National Research Nuclear University «MEPhI»
Department «Elementary Particle Physics»

INSTRUMENTS and FACILITY in HIGH ENERGY PHYSICS

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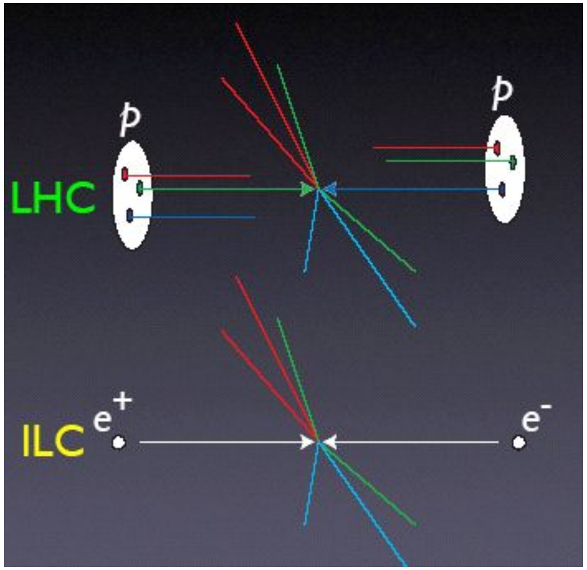
Part 1 Accelerators

Lection 2

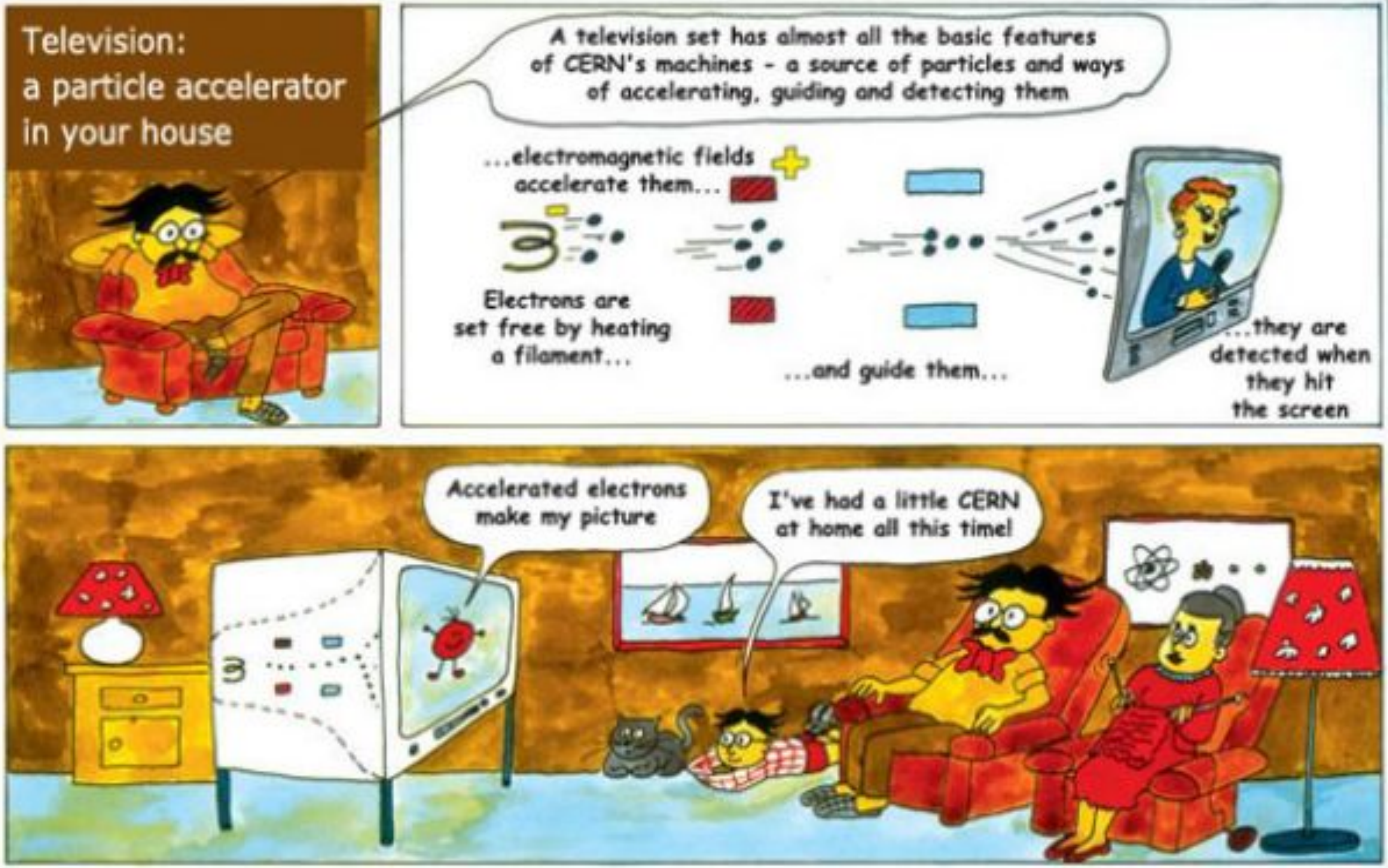
Linear Accelerators

Applications of Linear Accelerators

- **Medicine and technology**
- **Neutron generators**
- **Neutral particle beams**
- **Energy recovery linacs ERL (synchrotron radiation sources)**
- **X-ray free electron laser X-FEL**
- **High energy physics – Linear collider**



In 2002 more than 7500 medicine electron Linacs were in the world

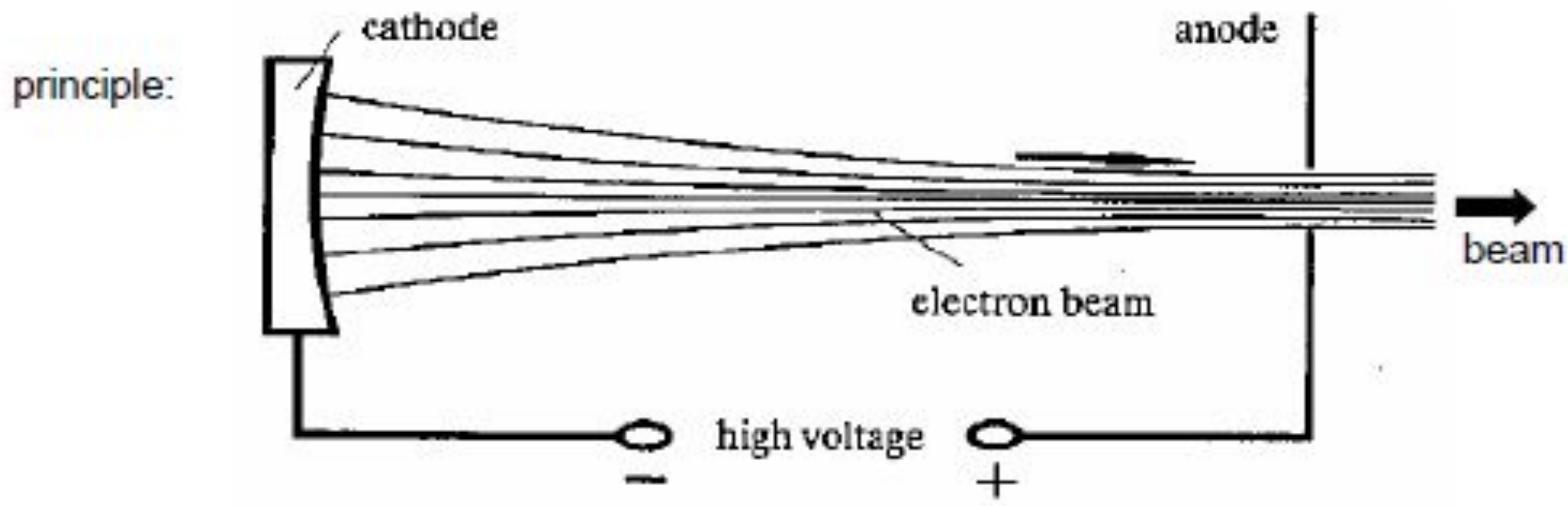

Television:
a particle accelerator
in your house
A television set has almost all the basic features of CERN's machines - a source of particles and ways of accelerating, guiding and detecting them
Electrons are set free by heating a filament...
...electromagnetic fields accelerate them...
...and guide them...
...they are detected when they hit the screen
Accelerated electrons make my picture
I've had a little CERN at home all this time!

Linac

- Linacs are single pass accelerators for electrons, protons, or heavy ions
  - Thus the KE of the beam is limited by length of the accelerator
    - Medical (4-25 MeV) – 0.5-1.5 m
    - SLAC (50 GeV) – 3.2 km
    - ILC (250 GeV) - 11 km
- Linac – static field, induction (time varying B field), RF
  - Operate in the microwave region
  - Typical RF for medical linacs ~ 2.8 GHz
  - Typical accelerating gradients are 1 MV/m – 100 MV/m

DC Voltage Accelerators

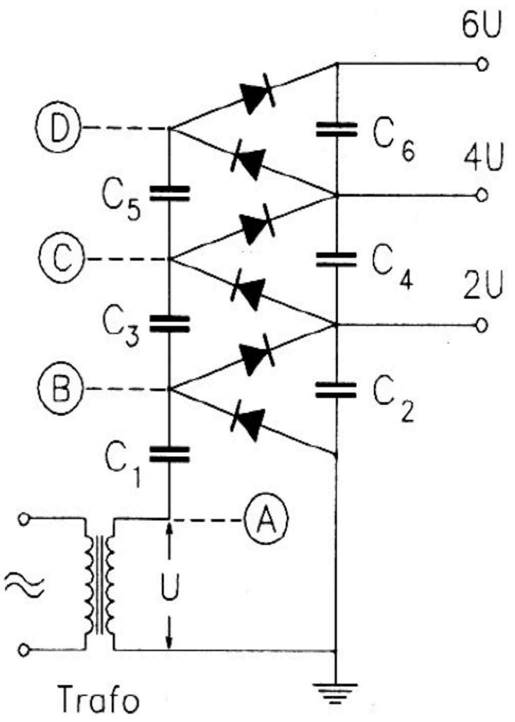
$$\vec{F} = \frac{d\vec{p}}{dt} = q \cdot \vec{E}$$



maximum voltage ~ 5-10 MV in Van der Graaff generators

- Voltage multiplier cascade (Cascade accelerators, Cockcroft and Walton)
- Electrostatic generator (Van de Graaff accelerators)

Cascade Accelerators



John Douglas Cockcroft

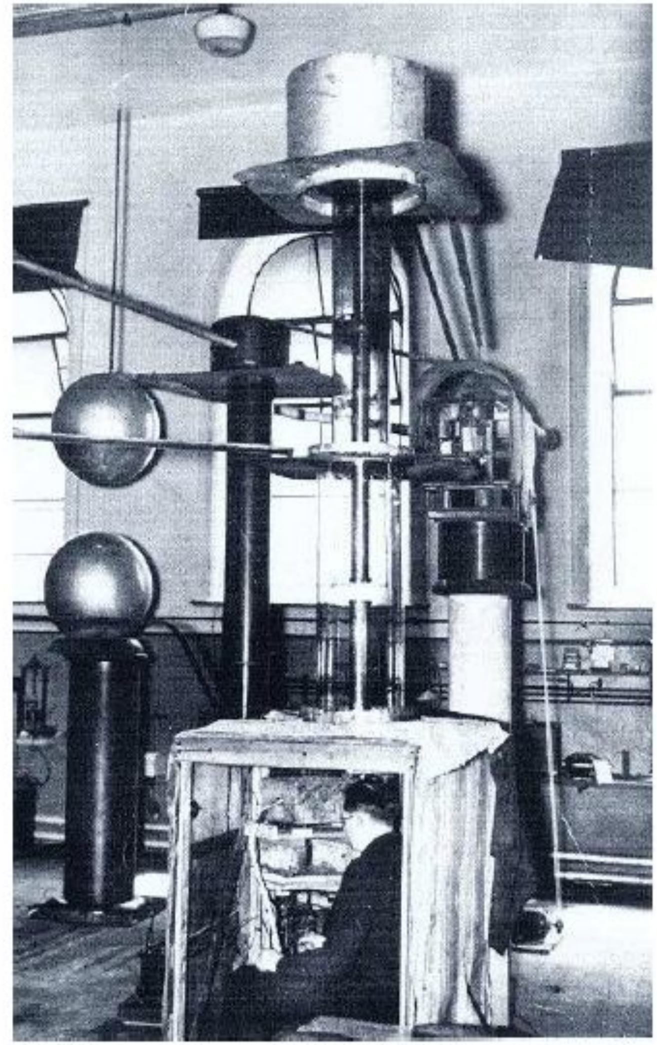
Ernest Thomas Sinton Walton

Nobel Prize - 1951

for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles

The basic method implemented in the cascade generator is a voltage multiplication across the plates of a capacitor. A set of capacitors are charged through appropriately placed diodes from an alternating current source

John Cockcroft, Ernest Rutherford, and E.T.S. Walton.

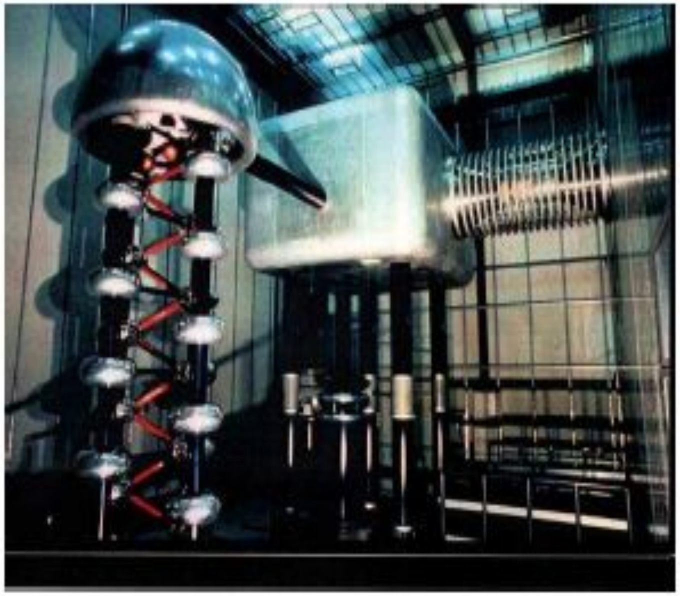


Cockcroft-Walton accelerator installation at the Cavendish Laboratory in Cambridge, England.

•This is the first accelerator to demonstrate disintegration of atomic nuclei by artificially accelerated particles! They induced the nucear reaction:

$$Li + p \rightarrow 2He$$

Cascade Accelerators



A modern version :
the 810 kV, 30 mA Cockcroft-Walton injector at the PSI Mega-Watt cyclotron, using a voltage multiplier.

Tevatron injector at FermiLab (source, C-W and transfer lines are doubled for minimal down-time). H-, 20 keV DC beam, accelerated to 750 keV prior to bunching and injection into a DTL.

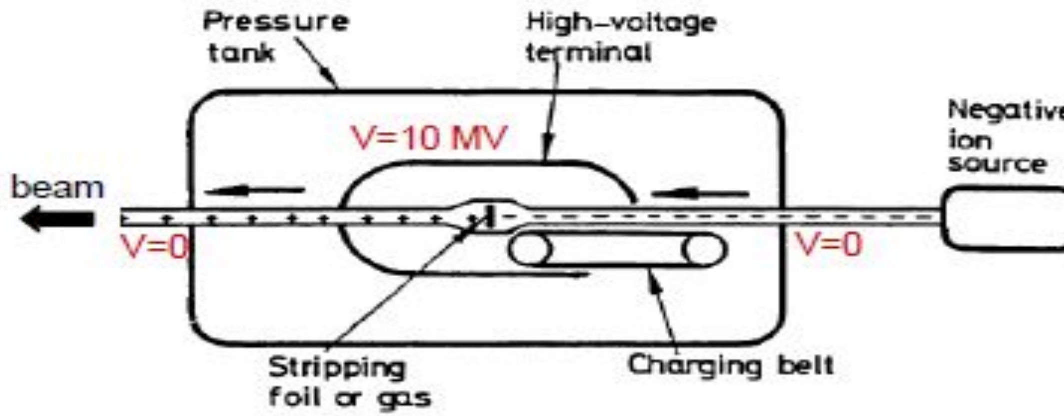
And a trend, replacement by RFQ :

"[...] to reduce the maintenance requirements of the 750-keV pre-accelerator system, the replacement of the present Cockcroft-Walton accelerators with a single RFQ accelerator is proposed." (December 2008)

Proton Pre-Accelerator

Van der Graaf Accelerators

1929 – 0.08 MV
1931 – 7.0 MV

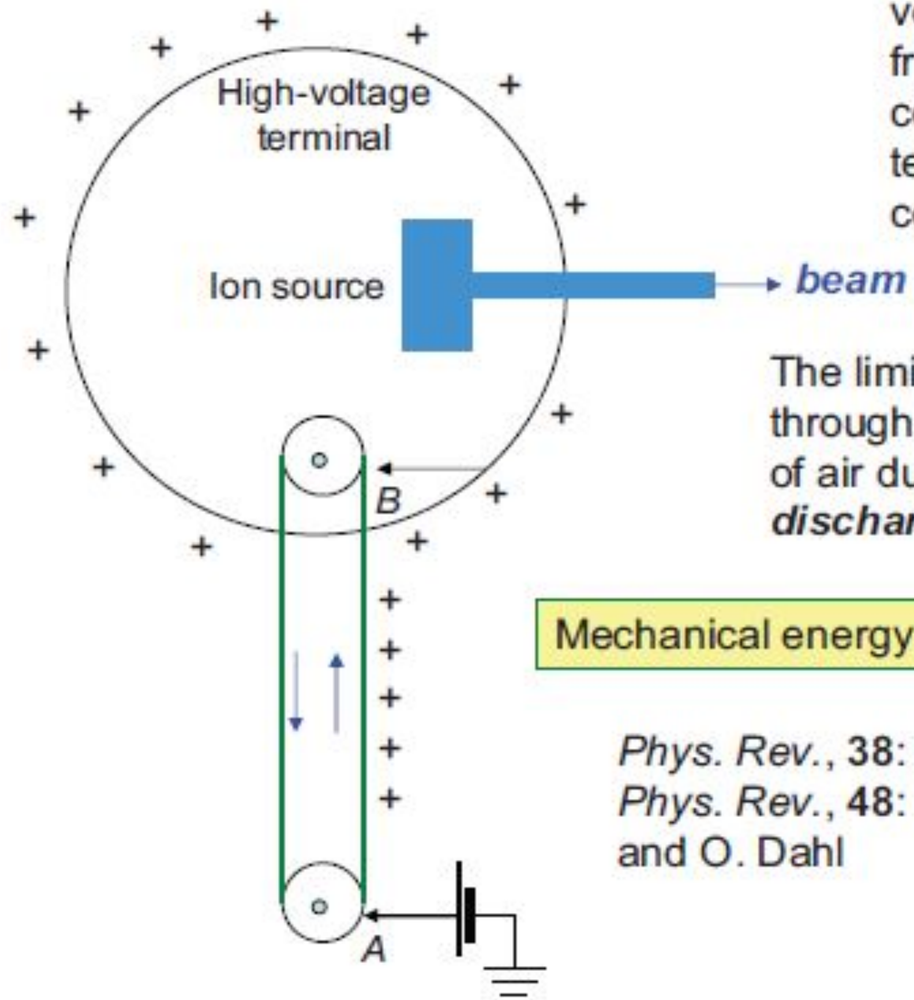


Tandem Van der Graff accelerator

tandem = "two things placed one behind the other"

Van der Graaf Accelerators

Belt-charged Electrostatic Generator (invented by R.J. Van de Graaff)



Charge is sprayed from a sharp tip at ***A*** on a moving belt (insulating material). The belt carries the charge to the high-voltage terminal, where it is removed from the belt at ***B*** (a sharp tip connected to the outer conductor of terminal) and transfers to the outer conductor of terminal.

The limiting factors: leakage of charge through the insulating supports, breakdown of air due to the moisture (***corona discharge***: near sharp points or edges)

Mechanical energy (motor) → Electrical potential energy

Phys. Rev., **38**: 1919 (1931), R.J. Van de Graaff
Phys. Rev., **48**: 315 (1935), M.A. Tuve, L.R. Hafstad, and O. Dahl

Van der Graaf Accelerators

12 MV-Tandem van de Graaff Accelerator
at MPI Heidelberg, GE

One of the two (face-to-face) stages of the 15 MV Tandem-Van de Graaff at BNL. Can accelerate 40 different types of ions.

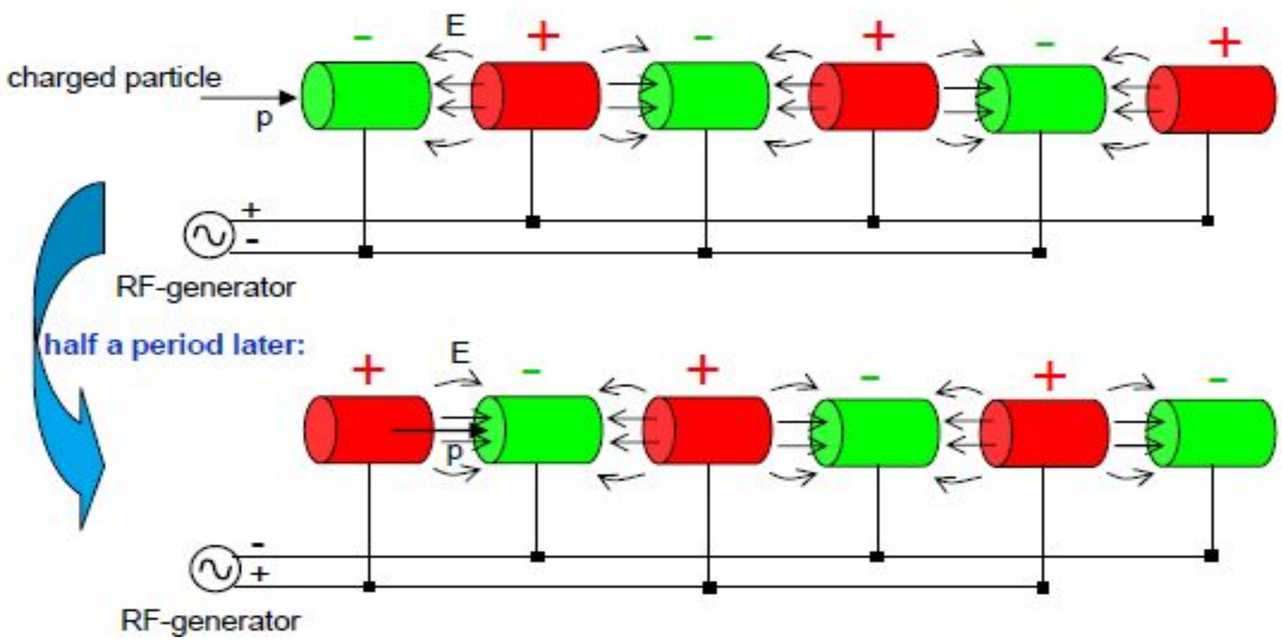
20 MV-Tandem
at Daresbury, UK

Layout of RF Linear Accelerator

Structure:

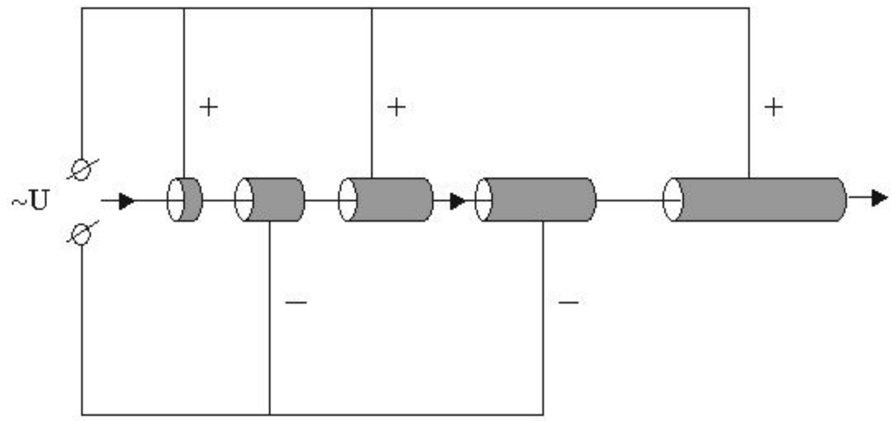
- **A series of drift tubes alternately connected to high frequency oscillator.**
- **Particles accelerated in gaps, drift inside tubes .**
- **For constant frequency generator, drift tubes increase in length as velocity increases.**
- **Beam has pulsed structure.**

Wideroe (1928): apply acceleration voltage several times to particle beam



Length of the n-th drift tube:

$$l_n = v_n * \frac{\tau_{RF}}{2} = v_n * \frac{1}{2\nu_{RF}}$$



Particles are accelerated in a gap between drift tubes. When the field becomes decelerating the ions drift inside the tube

Linac

- **A linac uses an oscillating EM field in a resonant cavity or waveguide in order to accelerate particles**
  - **Why not just use EM field in free space to produce acceleration?**

- **We need a metal cavity (boundary conditions) to produce a configuration of waves that is useful**
  - **Standing wave structures**
  - **Traveling wave structures**

Resonant Cavities

Limitations of drift tube accelerators:

- only low freq. (<10 MHz) can be used

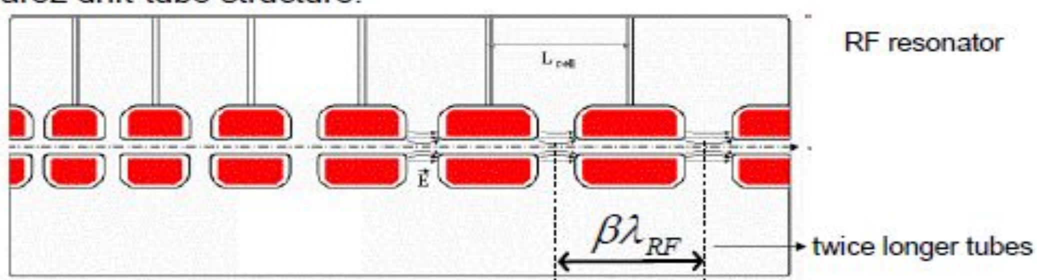
$$L_{tube} = \beta\frac{\lambda}{2} = \beta\frac{c}{2f}$$ → 30 m for β=1 and f=10 MHz

→ drift tubes are impracticable for ultra-relativistic particles (β=1)

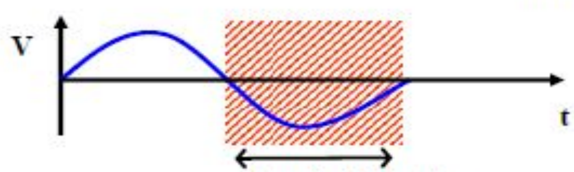
→ only for very low β particles

Resonant cavities

Alvarez drift-tube structure:



higher frequencies possible → shorter accelerator



still preferred solution
for ions and protons
up to few hundred MeV

In Alvaretz structure the electric field in all the gaps has the same direction and phase, therefore the synchronism condition is L=β·λ

RF Cavities – Techniques

Pulsed, High Power up to GHz RF generators – Klystron, allowing wavelengths in meter range

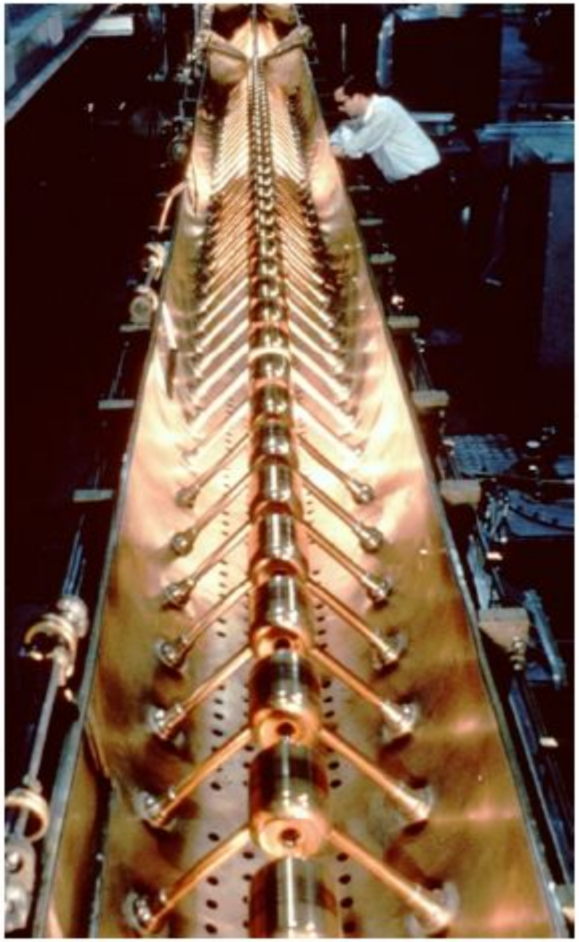
RF phasing : an accelerating standing wave fills the cavity.

Electromagnetic power is stored in a resonant volume.

RF power feed into cavity, originating from RF power generators, like klystrons.

RF power oscillating (from magnetic to electronic energy), at the desired frequency.

RF cavities requires bunched beams.

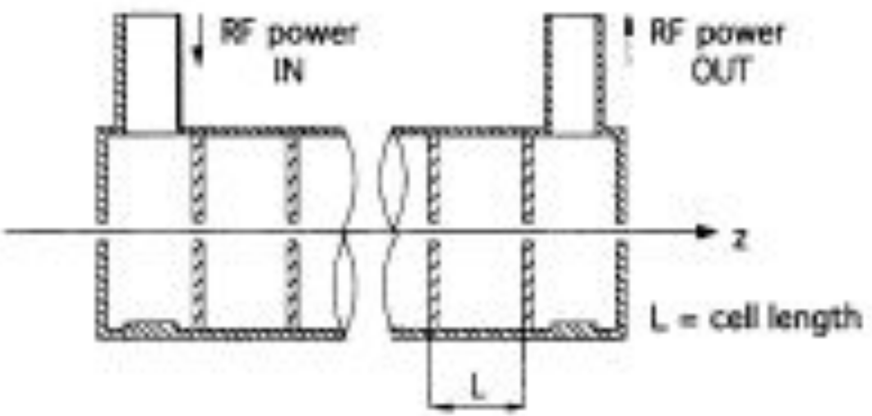


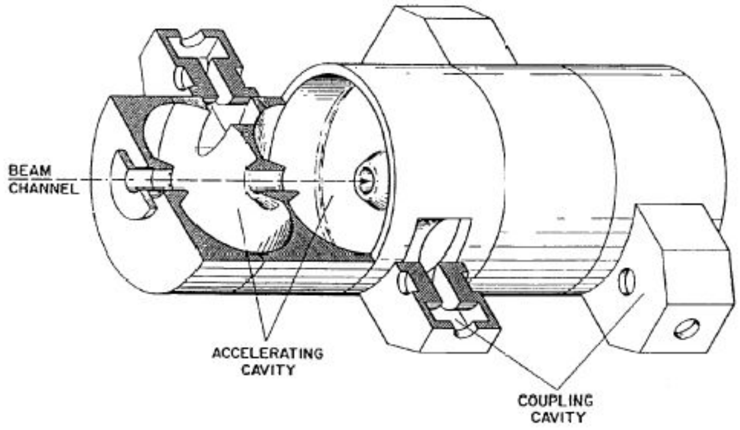
Alvarez structure at CERN

JINR Alvarez – injector for the Nuclotron

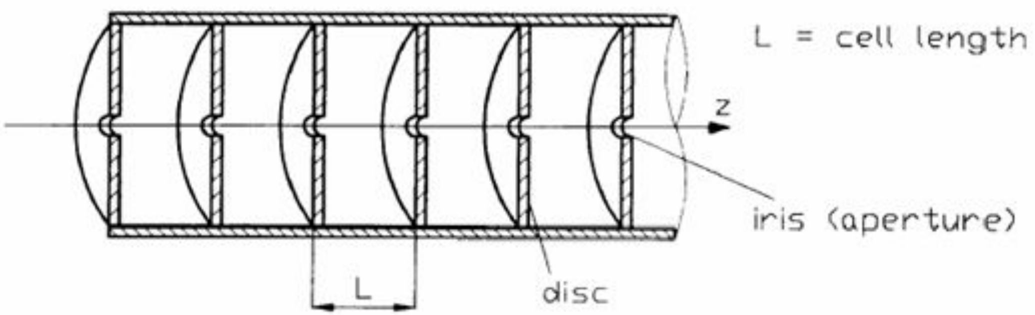
Traveling wave structures

For acceleration of relativistic particles different types of traveling wave structures operated at frequency from a few hundreds of MHz to a few GHz are used.





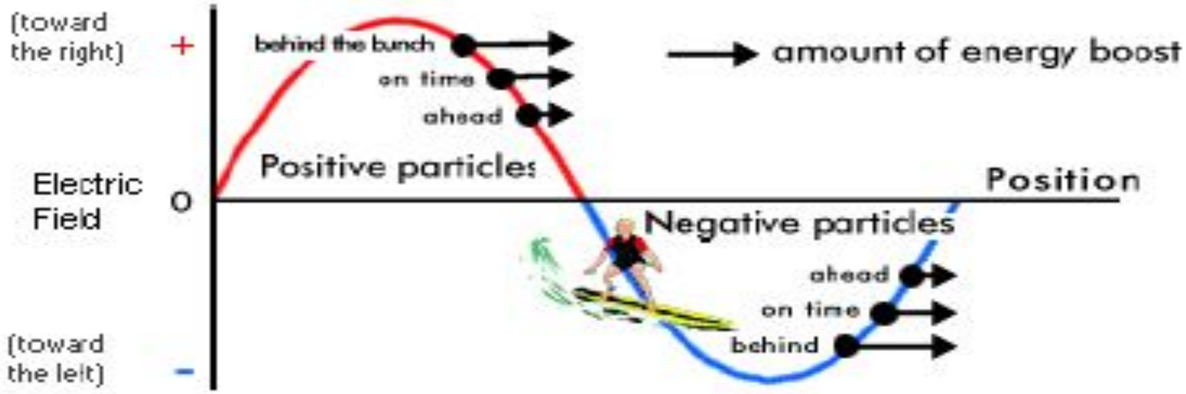
Side coupled structure

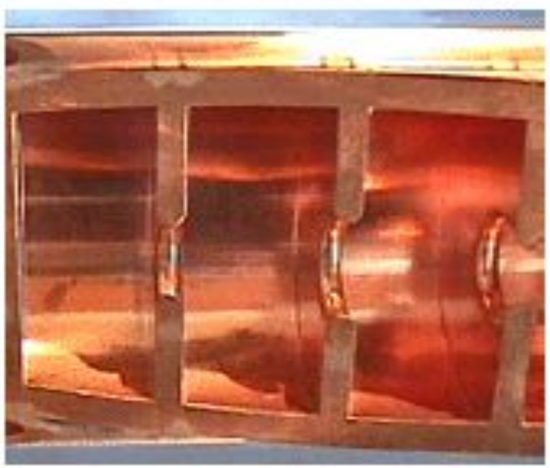


Disc loaded round wave guide

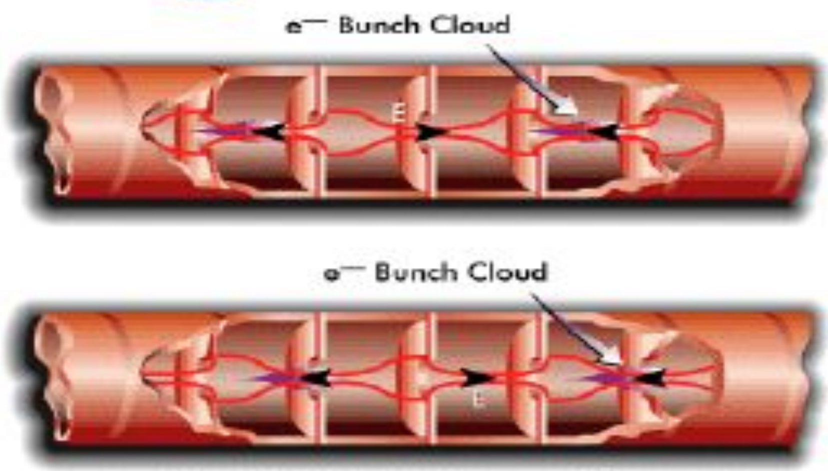
Auto Phasing Principle

Electron Linac (disk loaded structure)





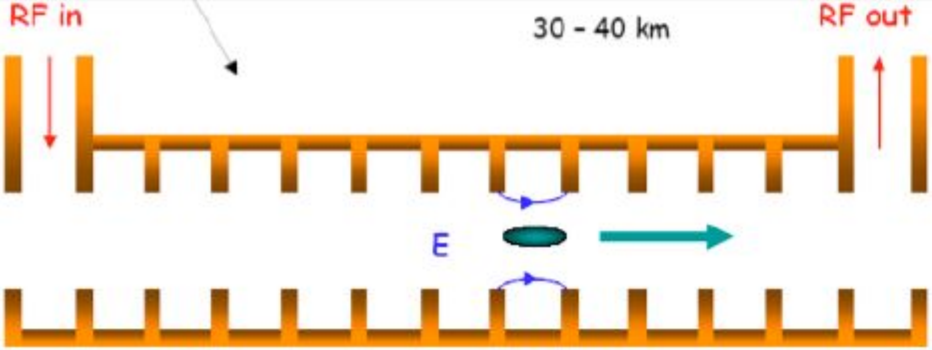
[Ref.] http://www.slac.stanford.edu



1/20,000,000,000 second later
(notice how far the bunches have moved)

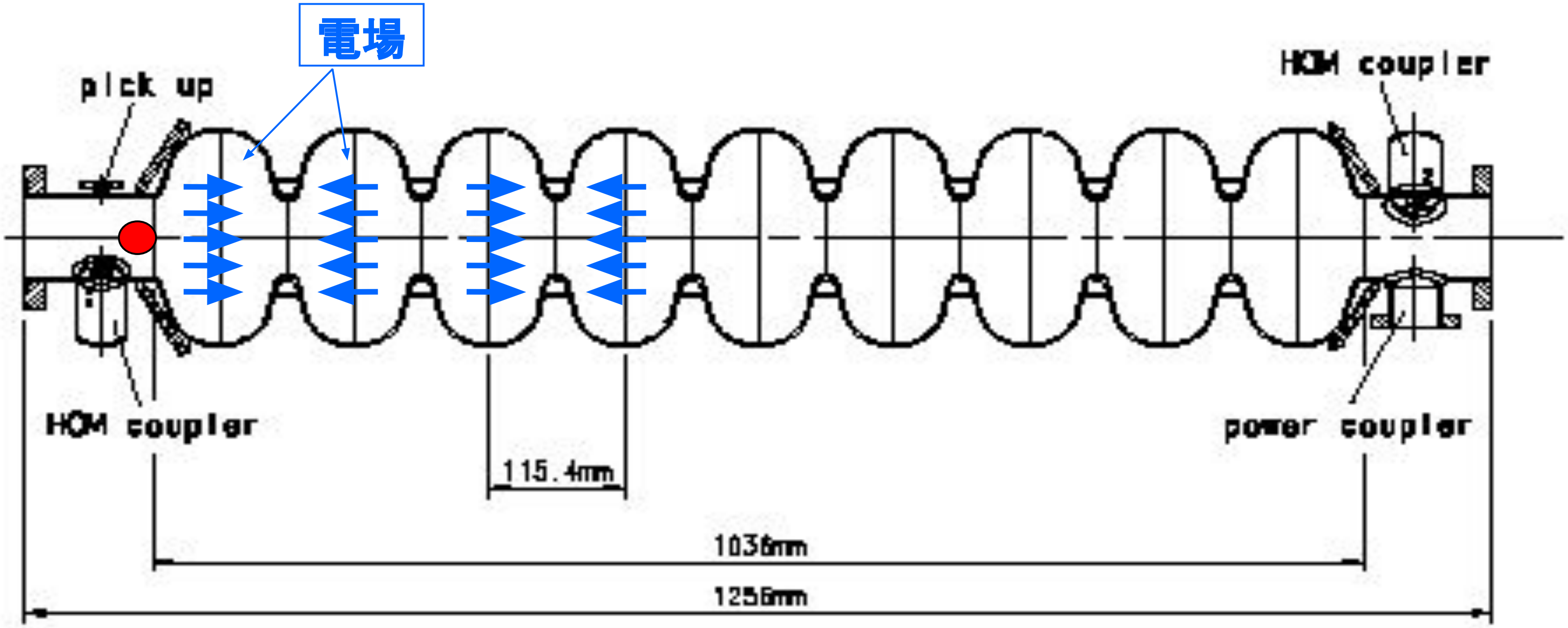
Electron Linear Accelerators

Electron linear accelerators: v = c. Travelling wave coupled structures can be seen as a waveguide (v_p > c) with irises to reduce phase-velocity to v_p =c.

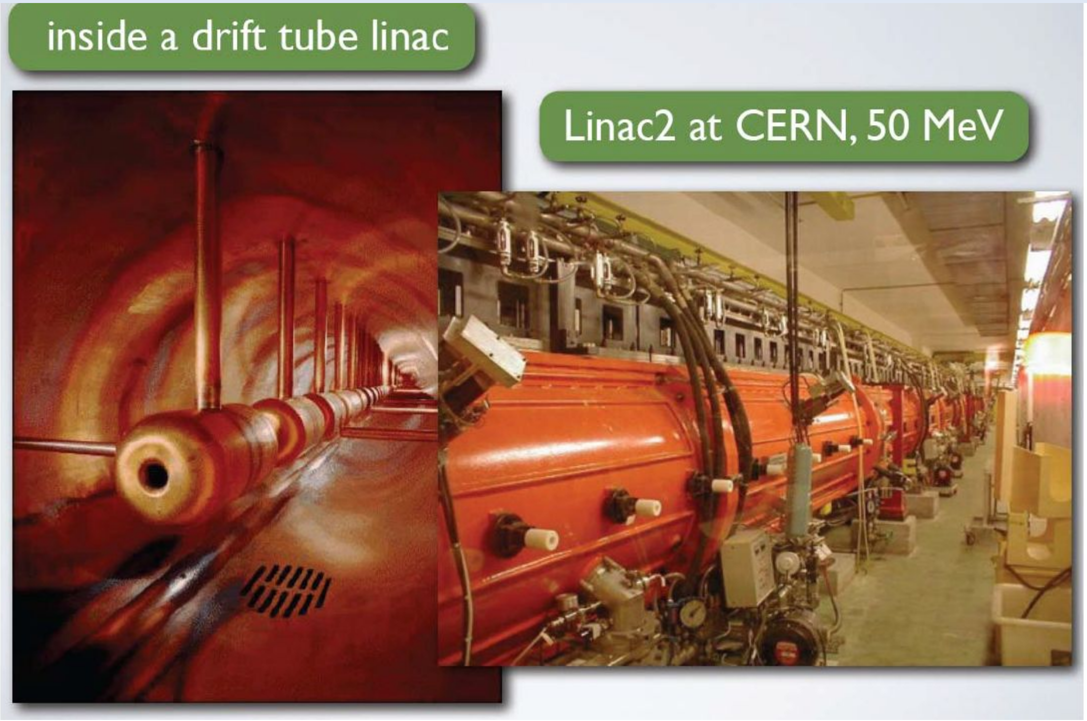


Superconductivity in Linacs

Standing wave accelerator consists of a multi-gap RF cavity. Synchronism between a particle and RF voltage is provided by appropriate phase shift between the fields in the cavities

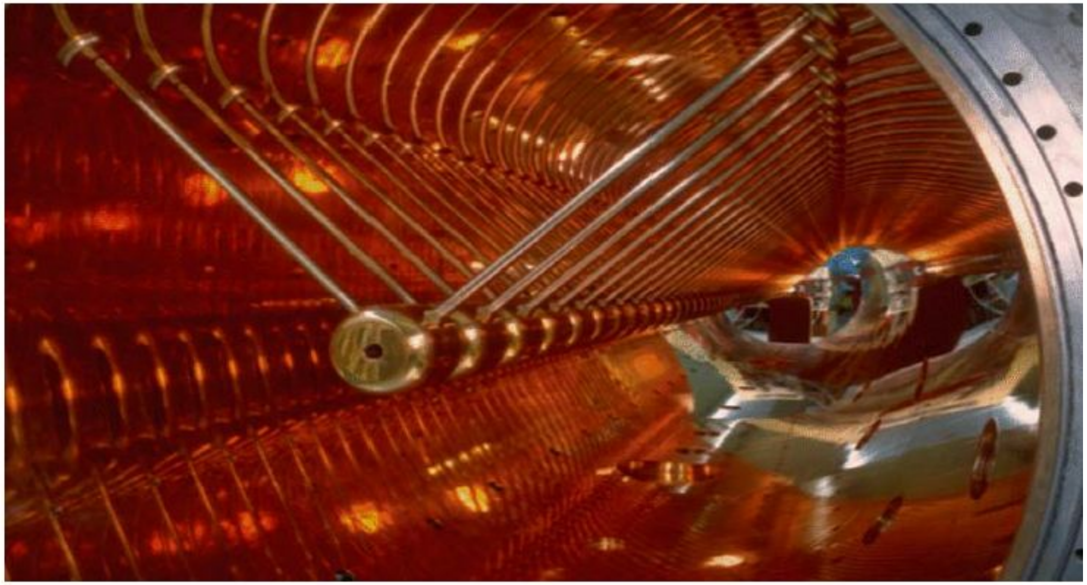


Alvarez Drift-Tube Struvture

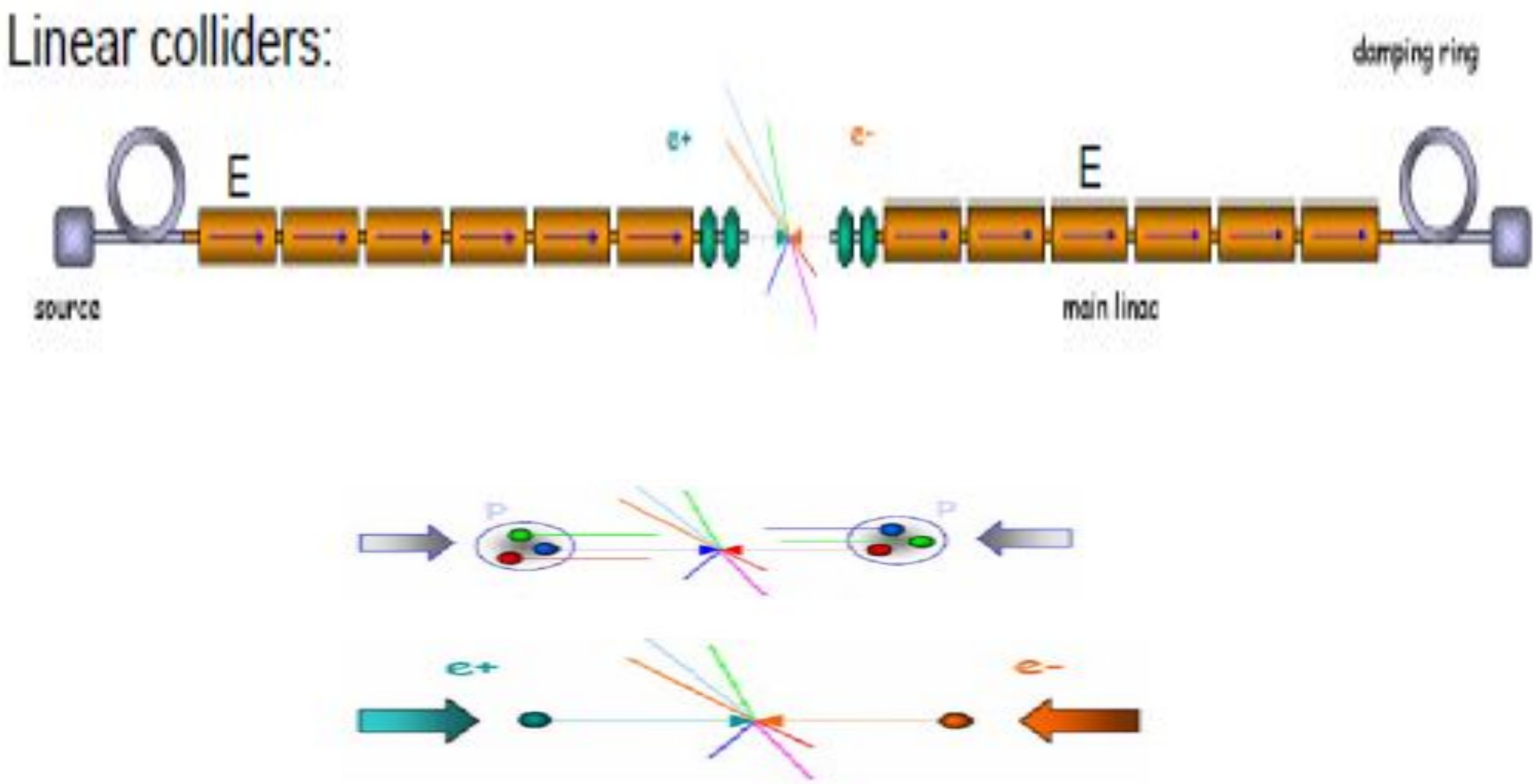


GSI Unilac

E ≈ 20 MeV per Nukleon
$\beta \approx 0.04 \ldots 0.6$
Protons/Ions



Linear Colliders



SLAC, ILC, CLIC

Stanford Linear Accelerator Center (SLAC)