Physics 696
Topics in Advanced Accelerator Design I

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Energy Units

- When a particle is accelerated, i.e., its energy is changed by an electromagnetic field, it must have fallen through an Electric Field (we show later by very general arguments that Magnetic Fields cannot change particle energy). For electrostatic accelerating fields the energy change is

$$\Delta E = q\Delta\Phi = q\left(\Phi_a - \Phi_b\right)$$

q charge, Φ, the electrostatic potentials before and after the motion through the electric field. Therefore, particle energy can be conveniently expressed in units of the "equivalent" electrostatic potential change needed to accelerate the particle to the given energy. Definition: 1 eV, or 1 electron volt, is the energy acquired by 1 electron falling through a one volt potential difference.

Energy Units

$$1\ \text{eV} = 1.6\times10^{-19}\ \text{C} \times 1\ \text{V} = 1.6\times10^{-19}\ \text{J}$$

$$1\ \text{MeV} = 10^{6}\ \text{eV} = 1.6\times10^{-13}\ \text{J}$$

To convert rest mass to eV use Einstein relation

$$E_0 = mc^2$$

where m is the rest mass. For electrons

$$E_{electron,0} = 9.1\times10^{-31}\ \text{kg}\left(3\times10^{8}\ \text{m/sec}\right)^2 = 81.9\times10^{-15}\ \text{J}$$

$$= 0.512\ \text{MeV}$$

Recent "best fit" value 0.51099906 MeV

Methods of Acceleration

- Acceleration by Static Electric Fields (DC) Acceleration
  - Cockcroft-Walton
  - van de Graaf Accelerators
  - Limited by voltage breakdowns to potentials of under a million volts in 1930, and presently to potentials of tens of millions of volts (in modern van de Graaf accelerators). Not enough to do nuclear physics at the time.
- Radio Frequency (RF) Acceleration
  - Main means to accelerate in most present day accelerators because one can get to 10-100 MV in a meter these days. Reason: alternating fields don't cause breakdown (if you are careful!) until much higher field levels than DC.
  - Ideas started with Ising and Wideröe

Cockcroft-Walton

Proton Source at Fermilab, Beam Energy 750 keV

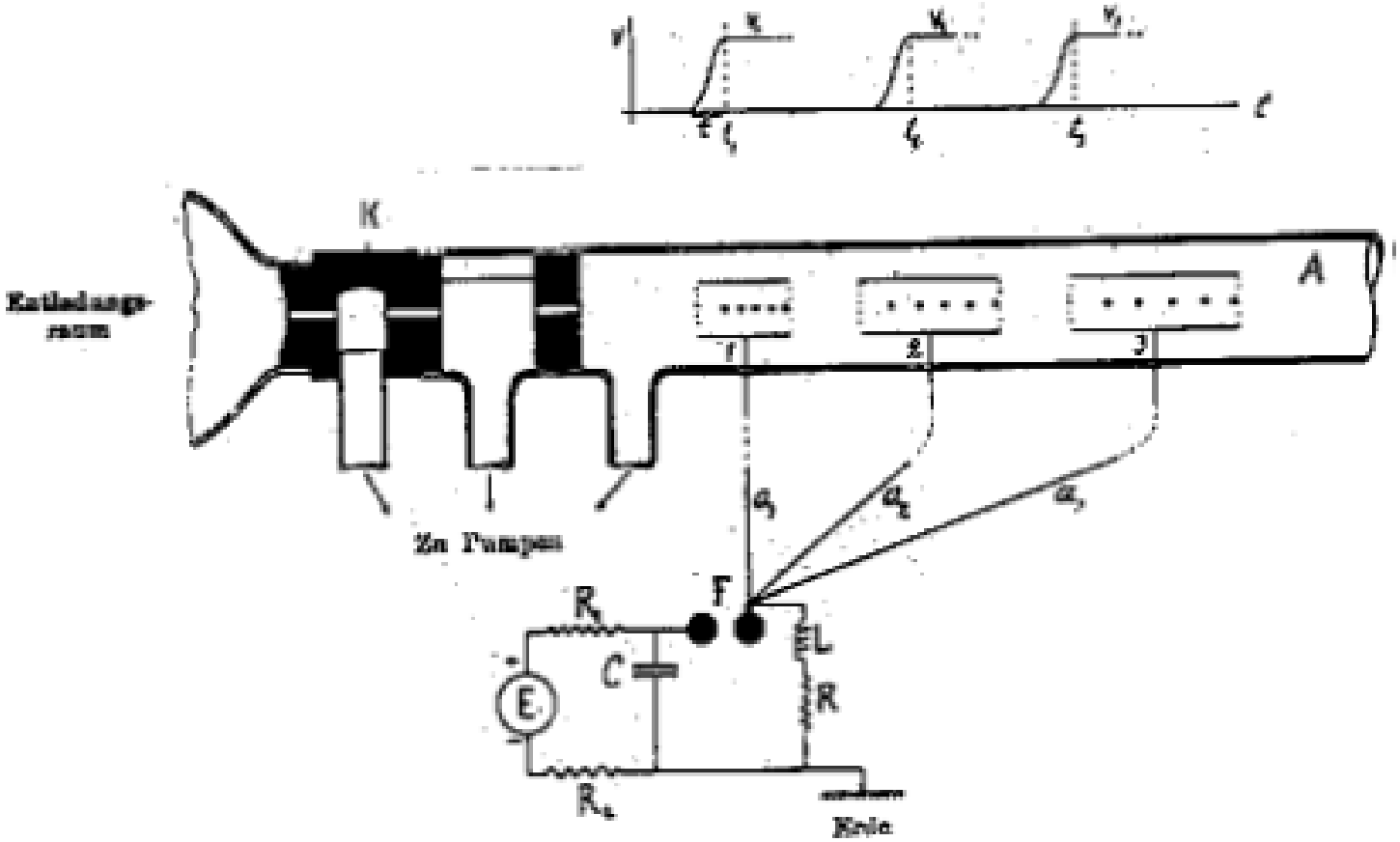
van de Graaf Accelerator

Generator

Brookhaven
Tandem
van de Graaf
~ 15 MV

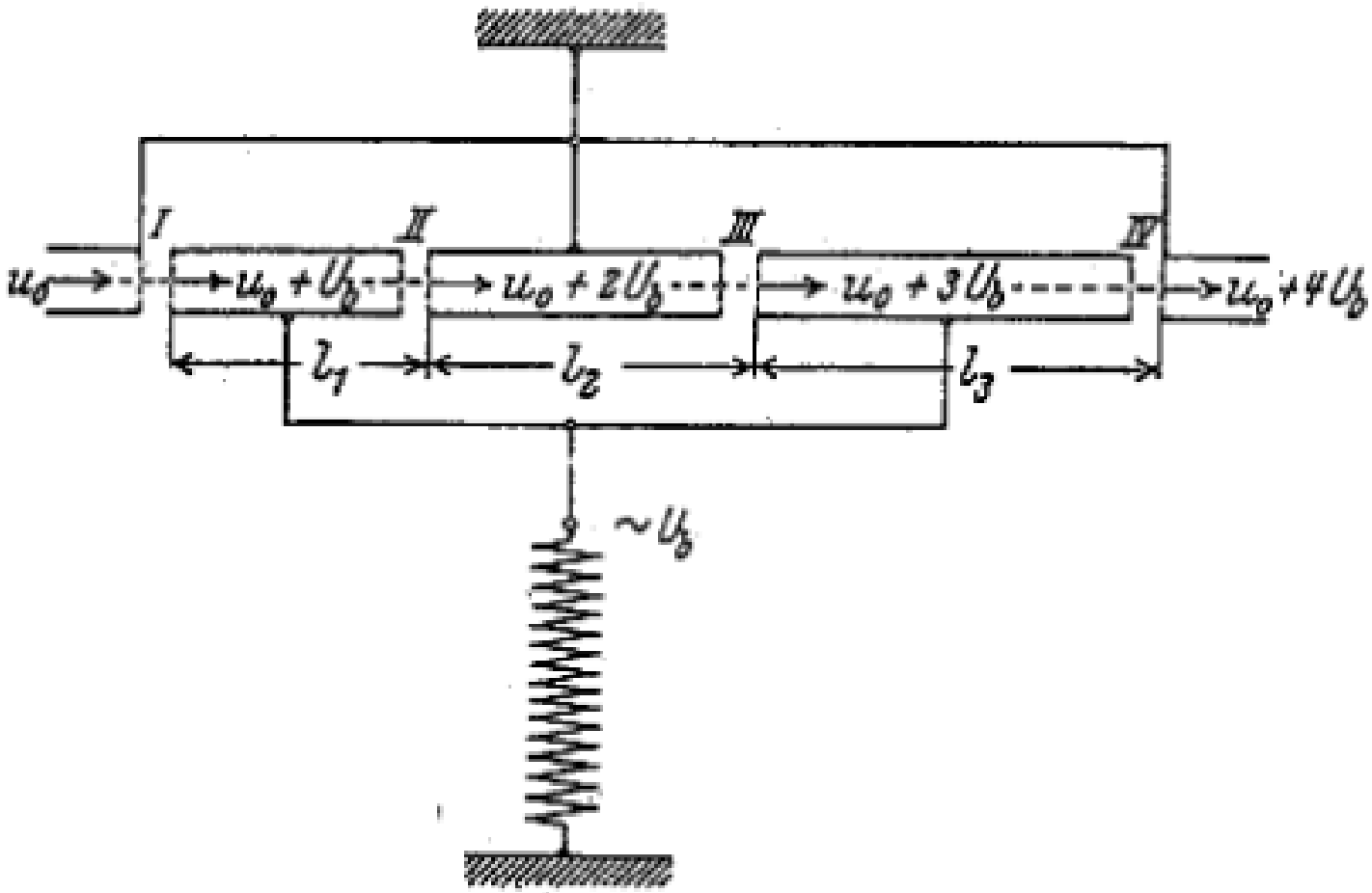
Tandem trick multiplies
the output energy

Ising's Linac Idea



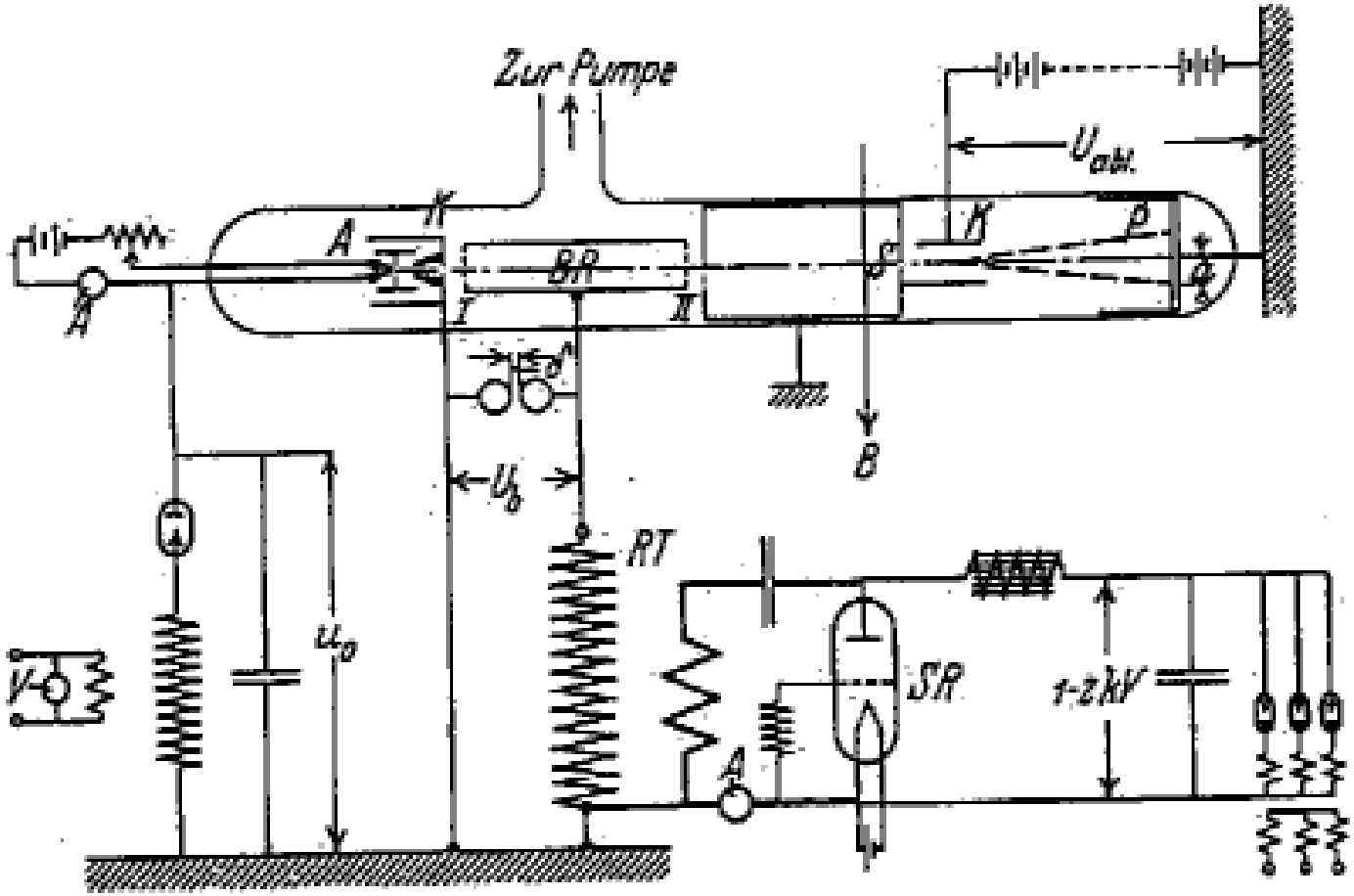
Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl' (in German), Arkiv för matematik o. fysik, 18, Nr. 30, 1-4 (1924).

Drift Tube Linac Proposal



Idea Shown in Wideröe Thesis

Wideröe Thesis Experiment



Über ein neues Prinzip zur Herstellung hoher Spannungen, *Archiv für Elektrotechnik* **21**, 387 (1928)

(On a new principle for the production of higher voltages)

Sloan-Lawrence Heavy Ion Linac

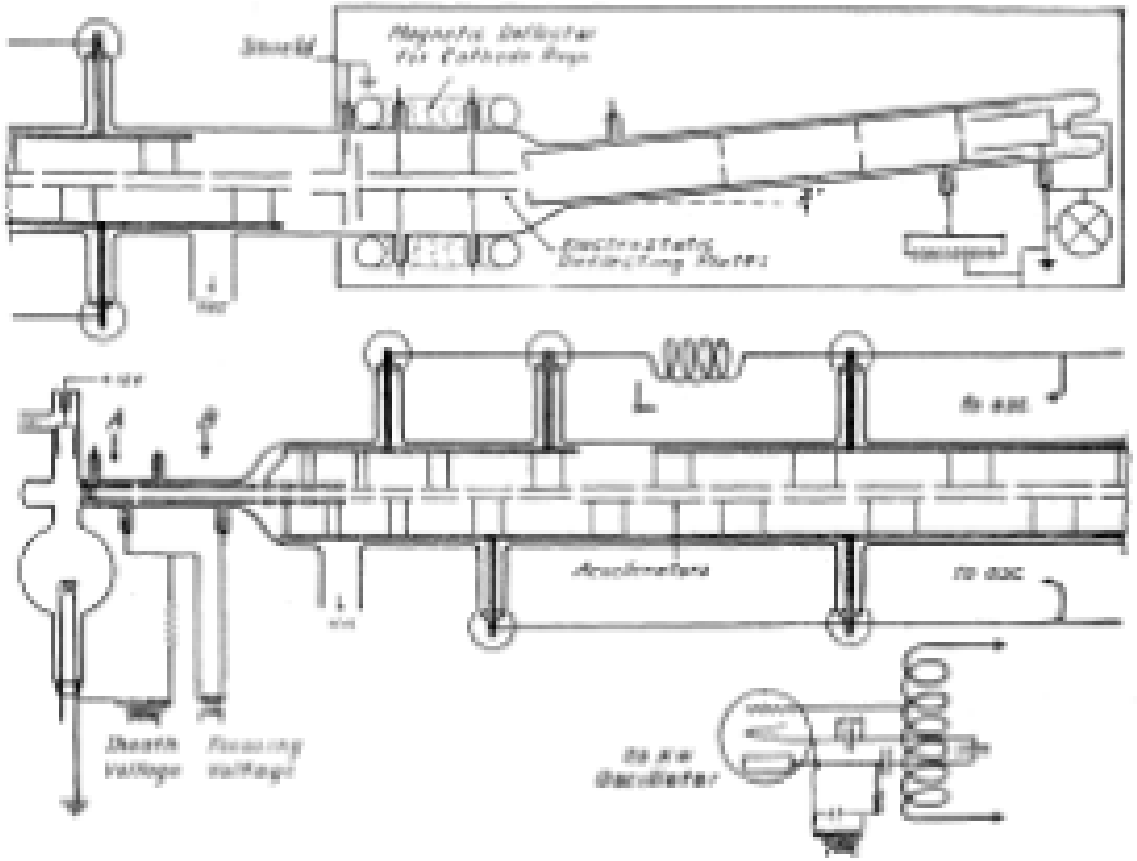


Fig. 1. Diagram of apparatus.

The Production of Heavy High Speed Ions without the Use of High Voltages
David H. Sloan and Ernest O. Lawrence Phys. Rev. **38**, 2021 (1931)

Alvarez Drift Tube Linac

- The first large proton drift tube linac built by Luis Alvarez and Panofsky after WW II

. (1945-1955) Alvarez Proton Linac

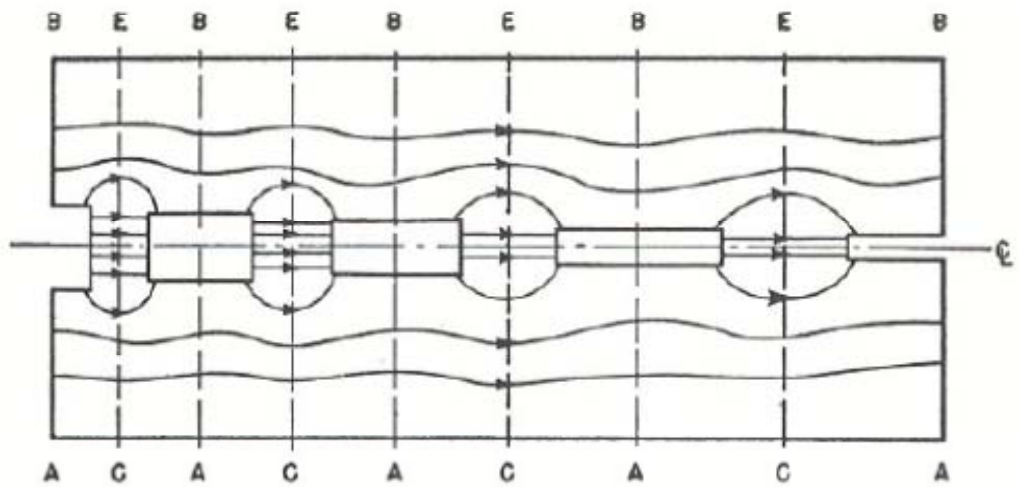
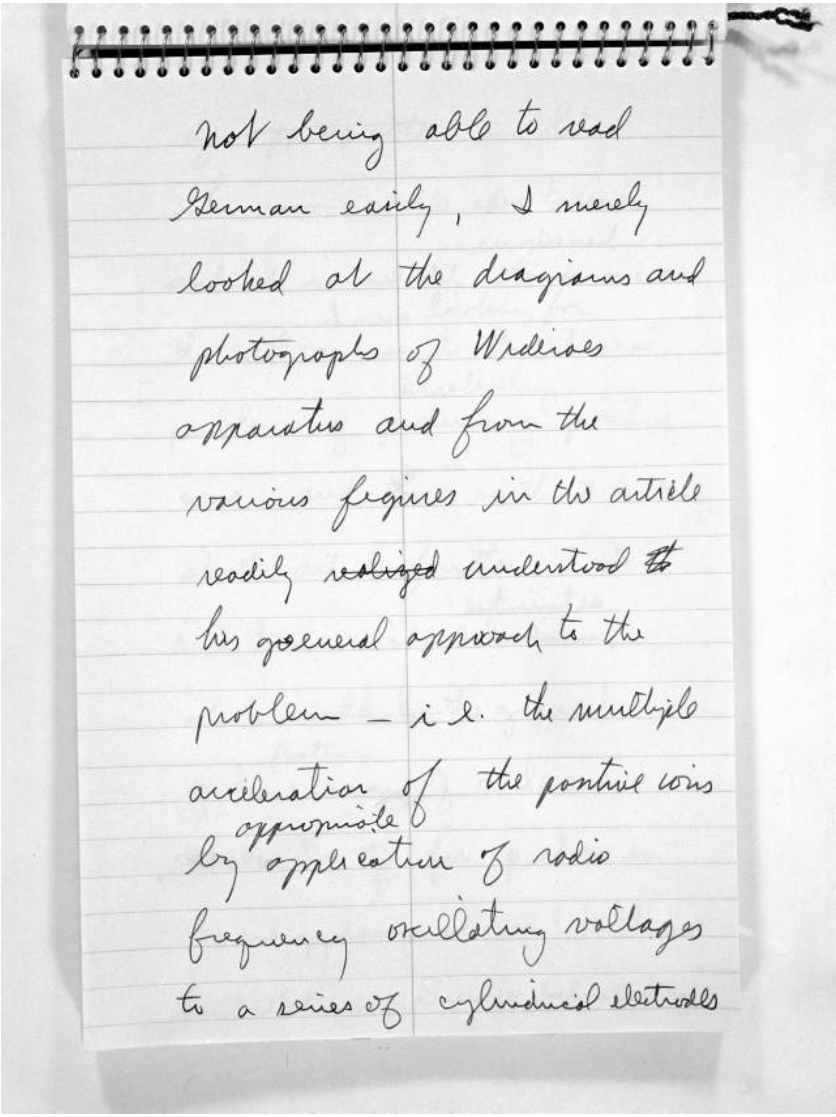


FIG. 2. Linear accelerator produced by introducing drift tubes into cavity excited as in Fig. 1. Division into unit cells.

Alvarez, Bradner, Frank, Gordon, Gow, Marshal, F. Oppenheimer, Panofsky, Richman, and Woodyard, Rev. Sci. Instrum., **26**, 111-133, (1955)

Earnest Orlando Lawrence

Germ of Idea*



not being able to read
German easily, I merely
looked at the diagrams and
photographs of Wideroes
apparatus and from the
various figures in the article
readily ~~realized~~ understood ~~the~~
his general approach to the
problem – i.e. the multiple
acceleration of the positive ions
by application of suitable
frequency oscillating voltages
to a series of cylindrical electrodes

*Stated in
E. O. Lawrence
Nobel Lecture

Lawrence's Question

- Can you re-use "the same" accelerating gap many times?

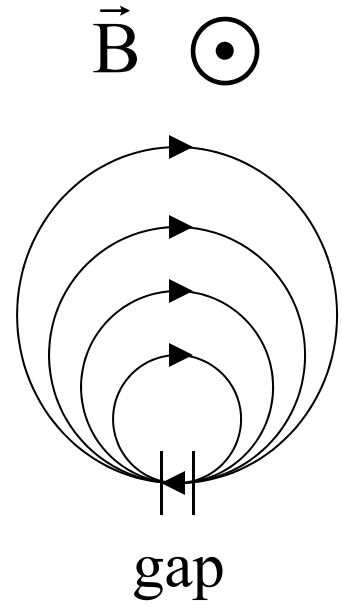
$$\vec{F} = m\vec{a} = q\vec{\mathrm{v}} \times \vec{B}$$

$$\frac{d^2x}{dt^2} = \frac{qB}{m}\mathrm{v}_y \quad \rightarrow \frac{d^2\mathrm{v}_x}{dt^2} + \Omega_c^2 \mathrm{v}_x = 0$$

$$\frac{d^2y}{dt^2} = -\frac{qB}{m}\mathrm{v}_x \rightarrow \frac{d^2\mathrm{v}_y}{dt^2} + \Omega_c^2 \mathrm{v}_y = 0$$

$$\frac{d}{dt}\left(\mathrm{v}_x^2 + \mathrm{v}_y^2\right) = \frac{qB}{m}\left(\mathrm{v}_x\mathrm{v}_y - \mathrm{v}_y\mathrm{v}_x\right) = 0$$

$$\mathrm{v}_0 = \sqrt{\mathrm{v}_x^2(t) + \mathrm{v}_y^2(t)}$$ is a constant of the motion



Cyclotron Frequency

$$\mathrm{v}_x(t) = \mathrm{v}_0 \cos(\Omega_c t + \delta); \mathrm{v}_y(t) = -\mathrm{v}_0 \sin(\Omega_c t + \delta)$$

$$x(t) = x_0 + \frac{\mathrm{v}_0}{\Omega_c} \sin(\Omega_c t + \delta); y(t) = y_0 + \frac{\mathrm{v}_0}{\Omega_c} \cos(\Omega_c t + \delta)$$

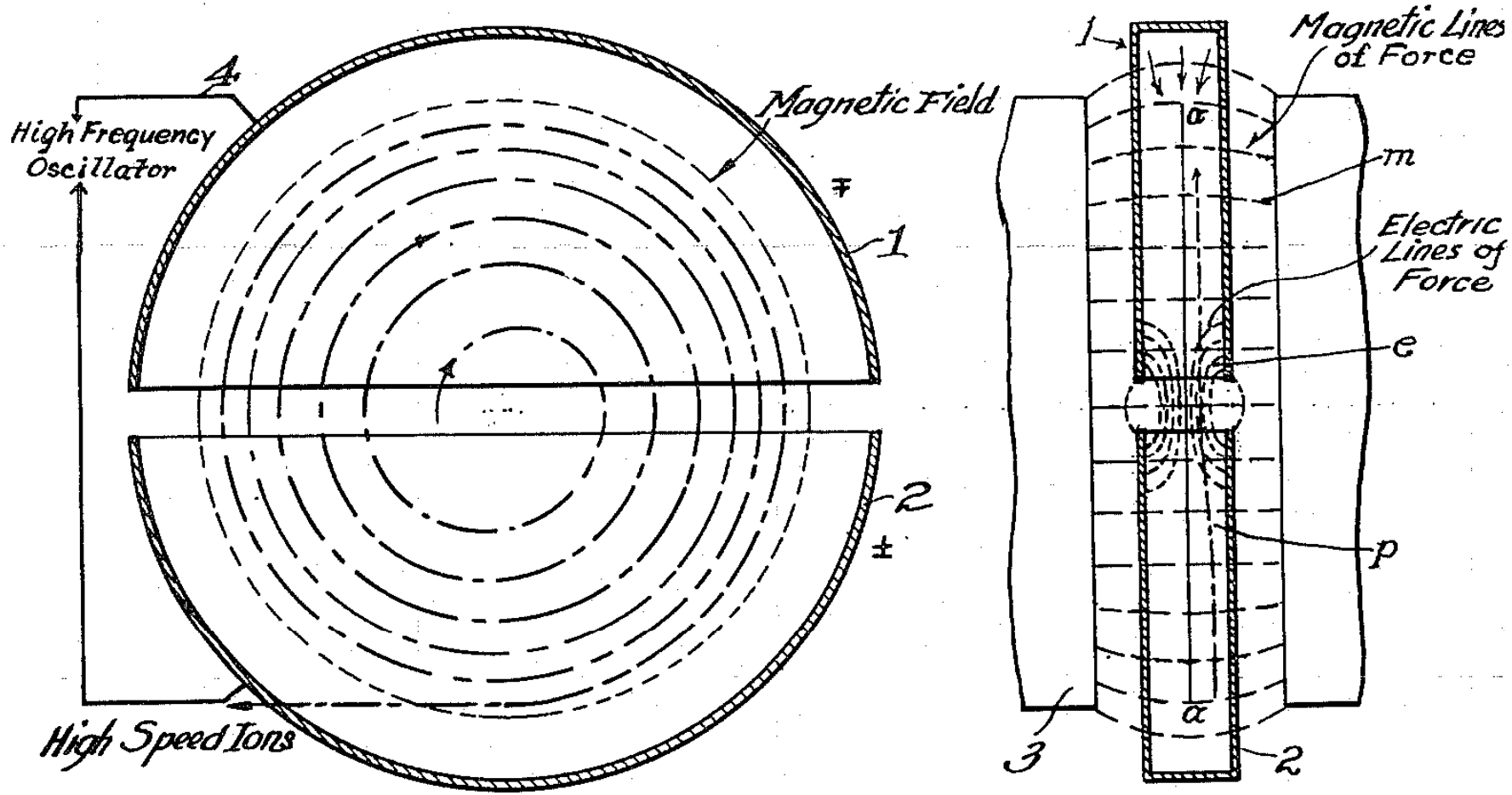
The radius of the oscillation $r = \mathrm{v}_0/\Omega_c$ is proportional to the velocity after the gap. Therefore, the particle takes the same amount of time to come around to the gap, independent of the actual particle energy!!!! (only in the non-relativistic approximation). Establish a resonance (equality!) between RF frequency and particle transverse oscillation frequency, also known as the Cyclotron Frequency

$$f_{rf} = f_c = \Omega_c / 2\pi = \frac{qB}{2\pi m}$$

What Correspond to Drift Tubes?

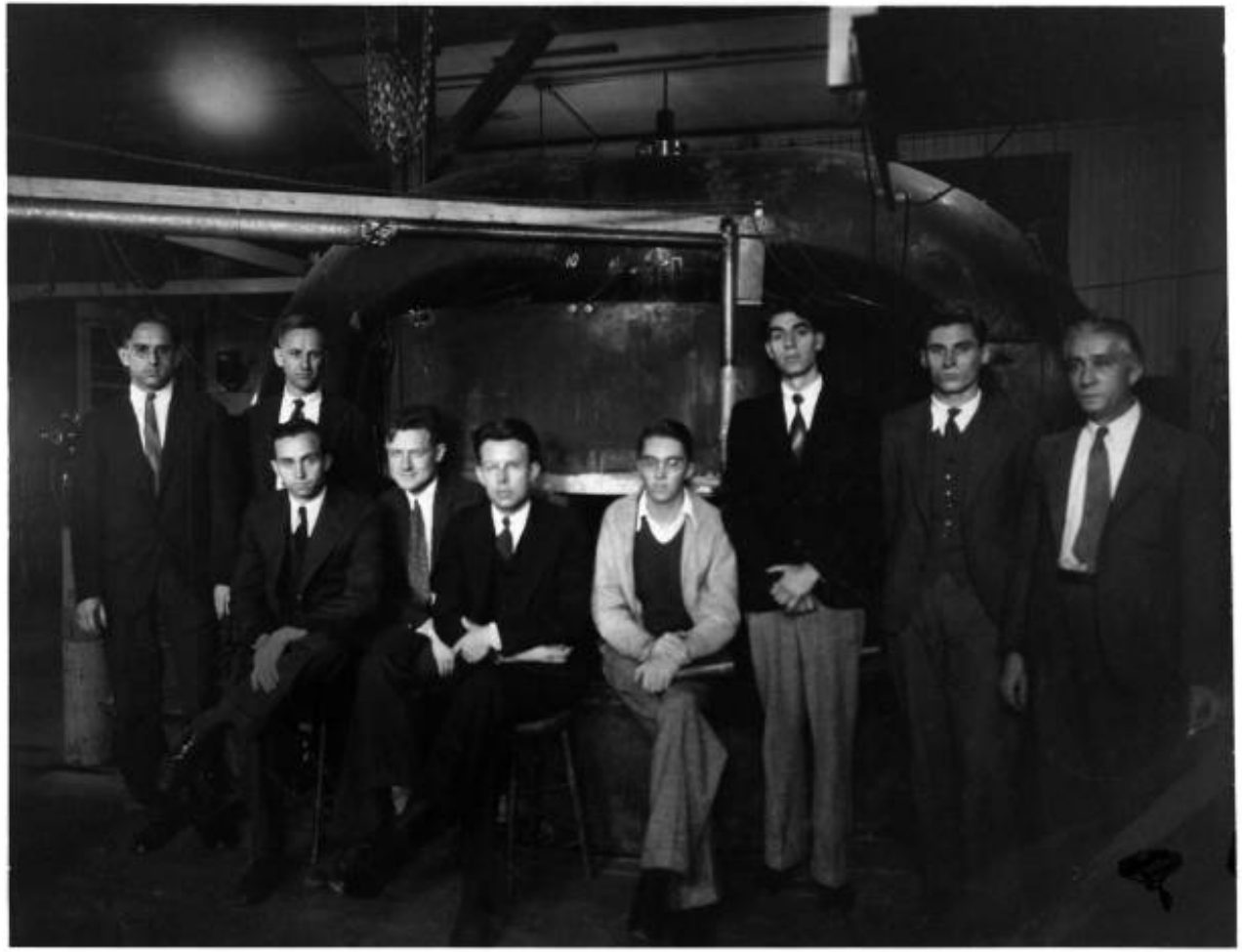
- Dee's!

U. S. Patent Diagram



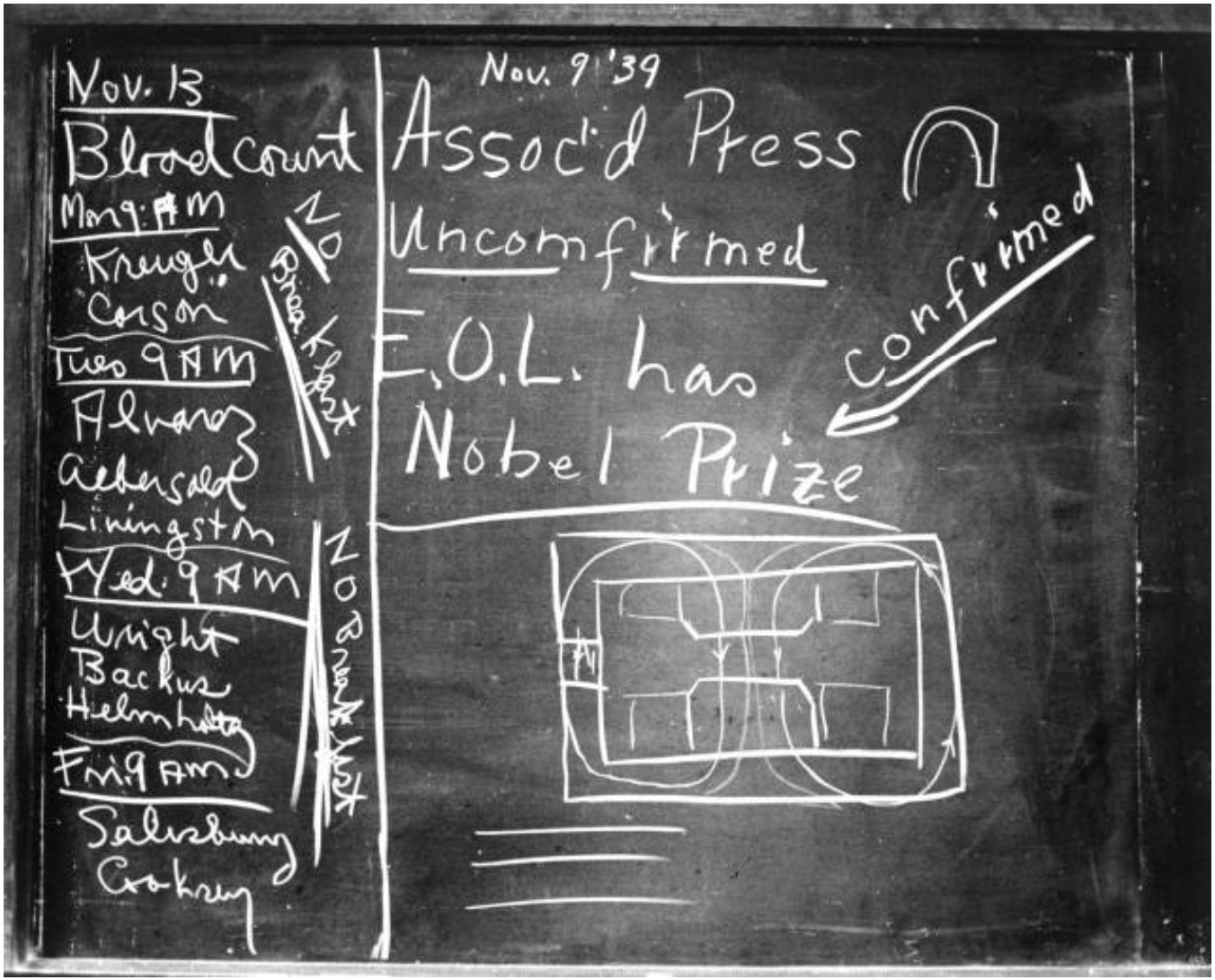
Magnet for 27 Inch Cyclotron (LHS)

Lawrence and "His Boys"

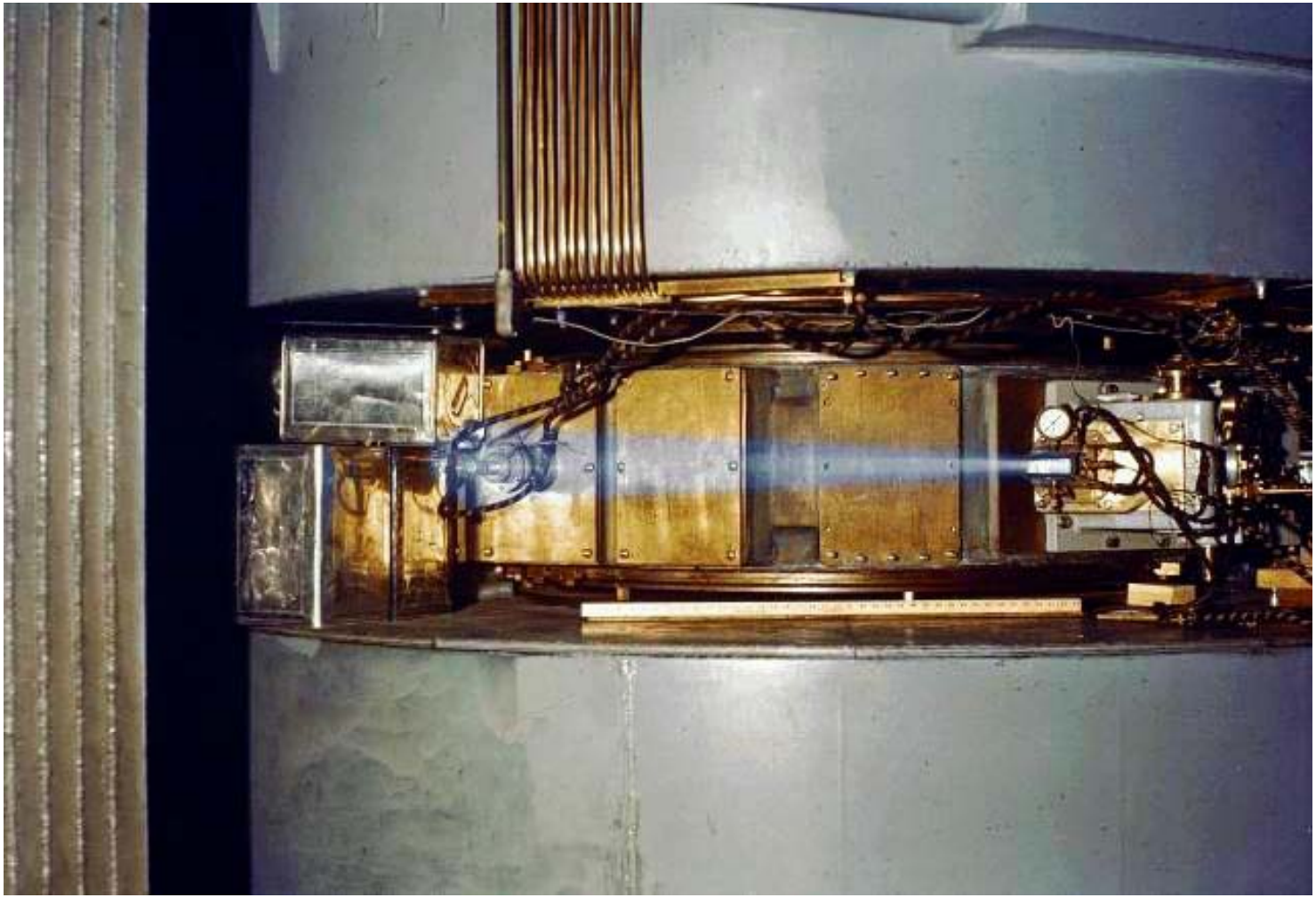


1-4: Jack Livingood, Frank Exner, M.S.Livingston, David Sloan, E.O.Lawrence, Milton White, Wesley Coates, L.Jackson Laslett and Commander T. Lucci - 1933

And Then!

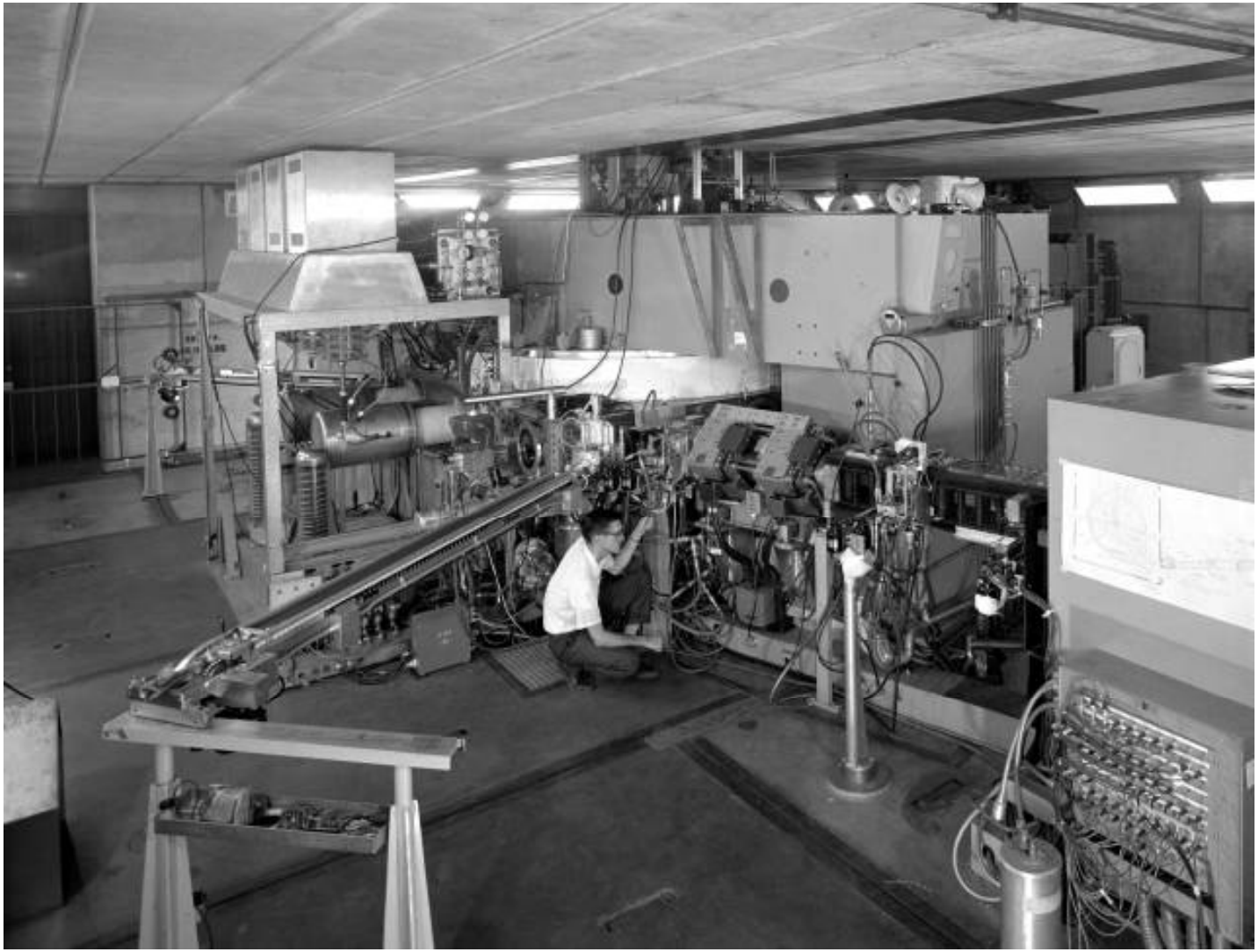

Nov. 13
Broadcast
Mon 9 AM
Kruger
Carson
Tues 9 AM
Alvarez
Oebersold
Livingston
Wed. 9 AM
Wright
Backus
Helmholtz
Fri 9 AM
Salisbury
Cockroft
No Broadcast
No Broadcast
Nov. 9 '39
Associ'd Press
Uncomfirmed
E.O.L. has
Nobel Prize
confirmed

Beam Extracted from a Cyclotron



Radiation Laboratory 60 Inch Cyclotron, circa 1939

88 Inch Cyclotron at Berkeley Lab



Relativistic Corrections

When include relativistic effects (you'll see in the HW!) the "effective" mass to compute the oscillation frequency is the relativistic mass γm

$$f_c = \Omega_c / 2\pi = \frac{qB}{2\pi\gamma m}$$

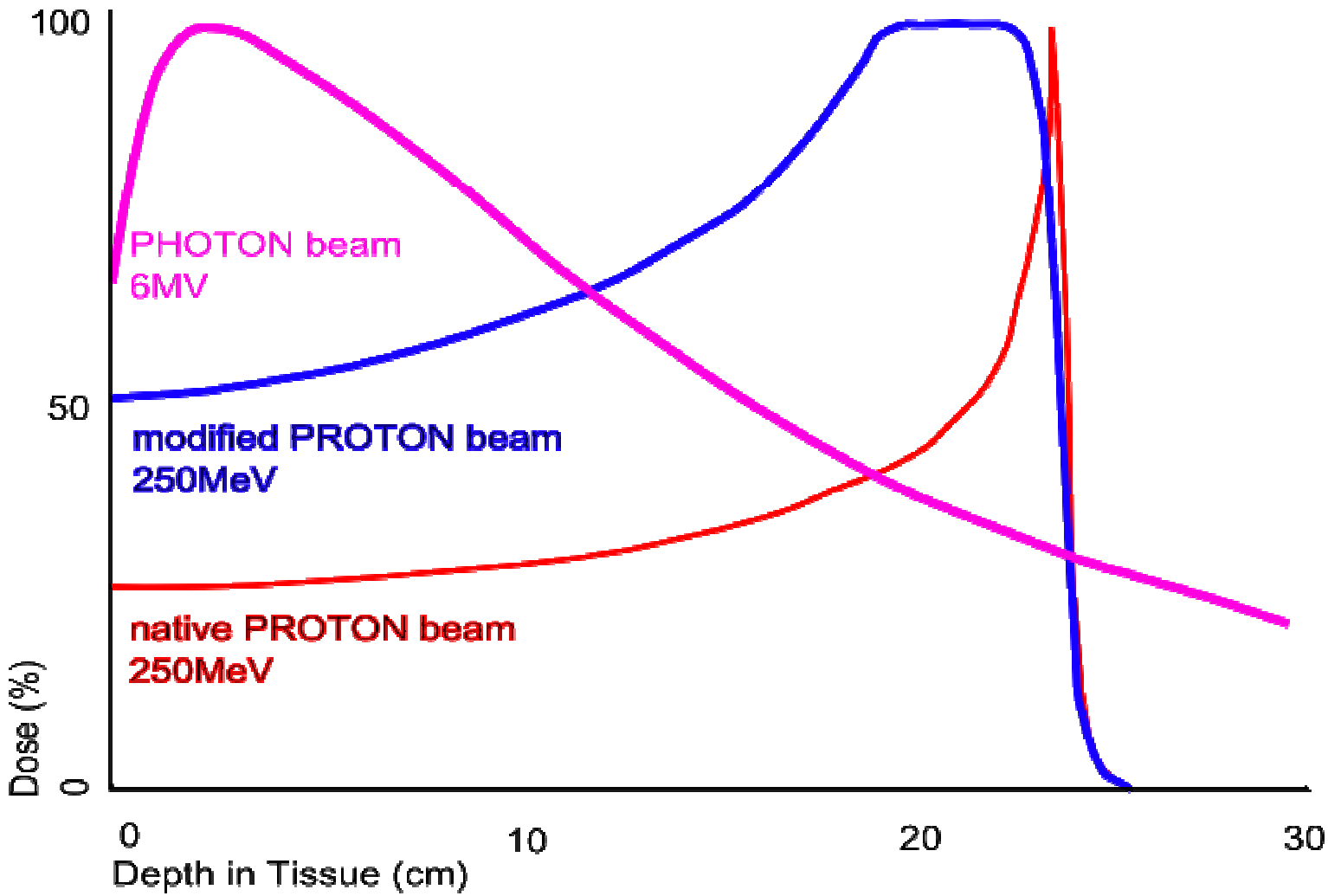
where γ is Einstein's relativistic γ, most usefully expressed as

$$\gamma = \frac{E_{tot}}{E_0} = \frac{E_0 + E_{kin}}{E_0} = \frac{mc^2 + E_{kin}}{mc^2}$$

m particle rest mass, E_{kin} particle kinetic energy

Cyclotrons for Radiation Therapy

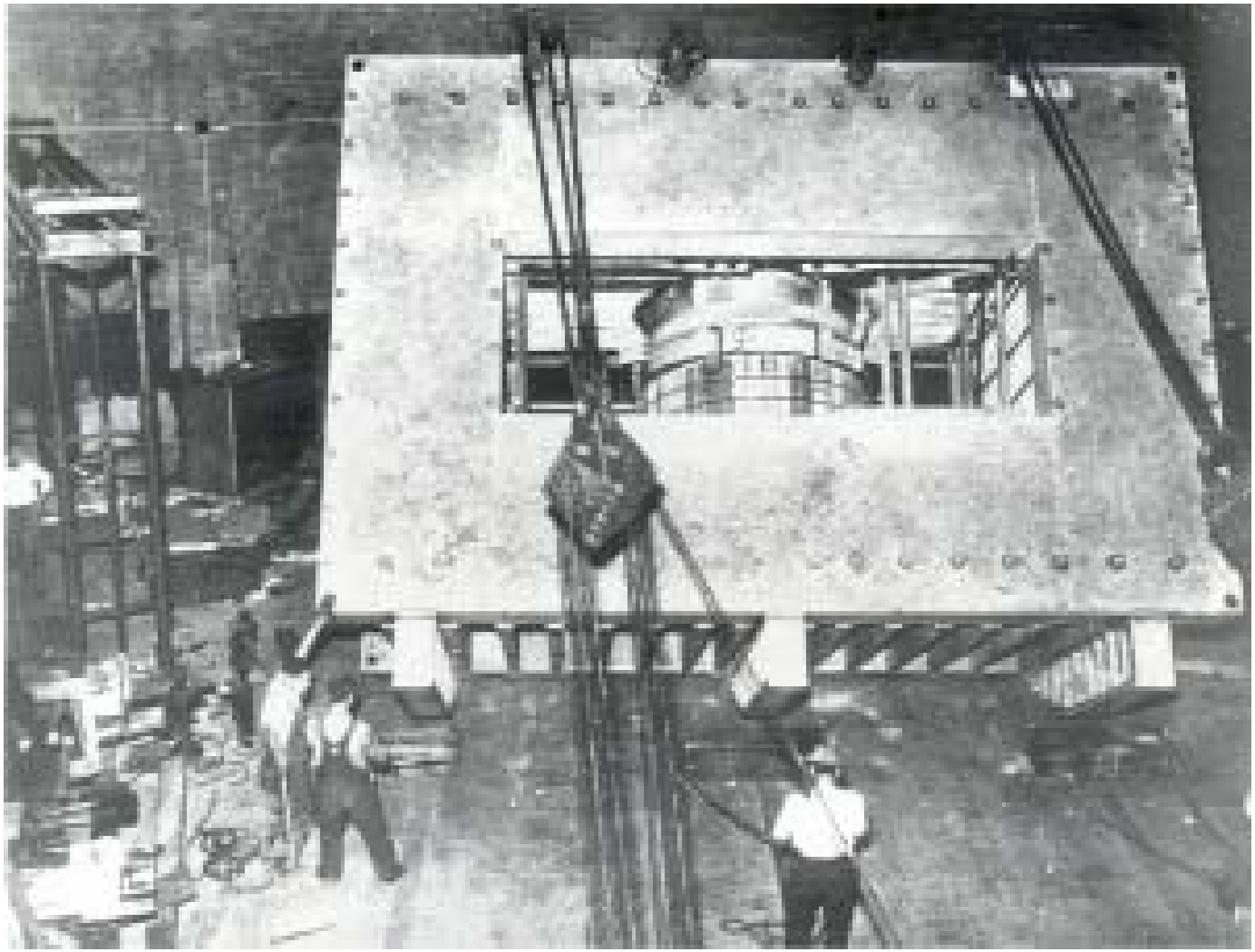
Bragg Peak


100
50
0
Dose (%)
PHOTON beam
6MV
modified PROTON beam
250MeV
native PROTON beam
250MeV
0
10
20
30
Depth in Tissue (cm)

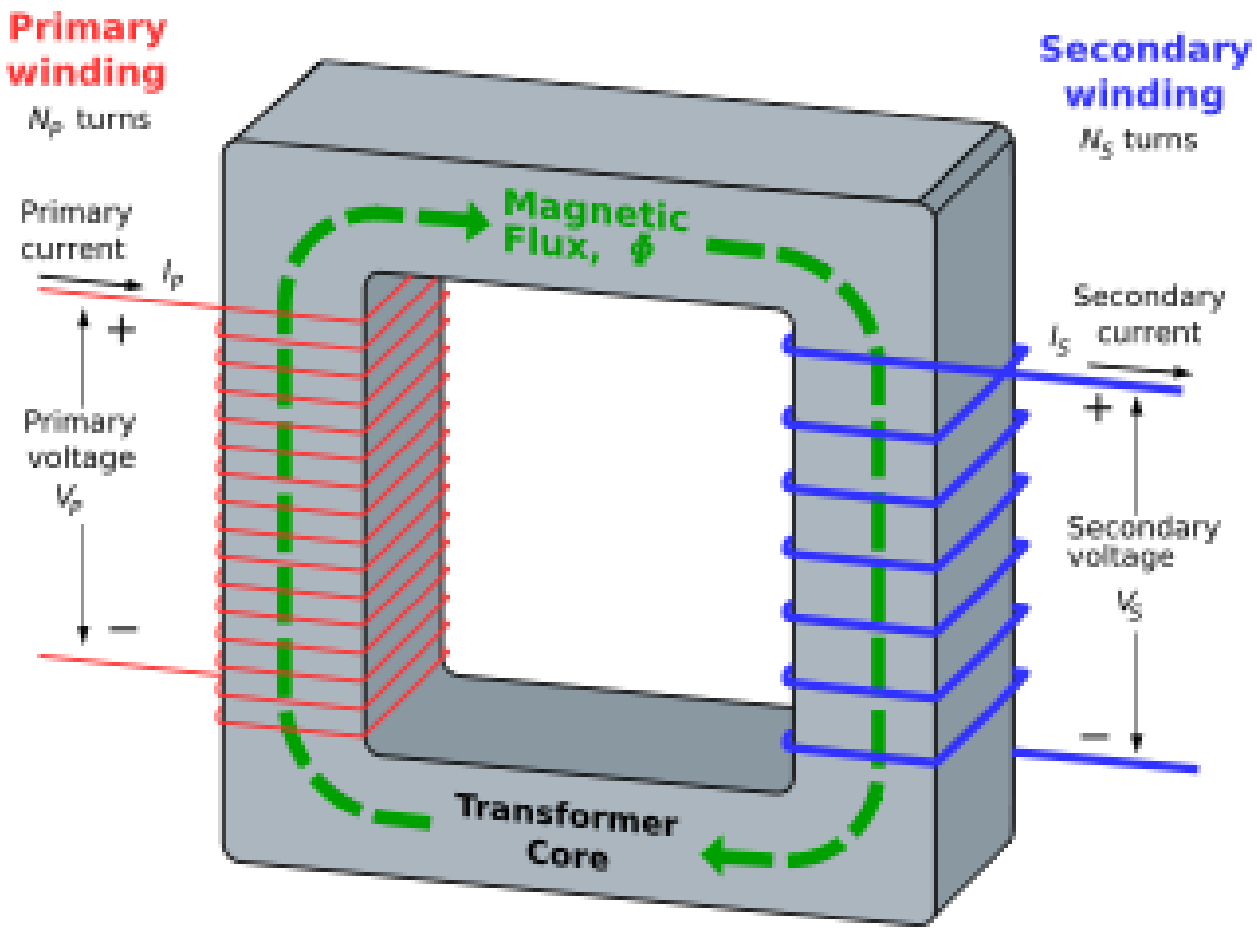
Betatrons

25 MeV electron accelerator with its inventor: Don Kerst. The earliest electron accelerators for medical uses were betatrons.

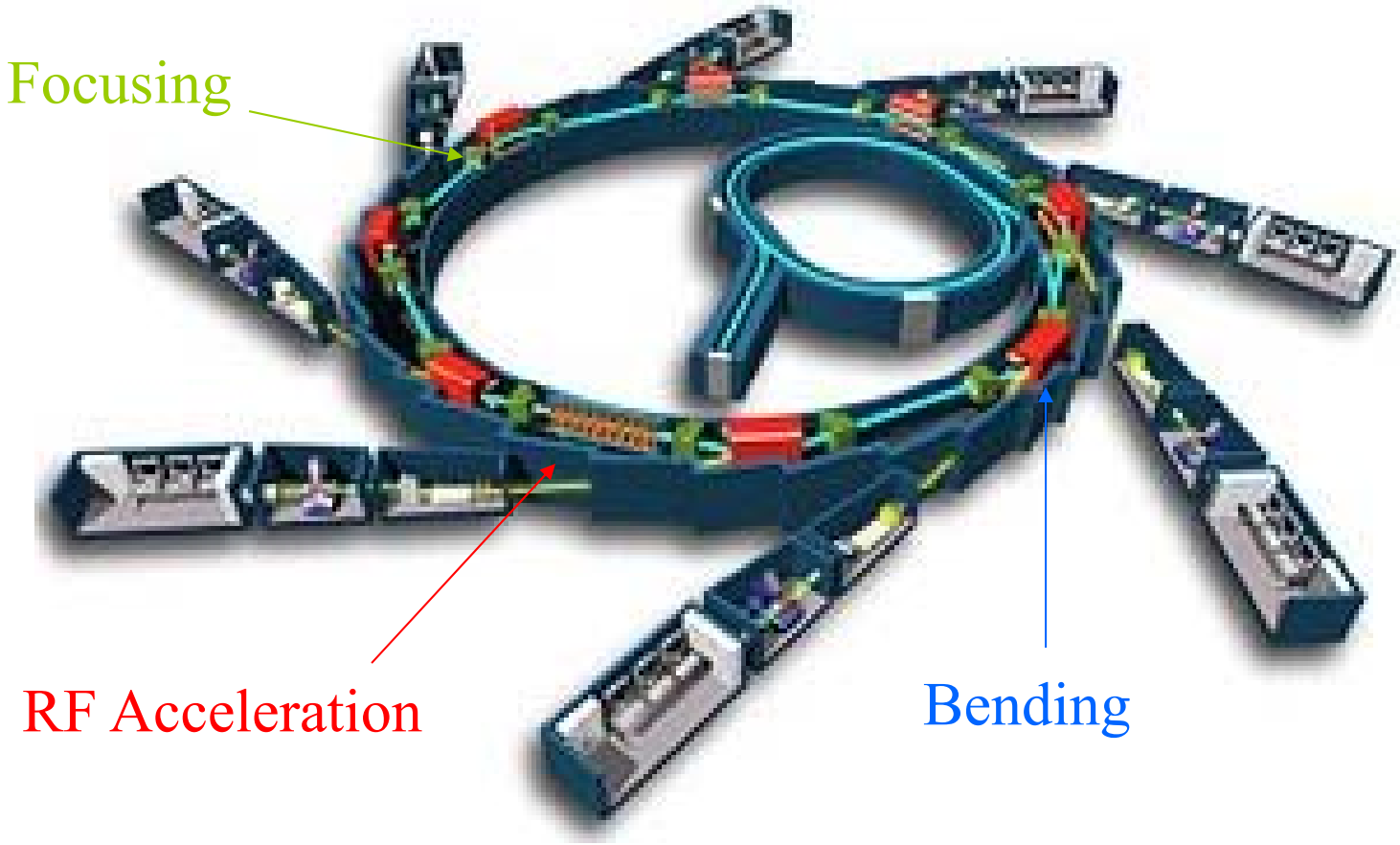
300 MeV ~ 1949



Transformer



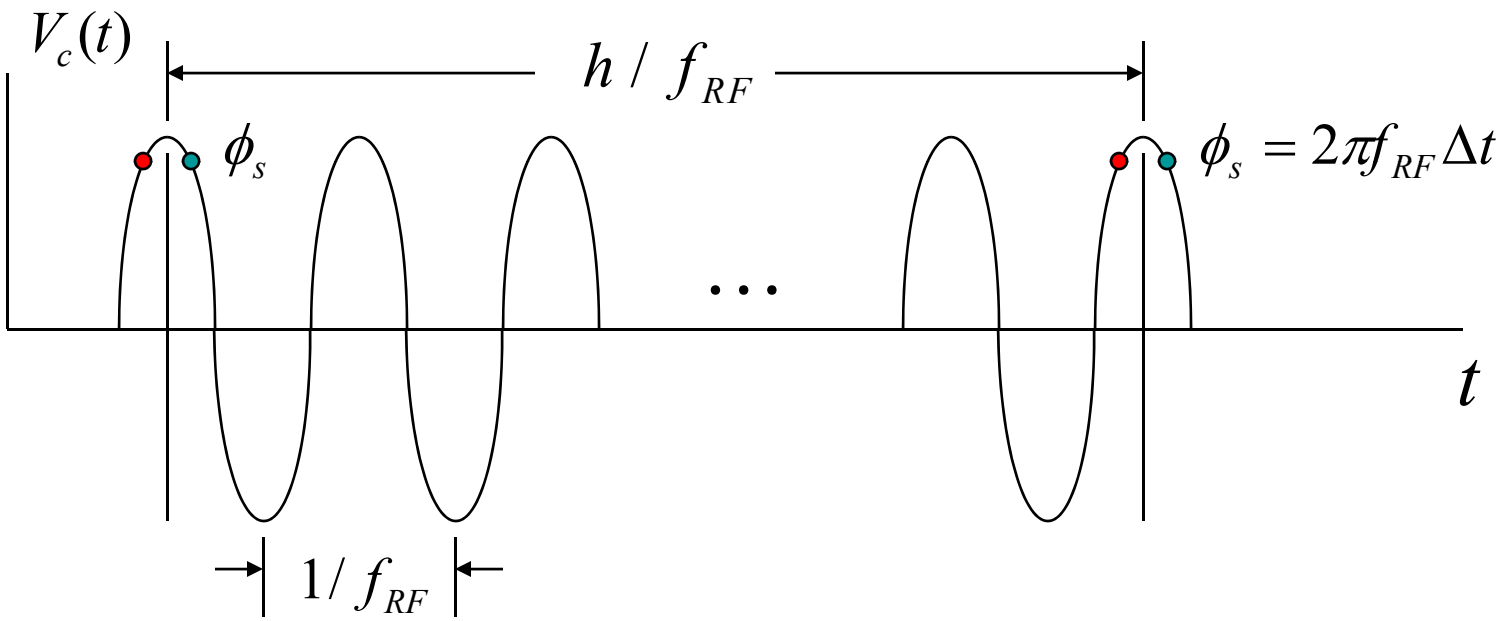
Generic Modern Synchrotron



Spokes are user stations for this X-ray ring source

Synchrotron Phase Stability

Edwin McMillan discovered phase stability independently of Veksler and used the idea to design first large electron synchrotron.



$$h = L f_{RF} / \beta c$$

Harmonic number: # of RF oscillations in a revolution

Transition Energy

Beam energy where speed increment effect balances path length change effect on accelerator revolution frequency. Revolution frequency independent of beam energy to linear order. We will calculate in a few weeks

- Below Transistion Energy: Particles arriving EARLY get less acceleration and speed increment, and arrive later, with repect to the center of the bunch, on the next pass. Applies to heavy particle synchrotrons during first part of acceleration when the beam is non-relativistic and accelerations still produce velocity changes.

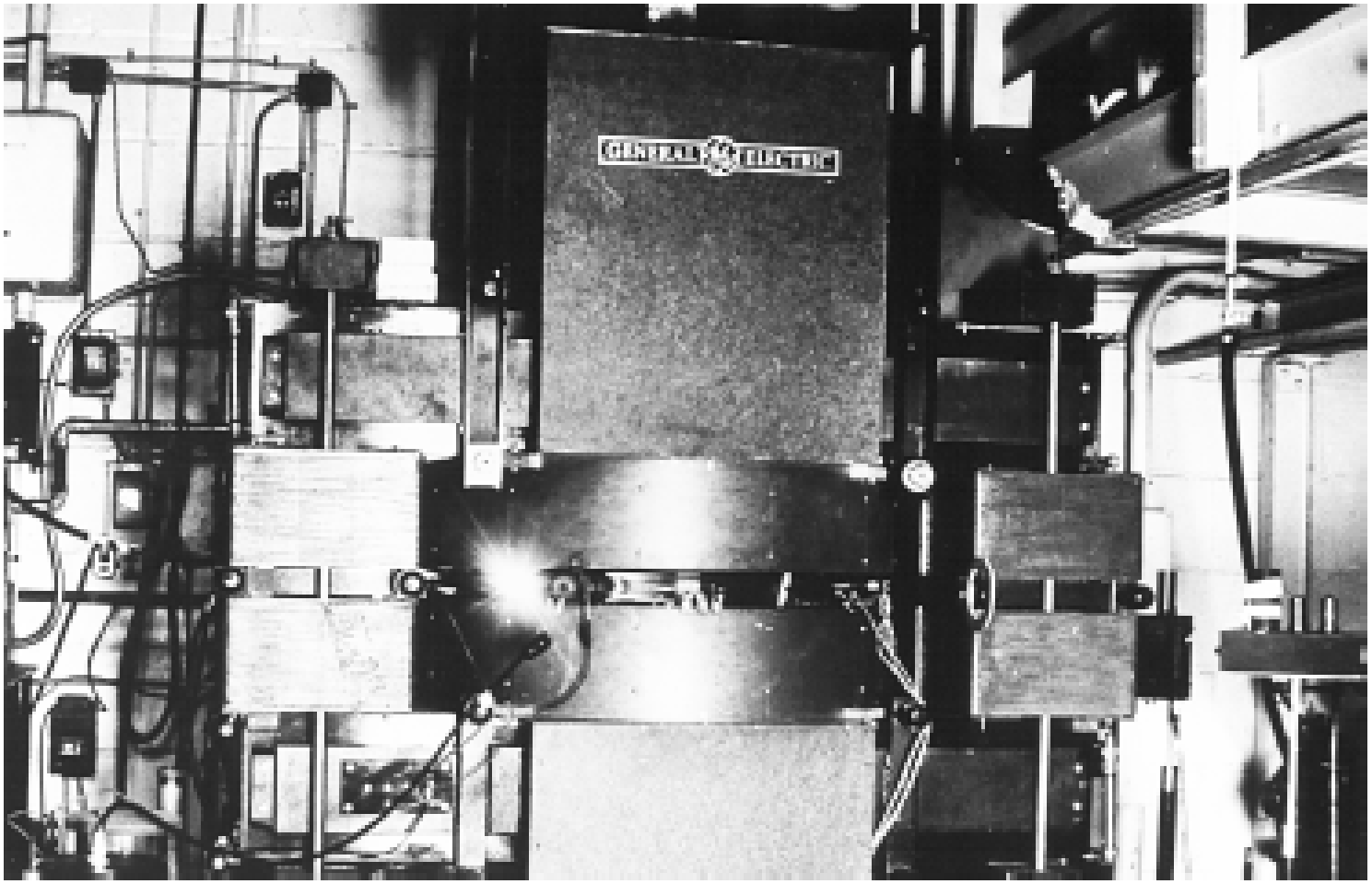
- Above Transistion Energy: Particles arriving EARLY get more energy, have a longer path, and arrive later on the next pass. Applies for electron synchrotrons and heavy particle synchrotrons when approach relativistic velocities. As seen before, Microtrons operate here.

Ed McMillan

Vacuum chamber for electron synchrotron being packed for shipment to Smithsonian

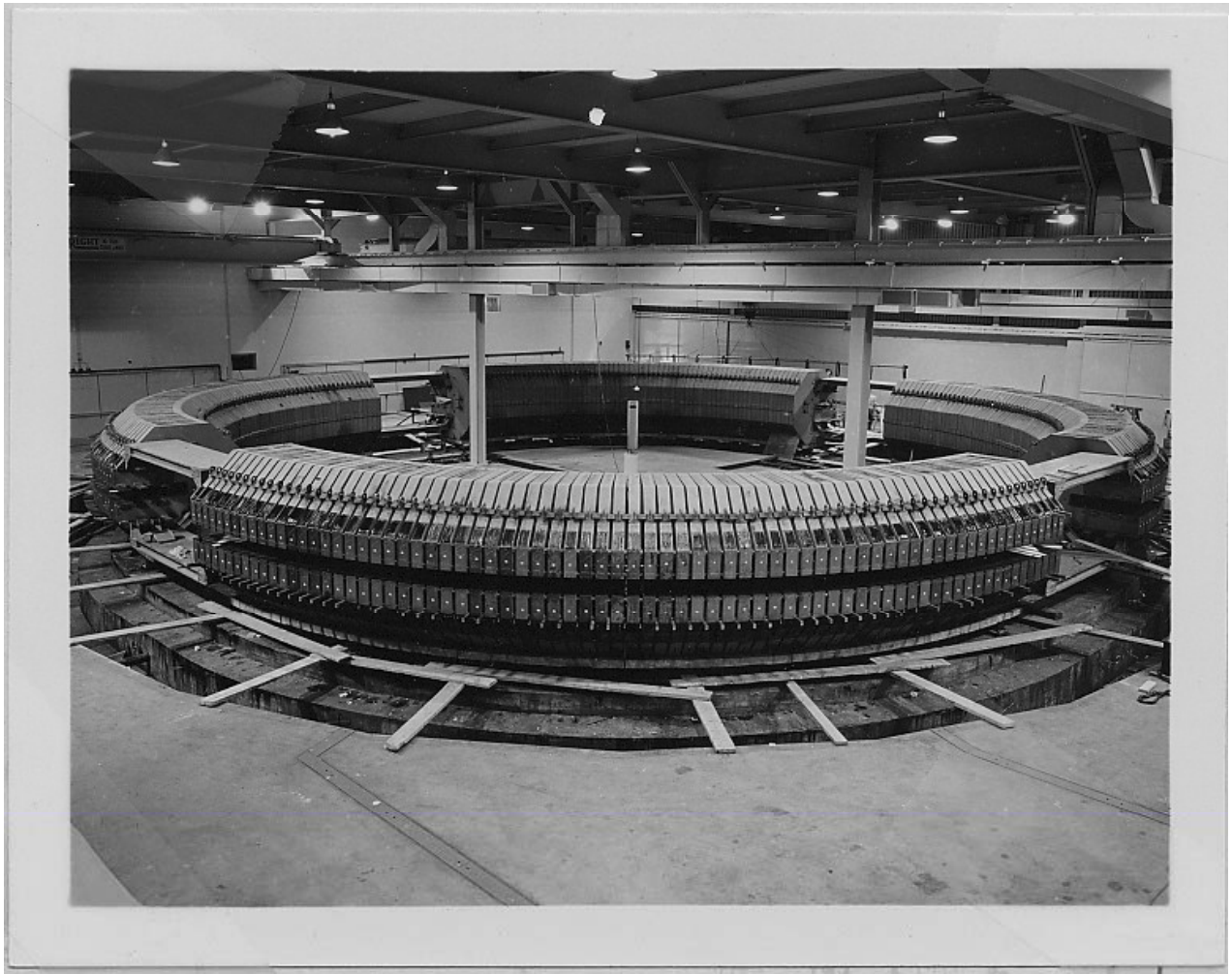
Full Electron Synchrotron

GE Electron Synchrotron



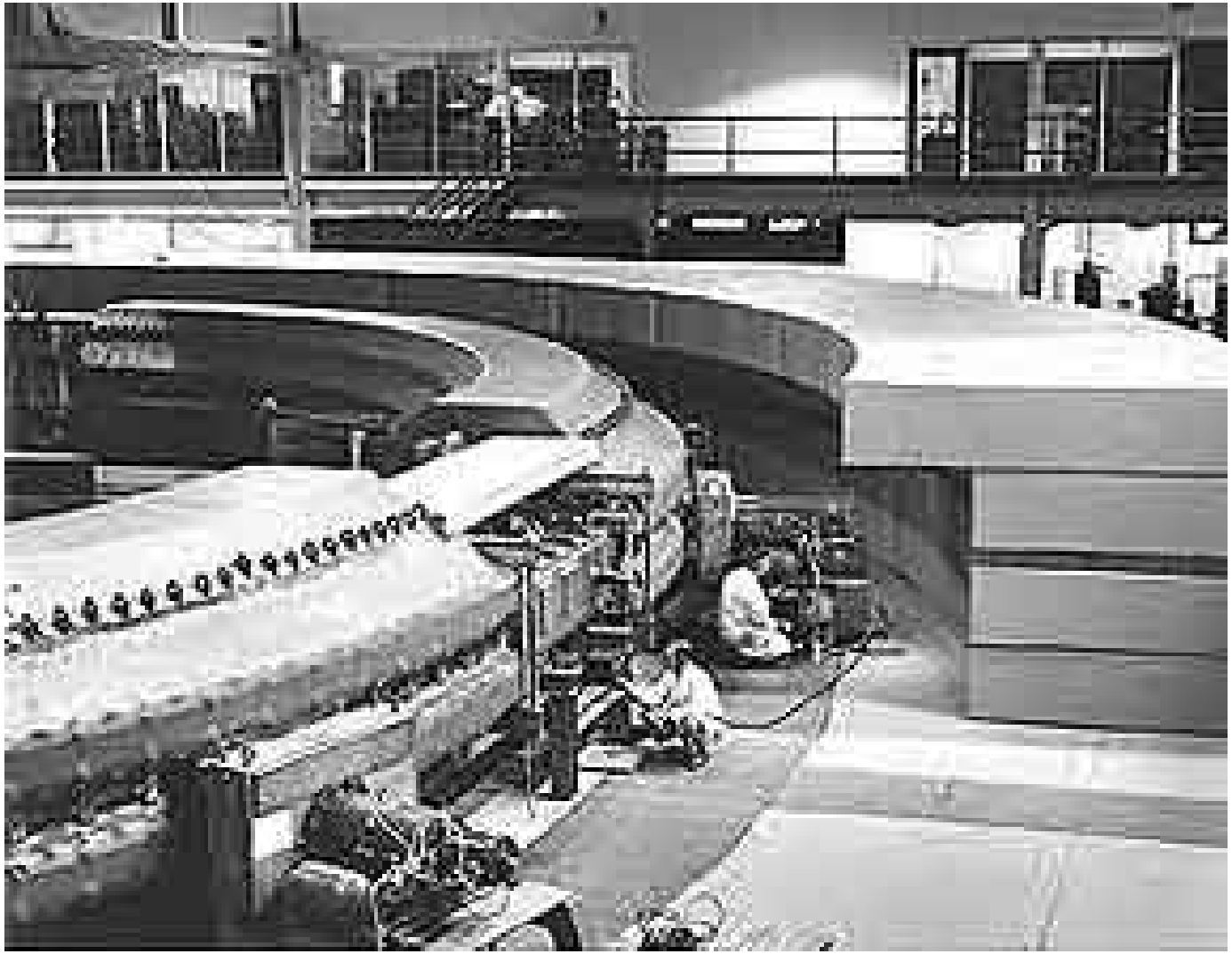
Elder, F. R.; Gurewitsch, A. M.; Langmuir, R. V.; Pollock, H. C., "Radiation from Electrons in a Synchrotron" (1947) *Physical Review*, vol. 71, Issue 11, pp. 829-830

Cosmotron (First GeV Accelerator)

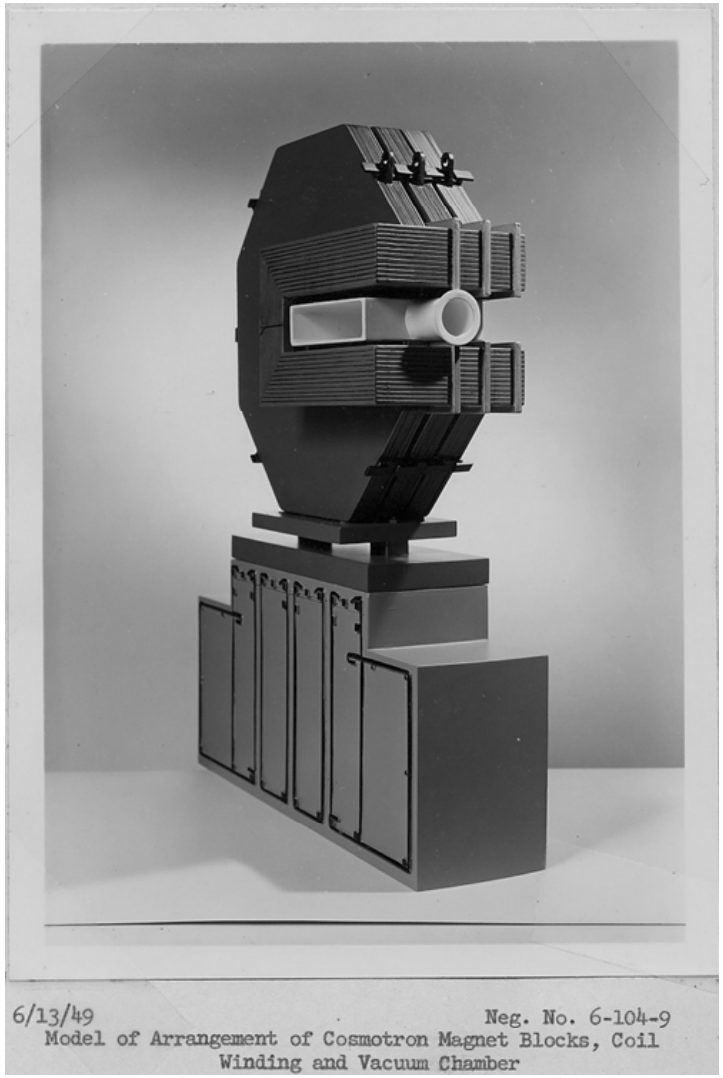


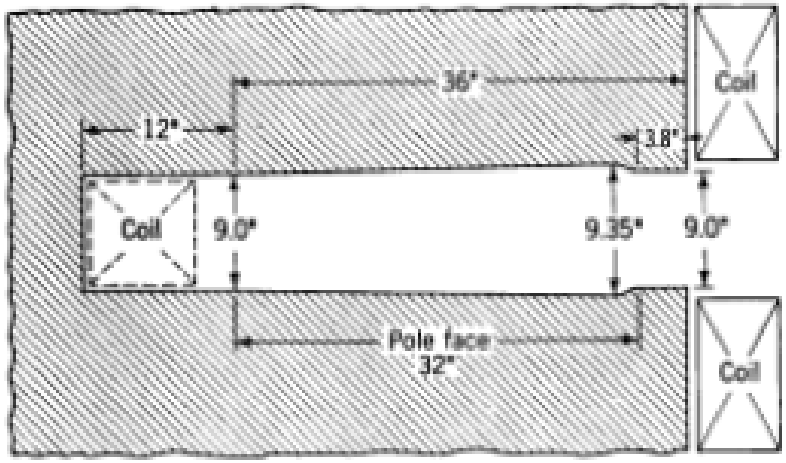
6/15/50 Neg. No. 6-151-0
View of Cosmotron Magnet Blocks after Leveling and Spacing

BNL Cosmotron and Shielding



Cosmotron Magnet





The Cosmotron magnet

Cosmotron People

E.Courant -Lattice Designer

Stan Livingston - Boss

Snyder -theorist

Christofilos - inventor

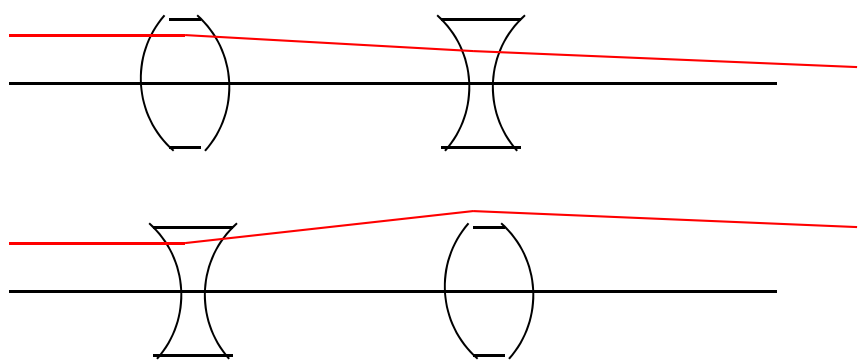
Bevatron

Designed to discover the antiproton; Largest Weak Focusing Synchrotron

Strong Focusing

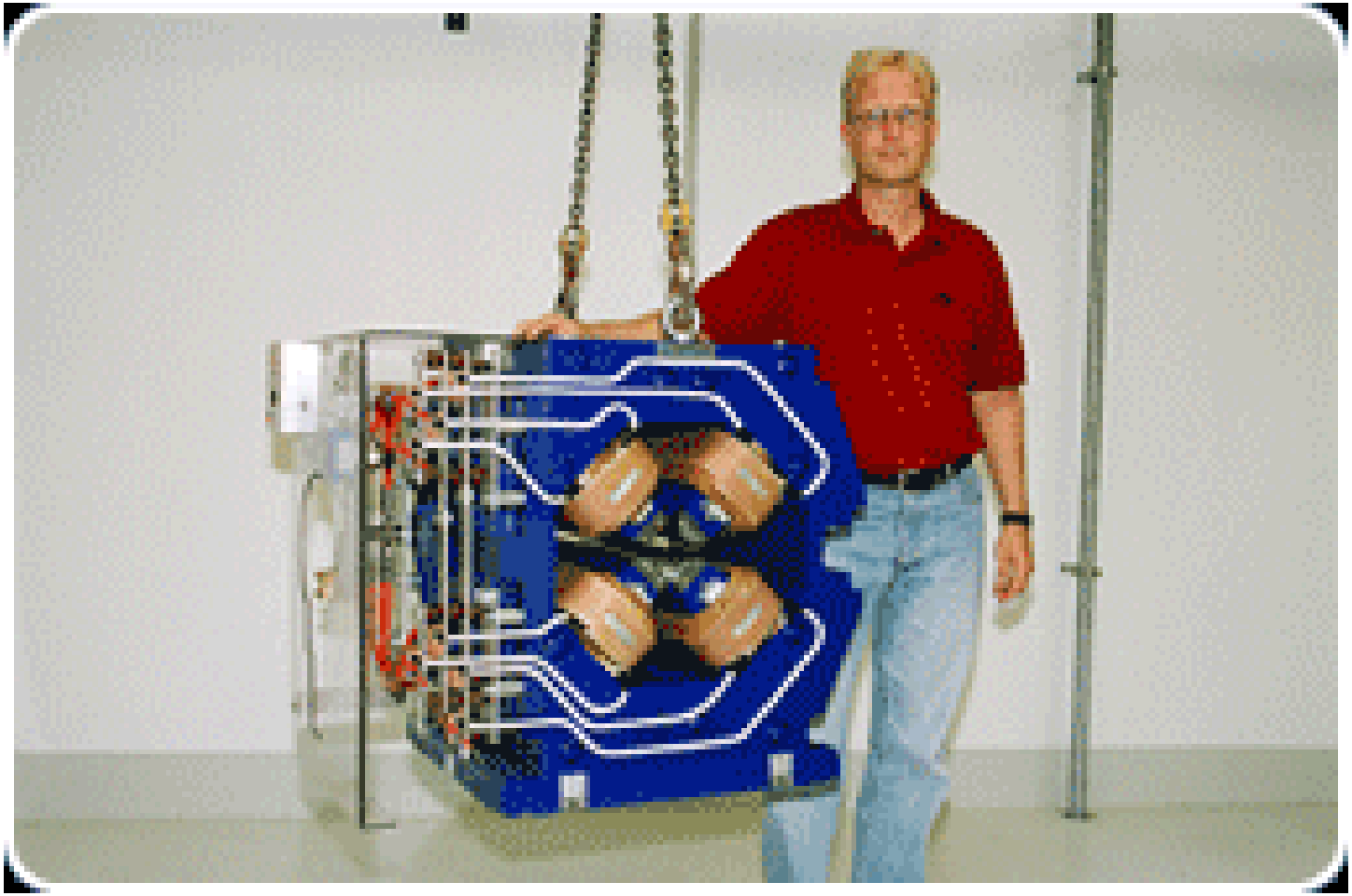
- Betatron oscillation work has showed us that, apart from bend plane focusing, a shaped field that focuses in one transverse direction, defocuses in the other
- Question: is it possible to develop a system that focuses in both directions simultaneously?

- Strong focusing: alternate the signs of focusing and defocusing: get net focusing!!



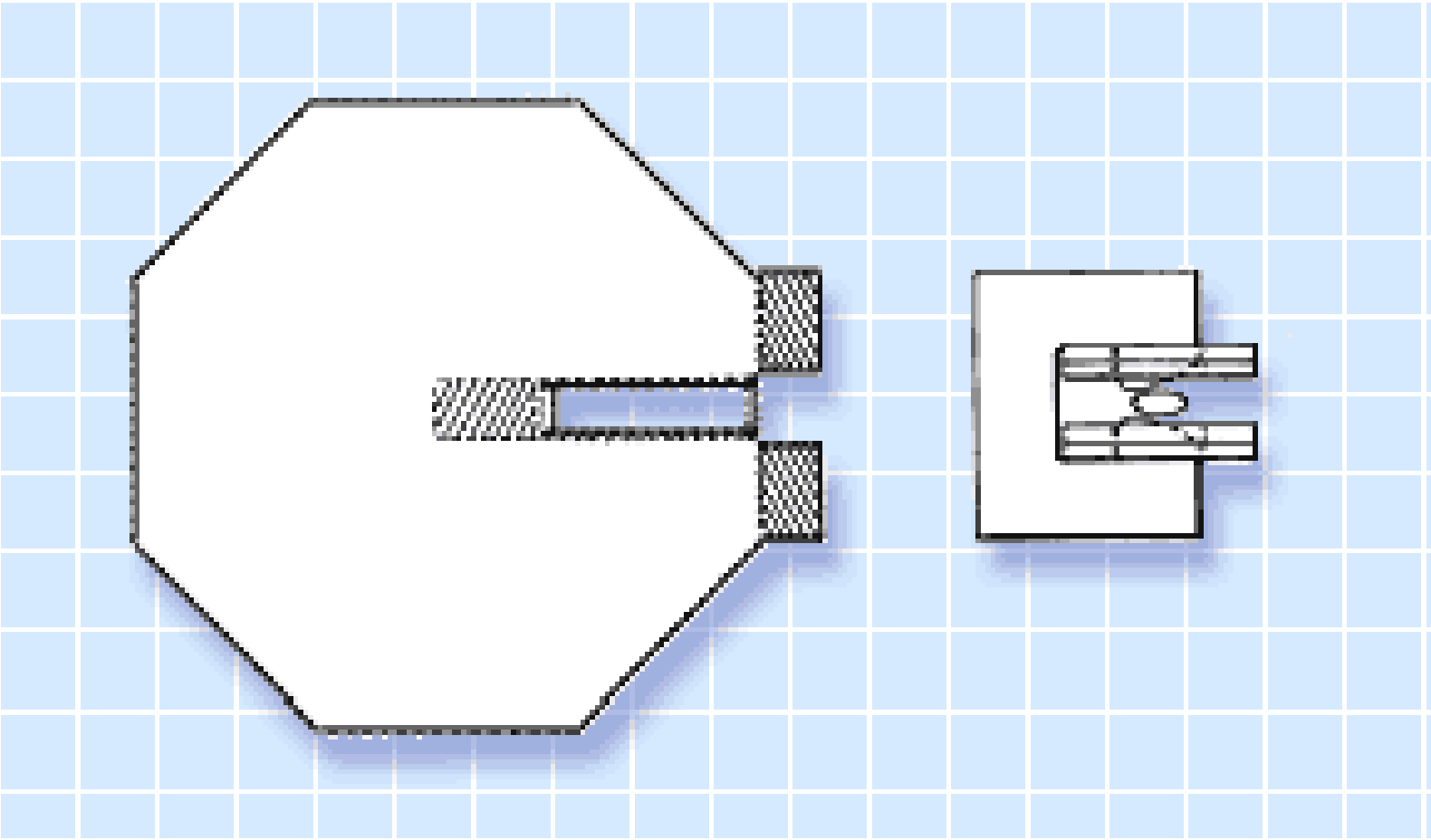
Order doesn't matter

Linear Magnetic Lenses: Quadrupoles



Source: Danfysik Web site

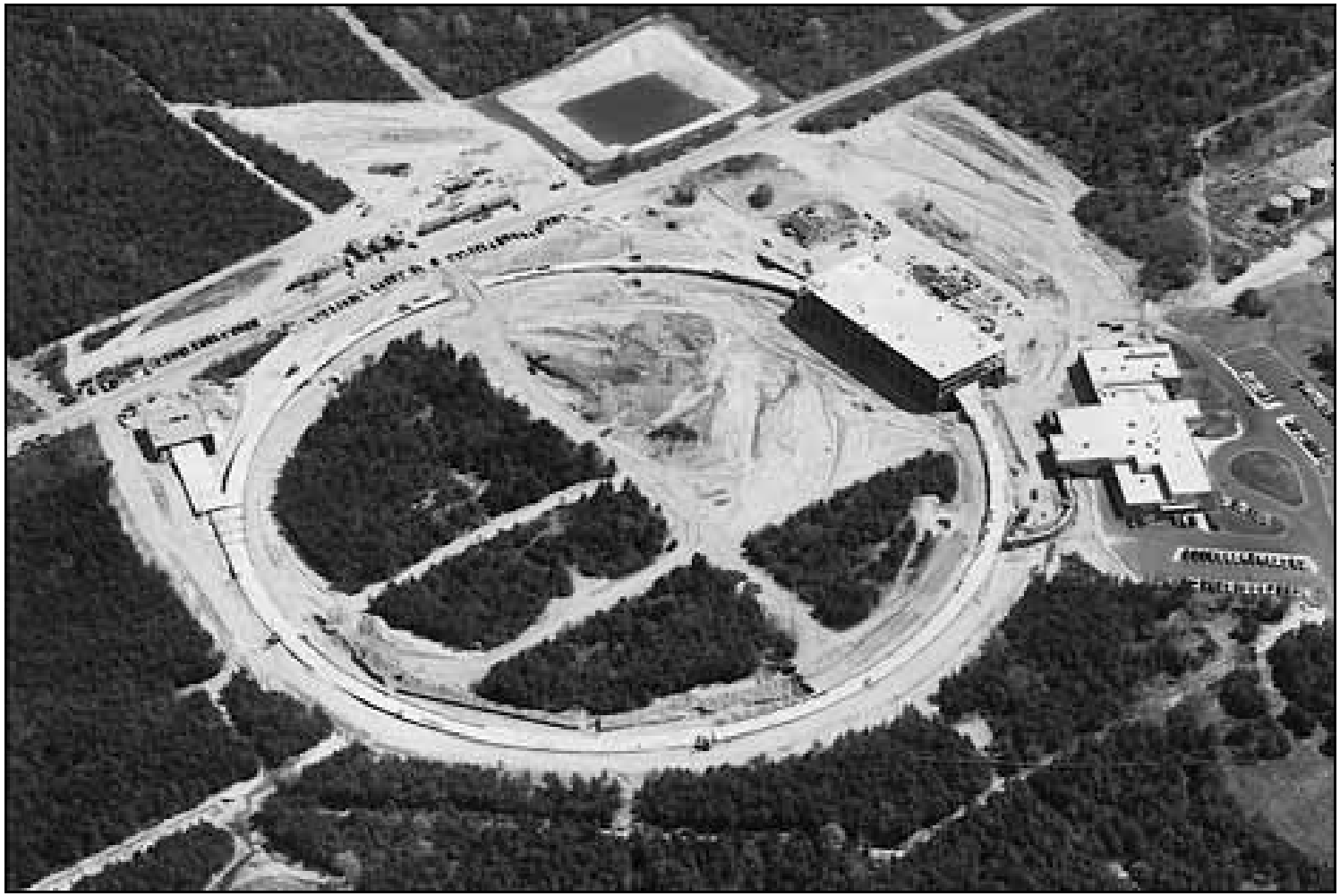
Weak vs. Strong Benders



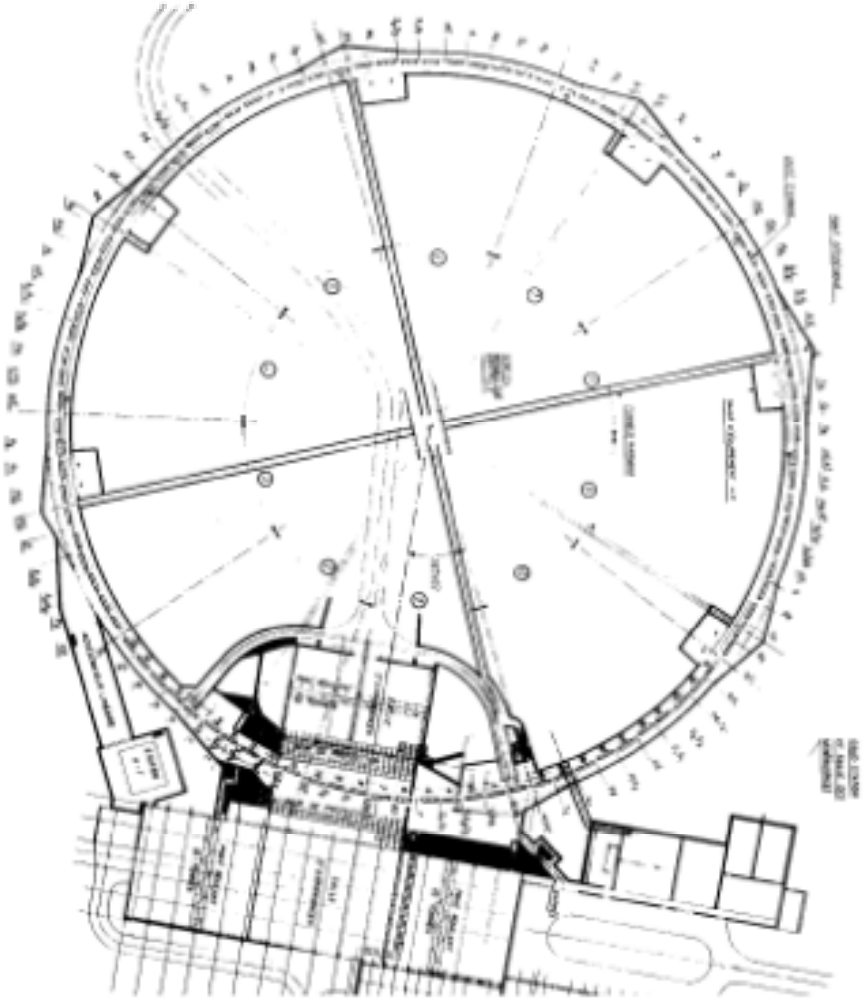
First Strong-Focusing Synchrotron

Cornell 1 GeV Electron Synchrotron (LEPP-AP Home Page)

Alternating Gradient Synchrotron (AGS)



CERN PS



25 GeV Proton Synchrotron

CERN SPS

Eventually 400 GeV protons and antiprotons

FNAL

First TeV-scale accelerator; Large Superconducting Benders

LEP Tunnel (Now LHC!)

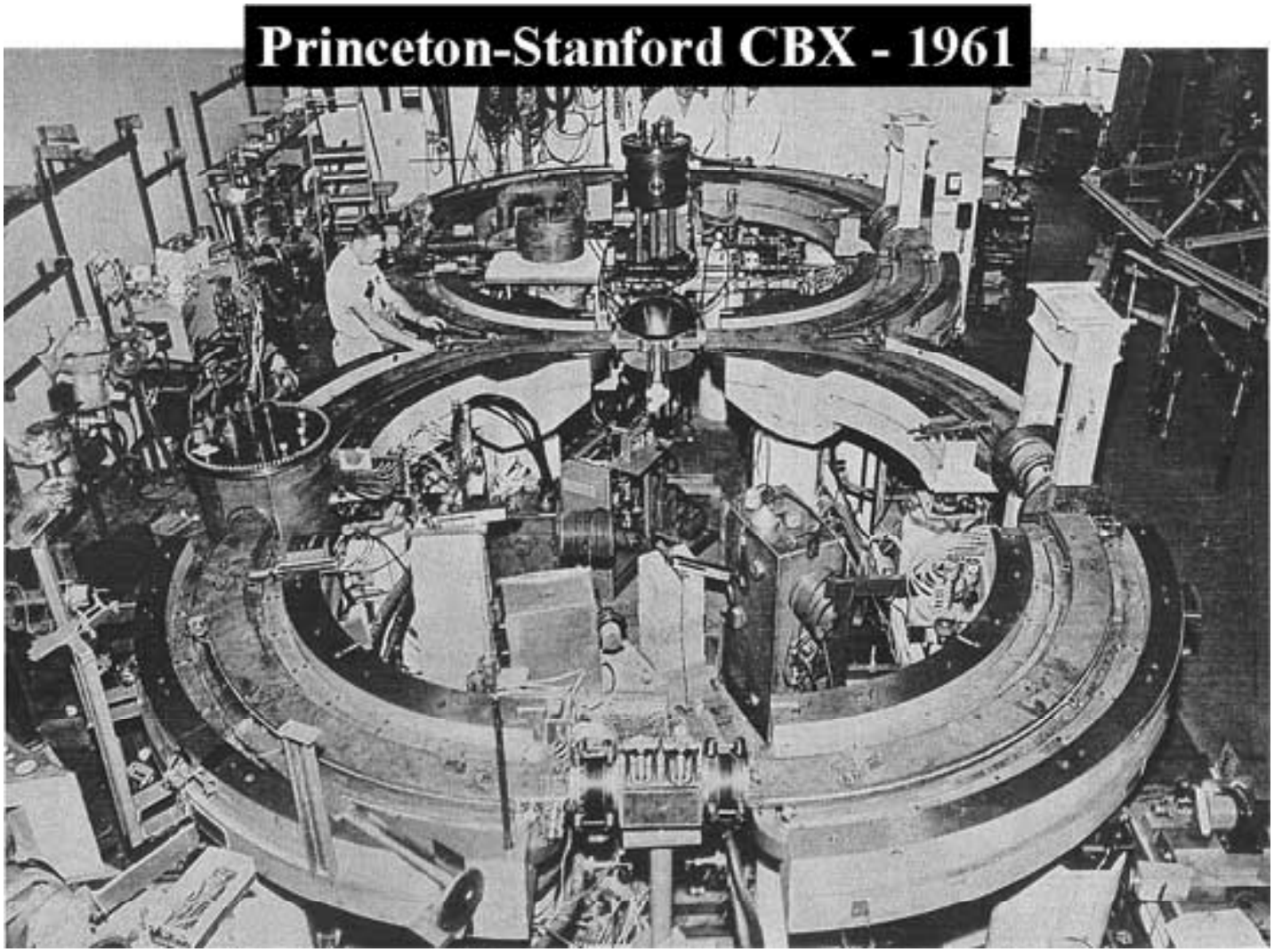
Empty

LHC

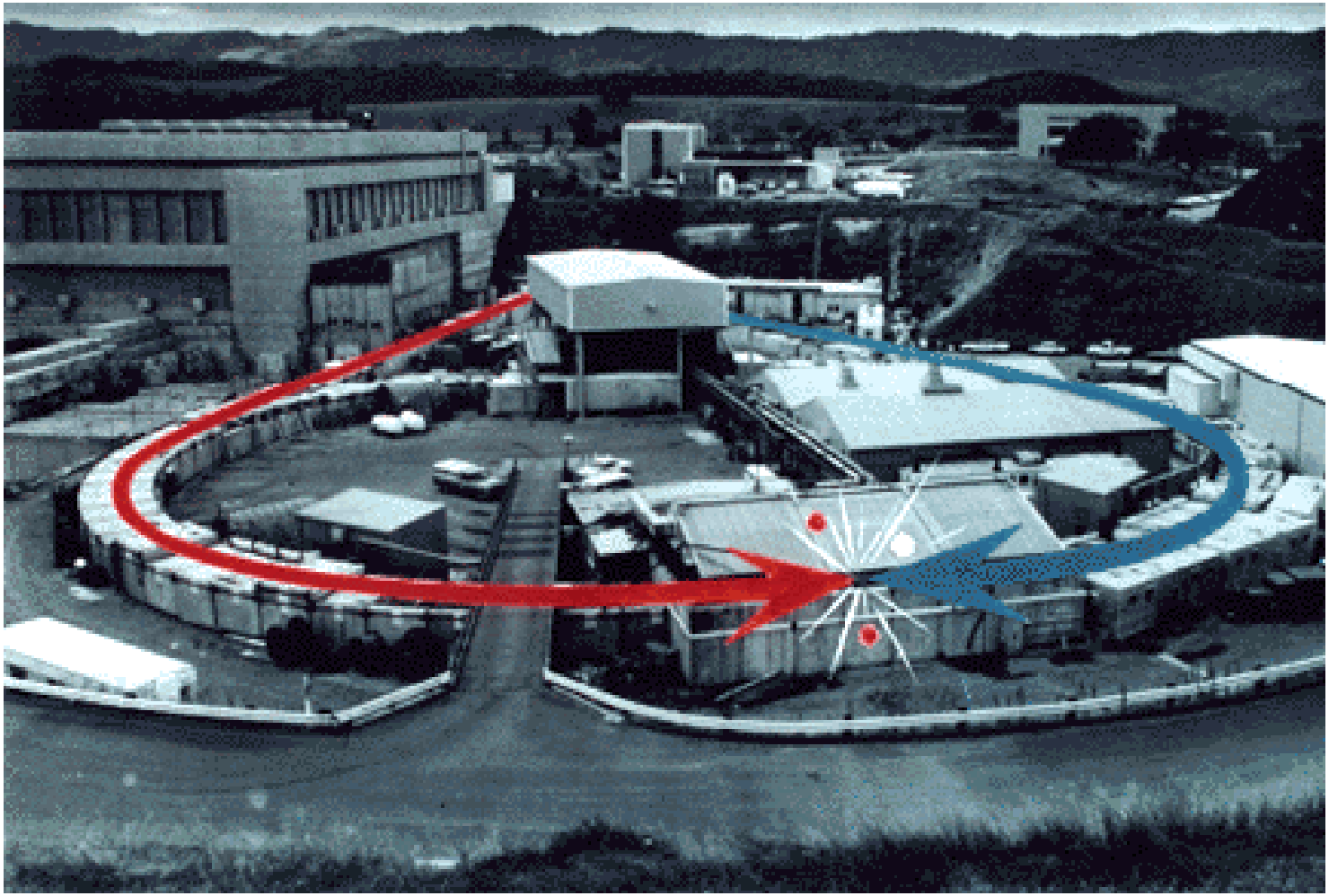
Storage Rings

- Some modern accelerators are designed not to "accelerate" much at all, but to "store" beams for long periods of time that can be usefully used by experimental users.
  - Colliders for High Energy Physics. Accelerated beam-accelerated beam collisions are much more energetic than accelerated beam-target collisions. To get to the highest beam energy for a given acceleration system design a collider
  - Electron storage rings for X-ray production: circulating electrons emit synchrotron radiation for a wide variety of experimental purposes.

Princeton-Stanford Collider



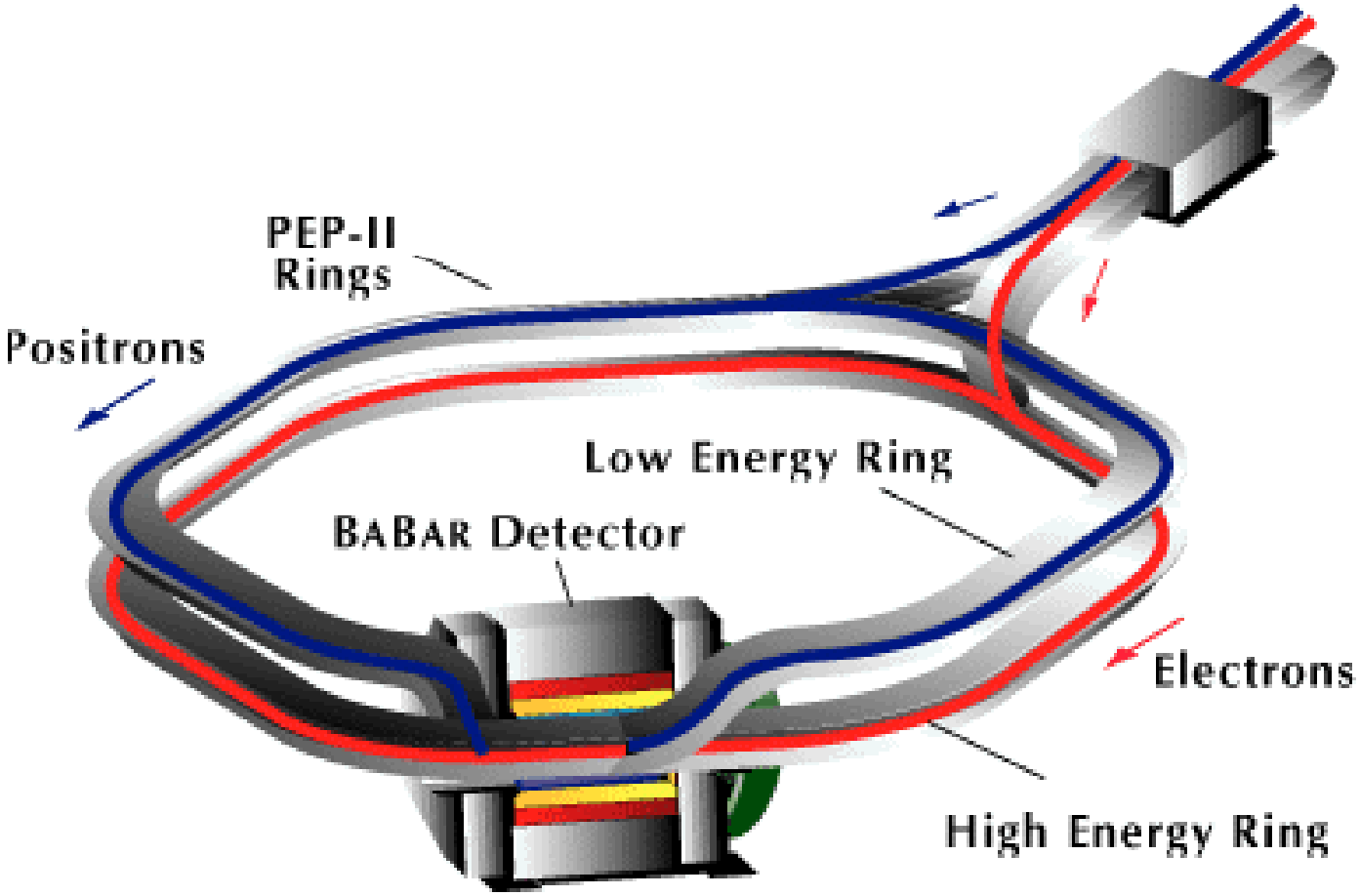
SPEAR



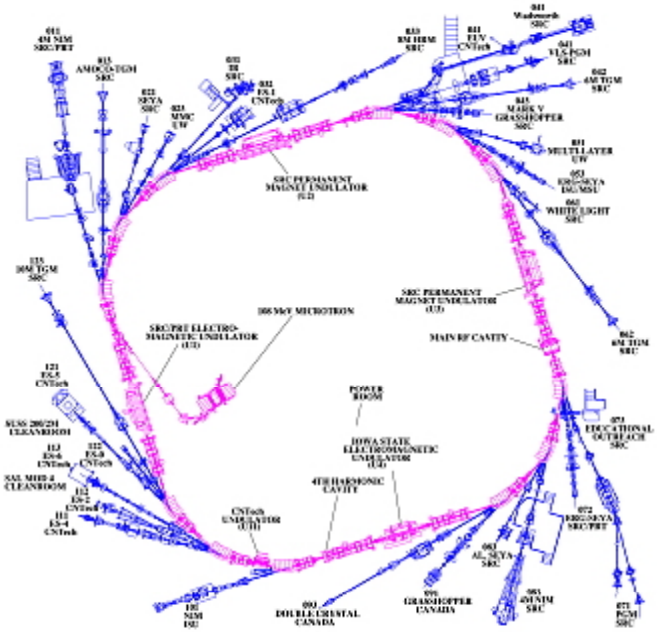
Eventually became leading synchrotron radiation machine

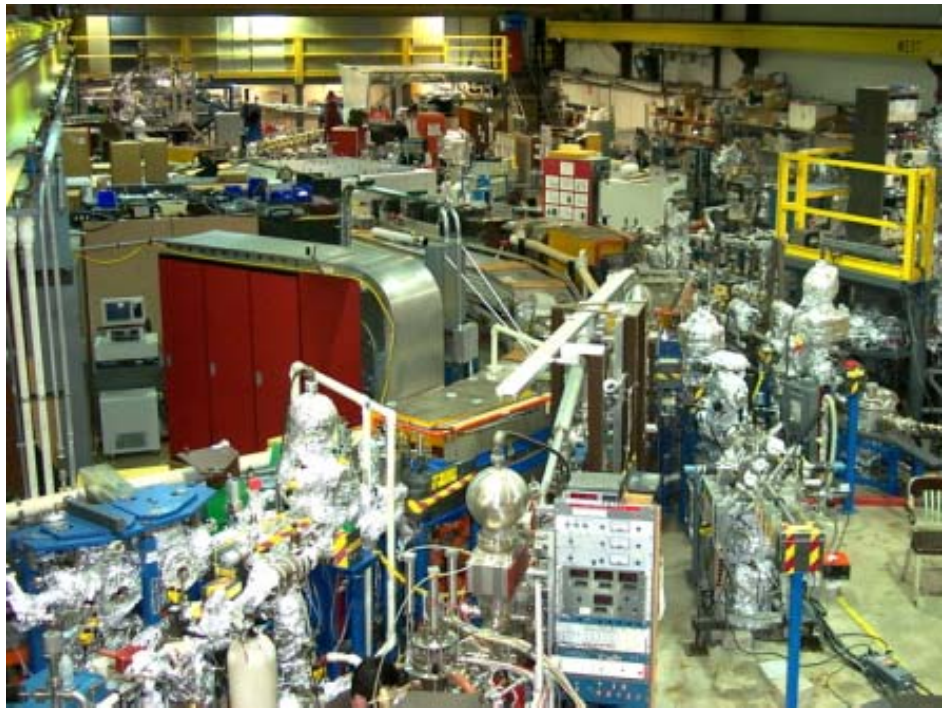
Cornell 10 GeV ES and CESR

SLAC's PEP II B-factory



ALADDIN at Univ. of Wisconsin

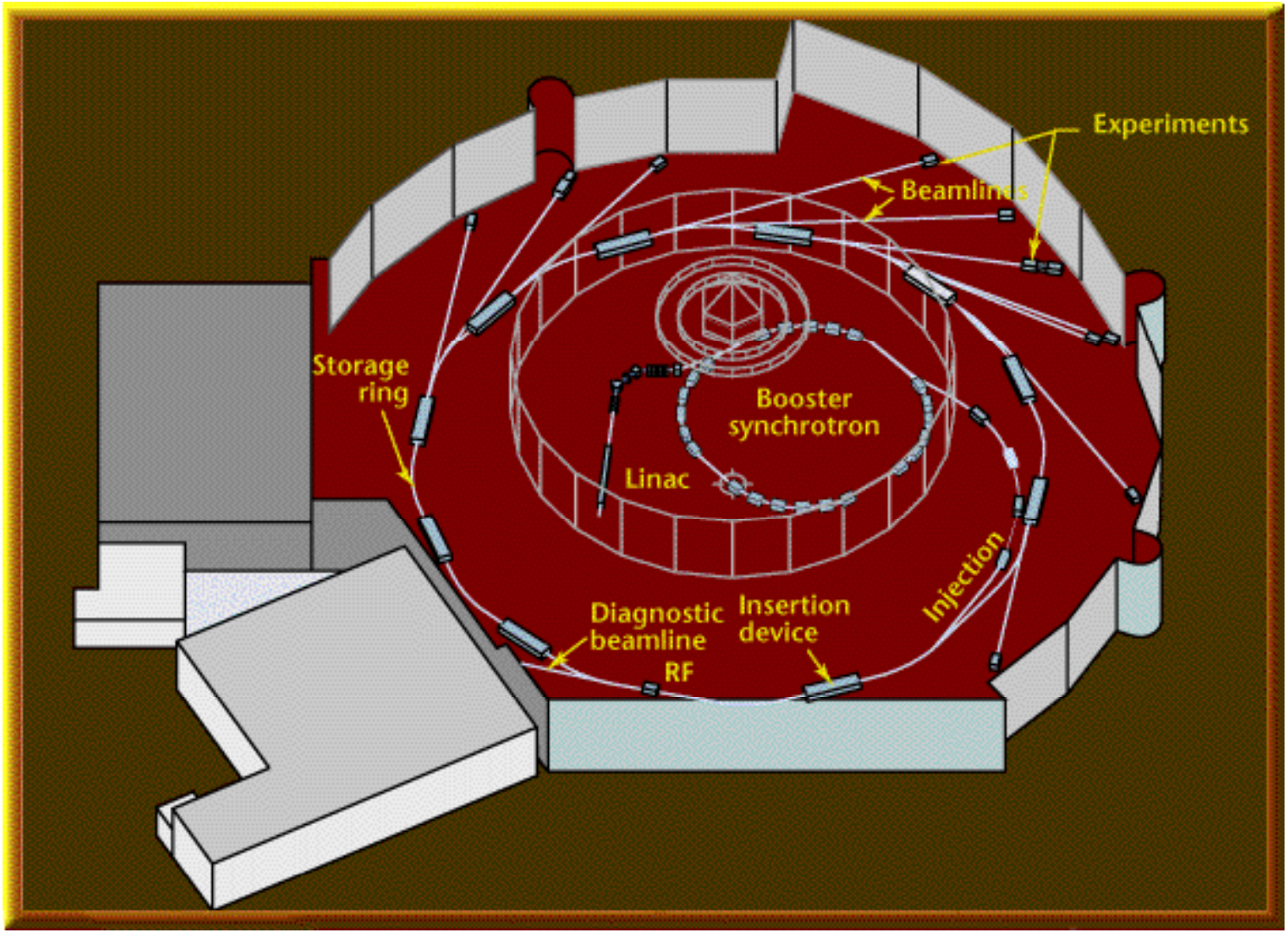




VUV Ring at NSLS

VUV ring “uncovered”

Berkeley's ALS



Argonne APS

ESRF