Accelerators

Summer Student Lectures

Oliver Brüning AB/ABP

http://bruening.home.cern.ch/bruening/summer−school/lecture1

Particle Accelerators

Physics of Accelerators:

High power RF waves

Cryogenics

Super conductivity

Magnet design + construction

Vacuum

→ surface science, solid state physics, electro dynamics, engeneering, computer science

Physics of Particle Beams:

Single particle dynamics

Collective effects

Two beam effects

→ classical and quantum mechanics, non-linear dynamics, relativity, electro dynamics, computer science

Overview

I) Particle Acceleration

II) Storage Rings +
Trajectories

III) Orbit Stability +
Long Term Stability

IV) Synchrotron Radiation +
Collective Effects

V) LEP,LHC + more

Overview and History:

- S. Weinberg, 'The Discovery of Subatomic Particles', Scientific American Library, 1983. (ISBN 0-7167-1488-4 or 0-7167-1489-2 [pbk]) (539.12 WEI)
- C. Pellegrini, 'The Development of Colliders', AIP Press, 1995. (ISBN 1-56396-349-3) (93:621.384 PEL)
- P. Waloschek, 'The Infancy of Particle Accelerators', DESY 94-039, 1994.
- R. Carrigan and W.P. Trower, 'Particles and Forces - At the Heart of the Matter', Readings from Scientific American, W.H. Freeman and Company, 1990.
- Leon Lederman, 'The God Particle', Delta books 1994
- Lillian Hoddeson (editor), 'The rise of the standard model: particle physics in the 1960s and 1970s', Cambridge University Press, 1997
- S. Weinberg, 'Reflections on Big Science', MIT Press, 1967 (5(04) WEI)

Introduction to Particle Accelerator Physics:

- Mario Conte and William McKay, 'An Introduction to the Physics of Particle Accelerators', Word Scientific, 1991
- H.Wiedemann, 'Particle Accelerator Physics', Springer Verlag, 1993.
- CERN Accelerator School, General Accelerator Physics Course, CERN Report 85-19, 1985.
- CERN Accelerator School, Second General Accelerator Physics Course, CERN Report 87-10, 1987.
- CERN Accelerator School, Fourth General Accelerator Physics Course, CERN Report 91-04, 1991.
- M. Sands, 'The Physics of Electron Storage Rings', SLAC-121, 1970.
- E.D. Courant and H.S. Snyder, 'Theory of the Alternating-Gradient Synchrotron', Annals of Physics **3**, 1-48 (1958).
- CERN Accelerator School, RF Engeneering for Particle Accelerators, CERN Report 92-03, 1992.
- CERN Accelerator School, 50 Years of Synchrotrons, CERN Report 97-04, 1997.
- E.J.N. Wilson, Accelerators for the Twenty-First Century - A Review, CERN Report 90-05, 1990.

Special Topics and Detailed Information:

- J.D. Jackson, 'Calssical Electrodynamics', Wiley, New York, 1975.
- Lichtenberg and Lieberman, 'Regular and Stochastic Motion', Applied Mathematical Sciences 38, Springer Verlag.
- A.W. Chao, 'Physics of Collective Beam Instabilities in High Energy Accelerators', Wiley, New York 1993.
- M. Diens, M. Month and S. Turner, 'Frontiers of Particle Beams: Intensity Limitations', Springer-Verlag 1992, (ISBN 3-540-55250-2 or 0-387-55250-2) (Hilton Head Island 1990) 'Physics of Collective Beam Instabilities in High Energy Accelerators', Wiley, New York 1993.
- R.A. Carrigan, F.R. Huson and M. Month, 'The State of Particle Accelerators and High Energy Physics', American Institute of Physics New Yorkm 1982, (ISBN 0-88318-191-6) (AIP 92 1981) 'Physics of Collective Beam Instabilities in High Energy Accelerators', Wiley, New York 1993.

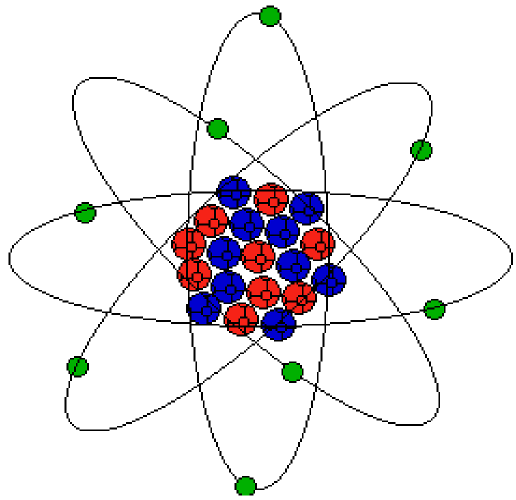
I) Particle Acceleration

- Motivation
- Particle Sources
- Acceleration Concepts:
  - Equations and Units
  - DC Acceleration
  - RF Acceleration
- Summary

Search for Elementary Particles

Stage I:

Nuclear Physics



- **Chronology:**

- 1803: Dalton → Atom
- 1896: M & P Currie → Atoms can decay
- 1896: Thomson → Electron
- 1906: Rutherford → Nucleus + Electron
- 1911: Rutherford → $\alpha + N \rightarrow O + H^{+}$

→ Disintegration of Nuclei!

→ Particle Accelerators

Stage II:

Particle Physics

Chronology (Theory):

- 1905: Einstein ⟶ $E = mc^2$
- 1930: Dirac ⟶ Antimatter
- 1935: Yukawa ⟶ π - Meson

Chronology (Experiments):

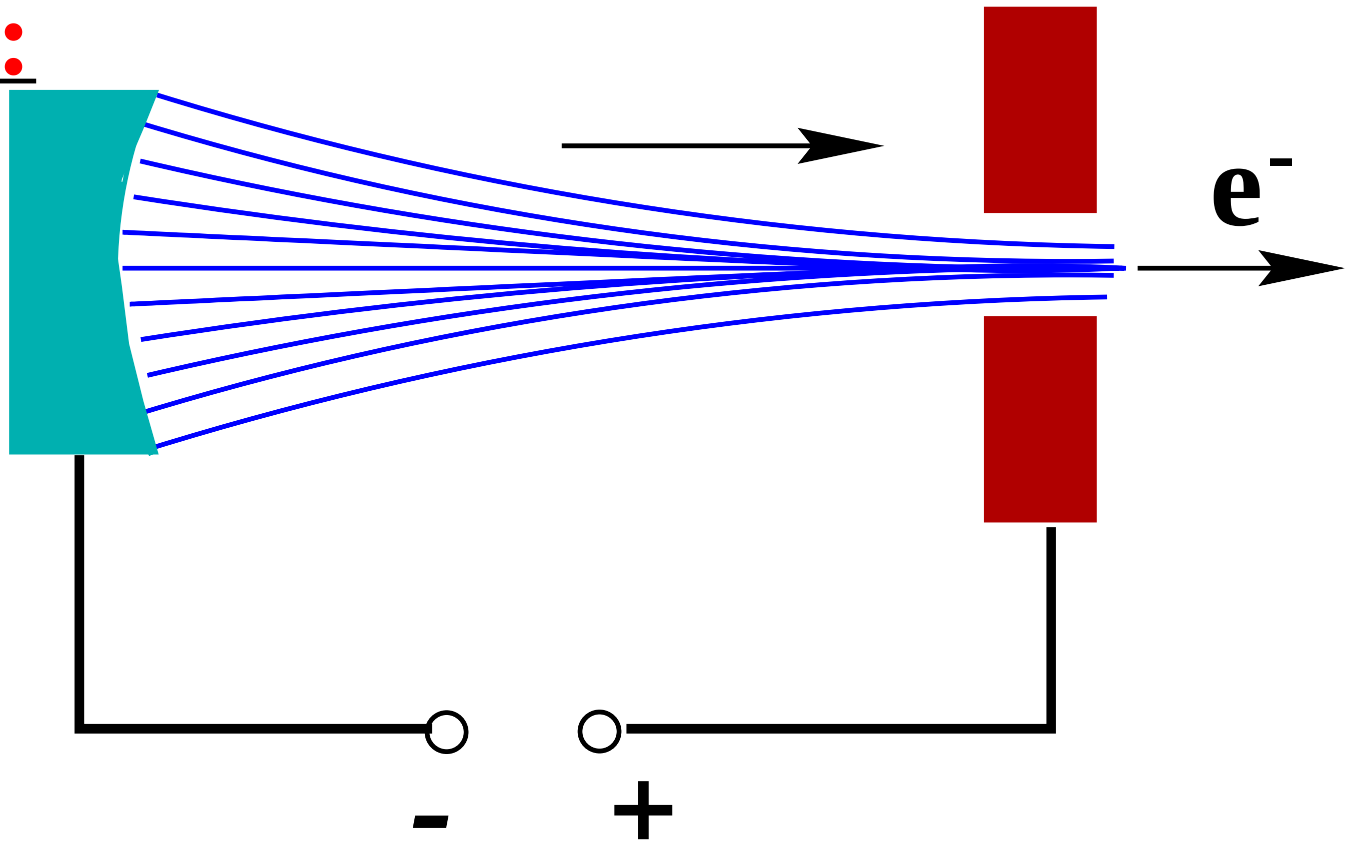
(Cosmic Rays)

- 1932: Anderson ⟶ e^+
- 1937: Anderson ⟶ μ

$$\left.\begin{matrix} p^- \\ \pi \end{matrix}\right\} ? \longrightarrow \text{Accelerators}$$

Particle Sources:

e^-:



→ *Cathode Rays*

p^+: *Cathode Tube with* H

$$H_2 + e^- \rightarrow H_2^+ + 2e^-$$
$$H_2^+ + e^- \rightarrow H^+ + H + e^-$$
$$H + e^- \rightarrow H^+ + 2e^-$$

Antimatter: *Pair Production*

Acceleration Concepts

- **Lorentz Force:**

$$\frac{d\vec{p}}{dt} = Q * (\vec{E} + \vec{v} \times \vec{B})$$

→ ***Energy gain only due to E field!***

- **Scalar and Vector Potential:**

$$\vec{E} = -\text{grad}\ \phi - \frac{1}{c}\frac{\partial \vec{A}}{\partial t} \qquad \vec{B} = \text{rot}\ \vec{A}$$

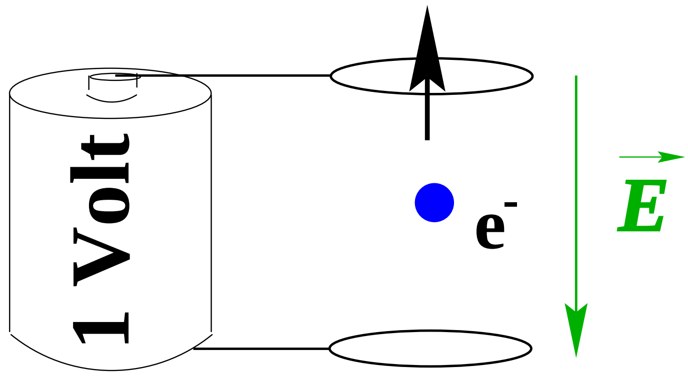
→
- ***Electrostatic fields (A = 0)***
- ***Time varying fields (ϕ = 0)***

Units

Energy Gain:

1 eV

→ $(1.6 * 10^{-19}\ J)$



Common Units: keV, MeV, GeV, TeV

$(10^3,\ 10^6,\ 10^9,\ 10^{12})$

Total Particle Energy:

- **Relativity:** $E = mc^2$; $m = \gamma * m_0$

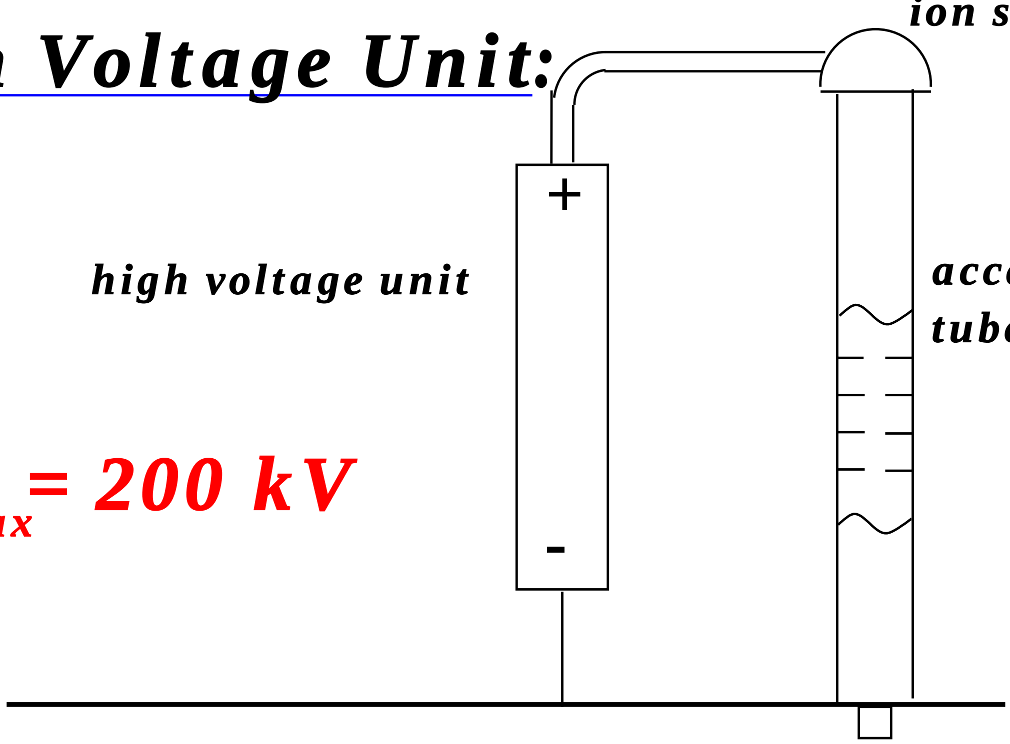
  $\gamma = 1/\sqrt{1 - \beta^2}$; $\beta = v/c$

- **Electron:** $m_0 = 9.11*10^{-31}$ kg; 0.51 MeV

- **Proton:** $m_0 = 1.67*10^{-27}$ kg; 0.94 GeV

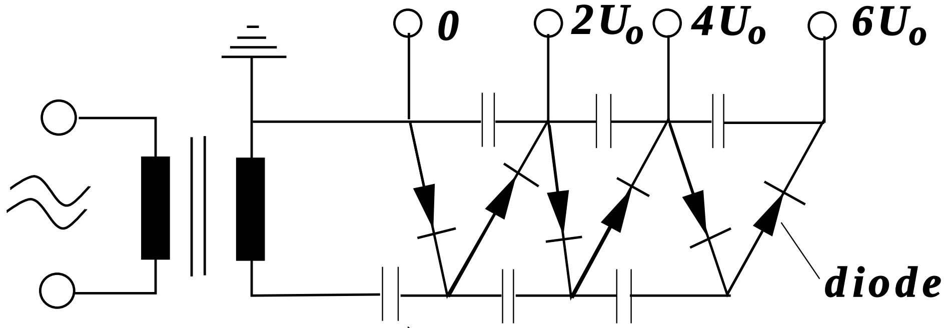
Electrostatic Fields

High Voltage Unit:



$V_{max} = 200\ kV$

Cascade Generator:

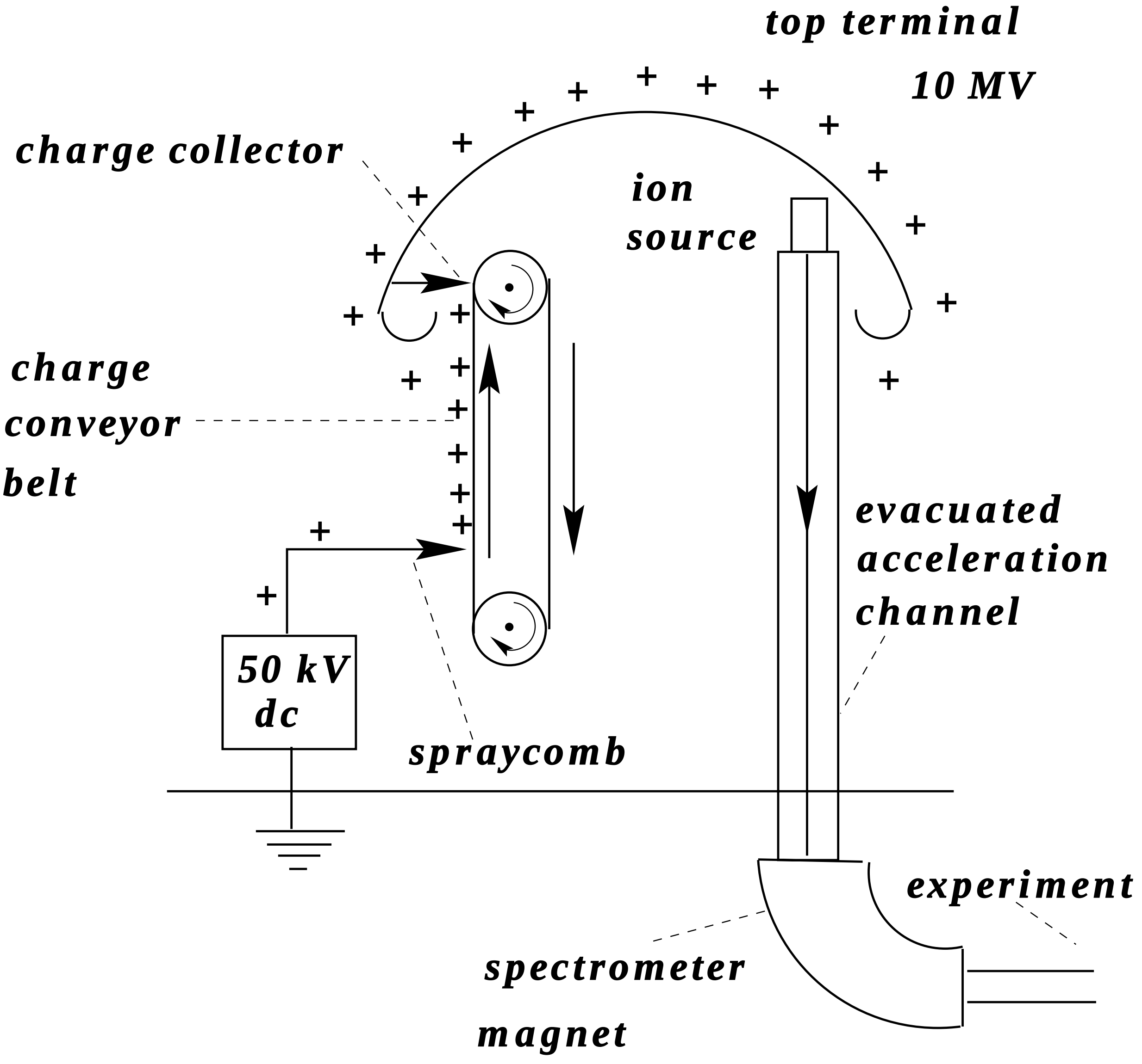


- **1928:** Cockroft + Walton 800kV
- **1932:** $p + Li \rightarrow 2\ He$ 700kV (p)

(Nobel Prize 1951)

Van de Graaf Generator

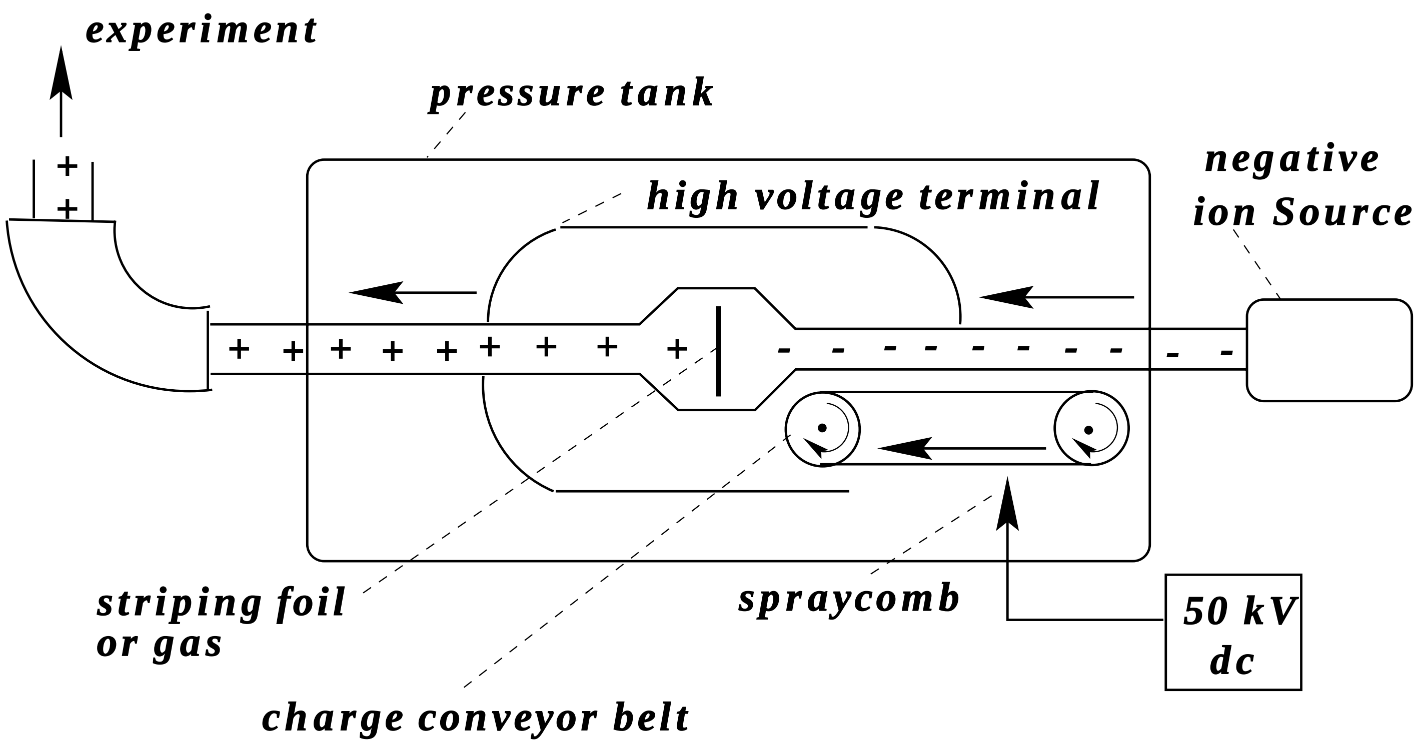
Single Unit:



$V_{max} = 10$ MVolt

Van de Graaf Generator

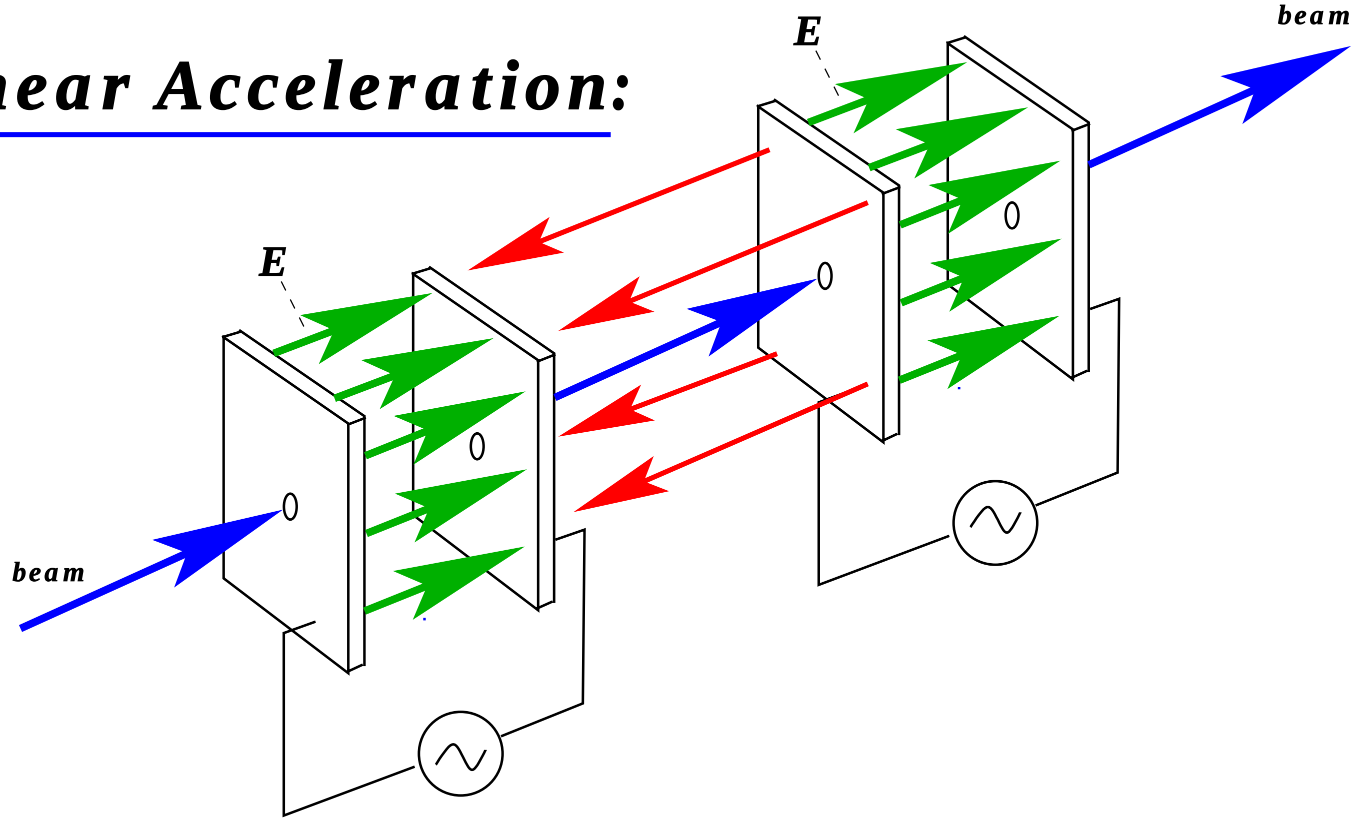
Tandem generator:



$\rightarrow$ $V_{max} = 25\ MVolt$

Time Varying Fields

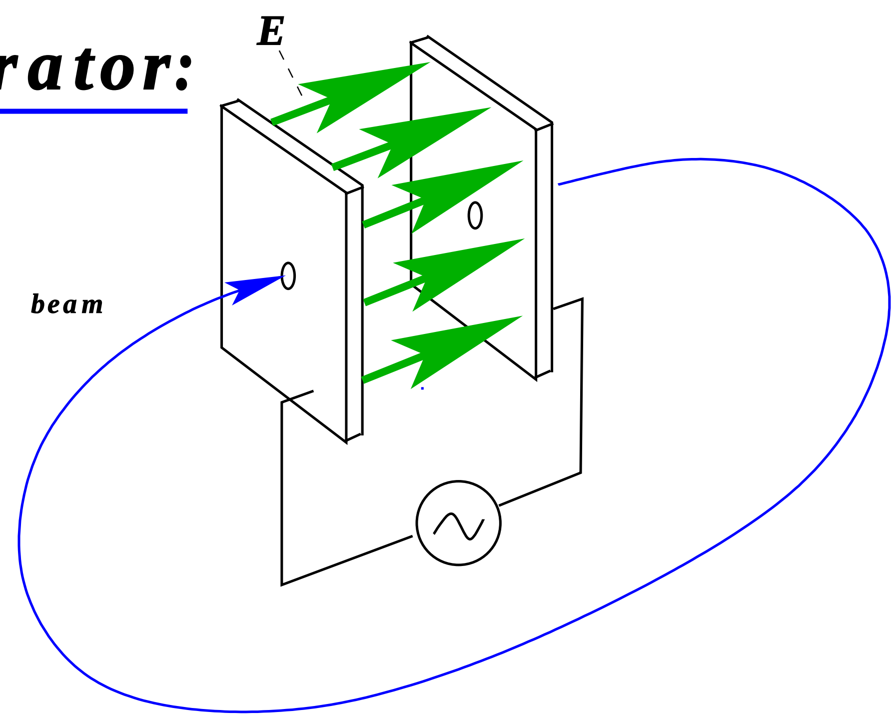
Linear Acceleration:



→ bunched beam

→ long accelerator!

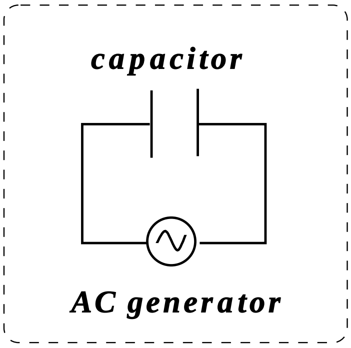
Circular Accelerator:

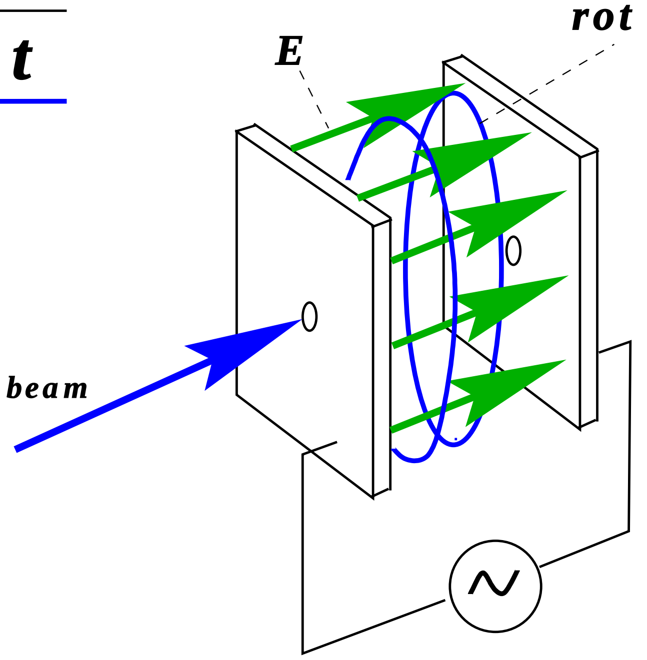


Time Varying Fields

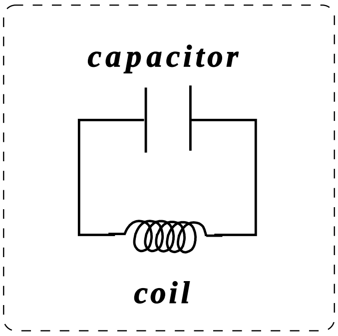
$$E = -\frac{1}{c}\frac{\partial A}{\partial t}$$

$$rot\ B = \frac{\mu\varepsilon}{c}\frac{\partial E}{\partial t}$$



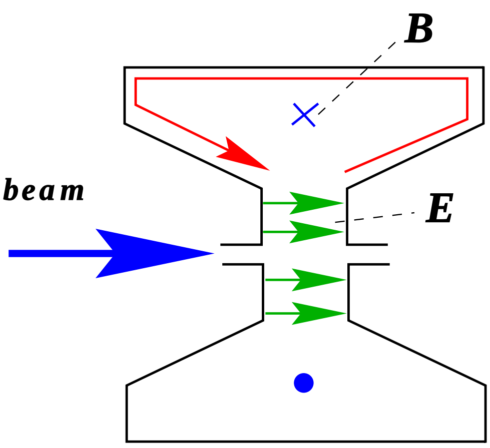


Resonator:

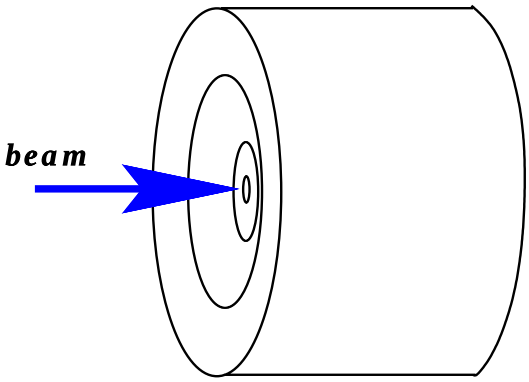


$$L = \frac{\mu_0 \cdot N^2 \cdot A}{l}$$

$$C = \frac{\varepsilon_0 \cdot A}{d}$$



cavity

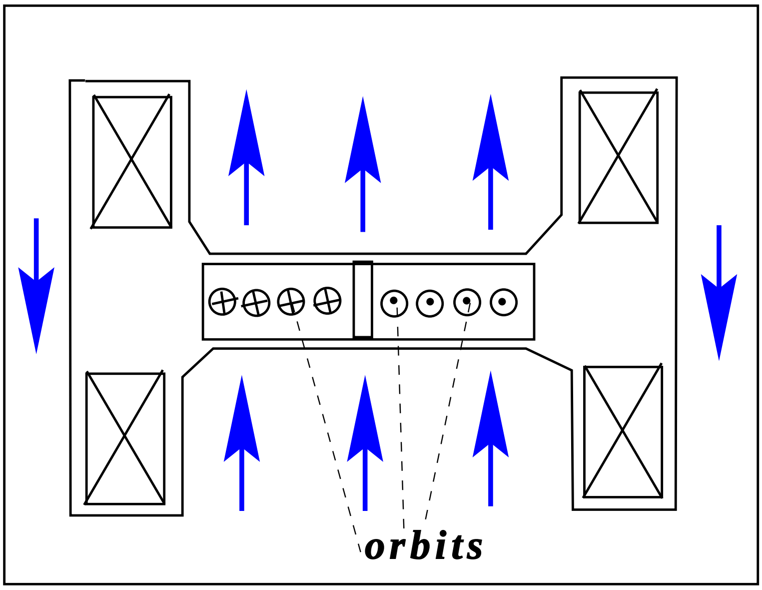


cavity

→ f; Q; R

Circular Accelerators I

- **1929:** Lawrence → Cyclotron



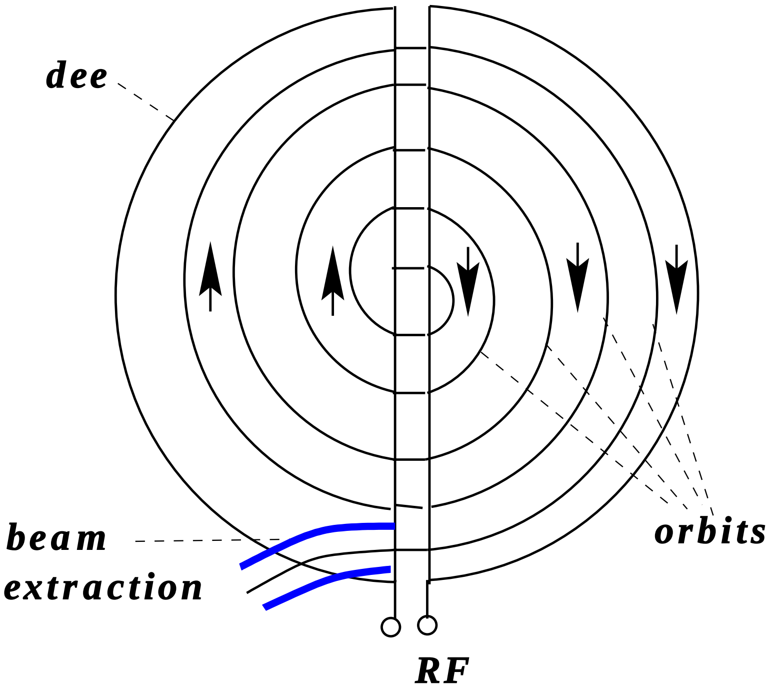
$$\omega = \frac{Q}{m} \cdot B$$

$$r = \frac{m}{Q} \cdot \frac{v}{B}$$

$m = const$

→ $f_{RF} = const$

$B = const$



- **1931:** Livingston → H^- to 80 keV
- **1932:** Lawrence → p to 1.2 MeV (NP 1939)

Disadvantage:

- **High Energy:**

$\gamma >> 1$ → $f_{RF} \neq const.$

→ short bunch trains

→ large dipole magnet

- **Synchrotron:** $R = const.$

$$\omega_0 = \frac{Q}{m_0} \cdot \frac{B}{\gamma}$$

$$r = \frac{m_0}{Q} \cdot \frac{\gamma}{B} \cdot v \rightarrow B \neq const.$$

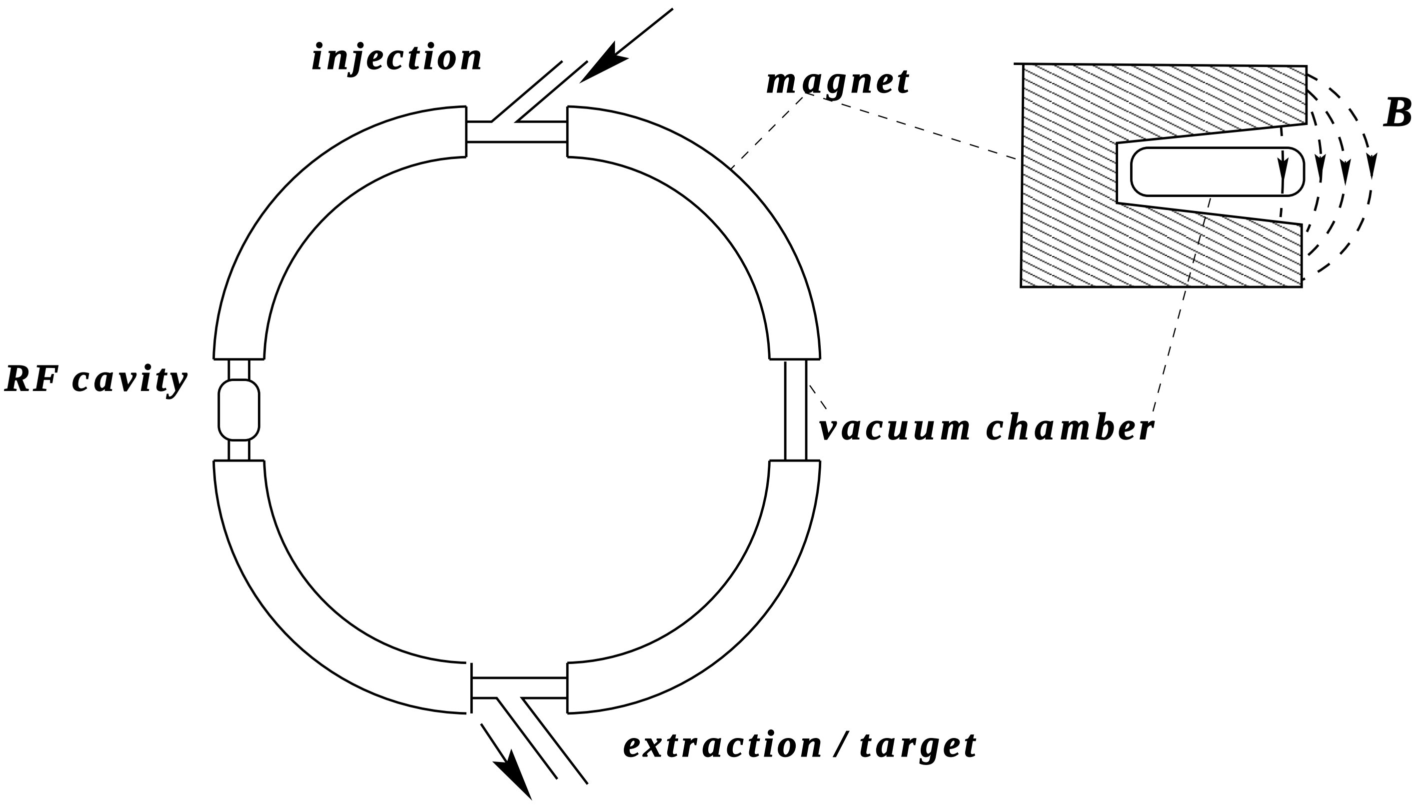
→ Small magnets,

$v = c$ → $f_{RF} = const.$

Circular Accelerators II

Synchrotron:

- **1952:** Cosmotron 3 GeV protons
- **1949:** electrons



- **1955:** Bevatron 6 GeV protons

→ $\bar{p}$ (fixed-target experiment)

$$E_{cm} = 2 \cdot m_0 \cdot c^2 \left(\sqrt{1 + \frac{E}{2 \cdot m_0 \cdot c^2}} - 1 \right)$$

Summary

- **Acceleration Concept:**
  - *Static field* — 25 MeV — discharge
  - *AC field* — no limit — length

multiple passages

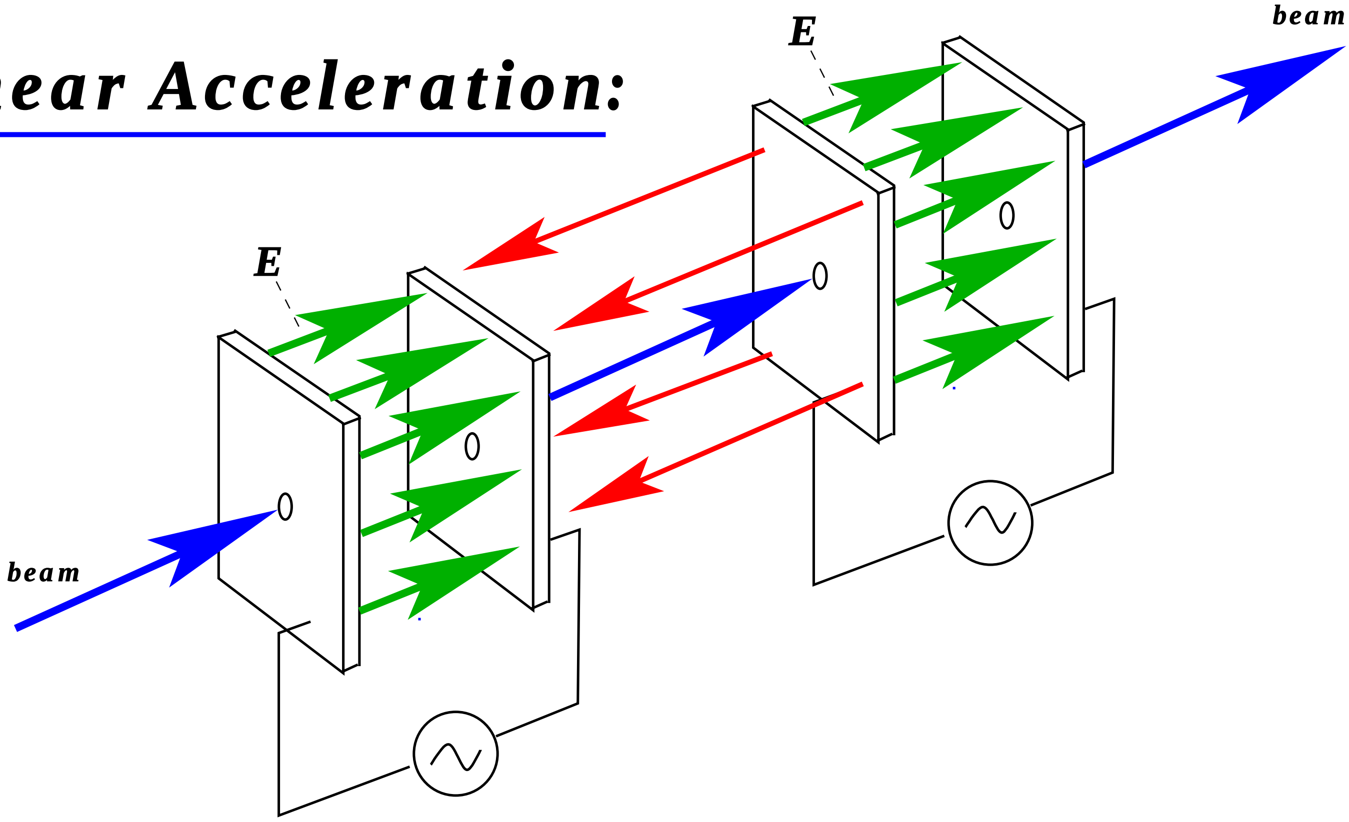
- **Circular Acceleration:**
  - *Cyclotron* — 25 MeV — non-relativistic
  - *Synchrotron* — no limit — small magnets

- **In Practice:**

Combination of several options

Time Varying Fields

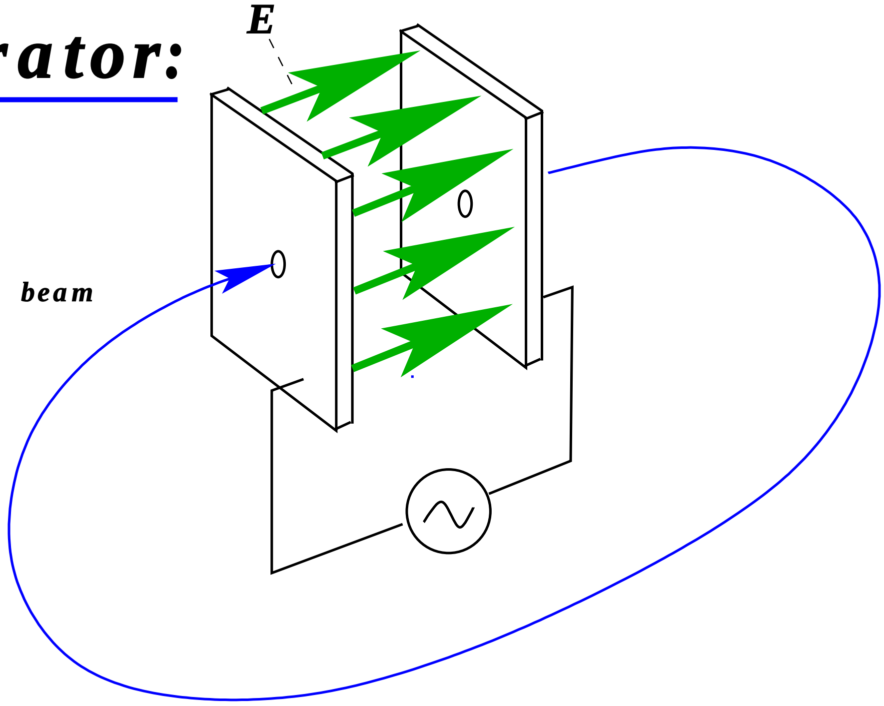
Linear Acceleration:



→ bunched beam

→ long accelerator!

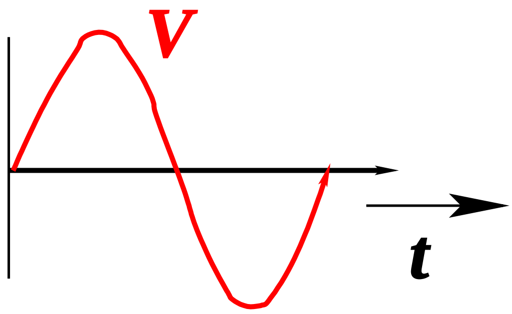
Circular Accelerator:



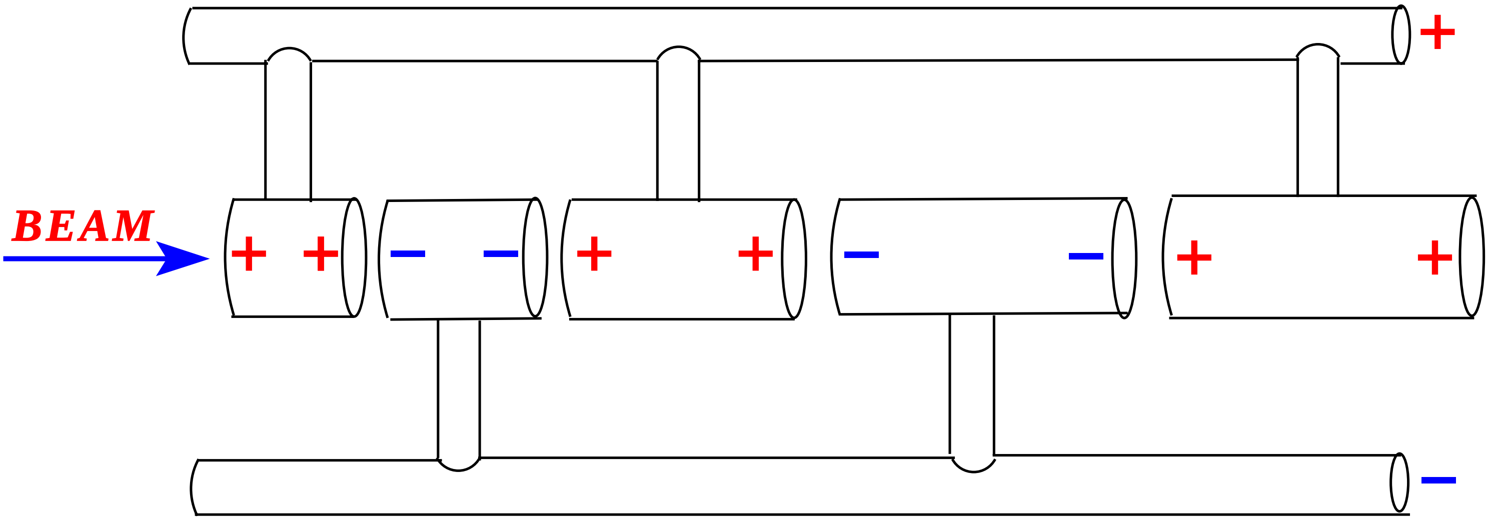
Drift Tubes

- **1924:** Ising

AC Voltage:



Symmetric line:



→ $l = v_{part} \cdot T/2$

- **1928:** demonstrated by Wideroe

1MHz, 25kV oscillator

→ 50kV potassium ions

Lawrance:

1.3MV mercury ions with 48kV

- **But:** $f < 7MHz$ ($l = 21$ meter)!

Time Varying Fields

Maxwell Equations without Sources

a) $\vec{\nabla} * \vec{E} = 0$

b) $\vec{\nabla} \times \vec{E} + \frac{1}{c}\frac{\partial \vec{B}}{\partial t} = 0$

c) $\vec{\nabla} * \vec{B} = 0$

d) $\vec{\nabla} \times \vec{B} - \frac{\mu\varepsilon}{c}\frac{\partial \vec{E}}{\partial t} = 0$

Rotation on b) and d)

plus: $\vec{\nabla} \times (\vec{\nabla} \times \vec{V}) = \vec{\nabla} \cdot (\vec{\nabla} \cdot \vec{V}) - \vec{\nabla} \cdot \vec{V}$

→ ***Wave equation:***

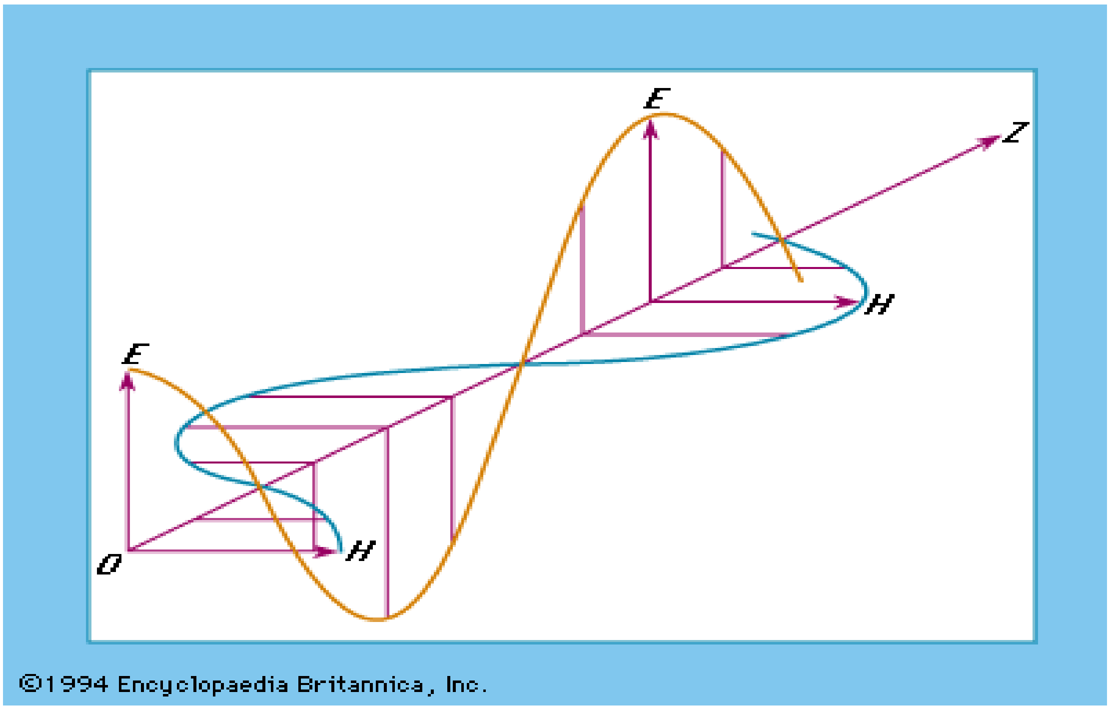
$$\frac{\partial^2 \vec{E}}{\partial t^2} = \frac{c^2}{\mu\varepsilon} \nabla^2 \vec{E} \qquad \frac{\partial^2 \vec{B}}{\partial t^2} = \frac{c^2}{\mu\varepsilon} \nabla^2 \vec{B}$$

Time Varying Fields

Plane Electro Magnetic Wave:

$$\vec{E} = \vec{E}_0 \cdot e^{ik\vec{n}\cdot\vec{x} - \omega t} \qquad \vec{B} = \vec{B}_0 \cdot e^{ik\vec{n}\cdot\vec{x} - \omega t}$$

$$\vec{B}_0 = \sqrt{\mu\varepsilon} \cdot \vec{n} \times \vec{E}_0 \qquad k = \frac{2\pi}{\lambda}$$



No acceleration in the direction of propagation!

Boundary Conditions I

Transverse Electric Waves (TE):

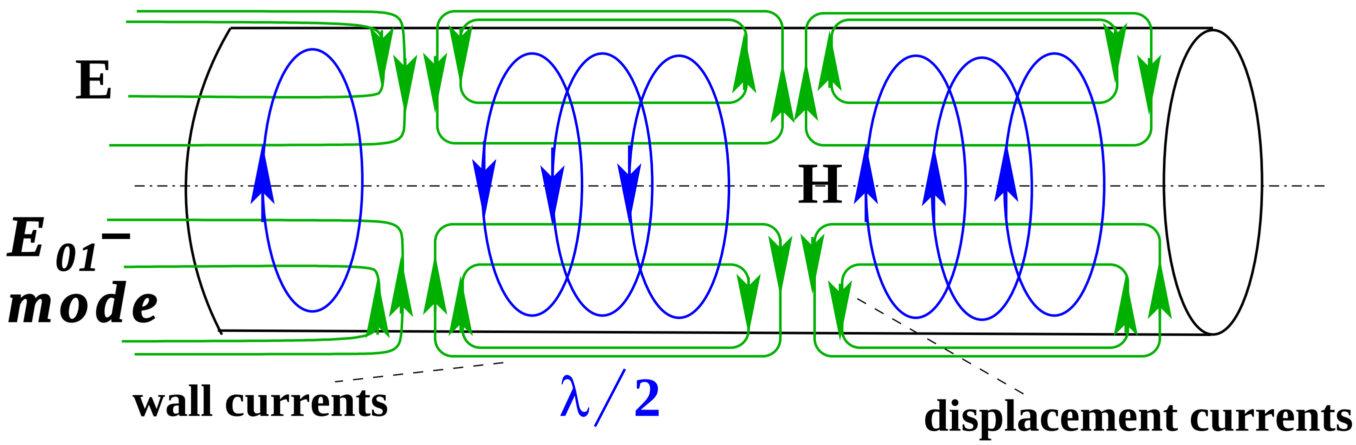
$E_z = 0$ *everywhere;*

Boundary condition: $\left.\frac{\partial B}{\partial n}\right|_s = 0$

Transverse Magnetic Waves (TM):

$B_z = 0$ *everywhere;*

Boundary condition: $\left. E_n \right|_s = 0$



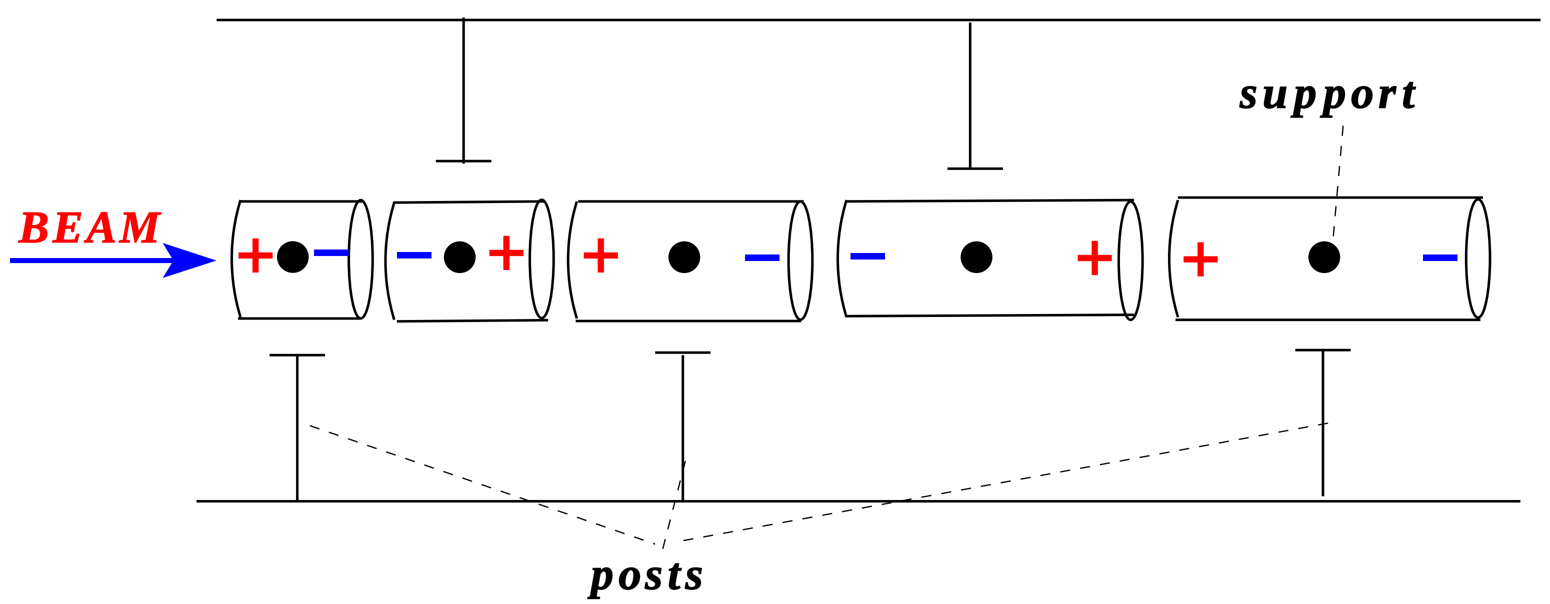
Problem: $v_{ph} > c$

→ ***Shielding or change*** v_{ph}

Resonance Tank

- **Alvarez:**

$l = v_{part} \cdot T$



- **Tubes are passive**

  → **higher frequencies!**

  (f = 200 MHz gives good tube size)

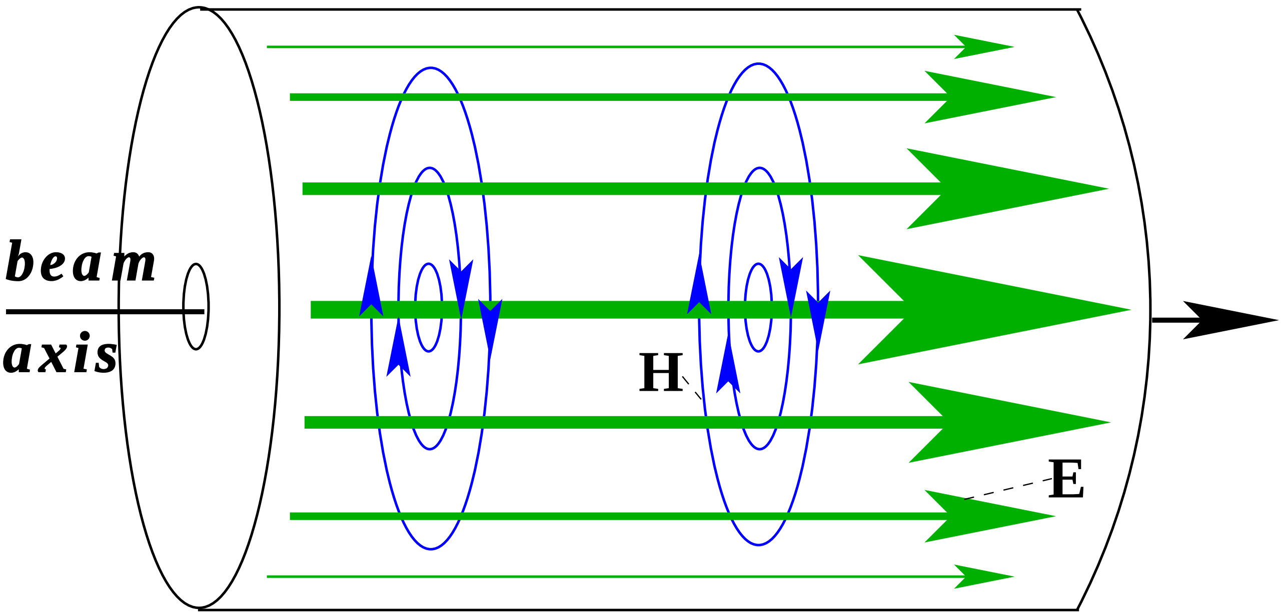
- **Posts** → $v_{gr} \neq 0$

- **Pre−accelerator for most proton acclelerators**

Boundary Conditions II

Cavity Resonator:

TM mode with longitudinal boundary;



Short Section:

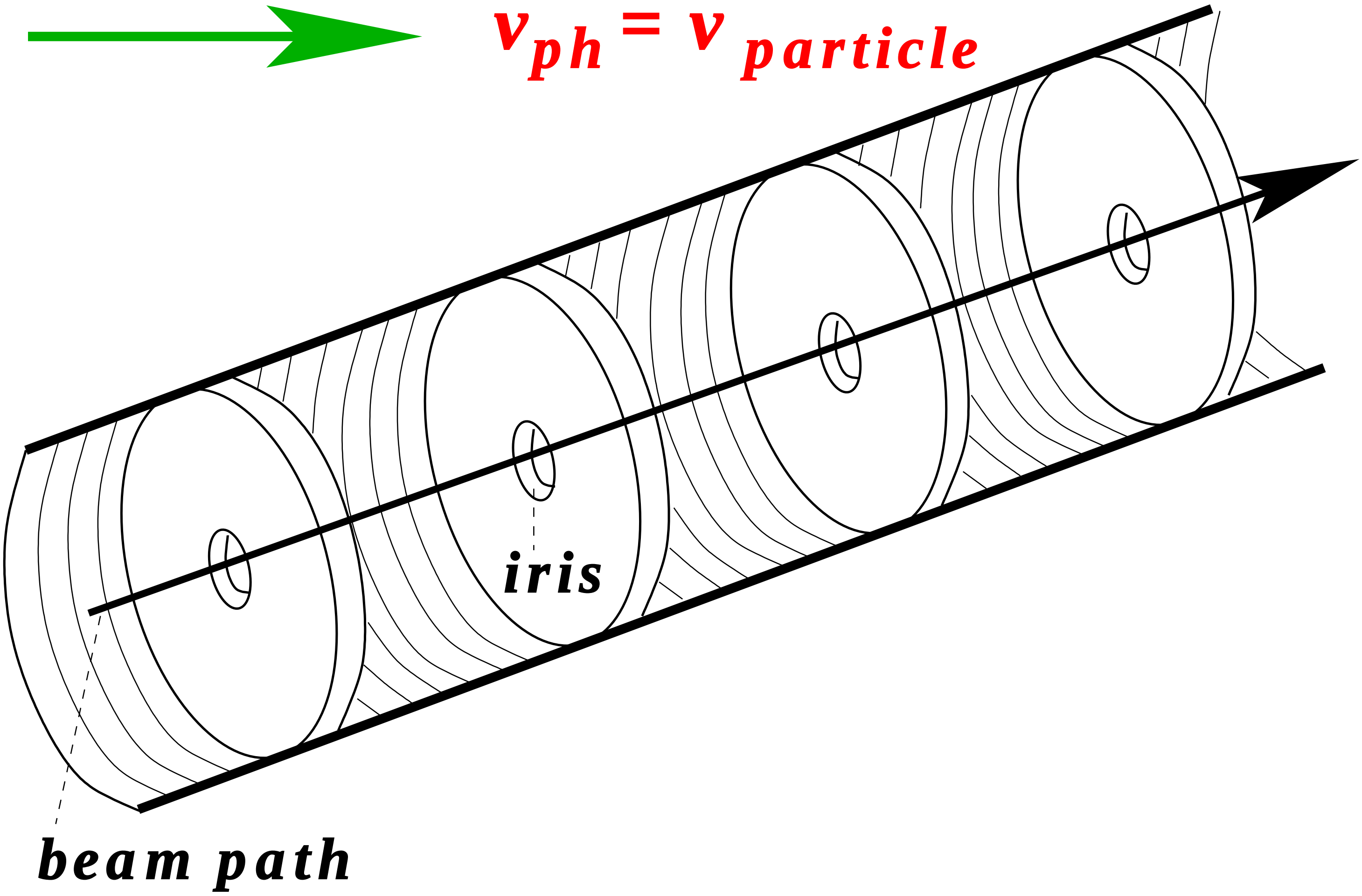
→ *multi-cell*

→ *multi-passage*

Boundary Conditions III

Loaded Wave Guide:

$v_{ph} = v_{particle}$



But:

Concept of linear acceleration is limited by power of RF generator!

→ Not feasible before World War II