Purdue University Department of Physics

Physics 56400
Introduction to Elementary Particle Physics I

Lecture 9

Fall 2019 Semester

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Particle Accelerators

- In general, we only need classical electrodynamics to discuss particle acceleration.
- Force on a charged particle:

$$\vec{F} = q(\vec{v} \times \vec{B} + \vec{E})$$

- Work done on a charged particle:

$$W_{ab} = \int_a^b \vec{F} \cdot \overrightarrow{dx} = q \int_a^b \vec{E} \cdot \overrightarrow{dx}$$

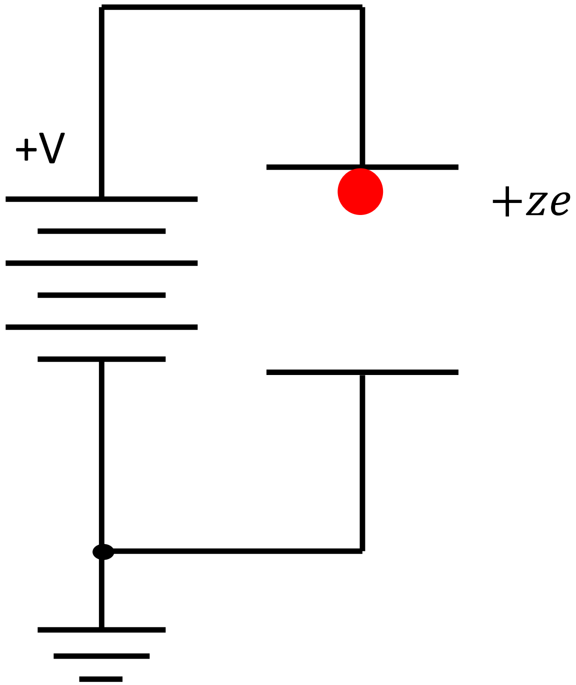
- Electric potential:

$$\vec{E} = -\nabla V$$

- Change in energy:

$$\Delta E = -W_{ab} = q(V_a - V_b)$$

Simplest Particle Accelerator



- The (positive) charge gains energy $\Delta E = V \cdot ze$
- That's one reason why we use electron-volts to measure energy.
- This is how electrons are accelerated in x-ray machines, cathode ray tubes, vacuum tubes,…

Particle Accelerators

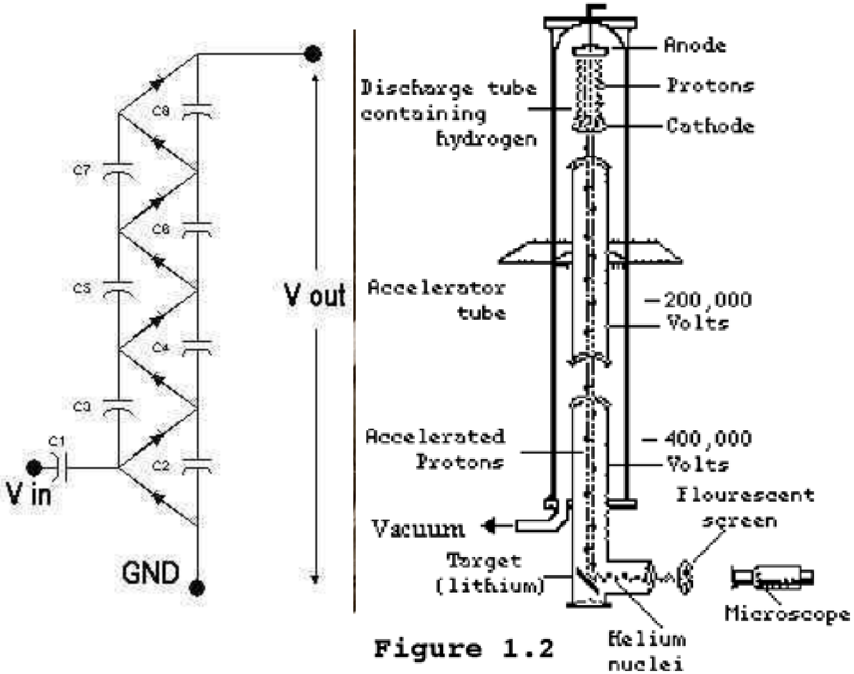


Figure 1.2

- In 1932, Cockroft and Walton accelerated protons to 600 keV, produced the reaction

$$p + Li \rightarrow He + He$$

and verified E=mc^2.

$$m_p = 938.272 \text{ MeV}$$
$$m_{^7Li} = 6535.366 \text{ MeV}$$
$$m_{He} = 3728.398 \text{ MeV}$$

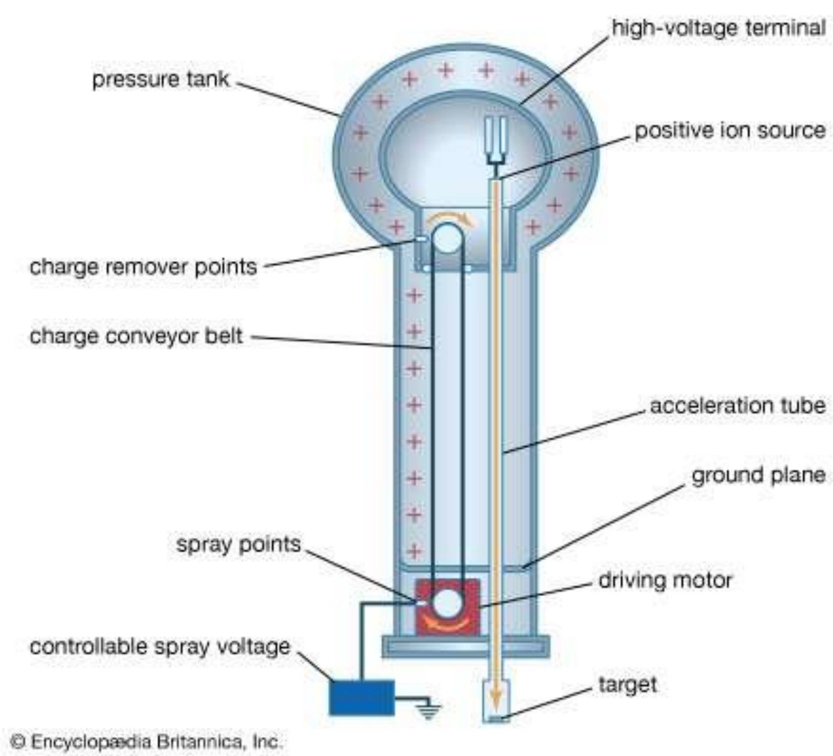
$$m_p + m_{^7Li} = 7473.638 \text{ MeV}$$
$$2\, m_{He} = 7456.796 \text{ MeV}$$

The process is not forbidden but we still have to bring the proton close to the Lithium nucleus.

$$W = \frac{Ze^2}{R}$$
$$R = r_0\, A^{1/3} \sim 2.4 \text{ fm}$$
$$e^2 = \frac{\hbar c}{137}$$
$$W = \frac{3 \cdot 197.327 \text{ MeV} \cdot \text{fm}}{137 \cdot 2.4 \text{ fm}} = 1.8 \text{ MeV}$$

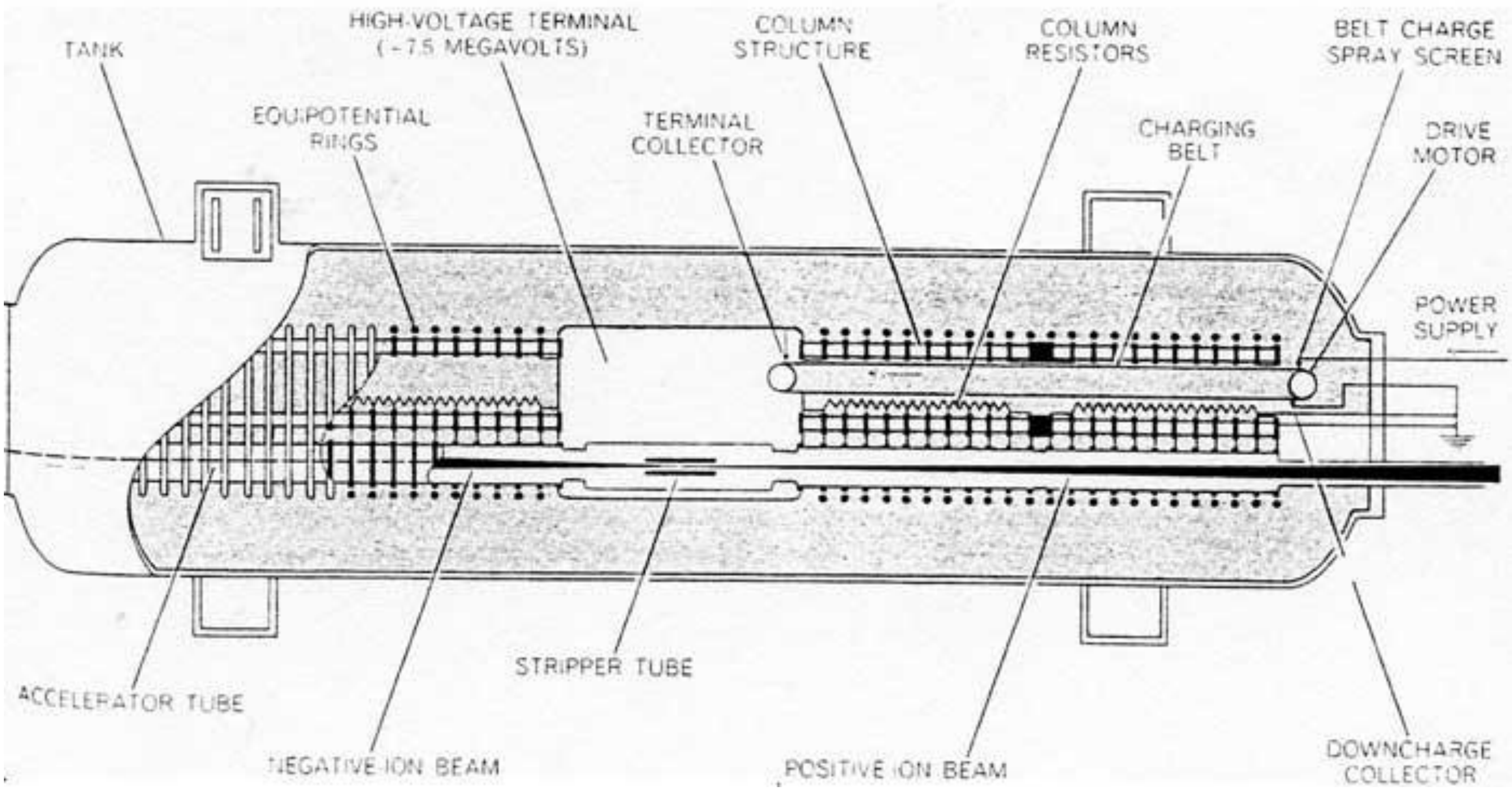
Van de Graaf Accelerators

- Because very little current is required, static electricity provides a way to get high voltages

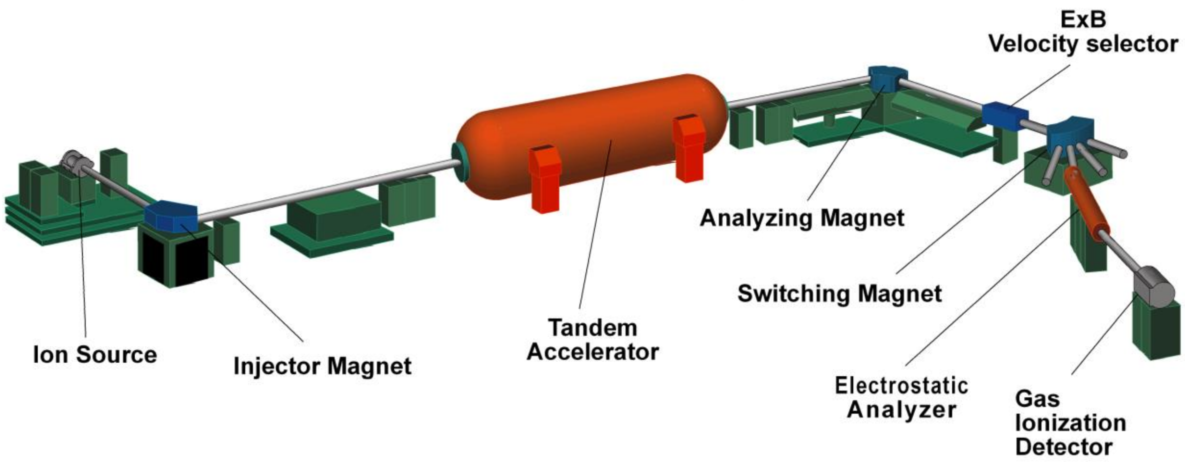


Tandem Van de Graaff Accelerators

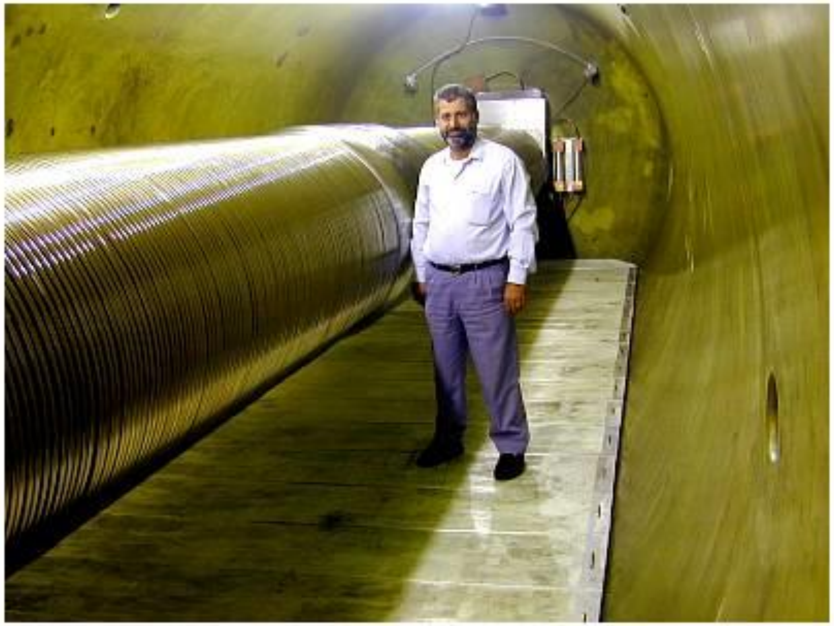
- Negative ions are accelerated and then stripped of their electrons.



Tandem Van de Graaff Acclerators

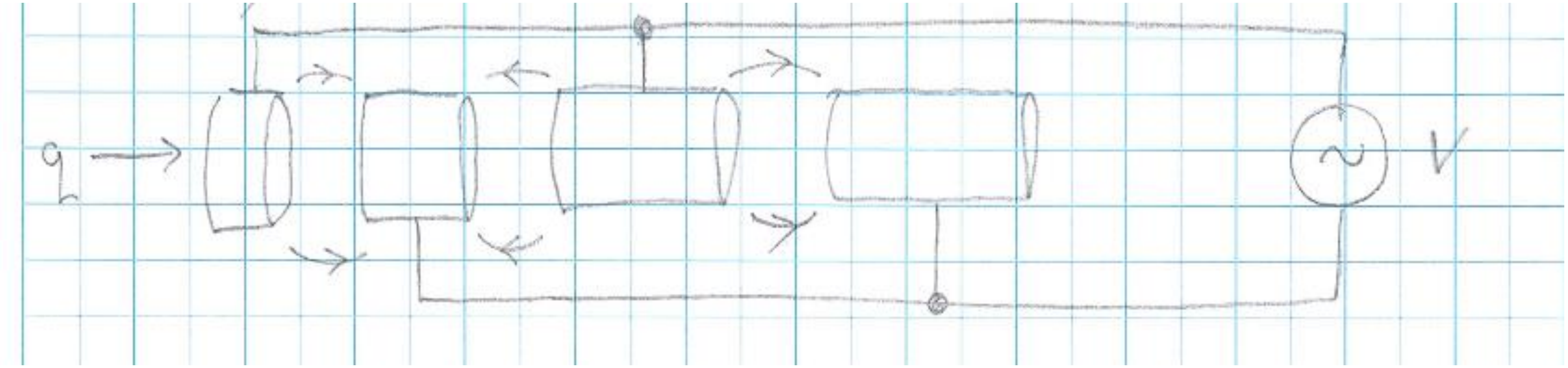


8 MV – primarily used for mass spectroscopy.



Linear Accelerators

- Recall that inside a conducting cavity, there is no electric field because the entire surface is at the same electric potential.
- There will be an electric field between conducting cavities at different potentials.



- If the voltage source changes phase when particles are inside the cavities, then they will be accelerated in the gaps between the cavities.

Linear Accelerators

- Non-relativistic:

$$\beta = \sqrt{\frac{2T}{mc^2}}$$

- RF frequency f, wavelength $\lambda = c/f$.
- Distance travelled in one period:

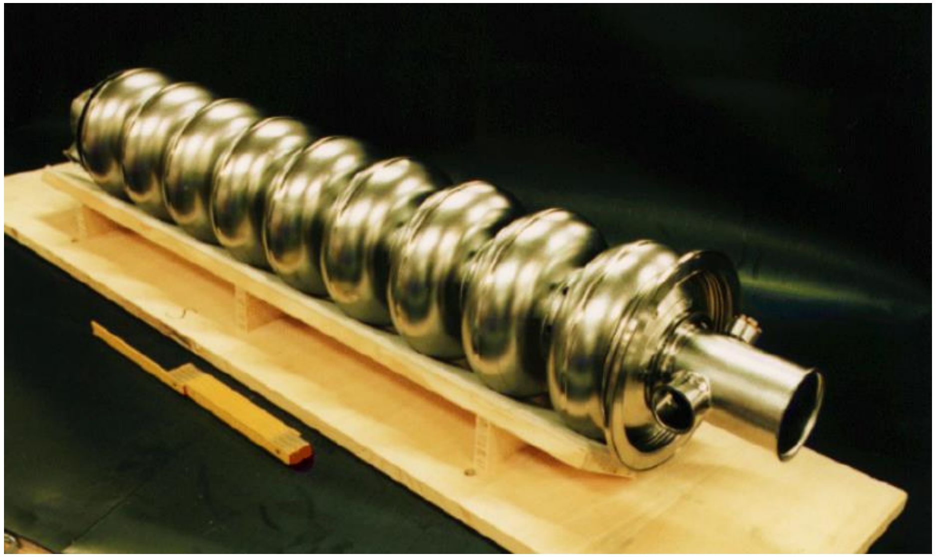
$$\Delta z = \beta c t = \frac{\beta c}{f} = \beta\lambda$$

- Particles gain energy $e \cdot V$ across each gap.
- As $\beta \to 1$, it is convenient to keep $\Delta z \sim 30\ \mathrm{cm}$

$f \sim 1\ \mathrm{GHz}$ (microwaves)

Linear Accelerators

- High power microwaves are produced by klystrons
- Microwave cavities act as coupled oscillators



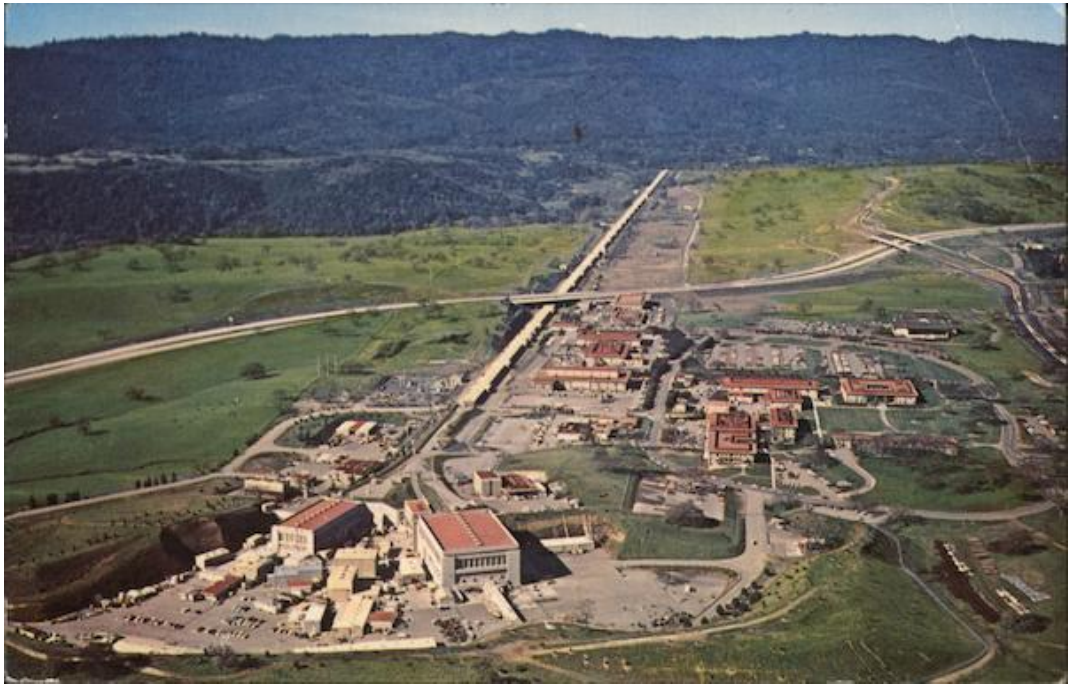
Field gradient: $20\ \mathrm{MV/m}$

Length required to achieve a total energy of 50 GeV:

$$L = 2.5\ \mathrm{km}$$

9-cell TESLA cavity Q-factor: $5\ \times 10^9$

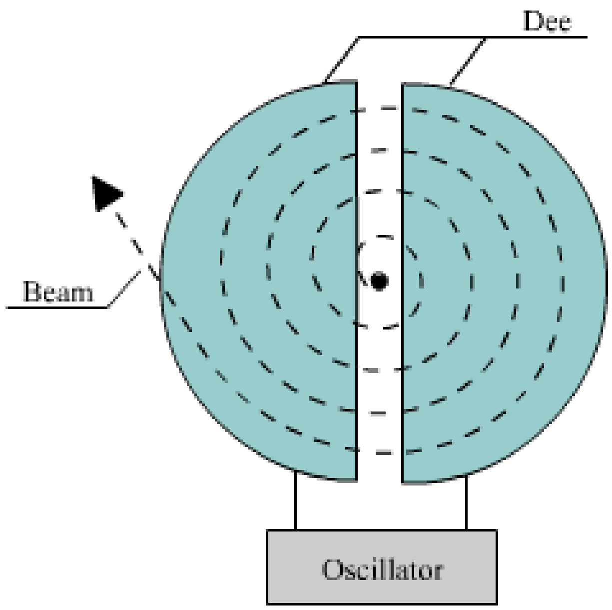
Stanford Linear Accelerator

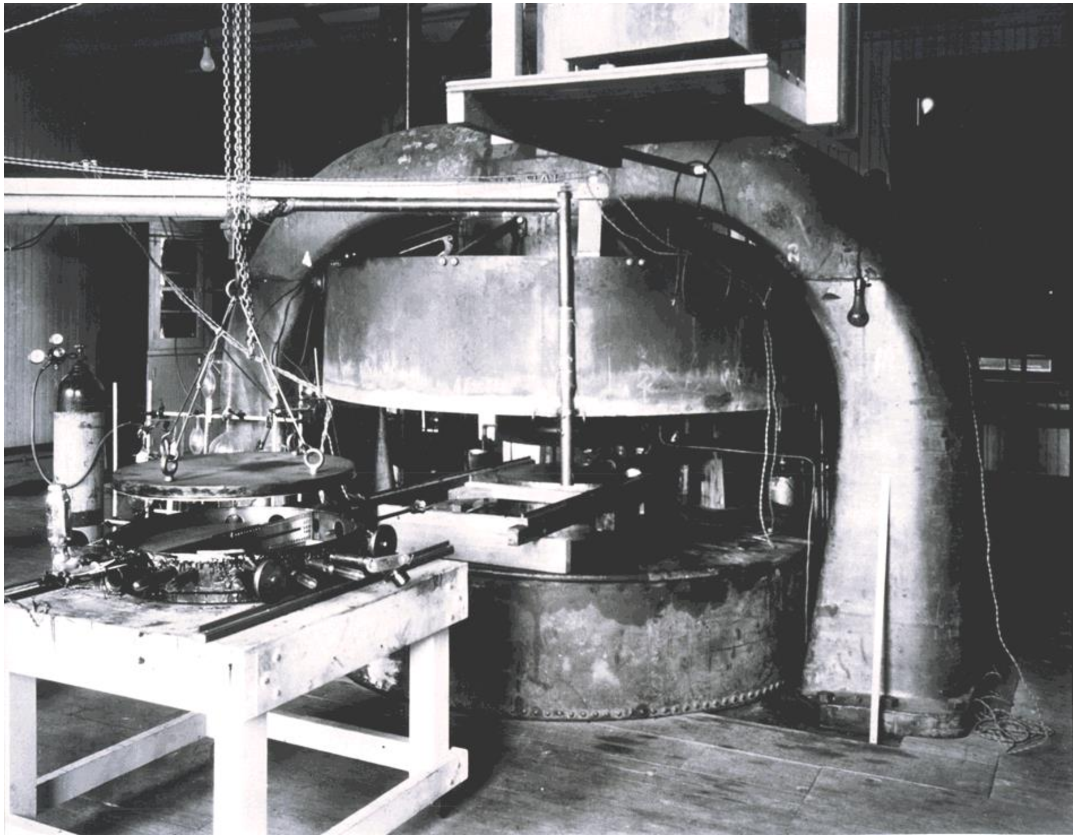


Energy (GeV)	Date
18.4	June 2, 1966
19.0	December 16, 1966
20.16	January 10, 1967
20.58	August 16, 1968
21.0	September 13, 1968
21.5	April 27, 1969
22.10	August 23, 1970
22.28	July 25, 1973
22.74	November 11, 1974
33.4	March 5, 1980
53.0	January, 1987

Circular Accelerators

From 1930-1939, Lawrence built bigger and bigger cyclotrons, accelerating protons to higher and higher energies: 80 keV → 100 MeV.





Cyclotrons

- Energy increases by ΔV each time a particle crosses the gap between the dees.

$$F = \frac{mv^2}{r} = qvB$$

$$v = \frac{qBr}{m}$$

- Period of orbit:

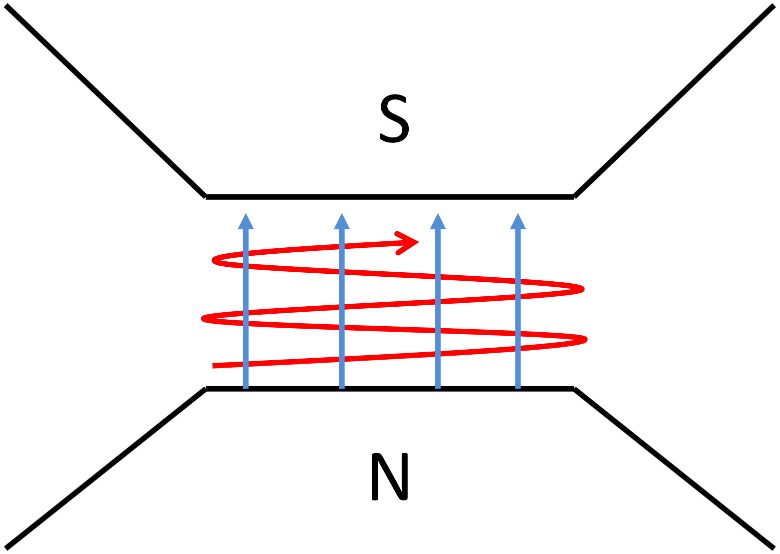
$$T = \frac{2\pi r}{v} = \frac{2\pi m}{qB} = const.$$

- Velocity increases linearly with radius of orbit.
- Kinetic energy:

$$E = \frac{1}{2}mv^2 = \frac{q^2B^2r^2}{2m}$$

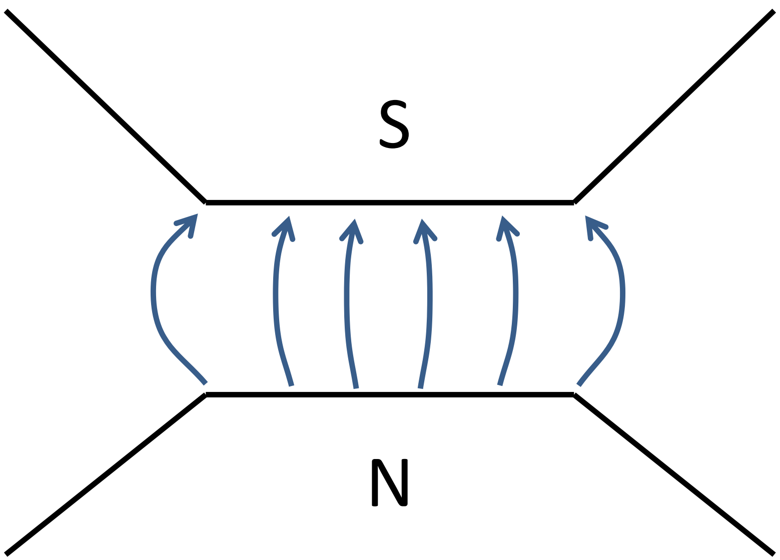
Cyclotrons

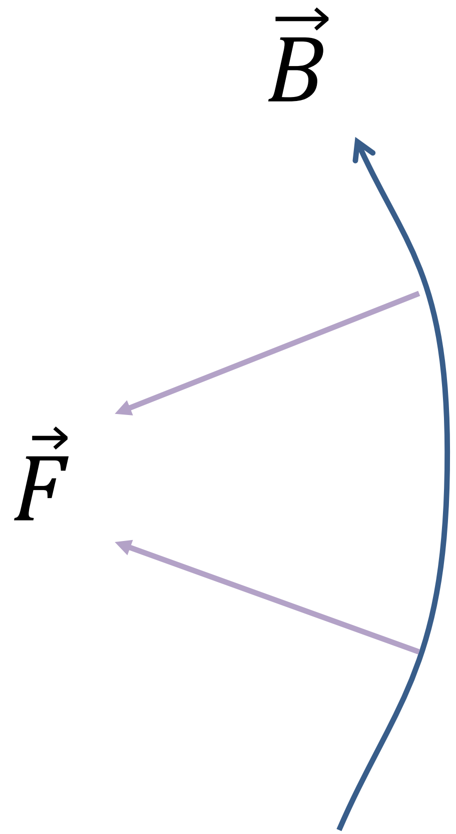
- If the magnetic field were perfectly uniform, then the particles would travel in helices and eventually hit the magnetic poles.
- The beam is unstable…



Cyclotrons

- It is desirable to have a slightly non-uniform magnetic field:

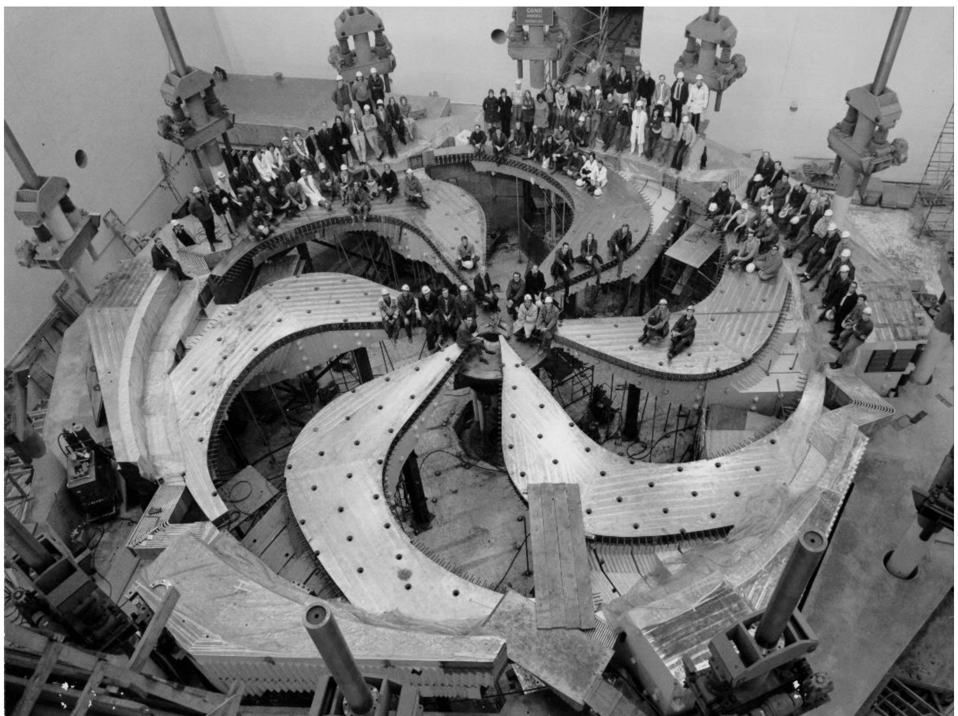




$$\frac{dB}{dz} \neq 0$$

Cyclotrons

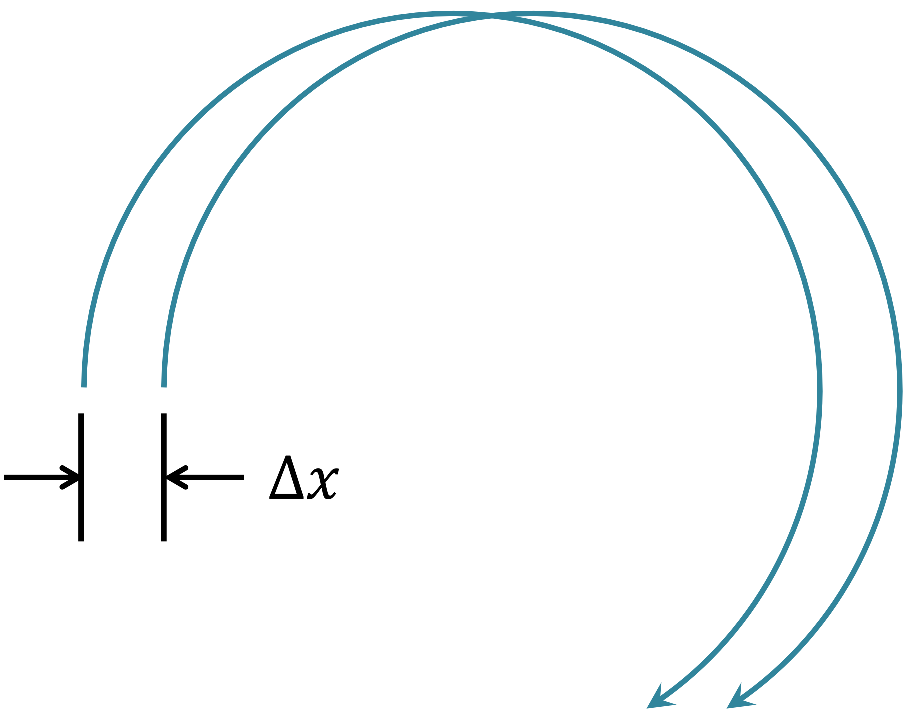
- Careful consideration goes into the design of the magnet
  - it also has to compensate for relativistic effects
  - at high energies the period is no longer constant

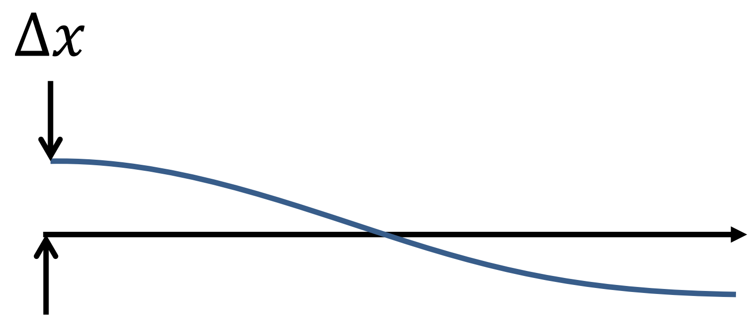


TRIUMF cyclotron magnet (1972): 500 MeV protons.

Weak Focusing

- A uniform magnetic field does not have a focusing effect on a displaced beam:



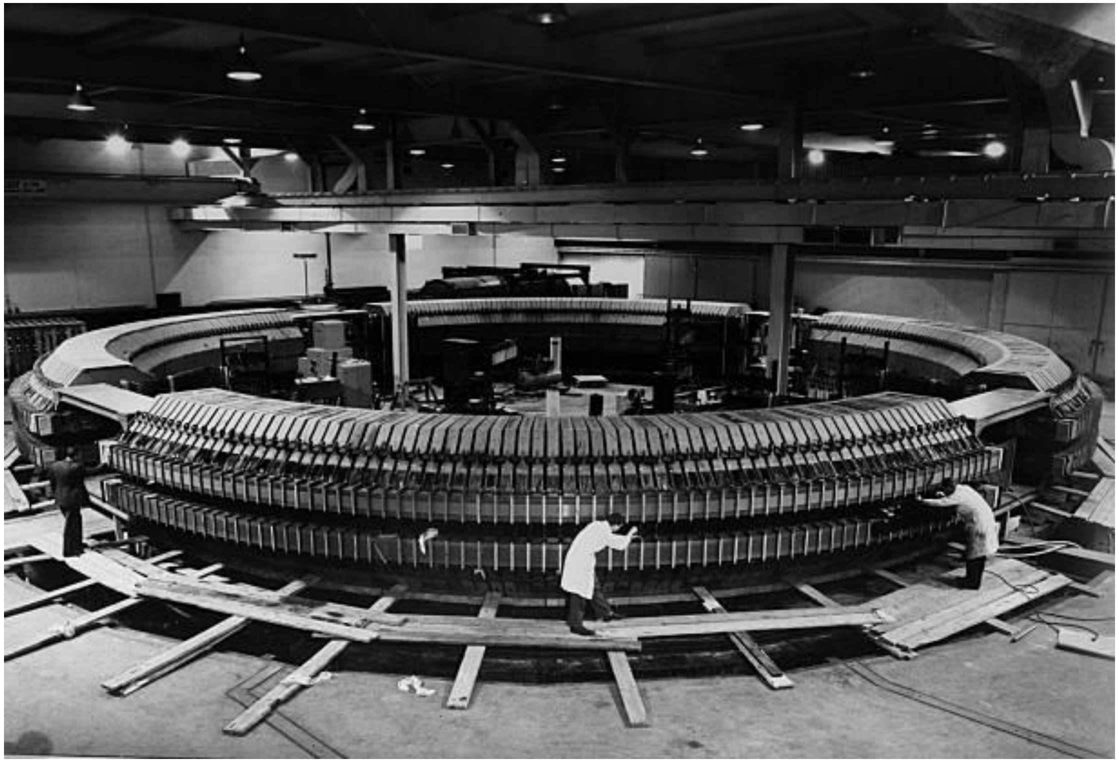


The size of the required aperture scales linearly with the beam energy.

Weak Focusing

- Brookhaven Cosmotron (1953-1968)

$$B = 1.5\ \mathrm{T} \qquad \mathrm{E} = 3\ \mathrm{GeV}$$



Beam aperture:

6 in x 26 in

Weak Focusing

- Berkeley Bevatron (1954-1993)

$$E = 6\ \mathrm{GeV}$$

Beam aperture:

12 in x 48 in

Such large beam apertures are not cost effective for higher energies.

Weak Focusing

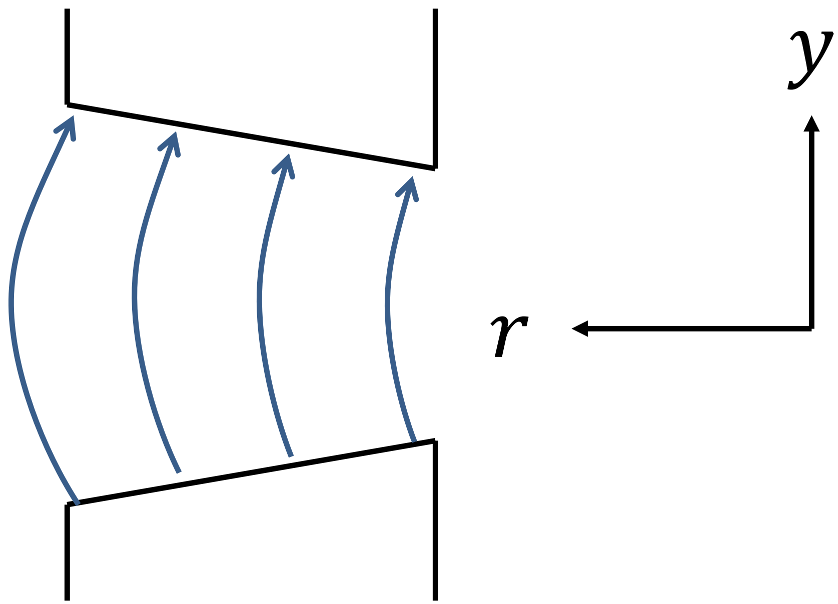
- Argonne Zero Gradient Synchrotron (1964-1979)

$$E = 12.5\ \mathrm{GeV}$$

Betatron Oscillations

- To first order, magnets are constructed so that
$$B(r) = B_y = const.$$
- A non-uniform field can be created using tapered pole pieces:

$$B_y = B_0 \left(\frac{r}{R}\right)^{-n}$$



- Change of variables:

$$\xi = y/R \quad \rho = r/R - 1$$

$$B_y = B_0(1+\rho)^{-n}$$
$$\approx B_0(1 - n\rho)$$

Betratron Oscillations

- Maxwell's equations in free space for static fields:

$$\nabla \times \vec{B} = 0$$

$$\left(\nabla \times \vec{B}\right)_z = \frac{\partial B_r}{\partial y} - \frac{\partial B_y}{\partial r} = 0$$

$$\left.\frac{\partial B_y}{\partial r}\right|_R = -\frac{B_0 n}{R} = \frac{\partial B_r}{\partial y}$$

- The radial component of the field is:

$$B_r = -\frac{B_0 n}{R} \cdot y$$

Betatron Oscillations

- Lorentz force: $\vec{F} = q\vec{v}_z \times \vec{B}$

$$F_r = q\, v_z B_r$$

$$F_y = -q\, v_z\, \frac{B_0 n}{R} \cdot y = m\ddot{y}$$

- This describes simple harmonic motion along the vertical axis

$$\ddot{y} + \omega_0^2 y = 0$$

$$\omega_0^2 = q\,\frac{v_z B_0 n}{R}$$

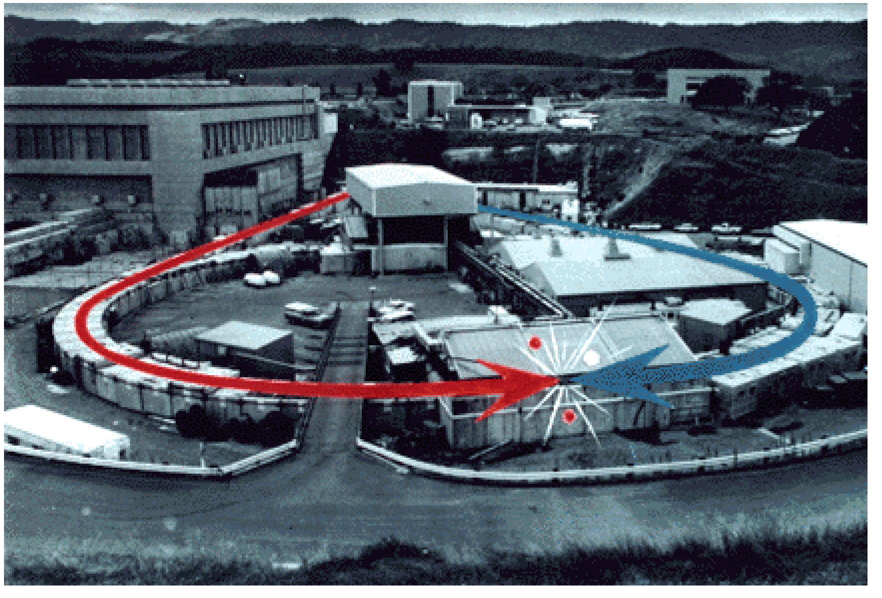
Strong Focusing

- Most accelerators use alternating sets of magnets with opposite tapers
  a) With $n \gg 0$: focuses in y and defocuses in r
  b) With $n \ll 0$: focuses in r and defocuses in y
- The combination focuses in both r and y
- Examples:
  - CERN PS (1959): 28 GeV, beam aperture 3”x6”
  - Brookhaven AGS (1960): 33 GeV, 3”x7”

Circular Electron Colliders

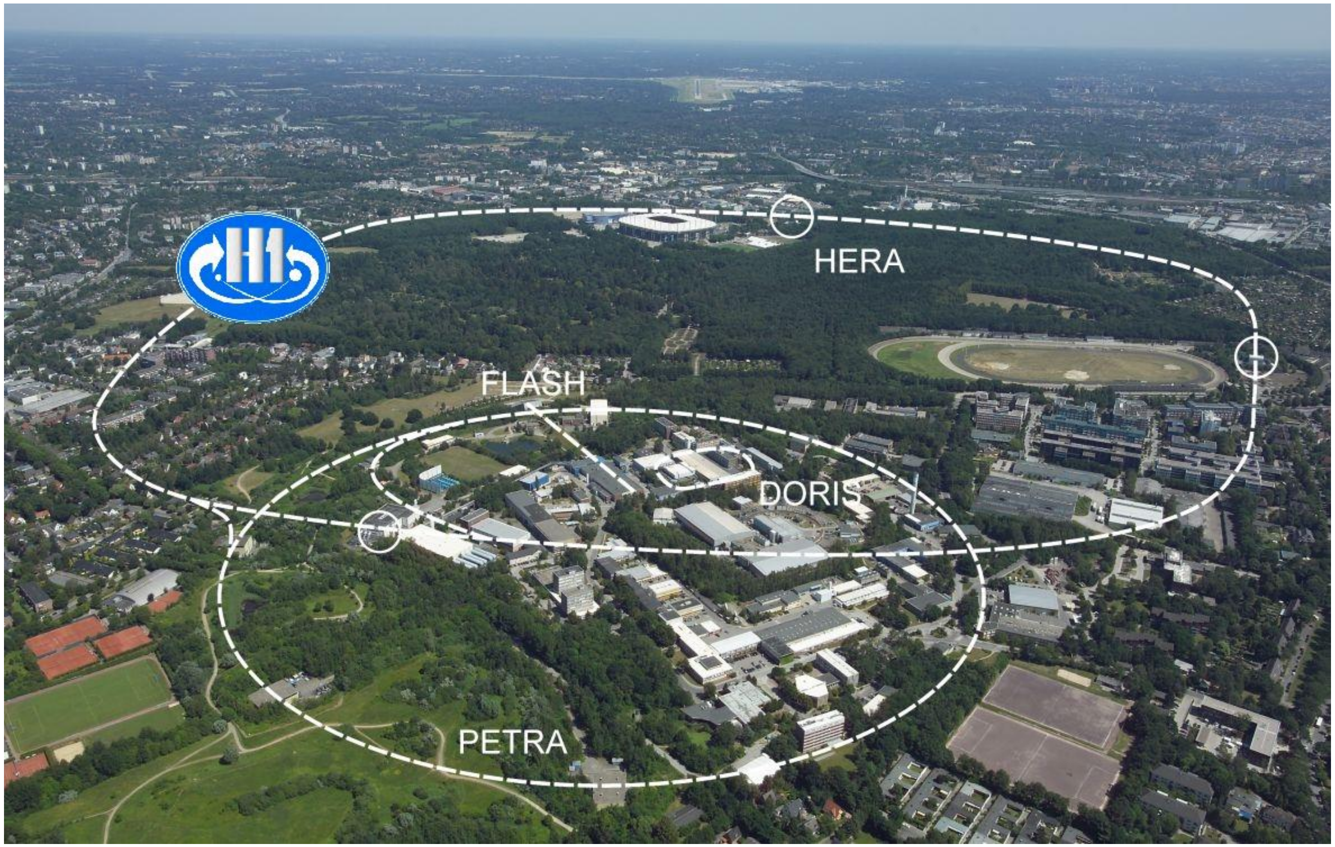
Stanford Linear Accelerator Center

SPEAR (1972): e^+e^- collisions at up to $E_{cm} = 8\ \mathrm{GeV}$



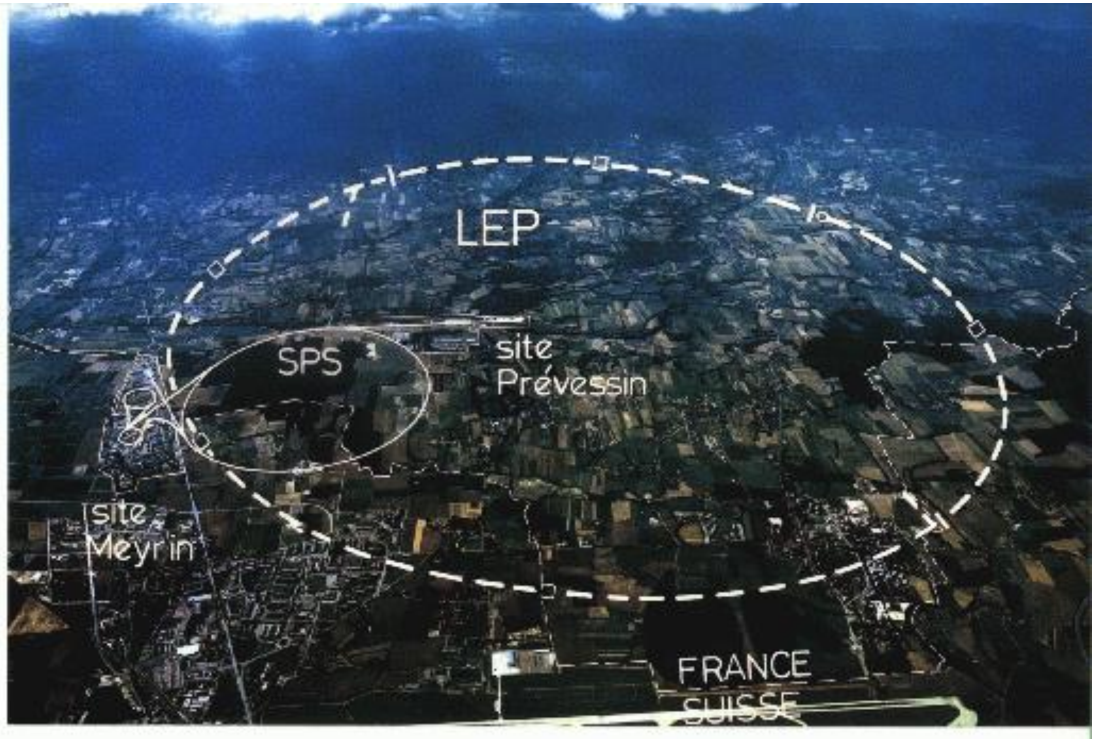
– Discovery of the charm quark and tau leptons.

Circular Electron Accelerators



DORIS (1974-1993): e^+e^- collisions at $E_{cm} = 10$ GeV
PETRA (1978-1990): e^+e^- collisions at $E_{cm} = 38$ GeV
HERA (1990-2007): $e - p$ collisions, $E_{e^-} = 27.5$ GeV, $E_p = 920$ GeV

Circular Electron Accelerators



Year	E_{cm} (GeV)
1989	91
1995	130-140
2000	209

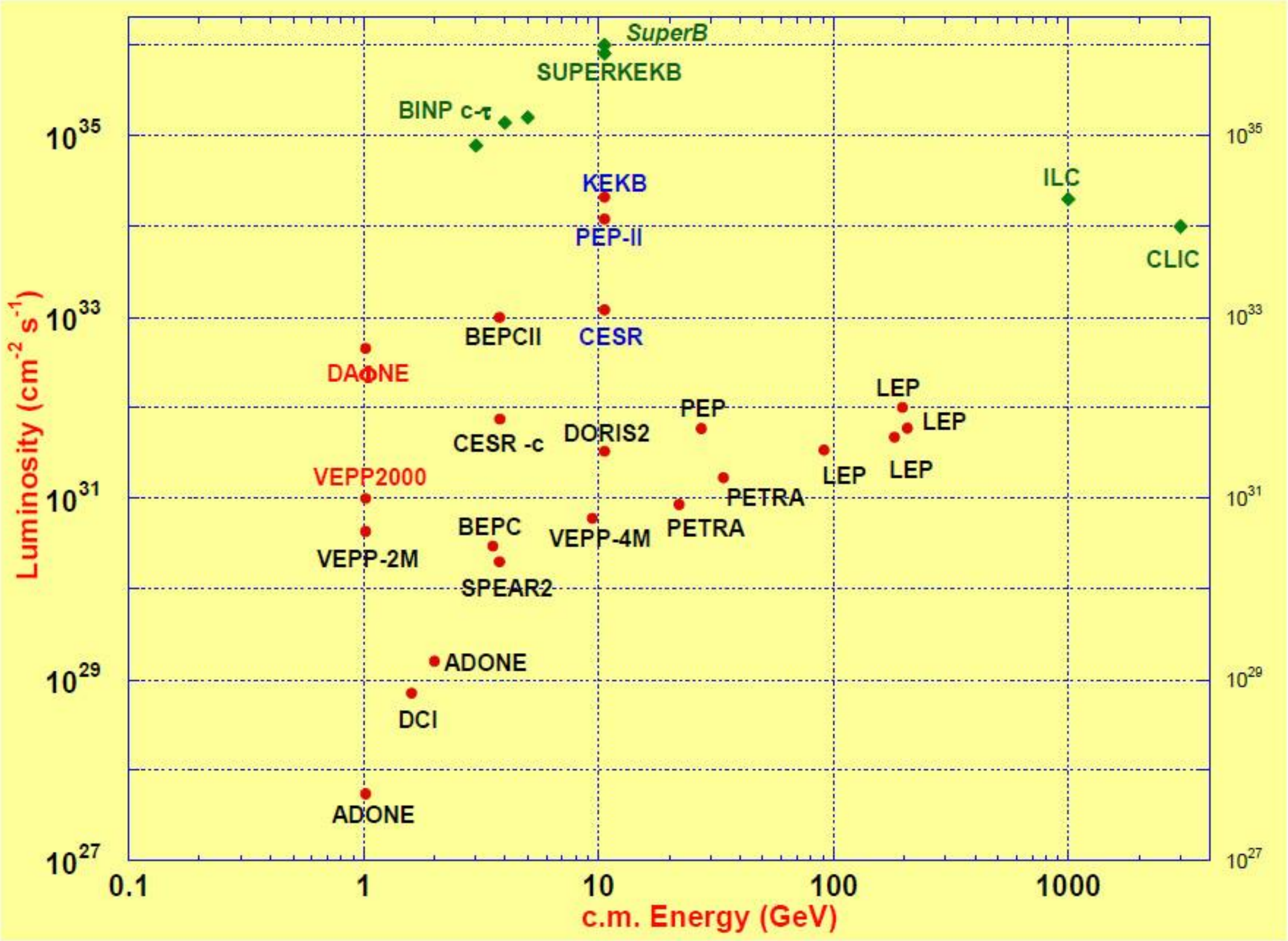
The original LEP tunnel now contains the Large Hadron Collider.

High Intensity B-factories

- High intensity e^+e^- colliders with $E_{cm} \sim 10\ \mathrm{GeV}$ are very useful for producing lots of B mesons
  - DORIS collider/ARGUS detector
  - PEP-II collider/BaBar detector (1999-2008)
  - CESR collider/CLEO detector (1979-2002)
  - KEK-B collider/Belle detector (1999-)

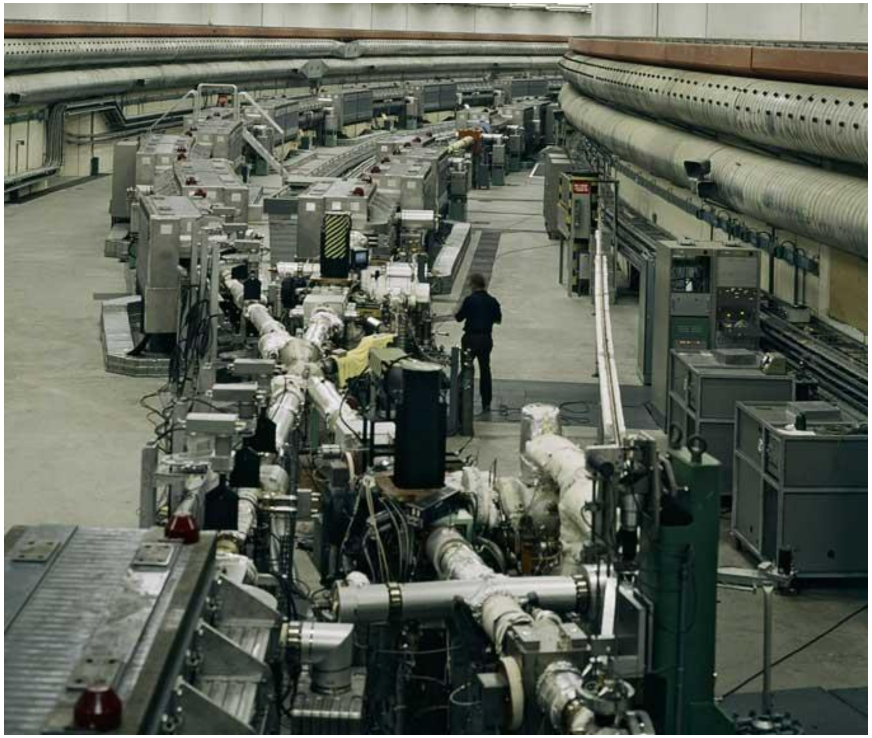
- Also important sources of charm quarks and tau leptons.

Electron-Positron Colliders



Circular Proton Colliders

- CERN PS (Proton-Synchrotron): 25 GeV
  - Now used as a booster
- CERN ISR: pp collisions at $E_{cm} = 62\ GeV$



Technical challenge: beam cooling

- Large, diffuse beams have low luminosity
- Beams need to be physically small and have small amplitude betatron oscillations

- Stochastic cooling:

Simon van der Meer (Nobel Prize 1984)

Circular Proton Accelerators

- CERN SPS (Super Proton Synchrotron): 450 GeV

Circumference: 7 km

Constructed using conventional magnets

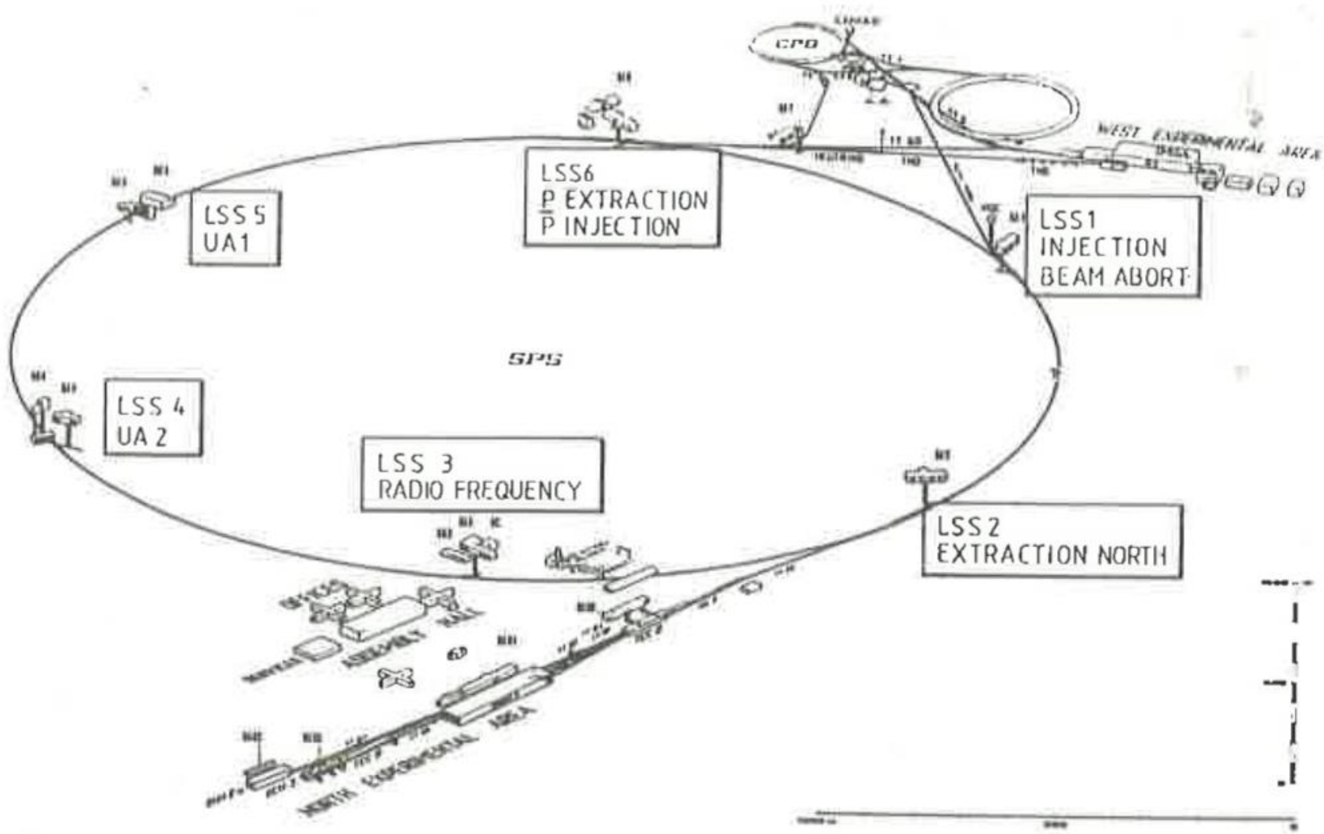
Circular Proton Accelerators

- Fermilab Main Ring: 200-400 GeV protons
- Fermilab Energy Doubler: 500 GeV protons using superconducting magnets

  4.5 Tesla field, discovery of W and Z

Proton-Antiproton Collisions

- SPS converted into a $p\bar{p}$ collider (1981-1991)
- Achieved $E_{cm} = 630\ \text{GeV}$



Fermilab Tevatron

- $p\bar{p}$ collisions at 1.8 TeV (1986)
  - CDF and D0 experiments discover top quark (1995)
- Run II: $p\bar{p}$ collisions at 1.96 TeV (2001-2011)

Large Hadron Collider

- Proton-proton collisions at $E_{cm} = 14\ \mathrm{TeV}$
  - 8.3 Tesla superconducting magnets