Unit 2 - Lecture 5b
The development of accelerator concepts

William A. Barletta

Director, United States Particle Accelerator School

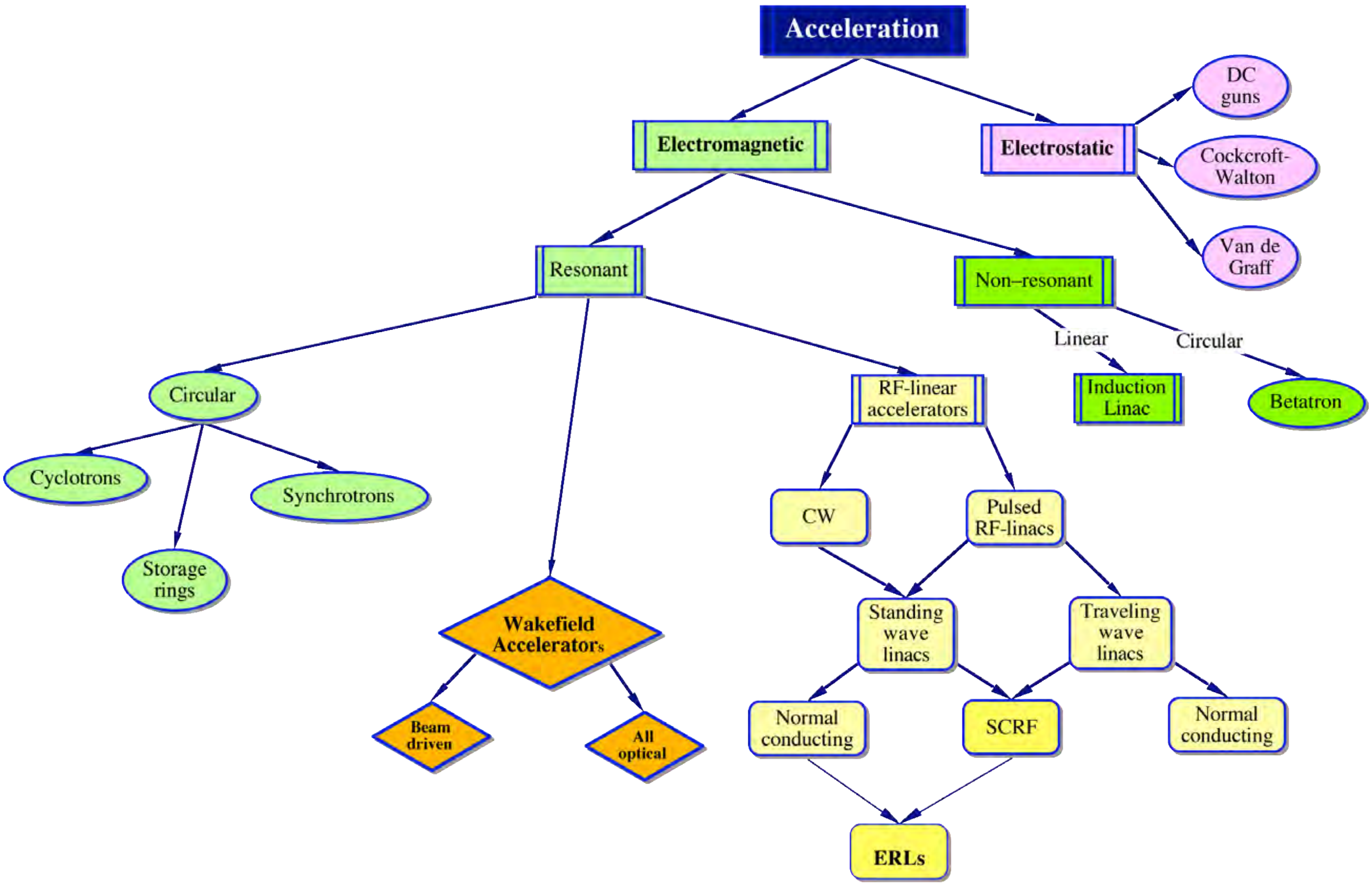
Dept. of Physics, MIT

The history of accelerators is a history of 100 years of invention

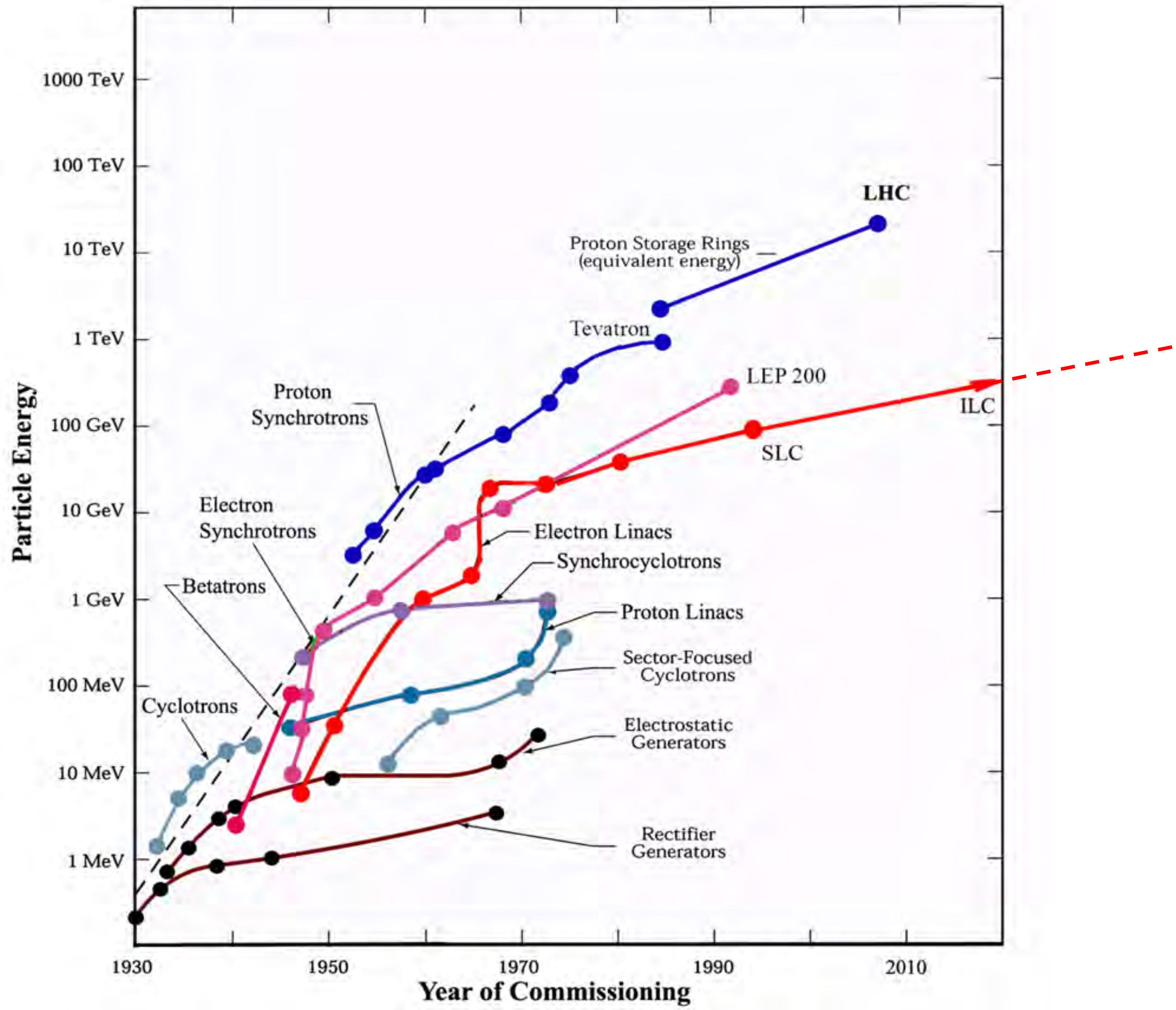
- ***Great principles*** of accelerator physics
  - ➙ phase stability,
  - ➙ strong focusing
  - ➙ colliding beam storage rings;
- ***Dominant accelerator technologies***
  - ➙ superconducting magnets
  - ➙ high power RF production
  - ➙ normal & superconducting RF acceleration
- ***Substantial accomplishments*** in physics & technology
  - ➙ non-linear dynamics, collective effects, beam diagnostics, etc.;
- ***Years of experience*** with operating colliders.
  - ➙ Overcoming performance limits often requires development of sophisticated theories, experiments, or instrumentation

From R. Siemann: SLAC-PUB-7394January 1997

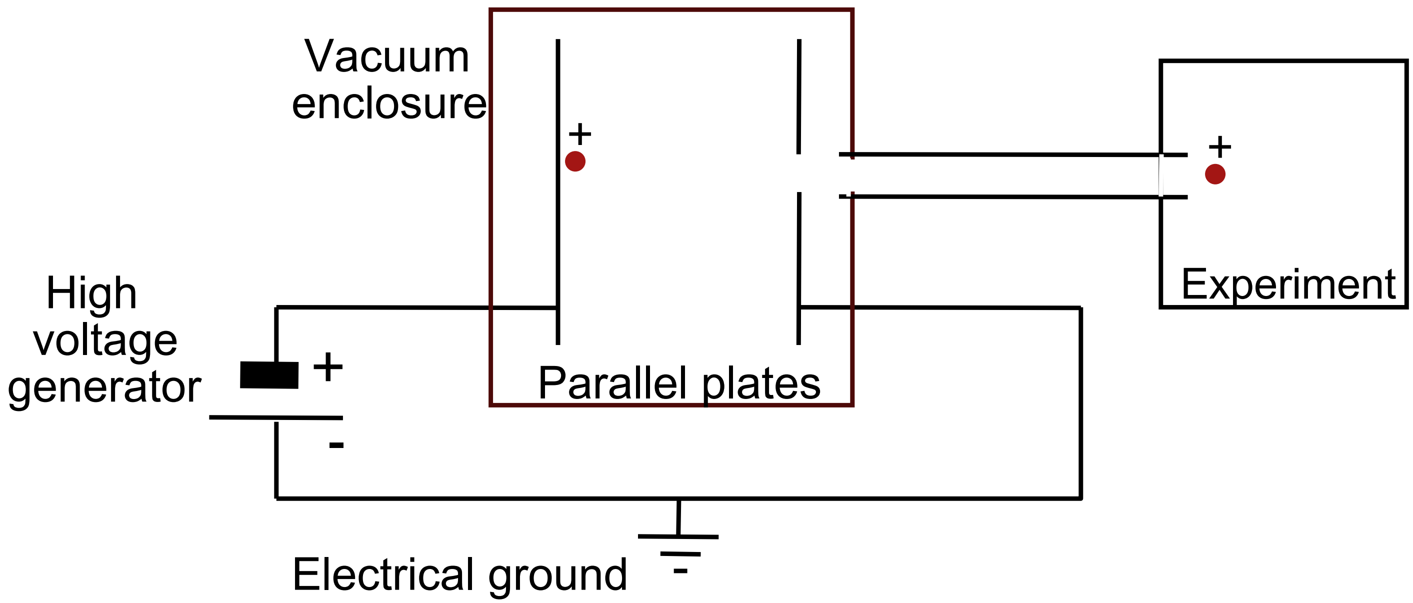
Taxonomy of accelerators



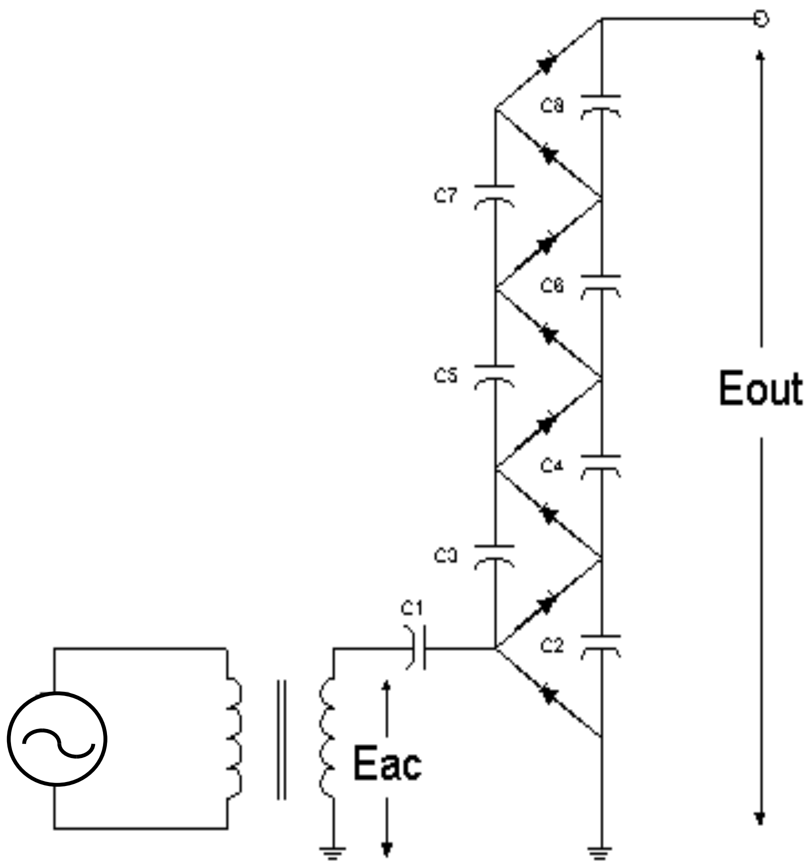
How do we get energy into the beam particles?



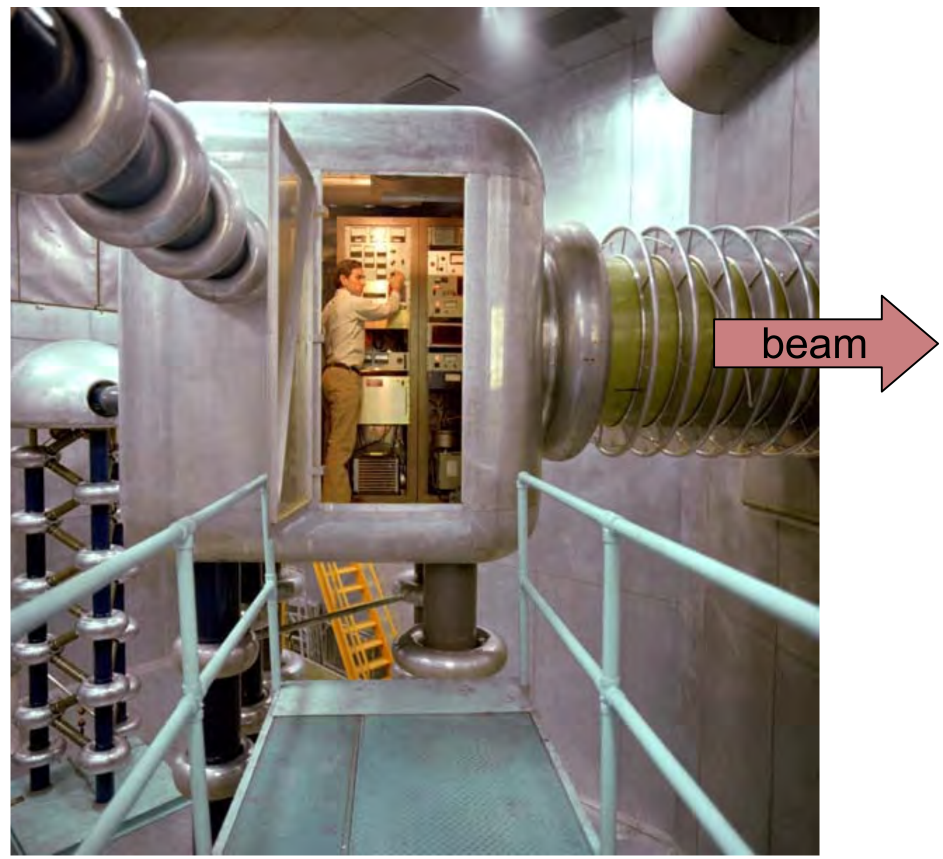
Simple DC (electrostatic) accelerator



Crockroft Walton
high voltage dc accelerator column

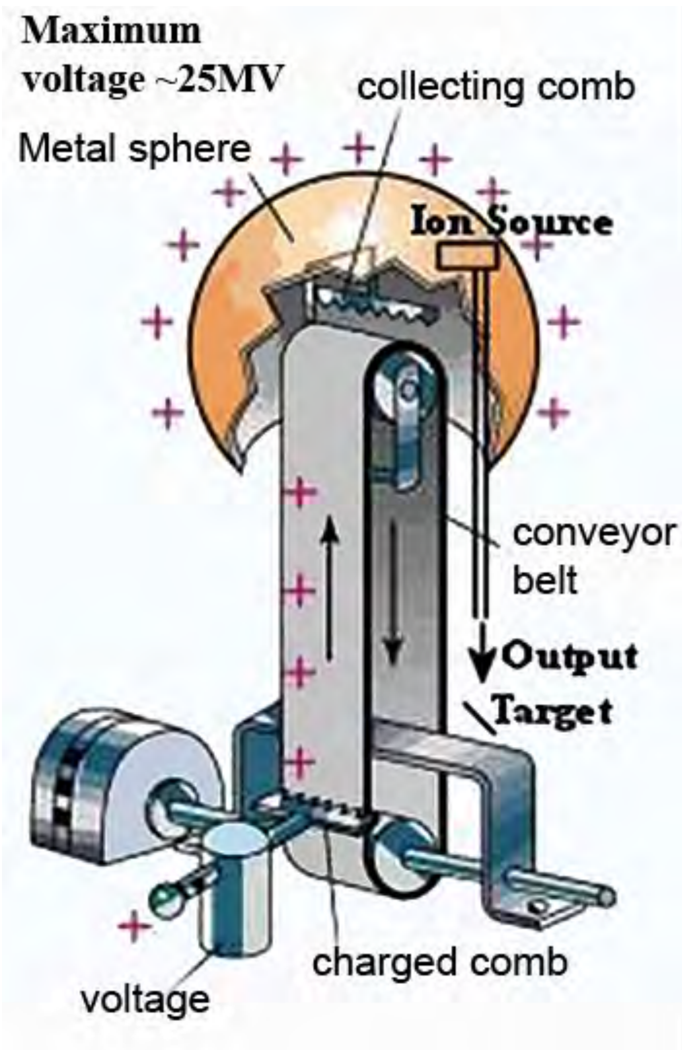


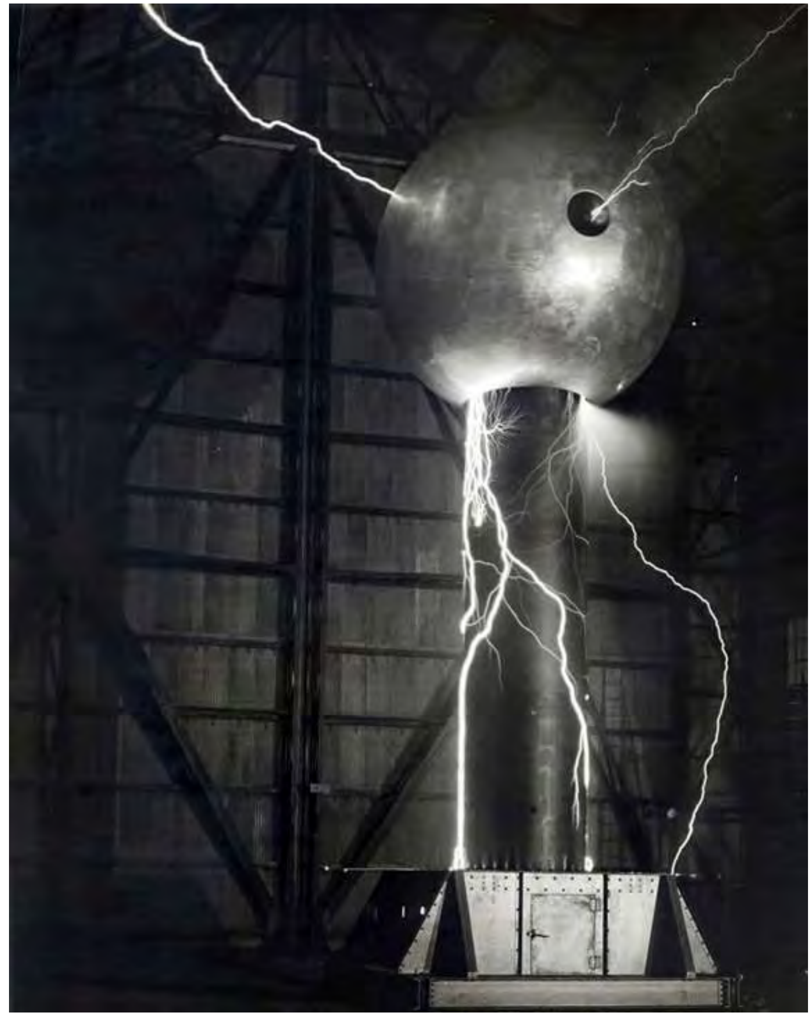
$$E_{out} = N_{stage} E_{ac}$$



Crockroft-Walton at FNAL accelerates H^- to 750keV

Van de Graaff generators

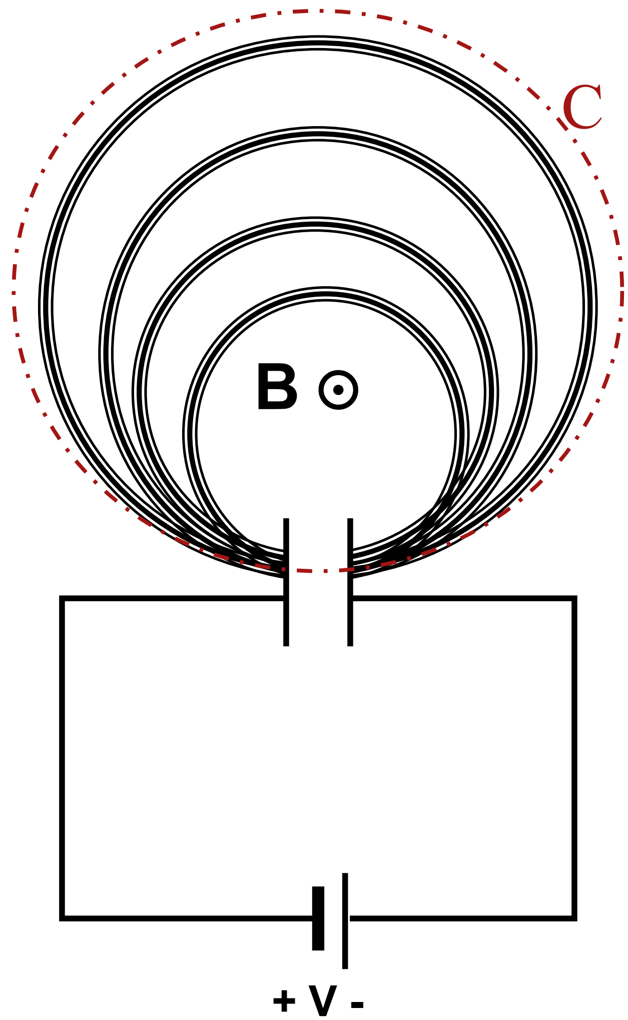




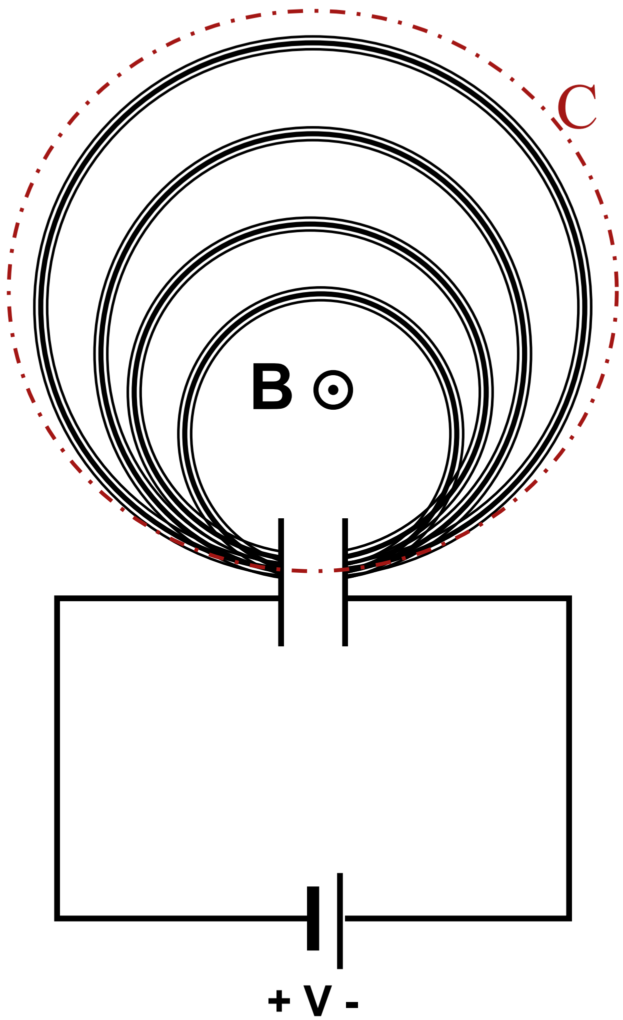
Van de Graaff's generator a Round Hill MA

Why do we need RF structures & fields?

Possible DC accelerator?



Maxwell forbids this!



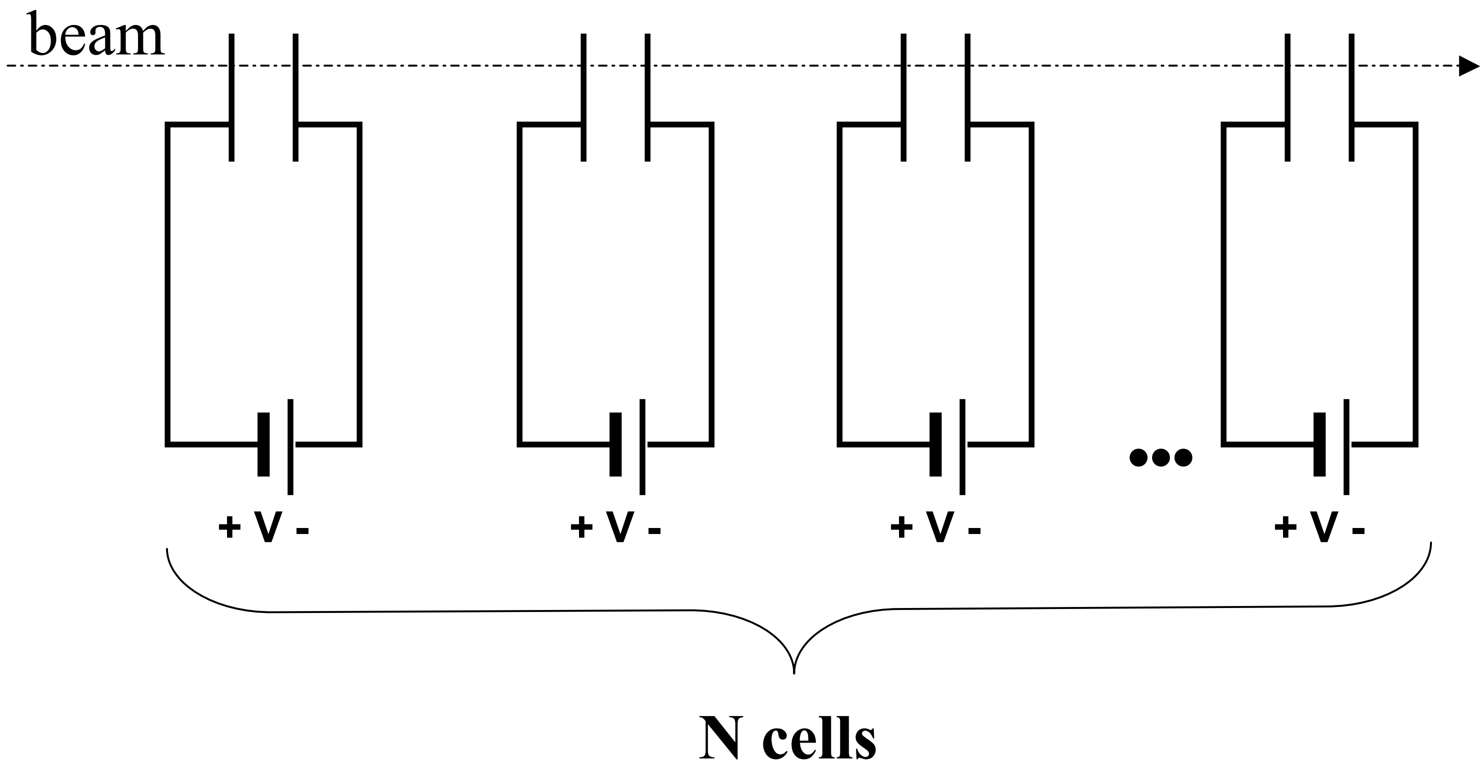
$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$$

or in integral form

$$\oint_C \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial}{\partial t} \int_S \mathbf{B} \cdot \mathbf{n} \, da$$

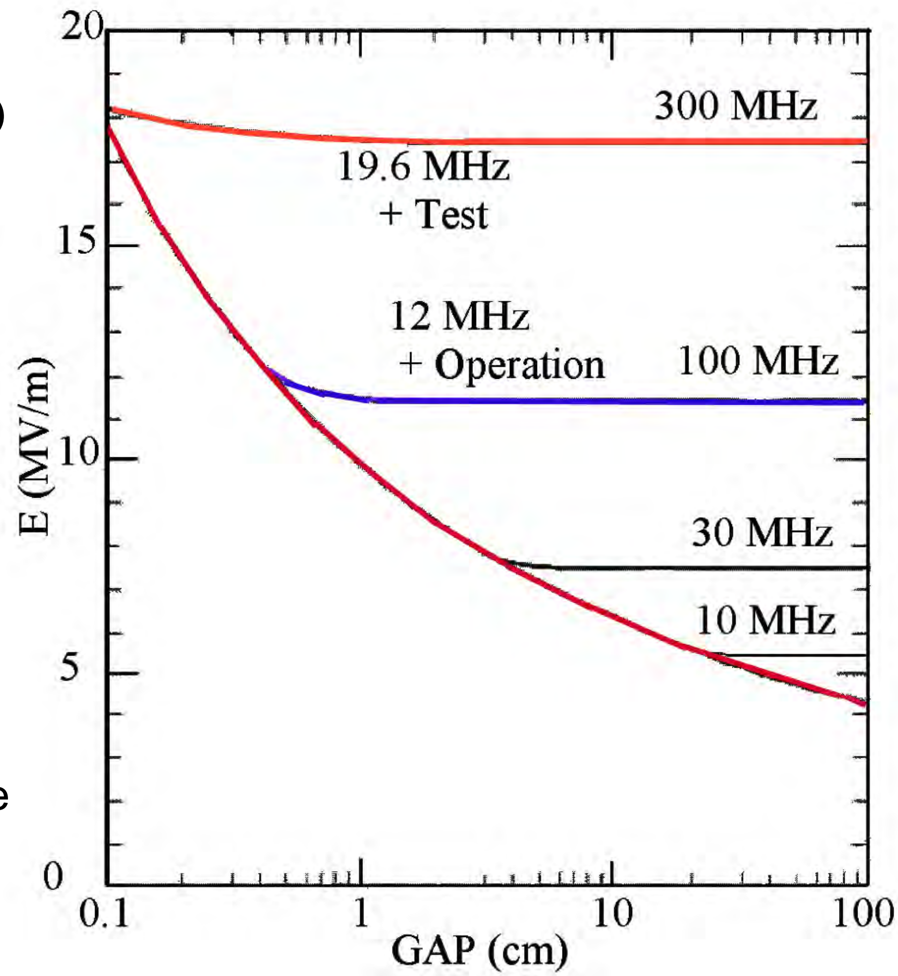
∴ There is no acceleration without time-varying magnetic flux

What is final energy of the beam?



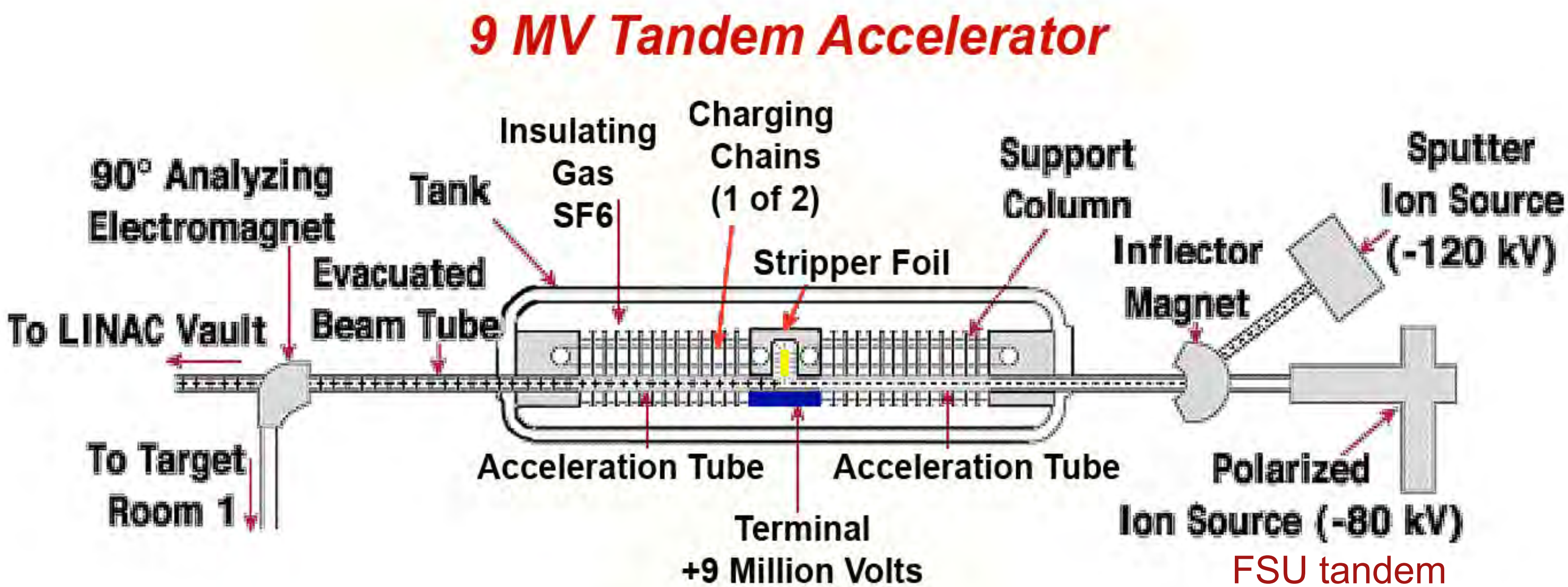
Characteristics of DC accelerators

- Voltage limited by electrical breakdown (~10 kV/cm)
  - → High voltage
    - ==> Large size (25 m for 25 MV)
  - → Exposed high voltage terminal
    - ==> Safety envelope
- High impedance structures
  - → Low beam currents
- Generates continuous beams



Sparking electric field limits in the Kilpatrick model, including electrode gap dependence

The Tandem "Trick"



Change the charge of the beam from - to + at the HV electrode

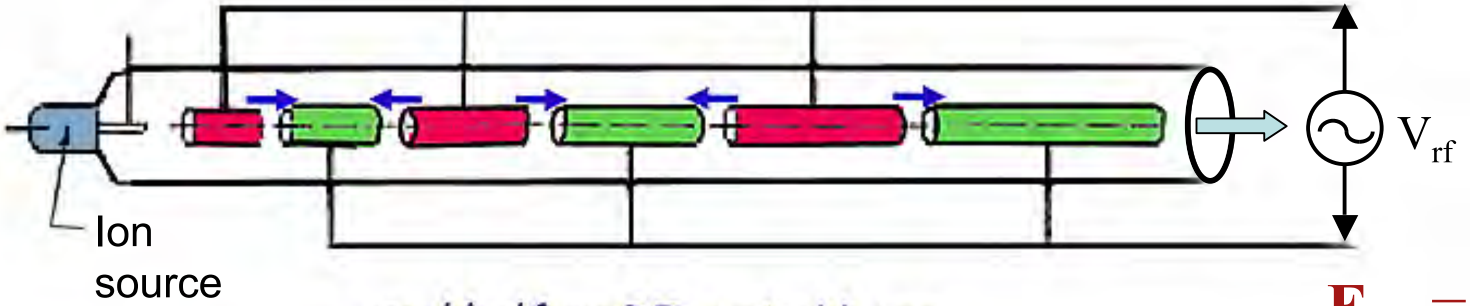
Inside the Tandem van de Graaff at TUNL (Duke University)

Practical RF accelerators

RF voltage generators allow higher energies in smaller accelerators

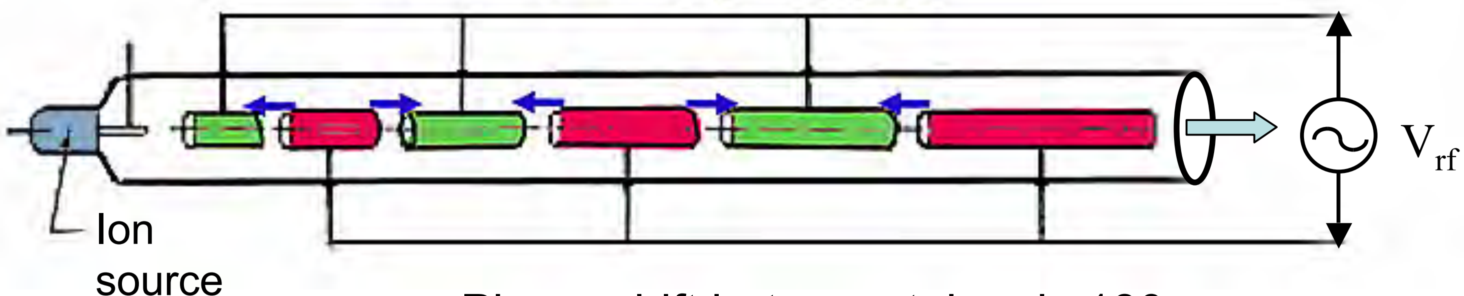
- Beam duration must be a small fraction of an rf-cycle
- Gap should be a small fraction of an rf-wavelength
- No very high voltage generator
- No exposed HV hazard
- High voltage beam obtained by replicated structure

The ion linac (Wideroe)



... and half an RF period later

$$E_{tot} = N_{gap} \bullet V_{rf}$$

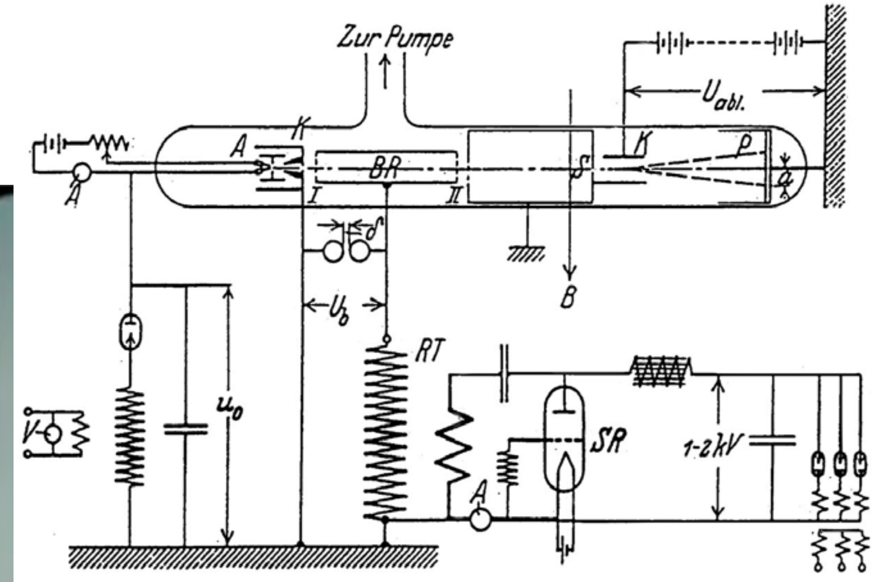


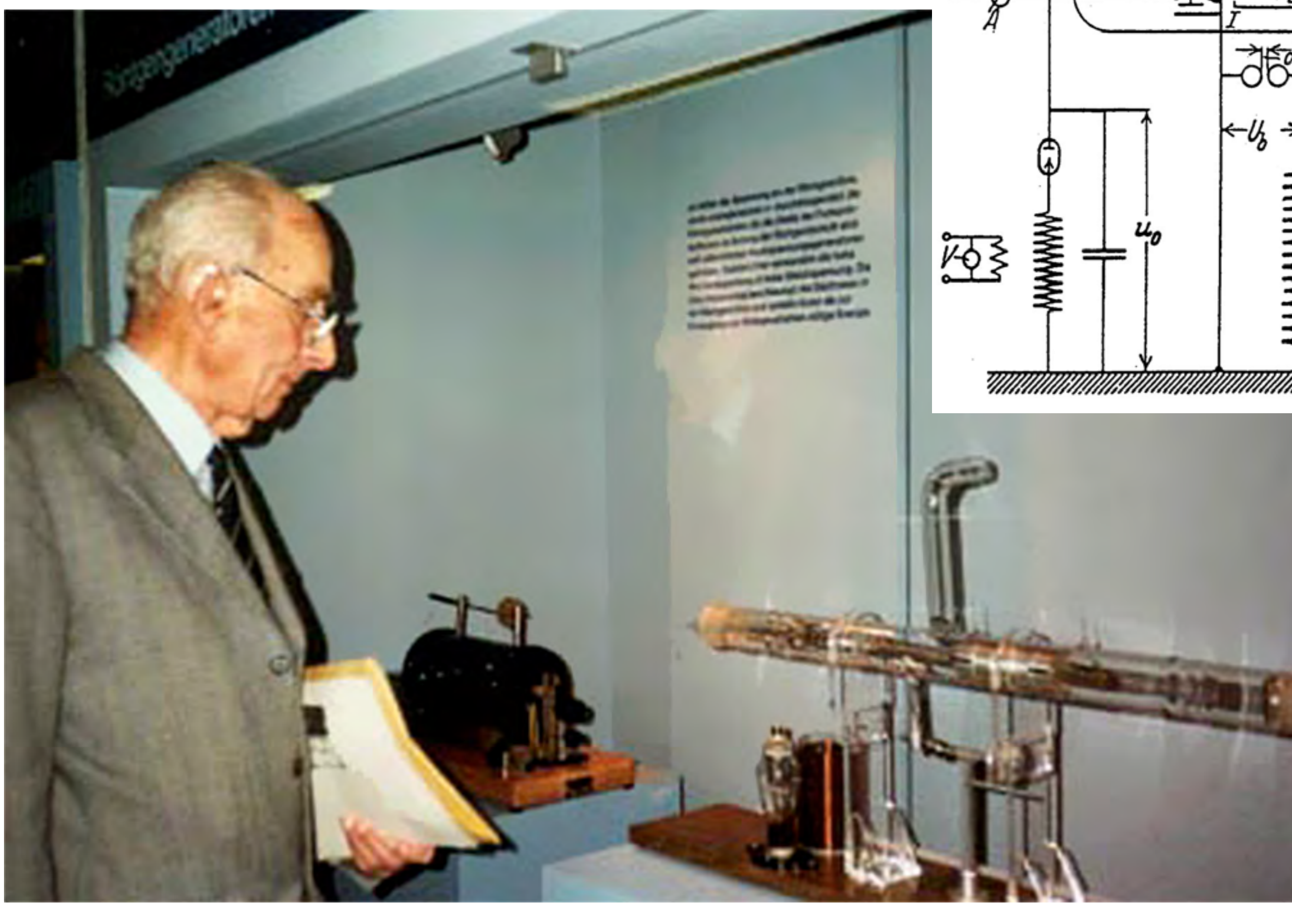
Phase shift between tubes is 180°

As the ions increase their velocity, drift tubes must get longer

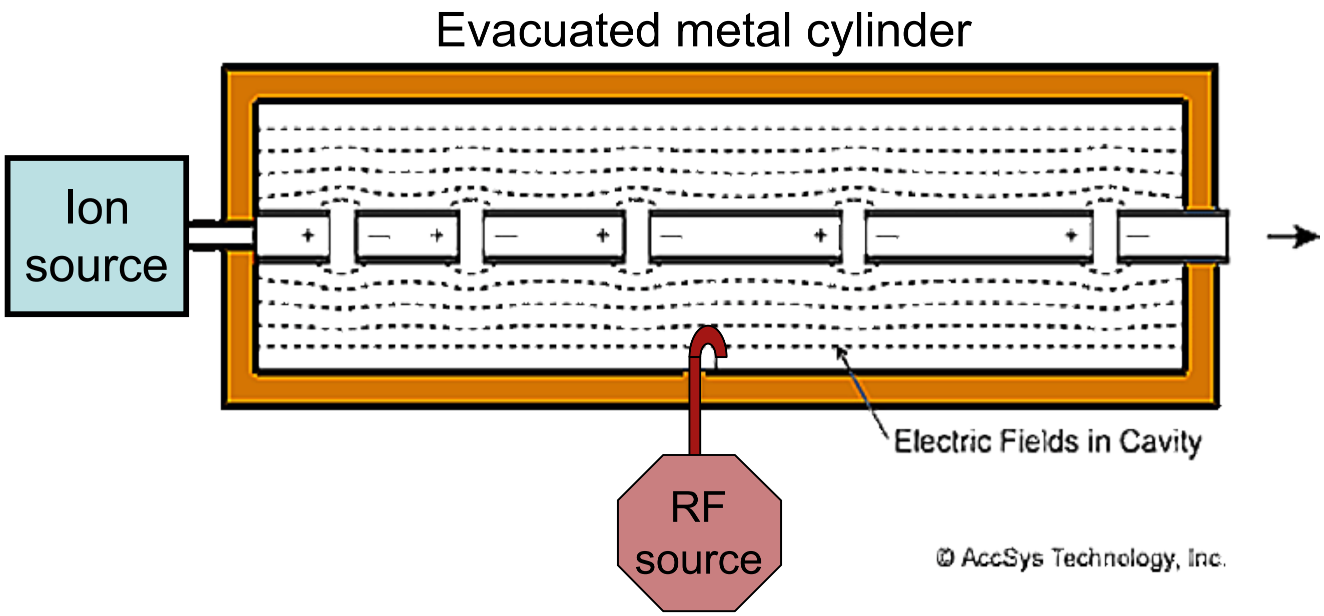
$$L_{drift} = \frac{1}{2}\frac{v}{f_{rf}} = \frac{1}{2}\frac{\beta c}{f_{rf}} = \frac{1}{2}\beta\lambda_{rf}$$

Wiederoe and his linac: A missed Nobel prize





Alvarez linac

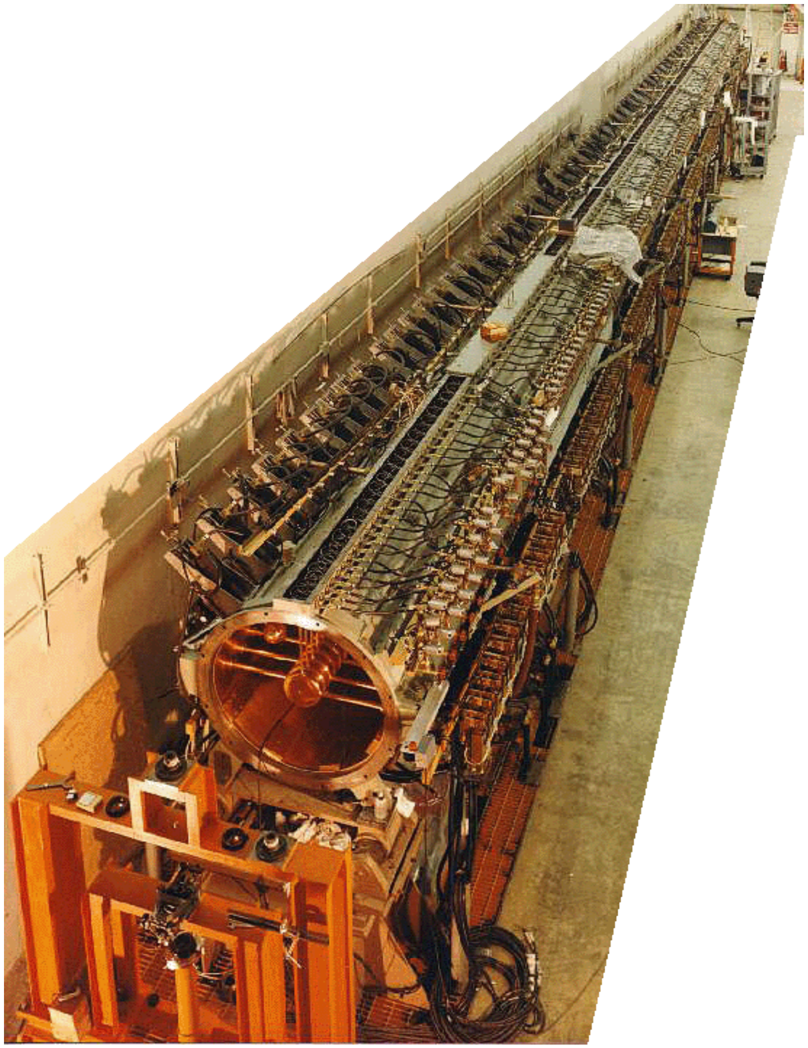


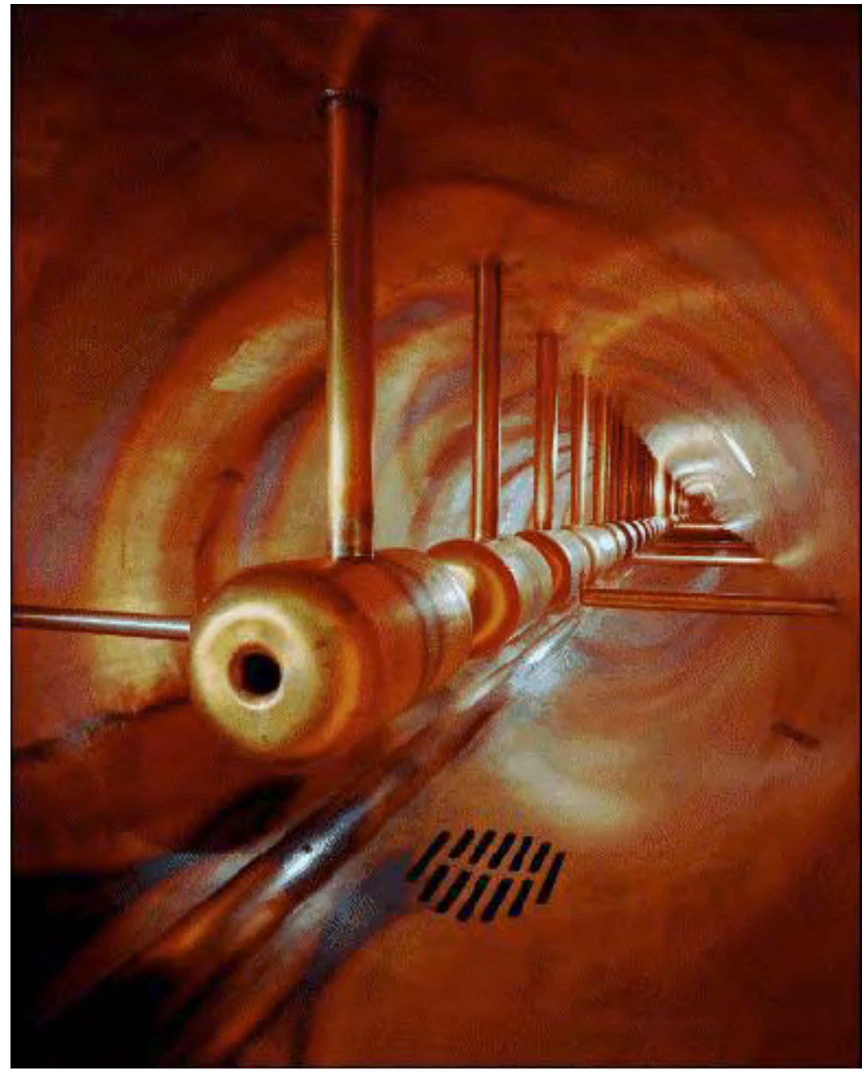
Alternate drift tubes are not grounded (passive structures)
==> phase shift between tubes is 360°

$$L_{drift} = \beta\lambda_{rf}$$

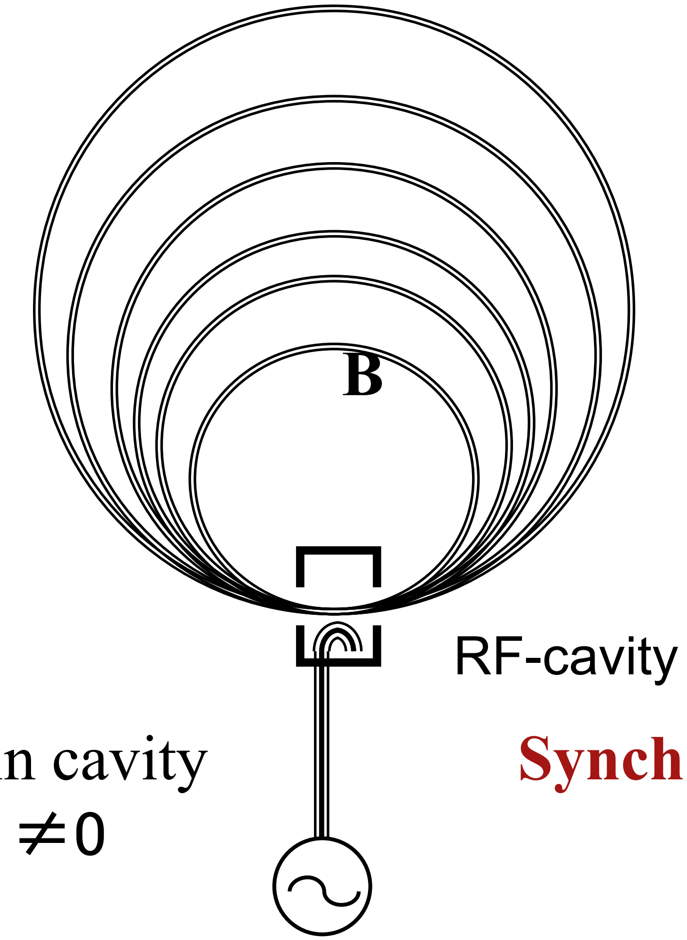
N.B. The outside surface is at ground potential

The Alvarez linac





Linac size is set by E_{gap}; why not one gap? Microtron

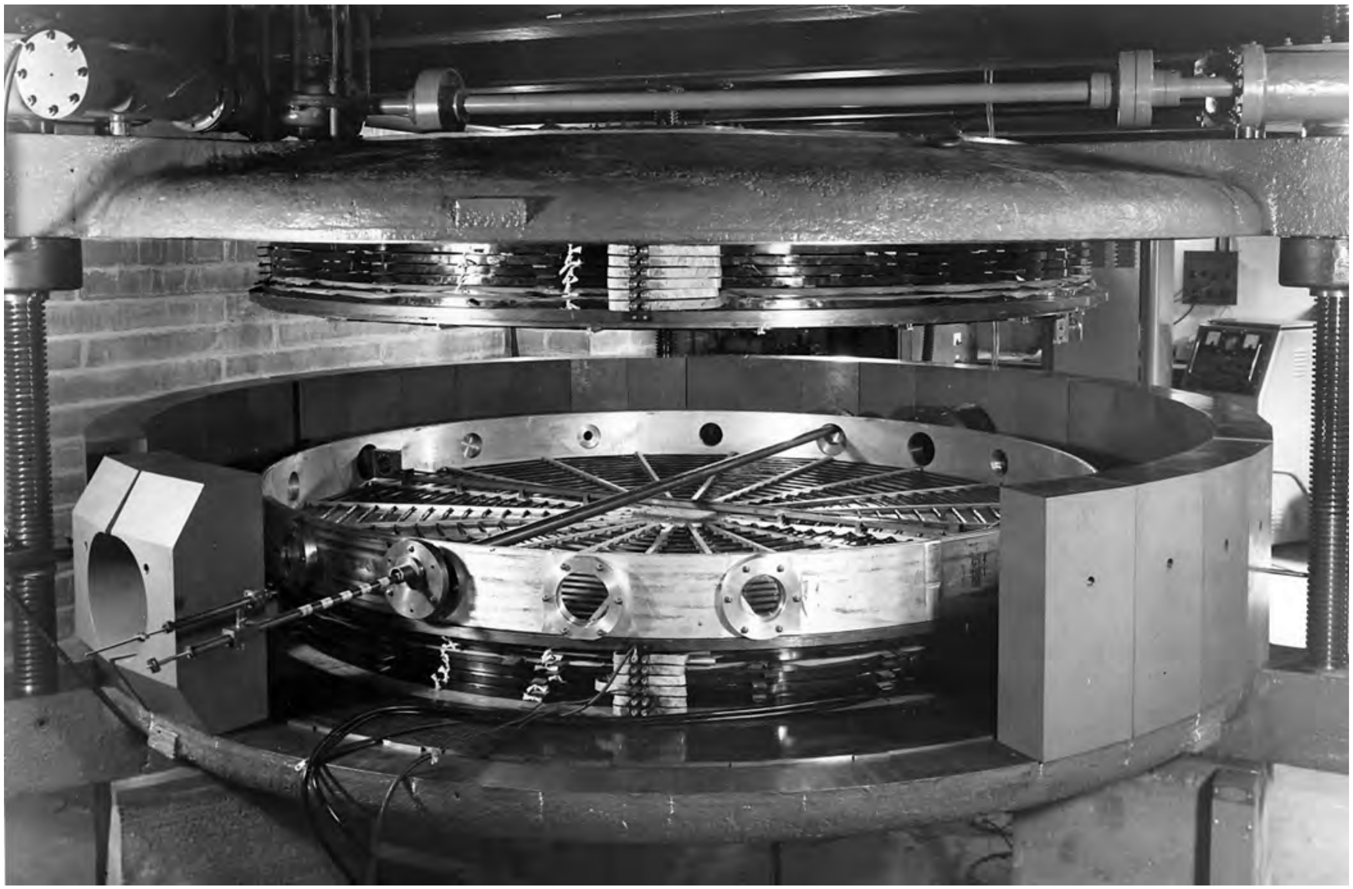


Note that in cavity
dB/dt ≠0

Synchronism condition:

$\Delta\tau_{rev} = N/f_{rf}$

28 MeV Microtron at HEP Laboratory University College London



Synchronism in the Microtron

$$\frac{1}{r_{orbit}} = \frac{eB}{pc} = \frac{eB}{mc^2\beta\gamma}$$

$$\tau_{rev} = \frac{2\pi r_{orbit}}{v} = \frac{2\pi r_{orbit}}{\beta c} = \frac{2\pi\, mc}{e}\frac{\gamma}{B}$$

Synchronism condition: $\Delta\tau_{rev} = N/f_{rf}$

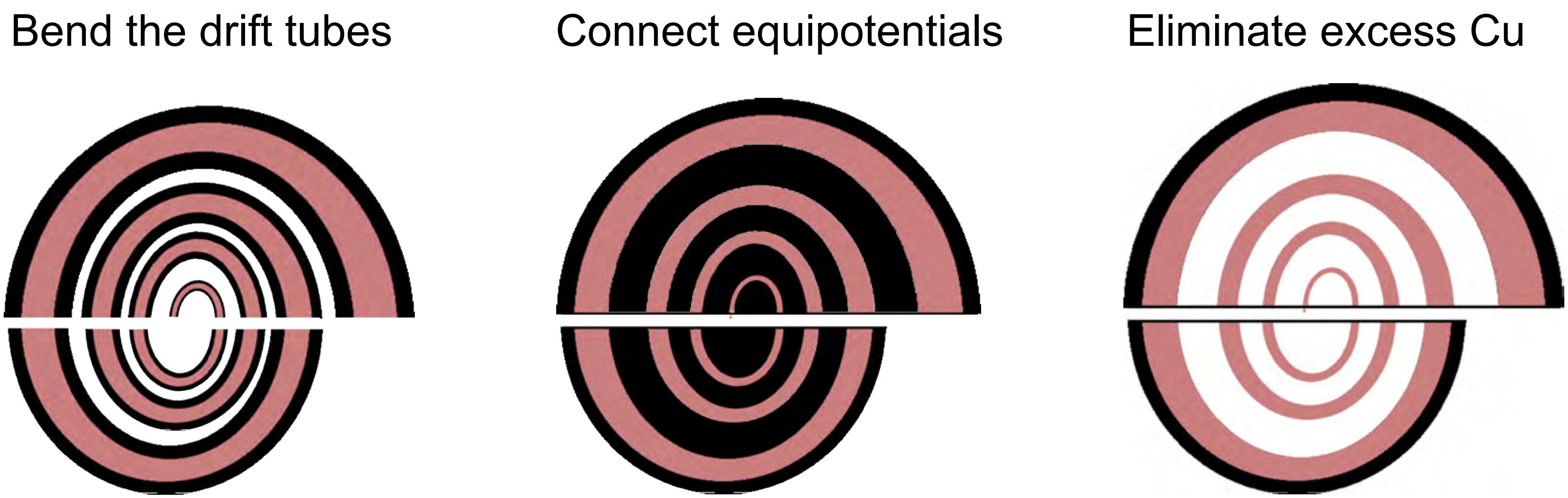
$$\Delta\tau = \frac{N}{f_{rf}} = \frac{2\pi\, mc}{e}\frac{\Delta\gamma}{B} = \frac{\Delta\gamma}{f_{rf}}$$

If N = 1 for the first turn @ $\gamma \sim 1$

Or $\Delta\gamma = 1 \Longrightarrow E_{rf} = mc^2$

Possible for electrons but not for ions

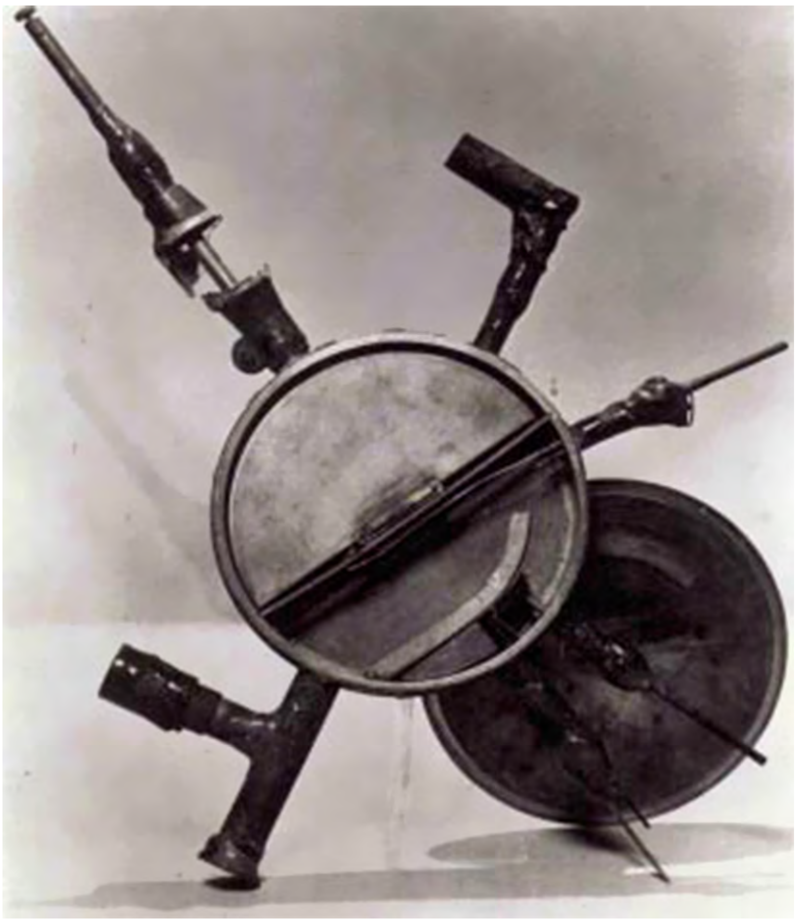
But long as $\gamma \approx 1$, $\tau_{rev} \approx$ constant! Let's curl up the Wiederoe linac

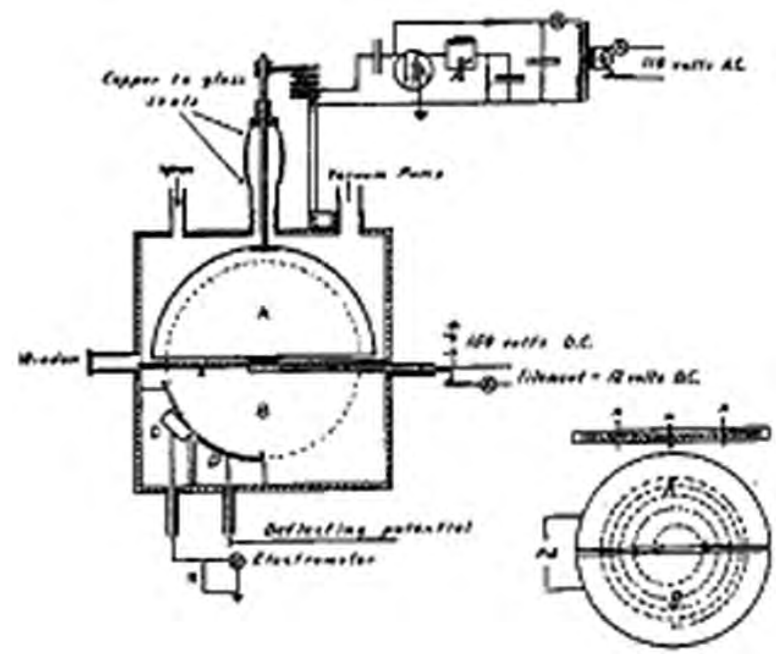


Supply magnetic field to bend beam

$$\tau_{rev} = \frac{1}{f_{rf}} = \frac{2\pi\, mc}{eZ_{ion}} \frac{\gamma}{B} \approx \frac{2\pi\, mc}{eZ_{ion} B} = const.$$

And we have…

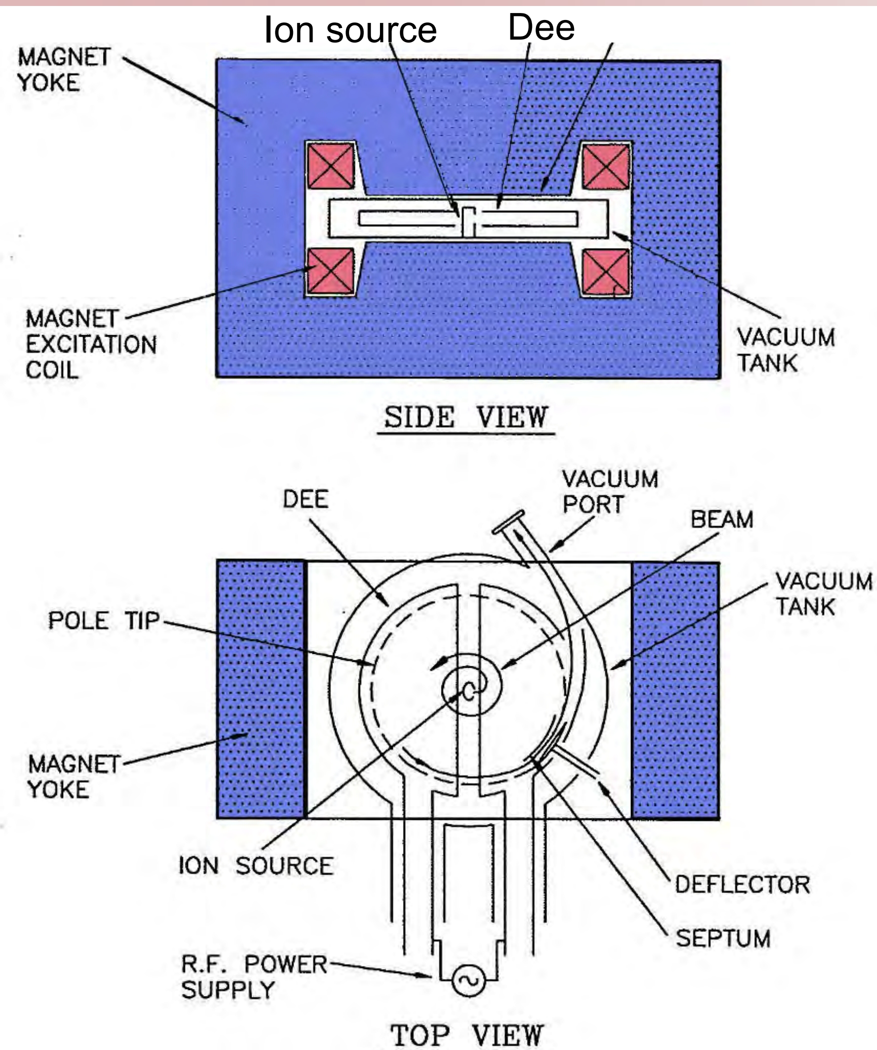


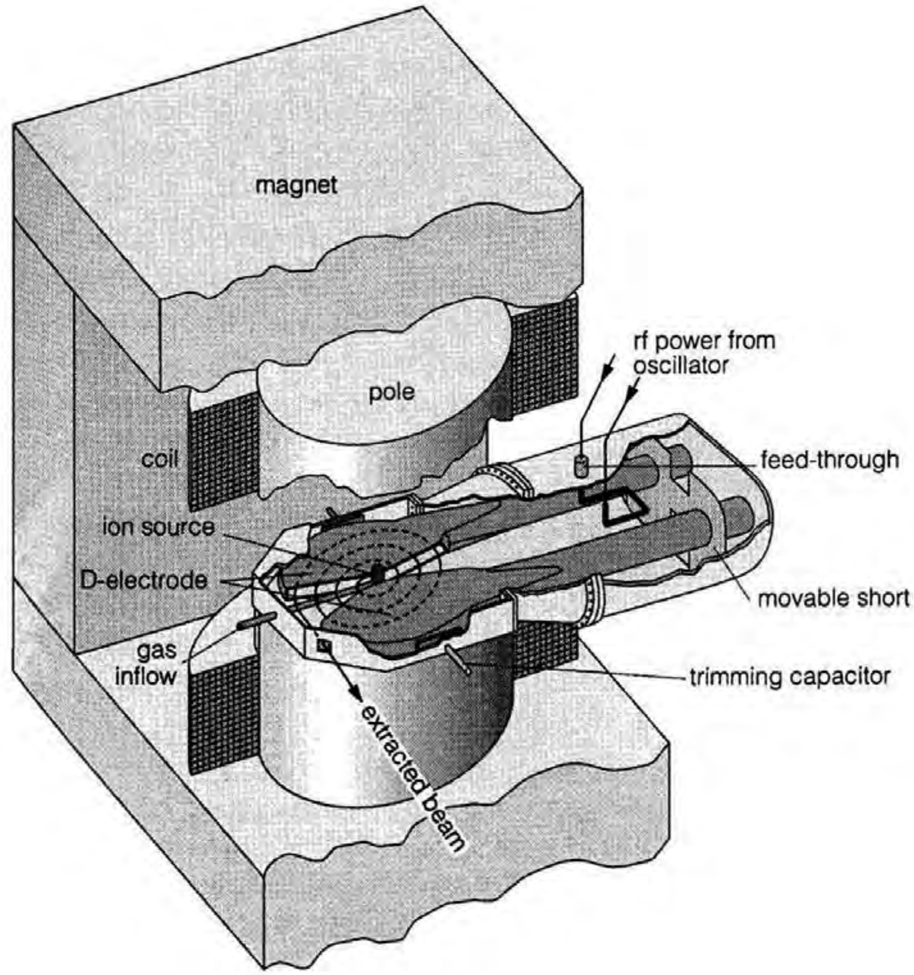


Lawrence, E.O. and Sloan, D.: Proc. Nat. Ac. Sc., 17, 64 (1931)

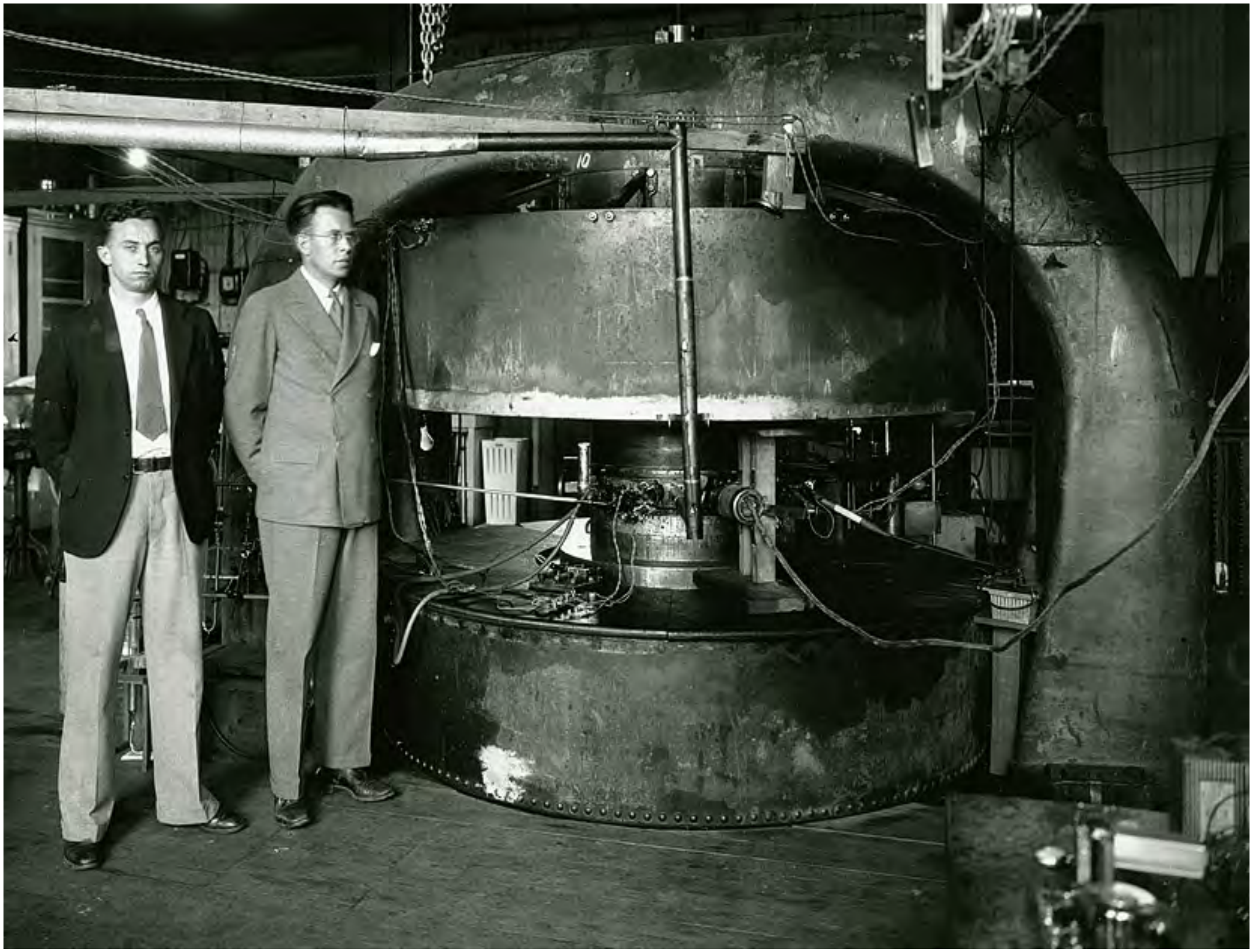
Lawrence, E.O. & Livingstone M.S.: Phys. Rev 37, 1707 (1931).

The classic cyclotron

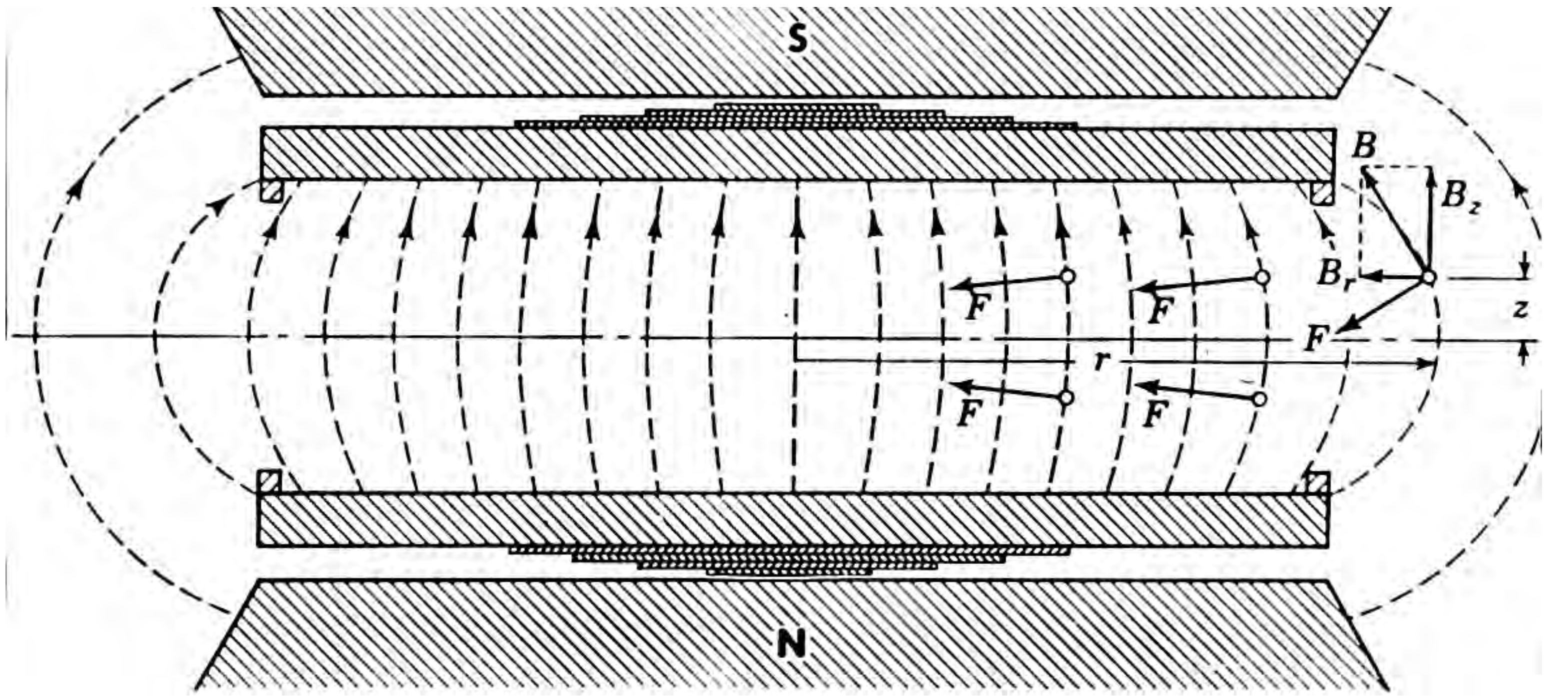




E.O. Lawrence & the 25-inch cyclotron



The flux of particles was low until McMillan did something "strange"



The shims distorted the field to restore wayward particles to the midplane
==> Vertical focusing

This approach works well until we violate the synchronism condition

- Recall that

Synchronism condition: $\Delta\tau_{rev} = N/f_{rf}$

and

$$\tau_{rev,o} = \frac{2\pi\, mc}{e}\frac{\gamma}{B} \approx \frac{2\pi\, mc}{eB}$$

- What do we mean by violate?
  - ➙ Any generator has a bandwidth Δf_{rf}

- Therefore, synchronism fails when

$$\tau_{rev,n} - \tau_{rev,o} = \frac{2\pi\, mc}{e}\frac{(\gamma_n - 1)}{B} \approx \Delta f_{rf}$$

One obvious way to fix this problem is to change f_{rf} ==> the synchro-cyclotron

- Keeping B = constant, to maintain synchronism

$$f_{rf} \sim 1/\gamma(t)$$

- The energy for an ion of charge Z follows from $\frac{1}{r} = \frac{ZeB}{cp}$

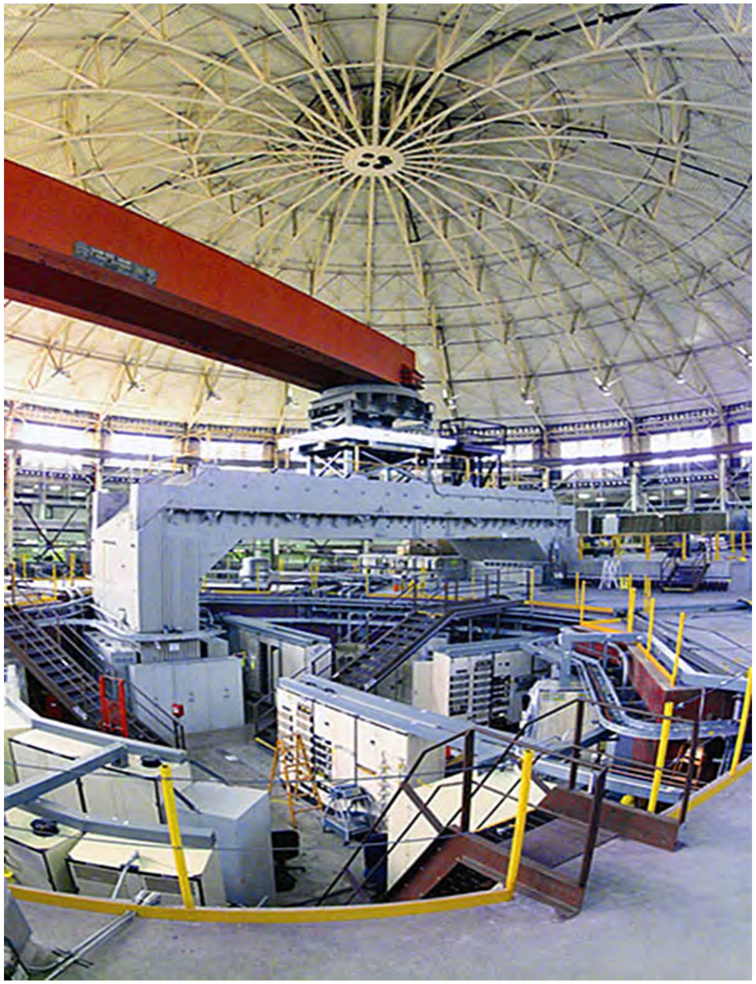
184-in cyclotron

R_{max} = 2.337 m
B = 1.5 T
M_{yoke} ≈ 4300 tons !!

For equal focusing in both planes

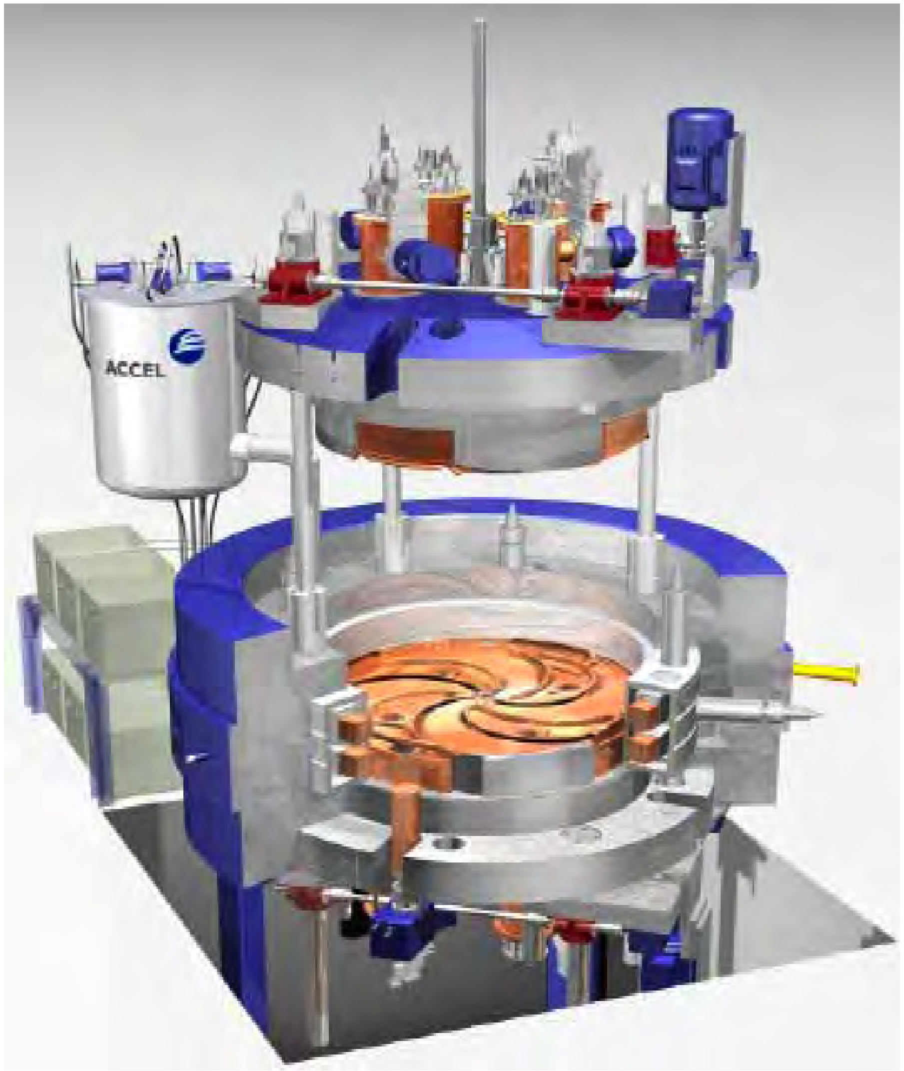
$$B_y(r) \sim \frac{1}{\sqrt{r}}$$

Just how large is a 4300 ton yoke?

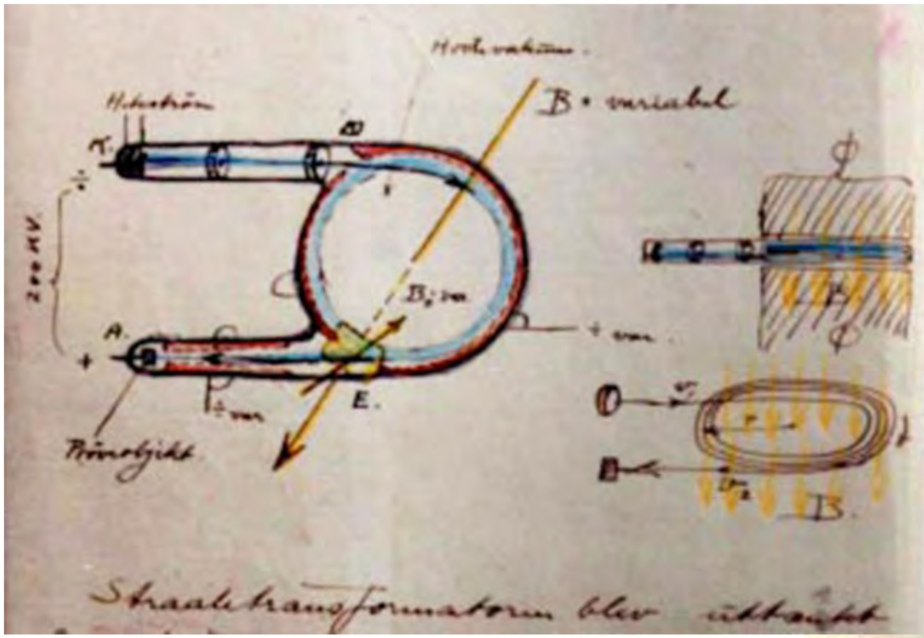


…and what about ultra-relativistic particles?

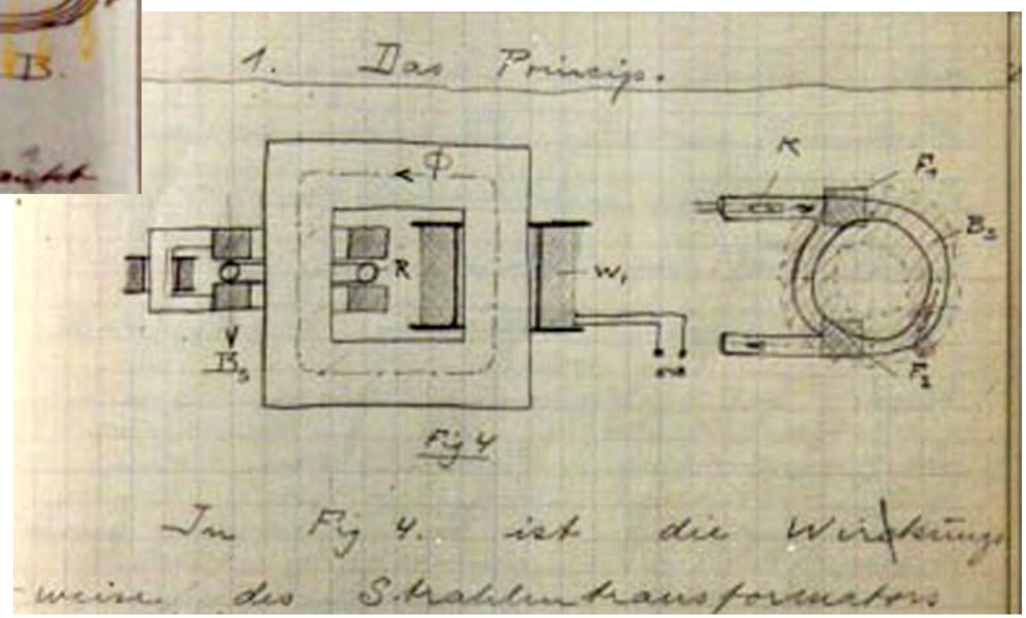
Cyclotrons for radiation therapy



Wiederoe’s Ray Transformer for electrons



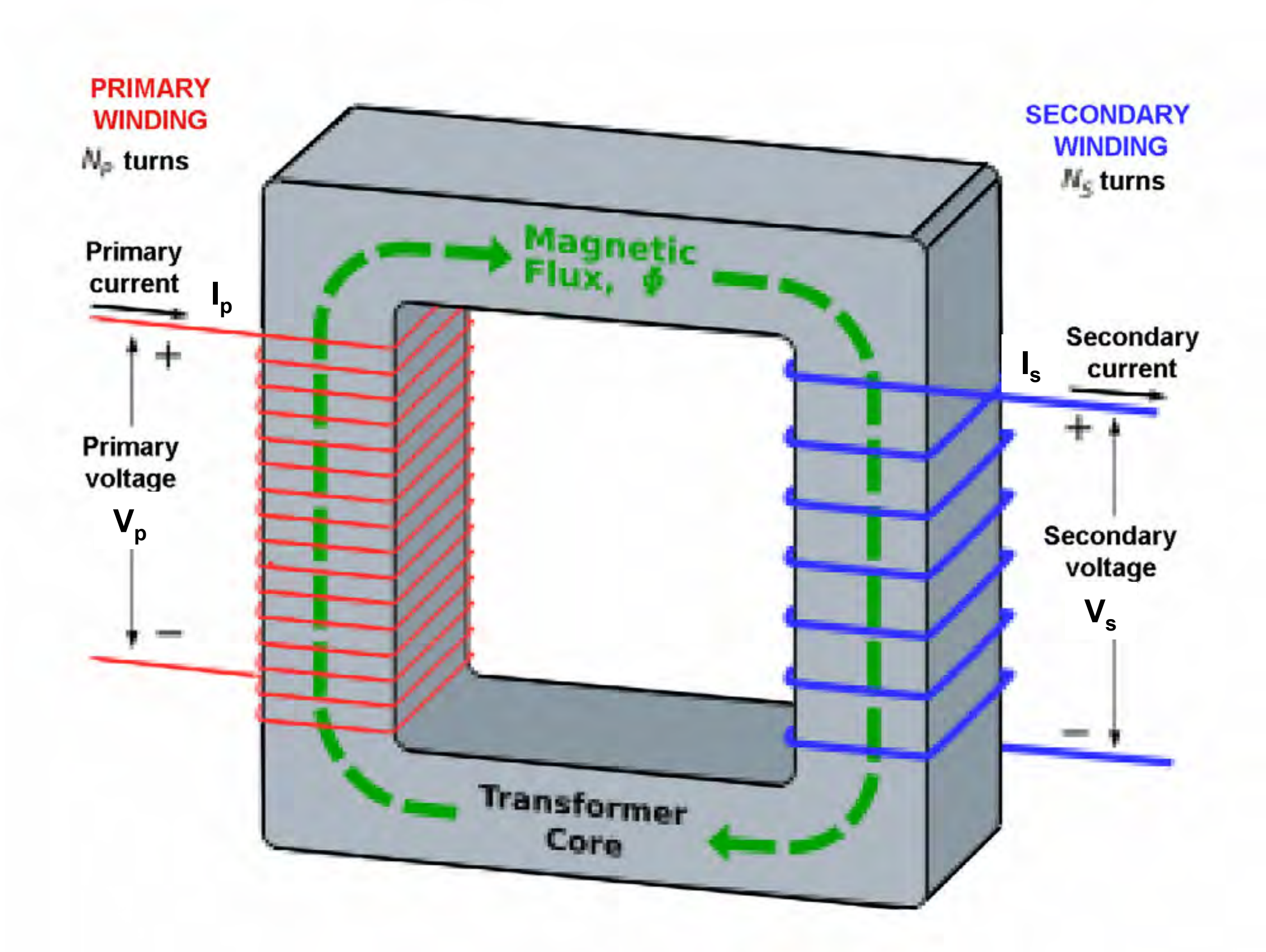
From Wiederoe’s notebooks (1923-’28)



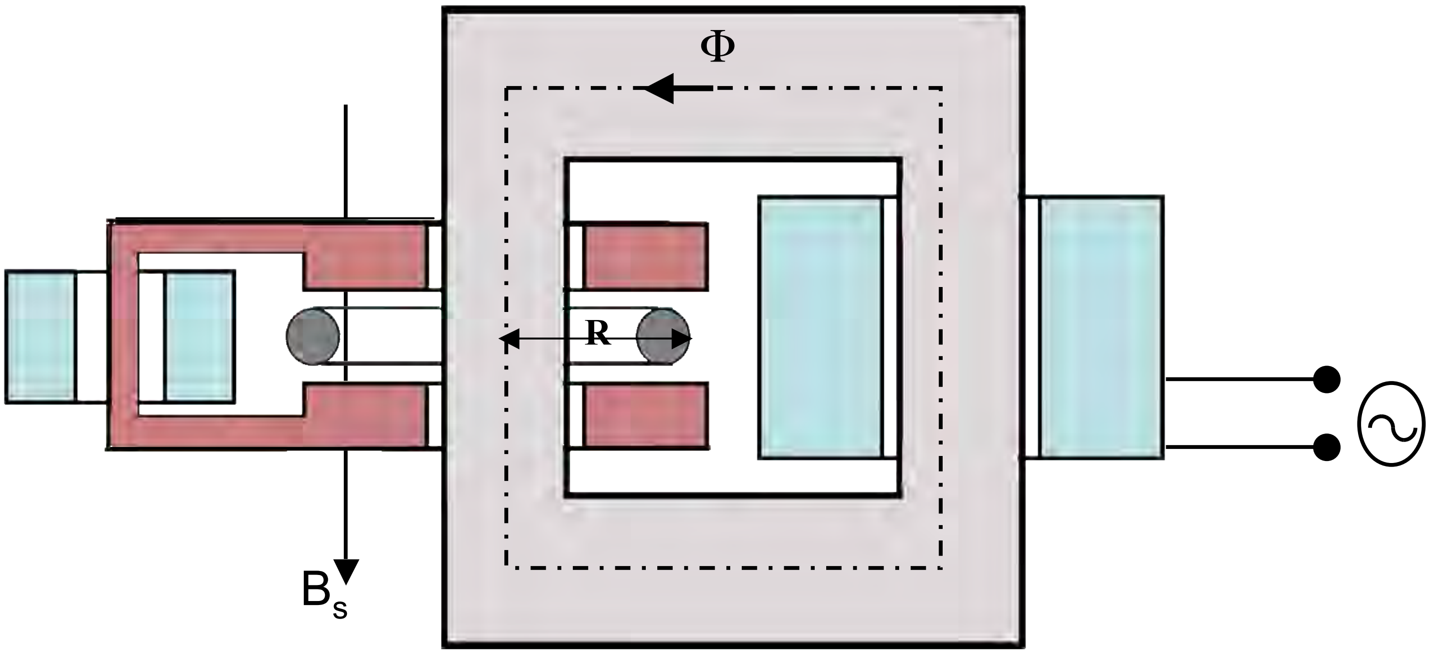
He was dissuaded by his professor from building the ray transformer due to worries about beam-gas scattering

Let that be a lesson to you!

Transformer basics



The ray transformer realized as the Betatron (D. Kerst, 1940)



The beam acts as a 1-turn secondary winding of the transformer

Magnetic field energy is transferred directly to the electrons

Betatron as a tranformer

- Ampere's law

$$2\pi R E_\vartheta = -\frac{d}{dt}\Phi = -\dot{\Phi}$$

- Radial equilibrium requires

$$\frac{1}{R} = \frac{eB_s}{pc}$$

- Newton's law

$$\dot{p} = eE_\vartheta = \frac{e\dot{\Phi}}{2\pi R}$$

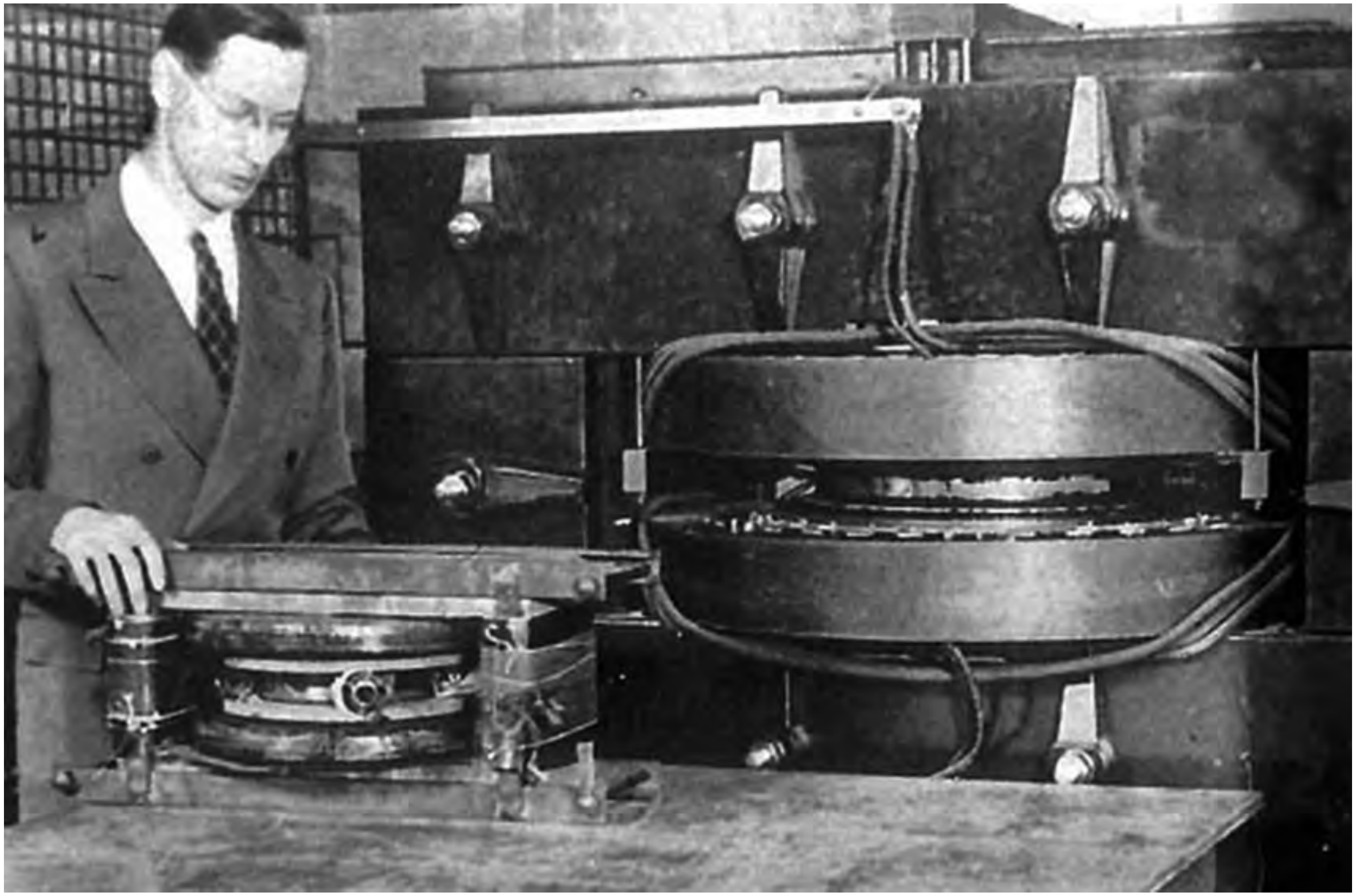
For the orbit size to remain invariant:

$$\frac{1}{R} = \frac{eB_s}{pc} \Rightarrow -\frac{1}{R^2}\frac{dR}{dt} = \frac{e}{c}\left(\frac{\dot{B}_s}{p} - \frac{B_s}{p^2}\dot{p}\right) = 0$$

$$\Rightarrow \dot{p} = \frac{\dot{B}_s}{B_s} p \Rightarrow \frac{e\dot{\Phi}}{2\pi R} = \frac{\dot{B}_s}{B_s} p$$

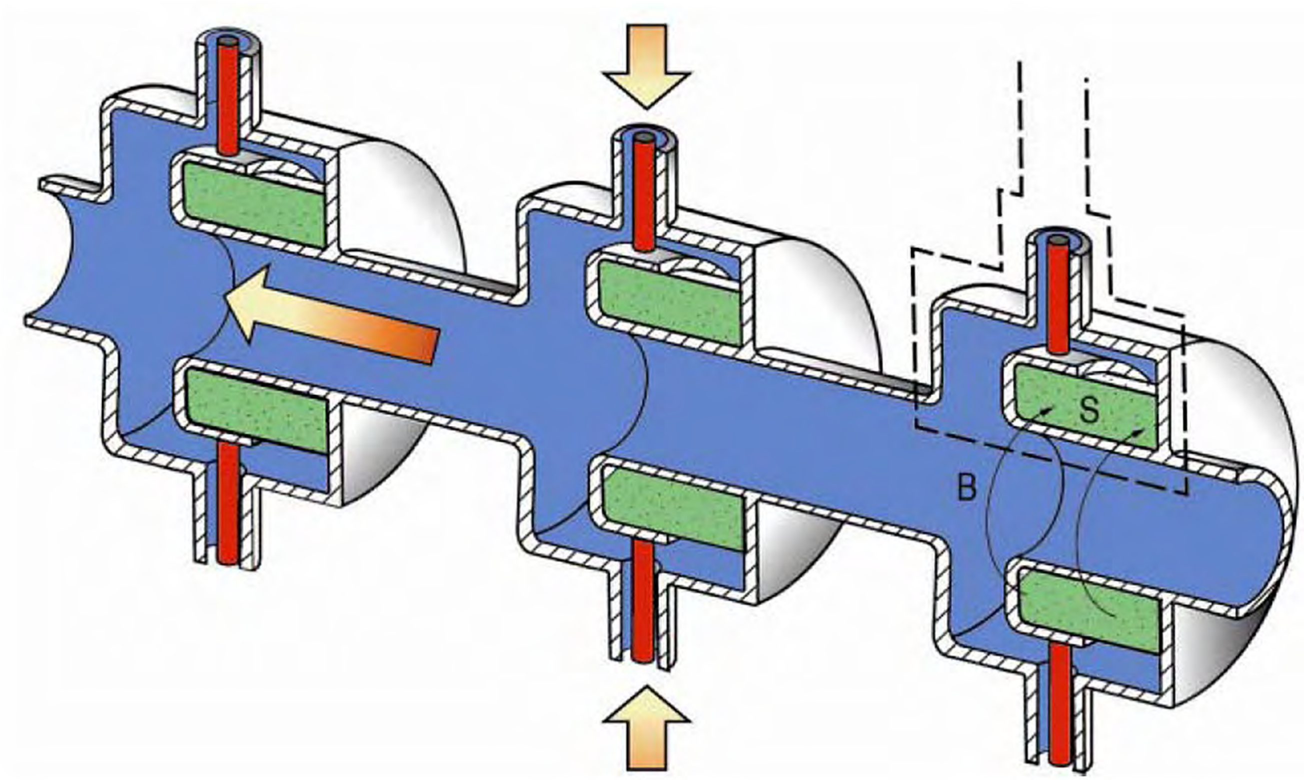
$$\boxed{\dot{\Phi} = 2\pi R^2 \dot{B}_s}$$

Donald Kerst's betatrons



Kerst originally used the phrase, Induction Accelerator

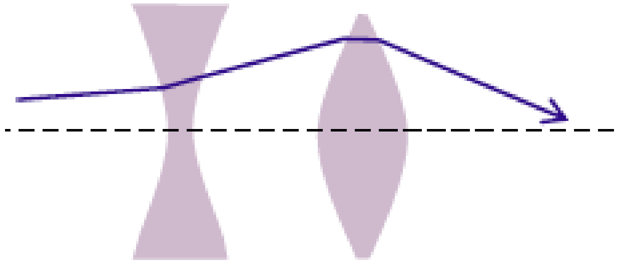
The Linear Betatron: Linear Induction Accelerator



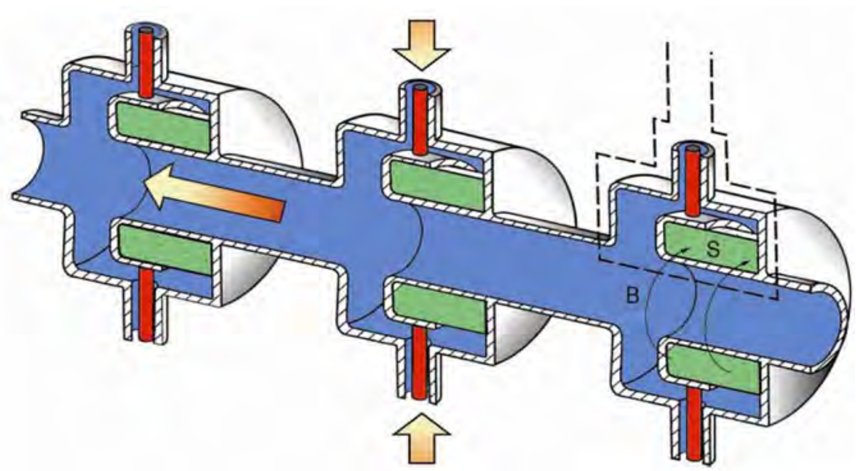
N. Christofilos

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial}{\partial t} \int_S \mathbf{B} \cdot d\mathbf{s}$$

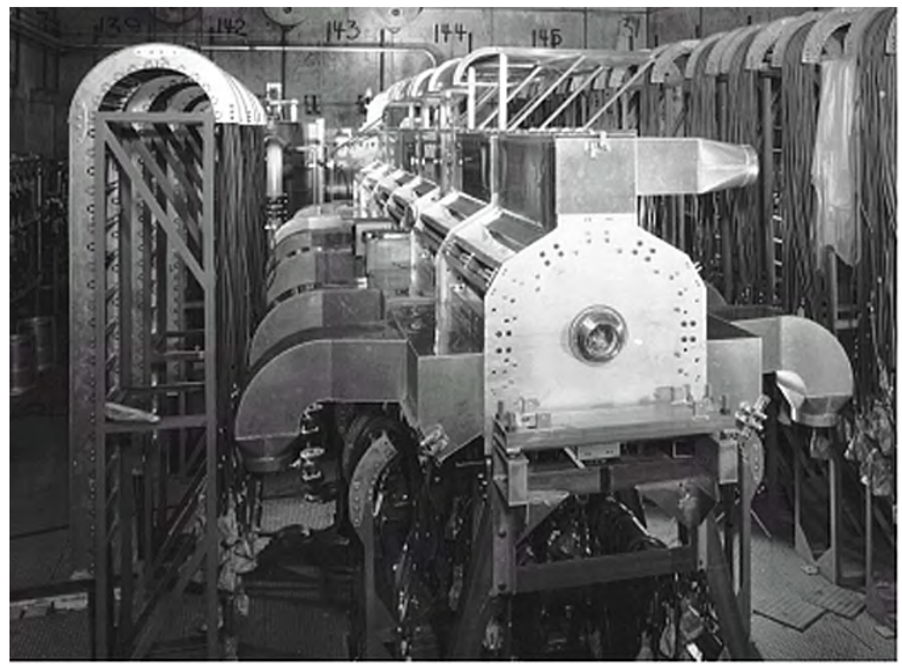
Christofilos' contributions to accelerator science



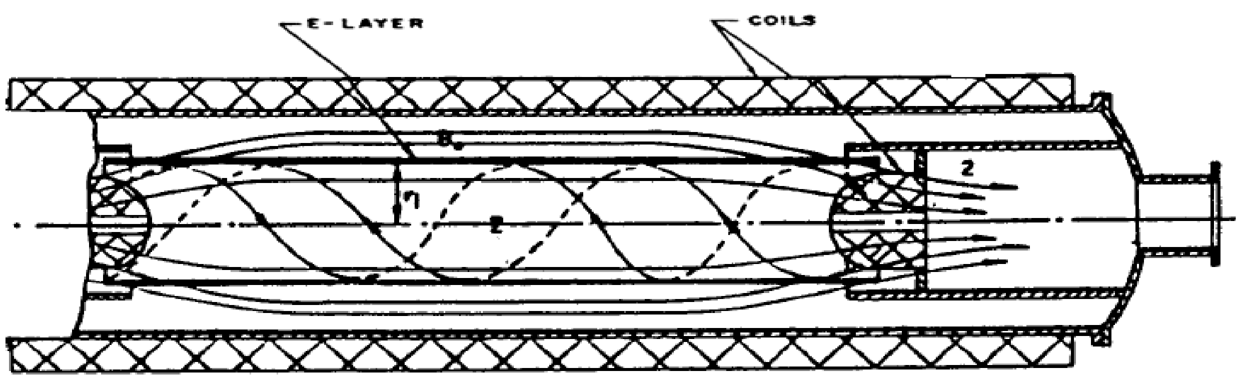
Strong focusing (1949)



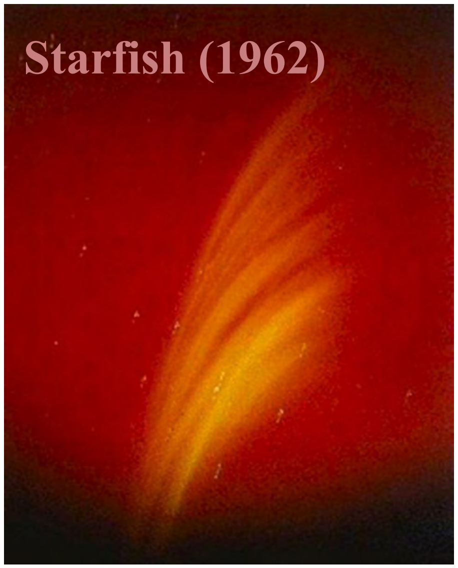
Induction linac (1949)

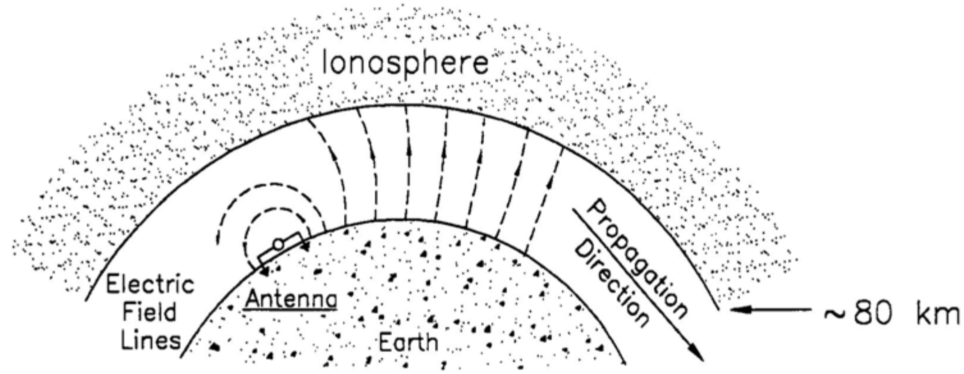


Christofilos' Astron Induction Linac & Astron CTR (1966)



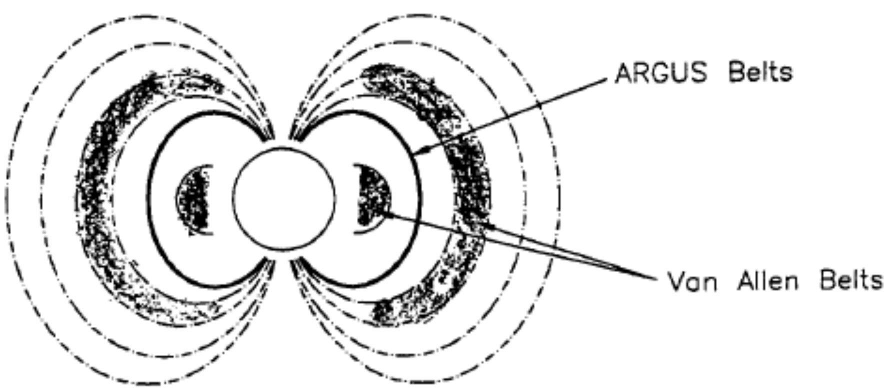
Christofilos' style: Think big

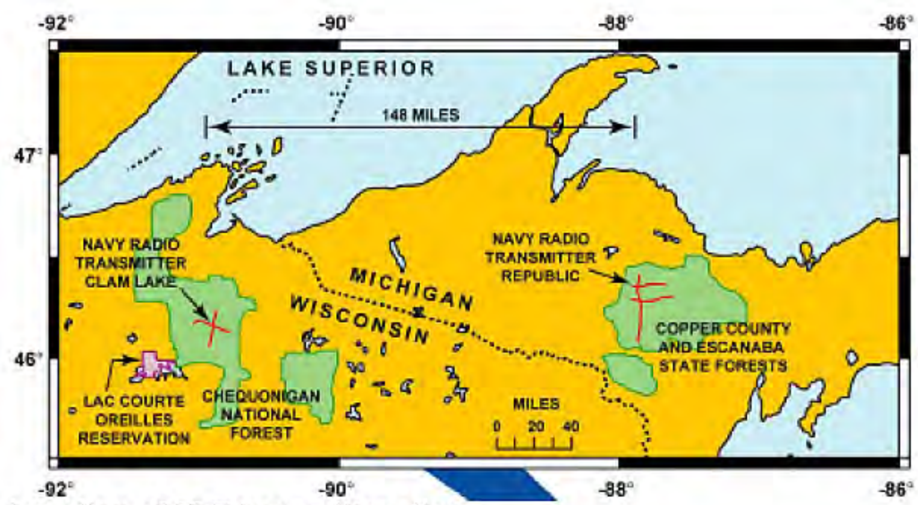




Project Sanguine (1962)

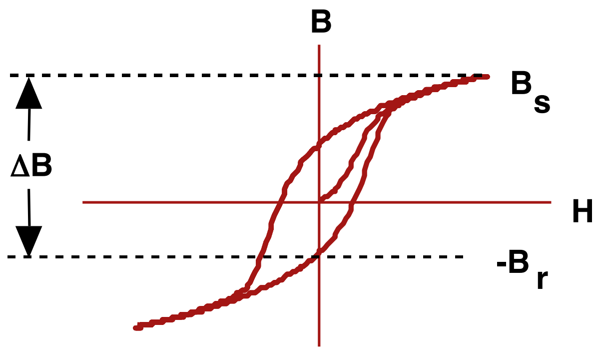
Argus: Earth's radiation belts (1958)



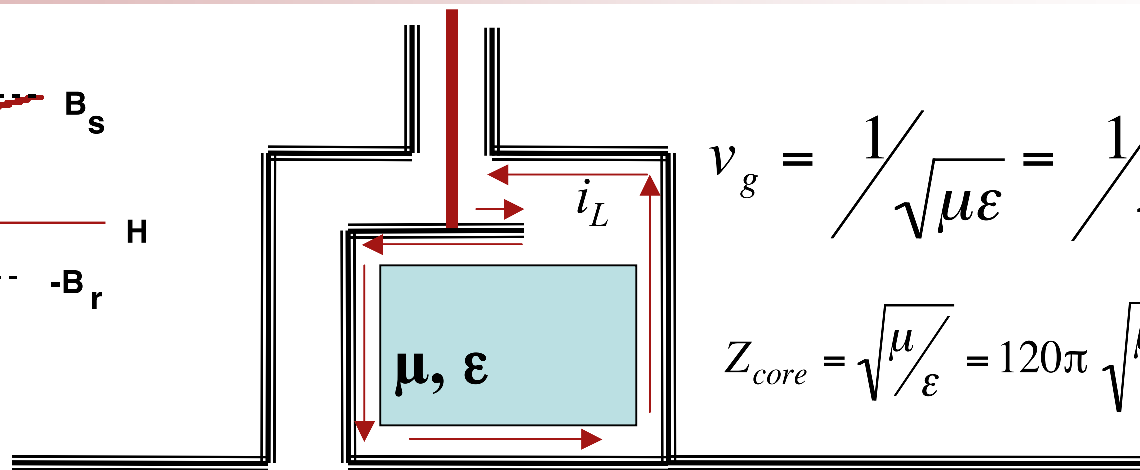


Location of ELF transmitter sites

A closer look at the induction cell



Core hysteresis loop



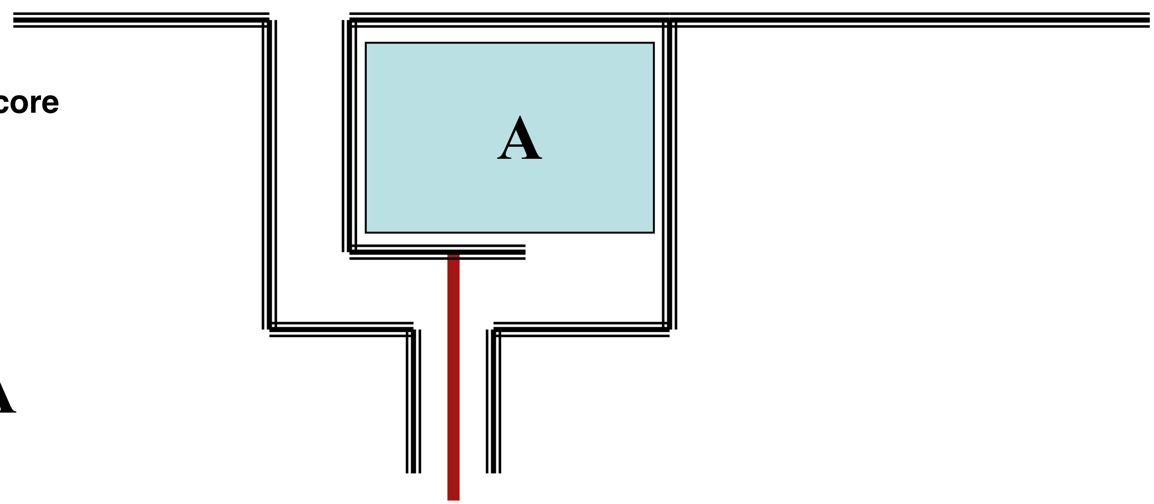
$$v_g = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_r \varepsilon_r}}$$

$$Z_{core} = \sqrt{\frac{\mu}{\varepsilon}} = 120\pi \sqrt{\frac{\mu_r}{\varepsilon_r}} \text{ Ohms}$$

Leakage current magnetizes core

$$i_L = \frac{V}{L_c} t$$

$$\mathbf{V \cdot \Delta t = \Delta B \cdot A}$$

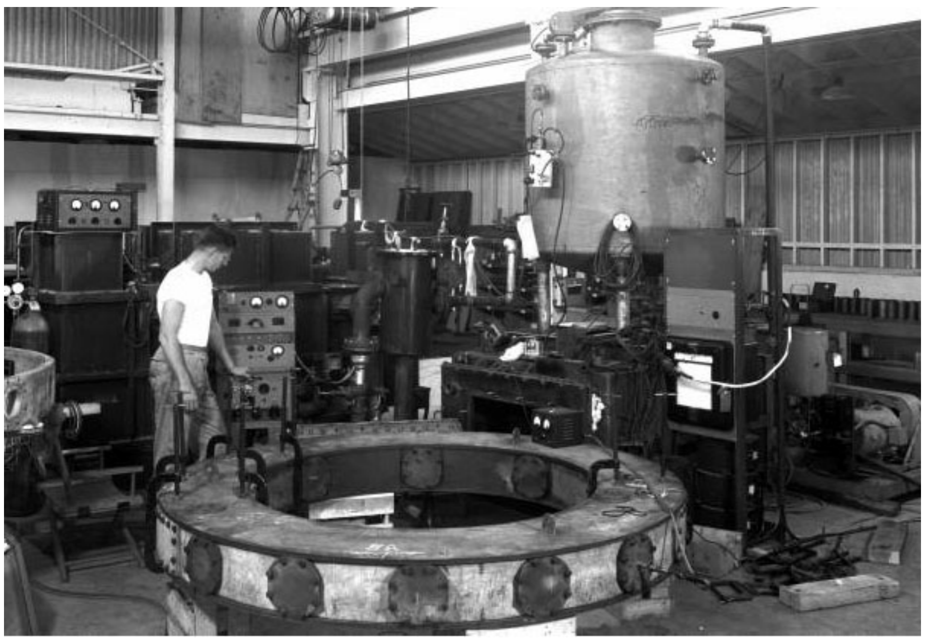


Induction accelerators occupy a special niche, but now on to the mainstream

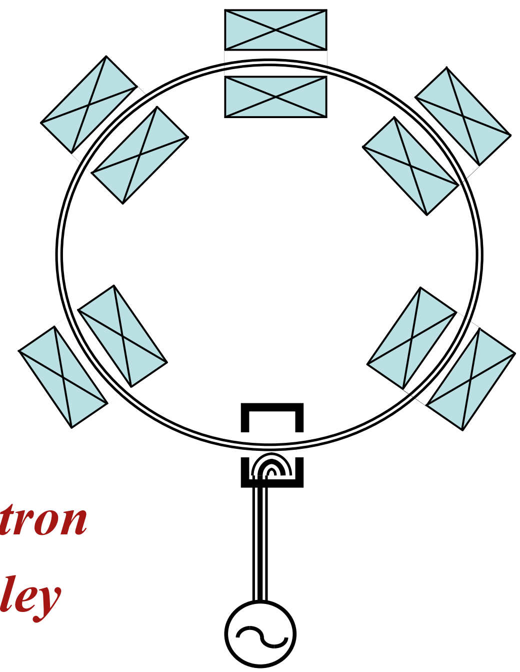
The size of monolithic magnets was getting beyond the practical

In a classified report Mark Oliphant suggested

- Change the B field as the particles gained energy to maintain a constant orbit size (= $N\lambda_{rf}$)
  - ➞ Could synchronism of the particles with the rf be maintained?



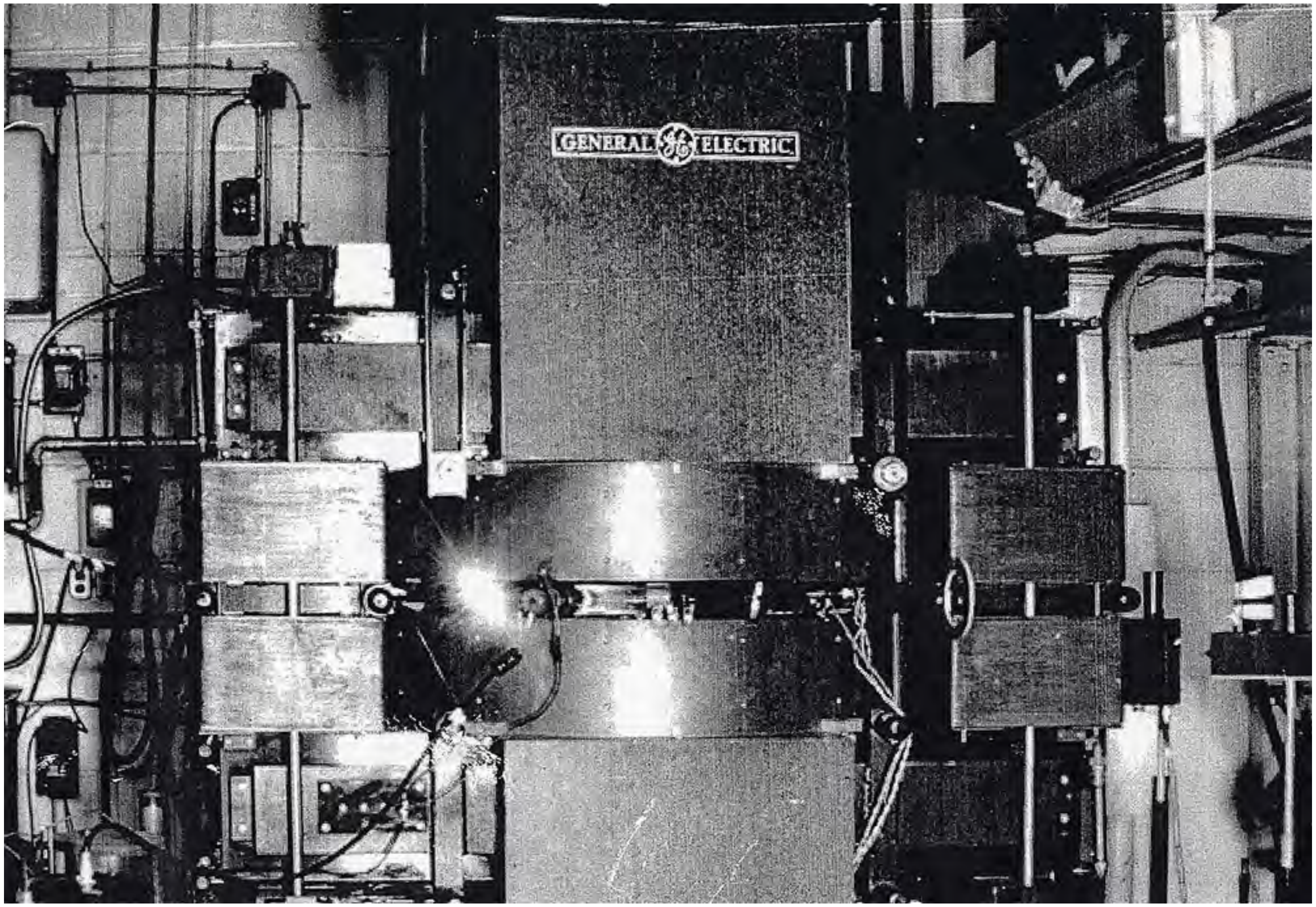
Synchrotron at Berkeley



Fundamental discovery by Veksler (1944) & MacMillan (1945)

The GE 70 MeV synchrotron was first to produce observable synchrotron light (1947)

The first purpose-built synchrotron to operate was built with a glass vacuum chamber

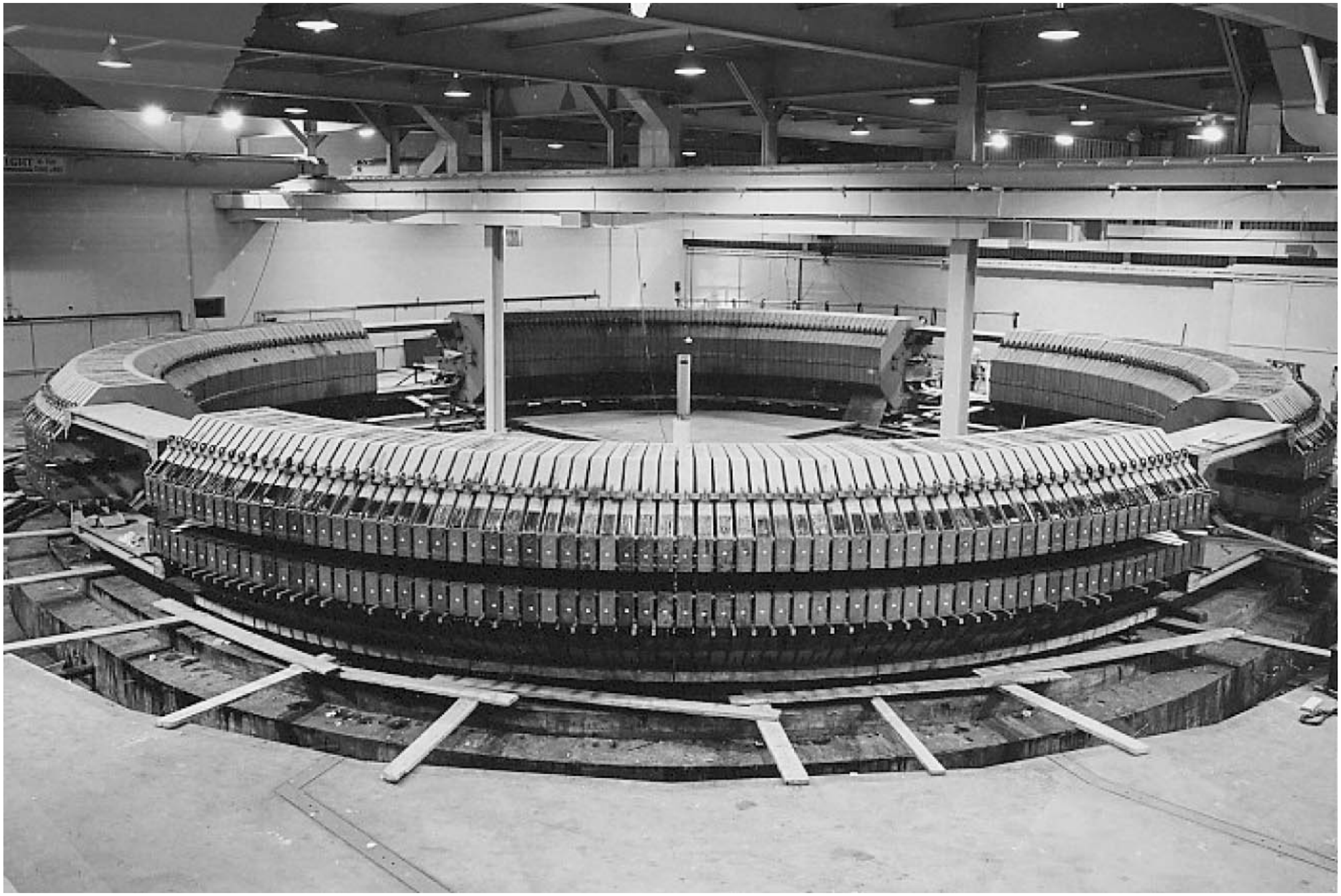


By the early 1950's 3 proton synchrotrons ad followed the first electron models

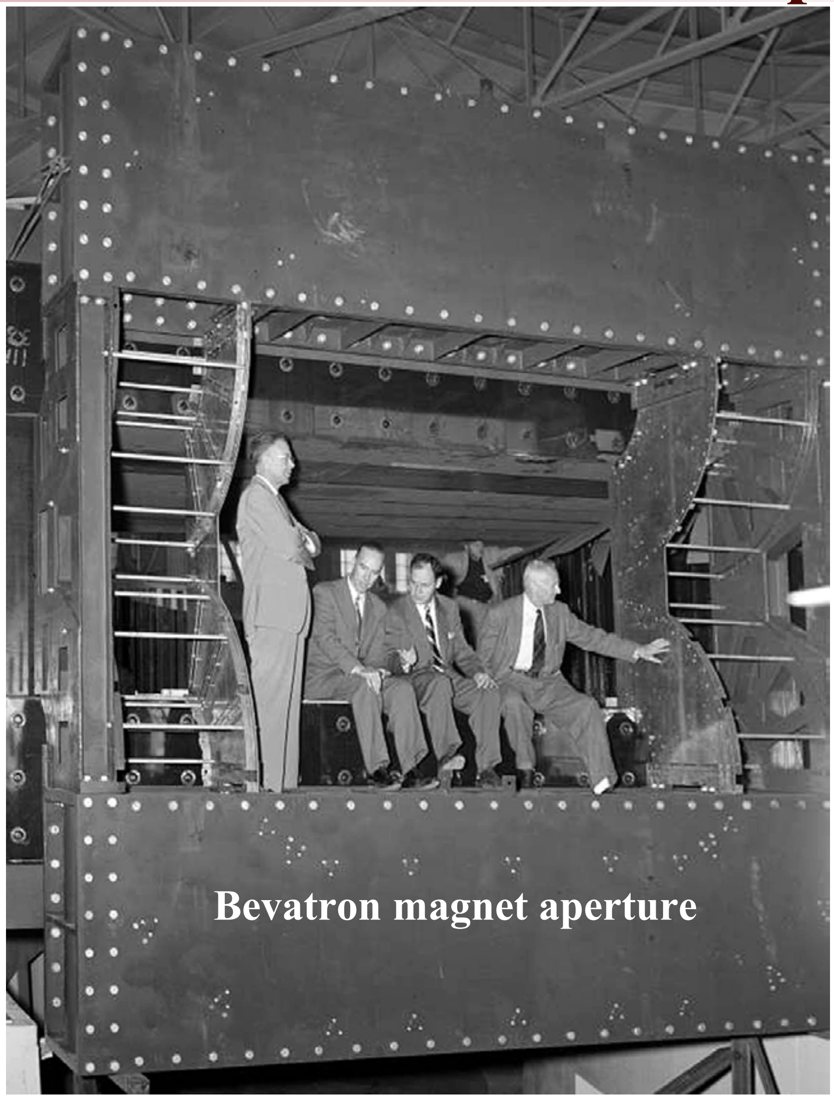
- 3-BeV "Cosmotron" at the Brookhaven (1952)
  - 2000 ton magnet in four quadrants
  - 1 second acceleration time
  - Shielding recognized as major operational issue
- 1-BeV machine at Un. of Birmingham (UK) in 1953
  - Laminated magnets, no field free straight sections
- 6 BeV "Bevatron" University of California Radiation Laboratory (1954)
  - Vacuum chamber ~ 3 feet high
- Weak focusing precluded such a design at ≥10 GeV

*Another **great invention** was needed*

The BNL Cosmotron w. 4-sector magnets

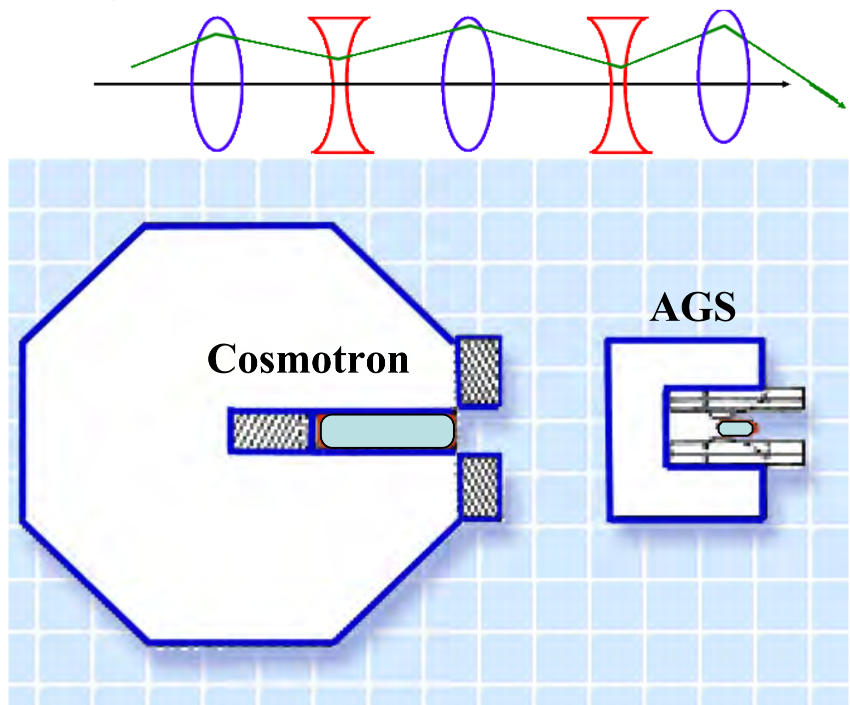


The vacuum chamber of the 6 GeV Bevatron could fit whole physicists



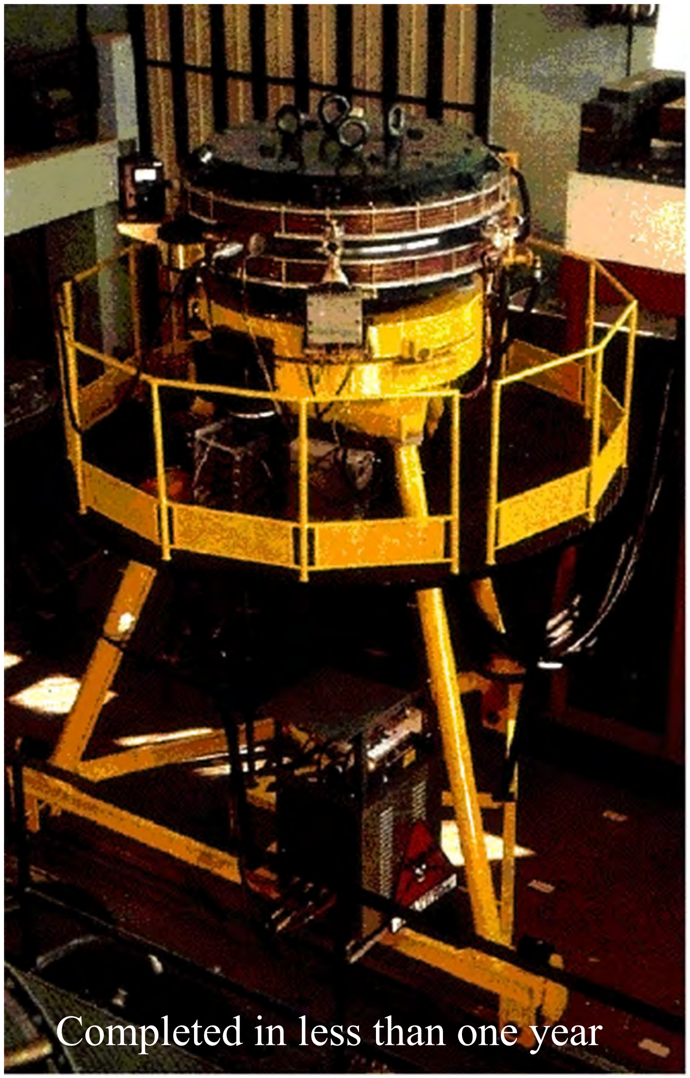
Strong focusing allowed shrinking the vacuum chamber to reasonable sizes

- Patented but not published by Christofilos (1949);
- Independently discovered and applied to AGS design by Courant, Livingston, and Snyder



*Small chambers meant much better vacuum making practical a **third great invention***

ADA - The first storage ring collider (e^+e^-) by B. Touschek at Frascati (1960)



Completed in less than one year

The storage ring collider idea was invented by R. Wiederoe in 1943

- Collaboration with B. Touschek
- Patent disclosure 1949

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM 11. MAI 1953

DEUTSCHES PATENTAMT

PATENTSCHRIFT

№ 876 279

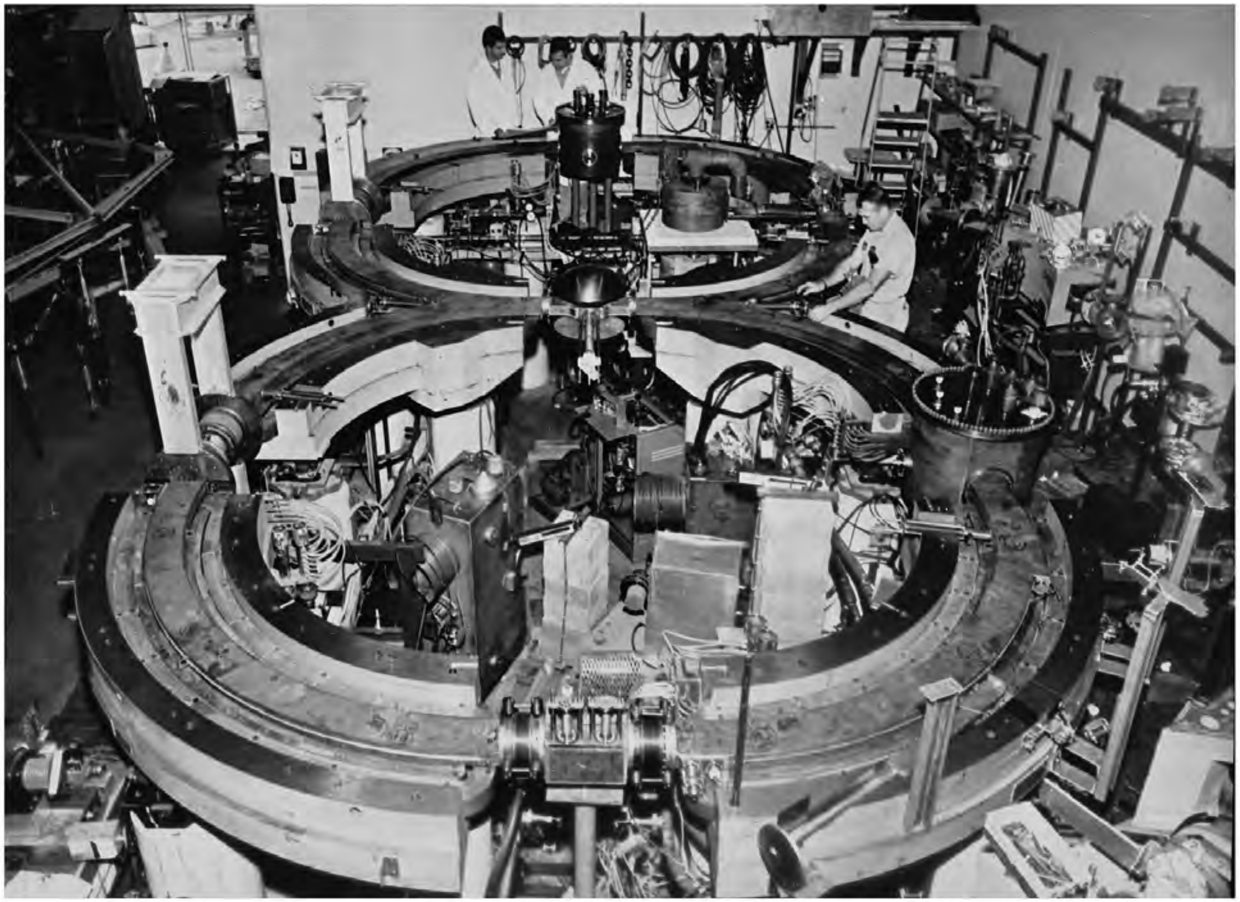
KLASSE 21g GRUPPE 36

Dr.-Ing. Rolf Wideröe, Oslo
ist als Erfinder genannt worden

Aktiengesellschaft Brown, Boveri & Cie, Baden (Schweiz)

Anordnung zur Herbeiführung von Kernreaktionen

G. O’Neill is often given credit inventing the collider based on his 1956 paper



Princeton-Stanford colliding beam storage rings - 1960

Panofsky, Richter, & O’Neill

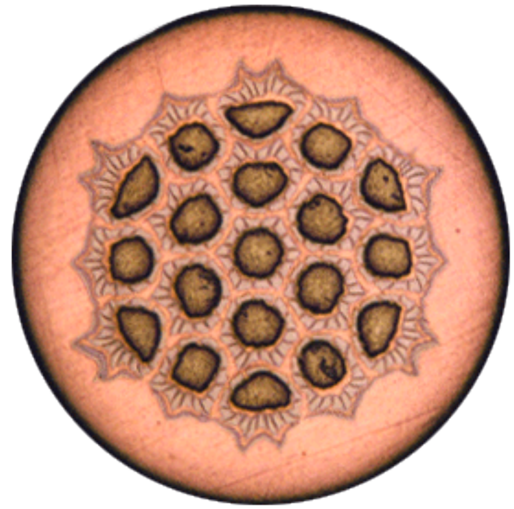
The next big step was the ISR at CERN

- 30 GeV per beam with > 60 A circulating current
  - ➞ Required extraordinary vacuum (10^{-11} Torr)
  - ➞ Great beam dynamics challenge - more stable than the solar system
- Then on to the 200 GeV collider at Fermilab (1972) and …
- The $Sp\bar{p}S$ at CERN
  - ➞ Nobel invention: Stochastic cooling
- And finally the Tevatron
  - ➞ Also requires a major technological advance

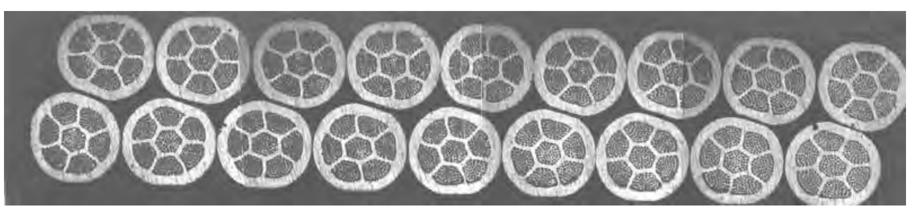
First machine to exploit superconducting magnet technology

Small things make a difference: SC wire and cable ==> TeV colliders

64-strand cabling machine at Berkeley



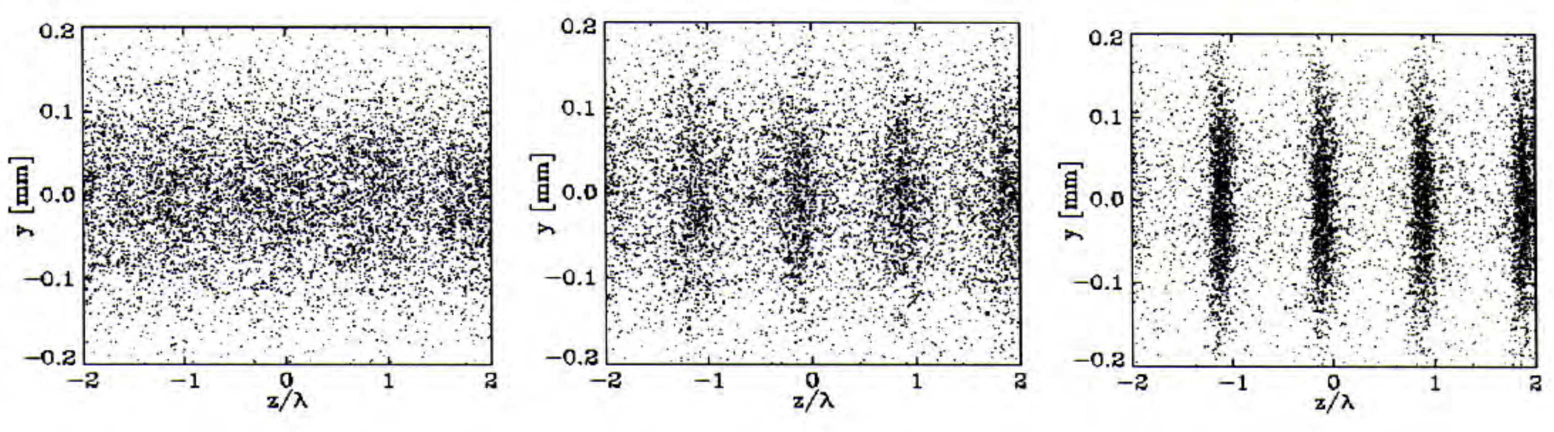
Sub-elements of a NiTi superconducting wire strand



BSSCO high temperature superconductor wound into a Rutherford cable

The 70's also brought another great invention

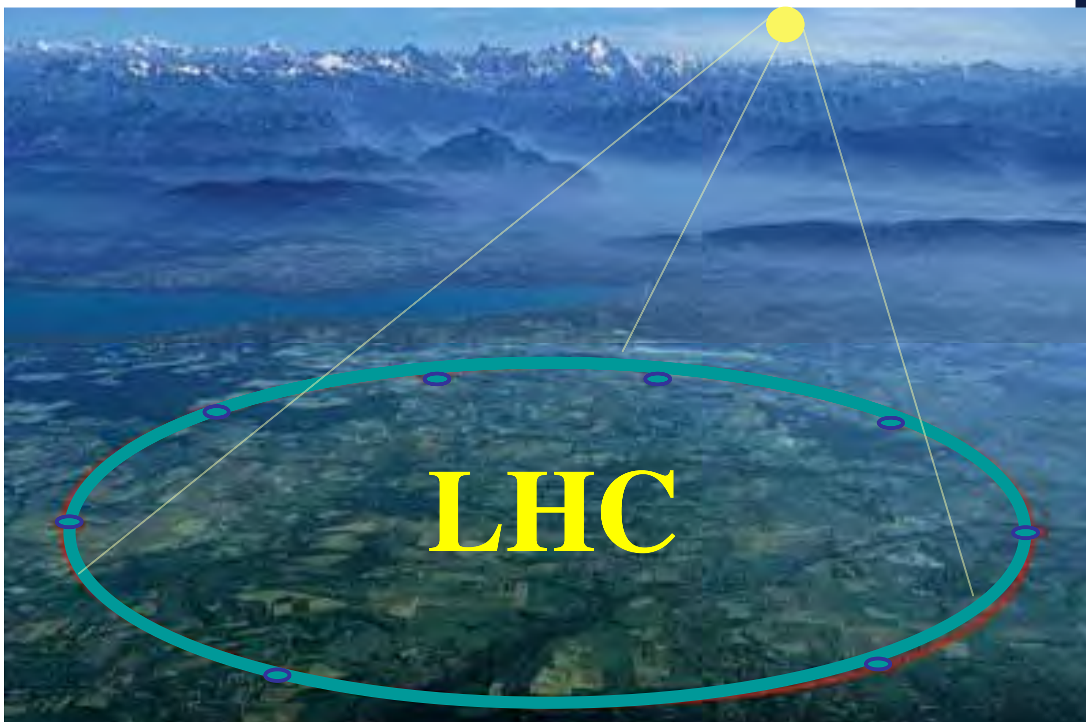
- The Free Electron Laser (John Madey, Stanford, 1976)
- Physics basis: *Bunched electrons radiate* *coherently*



START MIDDLE END

- Madey's discovery: the bunching can be self-induced!

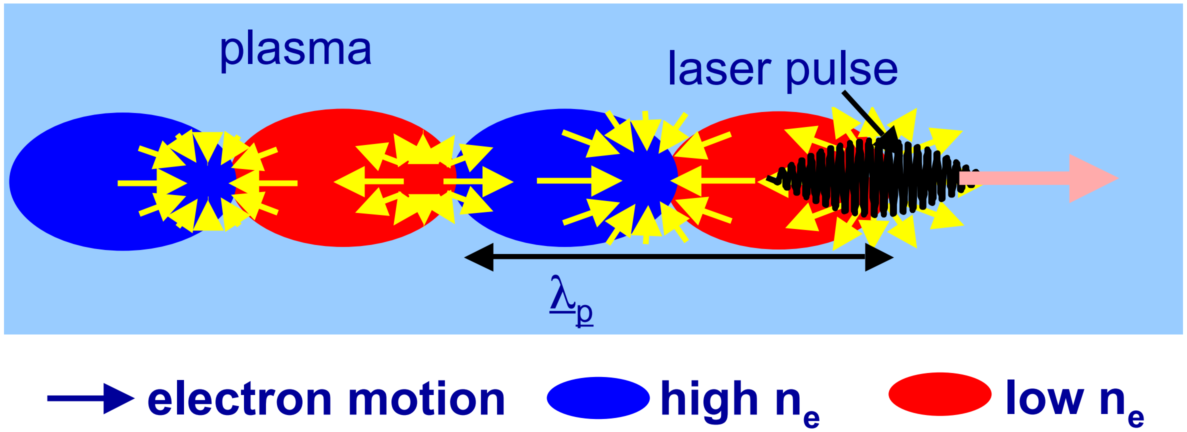
Which brings us to the present…

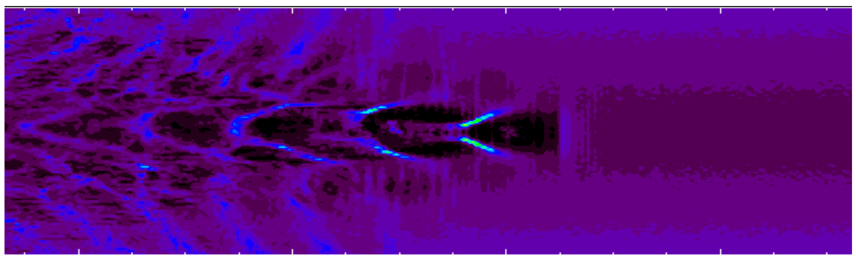


Is this the end of the line?

Maybe not… Optical Particle Accelerator

Standard regime (LWFA): pulse duration matches plasma period





- Accelerating field ~ Sqrt(plasma density)
- Phase velocity < c : particle and wave de-phase
- Energy gain $\Delta W = eE_z L_{acc}$

There are many possible special topics after we cover the basics

What interests you?