Accelerators

LISHEP

Lecture II

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Summary Lecture I

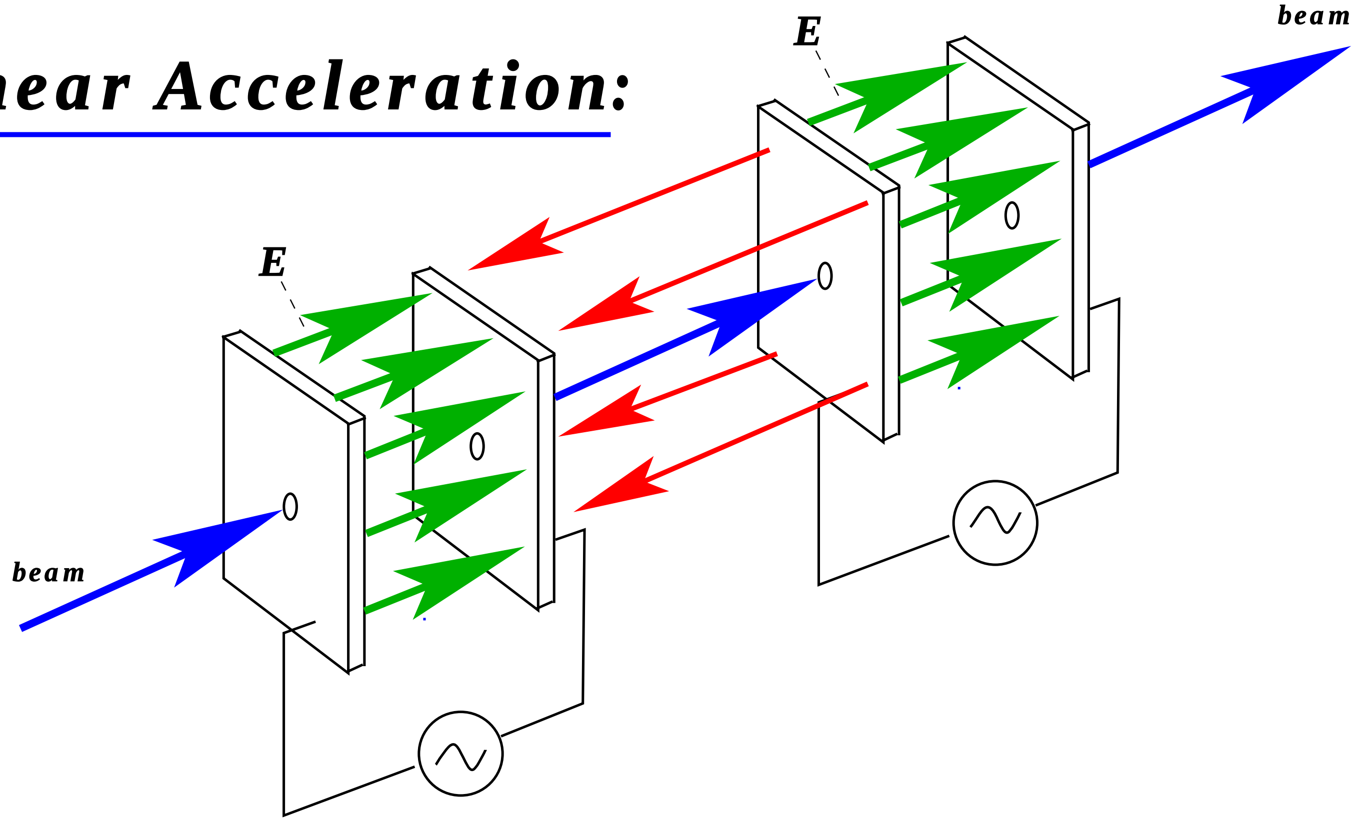
- Motivation & History
- Particle Sources
- Acceleration Concepts:
  - Equations and Units
  - DC Acceleration
  - RF Acceleration
  - Electro−Magnetic Waves & Boundary Conditions
- Summary

II) Circular Accelerators

- Cyclotron
- Synchrotrons
  - beam energy
- Collider Concepts:
  - need for focusing
  - collider versus fixed target
  - particle − anti particle collider
  - luminosity
- Summary

Time Varying Fields

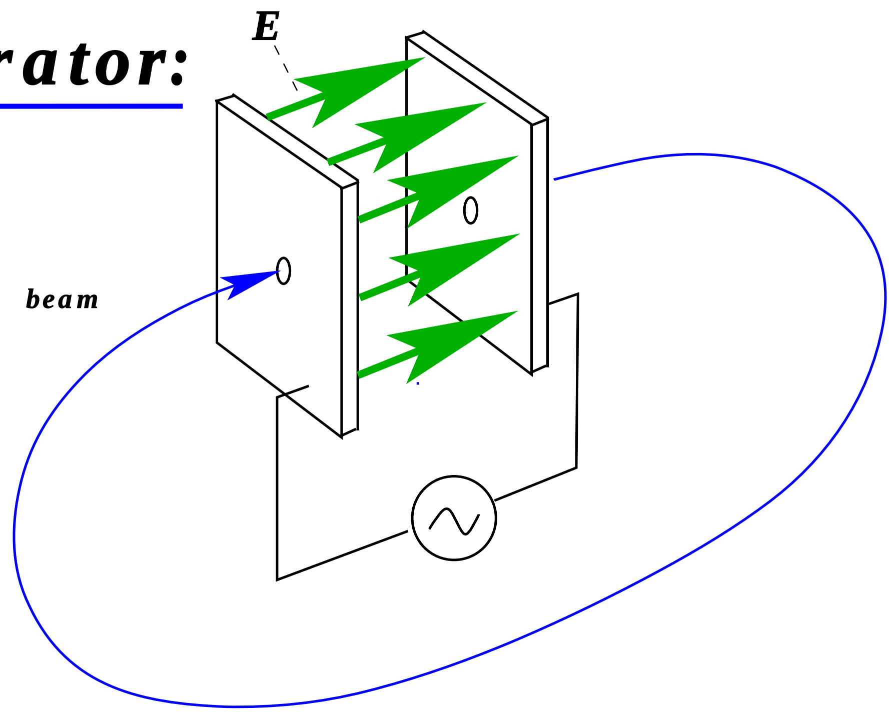
Linear Acceleration:



→ **bunched beam**

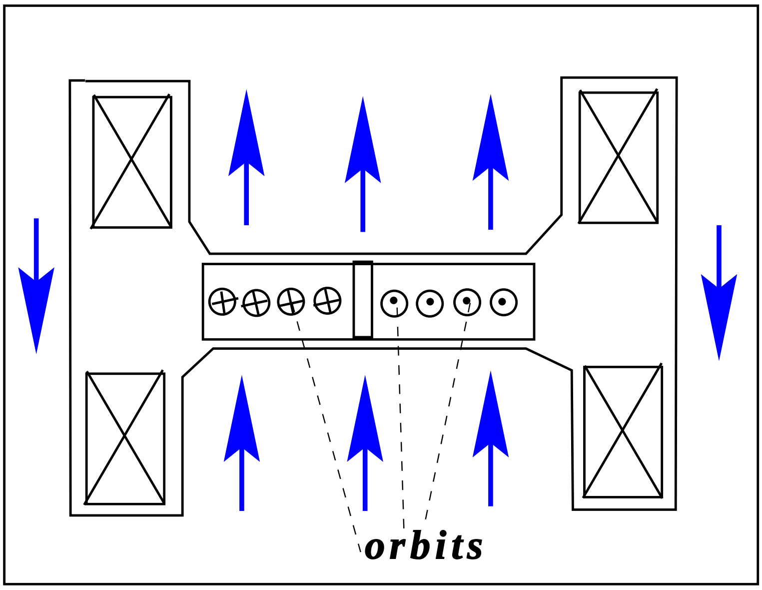
→ **long accelerator!**

Circular Accelerator:



Circular Accelerators I

- **1929:** Lawrence → Cyclotron



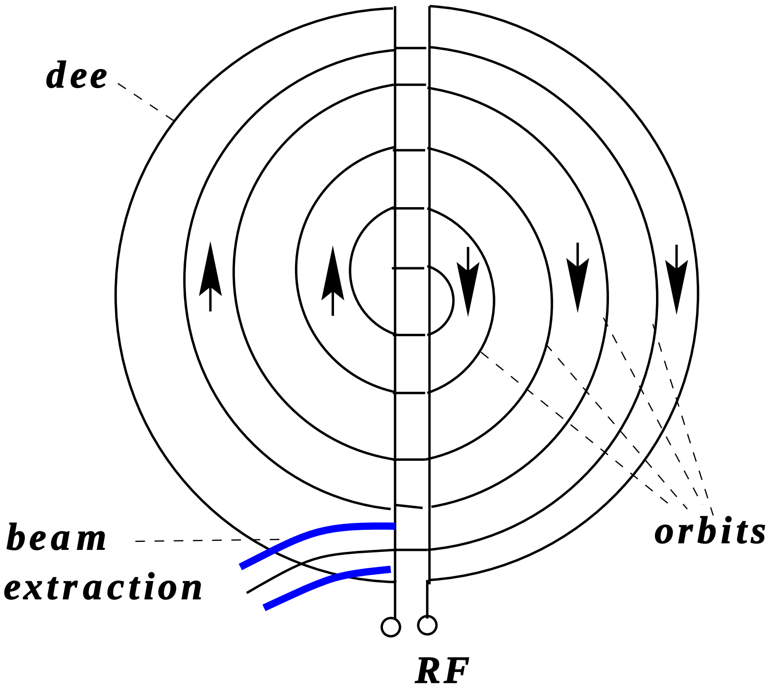
$$\omega = \frac{Q}{m} \cdot B$$

$$r = \frac{m}{Q} \cdot \frac{v}{B}$$

$m = const$

→ $f_{RF} = const$

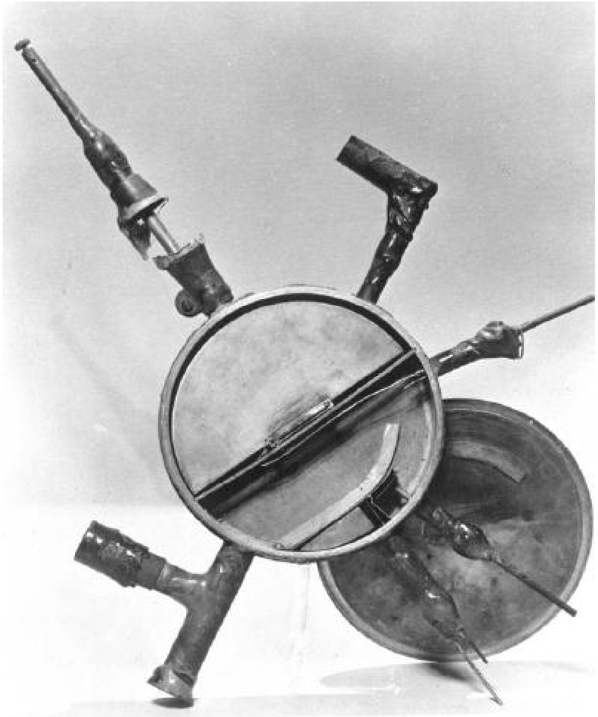
$B = const$



- **1931:** Livingston → H^- to 80 keV
- **1932:** Lawrence → p to 1.2 MeV (NP 1939)

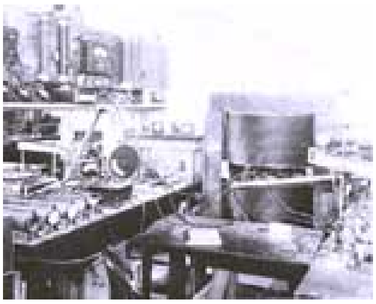
Cyclotron

- ***1931:***
  4.5 inch cyclotron by Livingston

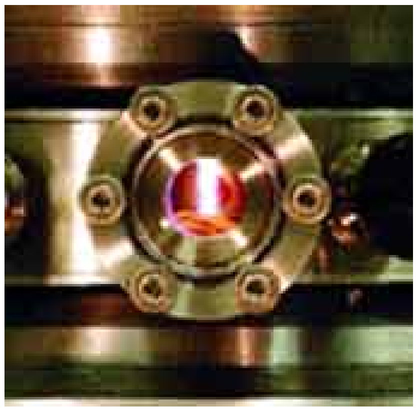


→ H^- ***to 80 keV***

- ***11 inch cyclotron by Lawrence:***



→ ***p to 1.2 MeV***



12 inch build by T. Koeth (1999)

Disadvantage:

High Energy:

$\gamma >> 1$ → $f_{RF} \neq const.$

→ short bunch trains

→ large dipole magnet

Synchrotron:

$R = const.$

$$\omega_0 = \frac{Q}{m_0} \cdot \frac{B}{\gamma}$$

$$r = \frac{m_0}{Q} \cdot \frac{\gamma}{B} \cdot v \rightarrow B \neq const.$$

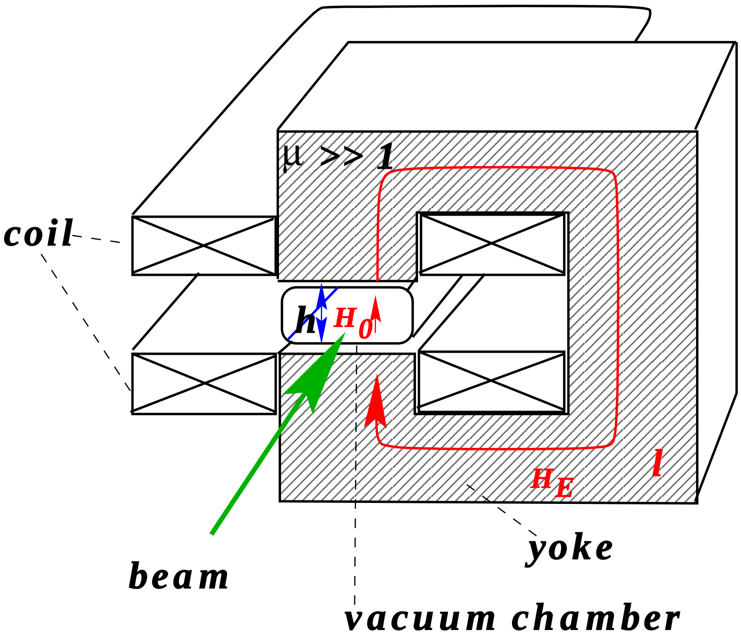
→ small magnets,

→ $v = c$ → $f_{RF} = const.$

→ high beam energy requires strong magnets & large storage ring!

Bending Magnet

- $\oint H = I \cdot N$ $\qquad B = \mu_0 \cdot \mu \cdot H$



$\mu < 1$: *Dia*

$\mu > 1$: *Para*

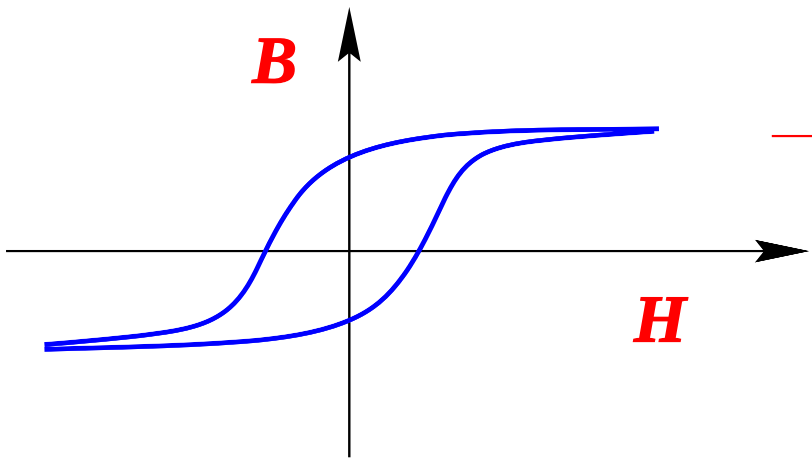
$\mu >> 1$: *Ferro*

- ***Maxwell Equations:***

$$B_{0\perp} = B_{E\perp}$$

$$\oint H = h \cdot H_0 + l \cdot H_E$$

$$H_0 = \mu \cdot H_E$$

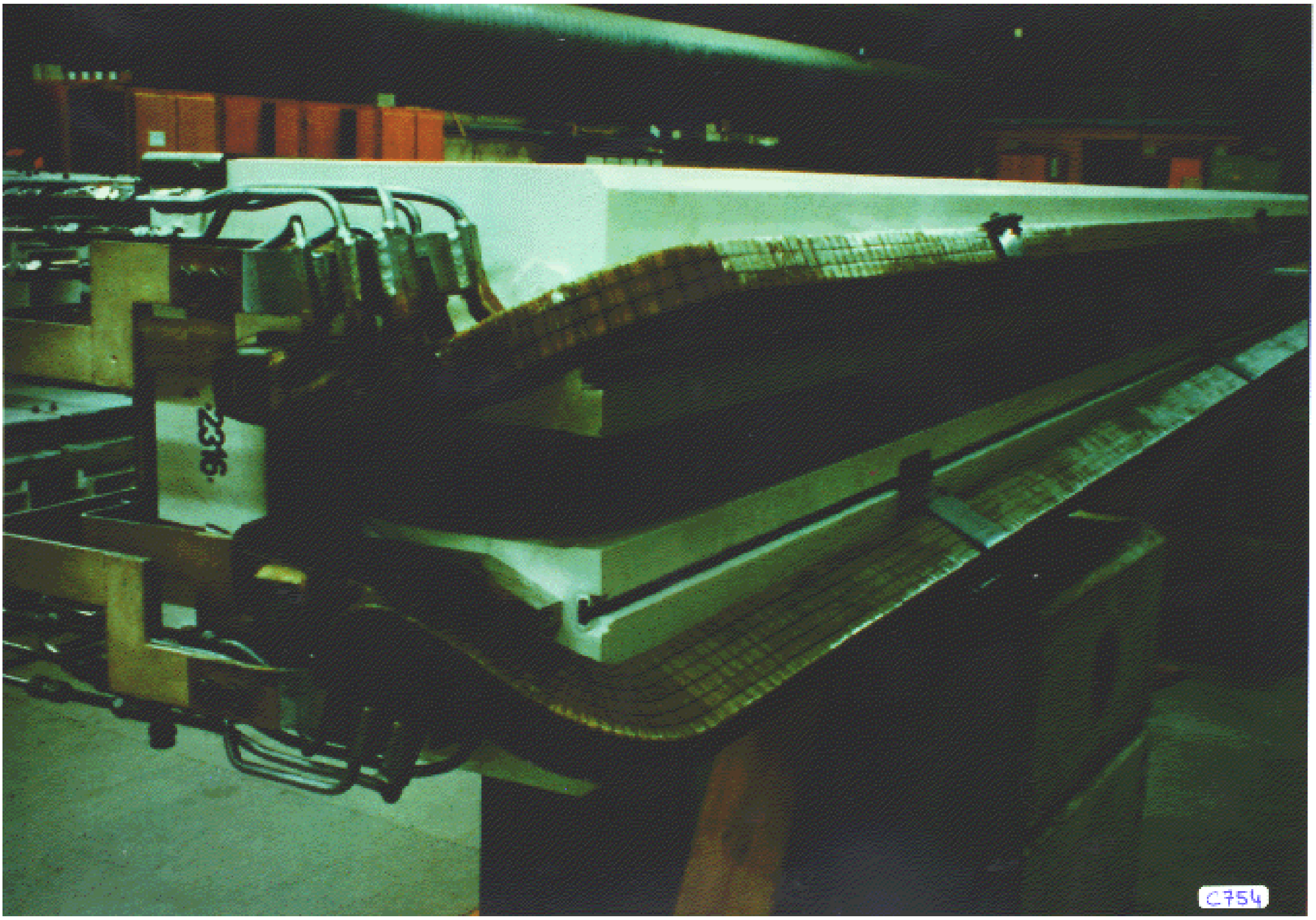


$$B_0 = \mu_0 \frac{N\,I}{h}$$

$$\frac{1}{\rho}\,[m^{-1}] = \frac{e \cdot B}{p} = 0.3 \cdot \frac{B\,[T]}{p\,[GeV]}$$

Bending Magnet

LEP injection area dipole magnet:



B = 0.135 T; I = 4500 A; R = 1 mΩ

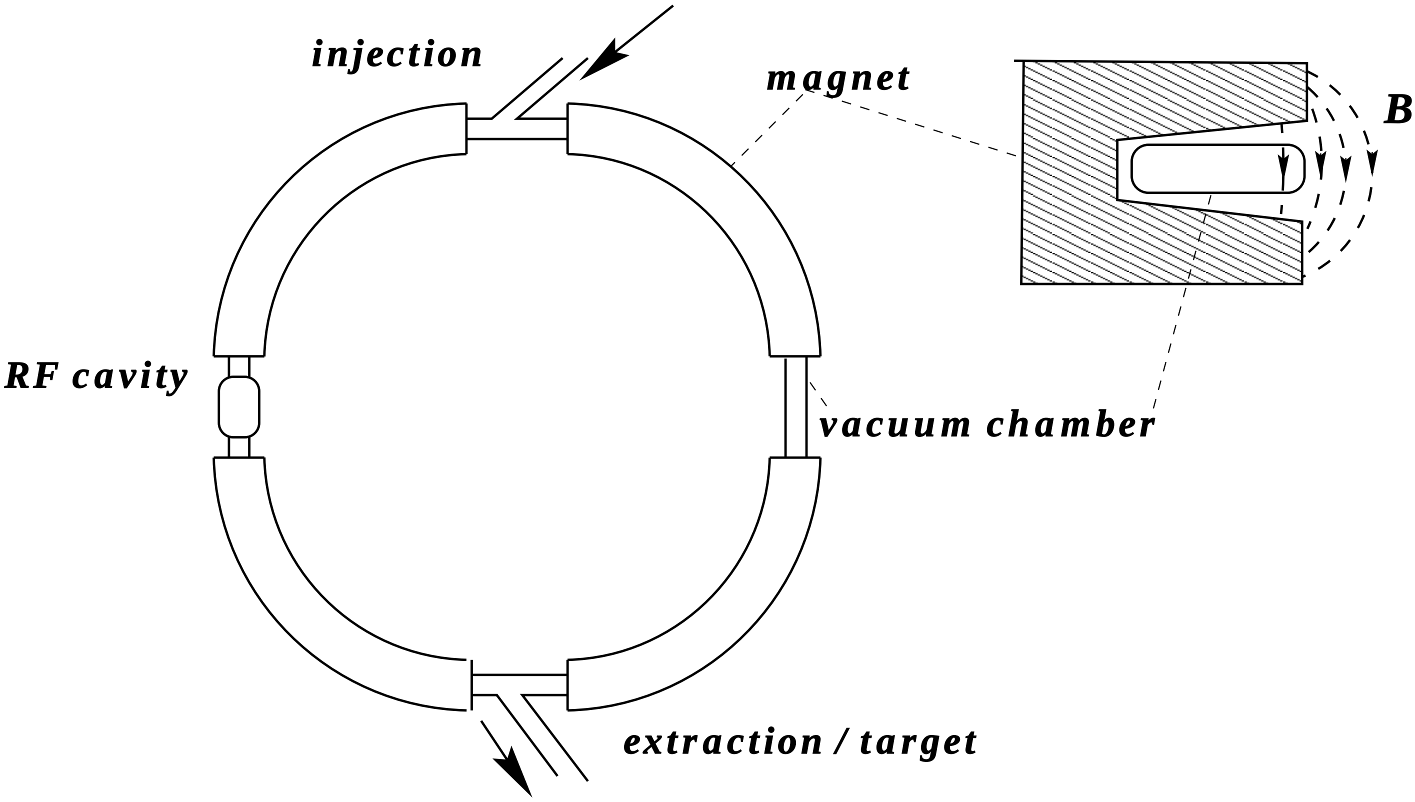
➤ P = 20 kW / magnet

ca. 500 magnets ➤ P = 10 MW

Circular Accelerators II

Synchrotron:

- **1952:** Cosmotron 3 GeV protons
- **1949:** electrons

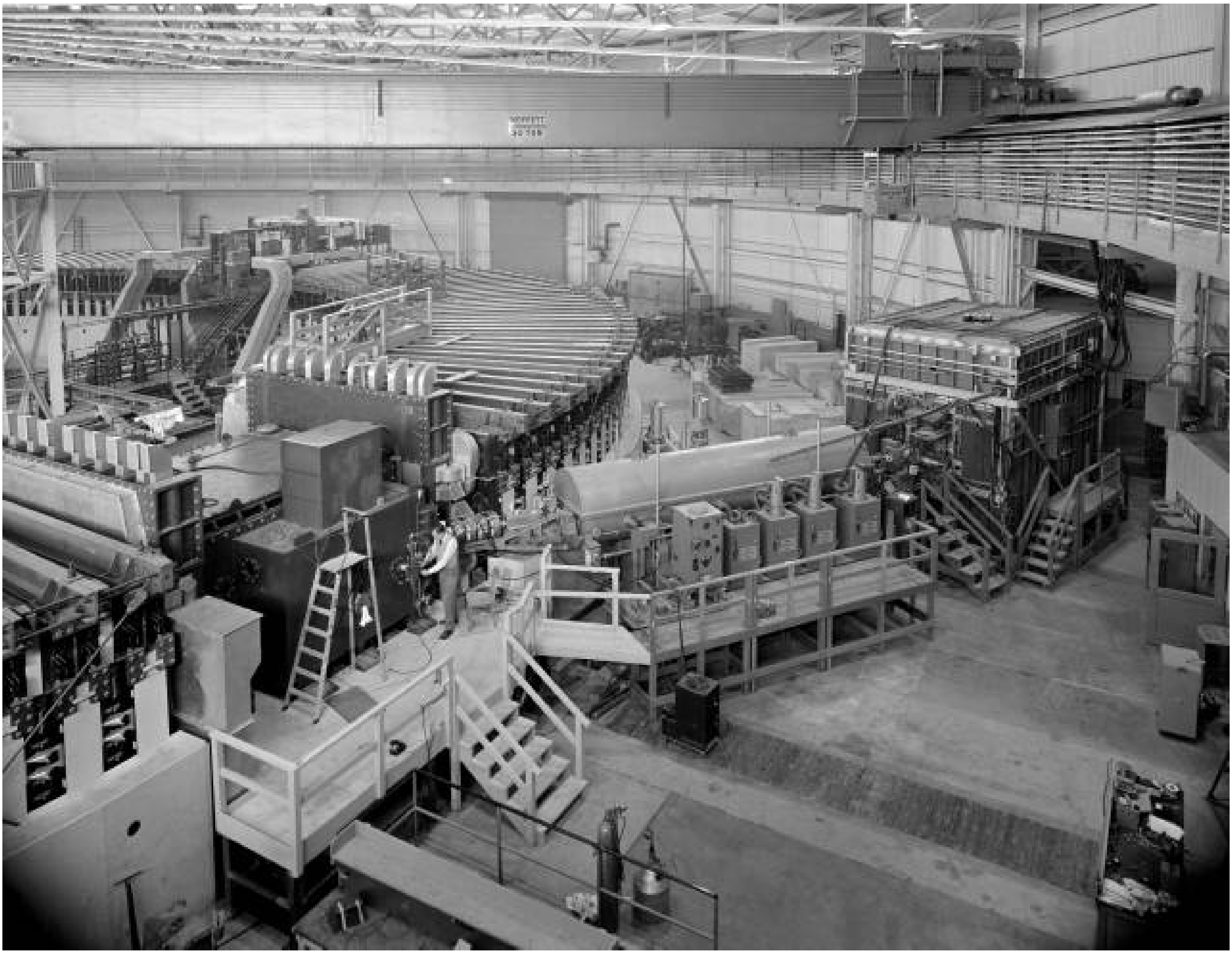


- **1955:** Bevatron 6 GeV protons

→ p^- (fixed-target experiment)

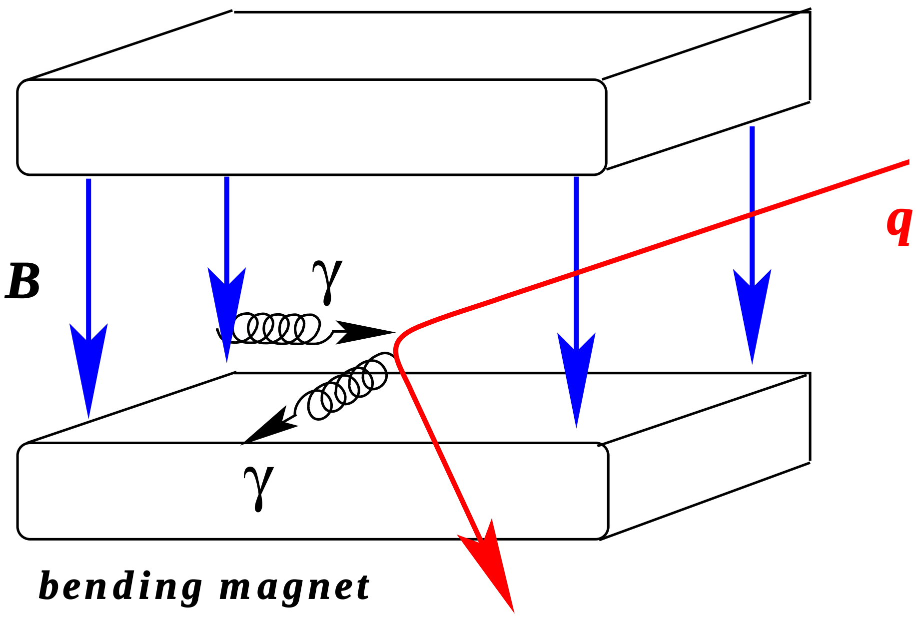
$$E_{cm} = 2 \cdot m_0 \cdot c^2 \left(\sqrt{1 + \frac{E}{2 \cdot m_0 \cdot c^2}} - 1 \right)$$

Berkeley Bevatron

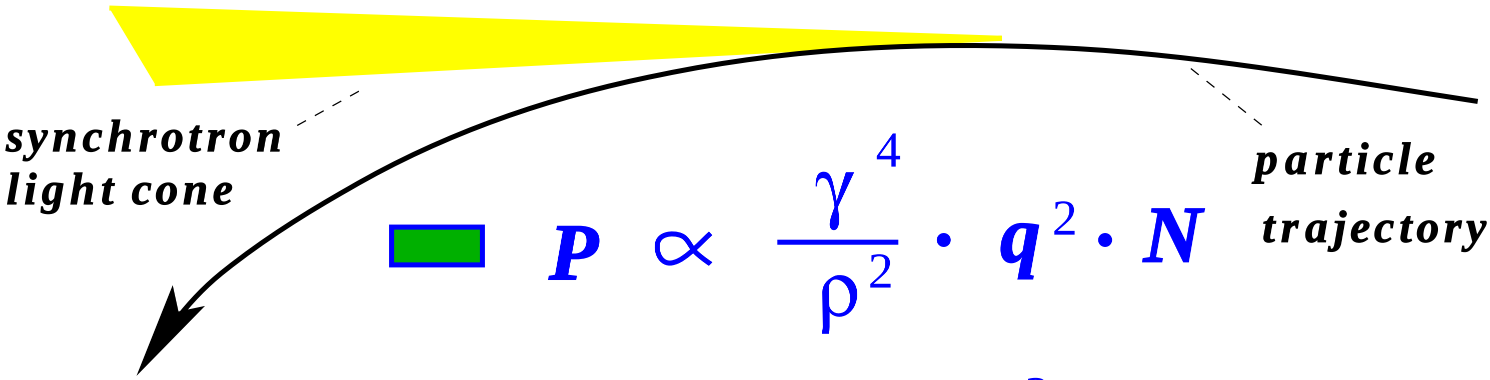


Synchrotron Radiation

Quantum Picture:



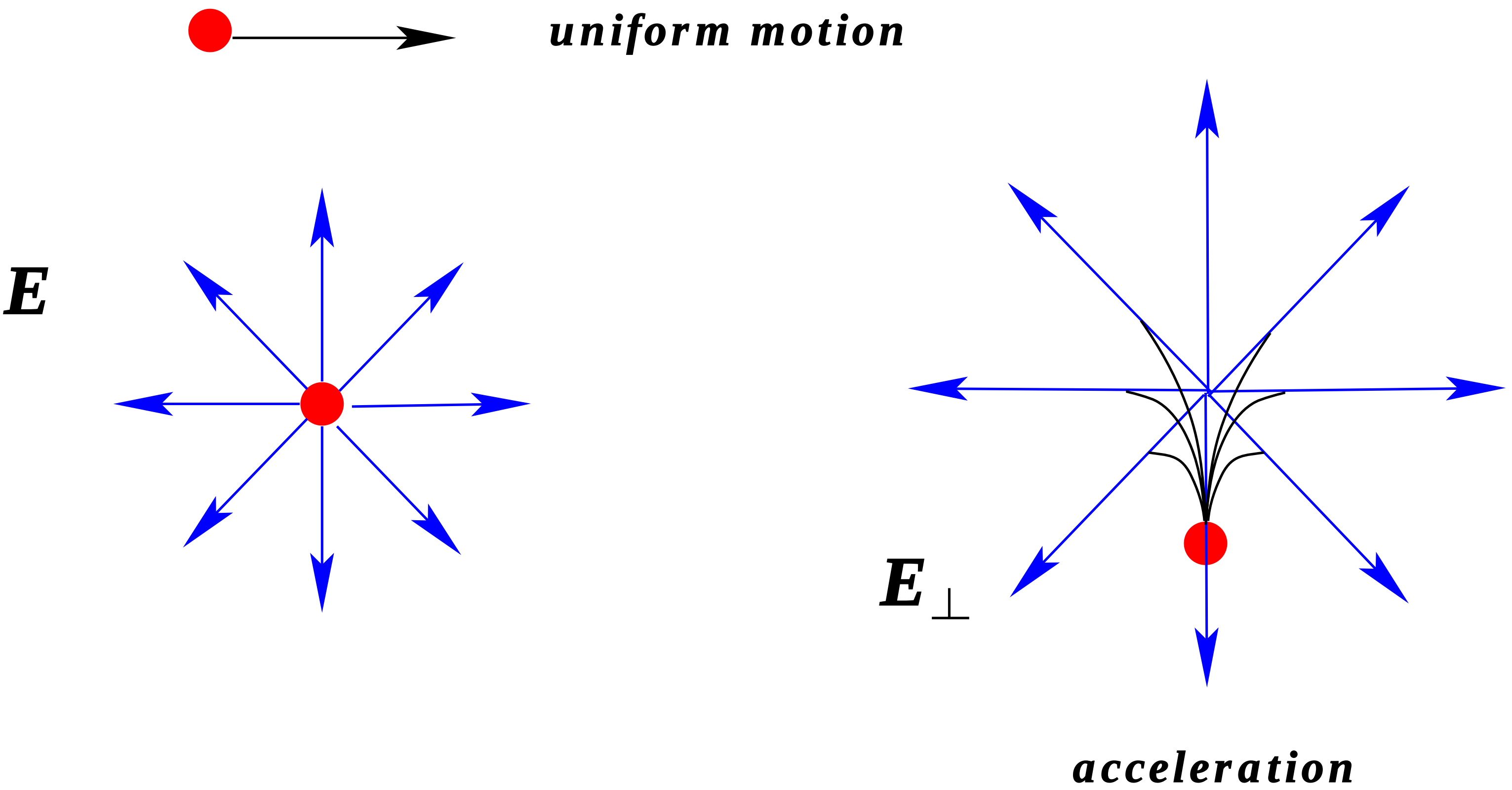
- ***radiation fan in bending plane***
- ***opening angle*** $\propto \frac{1}{\gamma}$

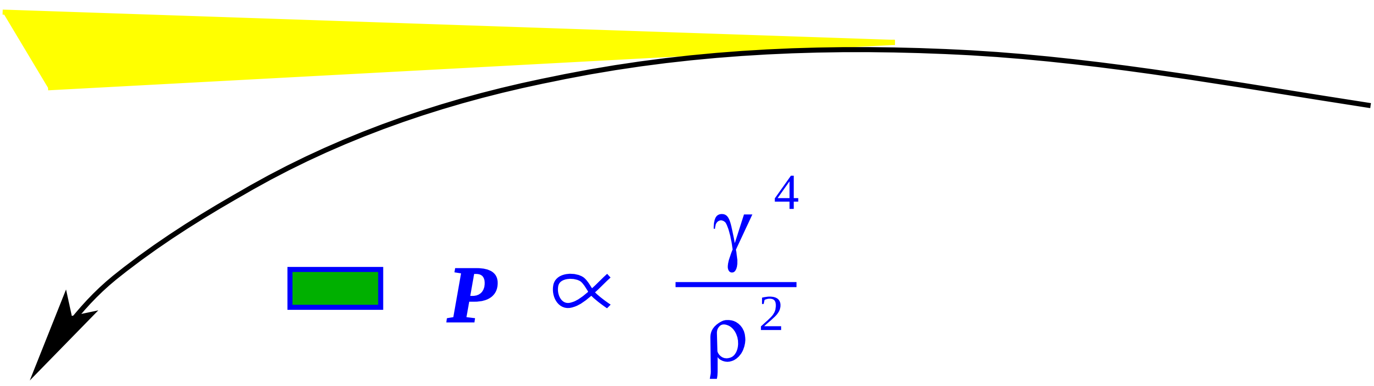


- $P \propto \frac{\gamma^4}{\rho^2} \cdot q^2 \cdot N$
- $\langle E_\gamma \rangle \propto \frac{\gamma^3}{\rho}$
- ***polarised***

Synchrotron Radiation

- **Acceleration:**





- $P \propto \frac{\gamma^4}{\rho^2}$

- **polarised**

Examples

	E [GeV]	ρ [km]	N [10^{12}]	U [MeV]	P [MW]	E_γ [keV]
LEP 1	45	3.1	4.7	260	2.1	90
LEP 2	100	3.1	4.7	2800	23	715
LHC	7000	3.1	312	0.007	0.005	0.04

- γ-rays: Co_{60} → 1.3 MeV
- X-rays: → keV
- Visible Light: → eV

LEP 1 → X-rays

LEP 2 → γ-rays

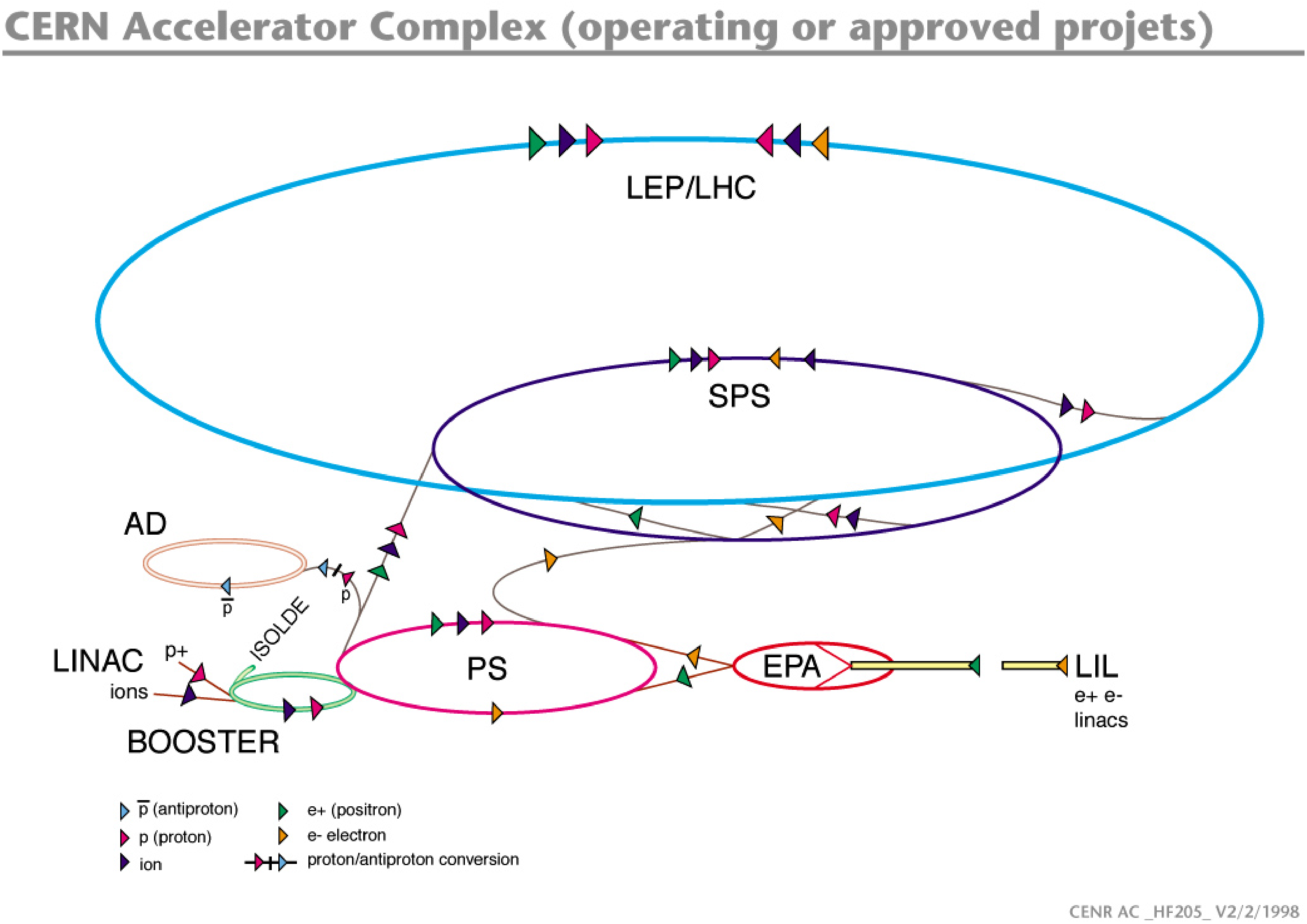
LHC → UV light

Summary

- **Acceleration Concept:**
  - Static field — 25 MeV — discharge
  - AC field — no limit — length
  - multiple passages
- **Circular Acceleration:**
  - Cyclotron — 25 MeV — non−relativistic
  - Synchrotron — no limit — small magnets — synchrotron radiation
- **In Practice:**

  Combination of several options

CERN Accelerator Complex



- ***searching at each acceleration stage for the most efficient acceleration concept one uses in practice a combination of several types!***

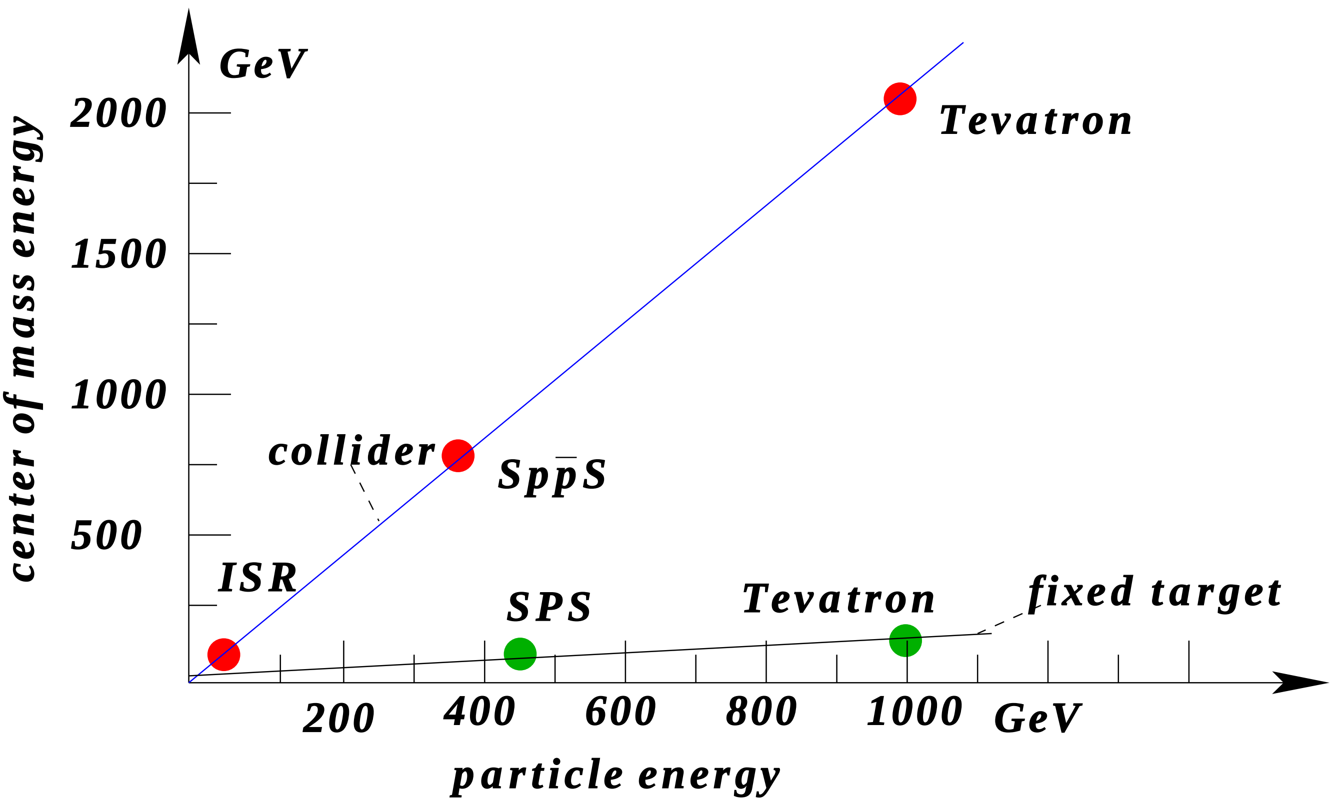
Collider Rings

→ **1960:** fixed target physics
(bubble chamber)

- **But:**

$$E_{cm} = 2 \cdot m_0 \cdot c^2 \left(\sqrt{1 + \frac{E}{2 \cdot m_0 \cdot c^2}} - 1 \right)$$

- **Collider:** $E_{CM} = 2 \cdot E_p$



1960 ↗: e^+/e^- collider

1970 ↗: p^+/p^- collider

Features (+/-)

Advantages:

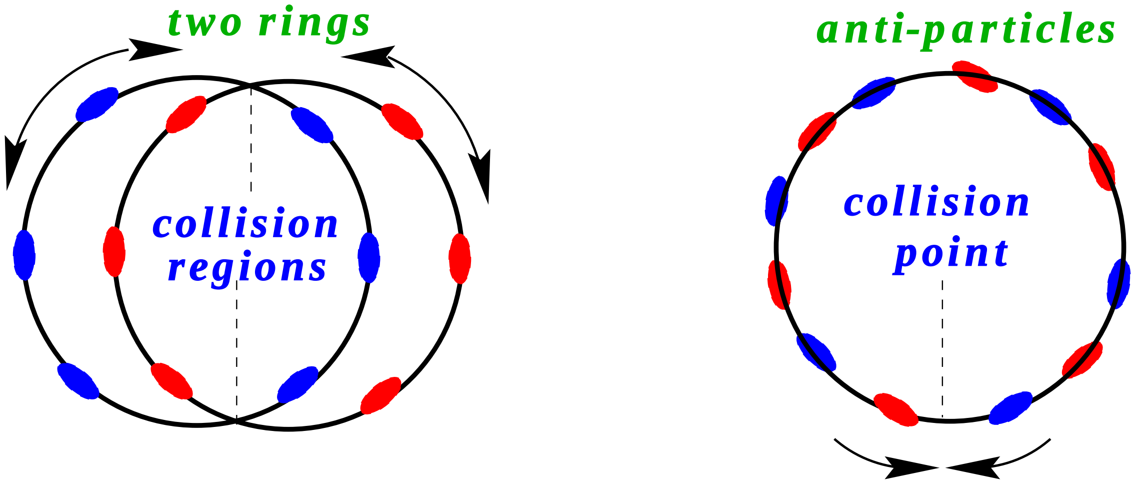
- $E_{CM} = 2 \cdot E_p$

Disadvantages:

- not all particles collide in one crossing

  → long storage times

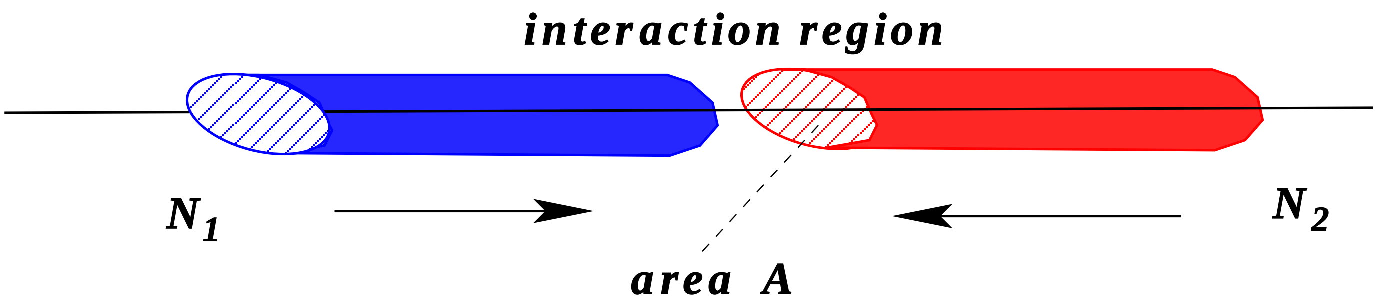
- requires 2 beams:



- beam-beam interaction

Luminosity

- $N_{ev} / sec = \sigma \cdot L \qquad [\,L\,] = cm^{-2} \cdot s^{-1}$



$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{A}$$

- **high bunch current**

  beam−beam; collective effects

- **many bunches**

  total current (RF); collective effects

- **small beam size**

  hardware

Beam-Beam Parameter

- the electro−magnetic fields of beam2 act on the particles of beam1

→ transform into moving frame of test particle and calculate Lorentz force

$$\vec{F} = q\cdot(\vec{E} + \vec{v} \times \vec{B}) = q\cdot(E_r + \beta c B_\phi)\cdot\vec{r}$$

Gauss theorem and Ampere's law:

$$\rightarrow \quad 2\pi\cdot r\cdot E_r = \frac{1}{\varepsilon_0}\cdot\int_0^r 2\pi r'\cdot\rho(r')\,dr'$$

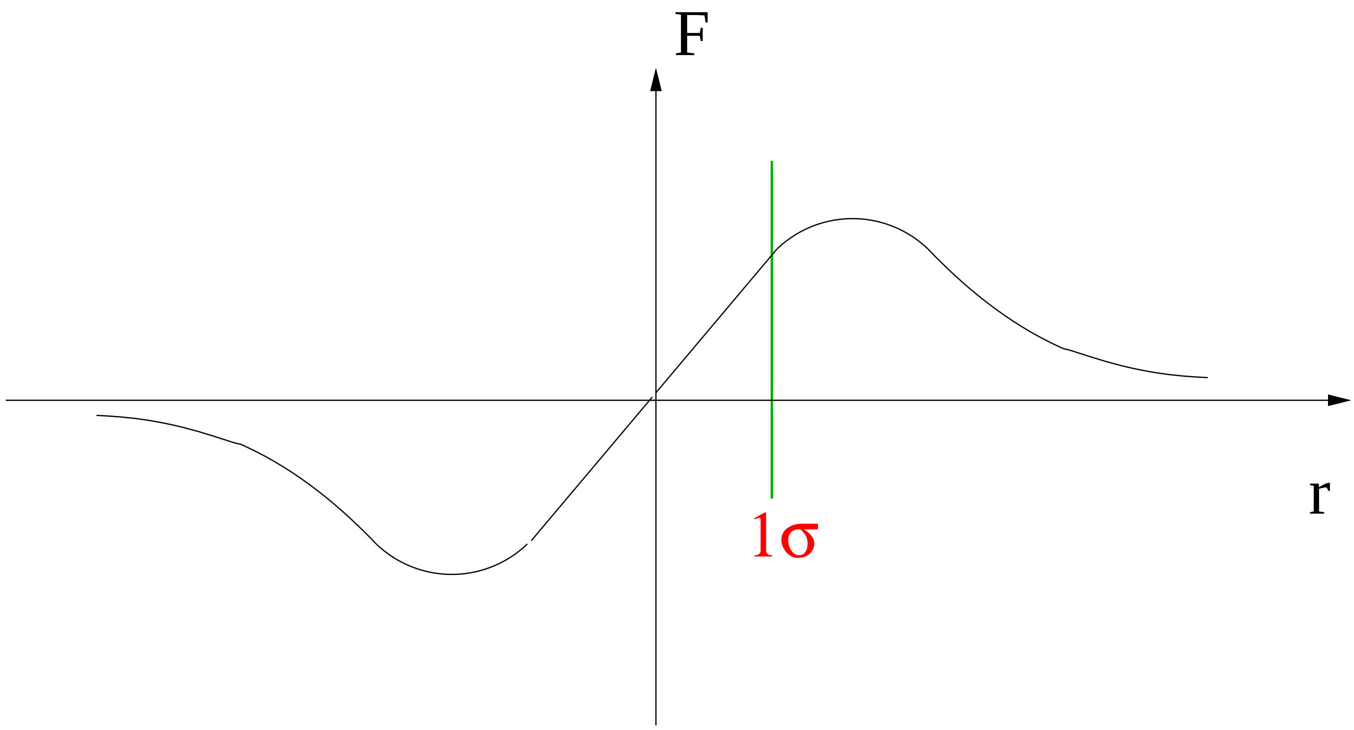
$$2\pi\cdot r\cdot B_\phi = \mu_0\int_0^r 2\pi r'\cdot\beta c\cdot\rho(r')\,dr'$$

- Gaussian distribution for round beam:

$$F(r) = \frac{N_2 q_1 q_2}{2\pi\varepsilon_0}\cdot\frac{(1+\beta^2)}{r}\cdot\left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$$

→ force acts in the radial direction

Beam–Beam Parameter



- small amplitudes (with $v \approx c$):

$$\frac{F}{v \cdot p} \approx \frac{N_2 \cdot r_p}{\gamma} \cdot \frac{r}{\sigma^2} \longrightarrow \text{quadrupole}$$

with: $r_p = \frac{e^2}{4 \cdot \pi \cdot \varepsilon_0} \cdot \frac{1}{m_p \cdot c^2}$

- strong non–linear field:

tune depends on oscillation amplitude

strong non–linear field

→ bunch intensity limited by non–linear resonances

Lepton versus Hadron Collider

- **Leptons:**
  - elementary particles
    → well defined energy
  - light particles ($\gamma >> 1$)
    → synchrotron radiation
    (size, damping, magnet type)
- **Hadrons:**
  - multi particle collisions
    → energy spread
    (discovery range vs. background)
  - heavy particles ($\gamma < 10000$)
    → no synchrotron radiation
    (no damping, superconducting magnets)
- **Example:** Z_0

1985	$Sp\bar{p}S$	p^+p^-
1990	LEP	e^+e^-

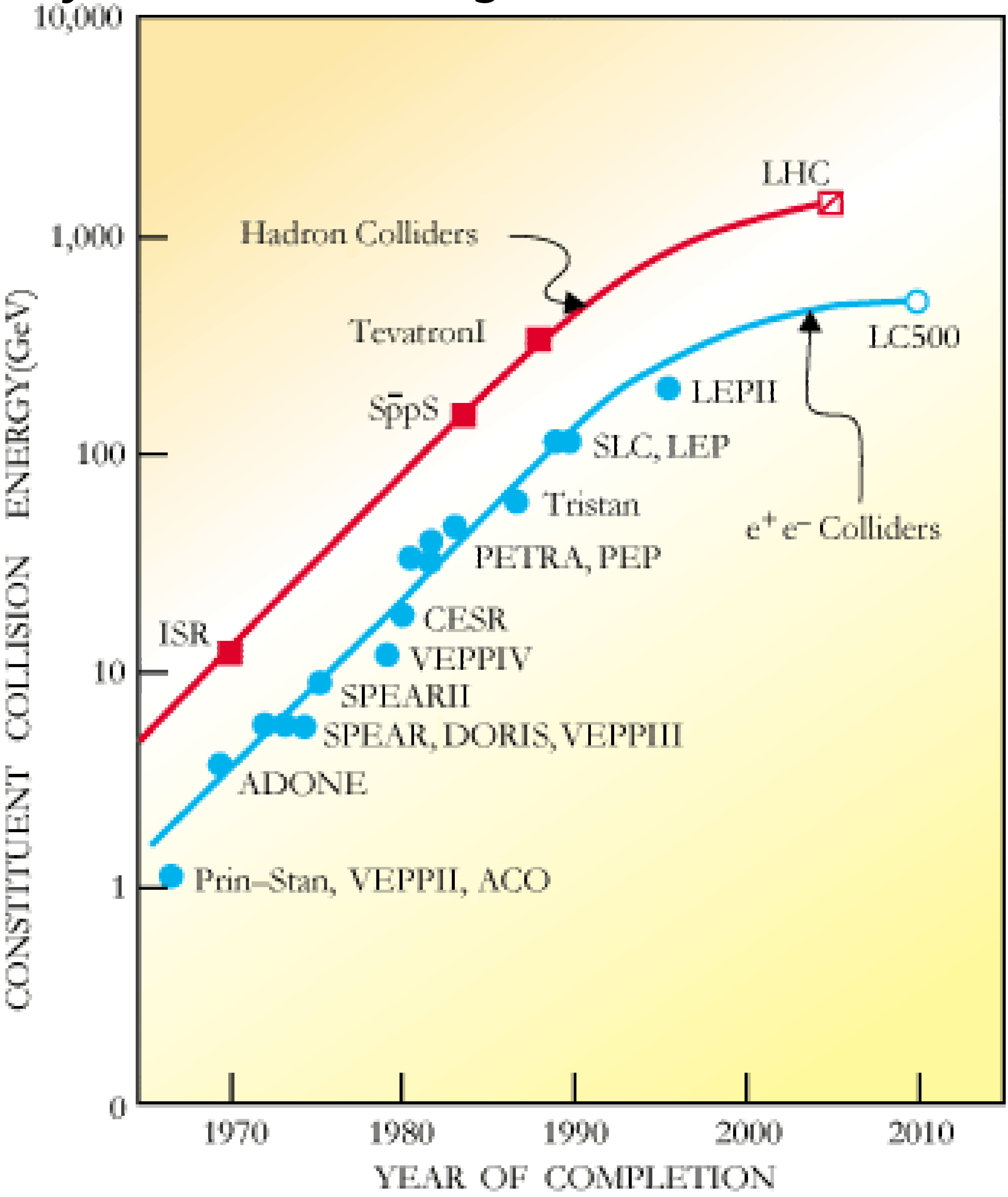
Collider Rings

1960 ↗ : e^+ / e^- collider

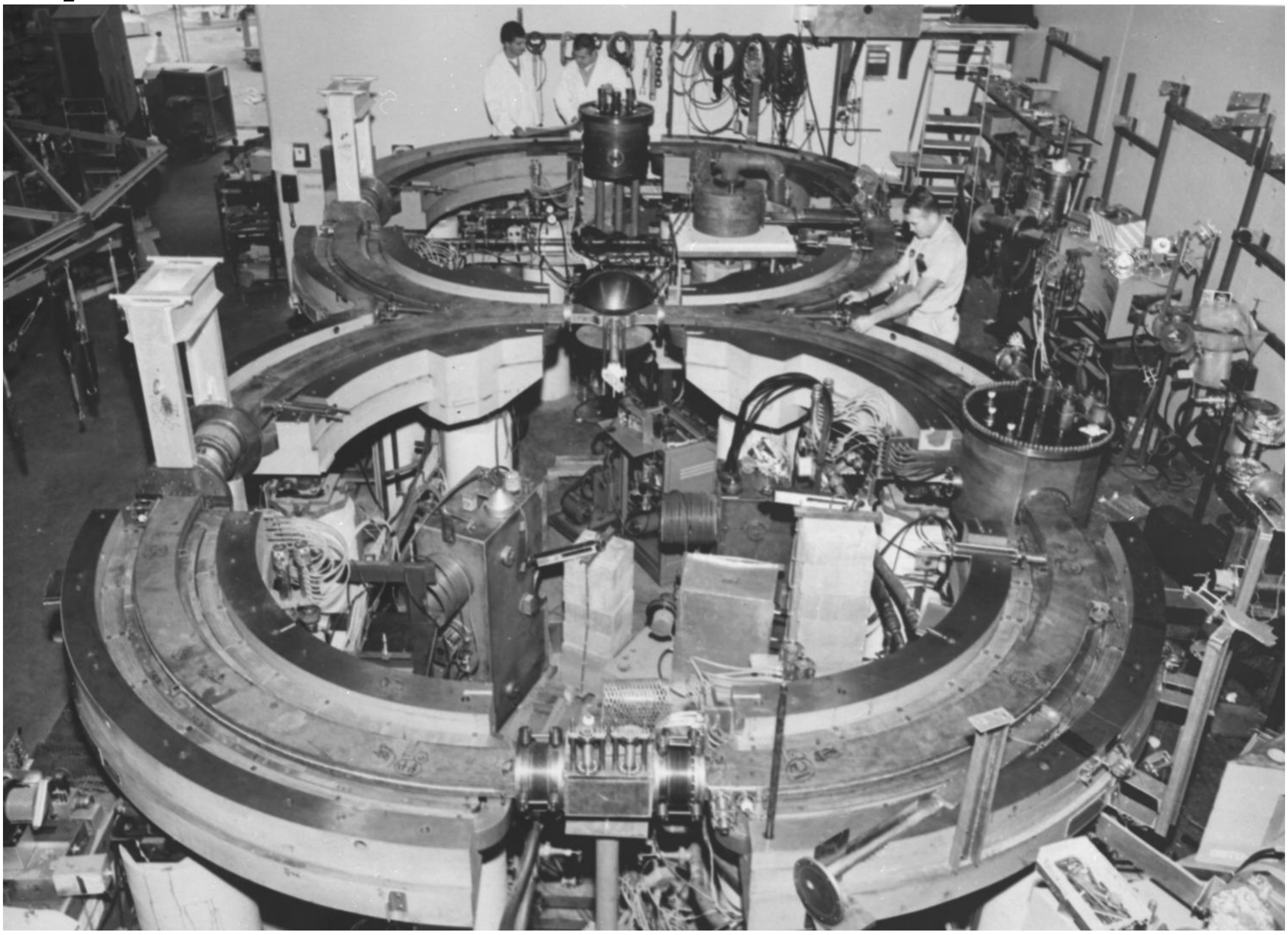
1970 ↗ : p^+ / p^- collider

$E_{CM} = 2 \cdot E_p$

Synchrotron rings as collider:

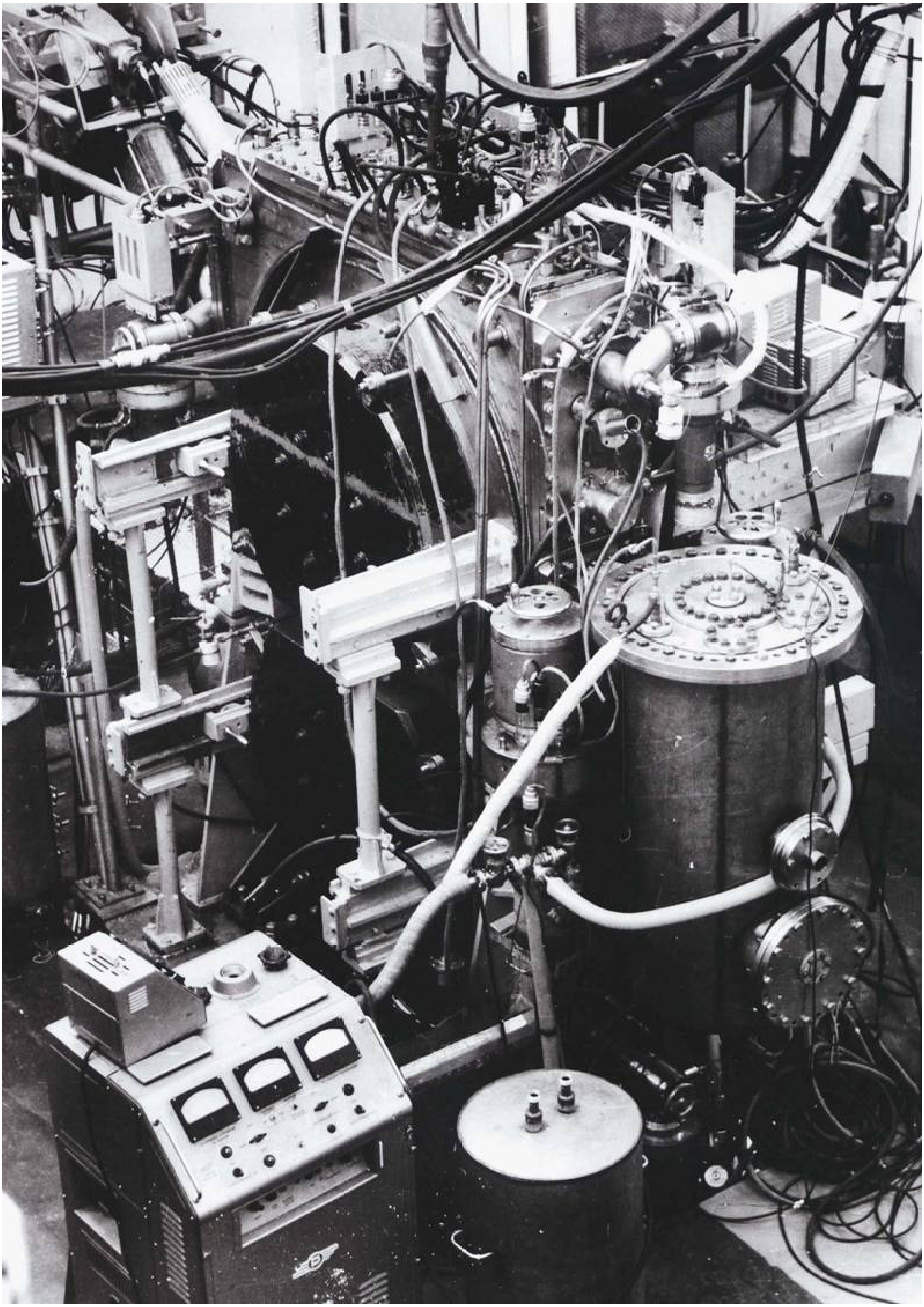


Stanford: *e− / e− collisions in 1959*



Ada: *electron − positron collision 1961*

VEP−1: electron / positron collider build in 1961 but no physics before ´64



ISR: proton – proton collider 1971

Trajectory Stability

Vertical Plane:

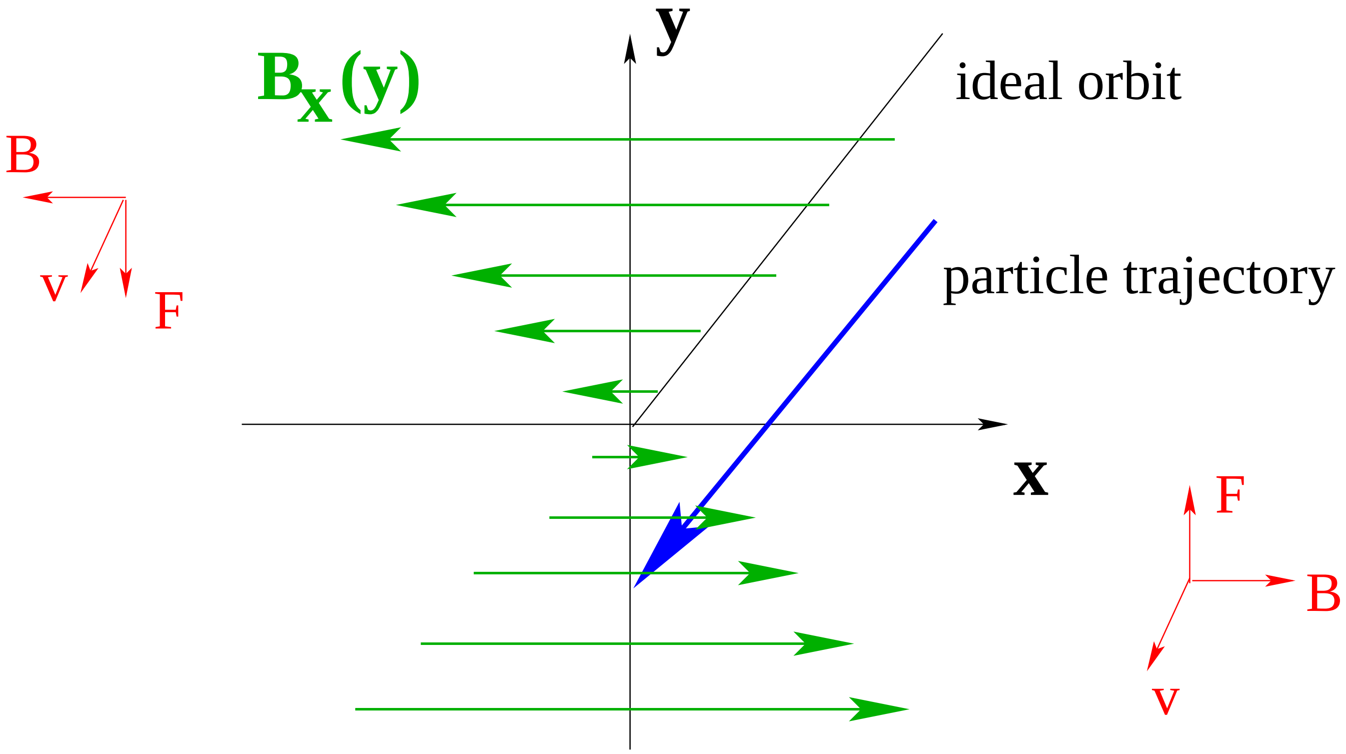
gravitation: $\Delta s = \frac{1}{2} \cdot g \cdot \Delta t^2$

$g = 10 \cdot m \cdot s^{-2}$

$\Delta s = 18\ mm$ $\Delta t = 60\ msec$

→ **660 Turns!**

→ **requires focusing!**



Quadrupole Focusing

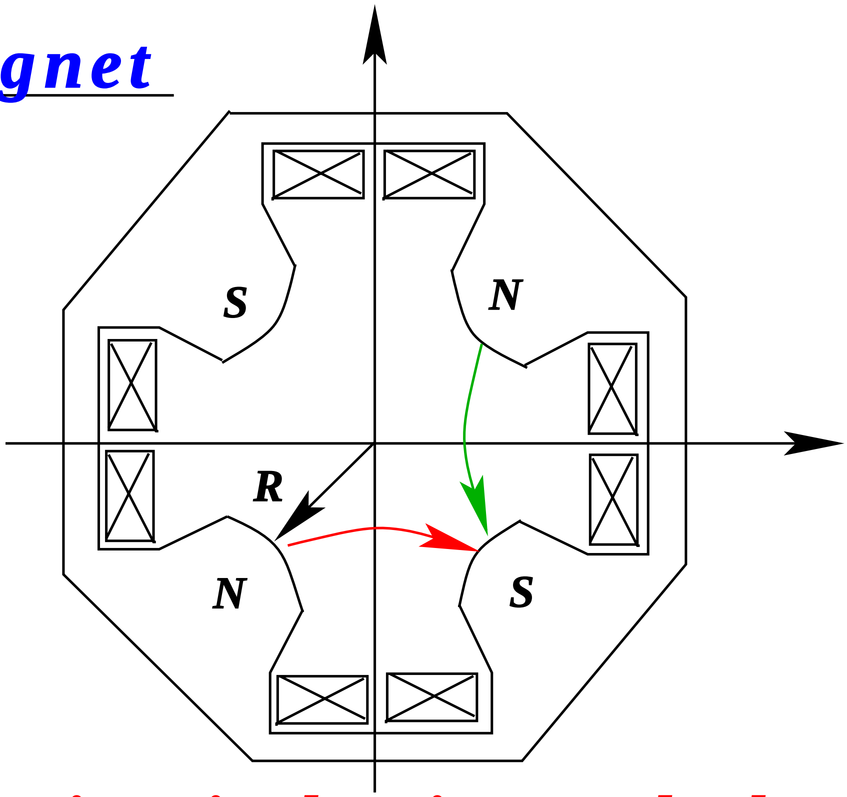
Quadrupole Magnet

$B_x = -g \cdot y$

$B_y = -g \cdot x$

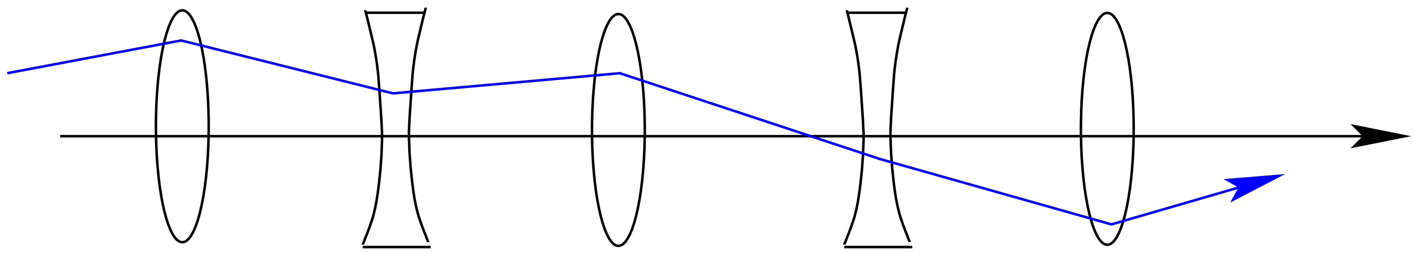
$F_x = g \cdot x$

$F_y = -g \cdot y$

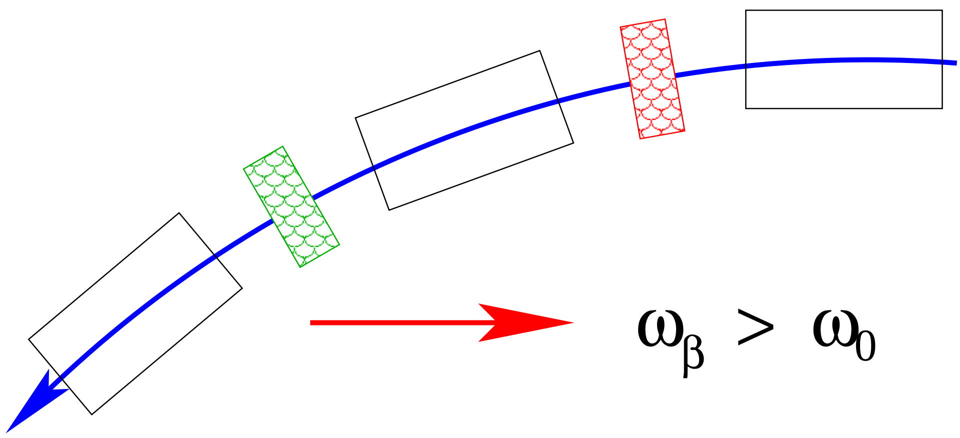


→ defocusing in horizontal plane!

Alternate Gradient Focusing



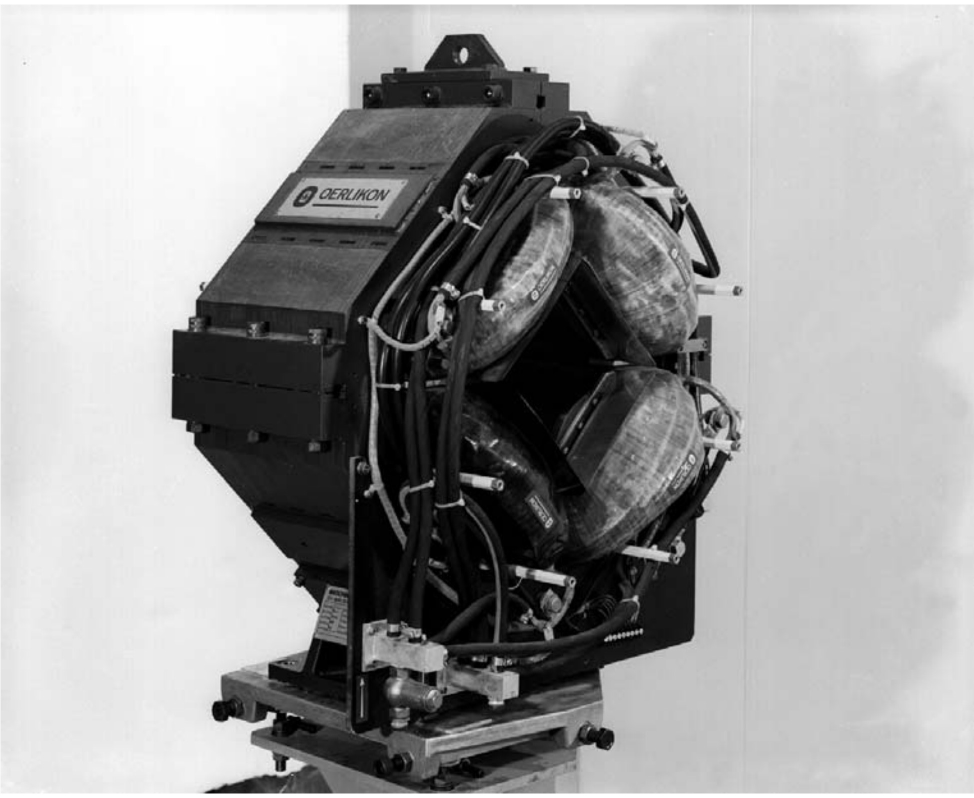
Idea: cut the arc sections in focusing and defocusing elements



→ $\omega_\beta > \omega_0$

Strong Focusing

ISR quadrupole magnet at CERN:



SPS magnet sequence in the tunnel:

Storage Ring

Tune:

$$Q = \frac{\text{number of oscillations}}{\text{turn}}$$

→ Q_x ; Q_y ; Q_s

Envelope Function:

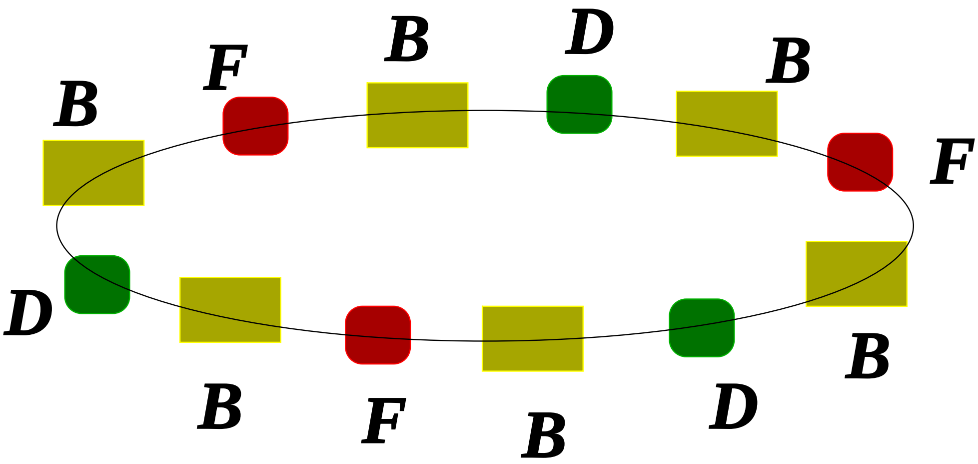
- $$y(s) = \sqrt{A \cdot \beta} \cdot \sin\left(\frac{2\pi}{L} \cdot Q \cdot s + \phi_0 \right)$$

  - A: amplitude term due to injector
  - β: amplitude term due to focusing
  - L: sorage ring circumference

- $$\beta(s + L) = \beta(s)$$

- $$Q = \frac{1}{2\pi} \cdot \oint \frac{1}{\beta(s)} \, ds$$

Closed Orbit



$$B_x = -g \cdot y$$

$$B_y = -g \cdot x$$

- **Orbit Offset in Quadrupole:**

$$x = x_0 + \tilde{x}$$

quadrupole

$$B_x = -g \cdot \tilde{y}$$

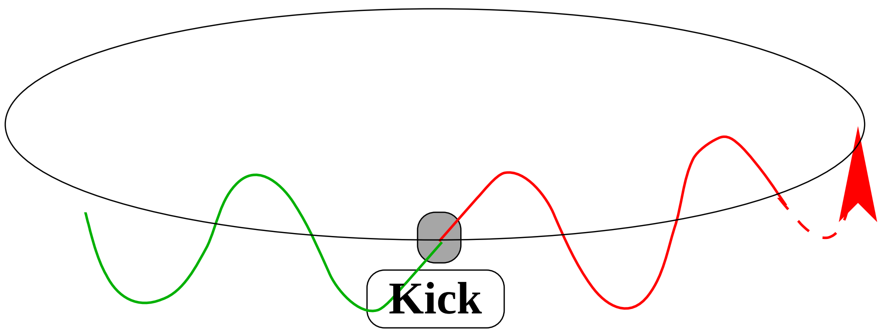
$$B_y = -g \cdot x_0 - g \cdot \tilde{x}$$

dipole component

→ orbit error

Dipole Error and Orbit Stability

■ *Q = N with dipole field perturbations:*



→ *the perturbation adds up*

↗ *resonance with instability!*

■ *arbitrary field imperfections:*

similar instabilities for:

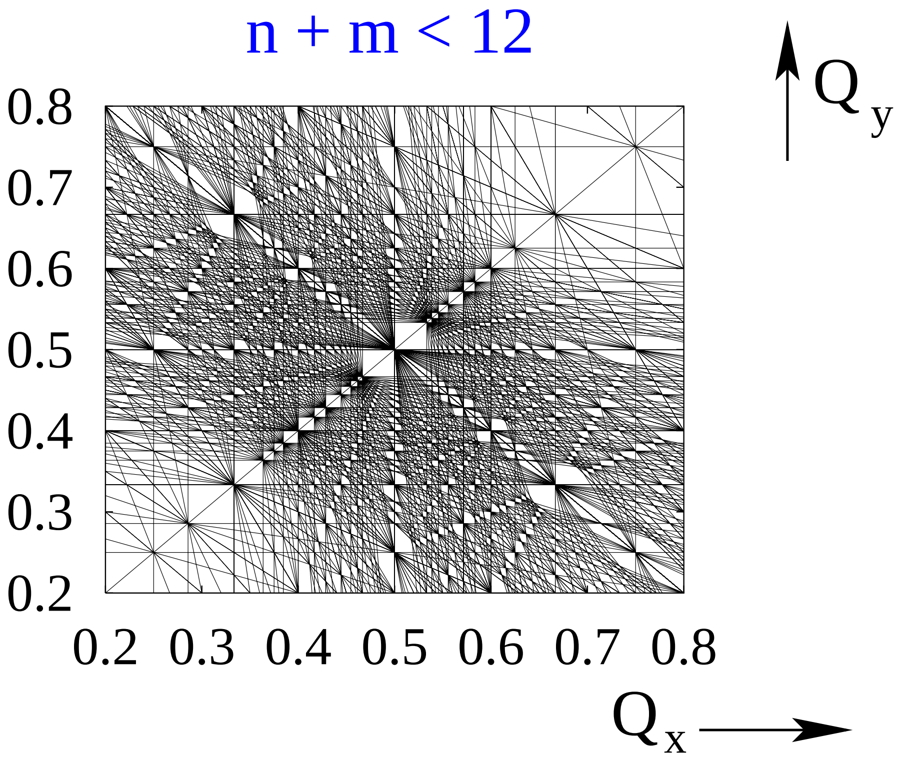
$$n\,Q_x + m\,Q_y = p$$

→ *avoid resonances!*

Resonances and Non-Linear Field Errors

- resonances in the tune diagram:

$$n \cdot Q_x + m \cdot Q_y = r$$



magnetic field imperfections drive resonances!

- resonances limit the long term stability of the protons:

$$h_{n,m} \propto A^{n+m}$$ → avoid 'low order' resonances

- experience from Sp$\bar{p}$S, Tevatron and HERA:

avoid resonances < 11th order!

→ requires high precision magnet field quality

→ dipole field error change in time!

→ limits maximum acceptable beam−beam force

Sources for Orbit Errors

- **Alignment:** +/− 0.1 mm
- **Ground motion**
  - slow drift
  - civilisation
  - moon
  - seasons
  - civil engineering
- **Error in dipole strength**
  - power supplies
  - calibration
- **Energy error of particles**

Example Quadrupole Alignment inLEP

Transversal tilt dispersion of the 3278 dipoles	$\sigma = \pm 0.34$ mrd
Vertical dispersion of the 784 quadrupoles (with respect to the smoothing polynomial)	$\sigma = \pm 0.65$ mm

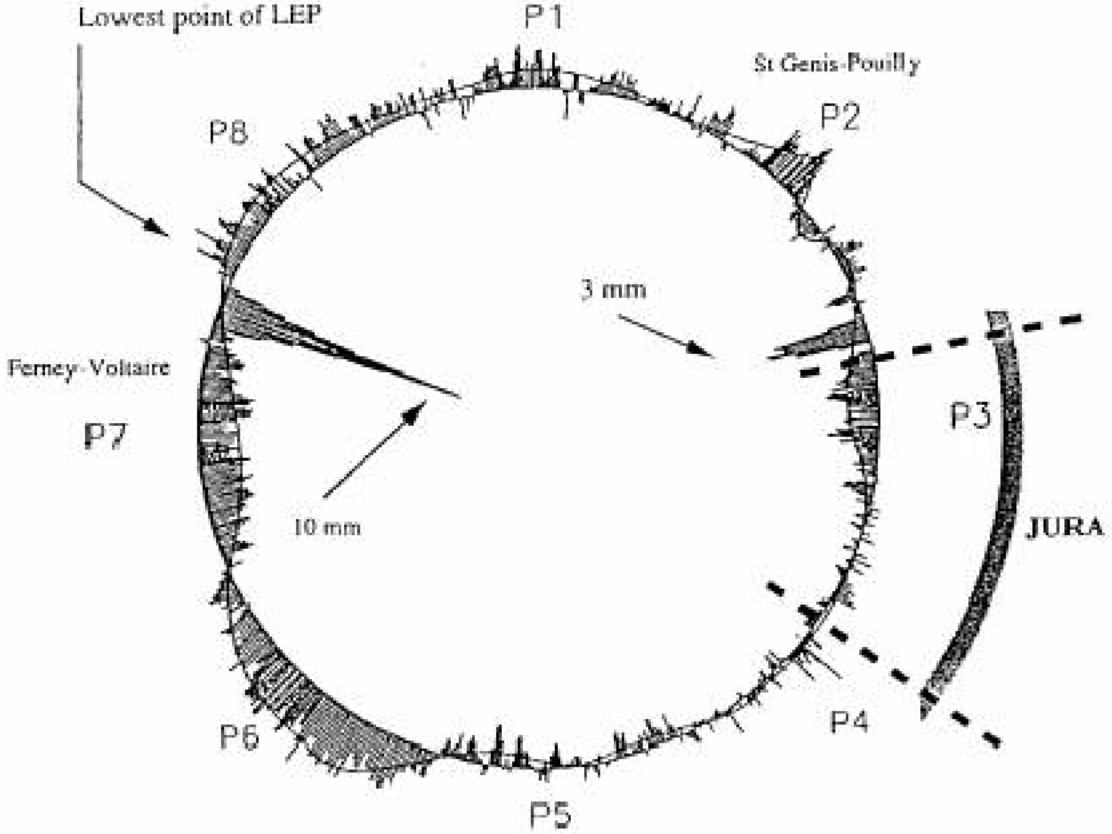


Figure 1 : observed status, end 1992

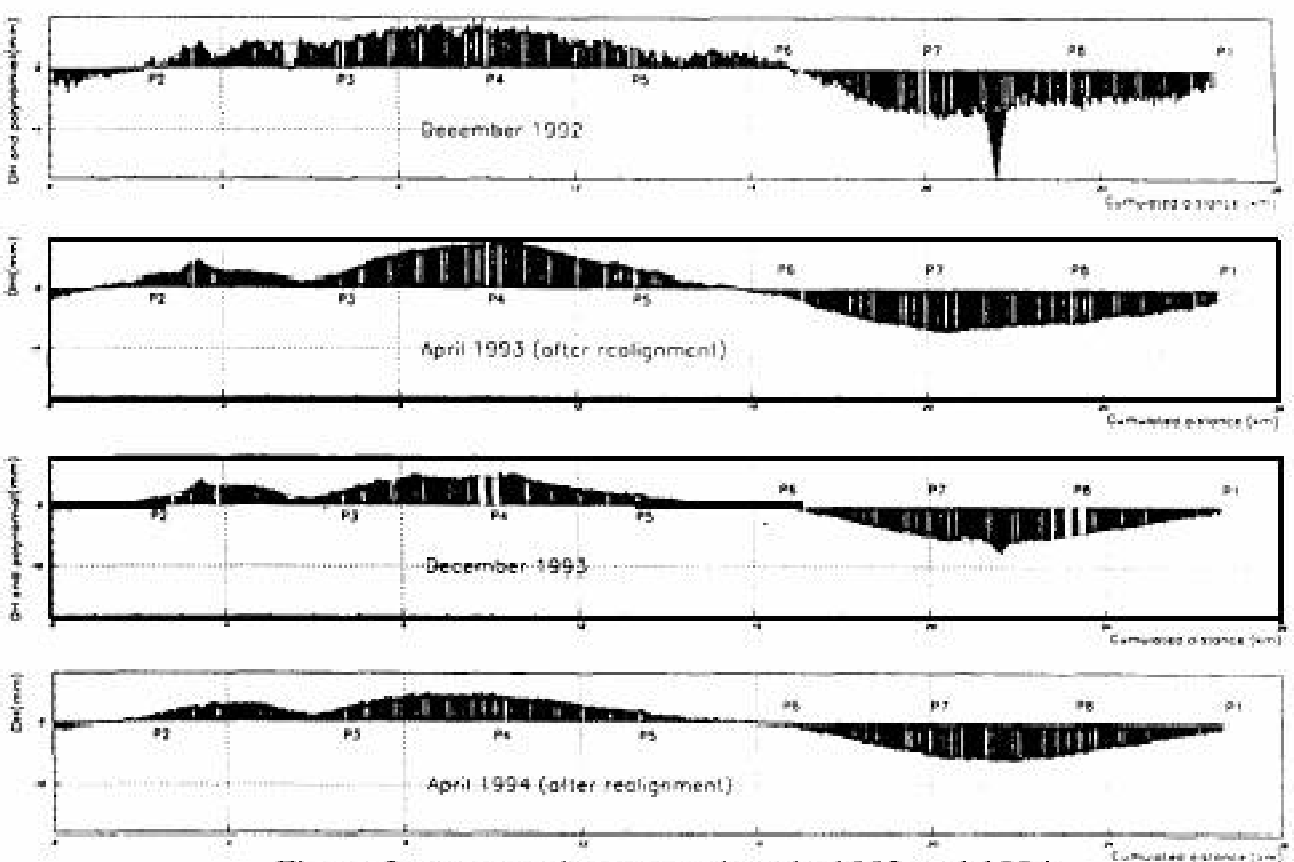
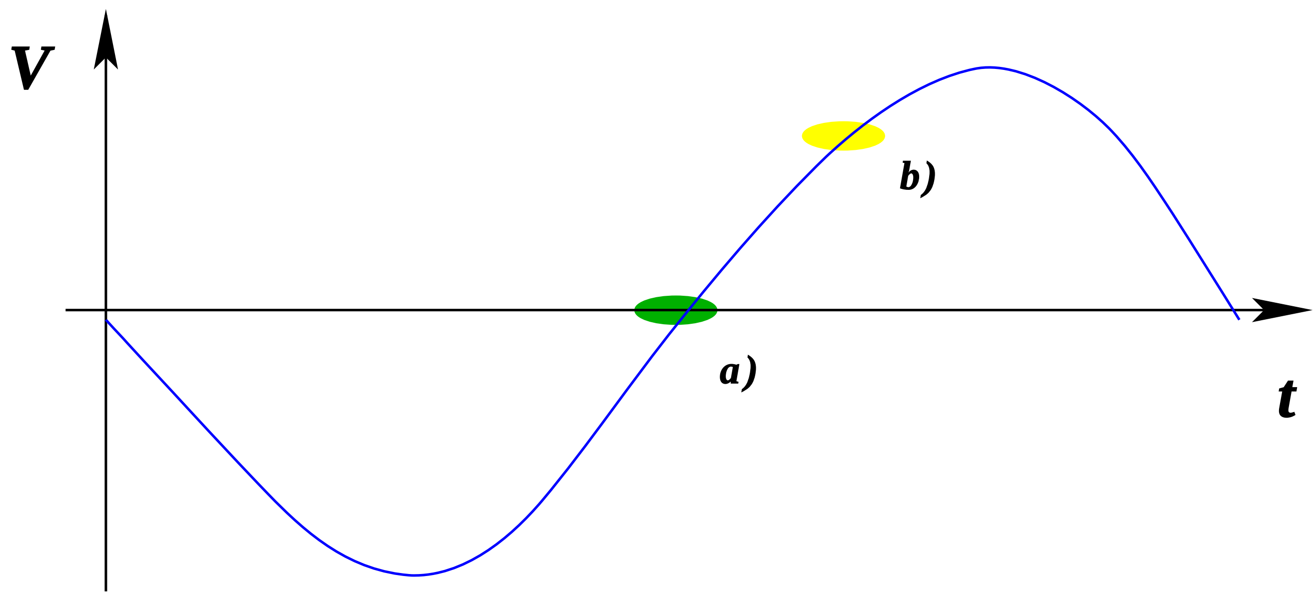


Figure 2 : progressive corrections in 1993 and 1994

Synchrotron:

→ ***the synchrotron circumference determines the particle energy!***

▬ ***assume: L > design orbit***



→ ***energy increase***

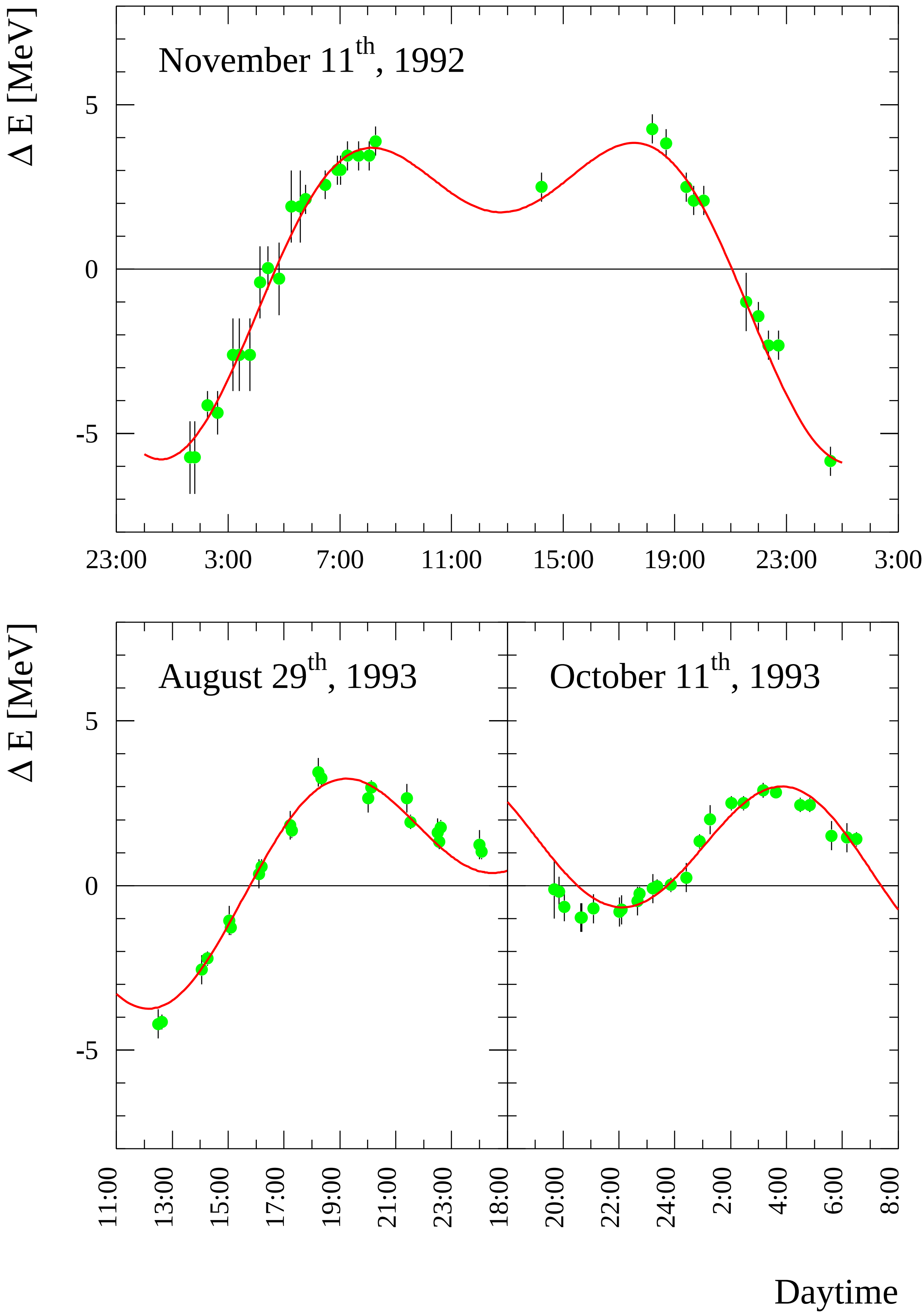
Equilibrium:

$$f_{RF} = h \cdot f_{rev}$$

$$f_{rev} = \frac{1}{2 \cdot \pi} \cdot \frac{q}{m \cdot \gamma} \cdot B$$

→ ***E depends on orbit and magnetic field!***

energy modulation due to tidal motion of earth

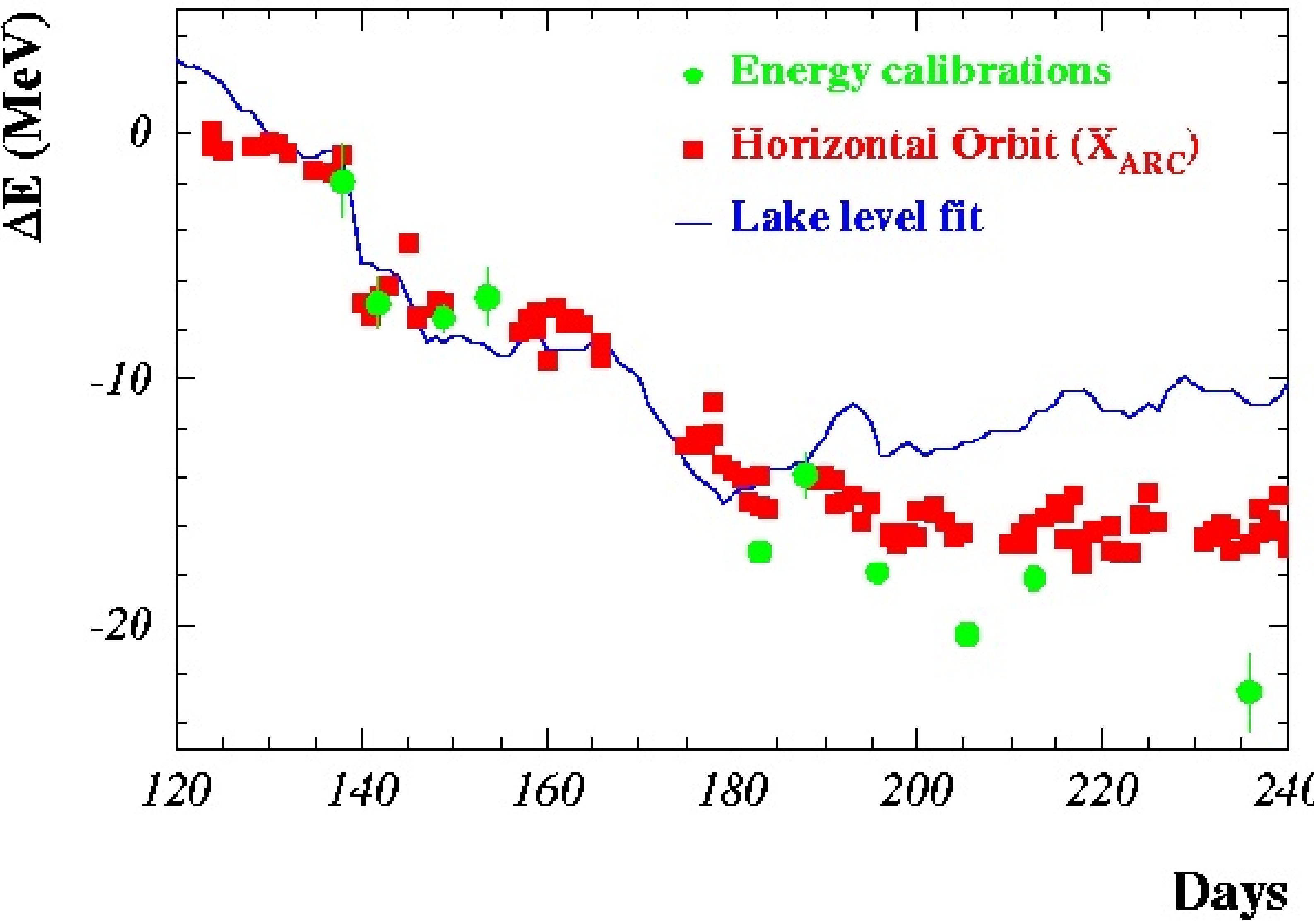


→ $\Delta E \approx 10$ MeV

energy modulation due to lake level changes

changes in the water level of lake Geneva change the position of the LEP tunnel and thus the quadrupole positions

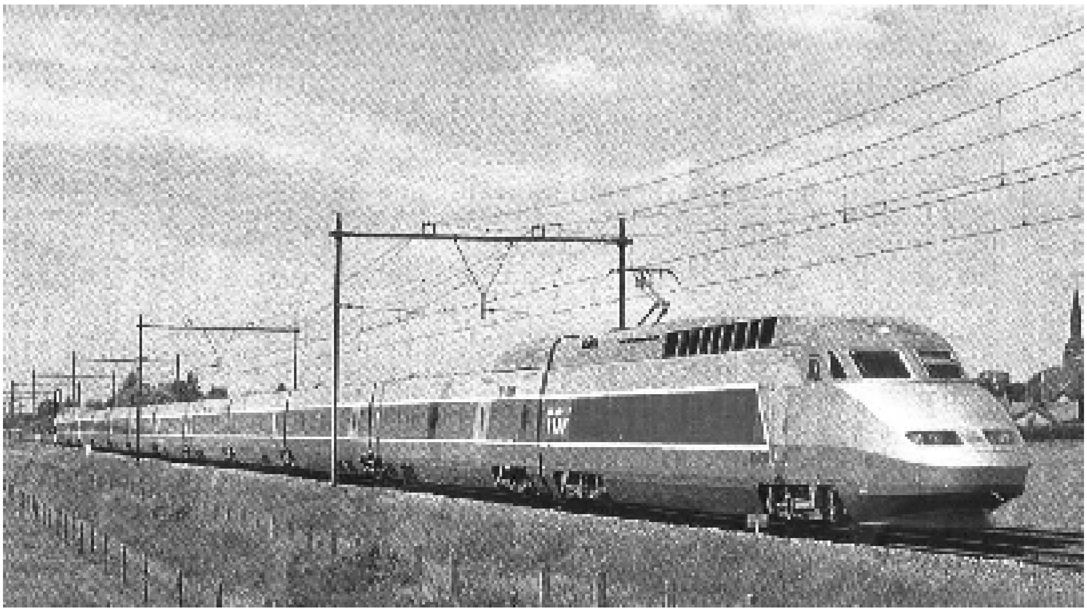
→ orbit and energy perturbations

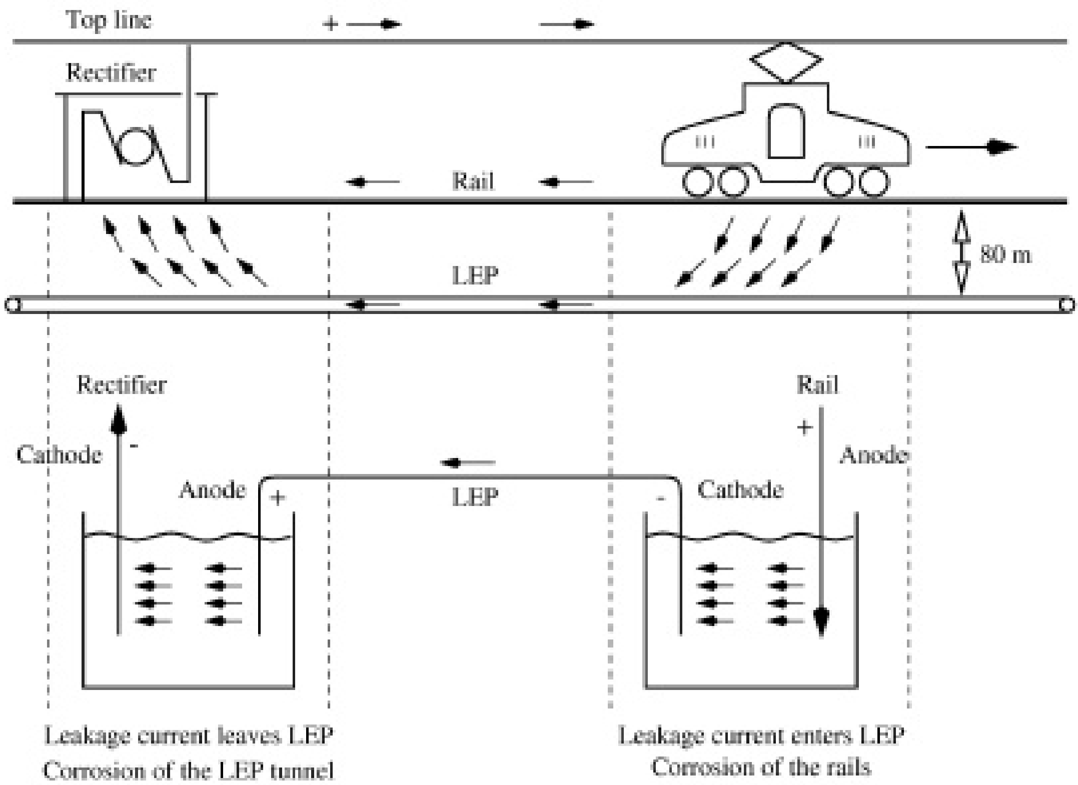


→ $\Delta E \approx 20\ MeV$

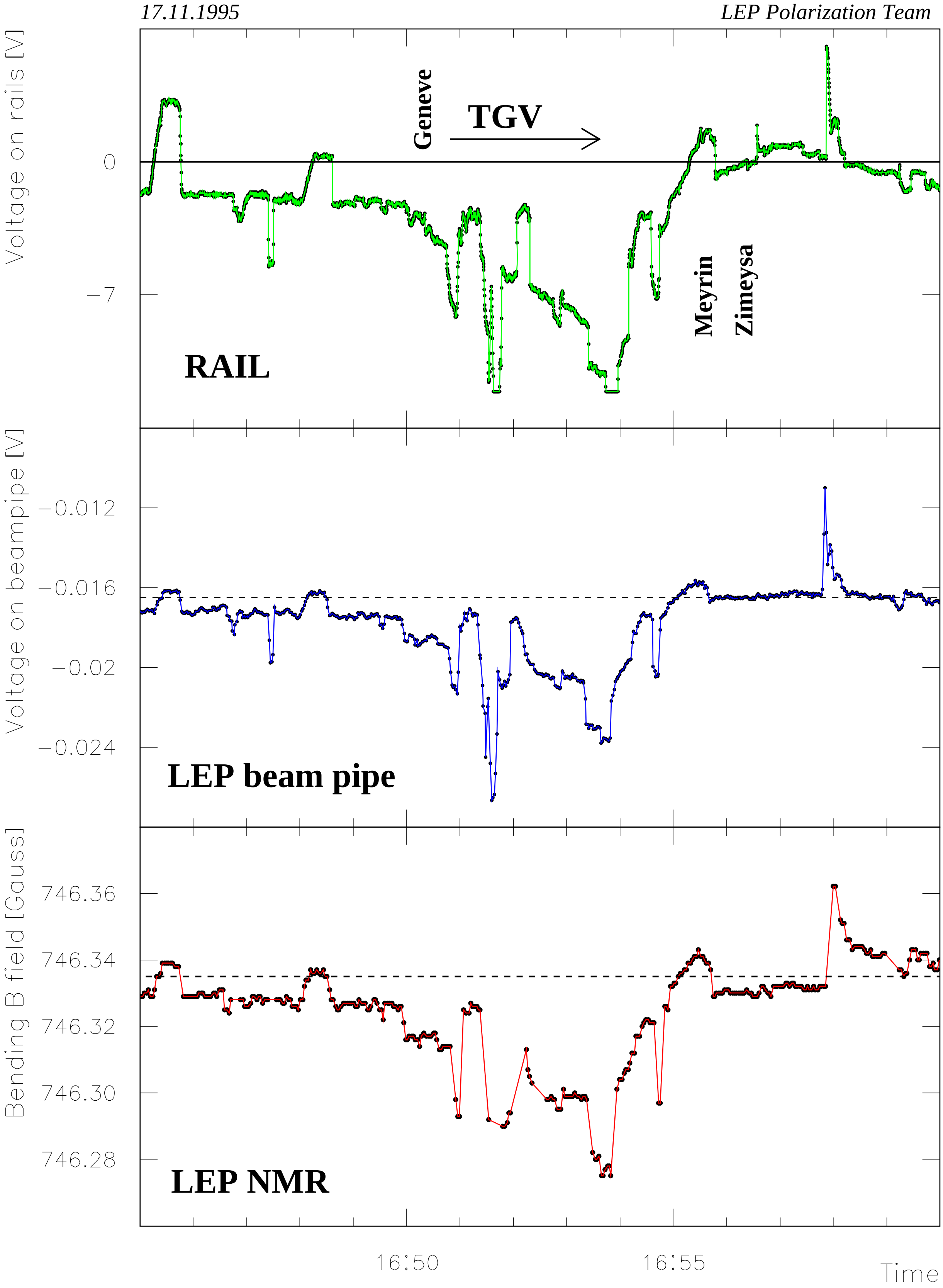
- energy modulation due current perturbations in the main dipole magnets

- TGV line between Geneva and Bellegarde





correlation of NMR dipole field measurements with the voltage on the TGC train tracks



ΔE ≈ 5 MeV for LEP operation at 45 GeV

ground motion due to human activity

quadrupole motion in HERA−p (DESY Hamburg)

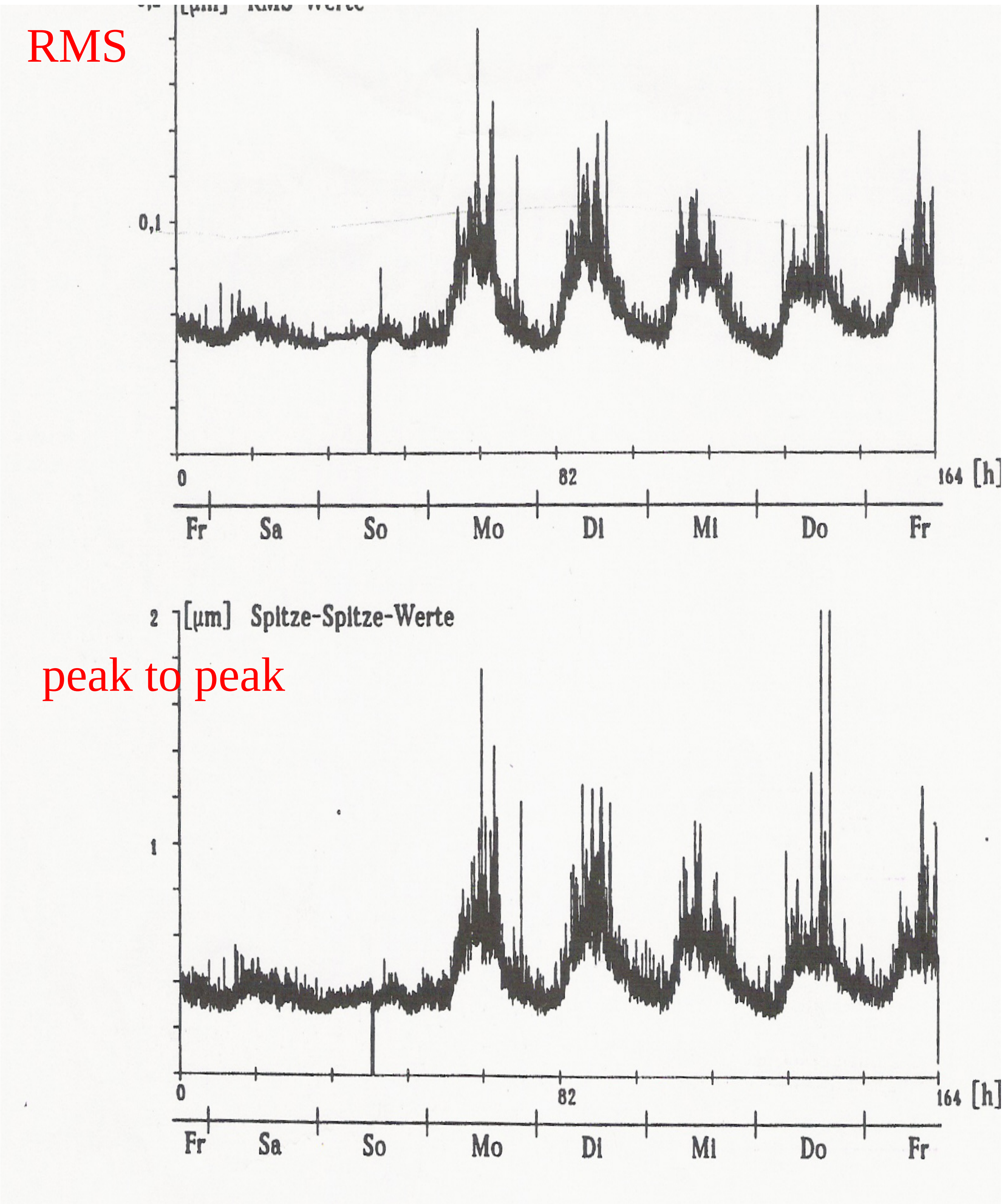


Abb. 3.13 Zeitabhängigkeit der Bodenbewegung
oben RMS-Werte
unten Spitze-Spitze-Werte