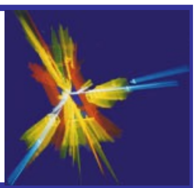


Particle Physics Experiments

PAP329: Particle Physics Experiments
A 5 ECTS credit course spring 2025

https://www.mv.helsinki.fi/home/osterber/experiments/

Lectures Mon 10-12 (Physicum D115)

weeks 3-7, 9,11-16

given by

Prof. Kenneth Österberg,

room C327, email: kenneth.osterberg(at)helsinki.fi

Exercise sessions Mon 12-13 (Physicum D116)

starting week 5

given by

MSc Anna Milieva,

room B321, email: anna.milieva(at)helsinki.fi

Course Content

Introduction

Accelerator part
(follows more-or-less E. Wilson: An Introduction to Particle Accelerators)

- Particle Accelerator History & Basics
- Transverse Beam Dynamics & Accelerator Lattice
- Longitudinal Beam Dynamics
- Accelerating Cavities
- Electron Dynamics
- Imperfections & Instabilities
- Colliders & Cooling; The Large Hadron Collider
- Future Colliders & Applications of Accelerator

Experiment part

- Particle Accelerator History & Basics
- Particle Interaction with Matter
- Tracking, Tracking Detectors & Vertexing
- Scintillation & Photon Detectors
- Energy measurement & Jet Reconstruction
- Particle Identification
- Detector Systems, Trigger and Data Acquisition
- The LHC Experiments
- Applications of Particle Detectors

Literature

Text books

- **E. Wilson: An Introduction to Particle Accelerators**, Oxford University Press, 2001.
- D. Green: The Physics of Particle Detectors**,** Cambridge University Press, 2005.
- C. Grupen and B. Shwartz: Particle Detectors, 2nd edition, Cambridge University Press, 2023.
- G. Knoll: Radiation Detection and Measurement, 4th edition, Wiley, 2010.

Other resources

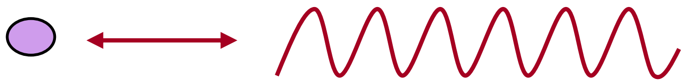
- **Particle Data Group: Reviews on Experimental Methods and Colliders:** pdg.lbl.gov especially
  - Accelerator physics of colliders
  - Passage of particles through matter
  - Particle detectors at accelerators
- **Proceedings of CERN Accelerator Schools (see links on course home page)**

Course Grading

- **Exercises (7-8 papers) 40 %, oral exam 60 %.**
- **Exercises given Fri, returned next Fri 12.00** (first exercise paper will be given next week)

Particle accelerators

To study structures « wavelength of light
need something else than (light)microscopes !!



particle **wave:** $\lambda = h/p$

h = Planck's constant
λ = wavelength
p = particle momentum

Use "particle microscopes" i.e. **accelerators**

In particle accelerators charged particles accelerated to light velocity in a vacuum chamber ("analog TV").

Modern particle accelerators usually "colliders" = two particle beams hit each other in controlled positions.

Natural units:

Special relativity: $E^2 = \bar{p}^2c^2 + m^2c^4$

Have 3 fundamental units: length L, time T and energy E

2 natural constants: $c = 3.0 \cdot 10^8$ m/s, $\hbar = 6.6 \cdot 10^{-25}$ GeVs

Set c = 1 = [L] / [T] ⇒ [T] = [L] (applied e.g. in four-vectors)

Also set ħ = 1 = [E] · [T] ⇒ [L] = [T] = 1/ [E] (= GeV^{-1})

One degree-of-freedom left so choose [E] = GeV

1 GeV is a tiny portion of energy. 1 GeV = $1.6 \cdot 10^{-10}$ J

m_{bee} = 0.25 g; v_{bee} = 3 m/s

→ E_{bee} = $m_{bee} v_{bee}^2/2$ = 1.1 $\cdot 10^{-3}$ J = 7000000 GeV

⇔ E_{LHC} = 6800 GeV (2024 LHC proton energy)

To rehabilitate LHC…

Record stored energy/beam in LHC (2024):

~3.76 $\cdot 10^{14}$ protons * 6800 GeV ≈ 410 MJ

Corres-pondance:

$m_{Pendolino}$ = 328 T

$v_{Pendolino}$ = 140 km/h

Now $E^2 = \bar{p}^2 + m^2$ ⇒ [E] = [p] = [m] = 1 GeV

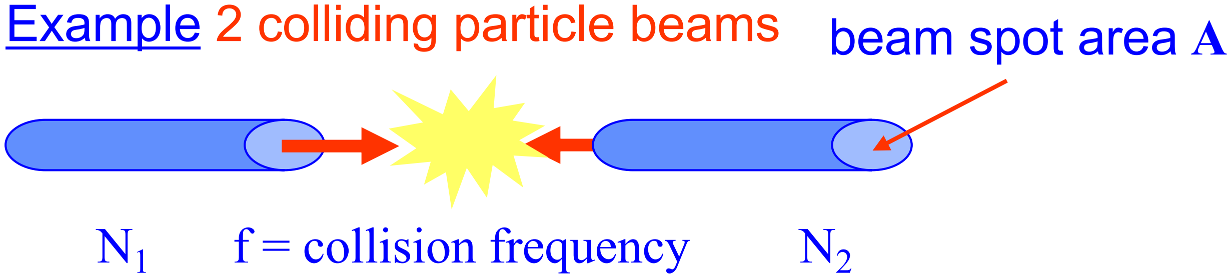
Define $\beta = \frac{v}{c}$ $(0 \le \beta < 1)$ $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ $(1 \le \gamma < \infty)$

e.g. β = p / E, γ = E / m, and <decay length> = $\beta \cdot \gamma \cdot c \cdot \tau_0$

The concept of cross section

Cross section σ or differential cross section $d\sigma/d\Omega$ is used to express the probability of interaction between elementary particles.

Example 2 colliding particle beams



What is the interaction rate R_{int} ?

$$R_{int} \propto \underbrace{f\, N_1 N_2 / A}_{\text{Luminosity } \mathcal{L}\ [cm^{-2}\, s^{-1}]} = \sigma \cdot \mathcal{L}$$

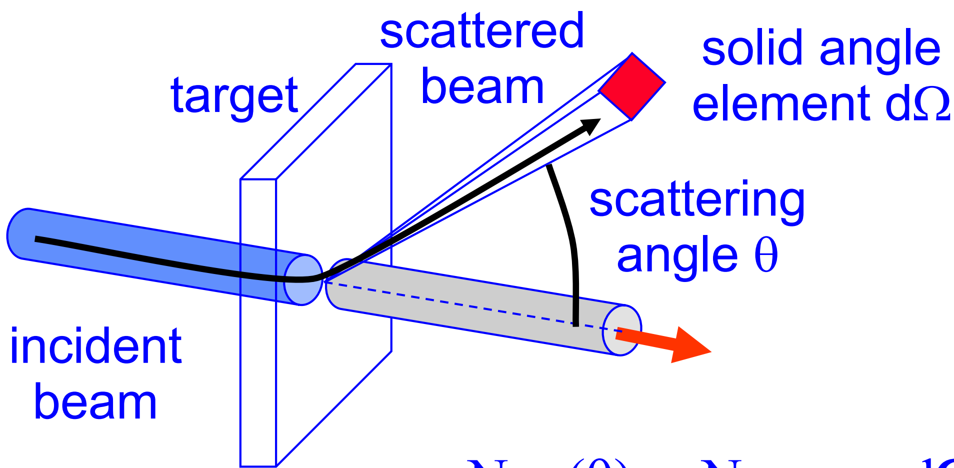
σ has dimension area !

Practical unit:

1 barn (b) = 10^{-24} cm^2

Example: Scattering from target

$N_{int} = R_{int}\, t$



Integrated luminosity $\int \mathcal{L}\, dt$ [cm^{-2}]

n_A = area density of scattering centers in target

$$N_{scat}(\theta) \propto N_{inc} \cdot n_A \cdot d\Omega$$

$$= d\sigma/d\Omega\,(\theta) \cdot \underbrace{N_{inc} \cdot n_A}_{} \cdot d\Omega$$

Define **luminosity** precisely:

imagine a particle colliding with a particle bunch of cross section area – A. Probability of collision is:

(E.Wilson)

$$\sigma \cdot N_{part/bunch} / A$$

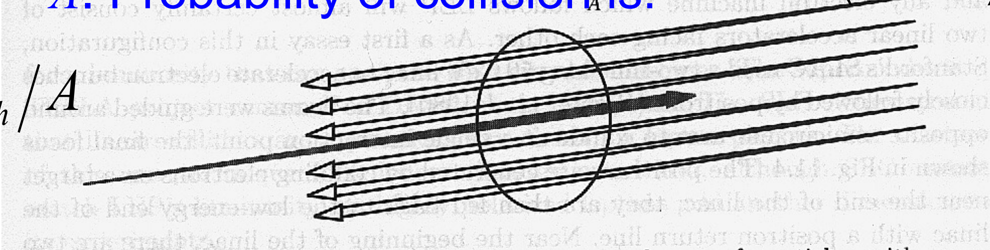


Fig. 11.3 A probe particle encounters a target—a beam of particles with cross sectional area A travelling in the opposite sense.

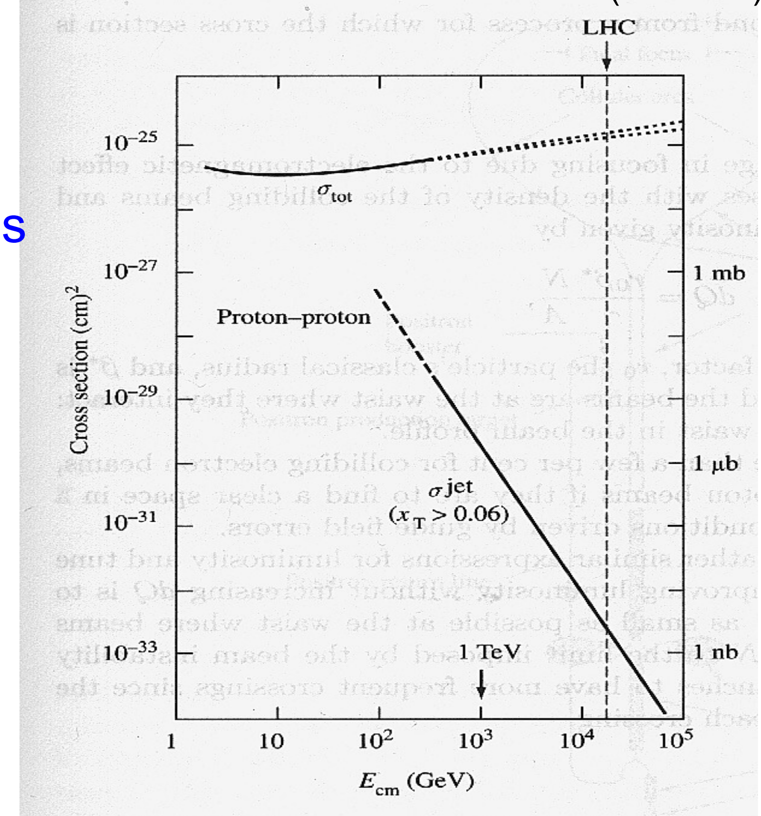
for $N_{part/bunch}$ particles in both beams $\sigma \cdot N^2_{part/bunch} / A$

and finally take into account the bunch crossing frequency f_b = # of bunches multiplied by the revolution frequency.

Event rate = $\mathcal{L} \cdot \sigma$, where $\mathcal{L} = f_b N^2_{\mathrm{part/bunch}} / A$ (= luminosity)

Ultimate challenge to high energy colliders: the production rate of "interesting" interactions fall as $1/s$ ($\propto 1/E_{CM}^2$), hence need to improve luminosity a factor 100 for each factor 10 energy increase to benefit from energy increase (distances at which structures probed $\propto 1/\sqrt{s}$).

(E.Wilson)



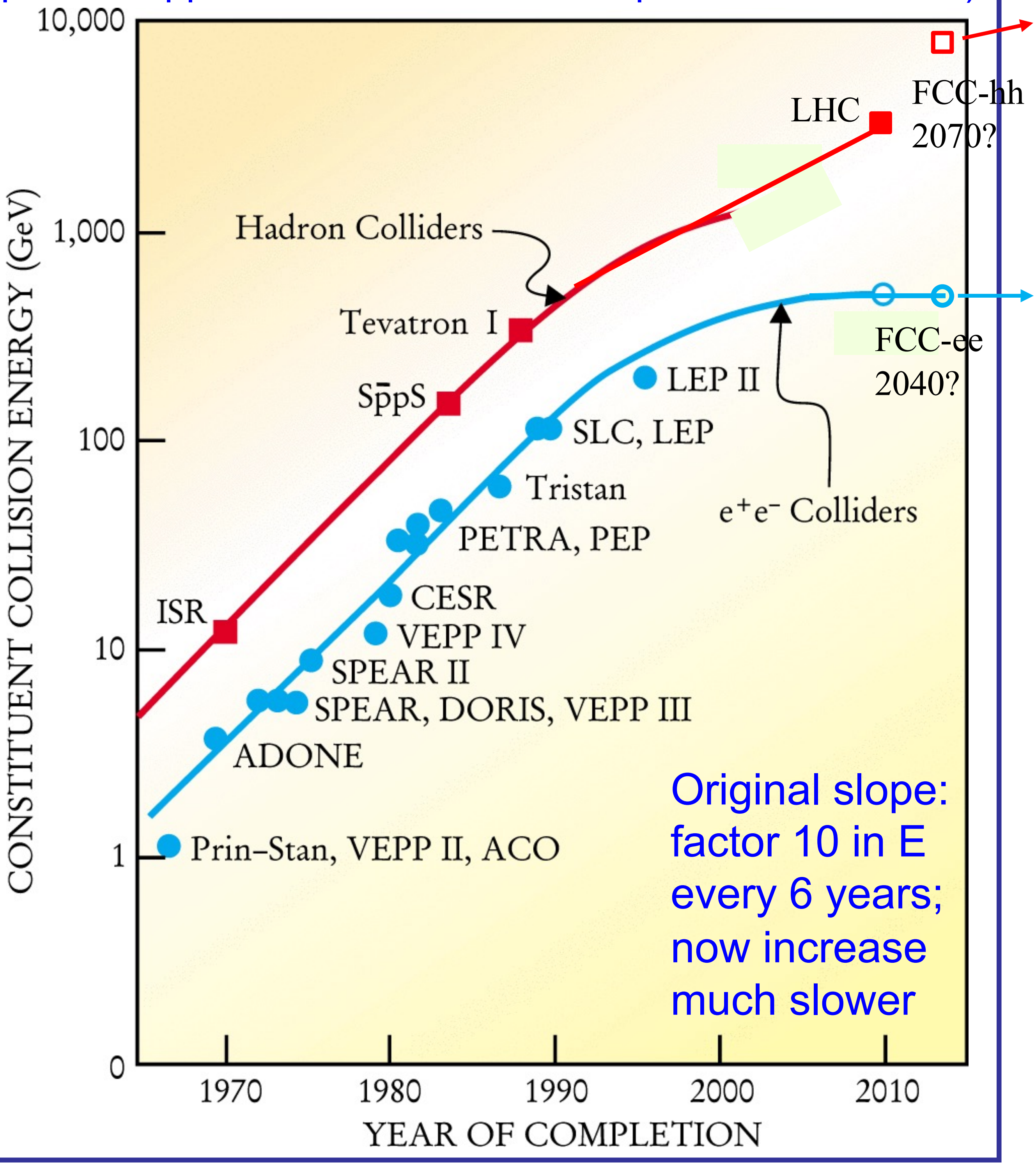
History of Accelerators:

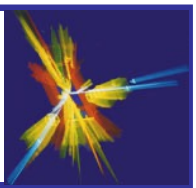
- need for accelerators
- electrostatic accelerators
- time dependent fields
- betatrons
- linacs
- cyclotrons
- weak focusing
- syncrotrons
- phase stability
- strong focusing
- colliders

$\lambda = h / p$ (1.2 fm / p [GeV]) (de Broglie, 1923)
$E = \gamma mc^2$ (Einstein, 1905)

Livingston plot (1954):

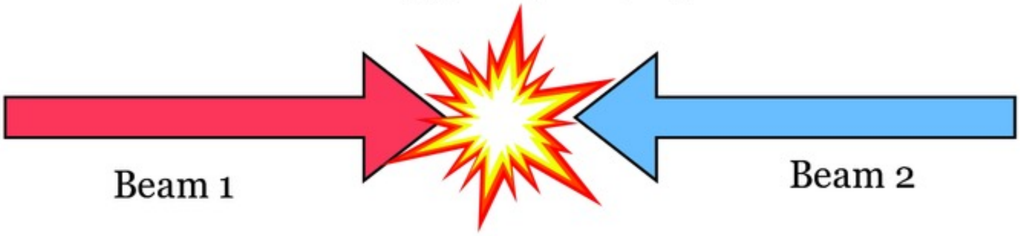
(protons approximated as 3 valence quarks with same E)

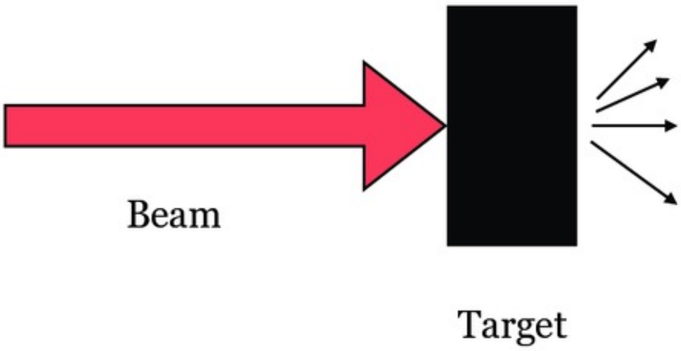




Following was known early...

$$E_{cm} = \sqrt{4E_1E_2}$$





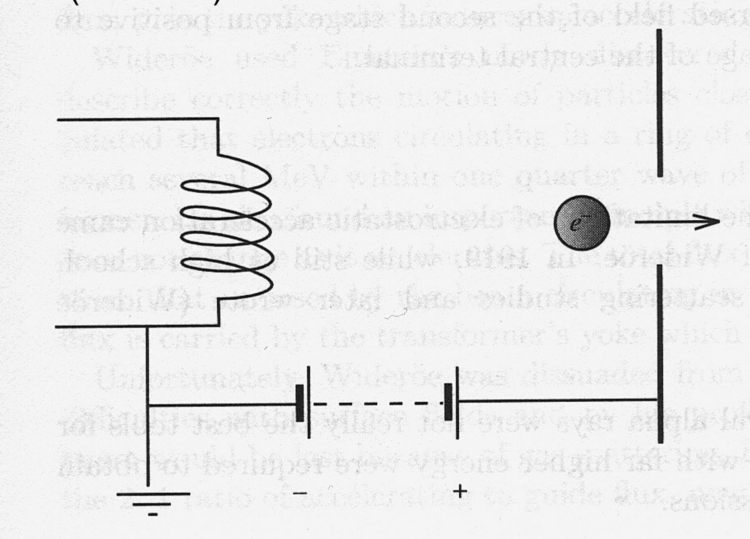
$$E_{cm} = \sqrt{2m_{target}E_{beam}}$$

but took a long time to realize sufficiently dense and well-controlled particle beams !!

Electrostatic accelerators

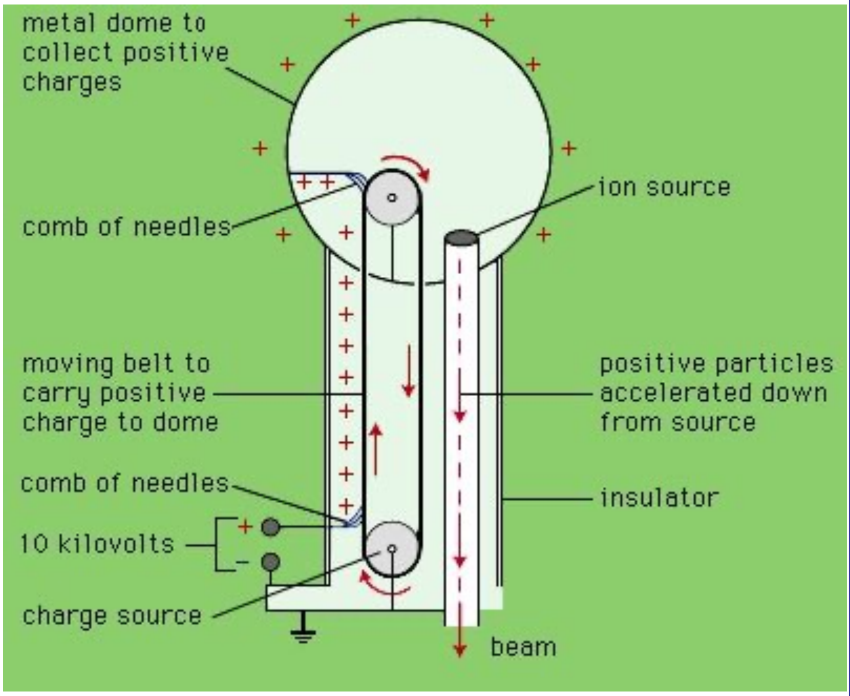
First accelerators <u>electrostatic</u> (like ”electron gun” in an old fashion TV), electrons emitted by heated filement in vacuum & accelerated in a static electric potential

(E.Wilson)



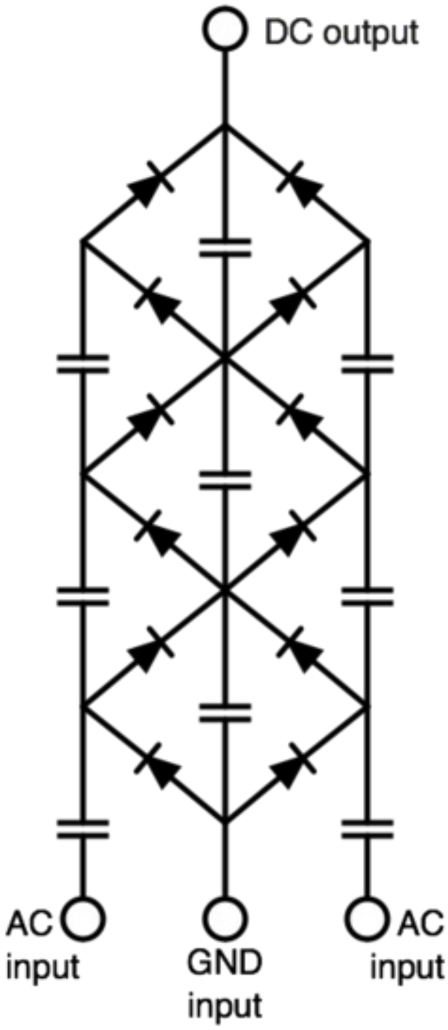
limited to ~ a few MeV (even in staged approach) due to electrical breakdown

van de Graaff (1931) – moving belt charging up a high-voltage terminal (e.g. a metal ball)



Cockcroft & Walton (1932) –
ladder of diodes & capacitors

1937 – 1 MeV accelerator



method still commonly used for ion sources, high voltage power supplies, lightning safety testing systems ...

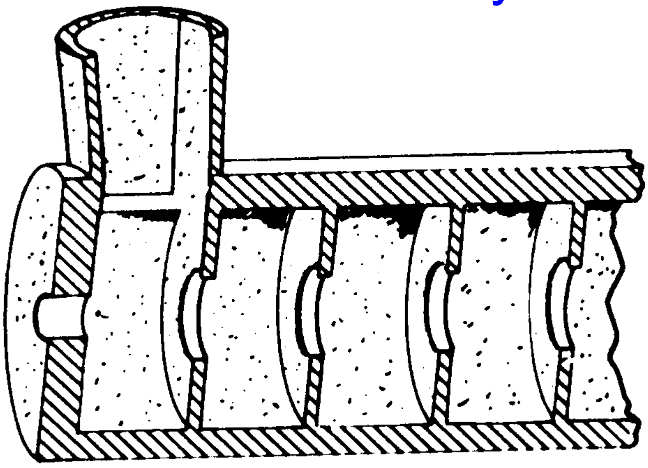
used in high voltage direct current applications

modern 100 keV equivalent

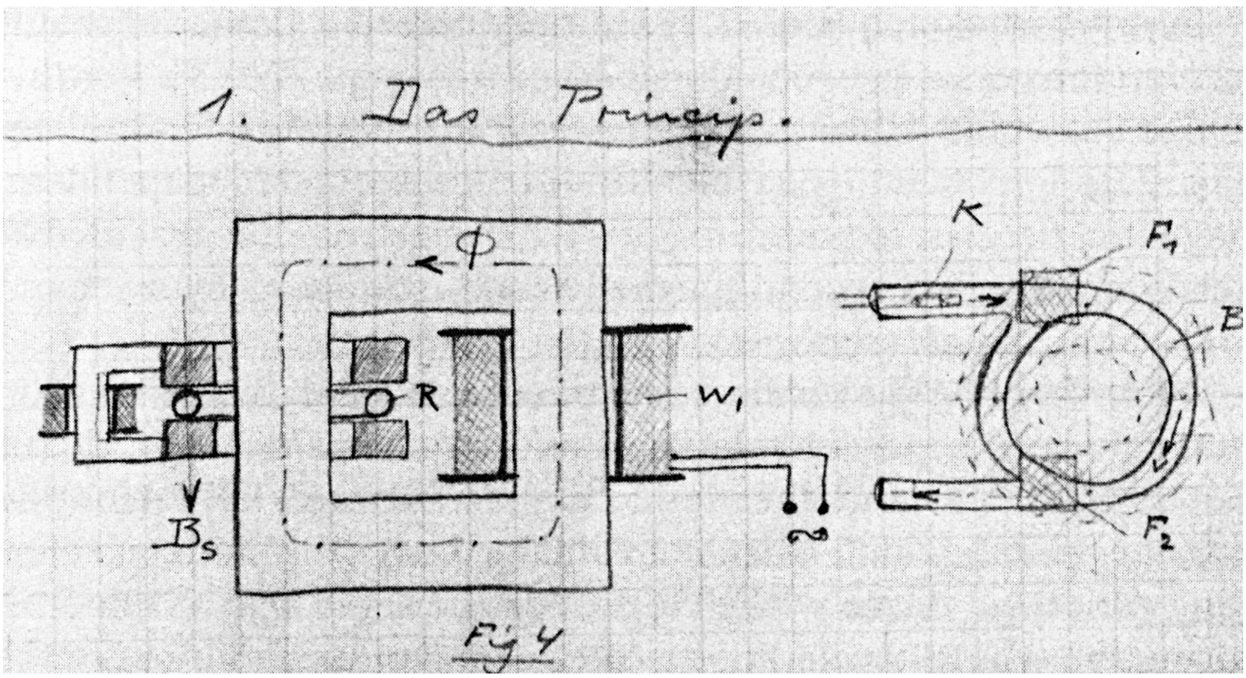
Continious acceleration through same gap ?
Maxwell equations → time dependent magnetic field

$$\overline{\nabla} \times \overline{E} = -\frac{dB}{dt} \quad \rightarrow \quad \int_{\Gamma} \overline{E} \cdot d\overline{s} = -\frac{\partial}{\partial t} \int_{S} \overline{B} \cdot \overline{n}\, da$$

Need suitable boundary conditions → iris structure

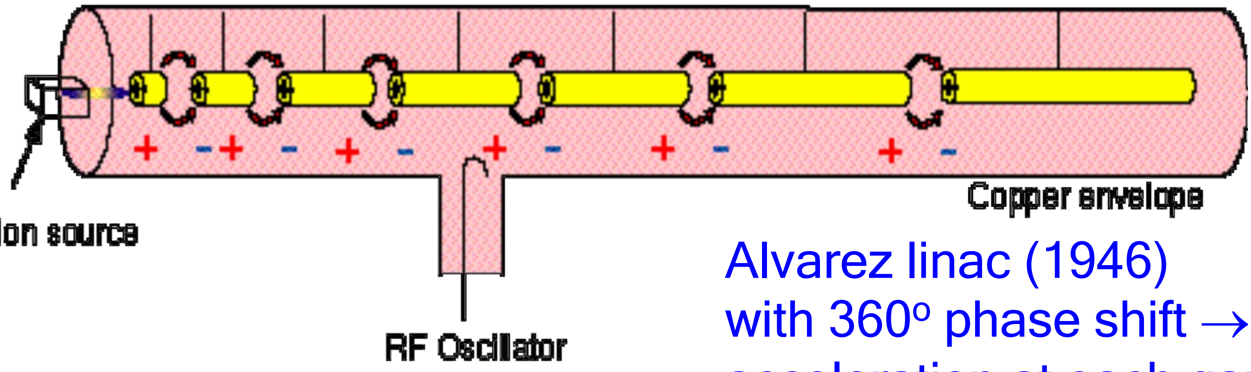


R. Wideröe 1928: ray transformer - varying magnetic field via induction



Linear accelerators

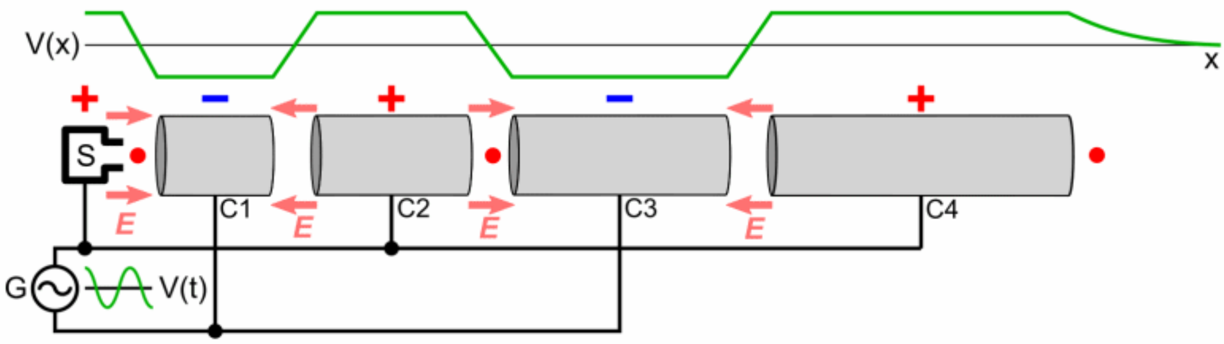
Next : pulsed operation in electrodes ("drift tube linac").
Realised in mid-40's, high frequency oscillators available.



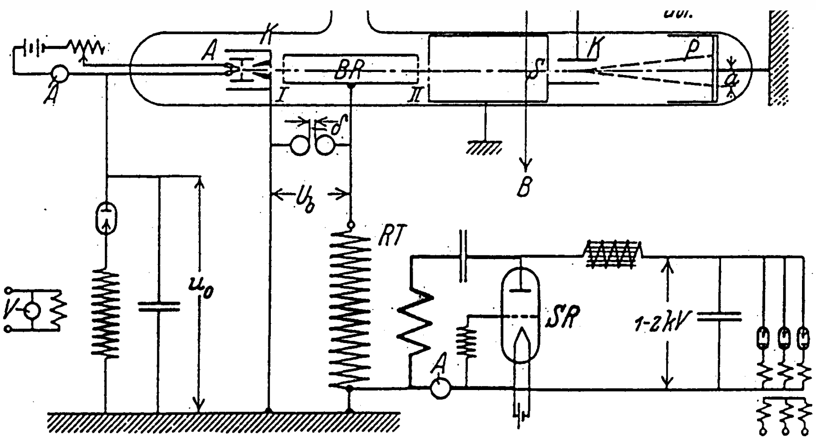
Alvarez linac (1946) with 360º phase shift → acceleration at each gap

- Particle gains energy at each gap
- Cylinder protects particles from deacceleration
- Lengths of drift tubes follow increasing velocity
- Spacing becomes regular as v approaches c

https://en.wikipedia.org/wiki/Linear_particle_accelerator

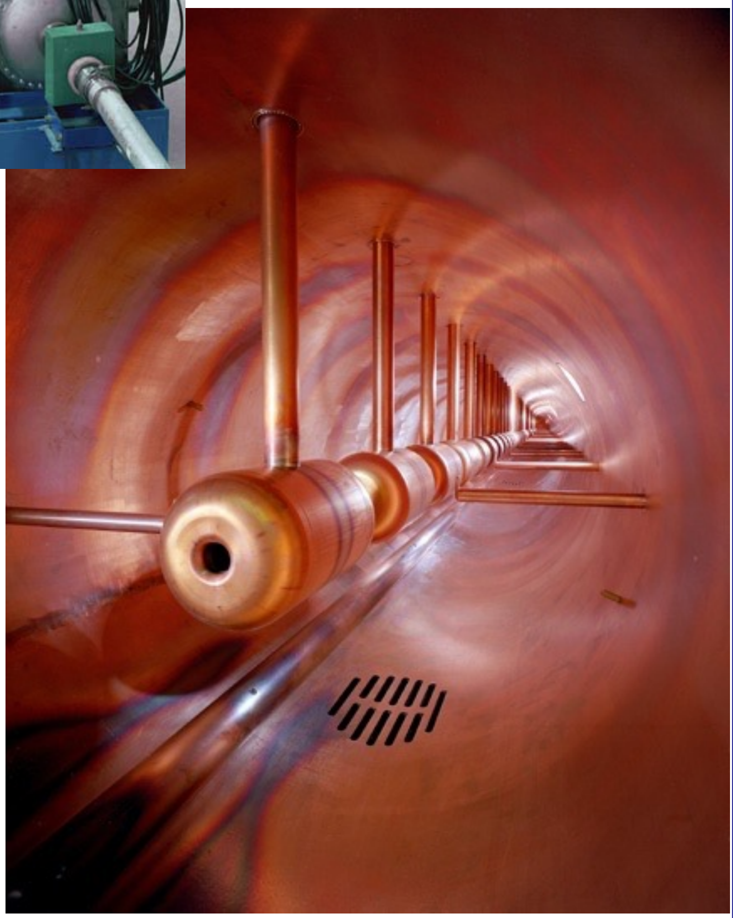


Wideröe's thesis work 1928: a 2-stage linac with 180º phase shift



Modern linacs

a 400 MeV linac at Fermilab



inside Fermilab linac

Lawrence 1930: make particle follow circular path between two magnetic poles & repeatedly accelerated in same gap

<u>Cyclotron:</u> (rf frequency constant when v << c)

(E.Wilson)

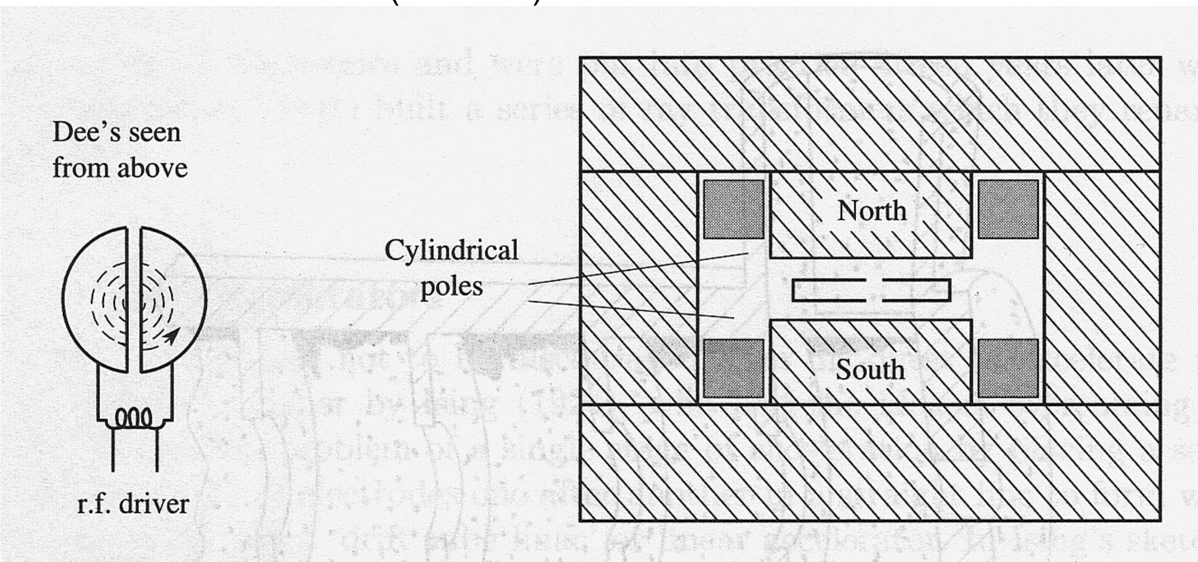
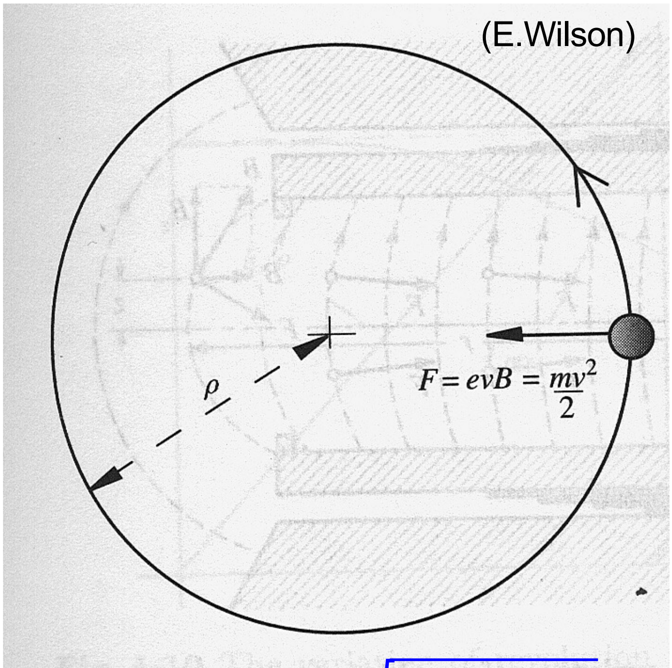


Fig. 1.7 The principle of the cyclotron (from Livingwood 1961).



$e\,v\,B = m\,v^2 / \rho$ (v << c)

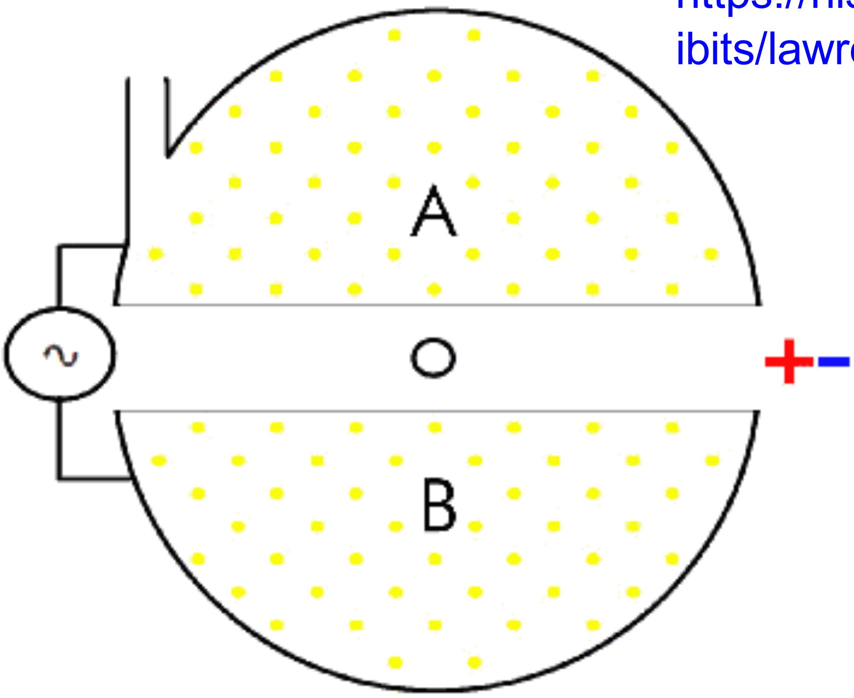
$\rightarrow \; B\,\rho = p / e$ (relativistic)

Cyclotron frequency:
$f = v / 2\pi\rho = e\,B / 2\pi m$

Used for protons & heavier ions.

$$E_{kinetic}^{relativistic} = \sqrt{p^2 + m^2} - m \qquad E_{kinetic}^{classical} = p^2/2m$$

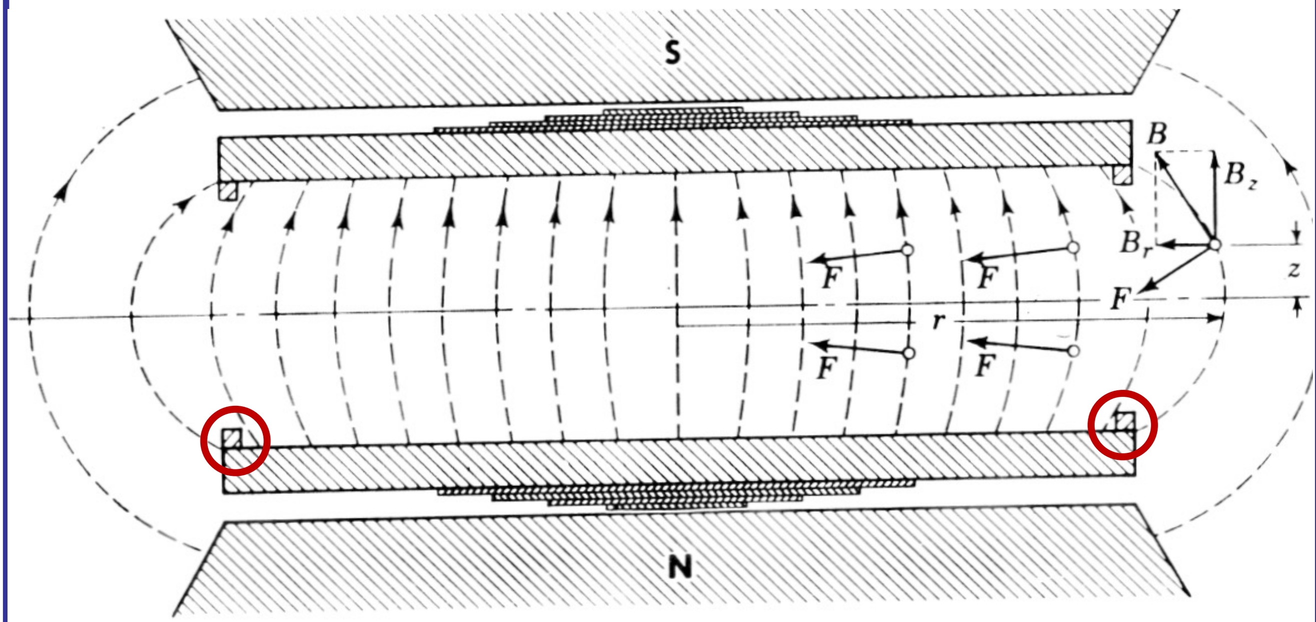
Cyclotron demo



https://history.aip.org/exhibits/lawrence/epa.htm

E. Lawrence (right) 1939 at LBL's 60-inch cyclotron

Weak focusing



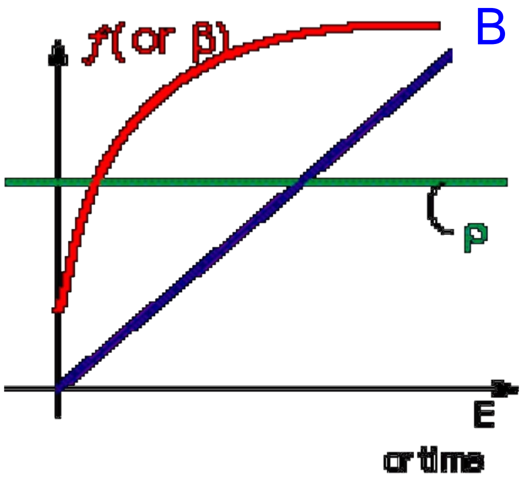
- In begining people just built cyclotrons
- Lawrence's student McMillan experimented with shims (= elements put at edges of ring to avoid defocusing field) indicated by O in picture → a non-expected result: cyclotron started accelerating much higher currents
- invented principle of vertical focusing in a cyclotron

Limitations of cyclotrons:

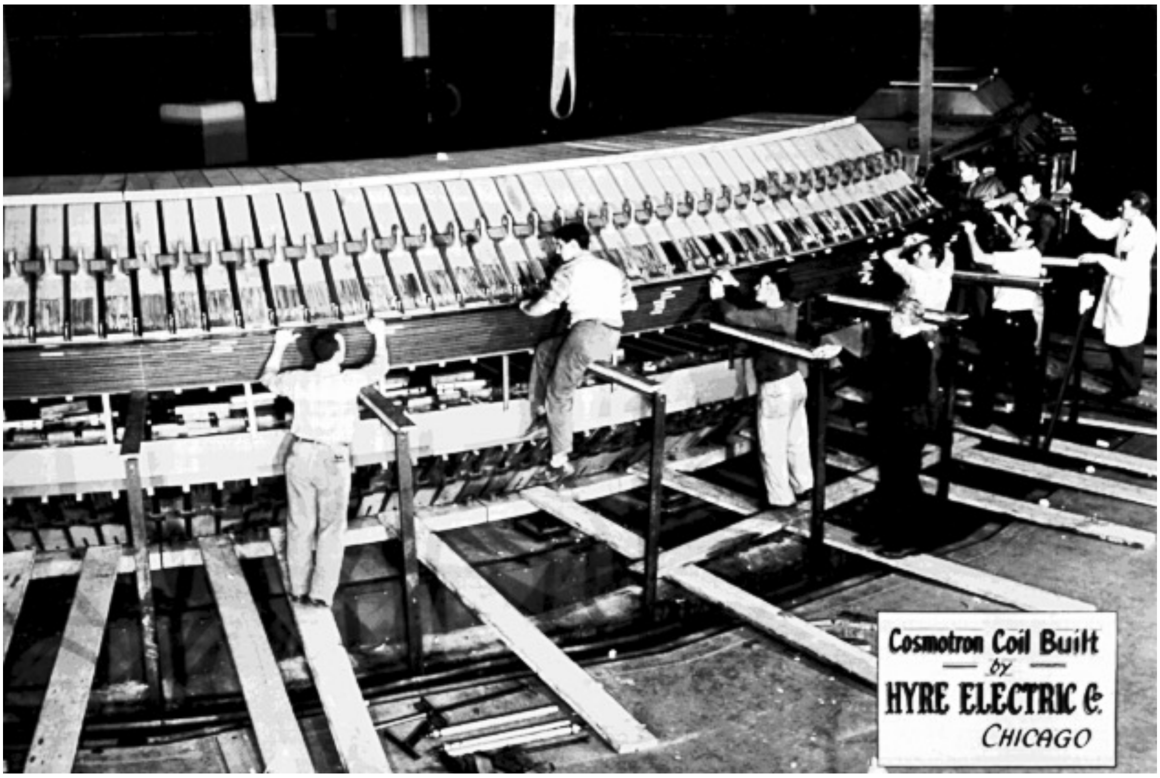
Need to change either field or frequency ("synchro-cyclotrons") once particle becomes relativistic. With clever solutions several hundred MeVs attained. Cyclotrons still very popular today.

Veksler 1944 / McMillan 1945: vary both frequency & magnetic field + fix particle trajectory to circle while accelerating.

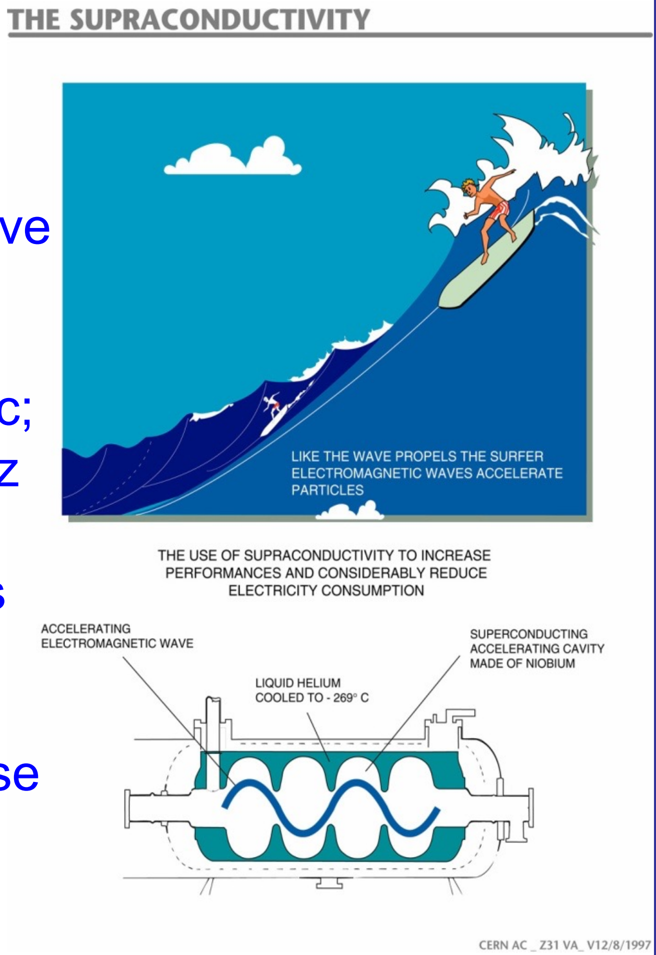
Synchtrotron: frequency and magnetic field vs E

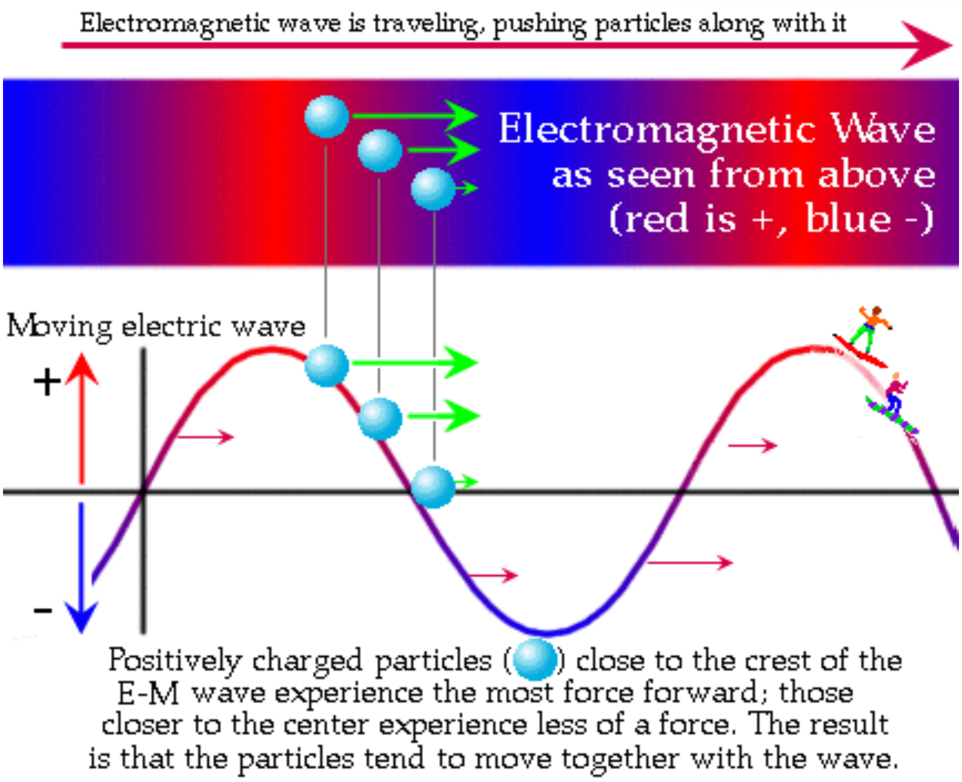


The 3 GeV Cosmotron at Brookhaven 1952



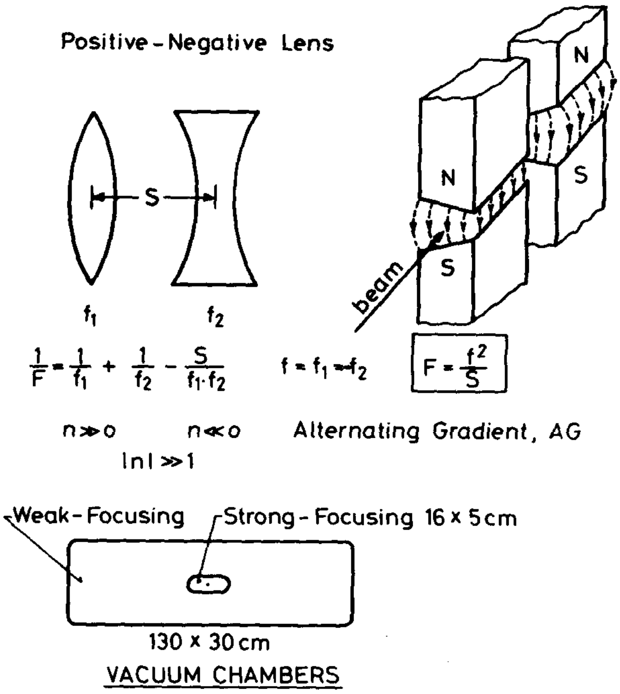
• electric fields accelerate charged particles
• most efficient electric field source: electromagnetic wave
• use Radio Frequencies to match velocity of particles: e.g. LHC $2\pi R = 27$ km; $v = c$; frequency $= c/\,2\pi R = 11$ kHz
• in RF cavity longitudinal component of E field moves in phase with beam
• particles continuously accelerated as long as phase relationship maintained



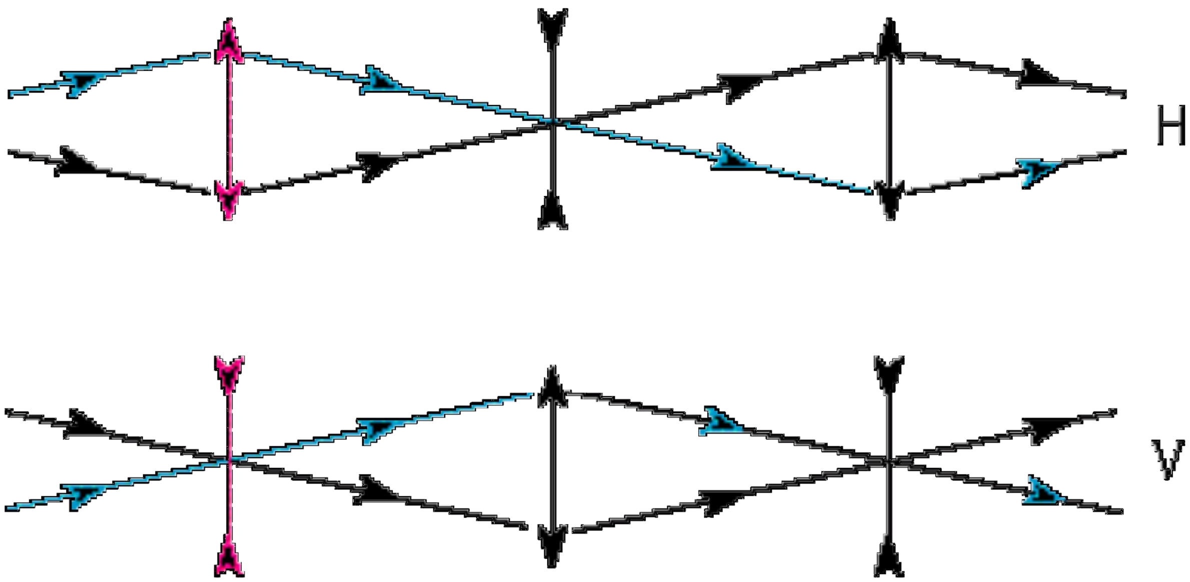


Principle of phase stability (particles lagging behind accelerated more than average & vice versa) - Veksler & McMillan 1945

1950's strong focusing ("alternating-gradient"): particles focused by alternating convex/concave lenses through the centres of (de)focusing lenses. Focusing improved significantly.



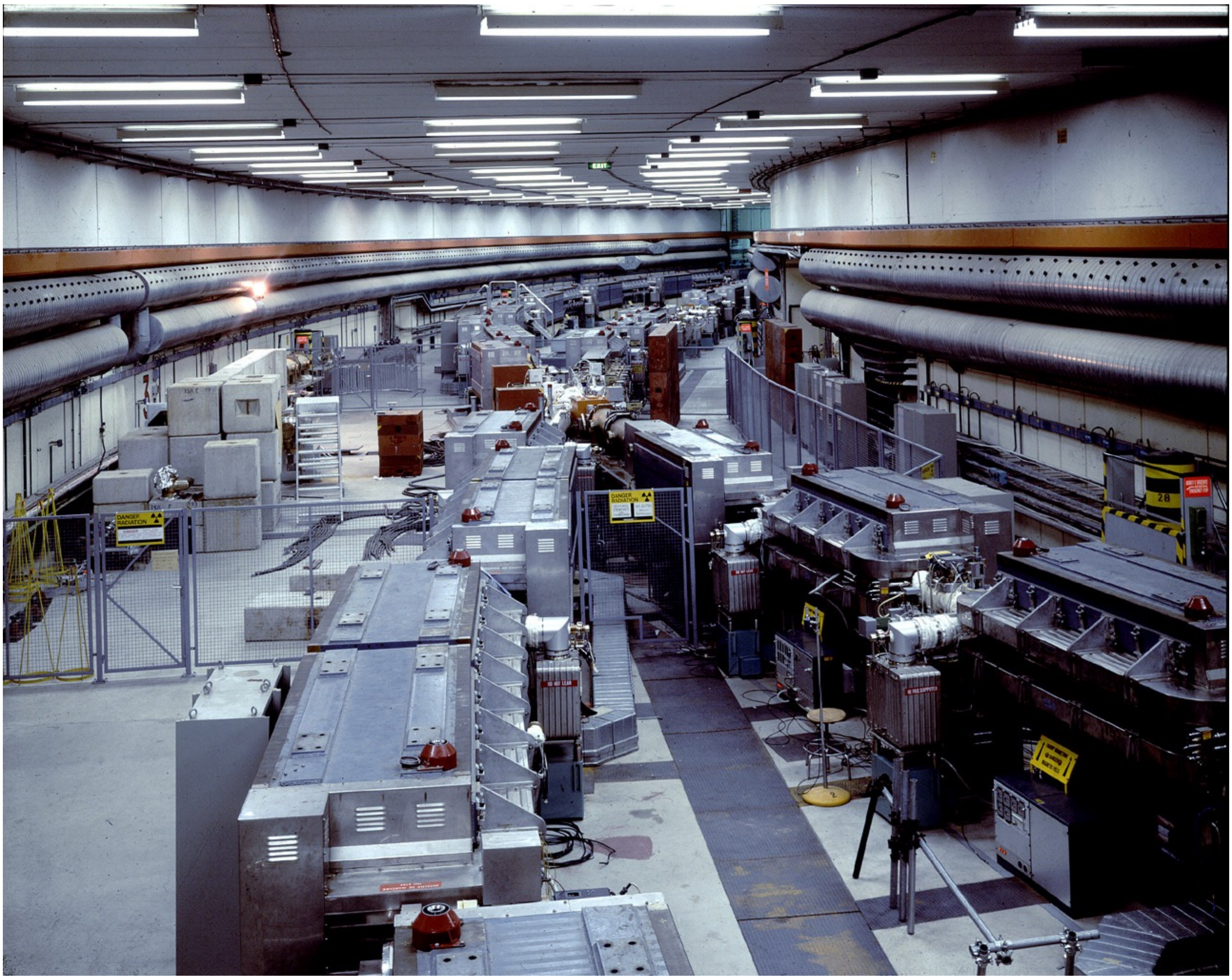
Strong focusing at the Cosmotron – Courant, Livingston & Snyder 1958



Colliders

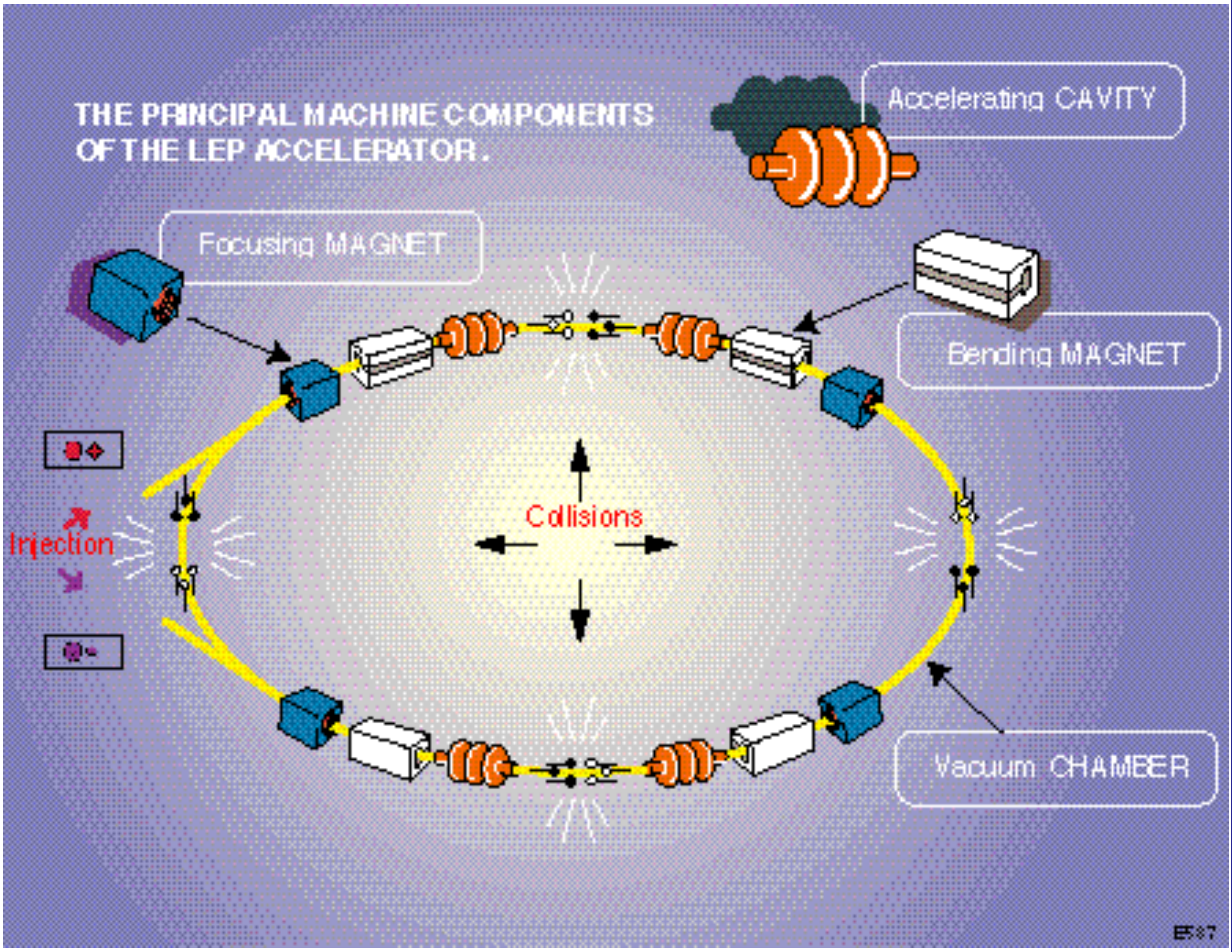
very focused particle beams → colliders

Intersecting Storage Ring (ISR) @ CERN (1971-84)



two ring collider providing either proton-proton – like LHC – or proton-antiproton collisions

principal components of a particle accelerator



- accelerating cavities
- bending magnets
- focusing magnets
- vacuum chamber

Super Proton Syncrotron (SPS) @ CERN (1976-91)

proton-antiproton collider upgrade 1981: protons & antiprotons circulating opposite ways in same tube

stochastic cooling (for sufficient antiproton luminosity)

discovery of W & Z – 1983

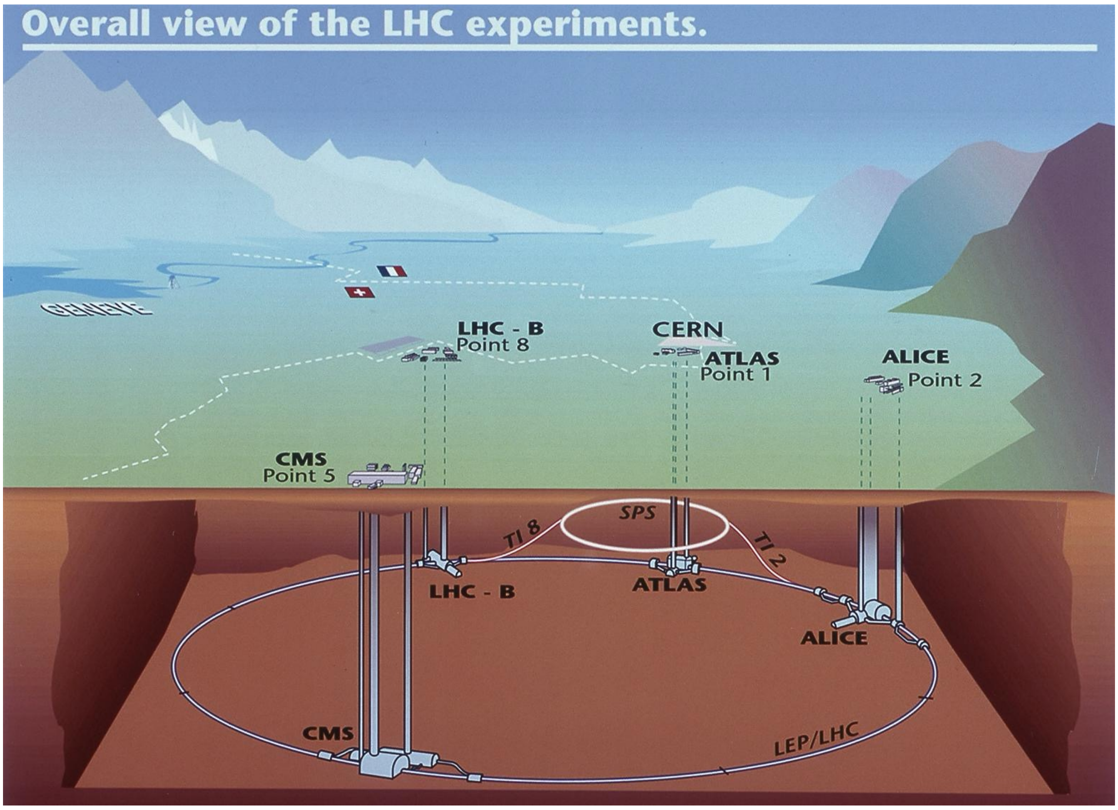
Tevatron @ Fermilab (1983-2011): 1.8-1.96 TeV proton-antiproton collider similar to SP$\overline{\mathrm{P}}$S.

discovery of top quark - 1995

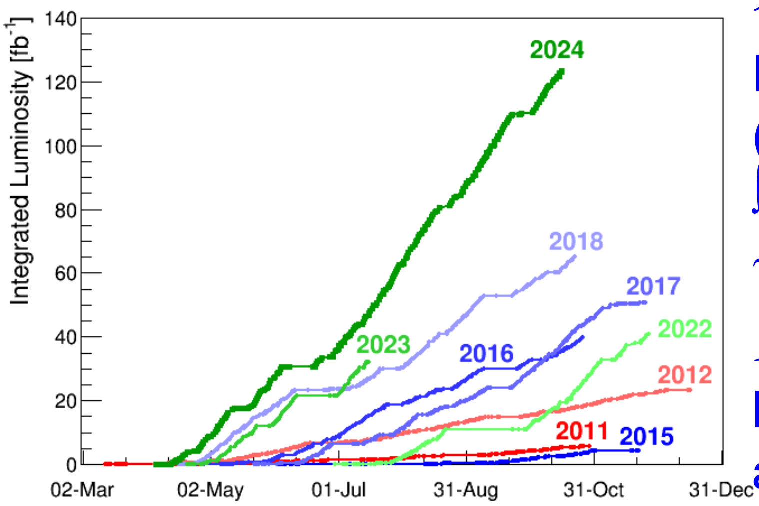
Z factory (e^+e^- collider at $\sqrt{s} = m_Z$) → LEP (1989-2000) – 27 km circumference (same tunnel as LHC)

electron (positron) against proton →
HERA @ DESY, Hamburg (1992-2007)

Large Hadron Collider



Succesfully started Nov 2009, proton-proton collisions at $\sqrt{s}$ = 7-8 TeV (2010–12, Run1),13 TeV (2015–18, Run2) & 13.6 TeV (2022–26, Run3). 2030–: 14 TeV expected, Run4



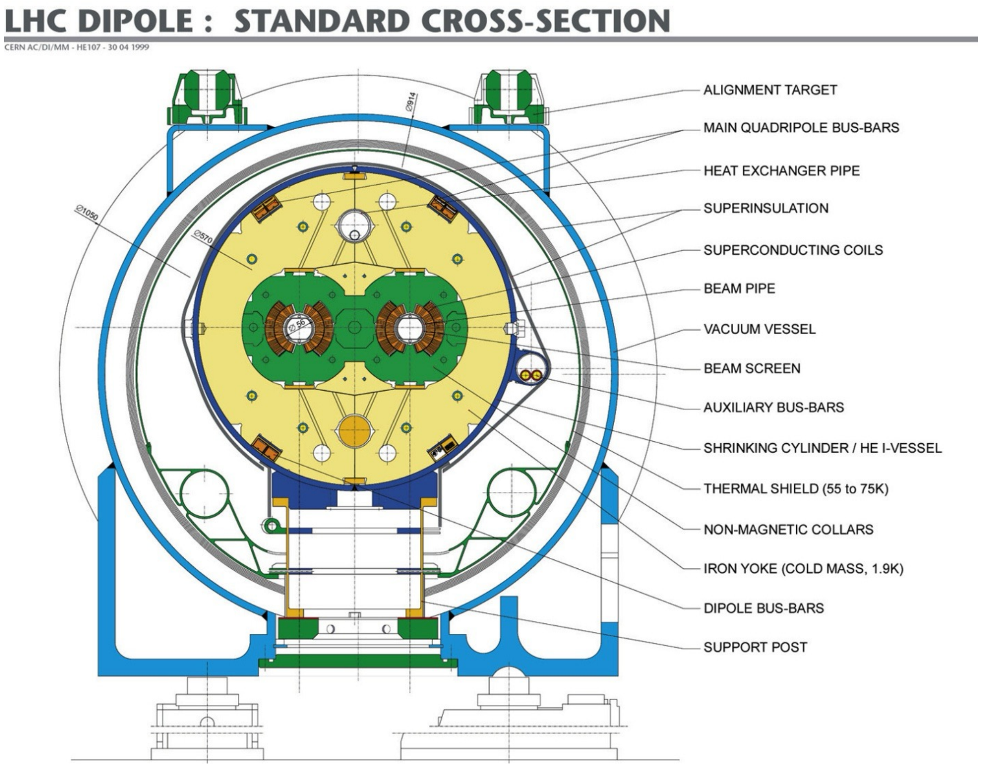
$\sqrt{s}$ = 13.6 (13, 8, 7) TeV; For "big" experiments (ATLAS & CMS) so far $\int \mathcal{L}\,dt$ ~180 (~140, ~23, ~ 6) fb^{-1} on disk

$\mathcal{L} > 2 \cdot 10^{34}$ cm^{-2}s^{-1} @ best; (exceeding original aim of ~10^{34} cm^{-2}s^{-1})

Highlight: ATLAS & CMS Higgs boson discovery 2012

Now: Run3 (2022–26) aim: $\int \mathcal{L}\,dt > 300$ fb^{-1} at $\sqrt{s}$ = 13.6 TeV

bending power limit for conventional magnets at 2 T
→ superconducting dipole magnets 7-8 T @ LHC



What next?

- High luminosity upgrade of LHC (5-7 $\cdot 10^{34}$ cm^{-2}s^{-1}) to discover new physics beyond standard model
- High-precision collider to determine exact nature of Higgs boson discovered at LHC. Synchrotron radiation limit for electron-positron colliders → high-intensity linear / large circular (FCC) collider
- Larger circular collider (FCC, ~90 km circumference) to discover new physics beyond standard model

alternative approach?
muon colliders / plasma wake field acceleration / …