Új Nemzeti
Kiválóság Program

V. Accelerators

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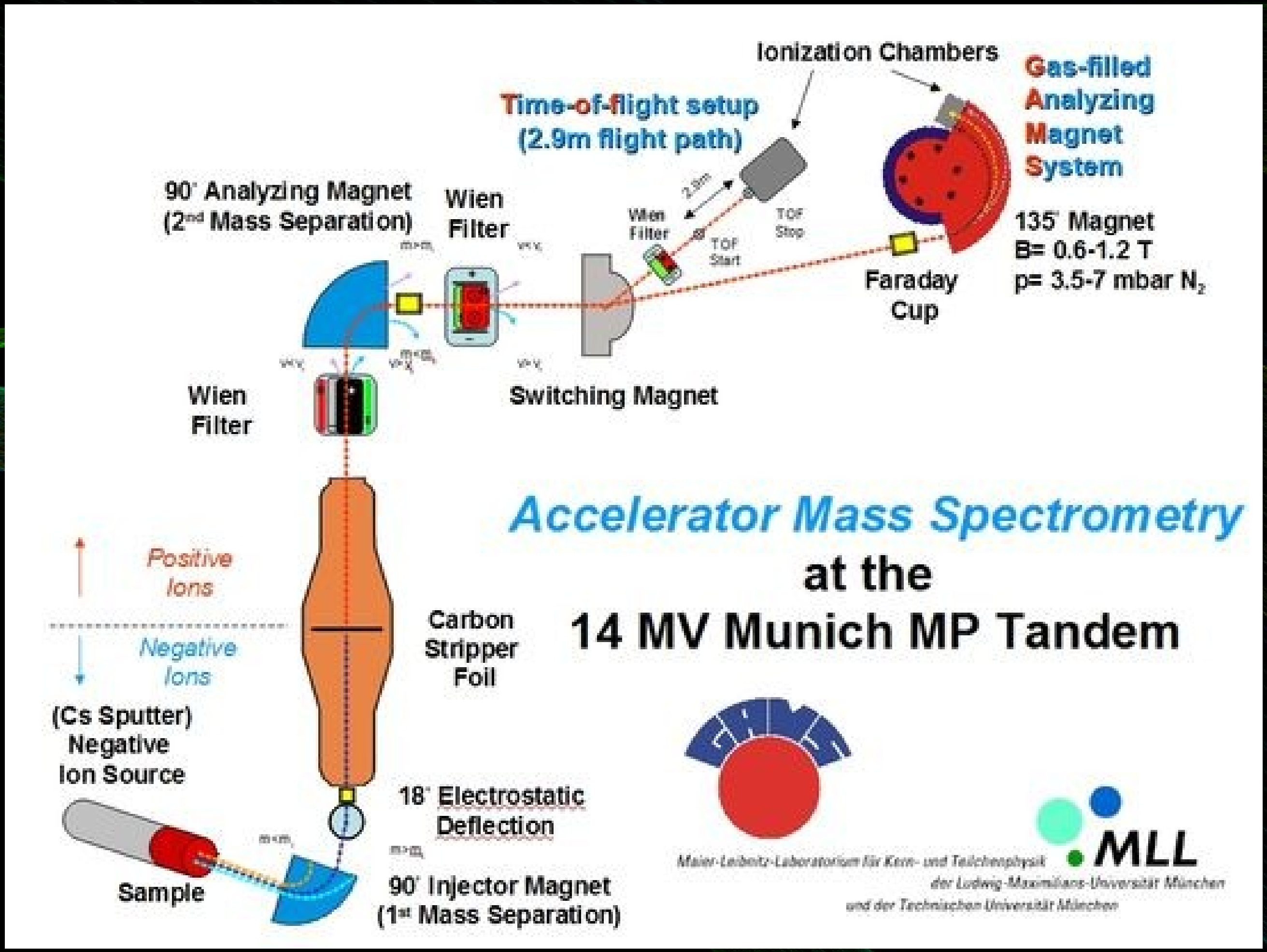
Accelerators: types

- Fisrt accelerator induced nuclear reaction: $^{7}Li + ^{1}H \rightarrow ^{4}He + ^{4}He$
  - until that time reactions were induced by radioactive sources (and cosmic rays) → no chance to measure the excitation function of a reaction σ(E)
- Accelerators for particle physics:
  - to study elementary particles resonances and interactions between them → demand for higher and higher energy
- Accelerators for nuclear physics:
  - moderate energy
  - high intensity
  - high precisity
  - wide range of availeble ions
- Special accelerators for nuclear physics:
  - heavy ion accelerators
  - radioactive beam factories

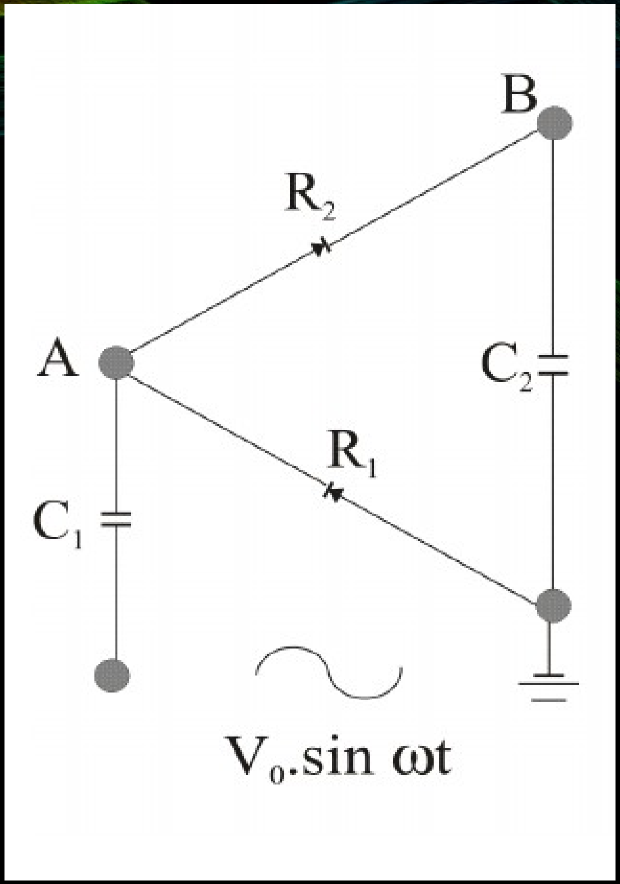
Accelerators: basics

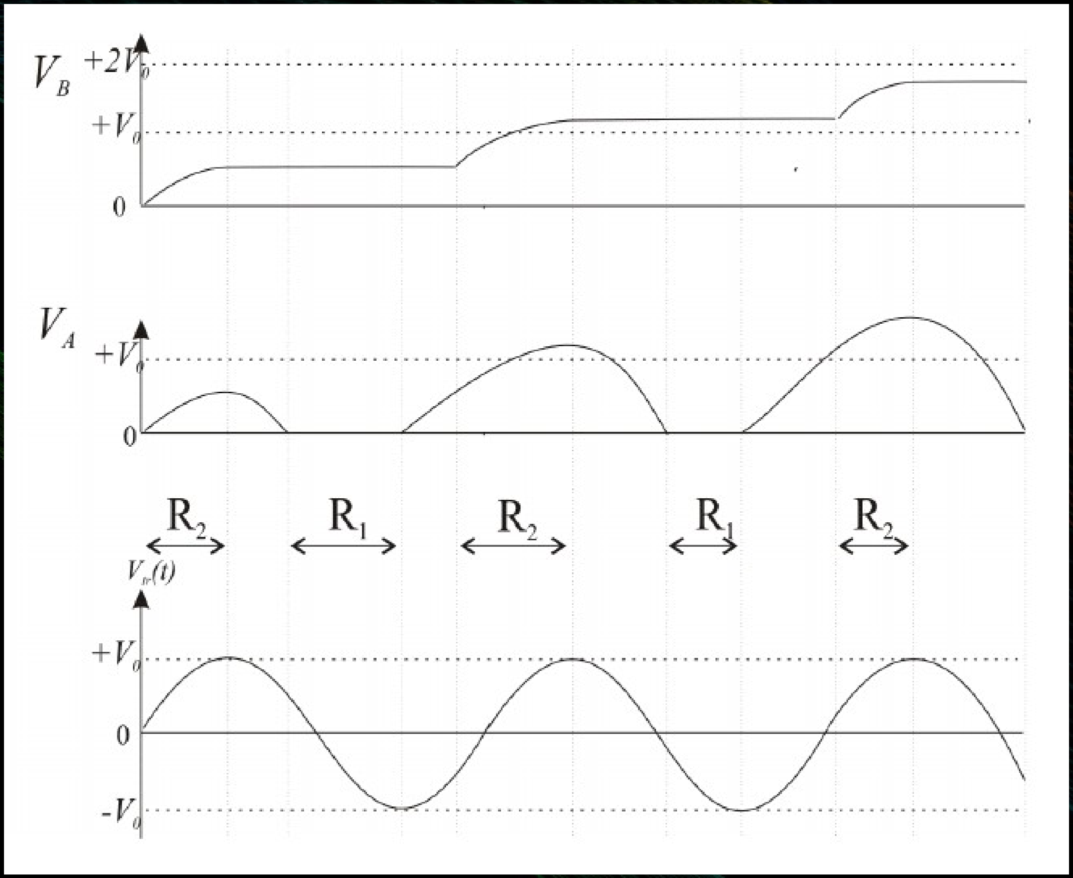


- Components of a typical accelerator facility:
  - ion source, accelerator, analyzing magnet, swicthing magnet, beamline, detection systems
  - focusing magnets, vacuum systems, collimators

Cockroft-Walton cascade generator

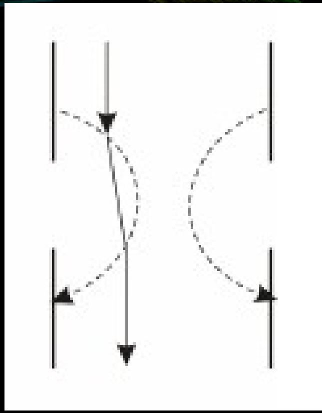
- simple structure, low energy (0.1-1 MeV), high intensity (1-10 mA)
- high voltage is produced by cascade connections of capacitors and diodes:
  - alternating charge of C_1 and C_2 → V_B=2V_0 after a short time!

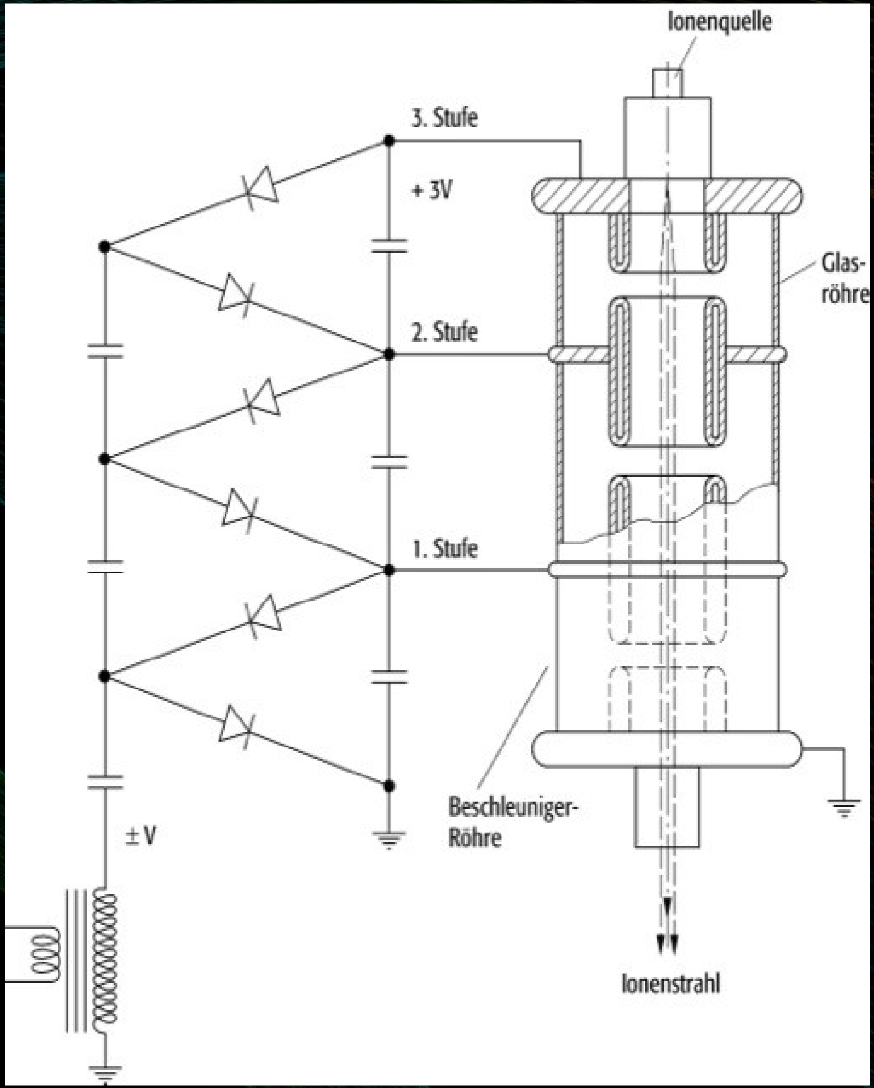




Cockroft-Walton cascade generator

- Vacuum in the accelerator tube
- Self-focusing by the inhomogenous electic field:
  - focusing in the first part, than acceleration, finally defocusing but meanwhile the velocity was increased!





- Neutron generators:
  - $^2H + ^2H \rightarrow ^3He + n$ (E= 2.5 MeV)
  - $^2H + ^3H \rightarrow ^4He + n$ (E= 14 MeV)
  - Coulomb barrier is small: only 200-300 keV is needed (CW is good!)

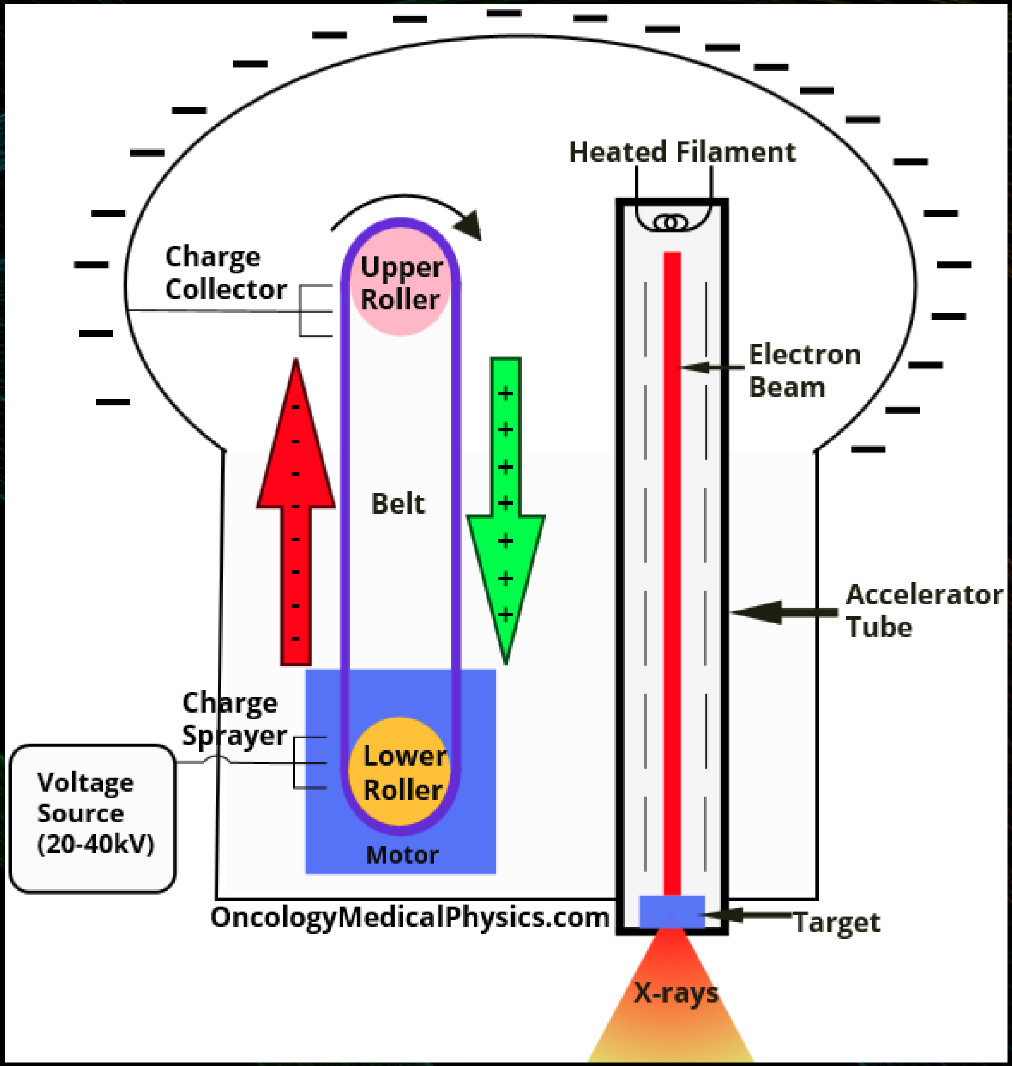
bad energy stability: voltage fluctuactions!

Cockroft-Walton accelerator

- Using as pre-accelerator: Fermilab (Ilinois) 750 kV or ISIS (England) 665 keV

Van de Graaff accelerator

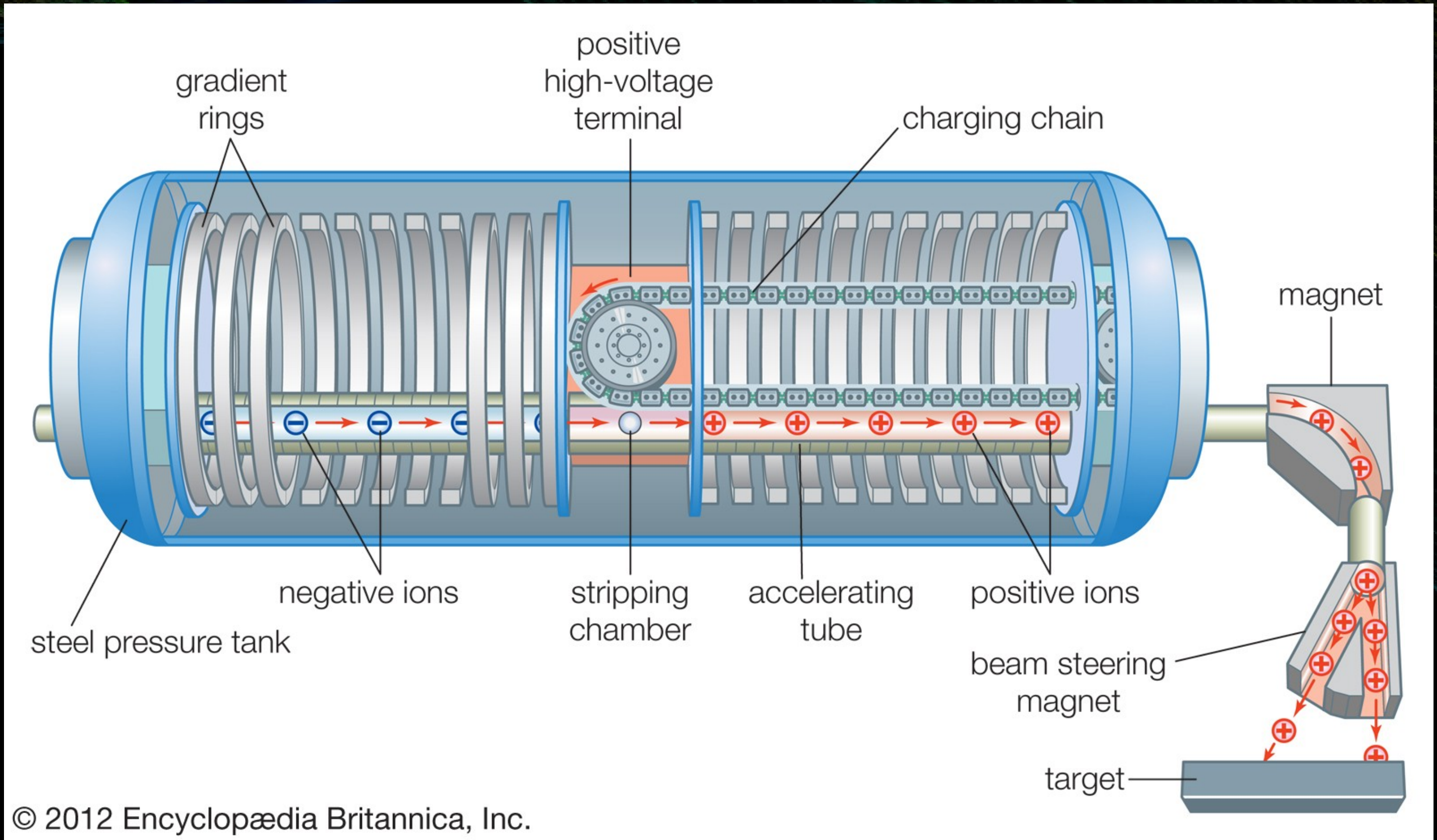
- 10-100 kV charging device → charge transportation to a metallic sphere by an insulating belt
- accelerator tube is equipotential plates and insulators between them
- accelerator field is by resistive voltage dividers → homogenous electric field
- maximal high voltage is defined by the size of electrode and the breakdown limit of surrounding gas:
  - in air 1-2 MV
  - with high pressure 10-20 bar gas mixture (80% N_2 20%CO_2) 5-10 MV



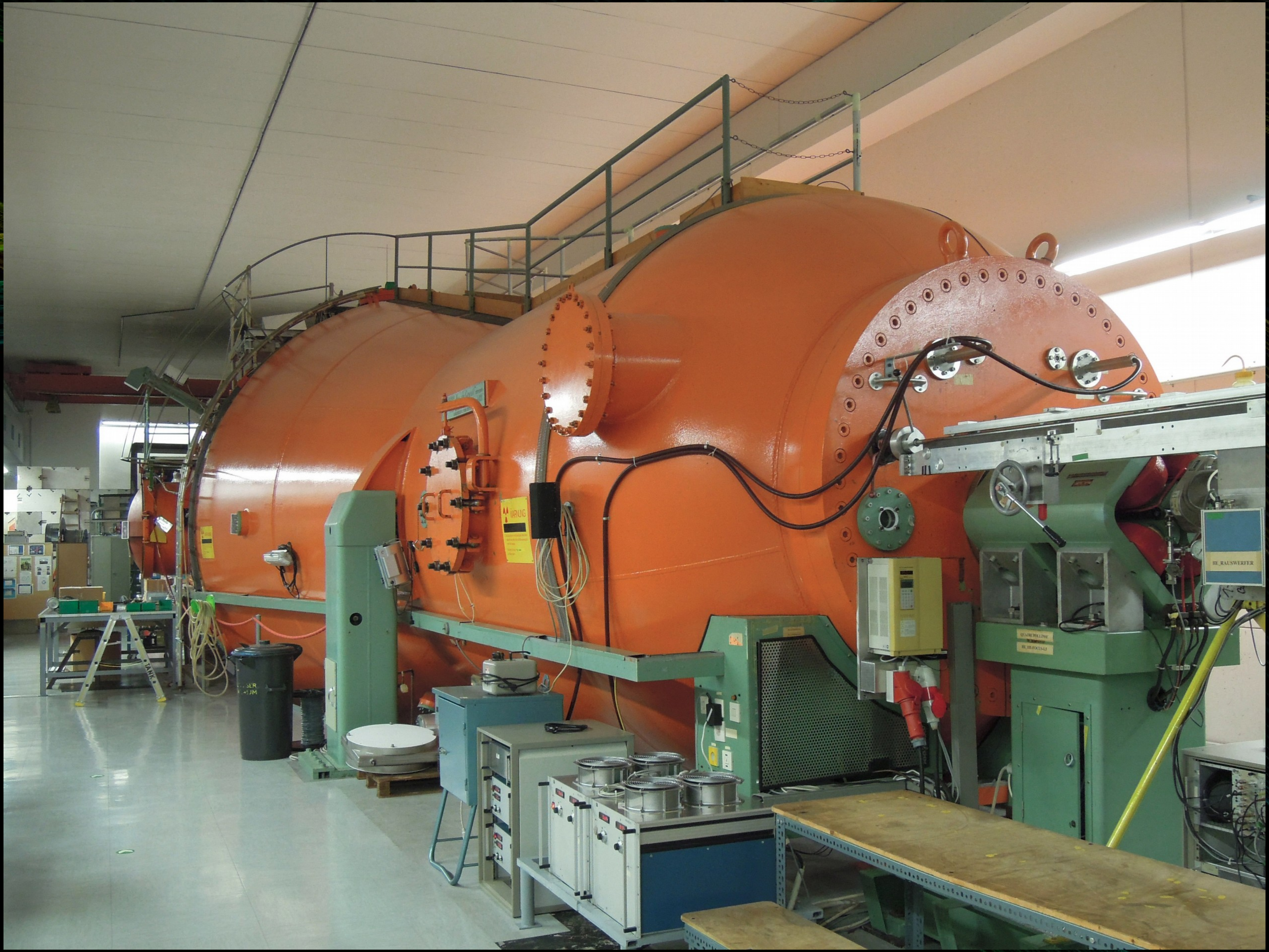
- lower current than CW, but better energy stability ($dE/E=10^{-5}$), easily variable energy, and higher beam energies

Tandem Van de Graaf

- Using the accelerator voltage V two times
- Negative ions accelerate to the high voltage terminal at the center → stripping off electrons by a thin (^{12}C) stripper foil → positive ions accelerate to ground potential
- advantage: for heavy ions high ionization can be achieved → E= (n+1)qV
  - 30 MV tandem accelerator, $^{238}U^{60+}$→ E=900 MeV ! (with several stage stripping)

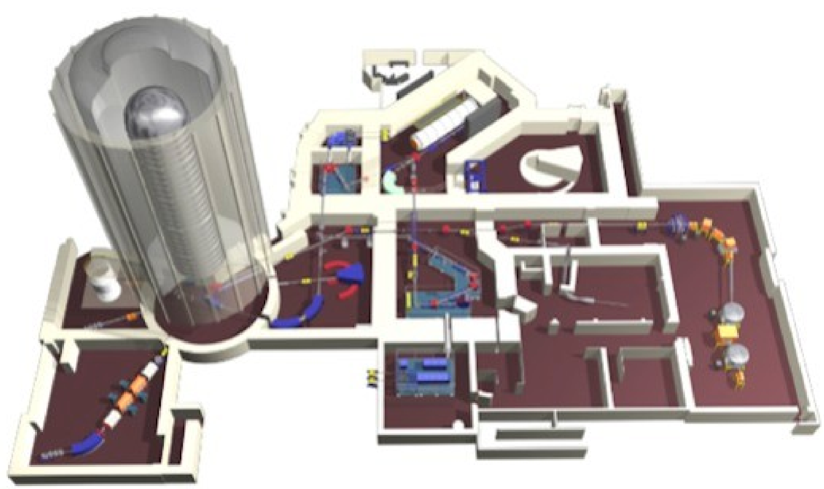


Tandem Van de Graaf accelerator



Van de Graaf accelerators

- Oak Ridge VDG: the largest Van de Graaf accelerator in the word
  - height is 30 m, 25.5 million Volt !!



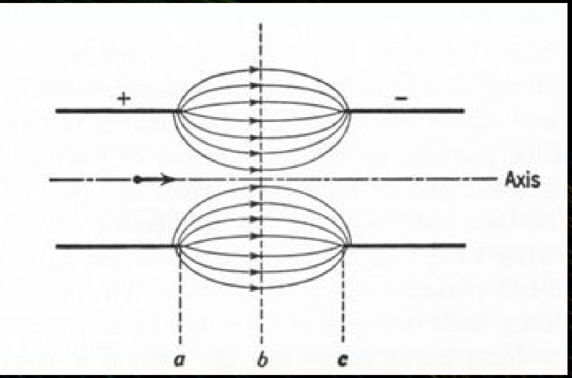
Holifield Facility

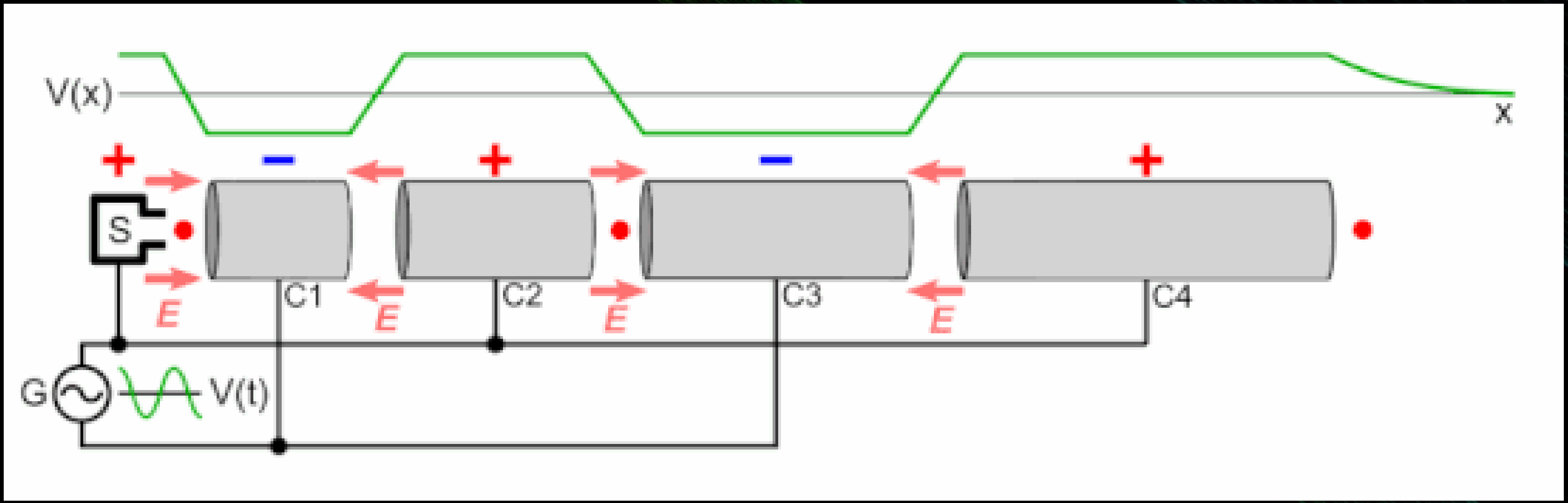
A 3D view of the Holifield Radioactive Ion Beam Facility (HRIBF), capable of producing intense beams of unstable nuclei for basic and applied nuclear science research

Linac

- Much higher energies can be achieved if we use an accelerating voltage many time resonantly:
  - we avoid electric discharge, breakdown which is a limitation on electrostatic acceleration
- oscillating electric field between the drift tubes (acting as Faraday cage) → acceleration
- length of the cage should increas with velocity
- bunched beam:
  - bunch length: $t << 1/f_{RF}$
  - bunch separation: $t = 1/f_{RF}$

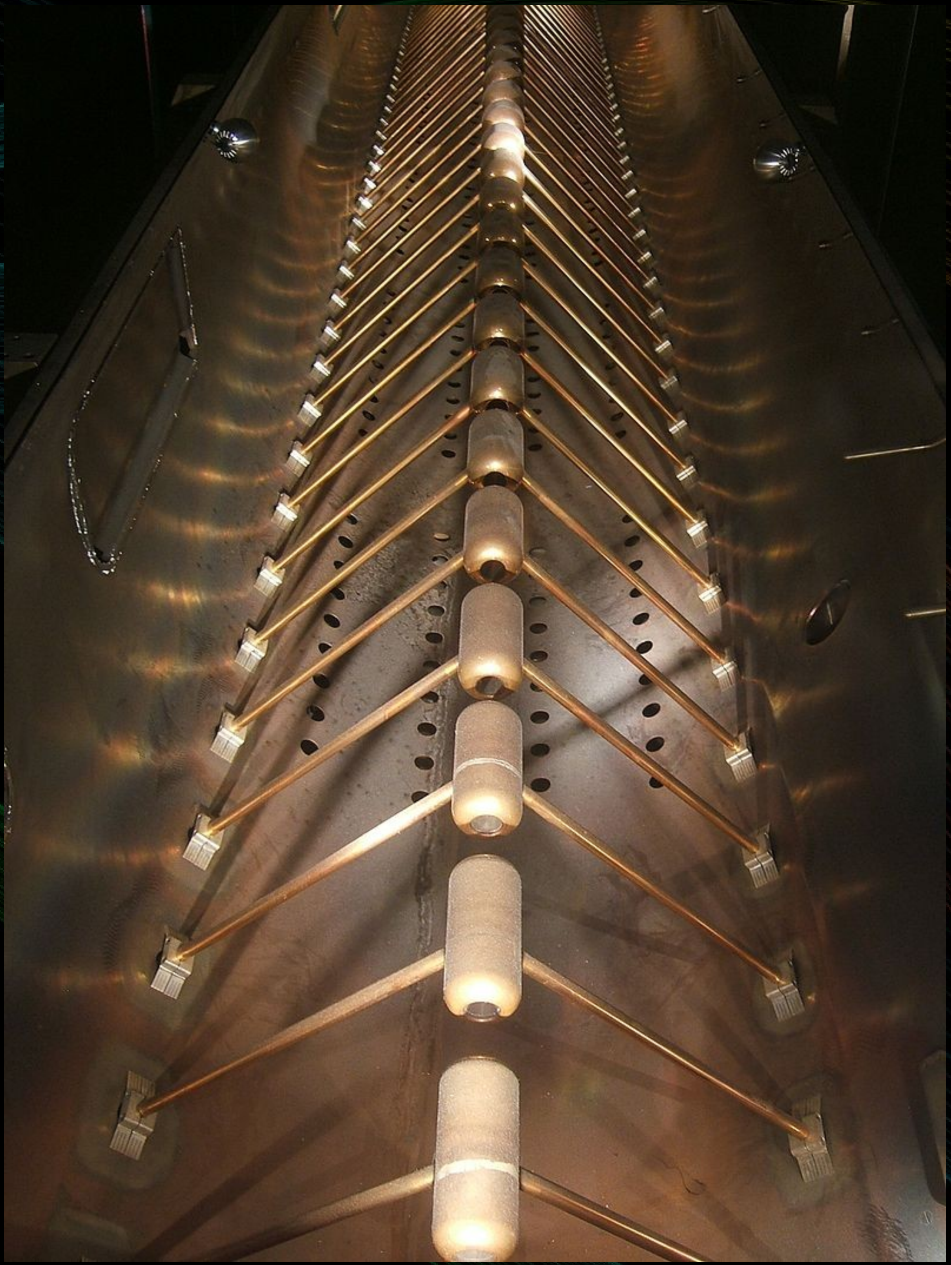
$$L_n \approx \frac{1}{f}\sqrt{\frac{nV}{m}}$$

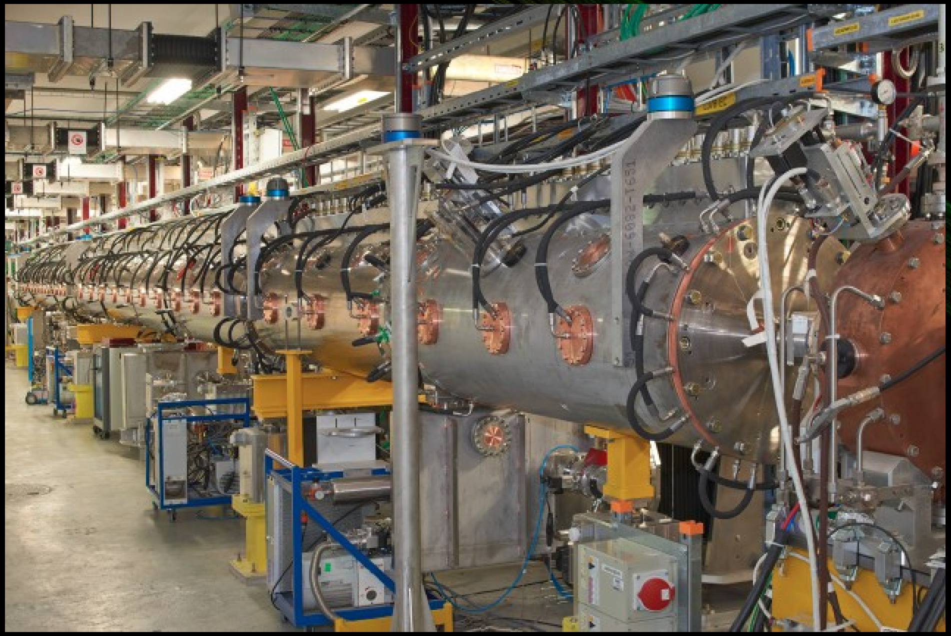




Linac

- Today they are still important as pre-accelerators of proton and heavy ion accelerators

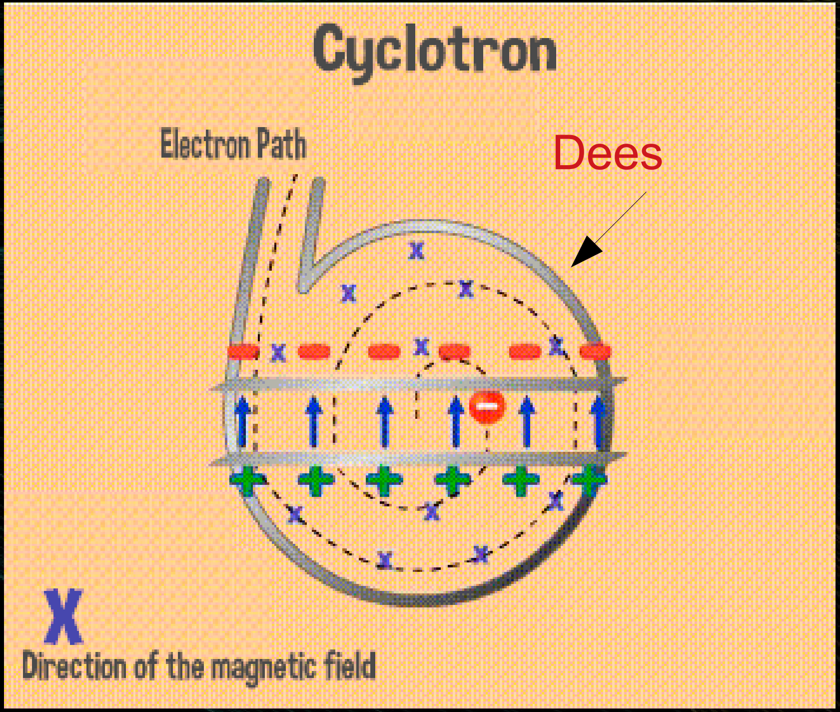




Cyclotron

- E. Lawrence (1934): first cyclotron
  - only 4’’ in diameter
- Operation principle is similar to LINACs but orbital

$$evB = \frac{Mv^2}{r} \rightarrow \omega = \frac{e}{m} B$$

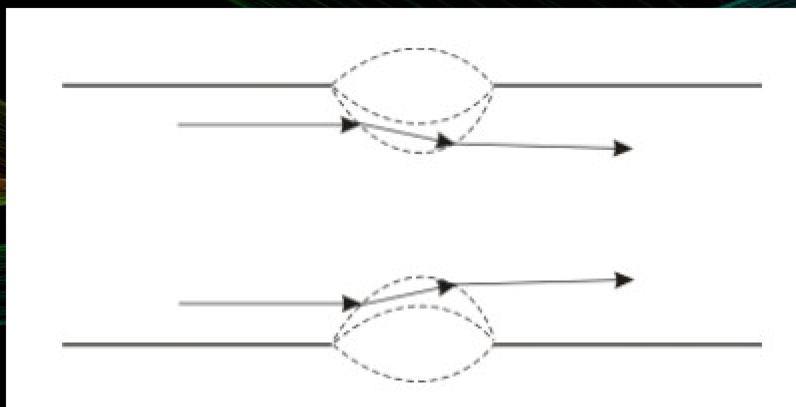


$$E_{max} = \frac{q^2}{2m} BR_{max}$$

- until m is constant → cyclotron frequency is constant (~B)
- outer trajectories are separated by ~cm → extraction electrode

Cyclotron - considerations

- Focusing between *D* electrodes:



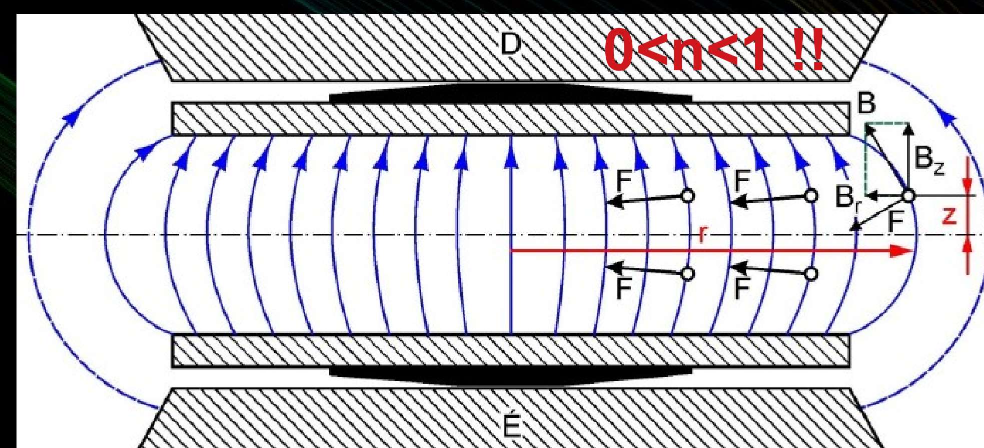
- Beam stability:
  - finite beam size → deviation from r
  - applying B decreasing with r
  - vertical Lorentz force→ betatron oscillation (weak focusing)

$$B_z(r) = \frac{k}{r^n}$$

n: magnetic field index

- bremsstrahlung radiation causes energy loss in an orbital motion of charges:
  - large for small M_0: electron
  - linear accelerators for energetic e-

$$\frac{\Delta E}{\Delta x} \sim -\frac{1}{r}\left(\frac{E}{M_0 c^2}\right)^4$$



Cyclotron: properties

- High beam current can be produced → isotope production
- Relativistic mass at high velocity (particles are delayed to ω)

$$evB = \frac{Mv^2}{r} \rightarrow \omega = \frac{e}{m} B$$

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

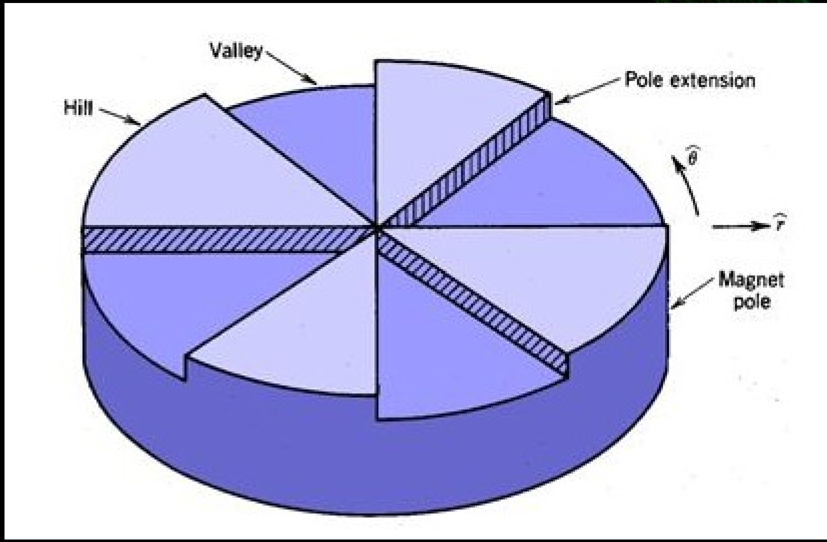
- v_{max} 0.2c → 20 MeV proton and 40 MeV deuteron
- First idea: one should increase *B* with *R* → beam defocusing since $n < 0$
- One solution: **synchrocyclotron:**
  - ω(t) is decreased during acceleration
  - high energy (Dubna : Ep=700 MeV) → first artifical meson production (π-meson)
  - low intensity
  - mass of the magnet is 2000-8000 t (!!)
  - very expensive, many technical problems

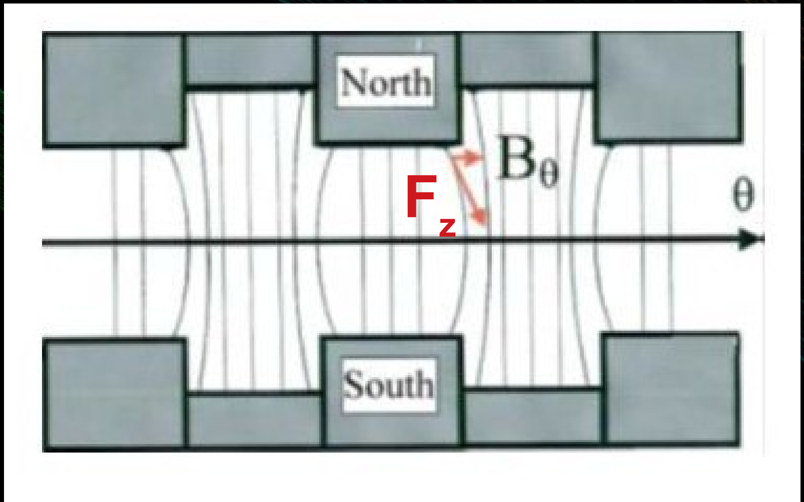
Sector-focusing (AVF) cyclotron

- frequency is constant in time, but B is increased as:

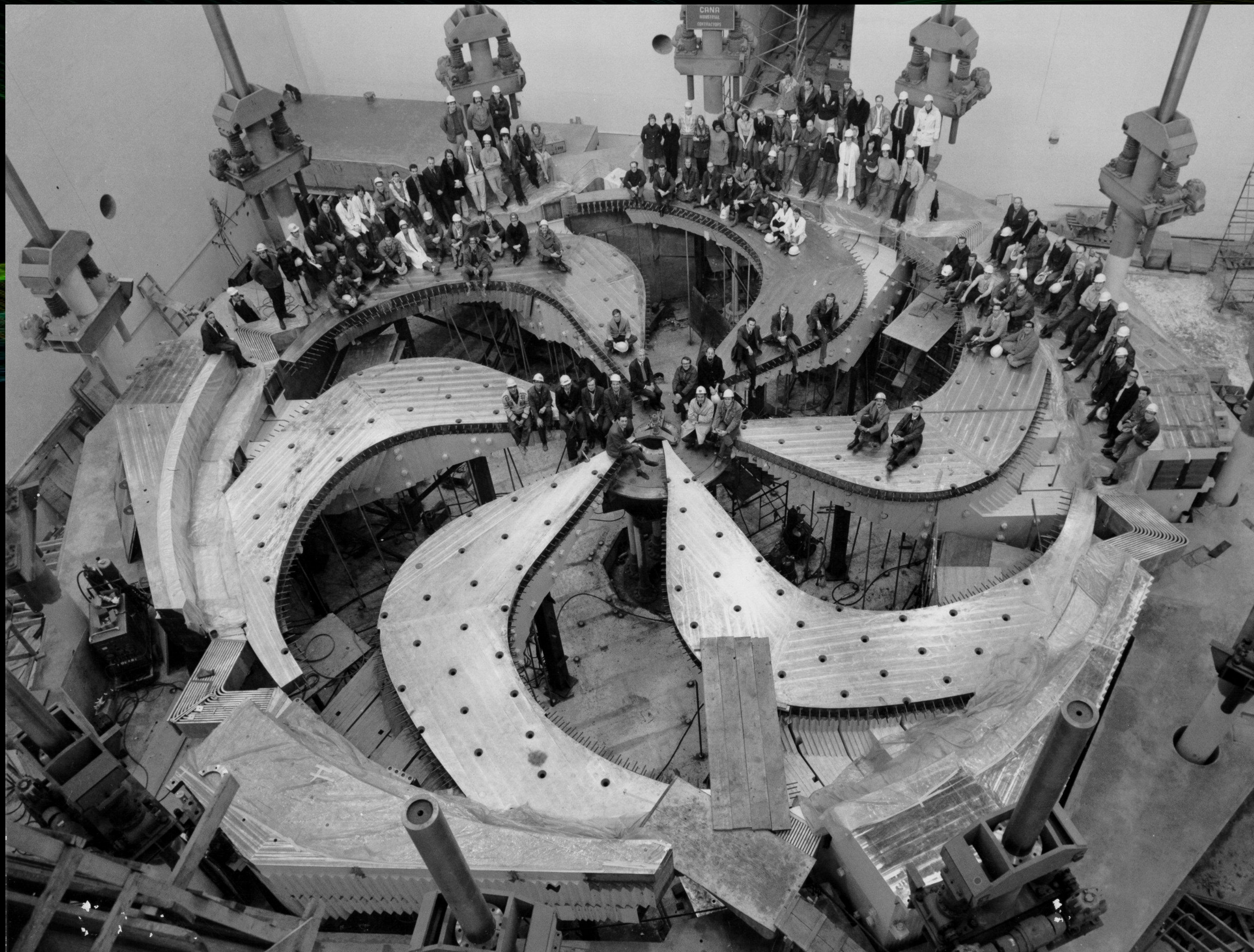
$$B = \frac{B_0}{\sqrt{1-\frac{v^2}{c^2}}} \approx B_0\left[1+\frac{1}{2}\frac{r^2\omega^2}{c^2}\right]$$

- But n<0 → vertical beam instability !
- Solution: dividing the magnetic field into sectors and using alternating gap sizes for the sectors (so different B strength) → the inhomogenous field at sector boundaries focusing the beam vertically



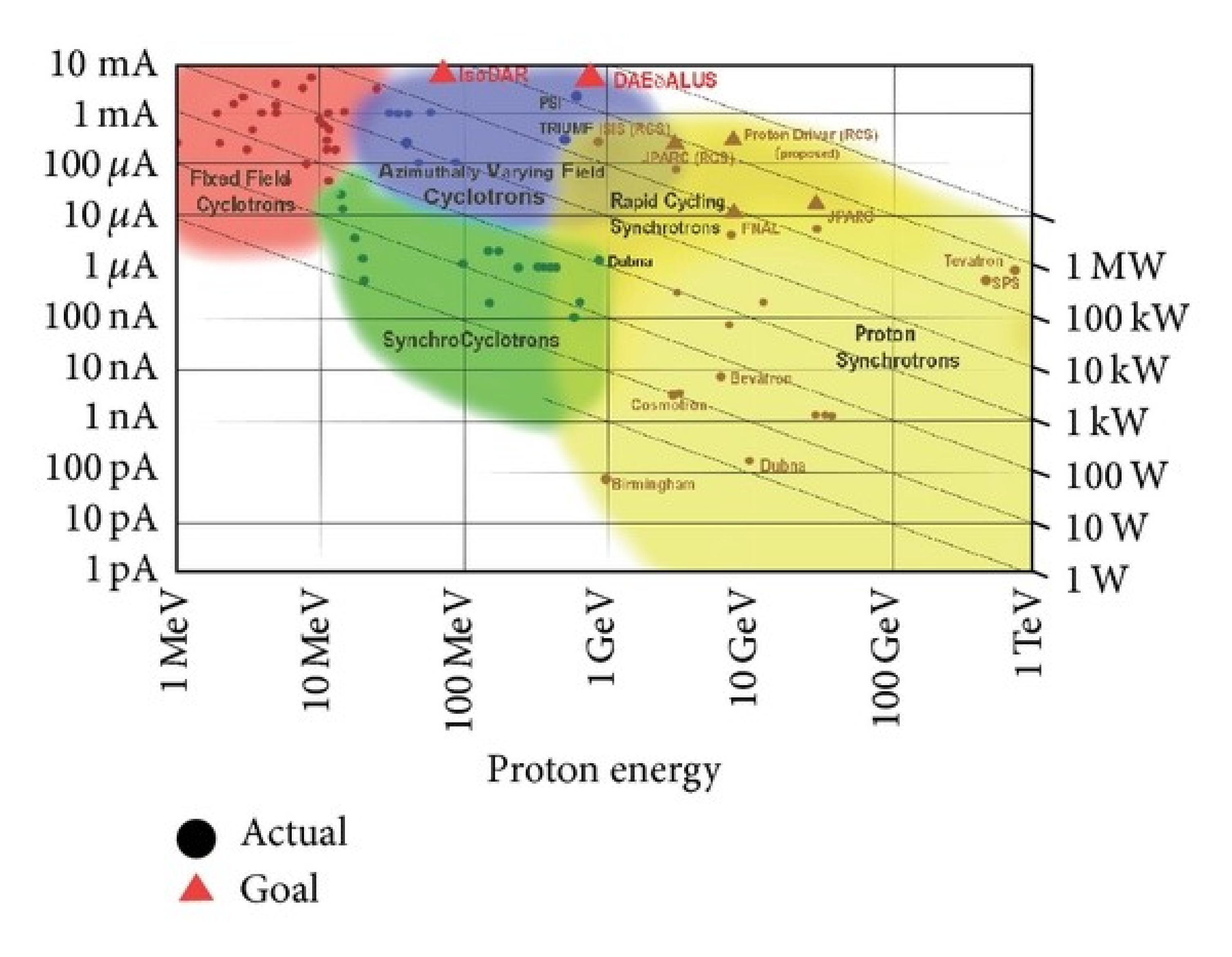


AVF cycolotron: TRIUMF - Canada



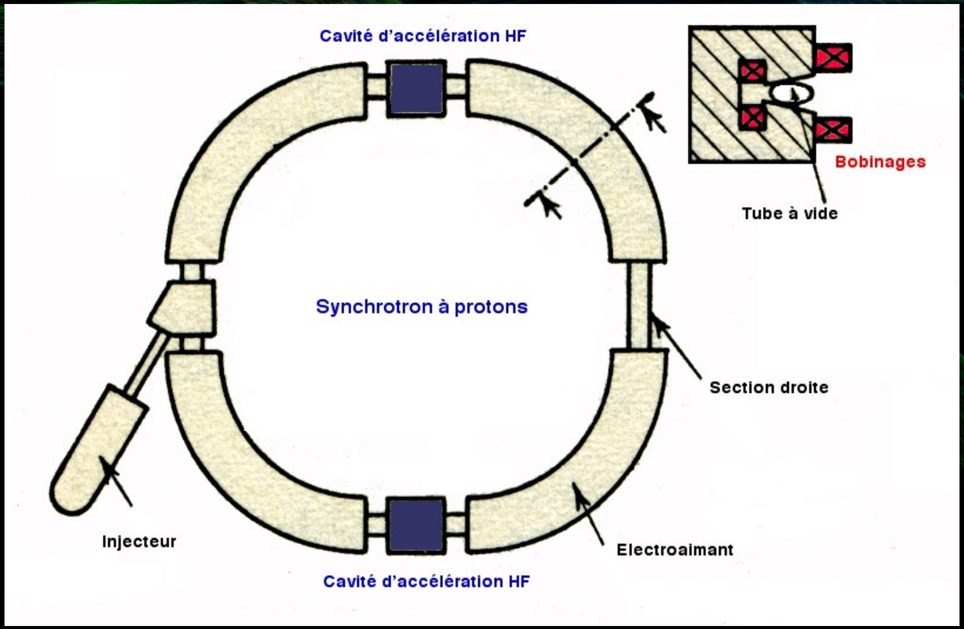
with spiral geometry, the focusing is even better!

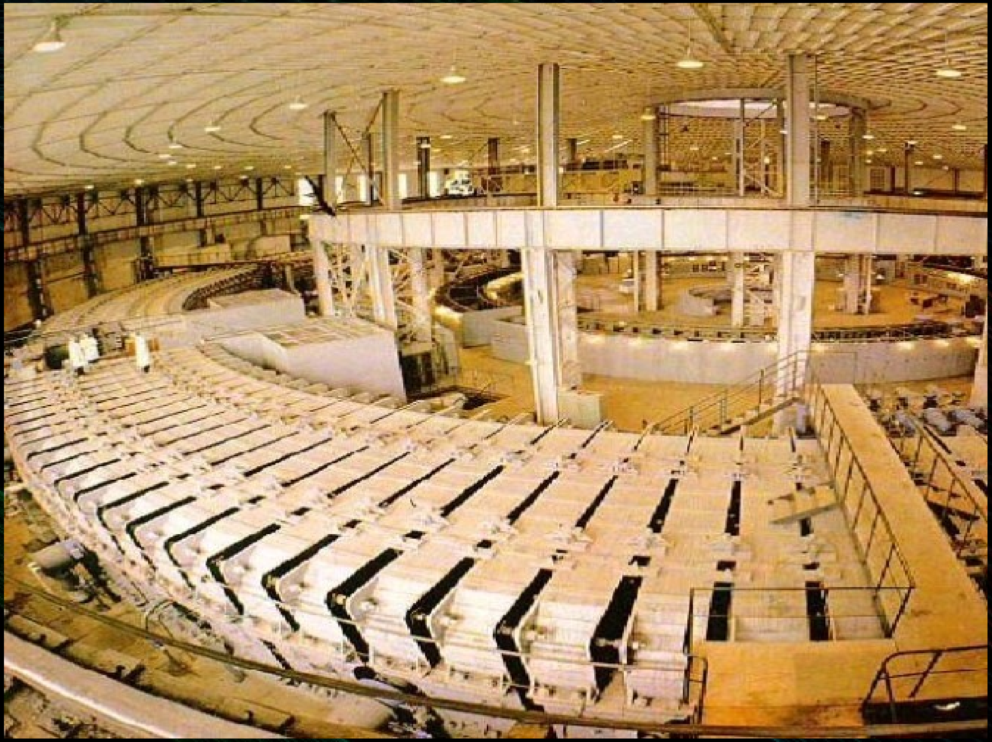
Cyclotron types: a summary



Proton synchrotron

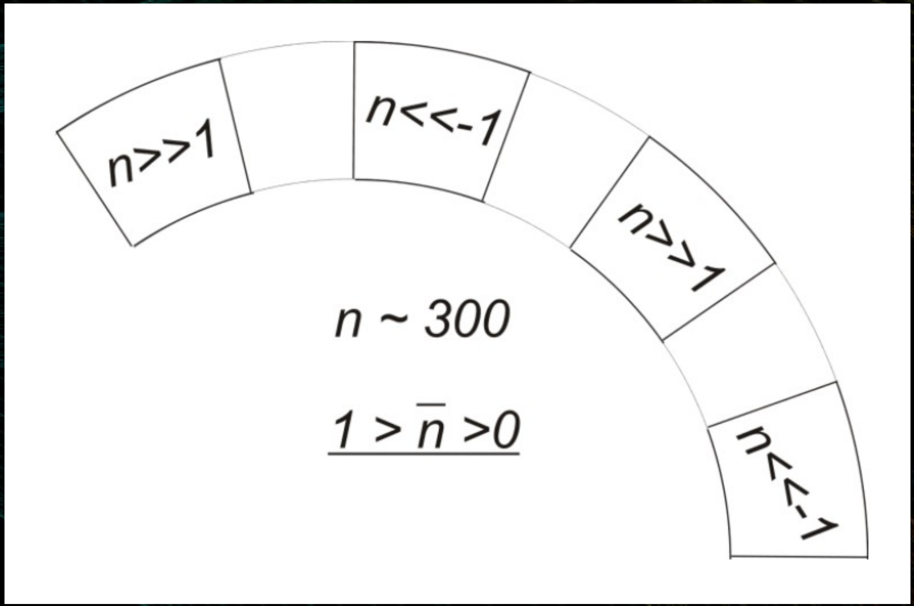
- B(t) and ω(t) is varied, R (≈10 m) is kept constant
- magnetic field has n≈0.7 → vertical focusing
- E_p up to 10 GeV





Strong focusing synchrotrons, storage rings

- Based on the idea of AVF cyclotrons
- Sectors have n >> 1 followed by n << -1 → on the avarage (pairs) has 0<n<1
- much cheaper than having one, compact magnetic field (ring)
- for E_p>20 GeV



- Fixed target