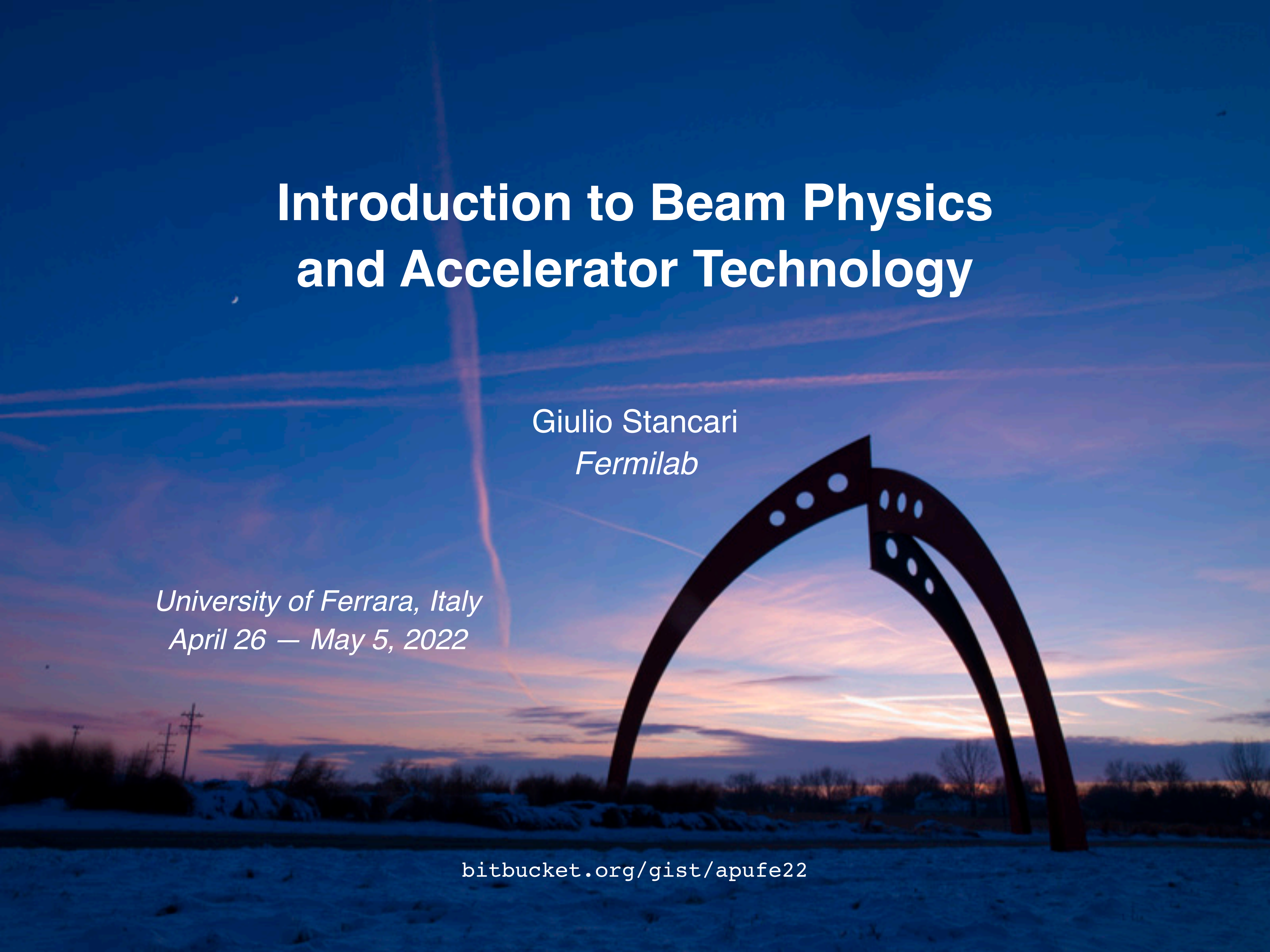

Introduction to Beam Physics and Accelerator Technology

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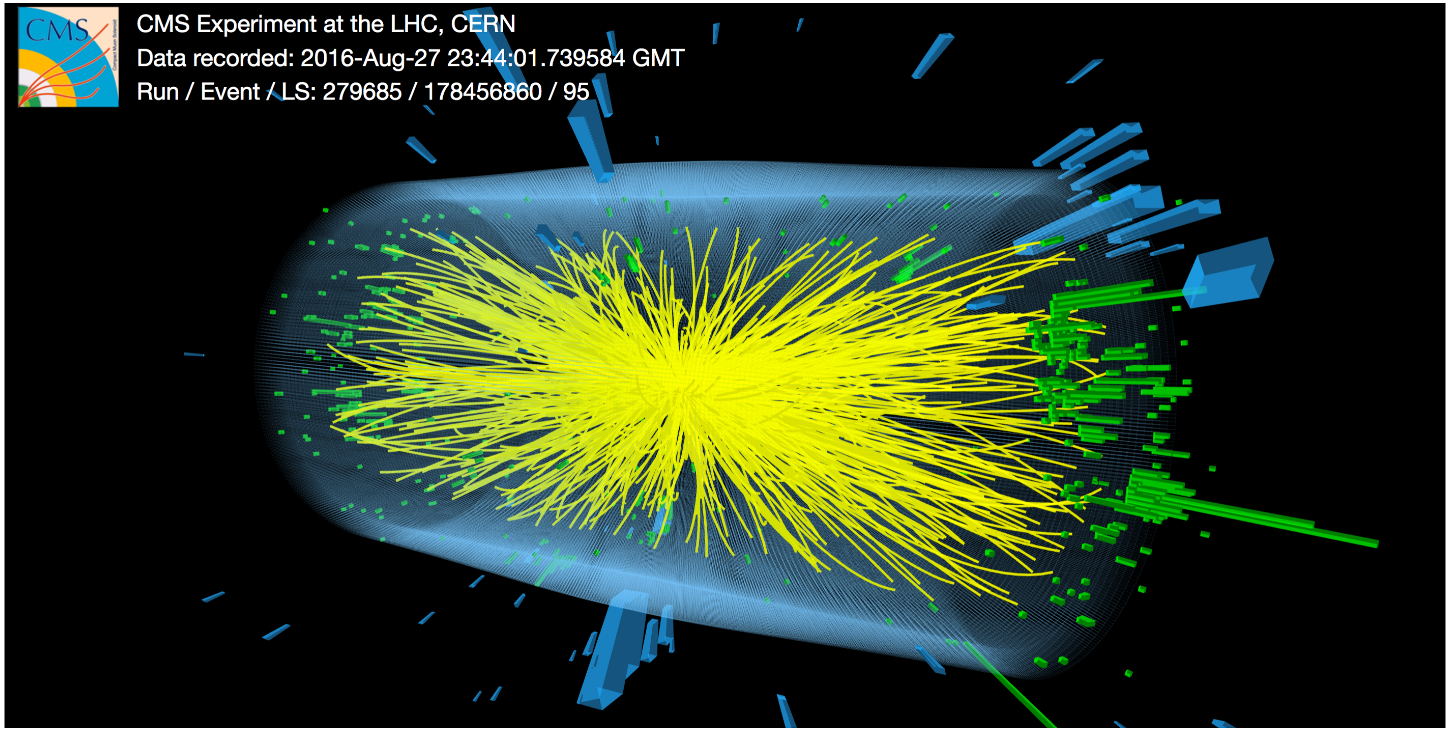
bitbucket.org/gist/apufe22

Evolution of accelerator physics

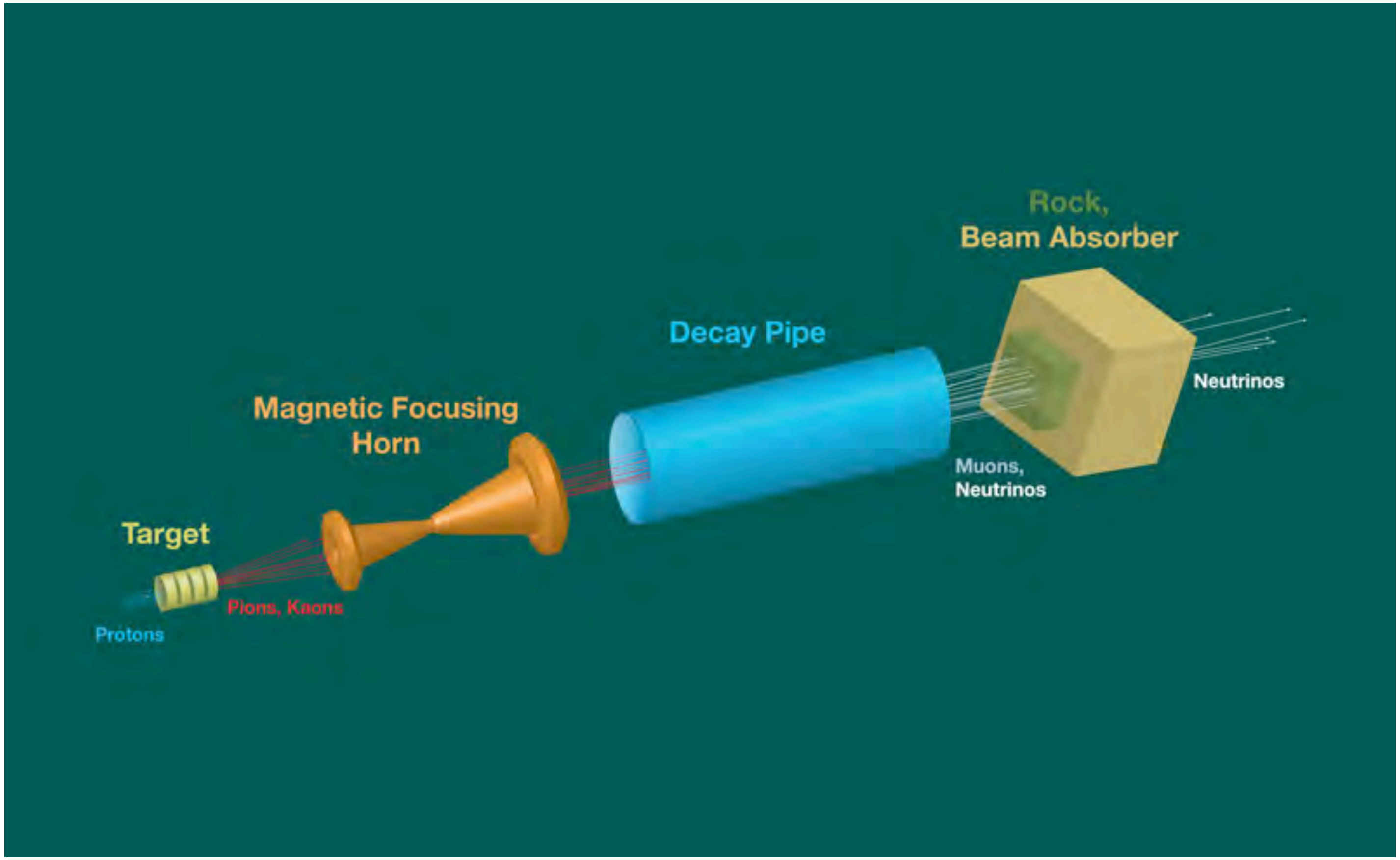
Why accelerate? And how?

1. The surprising phenomenon of **conversion of kinetic energy into mass** ($E = mc^2$) allows us to **discover and study different forms of matter**



Why accelerate? And how?

2. Primary beams of high-energy particles are used to create **intense and focused secondary beams** that do not occur naturally: pions, muons, antiprotons, positrons, photons, neutrinos, etc.



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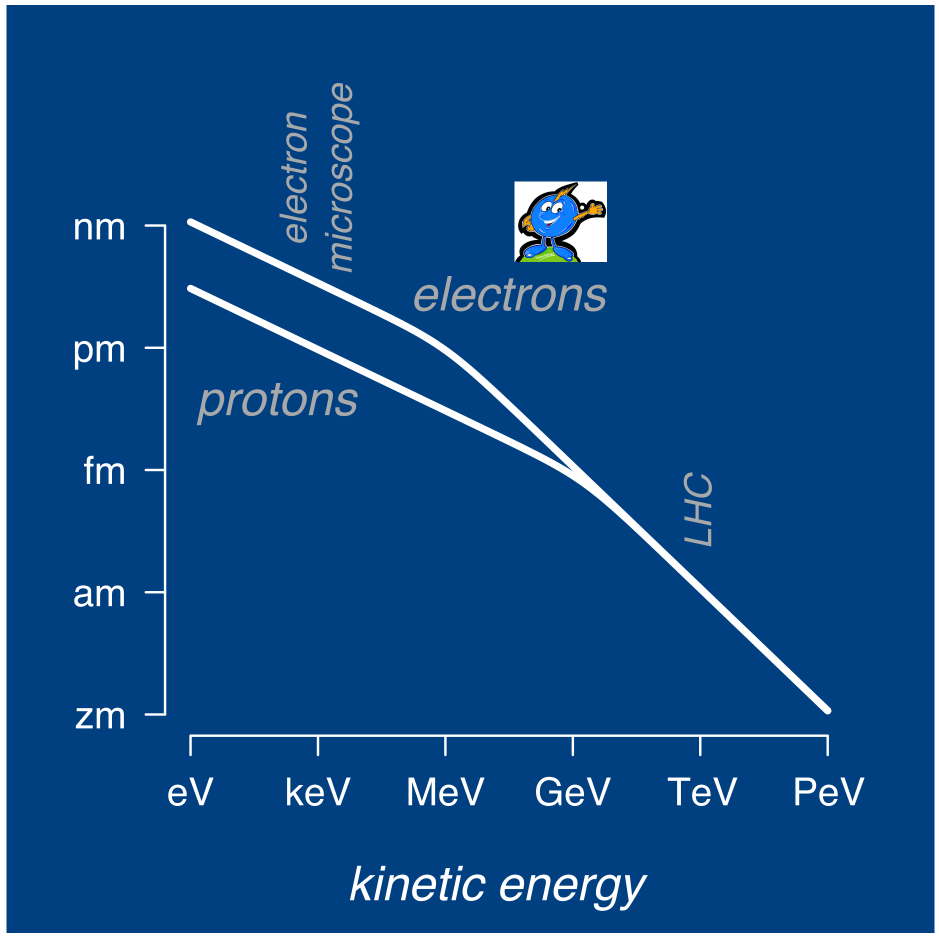
Why accelerate? And how?

3. Because of their quantum properties, elementary particles are used as **probes for the microscopic world**

De Broglie wavelength

$$\lambda = \frac{h}{p} = \frac{2\pi\hbar c}{pc}$$



proteins

atoms

nuclei

quarks and gluons

?

mesons, barions

Higgs

?

Examples

What is the De Broglie wavelength of an α particle (rest energy 3.73 GeV) from radon decay (kinetic energy 10 MeV)?

To probe the structure of the proton, one needs electrons with a De Broglie wavelength of about 0.1 fm. What is the corresponding kinetic energy?

Use $\hbar c = 197\ \mathrm{MeV} \cdot \mathrm{fm}$

De Broglie wavelength of 10-MeV alpha particle

De Broglie wavelength of 10-MeV α particle
(rest energy $m_\alpha c^2 = 3.73$ GeV)

$$\lambda = \frac{h}{p} \underset{\text{(non relativistic)}}{=} \frac{h}{\sqrt{2 m_\alpha T}} = \frac{2\pi \hbar c}{\sqrt{2 (m_\alpha c^2) T}}$$

$$= \frac{2\pi \, (197 \text{ MeV} \cdot \text{fm})}{\sqrt{2 \, (3.73 \text{ GeV})(10 \text{ MeV})}} = 4.5 \text{ fm}$$

Kinetic energy of 0.1-fm-wavelength electron

Kinetic energy of electron with DeBroglie wavelength $\lambda = 0.1$ fm

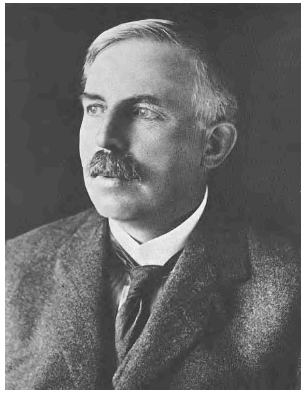
$$T = E - m_e c^2 = \sqrt{(pc)^2 + (m_e c^2)^2} - m_e c^2 =$$

$$= \left[\left(\frac{2\pi \hbar c}{\lambda} \right)^2 + (m_e c^2)^2 \right]^{1/2} - m_e c^2 =$$

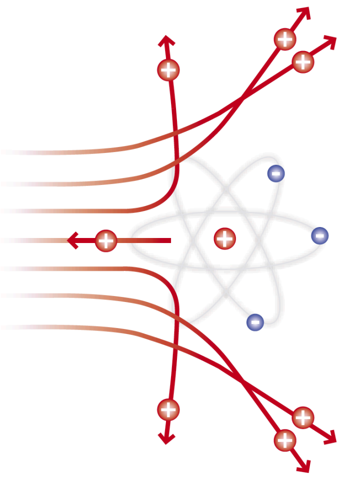
$$= \left\{ \left[\frac{(6.28)(197 \text{ MeV} \cdot \text{fm})}{(0.1 \text{ fm})} \right]^2 + (0.511 \text{ MeV})^2 \right\}^{1/2} - (0.511 \text{ MeV})$$

$$= 12 \text{ GeV}$$

Rutherford: the atomic nucleus and the need for better sources



Alpha particles from radioactive decay on gold foil:
discovery of the atomic nucleus



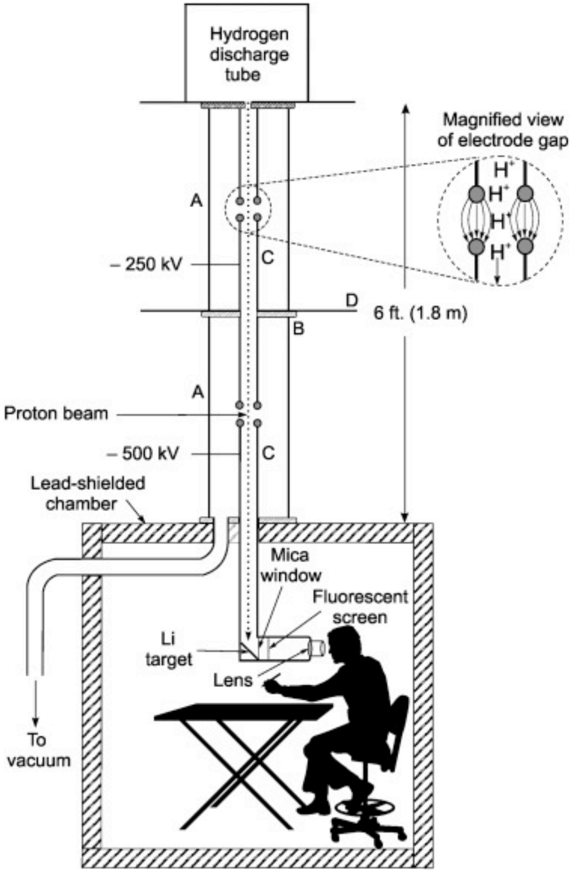
Alpha particles on nitrogen gas:
transmutation (transformation into oxygen)

The **need** for particle sources with **higher energies** and **intensities**:

"It has long been my ambition to have available for study a copious supply of atoms and electrons which have an individual energy far transcending that of the α and β-particles from radioactive bodies. I am hopeful that I may yet have my wish fulfilled, but it is obvious that many experimental difficulties will have to be surmounted before this can be realised on a laboratory scale."
—*Rutherford, Proc. Royal Society, 1927*

Direct acceleration methods: producing high voltages

At the Cavendish Laboratory, **Cockcroft and Walton** (1932) generate high voltages with transformers, capacitors and diodes (Greinacher multiplier)

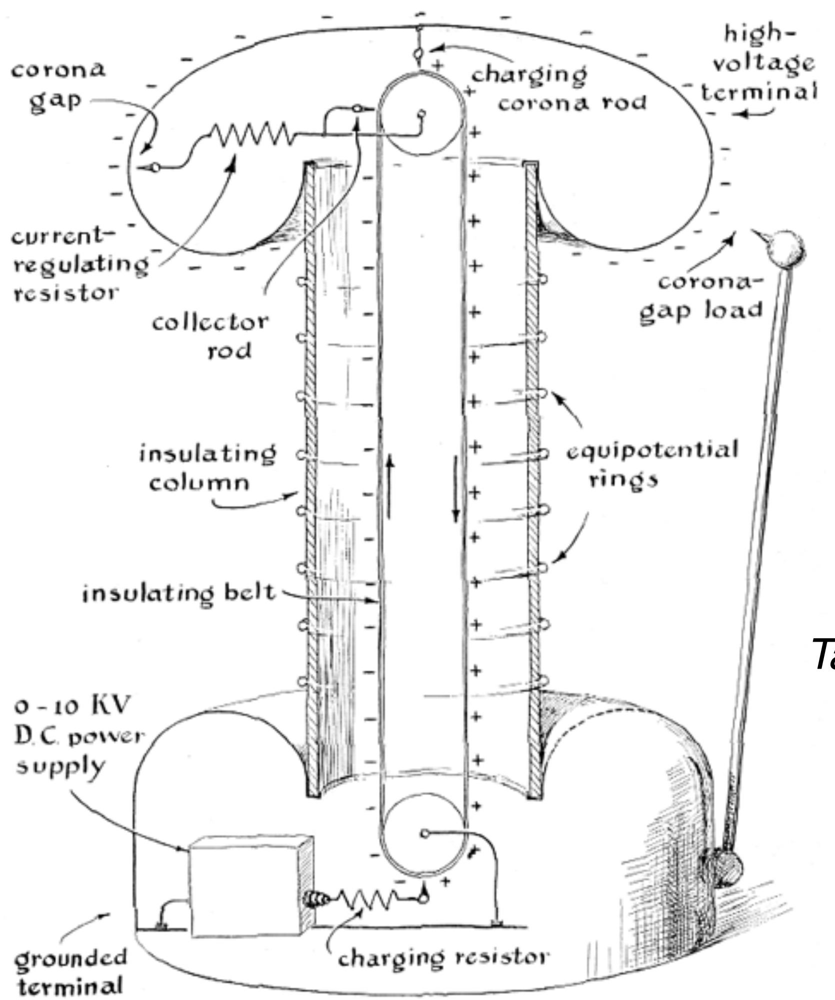


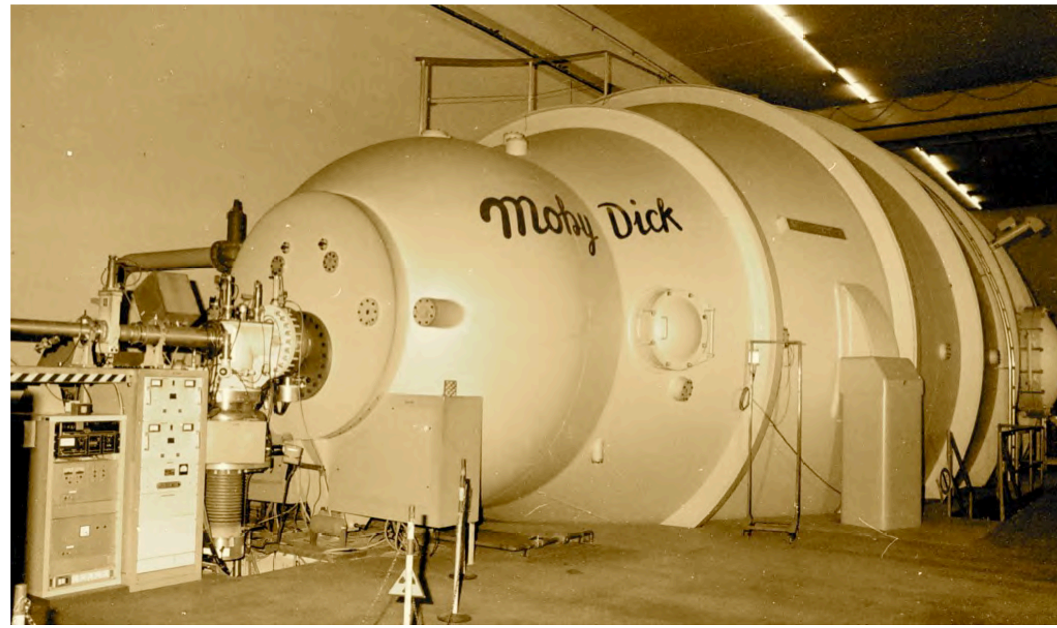
Protons accelerated up to **600 keV** are **sufficient to overcome the Coulomb barrier** (nuclear repulsion)

First artificial transmutation! Lithium in the target transformed into beryllium

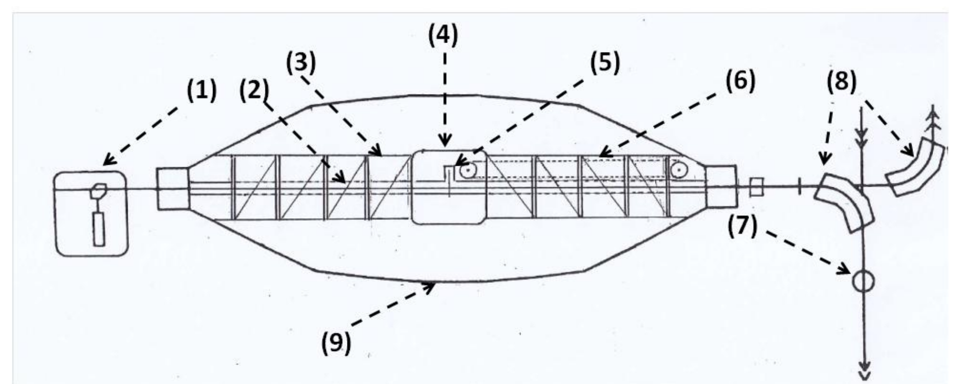
Direct acceleration: production of high voltages

The **Van de Graaff generator** (1929) converts the mechanical energy necessary to move a charged belt into electrical potential

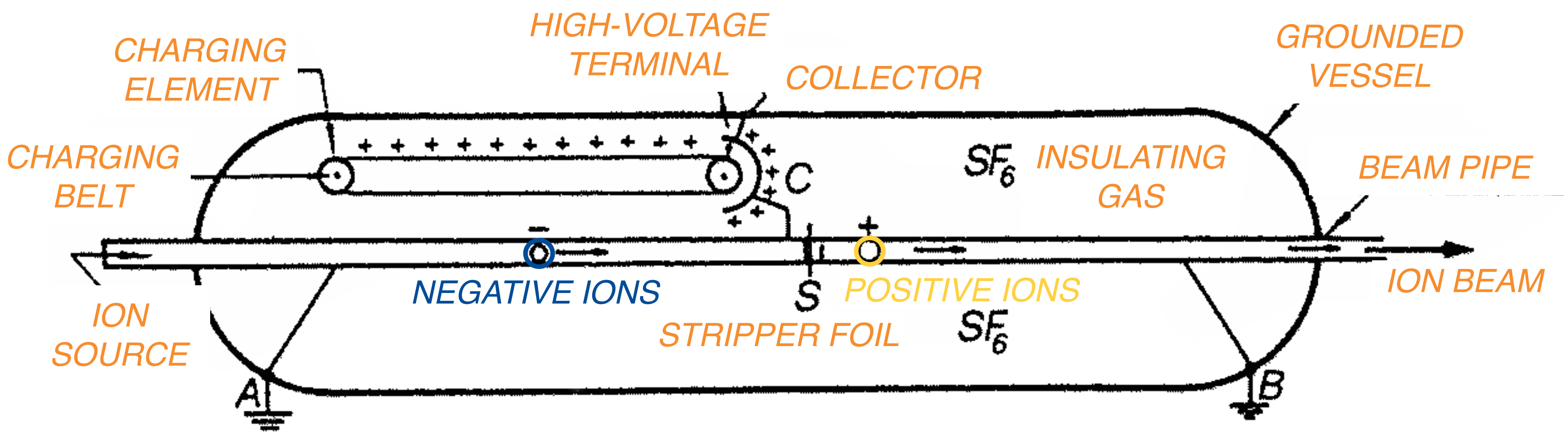




Tandem/XTU (15 MV) at INFN Laboratori Nazionali di Legnaro



The tandem electrostatic accelerator



The source of a tandem accelerator for nuclear physics generates O^- ions with a kinetic energy of 0.2 MeV. The high-voltage terminal is at +14 MV. While traversing the stripper foil, the ions change charge state, from O^- to O^{6+}. What is the final kinetic energy of the ions?

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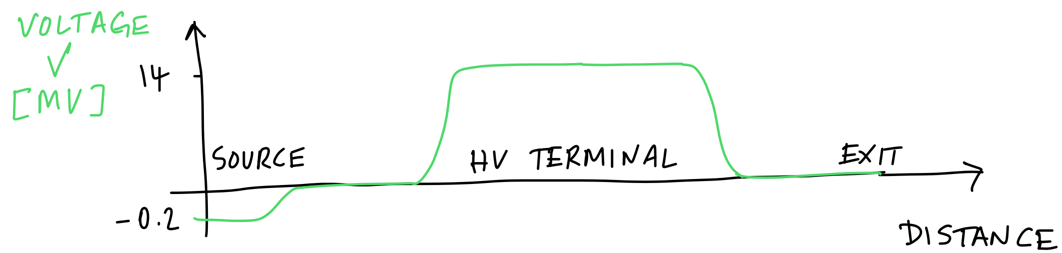
Final kinetic energy of oxygen ions from the tandem accelerator

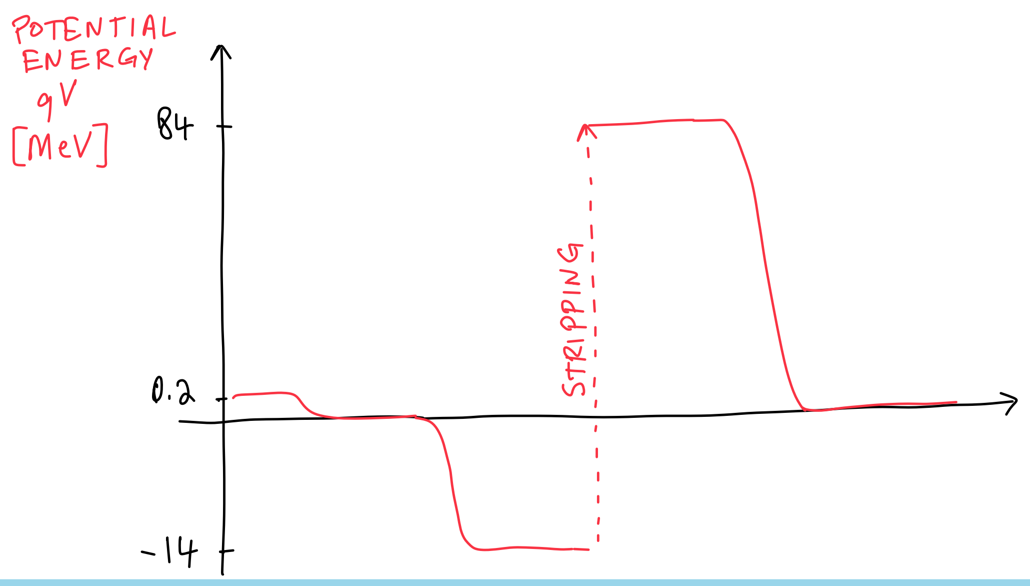
Kinetic energy of ions from the tandem accelerator:

$$T = 0.2\ \text{MeV} + (1e)(14\ \text{MV}) + (6e)(14\ \text{MV})$$

SOURCE — ACCELERATION AS O^- — ACCELERATION AS O^{6+}

$$= 98.2\ \text{MeV}$$





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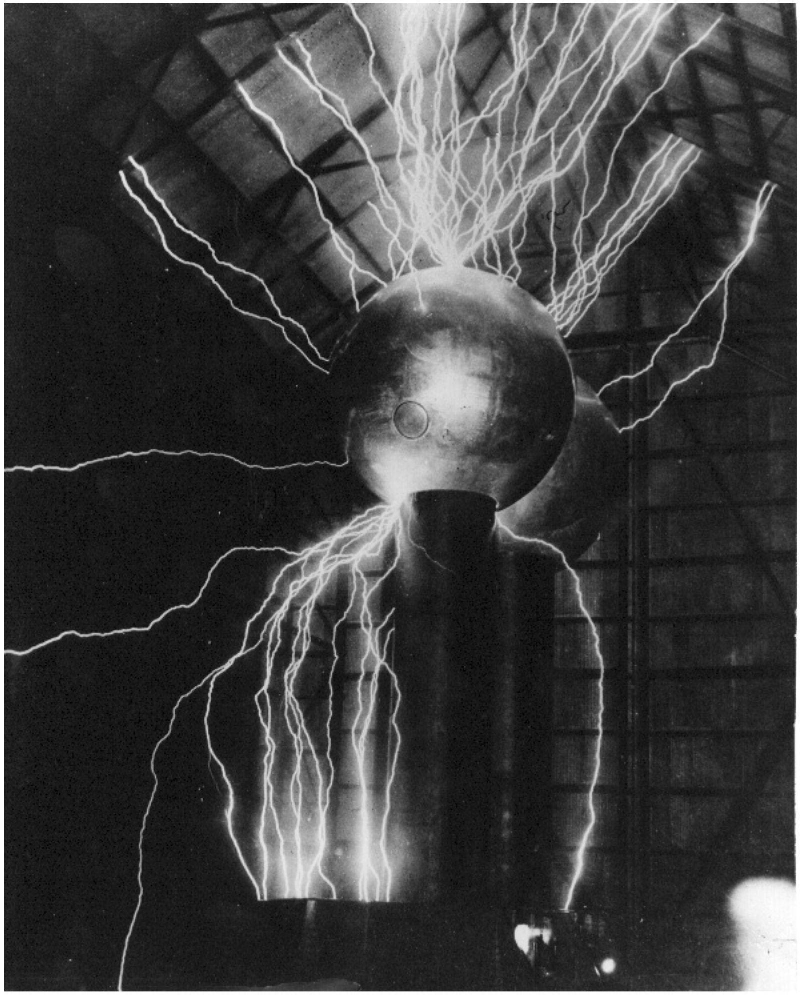
Demonstration of a special electrostatic accelerator (video)

Ping-pong ball accelerator by Todd Johnson (Fermilab)

youtu.be/EKxzXAQJvB8

Advantages and limits of electrostatic machines

- Energies up to ~100 MeV, **well suited for studying nuclear processes**
- **Good voltage stability**, important for cross-section measurements as a function of energy
- **Intensities** up to ~ 0.1 mA
- Limited by **high-voltage breakdowns** above 20–30 MV
- How can one obtain higher energies?



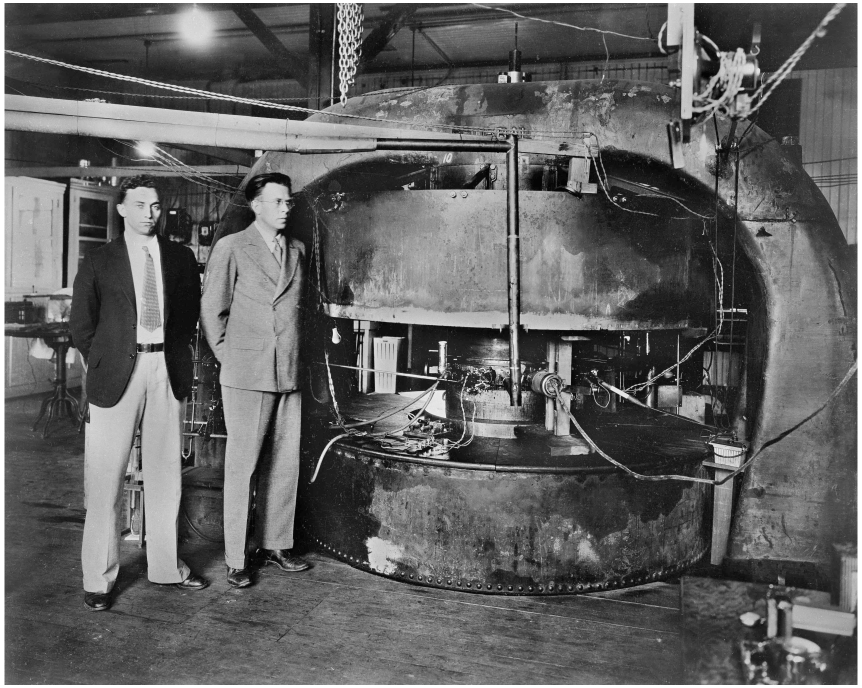
AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)

Resonant acceleration

To avoid high voltages, several scientists (Ising, Widerøe, Gabor, Szilard, Steenbeck) suggest

1. Small accelerations, repeated many times
2. Recirculation of the particle beam

Lawrence and Livingston build the first cyclotrons at Berkeley (1930—1932)



Resonant acceleration: the cyclotron

An ***alternating electric field*** *accelerates particles*

A ***constant magnetic field*** *confines particles on spiral orbits*

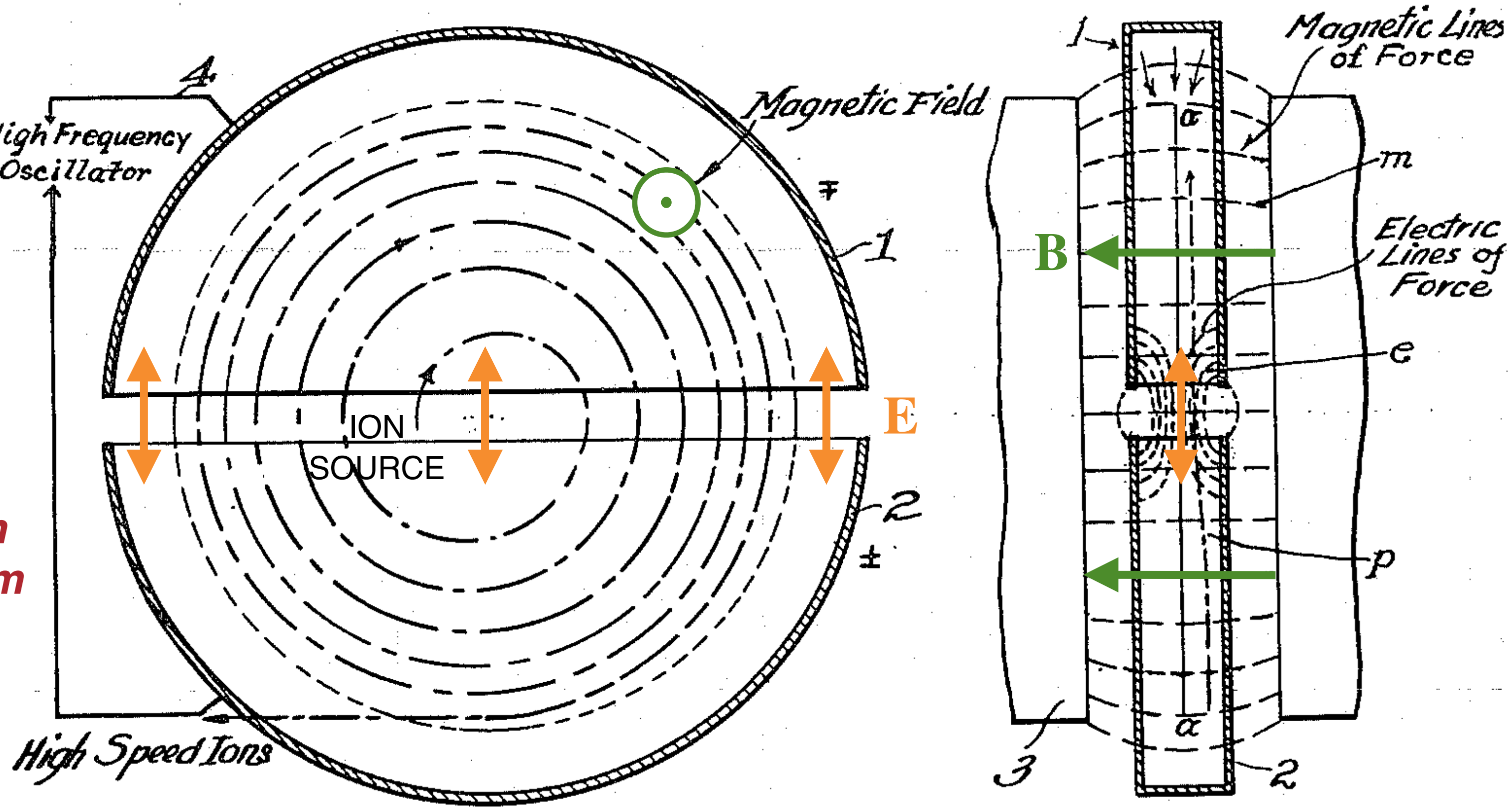
"Weak focusing" is generated by the curvature of the magnetic field lines

Cyclotron frequency

$$f = \frac{qB}{2\pi\gamma m}$$

Maximum momentum

$$p = qBR$$



Key principle: as particles are accelerated, **the higher velocity is exactly compensated by the longer orbits** — the **revolution frequency is independent of energy** (for non-relativistic particles)

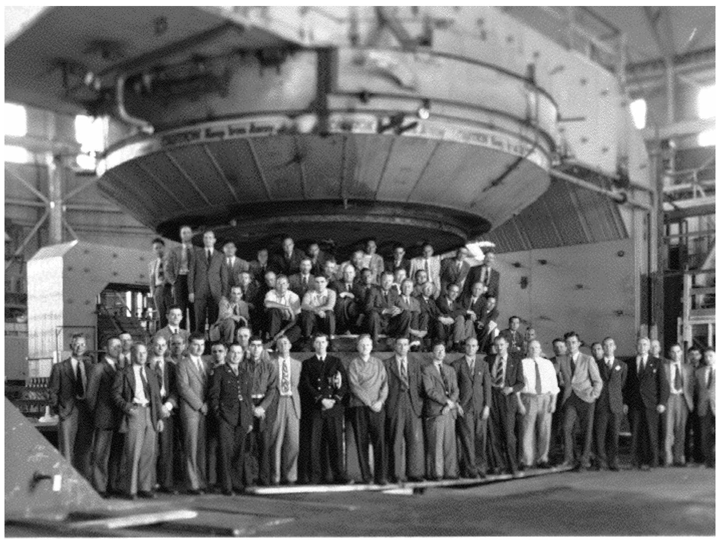
A mechanical analogue of the cyclotron (video)

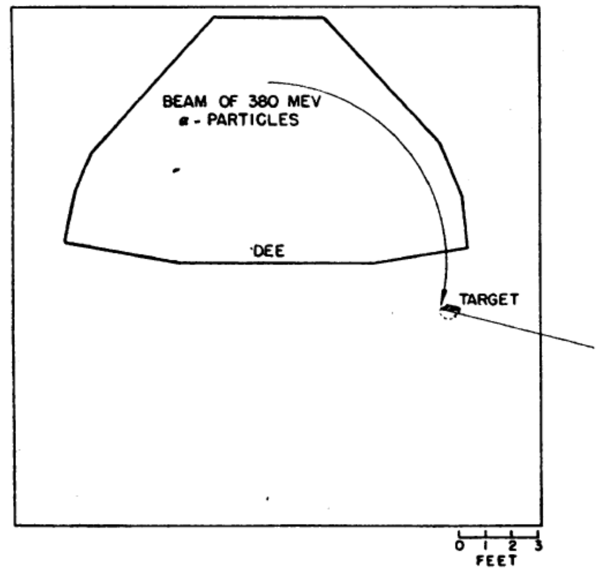
Ernest O. Lawrence demonstrates the cyclotron concept

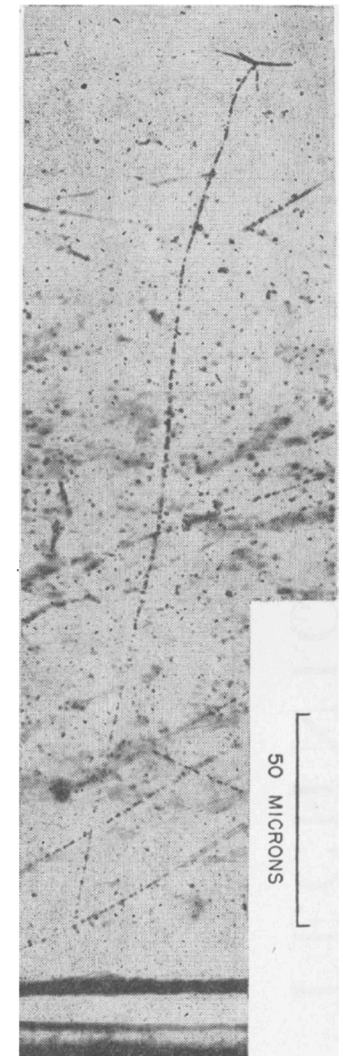
youtu.be/cutKuFxeXmQ

Example of discovery enabled by cyclotrons

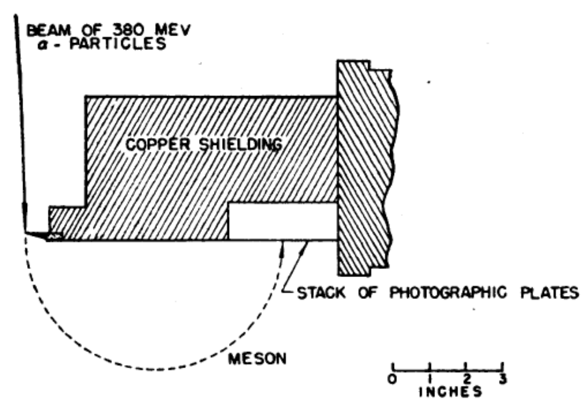
In 1948 at Berkeley, the 4.7-m (184-in) cyclotron accelerates alpha particles up to 380 MeV. Using carbon and beryllium targets, the **first artificially produced mesons are observed**, confirming cosmic-ray observations.







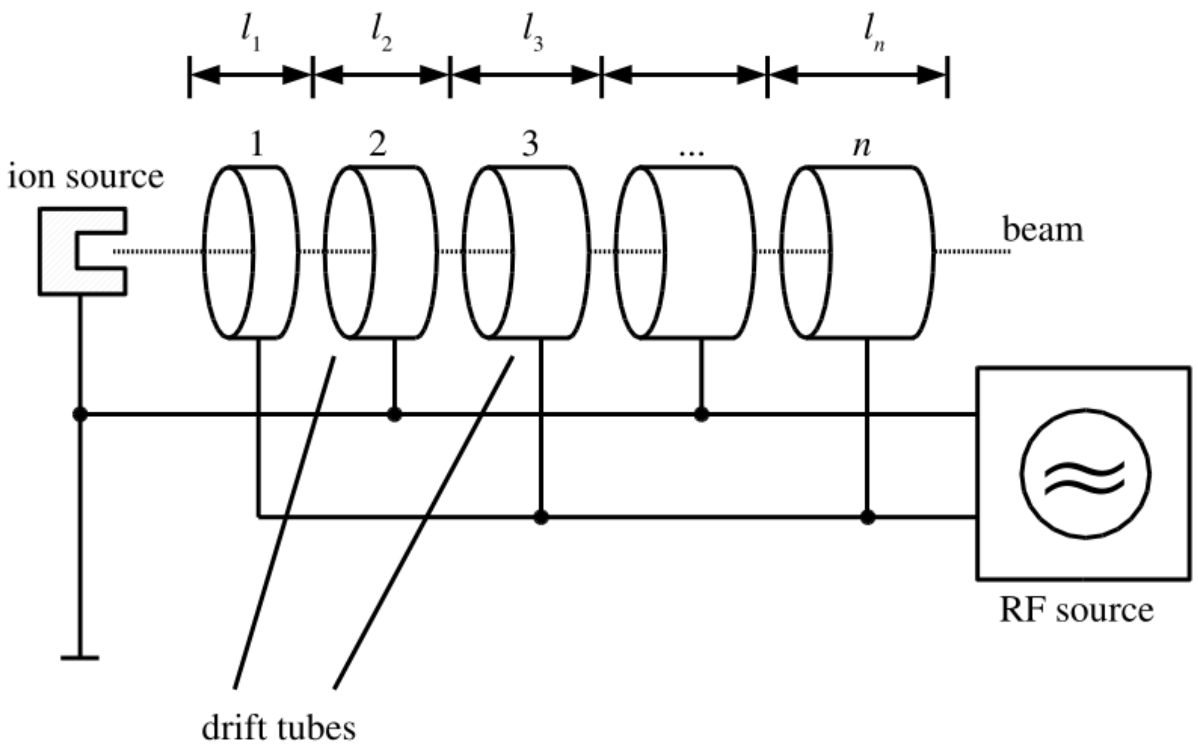
Lattes and Gardner



Resonant acceleration: the linear accelerator ("linac")

Concept developed by Ising (1924) and Widerøe (1928)

Multiple accelerations generated by **alternating electric fields** applied to **conducting cylinders**. When the field is out of phase, the particles are shielded.



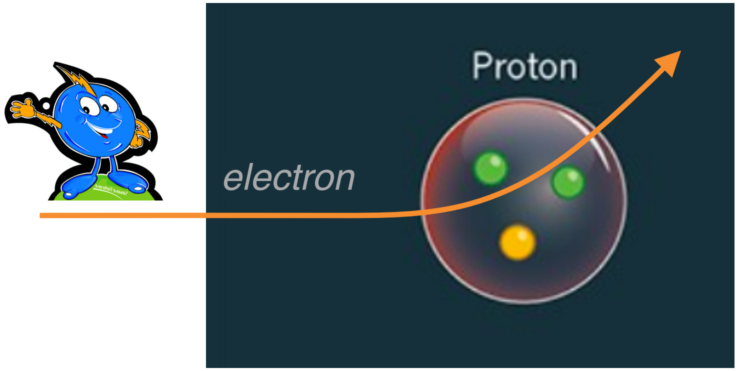
400-MeV linac at Fermilab

First device built by **Sloan and Lawrence** in 1931 for heavy ions. **Tube length** and **rf frequency increase with particle velocity**. **Maximum energy** determined by the **length** of the machine.

Example of physics with linacs: structure of the nucleon

The Stanford 3-km linac enabled the **study of the structure of nucleons**

- 1956, electrons at **188 MeV**: measurement of the **size of the proton**, ~ 0.7 fm
- 1969, electrons at **17 GeV**: discovery of **quarks**

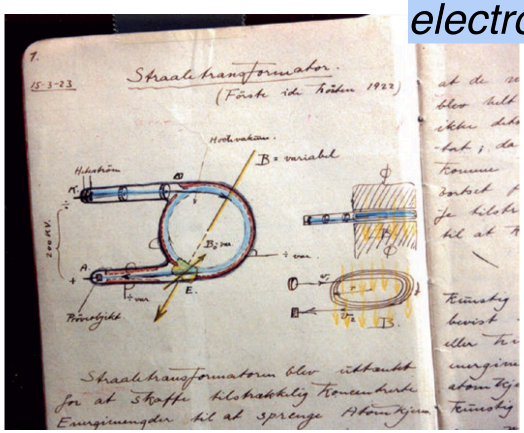


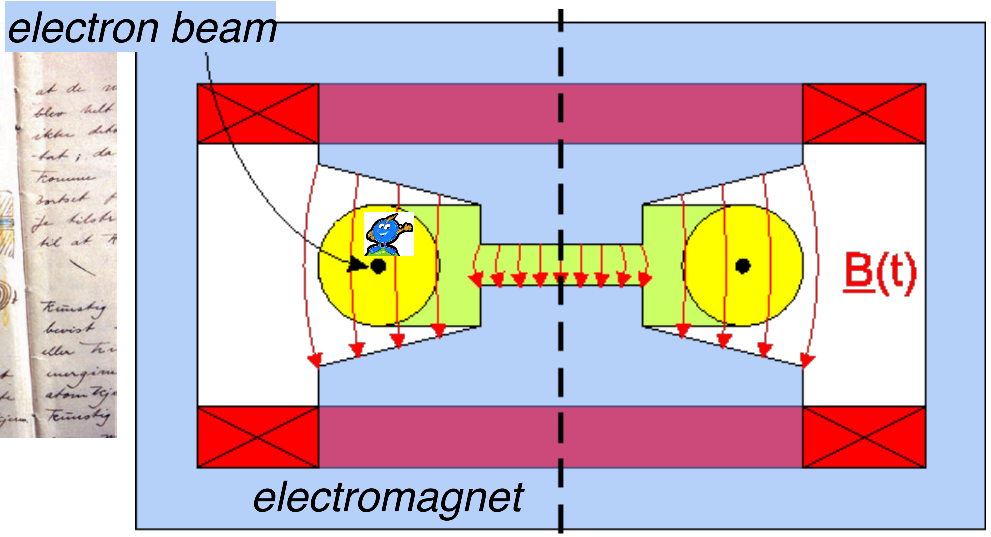
Induction acceleration: the betatron

Based on Faraday's law of **electromagnetic induction**

The **magnetic field** plays all major roles:

- **particle confinement**, with its vertical component
- **focusing**, with bent field lines at edges ("weak focusing")
- **acceleration**, using the electric field generated by the variable magnetic field



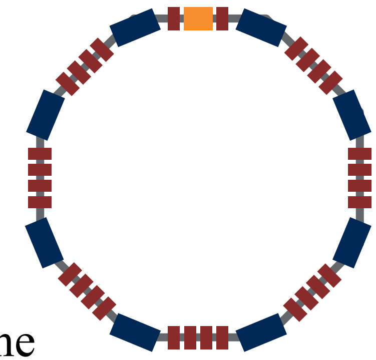


First betatron: 2.3 MeV, 1941

Proposed by Widerøe (1923), developed and built by Kerst and collaborators (1940)

Important for the development of orbit and focusing theory (Kerst e Serber, 1941)

Synchrotrons and phase stability



For cyclotrons and betatrons
(cost) ∝ (magnet volume) ∝ (radius)^3 ∝ (energy)^3 !
A very **strong limitation**

Oliphant (1943) outlines the **synchrotron concept**:

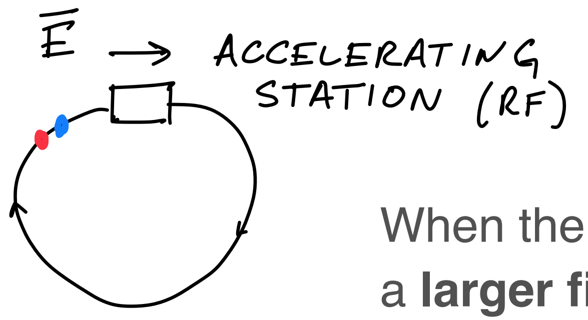
"Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field […] which would be varied in such a way that the radius of curvature remains constant as the particles gain energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes."

Veksler and McMillan (1945) independently discover **phase stability**:
By synchronously varying the accelerating frequency and the confining magnetic field, particles "follow" the fields and can stay on an orbit of constant radius as they gain energy.

Continuous beams → **pulsed** beams

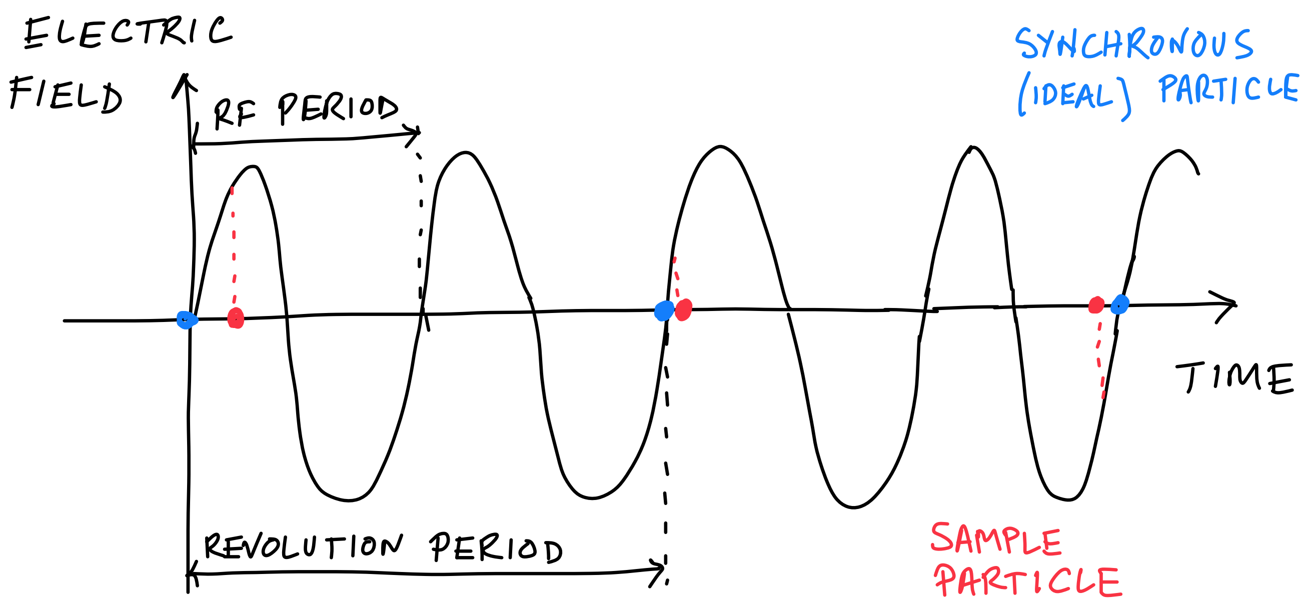
The central part of the electromagnet becomes superfluous. The machine is shaped like a **ring**.

Sketch of the phase stability concept



The ideal particle is always in phase with the electric field

When the sample particle is **late**, it sees a **larger field**, which accelerates it and brings it closer to the ideal particle



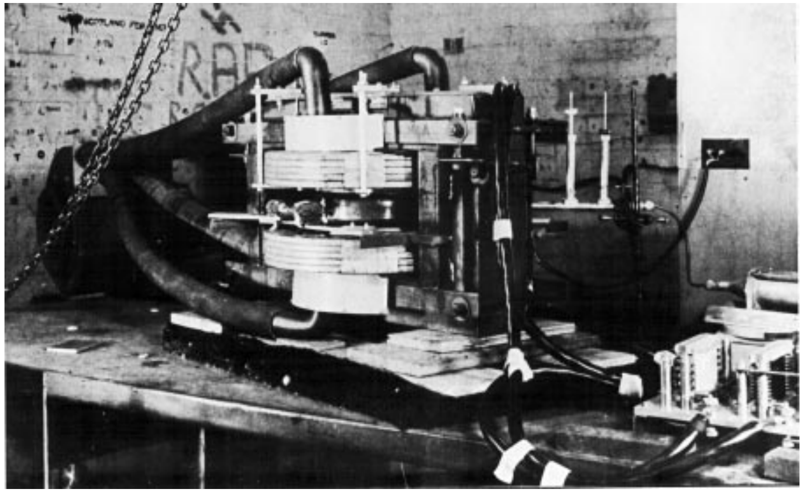
The revolution period is usually a large multiple of the rf period

The scheme needs to be slightly modified above the *transition energy* of the machine

Stable regions ("buckets") and synchrotron oscillations
around the ideal particle

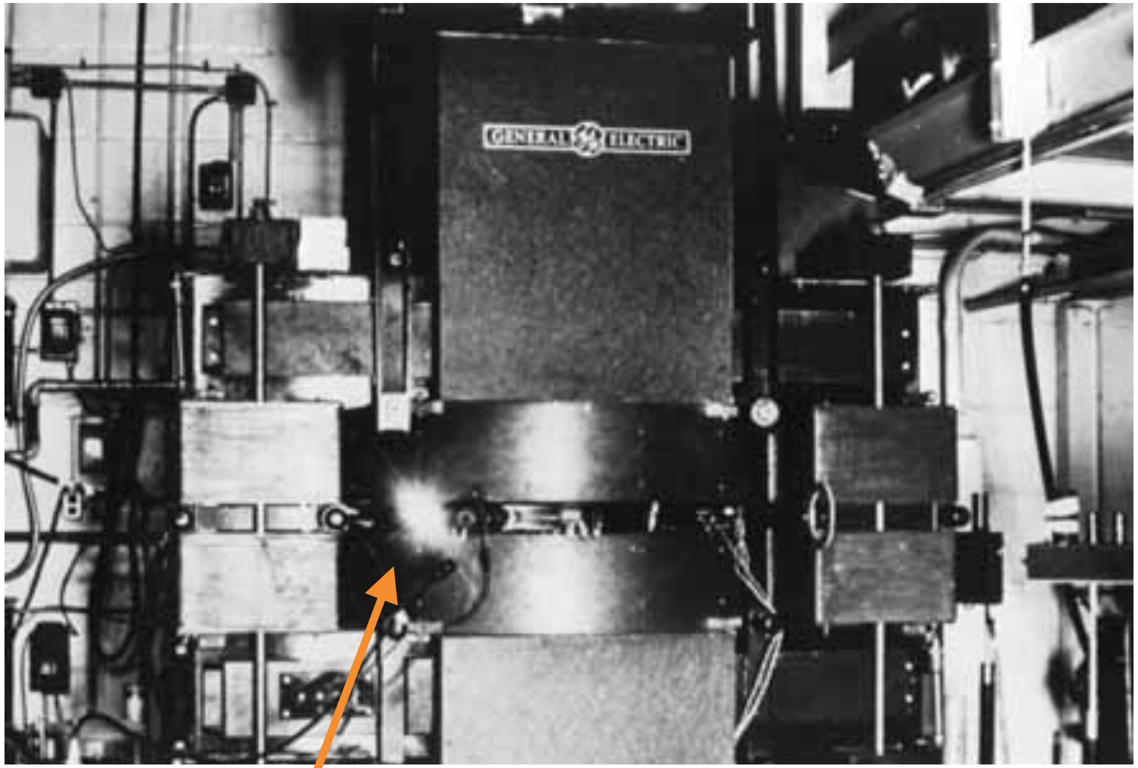
If the rf frequency changes slowly, particles adjust to it

The first synchrotrons



First synchrotron: F. Goward, UK (1946)
(modified betatron)

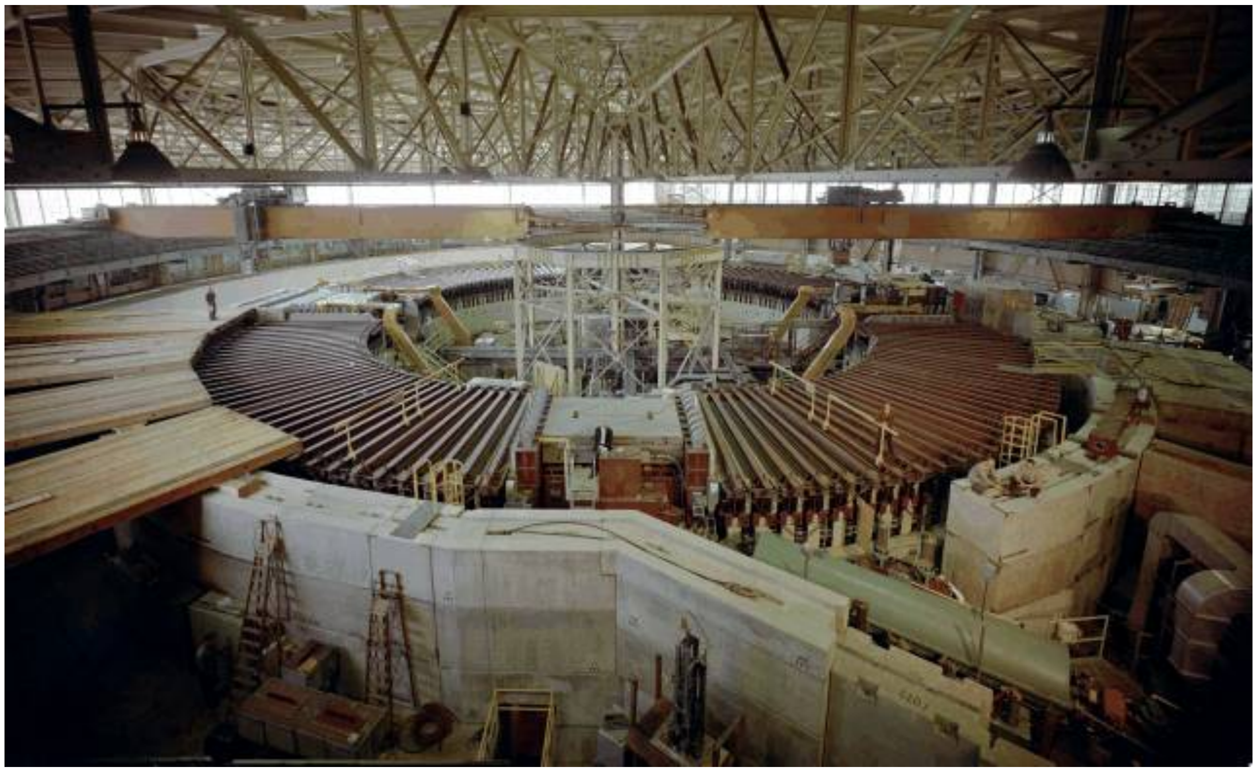
300-MeV synchrotron (General Electric, 1946)

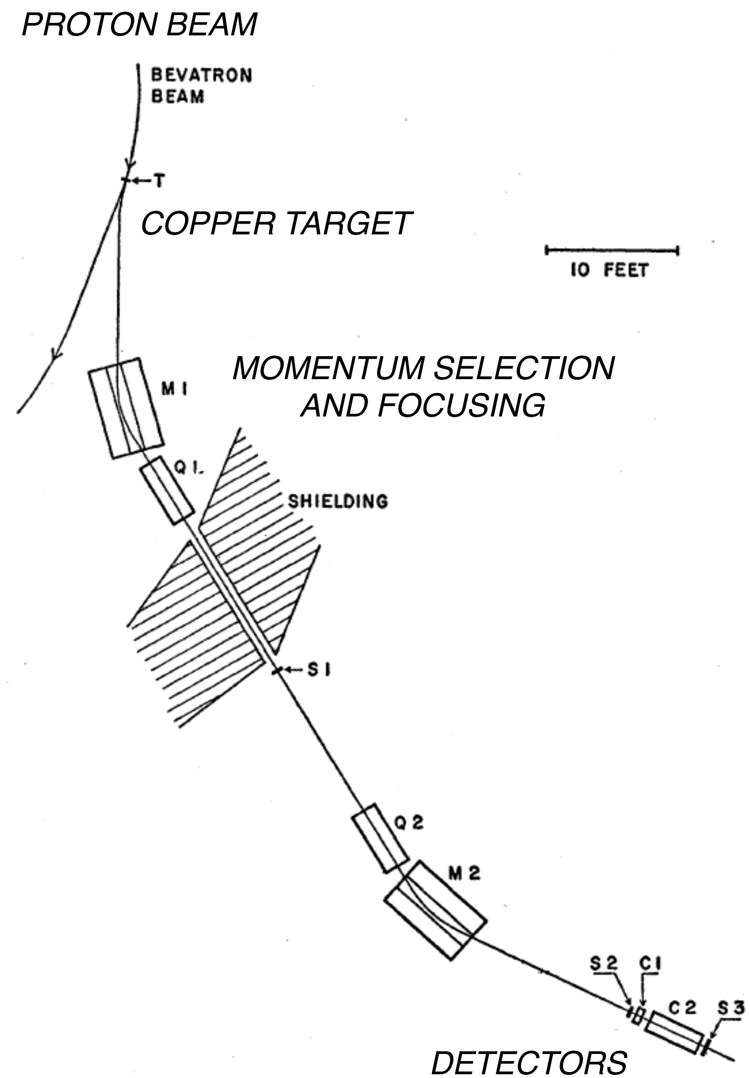


First direct observation of "synchrotron light"
radiated by electrons in circular motion

Example of discovery with synchrotrons: antiprotons

The Bevatron at Berkeley accelerates protons to 6 GeV, sufficient to **produce and observe antiprotons** (1955)

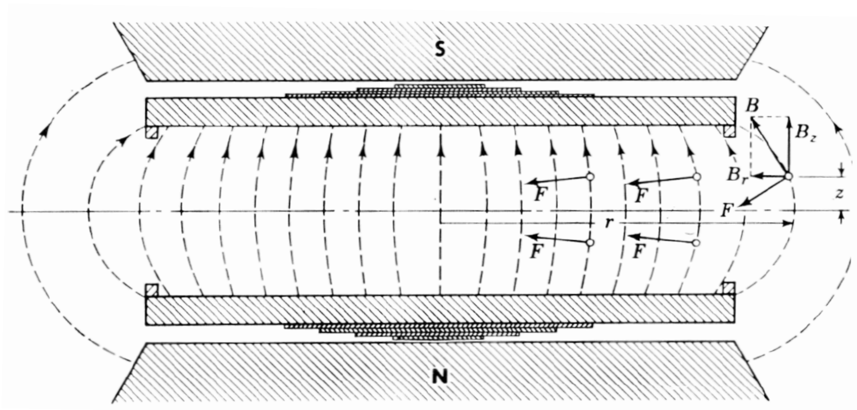




Alternating gradient and strong focusing

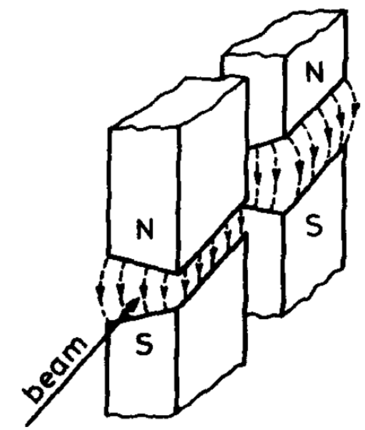
In analogy with light optics, Christofilos (1950) and Courant, Livingston and Snyder (1952) discover that a **more compact and efficient focusing** can be achieved by **increasing the magnetic field gradient** and **alternating its sign** (focusing and defocusing lenses)

weak focusing
(cyclotrons, betatrons, first synchrotrons)



wide orbit excursions,
large vacuum chambers
and large magnets

strong focusing *and* ***alternating gradient***



beams, magnets and vacuum chambers
are ***significantly more compact***

Separated-function synchrotrons

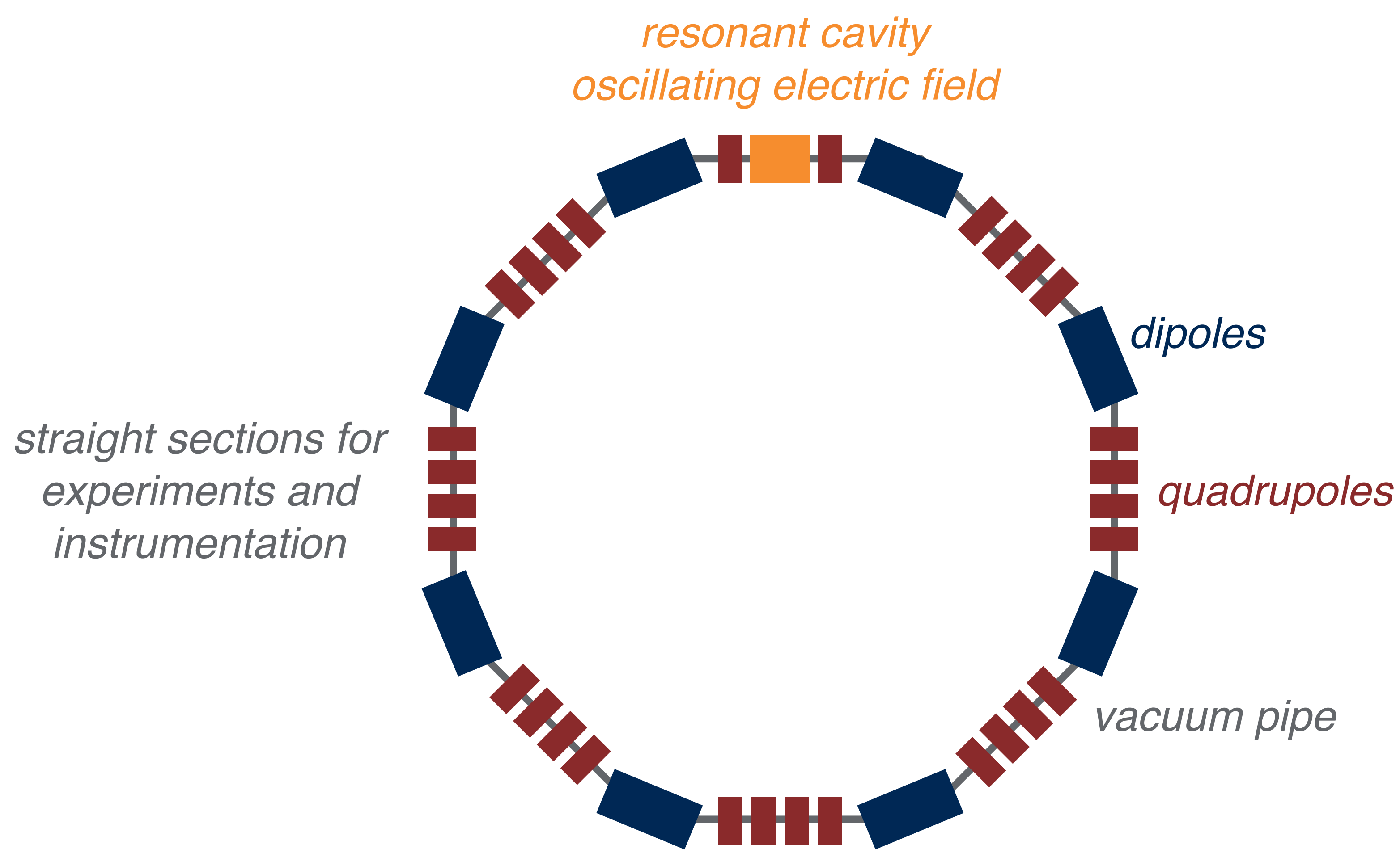
Dipoles for bending **Quadrupoles** for focusing

Fermilab Main Ring
400 GeV

Fermilab Tevatron
980 GeV

Separation between guiding (dipole magnets) and focusing (quadrupole magnets) functions for more efficient use of the magnets and for lattice considerations

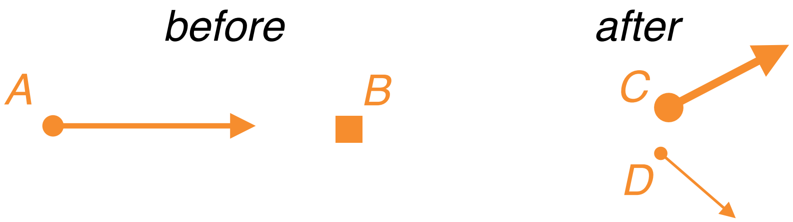
Schematic sketch of a modern synchrotron



Colliding beams

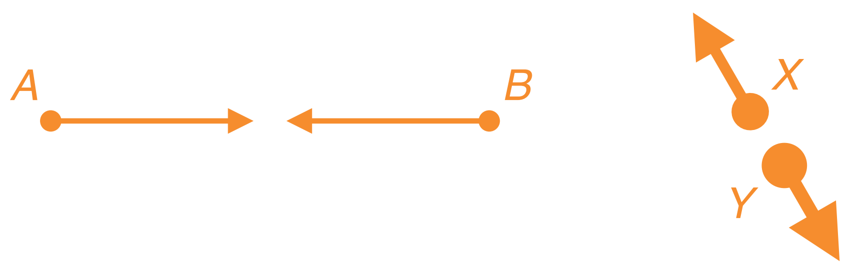
In **fixed target experiments**, some of the projectile's kinetic energy is "wasted" as kinetic energy of the products (conservation of energy and momentum). The available energy for the creation of new particles (**center-of-momentum energy**) is proportional to the **square root of the projectile's energy**

$$E_{\mathrm{cm}} = \sqrt{m_A^2 + m_B^2 + 2E_A m_B}$$



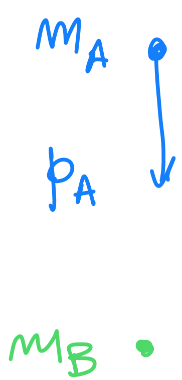
In **head-on collisions** ($\mathbf{p}_A = -\mathbf{p}_B$), **all the energy is available**

$$E_{\mathrm{cm}} = E_A + E_B$$



Center-of-momentum energy in fixed-target experiments

Center-of-momentum energy of projectile of mass m_A and energy E_A on stationary target of mass m_B



4-momenta

$(E_A, \bar{p}_A)$

$(m_B, \bar{0})$

$$P^\mu = (E_A + m_B, \bar{p}_A)$$

total 4-momentum

C.M. energy is the invariant contraction of the total 4-momentum

$$E_{cm} = \sqrt{P_\mu P^\mu} = \sqrt{(E_A + m_B)^2 - p_A^2}$$

$$= \sqrt{E_A^2 + 2 E_A m_B + m_B^2 - p_A^2}$$

$$= \sqrt{m_A^2 + m_B^2 + 2 E_A m_B}$$

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Colliders and storage rings are challenging

Particle beams are **much less dense** than solids, liquids or gases: small event rates

Beams need to be stored for hours: is motion stable on such time scales?
(Compare number of revolutions with the Solar System!)

Particle beams are charged: **strong repulsion** and **intensity effects**

The development of colliders stimulated enormous progress in beam physics and accelerator technology

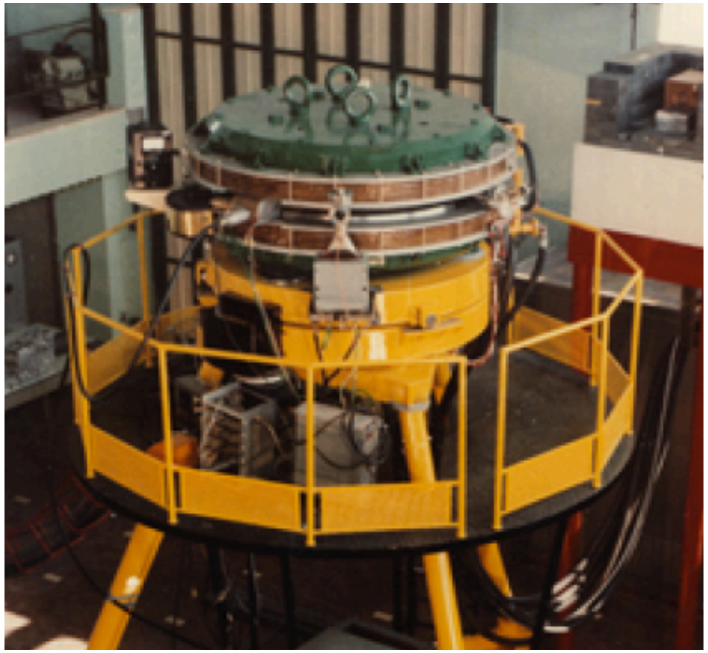
issues → understanding → new concepts and techniques

field nonlinearities
instabilities
wake fields
intrabeam scattering
beam-beam interactions

feedback systems
low-beta insertions
radiation damping
electron cooling
stochastic cooling

The first colliders

"crazy idea": **matter and antimatter** (same mass, opposite charge) stored in the same vacuum chamber to study annihilation products (Widerøe, Touschek)



AdA (Anello di Accumulazione)
First electron-positron collisions
250 MeV, 1.3 m diameter
Frascati (1961) and Orsay (1964)

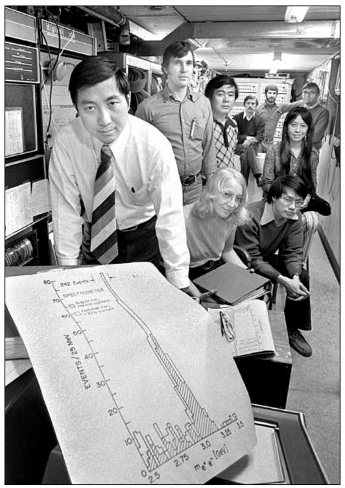
Alternative approaches for electron-electron collisions

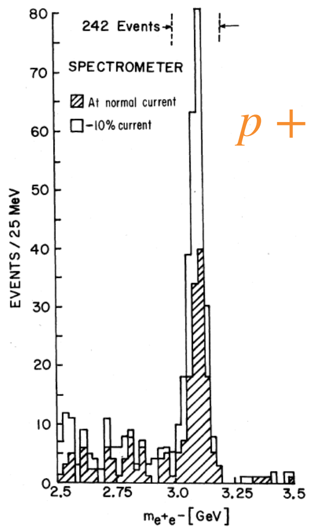
- Stanford-Princeton machine
- VEP1 in Novosibirsk

Discovery of the charm quark and charmonium: the J/ψ meson

In November 1974, two groups simultaneously observed
an **unexpected resonance at 3.1 GeV**

Alternating Gradient Synchrotron at Brookhaven
protons on fixed target

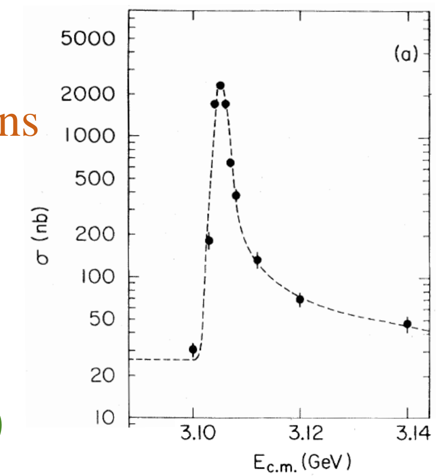




$$p + \mathrm{Be} \rightarrow e^+e^- + X$$

SPEAR at Stanford
electron-positron collisions

$$e^+e^- \rightarrow \text{hadrons}$$



Confirmed after a few hours(!)
at ADONE in Frascati

There are quarks that are heavier than protons!

Charmonium, the **bound state of two heavy quarks** $(c\bar{c})$, enabled the study of nuclear forces in a simple, non-relativistic system

Named the "**hydrogen atom of strong interactions**", in analogy with the hydrogen atom for electromagnetic interactions in quantum mechanics

Modern colliders

Many **discoveries** were enabled by colliders and storage rings

Modern colliders are some of the **most powerful** and **complex scientific instruments**

Superconductivity applied to accelerator technology

The Tevatron at Fermilab (1983—2011) was the **first large scale application of superconducting magnets**

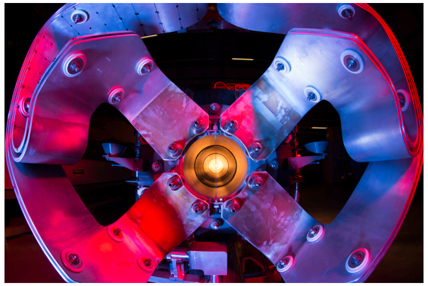


Superconductivity applied to magnets, accelerating cavities and other accelerator subsystems has **opened new horizons**

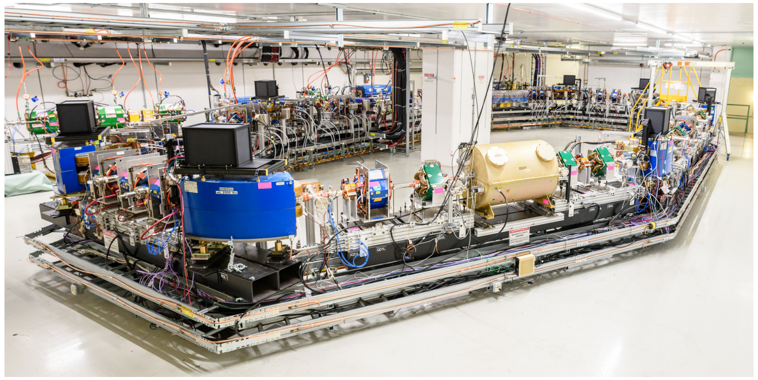



What’s next??

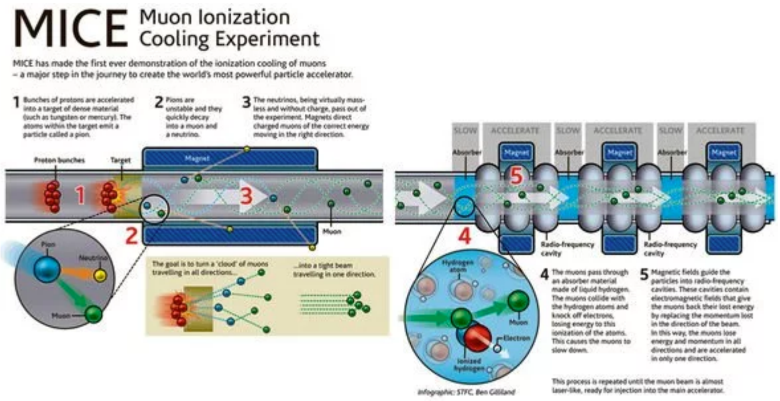
Production and control of **high-intensity beams** to study neutrinos and rare processes



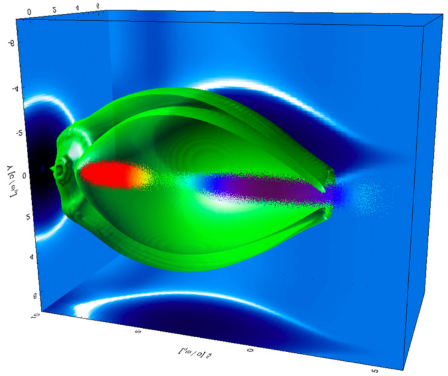
New **beam cooling techniques** for colliders and other applications

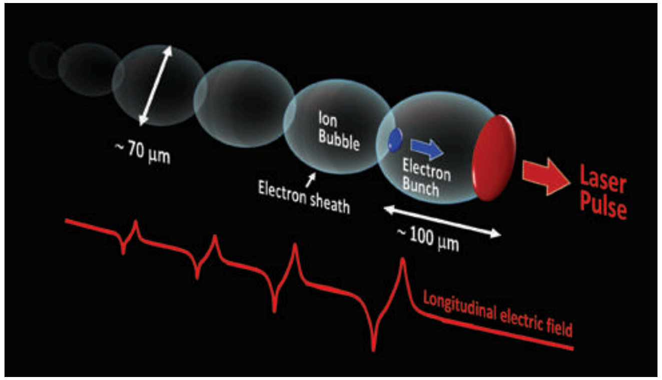


Acceleration in plasmas, driven by lasers or other primary beams



Many opportunities for **new ideas**…





Questions?