Accelerators

Lecture V

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http://bruening.home.cern.ch/bruening/summer−school/lecture5

V) LEP, LHC + more

- LEP
- LHC
- Other HEP Projects
- Future Projects
- What else?

LEP

- **Precision Experiment:**
  - **LEP1:**

    E = 45.6 GeV Z_0 $\frac{0}{0}$ **0.003%**

    (m_z = 91 GeV)
  - **LEP2:**

    E = 80.5 GeV $W^{+/-}$ $\frac{0}{0}$ **0.1%**

    (m_w = 80.5 GeV)
  - **E = 100 GeV** → **?**
- **Limits:**

  2• π• R = 27 km

  - **P > 20 MW**
  - **U > 2.8 GeV**
  - **P > 40 kW (10 MW)**
  - $\sigma \propto \gamma$

Luminosity

$$L \propto \frac{N_p^2 \cdot n_b}{\sigma_x \cdot \sigma_y}$$

● **$N_{b,\,max}$:**

- **LEP1:** **TMCI, beam-beam**
- **LEP2:** **heat loss**

$I_b = e \cdot N_b \cdot f_{rev} = 0.3 \div 1.0$ mA

● **I_{tot} :** **RF power** $(P = U \cdot I)$

8 mA ⟶ $n_b = 8 \div 12$ **bunches / beam**

● **σ:** **synchrotron radiation**
closed orbit

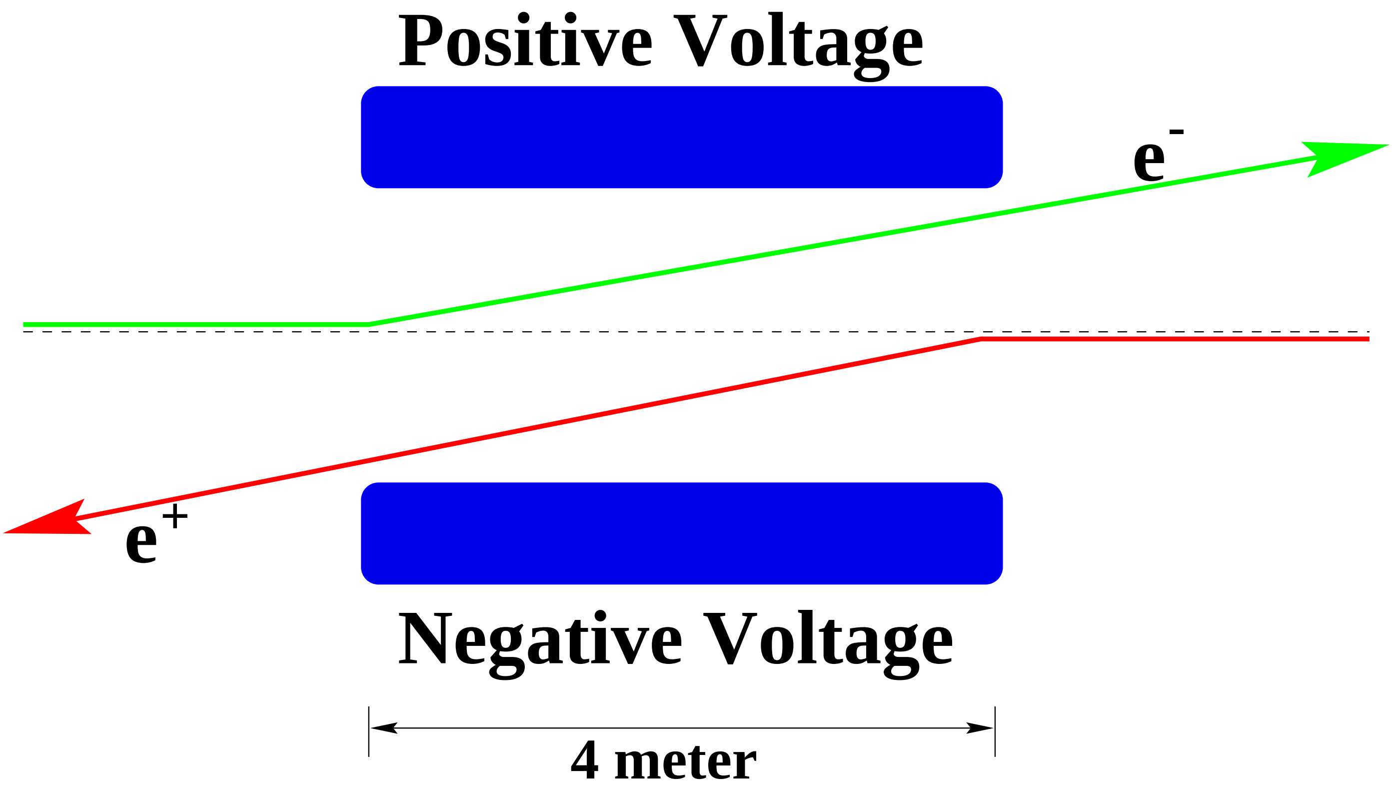
- $\sigma_x \propto \gamma$
- σ_y
  - **quantum excitations**
  - **coupling**
  - **vertical dispersion**

Beam Separation for e^-/e^+

- *Lorentz Equation:*

$$\vec{F} = e * \vec{E} + e * \vec{v} \times \vec{B}$$

→ **Electrostatic Separation**



Positive Voltage

e^-

e^+

Negative Voltage

4 meter

Sparking: **+/- 150 kVolt**

LEP Orbit

- **Horizontal Orbit:**
  - **beam offset in quadrupoles:**
    - → Lake Geneva
    - → moon
  - → energy error
- **Vertical Orbit:**
  - **beam offset in quadrupoles**
  - **beam separation**
  - → orbit deflection depends on particle energy
  - → vertical dispersion [D(s)]

$$\sigma_y = \sqrt{\varepsilon \cdot \beta_y + \delta_y^2 \cdot D^2}$$

→ **small vertical beam size relies on good orbit**

- 1994: 13000 vertical orbit corrections in physics

Average Luminosity

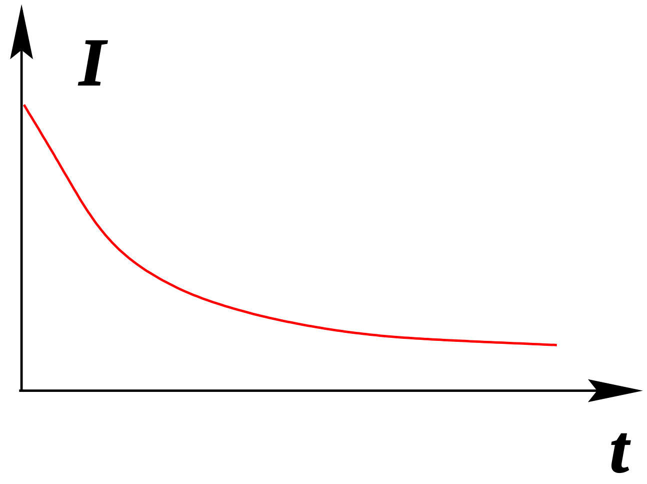
$$L \propto n_b \cdot \frac{I_{e^+} \cdot I_{e^-}}{\sigma_x \cdot \sigma_y}$$

- **beam size is determined by synchrotron radiation and optics**

→ constant

- **Beam Lifetime:**

$$I(t) = I_0 \cdot e^{-t/\tau}$$



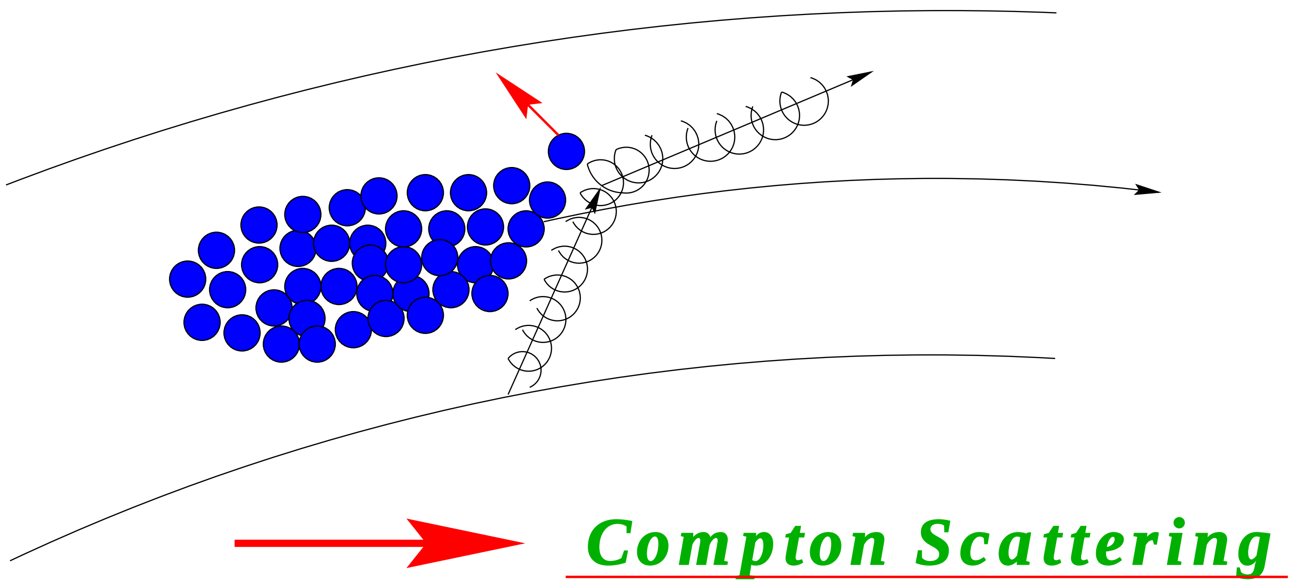
- **Residual gas pressure**

$P < 10^{-8}$ Torr

[atmosphere: P = 750 Torr]

- **Compton scattering**

Thermal and Synchroton Radiation Photons:



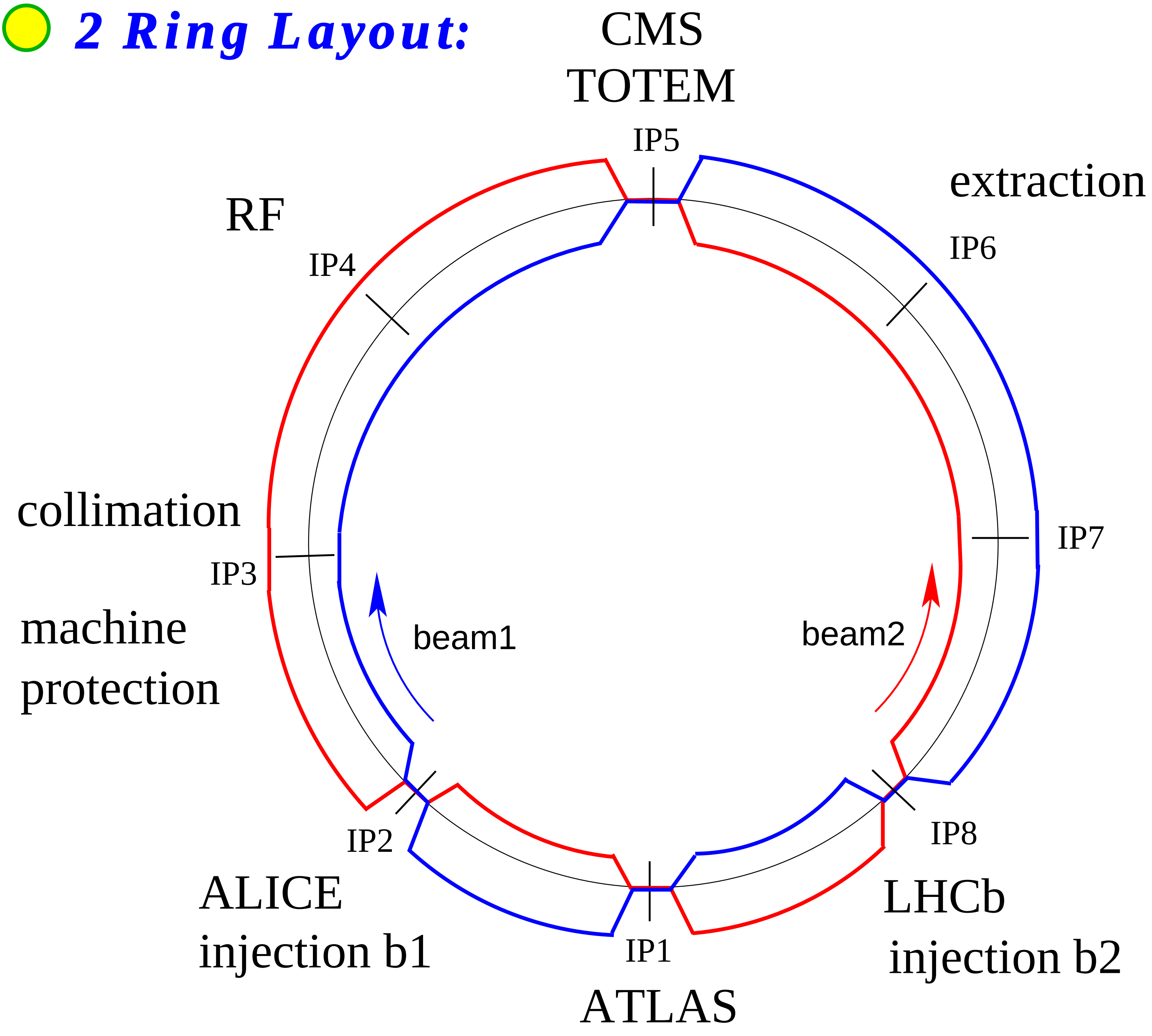
Beam Gas 10^{-10} Torr	τ_g = 200 hours
Beam thermal photons	τ_{tp} = 80 hours
Beam synchrotron photons	τ_{sp} = 134 hours
Total	τ_{tot} = 40 hours

LHC - Hardware

- **7 TeV p-p Collider:**
  → discovery potential (Higgs)
- **LEP Tunnel:** ($2\pi R = 27$ km)
  → $B = 8.4$ T
- **Superconducting Magnets:**
  - $f(T, B, I)$ $I = 11700$ A $T = 1.9$ K
    → magnet quench!
  - double bore; $L = 15$ m
  - field quality
- **Cooling:** superfluid He
  30 kTons coldmass; 90 Tons He
- **p-p and Ion Beams:** (Pb; Ca)
- **4 Experiments** (2 + 2)

LHC Layout

● 2 Ring Layout:



🟩 2−in−1 magnet design

🟩 4 proton experiments + 1 ion experiment

→ beam cross−over in 4 IR's

Circular Accelerators

🟩 ***uniform B−field:*** ***R = const.***

$$r = \frac{m_0}{Q} \bullet \frac{\gamma}{B} \bullet v$$

$$p = Q \bullet \frac{B \bullet L}{2\pi} \approx E / c \quad \text{for } E >> E_0$$

🟩 ***realistic synchrotron:***

B−field is not uniform:
- drift space for installation
- different types of magnets
- space for experiments etc

$$E = \frac{Q \bullet c}{2\pi} \bullet \oint \vec{B} \bullet d\vec{l}$$

→ high beam energy requires:
- high magnetic field
- large packing factor ’F’

Why 8.4 Tesla?

- ***required maximum dipole field:***

$B \propto \gamma$

$$\rightarrow \quad \boxed{B[T] = \frac{2\pi}{0.3} \bullet \frac{p[GeV/c]}{F \bullet L[meter]}}$$

- ***Physics:*** → **p = 7000 GeV/c**

- ***LEP tunnel:*** **L = 27000 meter**

→ **arcs: L = 22200 meter**

- **only 80% of the arc are filled with dipoles:**

→ **F = 0.8**

$$\rightarrow \quad \boxed{B_{max} = 8.38\ T} \rightarrow$$

iron saturation: 2 Tesla

earth: $0.3 * 10^{-4}$ Tesla

Power Consumption

- **LEP:**

$$\boxed{P = R \cdot I^2}$$

B = 0.135 Tesla

I = 4500A; R = 1mΩ → P = 20 kW / magnet

ca. 500 magnets → P = 10 MW

- **LHC:**

$$\boxed{B \propto I}$$

→ B_{max} **= 8.38 T** → I = 280000 A

(current density!)

→ P > 78 MW / magnet

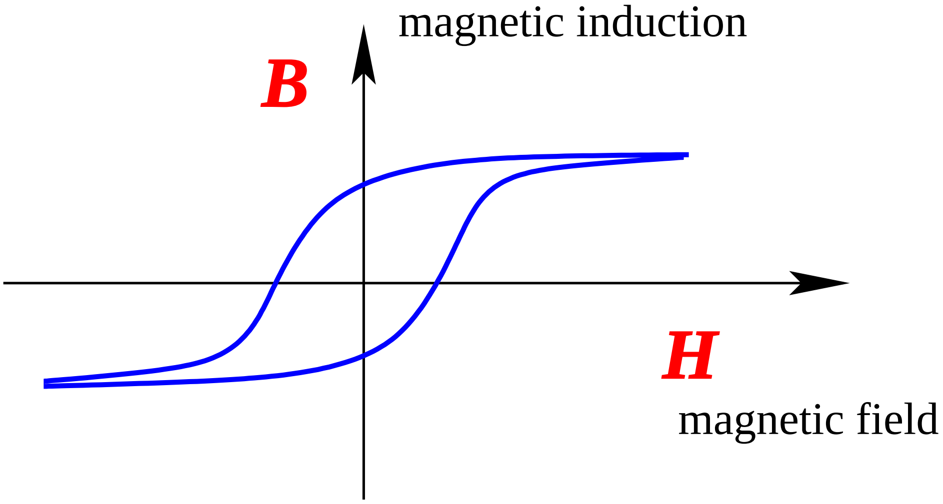
ca. 500 magnets → $\boxed{P > 39\ \text{GW}}$

→ ***superconducting technology!***

8.4 T is at the limit of available technology!

Bending Magnet

🟩 saturation



→ amplification process does not work
for fields above 2 Tesla!

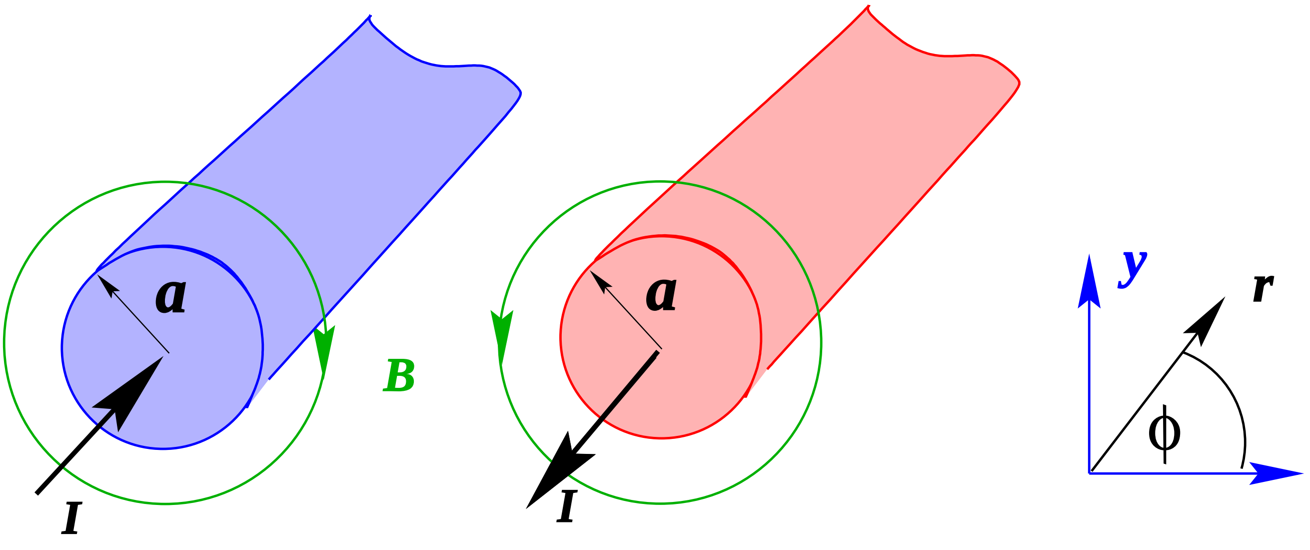
→ field quality control via pole face shape
does not work for the LHC magnets!

🟩 use the coil design to determine the field quality

→ cosine field distribution in the magnet
cross section generates a uniform vertical
dipole field

→ coil precision and stability is a major
concern for superconducting magnets!

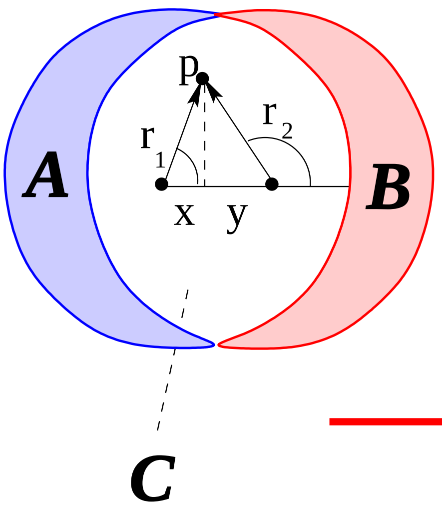
Superconducting Magnets



- **r > a:** $$\vec{B} = \frac{\mu_0 \cdot I}{2\pi r} \cdot [-\sin(\phi), \cos(\phi), 0]$$

- **r < a:** $$\vec{B} = \frac{\mu_0 \cdot j \cdot r}{2} \cdot [-\sin(\phi), \cos(\phi), 0]$$

- **Overlap the two cylinders:**

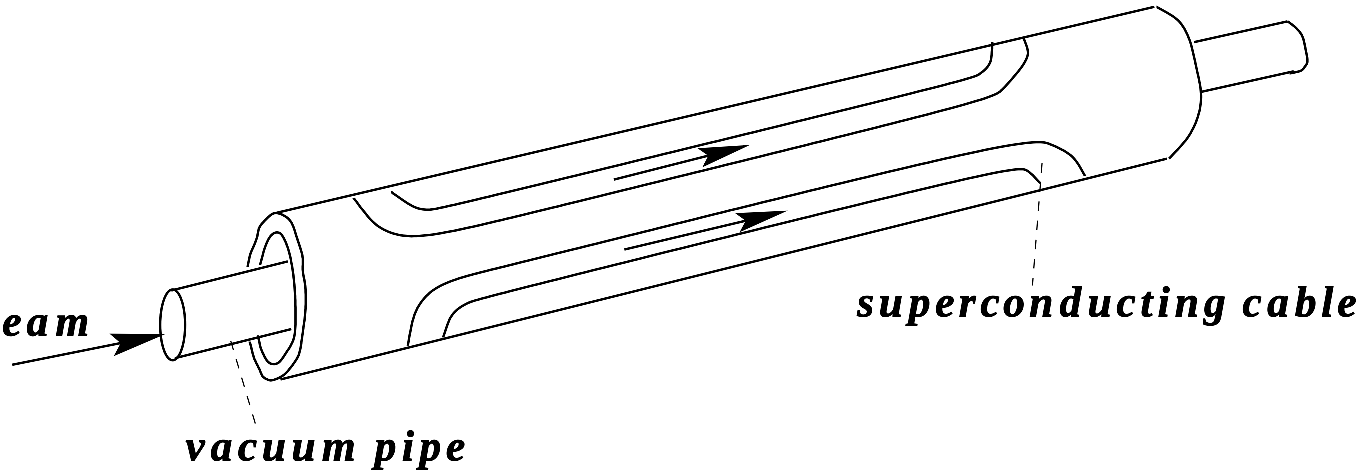


$$r_1 \cdot \cos(\phi_1) - r_2 \cdot \cos(\phi_2) = d$$

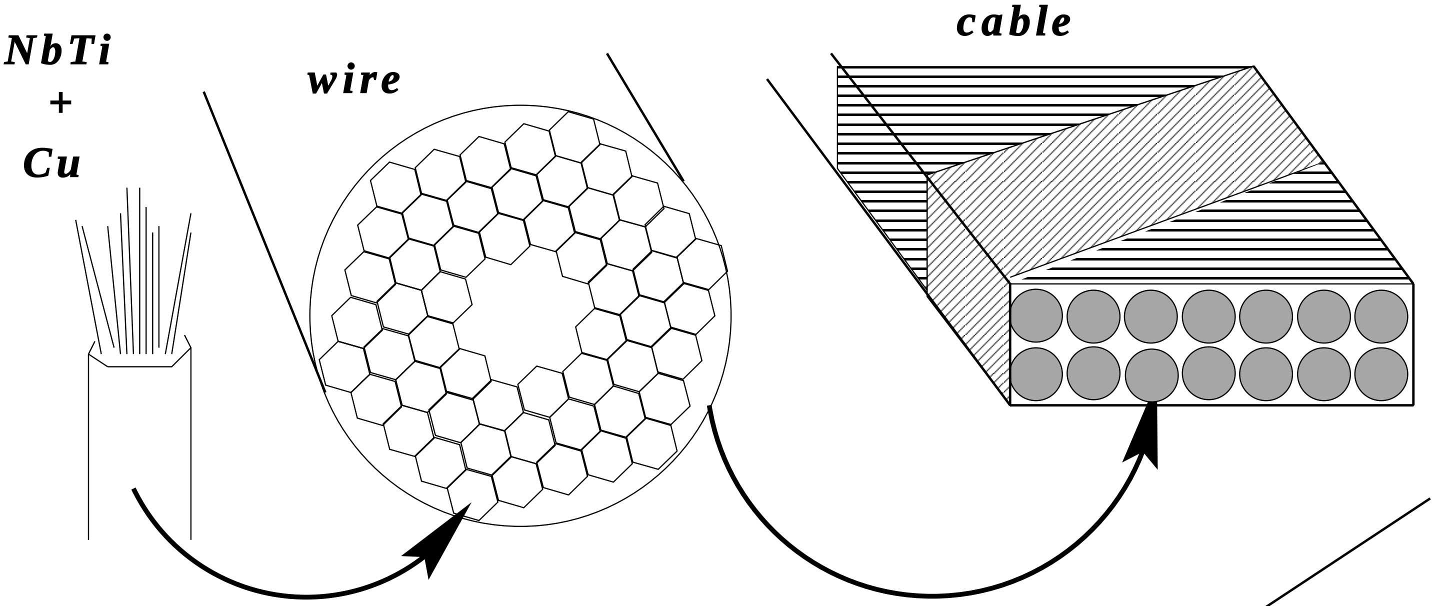
$$r_1 \cdot \sin(\phi_1) - r_2 \cdot \sin(\phi_2) = 0$$

$$\longrightarrow \left.\begin{array}{l} B_y = \text{const.} \\ B_x = 0 \\ j = 0 \end{array}\right\} \text{in } C$$

Coil Winding:

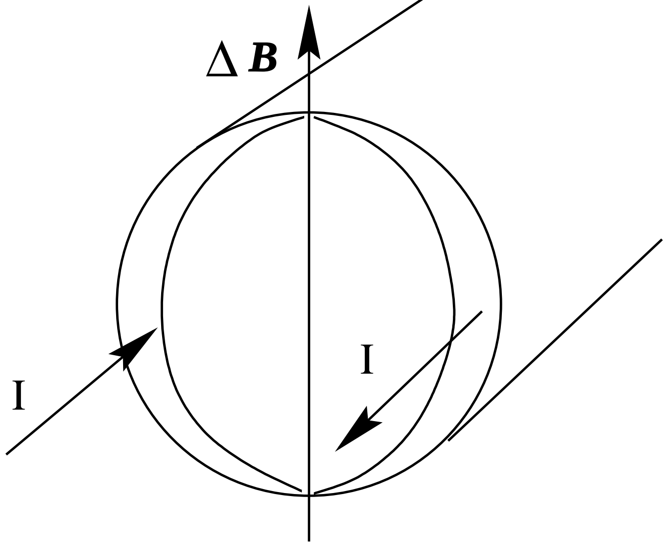


Superconducting Cable:



Persistent Currents:

$$\frac{\partial B}{\partial t} = -c \cdot \mathrm{rot}\, \vec{E}$$



LHC - Beam Parameter

$$L = \frac{N_p^2 \cdot n_b}{\varepsilon \cdot \beta} \cdot \frac{f_{rev}}{2 \cdot \pi}$$

- **Beam-Beam Interaction:**

$$\Delta Q \propto \frac{N_b}{\varepsilon} < 5 \cdot 10^{-3} \longrightarrow \boxed{N_p = 10^{11}}$$

- **Beam Size:**

magnet quality + aperture $\longrightarrow \varepsilon \longrightarrow N_p = 10^{11}$

- **β:** quadrupole strength + aperture

$\longrightarrow \beta = 0.5$ meter

$\longrightarrow n_b = 2835$

$\longrightarrow I_{beam} = 0.5$ A

Beam Power

$E = 300$ MJ

$\triangleq 120$ kg TnT

Synchrotron Radiation

$P = 0.5$ W/m

Summary LHC

- **Magnet Technology:**

  $B = 8.4$ T; field errors
  quench performance

- **Beam Energy:**

  $E = 7$ TeV; beam losses

- **Bunch Current:**

  $N_p = 10^{11}$; beam-beam limit

- **Beam Current:**

  $I = 0.5$ A; synchrotron radiation
  collective effects

Other Projects

- **Tevatron:** $p / \bar{p}$ $E = 1$ TeV 1985

  Chicago, USA

  6.3 km; 1 ring; $B = 4.5$ T; $T = 4.2$ K

  $n_b = 6 \leftrightarrow 36$; $I_{beam} = 2$ mA; range: 6

- **HERA:** e / p $E = 0.9$ TeV 1991

  Hamburg, Germany

  6.3 km; 2 rings; $B = 5.5$ T; $T = 4.4$ K

  $n_b = 180$; $I_{beam} = 0.5$ mA; range: 20

- **RHIC:** Au/Au; p / p

  New York, USA $E = 0.25$ TeV 1999

  3.8 km; 2 rings; $B = 3.5$ T; $T = 4$ K

  $n_b = 57 \leftrightarrow 114$; $I_{beam} = 13\,\mu$A; range: 7

- **LHC:**

  $B = 8.4$ T; $T = 1.9$ K; range = 16; $I_{beam} = 0.5$ A

Future

- **VLHC:** magnet technology

  95 km; 2 ring; B = 12 T; n = 20800

  520 km; 2 ring; B = 2 T; n = 130000

- **Muon Collider:** muon source

  muon lifetime $(\tau = 2.2\,\mu s)$

  lepton collider without
  synchrotron radiation

- **Linear Collider:** 500 GeV / 3 TeV

  - USA / Japan NC
  - Germany SC
  - CERN NC; 2 beams

Linear Collider

- **No Bending Field:**

→ reduced synchrotron radiation

- **Beam Size:** $\sigma \propto 1/\gamma$

- **High Frequency:**

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} \longrightarrow \text{high frequency}$$

$$\lambda = \frac{c}{f} \longrightarrow \text{small structure}$$

- **Tesla:** 1.3 GHz
- **NLC:** 11.4 GHz
- **CLIC:** 30 GHz

→ alignment and wakefields

What Else?

- High Energy Physics
- Nuclear + Atomic Physics:
  - LEAR: anti-hydrogen
- Synchrotron Radiation Sources:
  - solid state physics
  - chemestry
  - biology
- Hospitals: cancer treatment
- Industry:
  - surface treatment
  - sterilisation
  - nuclear waste disposal