# Historical developments of particle acceleration

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# Outline

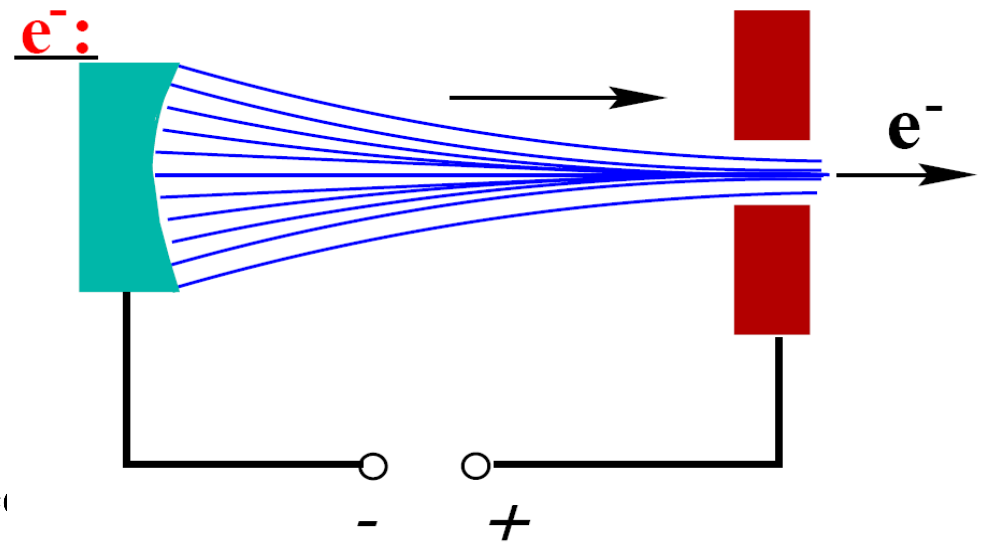
- Principles of Linear Acceleration
  - Electrostatic accelerators
    - Tesla transformer
    - Cascade generator
    - Van de Graaff generator
  - Acceleration by RF fields
    - Linacs
    - Phase stability
- Circular accelerators
  - RF fields
    - Cyclotron
    - Microtron
  - Betatron
    - Weak focusing
    - Strong focusing
  - Synchrotron

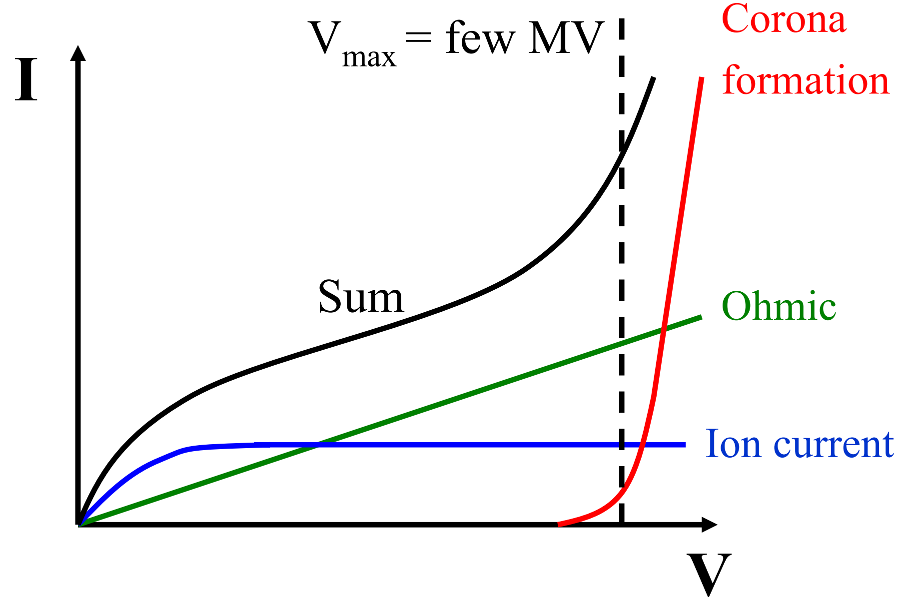
# Why accelerators?

- Study of the basic building blocks of matter
  - Particle physics
  - Spectroscopy
    - X-rays
    - Neutrons
- Applied science
  - Medicine
    - Tomography
    - Surgery
    - Cancer treatment
  - Chemistry - biology
    - Sterilization of food products
    - Material property change (nuclear waste transmutation)
  - Energy
    - Energy amplifier
    - Inertial fusion with heavy ion driver

# Direct voltage accelerator

- The simplest accelerator (vacuum tubes, monitors...)
  - Particle source in blue electrode
  - Accelerated by electric field in good vacuum
  - Particle exit in red electrode
  - Particle energies proportional to maximum voltage and thus limite
  - Current components
    - Ohmic
      - Proportional to voltage
    - Residual ion current
      - Saturates rapidly
    - Corona
      - Negligible for small voltages
      - Current grows exponentially for high voltages causing spark discharge and voltage breakdown

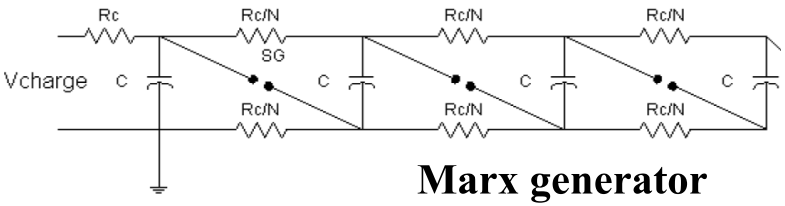


# Cascade generator

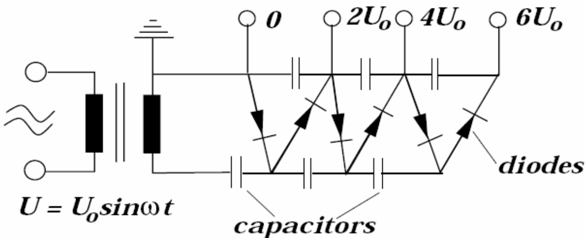
- Problem: generate high voltages to reach high energy
- **Cockcroft** and **Walton** (1932) developed generator based on multiple rectifiers
- Greinacker circuit operating principle
  - Transformer with sinusoidal voltage $V = V_0 \sin(\omega t)$
  - 2N diodes (current flows in one direction) ensure that max voltage in every 2 capacitors is $2V_0$, $4V_0$, $6V_0$ ,…,$2NV_0$
  - Reach voltage of about 4 MV but only pulsed beam currents of several hundreds of mA
- Cockcroft and Walton used accelerator to bombard Li with protons and produce an atomic reaction, giving two He nuclei (Nobel Prize 1951)
- Marx generator (1932) consists of series of resistors and capacitors, powered by high voltage $\mathbf{V}_{\mathbf{charge}}$
  - When spark discharge occurs, and as the resistance is very large, N capacitors powered in series giving total voltage of $\mathbf{NV}_{\mathbf{charge}}$

**Fermilab cascade generator**



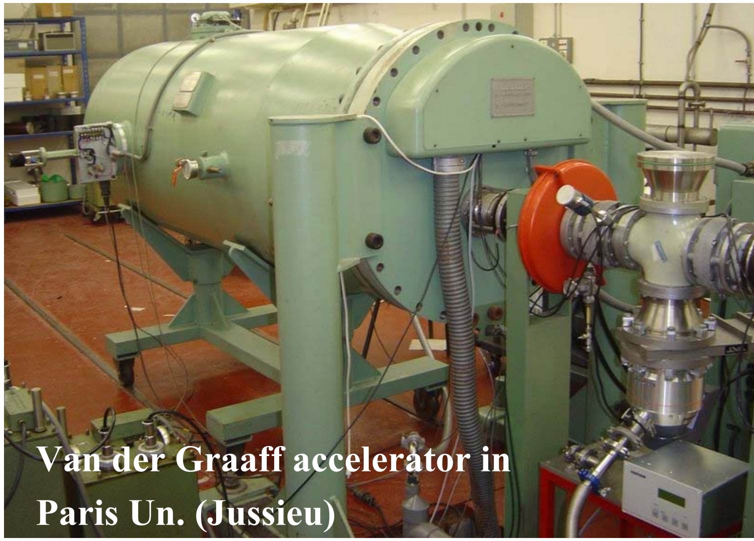

**Marx generator**

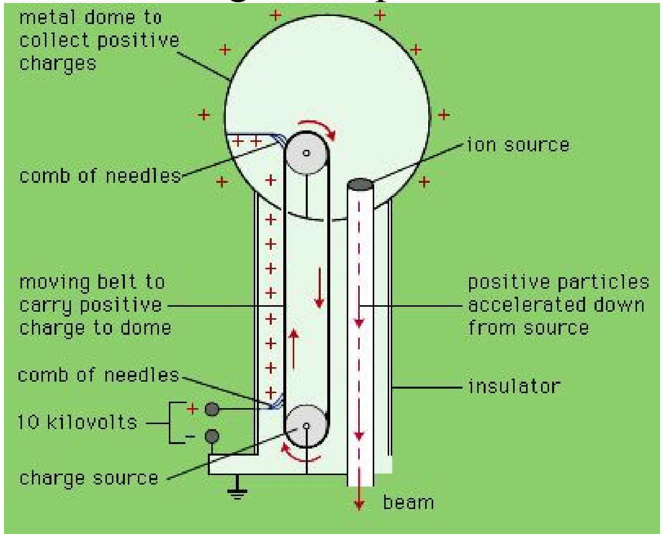
**Greinacker circuit**

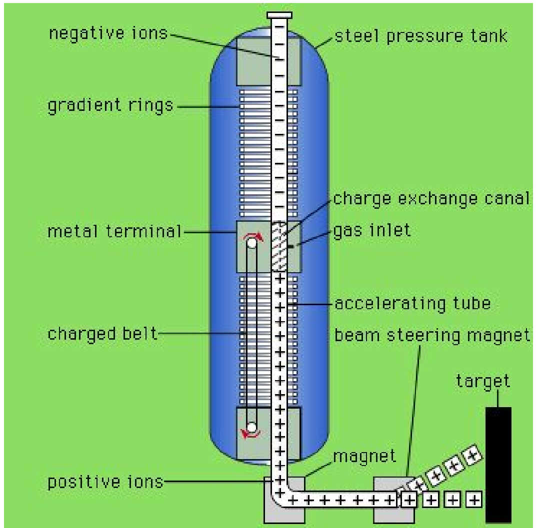


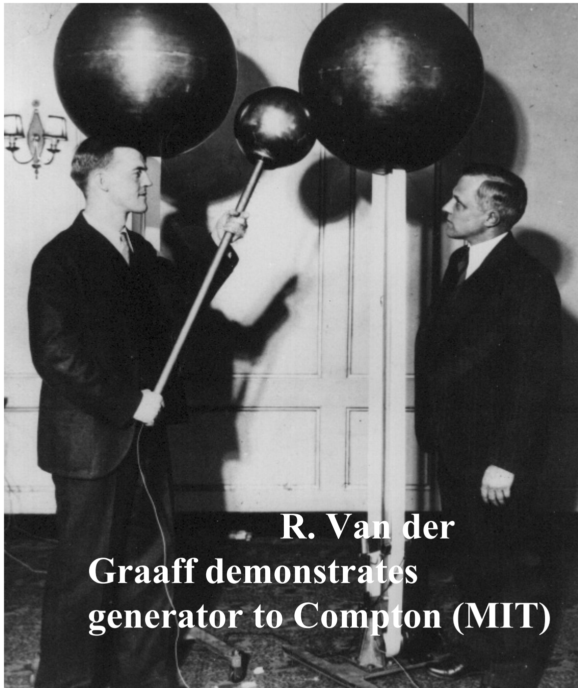
# Van der Graaff accelerator (1930)

- Charges produced in corona formation and transferred through isolating belt to dome charging it up to maximum voltage (2MV)
- Higher voltages (10MV) when system placed in tank with insulating gas (Freon, SF6)
- Dome connected to particle accelerator  with source and series of circular electrodes for even field distribution to avoid discharge
- Possibility to use twice the potential (**Tandem**)
  - Negative ions accelerated from ground voltage to V
  - Electrons get stripped by gas and second acceleration of positive ions from V to 0
  - Energies of up to 1 GeV with multiply ionized ions

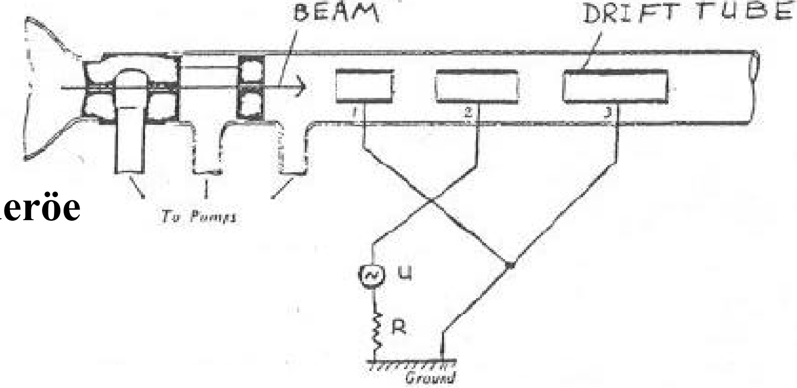

**Van der Graaff accelerator in Paris Un. (Jussieu)**



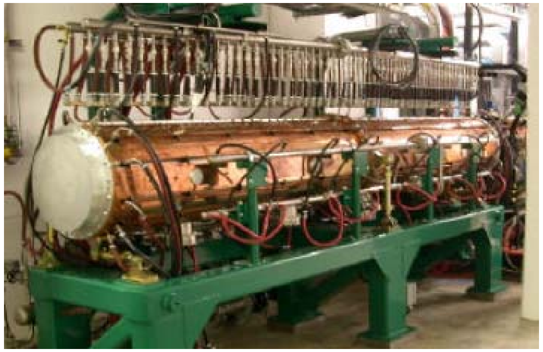



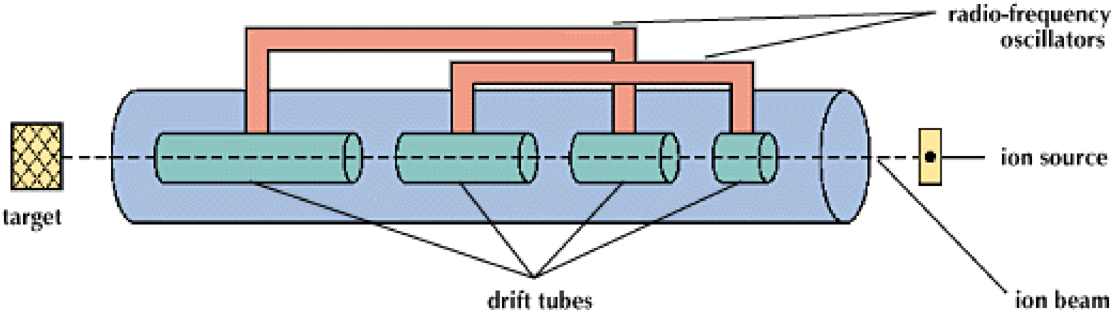


**R. Van der Graaff demonstrates generator to Compton (MIT)**

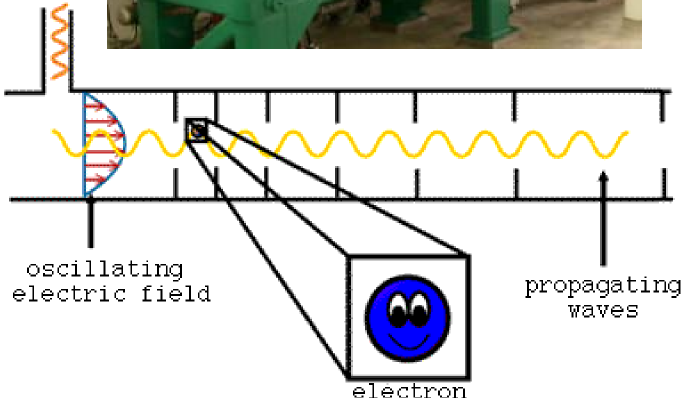
# Linear accelerators




- Original idea by **Ising** (1924), first working linac by **Wideröe** (1928) and high energy (1.3 MeV) linac by **Sloan** and **Lawrence** (1931)
- Series of drift tubes alternately connected to high (RF) frequency voltage oscillator
- Particles get accelerated in gap, no effect inside tube (act like Faraday cage)
- Field reversed and then exit tube to be reaccelerated until they reach energy $E_n = nqV_0 \sin(\Psi_0)$
- For constant RF frequency, drift tubes' length increases with velocity up to relativistic limit (electrons) $l_n = v_n T_{RF}/2$
- Synchronization of particle and RF field assured by **phase focusing**
- **Beams** (1933) developed first cavity structure linac (waveguides). **Hansen** and **Varian** brothers (1937) developed first klystron (frequencies up to 10GHz).
- **Alvarez** (1946) developed first DTL resonant cavity structure for protons and heavy ions





# Phase focusing

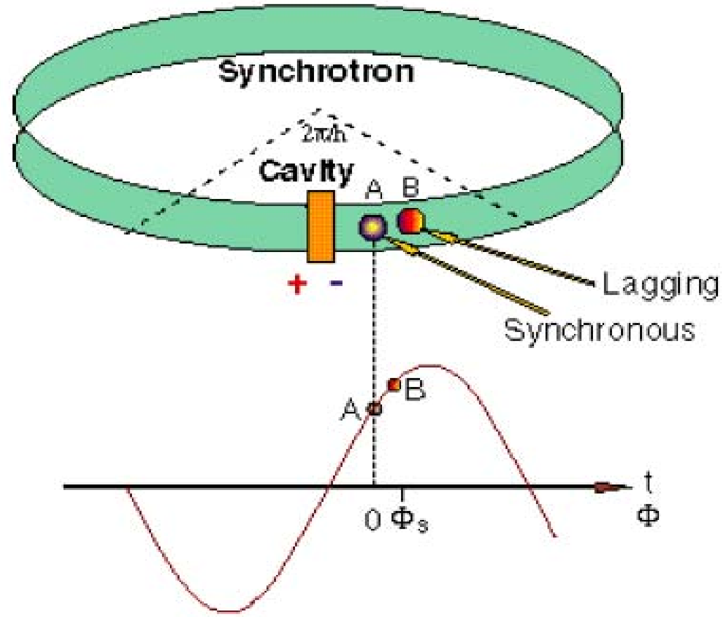
- Discovered independently by **McMillan** and **Veksler** (1945)
- Cavity set up so that particle at the centre of bunch, called the **synchronous particle**, acquires just the right amount of energy.
- Particles see voltage

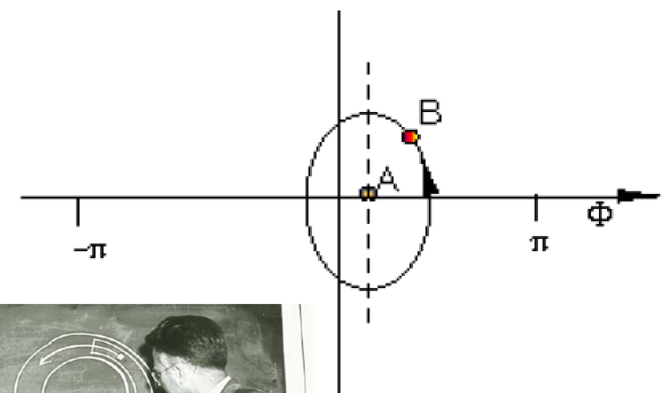
$$V = V_0 \sin(2\pi\omega_{RF}t) = V_0 \sin(\phi(t))$$

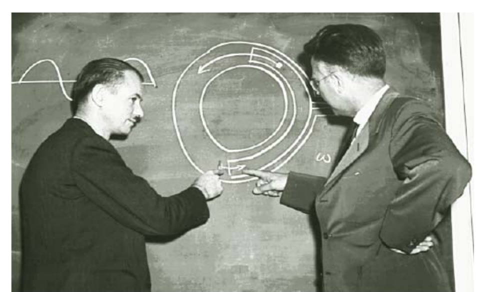
- In case of no acceleration, synchronous particle has $\boldsymbol{\varphi_s = 0}$
- To accelerate, make $\mathbf{0} < \boldsymbol{\varphi_s} < \pi$ so that synchronous particle gains energy

$$\Delta E = qV_0 \sin(\phi_s)$$

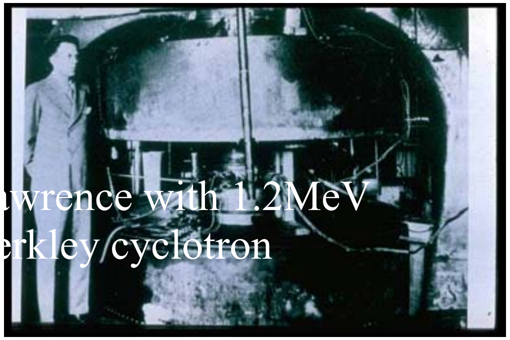
- Particles arriving early see $\varphi < \varphi_s$
- Particles arriving late see $\varphi > \varphi_s$
- Energy of those in advance is decreased relative to the synchronous particle and vice versa.
- The particles get grouped (**bunching effect**)

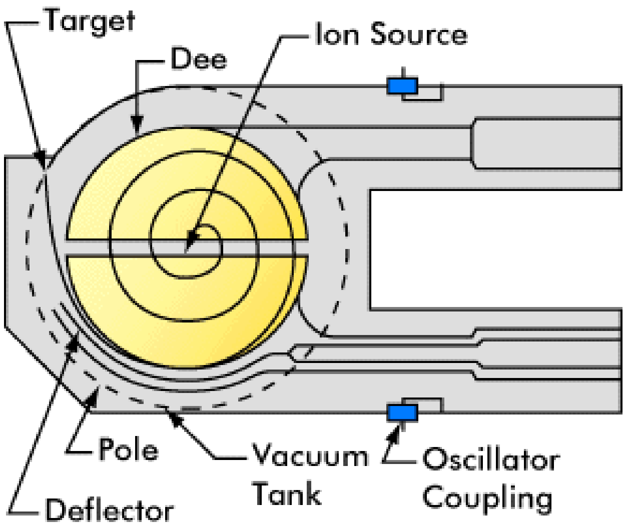


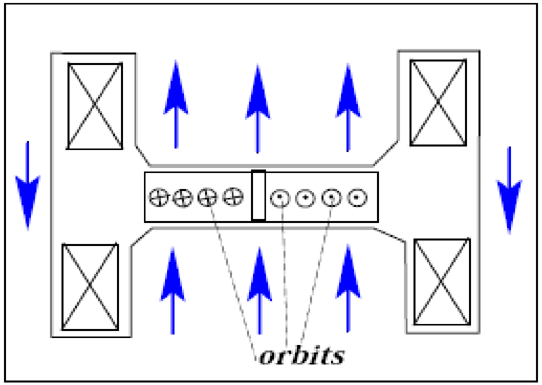



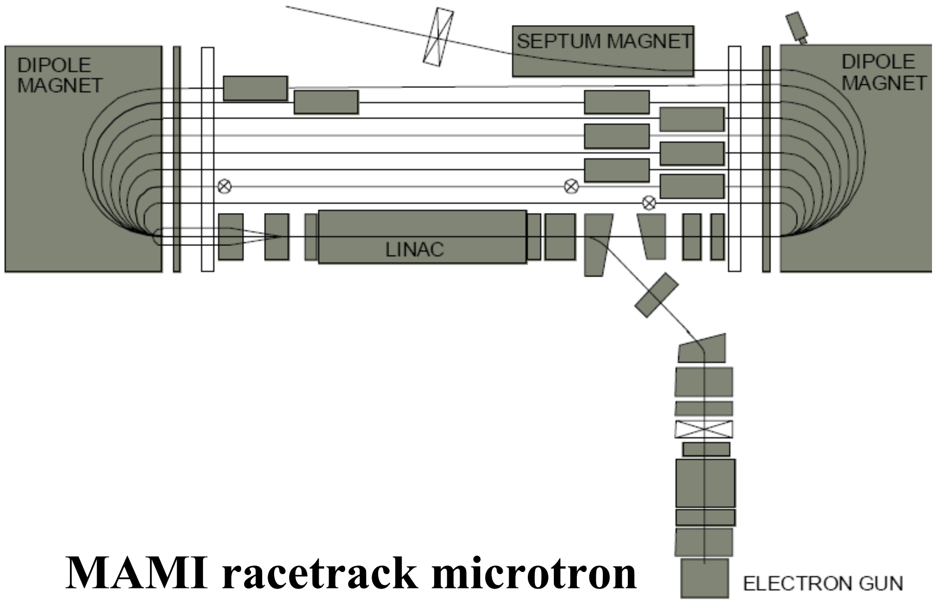
- Idea of **Lawrence** and **Edlefsen** (1930) built by **Lawrence** and **Livingston** (1932)
- Constant B **field** by H shaped magnet with cyclotron frequency $\omega_c = qB/m$ and radius increases with velocity, i.e. spiral trajectories ($\gamma$=1).
- Accelerating voltage synchronous with particle's passage in gap $\omega_{RF} = (2n+1)\omega_c$
- Used for accelerating heavy particles (protons, deuterons, alpha at low energies ~ 20MeV)
- For higher energies (relativistic particles), frequency decreases with mass (energy). **Synchro-cyclotron** principle (**McMillan** and **Veksler**, 1945): adjust RF frequency so that $\omega_{RF} \propto 1/\gamma$
- But different frequency for different particles. **Isocyclotron** principles: adjust magnetic field so that $\omega_{RF} \propto B/\gamma$ is constant. Energies of up to 600MeV can be reached
- Problem: changing magnetic field defocuses the beam and high energies need high field



# Microtron




**MAMI racetrack microtron**

- Idea of **Veksler** (1944) built only in by the team of **Kapitza** in the 60's.
- Electrons become very quickly relativistic and cyclotron is inefficient
- Choose high RF frequency and tune energy gain per turn so that larger trajectory matches an integer of the RF wavelength
- **Racetrack** principle: Particles bend by angle **π** with two opposite bending magnets, travel in straight lines and than reaccelerated
- Synchronicitv condition
$$\Delta t = k/\nu_{RF} = \frac{2\pi}{ec^2 B}\Delta E$$
- With one magnet, energies up to 20 MeV. For higher energies racetrack design is needed

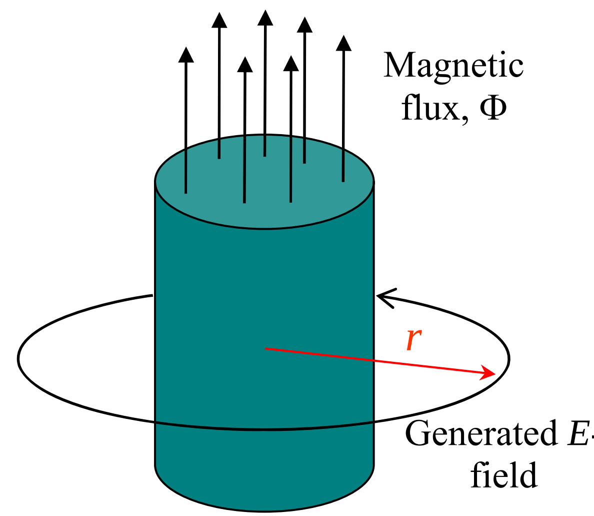
# Betatron

- Principle investigated by **Wideröe** (1928) , **Steenbeck** (1935) and first one built by **Kernst** (1940) (energy of 20 MeV)
- Beta particles (=electrons) accelerated by rotational electric field generated by induction from time varying magnetic field $\mathbf{B}(t) = \mathbf{B_0}\sin(\omega t)$
- The magnetic flux $\Phi = \iint\limits_A \mathbf{B}(r)\cdot d\mathbf{s} = \langle \mathbf{B} \rangle \pi r^2$
- From Faraday law of induction

$$2\pi r|E| = \oint \mathbf{E}\cdot d\mathbf{r} = -\iint\limits_A \dot{\mathbf{B}}(r)\cdot d\mathbf{s} = \dot{\Phi} = -\pi r^2 \frac{d}{dt}\langle \dot{\mathbf{B}} \rangle$$

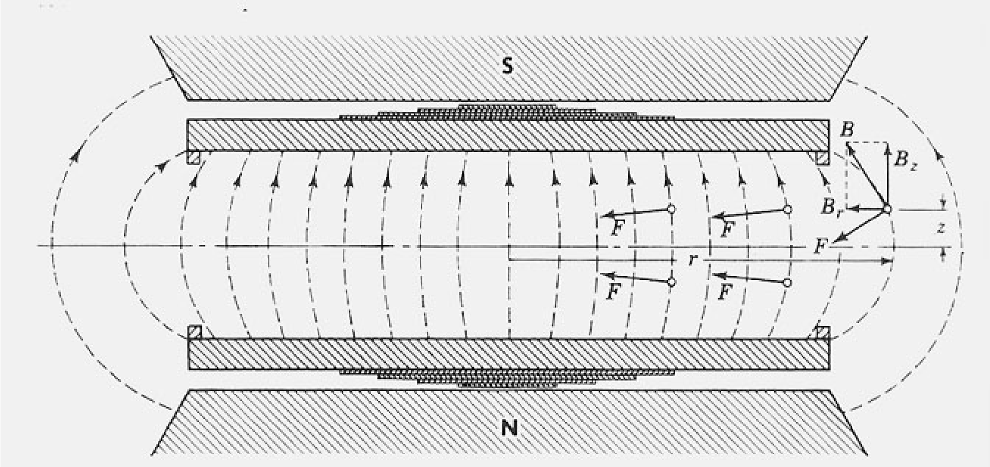
- Motion in uniform magnetic field imposes $|\mathbf{p}| = e\ r|\mathbf{B}|$
- Assuming a constant radius, the accelerating part of the Lorentz force $|\mathbf{F}| = -e|\mathbf{E}| = |\dot{\mathbf{p}}| = e\ r|\dot{\mathbf{B}}|$
- Equating the last equation with the one from Faraday's law we get **Wideröe's betatron condition**

$$\boxed{|\mathbf{B}(t)| = \frac{1}{2}\langle|\mathbf{B}(t)|\rangle + |\mathbf{B_0}|}$$



# Weak Focusing

- Particles injected transversely into uniform magnetic field follow circular orbit.
- Misalignment and injection errors cause particles to drift vertically and radially and hit walls, i.e. need for focusing




- Existence of vertical gradient field in magnet edges.
- The transverse field components are $(B_x, B_y) = B_0(-n\frac{y}{r}, 1 - n\frac{x}{r})$

with **field index** $\boxed{n = -\frac{r}{B_0}\frac{\partial B_y}{\partial x}}$

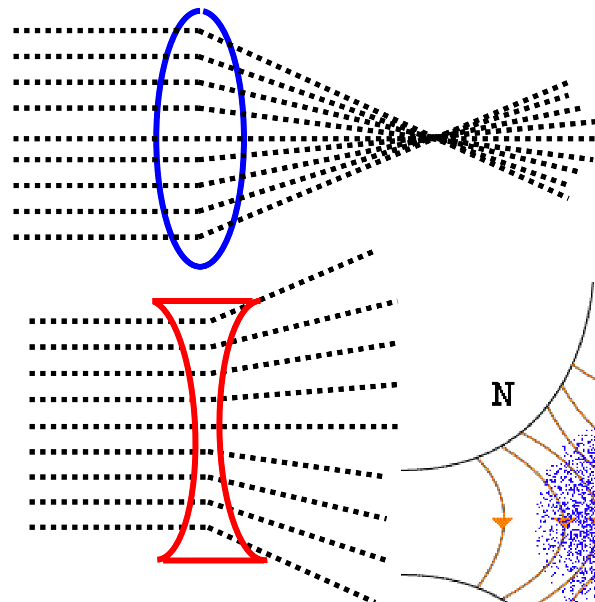
- Particles execute harmonic transverse oscillations called **betatron** oscillations with frequencies

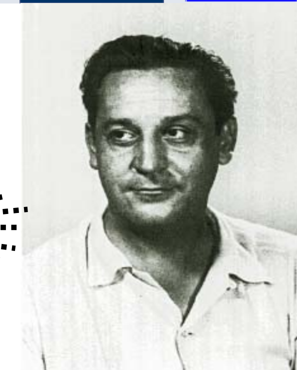
$$\omega_x = \frac{v}{R}\sqrt{1-n} \ , \ \omega_y = \frac{v}{R}\sqrt{n}$$

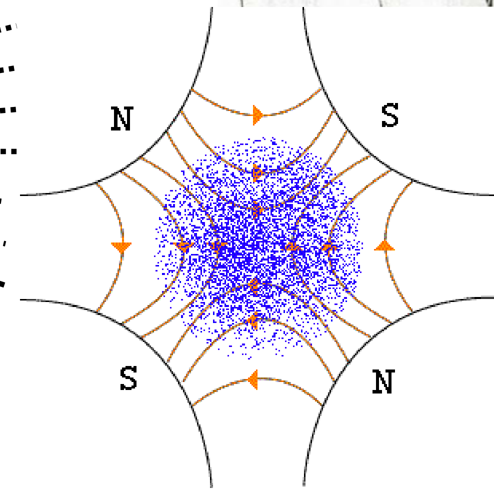
- The **Steenbeck** stability condition is imposed $\boxed{0 < n < 1}$

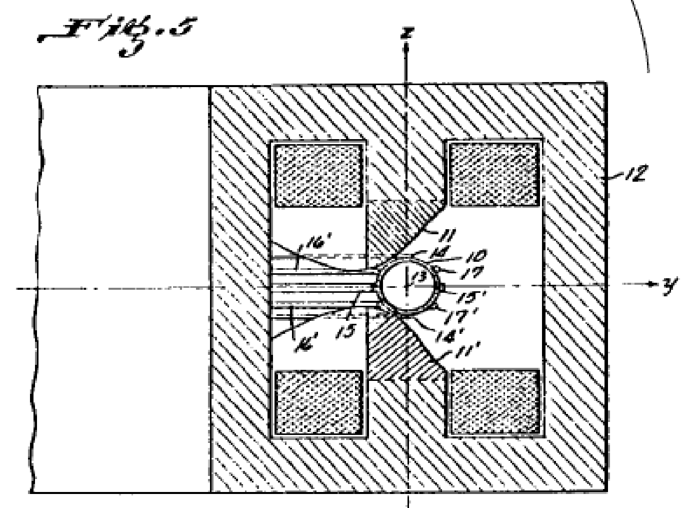
# Strong Focusing: Alternating Gradient Principle

- Principle invented by **Christofilos** (1950) and independently by **Courant, Livingston** and **Snyder** (1953).
- Nature of Maxwell equations prevents existence of focusing electromagnetic fields in both planes, i.e. quadrupoles focus **horizontally**, defocus **vertically** or vice versa.
- A sequence of focusing-defocusing fields provides stronger net focusing force.
- Forces are linearly proportional to displacement from axis.
- Succession of opposed elements enable particles to follow stable trajectories, making small (betatron) oscillations about the design orbit.







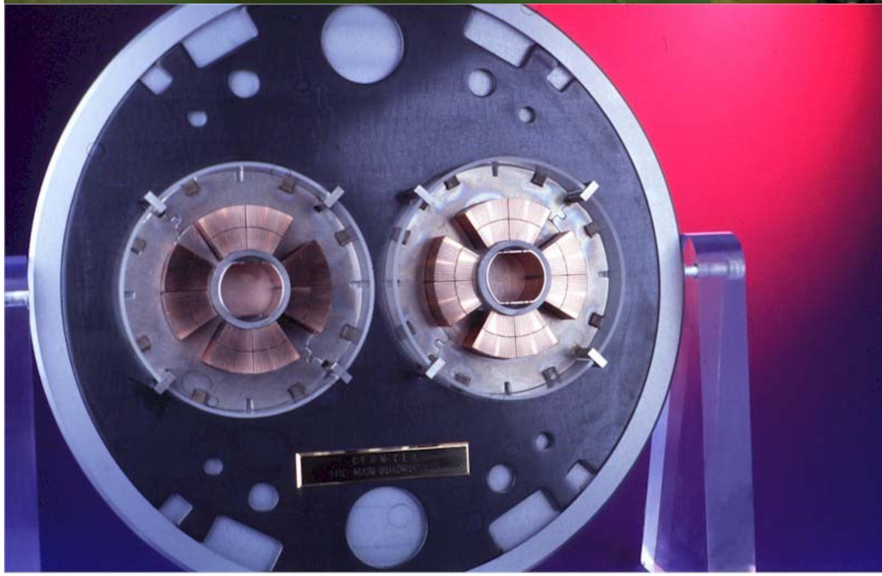



# Synchrotron

- Frequency modulated but also *B*-field increased **synchronously** to match energy and keep revolution radius constant.
- Magnetic field produced by several bending magnets increases with momentum. For high energies:

$$B\rho = \frac{p}{q} \approx \frac{E}{cq} \quad \text{and} \quad E[GeV] \approx 0.3 B\rho[T \cdot m]$$

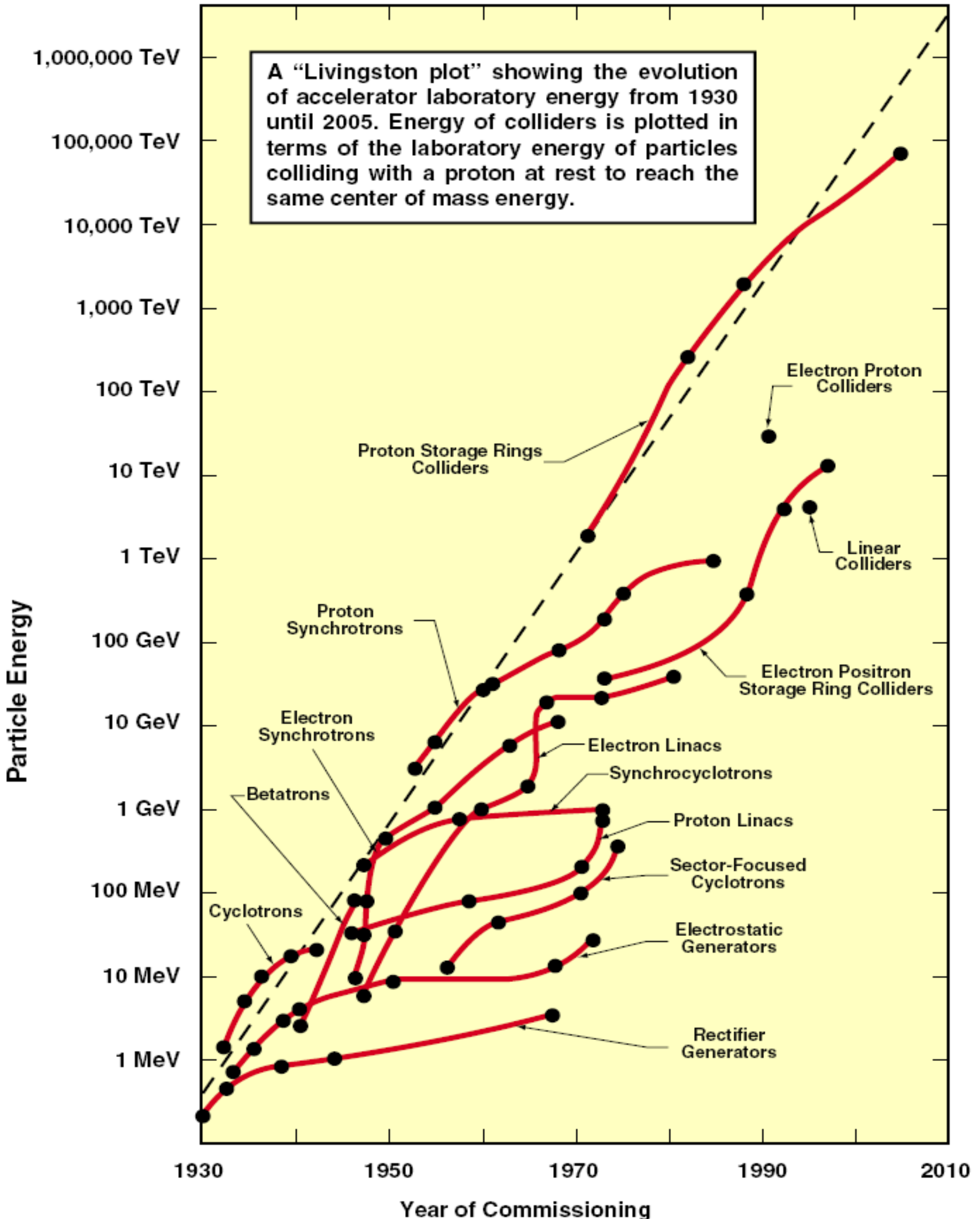
- Practical limitations for magnetic fields => high energies only at large radius
- Need of **super-conducting magnets,** e.g. for the **Large Hadron Collider** (LHC), with energy of **7TeV and** bending radius of **2.9km**, the dipoles need **8T**
- **Storage rings**: accumulate particles and keep circulating for long periods; used for high intensity beams to inject into more powerful machines or synchrotron radiation sources.
- **Colliders**: two beams circulating in opposite directions, made to intersect; maximises energy in centre of mass frame.



# Summary of Circular Machines

| Machine | RF frequency $f$ | Magnetic Field $B$ | Orbit Radius $\rho$ | Comment |
|---|---|---|---|---|
| Cyclotron | constant | constant | increases with energy | Particles out of synch with RF; low energy beam or heavy ions |
| Iso-Cyclotron | constant | varies | increases with energy | Particles in synch, but difficult to create stable orbits |
| Synchro-cyclotron | varies | constant | increases with energy | Stable oscillations |
| Synchrotron | varies | varies | constant | Flexible machine, high energies possible |

# Energy evolution




- Exponential growth of energy with time
- Increase of the energy by an order of magnitude every 6-10 years
- replaces previous one to get even higher energies
- Every new idea evolves up to a point of saturation and than is replaced by new one
- The process continues…
- Energy is not the only interesting parameter
  - Intensity
  - Cross section of the beam