Basic Introduction to Particle Accelerators and Radioactive Beam Facilities

Luca Doria
SFU & TRIUMF

Introduction

- Historical Introduction
- Dynamics of Charged Particles
- Linear Accelerators
- Circular Accelerators

- Summary

Why Particle Accelerators ?

After the discovery of radioactivity and its ability to induce nuclear reactions, it became quickly clear that an artificial source of radiation was needed for making substantial progress in the field.
The reasons are manyfold and among them:

- Need of sources more intense than radioactive elements.
- Need of higher energy sources.
- Need of complete control on the "projectiles".
- Need of different projectiles than the ones from radioactive sources.

In this lecture we are going to briefly discuss some (not all) particle accelerators which are the most relevant either historically and/or for modern applications.

Short History of Particle Accelerators

1870: Discovery of cathode rays by William Crookes
1896: JJ Thompson discovered that cathode rays were electrons
1895: Roentgen discovered X rays
1909: Rutherford discovered the nucleus with alpha-scattering
1920-1930:

- Cockroft-Walton Generator
- Wideroe and drift tube linear acceleration.
- van de Graaf Accelerator

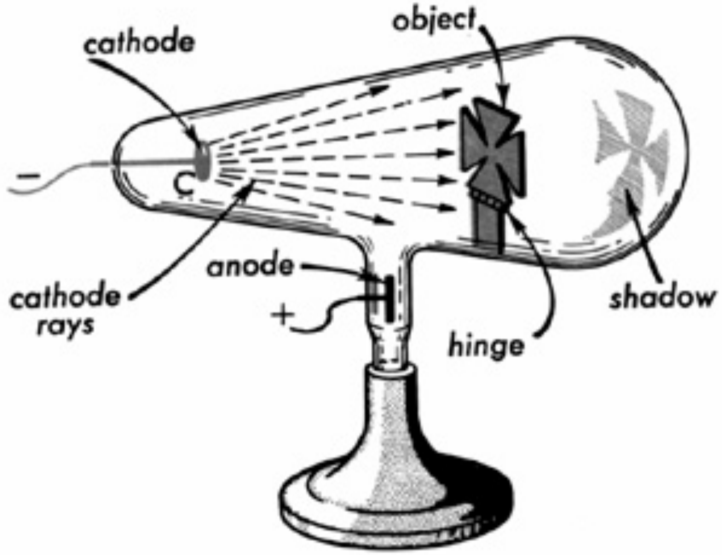
1931: The Cyclotron
1940s: Development of RF acceleration (resonant acceleration) and the Phase Stability concept
1950s: Alternating Gradient Focusing
1960s: Colliding beams concept
1980s: Tevatron (Fermilab)
2000s: LHC (CERN)

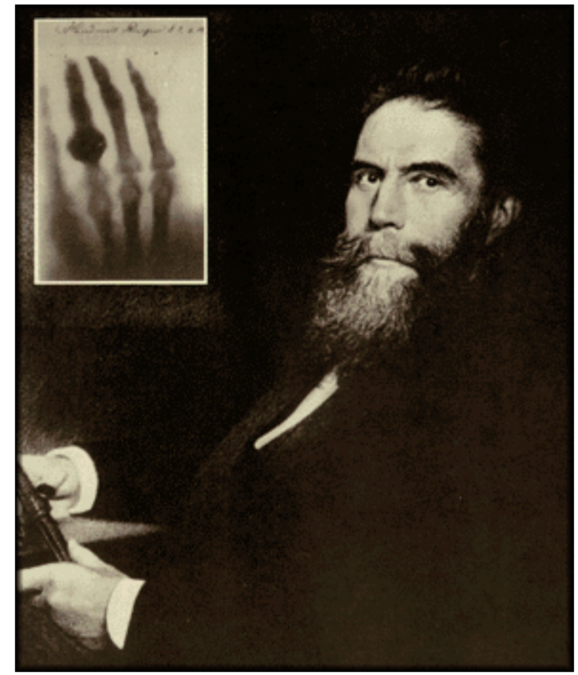
few keV
1MeV
25MeV
2GeV
400GeV
2 TeV
>10 TeV

ENERGY

The Crooks' Tube, Electrons and X-rays

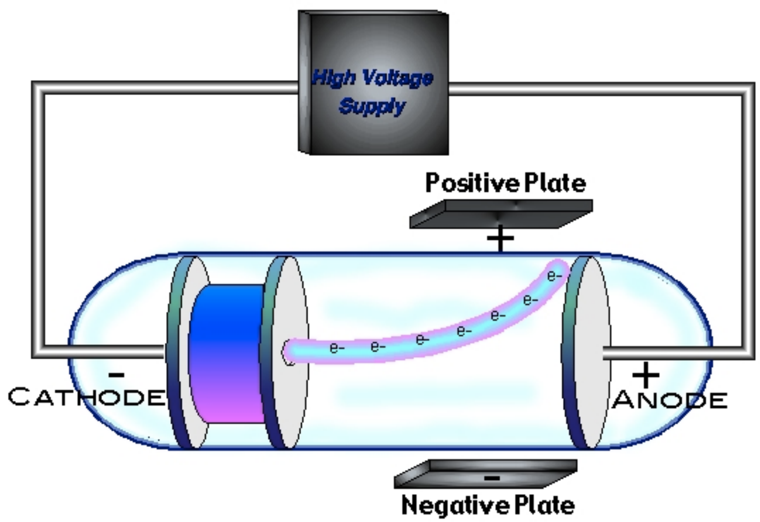
William Crookes
(1832-1919)



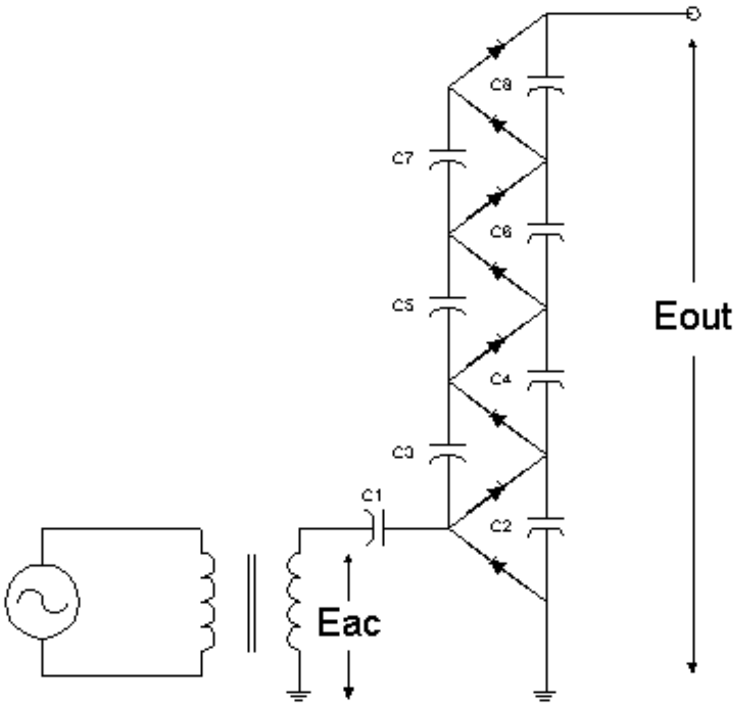


W. Roentgen

J.J. Thompson



Cockroft-Walton Generator



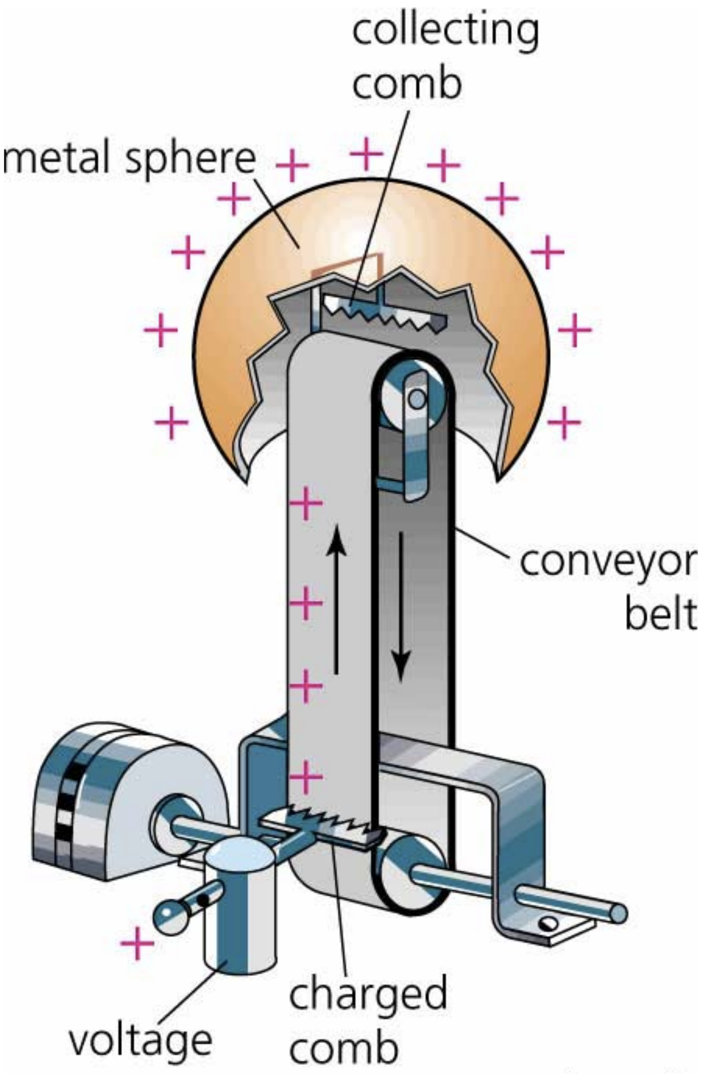
Cockroft and Walton designed a voltage divider made of capacitors and diodes for obtaining a high voltage difference. At each cycle of the alternating generator, a single stage of the divider is charged.
Few keV were obtained. It was sufficient to accelerate protons and split Lithium nuclei in Helium (1932)! Both received the Noble Prize in 1951.

Van de Graaf Generator

In 1929 van de Graaf proposed another method for obtaining high voltage differences:

This generator is mechanically powered: a conveyor belt runs from a low potential source to a high potential collector.

It can reach several MV of voltage difference and it is still used in some teaching applications.



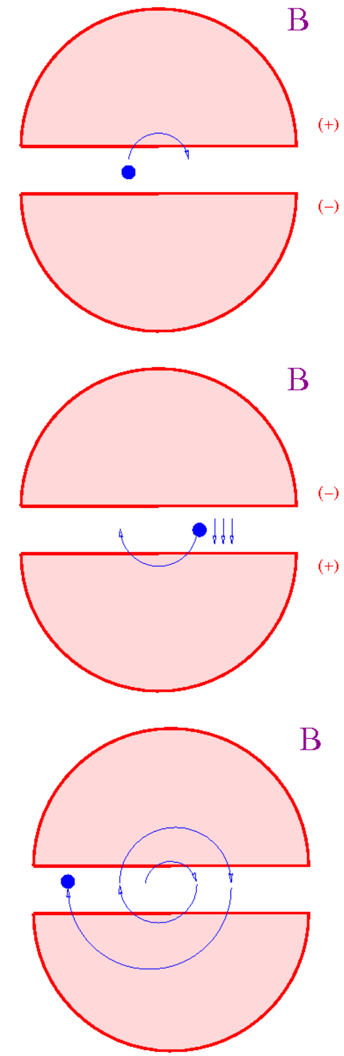
The Cyclotron (I)

It is very difficult to obtain DC fields of more than 20MV, therefore alternating fields were considered.

In 1931, E. Lawrence designed the Cyclotron: a circular design where two electrodes were placed in a magnetic field.

The magnetic field forces the particles in circular orbits. The electric field accelerates them at every turn. The final trajectory is a spiral.

At the beginning, Lawrence successfully accelerated protons up to 80kV. He won the Nobel price in Physics in 1939 for this achievement.



The Cyclotron (II)

Working principle of the cyclotron:

The magnetic field is orthogonal to the trajectory, therefore, neglecting here the acceleration force, the Lorenz force acting on the orbiting particle is:

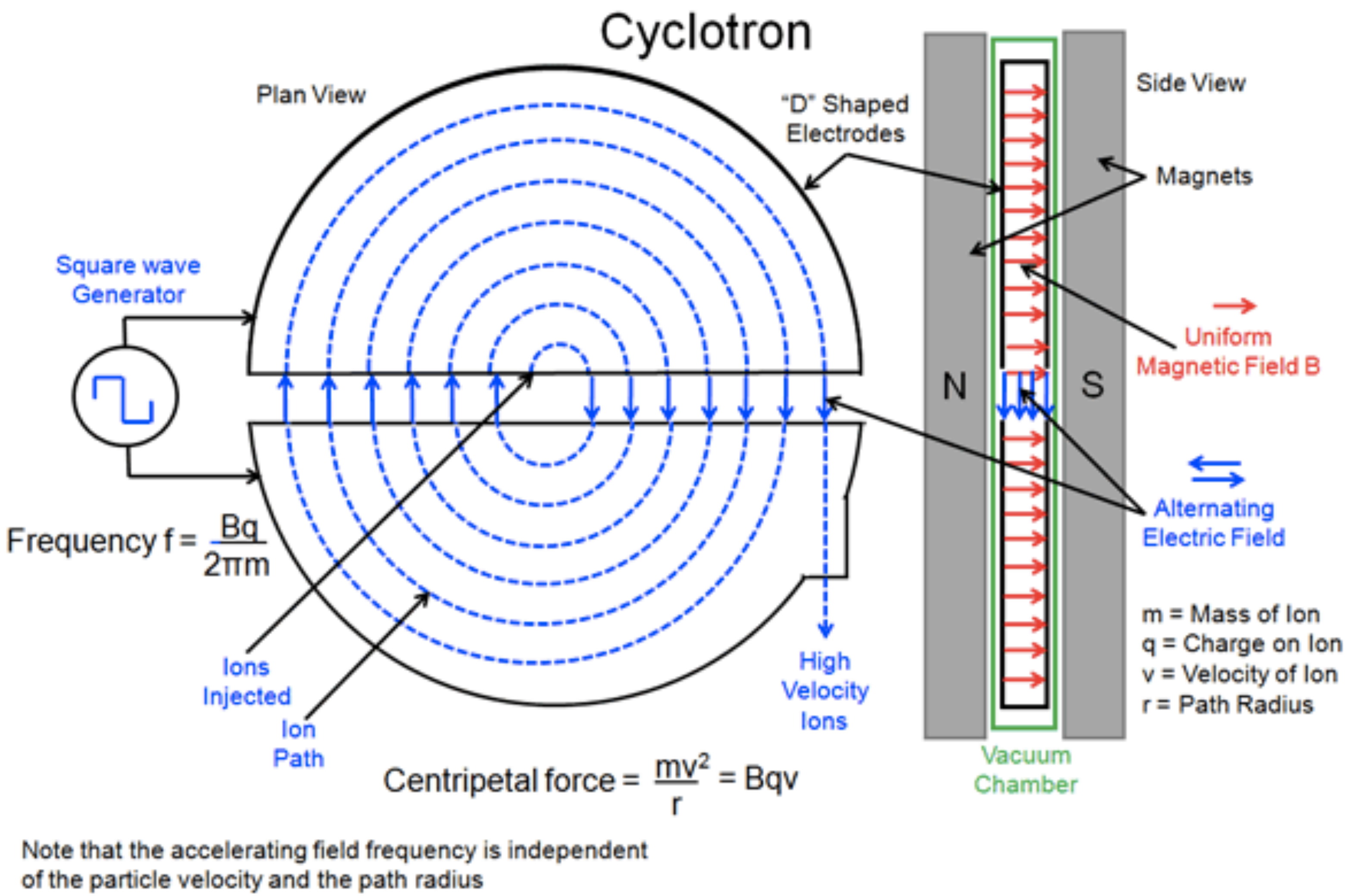
$$F = qv \times B = qvB$$

The centrifugal force is: $F_C = \frac{mv^2}{R}$ and in equilibrium $F_C = F$ yielding:

$$qvB = \frac{mv^2}{R} \Rightarrow \nu = \frac{1}{2\pi}\frac{qB}{m}$$

Important observation: the revolution frequency does not depend on the radius of the orbit, therefore we can use a fixed-frequency generator.
The longer trajectory at every turn is compensated exactly by the higher speed of the particle.

The Cyclotron (III)



The Cyclotron (IV)

The cyclotron was a great success, but it had relevant limitations:

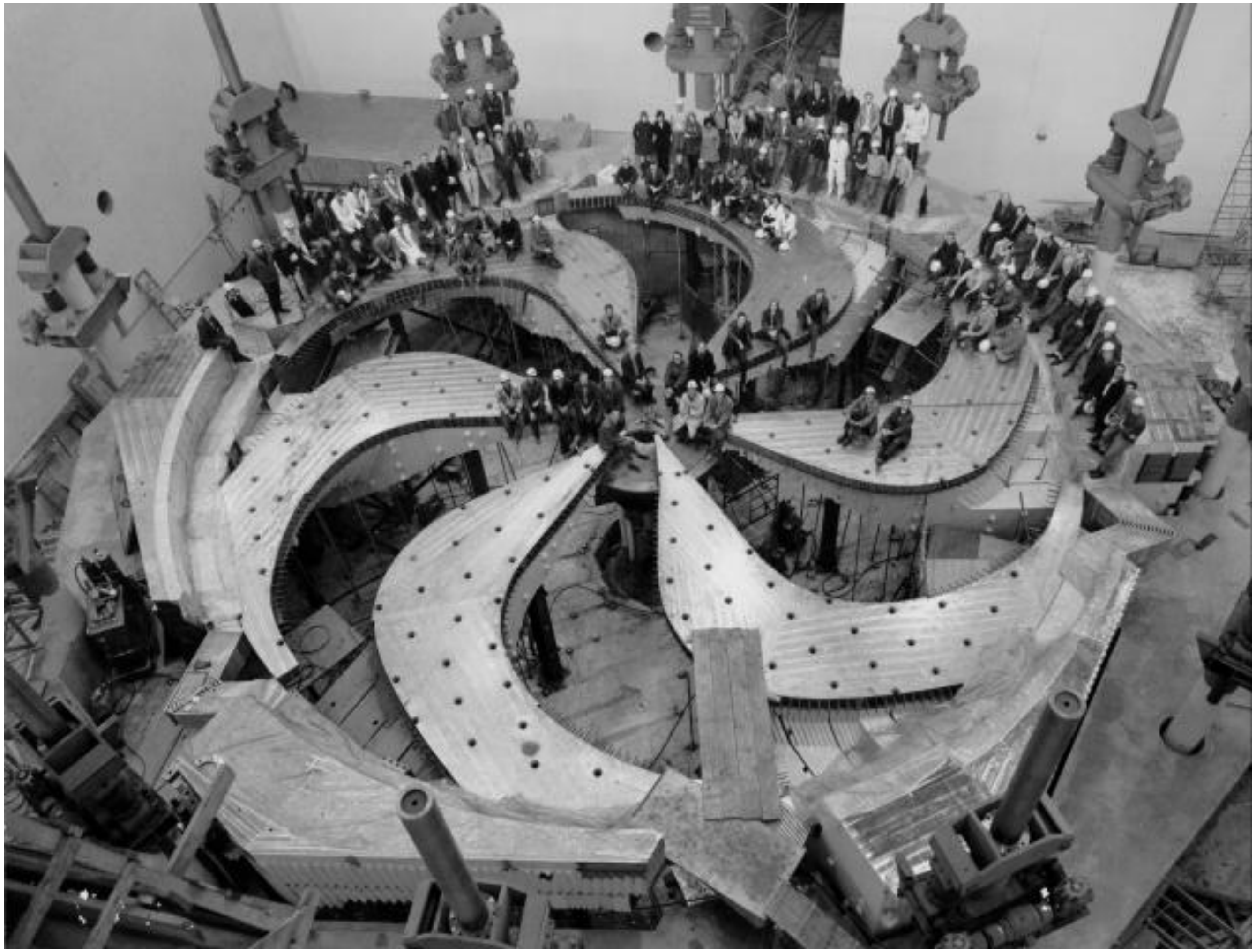
- When the speed becomes close to that of light, relativistic effects modify the last formula and therefore the frequency becomes a function of the radius.

- One can compensate for relativistic effects varying the frequency but then we are forced to accelerate bunches of particles instead of a continuous beam. Moreover, not all the particles in the beam have the same energy

- There are also stability issues at the edges of the cyclotron's magnets.

- Modern development: **radial sector cyclotrons with edge focusing.**

The Cyclotron (V)

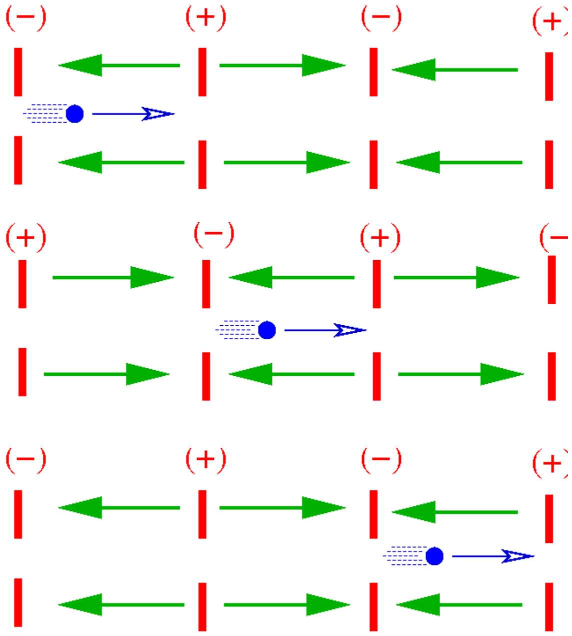


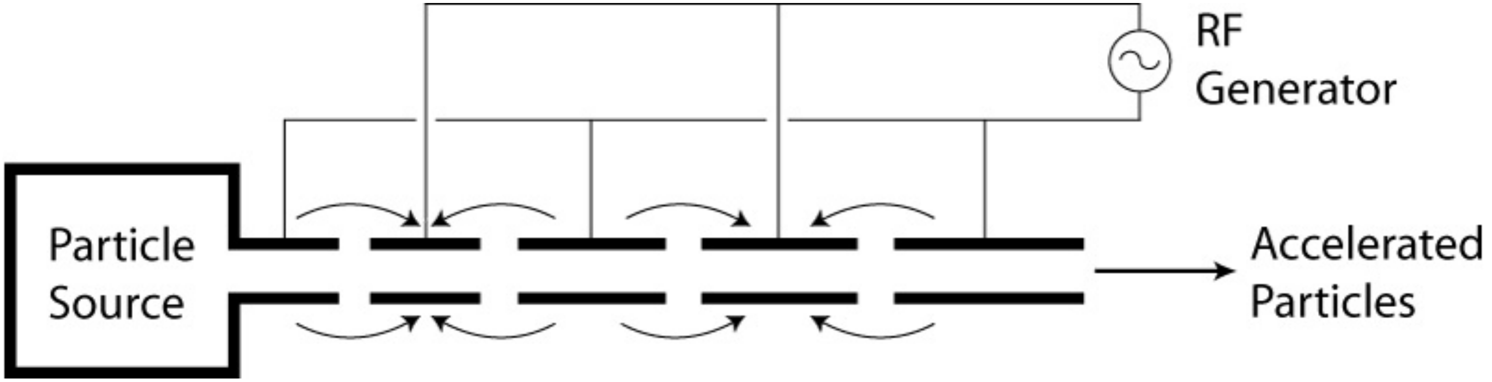
The TRIUMF cyclotron (Vancouver, BC) in an early stage of construction.

Linear Accelerators (I)

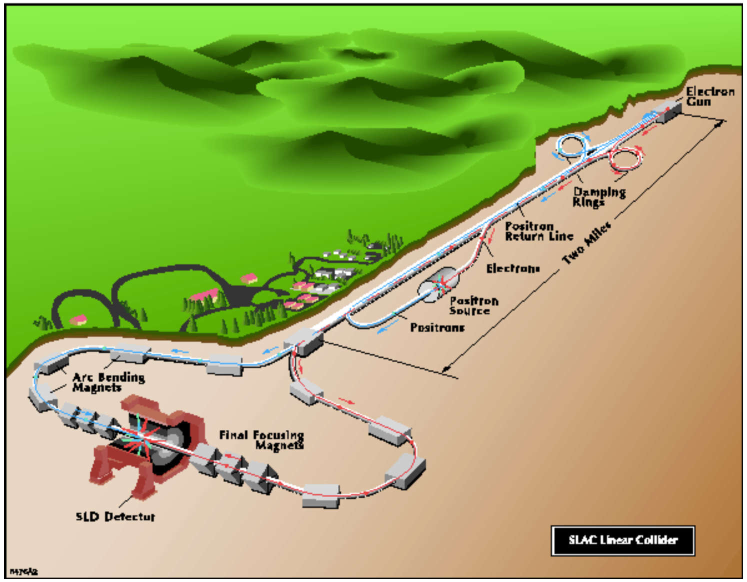
Another method for achieving high acceleration: successive cavities at alternating potential will achieve a push-pull scheme.

First proposed by R. Wideroe who patented it in 1928.





Linear Accelerators (II)



Stanford Linear Accelerator Laboratory,
Stanford, California (USA).
E>40GeV

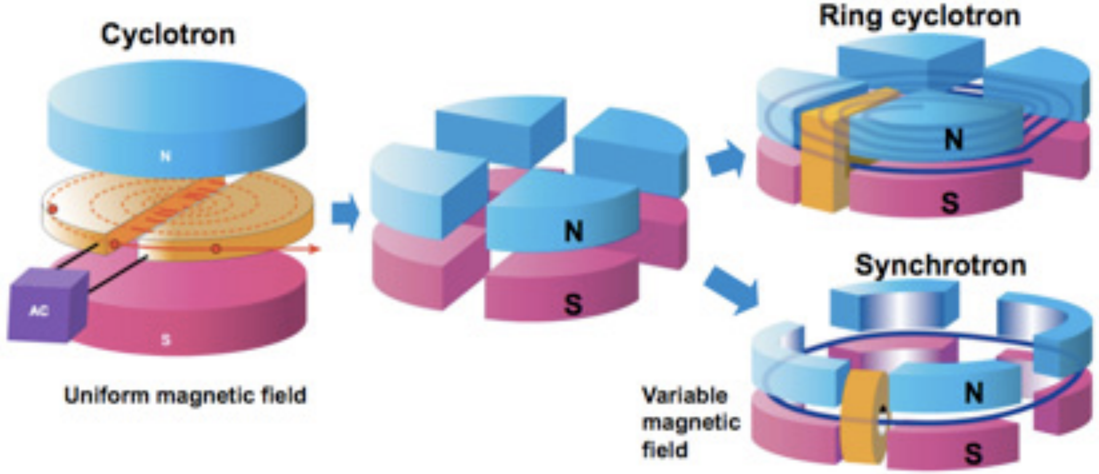
The Synchrotron (I)

In the cyclotron, the magnetic field and the alternating frequency were fixed. It is possible to consider accelerators which vary the last two parameters.

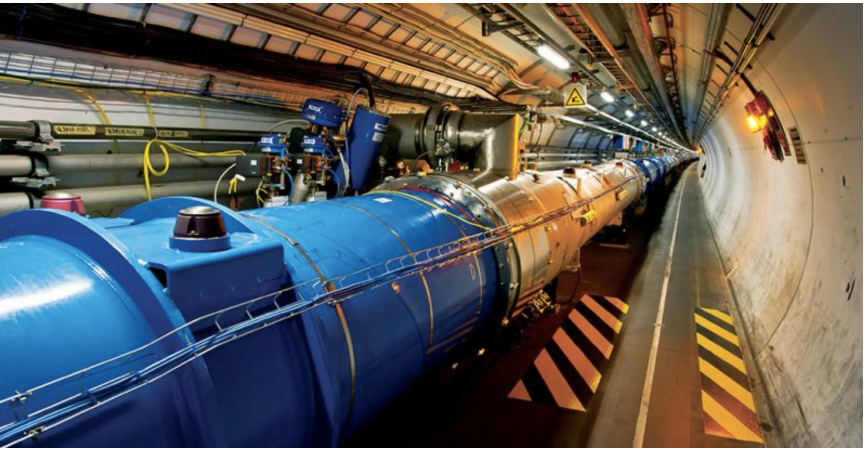
The most successful one is called **synchrotron**.

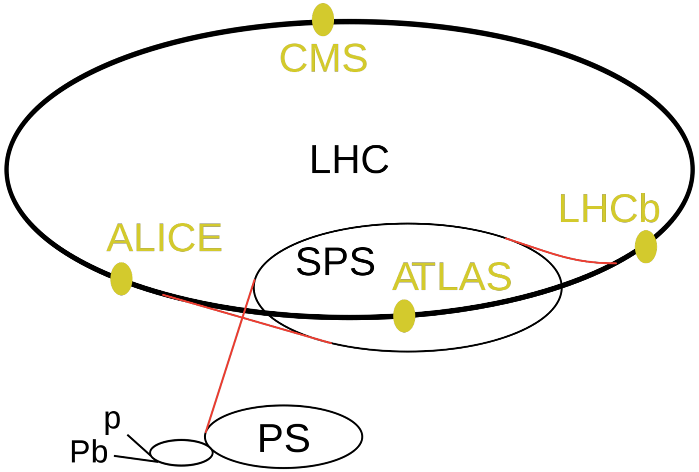
In a synchrotron, the particles are accelerated at every turn but they stay always on the same trajectory. This is achieved increasing the magnetic field synchronously with the energy of the particles.

The advantage over the cyclotron is that you can avoid constructing huge magnets and at the end these machines can achieve the highest energies today available.



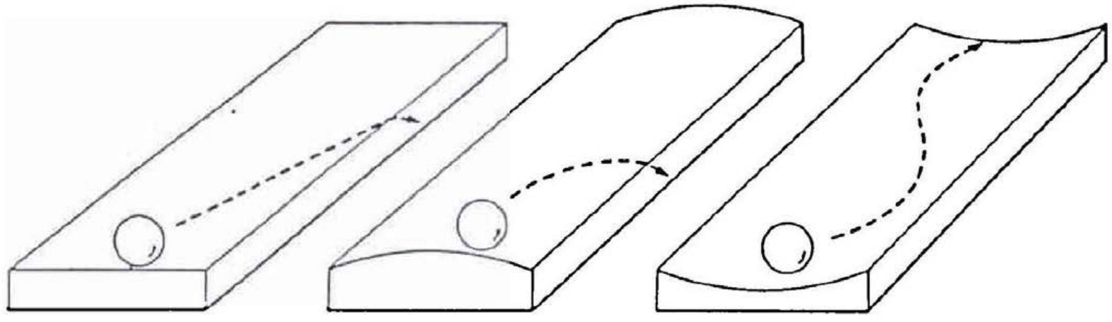
The Synchrotron (II)



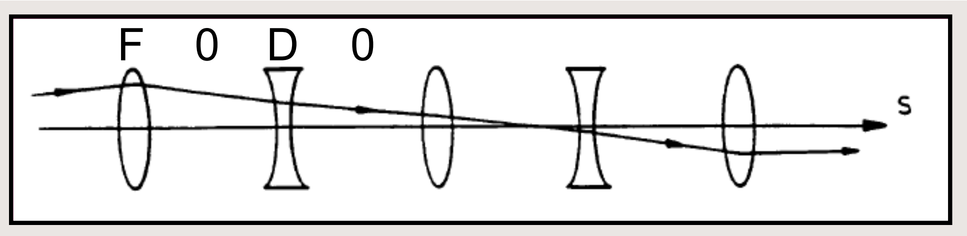


Stability

A central problem in accelerator science is the stability of the beams. Beams are groups of charged particles moving inside electromagnetic fields. In the process of guiding and accelerating the beams, the particles should not go out of control and e.g. hit beam-pipe walls which will result in the partial or total loss of the beam.

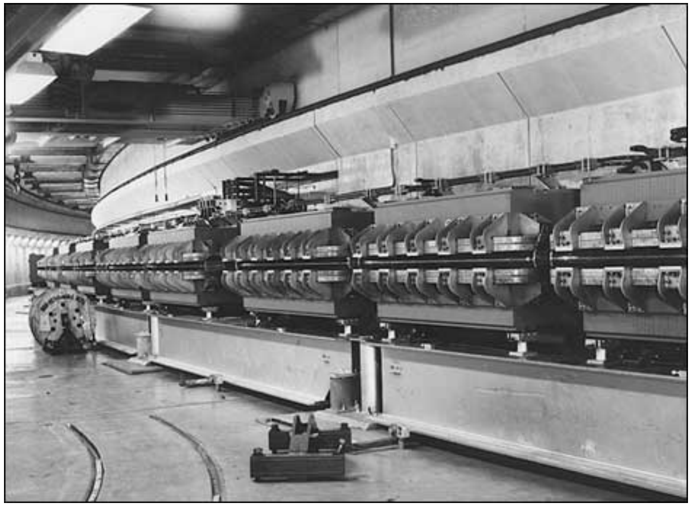


One of the key developments was **Strong Focusing** in synchrotrons: a periodic structure of fucusing/defocusing quadrupoles results in a net focusing effect.



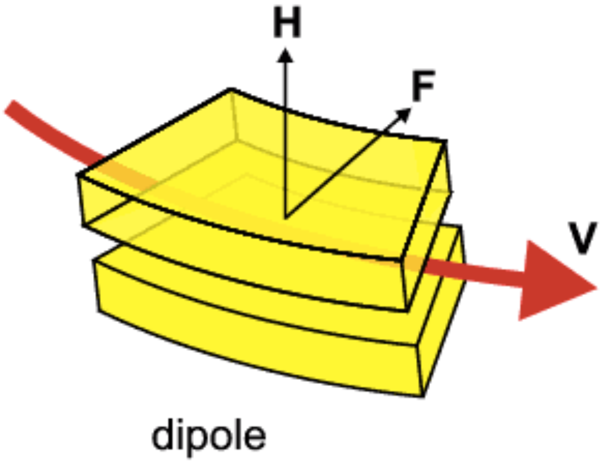
The Brookhaven Laboratories (US) synchrotron AGS was the first using strong focusing on the large scale in the 1960s.

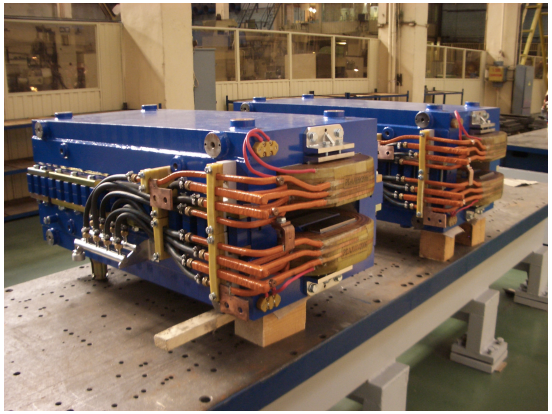
Phase stability is another key concept in accelerator science but we leave this topic for future study.



Magnets: Dipoles

Dipoles are used mainly for **steering** the beam:

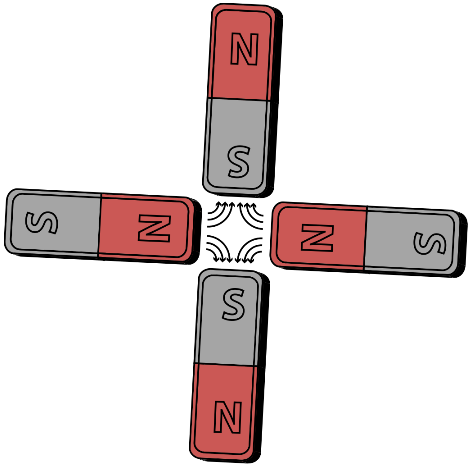


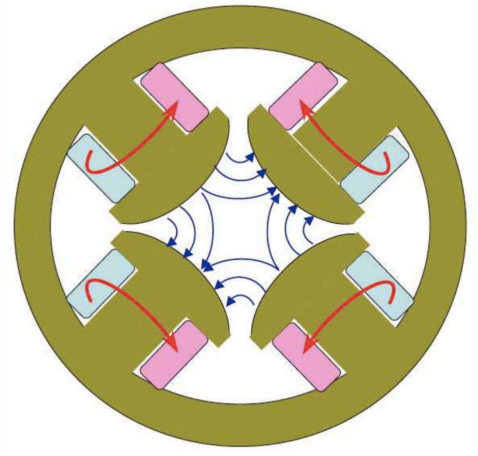


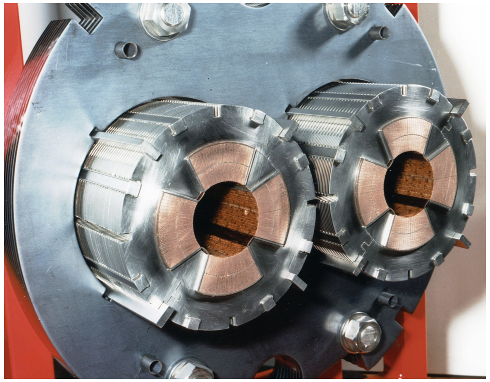
The dipole magnet forces the particle on an arc which is part of a circle according to the Lorenz force with a constant magnetic field.

Magnets: Quadrupoles

Quadrupoles are used mainly for **focusing** the beam:





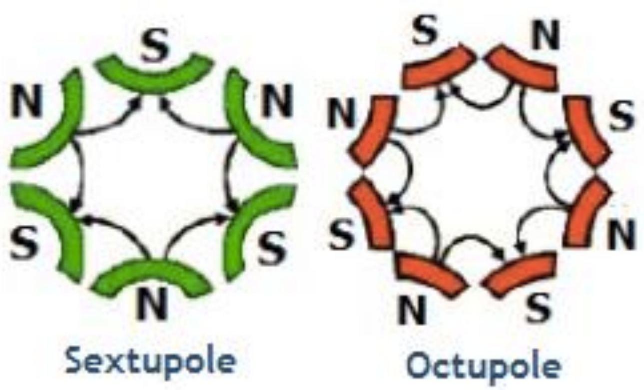


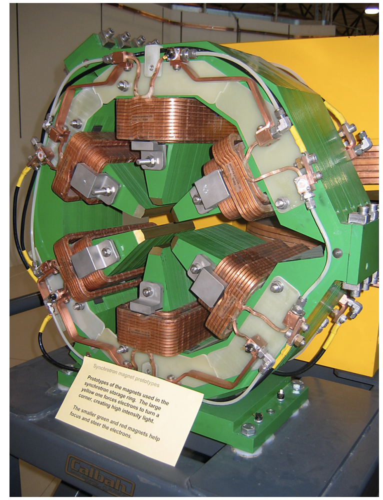
The magnetic field is linearly proportional to the distance to the pole:

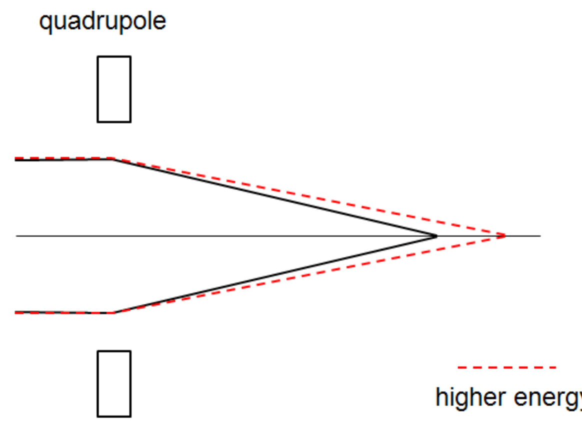
$$B_x = a \cdot x$$

$$B_y = a \cdot y$$

Magnets: Sextupoles







$$B_x = -6B_3xy$$

$$B_y = -3B_3(x^2 - y^2)$$

Sextupole magnets are used for correcting an effect called **chromaticity** (the fact that particles of different momentum are focused differently). The resulting fields are non-linear and coupled in the transverse plane therefore an analytical treatment of the equations of motion is difficult.

Production of Radioactive Beams

- How we produce and study unstable nuclei?

- They do not exist in nature: we have to produce them artificially.

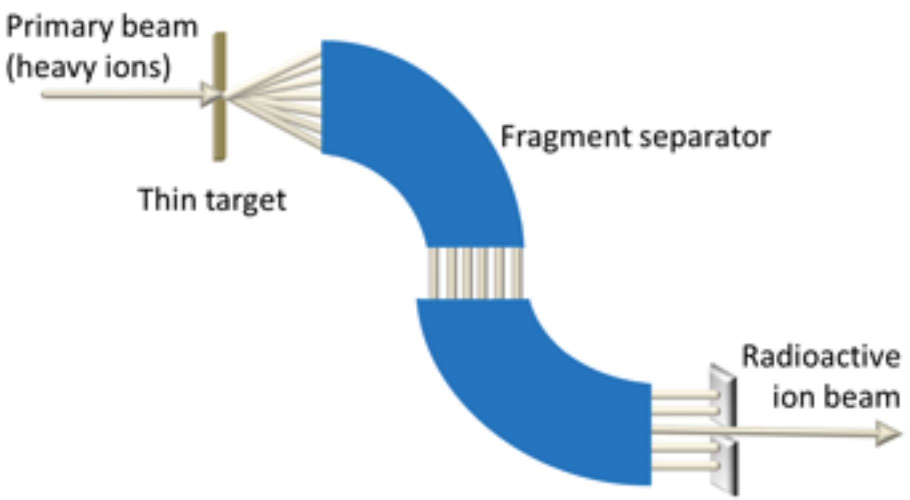
- We need an accelerator and an appropriate target.

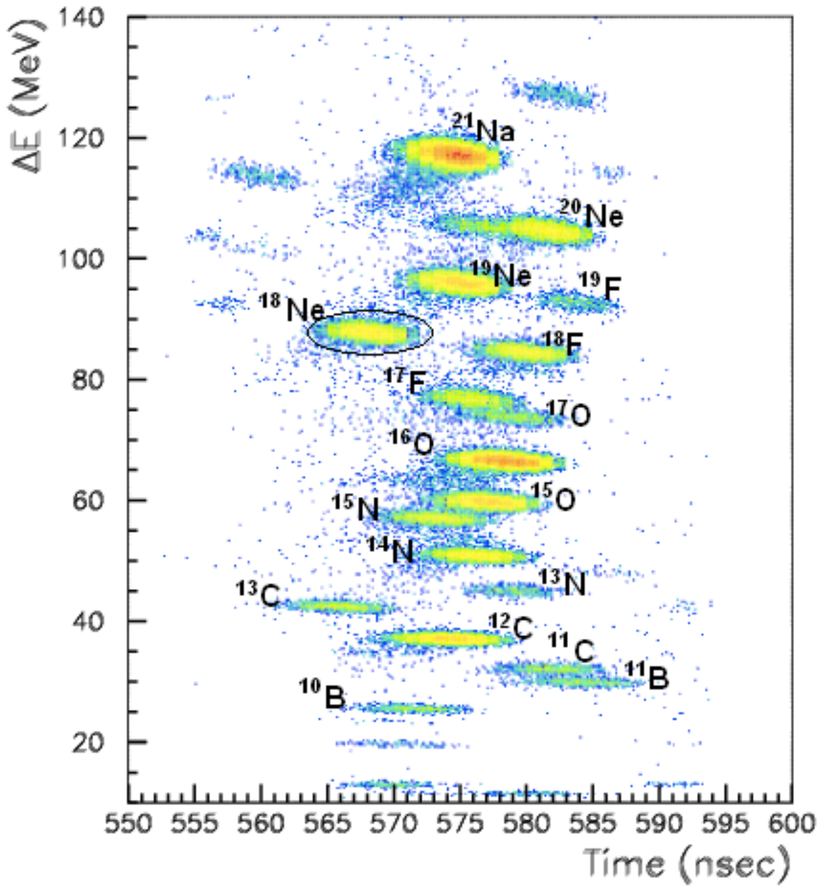
- Two main techniques:

    1) Fragmentation and in-flight separation

    2) Ion Separation On-Line (ISOL technique)

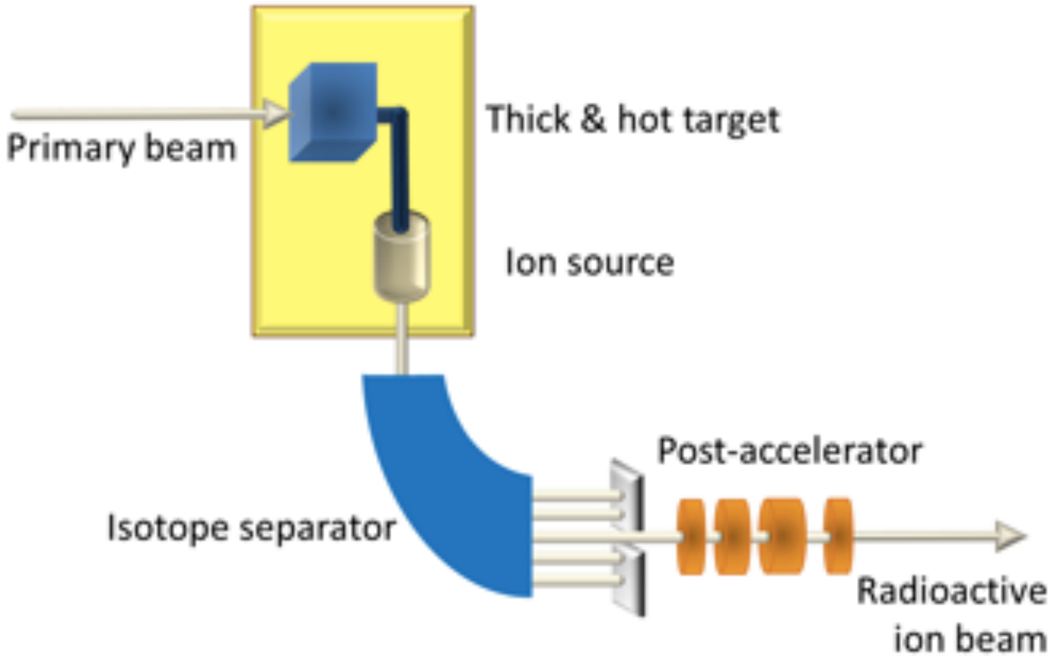
In-Flight Method





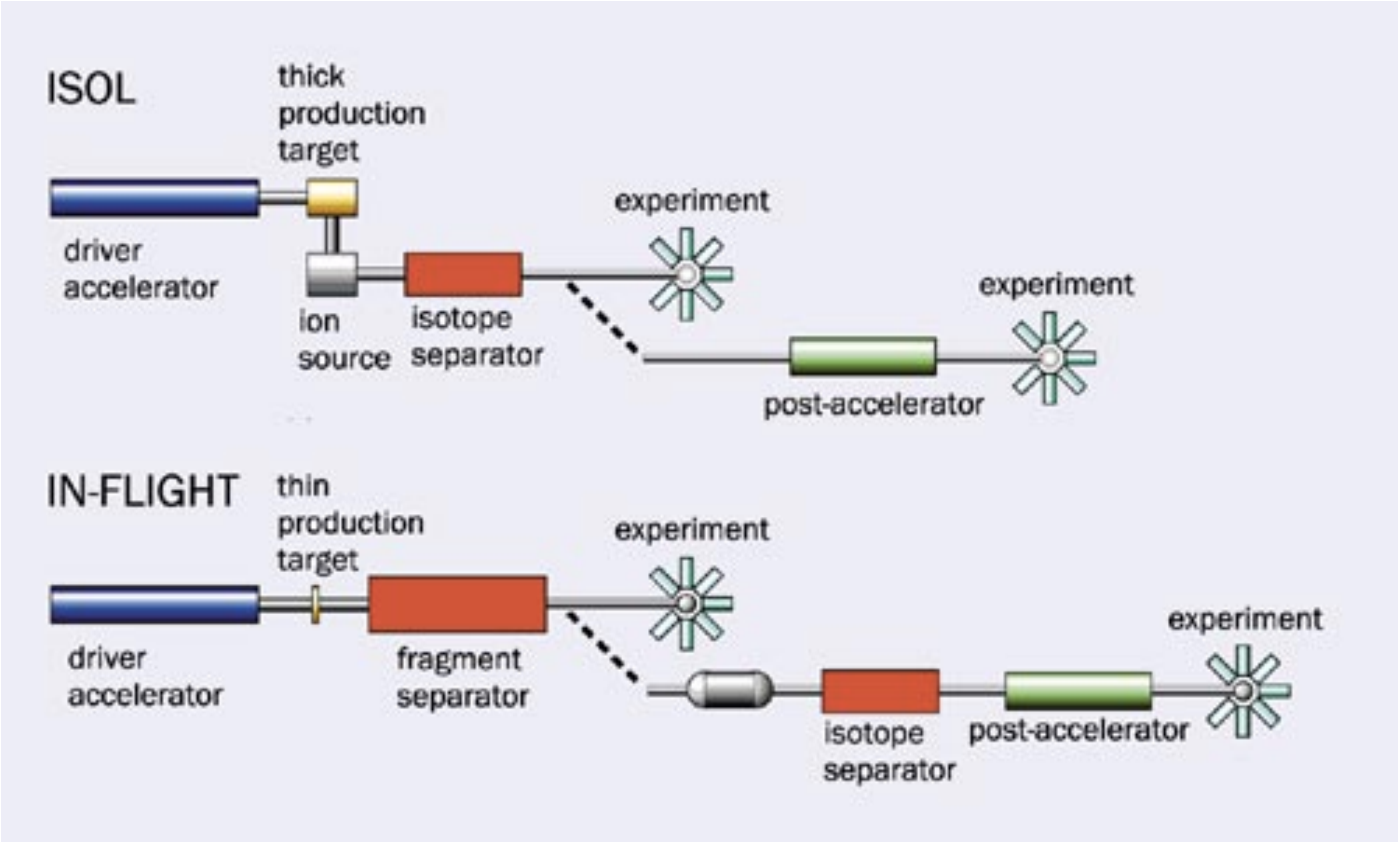
A primary beam is sent to a thin target and the high-momentum fragments are then separated electromagnetically by mass and charge.

ISOL Method

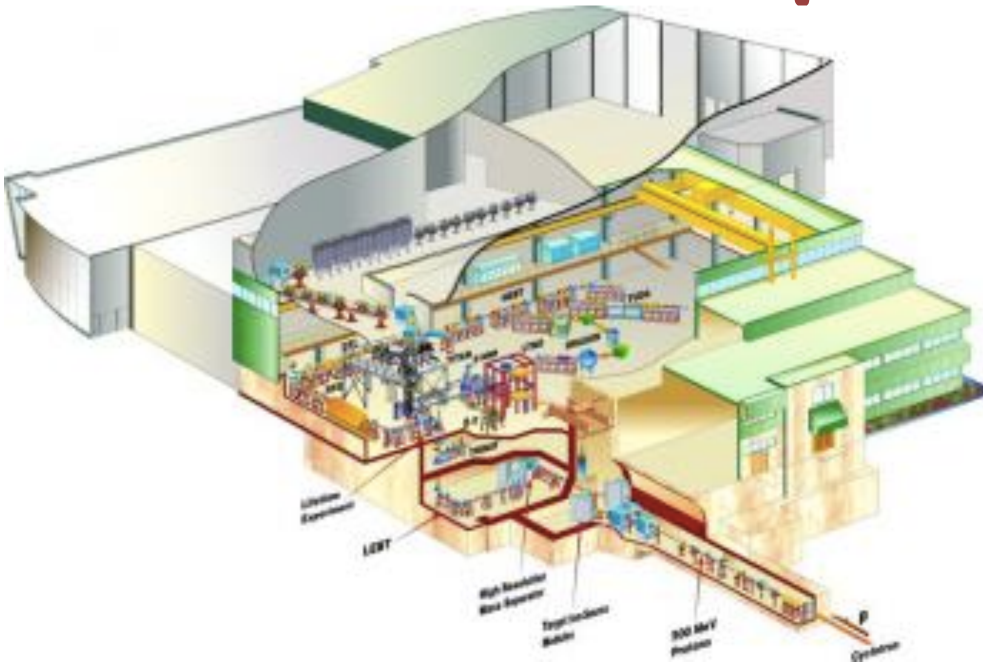


In the ISOL method, a primary beam is directed towards a thick target. The radioactive species diffuse out. They can be further ionized by e.g. lasers. The slow ions are then separated electromagnetically and sent to a post-accelerator which re-accelerates them towards the experiments.
One advantage of ISOL facilities is the high currents of radioactive beams obtainable. In-flight separation is more efficient for certain isotopes and can handle very short-lived nuclides. The two techniques are complementary.

ISOL/In-Flight Summary

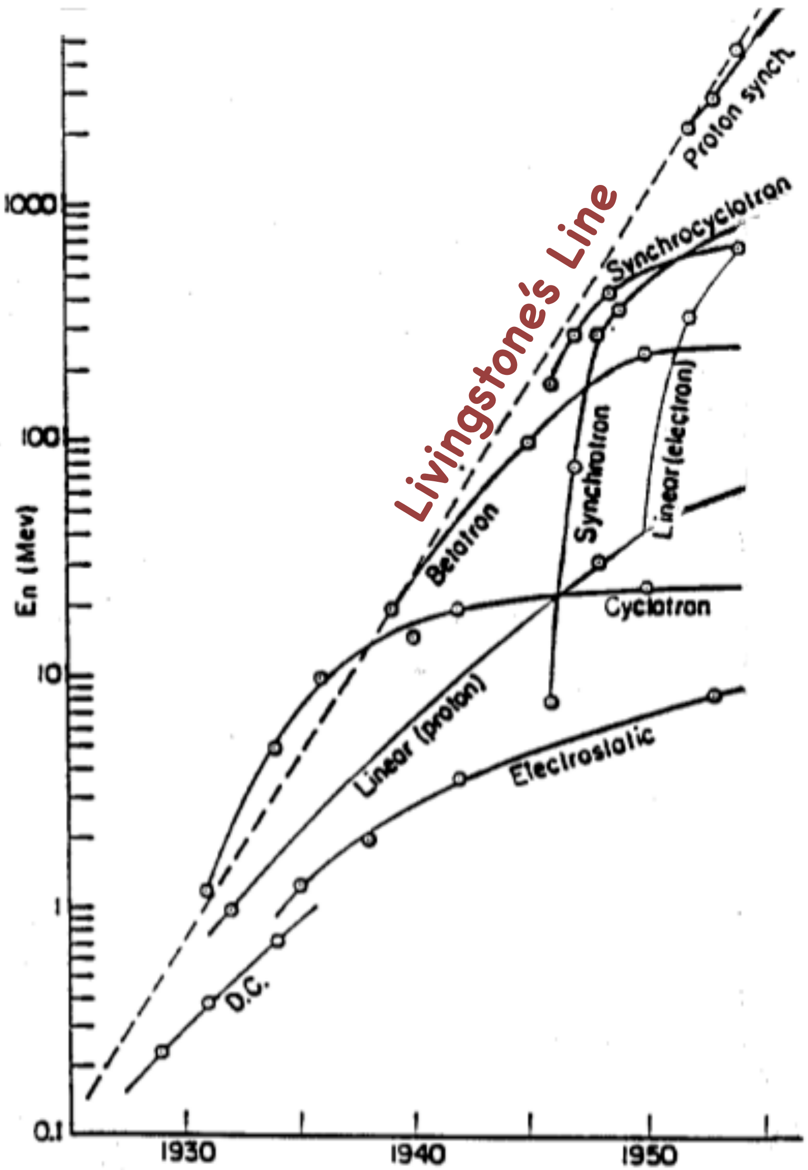


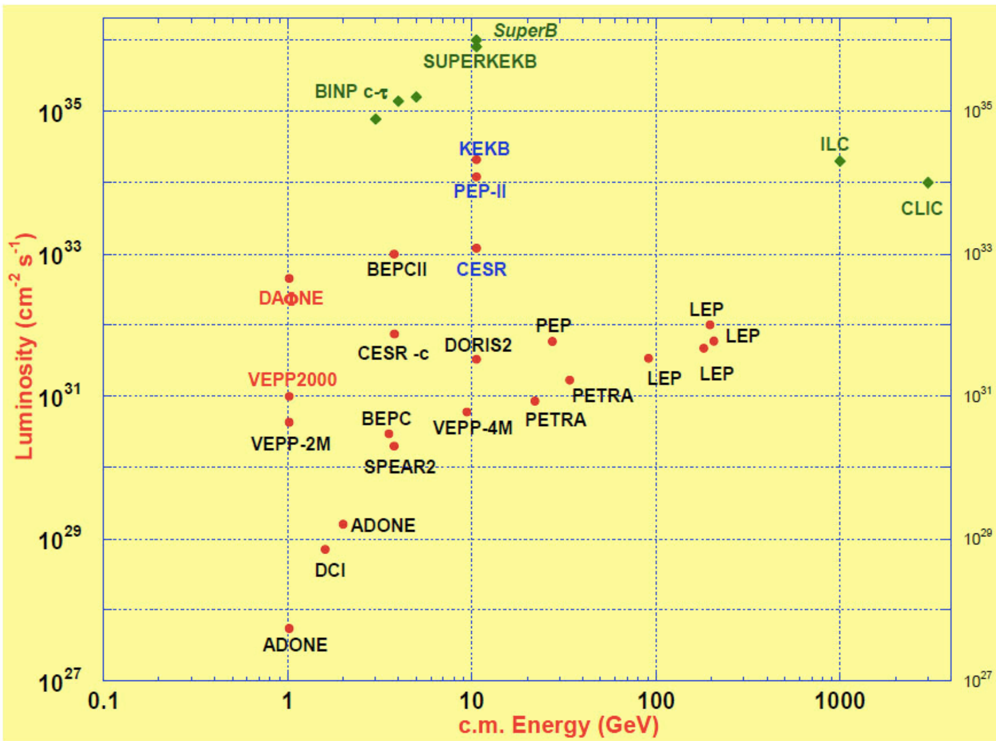
Example: TRIUMF



TRIUMF is Canada's laboratory for particle and nuclear physics. It is located on the UBC campus in Vancouver, BC.
The core of the complex is a 500MeV cyclotron which drives different projects in particle, nuclear and medical physics.
In particular, it serves as driver for an ISOL radioactive beam facility.

Accelerator's Evolution





$$\mathcal{L} = \frac{f_c N^+ N^-}{4\pi\, \sigma_x^* \sigma_y^*} \cdot S$$

Summary

- History of Particle Accelerators
- Linear Accelerators
- Circular Accelerators
- Magnets and Multipoles
- Radioactive Beams Facilities