Lecture 1
The development of accelerator concepts

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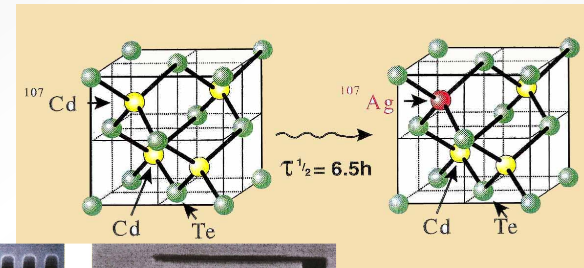
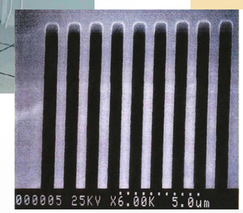
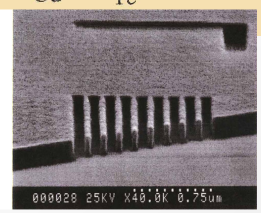
Motivations: Why does anyone care about accelerators?



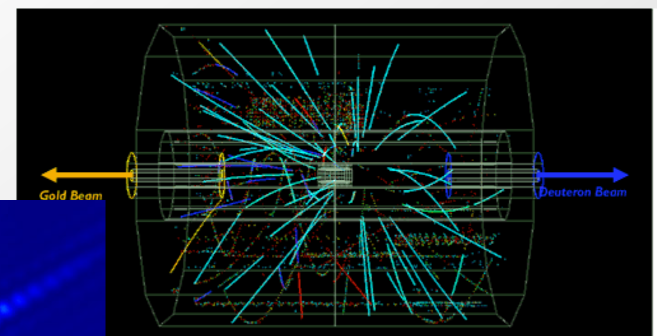




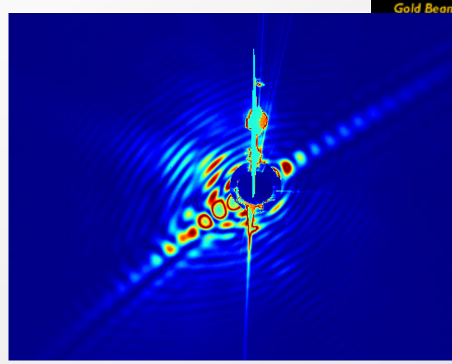
Materials

Medicine

Basic Research



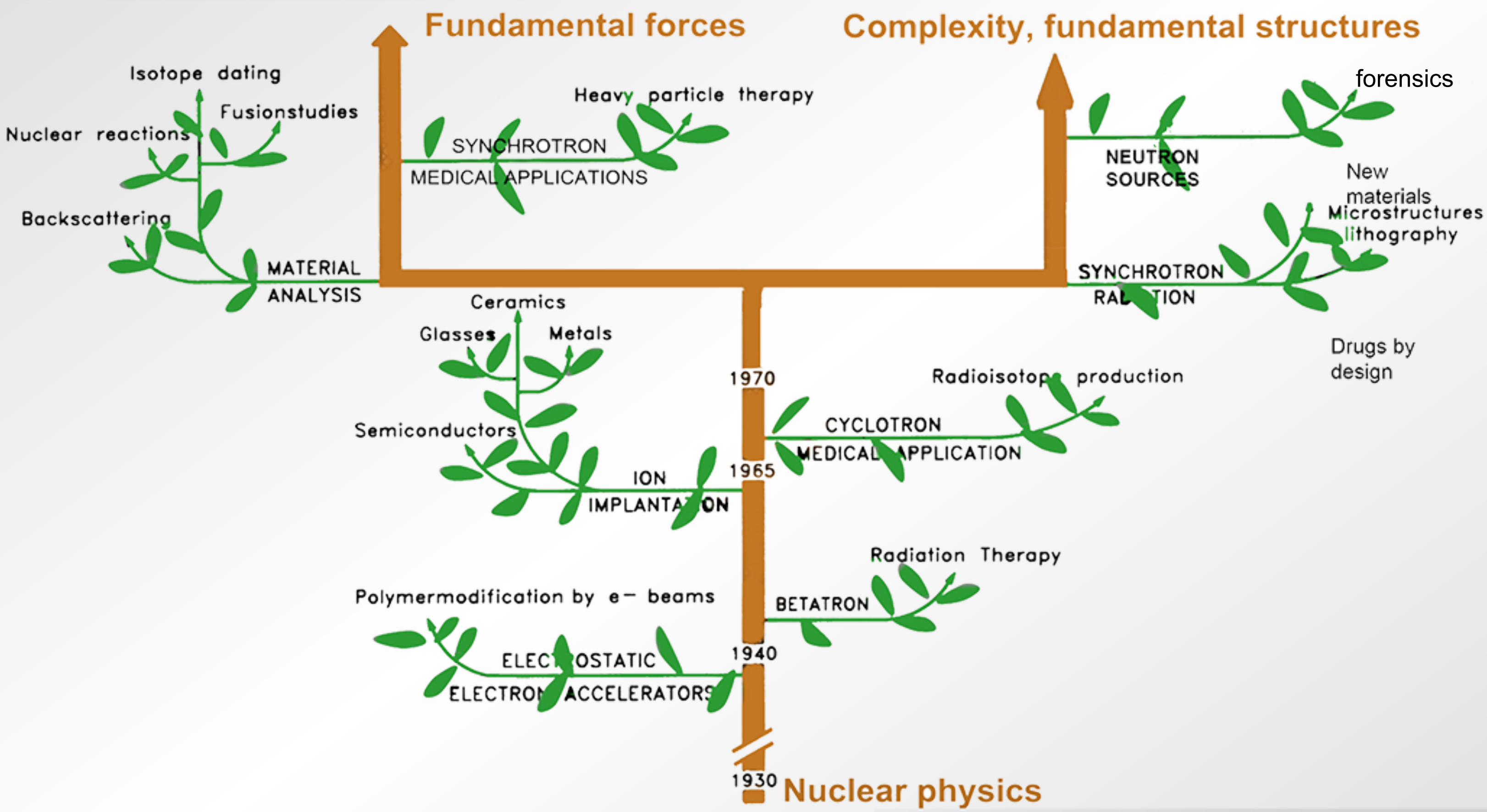
Brookhaven National Lab / RHIC-STAR Collaboration



Exciting products…

exciting opportunities

Accelerators are the hallmark
of highly technological societies

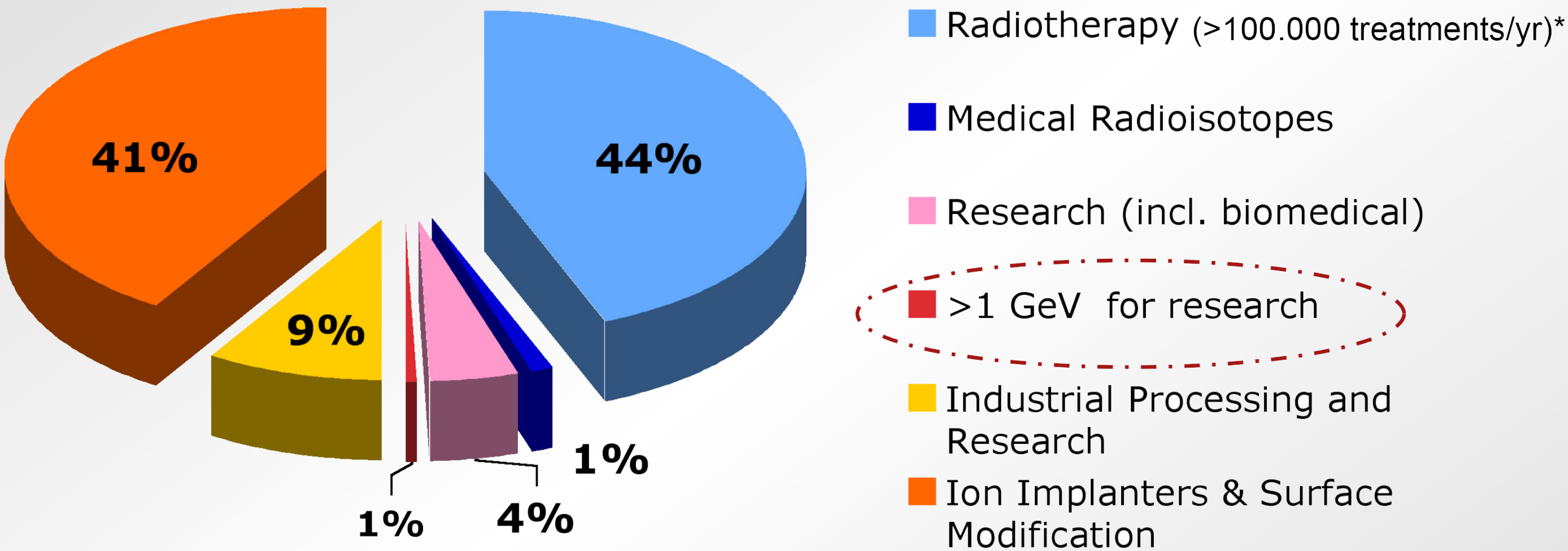


Societal applications & their technology develop from basic research

Source: U. Amaldi

Accelerators are big business

Number of accelerators worldwide
~ 26,000



Annual growth is several percent

Sales >3.5 B$/yr

Value of treated good > 50 B$/yr **

Major research machines are a tiny fraction of the total, but…

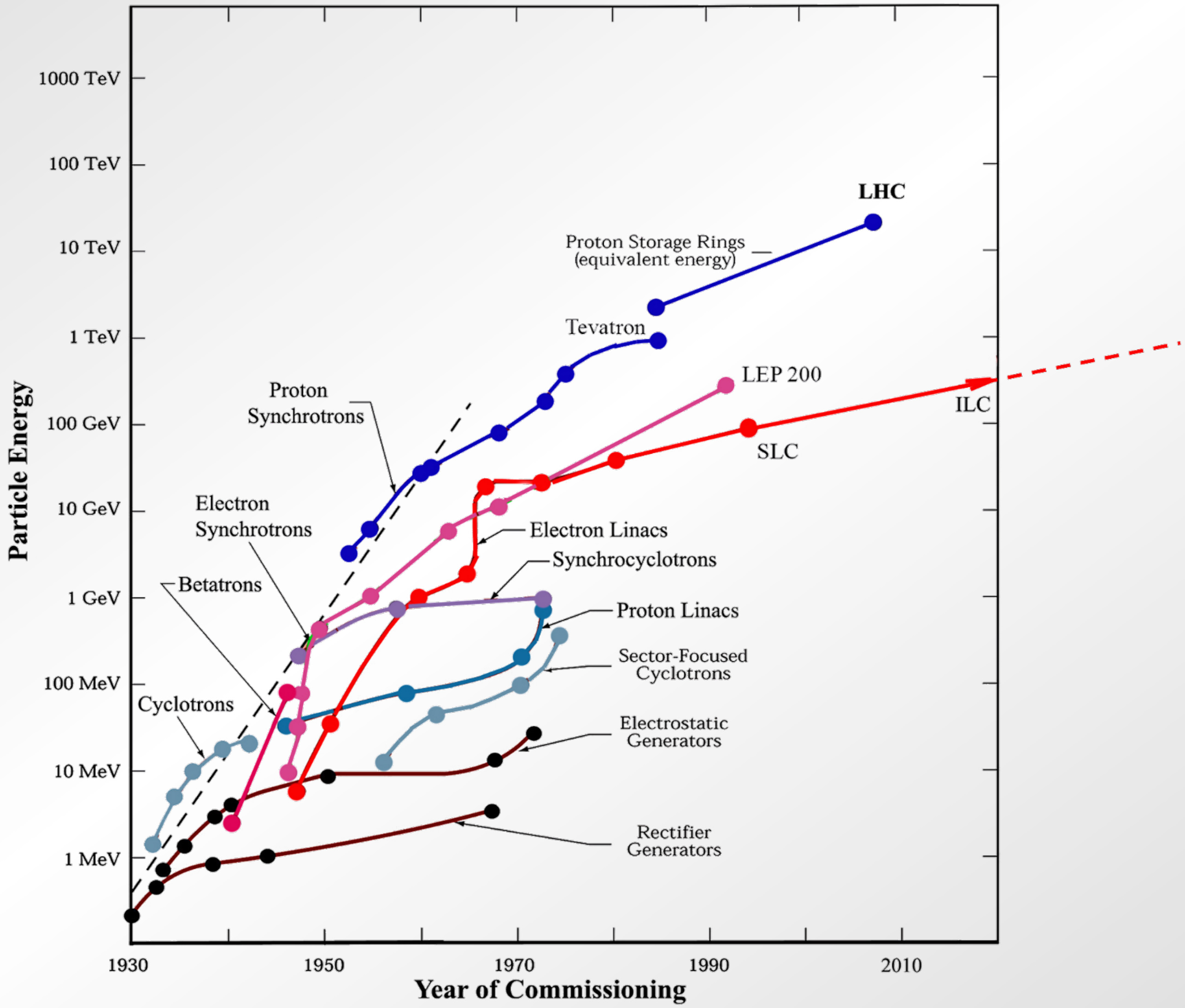
Sources: W. Maciszewski & W. Scharf, L. Rivkin, * EPP2010, ** R. Hamm

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

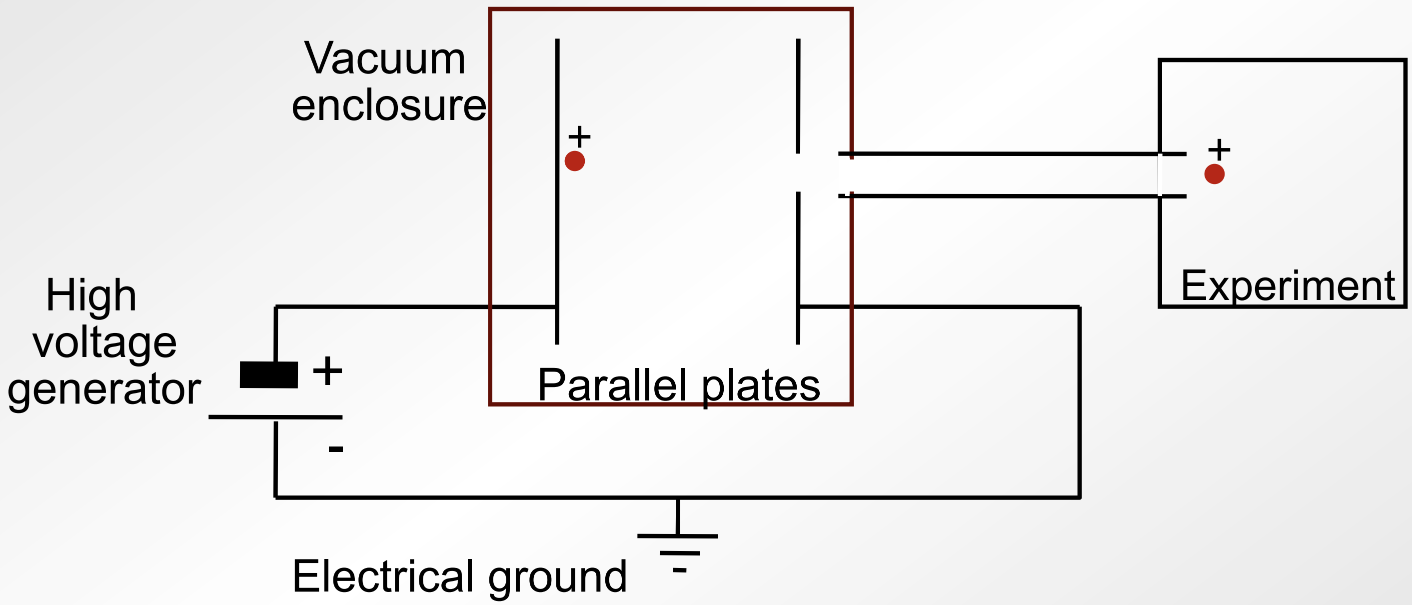
- ***Great principles*** of accelerator physics
  - phase stability,
  - strong focusing
  - colliding beam storage rings;
- ***Dominant accelerator technologies***
  - superconducting magnets
  - high power RF production
  - normal & superconducting RF acceleration
- ***Substantial accomplishments*** 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

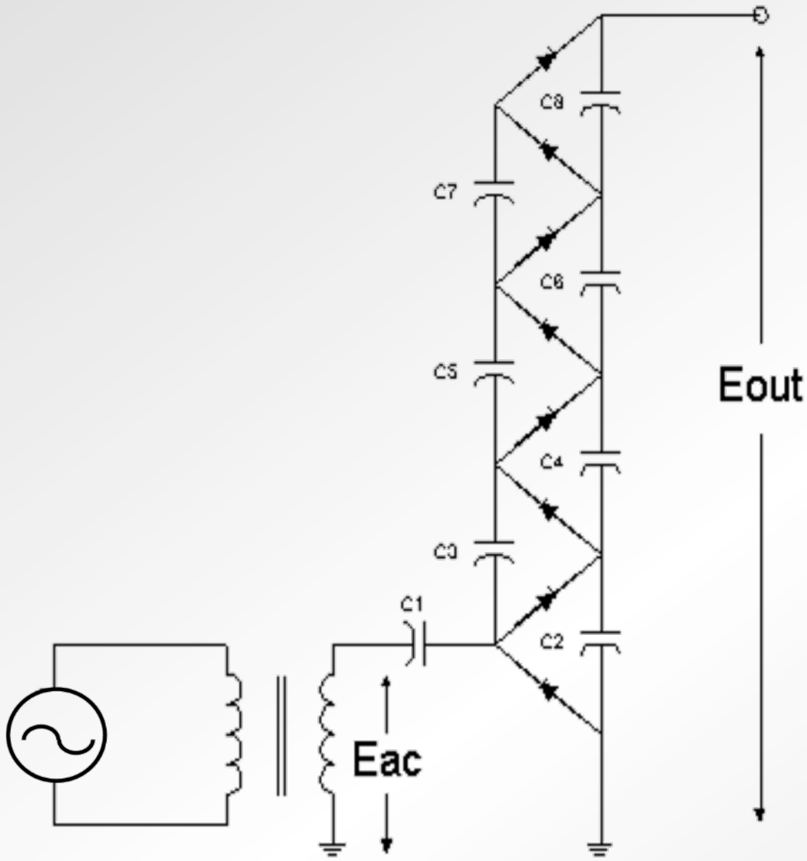
How do we get energy into the beam?



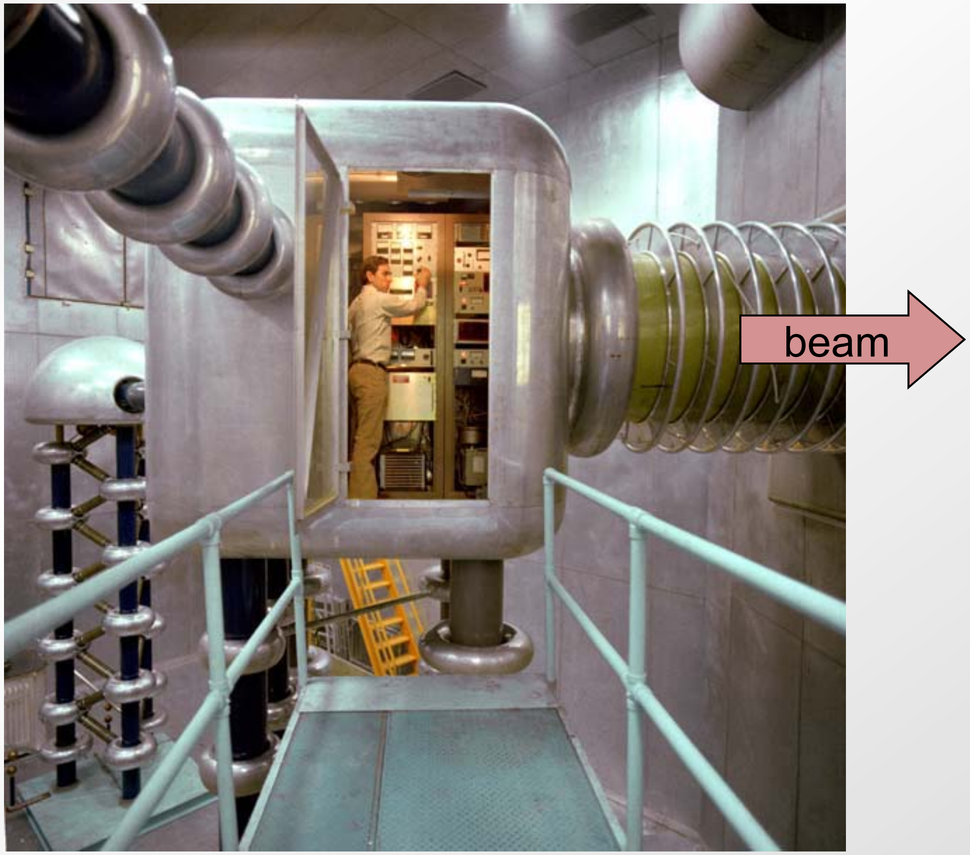
Simple DC (electrostatic) accelerator



Crockroft Walton
high voltage dc accelerator column

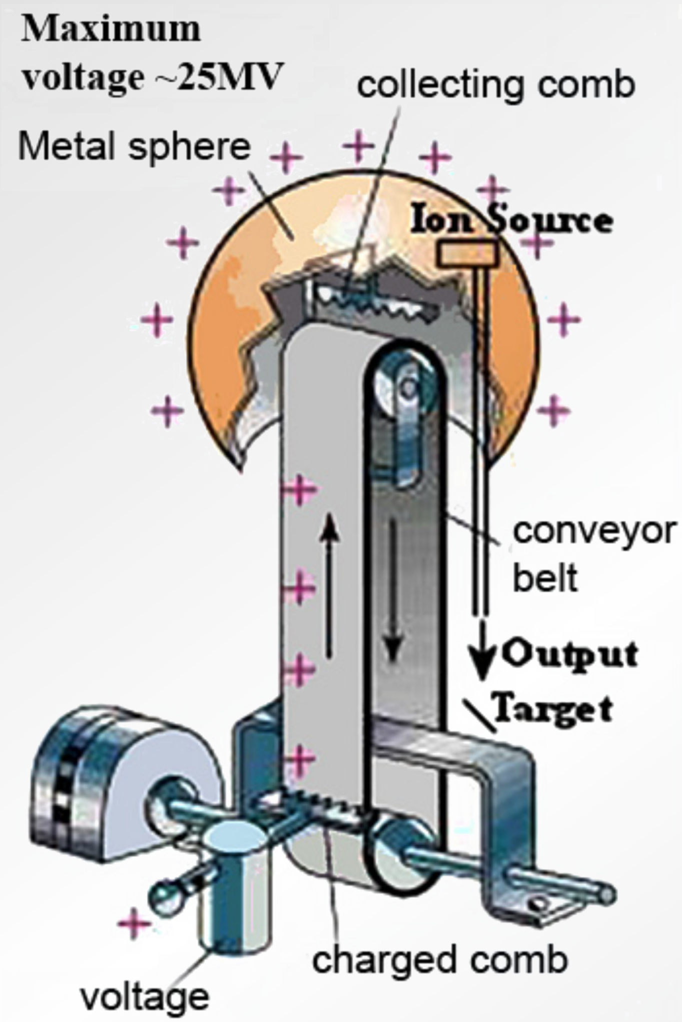


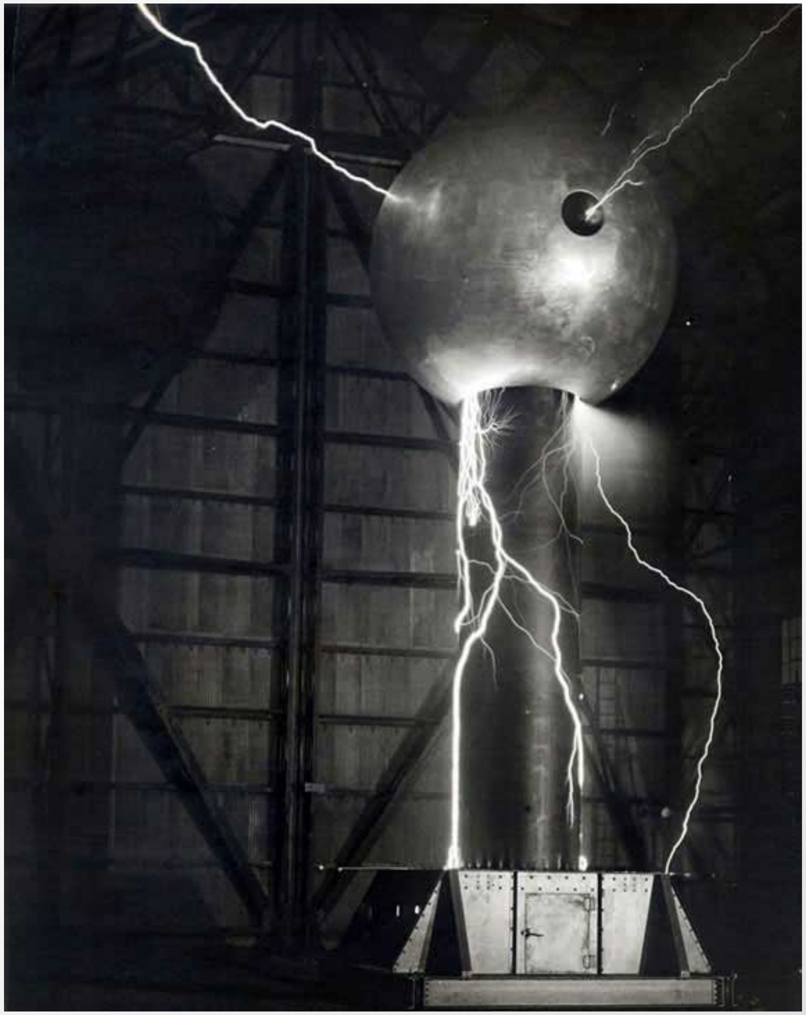
$$E_{out} = N_{stage} E_{ac}$$



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

Van de Graaff generators

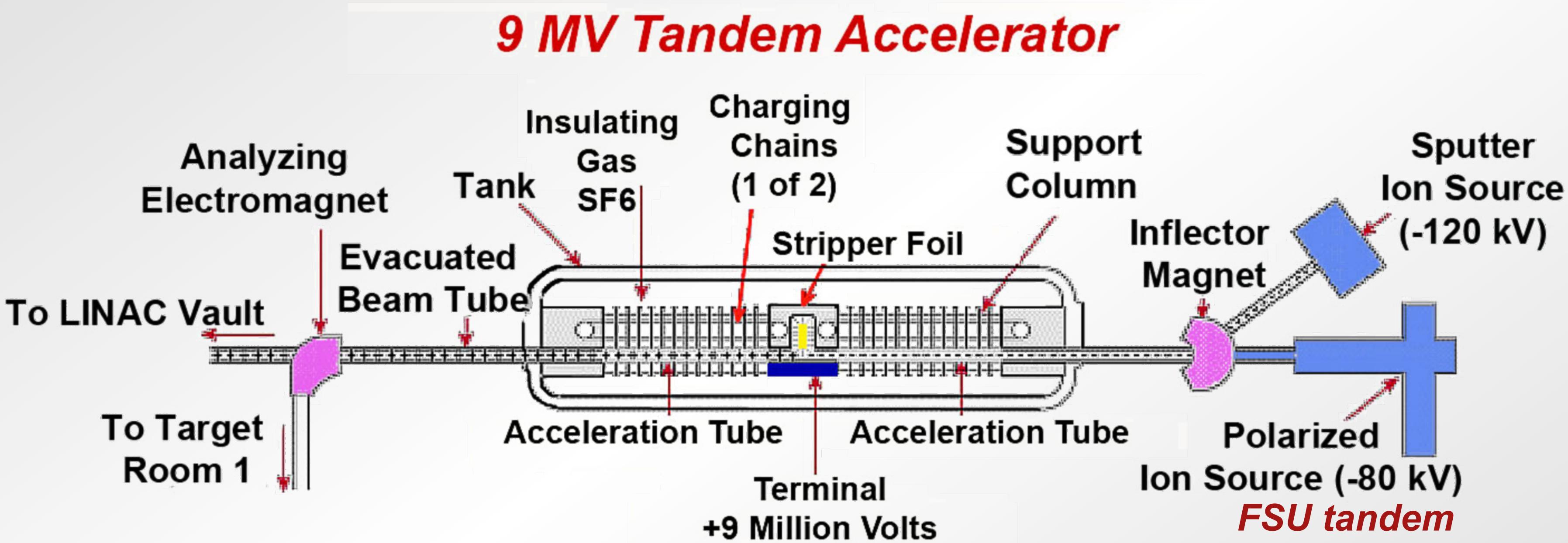




Van de Graaff’s generator a Round Hill MA

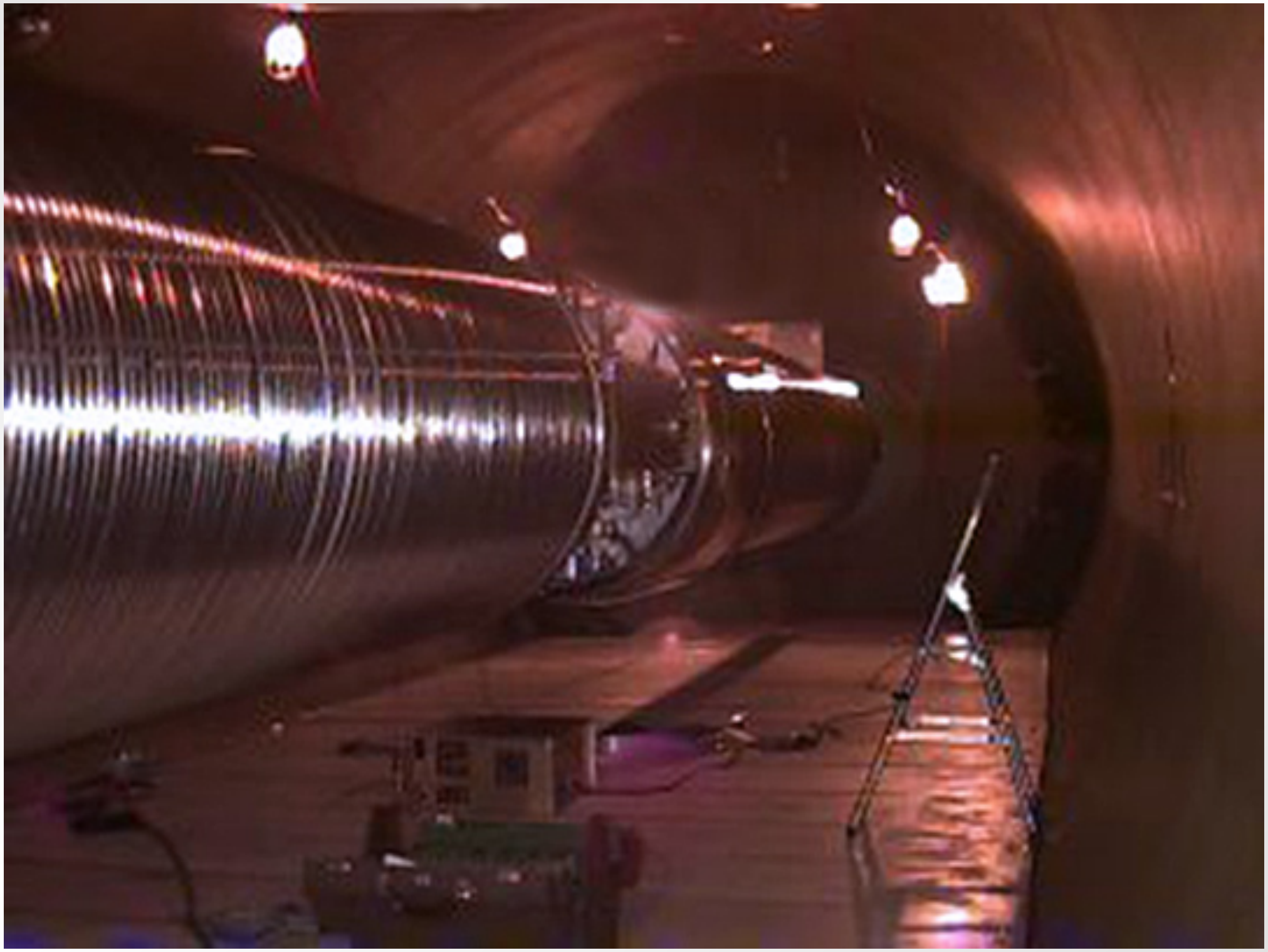
Suzie Sheehy:
Things not to do with a particle accelerator

Van de Graff accelerators are still used
The Tandem "Trick"



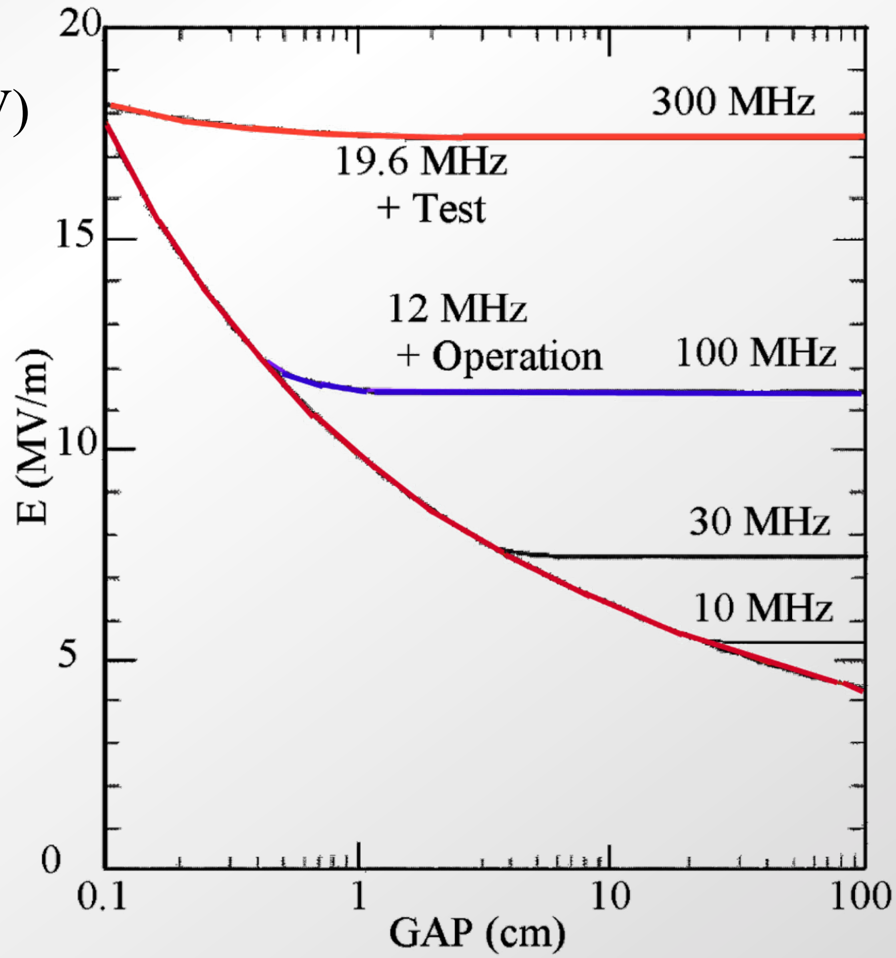
Change the charge of the beam from - to + at the HV electrode

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



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



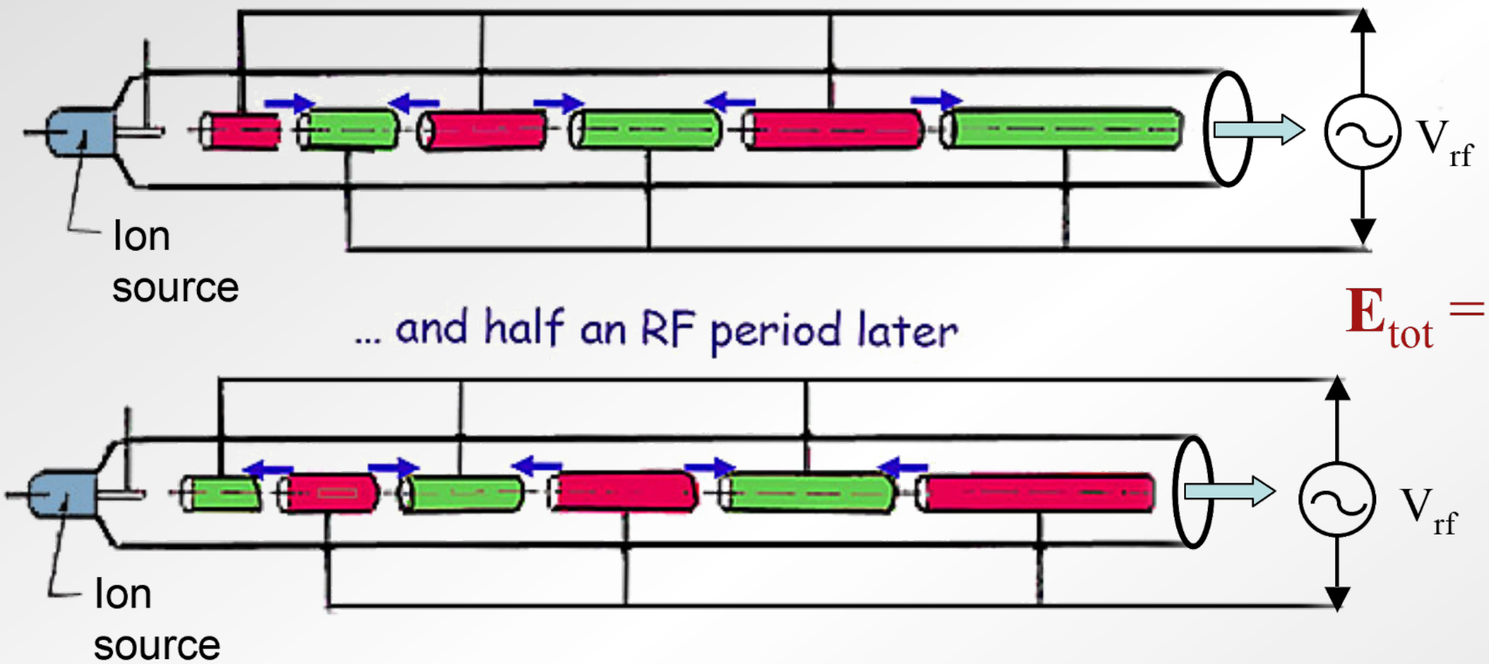
Sparking electric field limits in the Kilpatrick model, including electrode gap dependence

Why do we need RF structures & fields?

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 (Wiederoe)



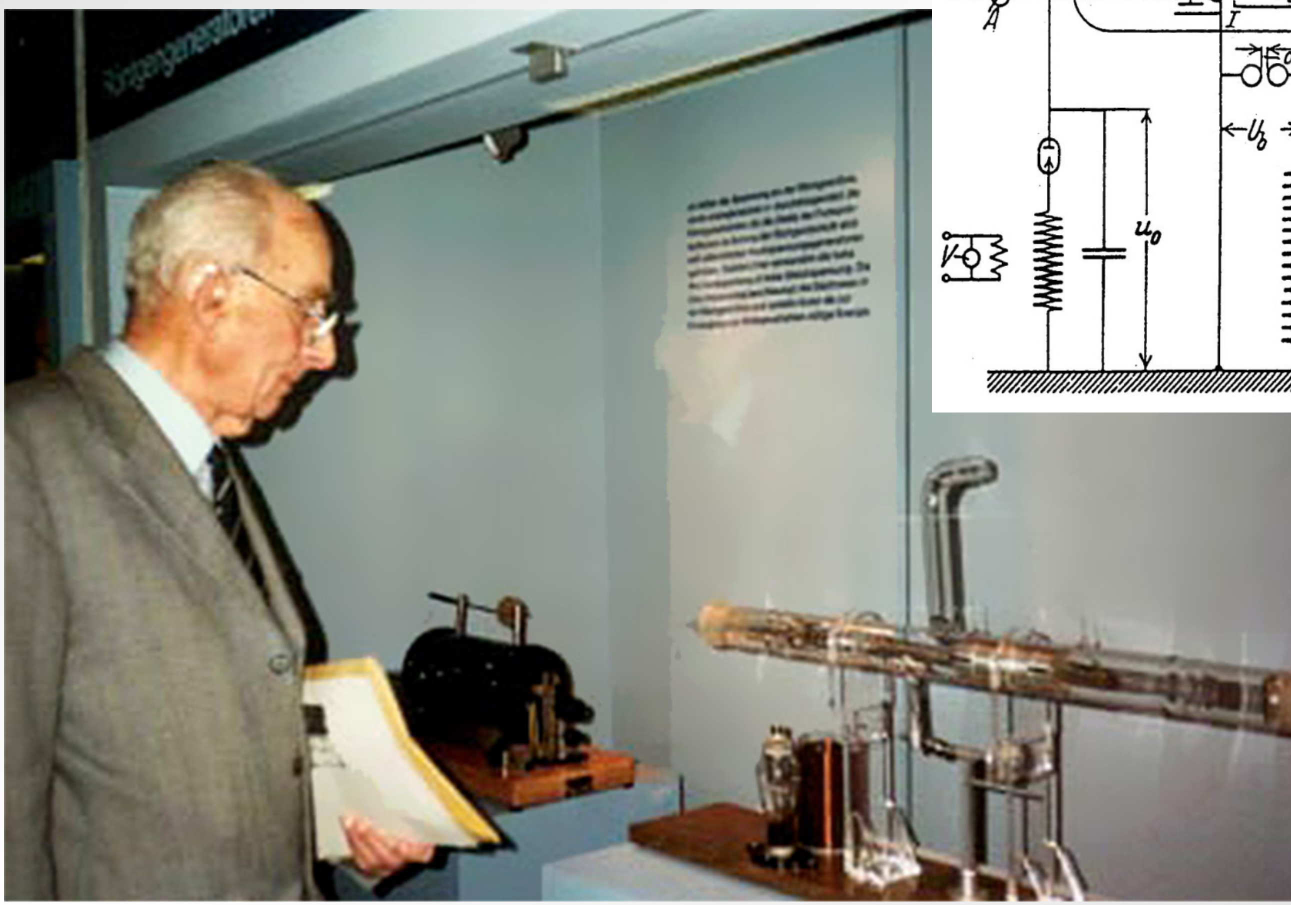
$$E_{tot} = N_{gap} \bullet V_{rf}$$

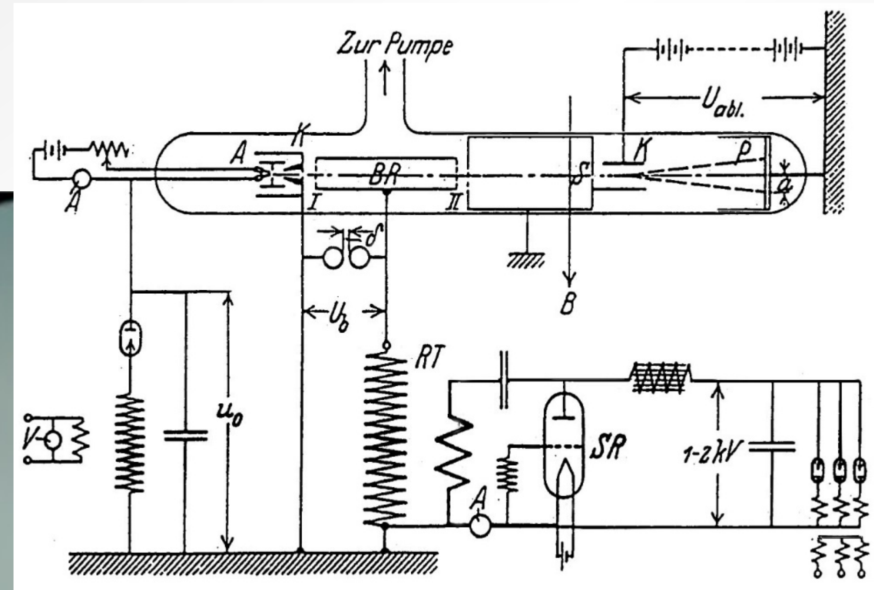
Phase shift between tubes is 180°

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

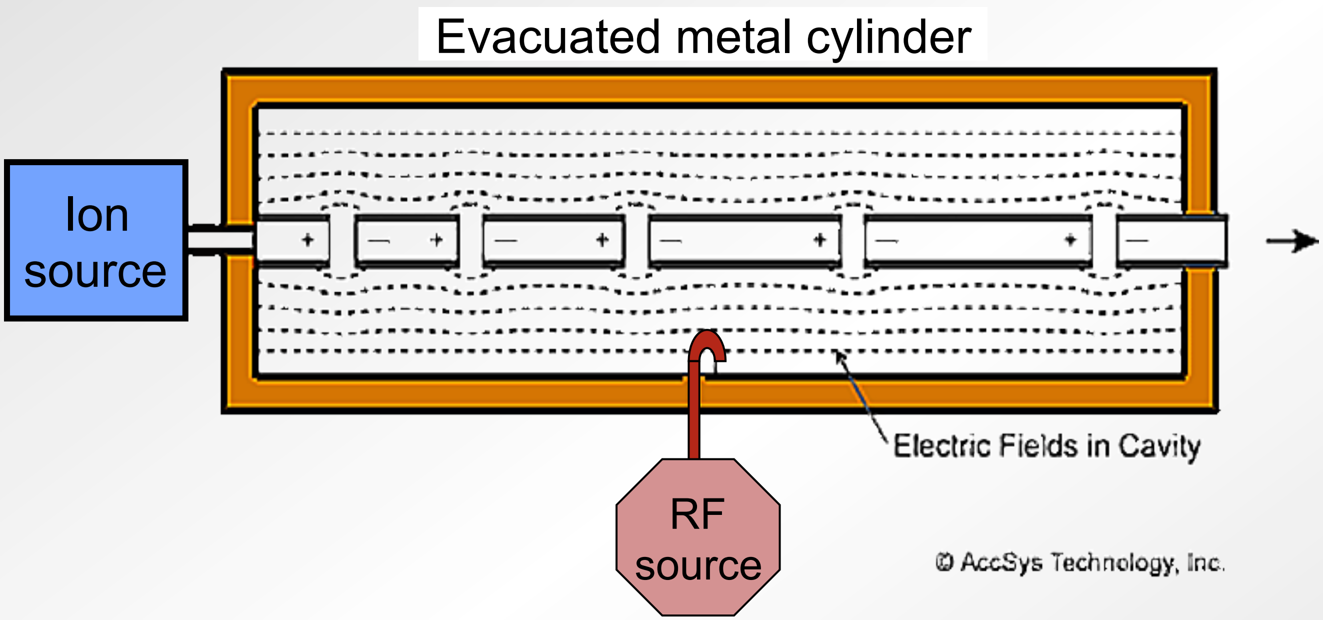
$$L_{drift} = \frac{1}{2}\frac{v}{f_{rf}} = \frac{1}{2}\frac{\beta c}{f_{rf}} = \frac{1}{2}\beta\lambda_{rf}$$

Wiederoe and his linac: A missed Nobel prize





Alvarez linac

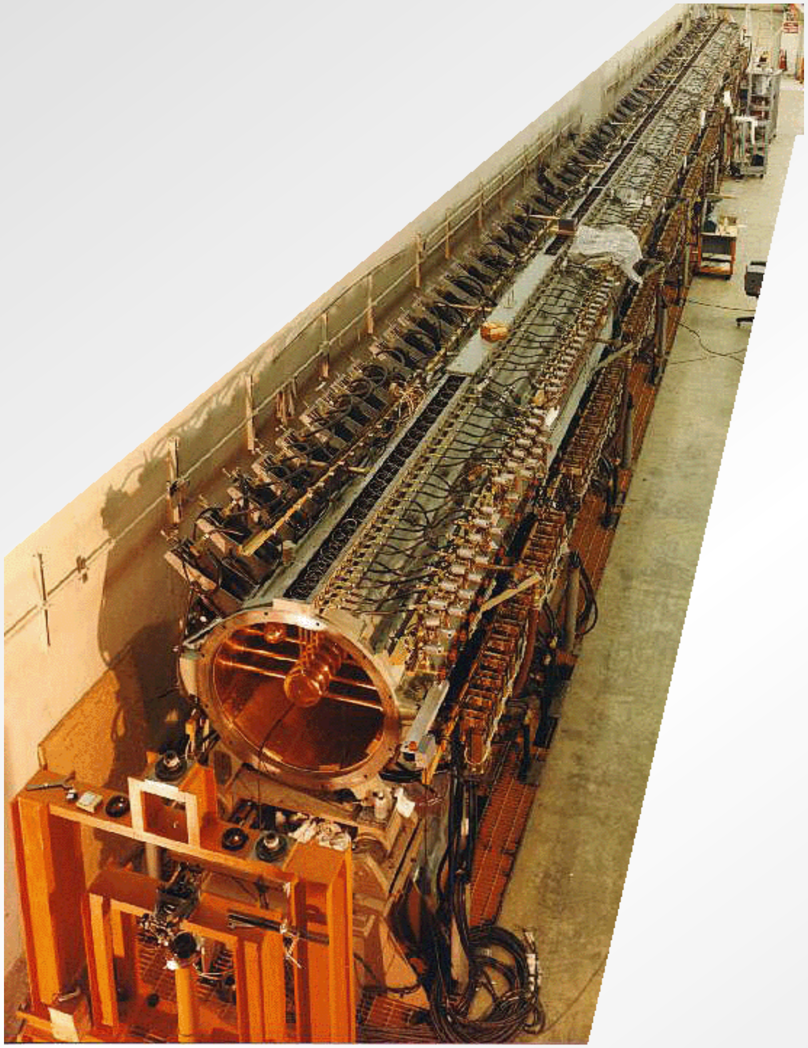


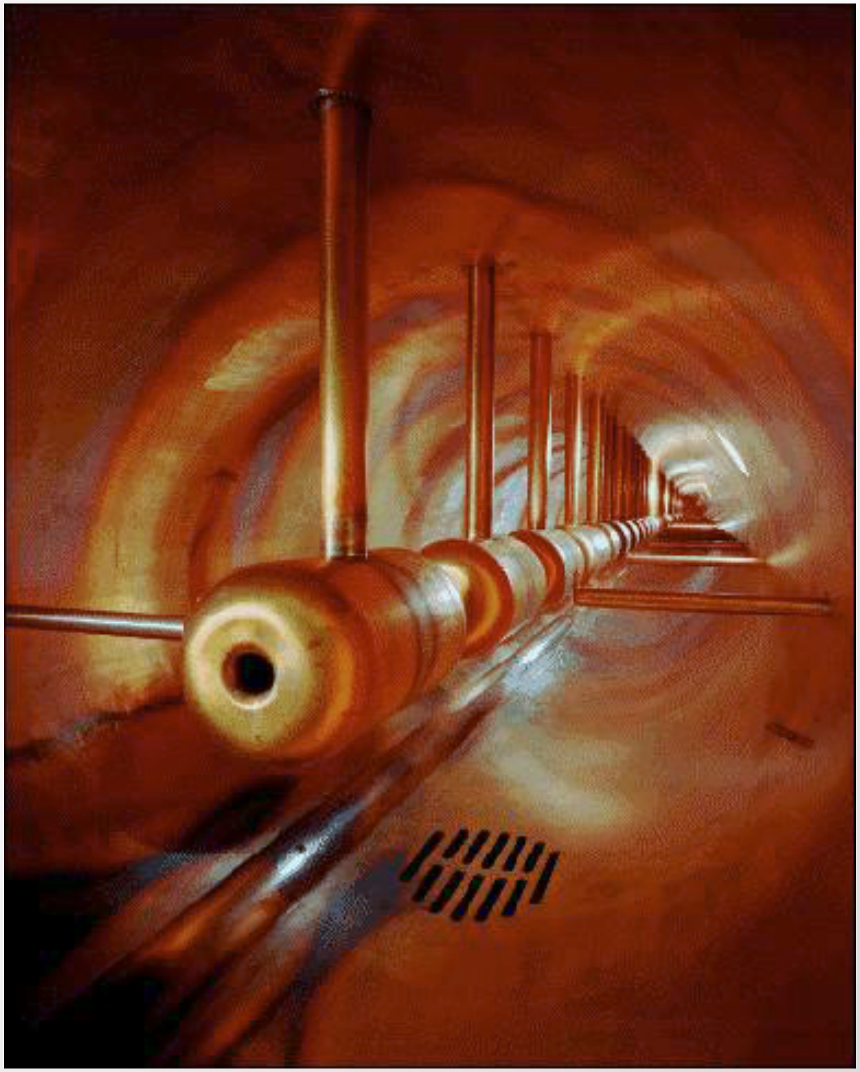
Alternate drift tubes are not grounded (passive structures)
==> phase shift between tubes is 360°

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

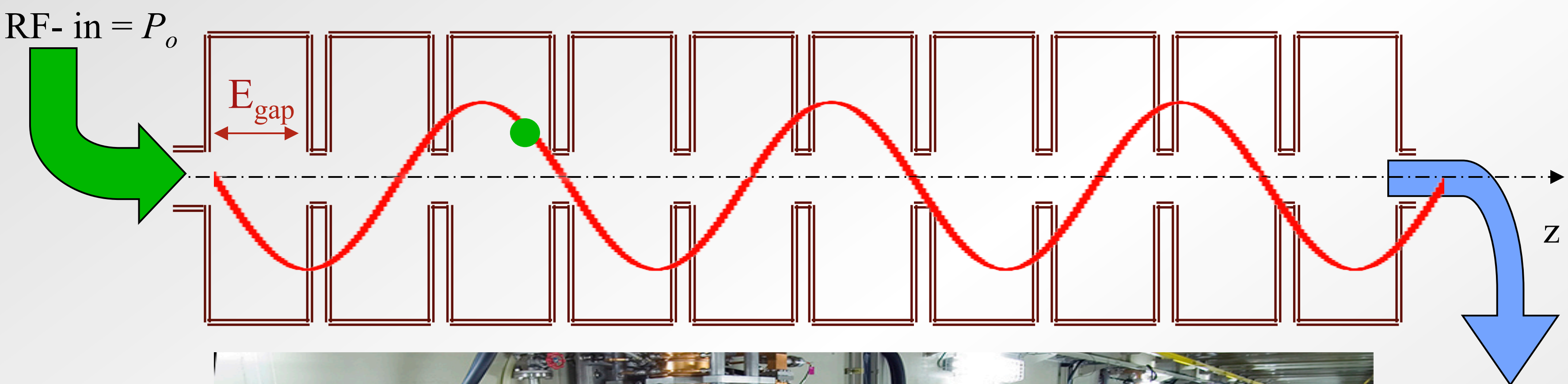
N.B. The outside surface is at ground potential

The Alvarez linac:
Time varying spatially stationary fields

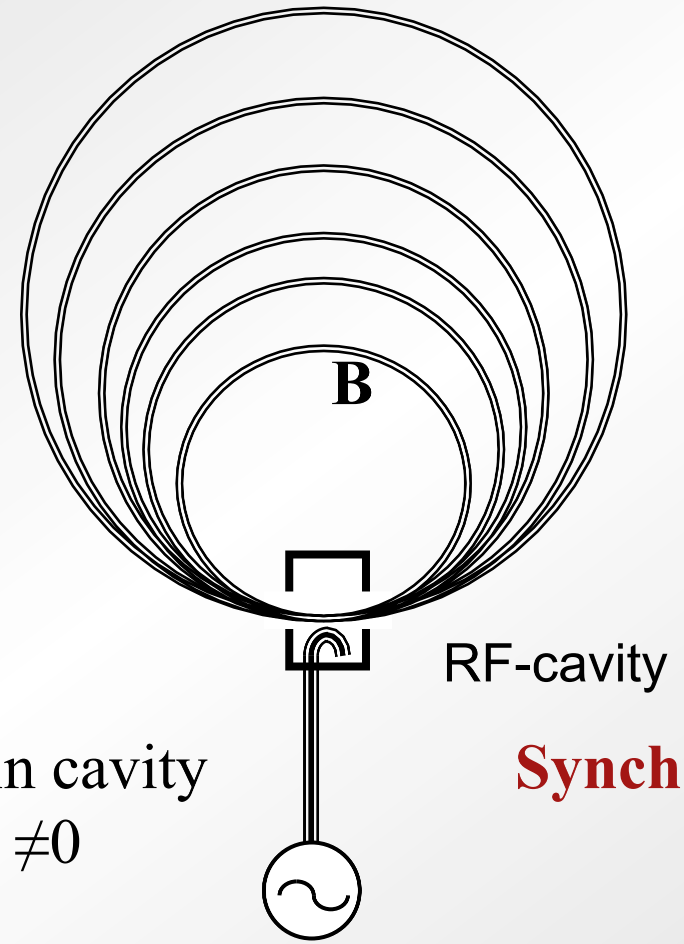




Ultra-relativistic particles can "surf" the RF-field traveling at c



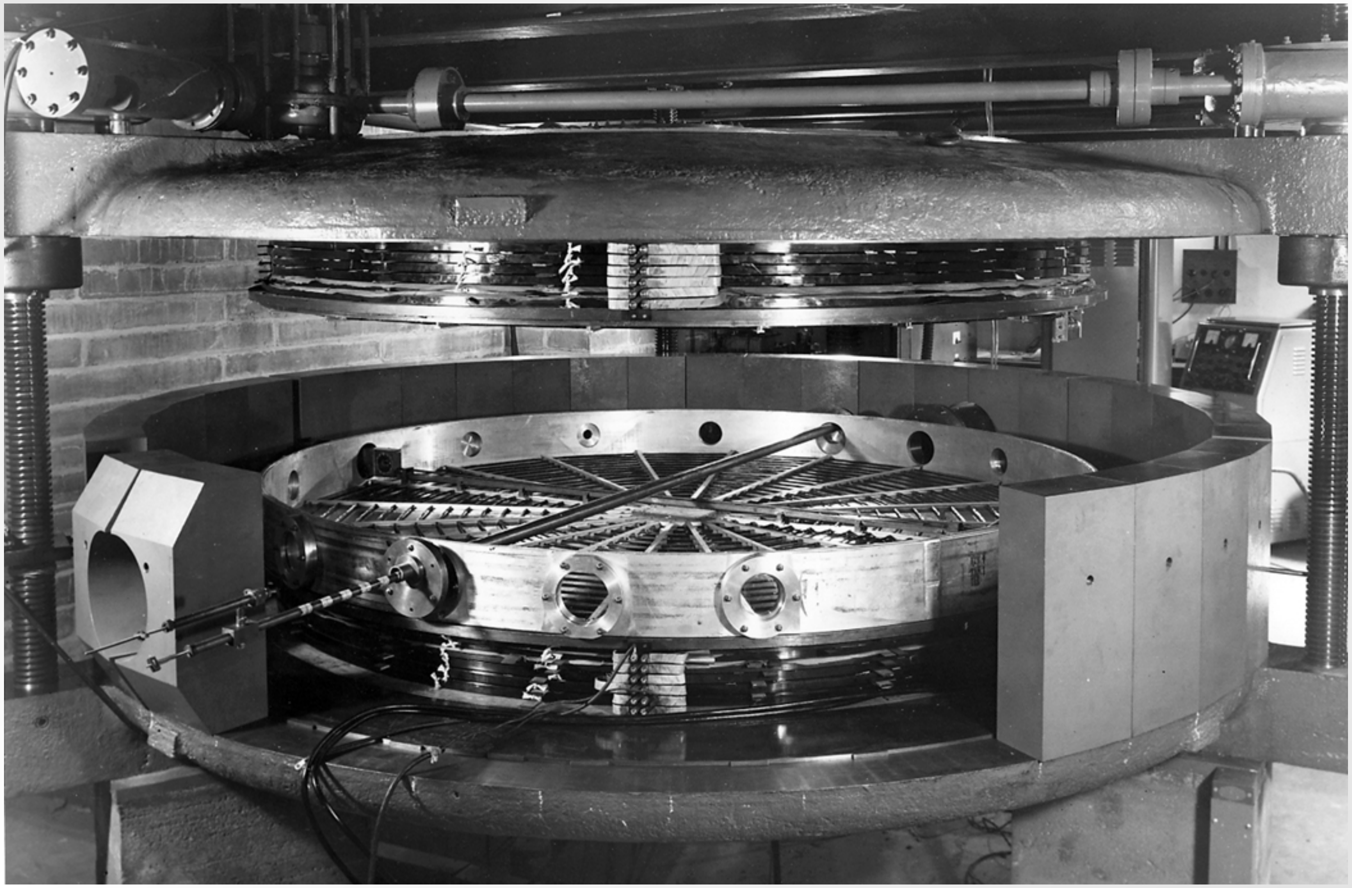
Linac size is set by E_{gap}; why not one gap? Microtron



Note that in cavity
$dB/dt \neq 0$

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

28 MeV Microtron at HEP Laboratory University College London



Synchronism in the Microtron

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

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

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

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

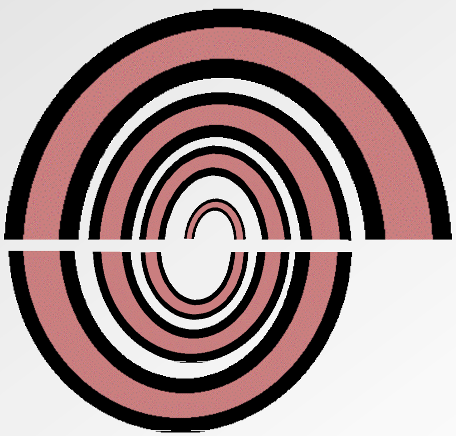
If N = 1 for the first turn @ $\gamma \sim 1$

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

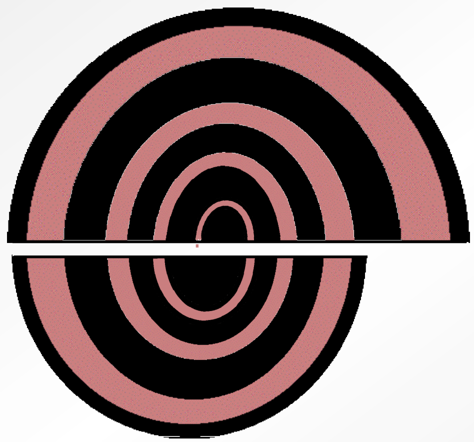
Possible for electrons but not for ions

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

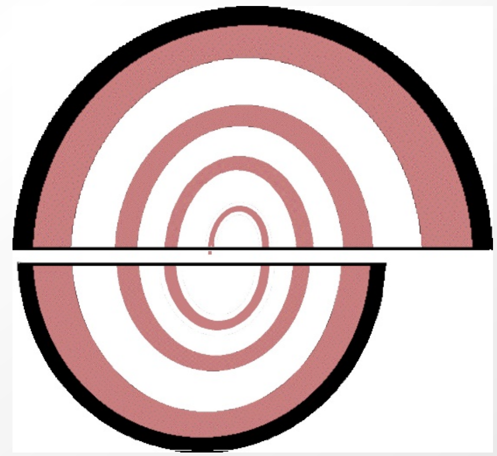
Bend the drift tubes



Connect equipotentials



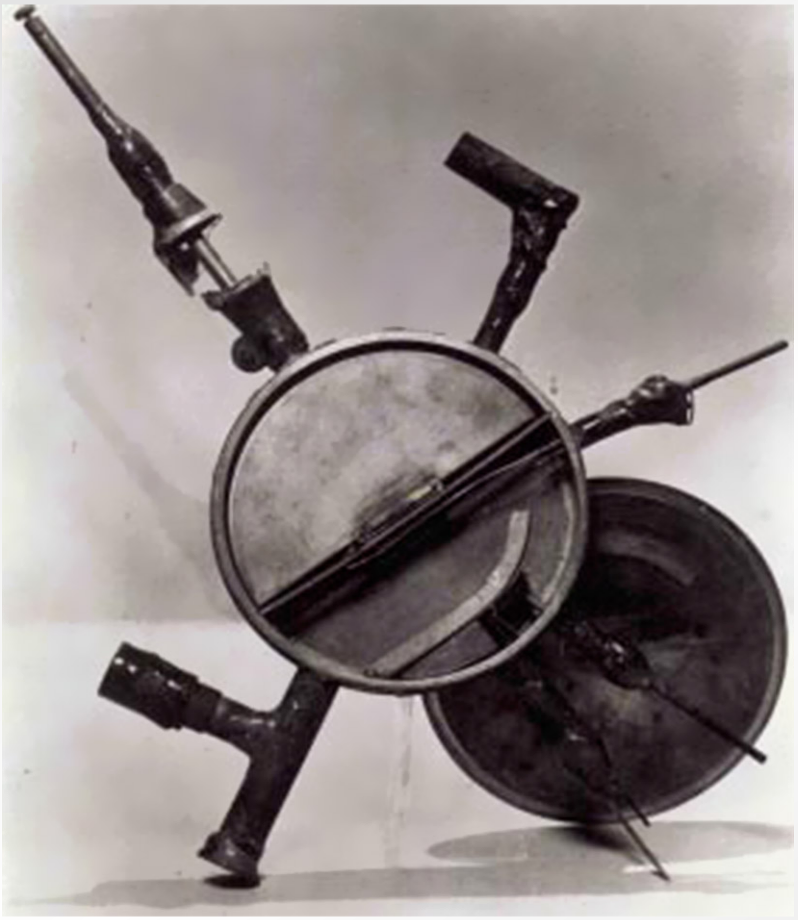
Eliminate excess Cu

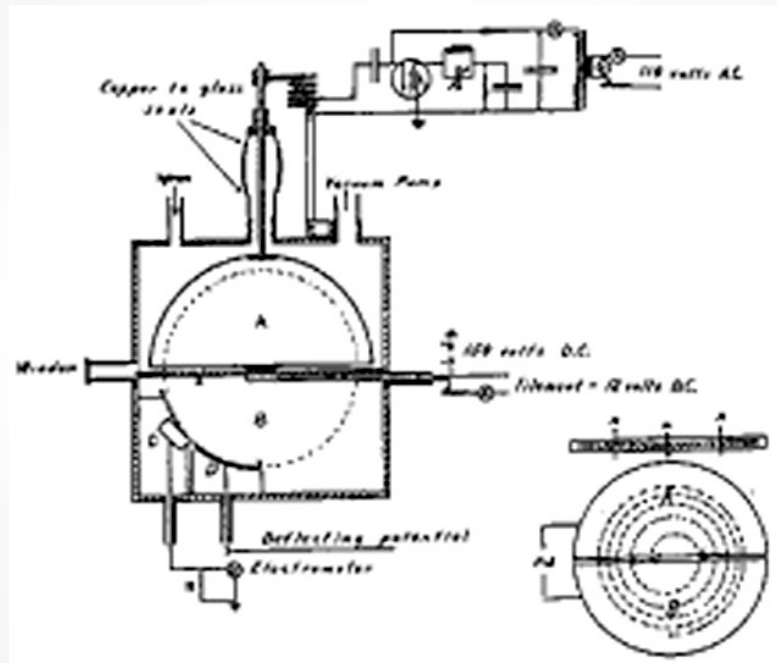


Supply magnetic field to bend beam

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

And we have…

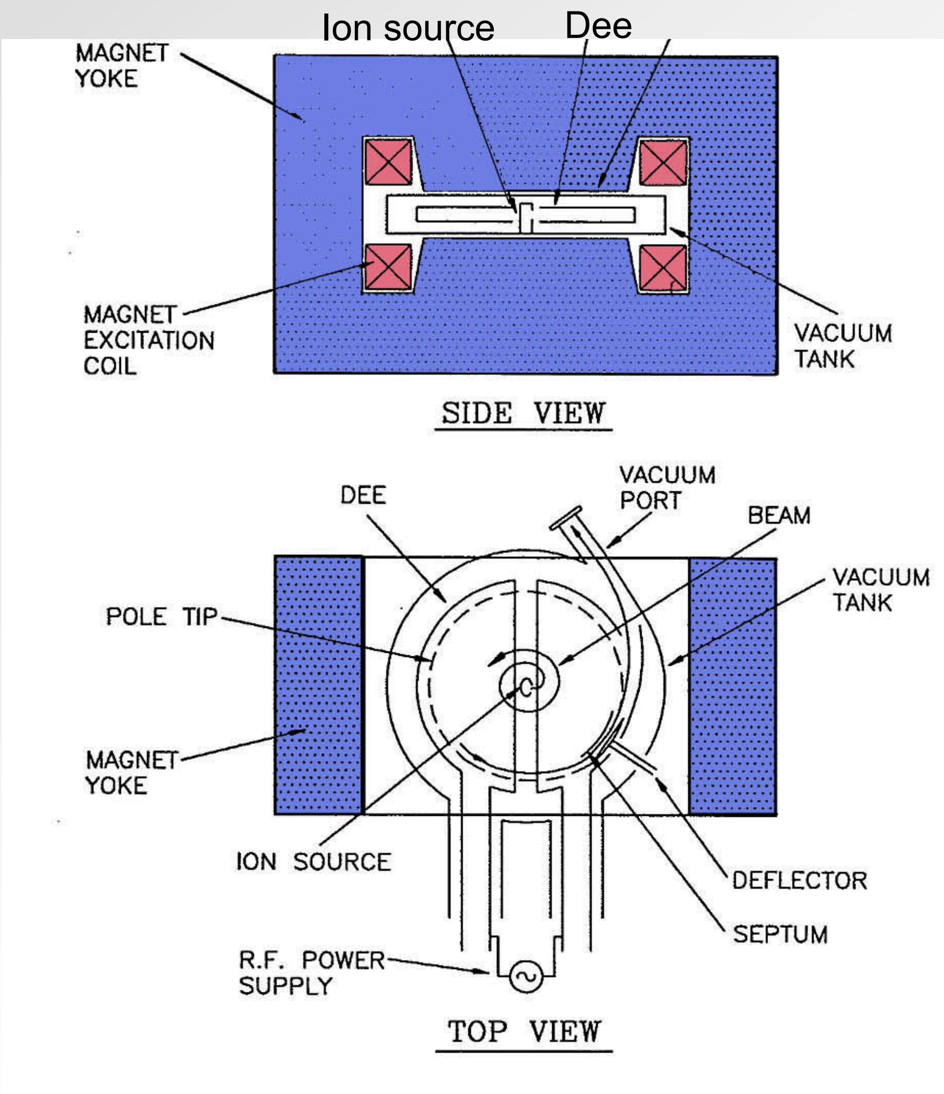


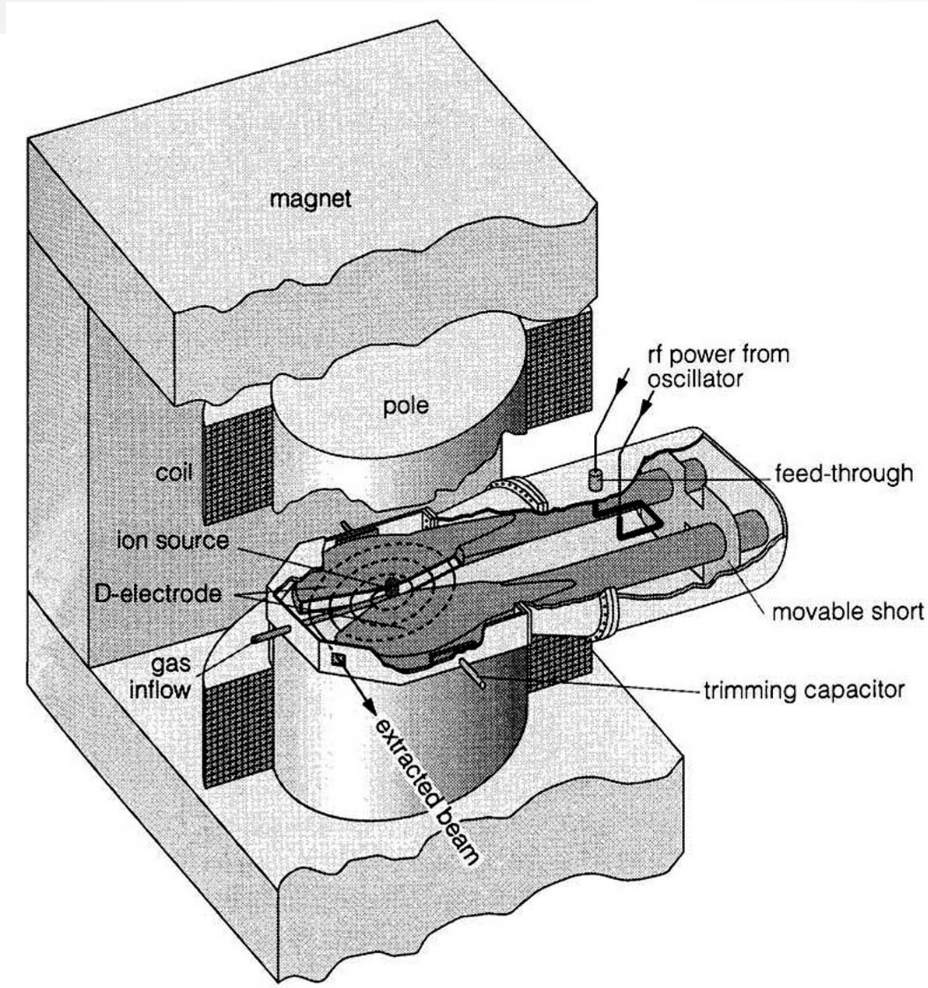


Lawrence, E.O. and Sloan, D.: Proc. Nat. Ac. Sc., 17, 64 (1931)

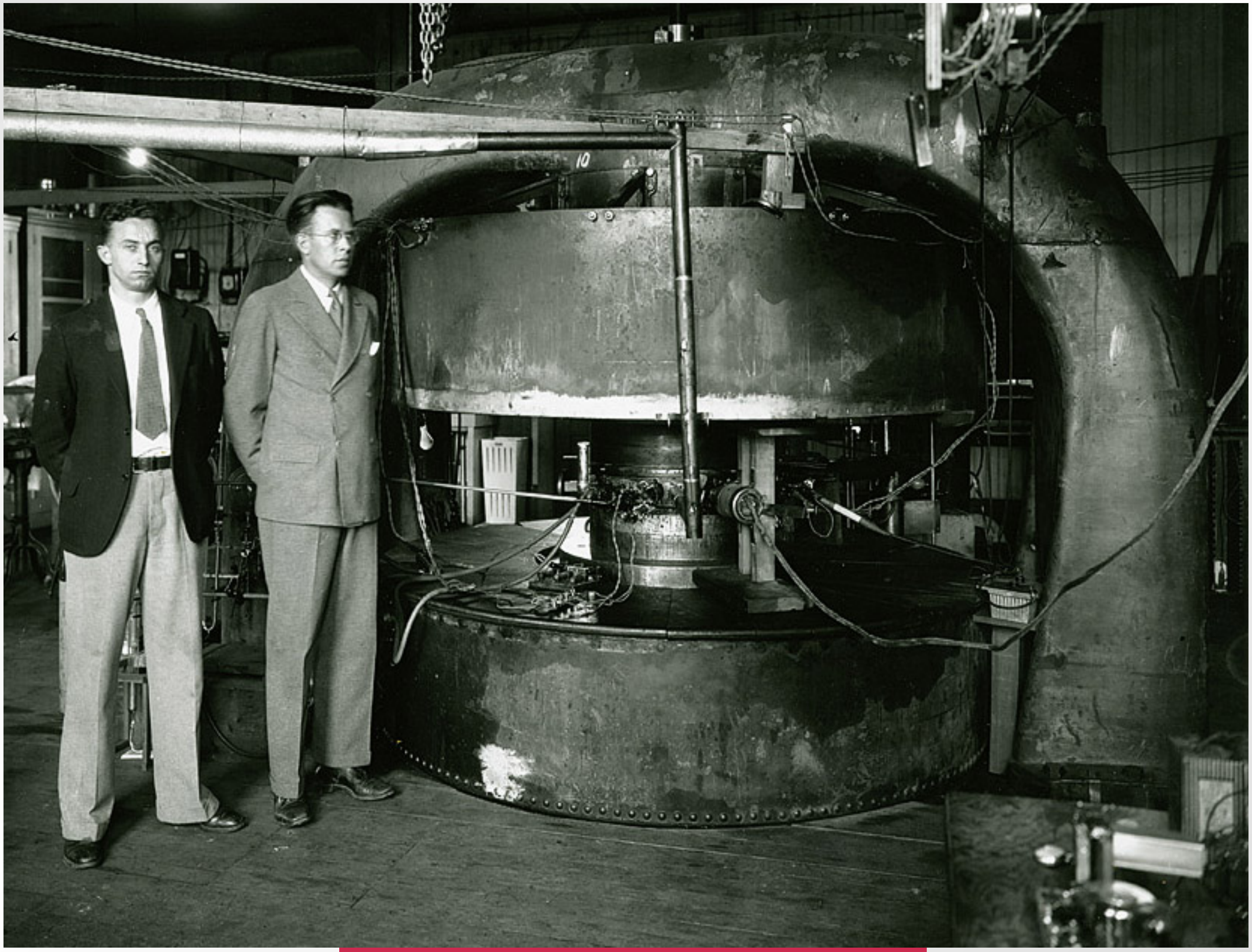
Lawrence, E.O. & Livingstone M.S.: Phys. Rev 37, 1707 (1931).

The classic cyclotron



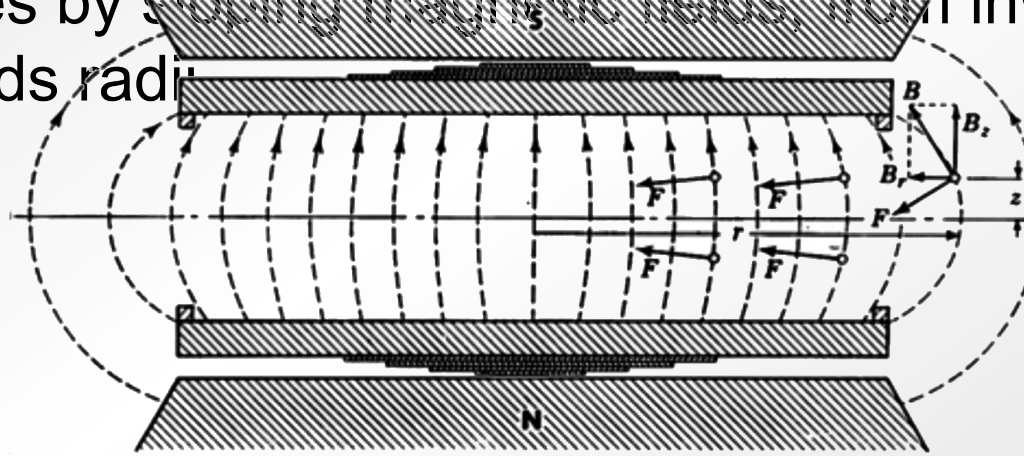


E.O. Lawrence & the 25-inch cyclotron



Orbit stability & weak focusing

- Early cyclotron builders found that the beam kept hitting the upper & lower pole pieces with a uniform field
- McMillan added vertical focusing of circulating particles by sloping magnetic fields, from inwards to outwards radii



- At any given moment, the average vertical B field sensed during one particle revolution is larger for smaller radii of curvature than for larger ones

This approach works well until we violate the synchronism condition

- Recall that

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

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

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

- Therefore, synchronism fails when

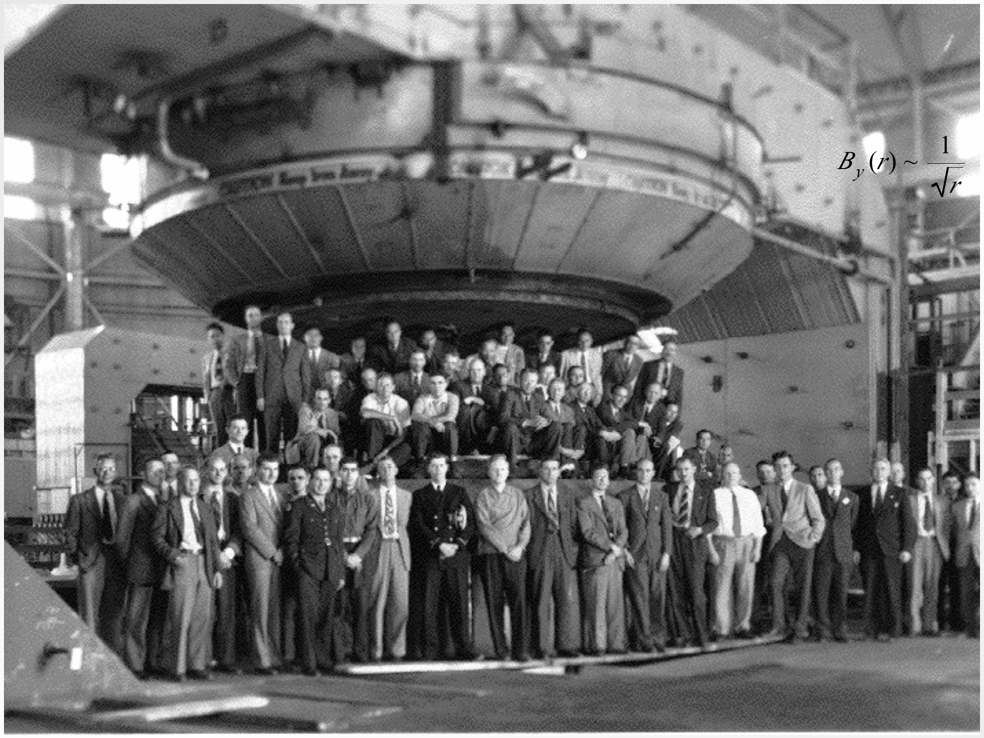
$$\tau_{rev,n} - \tau_{rev,o} = \frac{2\pi\, mc}{e}\frac{(\gamma_n - 1)}{B} \approx \Delta f_{rf}$$

An obvious invention fixes this problem: Change f_{rf} ==> the synchro-cyclotron

- For B = constant, to maintain synchronism

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

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



Ex: Lawrence's 184-in cyclotron

R_{max} = 2.337 m

B = 1.5 T

$M_{yoke} \approx$ 4300 tons !!

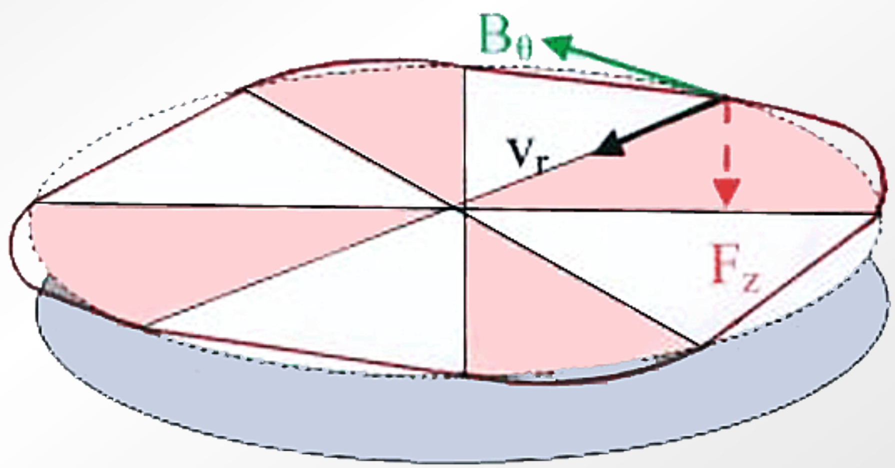
But this requires pulsed rather than CW operation

(one bunch in the machine at a time)

==> Average current is reduced by the number of turns to full energy (~1000x) to ~ 0.1 μA

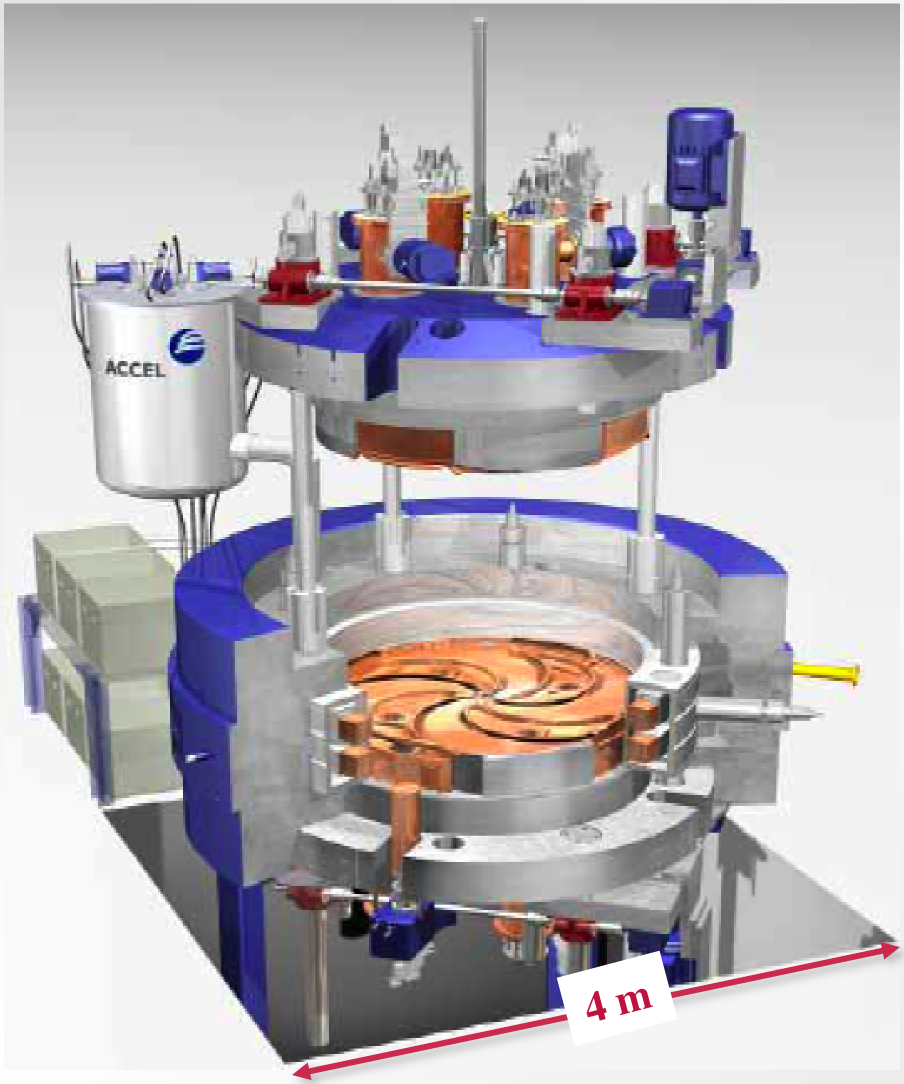
A different way to maintain synchronism: vertical (Thomas) focusing (1938)

- We need to find a way to increase the vertical focusing
- One can obtain $\mathbf{F_z}$ with $\mathbf{v_r}$, $\mathbf{B_\theta}$
- ==> find an azimuthal component B_θ & a radial velocity component $\mathbf{v_r}$
- ==> a non-circular trajectory



===> Sectors & B increases with radius

Spiraled cyclotrons for proton therapy



Energy range: ~100 - 230 MeV

Current: 5 nA - 500 nA

~ 240 tonnes

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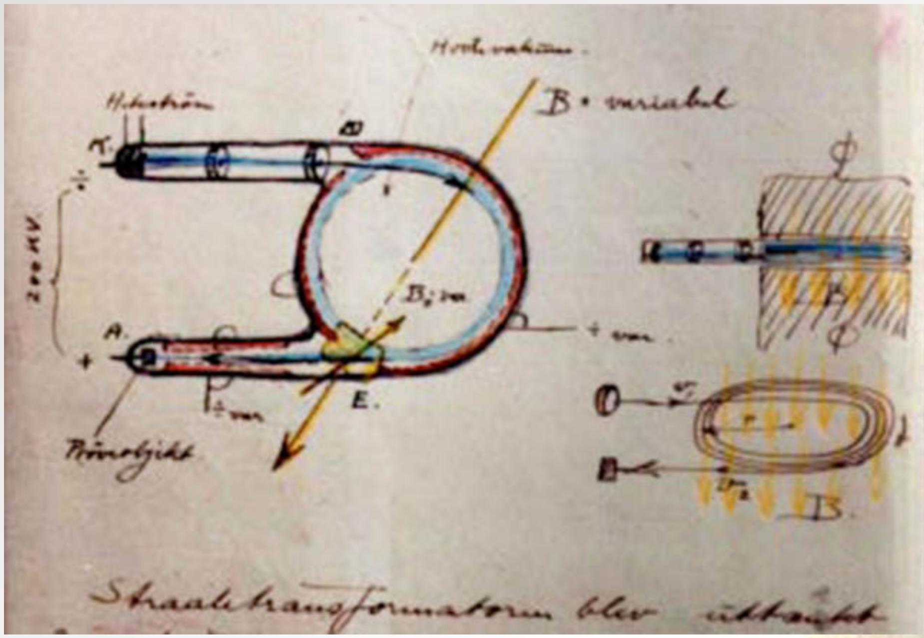
Can the cyclotron reach ultra-relativistic energies?

Remember

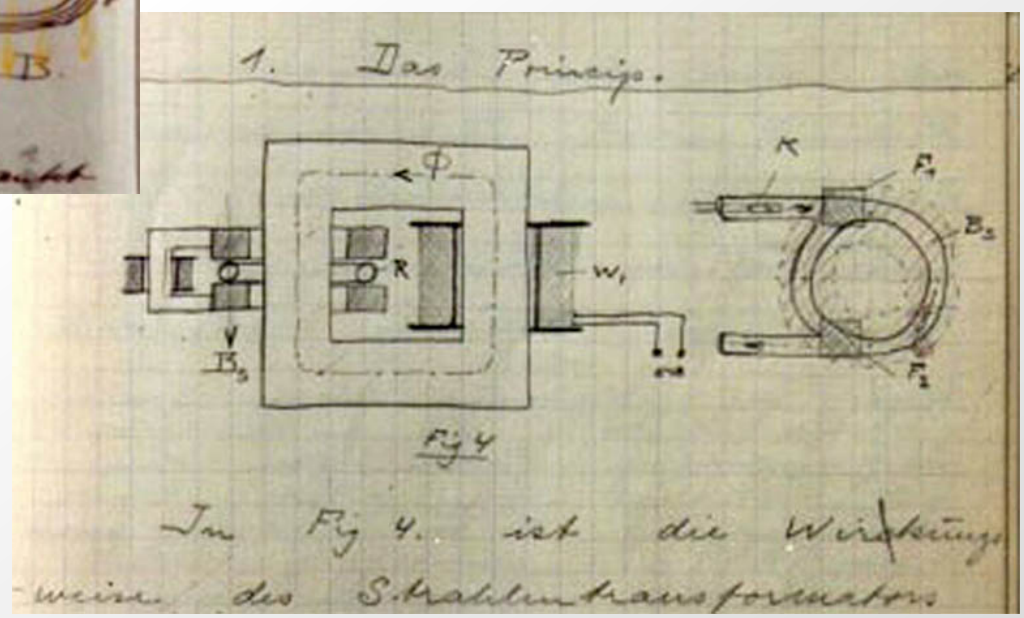
$$p \sim B\rho$$

(5 minute exercise)

Wiederoe's Ray Transformer for electrons



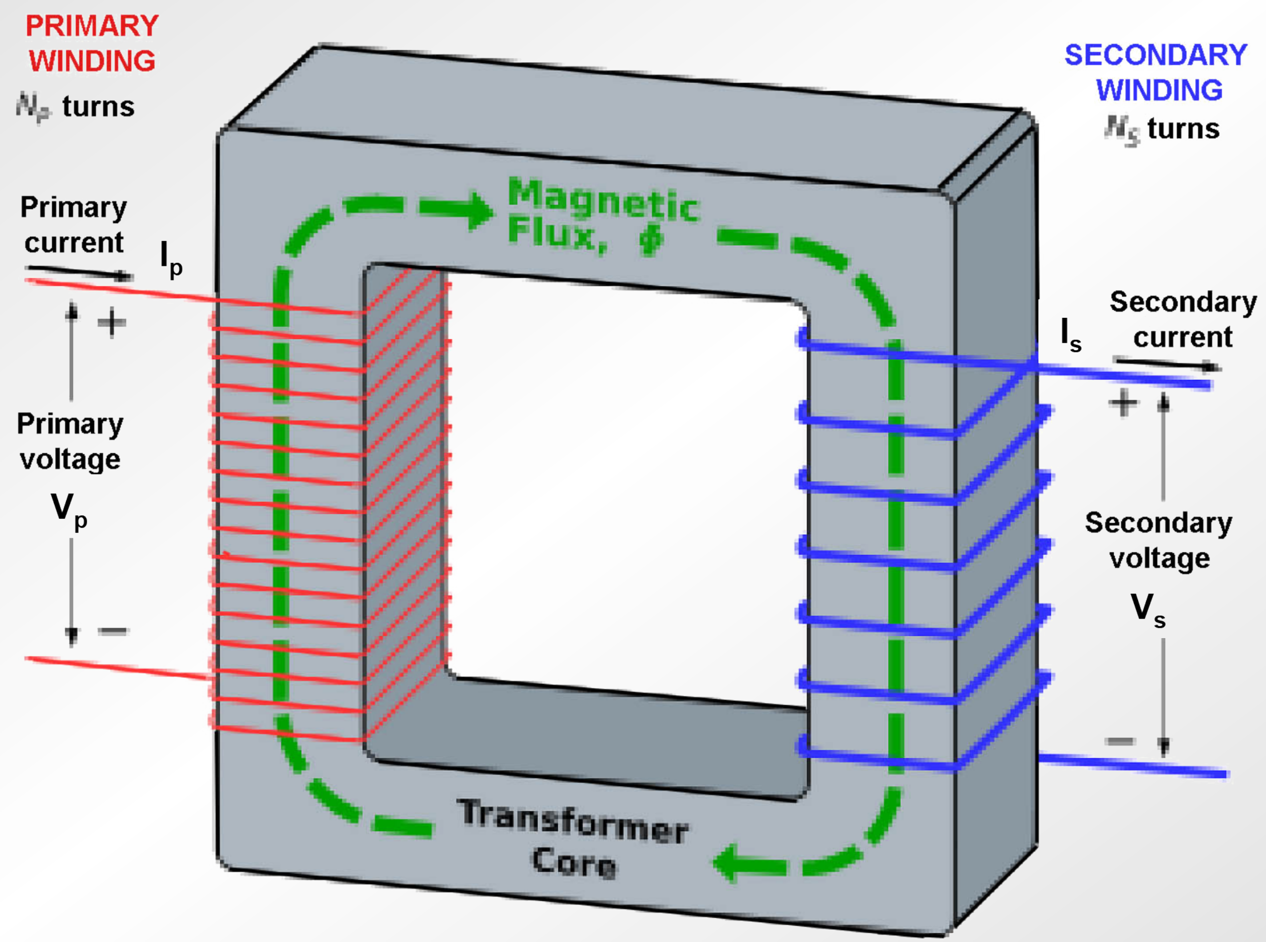
From Wiederoe's notebooks (1923-'28)



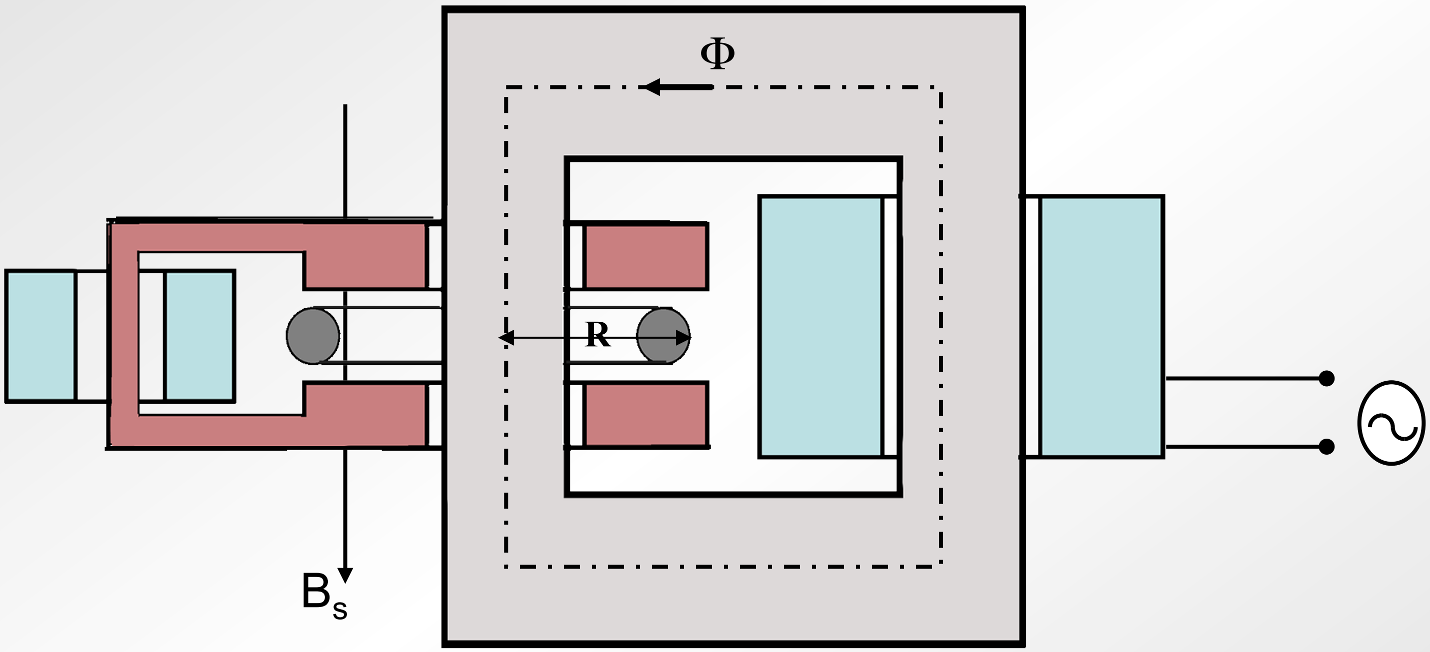
He was dissuaded by his professor from building the ray transformer due to worries about beam-gas scattering

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

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

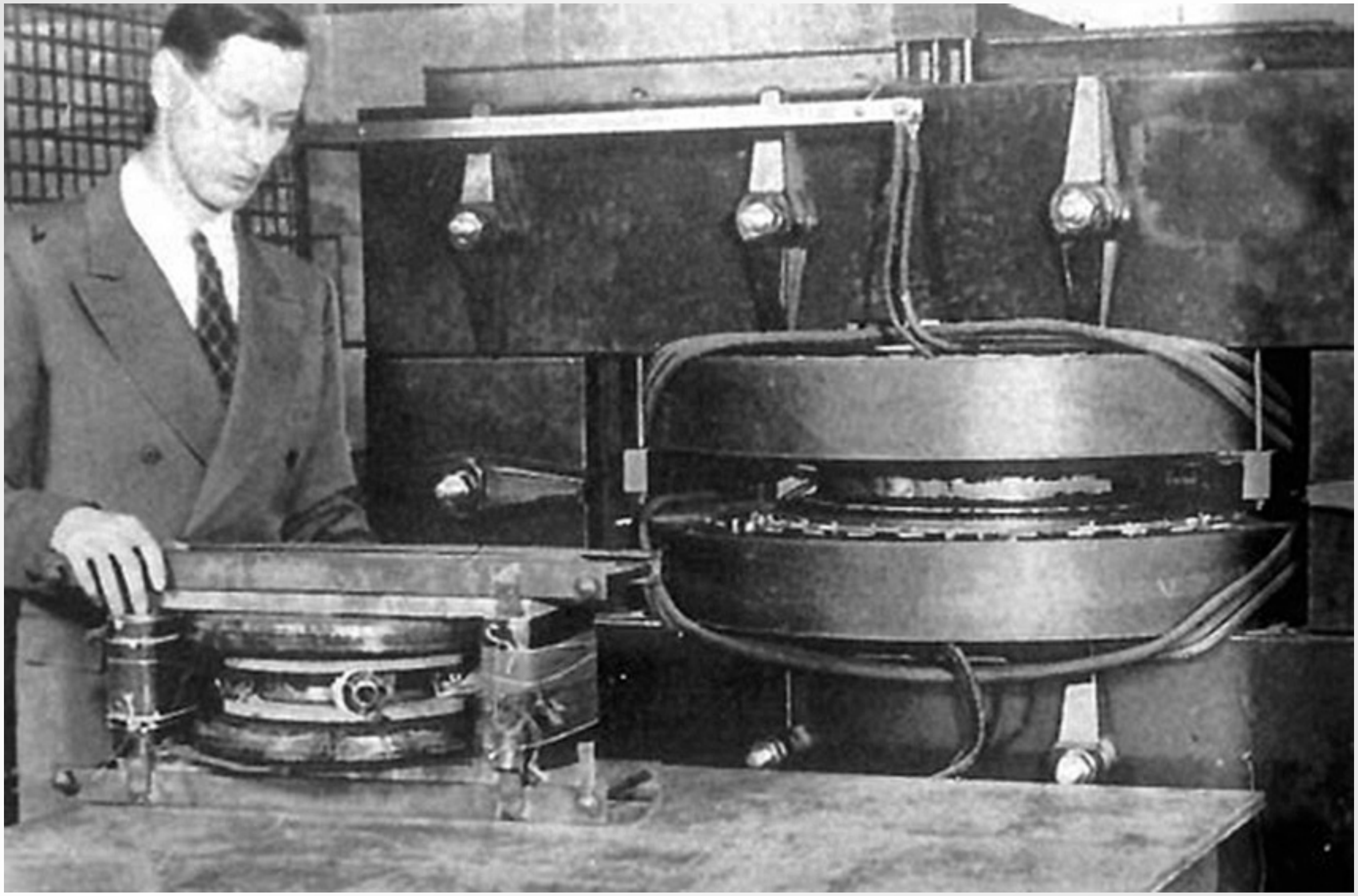
For the orbit size to remain invariant:

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

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

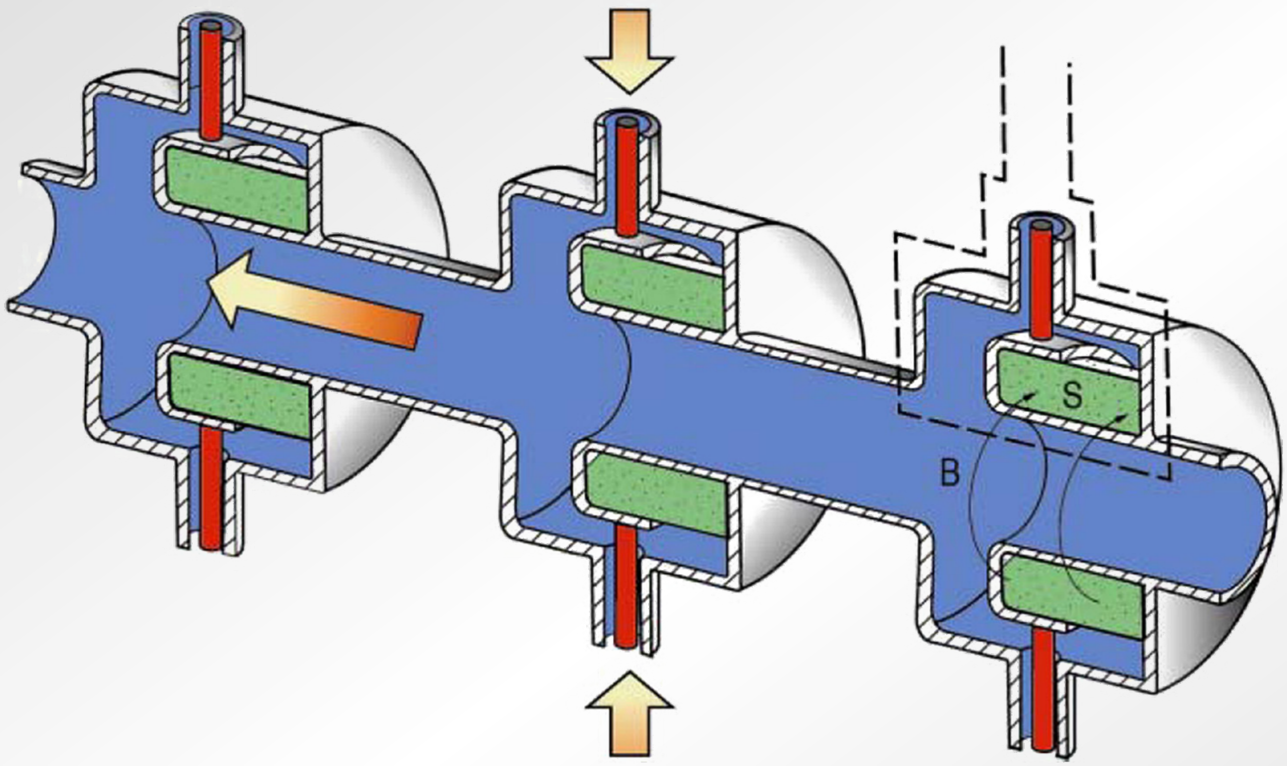
$$\boxed{\dot{\Phi} = 2\pi R^2 \dot{B}_s}$$

Donald Kerst's betatrons



Kerst originally used the phrase, Induction Accelerator

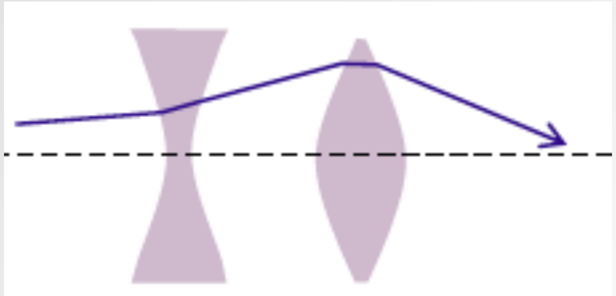
The Linear Betatron:
Linear Induction Accelerator



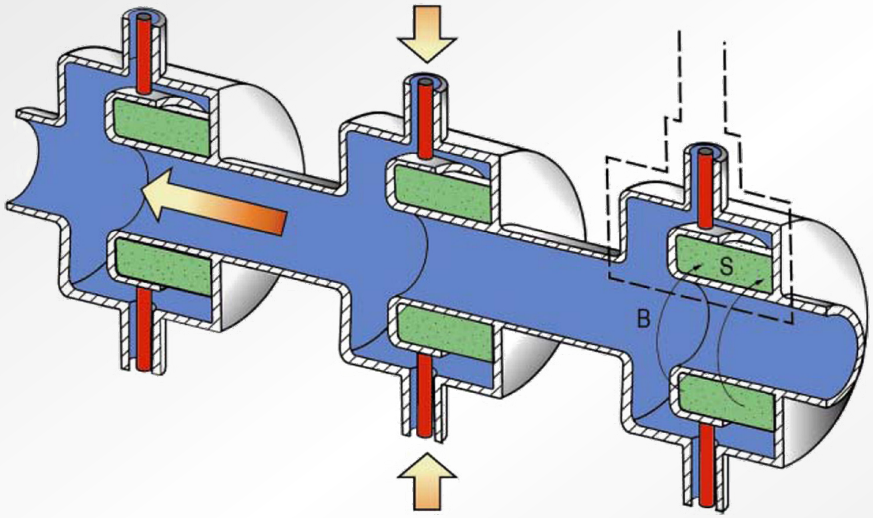
N. Christofilos

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

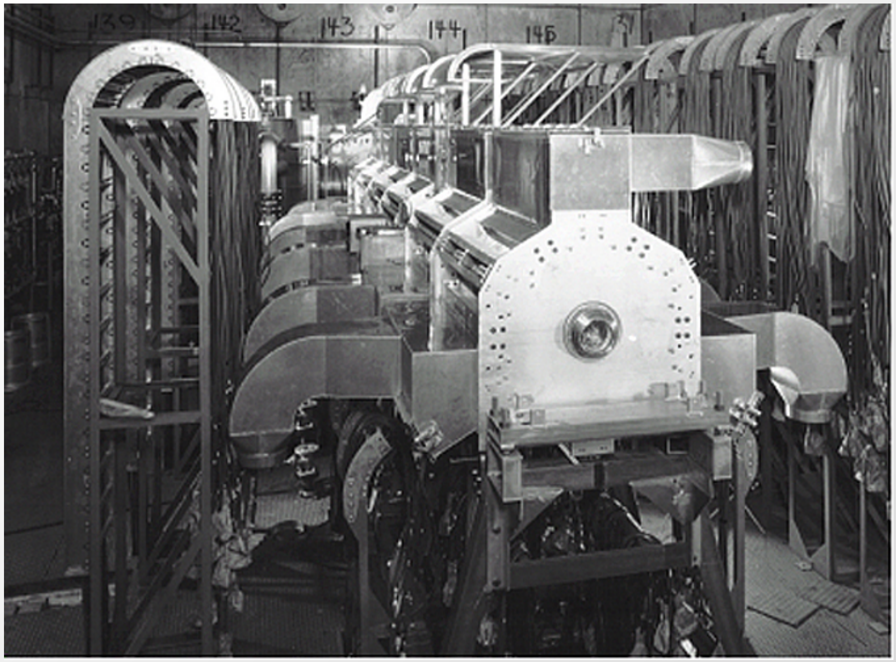
Christofilos' contributions to accelerator science



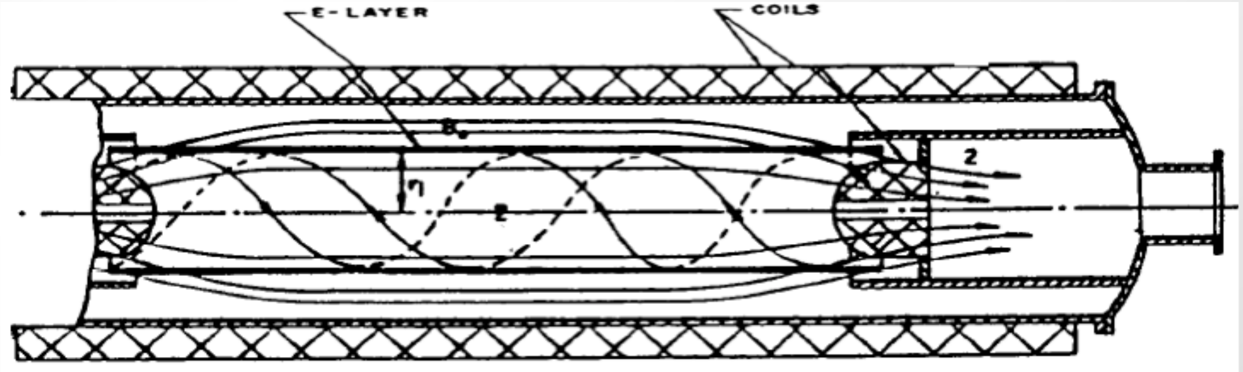
Strong focusing (1949)



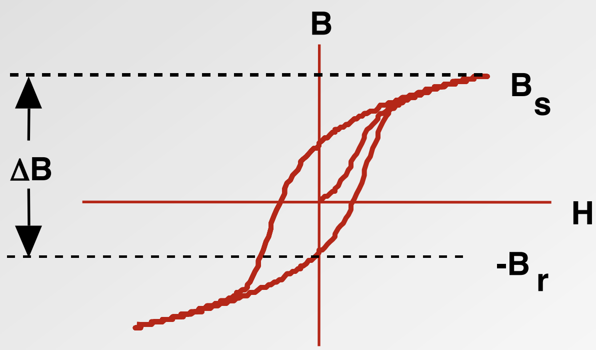
Induction linac (1949)



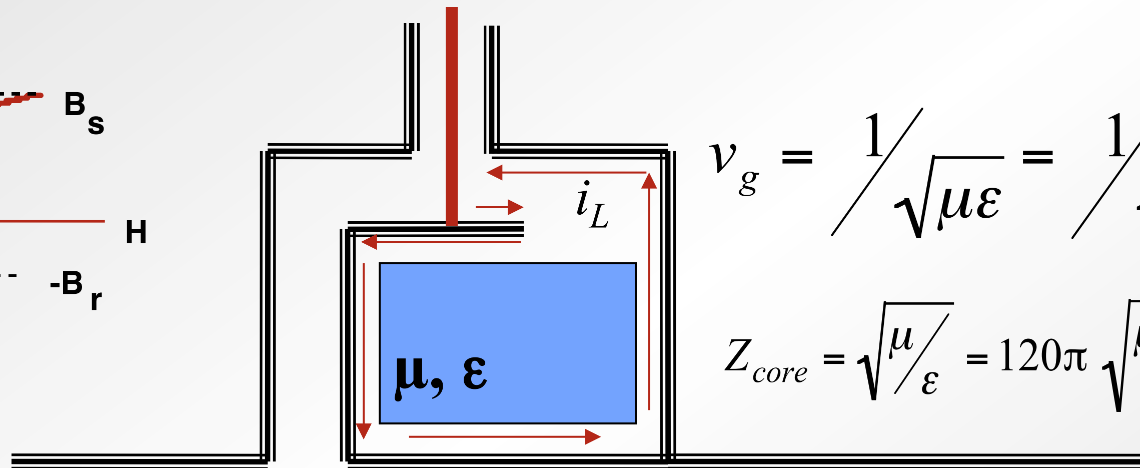
Christofilos' Astron Induction Linac & Astron CTR (1966)



A closer look at the induction cell



Core hysteresis loop



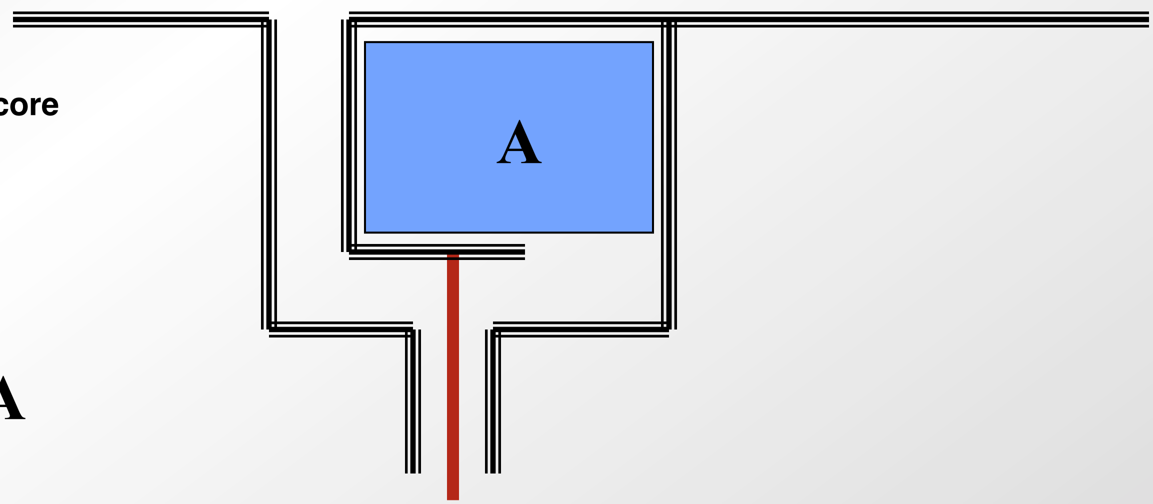
$$v_g = 1\Big/\sqrt{\mu\varepsilon} = 1\Big/\sqrt{\mu_r\varepsilon_r}$$

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

Leakage current magnetizes core

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

$$V \cdot \Delta t = \Delta B \cdot A$$

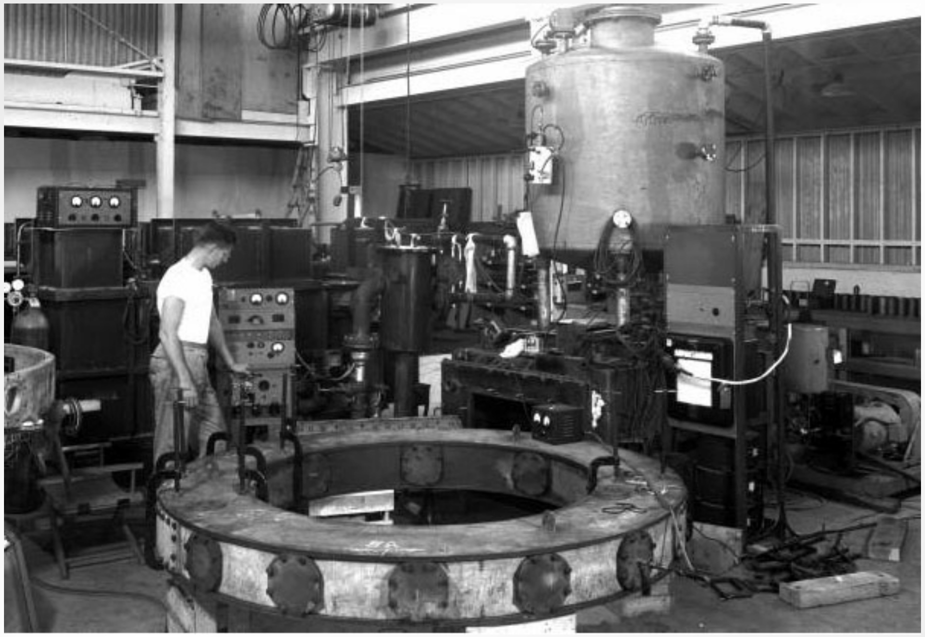


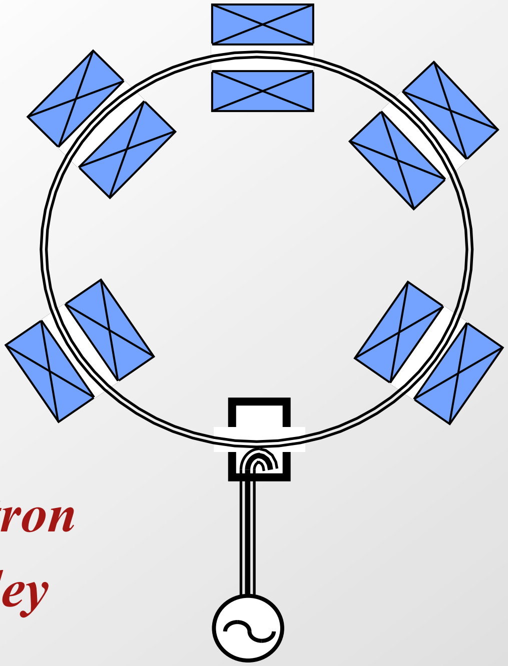
Induction accelerators occupy a special niche, but now on to the mainstream

The size of monolithic cyclotron 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?

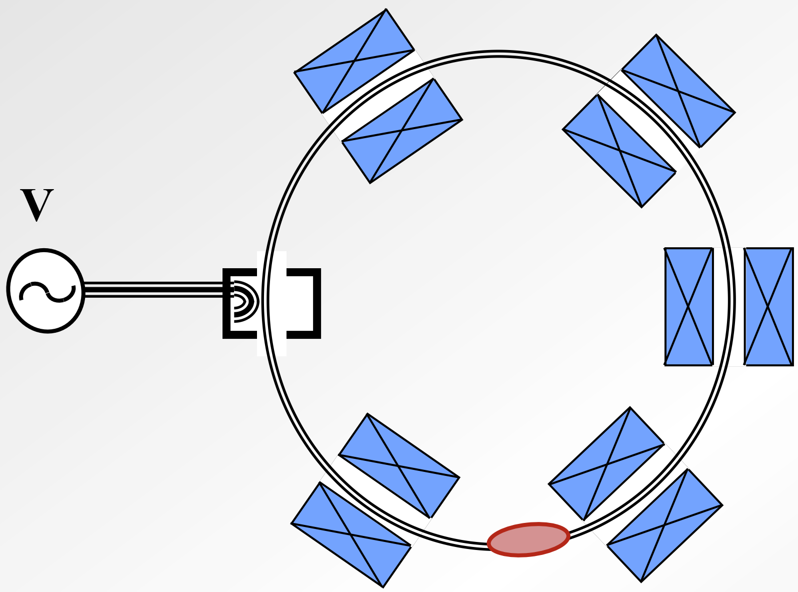




Synchrotron at Berkeley

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

Phase stability: Will bunch of finite length stay together & be accelerated?

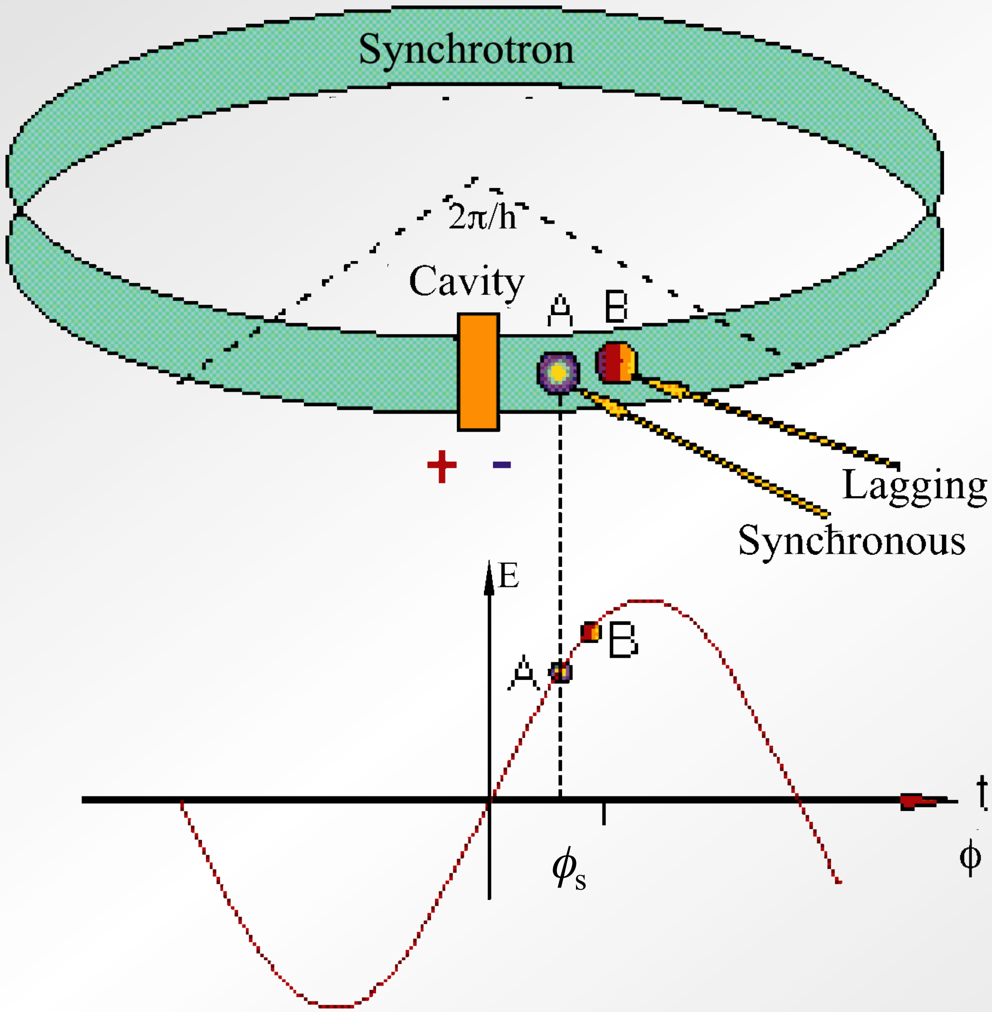


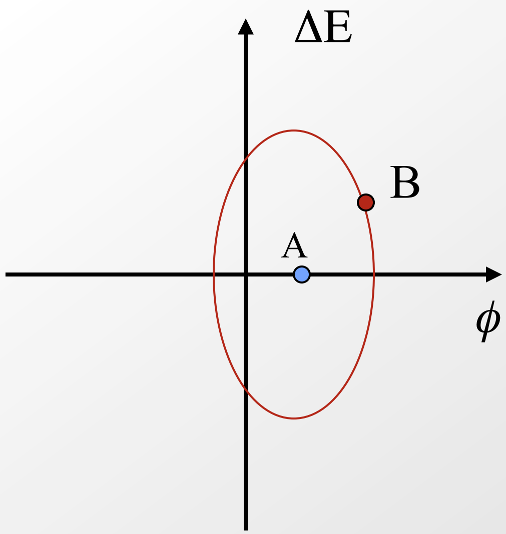
Let's say that the synchronous particle makes the i^{th} revolution in time: T_i

Will particles close to the synchronous particle in phase stay close in phase?

Discovered by MacMillan & by Veksler

What do we mean by phase?
Let's consider non-relativistic ions



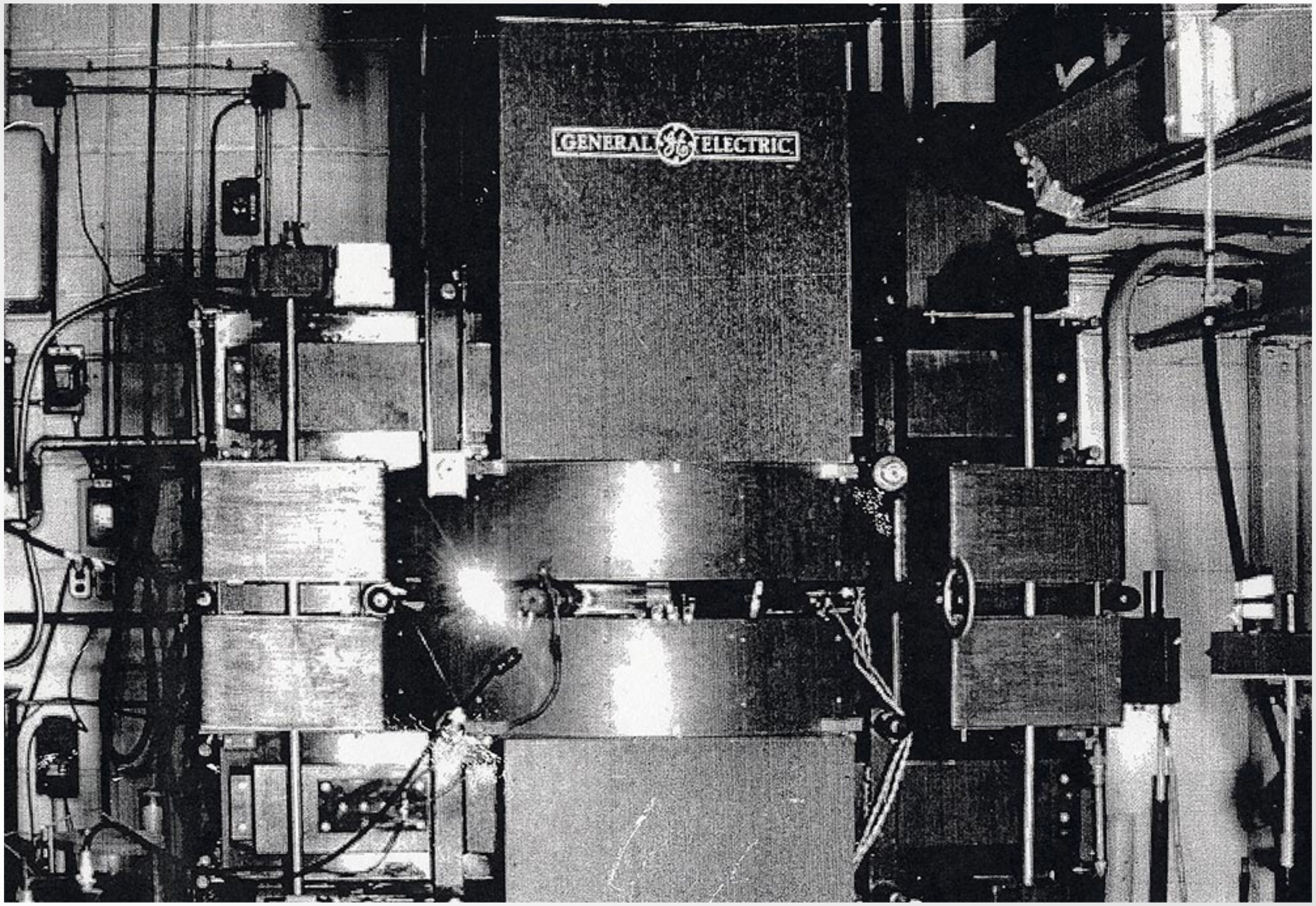


How does the ellipse change as B lags further behind A?

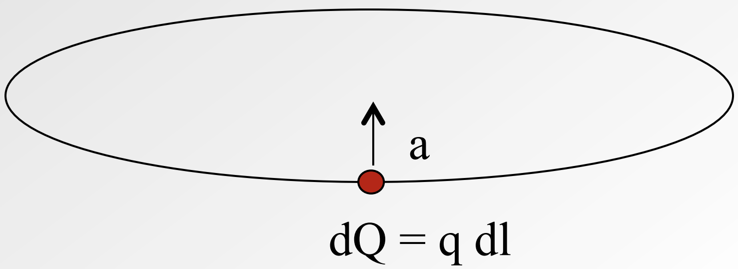
From E. J. N. Wilson CAS lecture

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

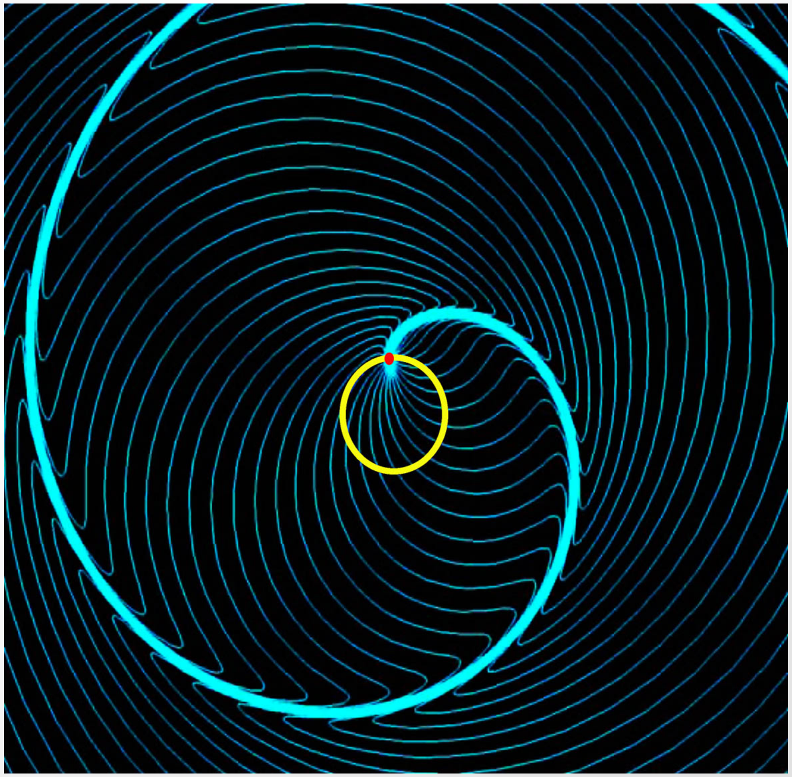


Charges in circular orbit at constant speed radiate incoherently in a $1/\gamma$ cone



$$N_\gamma = 2\pi\alpha\gamma N_e \text{ per revolution}$$

Electric field lines from a charge in circular motion



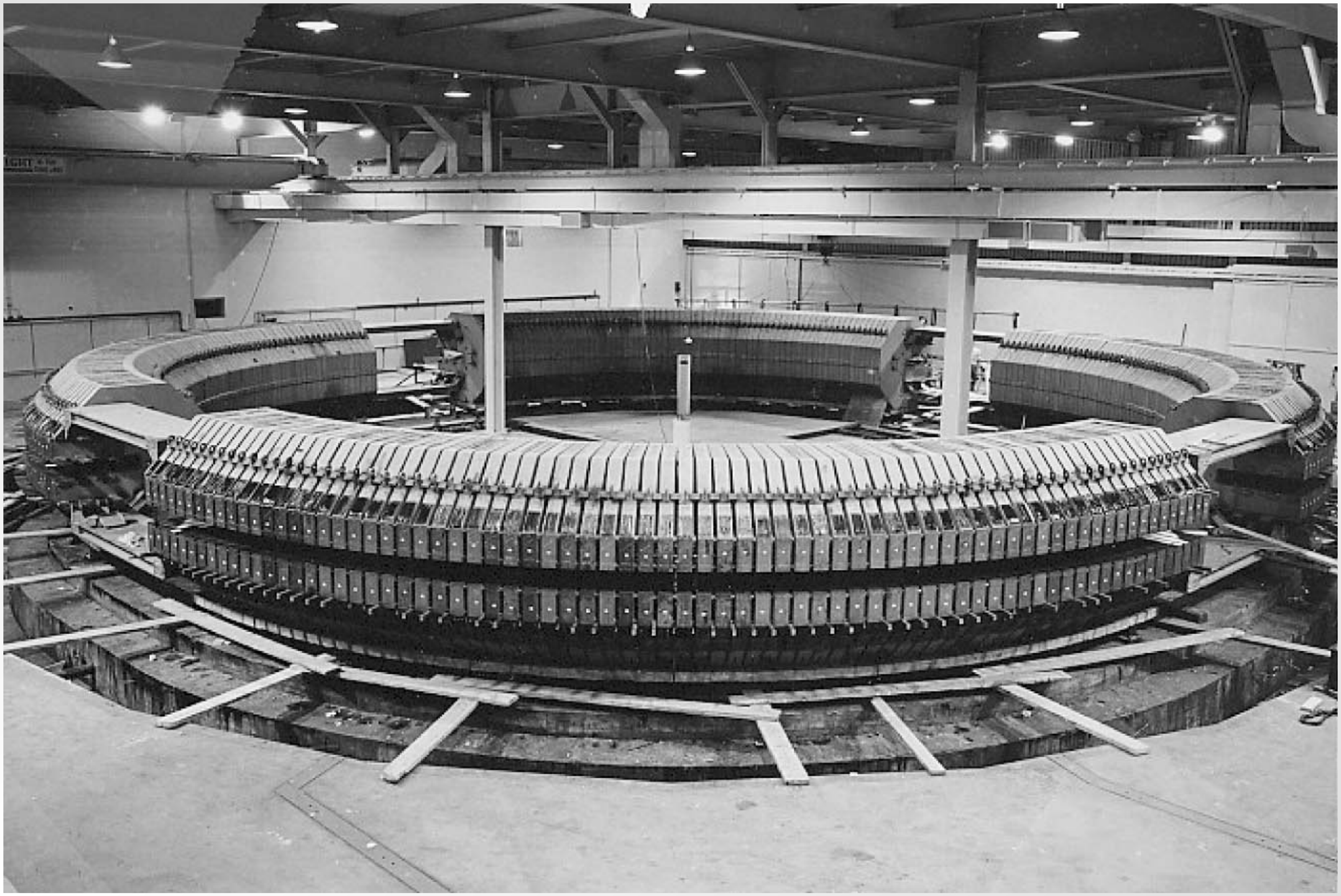
Field energy flows to infinity

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

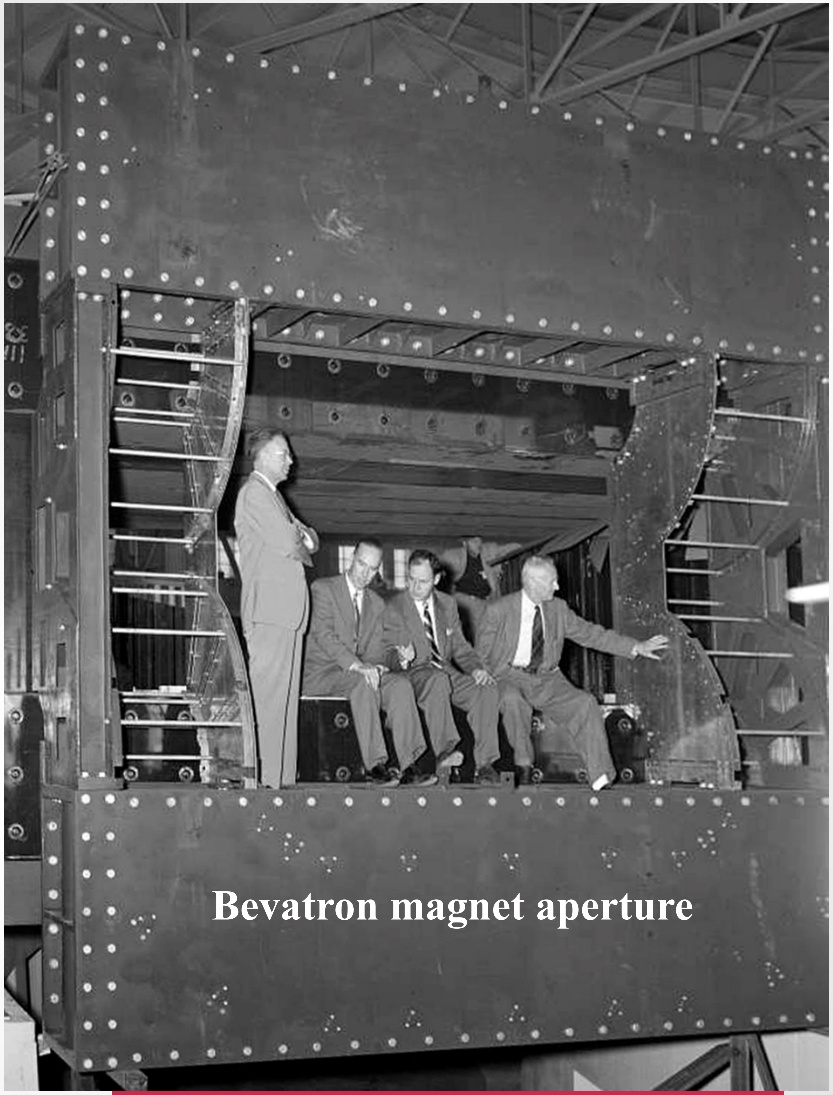
- 3-BeV "Cosmotron" at the Brookhaven (1952)
  - 2000 ton magnet in four quadrants
  - 1 second acceleration time
  - Shielding recognized as major operational issue
- 1-BeV machine at Un. of Birmingham (UK) in 1953
  - Laminated magnets, no field free straight sections
- 6 BeV "Bevatron" University 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

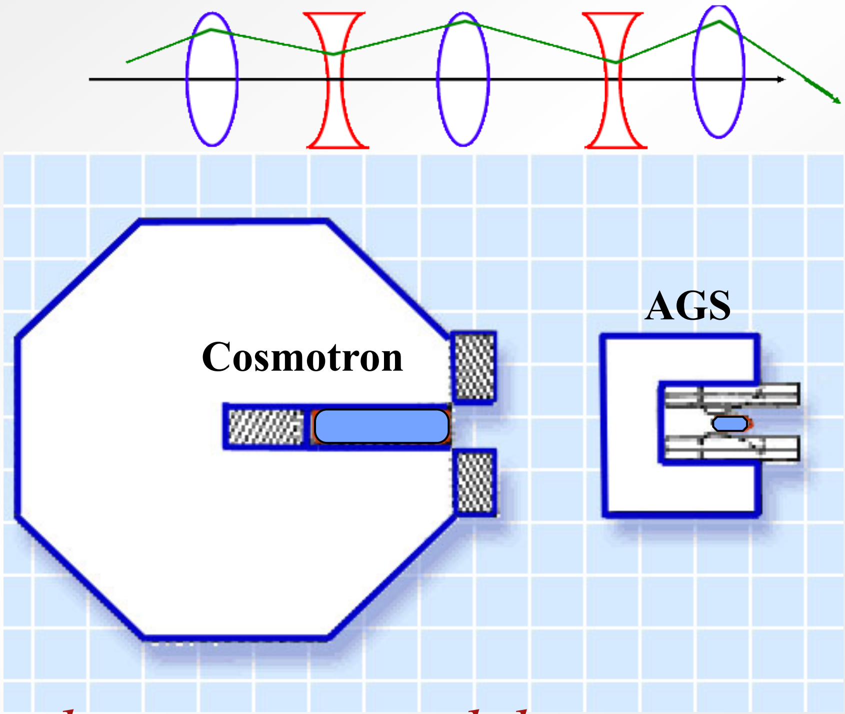


The vacuum chamber of the 6 GeV Bevatron could fit whole physicists



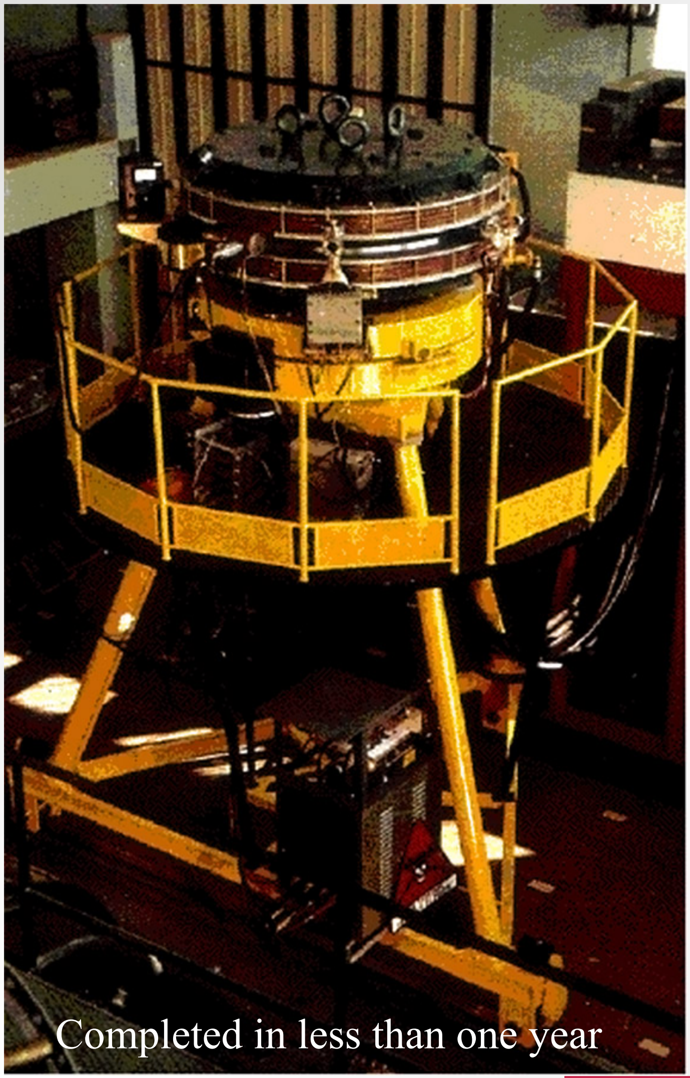
Strong focusing allowed shrinking the vacuum chamber to reasonable sizes

- 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 (WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM 11. MAI 1953

DEUTSCHES PATENTAMT

PATENTSCHRIFT

Nr. 876 279

KLASSE 21g GRUPPE 36

W 687 VIIIc / 21g

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

Aktiengesellschaft Brown, Boveri & Cie, Baden (Schweiz)

Anordnung zur Herbeiführung von Kernreaktionen

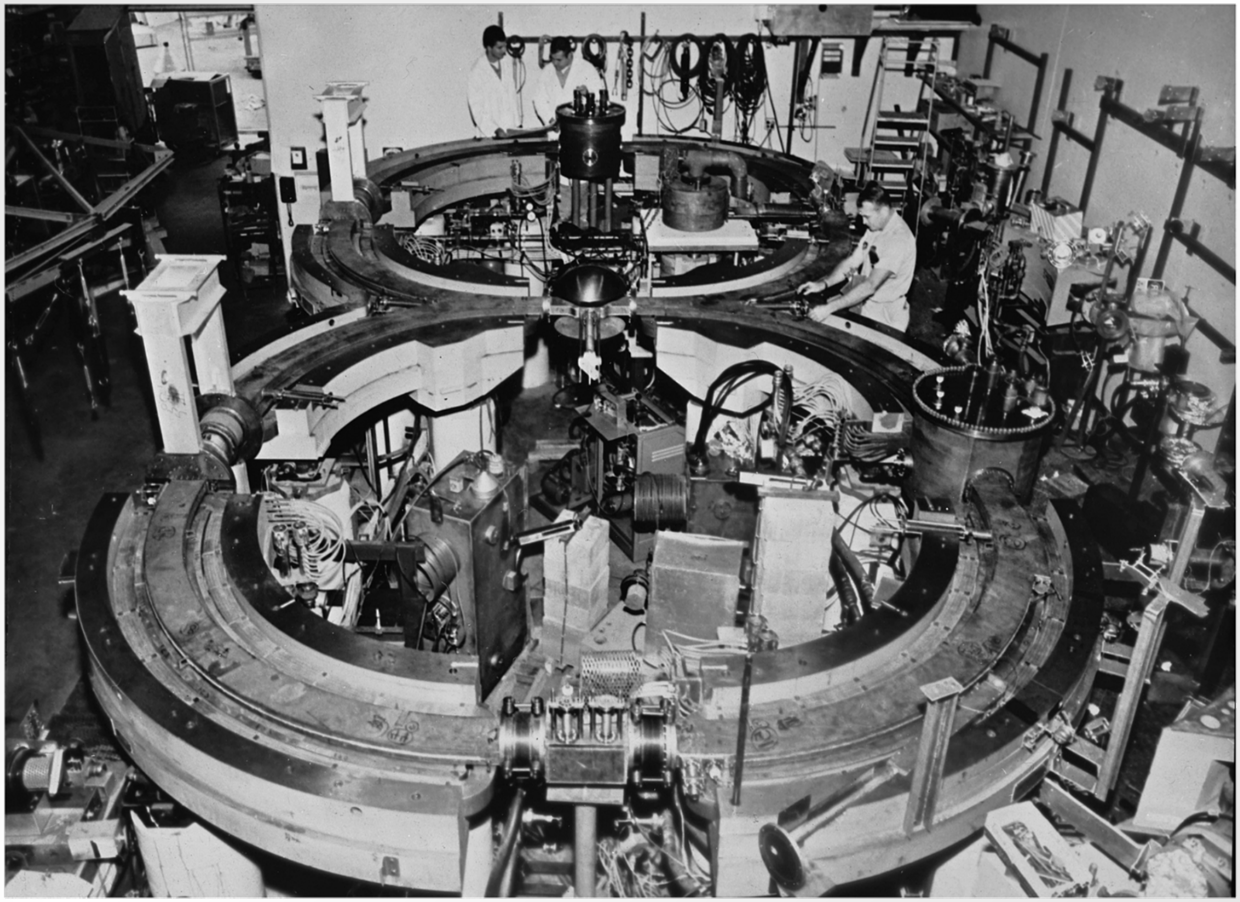
Patentiert im Gebiet der Bundesrepublik Deutschland vom 8. September 1943 an
Patentanmeldung bekanntgemacht am 18. September 1952
Patenterteilung bekanntgemacht am 26. März 1953

Kernreaktionen können dadurch herbeigeführt werden, daß geladene Teilchen von hoher Geschwindigkeit und Energie, in Elektronenvolt gemessen, auf die zu untersuchenden Kerne geschossen werden. Wenn die geladenen Teilchen in einen gewissen Mindestabstand von den Kernen gelangen, werden die Kernreaktionen eingeleitet. Da aber neben den zu untersuchenden Kernen noch die gesamten Elektronen der Atomhülle vorhanden sind und auch der Wirkungsquerschnitt des Kernes sehr klein ist, wird der größte Teil der geladenen Teilchen von den Hüllenelektronen abgebremst, während nur ein sehr kleiner Teil die gewünschten Kernreaktionen herbeiführt.

Erfindungsgemäß wird der Wirkungsgrad der Kernreaktionen dadurch wesentlich erhöht, daß die Reaktion in einem Vakuumgefäß (Reaktionsröhre) durchgeführt wird, in welchem die geladenen Teilchen hoher Geschwindigkeit gegen einen Strahl von den zu untersuchenden und sich entgegengesetzt bewegenden Kernen auf einer sehr langen Strecke laufen müssen. Dies kann in der Weise durchgeführt werden, daß die geladenen Teilchen zum mehrmaligen Umlauf in einer Kreisröhre gezwungen werden, wobei die zu untersuchenden Kerne auf derselben Kreisbahn, aber in entgegengesetzter Richtung umlaufen. Da die geladenen Teilchen dabei nicht von bei der Reaktion unwirksamen Elektronen abgebremst werden und andererseits auf einer sehr langen Wegstrecke gegen die Kerne sich bewegen können, wird die Wahrscheinlichkeit für das Eintreten der Kernreaktionen wesentlich größer und der Wirkungsgrad der Reaktion sehr stark erhöht.

Um die bei der Kreisbewegung entstehenden Zentrifugalkräfte aufzuheben, müssen die umlaufenden Teilchen von nach innen gerichteten Ablenkkräften gesteuert werden, während eine Diffusion der Teile mittels stabilisierender, von allen Seiten auf den Bahnkreis gerichteter Kräfte verhindert wird. Falls die gegen-

G. O' Neill is often given credit for 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

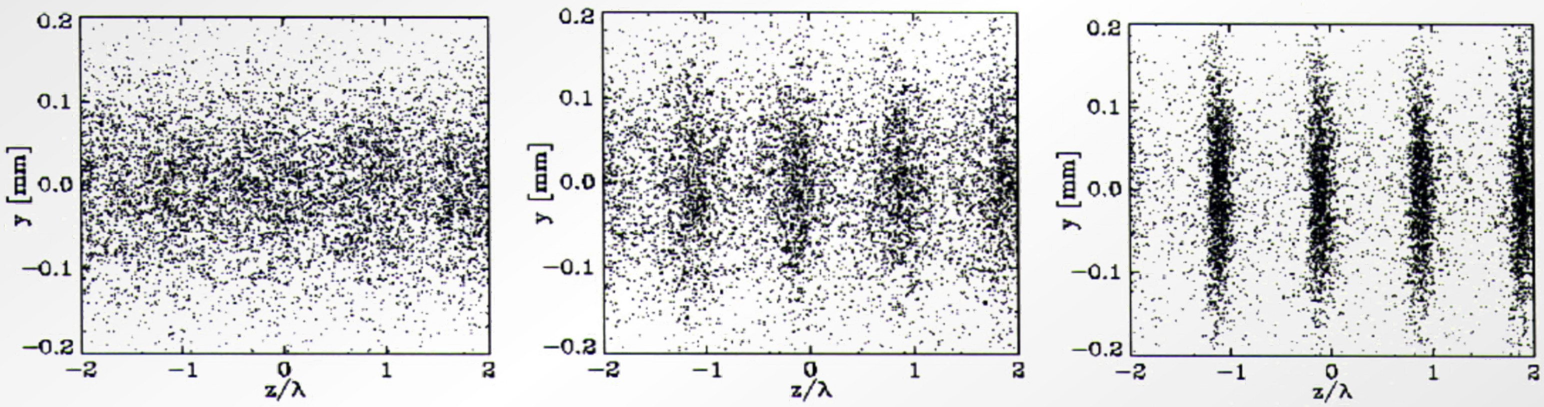
- 30 GeV per beam with > 60 A circulating current
  - Required extraordinary vacuum (10^{-11} Torr)
  - Great beam dynamics challenge - more stable than the solar system
- Then on to the 200 GeV collider at Fermilab (1972) and …
- The Sp$\bar{\text{p}}$S at CERN
  - Nobel invention:
    Stochastic cooling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

First machine to exploit superconducting magnet technology

The 70's brought another great invention

❖ The Free Electron Laser (John Madey, Stanford, 1976)

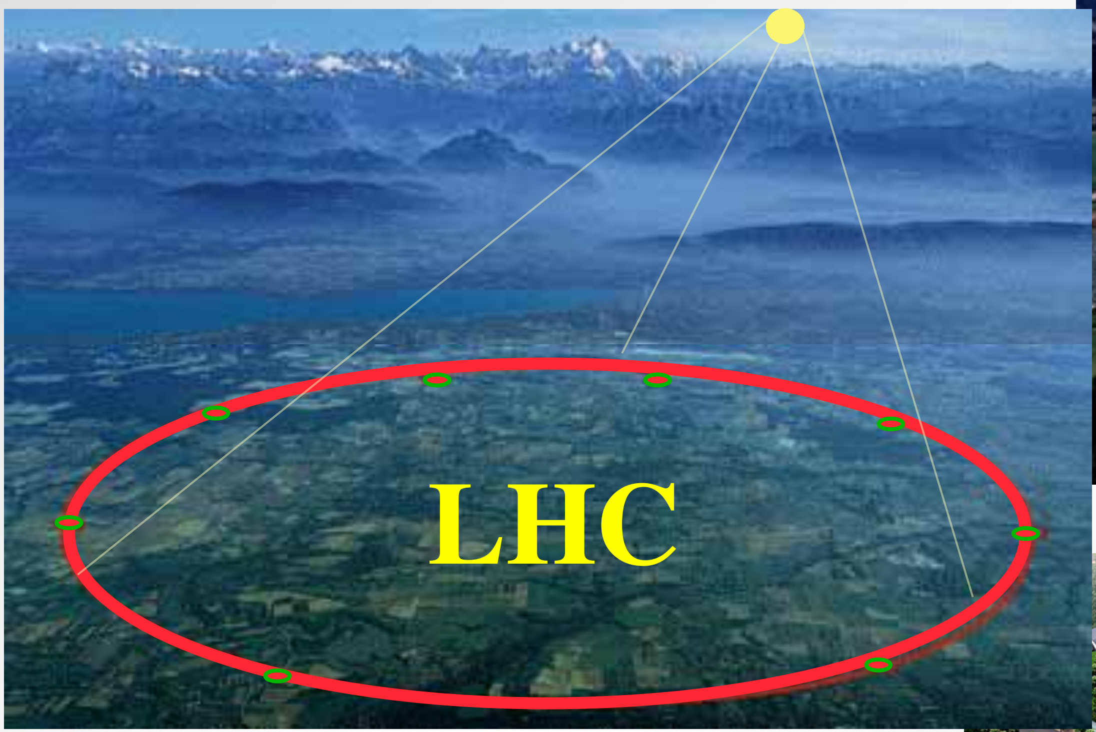
❖ Physics basis: *Bunched electrons radiate* ***coherently***



START MIDDLE END

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

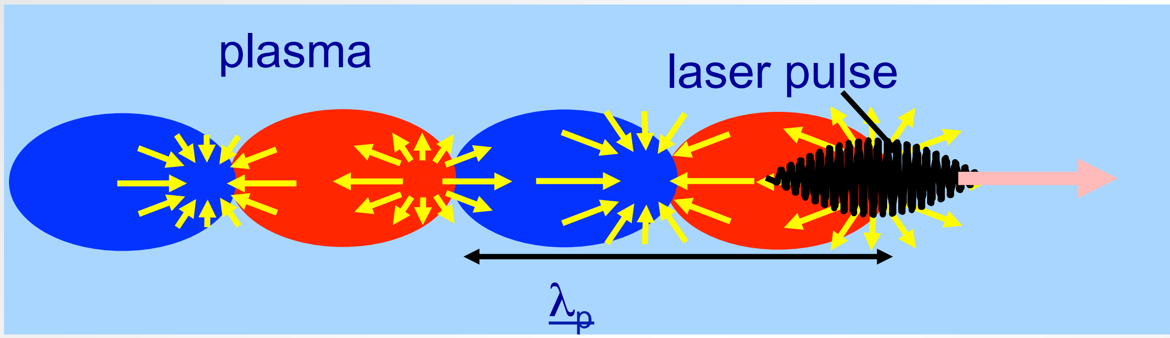
Which brings us to the present…



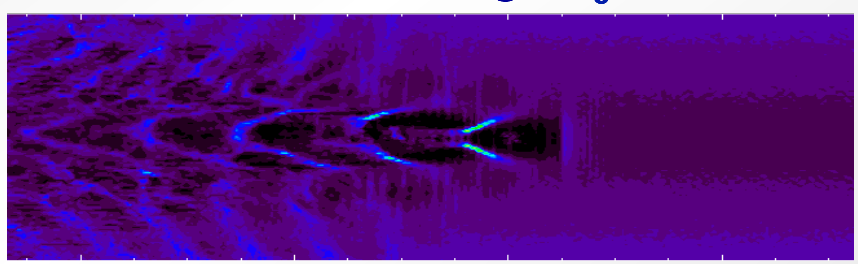
Is this the end of the line?

Maybe not… Optical Particle Accelerator

Standard regime (LWFA): pulse duration matches plasma period



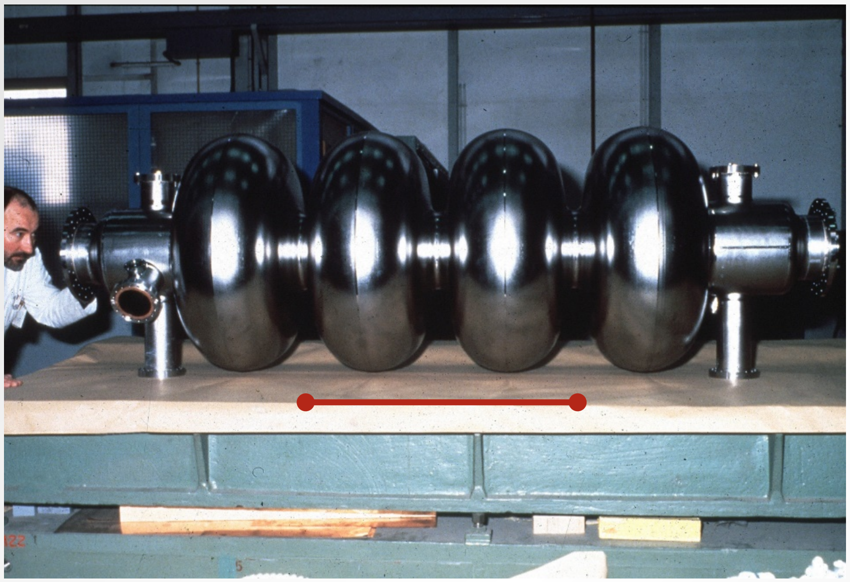
electron motion **high n_e** **low n_e**

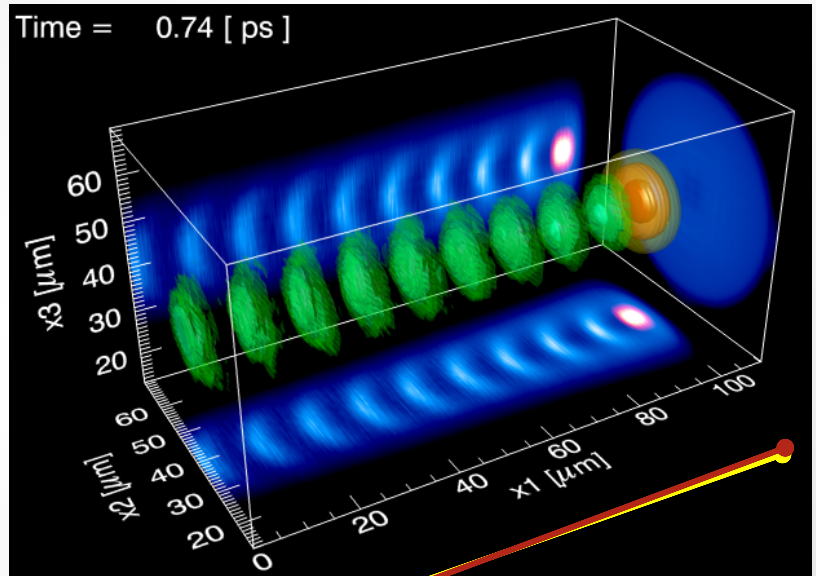


- Accelerating field ~ Sqrt(plasma density)
- Phase velocity < c : particle and wave de-phase
- Energy gain $\Delta W = eE_zL_{acc}$

RF-cavities in metal and in plasma
Think back to the string of pillboxes

Courtesy of W. Mori & L. da Silva





1 m

RF cavity

100 μm

Plasma cavity

$G \sim 30\ MeV/m$

$G \sim 30\ GeV/m$

University of Ljubljana
FACULTY OF ECONOMICS

There are many possible special topics after we cover the basics

What interests you?