PART V: Accelerators for industrial applications

Defining Industrial Applications of Accelerators?

- Generally, high energy particle beams induce nuclear reactions and activation
- In contrast, in industrial applications, nuclear reactions and activation are undesirable and avoided, but other effects of ionizing radiations are searched for
- These desired effects include:
  - Sterilization
  - Cross linking of polymers
  - Curing of composite materials
  - Modification of crystals
  - Improvement of semi conductors
  - Beam aided chemical reactions

What beams are used?

- The choice of particle beams used in industrial applications is defined, to a large extent, by the desire to avoid nuclear reactions and activation.
- Commonly used beams include:
  - Electron beams below 10MeV.
  - X-Rays from e-beams below 7.5MeV.
  - Intense, low energy proton beams.
  - Low energy heavy ion beams (well below the Coulomb barrier).
- Also, for industrial applications, large beam currents/powers are needed to reach industrial scale production rates. Beam powers from 50 kW to 1 MW are common.

IBA Industrial's Product Portfolio

Dynamitron

0.5 -> 5 MeV | 160 mA

Electron beam

Main application

E-beam Crosslinking

Rhodotron

3 -> 10 MeV | 42 mA | 420 kW

Electron beam and X-rays

Main application

E-beam box sterilization

eXelis

5 – 7 MeV | 80 mA | 560kW

X-rays

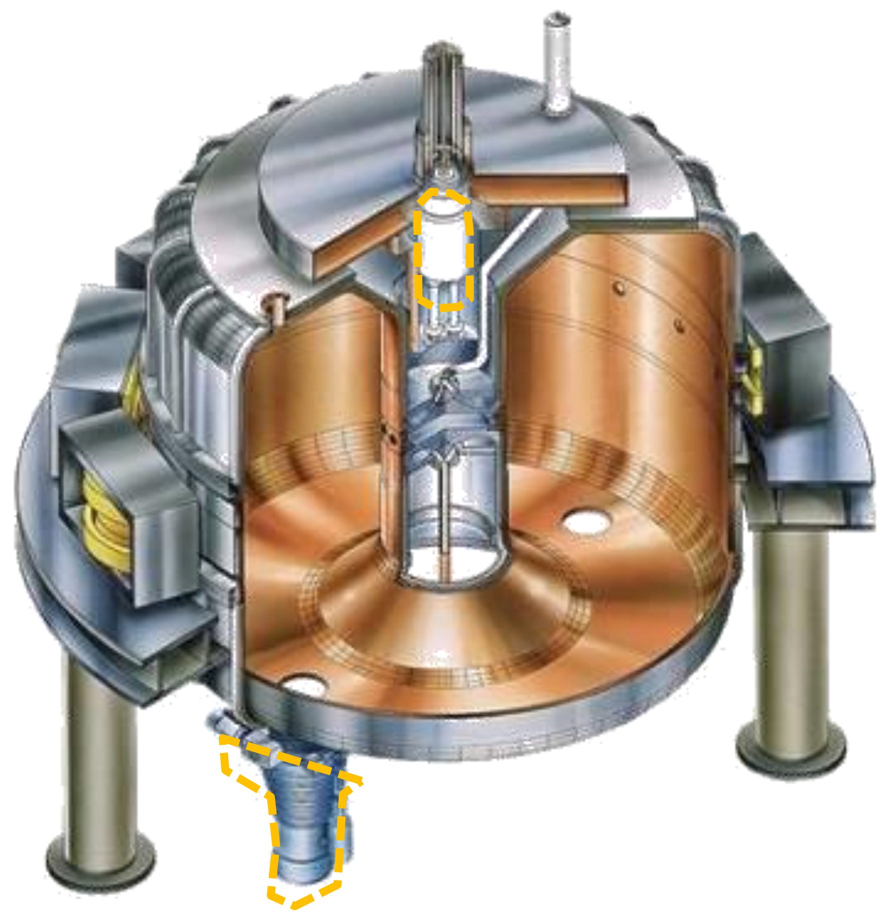
Main application

X-ray pallet sterilization

Linac's reach about 40-60 kW

Brief explanation of the Rhodotron:

The main components

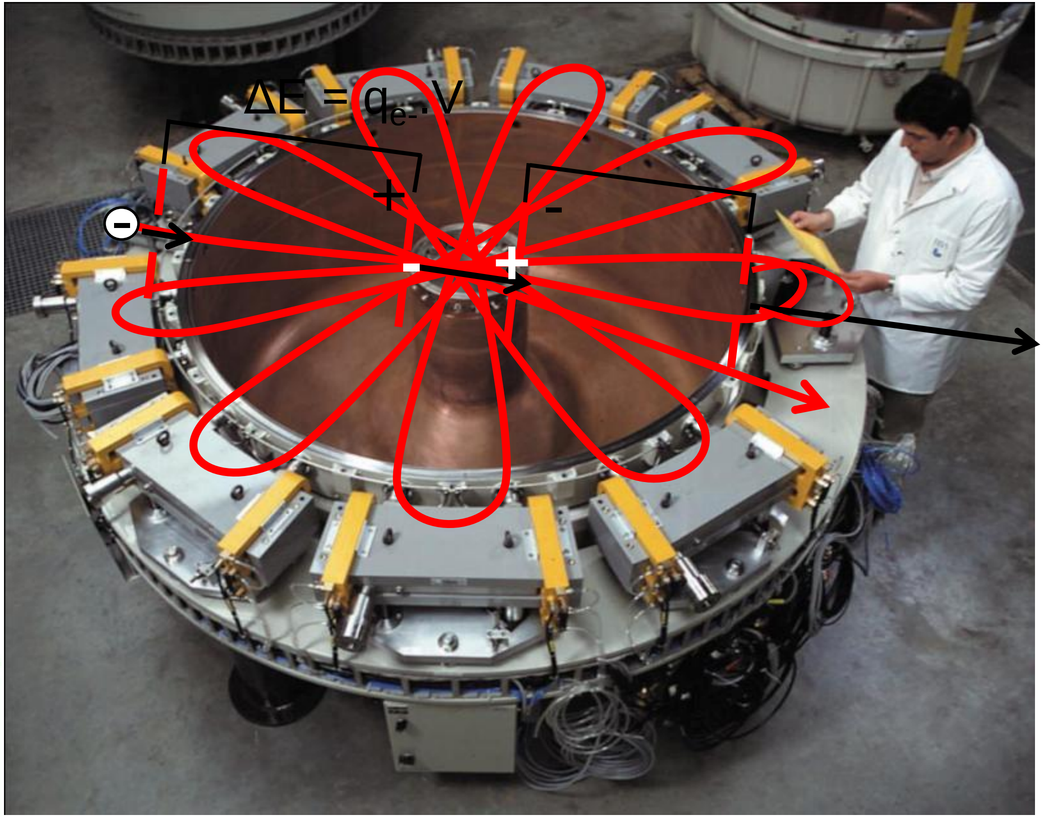


RF Cavity
E-Gun
Magnets
Final Power Amplifier

RF tube (Tetrode)
Vacuum system

Brief explanation of the Rhodotron:

Basic acceleration and re-circulation



Electrons are generated by the e-gun, then accelerated by the electric field in the cavity:

$$\Delta E_c = F.x = q.E.x = q.\frac{V}{x}.x$$

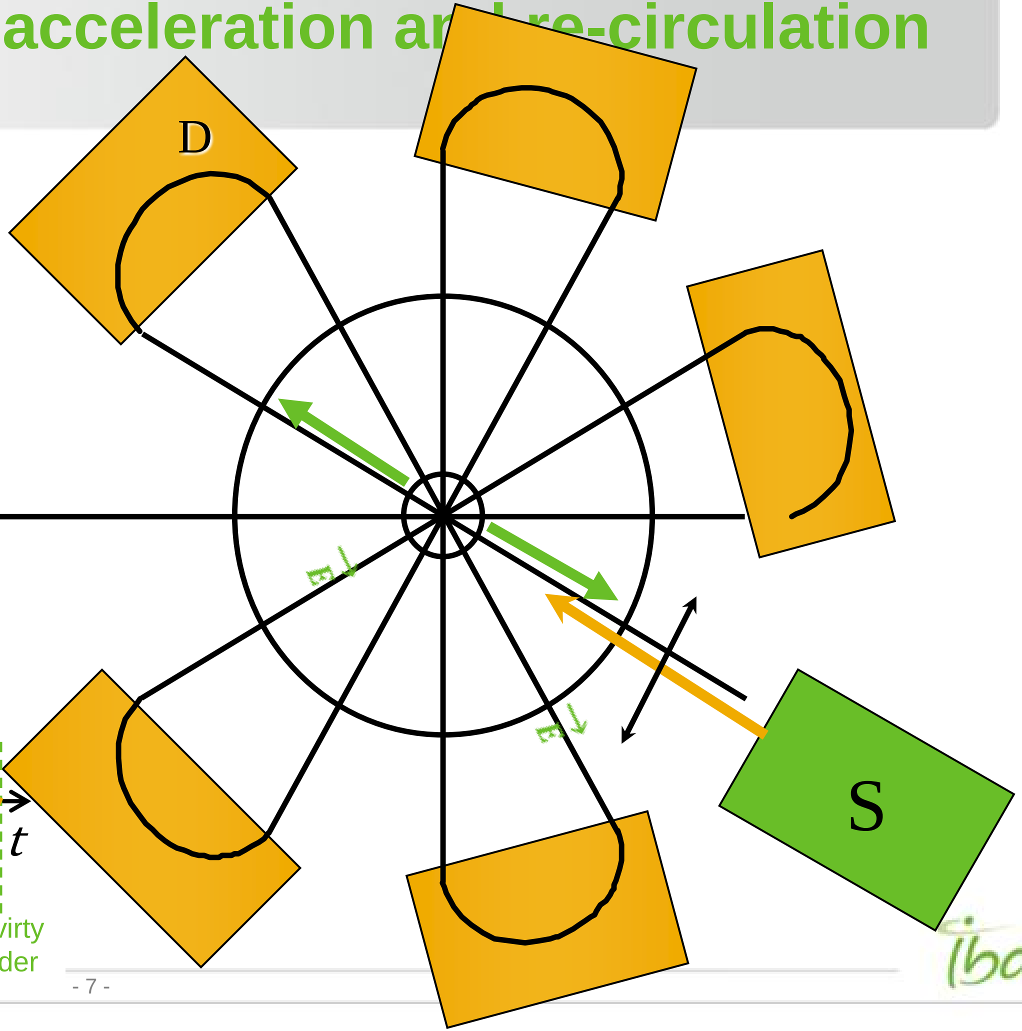
After the first acceleration pass, the electron path is curved by a magnetic field:

$$F = q.(E + v.B) = \frac{m.v2}{r} \Rightarrow B.r = \frac{m}{q}.v$$

Important: electrons are relativistic after first pass: v = constant !

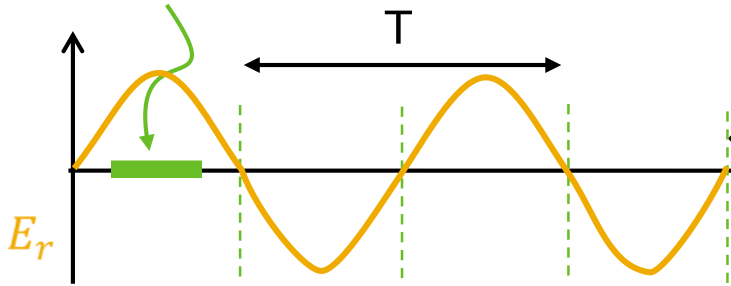
E (e^-)	50keV	1MeV	10MeV
β	0.41	0.94	0.99
γ	1.098	2.956	20.56

The Rhodotron: Basic acceleration and re-circulation



time in [0,T/4]

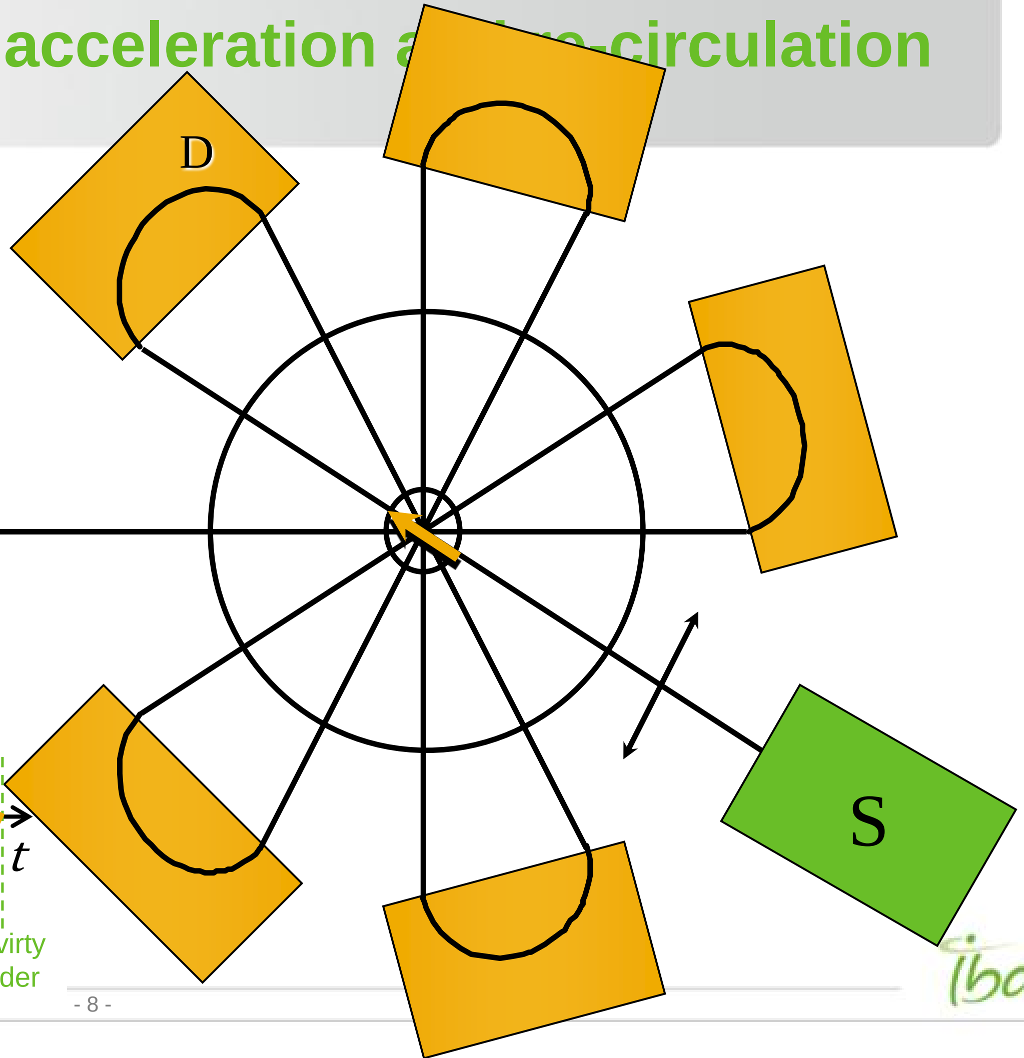
- Electric field outward facing
- Electrons injected and travel first half crossing

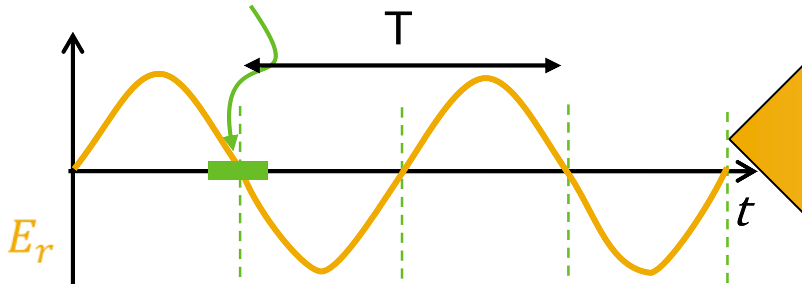


The Rhodotron: Basic acceleration and re-circulation

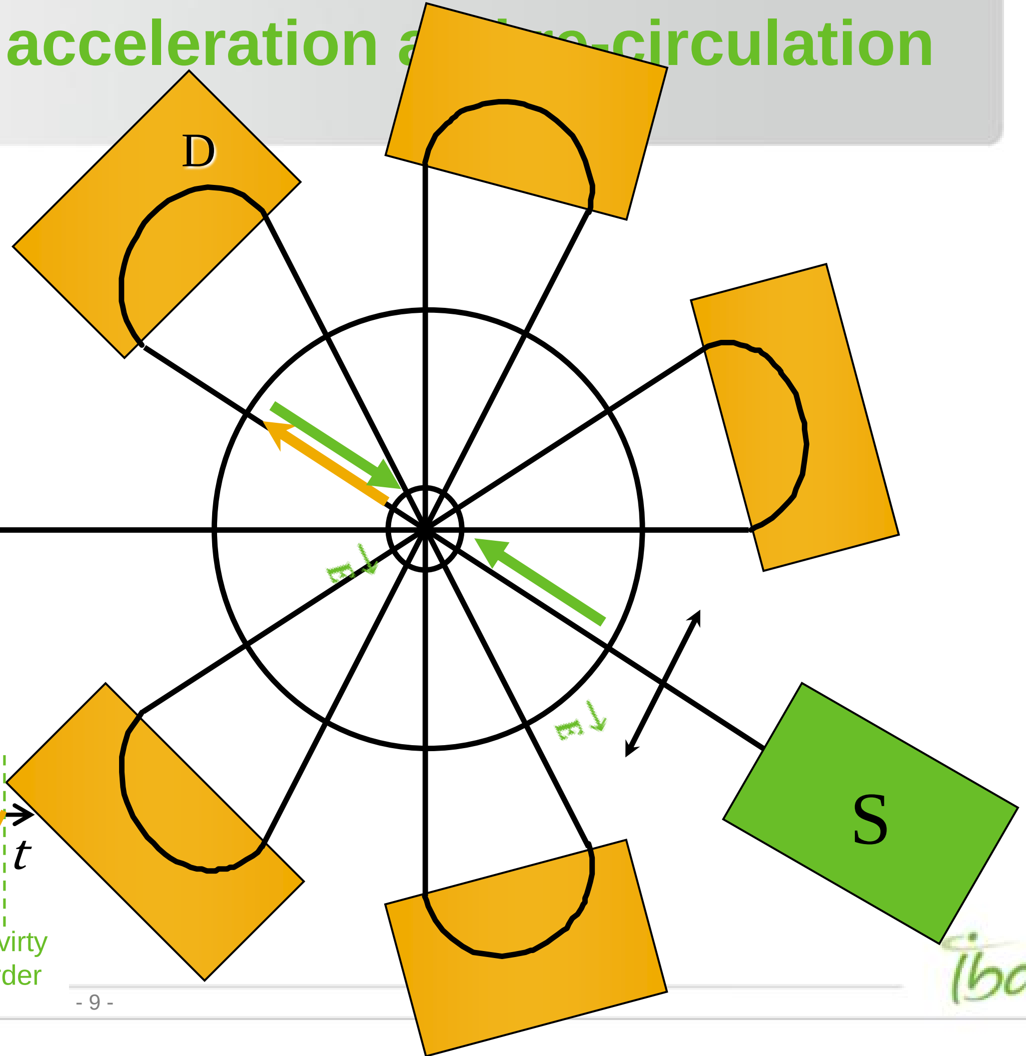
time in [T/4,T/2]

- Electrons cross inner cylinder holes (pillar)
- Electric field polarity reversing



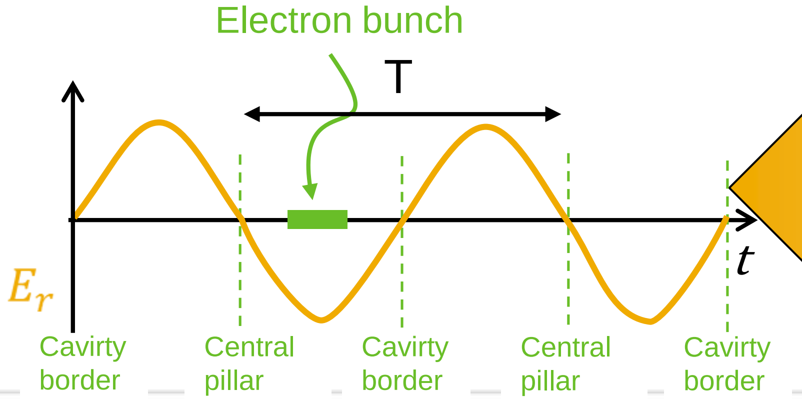


The Rhodotron: Basic acceleration a re-circulation



time in [T/2,3T/4]

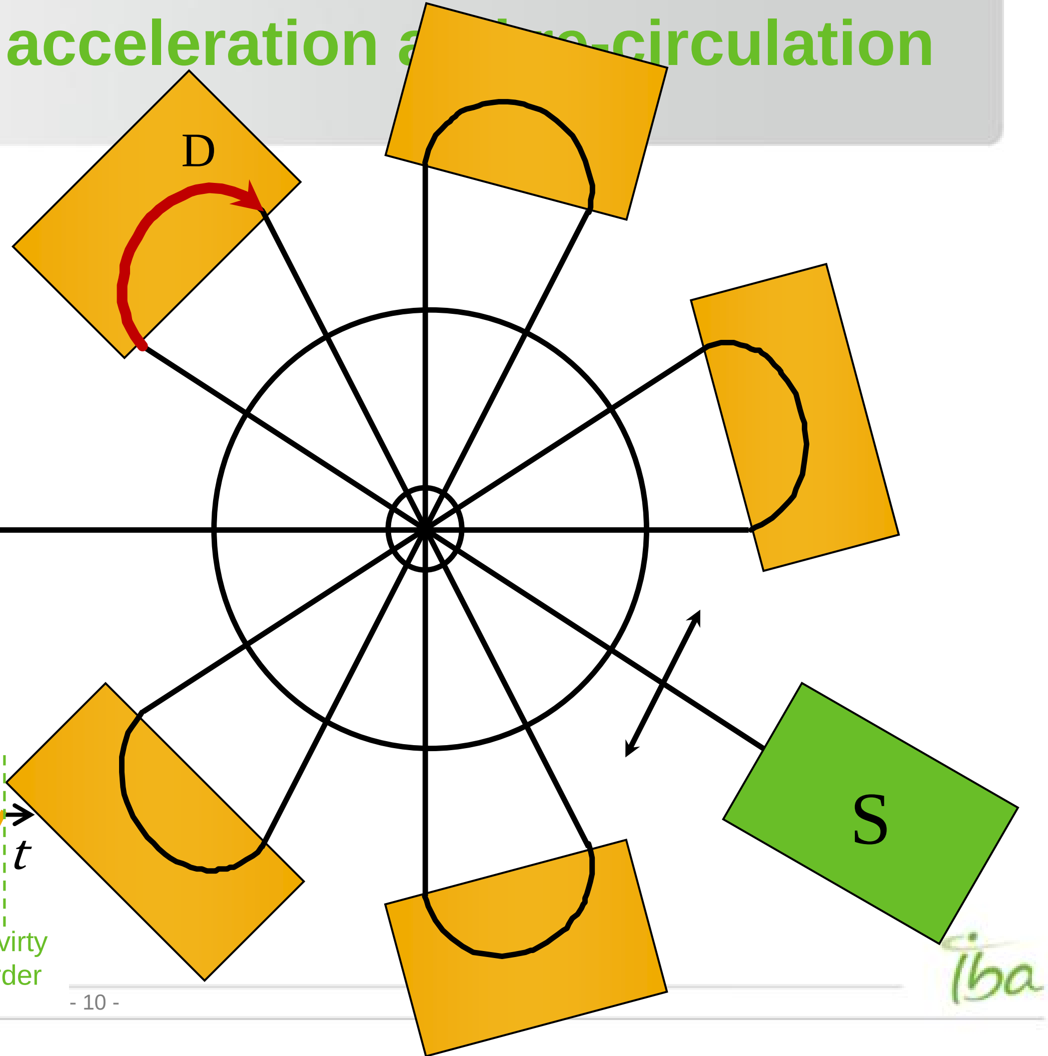
- Electric field inwards facing
- Electrons complete 2nd half of first crossing

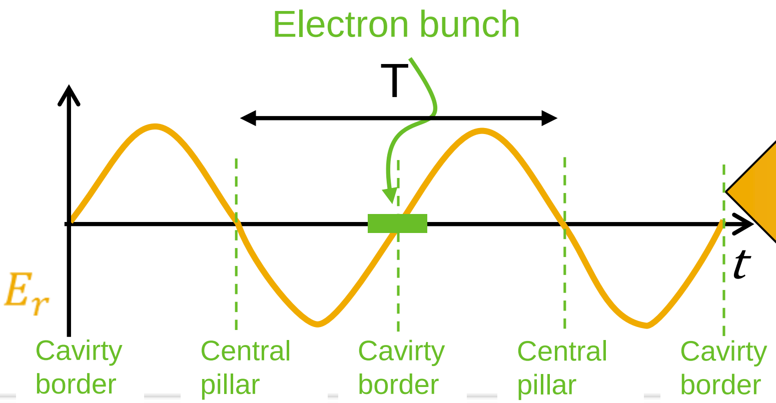


The Rhodotron: Basic acceleration and re-circulation

time in [3T/4,T]

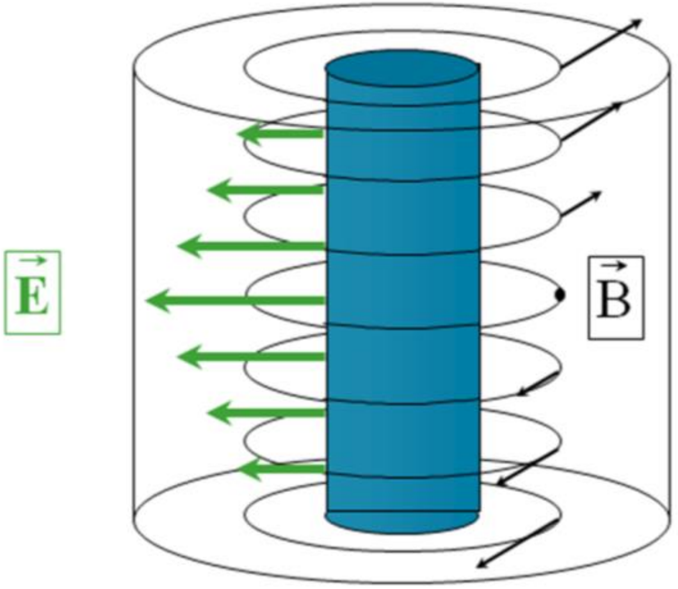
- Electrons deflected back into the cavity
- Electric field polarity reversing





The Rhodotron: Cavity Design

Introduction to Rhodotrons e-beam accelerators



Electric (E) and magnetic (B) fields in Rhodotron coaxial cavity

① RF sinusoidal electrical field ➔ coaxial cavity !

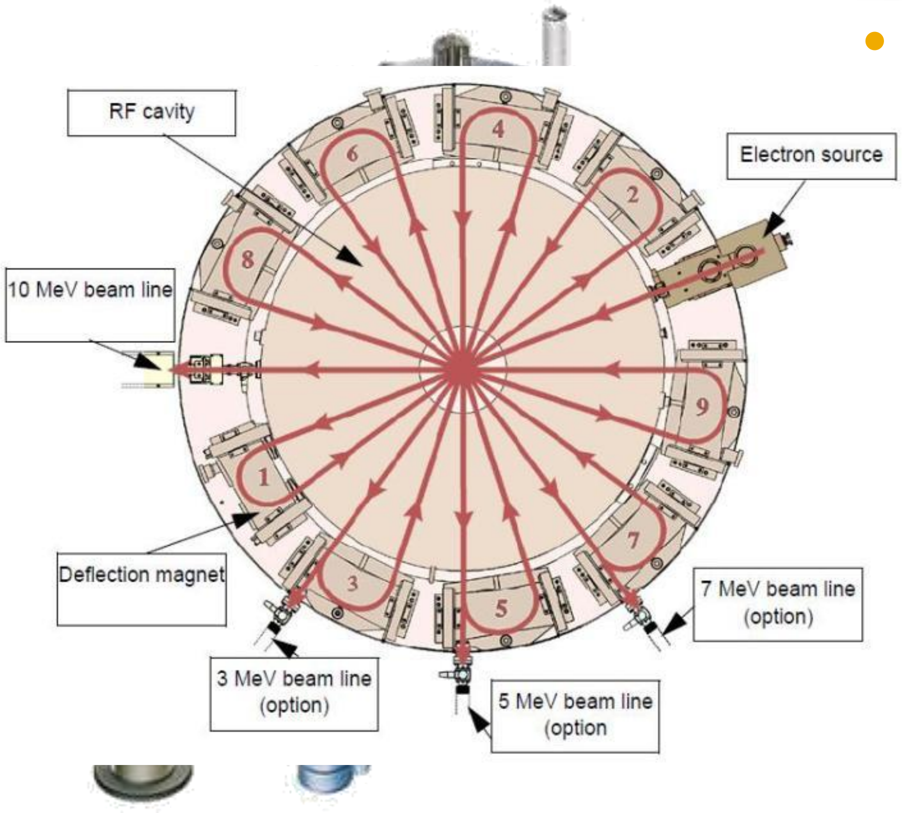
② Frequency is 107 MHz (215 MHz for TT100). Depends on tube availability ➔ best is FM band

- The size of the cavity is fixed by f:
  - Height = 0.5 λ
  - Radius ideal is 0.35 λ to allow transit in magnets
- Fundamental mode (TEM 1):
  - Radial E-field and azimuthal B-field
  - E-field varies as cos (z) / r
- Electrical losses increase with $f^{1/2}$
- Cost increase with size, small is complicated for beam optics: phase acceptance & transmission

↳ **Maximize energy gain vs losses & cost !**

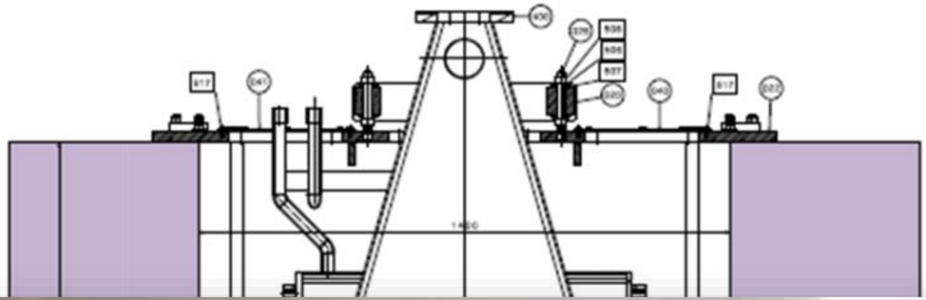
The Rhodotron: Cavity Design

Introduction to Rhodotrons e-beam accelerators



- **Interesting design notes:**
  - Beam can be extracted at each magnet
  - Cavity holes and space charge are critical
  - **First pass is the most critical because of beam low energy (50 keV to 1 MeV)!**

port line, Scanning, Horn

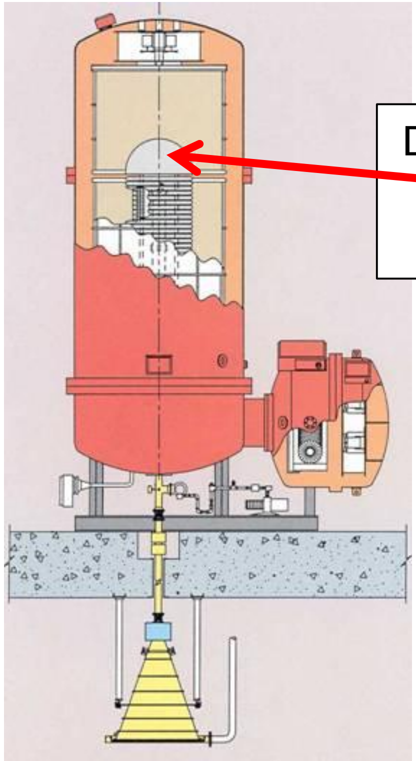


Goal of the BTL and horn ?

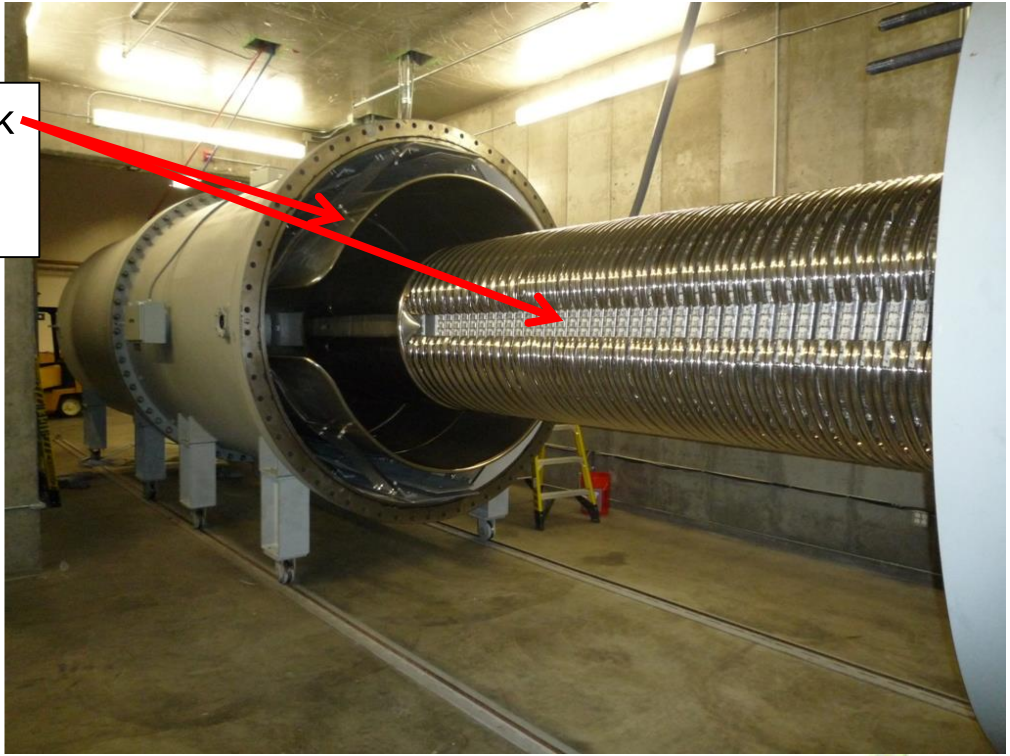
- Transport beam from Rhodo vault to target without any losses
- Scan the beam across the material to be treated according to conveyor speed
- Convert electrons to X-ray when needed

Dynamitron

High Voltage generation => similar to a Cockcroft-Walton



Dees and rectifier stack
Dome
SF6

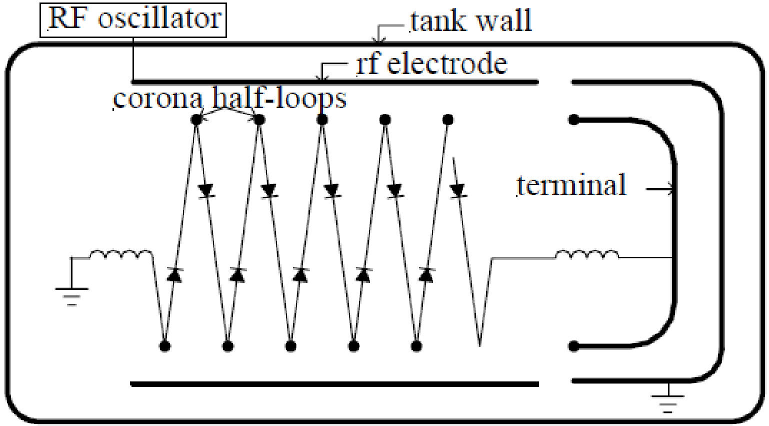


Dynamitron

Electron beam generation

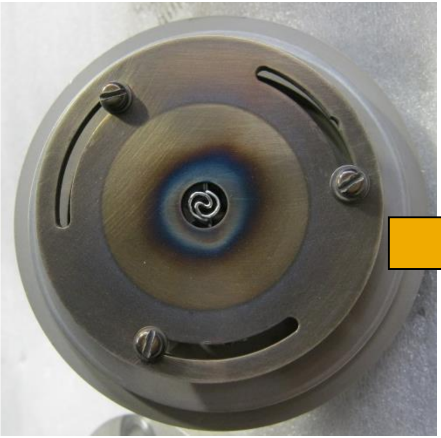
A linear accelerating column
DC acceleration

- Parallel fed cascade voltage multiplier
- Accelerated from voltage drop from High Voltage (up to 5 MV DC) to ground.
- Beam in a long acceleration tube under ultra high vacuum (10e-8 mbar range)

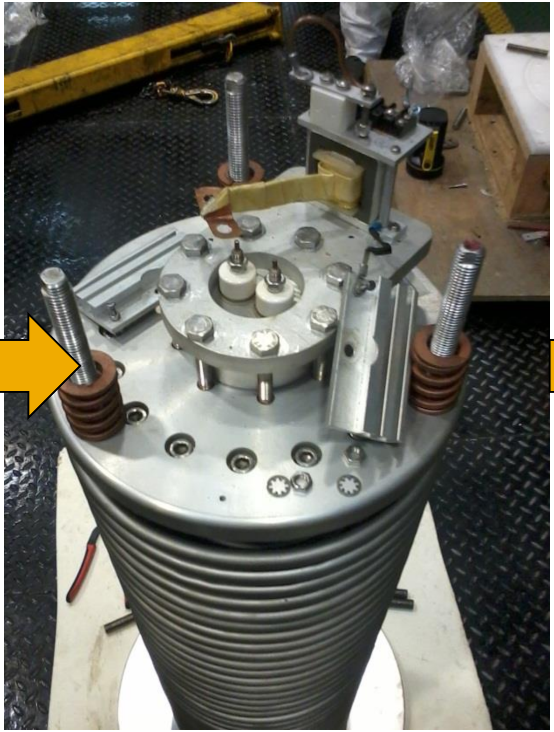


Dynamitron

Main components



Electrons from a heated filament



Beam tube

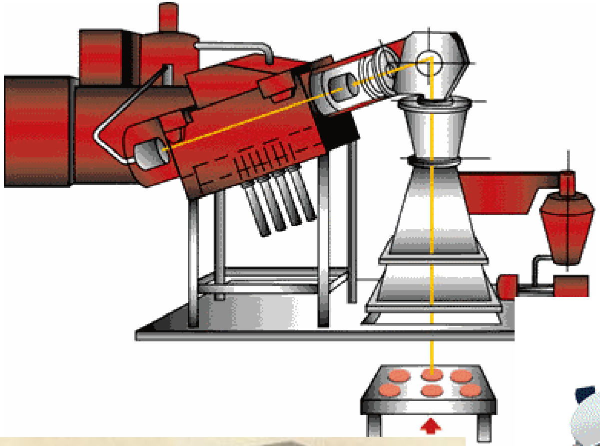
Scan Horn

Some Dynamitrons…

Easy-E-Beam

- Self Shielded
- Compact
- Right angle
- 800 kV
- 100 mA

High power E-beam accelerators => the Linacs



more compact
lower beam power