Physics 417/517 Introduction to Particle Accelerator Physics

G. A. Krafft
Jefferson Lab
Jefferson Lab Professor of Physics
Old Dominion University

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

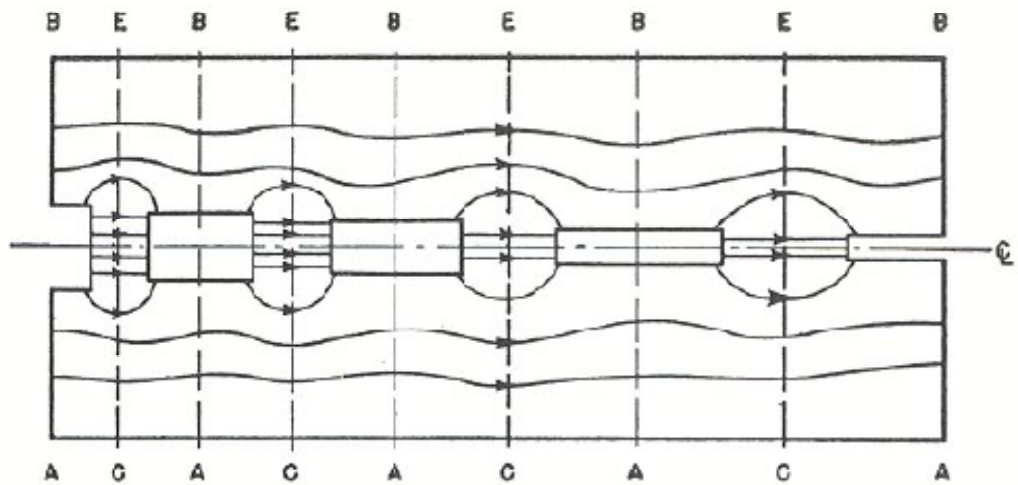
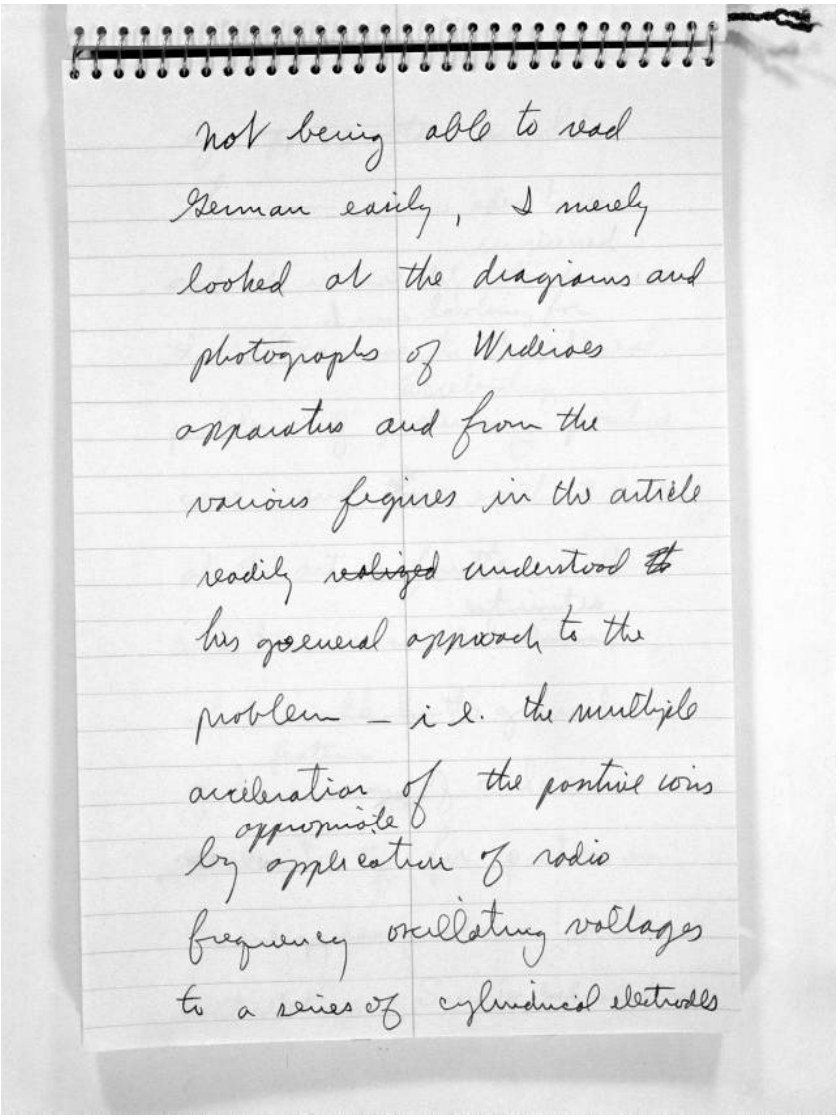


FIG. 2. Linear accelerator produced by introducing drift tubes into cavity excited as in Fig. 1. Division into unit cells.

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*



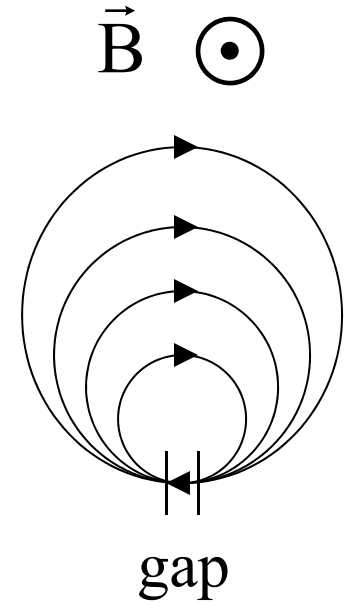
not being able to read
German easily, I merely
looked at the diagrams and
photographs of Wideroes
apparatus and from the
various figures in the article
readily ~~realized~~ understood ~~the~~
his general approach to the
problem – i.e. the multiple
acceleration of the positive ions
by application of appropriate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

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

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

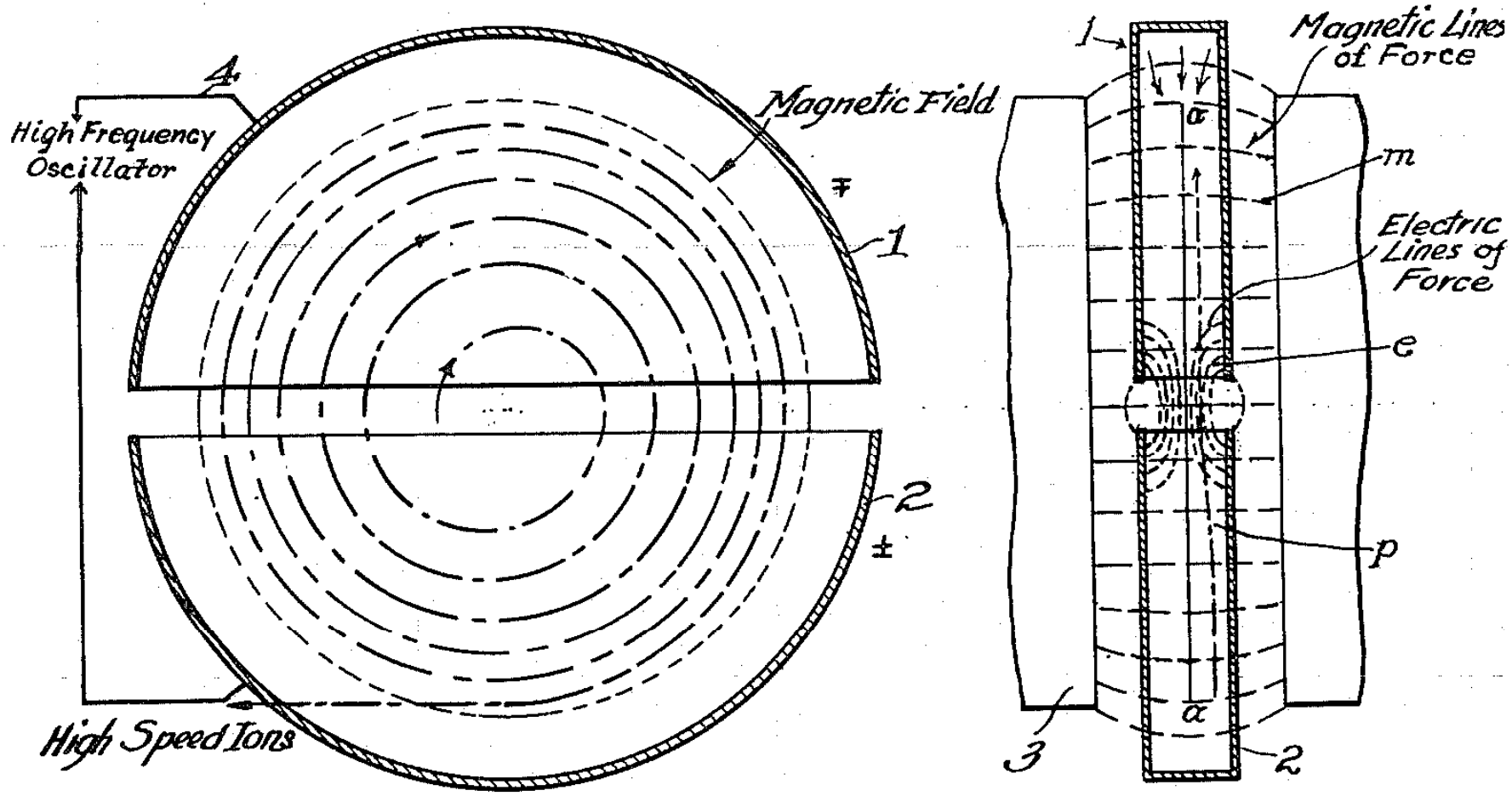
The radius of the oscillation $r = \mathrm{v}_0/\Omega_c$ is proportional to the velocity after the gap. Therefore, the particle takes the same amount of time to come around to the gap, independent of the actual particle energy!!!! (only in the non-relativistic approximation). Establish a resonance (equality!)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

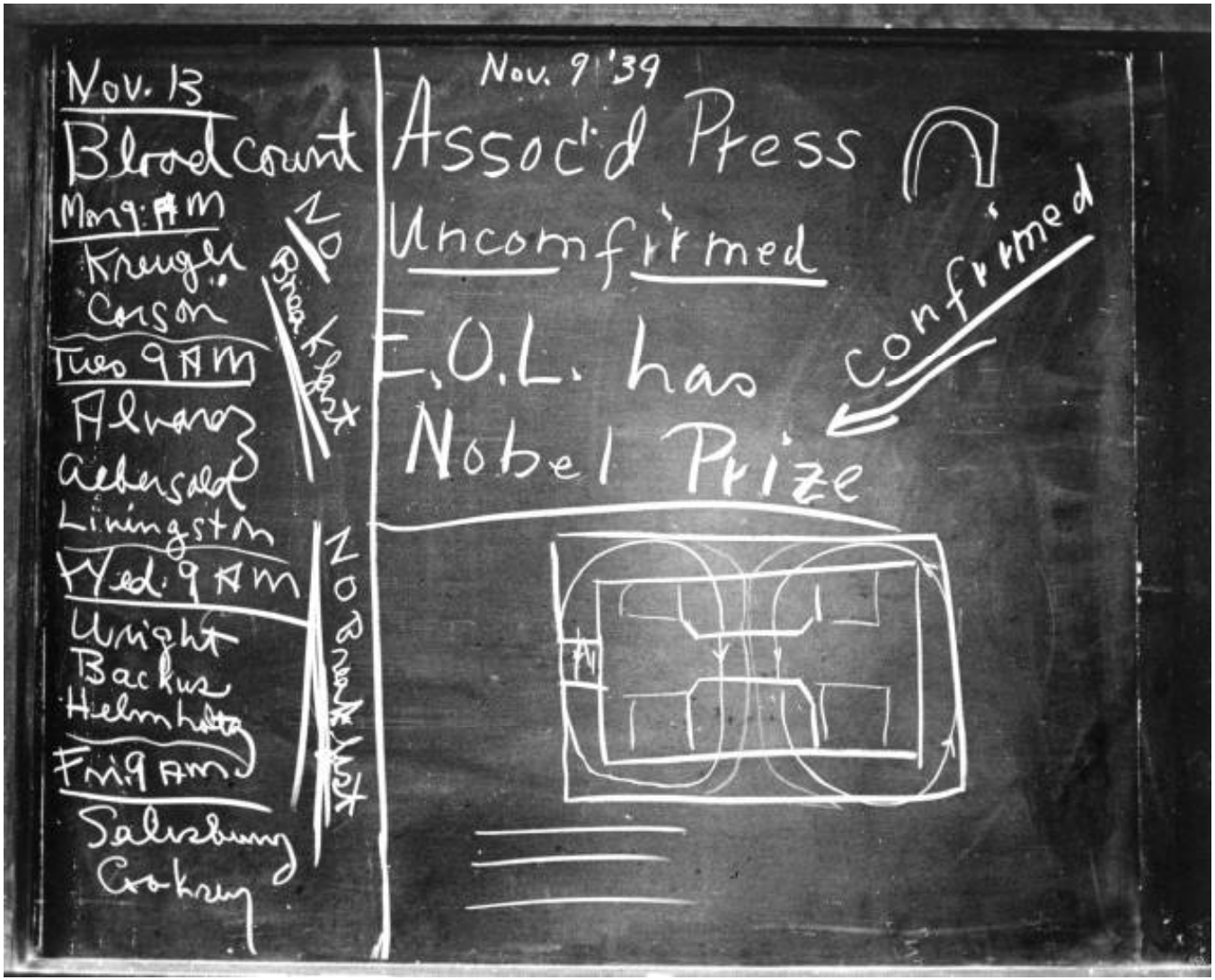


Magnet for 27 Inch Cyclotron (LHS)

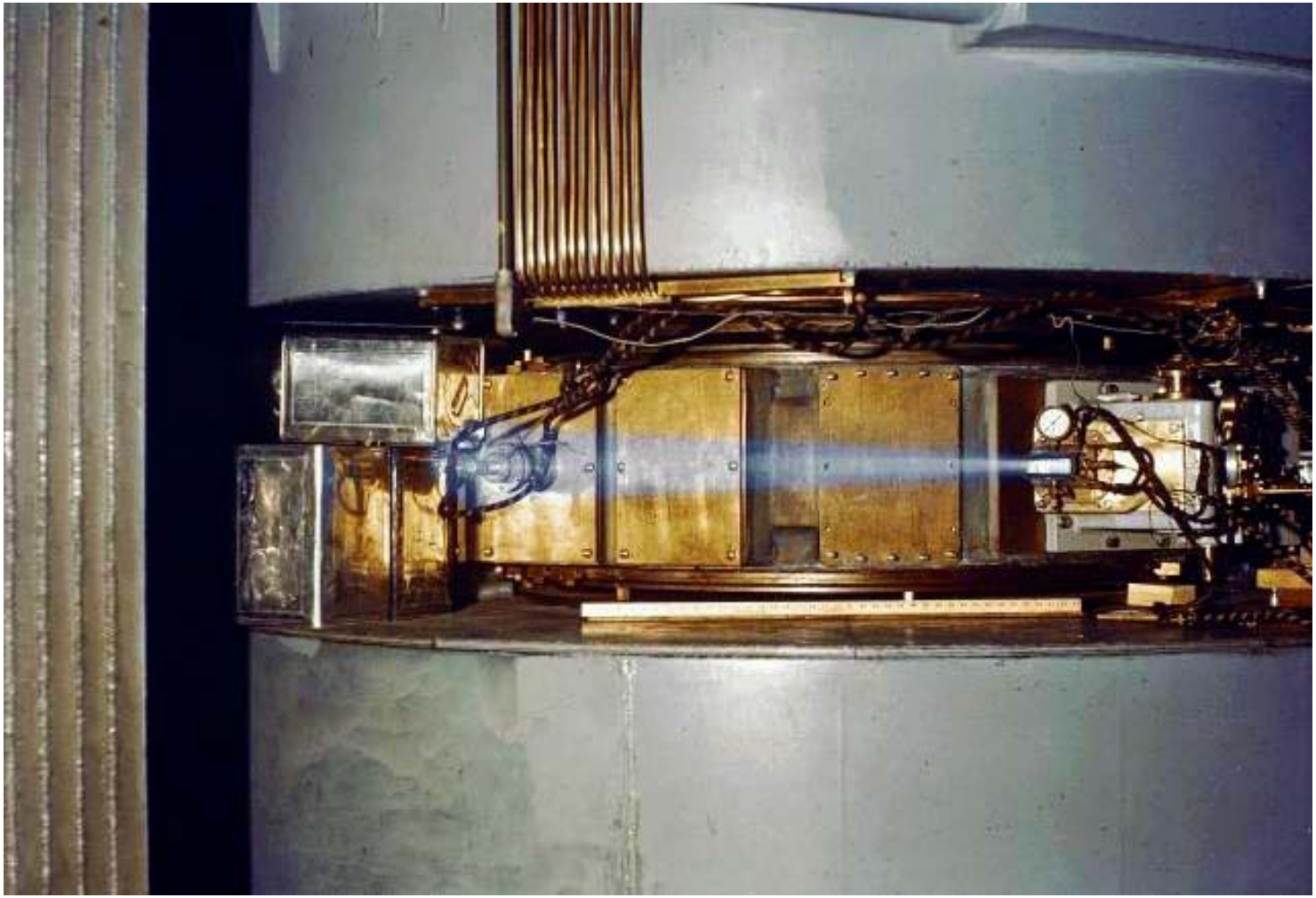
Lawrence and "His Boys"

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!

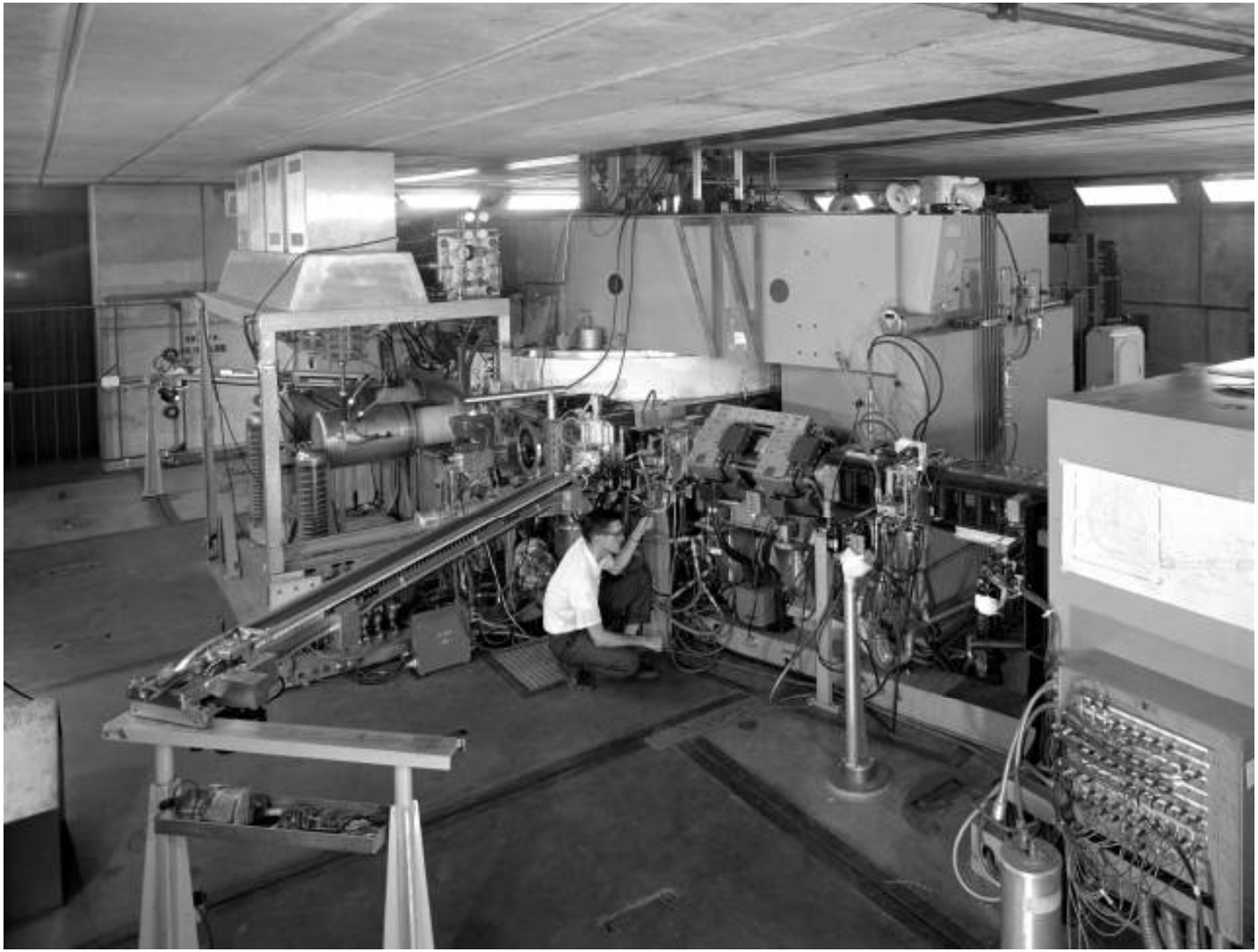

Nov. 13
Blood count
Mon 9 AM
Kruger
Carson
Tues 9 AM
Alvarez
Lawrence
Livingston
Wed. 9 AM
Wright
Backus
Helmholtz
Fri 9 AM
Salisbury
Cockroft
No Breakfast
No Breakfast
Nov. 9 '39
Assoc'd Press
Uncomfirmed
E.O.L. has
Nobel Prize
confirmed

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

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

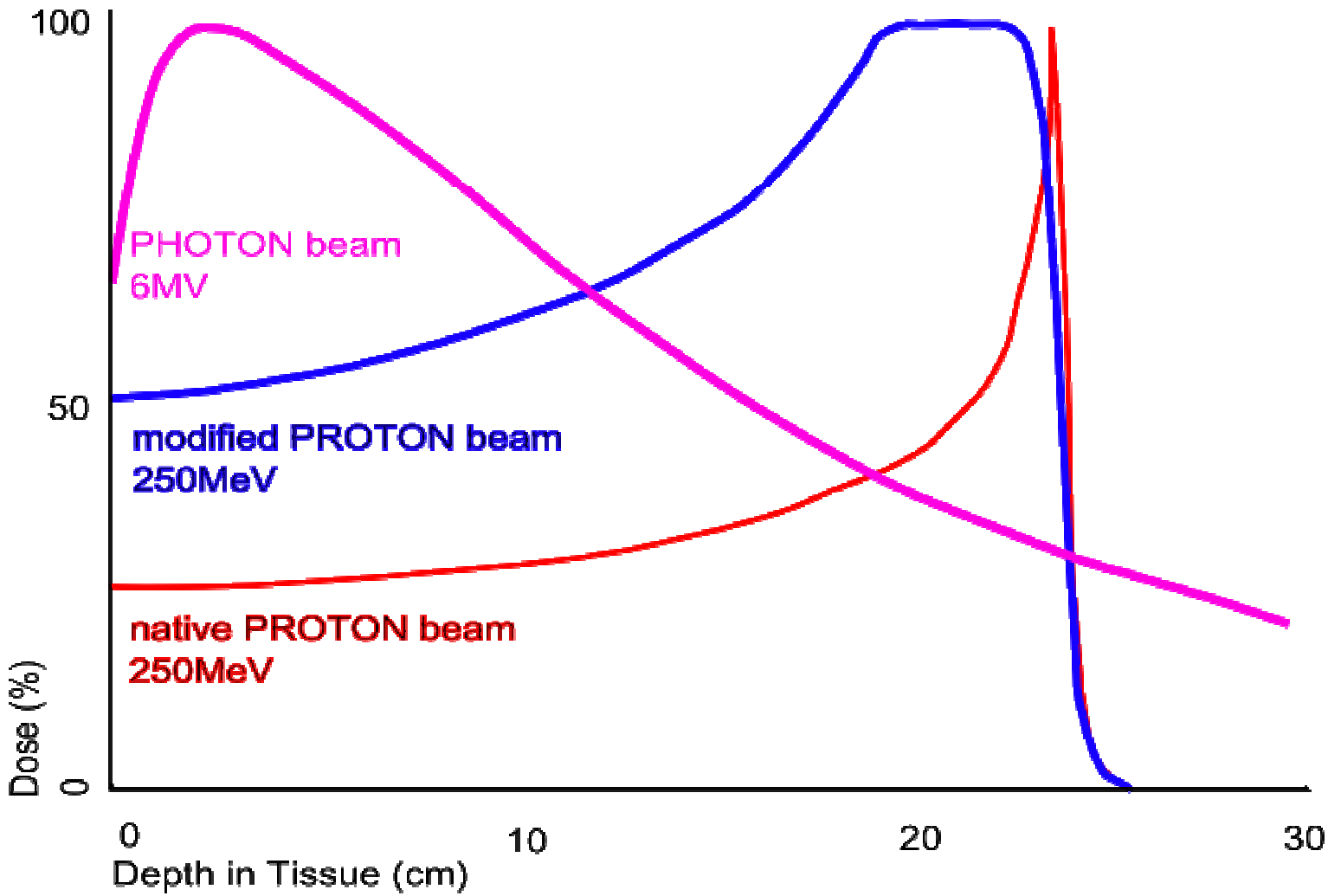
where γ is Einstein's relativistic γ, most usefully expressed as

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

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)