Hosting institutions

Elettra Sincrotrone Trieste

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Istituto Nazionale di Fisica Nucleare

IPAC23

14th International Particle Accelerator Conference

IPAC '23

7 - 12 May 2023

VENICE, ITALY

Overview of history and types of accelerators

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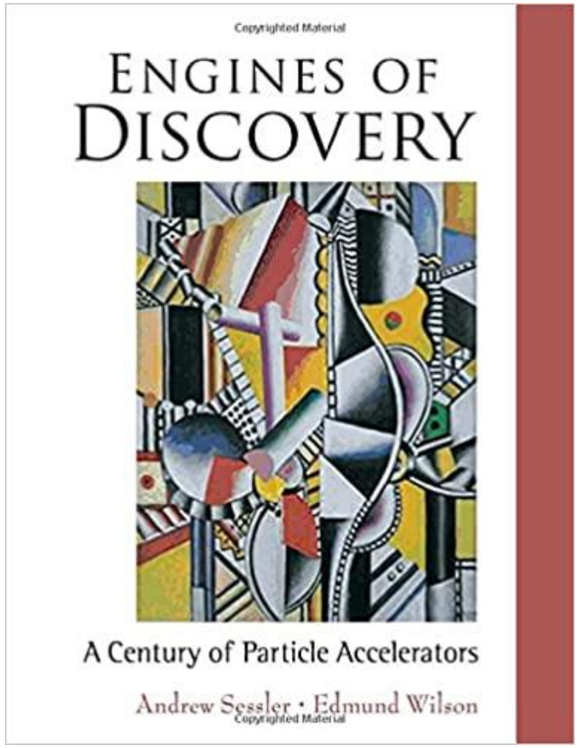
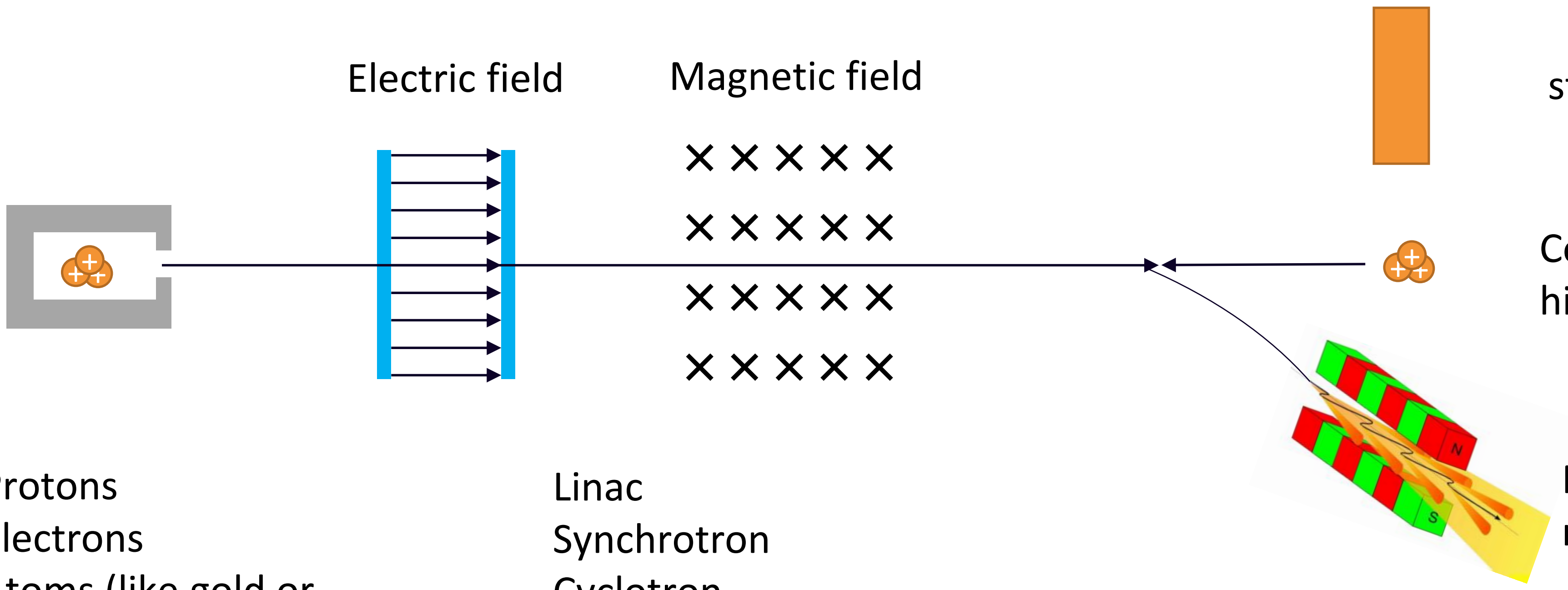
Acknowledgements



- Referred to many reports or articles of others.
- Courtesy of Y. Zhang, Y. Jiao, H.X. Xu, Q. Qin, Z. Duan, J. Peng, etc. for helping prepare the slides.

What is an accelerator?



stationary target

Colliding with another high speed beam

Producing synchrotron radiations

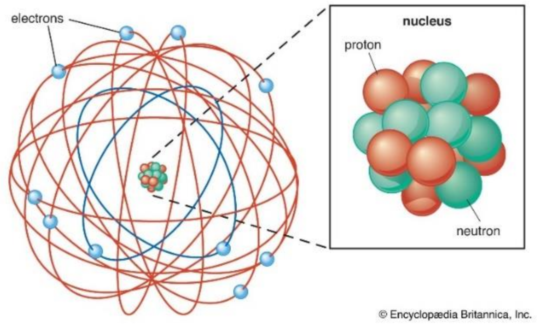
…

Protons
Electrons
Atoms (like gold or uranium)
…

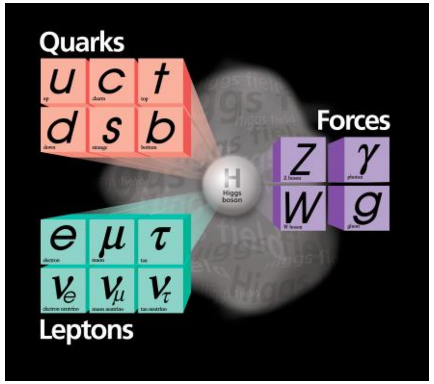
Linac
Synchrotron
Cyclotron
…

Why accelerators?

Huge microscopes for particle physics
(Study smallest constituents of matter
and basic forces governing the behavior)



Verify and improve the Standard Model



Material Research
(Photon Sources/Neutron Sources
Chemistry, biology, medicine…)

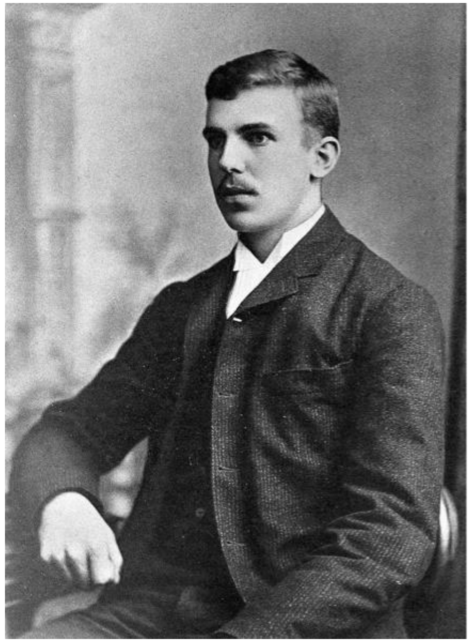
Industrial and medical applications

Container Scanning Machine

Varian medical systems

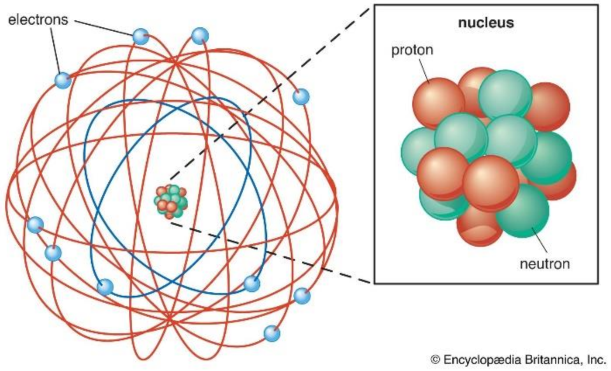
How did everything begins?

- Before accelerators, experiments on subatomic particles were largely based on natural radioactive sources and cosmic rays.



Ernest Rutherford

The father of nuclear science



Rutherford atomic model

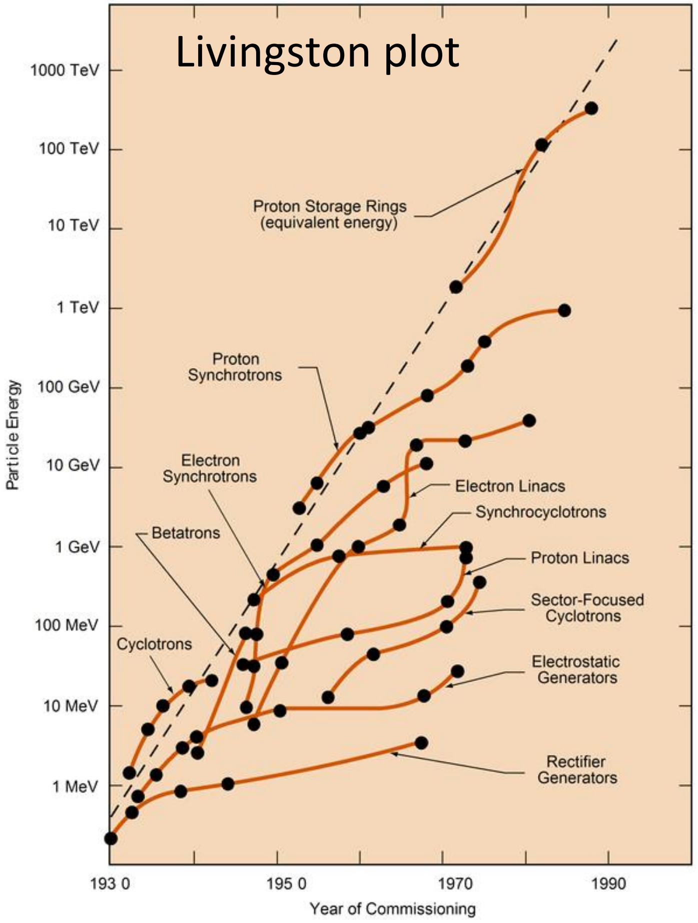
Nobel price, 1908

Reporting to the Royal Society in London:

"I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances"

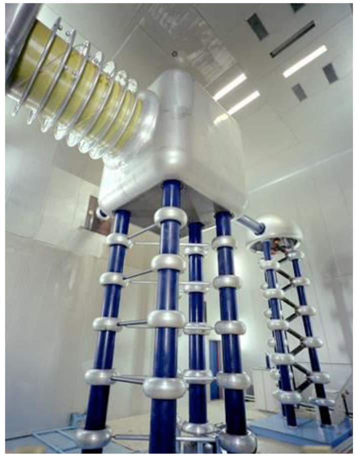
Starts the race to build accelerators of ever increasing energy, as well as ever higher beam current

Different types of accelerators

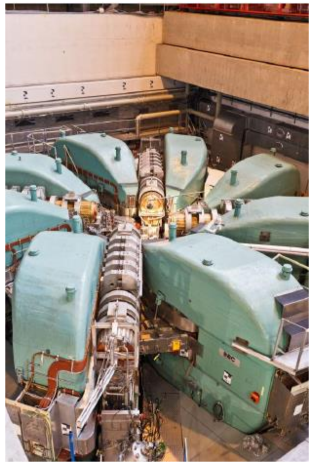


Originally produced by M. Stanley Livingston in 1954

Electrostatic Accelerators



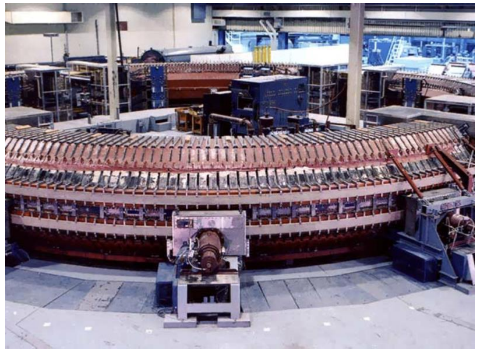
Cyclotrons



Linear accelerators

Betatrons

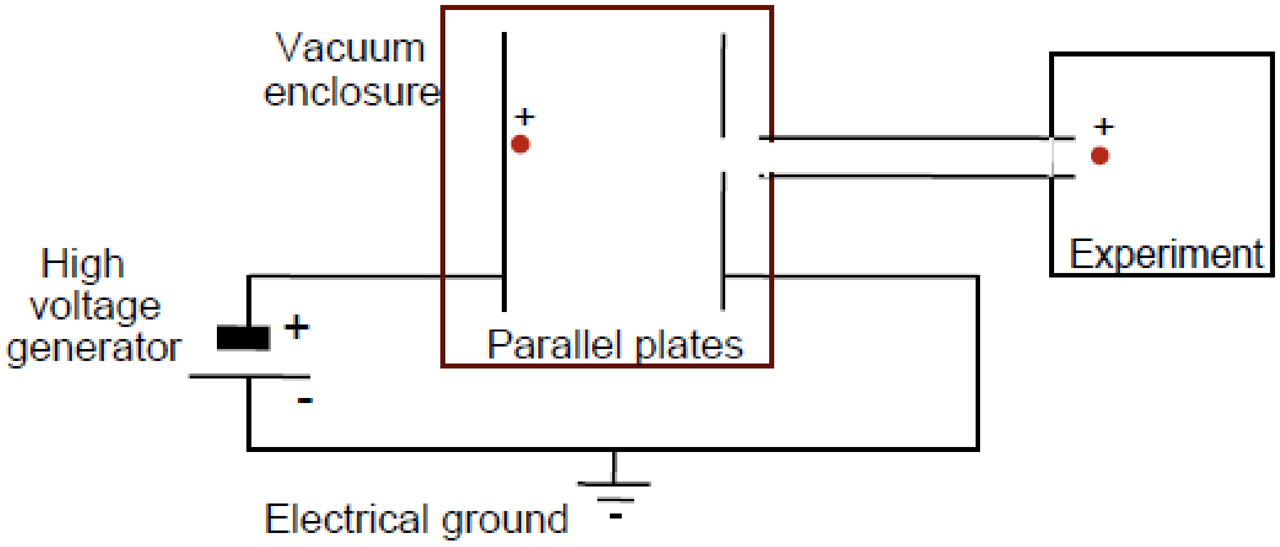
Synchrotrons



Colliders

- Also many other fancy accelerators not included.

Electrostatic Accelerators

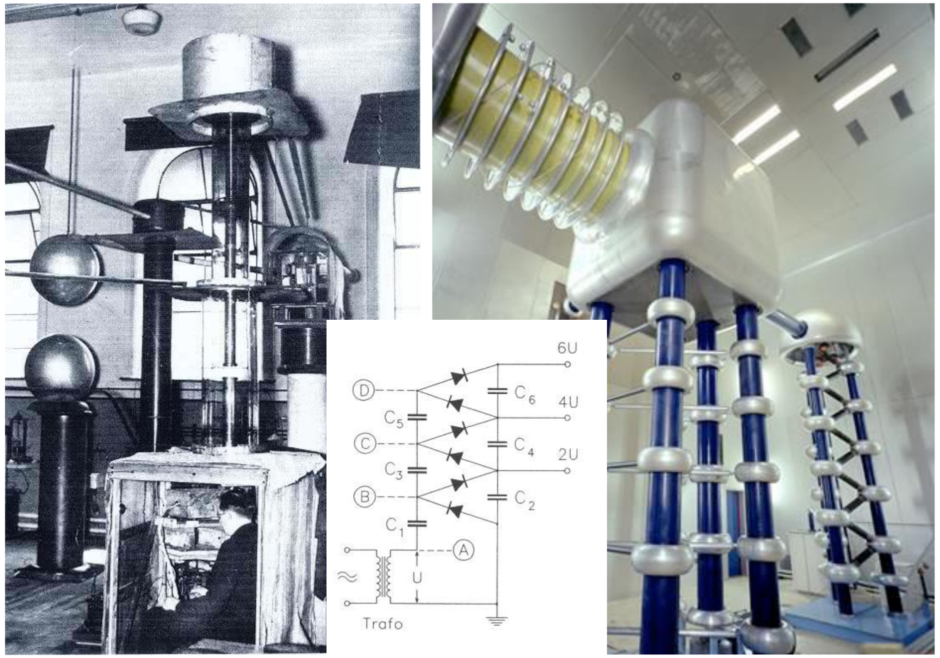


- Static voltage accelerator
- Simple concept is using electric field to increase the speed of a charged particle
- Energy gain of an elementary charge: 1eV=e*1Volt

Early Electrostatic Accelerators

- In the 1930s, Cockcroft, Walton and Graaff pushed this simple idea to high voltages.

Cockcroft-Walton accelerator
Single passage: 160~700keV



- Based on the idea of voltage multiplying column.

Normal alternating current was first rectified

↓

Apply the current to a number of condensers

↓

Connect the condensers in series

↓

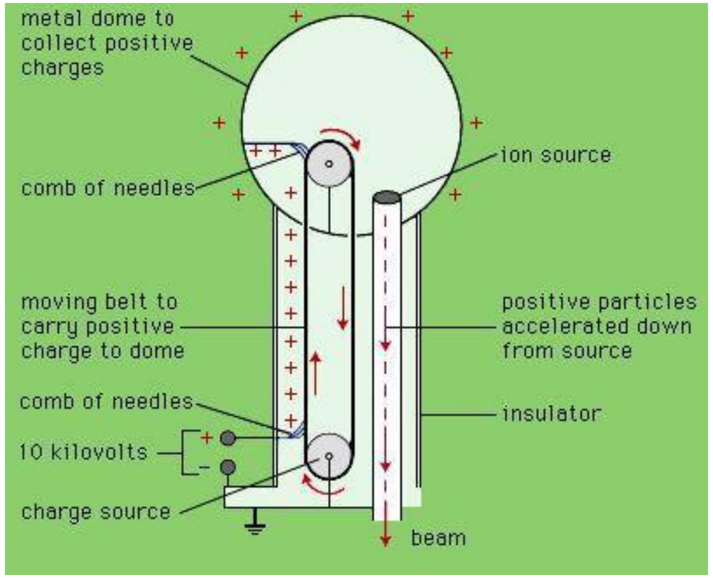
Connect to an accelerating column

↓

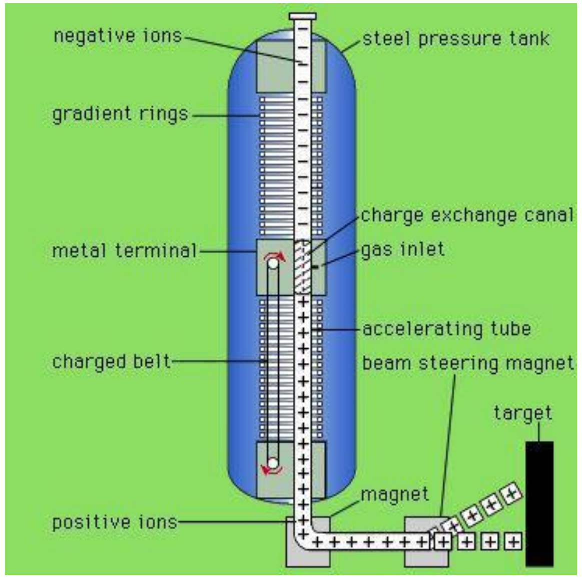
Accelerate particles

Early Electrostatic Accelerators

Van de Graaff generator



Tandem Van de Graaff generator
(clever idea to use the voltage twice)



Charge sprayed on a moving belt

Transported to a upper terminal and removed

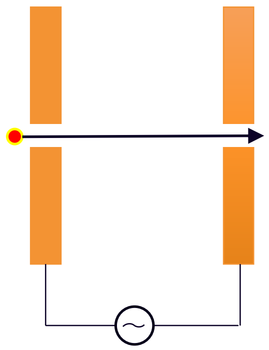
Build up voltage on the terminal

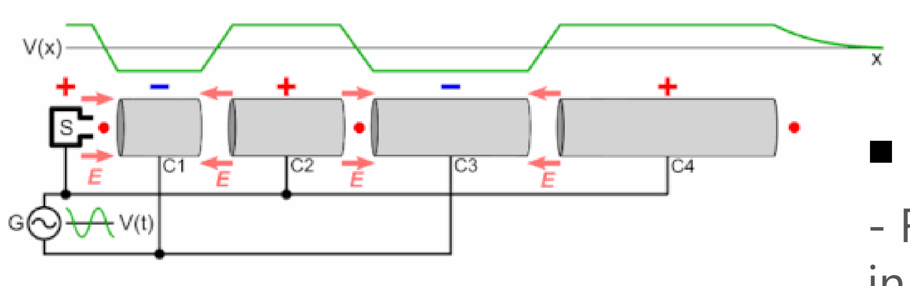
Apply to an accelerating column

Accelerate particles

- Cheap and clean.
- Energy limited due to voltage breakdown, less used in modern particle physics experiments.
- Continue to provide a useful source of low energy particles, applied to a wide range of scientific and industrial tasks.

Oscillating field accelerators

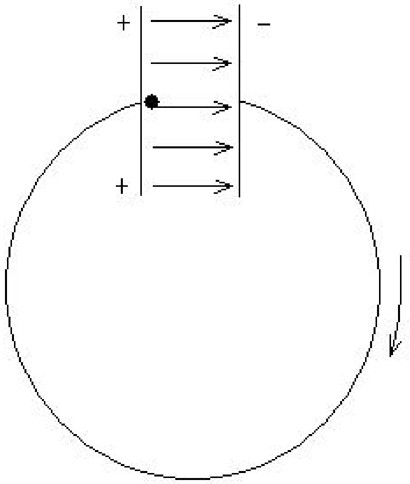




- Linear accelerators

- Repetitive acceleration in a straight line

$\sim V \sin\omega t$



- cyclotrons
- Synchrotrons

- Repeatedly pass through an accelerating structure
- Less space for acceleration
- Need bending magnet
- Loss energy by SR

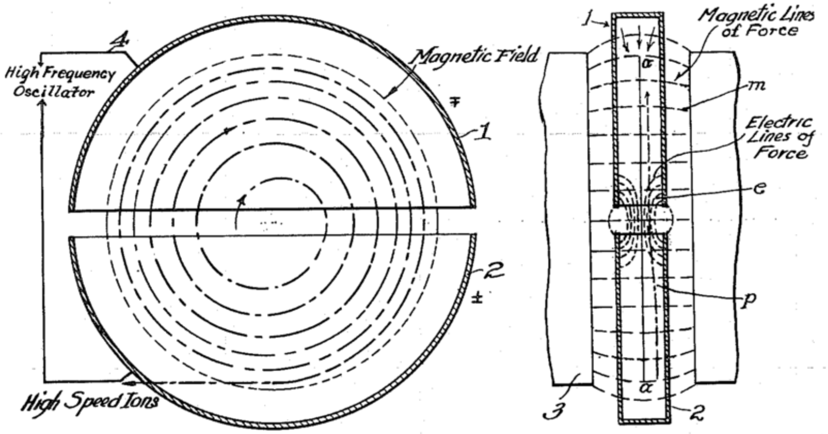
Applying smaller voltages that oscillate in direction

$$d = \frac{\beta c}{f} = \beta\lambda$$

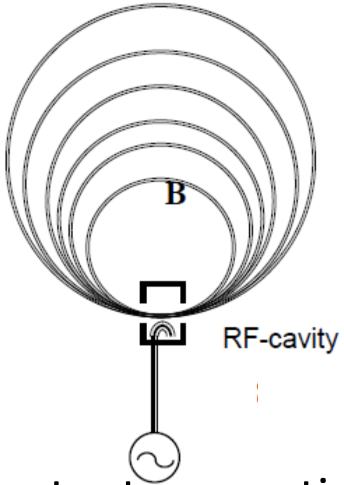
Cyclotrons

- First circular accelerators
- Work for particles whose velocity was much less than *c*

Ernest Orlando Lawrence
Inventor of the cyclotron
Nobel prize, 1939



E. Lawrence's 1934 patent



Centripetal force   Lorentz force

$$\frac{mv^2}{R} = qBv$$

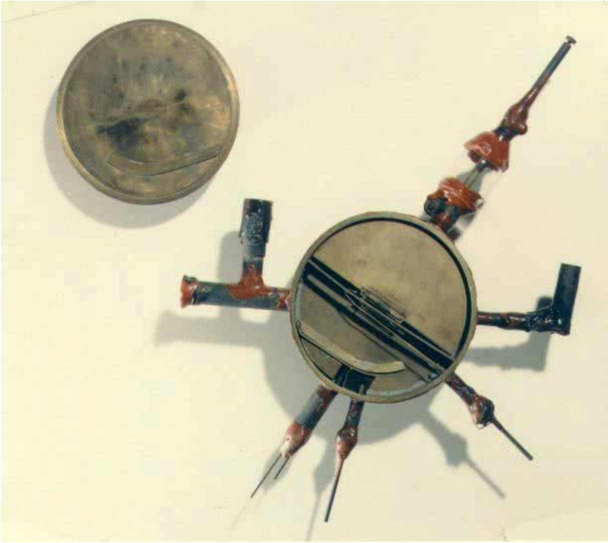
$$\omega_0 = \frac{v}{R} = \frac{qB}{m}$$

- Constant magnetic field, alternating voltage, increasing particle orbit radius
- Constant revolution frequency $\Rightarrow$ particles in time with the accelerating voltage
- Compact design, huge dipole, low energy

Classical Cyclotron

- Not a easy task to built a real machine.
- By the end of 1930, Milton Livingston constructed the first cyclotron.

Milton Stanley Livingston
Constructed the cyclotron

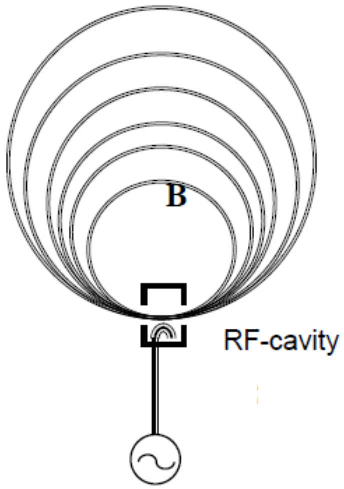


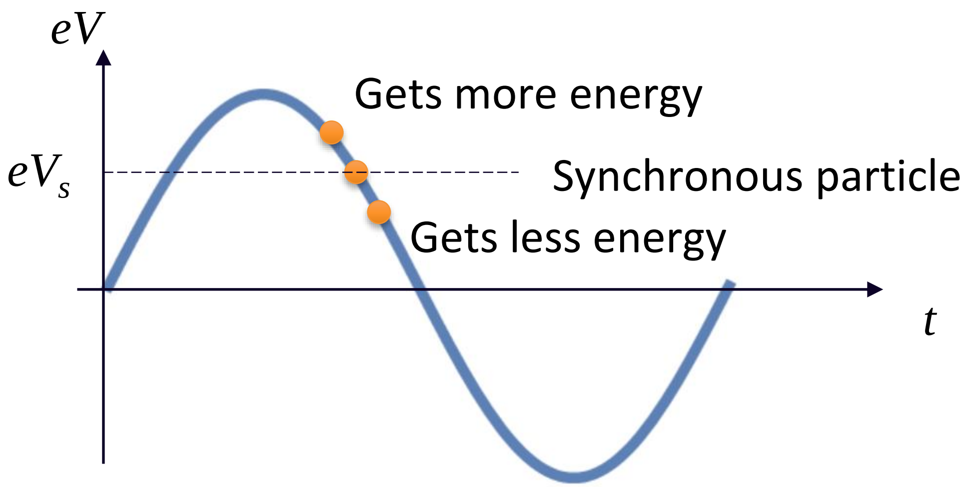
First 4-inch cyclotron, 80keV protons
A number of cyclotrons of increasing size followed.

- Relativistic limitation: As velocity increases, the protons began to feel the effect of relativity
  $\Rightarrow$the revolution frequency varies and couldn't match the accelerating frequency anymore

Synchro-Cyclotron (Phase focusing)

- Allow cyclotrons to overcome the relativistic limitation and accelerate to much higher energies.
- Proposed by Ed McMillan and V. Veksler independently in 1940s.



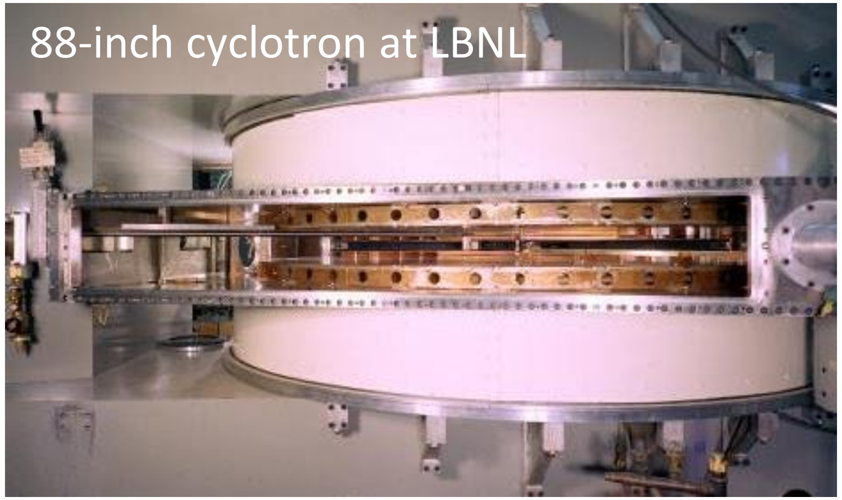


- Interrupt steady stream of particles into bunches.
- Accelerating frequency decreases with the beam revolution frequency ⇒ keep the particles in synchronism with the RF by “phase focusing”

Important concept also for synchrotrons and linacs

Modern cyclotrons

- Spiral sector cyclotrons for nuclear physics
  - With separated magnets and resonators
  - Introduce additional focusing with alternating contribution at entry and exit of the sector fields.
  - Raise the average magnetic field with γ.



Other applications

- Cancer therapy

PET Cyclotron and Radiopharmacy Facility

- Synchro-cyclotrons for medical applications

- Compact cyclotrons for isotope production or dating purpose

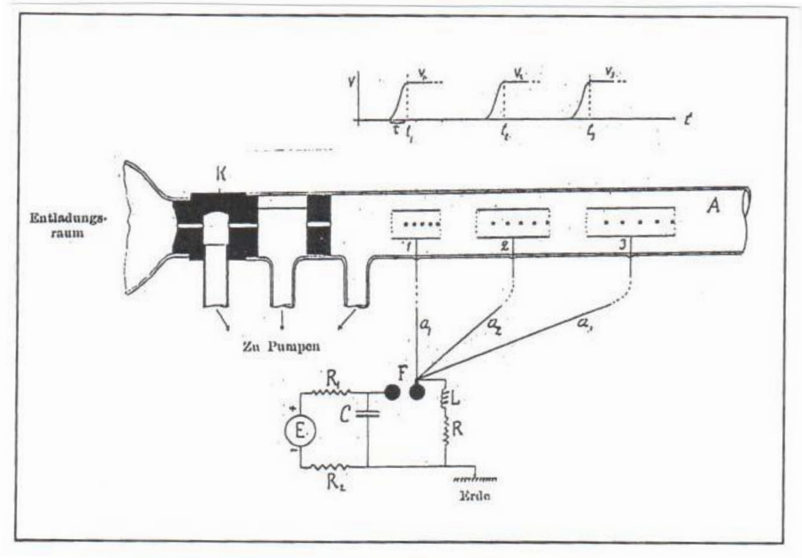
CYCLONE 30 (IBA) : H^- 15 à 30 MeV

Linear accelerators (Linacs)

In 1924, Gustav Ising proposed the linac idea

In 1928, Rolf Wideroe demonstrated RF acceleration for the first time with radio frequency oscillator⇒ limited by the low frequency radio transmitters

→ Avoided the breakdown problems of electrostatic machines and opened the door to all modern accelerators



A drawing from Ising's paper in 1924

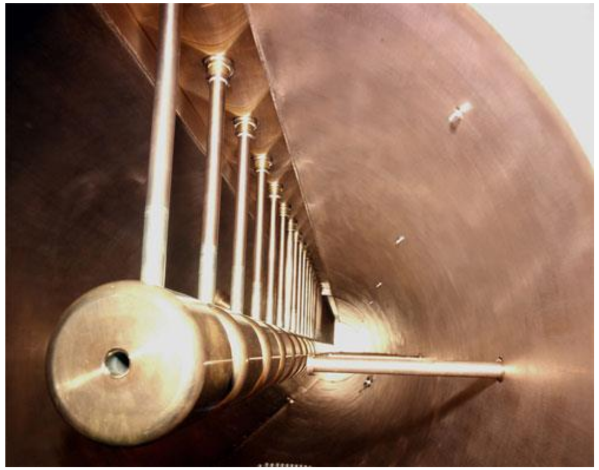
Condition for Synchronicity: $L \sim \beta\lambda$

$$\beta = v/c \quad \lambda = c/f$$

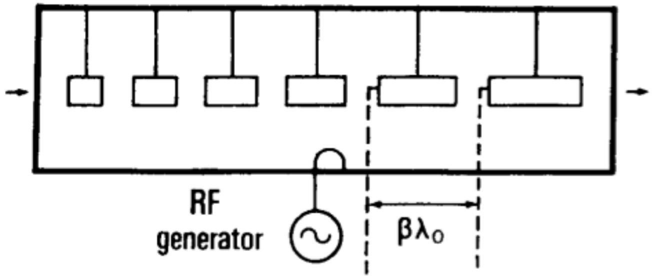
- Particles passing through a sequence of cylindrical metal "drift tube", hosted in a vacuum tube of nonconducting material.
- Energy gain with a rather modest voltage.
- n gaps: the particle reaches an energy of neV.
- Pulses vs. oscillating voltages with one powered drift tube

Proton Linac

- A new linear accelerator by using the powerful high frequency radio sources developed for radar.



DTL (Alvarez structure 1945)



Lius W. Alvarez
Constructed the first proton linac – a 32-MeV drift tube linac (DTL)

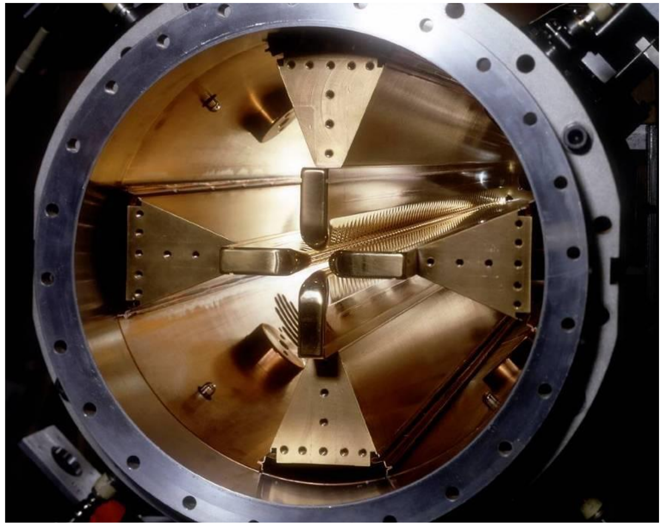
- Drift tubes suspended in a copper cylinder – a kind of waveguide.
- The length of the tubes was chosen so that the particles arrive at each gap just right and gain energy from the oscillating electric field between the tubes.
- Many proton linacs constructed in the years followed Alarez's work.
- Today still serve as the first stage in many accelerator complexes.
- Limited by energy due to length and single pass.

Radio Frequency Quadrupole (RFQ)

- Invented in 1970 by I.M. Kapchinskii and V.A. Teplyakov and promoted by Los Alamos.
- With four-vaned with appropriately spaced radial modulations, instead of drift tubes.
- Focuses, bunches and accelerates the beam at the same time.
- Fine periodicity $\Rightarrow$specially suited to low-velocity, high current beams (keV~ MeV).
- Soon replaced the large electrostatic injectors of synchrotrons.

Excited in an electrical quadrupole mode

- Natural transverse focusing
- Bunching and acceleration from radial van modulation



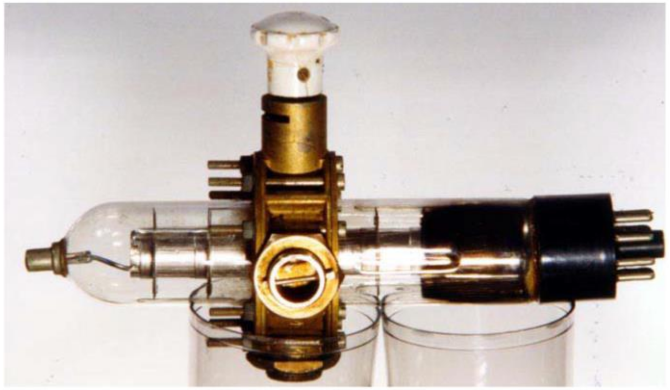
CSNS RFQ accelerate the proton from 50 keV to 3 MeV

Story begins with klystron

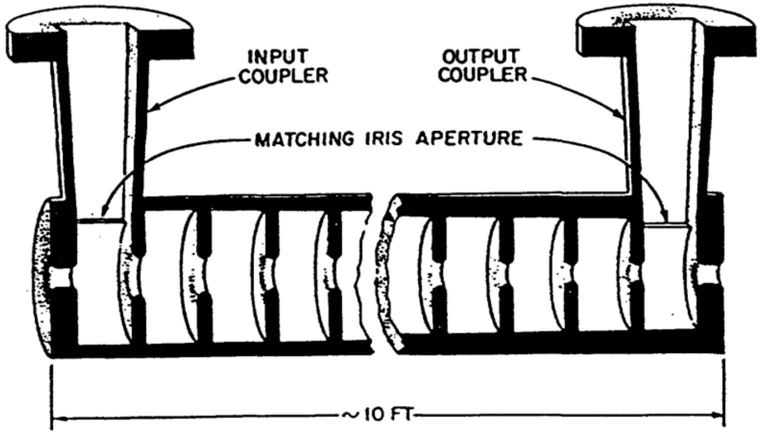
- Klystron, invented in 1937, high frequency power tubes (GHz range) available, and linacs for relativistic particles became feasible.

frequency	200 MHz (radar)	$\Rightarrow$	1~3 GHz (klystron)
wavelength	1.5m	$\Rightarrow$	30 cm~10 cm

- Practical electron linacs were first developed at Stanford University.



A WW2 3 GHz klystron

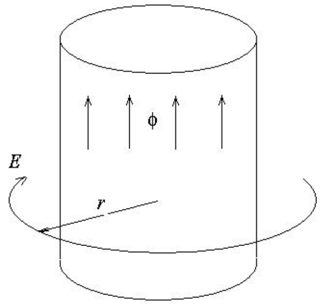


Sketch of SLAC 3 m section

- Distance travel in one cycle barely change.
- Conducting tube with periodic diaphragms with central holes – fulfill the function of drift tubes of Alvarez structure.
- Washers ensure ccelerating wave in phase with the particles.

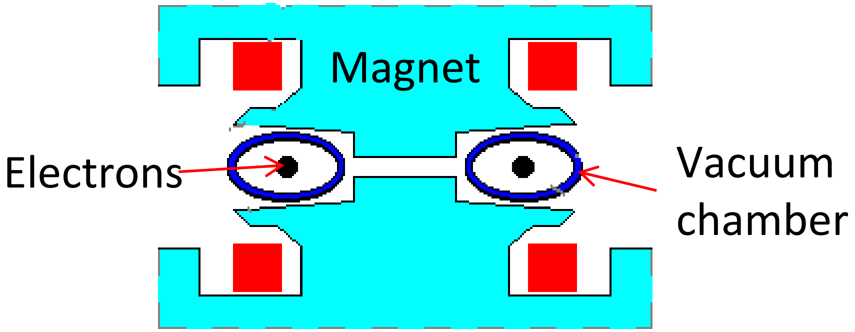
Betatrons

- Cyclotron was for heavy particles but not work with electrons due to the relativistic effect.
- At early times, electrons are not very interesting for physics, and mainly used to produce X-rays with energy of hundred keV (within the range of electrostatic generator).
- Later needs for intense, higher energy electron beams to treat tumors $\rightarrow$ Betatrons



$$\frac{mv^2}{r} = qBv$$

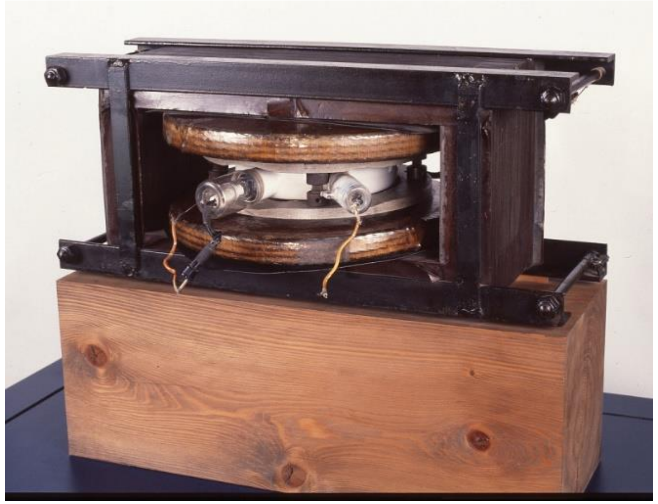
$$E = \frac{\dot{\phi}}{2\pi r}$$



- Circular accelerator accelerate electrons.
- Rising magnetic field serve for both acceleration and bending.
- With constant obit radius.
- Insensitive to relativistic effects.
- Robust and simple.
- First circular machines to have a rising field in step with the rising energy.

Development of Betatrons

- In 1940, Donald William Kerst operated the first successful betatron.
- The popularity was shortly lived in 1940s, in the energy range 5MeV~300MeV, soon replaced by the more compact and less expensive synchrotrons and linacs.
- Widely used for medicine applications in the early days.
- Nowadays, mainly used for portable x-ray sources up to 6 MeV.

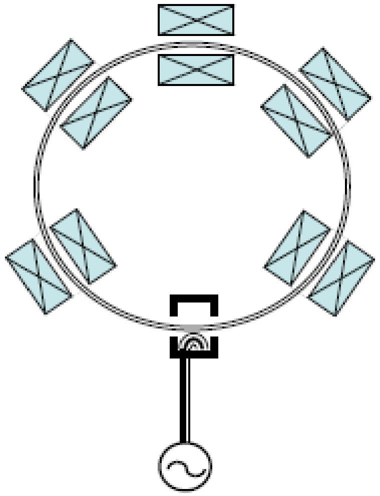


First betatron of Danald Kerst, 1940.

Compact betatrons to produce X-rays for defect detection

Synchrotrons

- For cyclotrons and betatrons, their size and cost grew with their output energy.
- Solution:
  - Use only the outer rim of the magnet for all energies
  - Particles injected into the machine in pulses
  - Keep the radius constant and to ramp B to match the momentum of beam
  - Synchronize both the rise in field and the accelerating frequency



Bending radius

Beam momentum

$$B\rho = \frac{p}{e}$$

Bending magnetic field

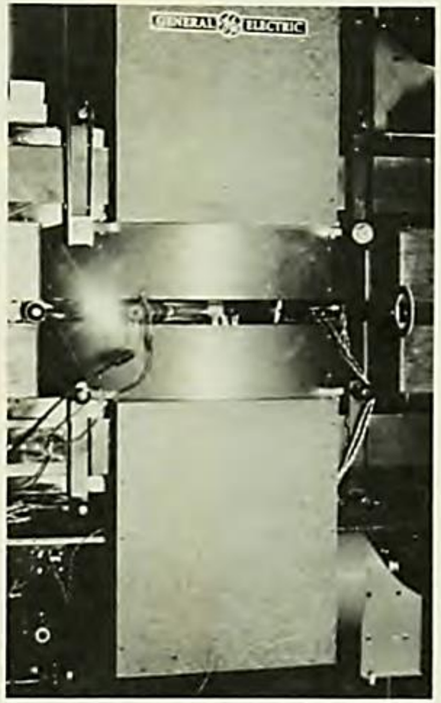
- Suitable for hadron and lepton
- Large size, small magnets
- High energy
- Fixed target
- Paved the way to colliders

Early history of Synchrotrons

- 1943: Marcus Oliphant proposed the idea:

  “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.”

- 1947: Frank Goward converted the Betatron into the first “proof of principle” synchrotron.
- The first purpose-built synchrotron was built one or two month later - first to produce synchrotron radiation in a visible form.

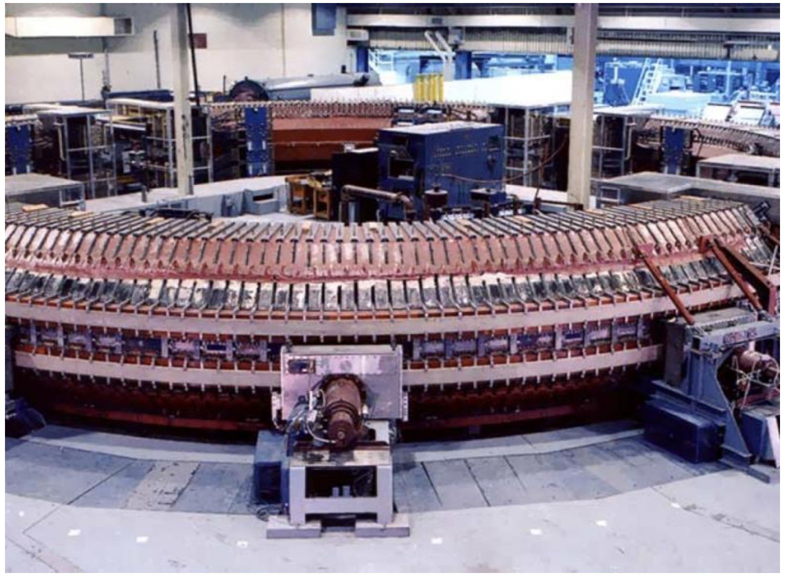


Synchrotron radiation from 70-MeV machine at General Electric Research Laboratory where it was first discovered in 1947.

Early Proton Synchrotrons

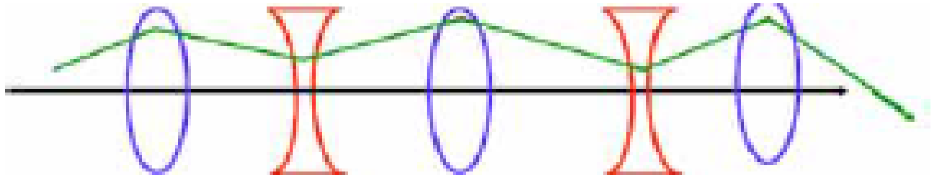
- Oliphant's machine reached just short of 1 GeV for the first time in 1953.
- A few month later, Cosmotron at Brookhaven reached 3 GeV.
- Closely followed Bevatron at Berkeley reached 6 GeV (found the antiproton).

Cosmotron, BNL
3GeV, 1953



Bevatron, Berkeley
6 GeV, 1954

Wake focusing → Strong focusing



- 1952, Stan Livingston proposed the idea of alternating the yokes of the Cosmotron.
- Later, Courant, Livingston and Snyder published the Alternating Gradient focusing idea.
- Then it was found that the strong focusing scheme had actually been patented earlier by Nick Christofilos.

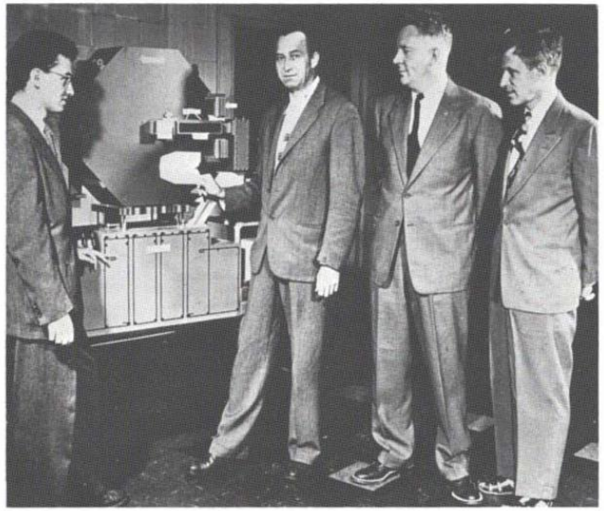
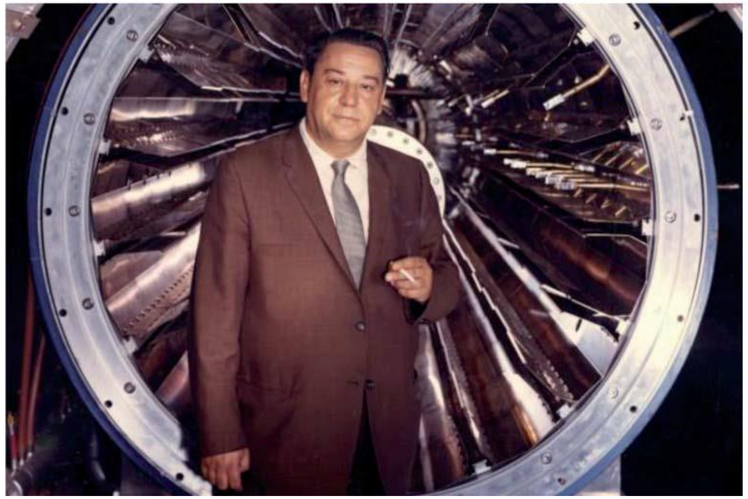
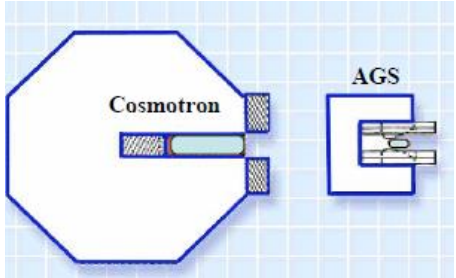


FIG. 27. E. D. Courant, M. S. Livingston, H. S. Snyder, and J. P. Blewett demonstrating the relative cross sections of the cosmotron magnet and a speculative alternating-gradient magnet of very large gradient.



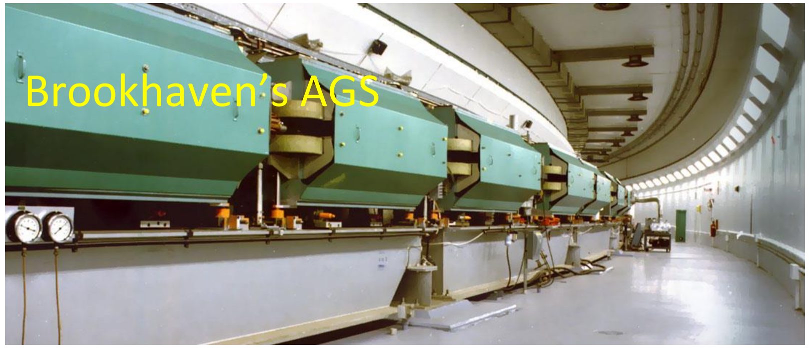
Nicholas Christofilos



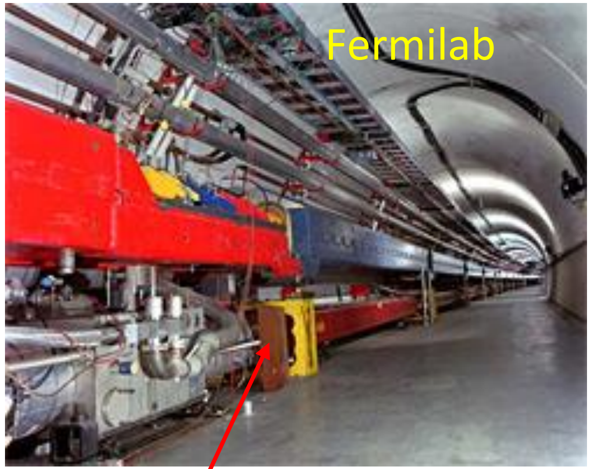
More compact ⇒ lower cost

Strong focusing Synchrotrons

- 1950s, ~30GeV



- 1970s, ~500 GeV, separate function of quad & dipole →squeeze more bending power



- 1980s, Tevatron, 1 TeV, superconducting →higher magnetic field

Colliders – Science motivation

Particle physicists → Theorists
- Seek mathematical descriptions of elementary particles and the interaction forces governing them.
- Often predict a new particle as the model improves.

Particle physicists → Experimenters
- Find the new particle by firing one beam at another.
- Measure its property and test the validity of the theory.

New particle discovered ☺

Nothing found ☹ (missed from analysis? not exist? energy not equate?)

⇓

Build a new machine with high enough energy!

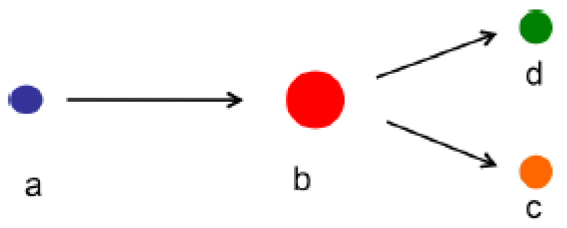
- Choice of collider species
  - Proton – Proton/antiproton (higher energy, one of the three quarks involved in the interaction)
  - Electron – Positron/electron (Lower energy, full energy involved in the interaction)
  - Heavy ions
  - Gamma rays

⇒ All contribute to a full picture of the forces that govern the interaction of particles

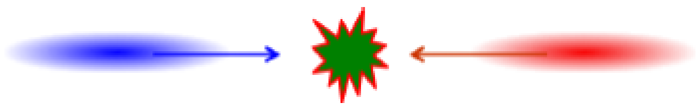
Colliders

- Needs from the atomic nucleus study:
  - Sufficient energy to allow two nuclei to be brought close enough to interact.
- The collider concept was first proposed by Rolf Wideröe in1940s.

Fixed target， $U_{cm} \sim (2U_a \times U_b)^{1/2}$



Colliding beams, $U_{cm} \sim 2U_a$



Proton-proton collider with Ek of 2×100 GeV
= proton beam with Ek of 20000 GeV heat a stationary target

- Circular (double/single ring) or linear
- Maximize center-of-mass energy

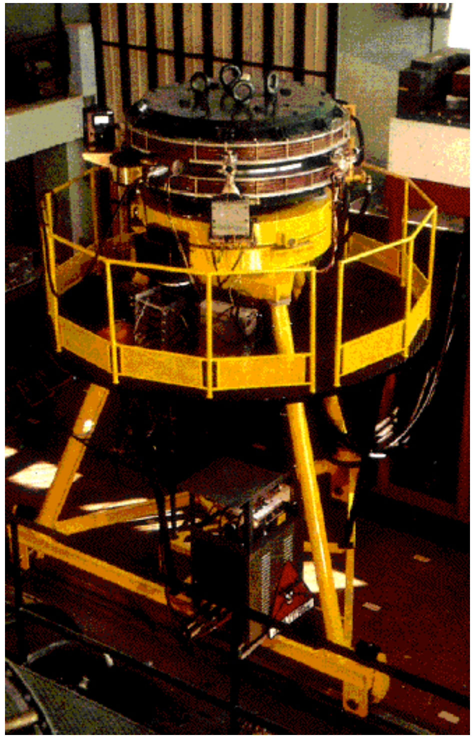
- Luminosity: the likelihood of seeing something interesting from a collision

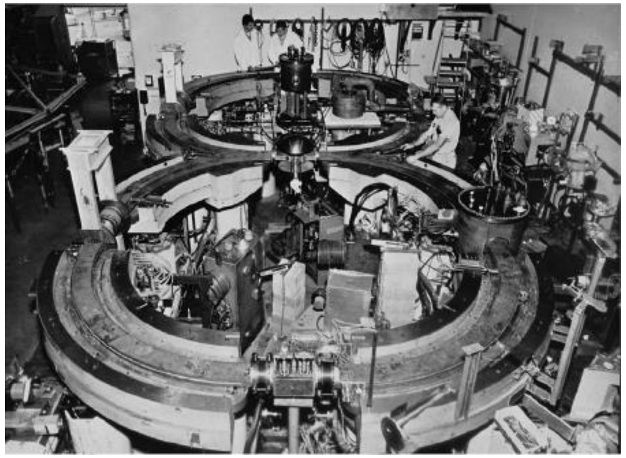
$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y}$$

Early Colliders

First successful e^-e^+ collider, ADA, at Frascati, Italy, proposed by Bruno Touschek (1960)

- Discovered Touschek lifetime





CBX e-e- collider, Stanford

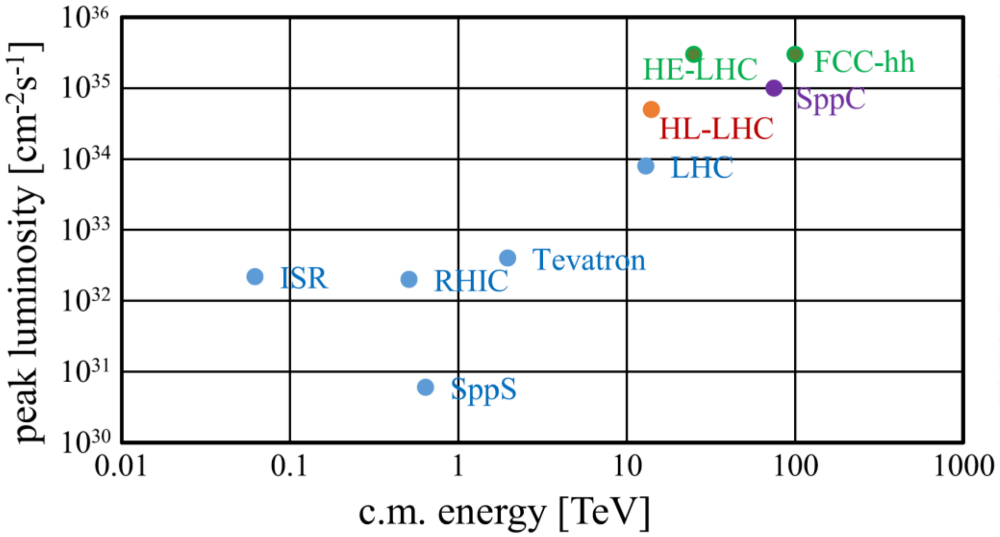
- Stored 1 A/beam
- Beam-beam tune shift observed

VEP-1 e-e- collider, Novosibirsk

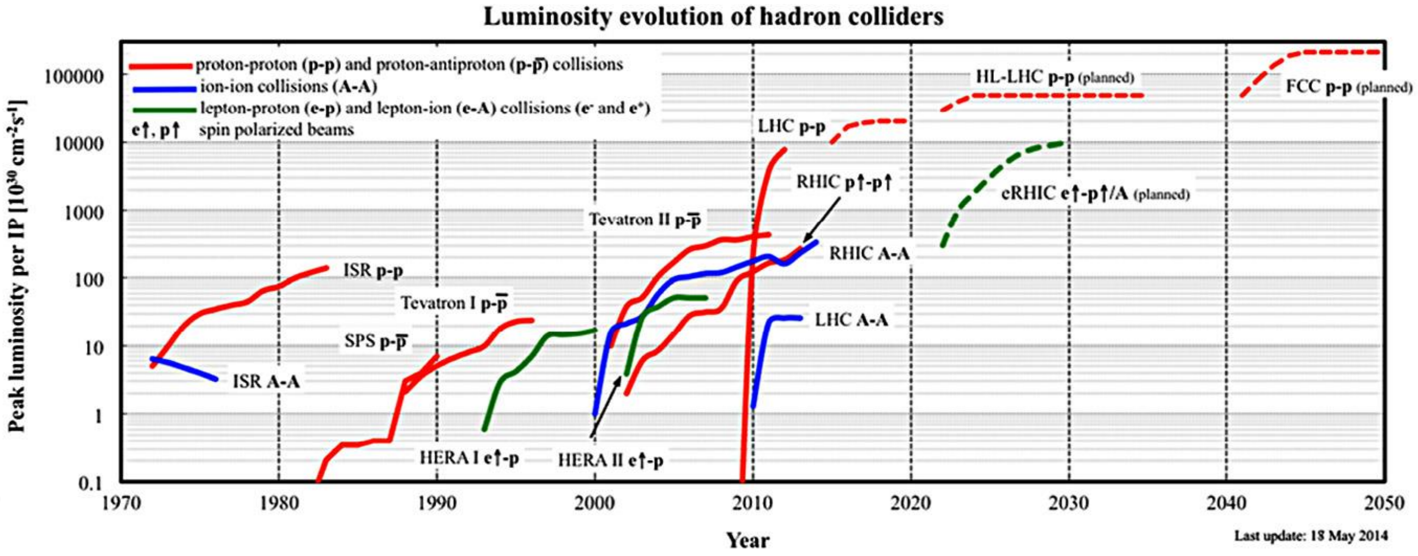
- Beam-beam effects found
- Beam-beam tune shift observed

Hadron Colliders

- Developed since 1970s, with increasing energy and luminosity.
- Discovery reach determined by the beam energy (dipole magnetic field, size of machine).
- Likely to determine the pace of particle-physics progress and essential for establishing the standard model of particle physics.

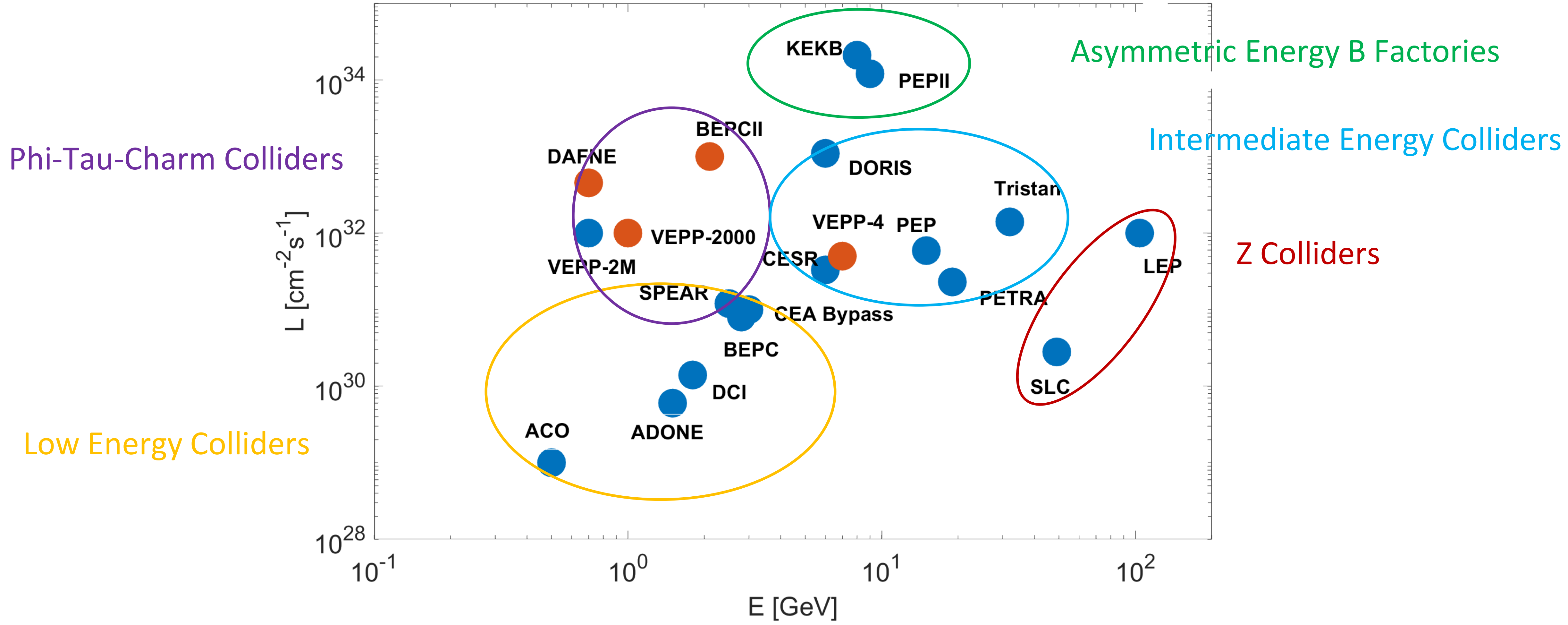


Luminosity vs. center-of-mass energy



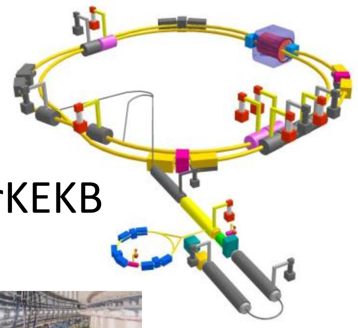
Hadron collider peak luminosity as a function of year

Electron-Positron Collider Family



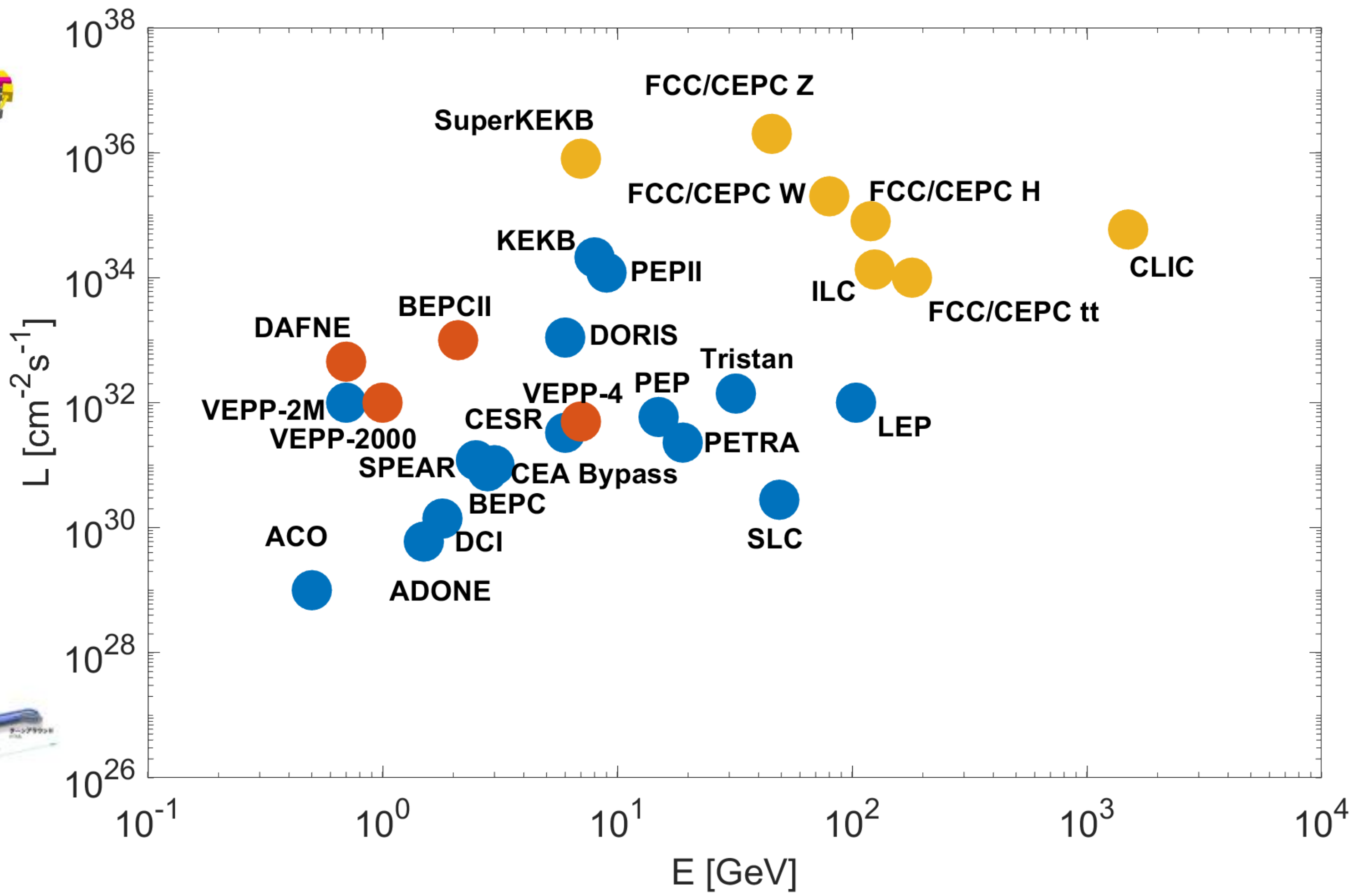
These facilities essentially shaped modern particles physics.

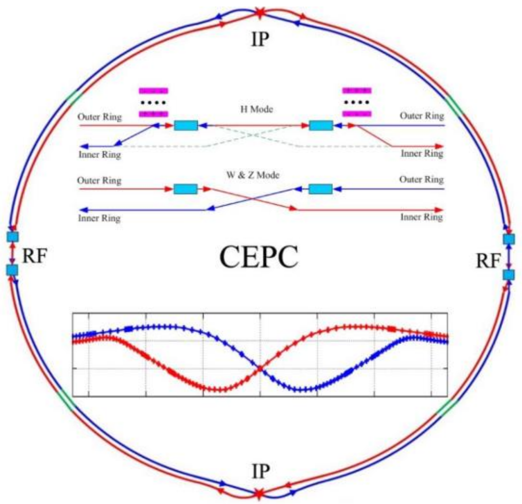
Future Electron-Positron Colliders

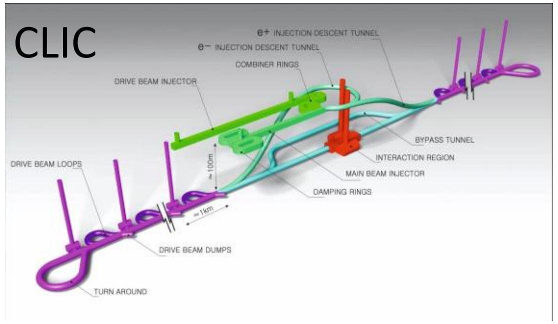


SuperKEKB

ILC

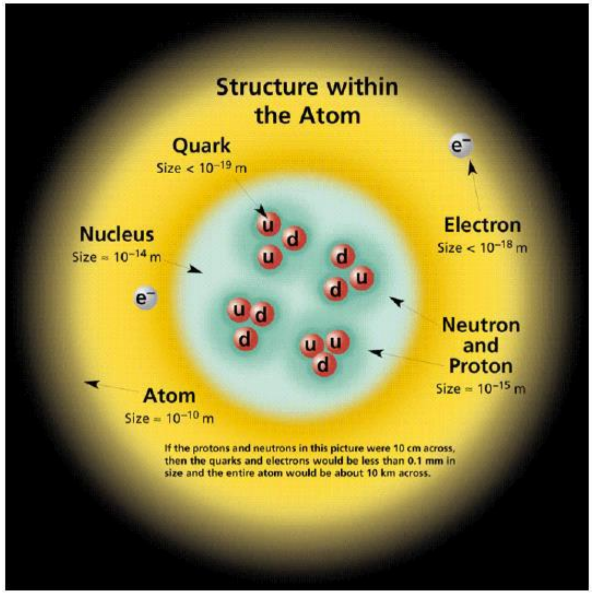






Livingston chart

- Keep construction of bigger and better machines, not a given type, for particle physics research.
- Show evolution of accelerator energy in the over 70 years $\Rightarrow$ 12 orders of magnitudes increase on the accelerator energy.
- Accelerators have become indispensable in the quest to understand nature at smaller and smaller scales.

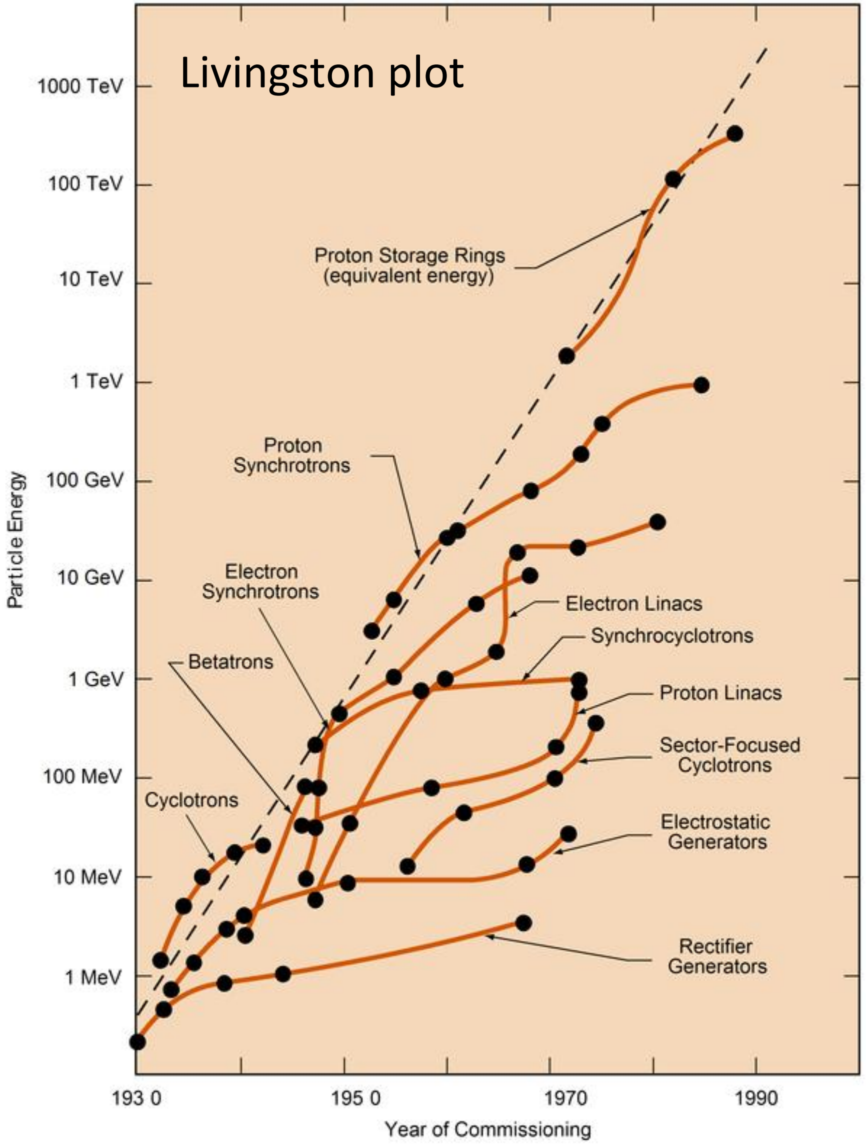


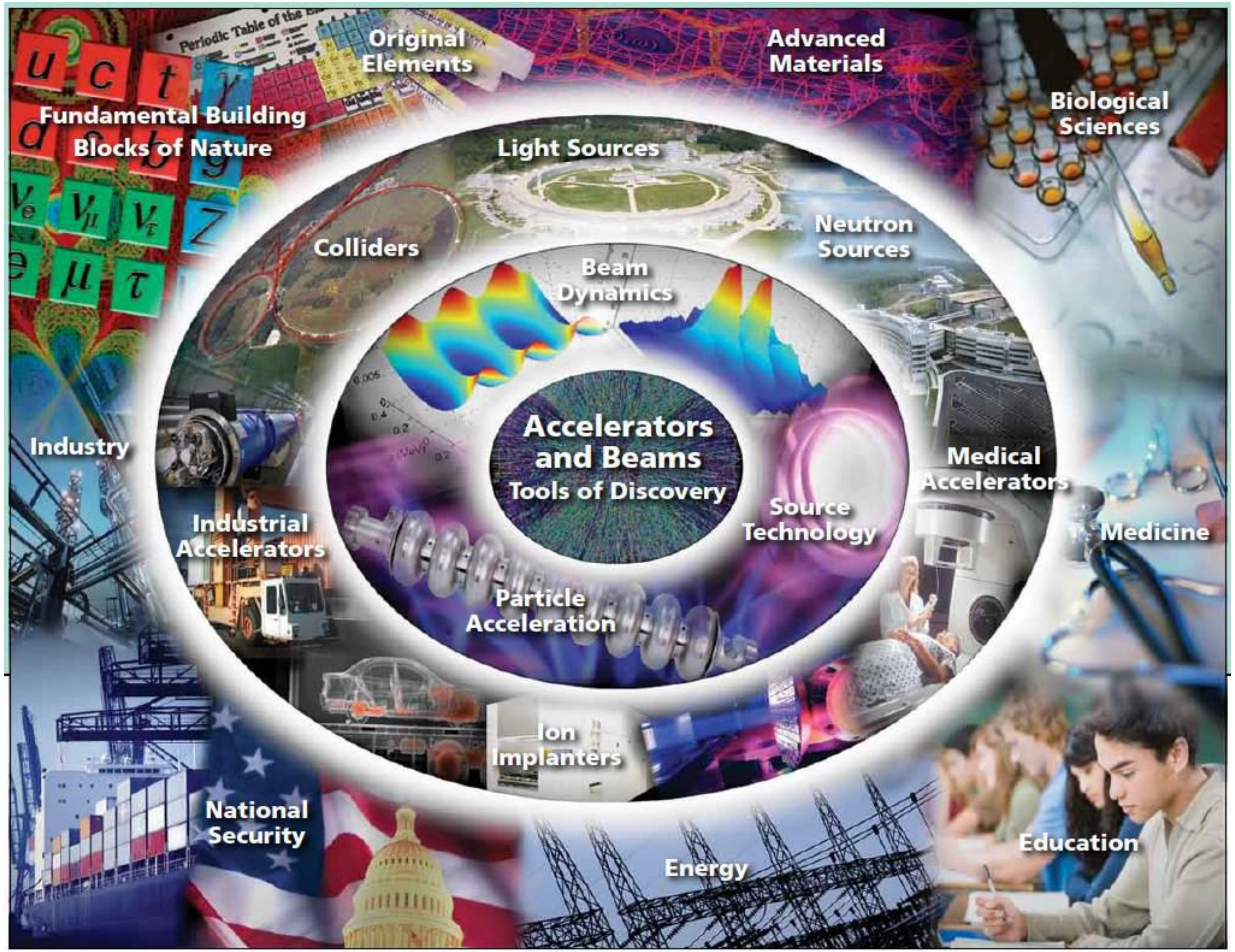
Higher energy $\Rightarrow$ shorter wavelength $\Rightarrow$ probe deeper into the structure:

Examine at the scale of atom: keV

At the scale of nucleus: MeV

Fine structure of the basic constituents of matter: GeV




Original Elements
Advanced Materials
Biological Sciences
Fundamental Building Blocks of Nature
Light Sources
Neutron Sources
Colliders
Beam Dynamics
Accelerators and Beams
Tools of Discovery
Industry
Medical Accelerators
Source Technology
Industrial Accelerators
Medicine
Particle Acceleration
Ion Implanters
National Security
Energy
Education

Accelerator related subjects

- Hinge upon many different physics subjects and advanced technologies

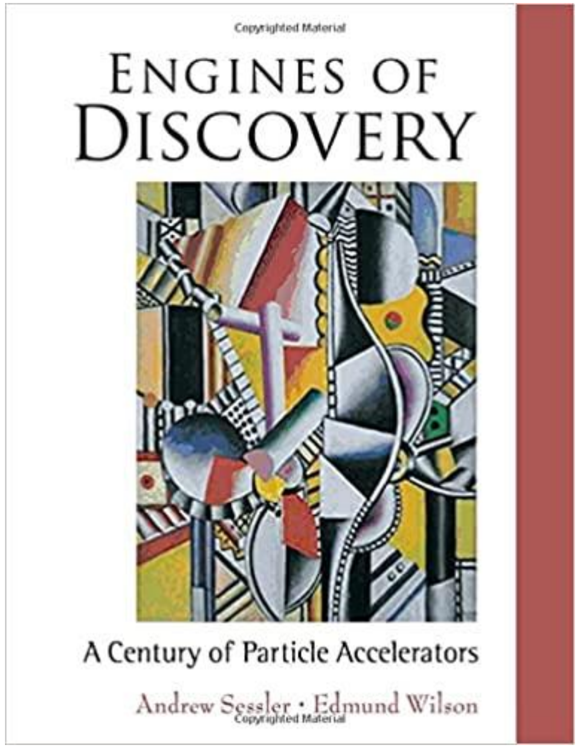
Physics

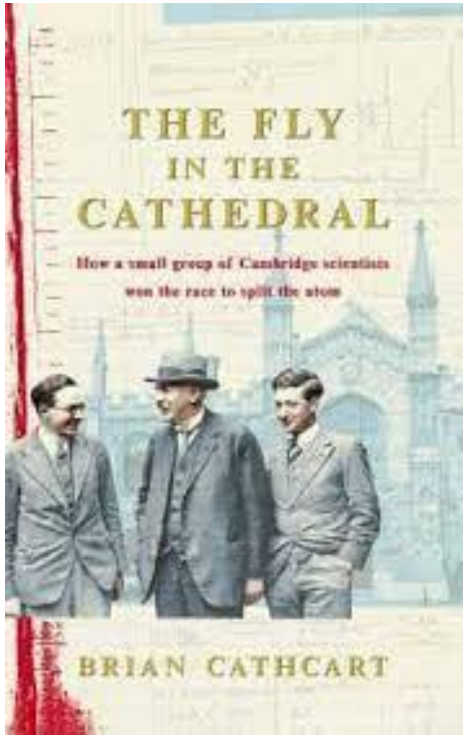
Relativistic dynamics
Electrodynamics
Plasma physics
…

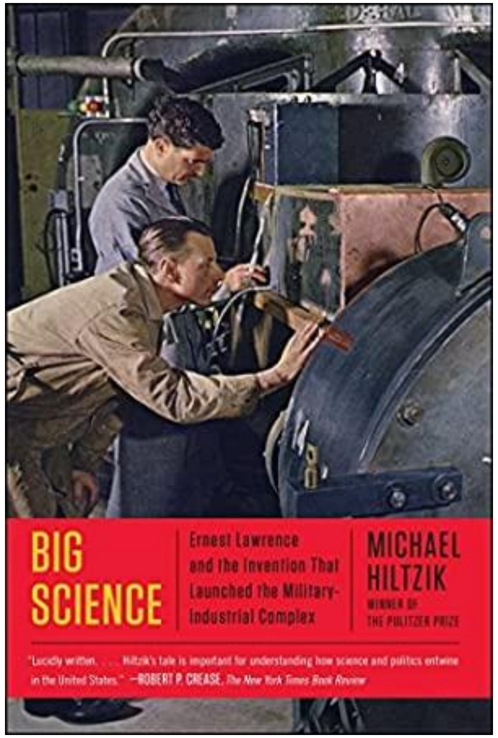
Technologies

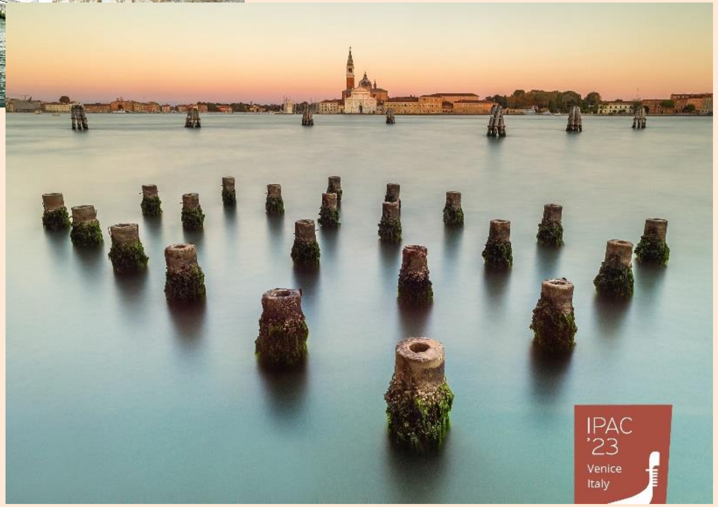
Vacuum
Radio frequency
Magnet
Power supply
Mechanics
Superconducting
Electronics
Computers
…

Recommended books









Thank you for your attention!