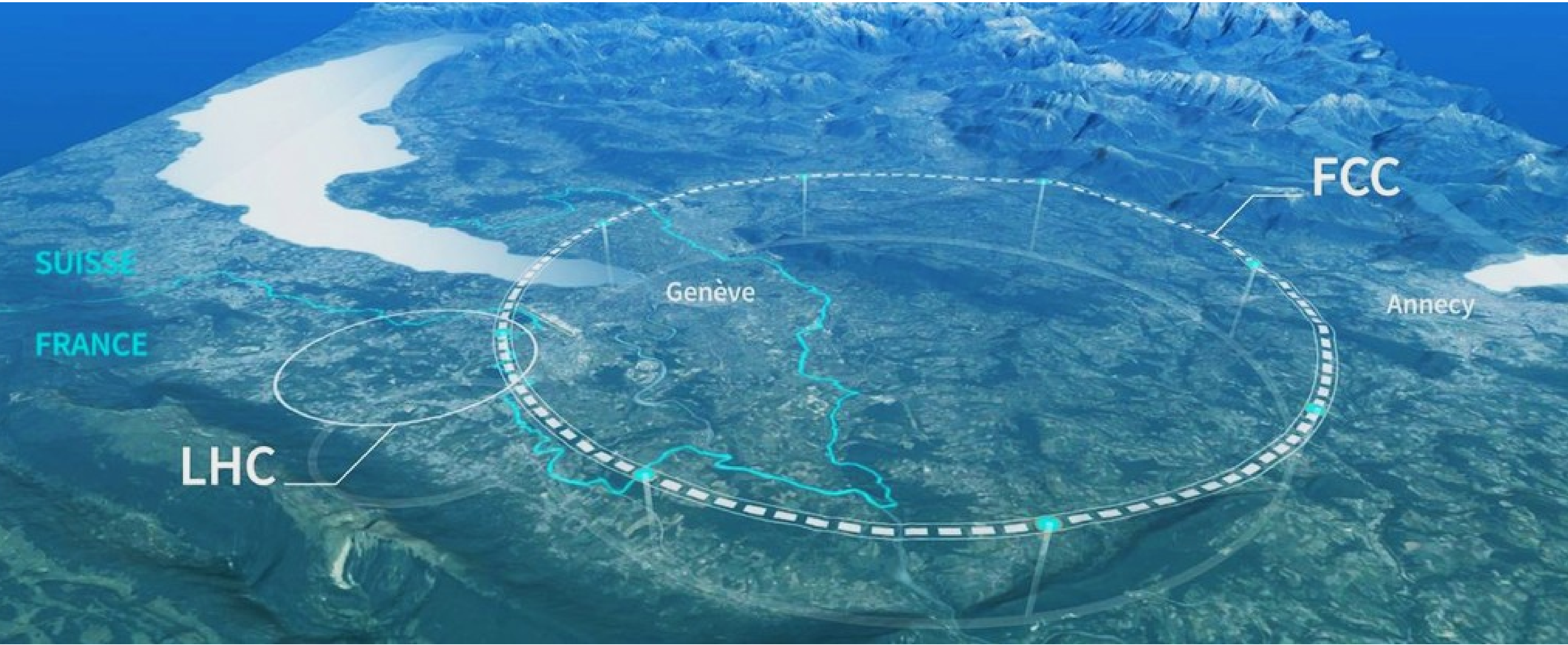
8.FCC - January Research Projects on the Future Circular Collider (FCC-ee)

Accelerators ... continued
[January 10, 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

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

$\rightarrow$ no increase in velocity, but changes direction

Only electric force increases particle energy

From the Maxwell equations:

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

static:

$$\vec{A} = 0$$

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

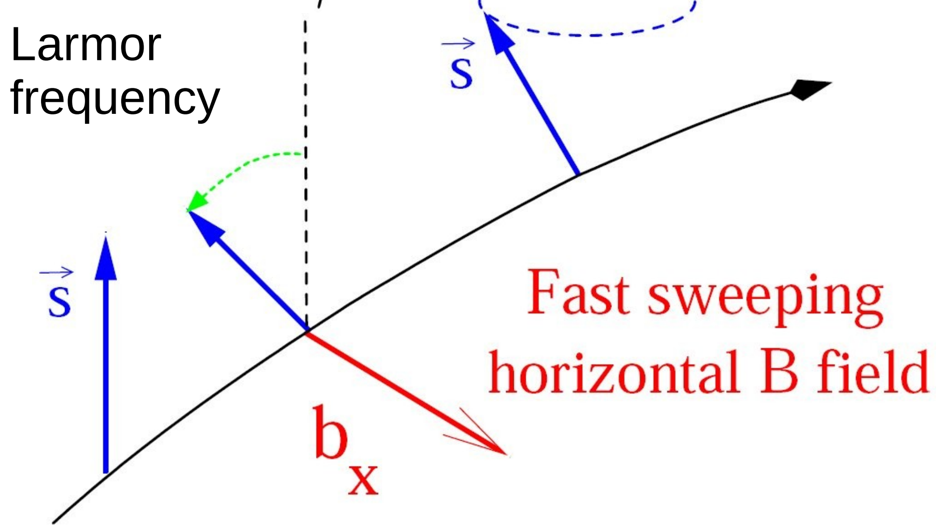
Complementary devices

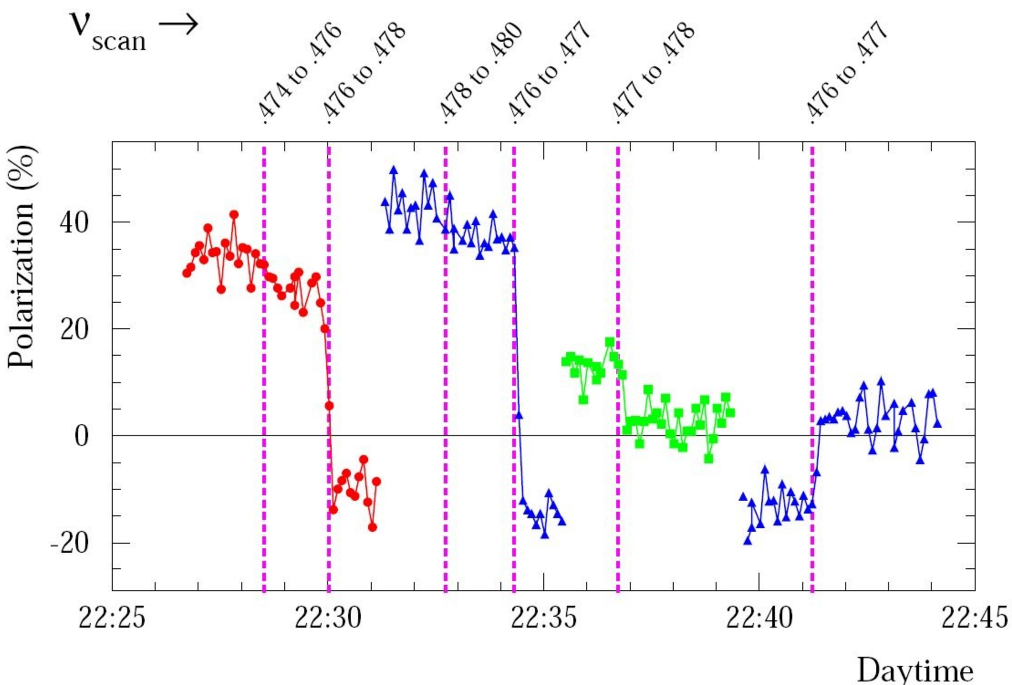
‘Modern’ Accelerators: LEP

Energy calibration (resonant depolarization)

- Transverse polarization automatically builds up (Sokolov-Ternov)
- Monitor transverse polarization level
- Kick rotating electrons with periodic magnetic field
- Tune in frequency which destroys polarization (resonance)
- Very sensitive method: about 0.5 MeV on 45 GeV beams

$$\omega_{s(g=2)} = \frac{eB}{mc\gamma}$$





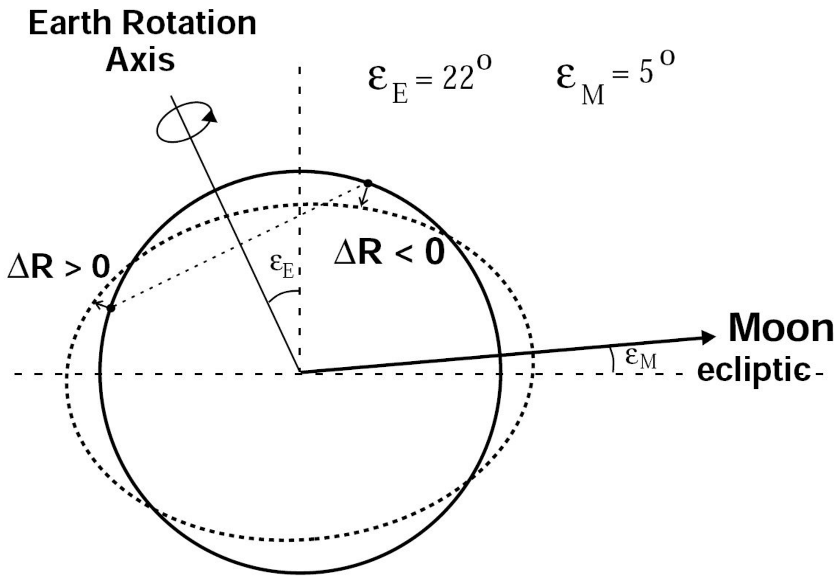
https://www.sciencedirect.com/science/article/pii/037026939290457F: *PLB 284,3 (1992) 431*

'Modern' Accelerators: LEP

Calibration nightmares: part 1

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

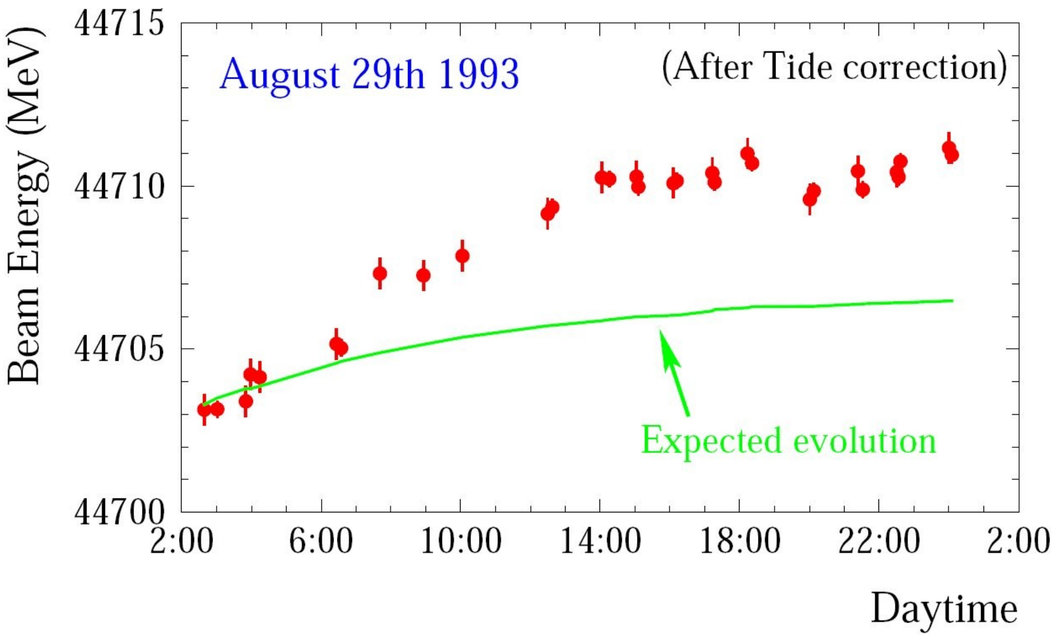
fluctuations in first calibrations explained by tides

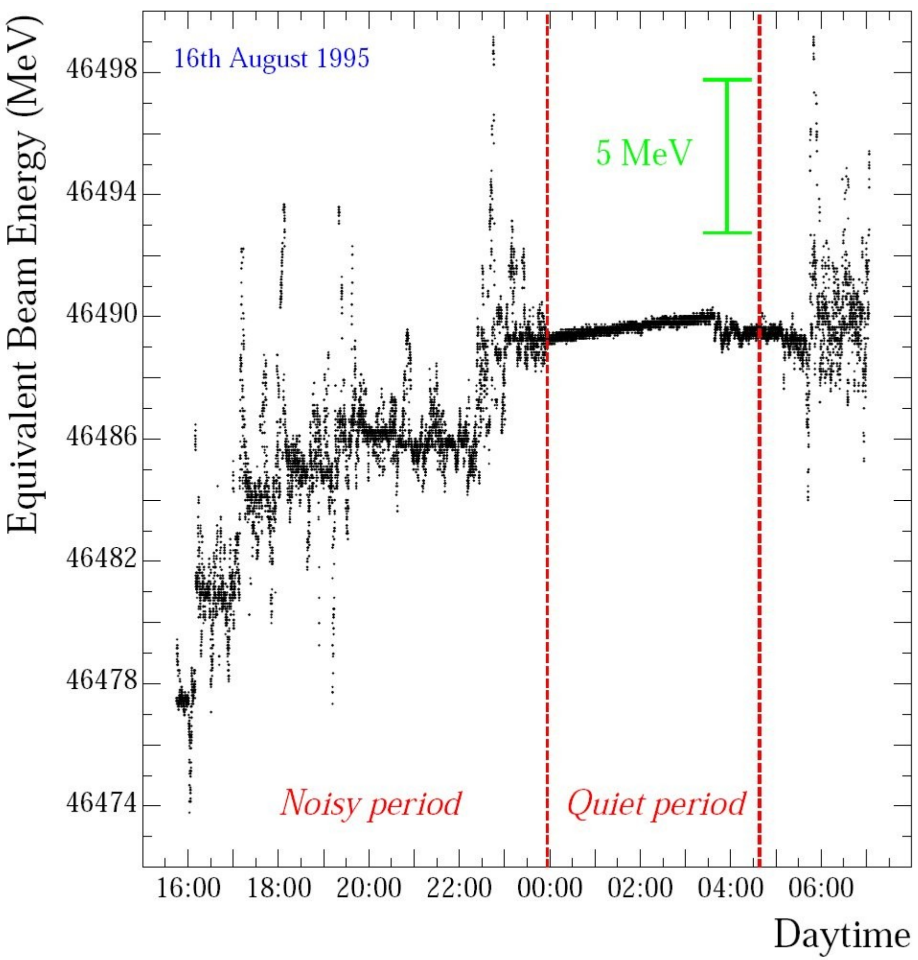


https://cds.cern.ch/record/250463/files/CM-P00061237.pdf

‘Modern’ Accelerators: LEP

Calibration nightmares: part 2





A daunting indication

- will remain unexplained for 2 years ....
- until an undergrad from Aachen (Mark Geitz) comes out for the summer

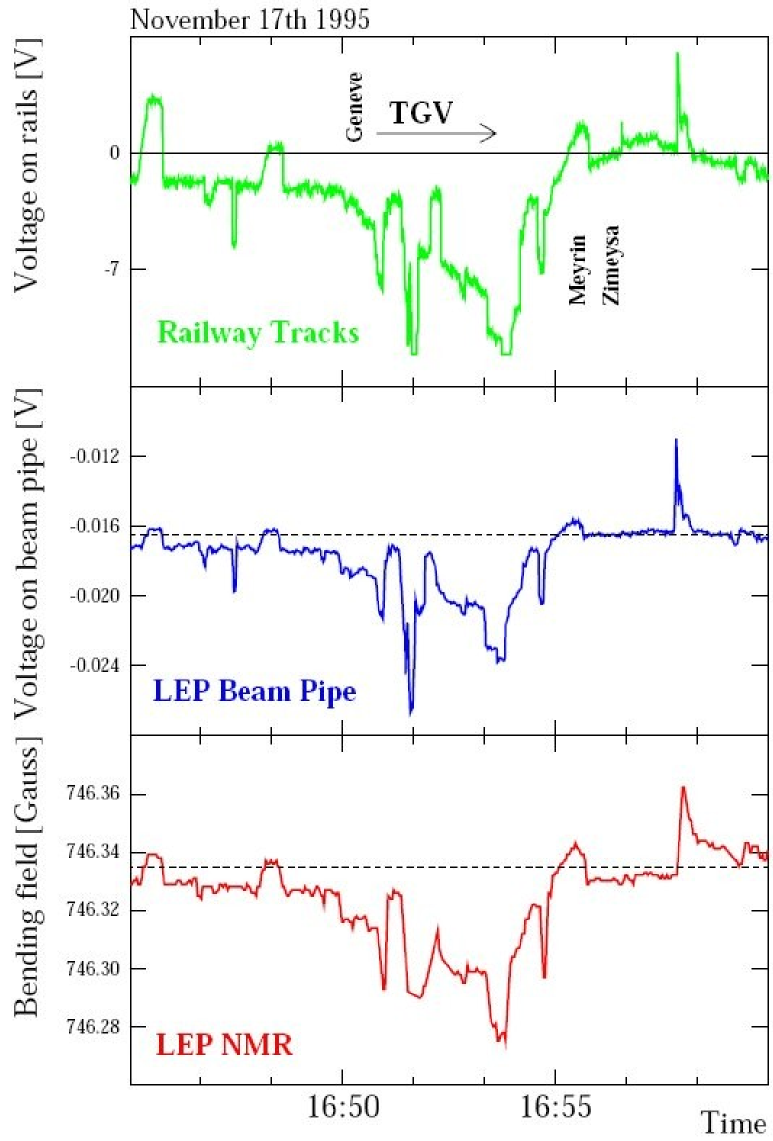
Smoking gun

- man made problem

https://cds.cern.ch/record/334095/files/sl-97-047.pdf

'Modern' Accelerators: LEP

The French DC trains caused the problem



1A current on beampipe

‘Modern’ Accelerators: LEP

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

The limits of LEP

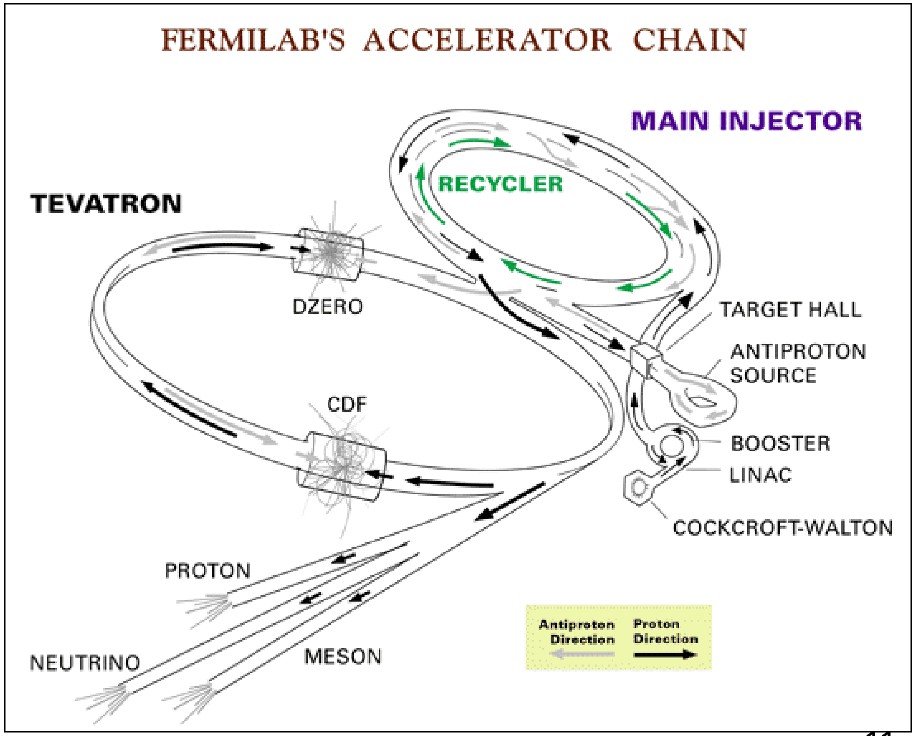
- synchrotron radiation energy: $E_{sync} \propto \gamma^4$
  - at 100 GeV: $\Delta E_{beam}/E_{beam} = 0.02 \rightarrow E_{loss}/\sqrt{s} = 0.10$
  - energy consumption: 20 MW (small village)
  - length of machine affects synchrotron radiation losses
- tunnel completely full of cavities (superconductive)
- 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

Derive gamma factor: https://www.youtube.com/watch?v=qXxtqK7G4Uw

'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

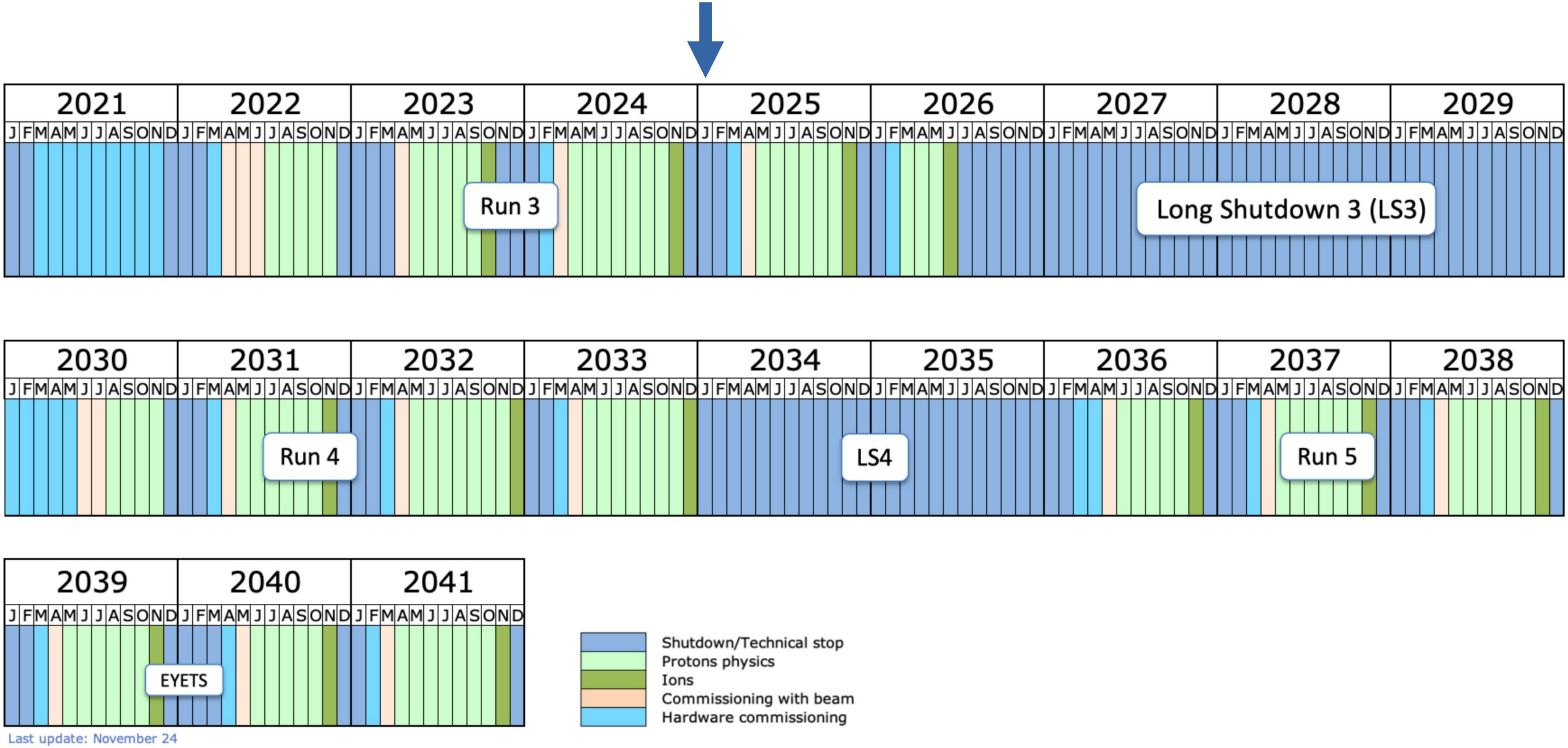
Large Hadron Collider (LHC)

- Synchrotron: 4.5 km radius
- Operational: 2007-2041?
- 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

Modern Accelerators: LHC

Large Hadron Collider (LHC)

- Long term schedule set into the early 40ies
- There are some uncertainties projecting forward for so long



LHC Dipoles Complete

LHC Layout

Dipoles at 8.4 T

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

momentum: 7000 GeV

tunnel: 27000 m

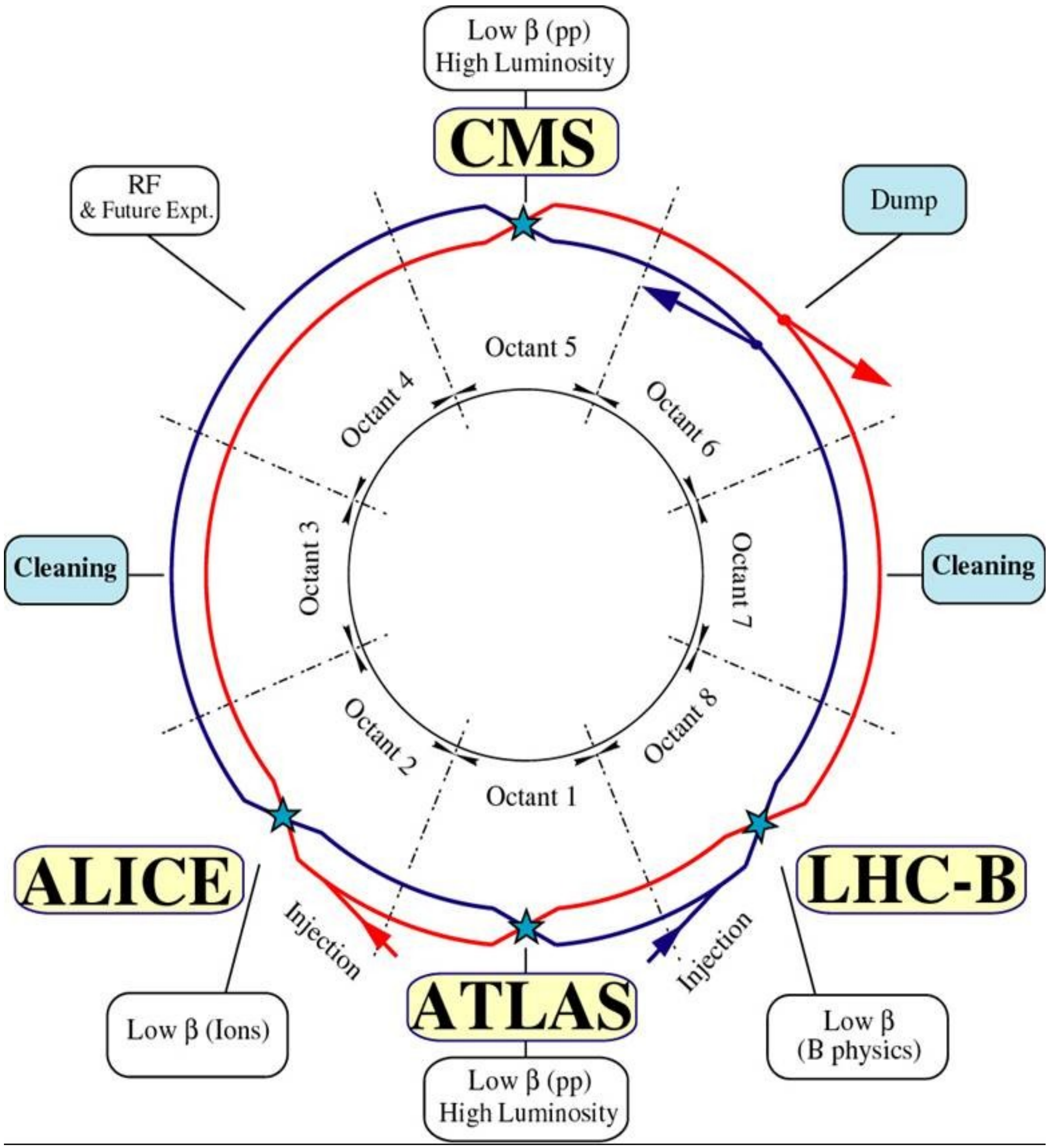
arcs length: 22200 m

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

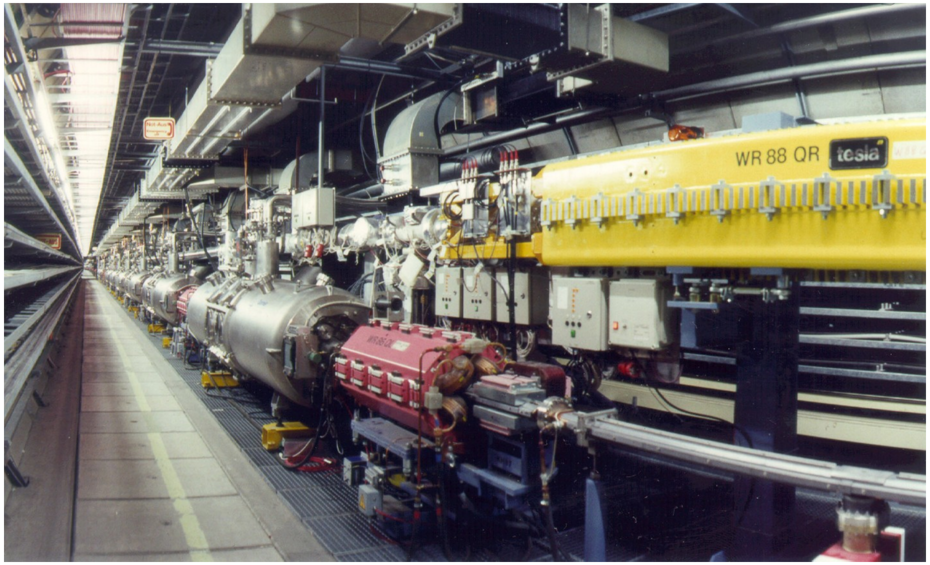
LHC

- 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 (~ FCC-hh)
- 520 km; B = 2 T; n = 130000

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

- lepton collider virtually without synchrotron 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