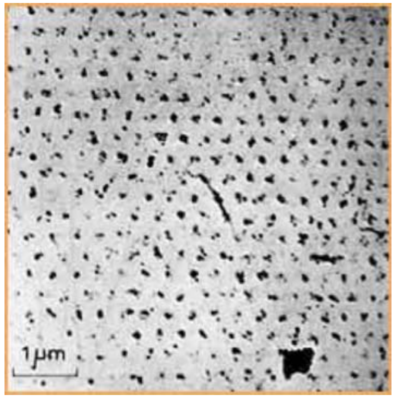
FOREWORD

- 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

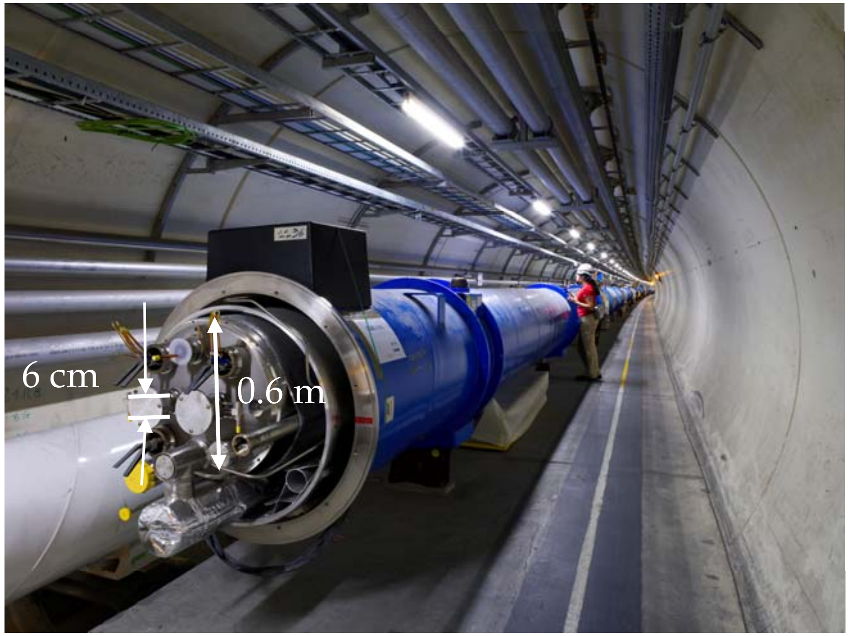
RHIC ring at BNL, Long Island, US

Main ring at Fermilab, Chicago, US

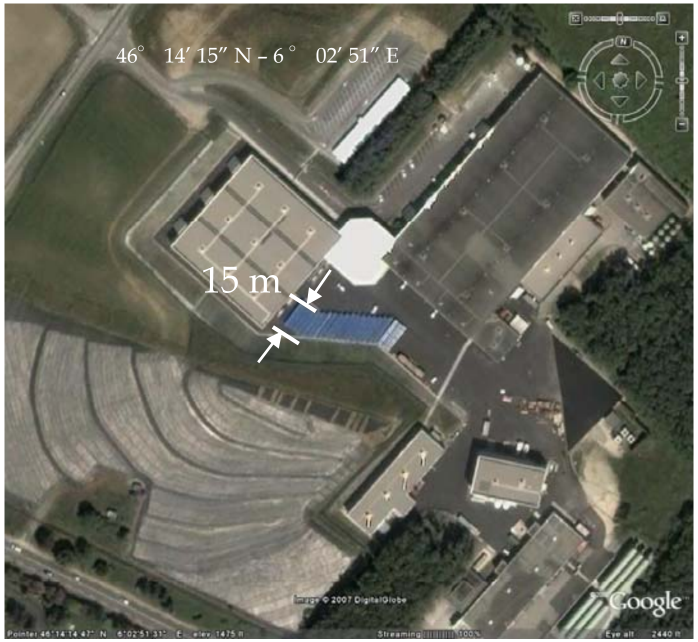
FOREWORD

- 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

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Introduction: the synchrotron and its magnets

Why do we need Km long accelerators to get TeV energies ?

What are the physical limits to create strong magnetic fields ?

- Hints on coil lay-out and normal conducting electromagnets
- Advantages of superconducting magnets, and basics of superconductivity (Nb-Ti limit: 13-14 T)

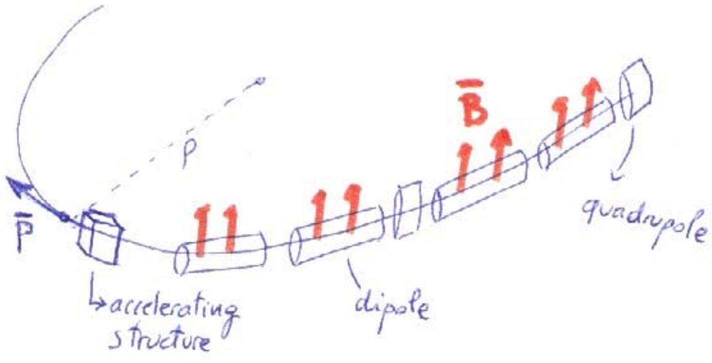
What are the practical limits imposed by magnet design and operation ?

- Coil lay-out and operational margins (Nb-Ti limit: 8-9 T)
- Hints on Nb_3Sn: towards 15-17 T ?
- Cables

Some features of magnets for detectors

1. INTRODUCTION: PRINCIPLES OF A SYNCHROTRON

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

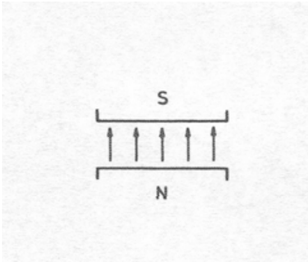


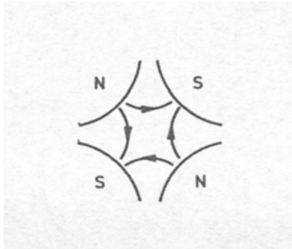
  - To drive particles through the same accelerating structure several times
  - As the particle is accelerated, its energy increases and the magnetic field is increased ("synchro") to keep the particles on the same orbit

- 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)

1. INTRODUCTION: NEEDED MAGNETIC FIELDS

- The arcs: region where the beam is bent

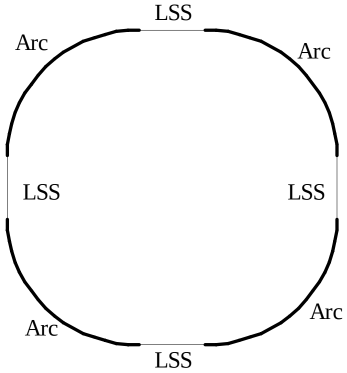




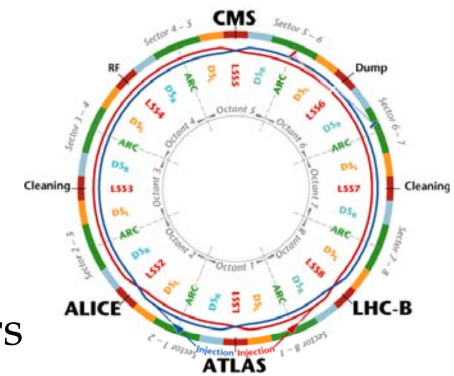
Dipoles for bending   Quadrupoles for focusing

Sextupoles, octupoles … for correcting

[see talk about accelerator physics by S. Gilardoni and E. Metral]



A schematic view of a synchrotron



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)

CONTENTS

2. WHY DO WE NEED MANY Km TO GET A FEW TeV ?

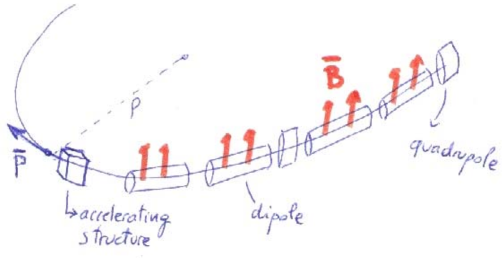
- Kinematics of circular motion
- Relativistic dynamics $\vec{p} = m\gamma\vec{v}$

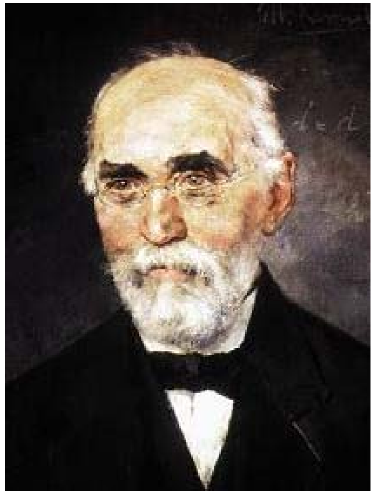
$$\left|\frac{d\vec{v}}{dt}\right| = \frac{v^2}{\rho}$$

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

- 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

$$F = evB$$

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

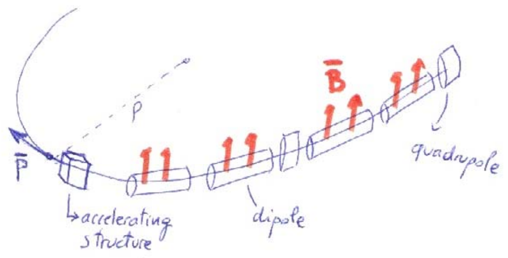
$$F = m\gamma\left|\frac{d\vec{v}}{dt}\right| = m\gamma\frac{v^2}{\rho}$$

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

$$p = eB\rho$$

2. WHY DO WE NEED MANY Km TO GET A FEW TeV ?

- 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

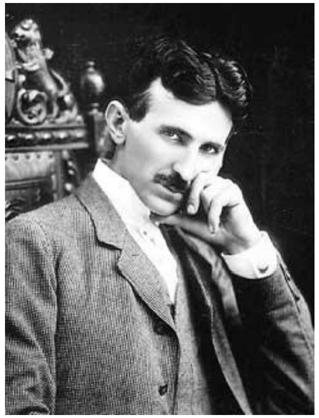
The magnetic field is in Tesla …

		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

TESLA INTERLUDE

Nikolai Tesla (10 July 1856 - 7 January 1943)

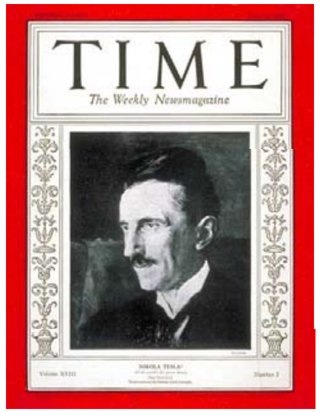
- Born at midnight during an electrical storm in Smiljan near Gospić (now Croatia)
- Son of an orthodox priest
- A national hero in Serbia



Career

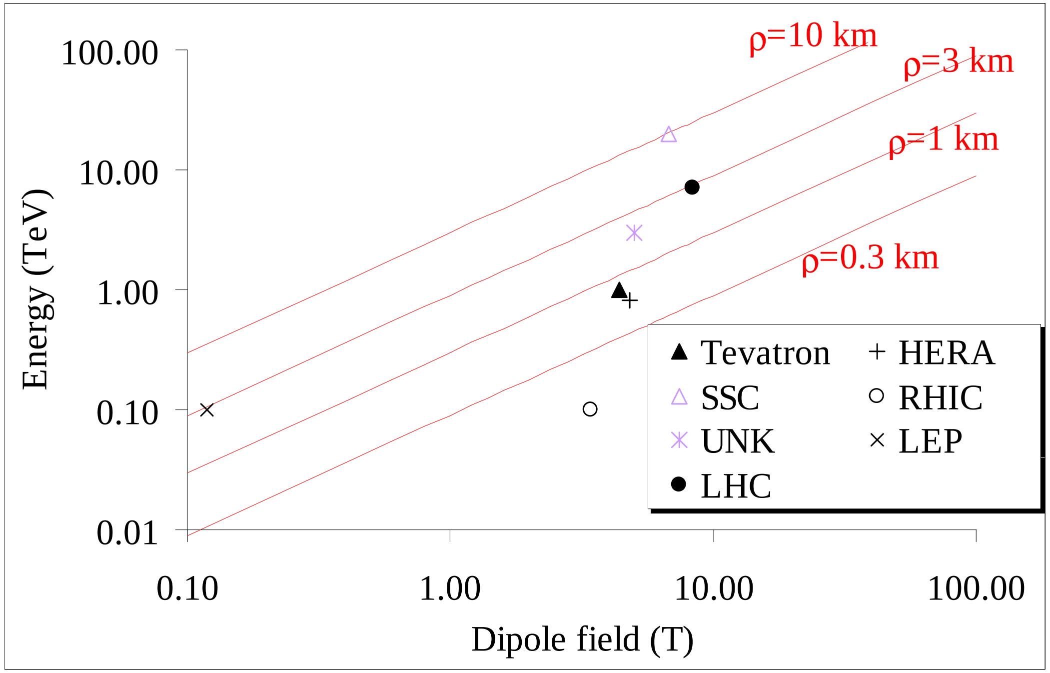
- Polytechnic in Gratz (Austria) and Prague
- Emigrated in the States in 1884
- Electrical engineer
- Inventor of the alternating current induction motor (1887)
- Author of 250 patents

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

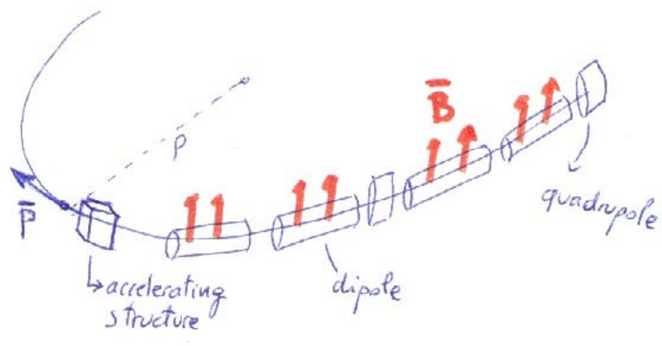


2. WHY DO WE NEED MANY Km TO GET A FEW TeV ?

- 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 now show why 8 T is the present limit



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



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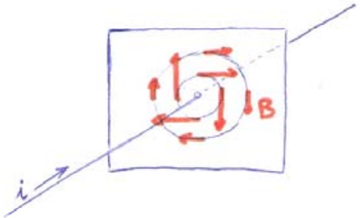
3. ULTIMATE LIMITS TO STRONG FIELDS: BIOT-SAVART LAW

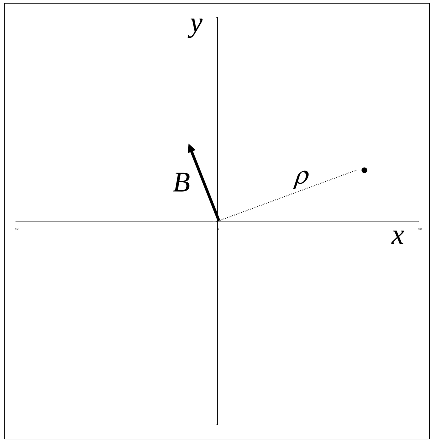
- A magnetic field is generated by two mechanisms
  - An electrical charge in movement (macroscopic current)
  - Coherent alignment of atomic magnetic momentum (ferromagnetic domains)

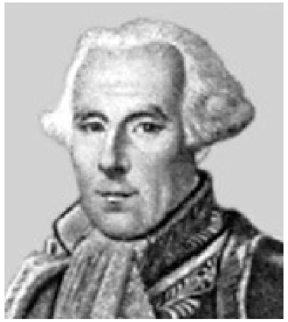


- Biot-Savart law: magnetic field generated by a current line is

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

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

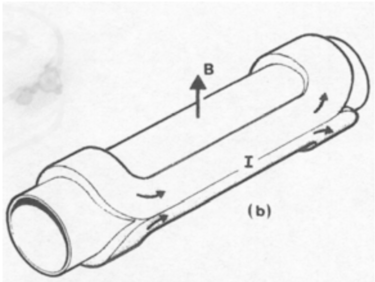




Félix Savart, French
(June 30, 1791-March 16, 1841)

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

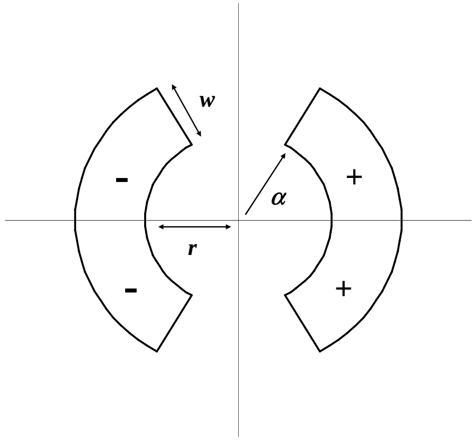
3. ULTIMATE LIMITS TO STRONG FIELDS: FIELD OF A WINDING



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

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

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



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

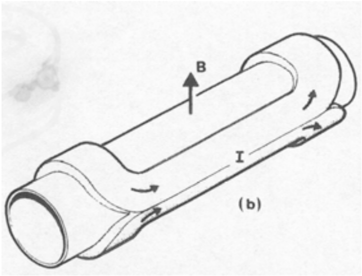
  - $B \propto$ current density (obvious)
  - $B \propto$ coil width w (less obvious)
  - B is independent of the aperture r (much less obvious)

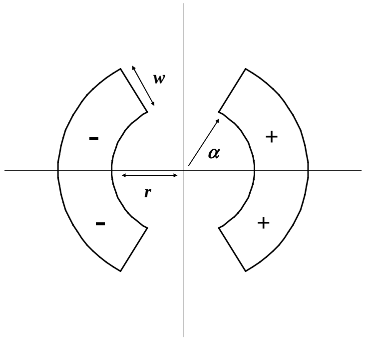
$$B[T] \approx 7\times10^{-4}\, j[\mathrm{A/mm^2}]\, w[\mathrm{mm}]$$

3. ULTIMATE LIMITS TO STRONG FIELDS: SUPERCONDUCTORS VERSUS NORMAL CONDUCTORS

- Magnetic field generated by a winding of width w

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





  - 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

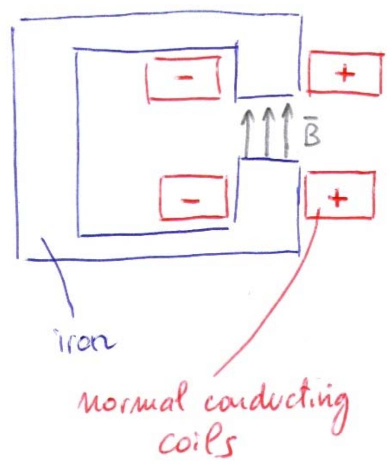
  - The current density in copper for typical wires used in transmission lines is ~ 5 [A/mm^2]

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

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

3. ULTIMATE LIMITS TO STRONG FIELDS: SUPERCONDUCTORS VERSUS NORMAL CONDUCTORS

- 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 …

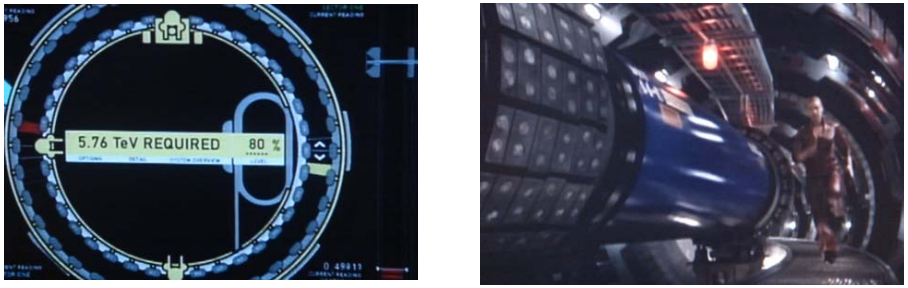
INTERLUDE: THE TERMINATOR-3 ACCELERATOR

We apply some concepts to the accelerator shown in Terminator-3 [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 ~ 700 T (a lot !)



Energy of the machine (left) and size of the accelerator (right)

- Why the magnet is not shielded with iron ?
  - Assuming a bore of 25 mm radius, inner field of 700 T, iron saturation at 2 T, one needs 700*25/2=9000 mm=9 m of iron … no space in their tunnel !
  - In the LHC, one has a bore of 28 mm radius, inner field of 8 T, one needs 8*25/2=100 mm of iron
- Is it possible to have 700 T magnets ??

A magnet whose fringe field is not shielded

3. ULTIMATE LIMITS TO STRONG FIELDS: BASICIS OF SUPERCONDUCTIVITY

- 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

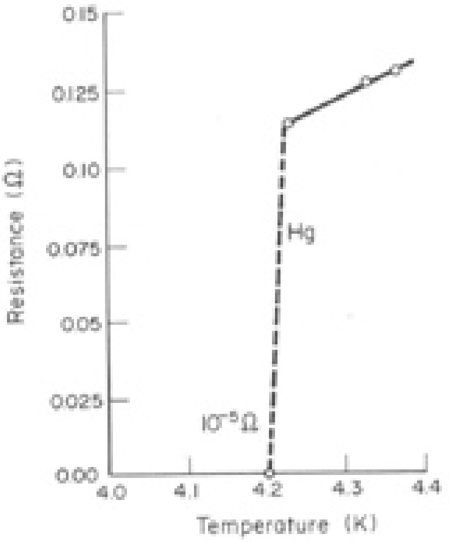
Heinke Kamerlingh Onnes

(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 …



3. ULTIMATE LIMITS TO STRONG FIELDS: BASICIS OF SUPERCONDUCTIVITY

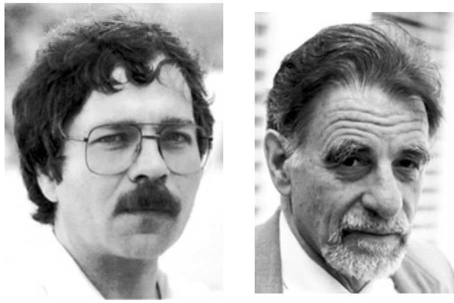
- 1950: Ginzburg and Landau propose a macroscopic theory (GL) for superconductivity
  - Nobel prize in 2003 to Ginzburg, Abrikosov, Leggett

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

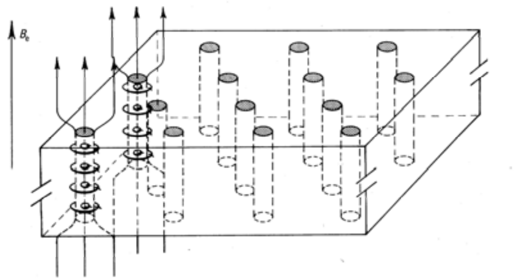
3. ULTIMATE LIMITS TO STRONG FIELDS: BASICIS OF SUPERCONDUCTIVITY

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

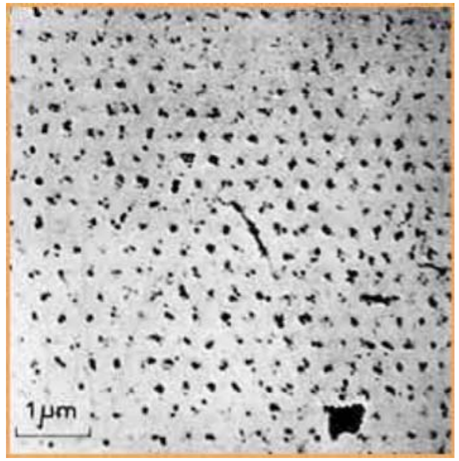
- Type II superconductors: they do not expel magnetic field (example: Nb-Ti)
  - The magnetic field penetrates locally in very tiny quantized vortex

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

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



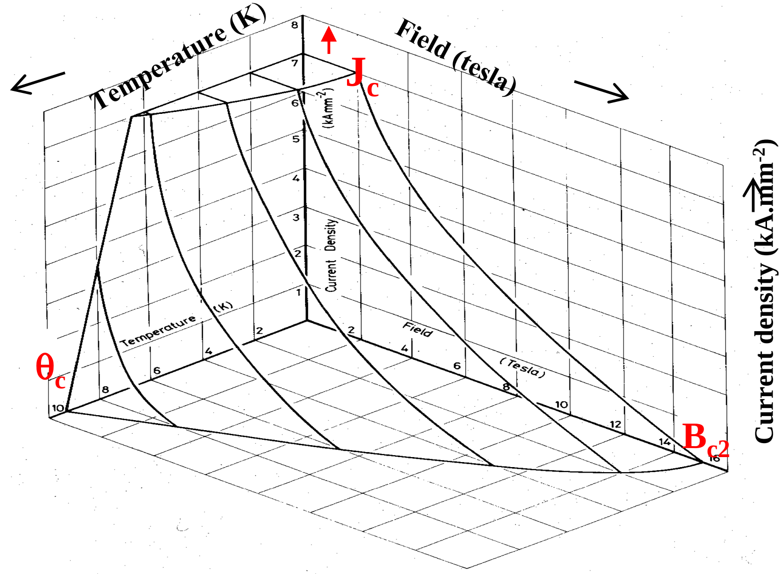
Artist view of flux penetration in a type II superconductor



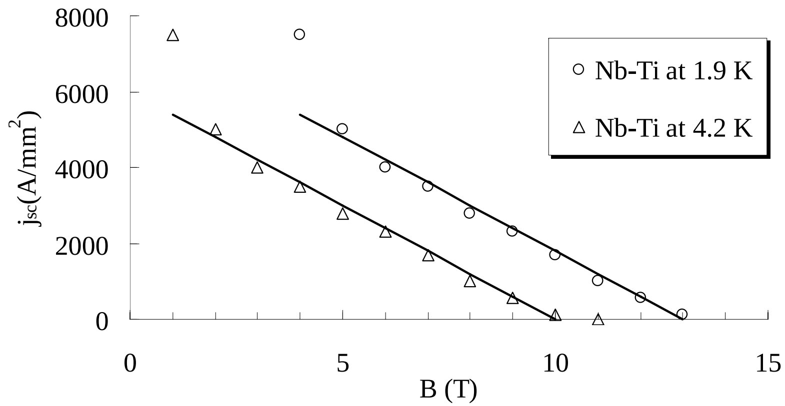
First image of flux penetration, U. Essmann and H. Trauble Max-Planck Institute, Stuttgart Physics Letters 24A, 526 (1967)

3. ULTIMATE LIMITS TO STRONG FIELDS: BASICIS OF 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
  - The obvious ultimate limit to Nb-Ti dipoles is 14 T at zero temperature and zero current density, and 13 T at 1.9 K
  - In reality, we cannot get 13 T but much less – around 8 T in the LHC – why ?



Critical surface for Nb-Ti



Section of the Nb-Ti critical surface at 1.9 and 4.2 K, and linear fit

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- Cables

Some features of magnets for detectors

4. LIMITS IN MAGNET DESIGN: COIL WIDTH AND MAGNET SIZE

- We compute what field can be reached for a sector coil of width *w*
  - We characterize the critical surface by two parameters

$$j_c = \kappa c (B^*_{c2} - B)$$

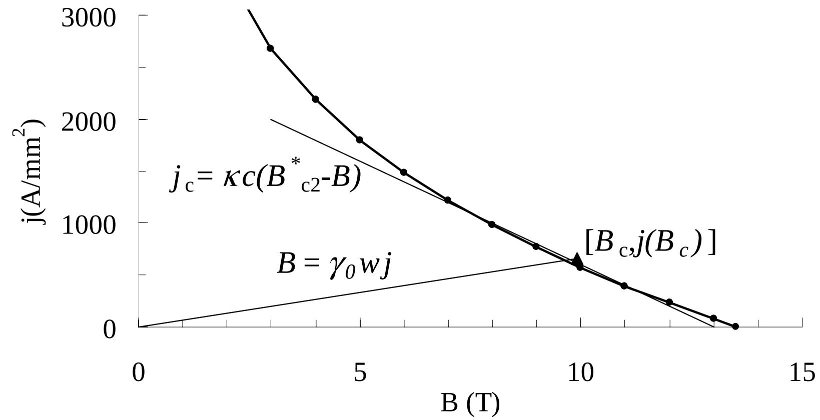
and we added κ which takes into account that only a fraction (~¼) of the coil is made up to superconductor

  - The relation between current density and field is $B = \gamma_0 w j$

and the field that can be reached is given by $B_c = \gamma_0 w j_c = \gamma_0 w \kappa c (B^*_{c2} - B_c)$

$$B_c = B^*_{c2} \frac{\kappa c \gamma_0 w}{1 + \kappa c \gamma_0 w}$$

  - The larger coil, the smaller j_c, the larger *B*

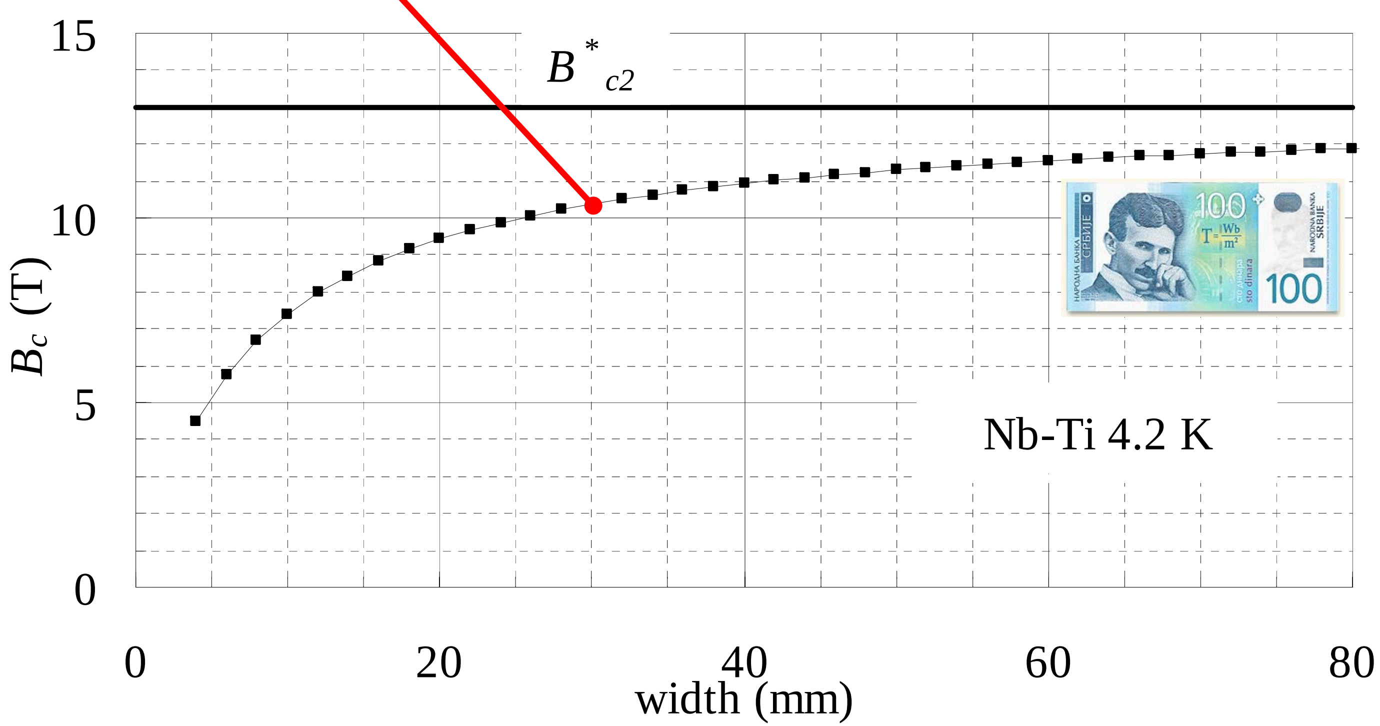


Critical surface for Nb-Ti: j versus B and magnet loadline

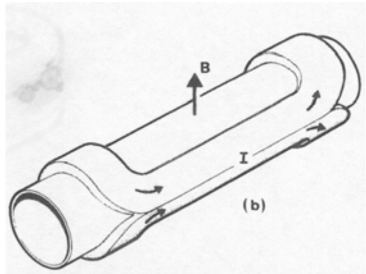
4. LIMITS IN MAGNET DESIGN: COIL WIDTH AND MAGNET SIZE

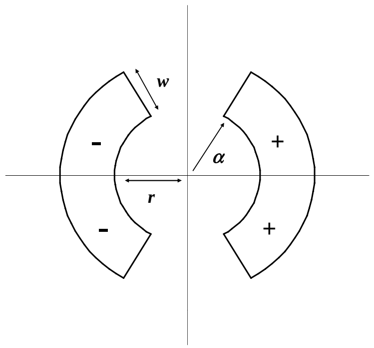
- We have computed what field can be reached for a sector coil of width *w* for Nb-Ti
  - There is a slow saturation towards 13 T
  - The last Tesla are very expensive in terms of coil
  - LHC dipole has been set on 30 mm coil width, giving ~10 T

$$B_c = B^*_{c2} \frac{\kappa c \gamma_0 w}{1 + \kappa c \gamma_0 w}$$



Field versus coil thickness for Nb-Ti at 1.9 K



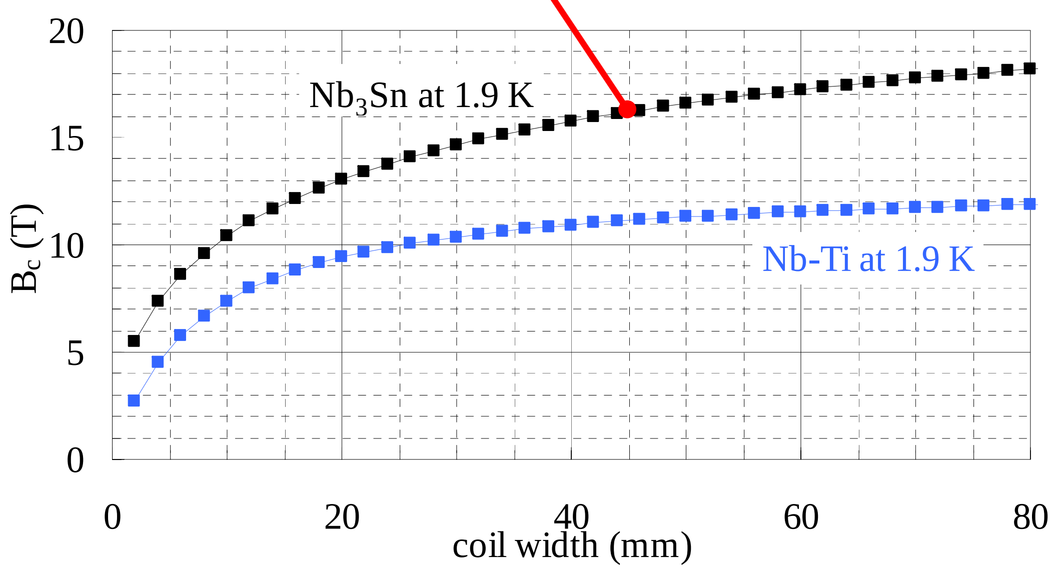


4. LIMITS IN MAGNET DESIGN: COIL WIDTH AND MAGNET SIZE

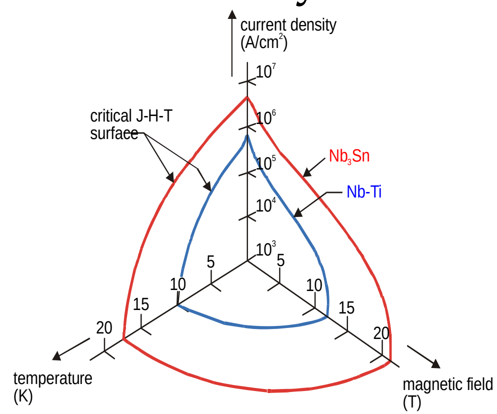
- One cannot work on the critical surface
  - Any disturbance producing energy (beam loss, coil movements under Lorentz forces) increases the temperature and the superconductivity is lost
    - In this case one has a transition called quench – the energy must be dumped without burning the magnet
    - The energy in the LHC dipoles is 8 MJ !
  - A margin of ~10-20% is usually taken
    - 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
    - Transverse size of the magnet: we will show that the needed aperture is ~25 mm, plus 30 mm of coil, mechanical structure and iron shield (100 mm) $\rightarrow$ less than one meter of diameter

4. LIMITS IN MAGNET DESIGN: HINTS ON Nb_3Sn

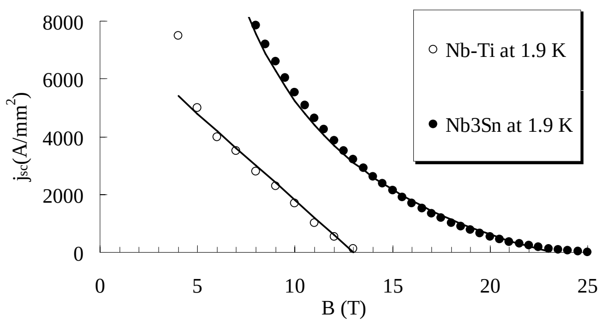
- Nb_3Sn has a wider critical surface
  - But the material is more difficult to manufacture
  - It has never been used in accelerators, but tested successfully in short models and used in solenoids
  - With Nb_3Sn one could go up to 15-18 T
  - World record is 16 T (HD1, Berkeley)



Field versus coil thickness for Nb-Ti and Nb_3Sn at 1.9 K

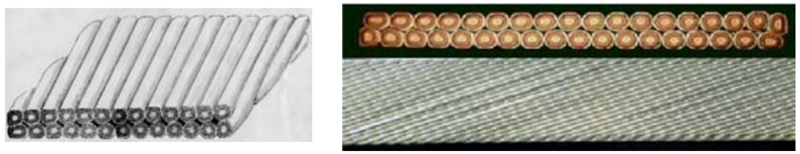


Critical surface for Nb-Ti and Nb_3Sn



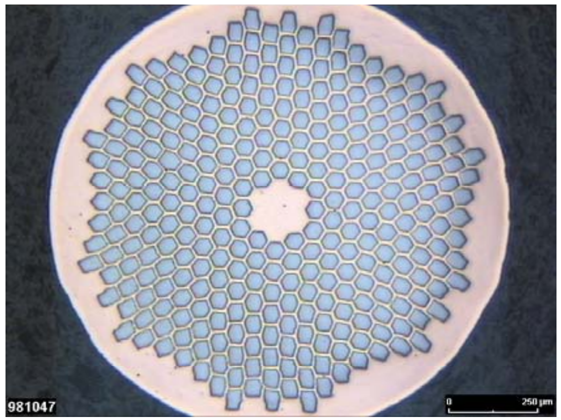
4. LIMITS IN MAGNET DESIGN: HINTS ON CABLE GEOMETRY

- The superconducting cables are not bulk material but have a complex geometry
  - The cable is made of several (20-40) strands of ~1 mm diameter
    - This to carry more current and therefore to reduce the stored energy
  - The strands are made of superconducting filaments of ~5-50 μm diameter inside a copper matrix
    - to stabilize the superconductor
    - to minimize field distortions due to superconductor magnetization
    - to protect the superconductor when the superconductivity is lost (the current flows in the copper and does not burn the sc)
  - Filaments and the strands are twisted
    - to reduce coupling currents and AC losses



Sketch of superconducting cable and cross-section

Superconducting cable made of strands



Superconducting strand

CONTENTS

5. MAGNETS FOR DETECTORS

- What is the beam size in an accelerator ?
  - Inverse proportional to the sqrt energy
    - The larger the energy, the smaller the beam !
    - Size of the beam pipe is given by the values at the injection energy
  - Proportional to the sqrt of the emittance ε_n (property of the injectors)
  - Proportional to the sqrt of the β function
    - This is related to the optics – the β function in the arc is proportional to the distance L between quadrupoles

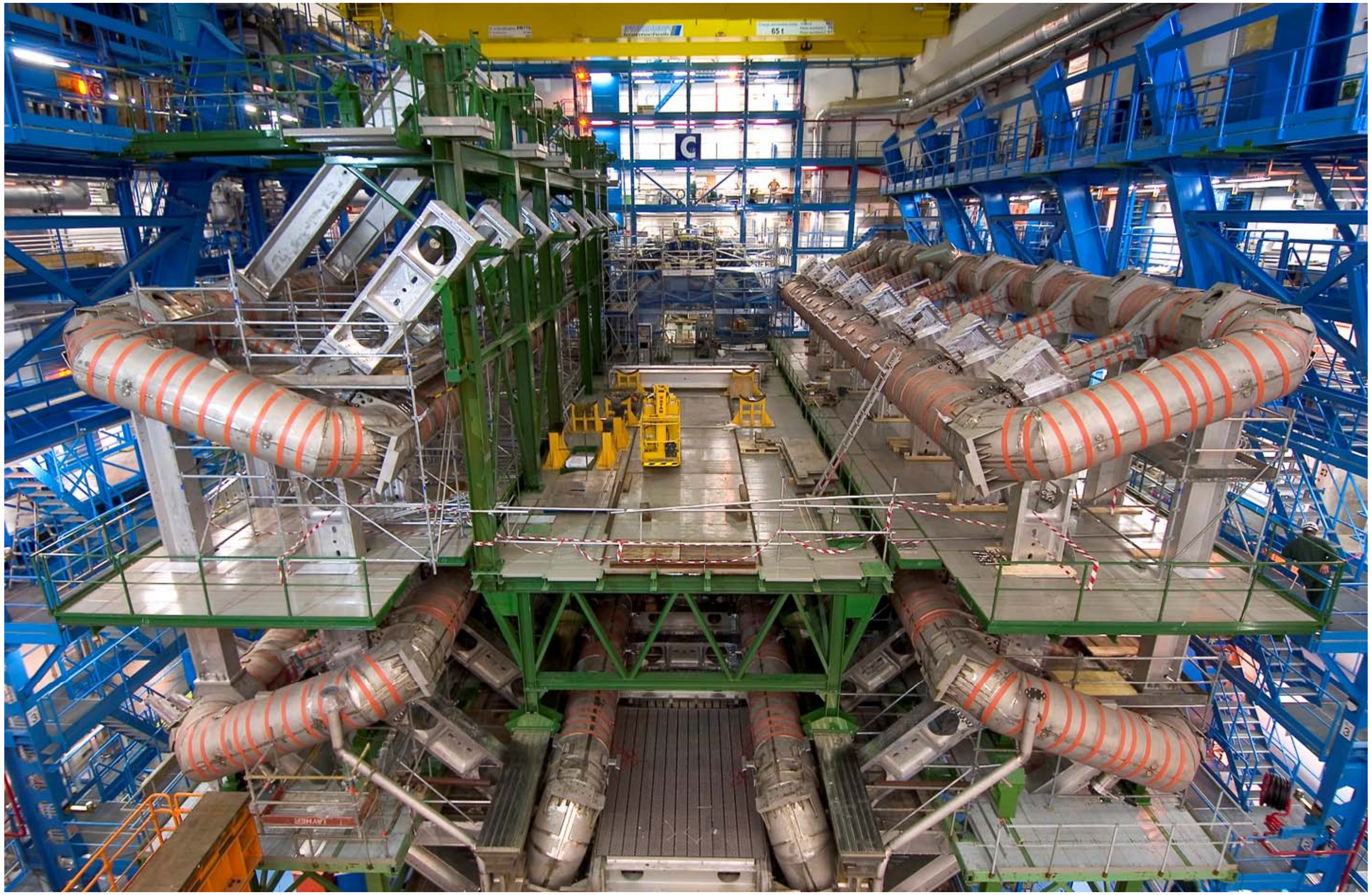
$$\sigma = \sqrt{\frac{\varepsilon_n \beta_f}{\gamma}}$$

$$\beta_f = (2+\sqrt{2})L \sim 3.4L$$

- Example: LHC
  - Injection energy 450 GeV, γ=480
  - Cell length L=50 m, β_f=170 m
  - ε_n=3.75×10^{-6}m rad
  - The beam size σ=1.2 mm – the magnet aperture (radius) is 28 mm to house 10σ plus some margin

5. THE INTERACTION REGIONS: DETECTOR SPECIFICATIONS

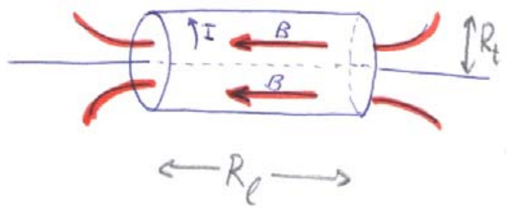
- The beam is small … why are detectors so large ?



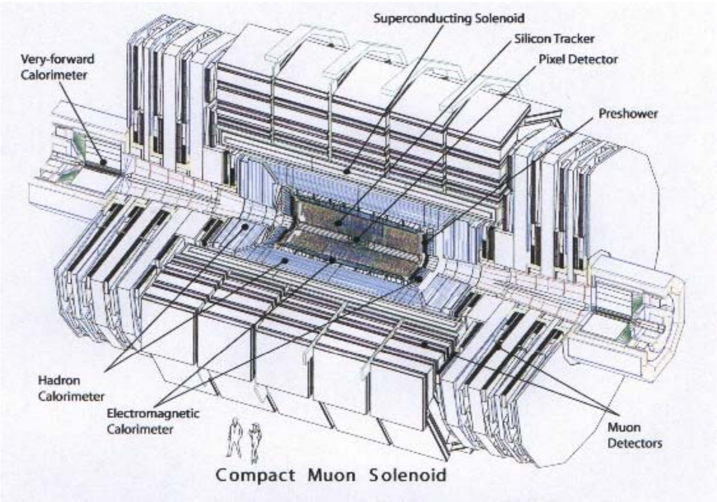
The toroidal coils of ATLAS experiment

5. THE INTERACTION REGIONS: DETECTOR SPECIFICATIONS

- Detector magnets provide a field to bend the particles generated by collisions (not the particles of the beam !)
  - The measurement of the bending radius gives an estimate of the charge and energy of the particle
- Different lay-outs
  - A solenoid providing a field parallel to the beam direction (example: LHC CMS, LEP ALEPH, Tevatron CDF)
    - Field lines perpendicular to *(x,y)*



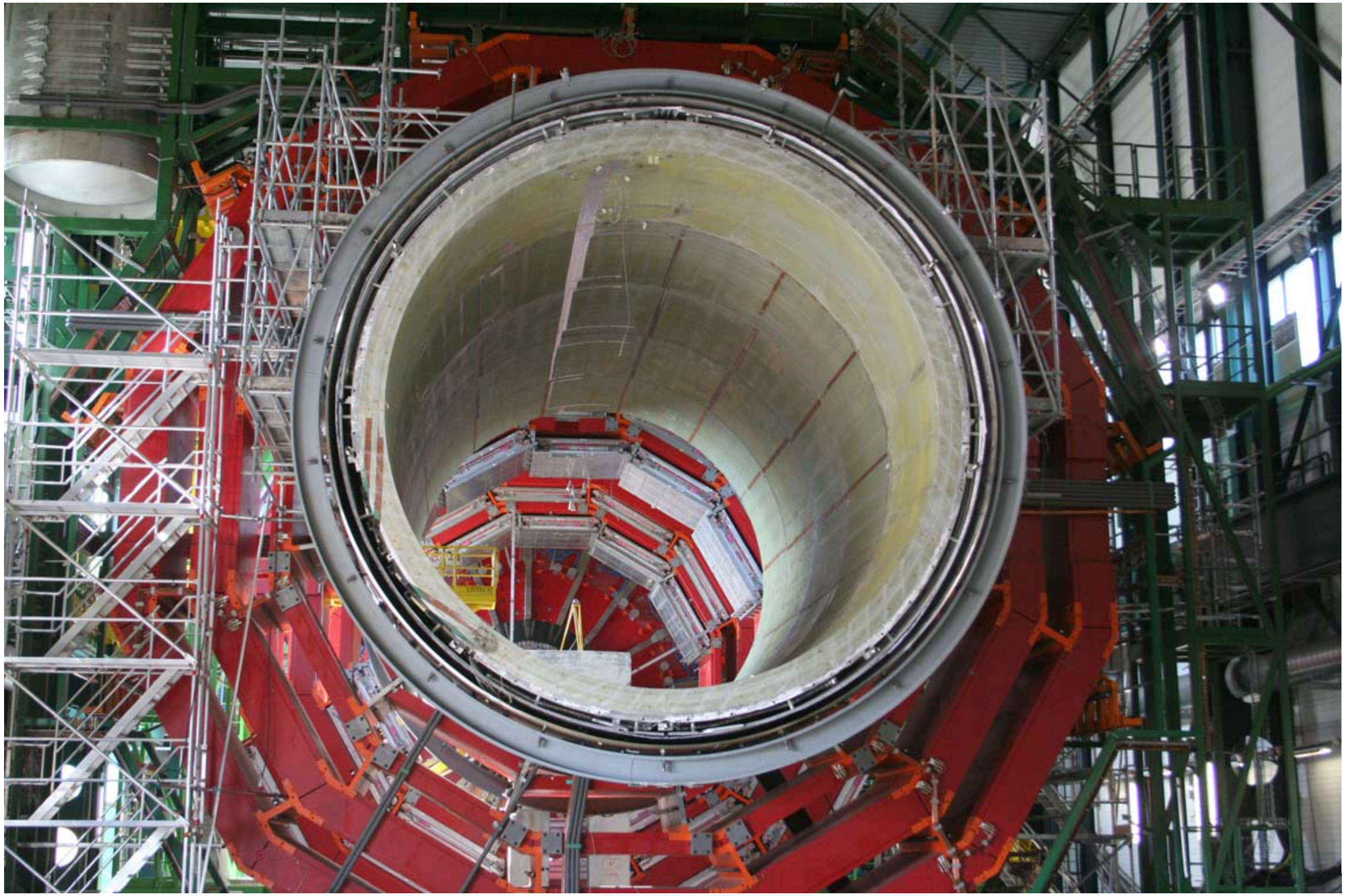
Sketch of a detector based on a solenoid



Sketch of the CMS detector in the LHC

  - A series of toroidal coils to provide a circular field around the beam (example: LHC ATLAS)
    - Field lines of circular shape in the *(x,y)* plane

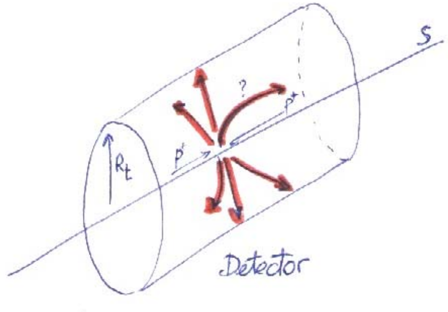
5. THE INTERACTION REGIONS: DETECTOR SPECIFICATIONS



The solenoid of CMS experiment

5. THE INTERACTION REGIONS: DETECTOR SPECIFICATIONS

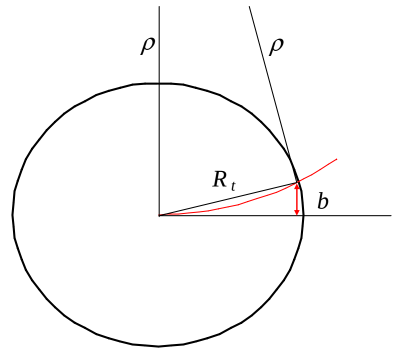
- Detector transverse size
  - The particle is bent with a curvature radius



$$E = eB\rho$$

  - B is the field in the detector magnet
  - R_t is the transverse radius of the detector magnet
  - The precision in the measurements is related to the parameter b
  - A bit of trigonometry gives

$$b = \frac{R_t^2}{2\rho} = \frac{e}{2}\frac{R_t^2 B}{E}$$



  - The magnetic field is limited by the technology
  - If we double the energy of the machine, keeping the same magnetic field, we must make a 1.4 times larger detector …

5. THE INTERACTION REGIONS: DETECTOR SPECIFICATIONS

- Detector transverse size
  - B is the field in the detector magnet
  - R_t is the transverse radius of the detector magnet
  - The precision in the measurements is $\propto 1/b$

$$b = \frac{R_t^2}{2\rho} = \frac{e}{2}\frac{R_t^2 B}{E}$$

$$b \sim 0.15 \frac{R_t^2 B}{E[\mathrm{GeV}]}$$

- Examples
  - LEP ALEPH: E=100 GeV, B=1.5 T, R_l=6.5 m, R_t=2.65 m, b=16 mm
    - that's why we need sizes of meters and not centimeters !

- The magnetic field is limited by technology
  - But fields are not so high as for accelerator dipoles (4T instead of 8 T)
  - Note that the precision with BR_t^2 – better large than high field …

- Detector longitudinal size
  - several issues are involved – not easy to give simple scaling laws

SUMMARY

- We recalled the principles of a synchrotron
  - Large magnetic field allow a more compact synchrotron or more a higher energy
- Principles of magnets
  - Why superconducting magnets are very effective
  - Their present limitations
  - The mechanisms behind superconductivity
- Main features of the design
  - The coils
  - The cable
- Detector magnets
  - The reasons for their huge size

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- M. N. Wilson, “Superconducting magnets”, Oxford University Press, London (1976)

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- Google Earth for the images of accelerators in the world
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- Columbia Pictures for some images of Terminator-3 the rise of machines