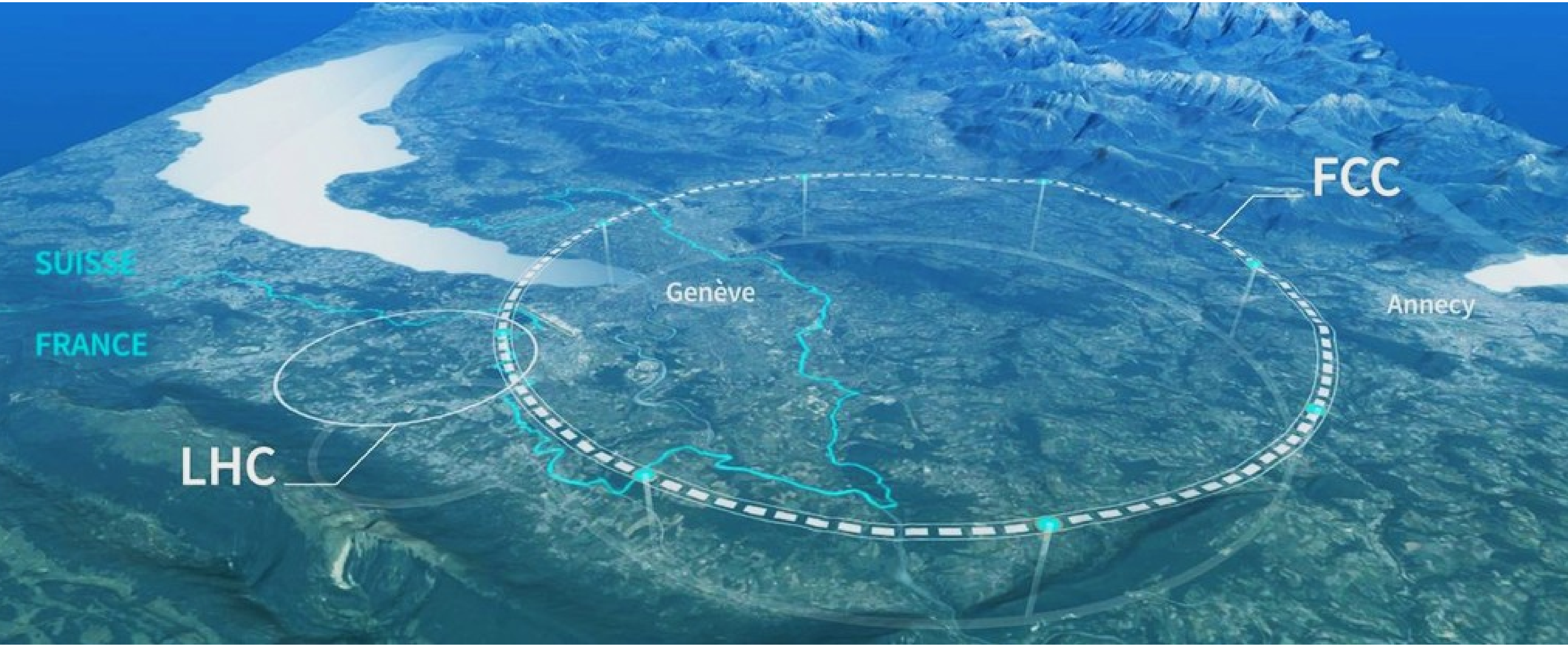
8.FCC - January Research Projects on the Future Circular Collider (FCC-ee)

Accelerators

[January 9, 2025]



Outline

Accelerators

- why do we accelerate particles?
- basic physics of accelerators
- various accelerator types
- hadron versus lepton colliders
- examples of accelerators today
  - LEP, TeVatron, LHC
- future of accelerators: ILC, FCC, muon collider

Why Do We Accelerate Particles?

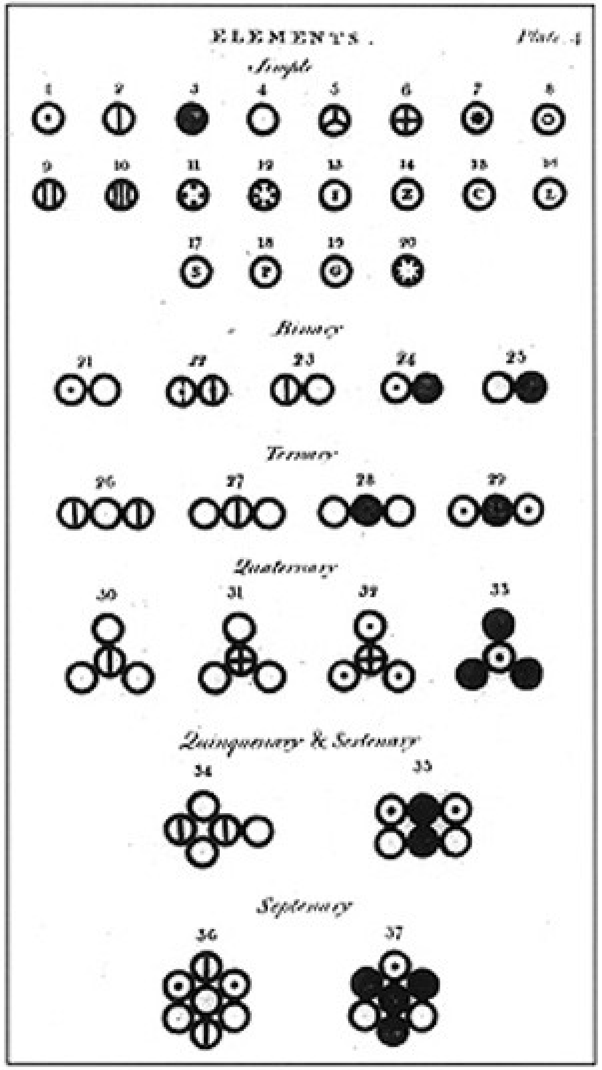
To take existing objects apart!

1803 J.Dalton's indivisable atom

daring theory for the elements

ammonia: 1 azote + 1 hydrogen

ammonia nitrate: 1 nitric acid + 1 ammonia + 1 water



1896 M.&P. Curie find atoms decay

1897 J.J. Thomson discovers electron

1906 E.Rutherford: goldfoil experiment

1911 E.Rutherford: $\alpha + N \rightarrow O + H^{+}$

Physicist broke the nuclei shooting particles on it

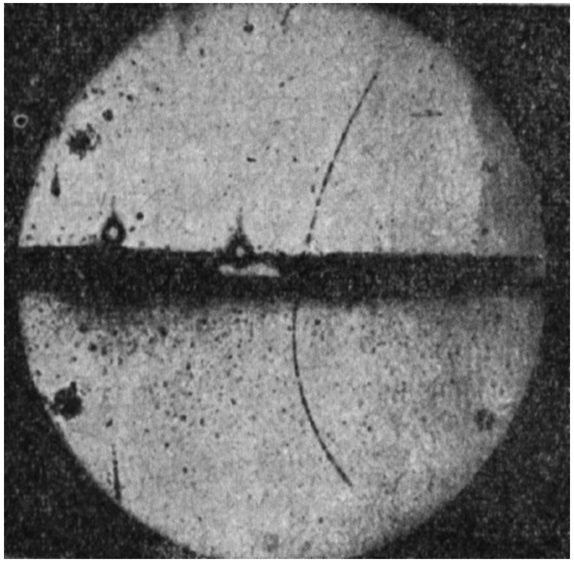
Why Do We Accelerate Particles?

To create new particles

1905 A. Einstein: energy is matter $E = mc^2$

1930 P. Dirac: math problem predicts antimatter

1932 C. Anderson: discovers positron in cloud chamber photos (electron curves other way)



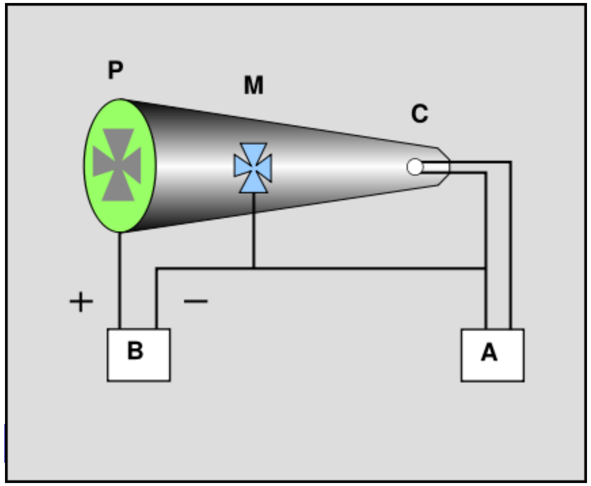
1935 H. Yukawa: neutron-proton reaction requires pion

1936 C. Anderson: discovers muon

C. Anderson used the big accelerator: The Universe

Search for heavier antiproton and pion motivates particle accelerators

Generating Particle



Particle sources

cathod ray to generate electrons

heat cathod to produce electrons

apply electric field to collect electrons

cathode tube with hydrogen to generate p

$$H_2 + e^- \rightarrow H_2^+ + 2e^-$$
$$H_2^+ + e^- \rightarrow H^+ + H + e^-$$
$$H + e^- \rightarrow H^+ + 2e^-$$

Antimatter?

use pair production mechanism

<u>very inefficient</u>

Basic Accelerator Physics

Lorentz Force: $\vec{F} = \frac{d\vec{p}}{dt} = q\vec{E} + q(\vec{v} \times \vec{B})$

electric force   magnetic force

Magnetic force perpendicular to velocity

==> no acceleration, changes direction

Only electric force accelerates particles

From the Maxwell equations:

static:

$$\vec{E} = -\nabla\phi - \frac{1}{c}\frac{\partial\vec{A}}{\partial t}$$

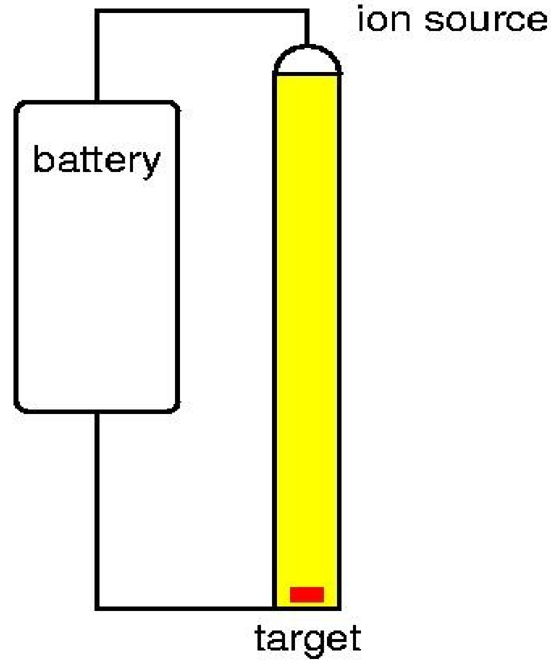
$$\vec{B} = \nabla \times \vec{A}$$

$$\vec{A} = 0$$

Accelerator Types

Simple battery

- limited by discharge: 200 kV
- electron gains energy of 1 eV per Volt
- max. accelerations: 200 keV



Cockroft-Walton (used at FNAL)

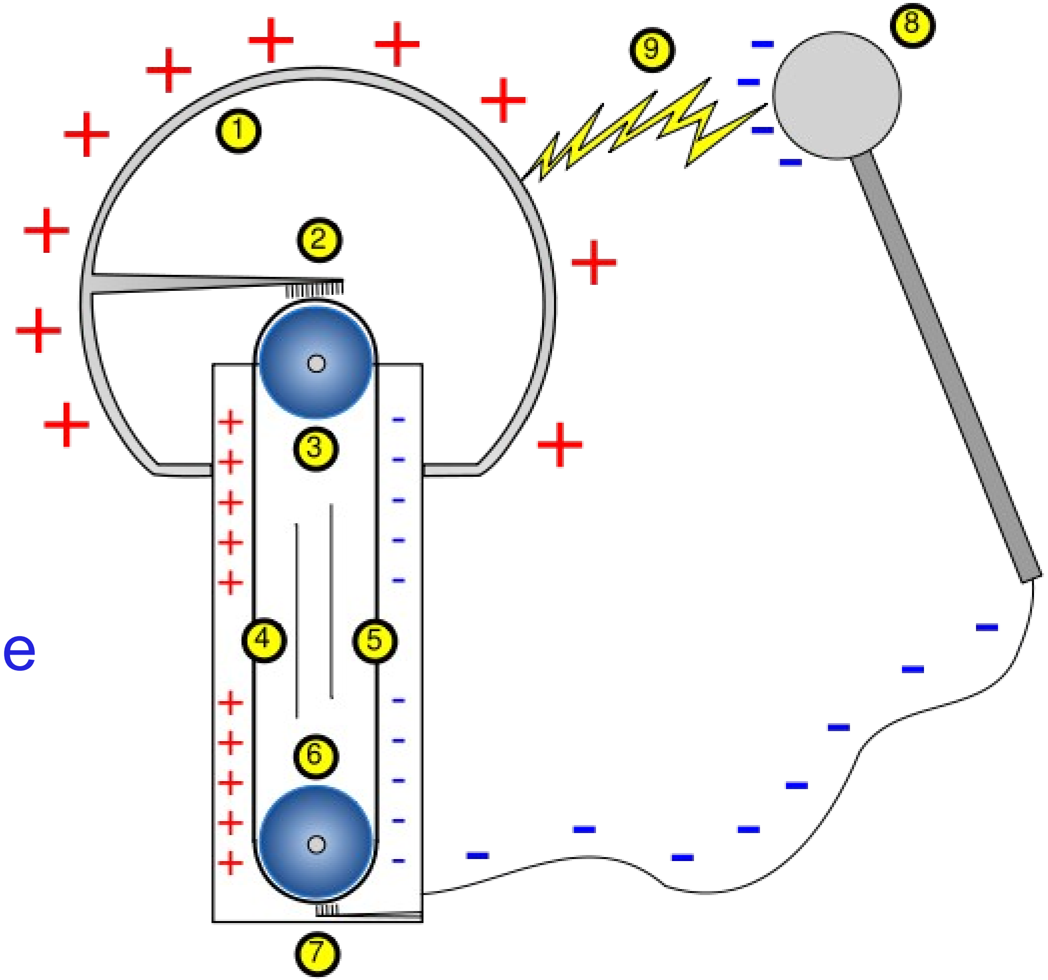
- create cascade of high voltage gaps interupted by diodes
- max. acceleration: 800 kV
- at 700 kV:

$$p + Li \rightarrow 2He$$

Accelerator Types

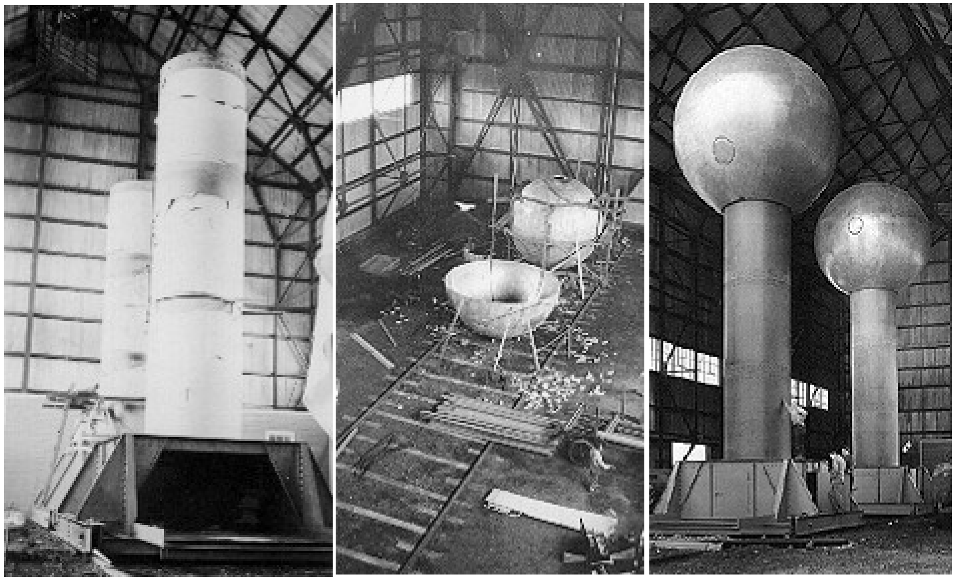
Van de Graaff generator

metallic sphere (pos.)
electrode connected to sphere
upper roller (plexiglass)
belt with pos. charges
belt with negative charges
lower roller (metal)
lower electrode (ground)
spherical device with negative charges, used to discharge the main sphere
spark from potential difference



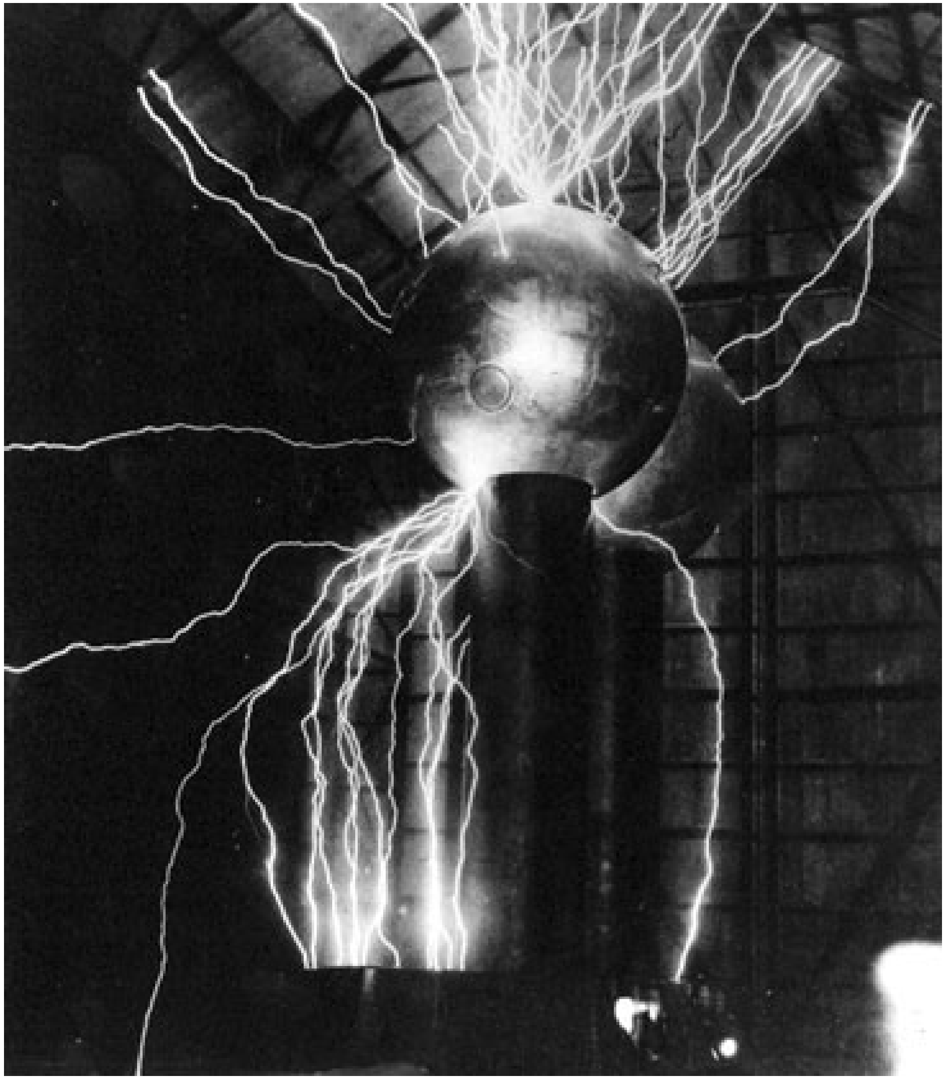
max. voltage 25 MV

Accelerator Types



Largest air insulated generator located at MIT

- Van de Graaff was Professor at MIT
- Museum of Science exhibits the generator

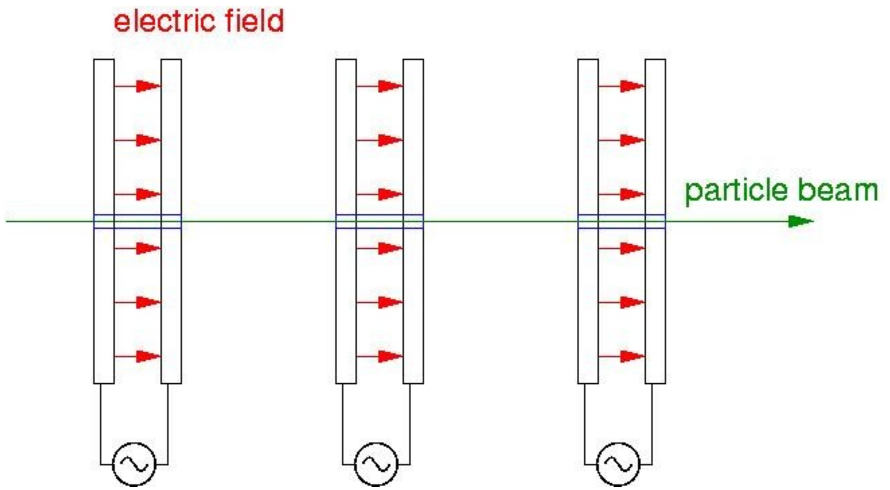


Limit of electrostatic accelerators

Accelerator Types

Alternating electric fields

- beams are bunched

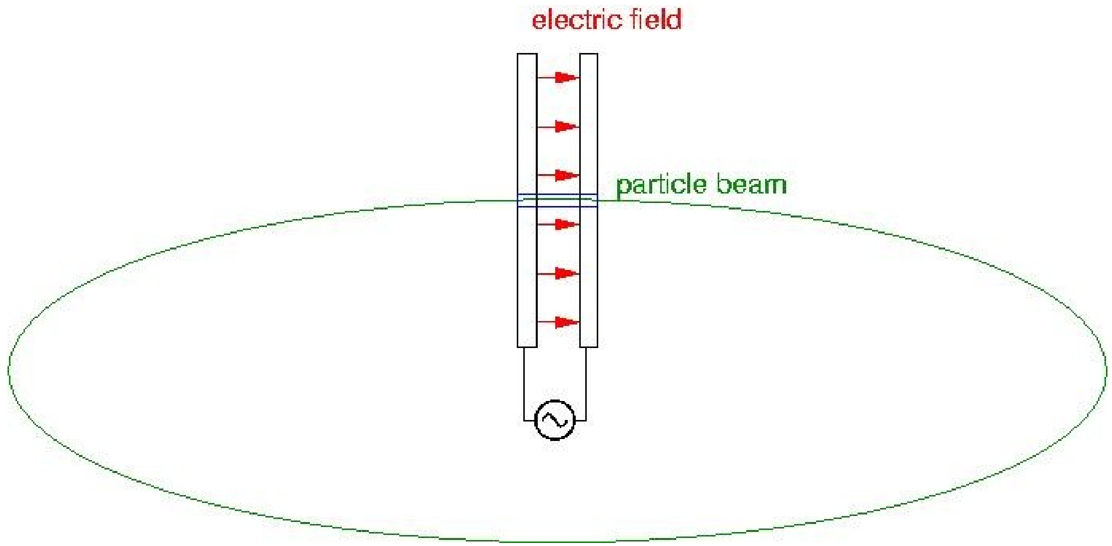


Linear acceleration

- long accelerators
- high powered RF cavities

Circular accelerator

- compact design with reasonable RF cavitites
- repeating sequence: resonance tuning *etc.*



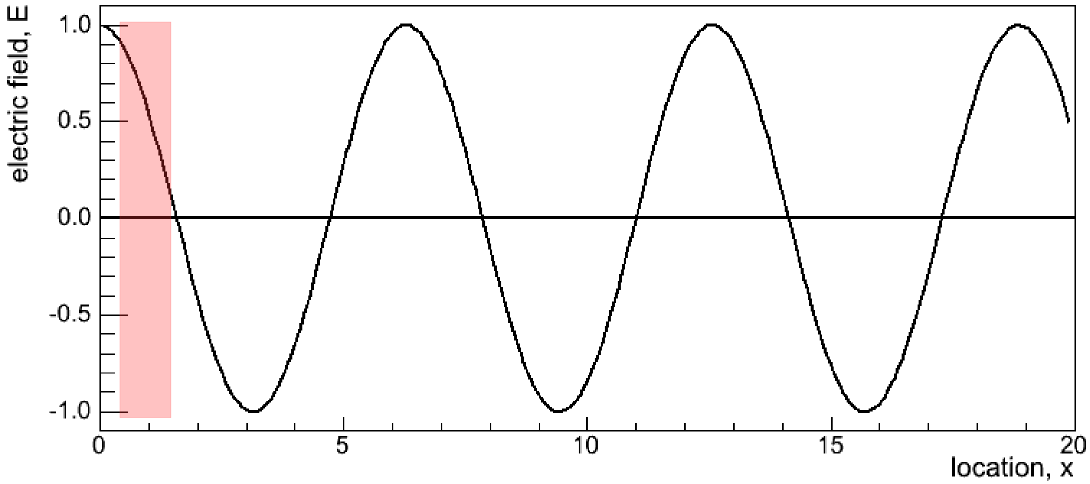
Surf's Up

Charged particle ride the electromagnetic wave

- create standing wave
- use an RF cavity
- high frequency
- high amplitude
- make particles arrive on time

Self regulating

- slow particle, larger push
- fast particle, small push
- oscillatory behavior

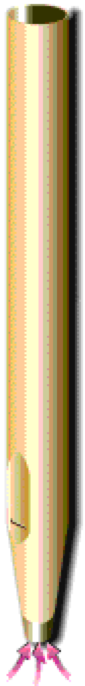


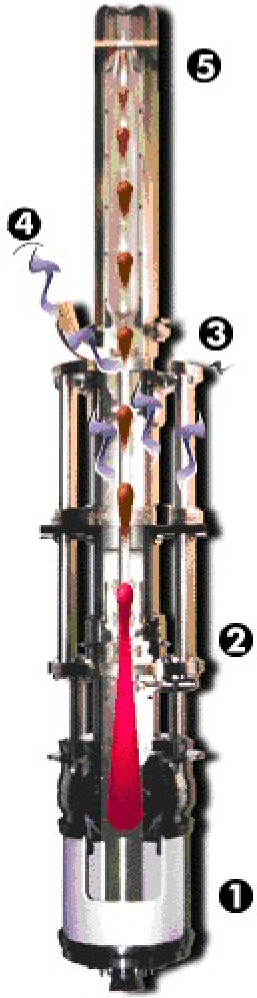
How to Create a Standing Wave?

Use a Klystron (klys – electron)

Compare to organ flute:

- air flows into the flute
- excites eigen modes of flute
- create sound waves



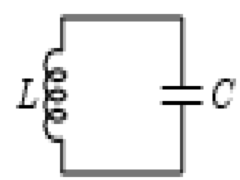


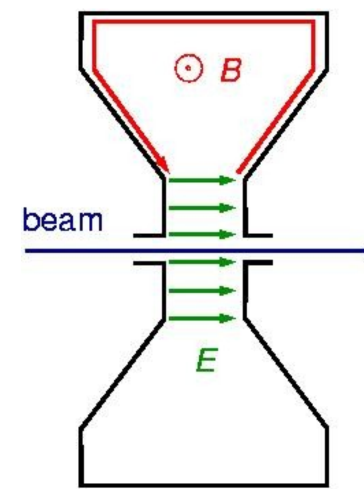
Correspondence with klystron

- air flow = electron beam
- flute = cavity
- sound wave = electromagnetic wave
- oscillation is induced by weak signal

Radio Frequency Cavity

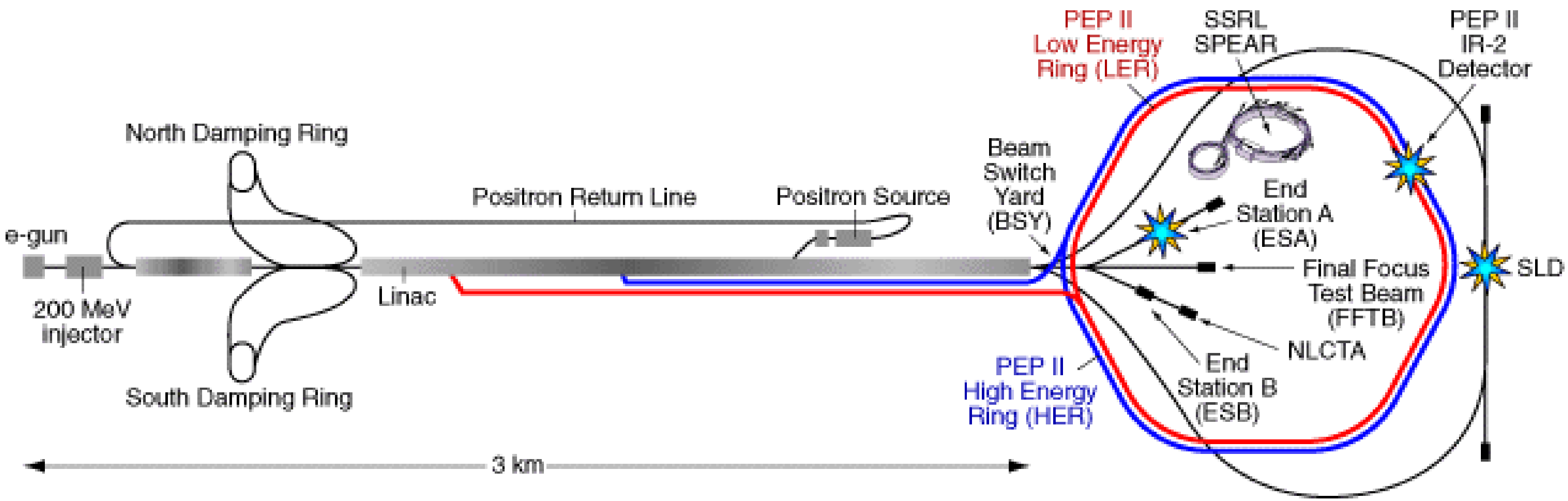
Cavity is resonator

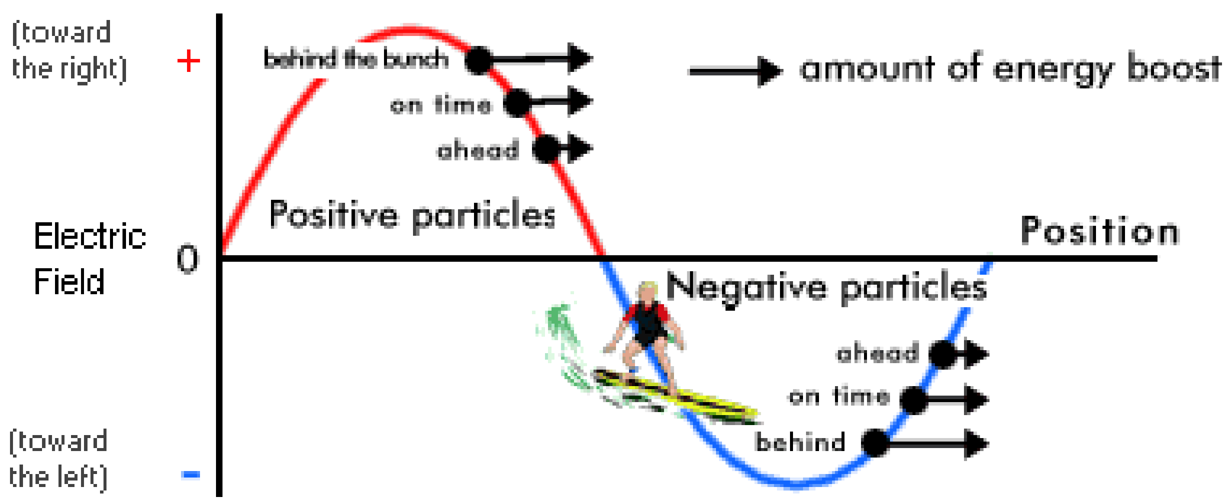




Linear Accelerator

Example of Stanford Linear Accelerator (2 miles)





Accelerator Types

Cyclotron (1929 E.O. Lawrence)

Physics idea

centripetal = magnetic

$$\frac{mv^2}{r} = qvB \rightarrow \omega = \frac{v}{r} = \frac{qB}{m}$$

no dependence on *r*

alternating electric field = constant acceleration

E_{beam} of up to 25 MeV

relativistic effects limiting

synchrocyclotron

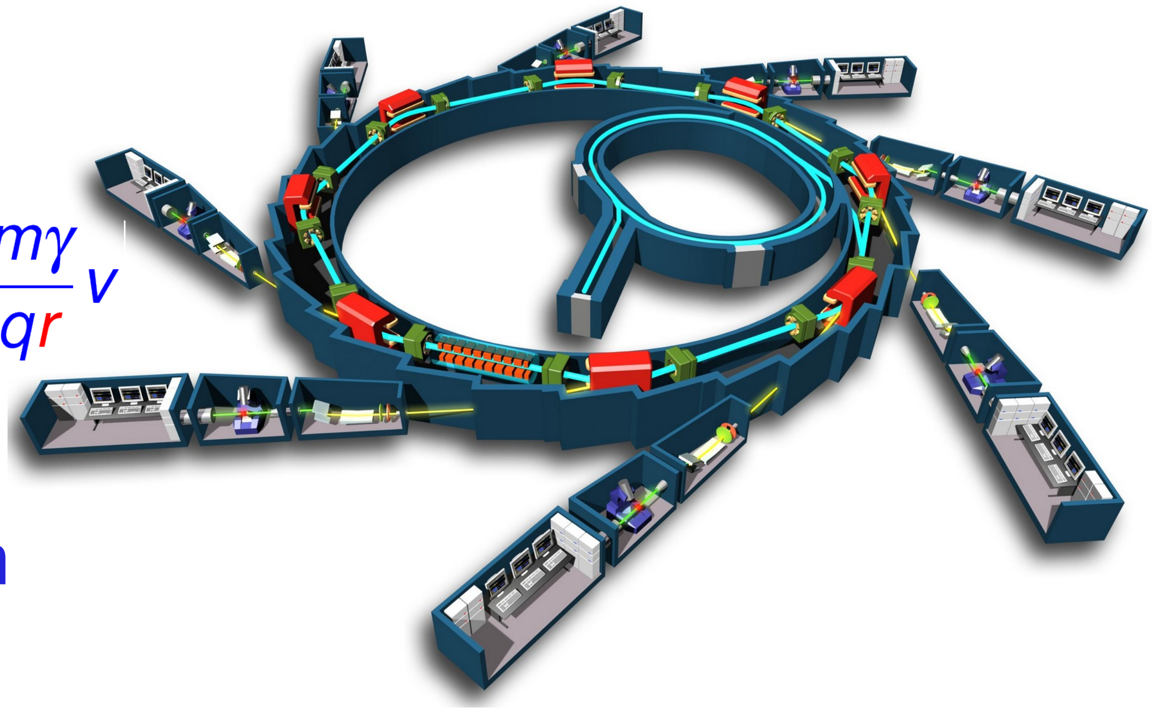
large dipole magnets

Accelerator Types

Synchroton (LEP, LHC)

- constant radius, *r*
- changing *E* and *B*

$$B = \frac{m\gamma}{qr} v$$



Design advantage

- use of beamline: vaccum
- size is quite expandable
- components can be designed freely
- big magnet replaced with several small magnets
- accommodates many acceleration sections

Design limitations

- synchrotron radiation for light particles (electrons)

Summary on Accelerator Types

Electrostatic accelerators

- Acceleration tube: breakdown at 200 keV
- Cockroft-Walton: improves to 800 keV
- Van de Graaff: best electrostatic device at 25 MeV

AC driven accelerators

- Linear: cavity design and length critical
- Circular accelerators:
  - cyclotron: big dipole magnet, non-relativistic, up to 25 MeV
  - synchrotron: vacuum beamline, expandable, small magnets and cavities, synchrotron radiation large for light particles

Hadron versus Electron Colliders

From the physics point of view

	electron	proton
elementary particle	yes	no
point like	yes	no
uses full beam energy	yes	no
transverse energy sum	zero	zero
longitudinal energy sum	zero	non-zero

From the accelerator point of view

	electron	proton
synchrotron radiation	large	small

Complementary devices

'Modern' Accelerators: LEP

Large Electron-Positron collider

- Synchrotron: 4.5 km radius
- operational: 1989-2001
- at CERN (Geneva, Switzerland)
- detectors: Aleph, Delphi, L3, Opal
- E_{CMS}: 90 – 206 GeV
- LEP1 (90 GeV): 3 light neutrinos
- LEP1 (90 GeV): $\delta m_Z = 2.1$ MeV
- LEP2(200 GeV): $\delta m_W = 33$ MeV
- LEP2(200 GeV): $m_H > 114$ GeV (95%)
- project was spectacular success

January 1987. A tired but happy tunneling crew in January 1987 having just completed the arc from point 2 to point 3.

‘Modern’ Accelerators: LEP

Luminosity: number of collisions per crossing

$$L \propto \frac{N_e^2 n_b}{\sigma_x \sigma_y} \quad \textit{with} \;\; N_e - \text{number of } e^{\pm}; \;\; n_b - \text{number of bunches}$$
$$\sigma_{x,y} - \text{emittance in } x, y$$

Limiting factors for luminosity

LEP1:

TMCI (transverse mode coupling instability)

beam-beam interactiones

LEP2: heat loss in cavities

current/bunch: $I_b = eN_e f_{\text{rev}} = 0.3 - 1.0\text{mA}$

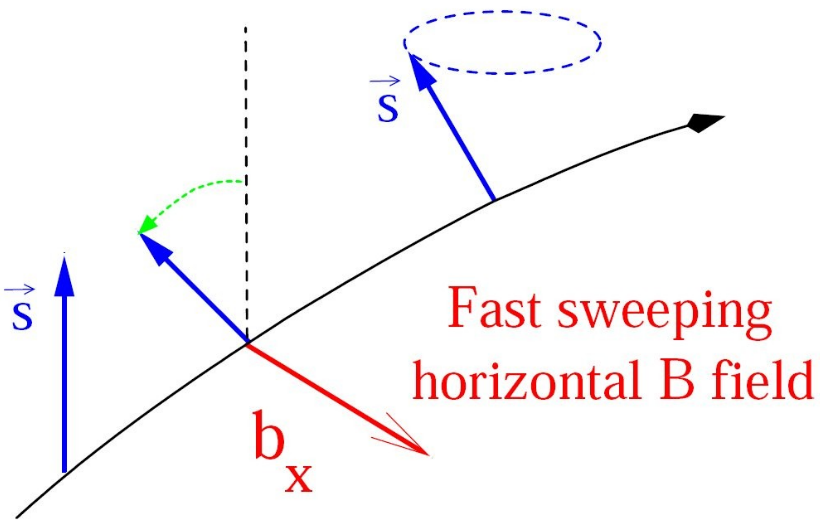
beam current driven by RF power: 8 mA

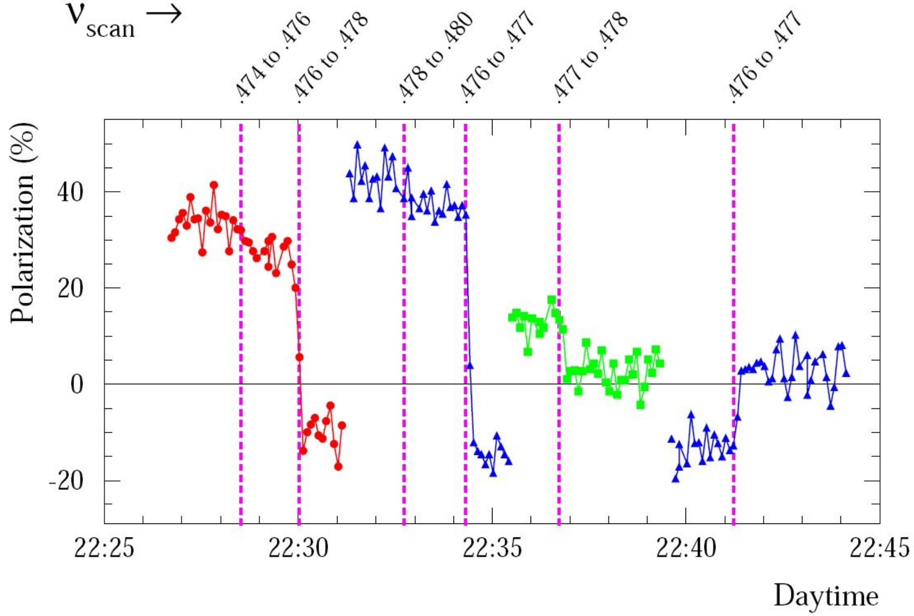
number of bunches between 8-12

‘Modern’ Accelerators: LEP

Energy calibration(resonant depolarization)

- polarization automatically builds up (Sokolov-Ternov)
- monitor transverse polarization level
- kick rotating electrons with periodic magnetic field
- tune in frequency which destroys polarization
- very sensitive method: about 0.5 MeV on 45 GeV beams



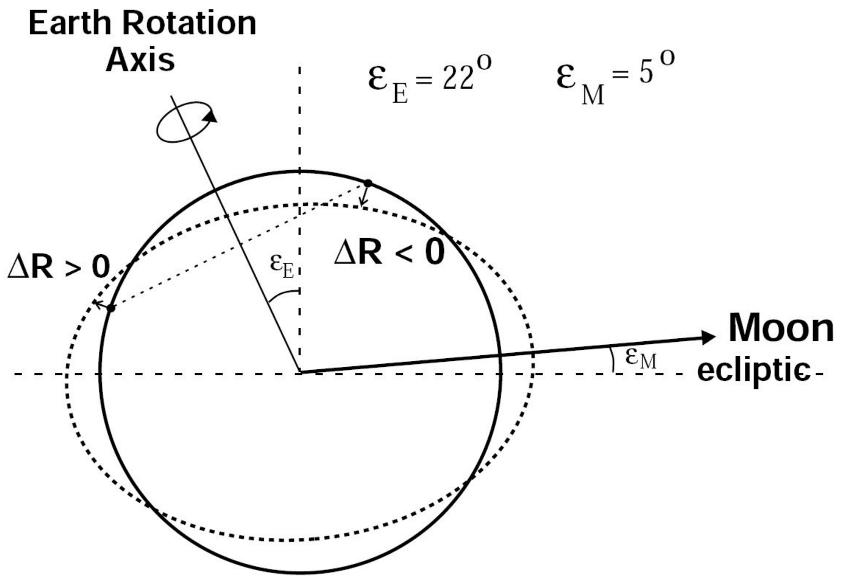


‘Modern’ Accelerators: LEP

Calibration nightmares: part 1

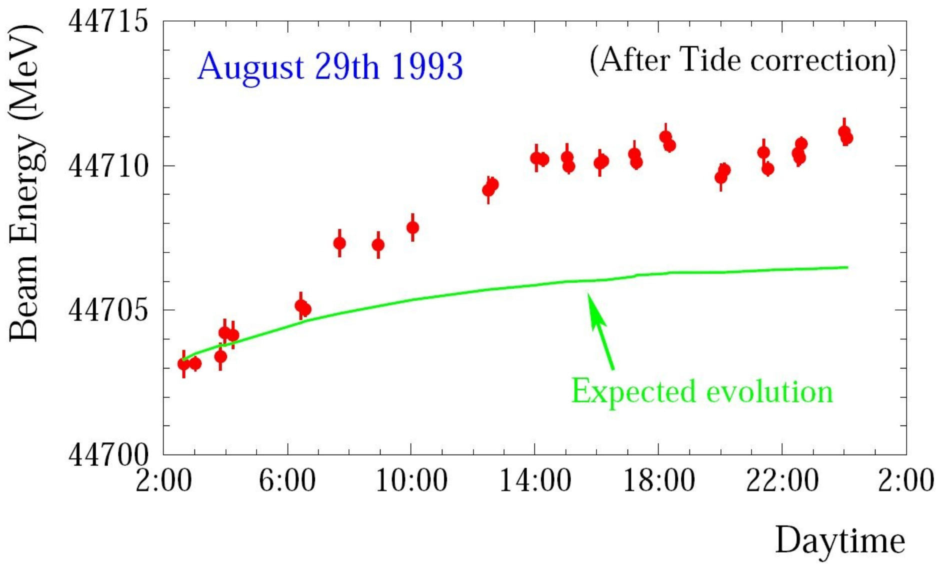
calibration changes sensitive to small changes in circumference: $\Delta C / C \approx 10^{-9}$

fluctuations in first calibrations explained by tides



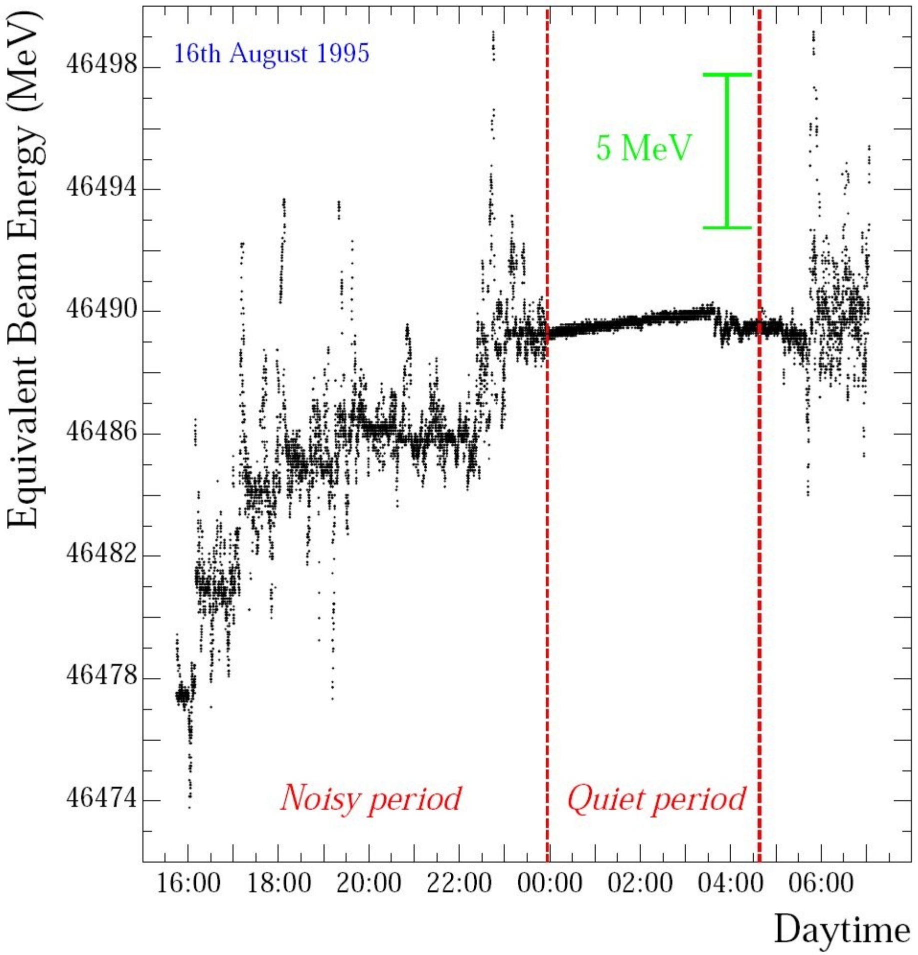
‘Modern’ Accelerators: LEP

Calibration nightmares: part 2



A daunting indication

- will remain unexplained for 2 years ....
- until undergrad from Aachen comes out for the summer

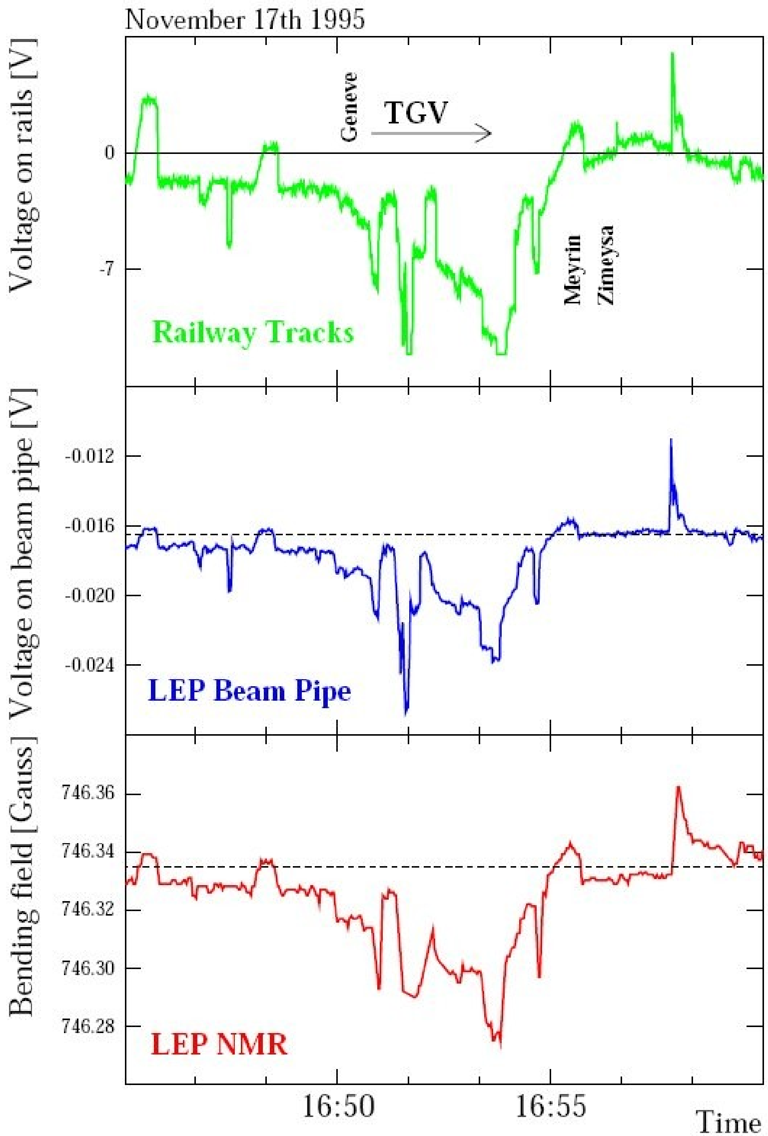


Smoking gun

- man made problem

'Modern' Accelerators: LEP

The French DC trains caused the problem



1A current on beampipe

'Modern' Accelerators: LEP

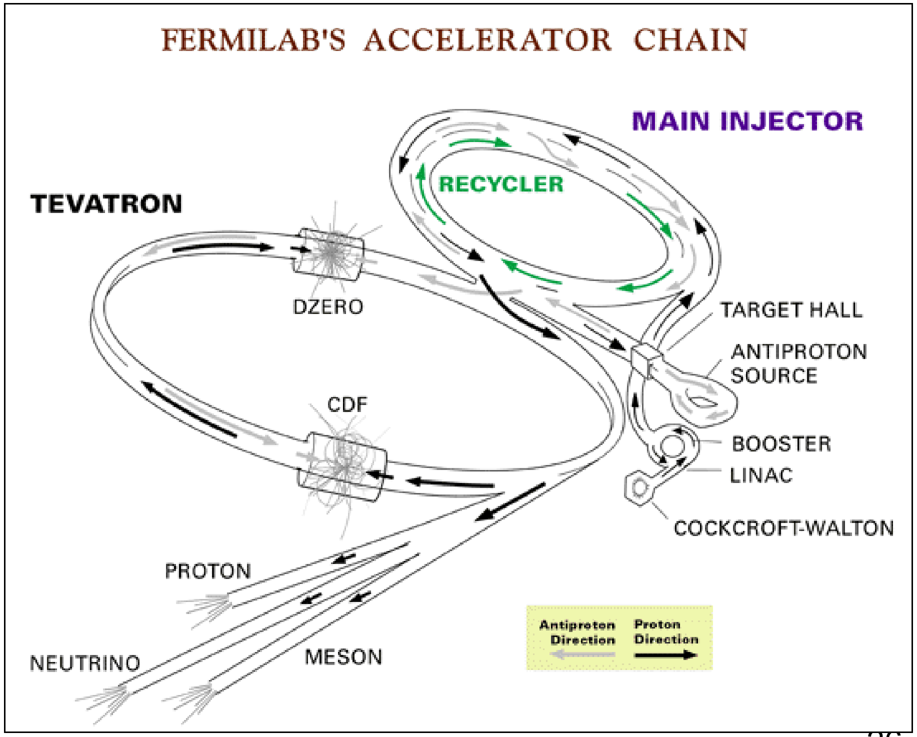
The limits of LEP

- synchrotron radiation energy: $E_{\text{synch}} \propto \gamma^4$
  - at 100 GeV: $\Delta E_{\text{beam}} = 0.02 \rightarrow \Delta E_{\text{loss}} = 0.10$
- energy consumption: 20 MW (small village)
- length of machine affects synchrotron radiation losses
- tunnel completely full of cavities (superconductive)
- wakefield: left in the cavity deposit energy
  - absorption of 40 kW at 4 K
  - corresponds to 10 MW energy needed
- horizontal beam size increase: $\sigma_x \propto \gamma$.
  - touched beampipe walls

‘Modern’ Accelerators: Tevatron

TeVatron

- Synchrotron: 1 km radius
- operational: 1985-2011
- at Fermilab (Chicago, USA)
- detectors: CDF, Dzero
- Ebeam: 1 TeV, p-pbar (1 mA)
- physics goals: Higgs, NP, top, *b*
- superconducting magnets: 4.2 T
- complex acceleration chain
  - Cockroft-Walton (750 keV, H^{--})
  - LINAC(400 MeV, strip to create *p*)
  - Booster (8 GeV)
  - Main Injector (120 GeV)
  - Tevatron (1 TeV)



Modern Accelerators: LHC

Large Hadron Collider (LHC)

- Synchrotron: 4.5 km radius
- Operational: 2007-203?
- at CERN (Geneva, Switzerland)
- detectors: Alice, Atlas, CMS, LHCb + smaller
- E_{beam}: 7 TeV proton (0.5 A) $\rightarrow \sqrt{s} = 14$ TeV
- schedule: pilot run 2007, physics run 2008
- physics goals: Higgs and New Physics Discovery
- dipole magnets, the core of LHC (1232)
  - superconducting dipoles: B=8.4 T; T=1.9 K, I=11.7 kA
  - superfluid helium cooling

LHC Dipoles Complete

LHC Layout

Dipoles at 8.4 T

$$B[T] = \frac{2\pi}{0.3}\frac{p[\text{GeV}]}{FL[m]}$$

momentum: 7000 GeV

tunnel: 27000 m

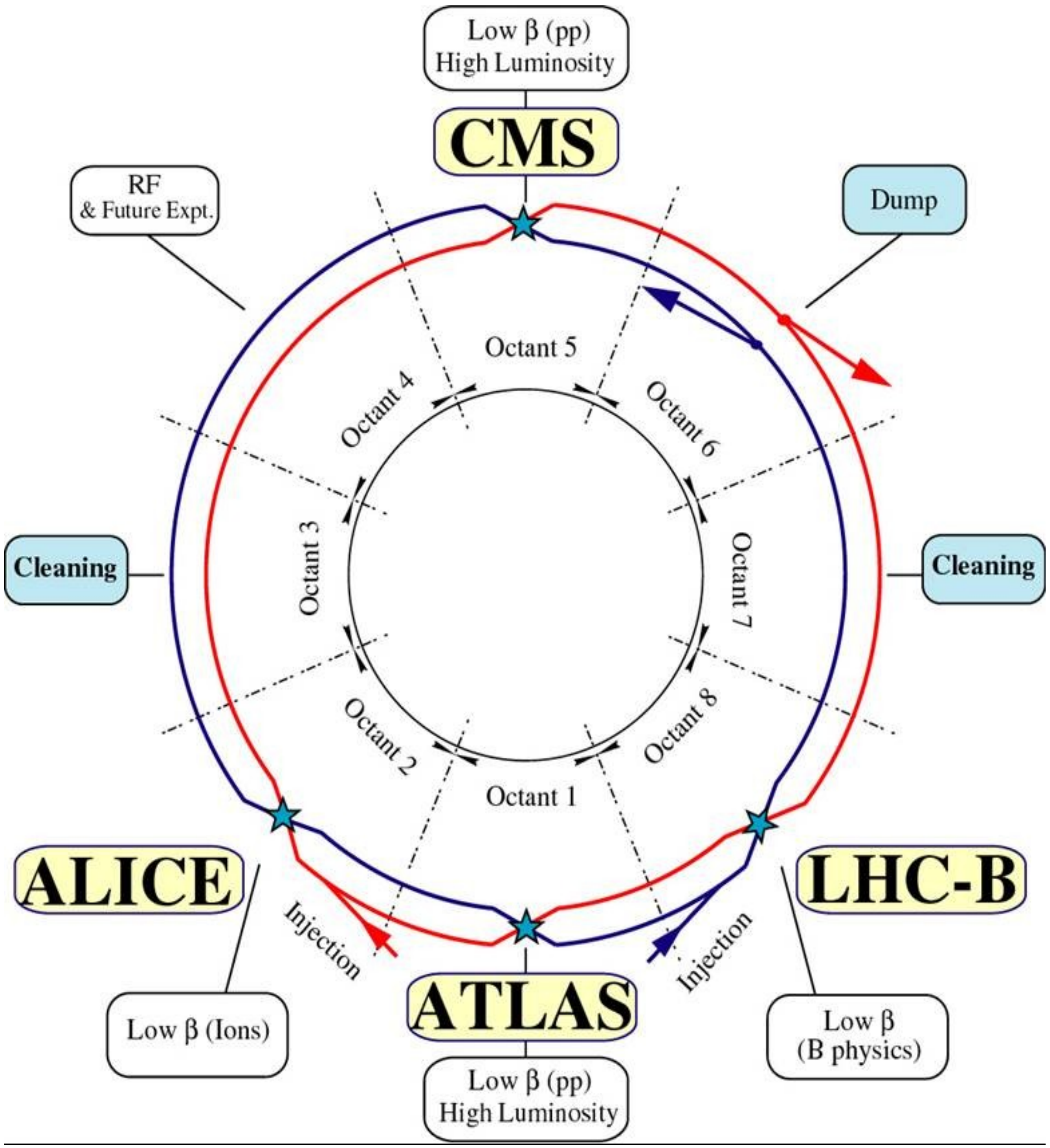
arcs length: 22200 m

80% of arcs filled: F = 0.8

compare to

iron saturation: 2 T

Earth magnet: $0.3 \times 10^{-4}\,T$



Energy Stored in an LHC Beam

Energy stored is huge

- beams store 700 MJ: battleship gun is about 300 MJ
- beam dump (70 μs) will create 10 TW of power, which is half the entire world's instantaneous power

Comparison

LEP

- Luminosity: 10^{32} cm^{--2} s^{--1}
- number of bunches: 8 x 8,
- bunch size: like a flat needle: 10 cm, 250 µm, 80 µm

TeVatron

- Luminosity: 3 x 10^{32} cm^{--2} s^{--1}
- number of bunches: 36 x 36, per bunch: p-10^{11}, pbar-10^{10}
- bunch size: 30 cm, 30 µm, 30 µm

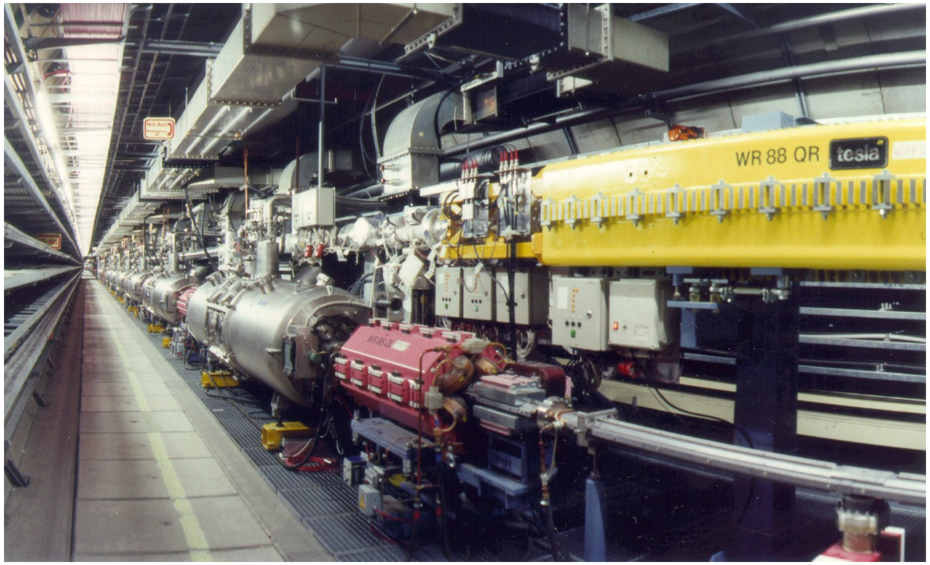
LHC

- Luminosity: $10^{34/35}$ cm^{--2} s^{--1}
- number of bunches: 2800

Other Accelerators

HERA, 1991 (Hamburg, Germany)

e (27.5 GeV) - p (920 GeV)
radius: 1 km, B = 5.5 T, T = 4.4 K
180 bunches, I = 0.5 mA



RHIC, 1999 (New York, USA)

Au - Au ... p – p at 250 GeV
radius: 0.60 km, B = 3.5 T; T = 4 K
57-114 bunches, I = 0.013 mA

Future of Accelerators

Linear collider, ILC (technically proven): 0.5-3 TeV

- strong international collaboration
- awaiting directions from LHC findings
- political decision of location

VLHC (issue: magnet development): 40-200 TeV

- 95 km; B = 12 T; n = 20800
- 520 km; B = 2 T; n = 130000

Muon collider (issues: source/lifetime) 0.5-4 TeV

- lepton collider virtually without synchroton radiation
- Higgs factory (40,000 times larger coupling then e^+e^{-})

Conclusions

Motivation for particle acceleration

- understand matter around us: “nuclear physics”
- create new particles : “particle physics”

Particle acceleration types

- electrostatic: limited to 25 MeV
- AC driven: linear or circular, open ended

Modern Accelerators

- LEP and LHC
- Future accelerators: FCC, ILC, muon collider ....

Next Lecture

Particle Detectors Overview

- Introduction and a bit of history
- General organization of detectors
- Particle interactions with matter
- Tracking
- Calorimetry
- Modern integrated detectors
- Conclusions and next lecture