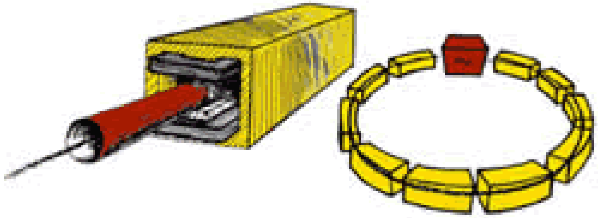
ACCELERATORS



- Basics
- Motivation
- History, R&D, and applications
  - Failed attempts
  - Getting warmer.
  - Linear accelerator concepts
  - Cyclotrons
  - SynchroCyclotron (Frequency Modulated cyclotron)
  - Synchrotron
- Rack’em, stack’em, and pack’em !
  - FNAL

Basic Accelerator

Two Types. 1st Linear

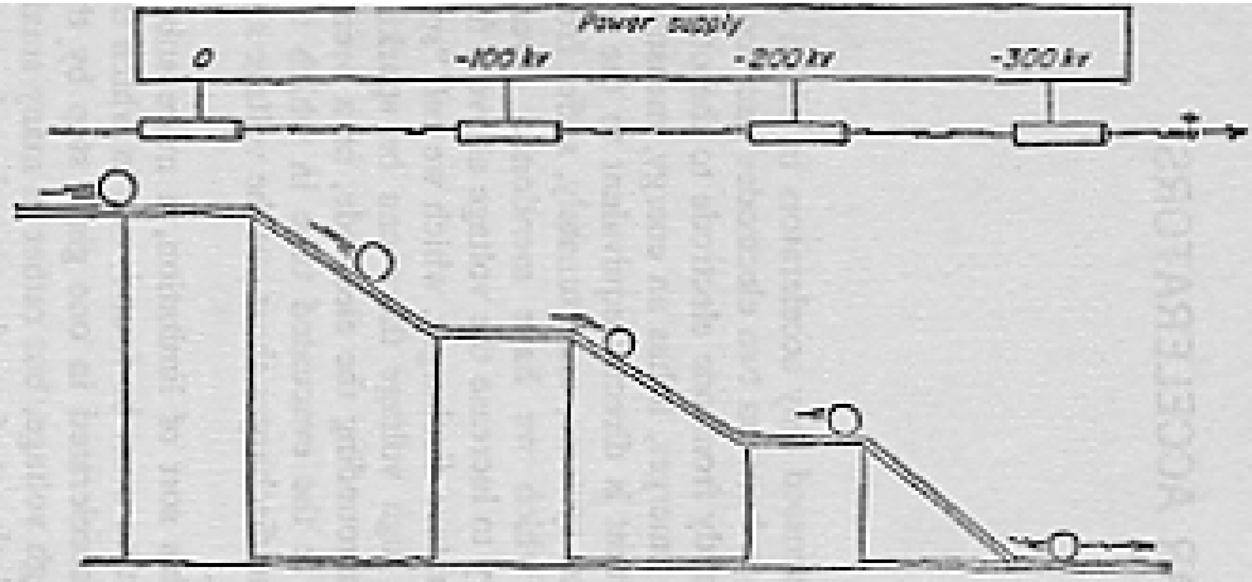


FIG. 14. *In this bowling-alley model of a particle accelerator, gravity accelerates the ball's motion on the sloping sections of track. The height of each horizontal section of track would correspond to a voltage source in a real particle accelerator. The amount of acceleration the ball would undergo is strictly limited by the difference in level between the top and the foot of the entire track.*

2nd: Circular

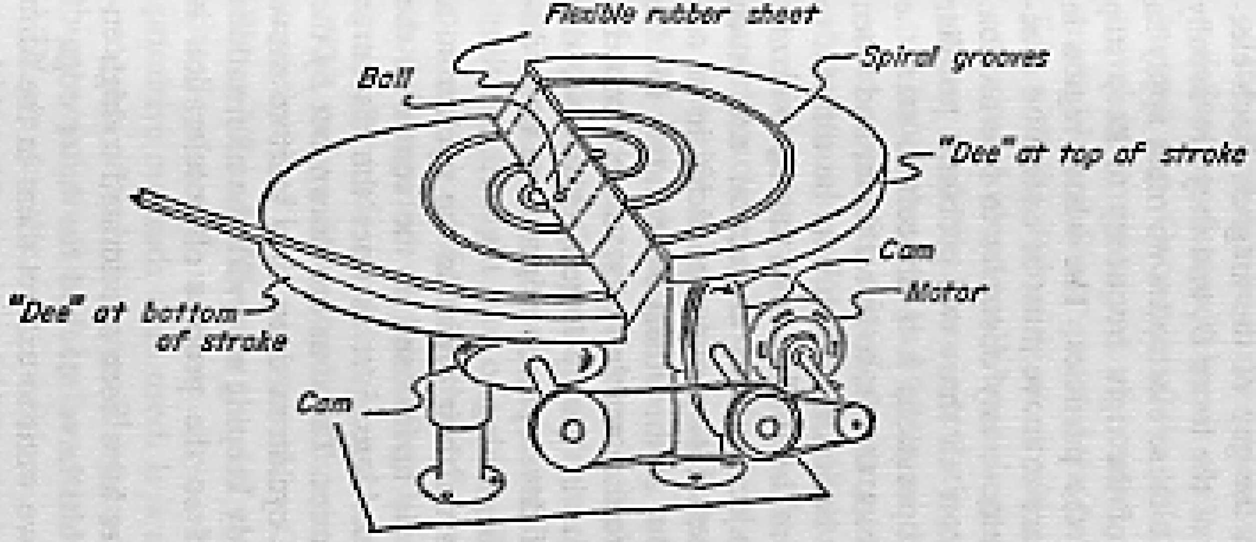


FIG. 24. *In this mechanical analog of the cyclotron the ball undergoes acceleration each time it rolls down the sloping section joining the two movable platforms, which correspond to the accelerating electrodes of the real machine. When correctly timed, the cam mechanism raises each platform as the ball traverses the spiral groove; thus the ball conserves its speed and makes a down-hill passage at the next crossing. The operation is quite similar to that of the movable bowling-alley track shown in Fig. 15,* B.

Nature's Particle Accelerators

- Naturally occurring radioactive sources:
  - Up to 5 MeV Alpha's (helium nuclei)
  - Up to 3 MeV Beta particles (electrons)
- Natural sources are difficult and limited:
  - Chemical processing: purity, messy, and expensive
  - Low intensity
  - Poor geometry
  - Uncontrolled energies, usually very broad

“Start the ball rolling…”

1927: Lord Rutherford requested a “copious supply” of projectiles more energetic than natural alpha and beta particles. At the opening of the resulting High Tension Laboratory, Rutherford went on to reiterate the goal:

> What we require is an apparatus to give us a potential of the order of 10 million volts which can be safely accommodated in a reasonably sized room and operated by a few kilowatts of power. We require too an exhausted tube capable of withstanding this voltage… I see no reason why such a requirement cannot be made practical.

FAILED ATTEMPTS

1928: Curt Urban, Arno Brasch, and Fritz Lange successfully achieved 15 MV by harnessing lightning in the Italian Alps !

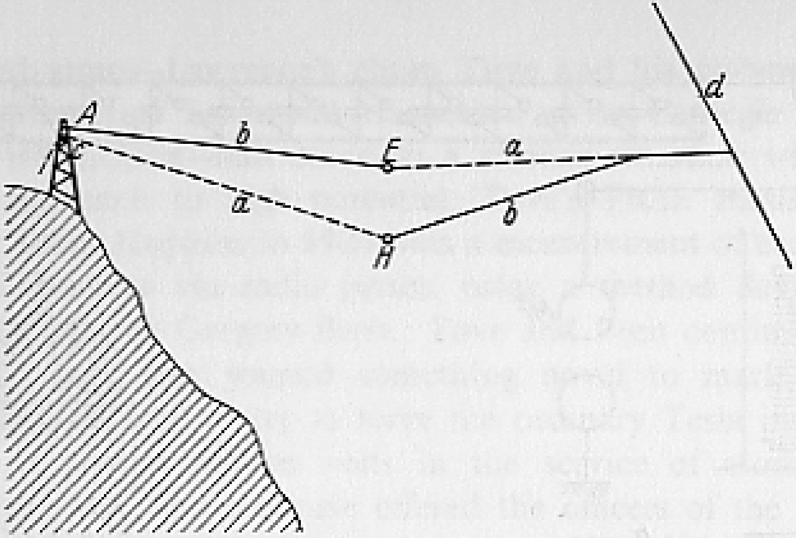


FIG. 2.1 Brasch and Lange's lightning catcher. E and H are the spheres between which the discharge occurs; AE, the antenna; a,a, insulators; b,b, conductors; d, a grounded wire. Brasch and Lange, *Zs. f. Phys.*, *70* (1931), 17.

The two who survived the experiment went on to design an accelerator tube capable of withstanding that voltage.

FAILED ATTEMPTS

1930

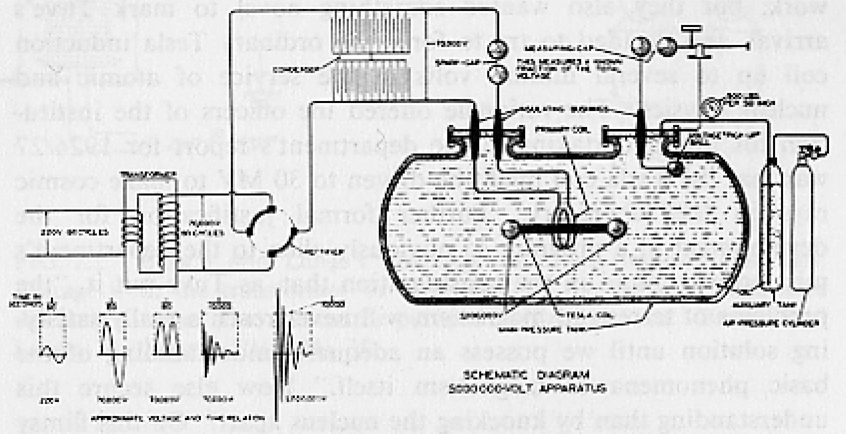


FIG. 2.3 Schematic of the installation of the Carnegie Institution's 5=mV Tesla coil. Breit, Tuve, and Dahl, *PR*, *35* (1930), 56.

- Intense power requirement
- Insulator technology was not available
  - Large oil filled tanks “archived” 5 MV
  - Still, no capable accelerating tube available

Small Victories

Try, Try and Try Again

1931

- Brash & Lange try again
  - Successful impulse generator
- Safer, but only 900 keV
  - Thought to be too low

→Back to the Alps

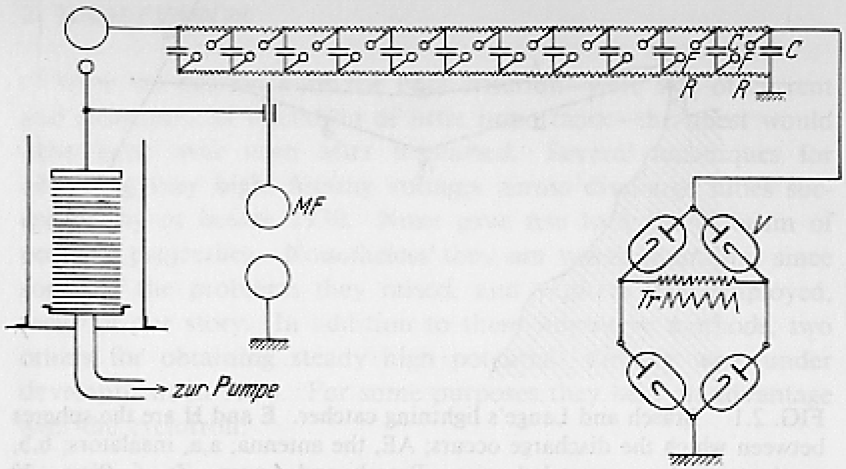


FIG. 2.2 Brasch and Lange's discharge tube and impulse generator. Voltage from the transformer Tr multiplied by the string of capacitors discharges across the constantly pumped laminated tube. Brasch and Lange, *Zs. f. Phys.*, *70* (1931), 30.

Enter Robert J. Van de Graff

1931-4

Van de Graff (VDG) achieved 1.5 MV in 1931, with two VDG metal spheres.

Proposed 10 MV with two 20 foot spheres on 20 foot towers.

It worked ! But progress was slow…

VDG generators are still used today

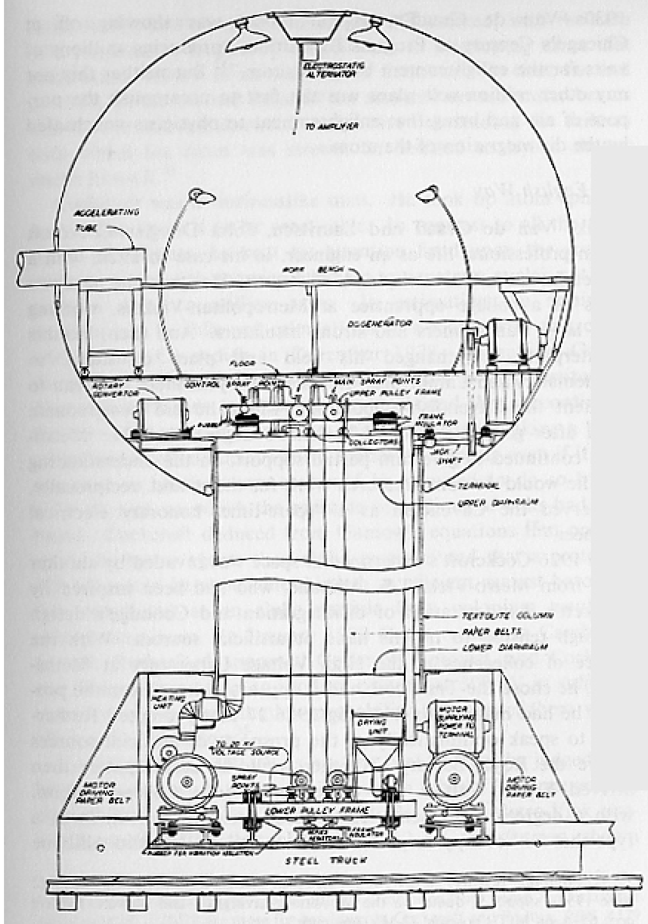


FIG. 2.9 An insider's view of the 15-foot generator. It delivered 1.1 mA to the accelerating tube under a tension of 5.1 MV. Van Atta et al., *PR, 49* (1936), 762.

Van de Graff at Carnegie Inst.

He was a hit !

Many labs could easily obtain a Van de Graff.

- Low currents ☹
- High precision ☺

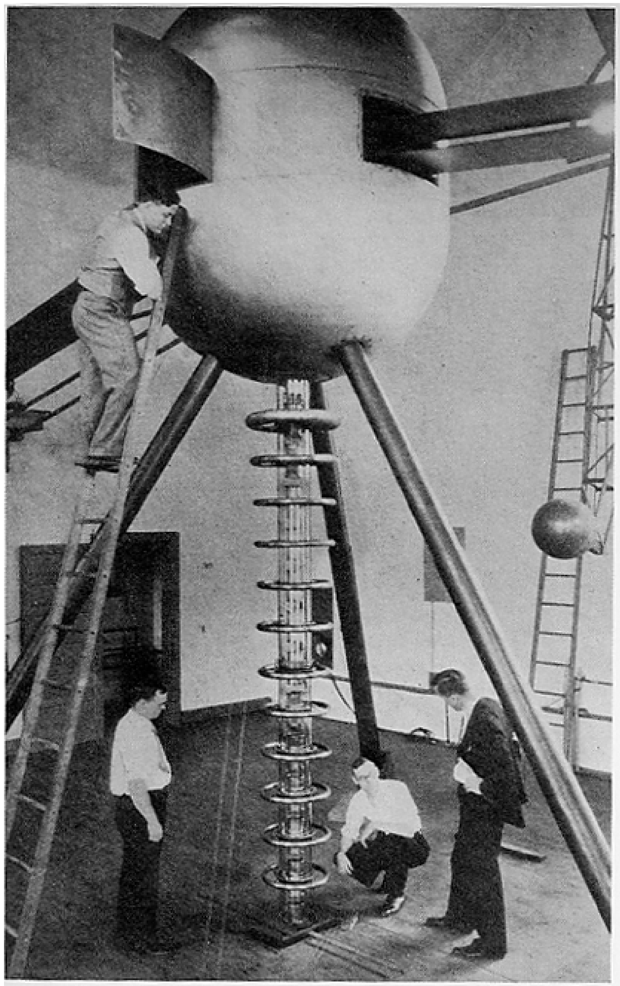
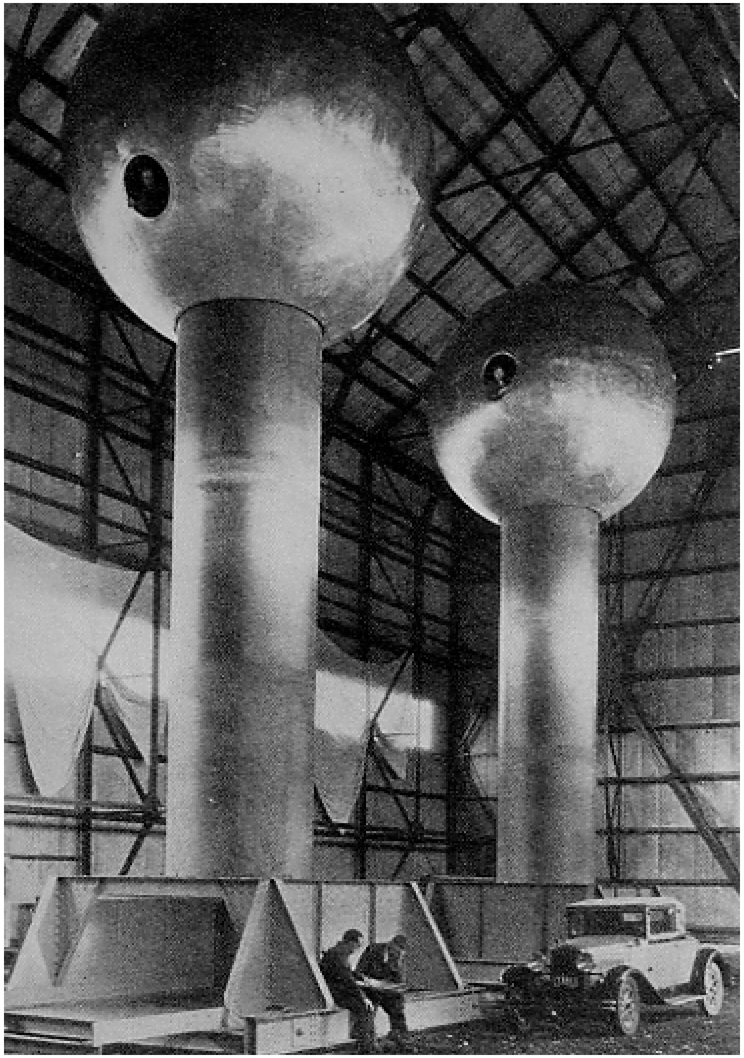


PLATE 2.4 The Carnegie Institution's two-meter Van de Graaff; Dahl is on the ladder, Tuve in the suit. The business end of the discharge tube, deflecting magnets, and pumps are under the floor. Tuve, Hafstad, and Dahl, *PR. 48* (1935), 322.

VDG’s 15-foot machine at MIT

- The awesome VDG installation at MIT stood 43 feet about the ground and the spheres were 15 feet in diameter.
- It promised 10 MV, but was not realized until after WWII



Accelerators the English way…

1932

- Cockcroft & Walton devised a voltage source that was capable of 600 kV
- Felt 100’s of keV needed more study
  - 1st goal was only 300 keV

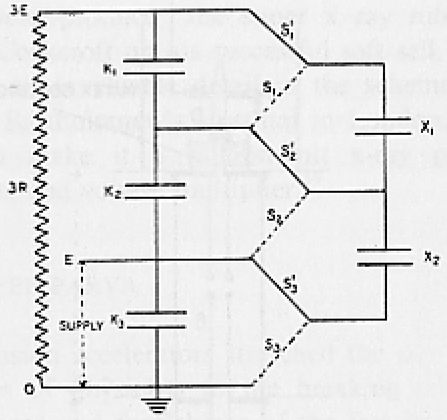


FIG. 2.10 Principle of the voltage multiplier constructed at the Cavendish. Cockcroft and Walton, *PRS, A136* (1932), 620.

Cockcroft-Walton Generator

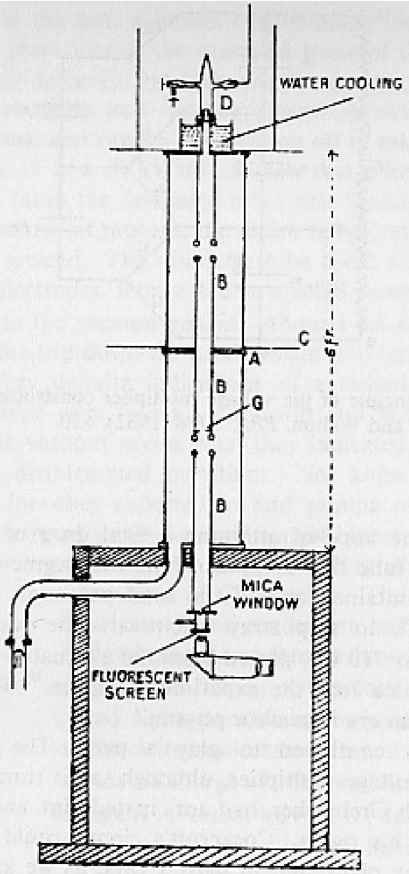


FIG. 2.11 Accelerating tube and target arrangement of the Cockcroft-Walton machine. The source is at D; C is a metallic ring joint between the two sections of the constantly pumped tube. The mica window closes the evacuated space. Cockcroft and Walton, *PRS, A136* (1932), 626.

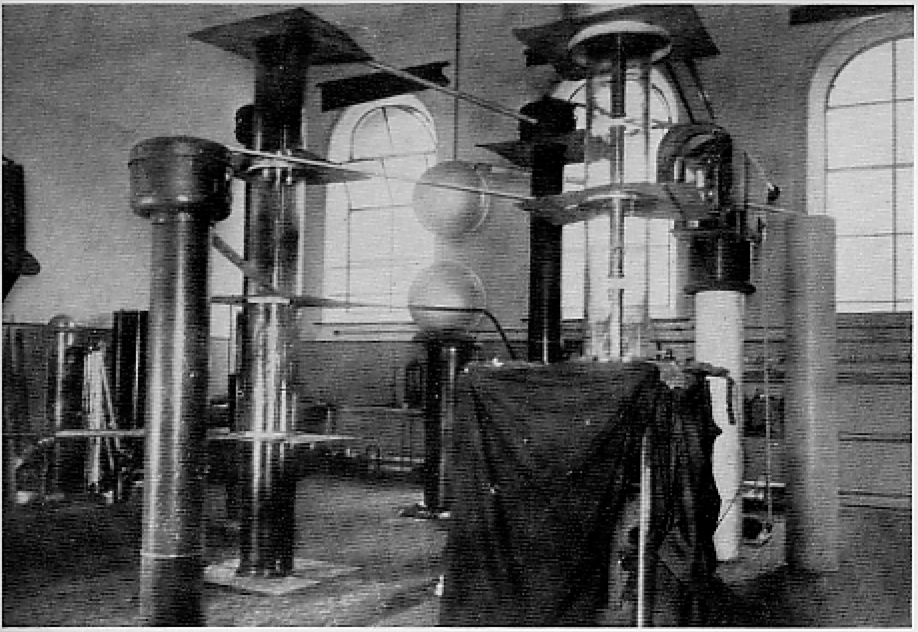
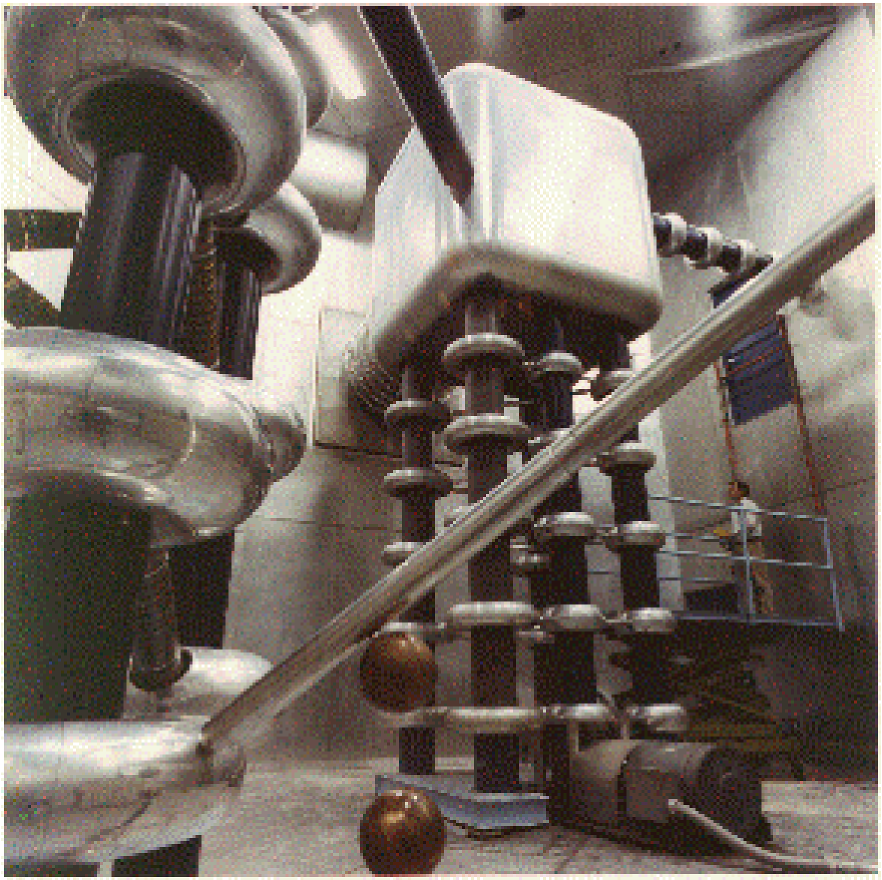


PLATE 3.7 Cockcroft and Walton's corner of the Cavendish. The tall transparent cylinder in the center is the discharge tube; the other cylinders are stacks of condensers and rectifiers. The curtained box is the observation center. Cockcroft and Walton, *PRS, A136* (1932), 625, plate 11.

Cockcroft & Walton Left their Mark



The 1st stage of Fermilab's huge accelerator is a Cockcroft-Walton Machine

750 keV

(Upper limit)

The Million Volt Barrier

Summary of Problems in getting HV ~ 1929

- Voltage Generators
- Insulators – 750 kV max holding !
- Power
- Safety in using HV
- Funding
- Imagination

Let’s Get Serious Now…

Rolf Wideroe

1929

R. Wideroe proposed an accelerator by using an alternating voltage across many alternating “gaps.”

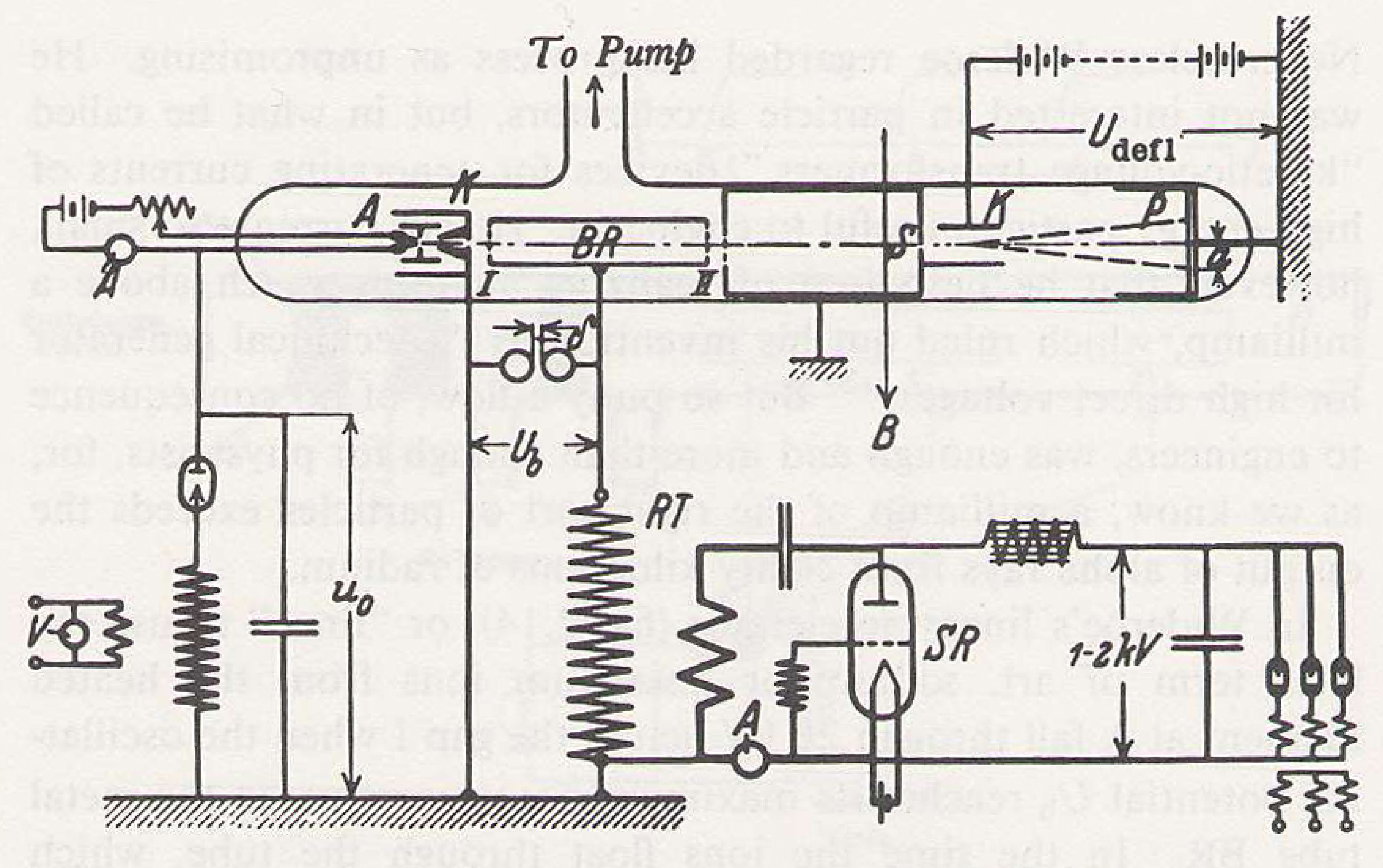
It was not without a myriad of problems

- Focusing of beam
- Vacuum leaks
- Oscillating high voltages
- Again, imagination

His professor refused any further work because it was “sure to fail.”

- Wideroe still published his idea in *Archiv fur Electrotechnic*

Schematic of Wideroe’s Linac



Ernest Orlando Lawrence

PLATE 1.4 Lawrence as a young associate professor. University Archives, TBL.

In April 1929, UC Berkley’s youngest Physics professor happened across *Archiv fur Electrotechnic*.

Not able to read German he just looked at the diagrams and pictures of the journal.

Immediately after seeing Wideroes schematic, Ernest fully comprehended it’s implications. He was excited !

“R cancels R”

Ernest quickly jotted down the following:

$F_r = mv^2/r$ and

$F_B = qvB$

thus:

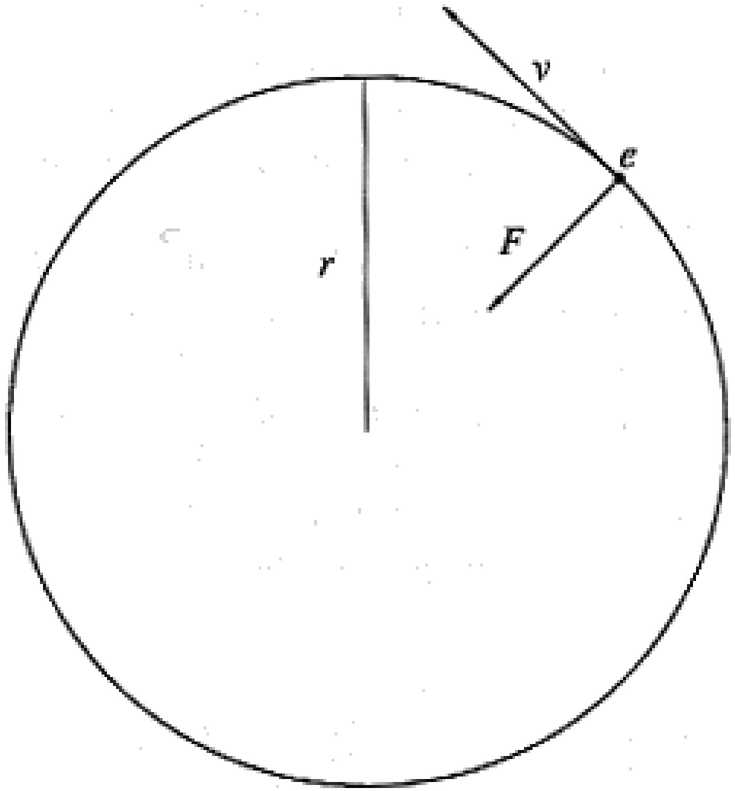
$r = mv/qB$

$\omega = 2\pi f = v/r$

substitute:

$f = qB/2\pi m$

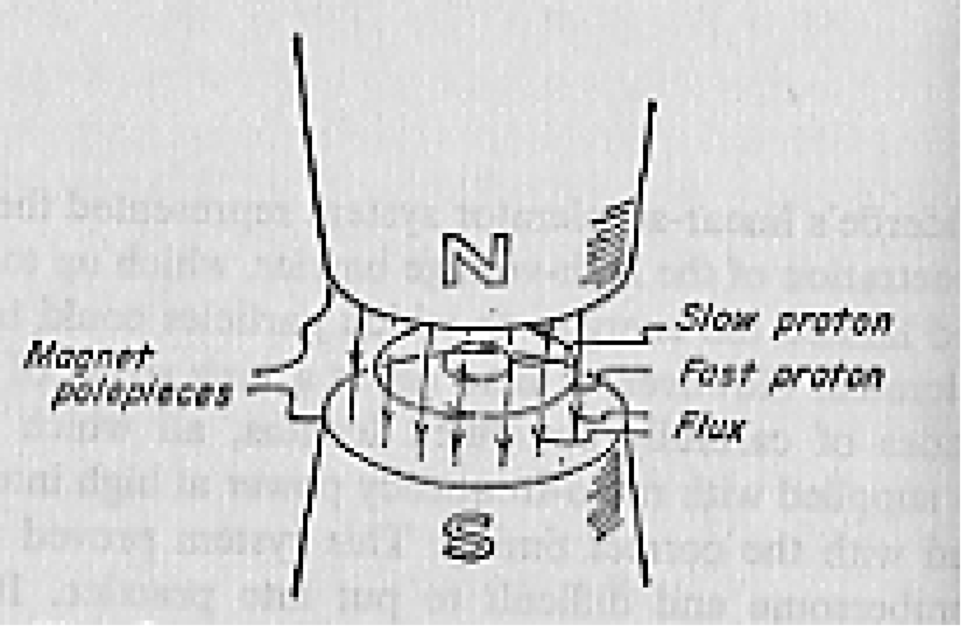
R cancels R !



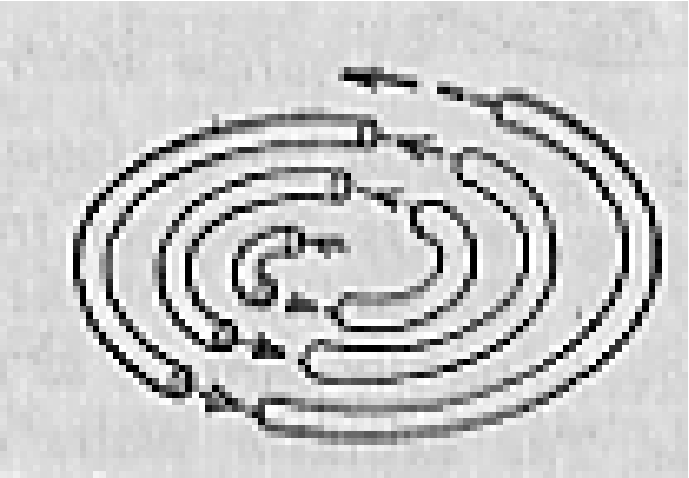
What does this mean ?

Ernest Lawrence recognized that the ion’s angular velocity does not depend on the radius

Mother nature was kind to cyclotroneers, for as the particle’s energy (speed) increased, so did it’s orbital path length. For a fixed particles q/m and magnetic field the angular frequency is constant.

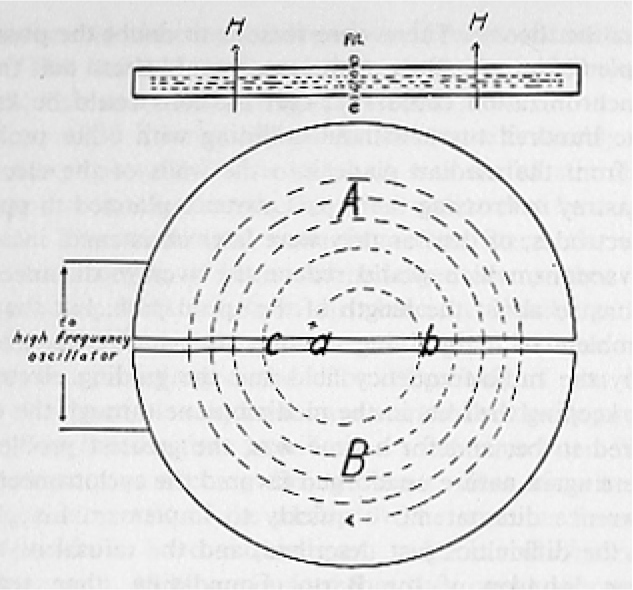


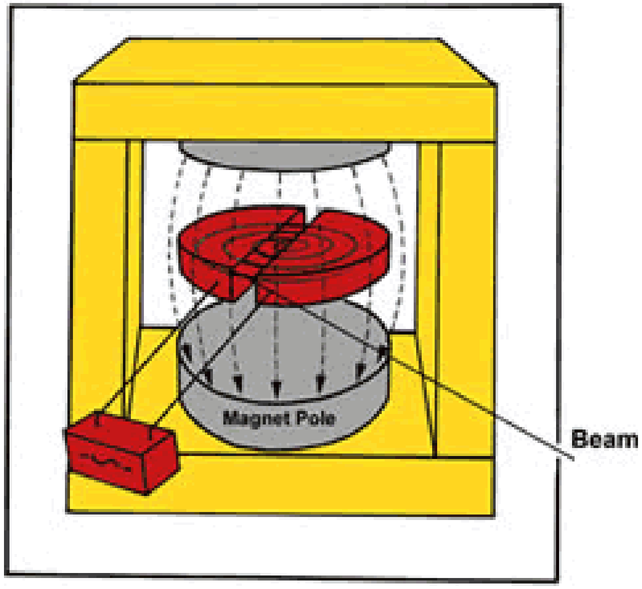
Conceptual Cyclotron Design



Ernest Lawrence proposed a modification to Wideroe's double gap linac: bend the tubes and apply a magnetic field to bend the ion's path.

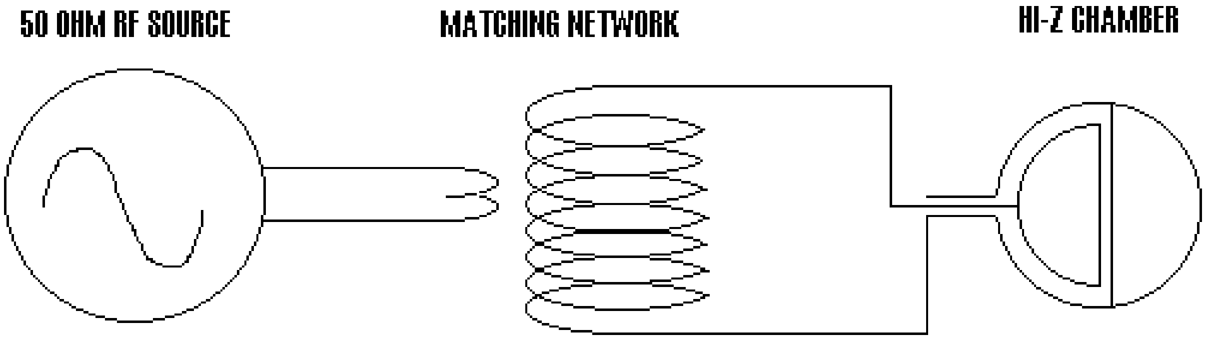
Making the Cyclotron a Reality





It was quickly realized that two hollow, semi-circular electrodes (named DEE’s for their shape) in a strong magnetic field would best serve as the accelerating gap and ion storage.

A Little Bit About the RF Oscillator



We know that:

$$f = \mathbf{qB/2\pi m}$$

The DEE has capacitance **C** so **L** is choosen:

$$f\mathbf{r=1/2\pi\sqrt{(LC)}}$$

For $^1p_1$ & 1 Tesla B-field the ***f*****r ~ 15 MHz** **(RF)**

The First Cyclotron

The first 4-inch cyclotron was crude, but successfully demonstrated the magnetic resonance principle.

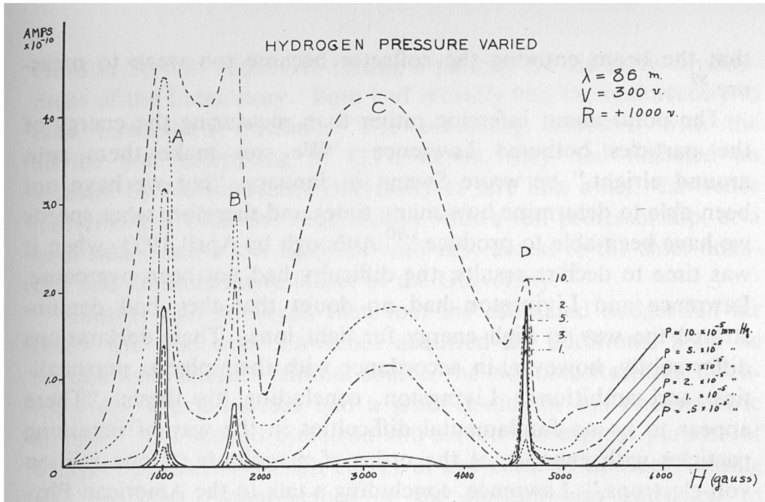
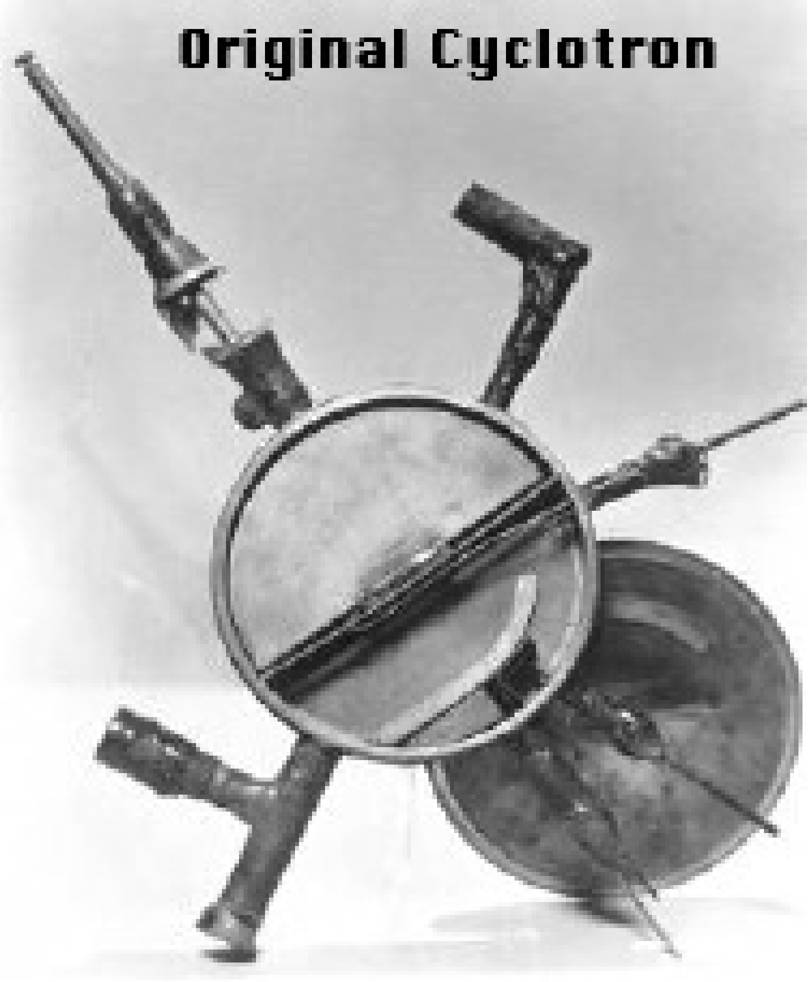


FIG. 2.22 Livingston's thesis results, 2: i_D against H at several pressures in the "vacuum" chamber. Livingston, *Production*, fig. 8.

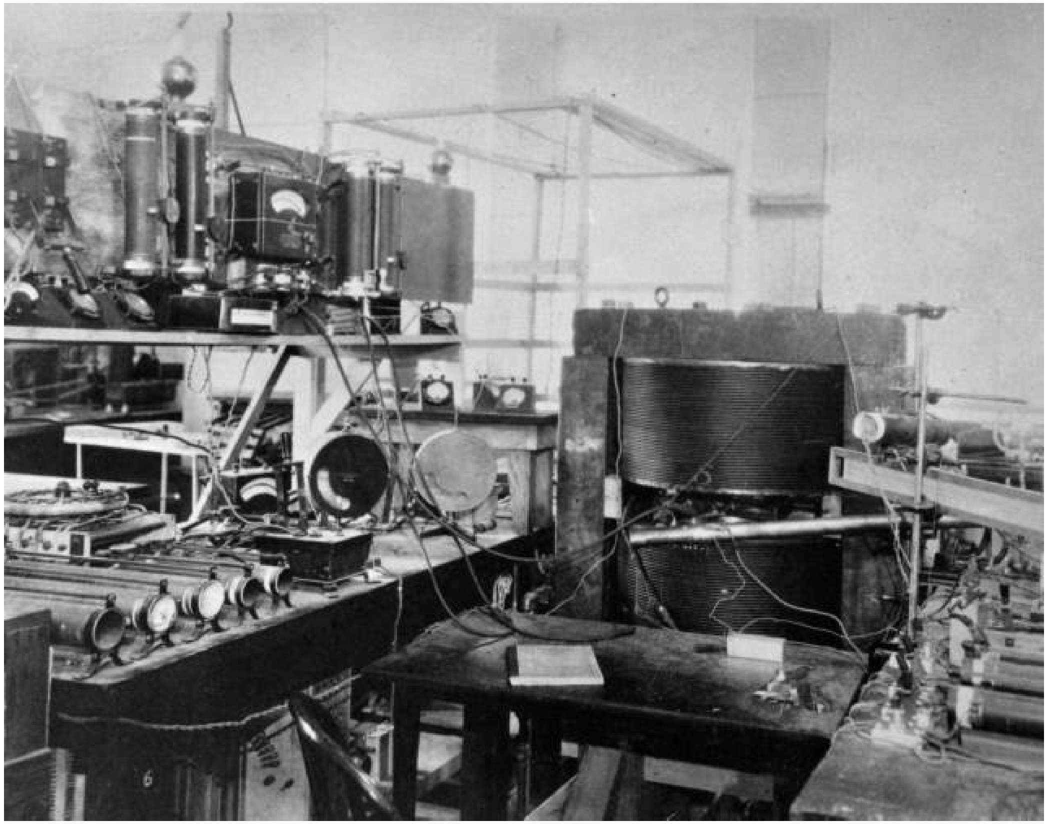


The 11 inch 1.1 MeV

January 1932

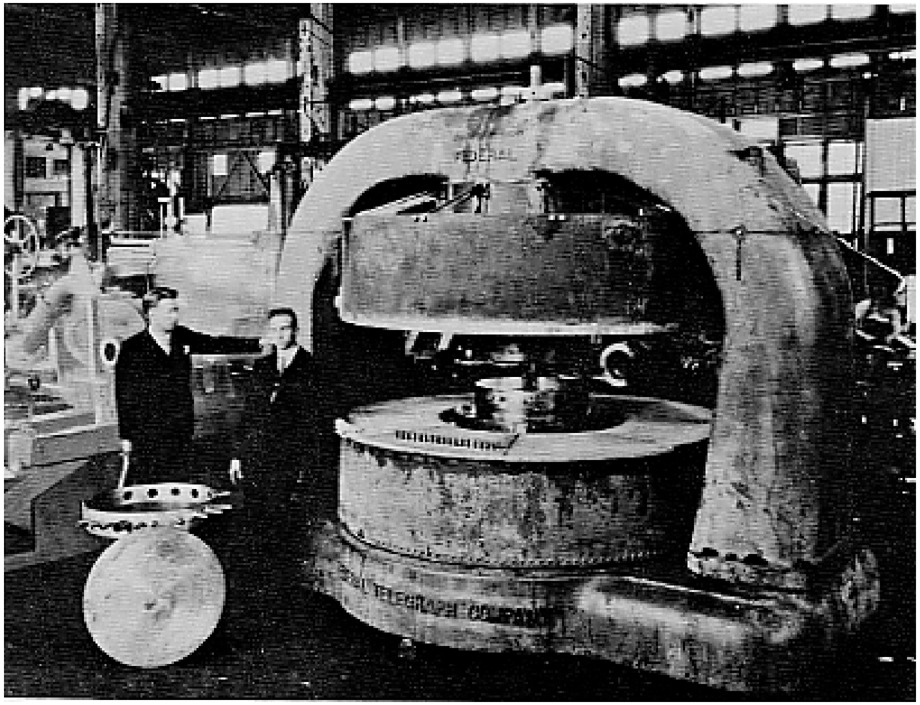
Telegram to Lawrence:

> "Dr. Livingston has asked me to advise you that he has obtained 1,100,000 volt protons. He also suggested that I add 'Whoopee'!"

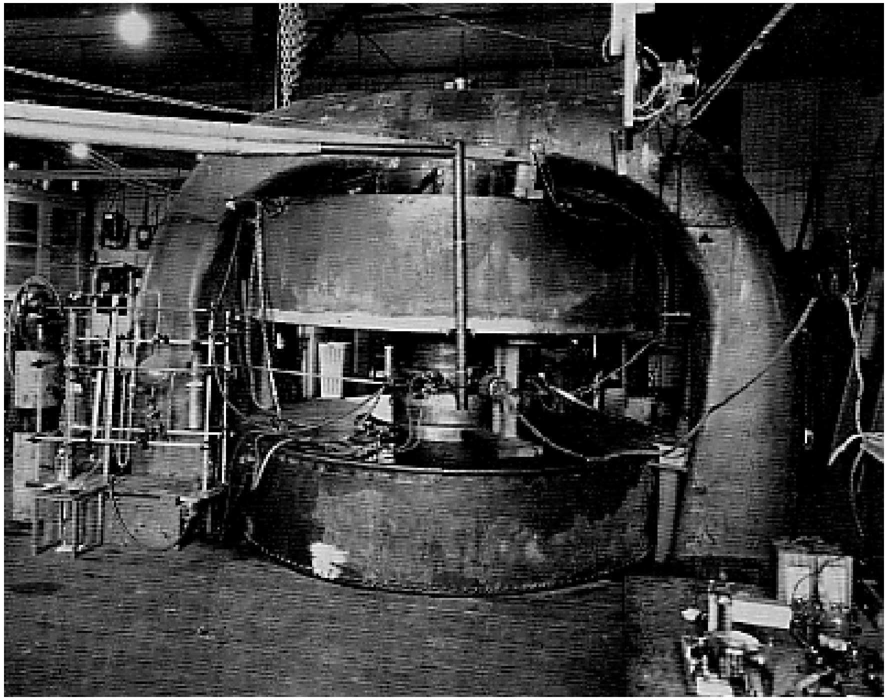


Pace of Development was Unprecedented

Feburary 1932



September 1932



Even before the 11-inch was completed, the 27 inch was being designed.

Left Photo is of Ernest Lawrence and M.S. Livingston (L to R)

A Lesson to be Learned

(1934)

Joliot announced induced radioactivity using a small alpha source and Al targets.

Although swamped in radioactivity for months, the Berkley Cyclotron “Rad-lab” missed the discovery:

“…the Laboratory missed the discovery because the same switch operated the cyclotron and the Geiger counter.” – “We felt like kicking our butts.”

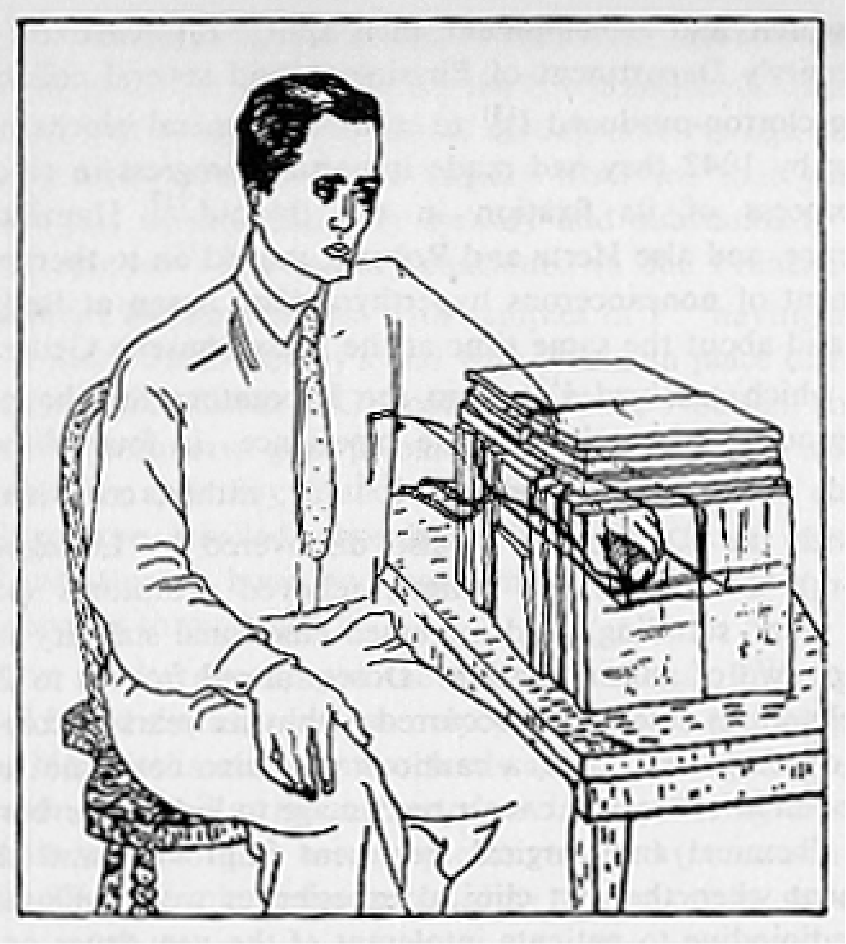
[Thornton]

A Cool Trick at Parties !

As time went on more radioactive substances were made, including Na-22.

Radioactive Drinks…

So began use of accelerators in medicine.



Neutron Therapy at the 27 inch

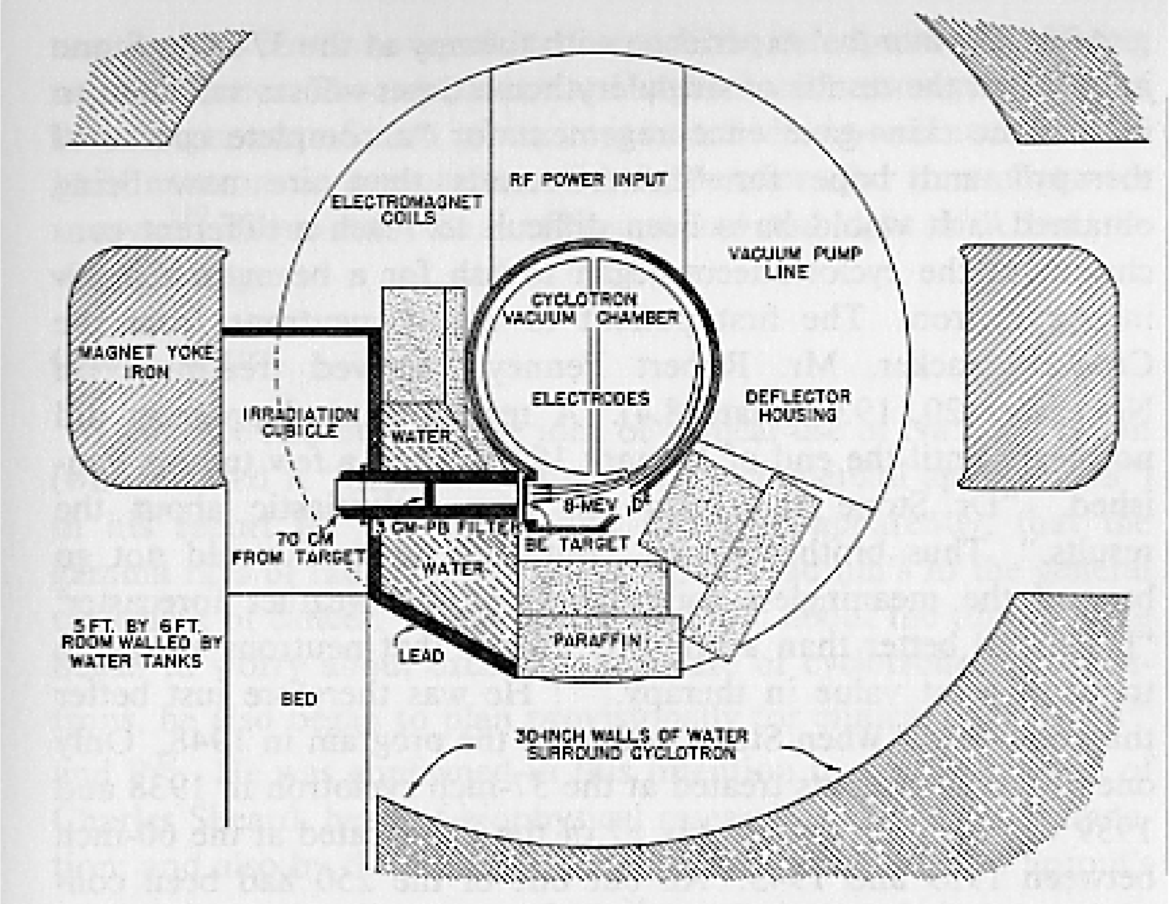


FIG. 8.5 Aebersold's arrangement for neutron therapy. The treatment room is at the left, within the magnet yoke. Not all the water tanks surrounding the cyclotron are shown. Aebersold, *PR, 56* (1939), 717.

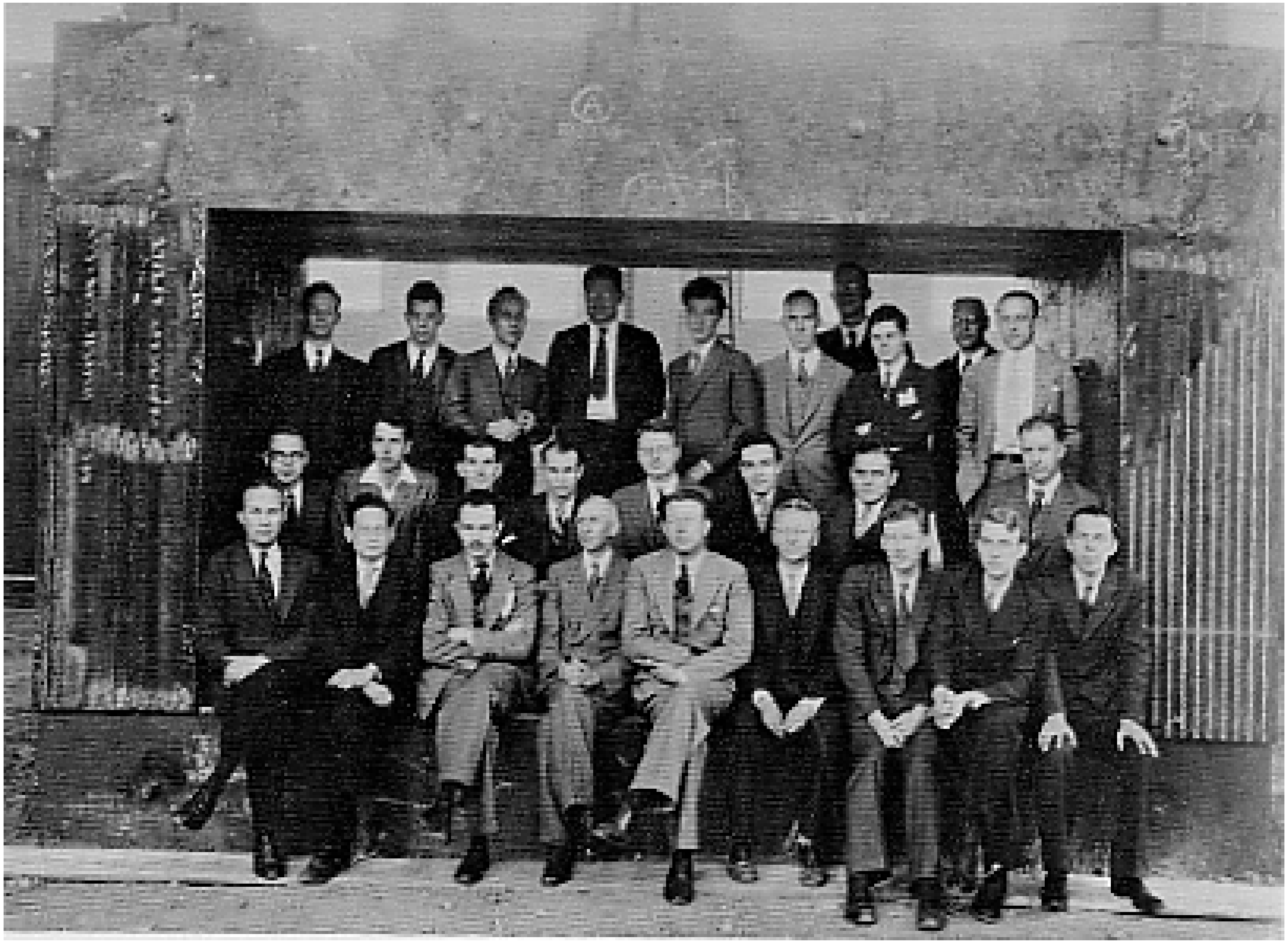
There Seemed to be No Limit…

To Ernest Lawrence, the only limit on energy was the size of the magnet. In his style, Ernest was planning for the 60-inch cyclotron before the 27-inch was complete. Such a cyclotron should be capable of 16 MeV. He even had visions of 100 MeV

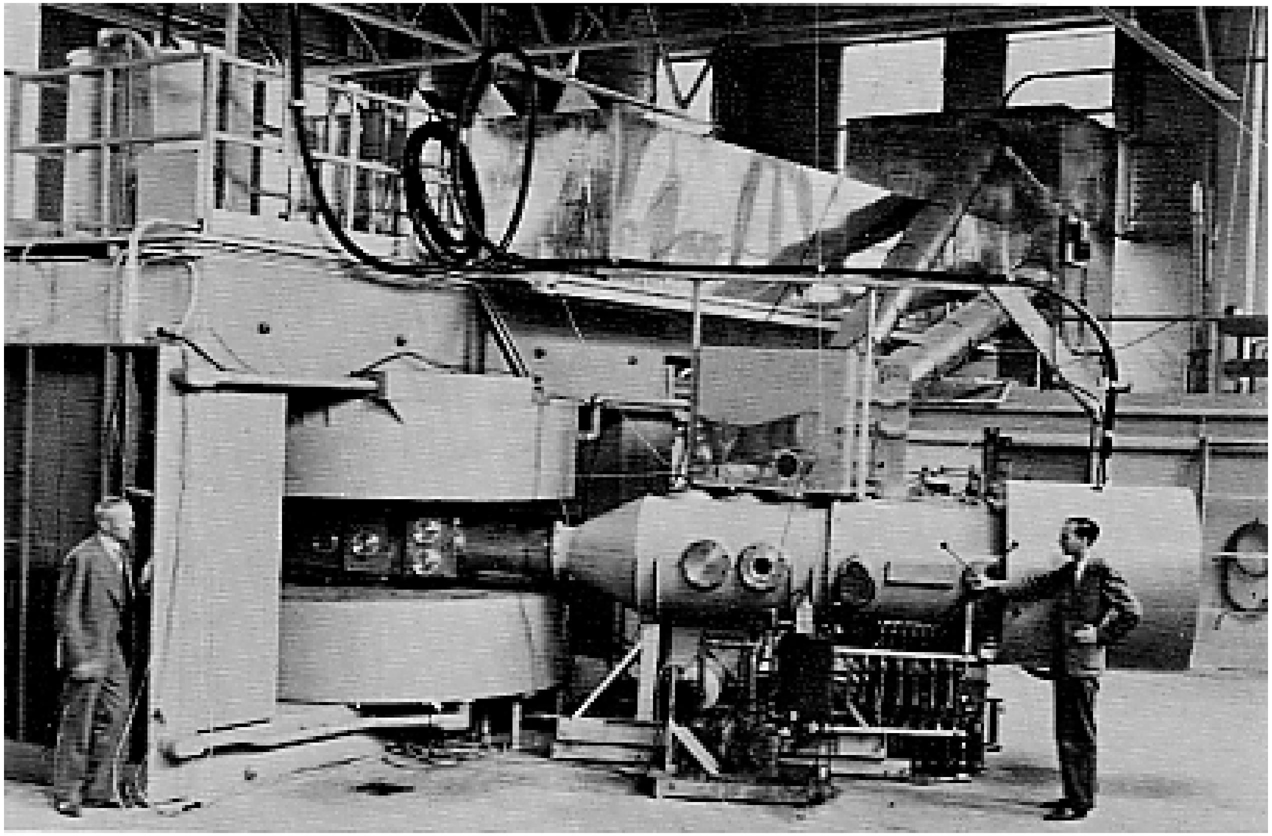
Theoretician Hans Bethe disagreed… Bethe calculated the upper limit of the cyclotron was 20 MeV for protons. Protons traveling any faster would become noticeably relativistic, thus gaining in mass. The increase in mass would cause the particle to fall out of sync with the magnetic resonance condition.

Ernest Lawrence was not discouraged & proceeded full steam

The Crocker 60-inch Cyclotron

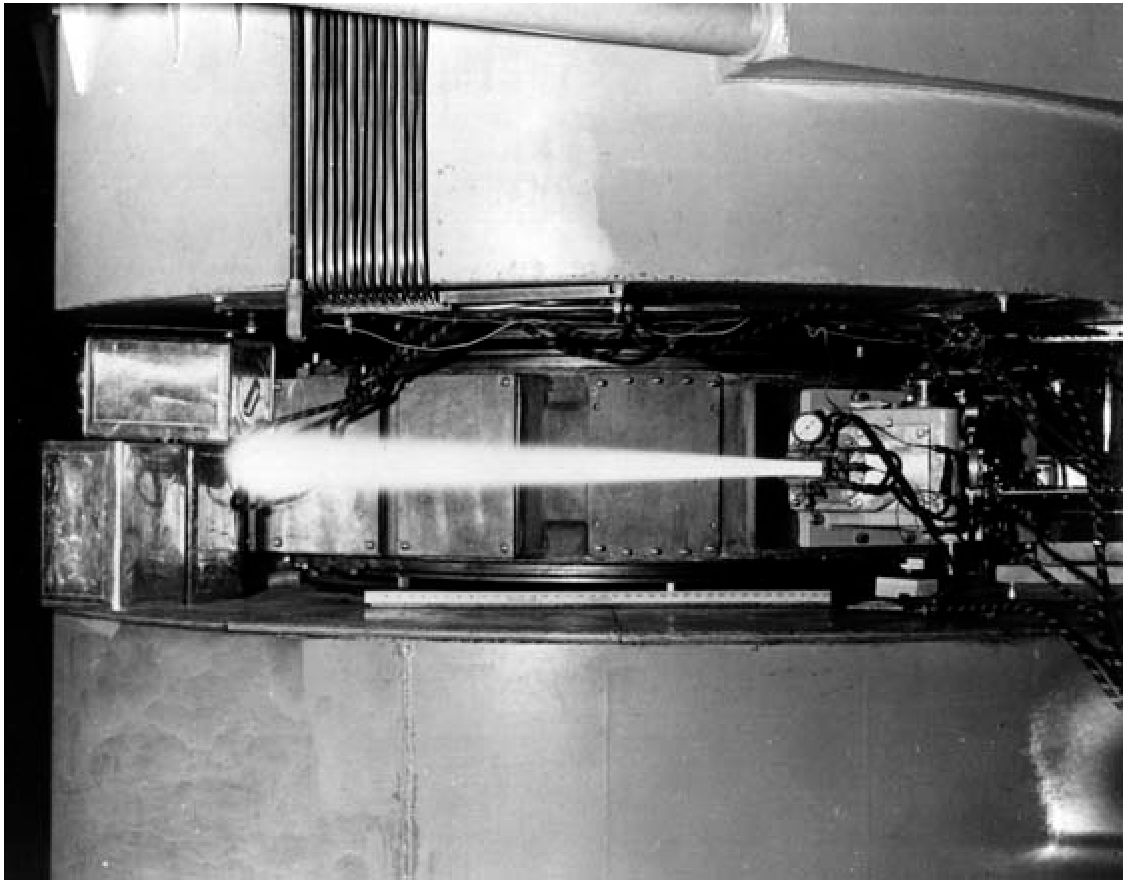


The Crocker 60-inch Cyclotron



The primary use of the 60 inch cyclotron was medical isotope production. However, it was heavily used in the the Plutonium war effort.

It’s a Beautiful Thing….



16 MeV Deuterons unleashed in to the air causes it to “glow purple and sizzle like bacon.”

WW II

World War II changed accelerator research from academic pursuits to the war effort.

Large accelerators called Calutrons were used to separate rare fissionable U^{235} from the abundant U^{238}.

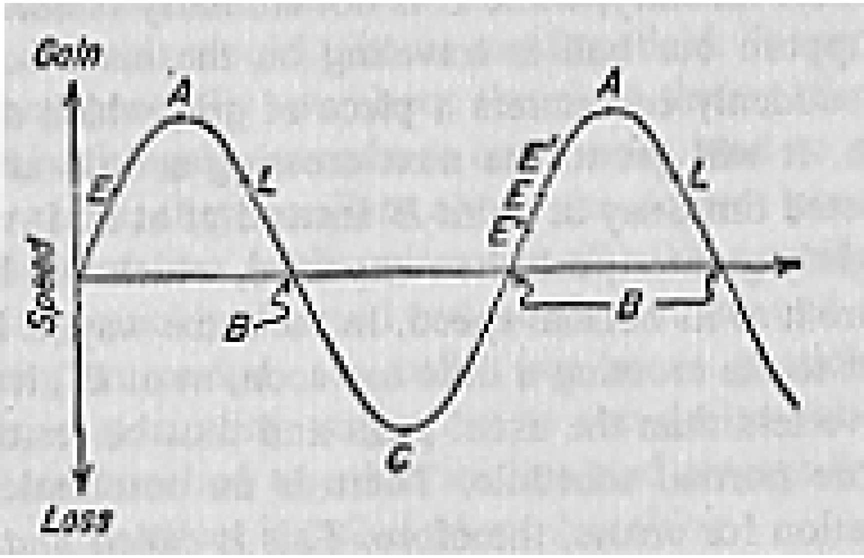
US Physicist’s role in winning WWII won them such popularity the field of accelerators more than made up for lost time.

The invention of RADAR (and it’s spin-offs) during the war found peacetime application in Linacs, i.e. Klystrons…

Phase Stability and Relativity

Edwin McMillan of UC Berkley, and the Russian V.I. Veksler independently discovered Phase stability in 1945.

Phase Stability and Relativity



Simply stated the principle of Phase Stability is:

- Fast traveling ions arrive at the next gap “early” & receive less push
- Slow traveling ions arrive at the next gap “late” & receive more push

A “band” of ions continuously oscillate about and follow the phase of “stability” during acceleration.

Phase Stability and Relativity

Bethe was not wrong, but Ernest Lawrence still came out on top.

Indeed the ions mass increased as it's velocity became relativistic, either the magnetic field needed to be increased (which causes a defocusing effect) or the oscillating voltage needed to be decreased.

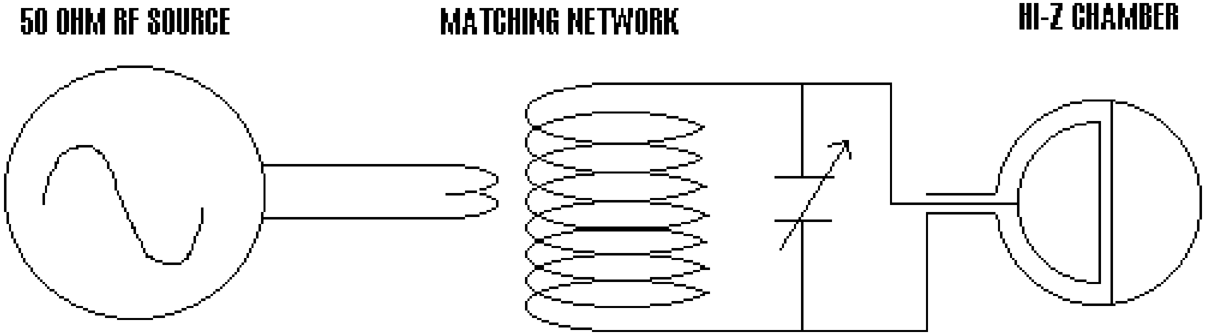
K. R. MacKenzie and V.B. Waithman demonstrated the relativistic effect with the 27-inch [turned 37-inch] cyclotron by severely tapering the magnet poles simulating the relativistic increase in mass. They modulated the RF frequency with a rotating capacitor, to sweep through the RF band corresponding to the resonance conditions of a particle increasing in mass. This variation on the cyclotron was named the Synchro-Cyclotron.

Upon first try an intense pulse of beam arrived at the collector at the end of every modulation cycle. SUCCESS !

RELATIVITY WAS OVERCOME !

Phase Stability and Freq. Modulation

A Little Bit About the FM Oscillator



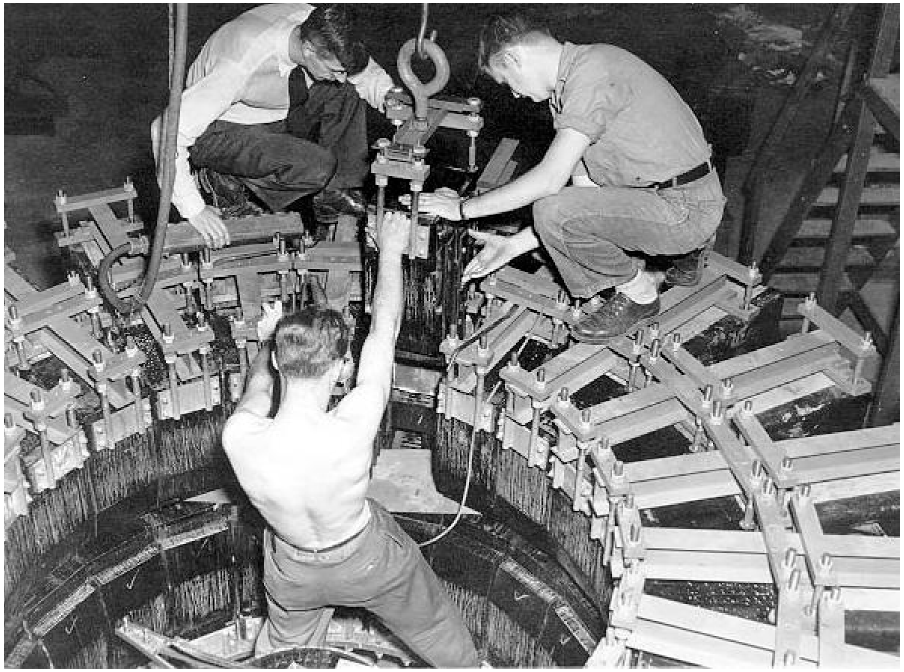
A rotating capacitor shifted the frequency (and wavelength) that the Synchro-Cyclotron operated at. The oscillator swept through the band of frequencies that satisfied the magnetic resonance condition

Focusing… an Added Bonus

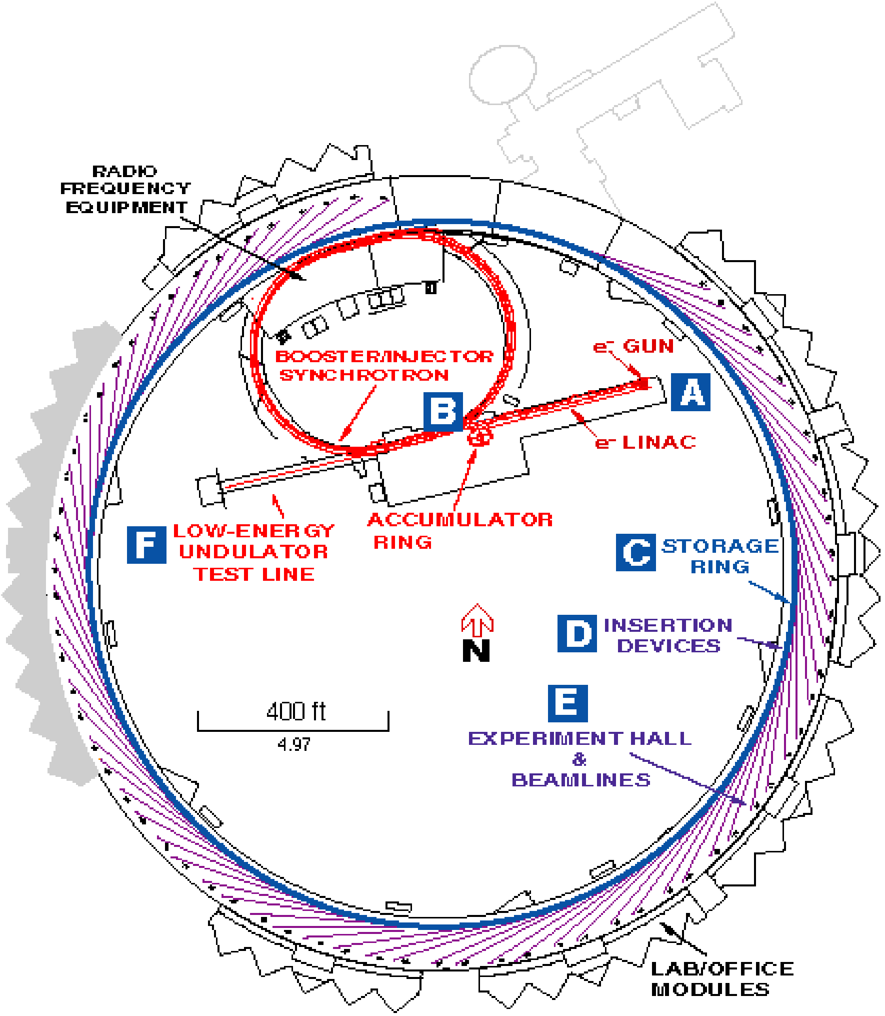
Once the principles of Phase Stability were understood and applied, an intentional radial decrease in magnetic field caused a focusing affect. This is now known as weak focusing. Focusing and Frequency Modulation made the 184 inch Synchro-Cyclotron a success at 350 MeV

The Proton Synchrotron

- The limit in energy is the size of the magnet
  - -A Cyclotron magnet 2 kilometers in diameter is unpractical.
- The Synchrotron maintains a fixed orbital radius while adjusting the magnetic field to contain the accelerated beam.



Electron Synchrotron

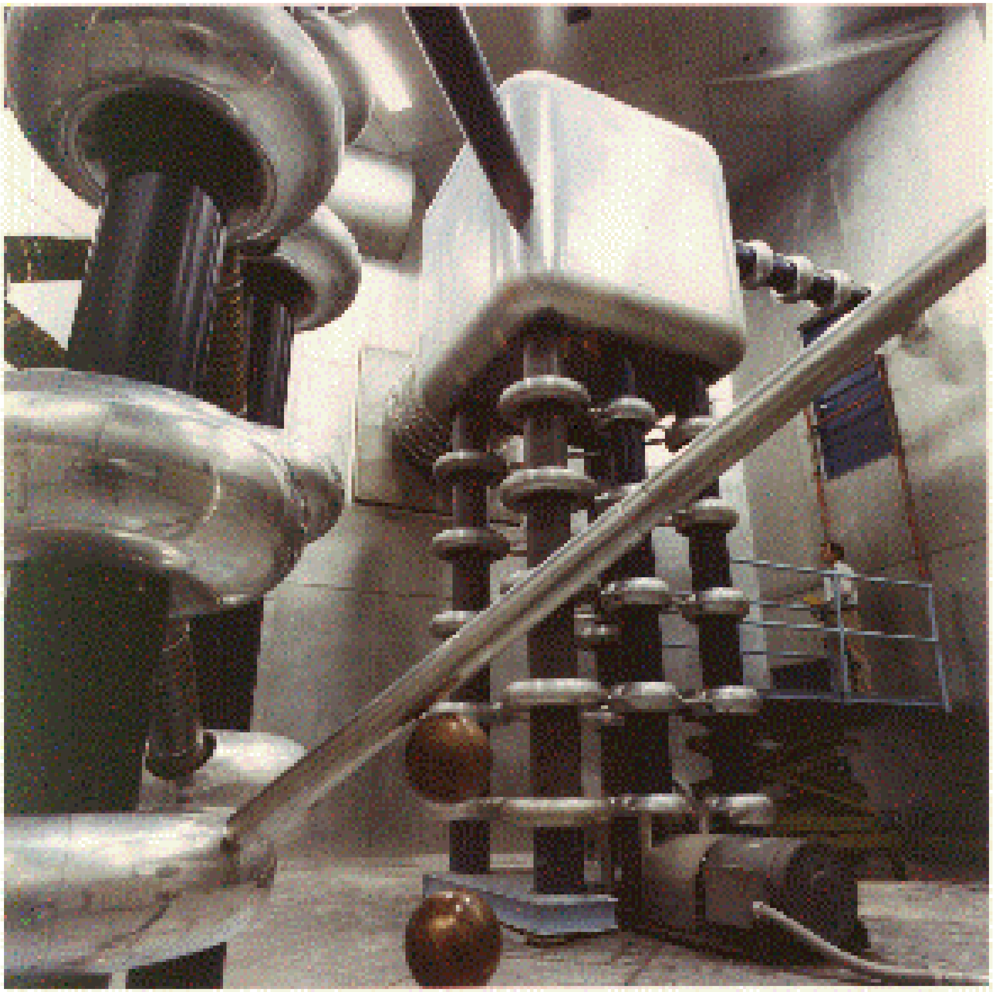


Fermilab Has it All. 2 TeV

Cockcroft-Walton, Linac, Booster, Synchrotron

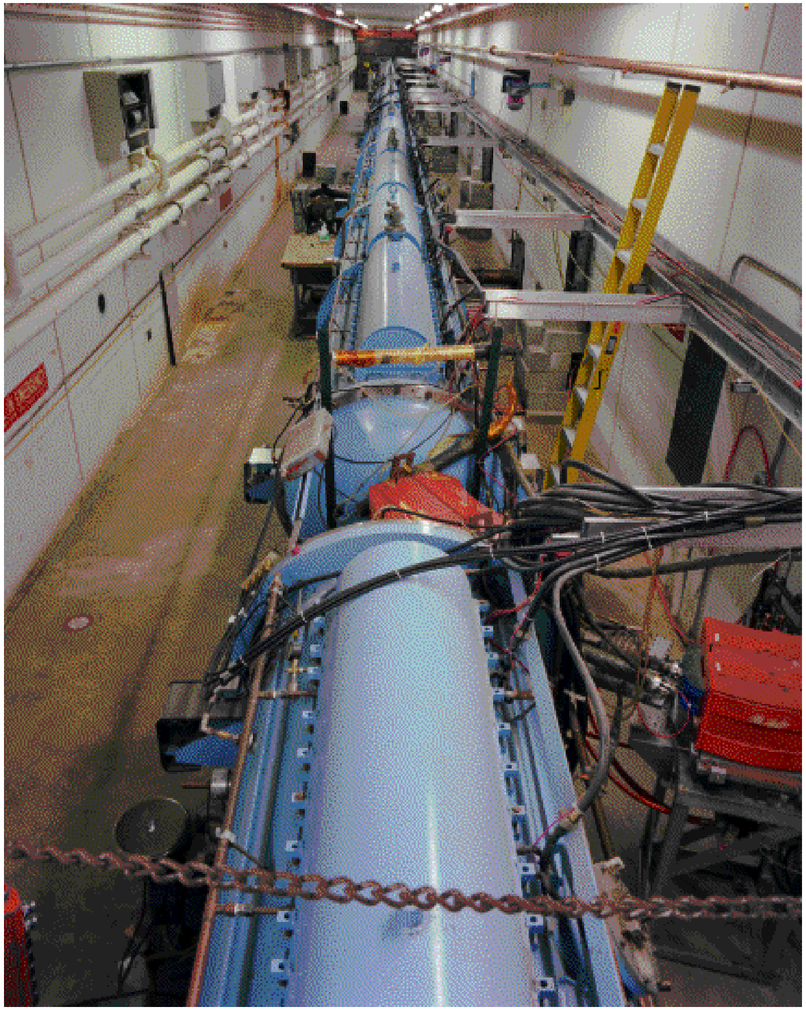
FNAL: Cockcroft Walton

750 keV



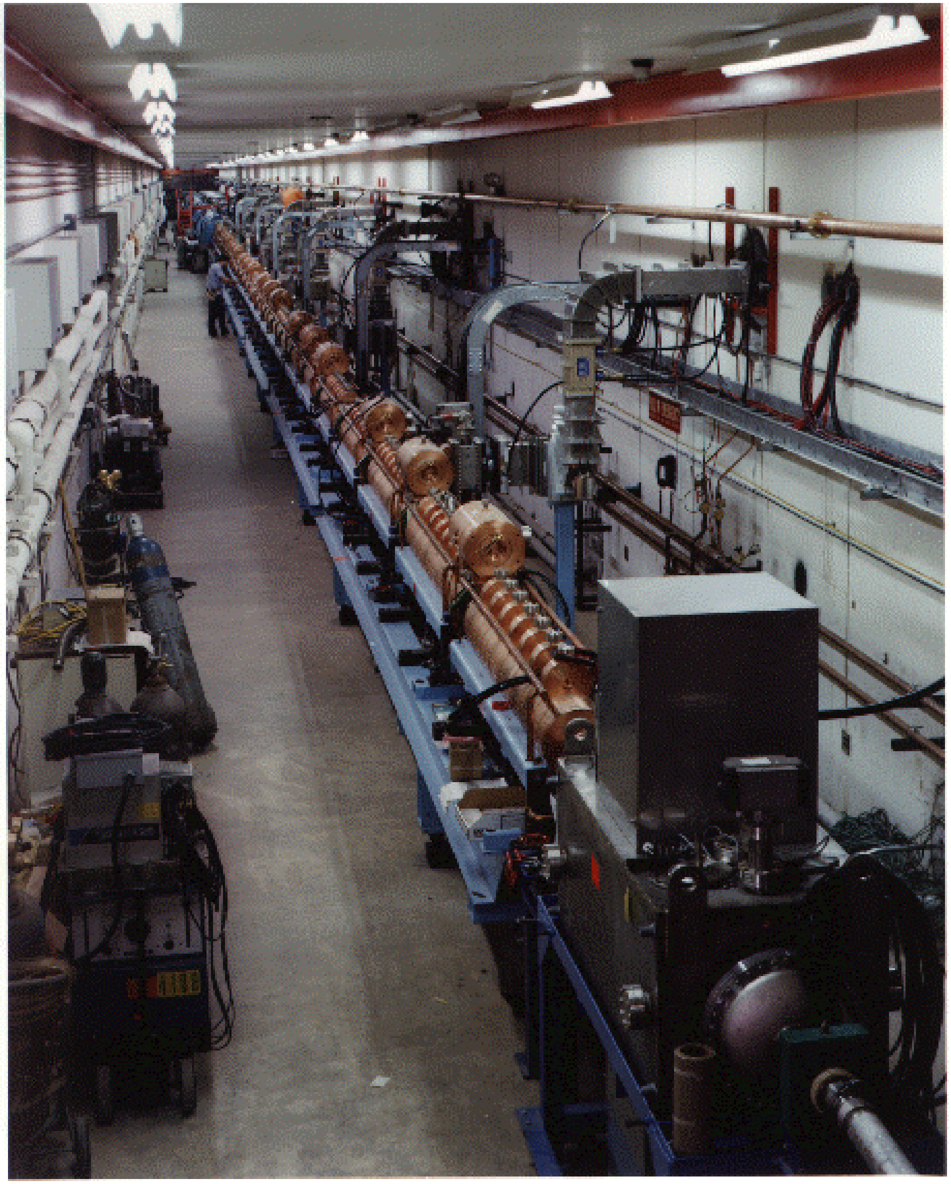
FNAL: 208 MHz DT Linac

116 MeV



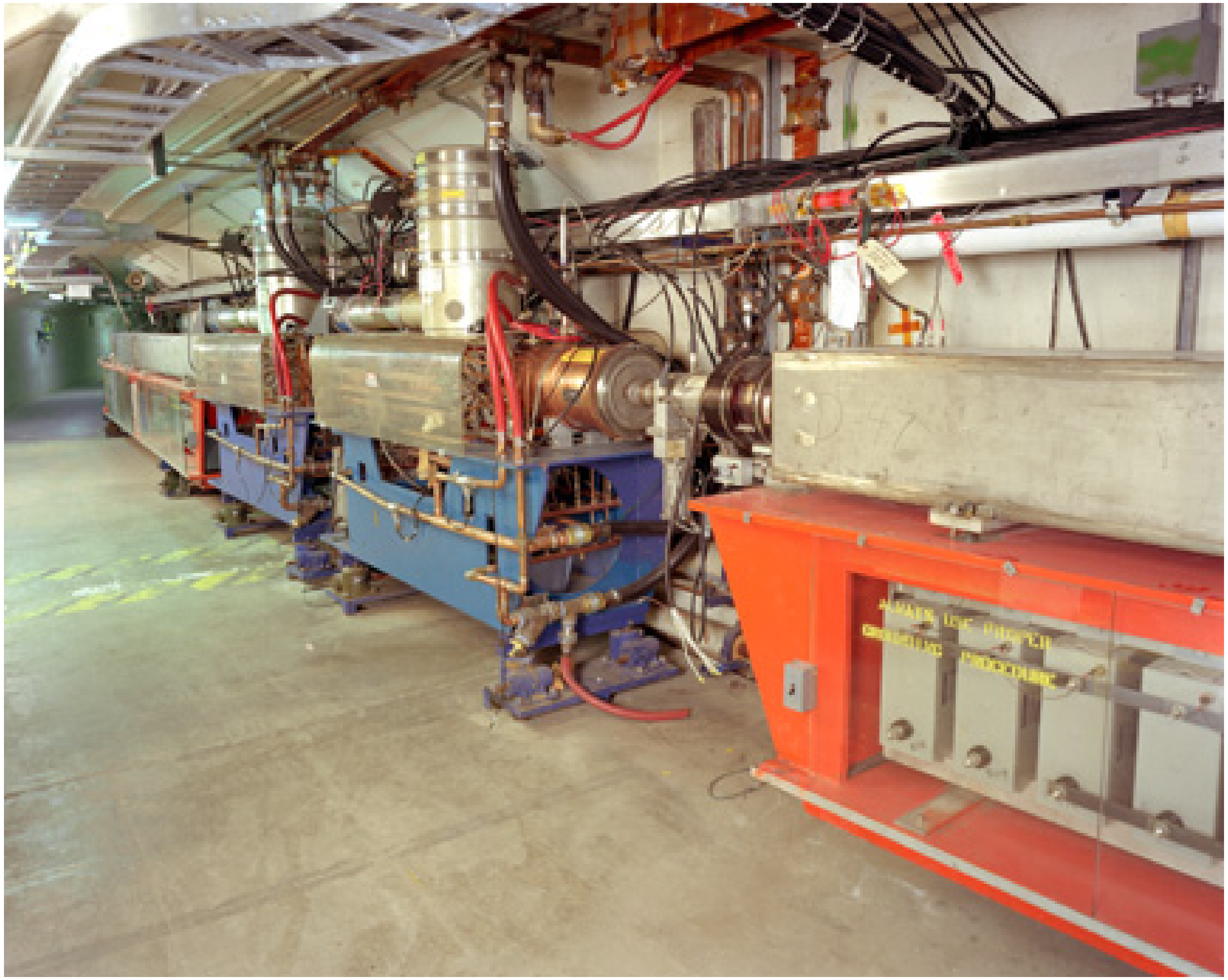
FNAL: 805 MHz SCC Linac

400 MeV



FNAL: Proton Synchrotron Booster

8 GeV



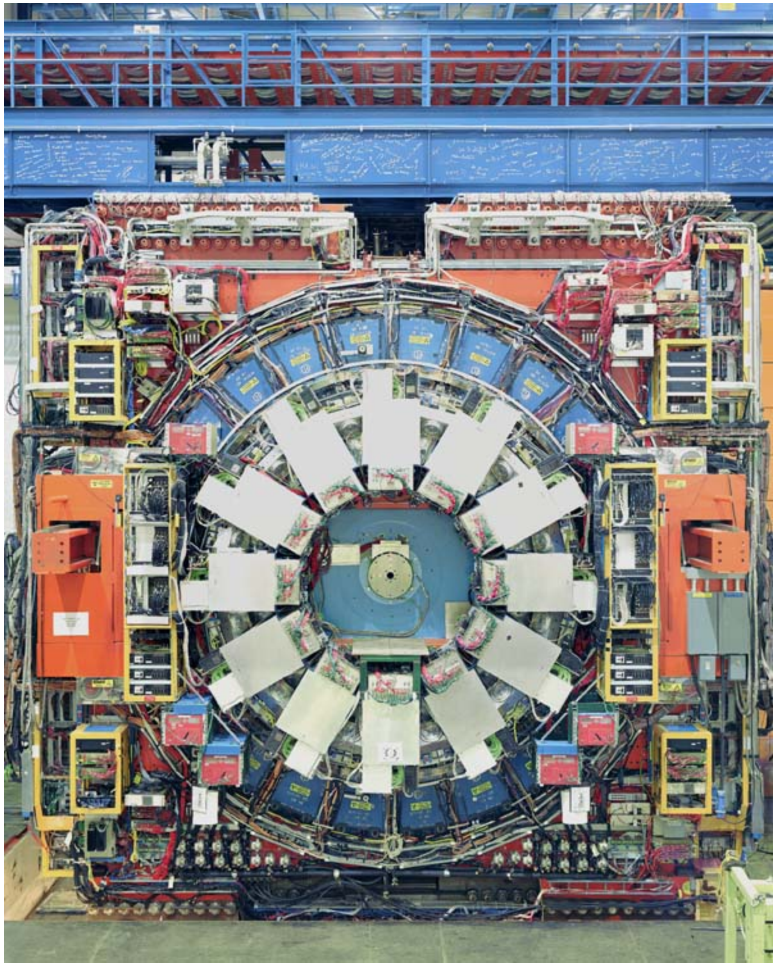
FNAL: Main Injector (& Recycler)

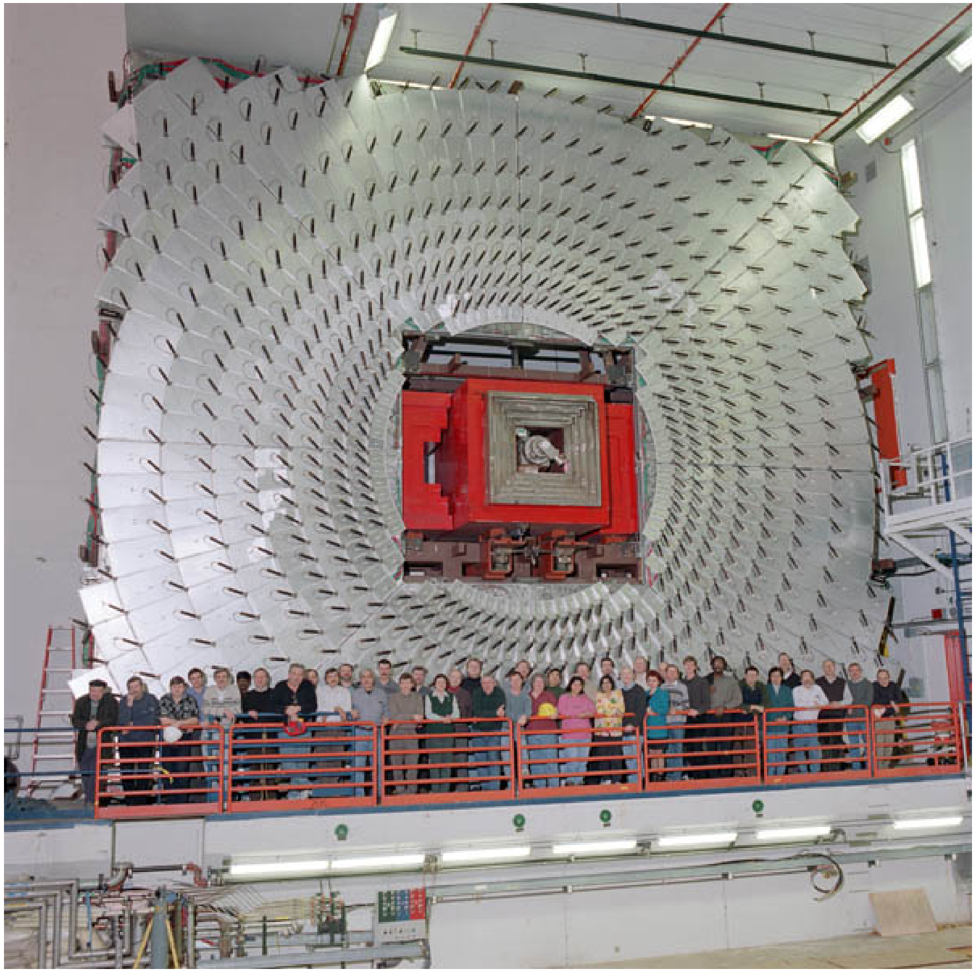
160 GeV

FNAL: TeVatron PS

2 TeV

FNAL: CDF & DZero





FNAL: Fixed Target

Web Pages:

- www.fnal.gov
- www.anl.gov
- www.bnl.gov
- www.cern.ch
- www.physics.rutgers.edu/~koeth/cyclotron

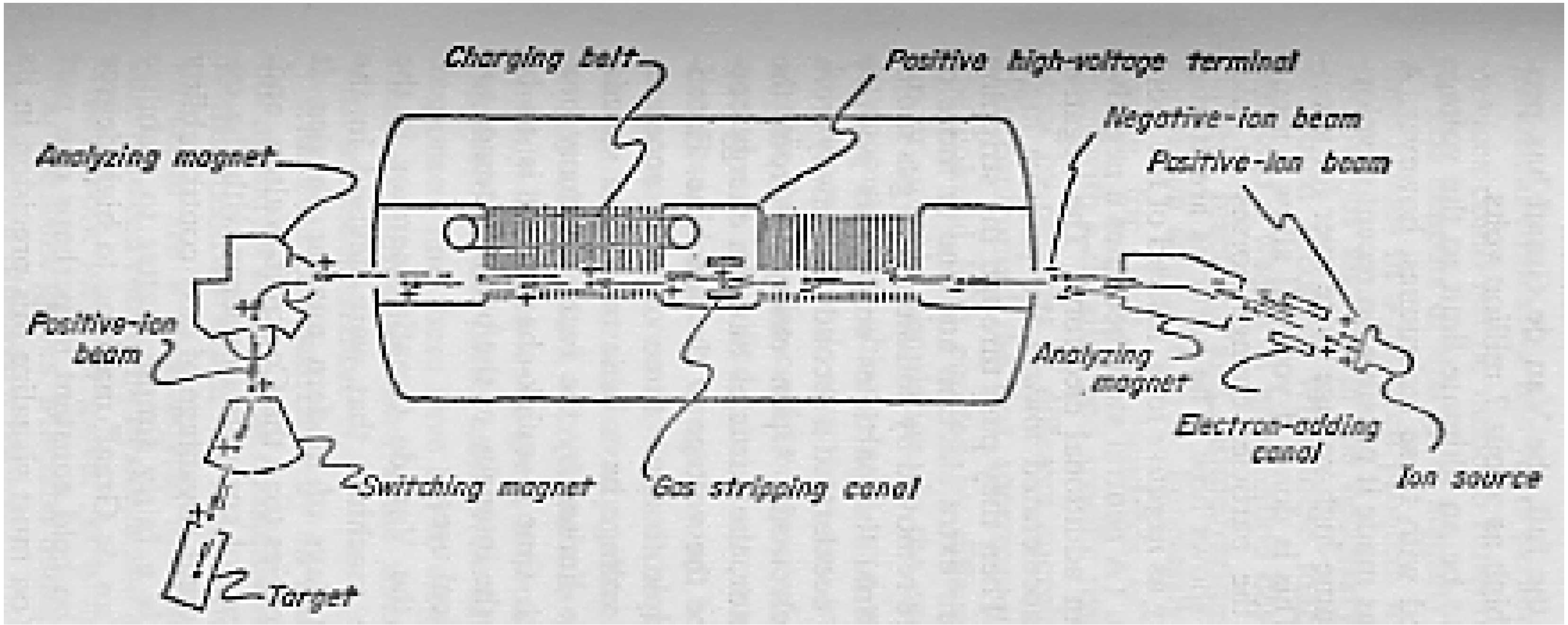
Accelerators At Rutgers

20 MeV Tandem Van de Graff

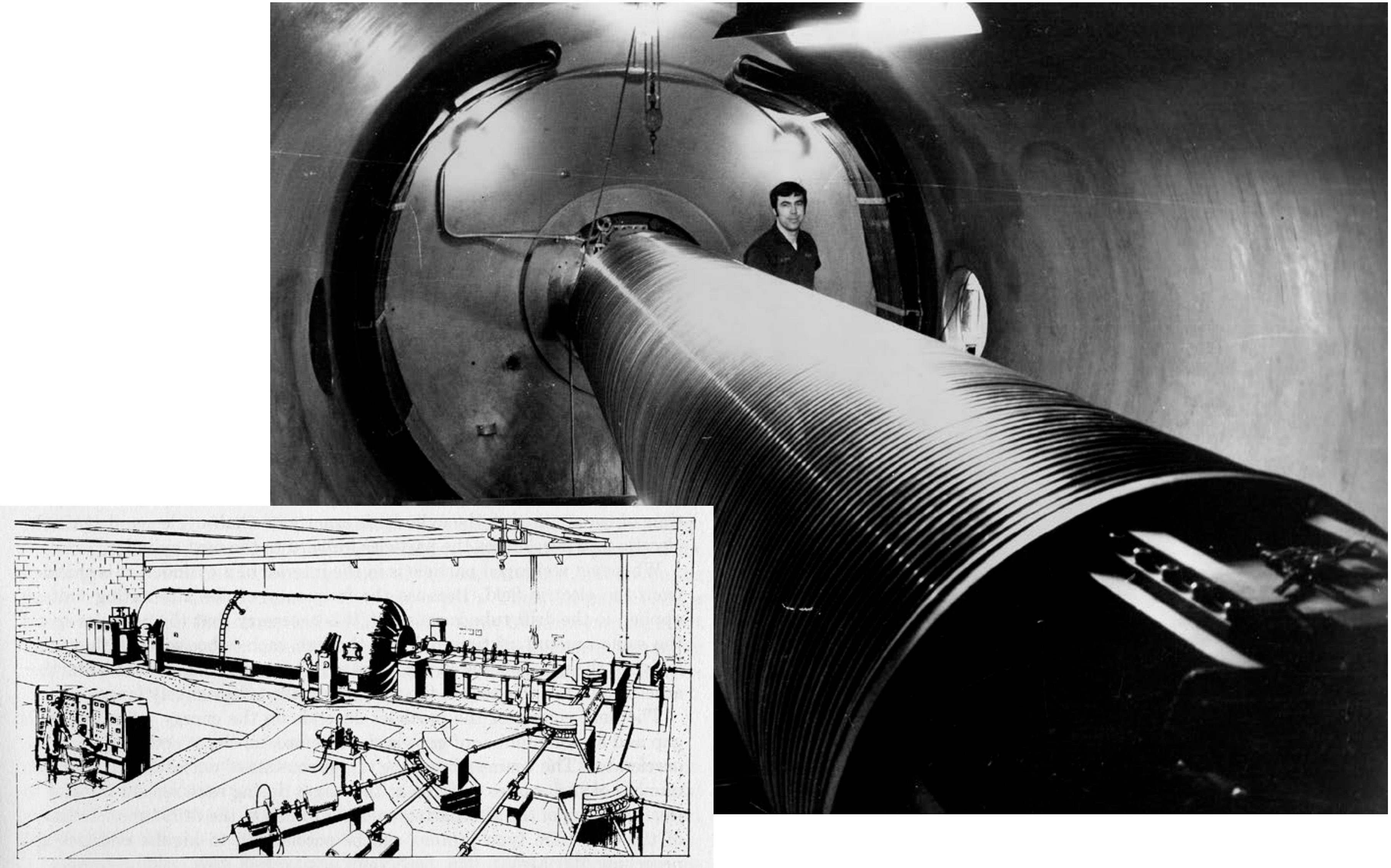
1.7 MeV Tandetron

1.2 MeV Cyclotron

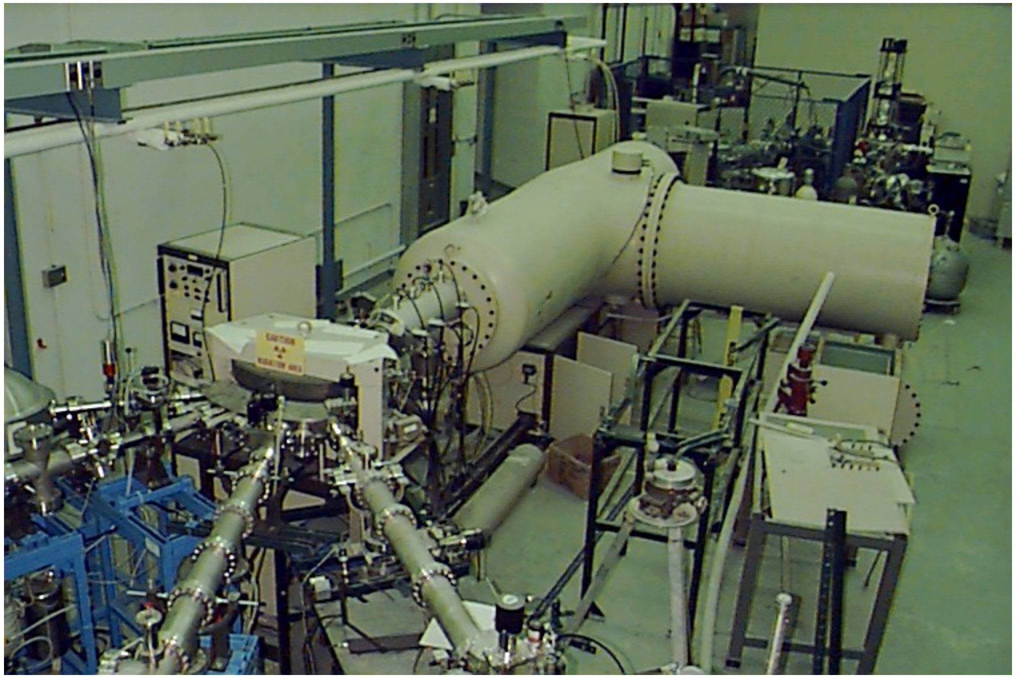
20 MeV Van de Graff



20 MeV Van de Graff ’62 – ‘84



1.7 MeV Tandetron



Primarily used for surface science

12-inch 1.2 MeV Cyclotron