Basic Introduction to Particle Accelerators
SAINTS Summer School

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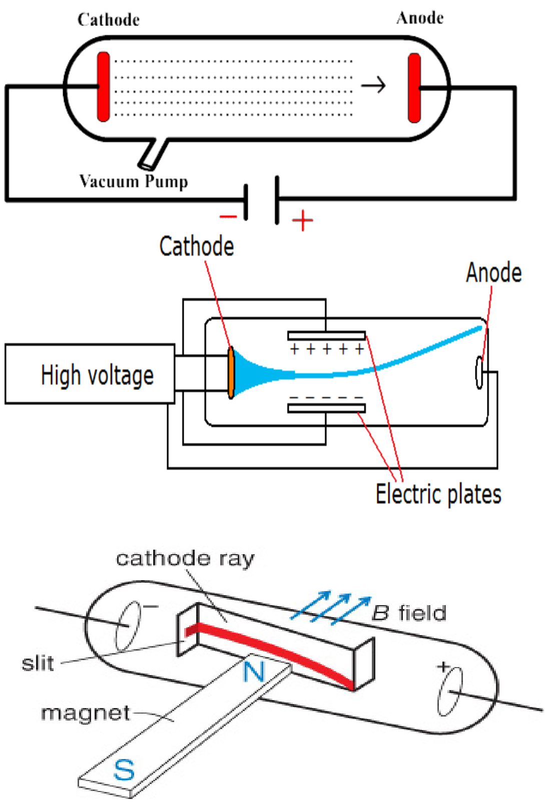
History of Accelerators

- The first major **discovery** that set off modern **atomic** theory was due to the **discovery** of electron in 1897 by **J. J. Thompson.**
- He then proposed a "**plum pudding**" model for the atom.
- In 1911, **Rutherford**, Marsden and Geiger **discovered** the dense atomic **nucleus** by bombarding a thin gold sheet with the **4.6 MeV α** particles emitted by **radium**.
- The first **electrostatic accelerator** was invented in October 1929 at Princeton New Jersey by an American Physicist called **Robert Van de Graaff**.
- **Rolf Wideröe:** demonstrated the concept of radio-frequency accelerator in 1928.
- **Ernest Lawrence:** Invented a cyclotron accelerator in 1934 by combining electric fields and magnets.

History of the Particle Accelerators

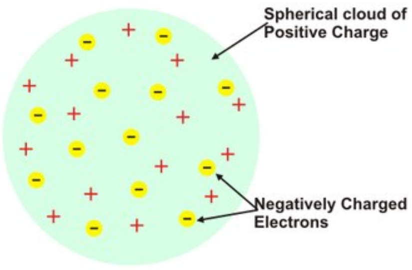
- History of Accelerators can be traced from separate roots, through rapid development to the present day.
- Firstly it was inspired by discovery of electrons in 1897 by JJ Thompson.
- Thompson used the cathode rays, firstly performed by Hertz.
- He placed charged parallel electrodes inside the vacuum chamber.
- He discovered that when the bottom plate was negatively charged, the rays moved up and the light appeared at the top of glass and vice versa.
- The deflection was proportional to the potential difference between the two plates.
- Same phenomenon was observed using magnetic field bar.
- With both magnetic and electric deflections observed, he could determine the charge of an electron.
- From the magnitude of the electrical and magnetic deflection, Thompsons could calculated the ratio of mass to charge for the electron.
- He discovered that the mass of the electron was very small, about 1800 times lighter than the hydrogen ion.



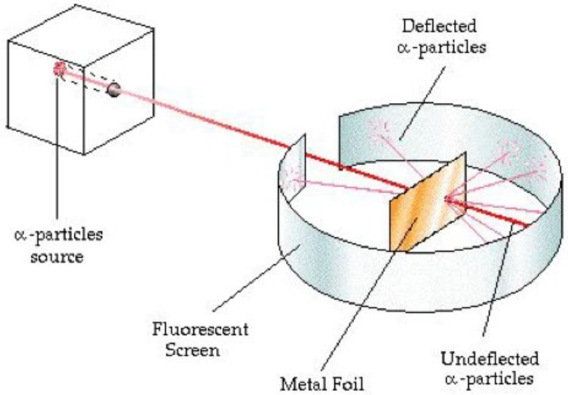
Courtesy of physicsopenlab.org

History of the accelerators continues

- Thompson postulated the model of an atom using what is called "plum-pudding" model, whereby negatively charged electrons are distributed throughout the atom in a sea of positive charge.
- This was until Rutherford, Geiger and Marsden discovered the nucleus when irradiating a thin gold foil with α-particles emitted from radioactive source.
- The foil was surrounded by a zinc sulphide screen that would show a flash of light when hit by scattered α-particles.
- The idea was to determine the structure of the atom and understand if Thomson model hold.
- They observed that although the majority of the particle went through undisturbed, some particle had deflected at small angle, and very small number of particle were reflected back.
- This observation of the backscattering of the α-particles disproved the model by JJ Thompson.
- This observation motivated for the development of machine to accelerate particle to high energy to overcome Coulomb barrier.

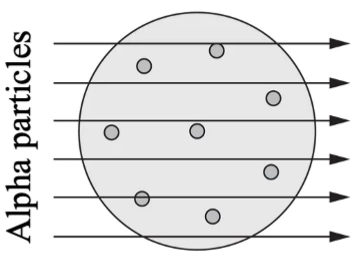


Thomson's Plum-Pudding Model

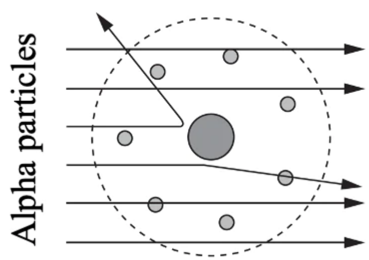


Thompson and Rutherford models of Atom

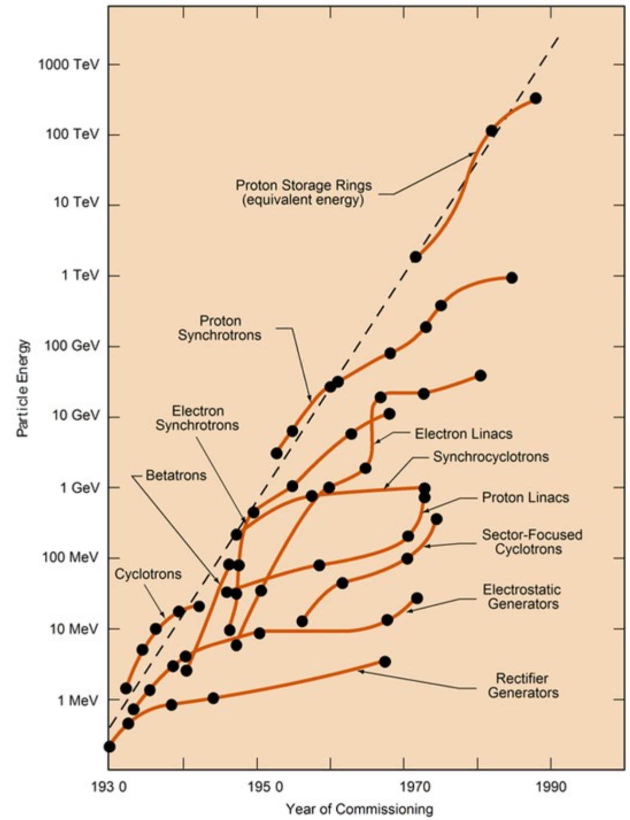
- This in turn gave birth to the first particle accelerators, which saw a rapid development through out the 20th century.
- This rapid development can be seen illustrated by the Livingston plot.
- The model predictions by both Thompson and Rutherford are illustrated as follows:



Prediction by Thomson's model



Prediction by Rutherford's model

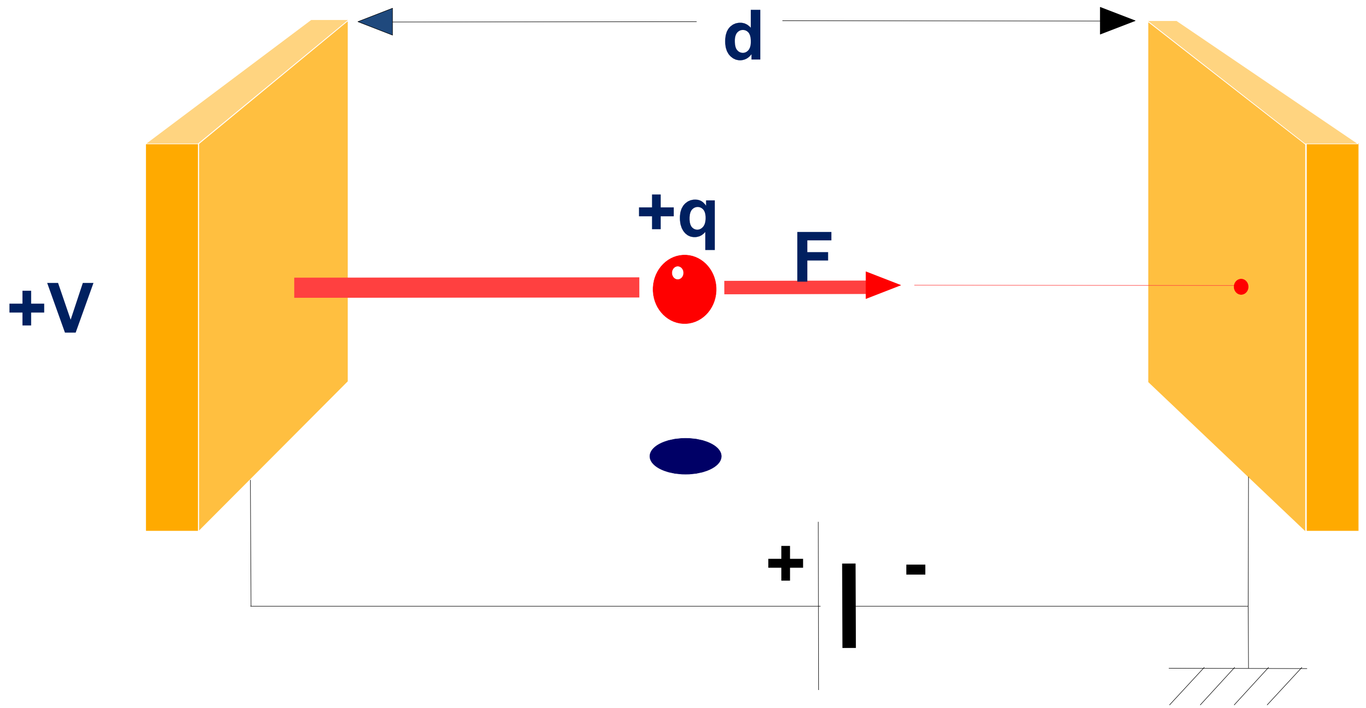


Basic Concept

In dealing with accelerators, it has been convenient to introduce the electron-volt (eV) as a unit of energy. The energy gained by a particle with a charge equal to that of an electron in falling freely across a 1-volt potential difference is called 1 electron-volt. Since the electron charge is equal to 1.6×10^{-19} coulomb:

e charge		$= 1.6\times10^{-19}$ Coulomb
1eV		$= 1.6\times10^{-19}$ Coulomb $\times$ 1 volt $= 1.6\times10^{-19}$ Joules
Electron	m_0	$= 511.0$ keV/c^2 $= 9.109\times10^{-31}$ kg
Proton	m_0	$= 938.3$ MeV/c^2 $= 1.673\times10^{-27}$ kg
Neutron	m_0	$= 938.6$ MeV/c^2 $= 1.675\times10^{-27}$ kg
1 keV		$= 10^3$ eV
1 MeV		$= 10^6$ eV
1 GeV		$= 10^9$ eV
1 TeV		$= 10^{12}$ eV

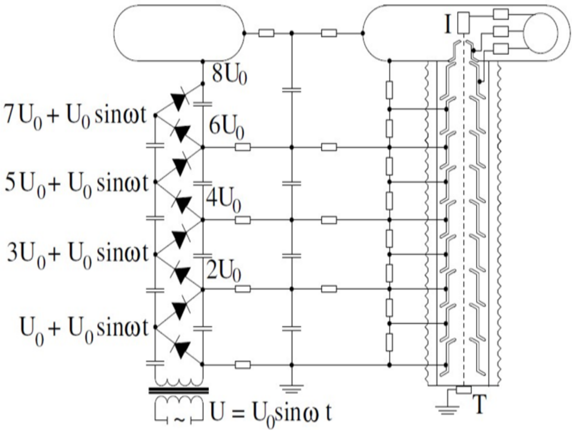
Acceleration of a Charged Particle



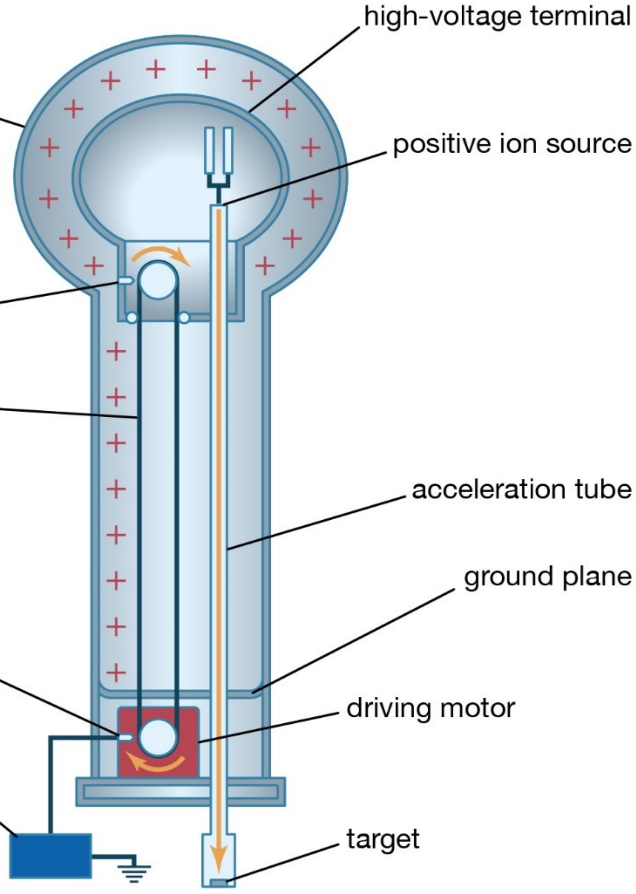
$E = \frac{V}{d}$ $F = qE$ $W = qV$

Cockcroft-Walton Accelerator

- The Cockcroft-Walton accelerator is the prototype of an electrostatic accelerator.
- High voltage generator of Cockcroft-Walton accelerator is a cascade generator or voltage multiplier circuit invented by Greinacher.
- It consist of HV transformer, HV capacitors, HV diodes
- Capacitors are stacked in two vertical columns (P and S) capped by a large rounded terminal electrode.
- The capacitors in the pushing column P are charged during the negative half-period of the sinusoidal AC voltage.
- The capacitors in the smoothing column S are charged during the positive half-period of AC voltage.
- U_0 is the amplitude of the AC voltage from the transformer.
- A high voltage of $2nU_0$ can be achieved with n stages of capacitors on the smoothing column.

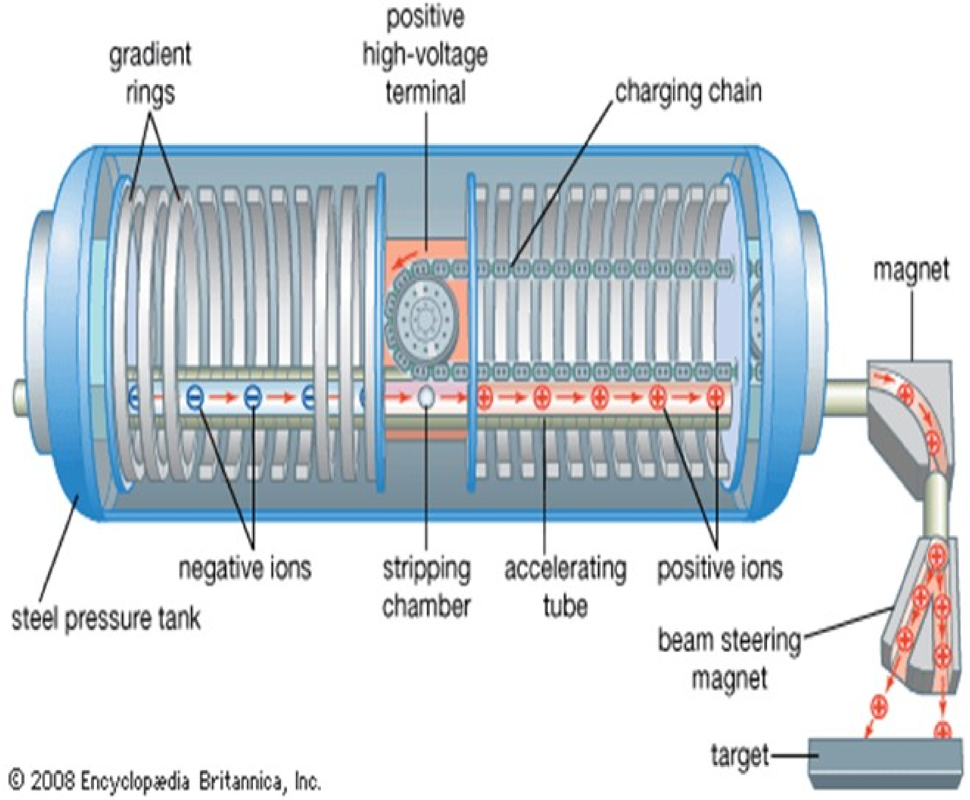


Van De Graaff Accelerator



Tandetron

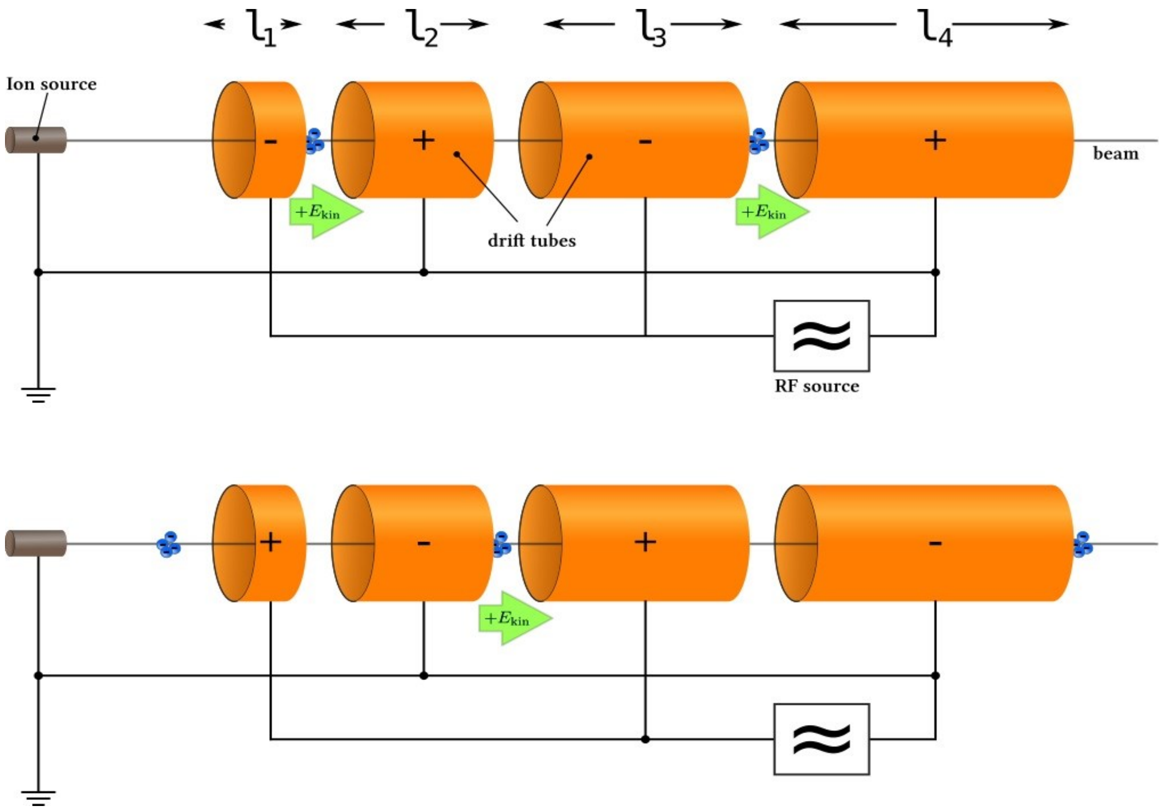
- The output beam energy of a Van de Graaff accelerator can be extended by a factor of 2 (up to the 12 MeV range) through the tandem configuration illustrated
- Negative ions produced by a source at ground potential are accelerated to a positive high-voltage terminal and pass through a stripping cell.
- Collisions in the cell remove electrons, and some of the initial negative ions are converted to positive ions. They are further accelerated traveling from the high-voltage terminal back to ground.



Tandetron Accelerator

First Linear Accelerator

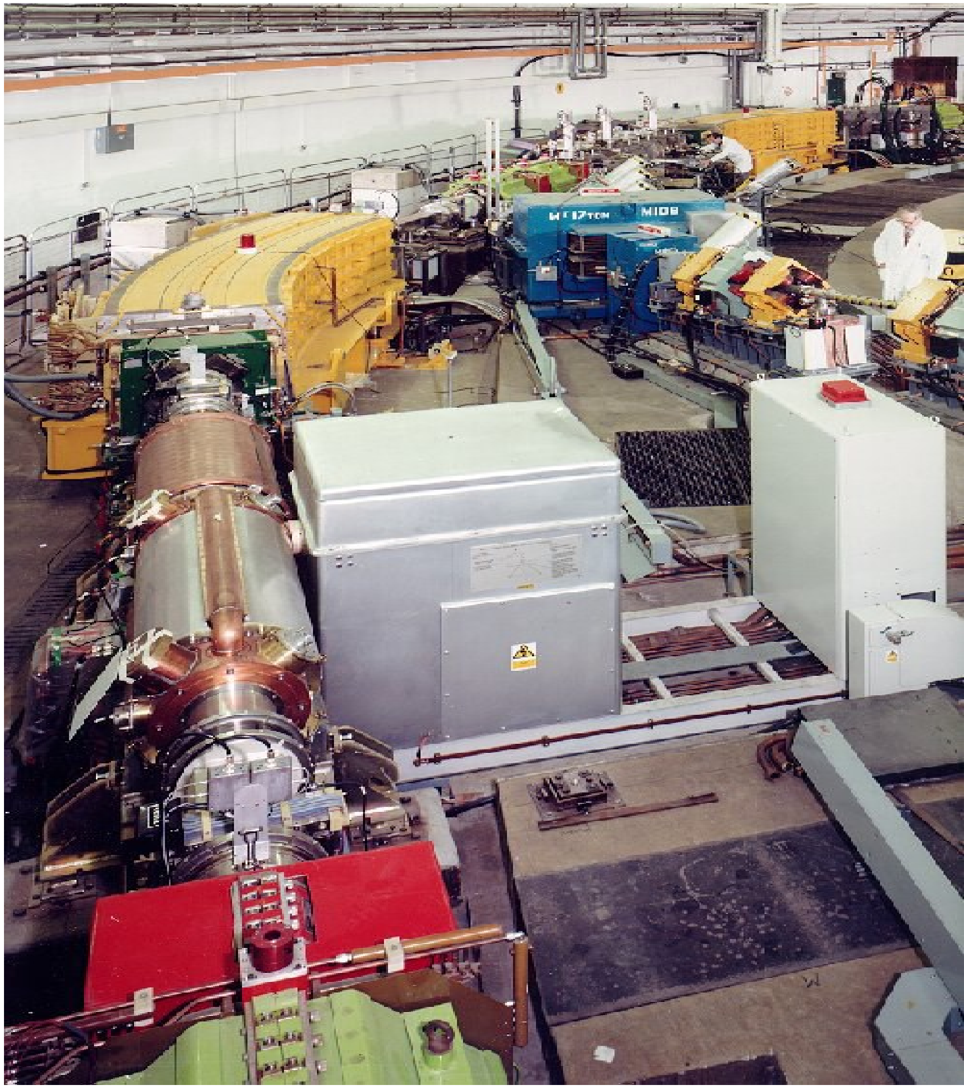
- Simplest example is a vacuum chamber with one or more DC accelerating structures with the *E*-field aligned in the direction of motion.
- To achieve energies higher than the highest voltage in the system, the *E*-fields are alternating at RF cavities.
- A series of drift tubes alternately connected 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.



The Wideröe accelerator. Each drift tube is charged to the opposite polarity from that of its neighbors

Types of Synchrotrons

- **Storage rings**:
  - accumulate particles and keep circulating for long periods;
  - used for high intensity beams to inject into more powerful machines such as SPS at CERN
  - synchrotron radiation factories like ISIS in UK, Elettra in Trieste, DESY in Hamburg, etc.
- **Colliders:**
  - two beams circulating in opposite directions
  - the beams are made to intersect at specific point
  - maximises energy in the centre of mass frame



Picture of the ISIS Synchrotrons

Principle of Synchrotron

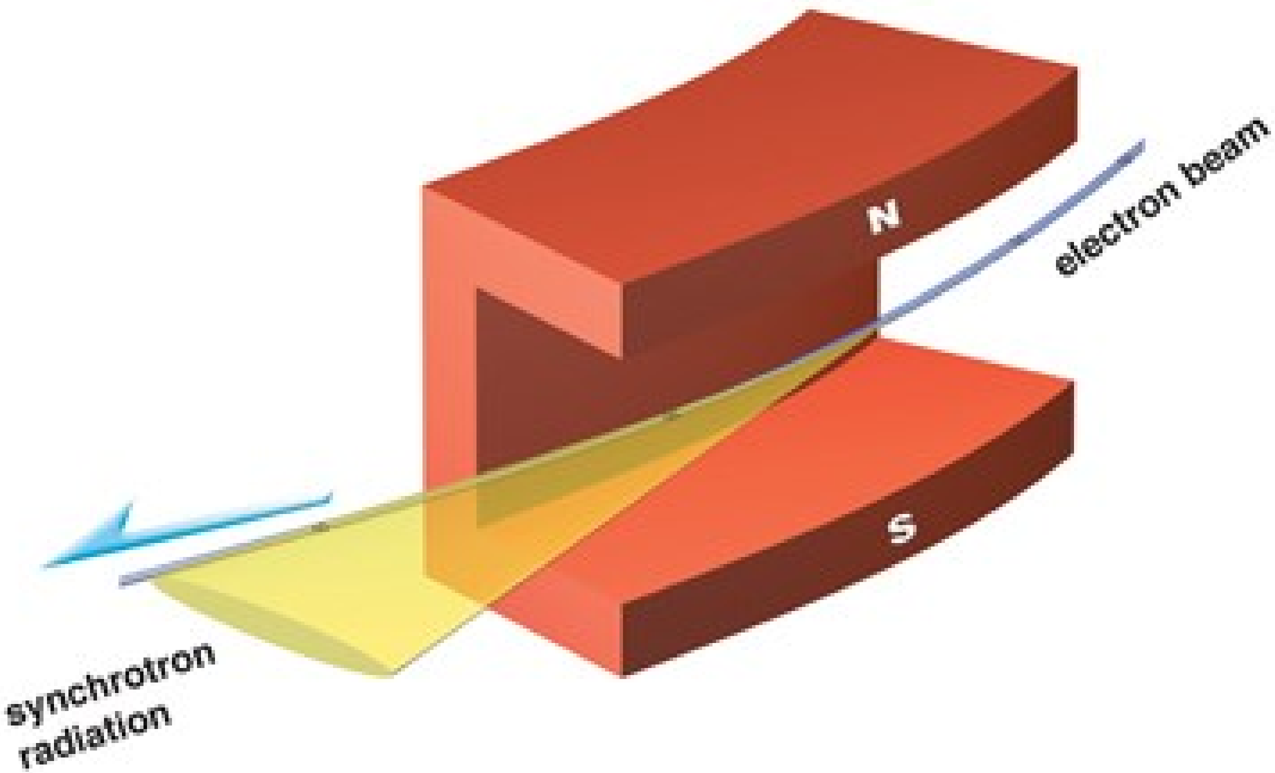
- Principle of synchrotron requires the frequency modulation as well as an increase in *B*-field to match increase in particle's kinetic energy and keep orbital radius constant.
- Magnetic field produced by several bending magnets (dipoles), increases linearly with momentum. For q=e and high energies:

$$B\rho = \frac{p}{e} \approx \frac{E}{ce}, E[GeV] \approx 0.3B[T]\rho[m]$$

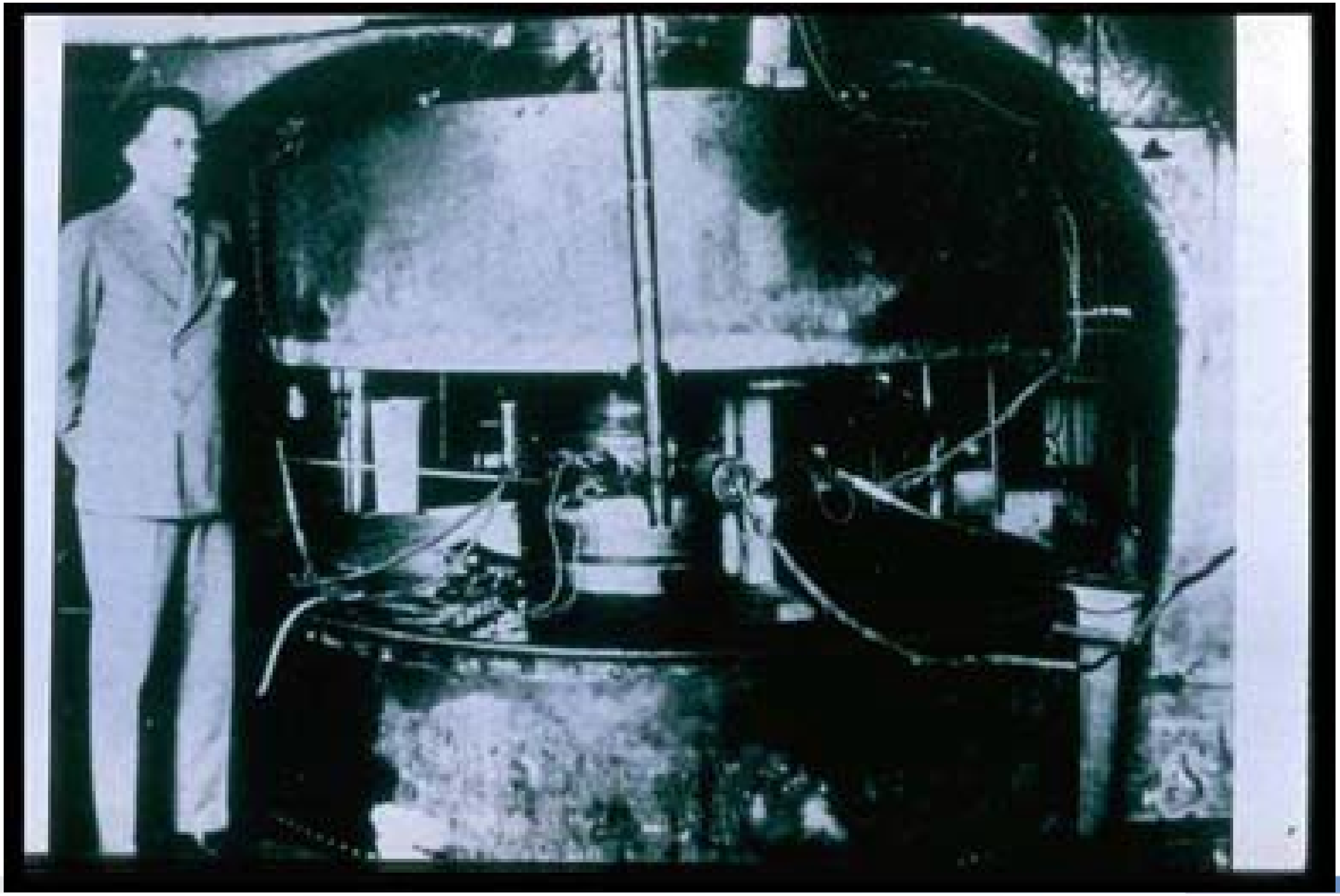
- Practical limitations for magnetic fields => high energies only at large radius.

e.g. LHC *E = 8 TeV, B = 10 T, ρ = 2.7 km*

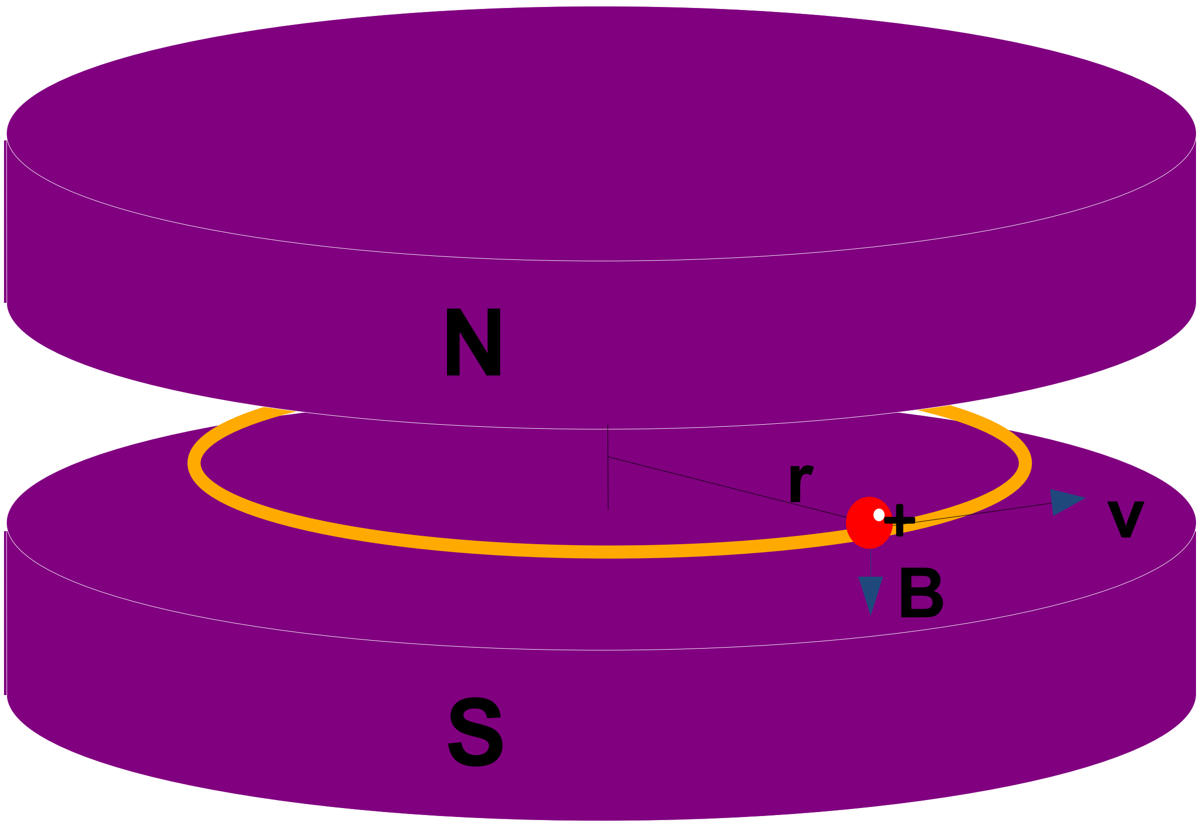
Synchrotron Radiation



Cyclotrons



Cyclotrons

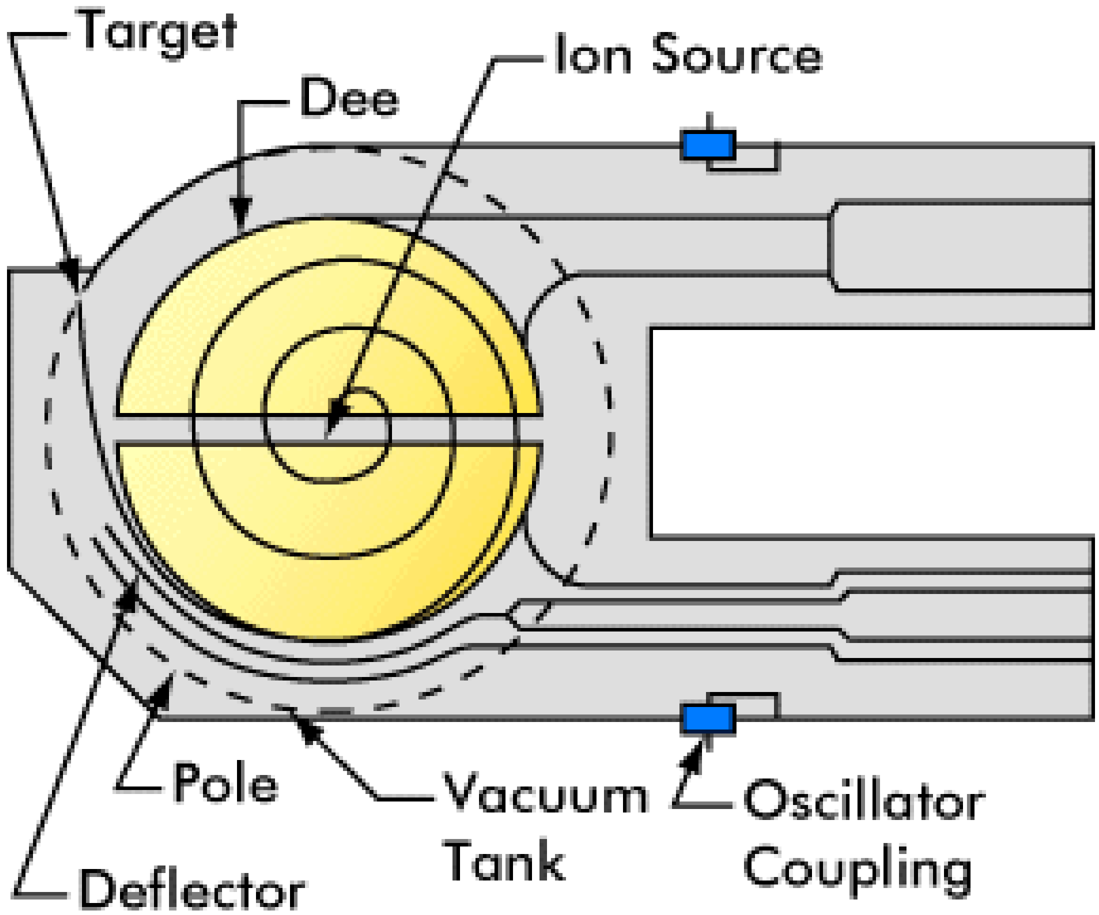


$$F = qvB = \gamma \frac{mv^2}{r} \quad v = \frac{qBr}{\gamma m} \quad \tau_p = \frac{2\pi r}{v} = \frac{2\pi \gamma m}{qB}$$

Method of Acceleration : Circular

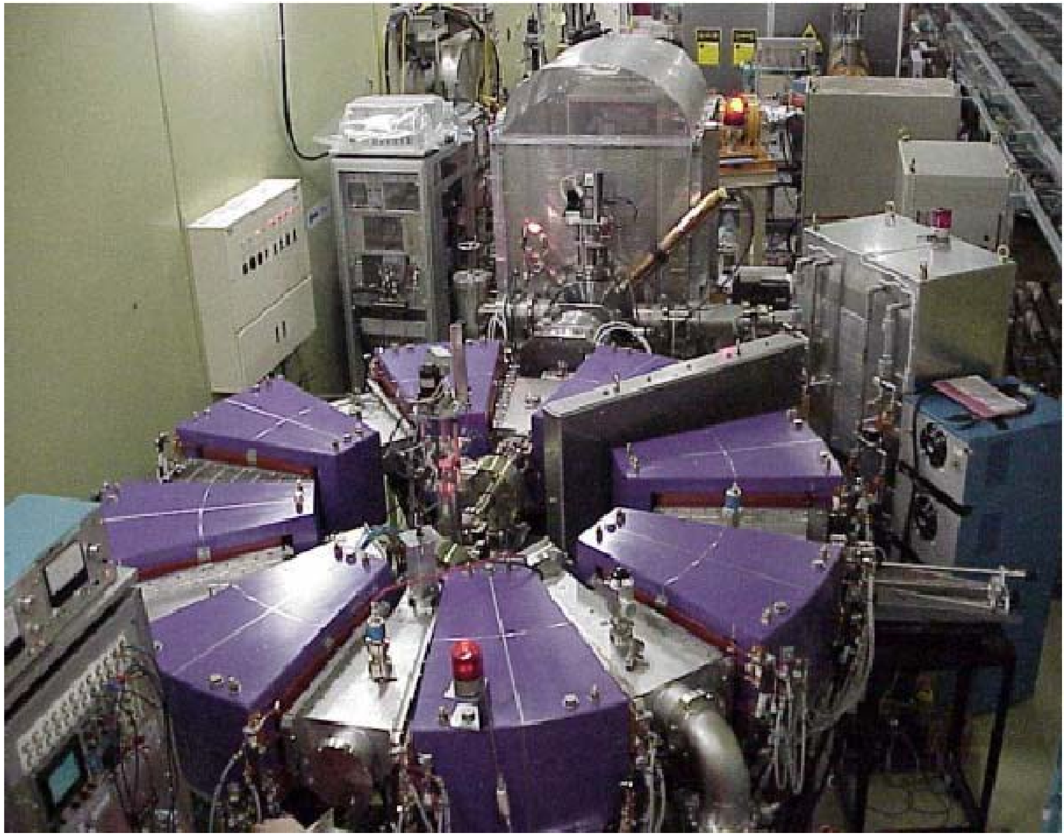
Use the magnetic fields to force particles to pass through accelerating fields at regular intervals

- Constant B field
- Constant accelerating frequency *f*
- Spiral trajectories
- For synchronism $f = n\omega$, which is possible only at low energies, γ~1.
- Use for heavy particles (protons, deuterons, α-particles, etc.).



Fixed Field Alternating Gradient (FFAG)

- An idea dating from 1950's, given a new lease of life with the development of new magnetic alloy cavities.
- Field constant in time, varies with radius according to a strict mathematical formula.
- Wide aperture magnets and stable orbits.
- **High gradient accelerating cavities** combine with fixed field for rapid acceleration.
- Good for particles with short half-lives (e.g. muons).



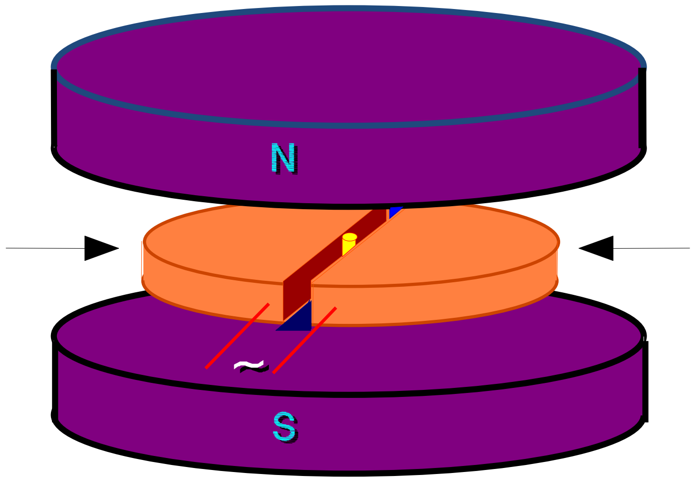
Prototype FFAG, accelerating protons from 50 keV to 500 keV, was successfully built and tested at the KEK laboratory in Japan, 2000.

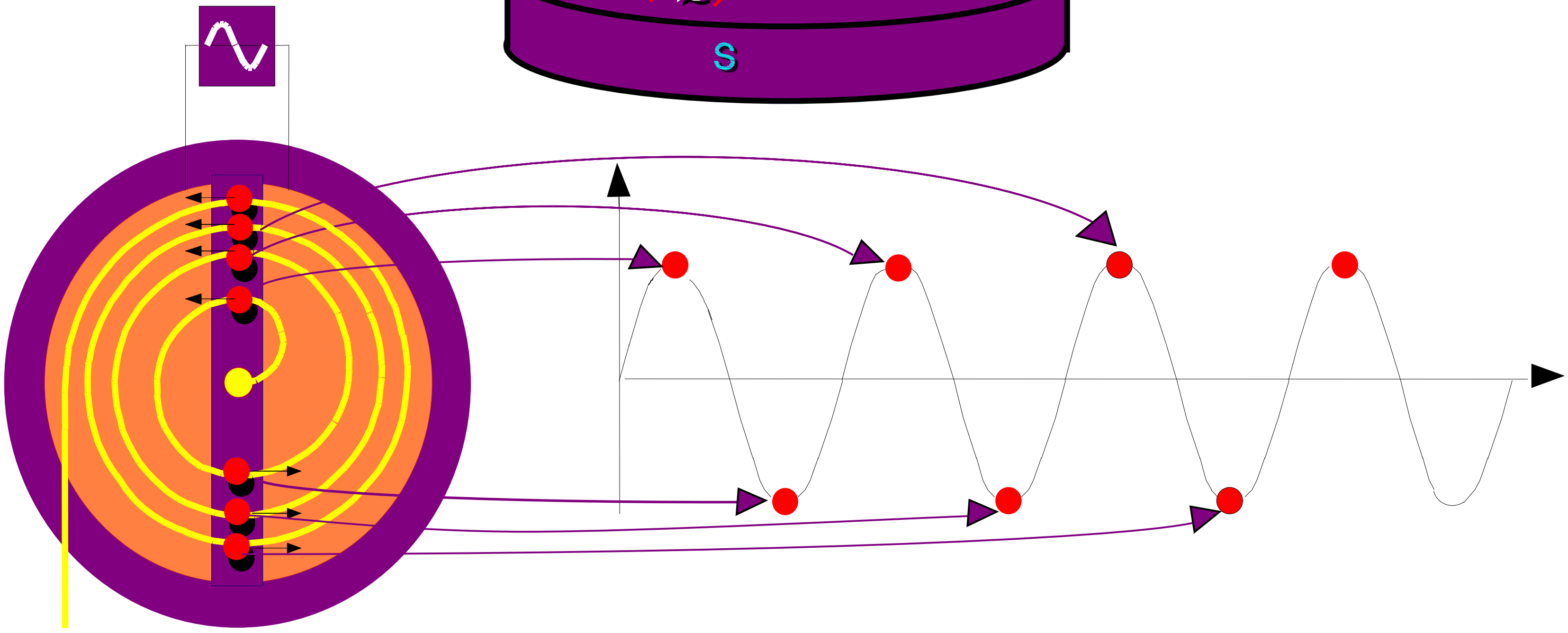
Effect on Particles in an RF Cavity

- Cavity set up so that particle at the centre of bunch, called the synchronous particle, acquires just the right amount of energy.
- Particles see voltage $V = V_0 \sin 2\pi\omega_{rf} t = V_0 \sin \varphi(t)$
- In case of no acceleration, synchronous particle has $\varphi_s = 0$
  - Particles arriving early see $\varphi < \varphi_s$
  - Particles arriving late see $\varphi > \varphi_s$
  - energy of those in advance is decreased relative to the synchronous particle and vice versa.
- To accelerate, $0 < \varphi_s < \pi$ so that synchronous particle gains energy: $\Delta E = V_0 \sin \varphi_s$

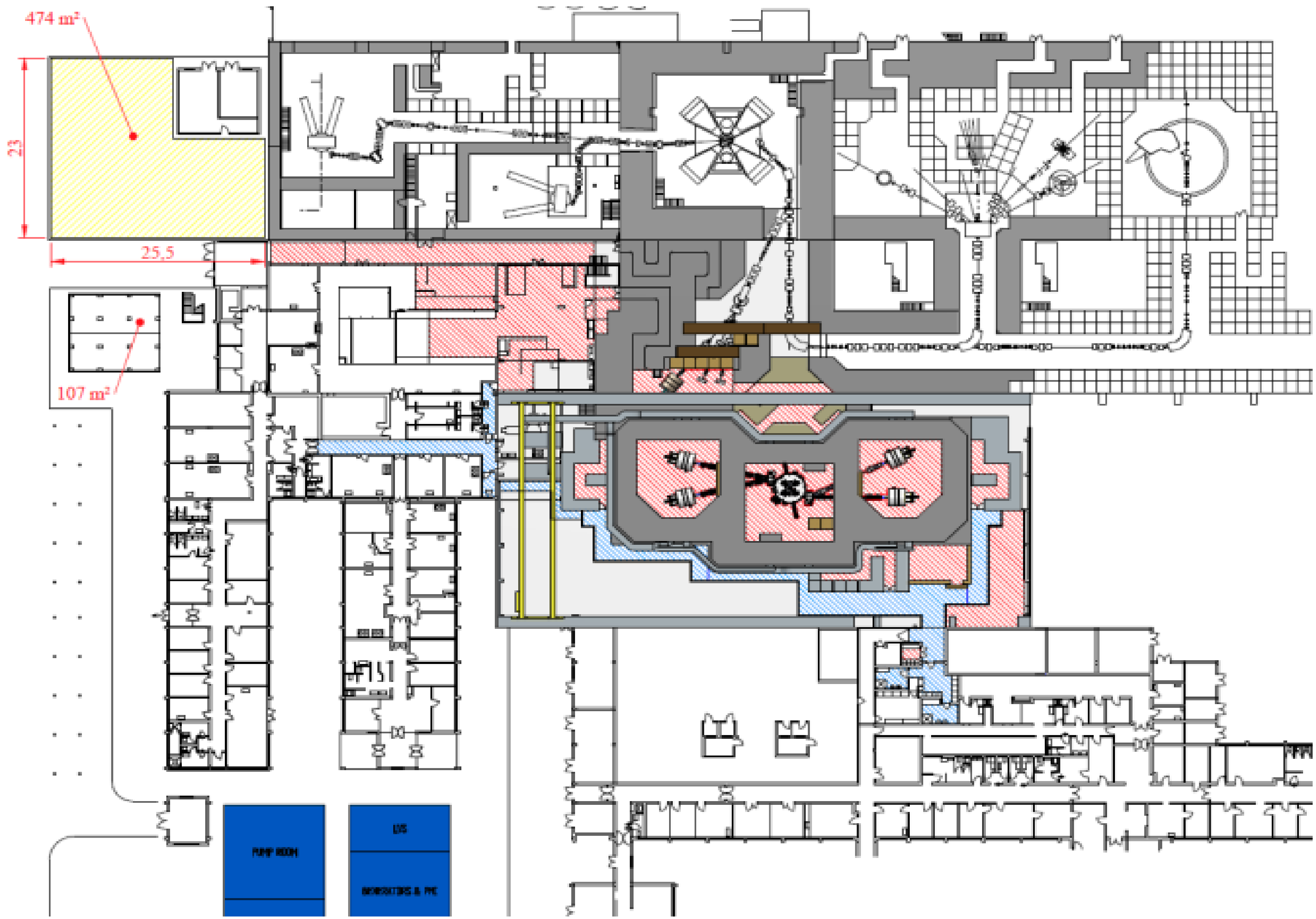
Acceleration with 'D'-electrodes

$$K = \frac{A}{q^2} E$$

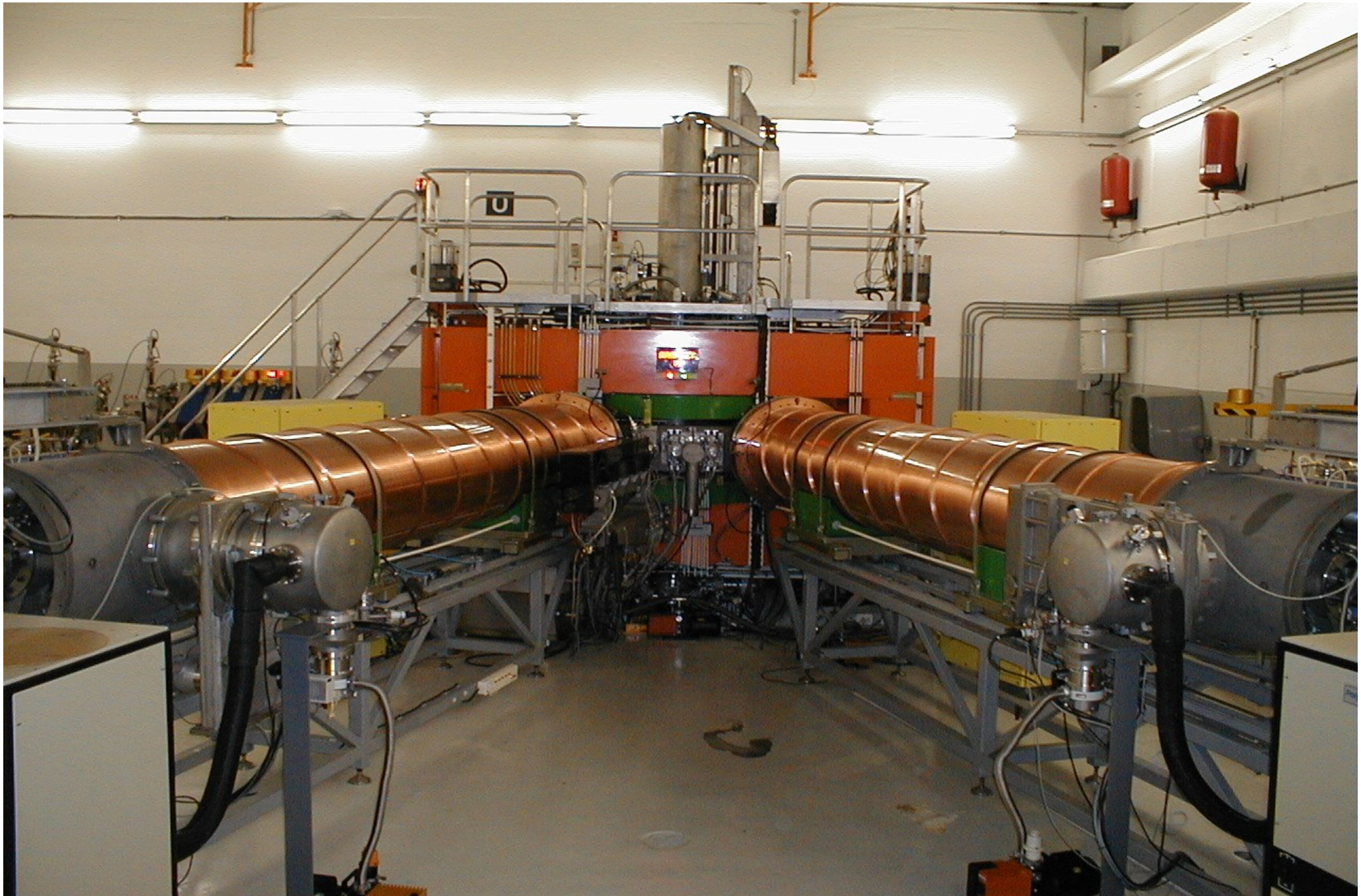




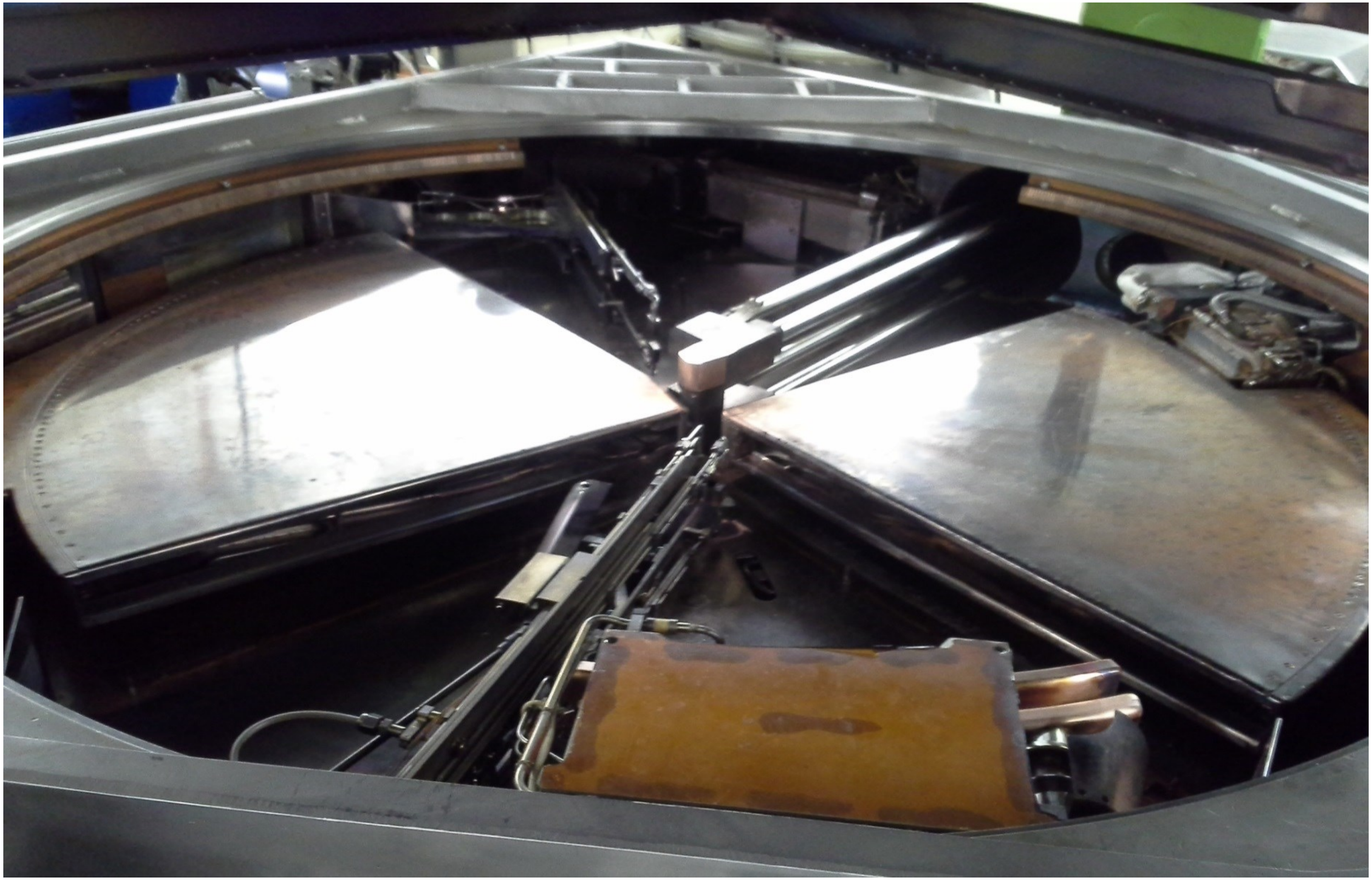
Cyclotron Facility



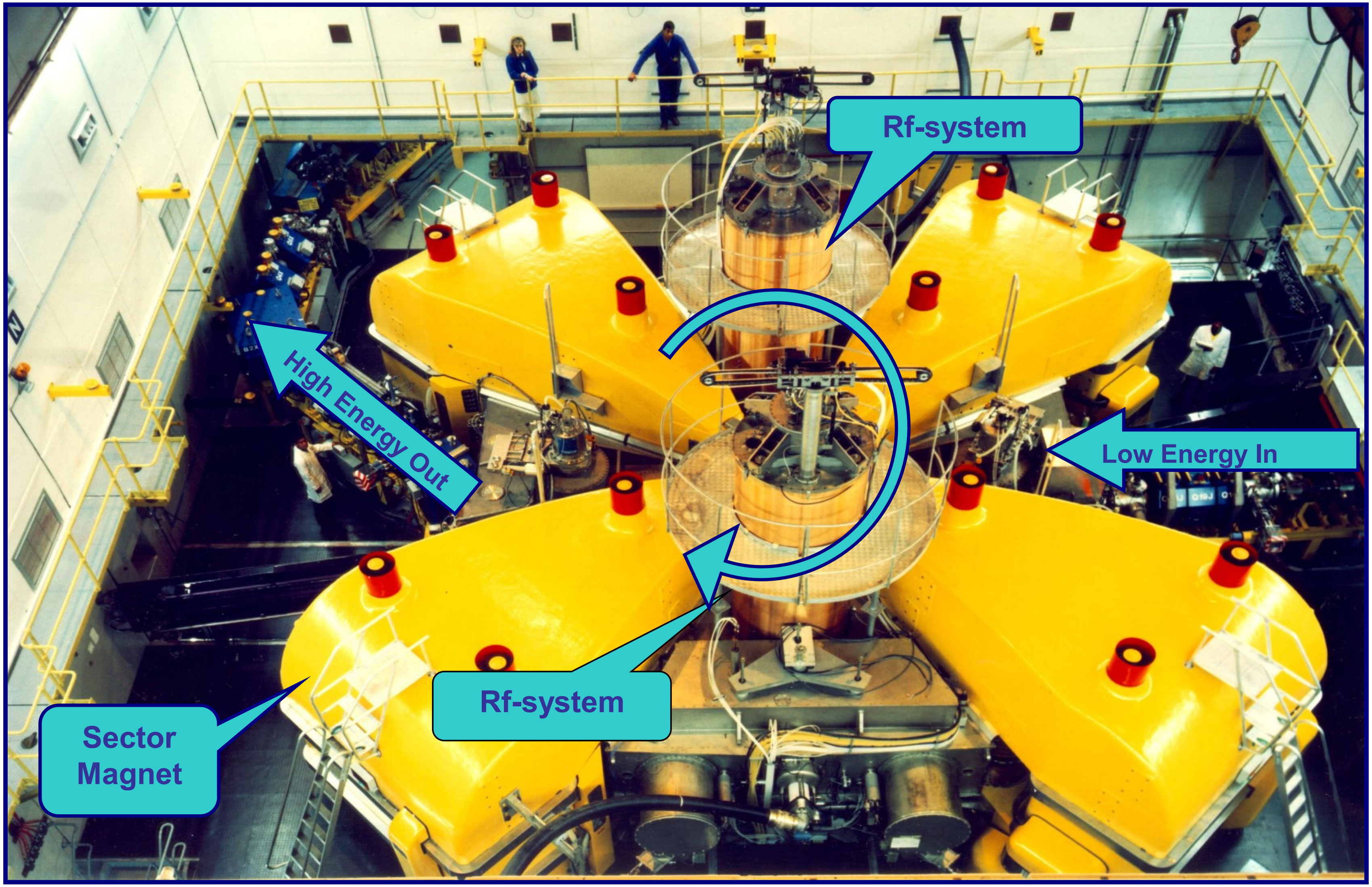
Solid-Pole Injector Cyclotron 2 (SPC2)



Solid-Pole Injector Cyclotron



The SSC


Rf-system
High Energy Out
Low Energy In
Rf-system
Sector
Magnet

11 MeV Eclipse Cyclotron

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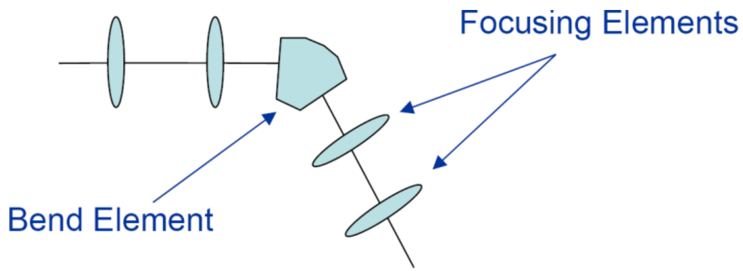
Introduction to Beam Optics

- ➢ Particles always have velocity normal to direction of motion due to the following.
- ❖ The random thermal motion of the particles.
- ❖ Space charge repulsion can accelerate particle away from axis.
- ➢ Forces must be applied to deflect particles back to the axis.
- ➢ Emittance is a measure for the average spread of particle coordinates in position-and-momentum phase space.
- ➢ Emittance is defined as 6-dimensional phase space (x, x', y, y', z, z').
- ➢ The particle propagation direction is defined as z-axis.
- ➢ Due to emittance ion trajectories can be converging, diverging or parallel.
- ➢ Ions travel similarly like light rays: optical lenses are substituted by electric and magnetic lens.

Definition of Beam Optics

Beam optics: The process of guiding a charged particle beam from A to B using magnets.

An array of magnets which accomplishes this is a *transport system*, or magnetic lattice.



Recall the Lorentz Force on a particle:

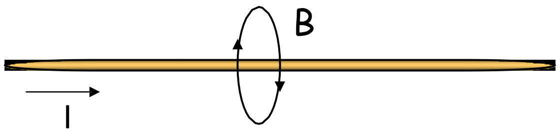
$F = ma = q(E + v \times B) = \frac{mv^2}{\rho}$, for relativistic particles we substitute mass with rest mass m_o and relativistic term γ, $m = m_o$

In magnetic transport systems, there are no electric field, $E = 0$,

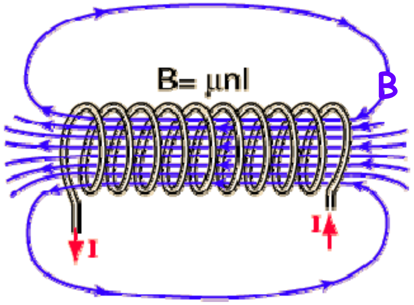
$$F = ma = qv \times B = \frac{m_o \gamma v^2}{\rho}$$

Magnetic Field B induced from current flow

Recall that a current in a wire generates a magnetic field B which curls around the wire



Or, by winding many turns on a coil we can create a strong uniform magnetic field.

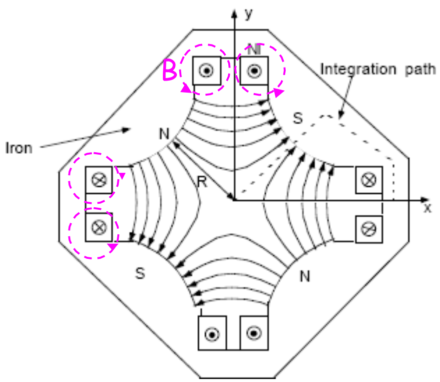


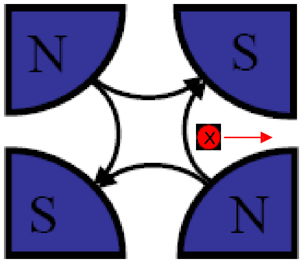
The field strength is given by one of Maxwell's equations:

$$\Delta \times \frac{B}{\mu_r} = \frac{4\pi}{c} J \qquad \mu_r = \frac{\mu_m}{\mu_o}$$

Quadrupole Current and Field Equation

As with a dipole, in an accelerator we use current-carrying wires wrapped around metal cores to create a quadrupole magnet:



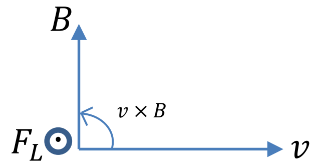


The field lines are denser near the edges of the magnet, meaning the field is stronger there.

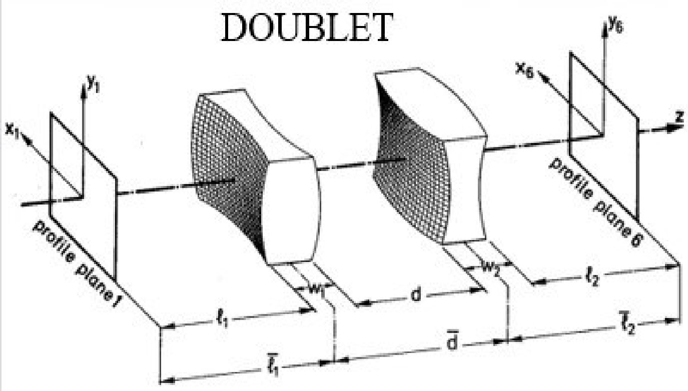
The strength of B_y is a function of x, and visa-versa. The field at the center is zero!

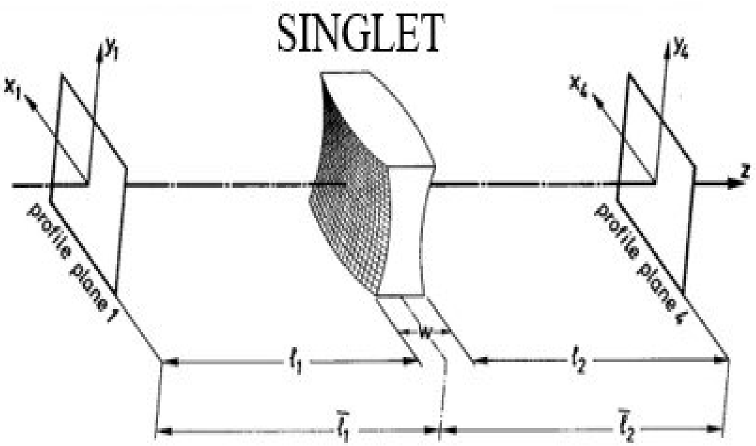
Using Maxwell's equation for B, we can derive the relationship between B in the gap, and I in the wires:

$$B' = \frac{dB_\varphi}{dr} = \frac{8\pi I}{cr^2}$$

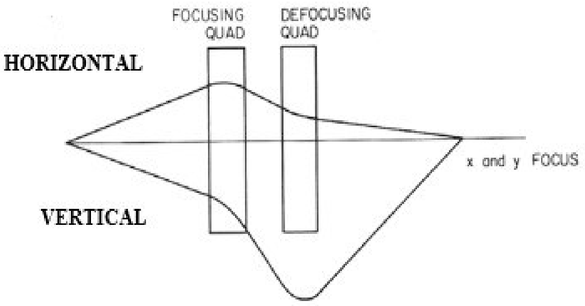


Ion optics of a quadrupole
SINGLET
& DOUBLET





POINT TO POINT FOCUS WITH DOUBLET

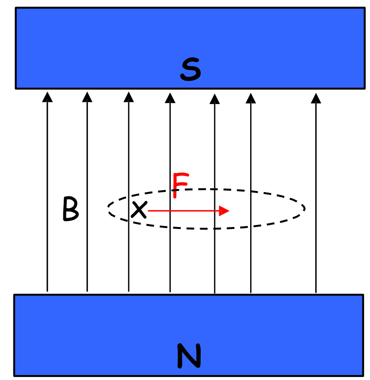


Quadrupoles

Dipole Magnets

A ***dipole magnet*** gives us a constant field, B.

The field lines in a magnet run from North to South. The field shown at right is positive in the vertical direction.



Symbol convention:

x - traveling into the page,

• - traveling out of the page.

In the field shown, for a positively charged particle traveling into the page, the force is to the right.

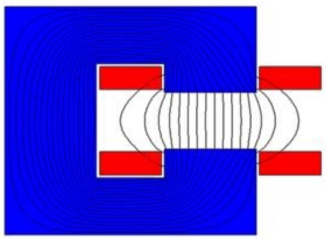
Lorentz Force $$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}}$$

$$\boldsymbol{F}_L = \frac{m\boldsymbol{v}^2}{r} = qvx\boldsymbol{B}$$

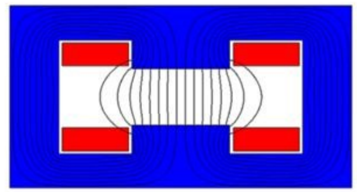
$$\frac{m\boldsymbol{v}}{q} = \boldsymbol{B}\rho$$

Types of Dipoles

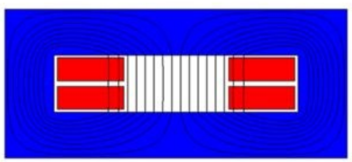
These are the most common types of resistive dipoles



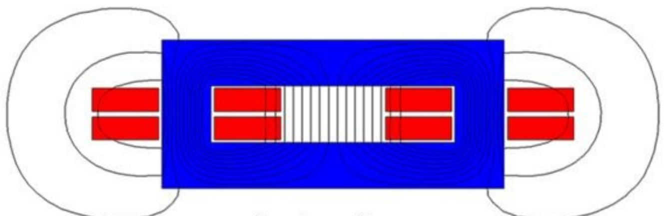
“C” dipole



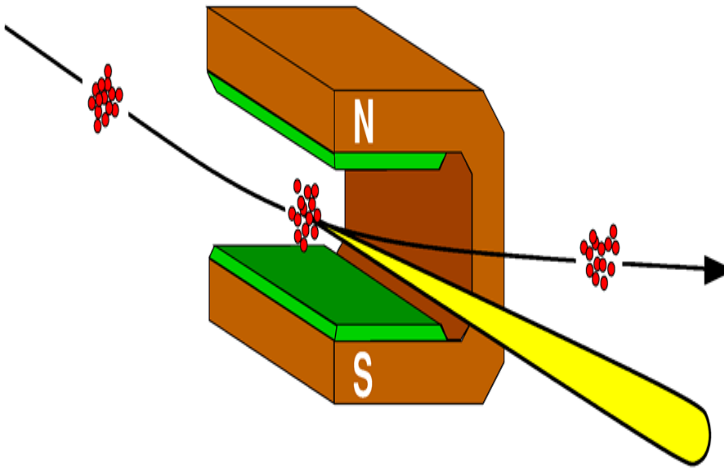
“H” dipole



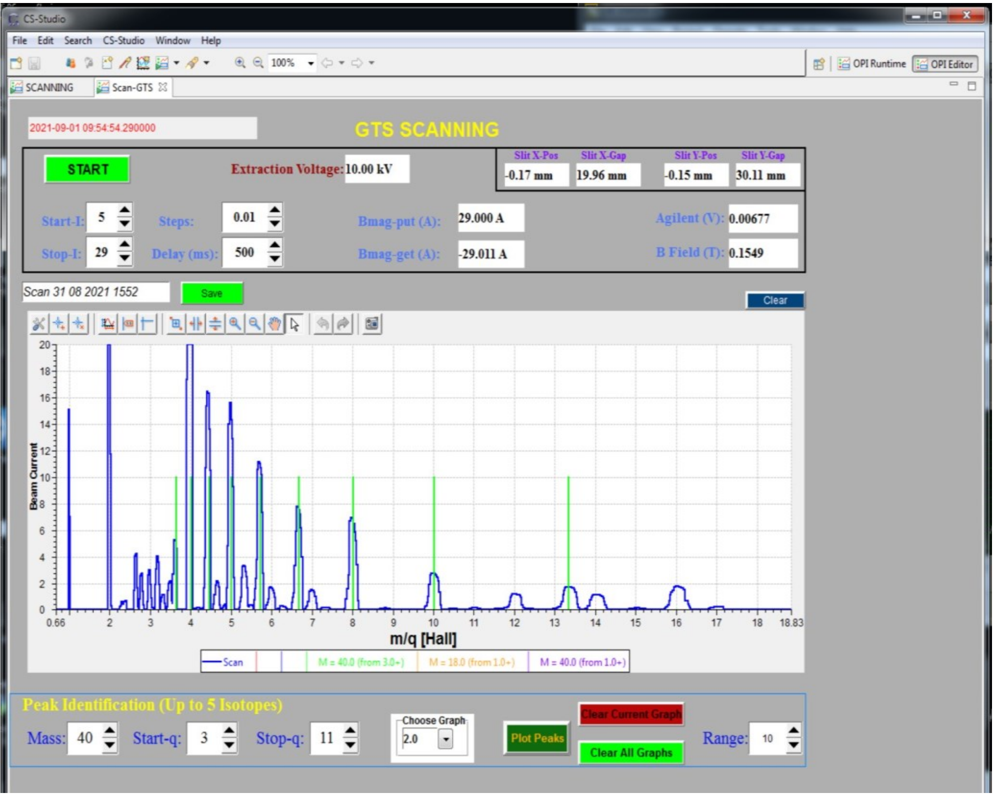
window frame dipole (“O” dipole)

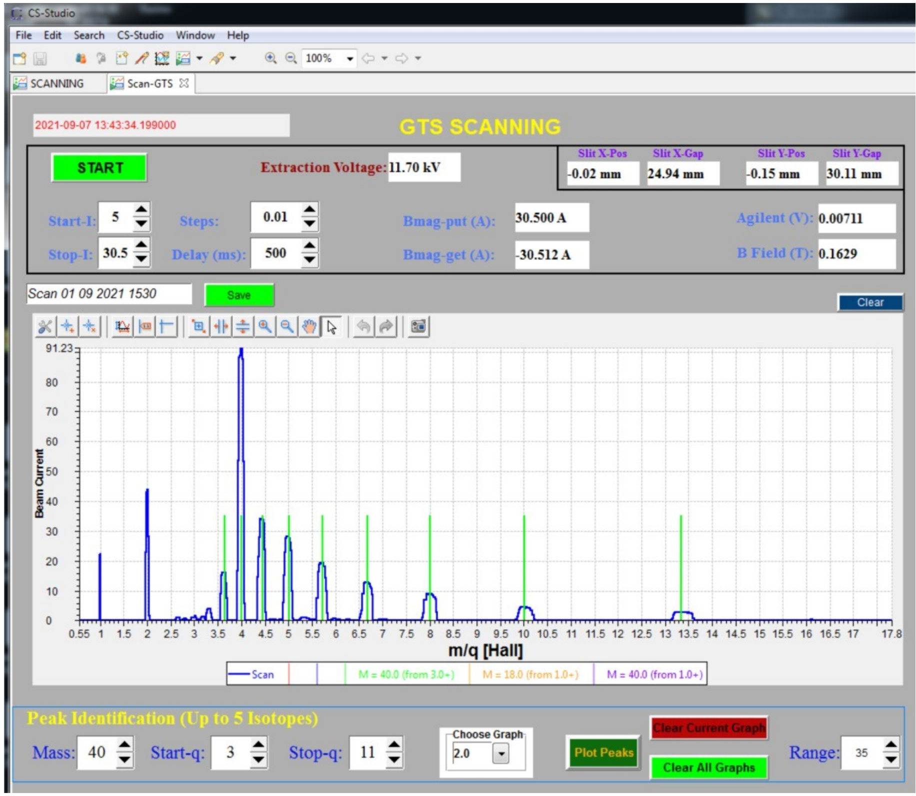


window frame dipole (“O” dipole)

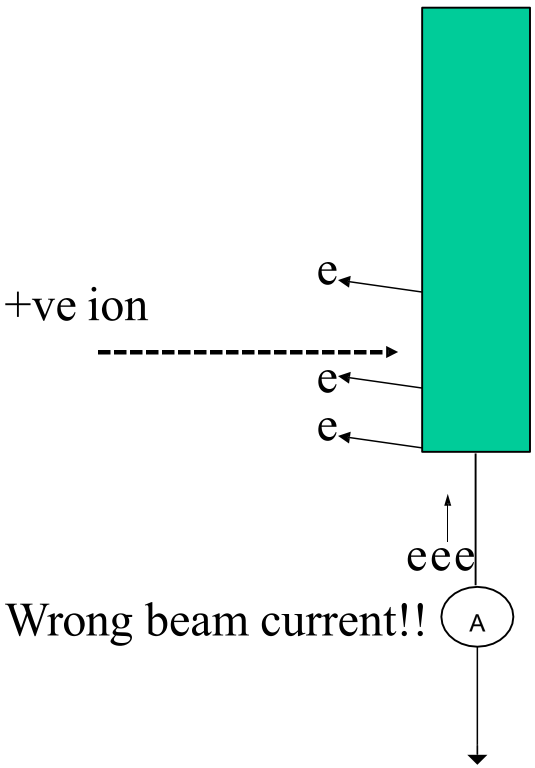


Scanning with Dipole Magnet





Beam Intensity Measurement with Faraday Cup



- Historically the first intensity-measuring device was the Faraday-cup
- The beam particles are captured by a piece of isolated conducting material
- The excess charge flows from this electrode to the ground through an ampere-meter
- For this method to work the beam has to be completely captured with no escaping electrons
- Stopping range increases with beam energy which make faraday cup only suited for low energy beams
- Production of perturbation current to the real beam current due to secondary electrons.

Interaction with Stopping Material

Stopping range

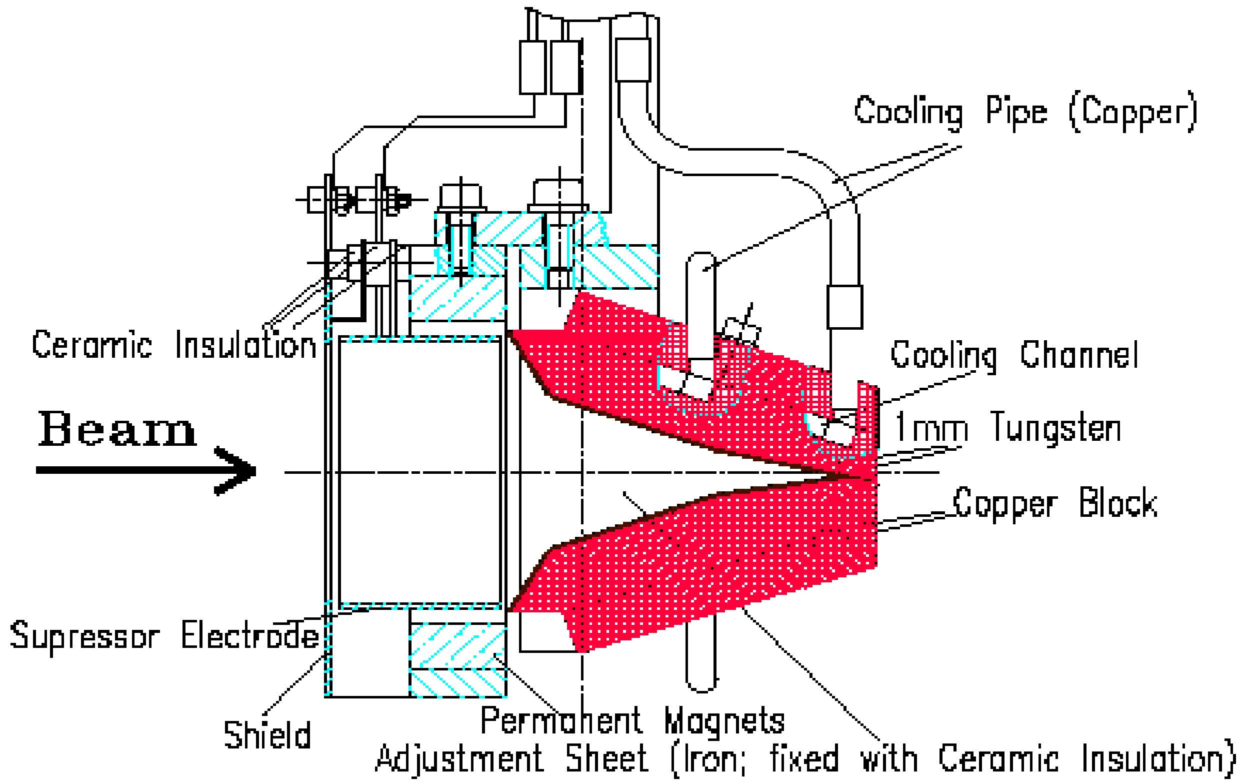
Proton energy		Stopping range in copper
500 keV	(Cockcroft-Walton)	0.003 mm
5 MeV	(Van de Graaff)	0.08 mm
50 MeV	(solid pole cyclotron)	4 mm
200 MeV	(separated sector cyclotron)	43 mm
1 GeV	(synchrotron)	520 mm

Stopping ranges for protons in copper

[redacted]

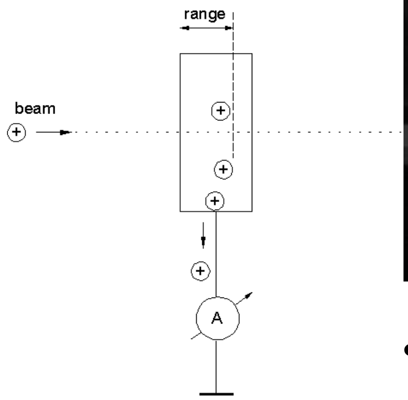
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

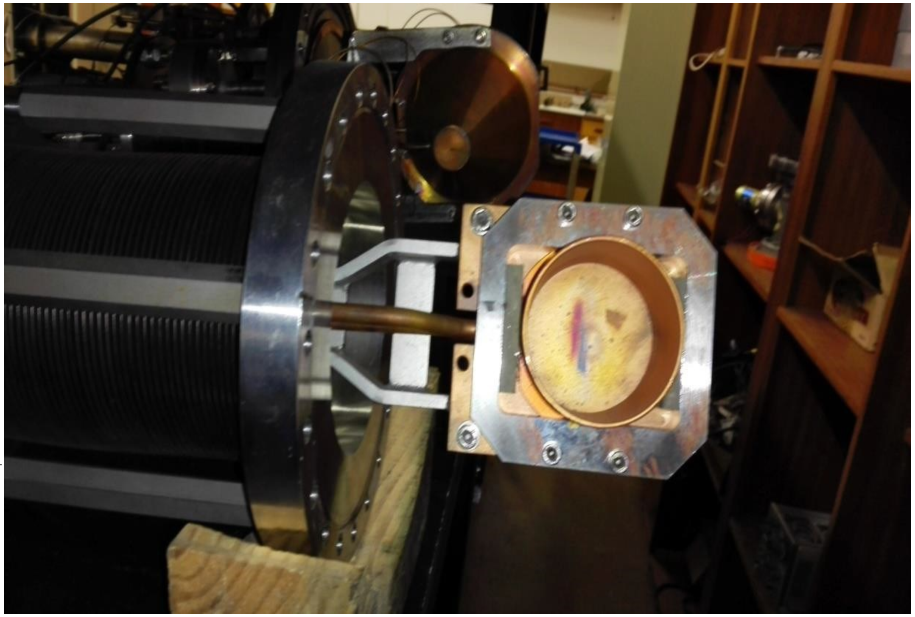
Faraday-cup and beam stopper for high-power accelerated beams



Faraday Cup

$$I_{beam} = \frac{qeN}{t} = \frac{qeN}{l}\beta c$$

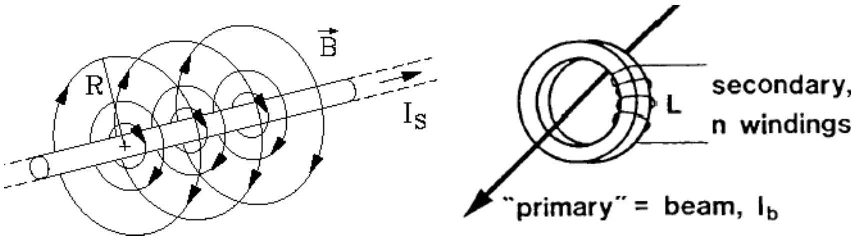




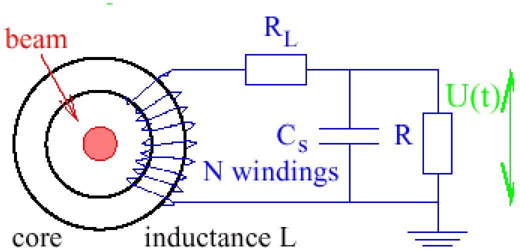
- Number of the accelerated particles (N)
- Moving charges (qe) => electric current

Non-destructive beam current measurement:

Beam transformer

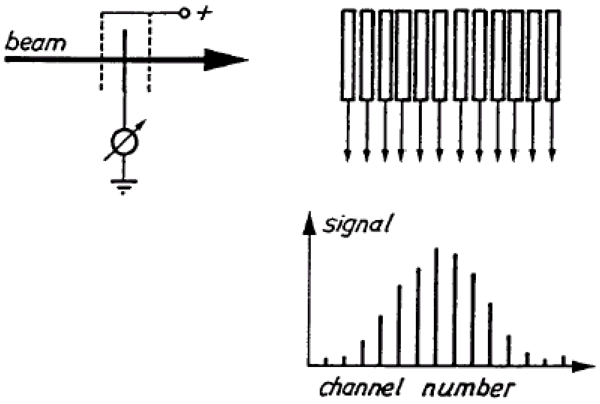


- equivalent electrical circuit:



Beam profile monitors:

- secondary emission grid (SEM)



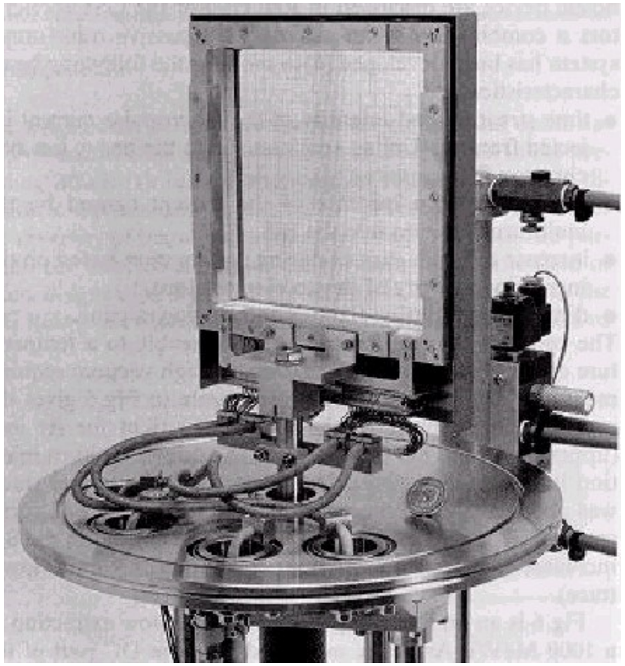
Advantages:

- only partially destructive
- high accuracy of delivered position information
- simultaneity of the measurement => no need for synchronization
- much higher dynamic range than that of a scintillator screen

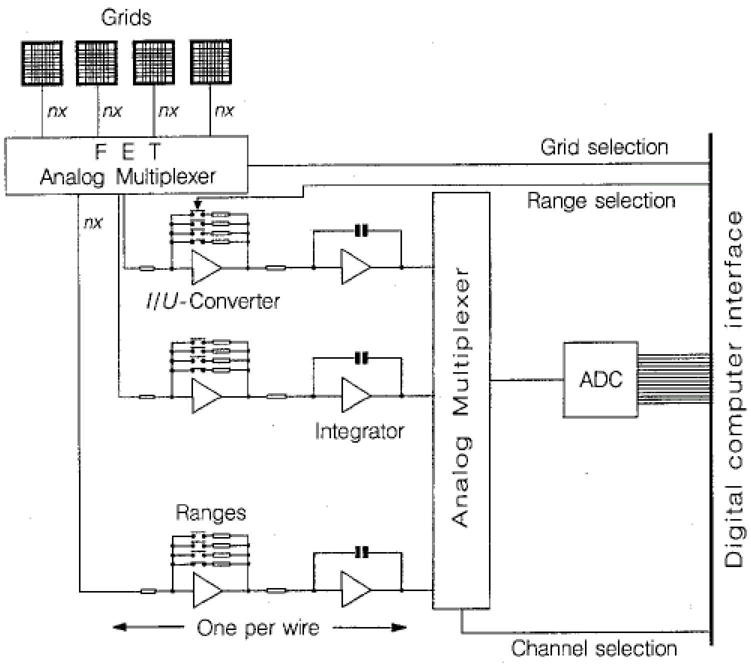
Drawbacks:

- limited spatial resolution
- applicable only to beams with low power density
- complicated (expensive) signal electronics

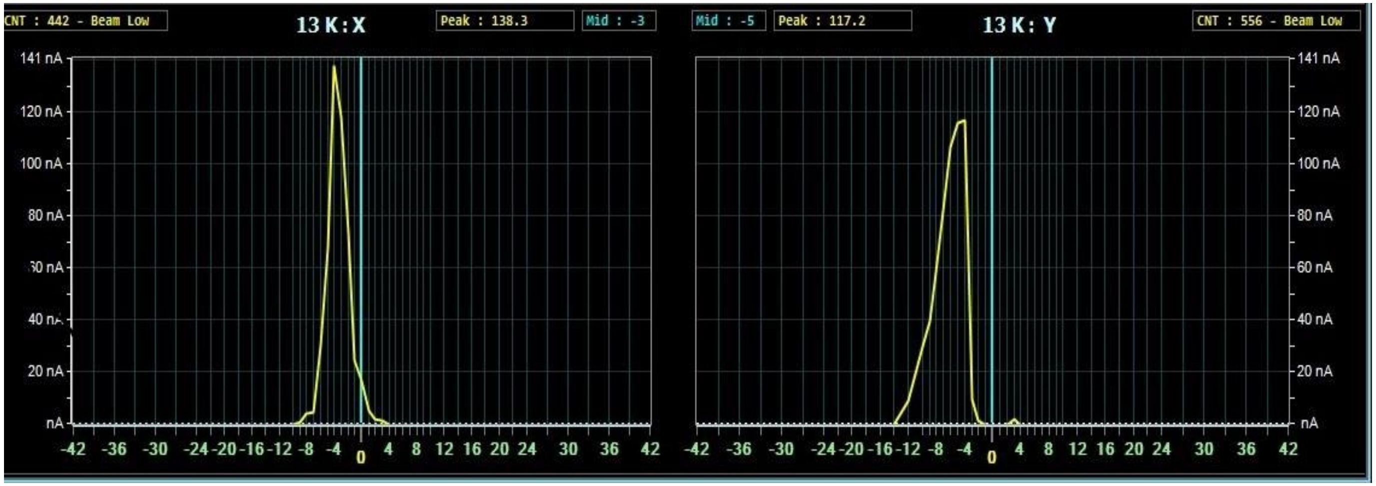
Large profile grid (for both planes) mounted on a vacuum feedthrough



Typical analog signal processing for a SEM-grid system



Example of Wire Grid Output in the K-Line



Kea leboha!!

Thank you!!