History & Science of the Cyclotron in the Manhattan Project

Timothy Koeth, February 2, 2021
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Introductions – the family tree

E.O.L. ~ 1939,
Inventor of Cyclotron

Robert Wilson
~ 1968,
PhD Student of EOL,
Cornell Professor,
Founding director of Fermilab

Helen Edwards
~ 1968
Post Doc of Robert Wilson,
Built TeVatron,
Co-Dir of SSC

Tim Koeth
~2009
PhD student of Helen Edwards

UMD UMER

Tim Koeth
~2018
CERN LHC CMS
"Heavy Ion Guy"

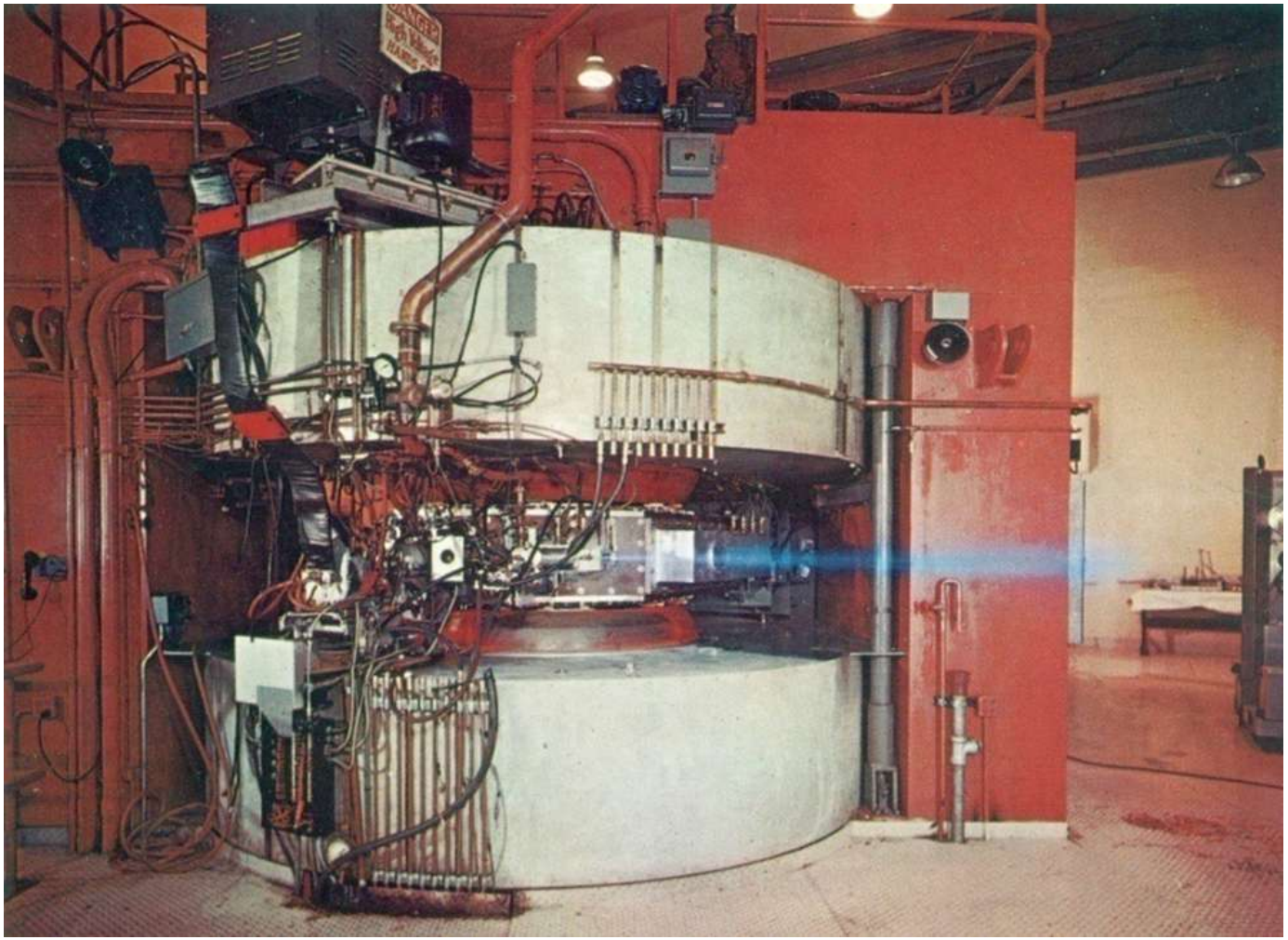
1st Cyclotron, 80 keV

National Accelerator Lab
"Fermilab" ~ 1TeV

SSC, Dallas TX, 50 TeV

1 MeV Cyclotron

Q: What is a Cyclotron
A: A type of Particle Accelerator
Q: What is a Particle Accelerator?



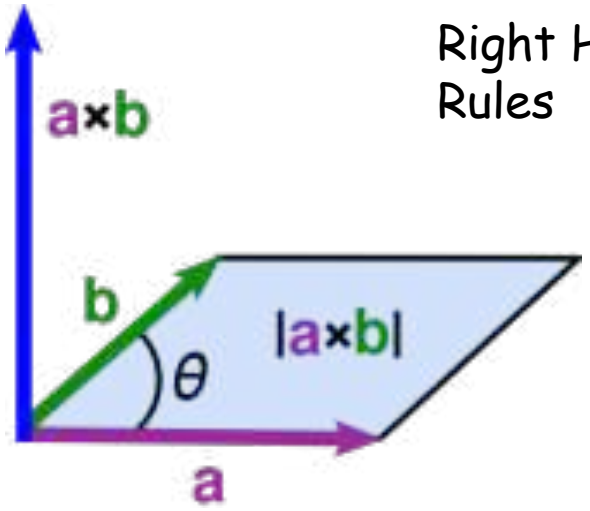
ANL 60”: 21 MeV Deuterons (1958)

Some Fundamentals (Hopefully a Review)

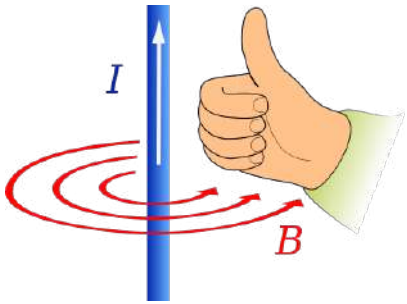
Lorentz Force covers it all:

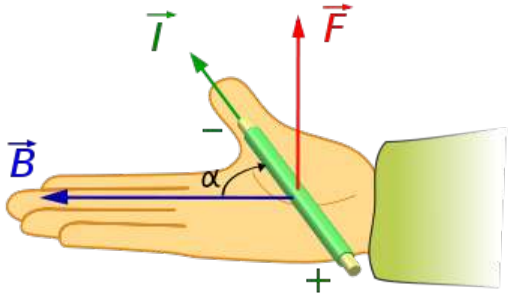
E-field: acceleration
B-field: no work

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



Right Hand Rules

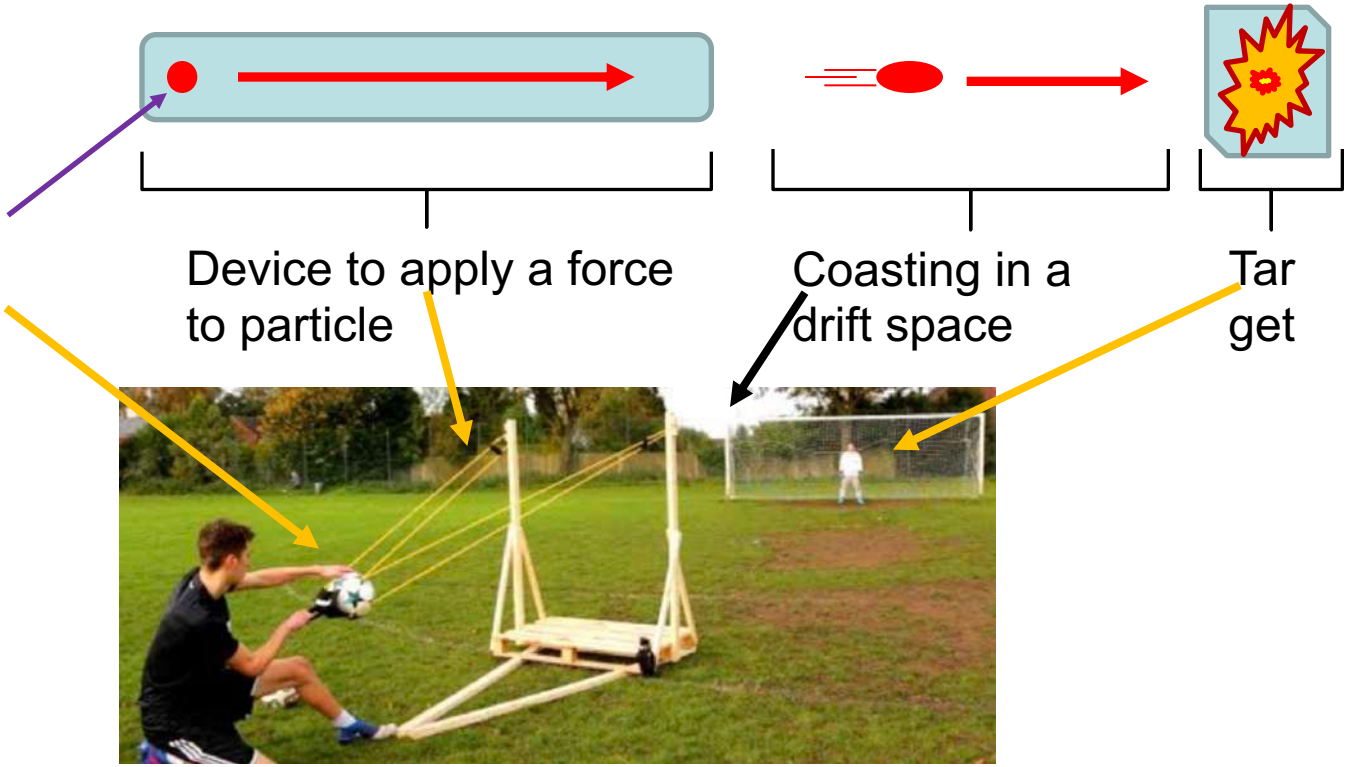




What is a Particle Accelerator ?

Lets take a step back..

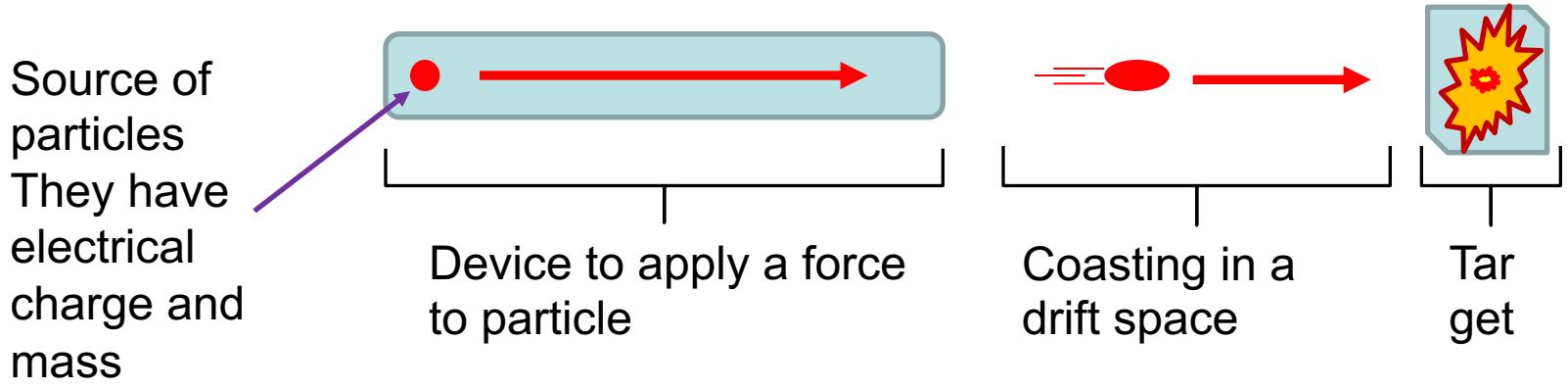
Source of particles
They have electrical charge and mass



https://www.youtube.com/watch?v=vfa2mbdfy_k

What is a Particle Accelerator ?

An example: UMD's fixed target electron linear accelerator:



Linear Accelerator – conceptual analog

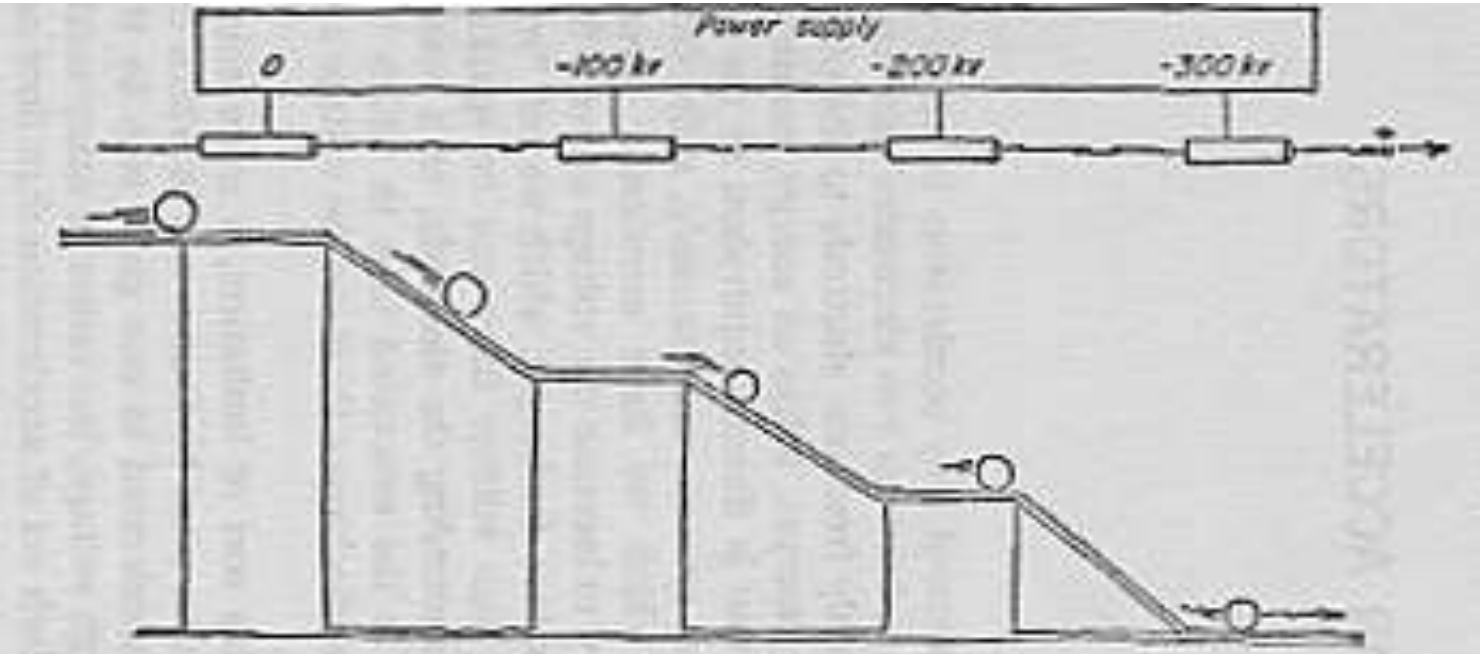
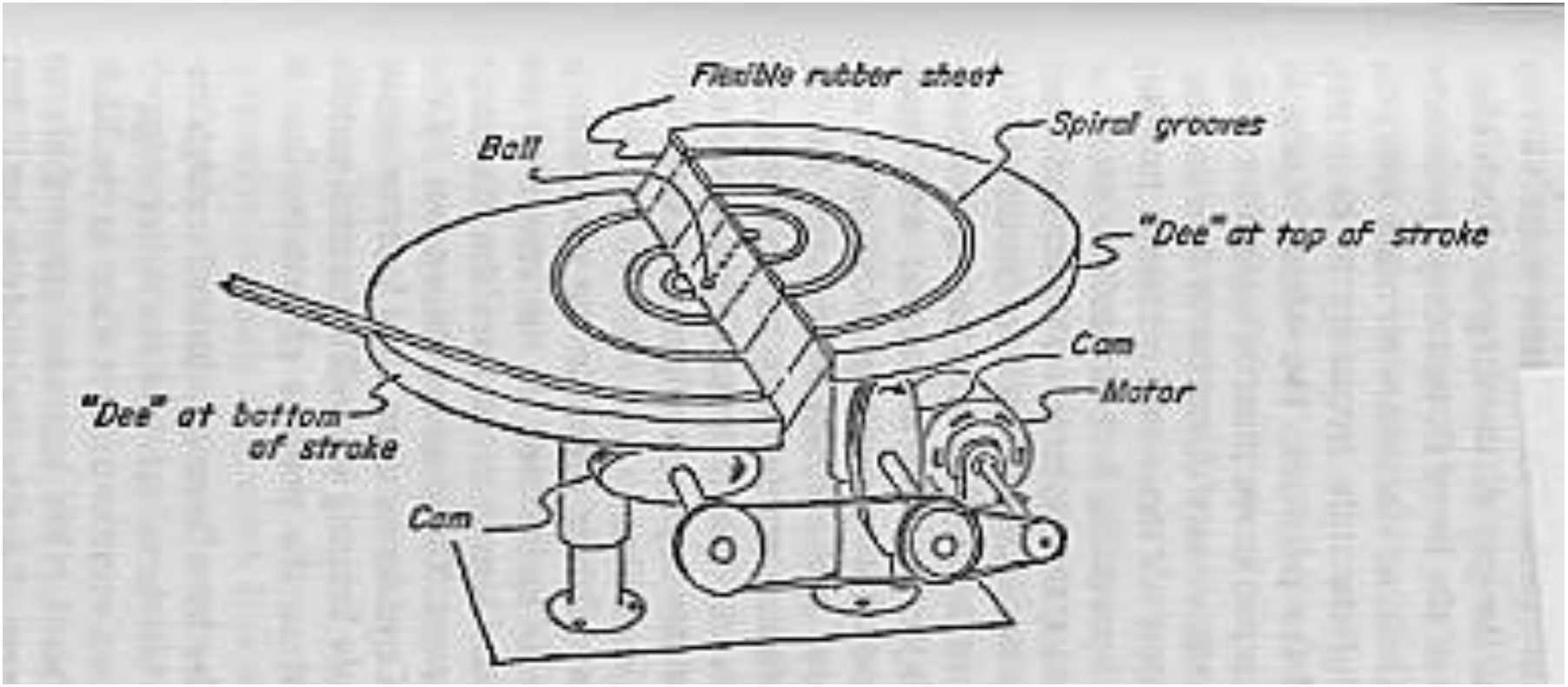
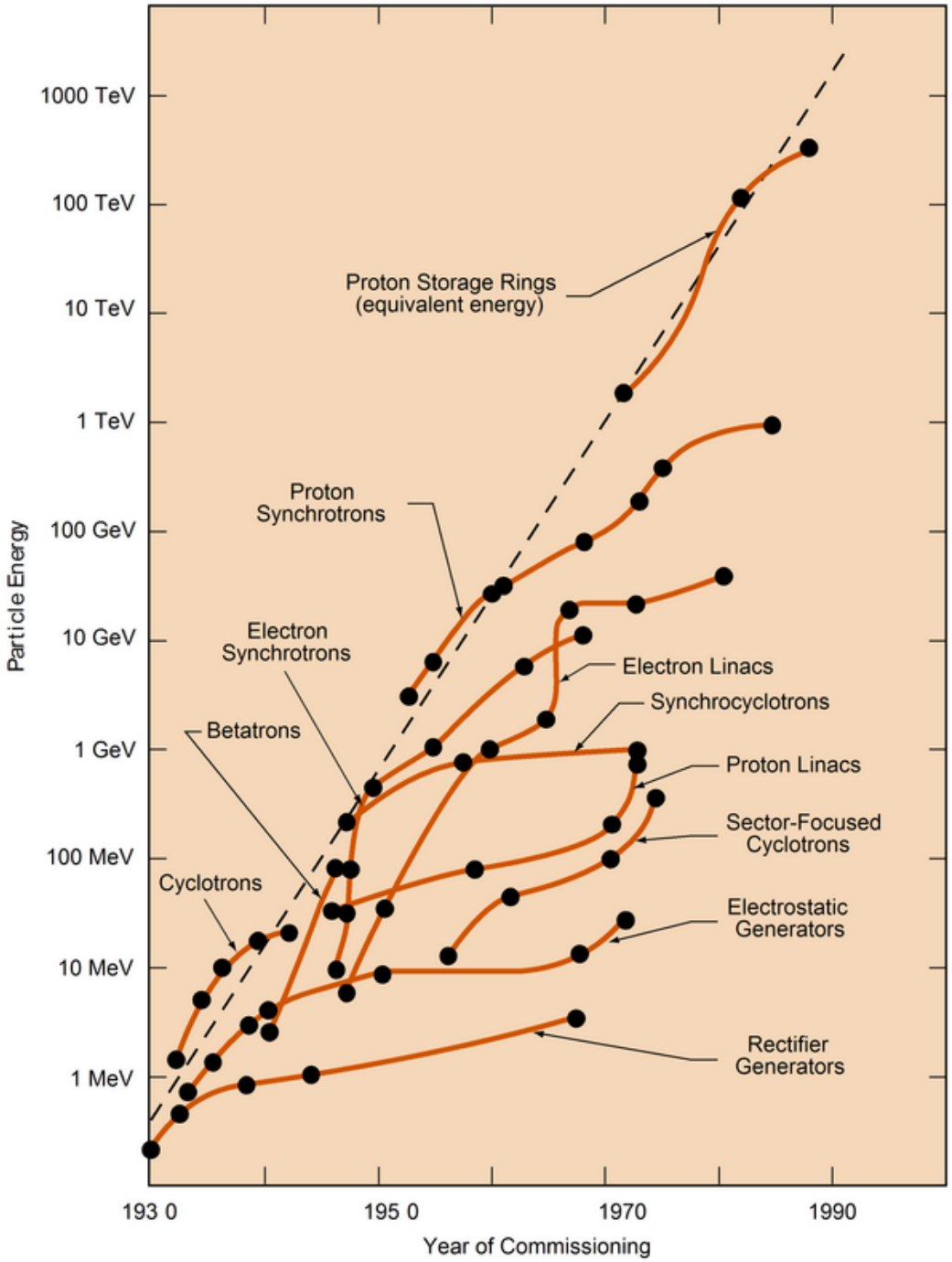


FIG. 14. *In this bowling-alley model of a particle accelerator, gravity accelerates the ball's motion on the sloping sections of track. The height of each horizontal section of track would correspond to a voltage source in a real particle accelerator. The amount of acceleration the ball would undergo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

Circular Accelerator – conceptual analog



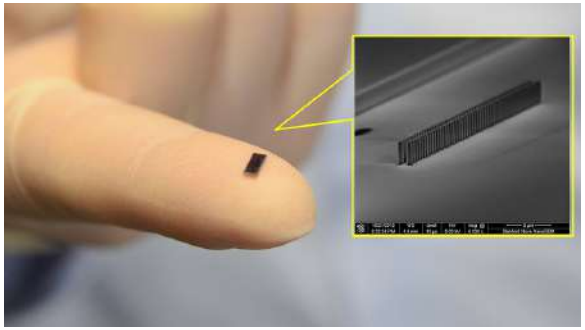
Livingston Plot



Physicists keep inventing new types of accelerators to propel charged particles to higher and higher energies

A summary of world wide advances in high energy accelerators summarized by M. Stanley Livingston

What is a Particle Accelerator ?



A particle accelerator on a chip

My cyclotron

The LHC and FCC

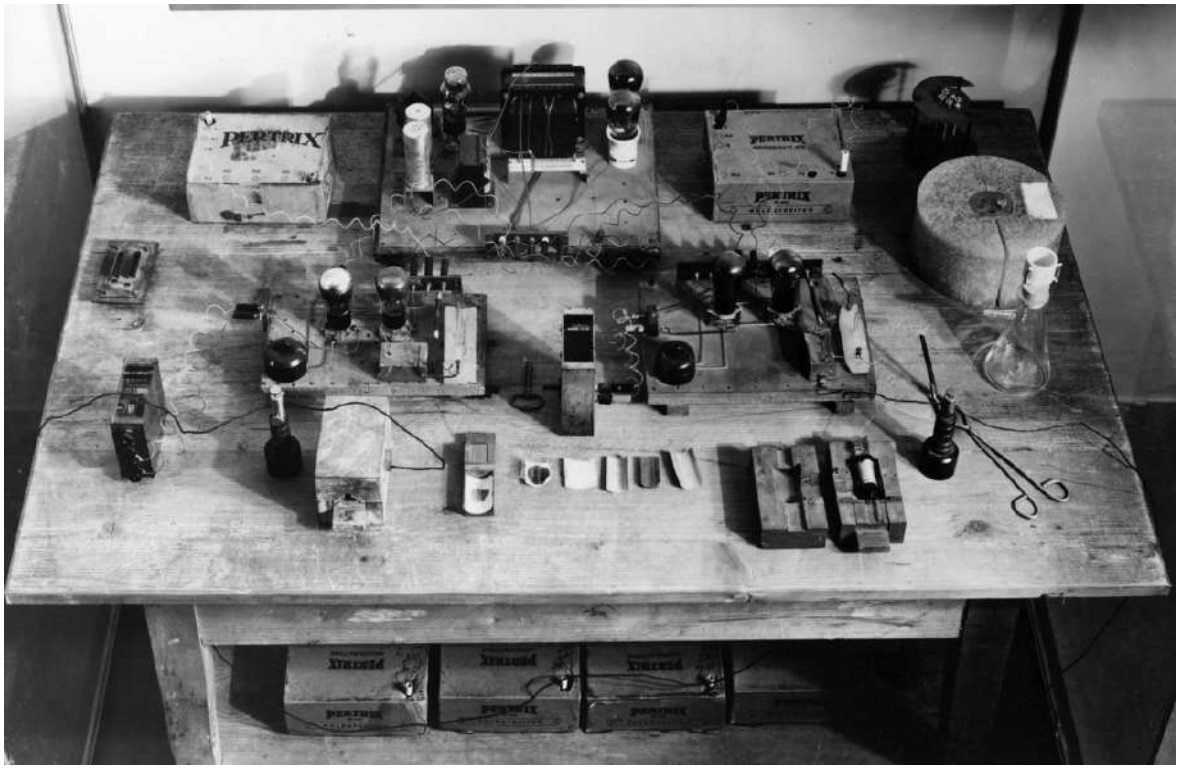
Nature's Particle Accelerators

- 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

Nature's Particle Accelerators

- Naturally occurring radioactive sources
  Radium's alpha's + Aluminum → Neutrons
  Neutrons + U235 --> fission + neutrons



Lise Meitner – discoverer of fission

“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 their 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.[1]

MANY FAILED ATTEMPTS

Just one example:

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

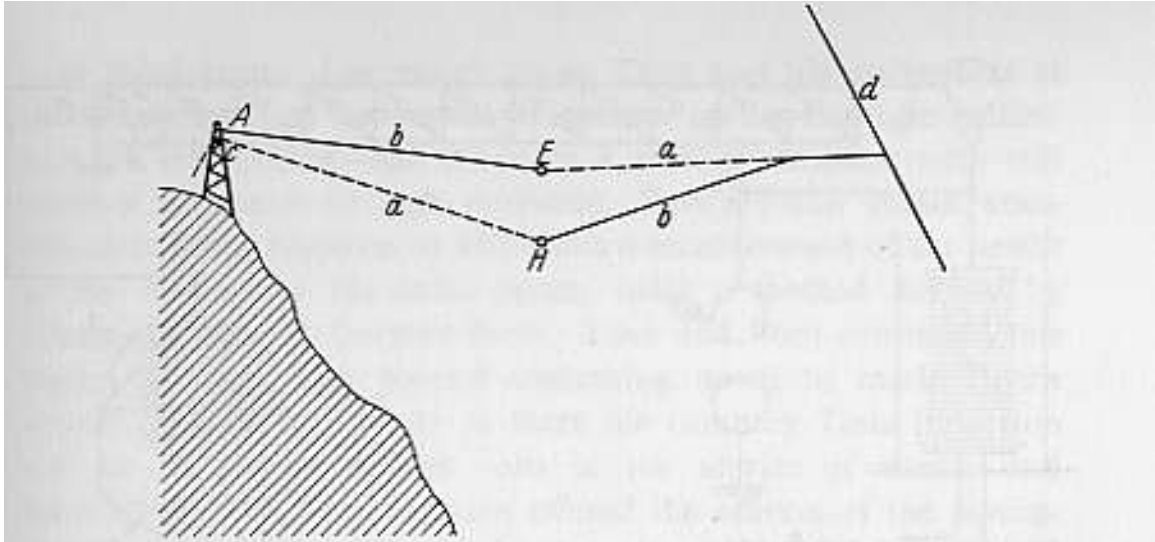


FIG. 2.1 Brasch and Lange's lightning catcher. E and H are the spheres between which the discharge occurs; AE, the antenna; a,a, insulators; b,b, conductors; d, a grounded wire. Brasch and Lange, *Zs. f. Phys., 70* (1931), 17.

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

Robert J. Van de Graaff

Van de Graaff (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

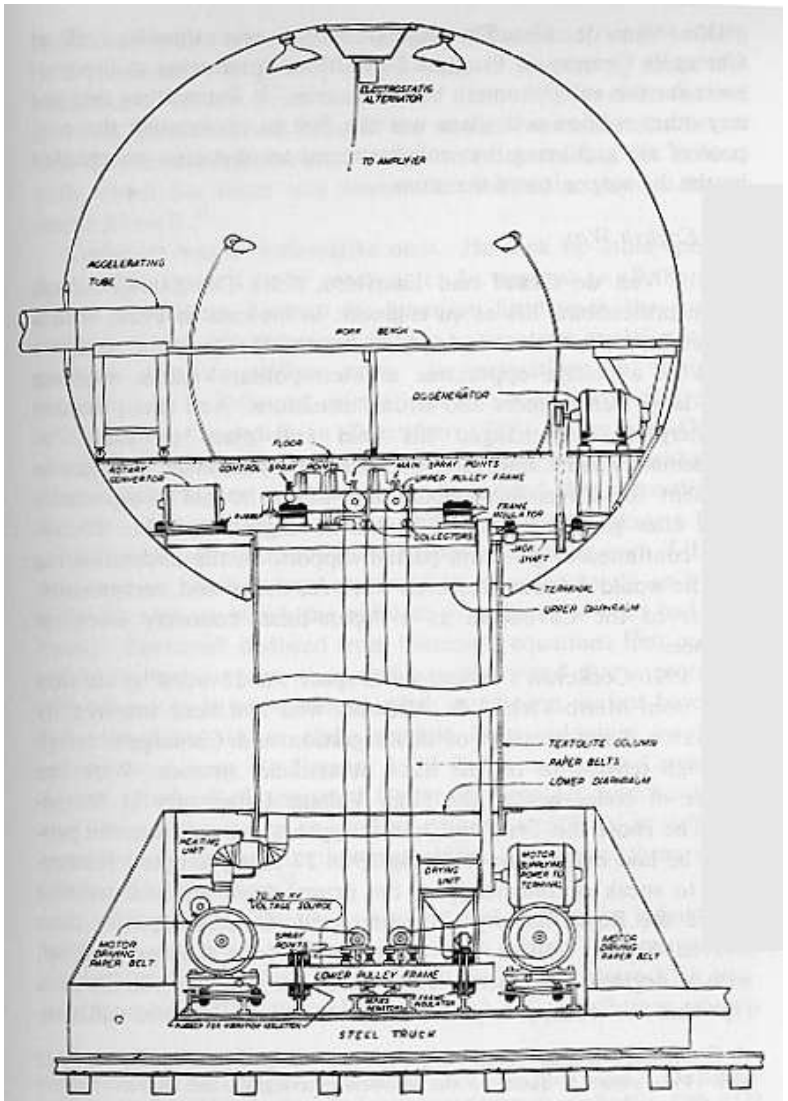


FIG. 2.9 An insider's view of the 15-foot generator. It delivered 1.1 mA to the accelerating tube under a tension of 5.1 MV. Van Atta et al., *PR. 49* (1936), 762.

Van de Graaff at Carnegie Inst.

Many labs could easily obtain a Van de Graaff.

- Low currents ☹
- High precision ☺

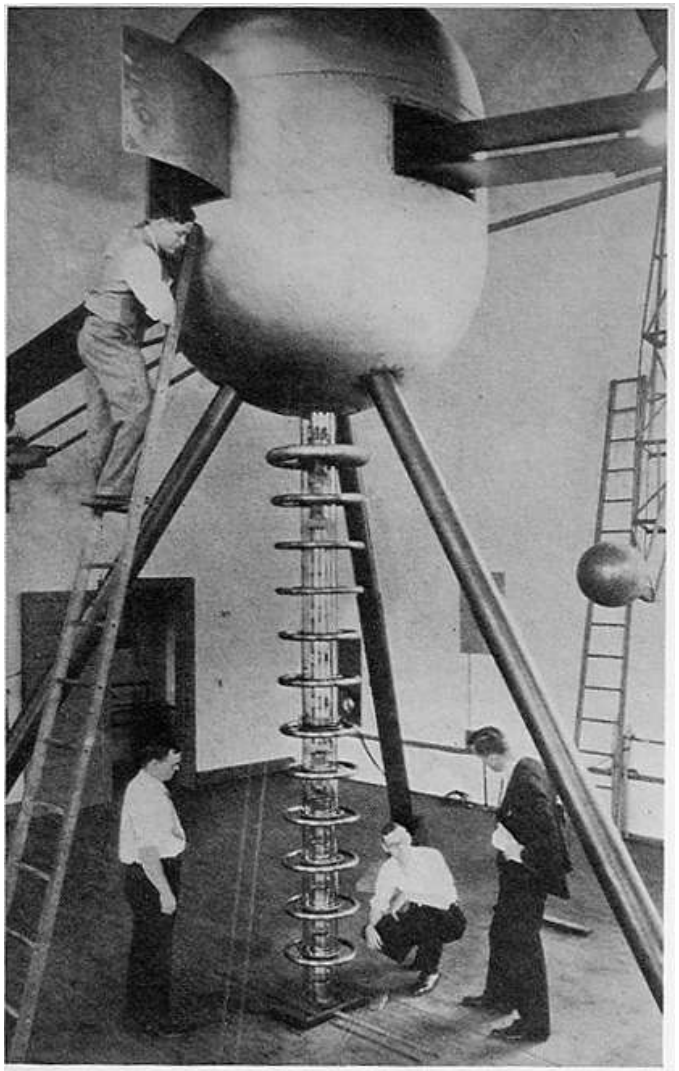
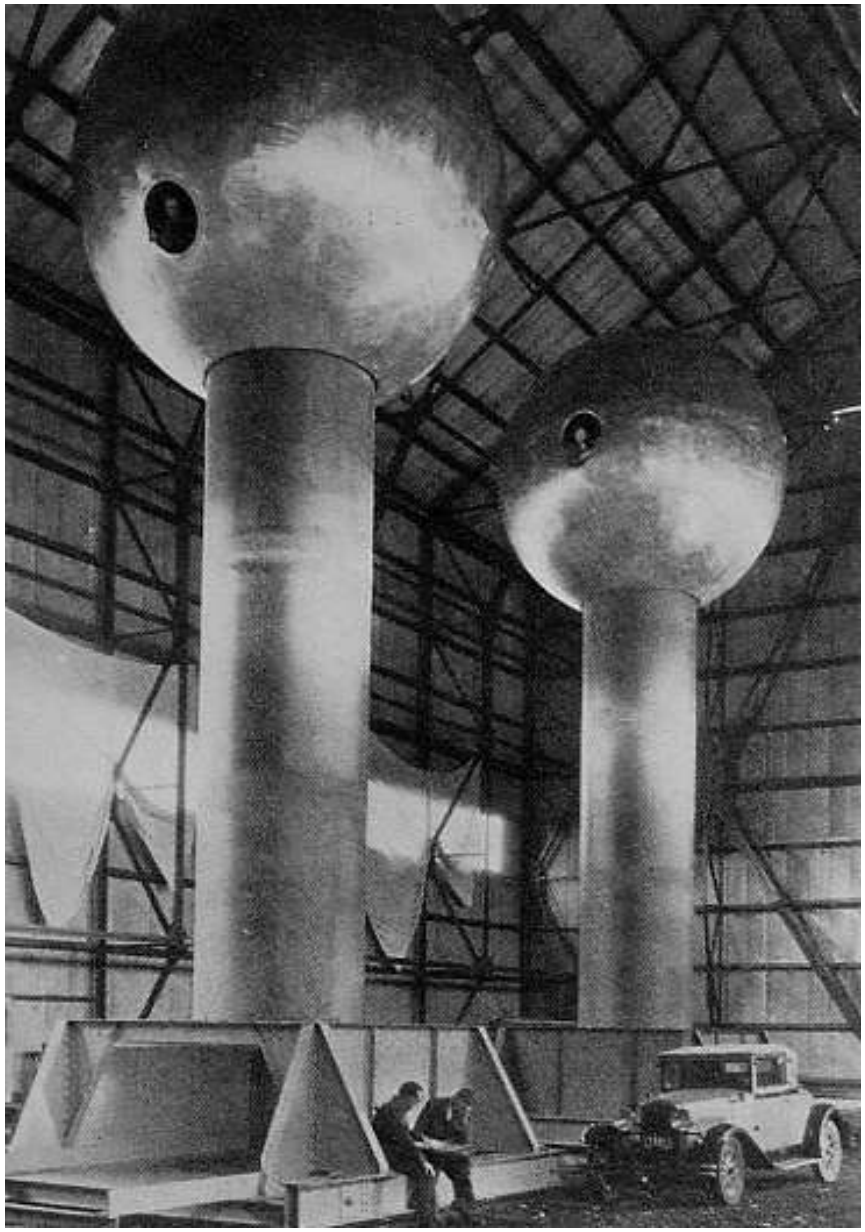


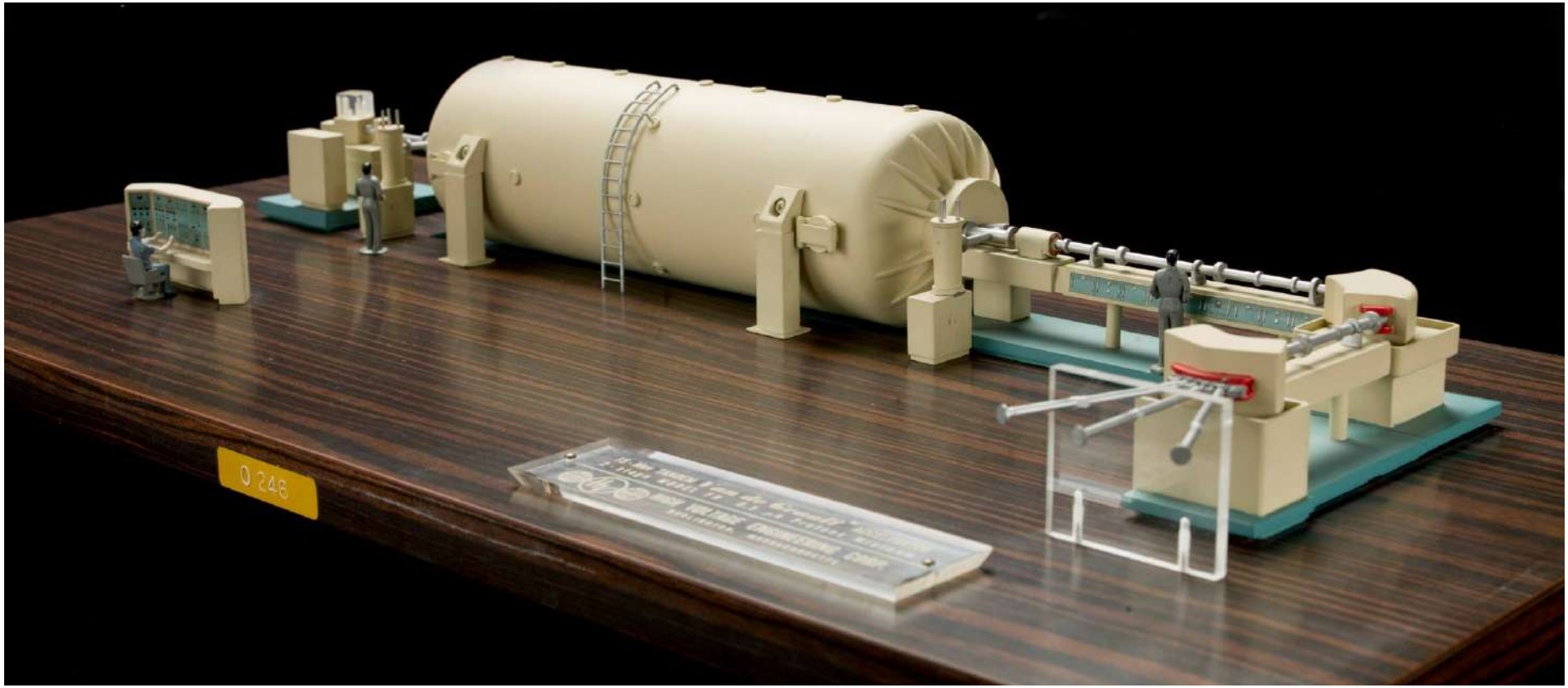
PLATE 2.4 The Carnegie Institution's two-meter Van de Graaff; Dahl is on the ladder, Tuve in the suit. The business end of the discharge tube, deflecting magnets, and pumps are under the floor. Tuve, Hafstad, and Dahl, *PR. 48* (1935), 322.

VDG's 15-foot machine at MIT

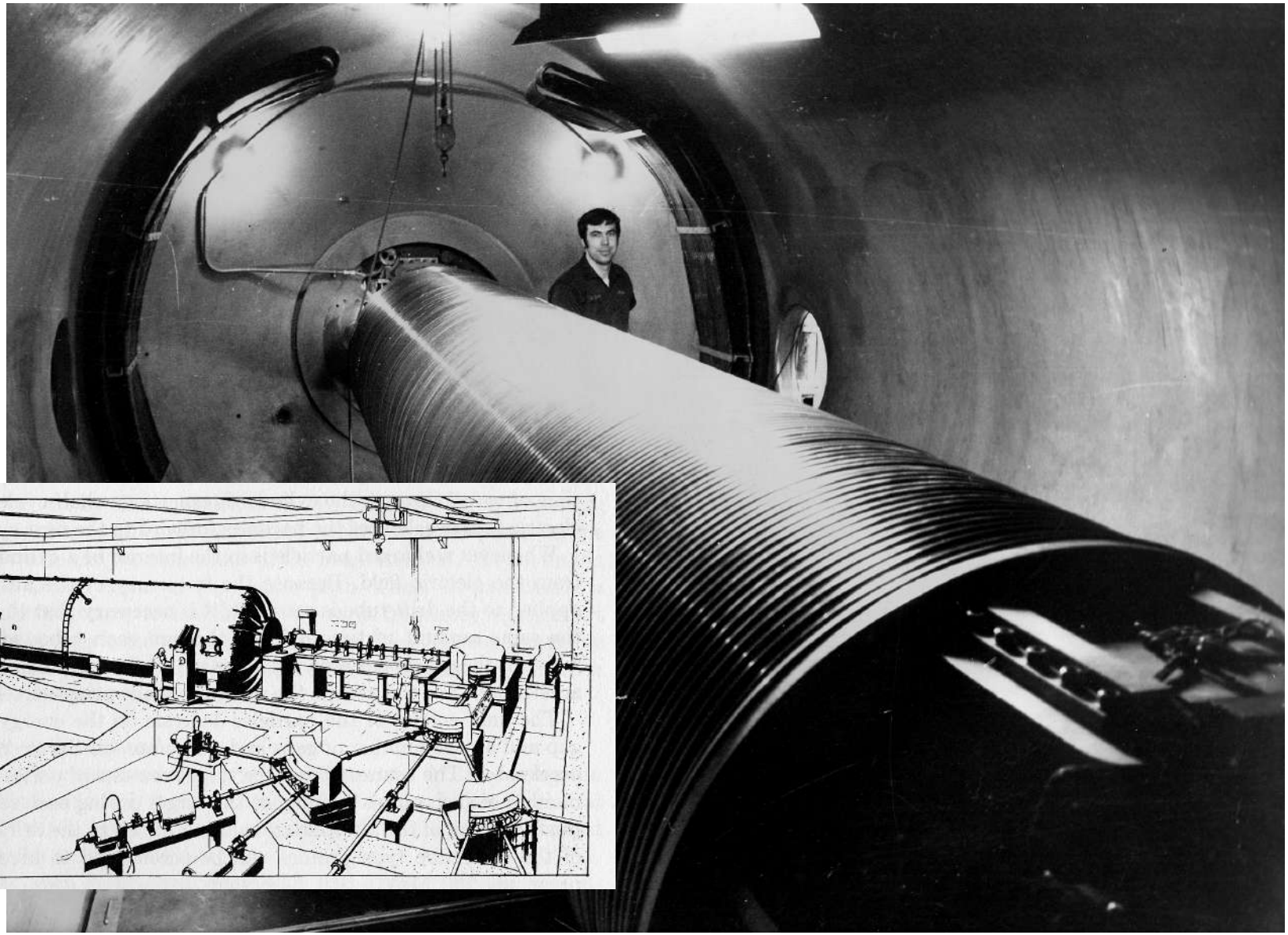
- The awesome VDG installation at MIT stood 43 feet about the ground and the spheres were 15 feet in diameter.
- It promised 10 MV, but was not realized until after WWII



RU's 20 MeV Van de Graaff '62 – '84

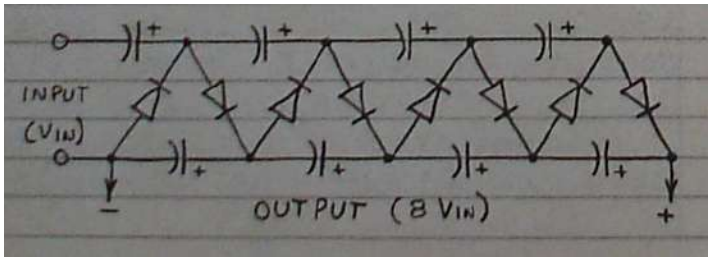


20 MeV Van de Graaff ’62 – ‘84



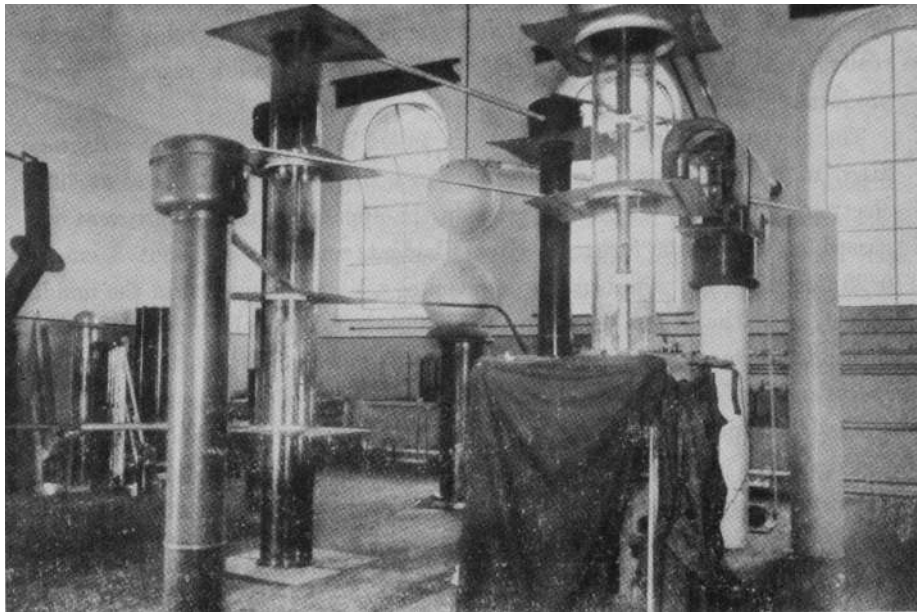
Cockcroft & Walton's Voltage Multiplier:

Cockcroft Rutherford Walton

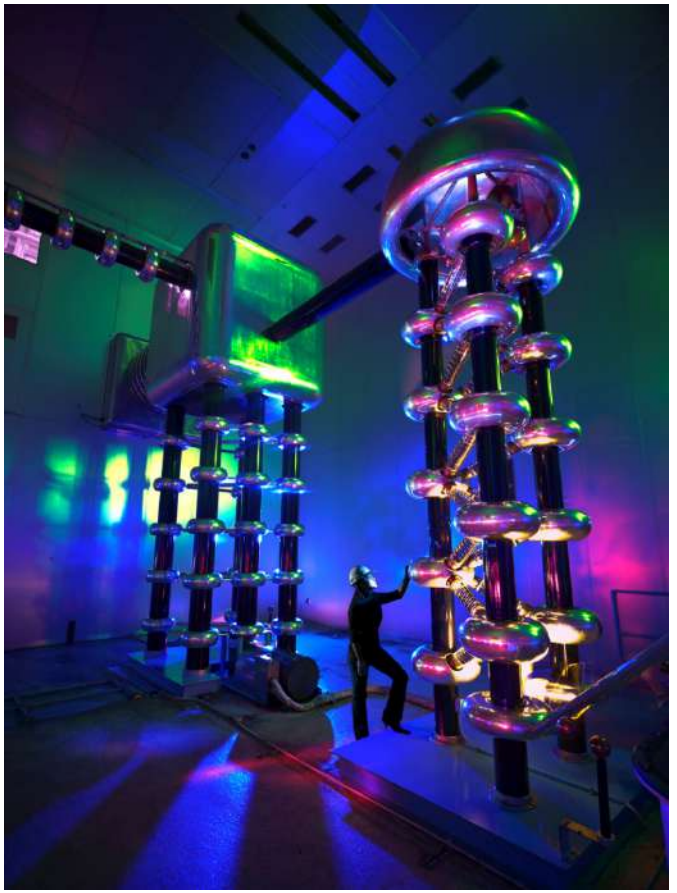


C&W 1951 Nobel Prize

Attributed with being the first to artificially disintegrate nuclei.



The multiplier worked, but is generally limited to 750kV.



Cockcroft-Walton Generator

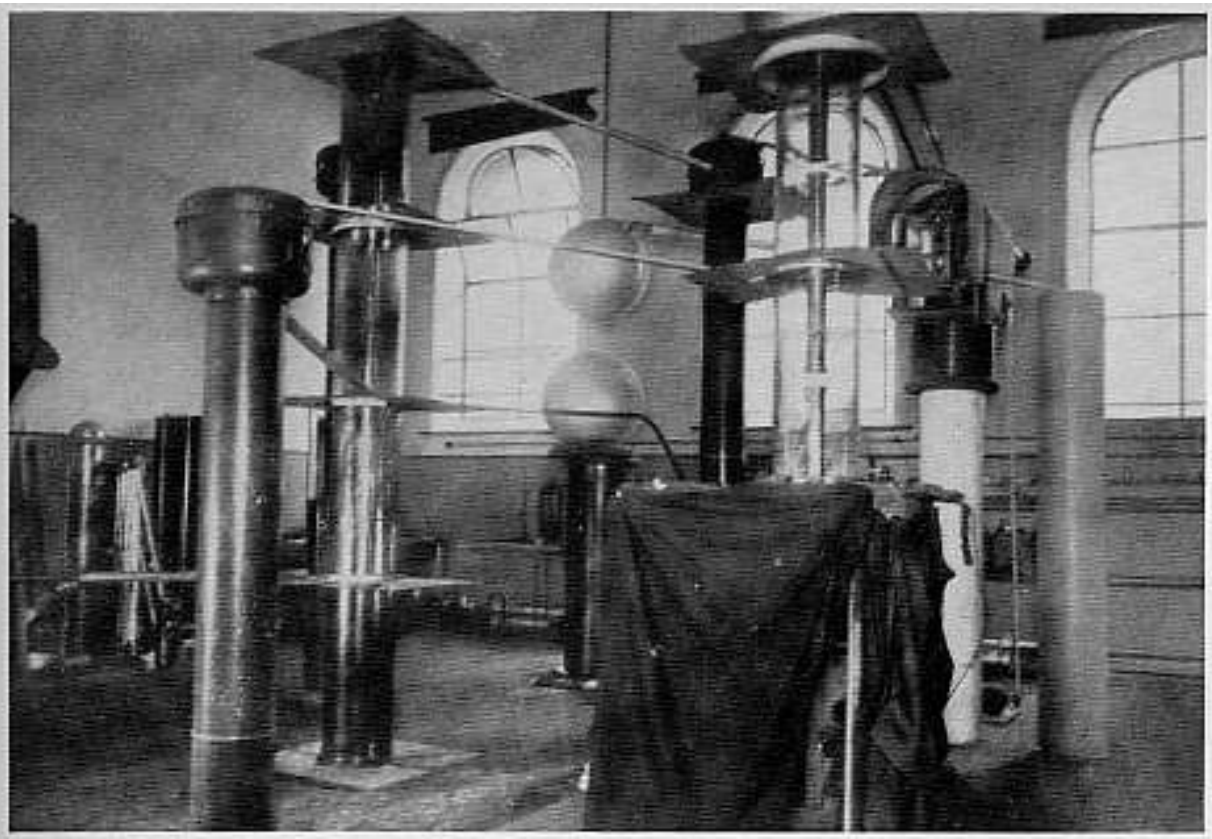
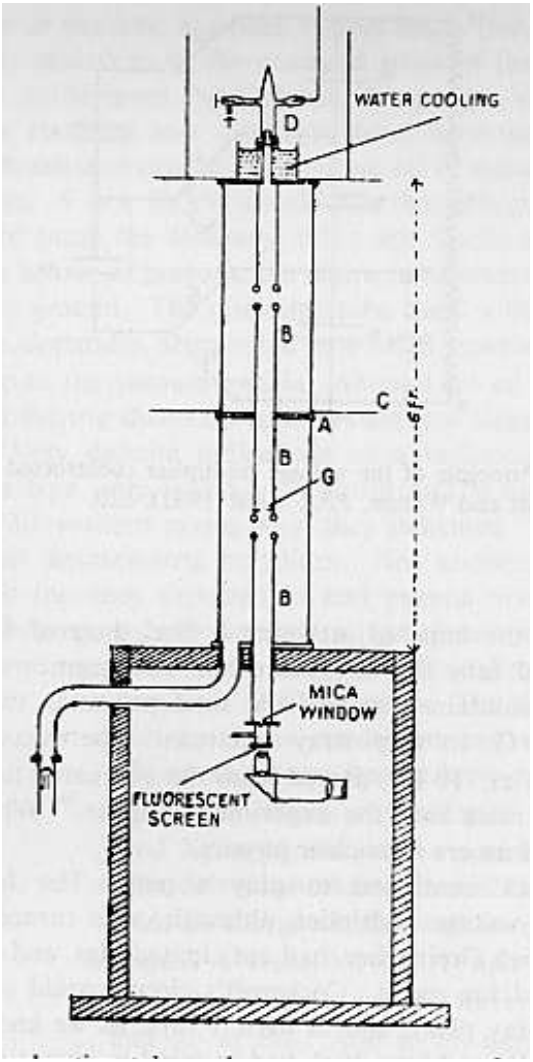


PLATE 3.7 Cockcroft and Walton's corner of the Cavendish. The tall transparent cylinder in the center is the discharge tube; the other cylinders are stacks of condensers and rectifiers. The curtained box is the observation center. Cockcroft and Walton, *PRS, A136* (1932), 625, plate 11.



Cockcroft & Walton Left their Mark

The 1st stage of CERN's & Fermilab's accelerator complex were, until recently, Cockcroft-Walton stacks

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

Wideroe Linac

1929: Rolf Wideroe

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

It was not without a myriad of problems

- Focusing of the beam
- Vacuum leaks
- Oscillating high voltages
- Length
- Imagination

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

Never the less, thankfully Wideroe still published his idea in *Archiv fur Electrotechnic*

Wideroe in the 1960’s having the last laugh…

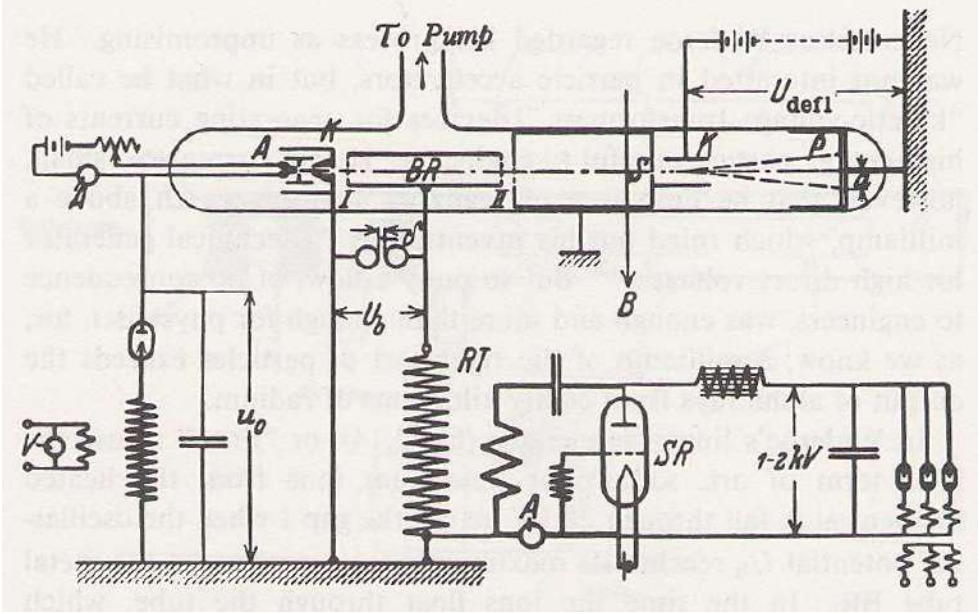
Ernest Orlando Lawrence

1909 – 1958

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*.

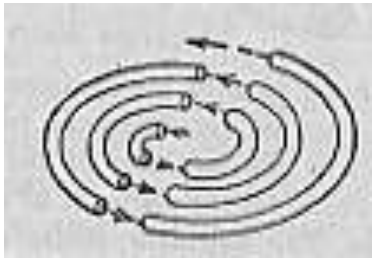
Not able to read German he just looked at the diagrams and pictures of the journal.

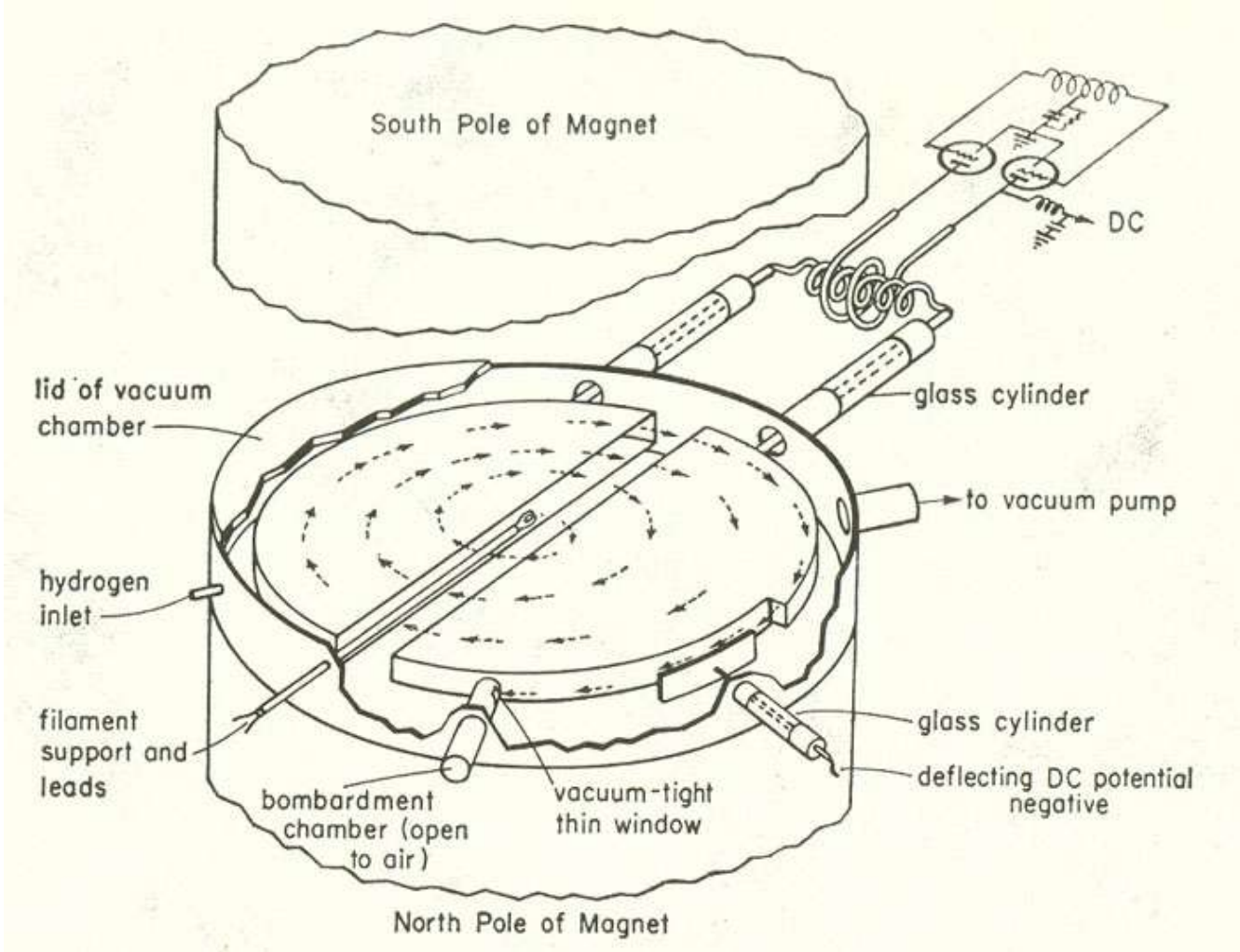


Immediately after seeing Wideroe's schematic, Ernest fully comprehended it's implications.

The Invention of the Cyclotron

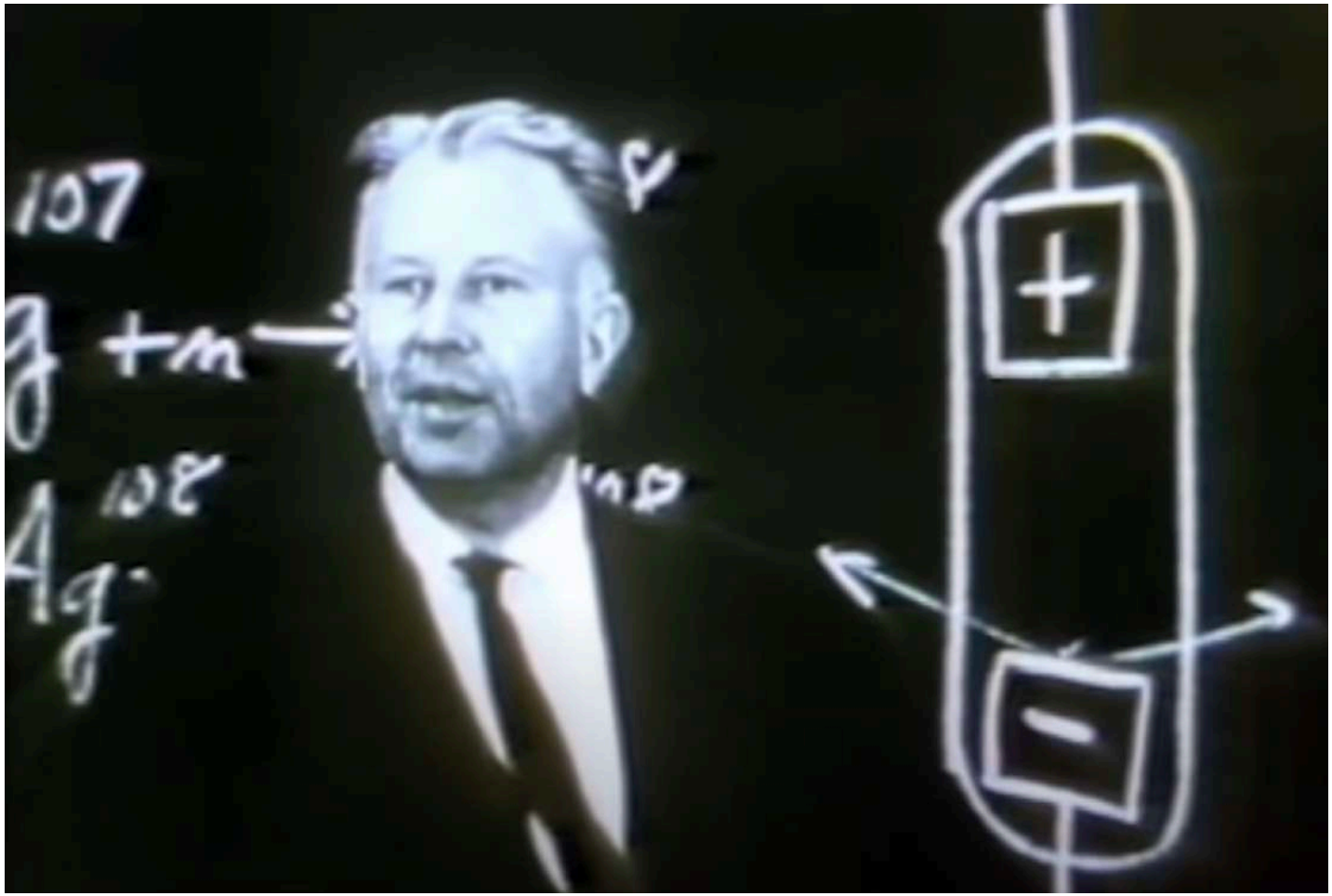
The ideal Cyclotron:

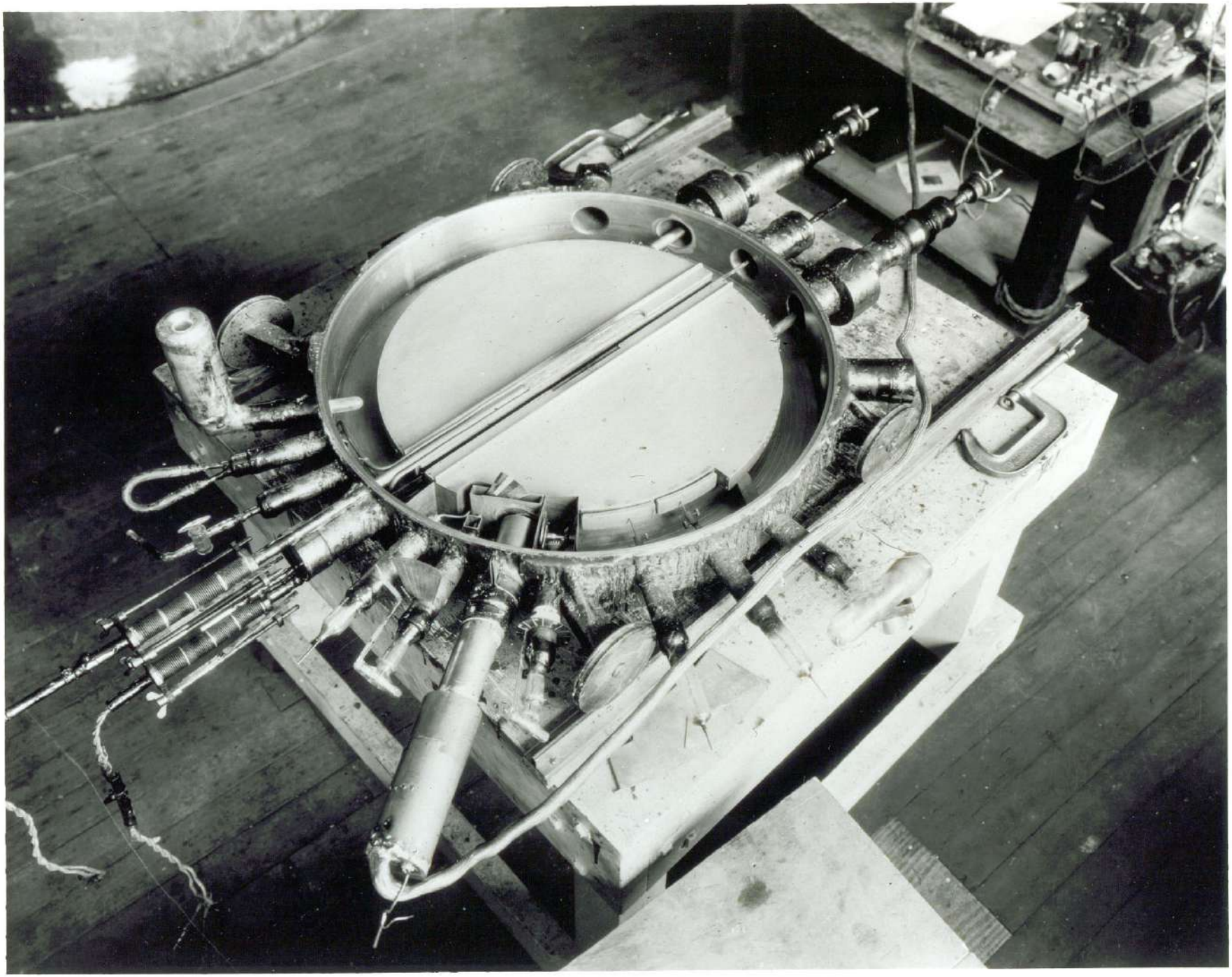




EOL Describes the Cyclotron

https://www.youtube.com/watch?v=cutKuFxeXmQ





“R cancels R !”

The generally reserved professor was seen running about campus shouting “R cancels R”

Most colleagues thought he had gone mad !

What he was ranting about was the general magnetic resonance acceleration principle:

$$F_r = mv^2/r \quad \text{and } F_B = qvB$$

and

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

substitute $v = r\omega$:

$$mr\omega = qBr$$

R cancels R !

rearrange:

$$\omega = qB/m$$

$$f = qB/2\pi m$$

Magnetic Rigidity

- Force equation:

$$\frac{mv^2}{r} = qvB \Rightarrow p = qBr$$

- Magnetic Rigidity, Br:

$$Br = \frac{p}{q}$$

- Measure of how well the field can keep the ions in orbit.

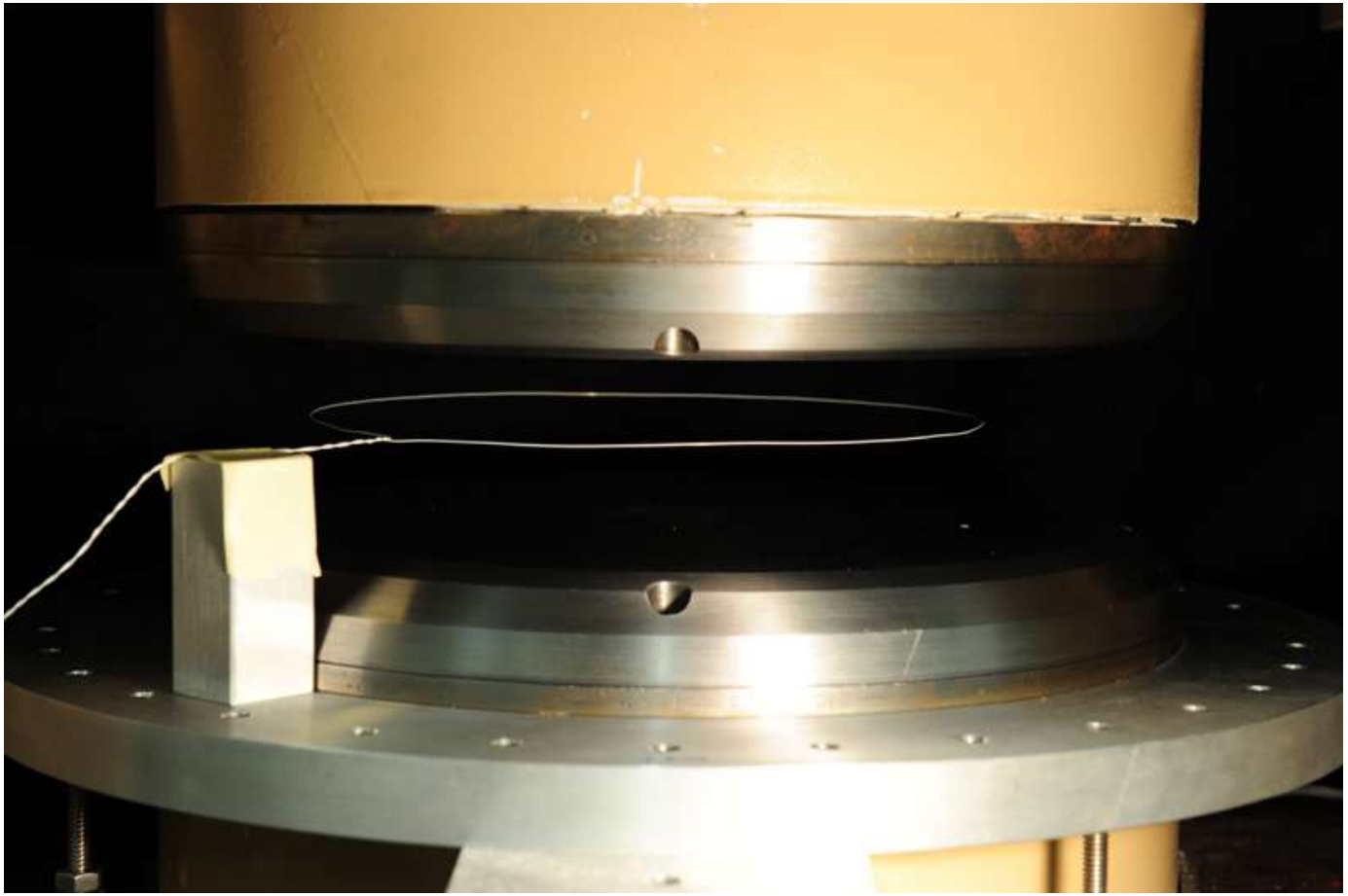
- Relativistic regime, $E >> E_0$:

$$Br = \frac{1}{300 \cdot Z}\left(T^2 + 2TE_0\right)^{1/2}$$

- where Z=charge state, T=final kinetic energy (MeV)
- E_0=rest mass (MeV)
- Br=magnetic rigidity (T-m).

Visualize orbit: Floating wire

Because loop tries to maximize the flux through it, the loop seeks to center itself in the radially decreasing field. The wire conforms to the orbit of the given circumference, revealing field errors. The *tension/current* is proportional to the *momentum/charge* of beam at the radius.



$$Bi = \frac{T}{r}$$

$$Br = \frac{T}{i}$$

$$\frac{mv^2}{r} = qvB$$

$$mv = qBr$$

$$\frac{mv}{q} = Br$$

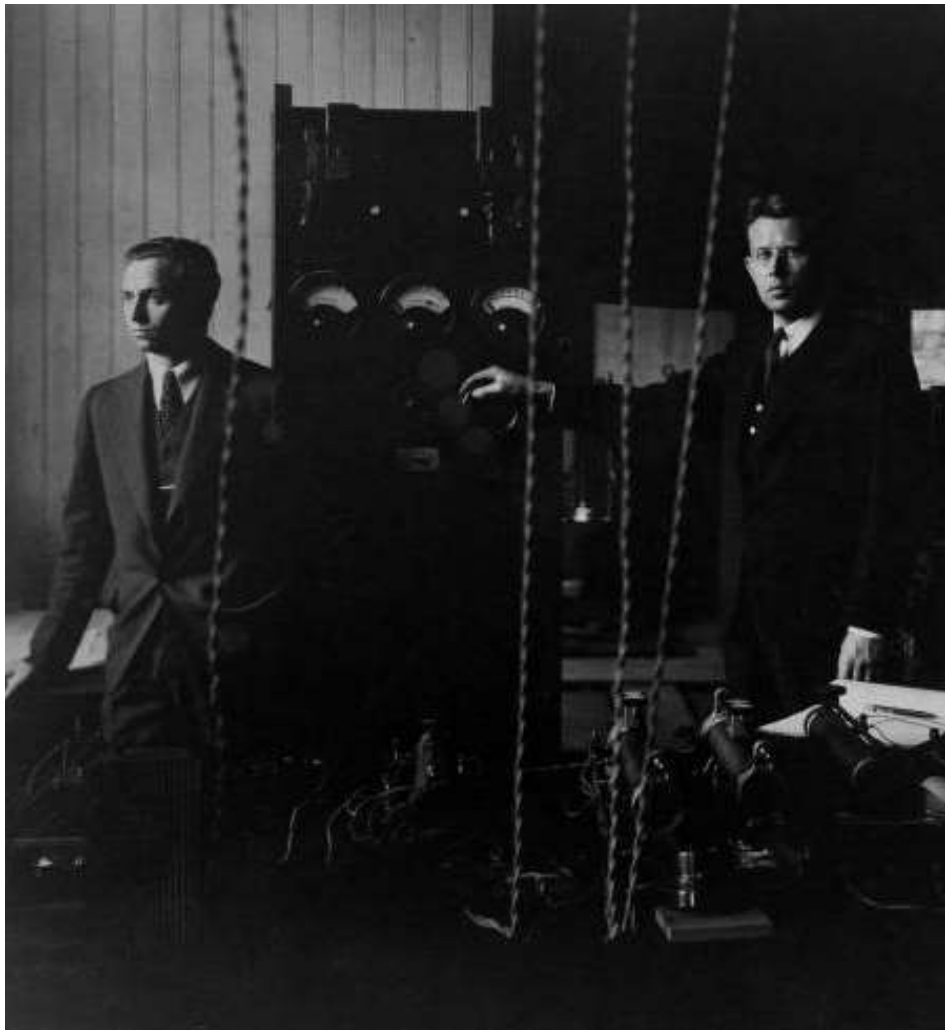
$$\frac{p}{q} = Br$$

$$\frac{p}{q} = \frac{T}{i}$$

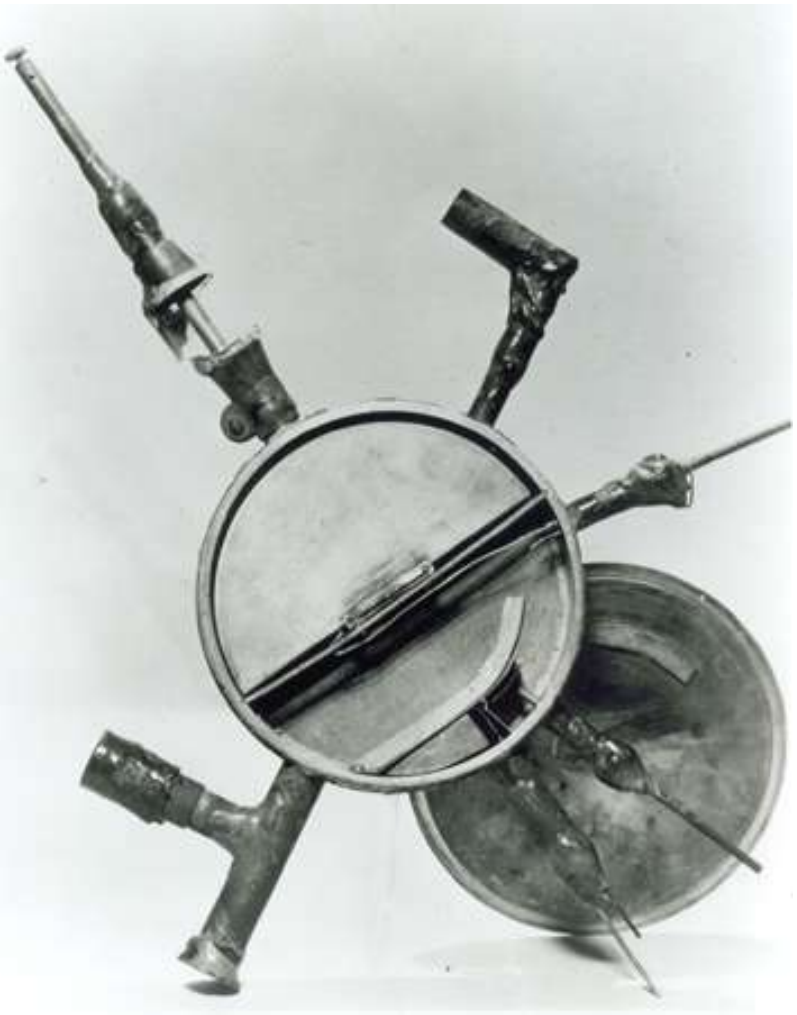
The First Cyclotrons

EOL first grad N. Edlefsen's, first failed attempts in 1930

Graduate Student M. Stanley Livingston



M. Stanley Livingston Ernest Lawrence



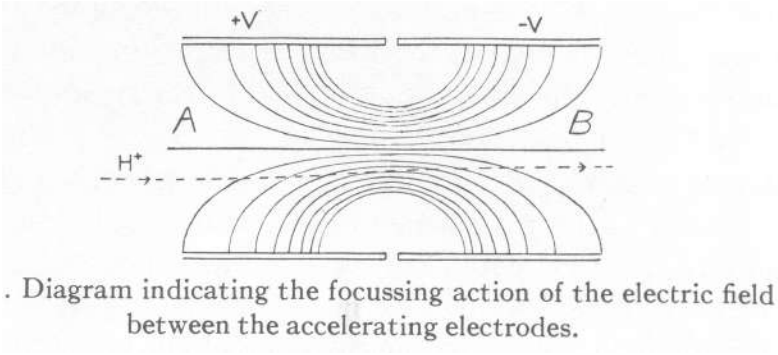
The First Operational Cyclotron

Weak Focusing

- Although the cyclotron worked, the beam intensity was very weak. Lawrence ☹
- Lawrence: wire grids and iron shims

Livingston removed the grids while Lawrence was out of town ➔ beam intensity shot up.

Livingston took this remarkable finding to Lawrence. To which Lawrence responded: "It's obvious what is happening…"



. Diagram indicating the focussing action of the electric field between the accelerating electrodes.

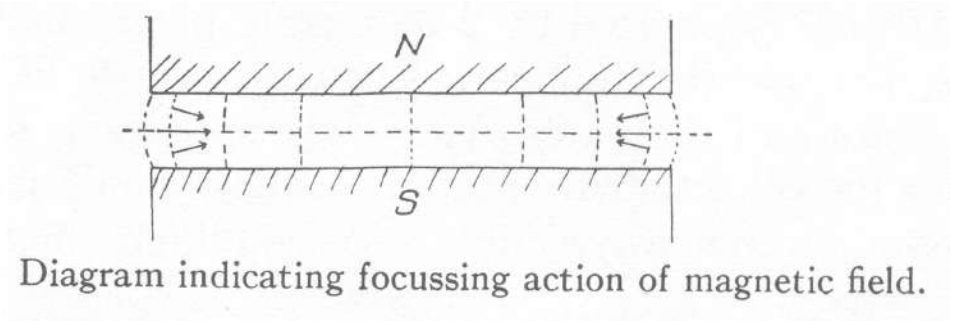


Diagram indicating focussing action of magnetic field.

Intentionally introduce radial B-field component at the cost of an vertical gradient: to be coined weak focusing.

It paid off, It worked !

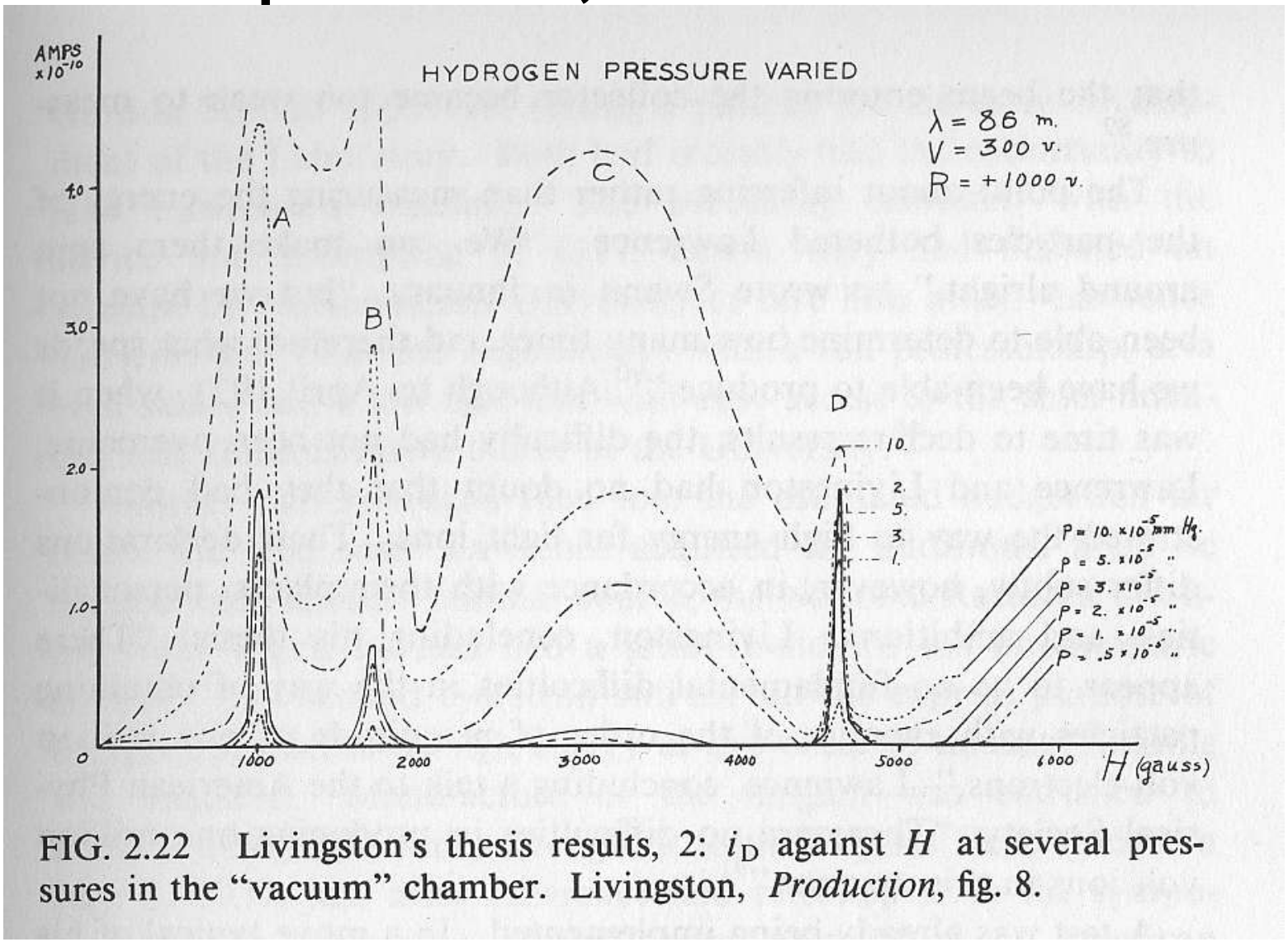


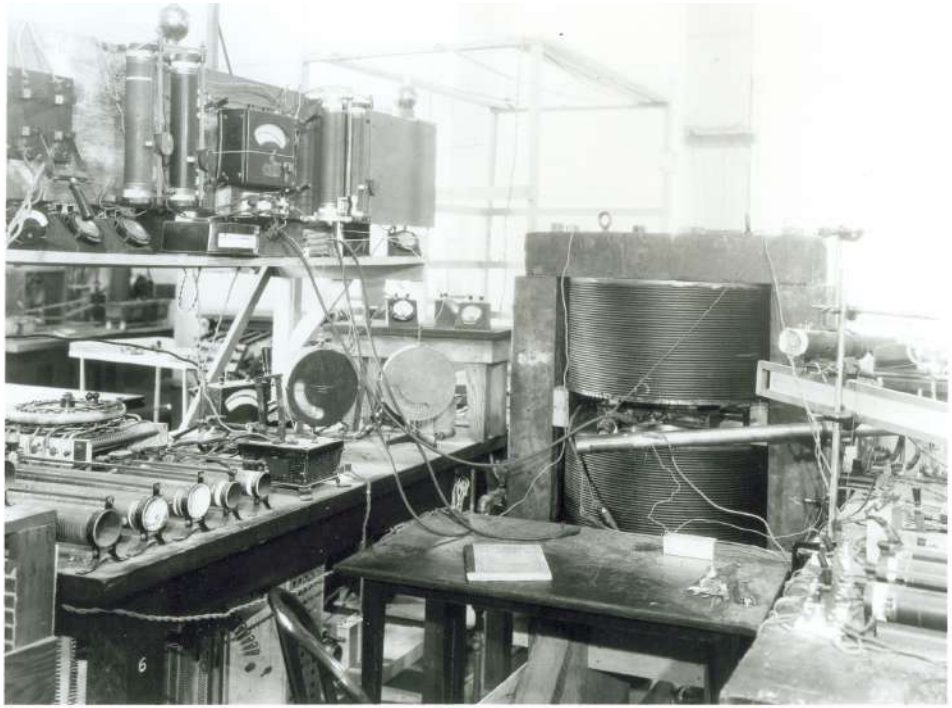
FIG. 2.22 Livingston's thesis results, 2: i_D against H at several pressures in the "vacuum" chamber. Livingston, *Production*, fig. 8.

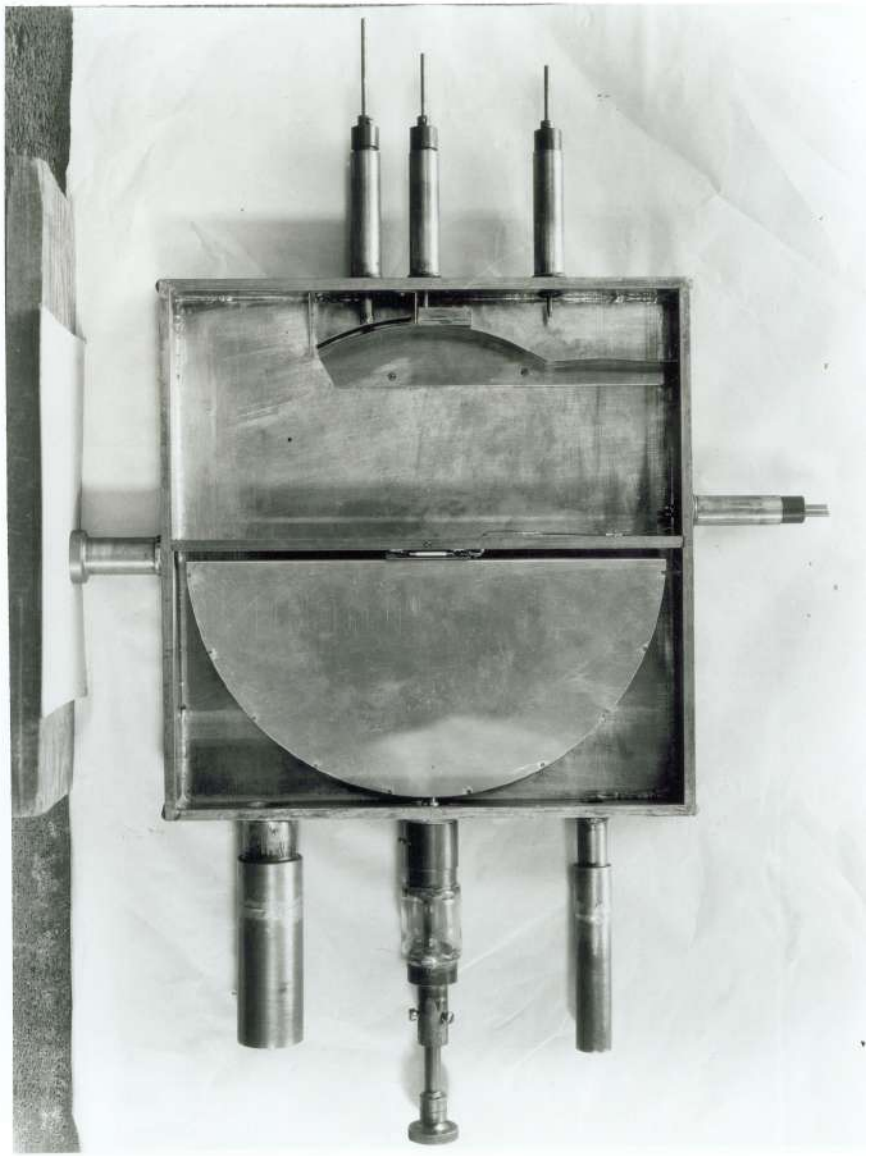
Berkeley Cyclotron History

The Cyclotron evolved quickly at Berkeley:

4”	(80keV protons)	1931
11”	(1MeV protons)	1932
27”	(5.5MeV Deuterons)	1937
37”	(8.0MeV Deuterons)	1938
60”	(16MeV Deuterons)	1939
184”	…	1945

11-Inch Cyclotron: 1 Million Volt

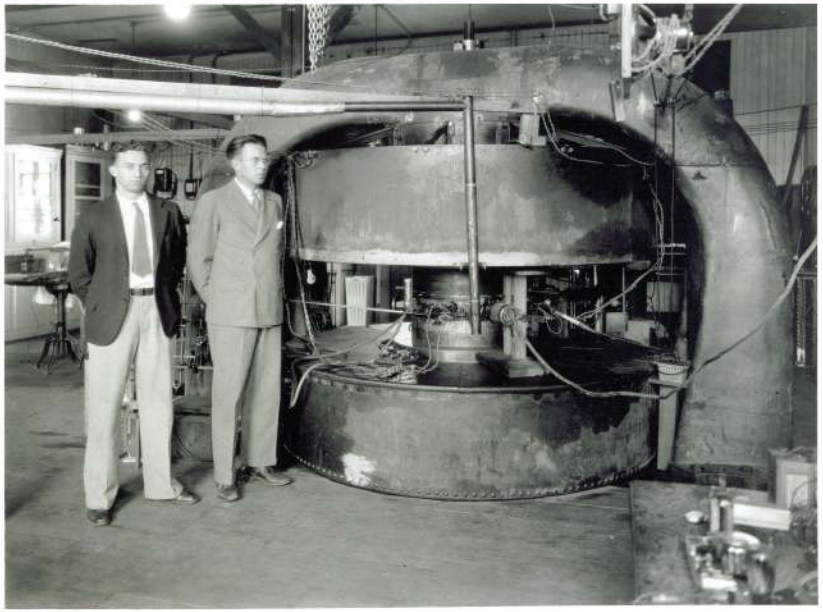


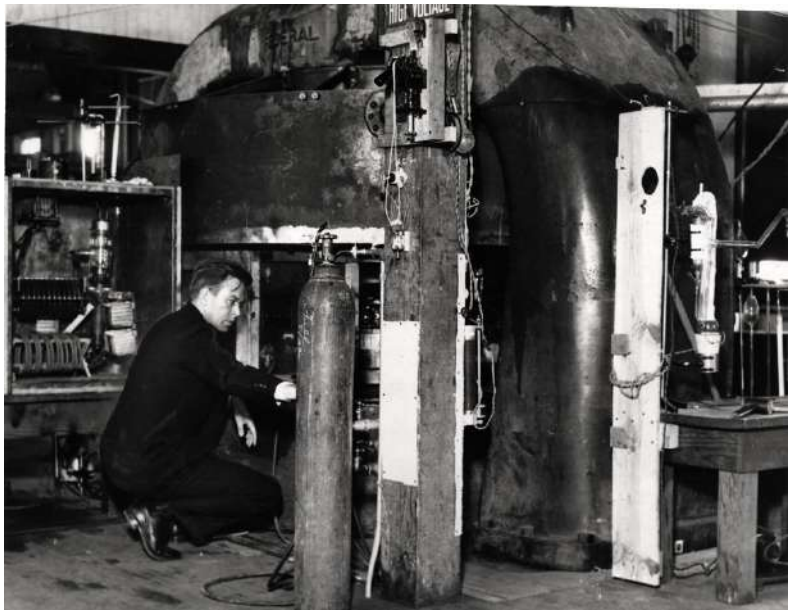


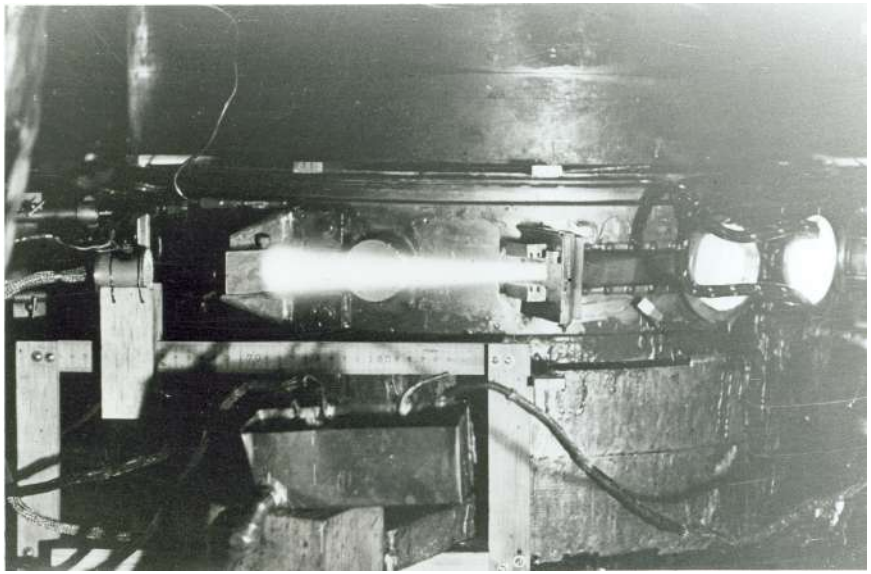
While vacationing in Connecticut August 1931, he received a telegram from his secretary that read:

“Dr Livingston has asked me to advise you the he has obtained 1,100,000 volt protons. He also suggested that I ‘Whoopee’ !”

The 27 Inch Cyclotron







2002 – Washington DC

1934: A hard lesson to learn:

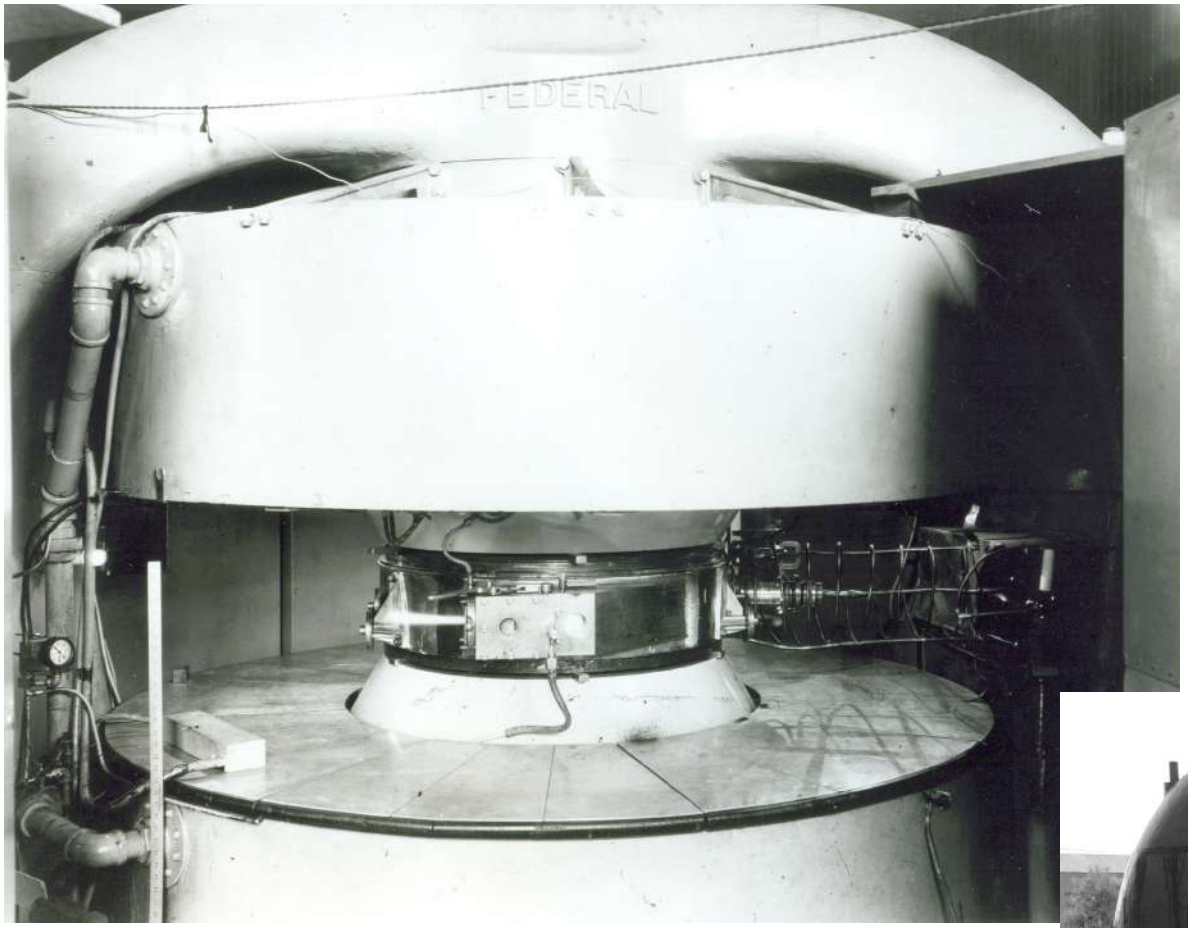
Joliot announced induced radioactivity using a small alpha source and Al targets.

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]

The 37-Inch Cyclotron



1938: 100uA 6.4 MeV Deuterons 20 hours a day

The Federal Magnet is now on display at LBL

EOL Radio Interview 1

https://www.youtube.com/watch?v=8tJrJ9dSLFg&t=7s

Ernest O. Lawrence Talks About the Evolution of the Cyclotron

Radio-Sodium

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

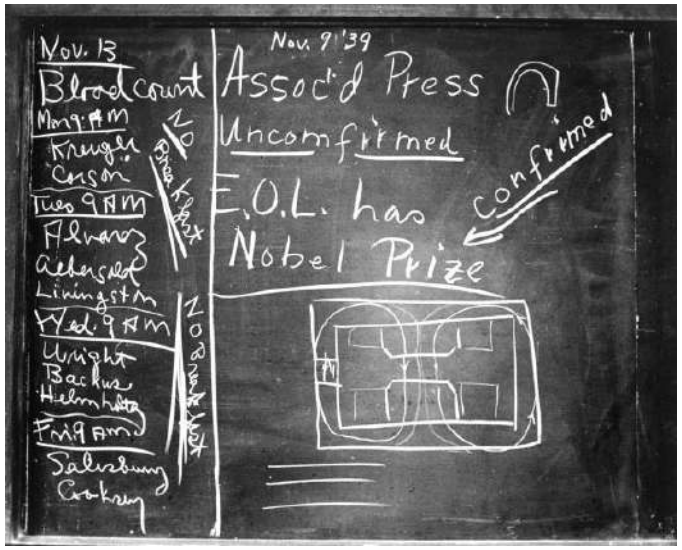
So began use of accelerators in medicine.

60” Cyclotron: End the Small Cyclotron Era at LBL.

By 1939 EOL had amassed an Impressive Scientific & Technical Staff

1939 EOL Wins Nobel Prize

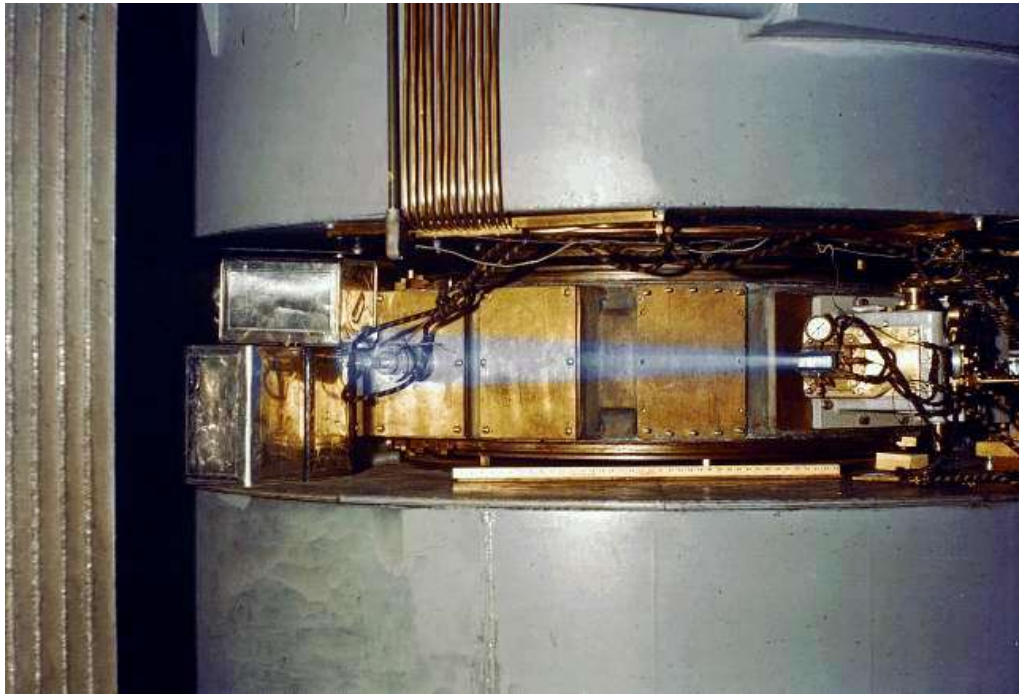
(ceremony held in Berkely due to WWII)



EOL Nobel Prize 1939

https://www.youtube.com/watch?v=9gcz-NULeF0

The 60-Inch Cyclotron



WWII

- Cyclotrons (and their cyclotroneers) contributed greatly to the Manhattan Project and to the war.
  - Discovery & measurement of Plutonium
    - Fission Cross Sections
    - Pu240 spontaneous fission
      - → Implosion Weapon (Nagasaki)
  - Electromagnetic Separation of U235/U238
      - → Gun method (Hiroshima)

The Discovery of Plutonium

Bombardment of Uranium with neutrons: $^{238}U+n \rightarrow {}^{239}U \rightarrow {}^{239}93 \rightarrow {}^{239}94$ (Plutonium)

The Plutonium Story

The Journals of Professor Glenn T. Seaborg 1939–1946

THESE ARE EXCERPTS FROM GLEN T SEABOARG NOTEBOOK.

Saturday, July 1, 1939: This is my first day in my new role as an instructor, I am now free to do my own research.

Monday, Sept 11, 1939: I've read the Physical Review article by Bohr & Wheeler entitled "Mechanism of Nuclear Fission" – I intend to digest it and report on it at next week's nuclear seminar.

Monday, June 1940: I have read a report by Edwin McMillan and Abelson that describes the first transuranium element with atomic number 93, it is radioactive with a half life of 2.3 days. It beta decays. Its daughter 239-94 is apparently to long lived to be observed. I was aware of this work as it was being carried out, and I find myself eager to work in this exciting field.

Friday, August 30, 1940: … I irradiated our first sample of uranium with neutrons. This was 5 grams placed directly behind a beryllium target bombarded with 16 MeV deuterons in the 60-inch cyclotron.

Thursday, October 10, 1940: We now are ready to look for an alpha emitting isotope of a new element with atomic number 94, such as might be produced in the deuteron bombardment of uranium, in which a new isotope of element 93 might be synthesized to decay by beta emission to a detectable element 94 daughter.

Friday, January 3, 1941: Fermi would like us to determine the yield of 239-93 from neutron bombardment in the 60-inch cyclotron. However, Lawrence suggested to determine fissionability of 239-93 and 239-94.

Friday, January 31, 1941: I prepared our first large Uranium sample: 575 grams

Sunday, February 23, 1941: at 7:15 PM I began bombardment of 1.2 kg of U.

Monday, February 24, 1941: The neutron bombardment of the 1.2 kg, of U was halted at 11 AM.

Tuesday, February 25, 1941: With final separation from thorium, it has been demonstrated that the alpha activity can be separated from all known elements and it is now clear that our alpha activity is due to the new element with the atomic number 94.

Tuesday April 1, 1941: … continued our measurements on the slow neutron fissionablity of 239-94… estimates are very rough.

Friday, April 4, 1941: I am preparing for my trip to American Cyanmid. Helen Griggs, Lawrence's attractive secretary made the reservations…

Wednesday April 17, 1941: made another comparison of the slow-neutron induced fission rate of [first] sample of 239-94 with U standard at the 37-inch cyclotron. The counting rates are 5 times higher, confirming that we are definitely observing the fission of 239-94.

Monday, May 5, 1941: I wandered into Lawrence's office today – I manufactured a flimsy excuse for the visit, but I really wanted only to talk with Helen Griggs.

Thursday, May 29, 1941: We say that the cross section for fission of 239-94 with slow neutrons is about 1.7 times that of 235U

Saturday, June 21, 1941: The neutron bombardment of 1.9 kg of uranium was completed with 14,000 uah of deuterons, we expect 3 micrograms of 239-94

Sunday, August 24, 1941: Helen Griggs went with me to a movie this afternoon – we saw Bob Hope in "Caught in the Draft"

Tuesday, October 28, 1941: Moved apparatus for the observation of spontaneous fission of 239-94 to East Hall, the old abandoned building on the south side…This more isolated site will be more free of electrical interference. The counting circuits must exhibit extraordinary stability in order to establish, reliably, the absence of spontaneous fission counts over long periods of observation.

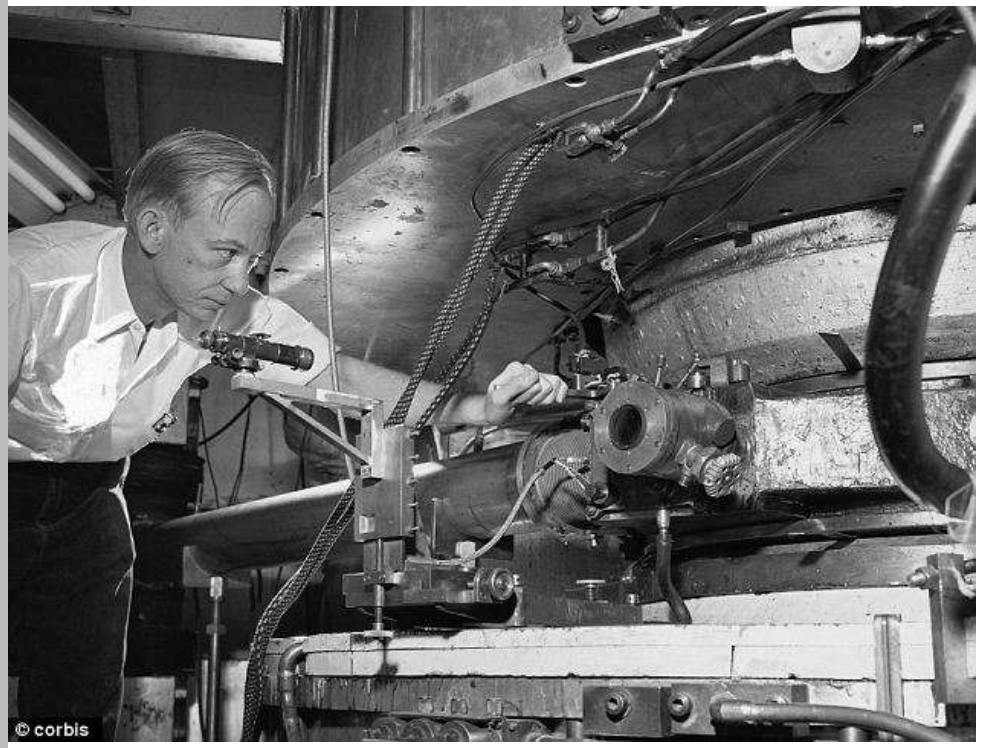
Sunday, December 7, 1941: I listened to the radio broadcast of the Chicago Bears-Chicago Cards football game from Comisky Park. At Half-time came the electrifying announcement that the Japanese bombed Pearl Harbor today. This undoubtedly will result in a speed up of the uranium (bomb) project.

Harvard Cyclotron → LASL

Hymer Friedell?, Robert R. Wilson[from Princeton], Percy Bridgeman[depart. chair] discussion of taking cyclotron to unkown destination

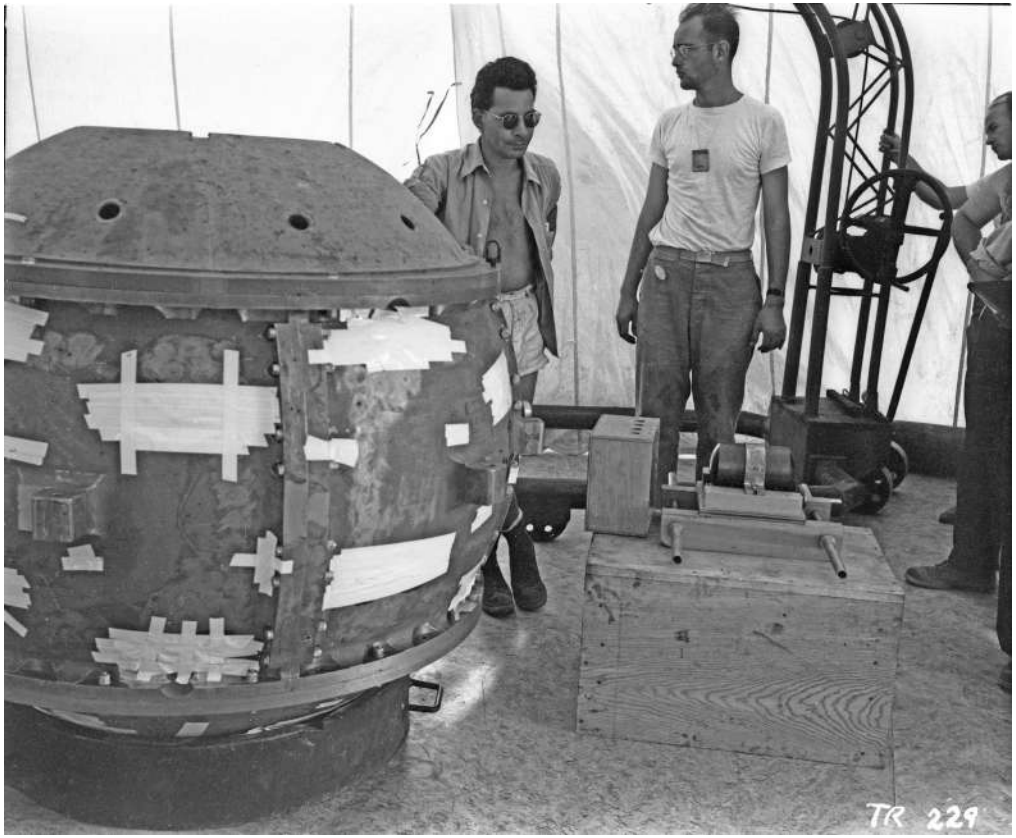
In 1943, the Manhattan project needed the Harvard cyclotron for nuclear studies. Radiologist Dr. Hymer Friedell came to Harvard with a "cover story" that it was needed to make isotopes for Army hospitals.
The photograph shows Hymer Friedell (left) discussing with the dpartment chairman Percy Bridgeman (right).Robert Wilson (middle) reported years later Percy Bridgeman's response:
"If you want it for what you say you want it for, you can't have it. If you want it for what I think you want it for, of course you can have it."

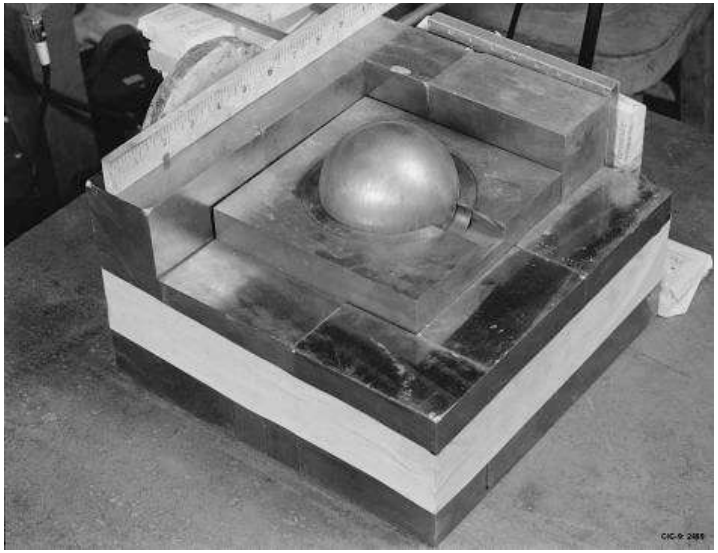
Measured spontaneous fission of ^{240}Pu



"If you want it for what you say you want it for, you can't have it. If you want it for what I think you want it for, of course you can have it."

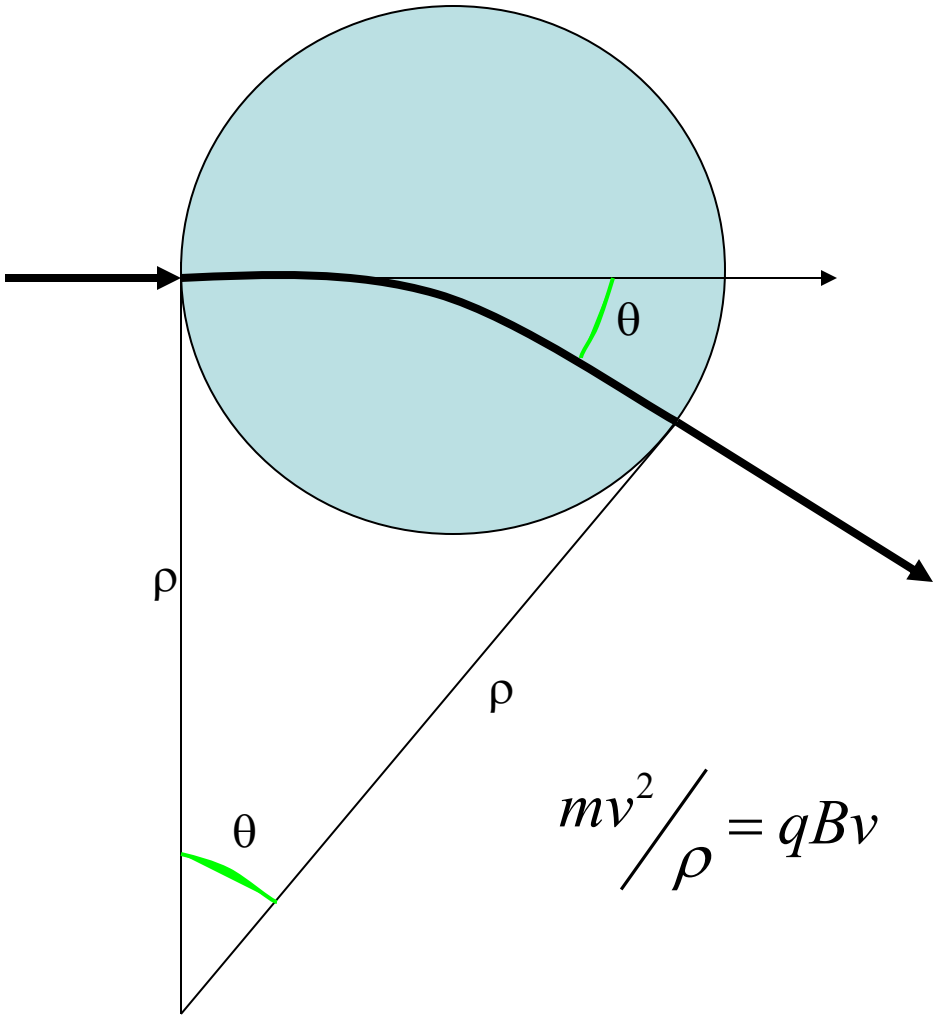
Trinity Test





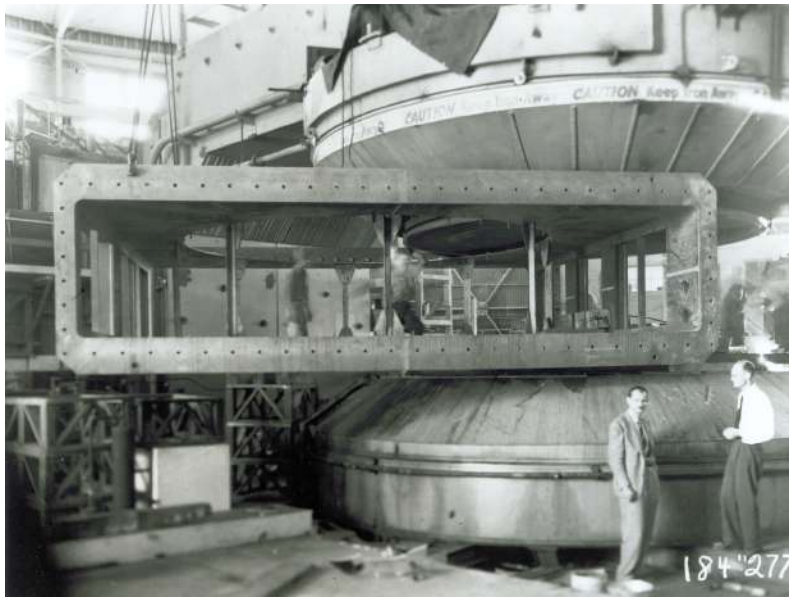
184 Inch, 100 MeV Cyclotron

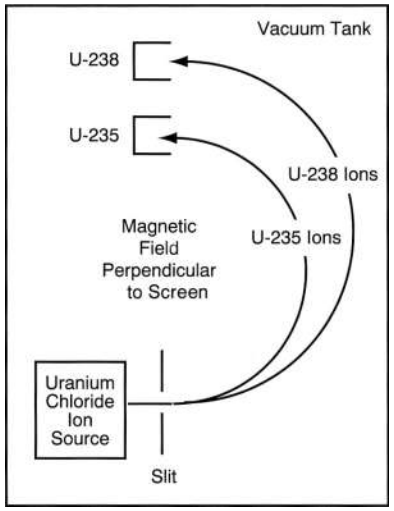
"Magnetic Rigidity"



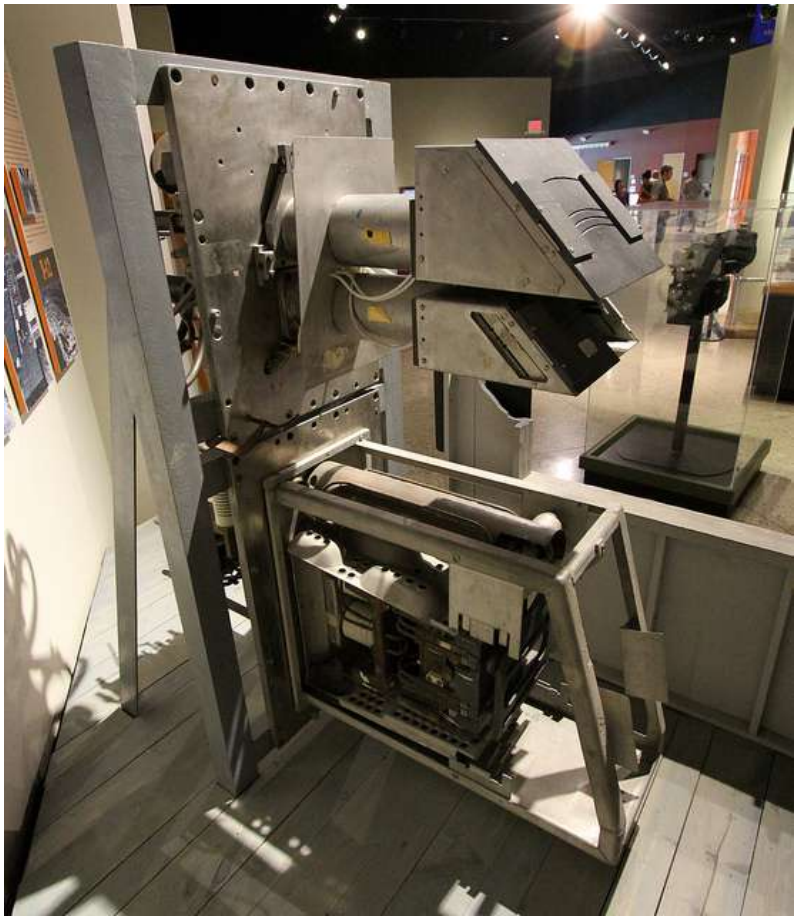
$$mv^2/\rho = qBv$$

"Guide Center"

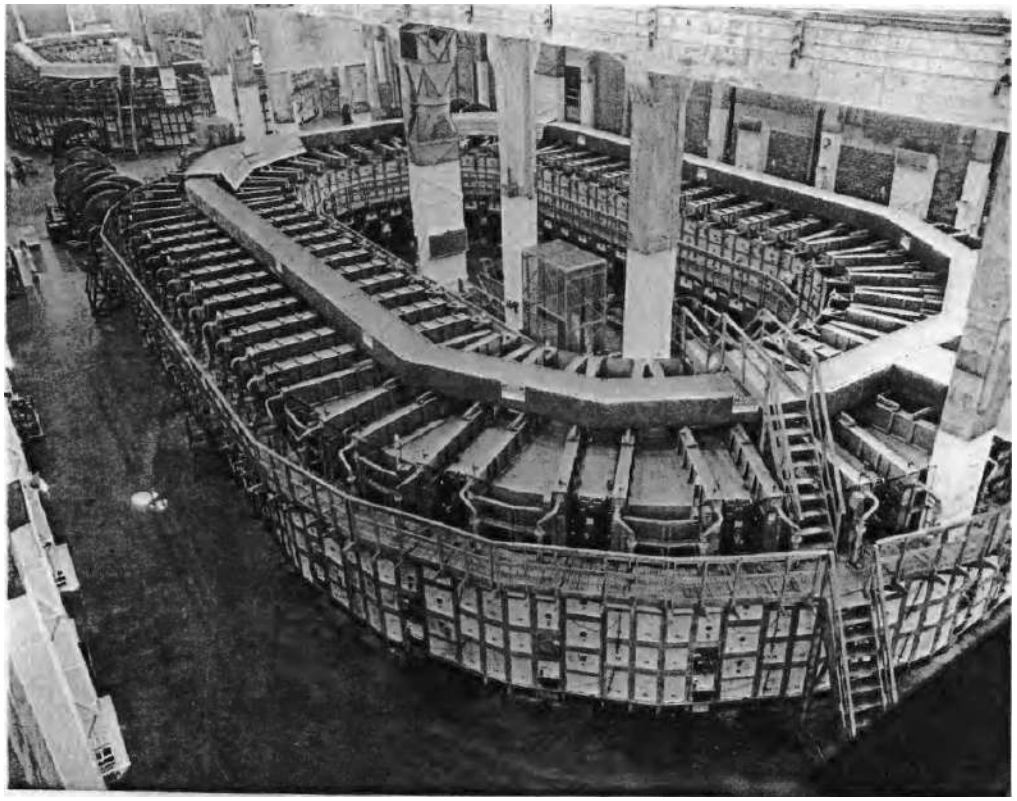




Calutrons



Copper was just not available, so, the electromagnet conductor was made from 395 million Troy ounces of silver borrowed from the US Treasurey

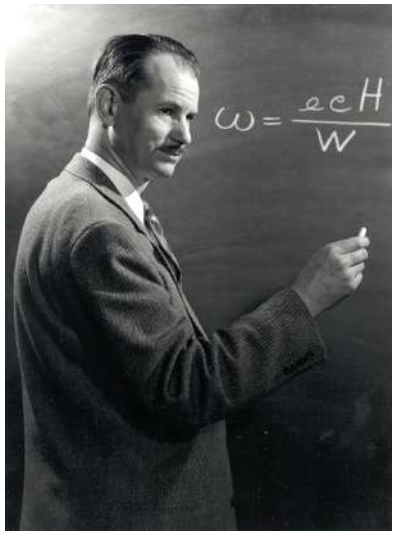


Atom by atom, ^{235}U was collected at best at a rate of 0.75 grams/day-calutron

6 Beta-stage Calutrons (36 tanks each). The dominant 235U quantity of the little boy bomb was separated by these.

Calutrons – Control Rooms

Discovery of Phase Stability



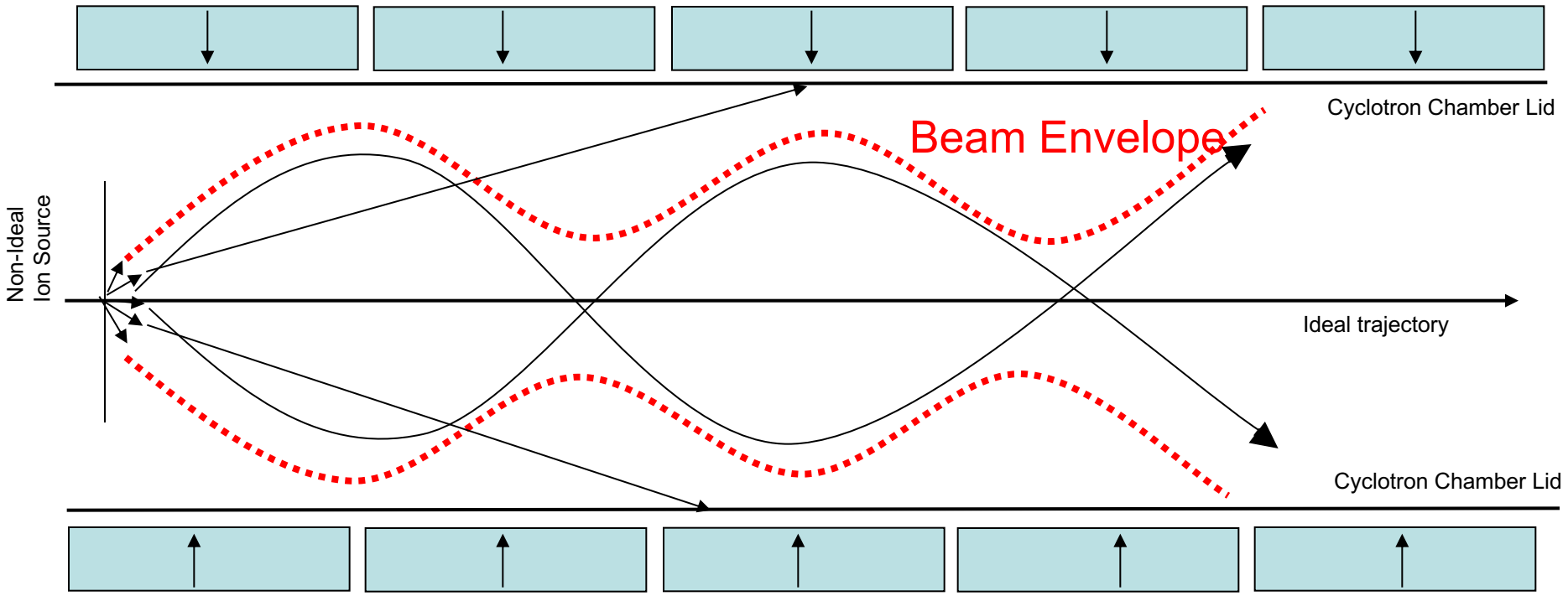
Edwin McMillan 1951 Nobel Citation

Vladmir Veksler

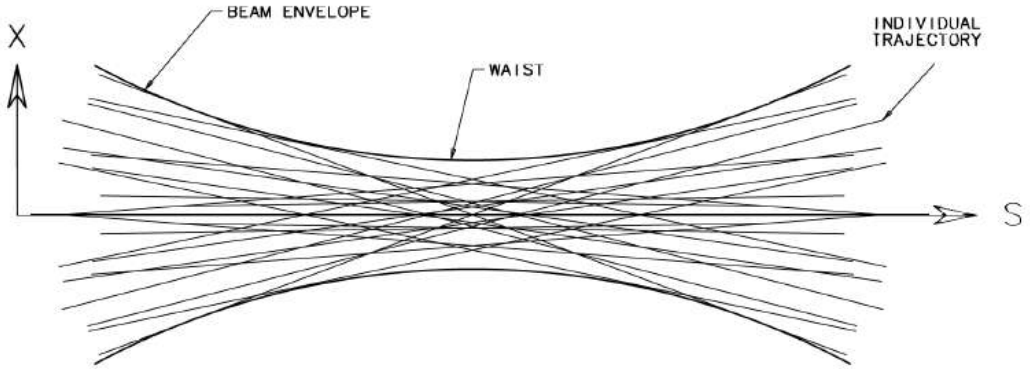
It was during 1945 that he had the idea of **"phase stability"** which led to the development of the synchrotron and synchro-cyclotron; these machines have already extended the energies of artificially accelerated particles into the region of hundreds of MeV and have made possible many important researches.

Stalin & Lenin Prizes

NEED FOR FOCUSING



The maximum beam transported is limited by what scrapes on the lids.



BOWLING ALLEY ANALOGY OF FOCUSING

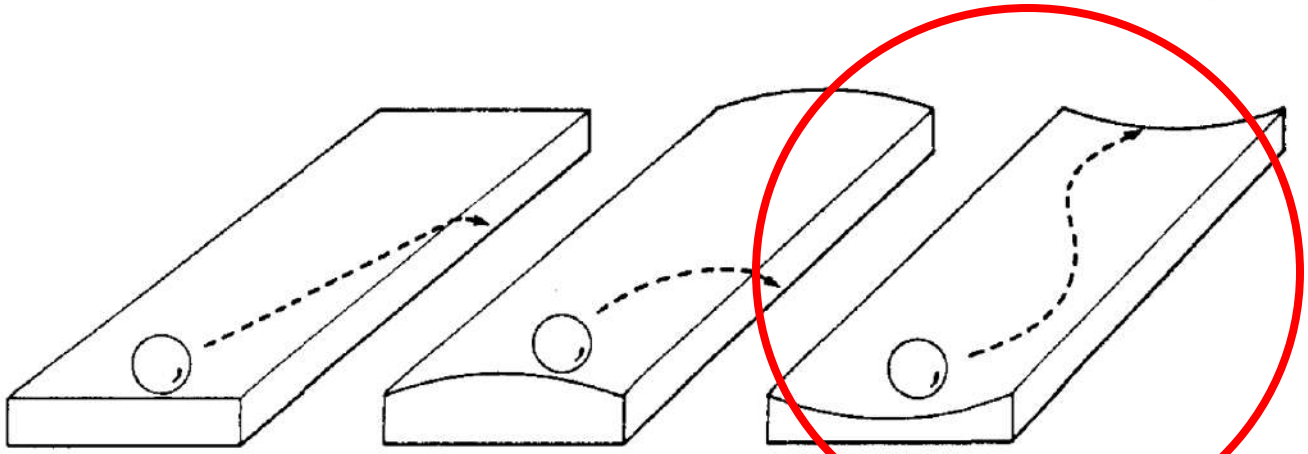


Fig. 2-1. Bowling alley analogy of systems of forces which produce neutral, unstable, or stable orbits.

- J.J. Livingood, Cyclic Particle Accelerators

Three magnetic field configurations that promote axial and radial stability.

1. Weak Focusing
2. Radial Sectored AVF focusing
3. Spiral sectored AVF focusing

"TUNE"

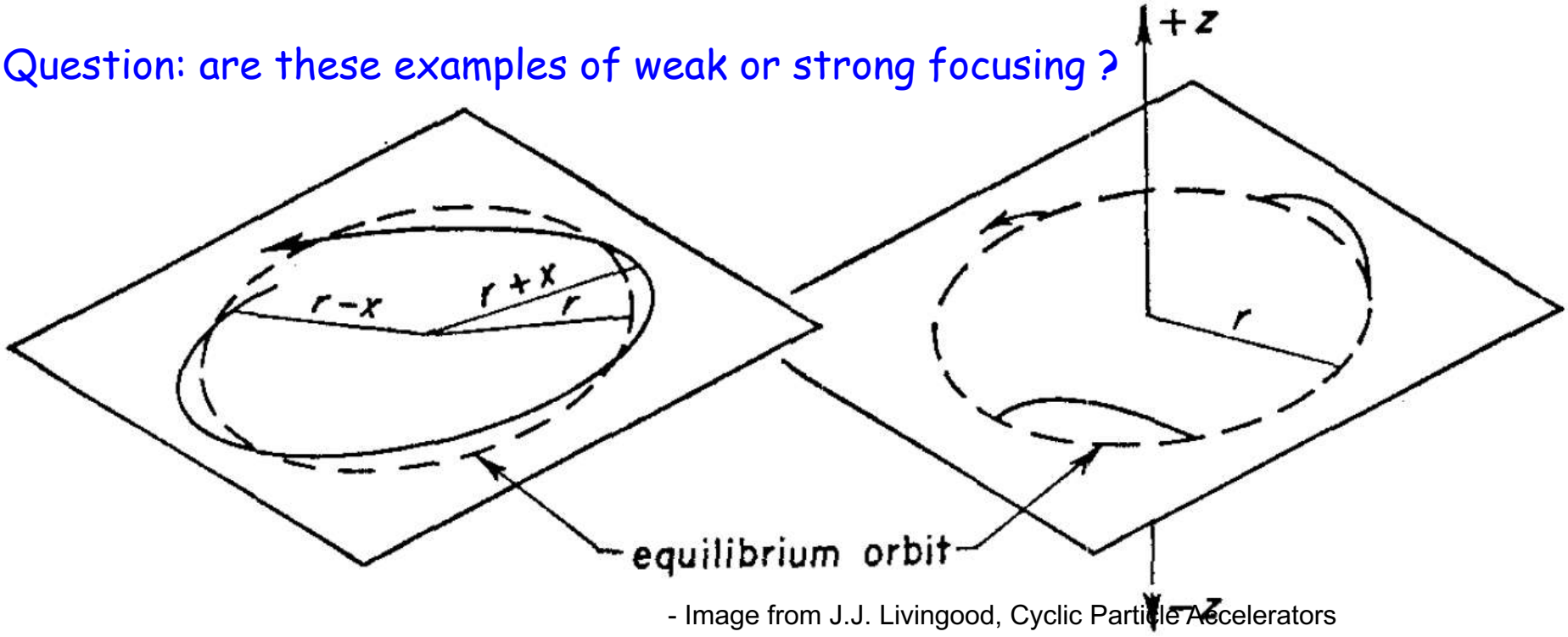
Definition: tune = # oscillations / beam revolution denoted ν_r (radial), ν_z (axial)

$$\nu_z = \frac{\omega_z}{\omega} \quad \nu_r = \frac{\omega_r}{\omega}$$

Definition: Weak Focusing = $\nu < 1$

Definition: Strong Focusing = $\nu > 1$

Question: are these examples of weak or strong focusing ?



- Image from J.J. Livingood, Cyclic Particle Accelerators

WEAK FOCUSING

Intentionally introduce radial B-field component to provide axial (vertical) stability:

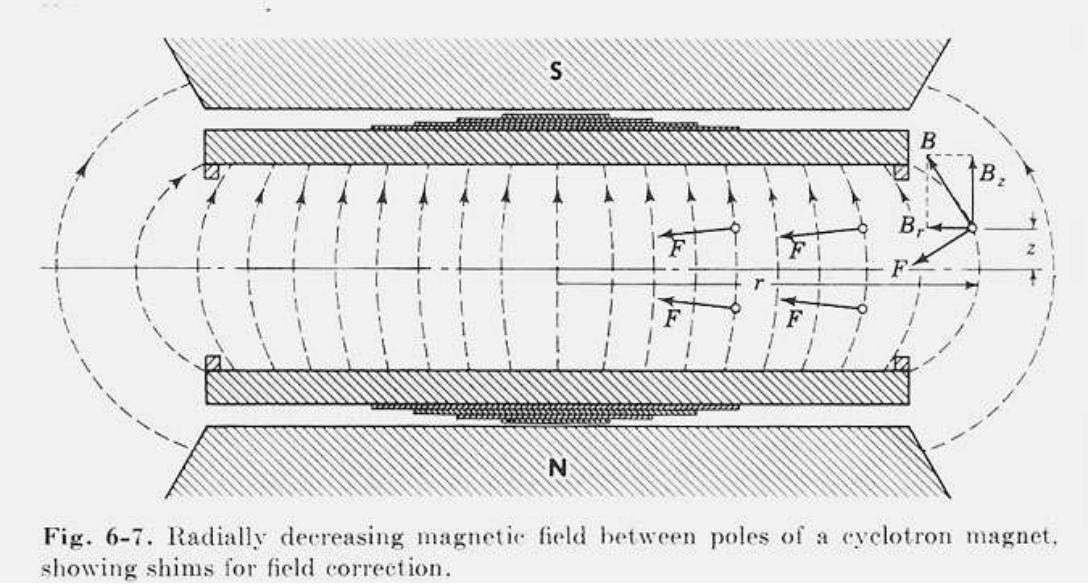


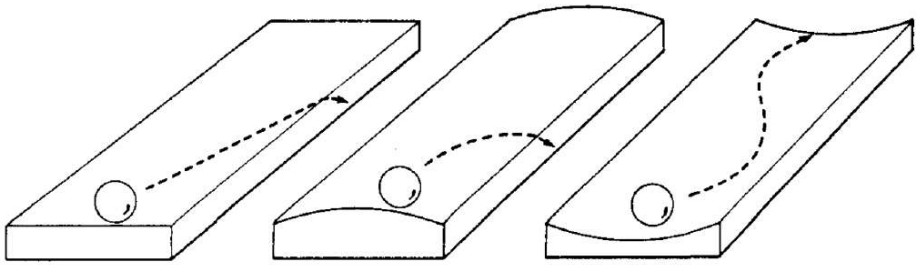
Fig. 6-7. Radially decreasing magnetic field between poles of a cyclotron magnet, showing shims for field correction.

The field index:

$$n = -\frac{r}{B}\frac{dB}{dr}$$

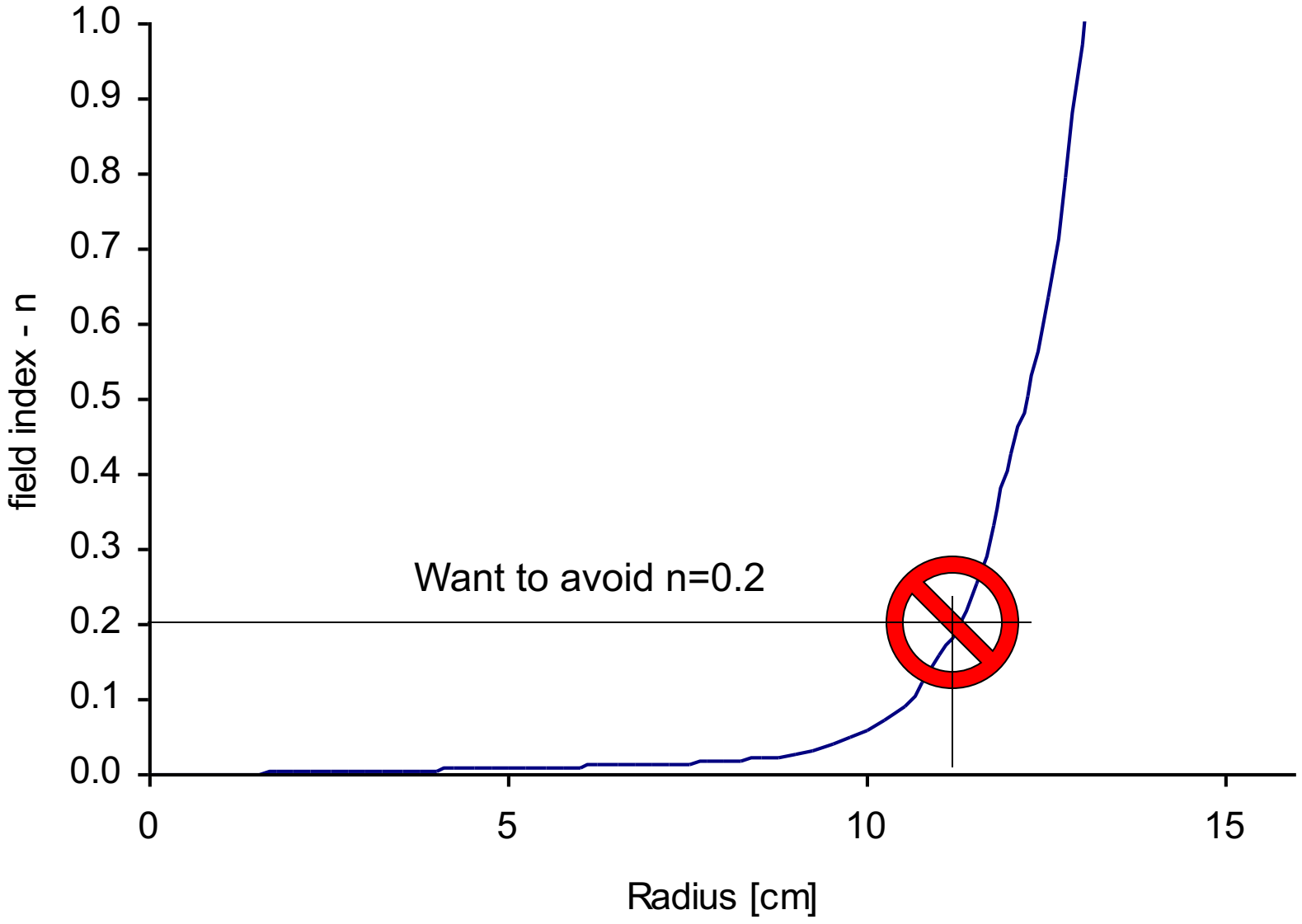
There are three possible cases:

1. $n < 0$ the field increases with r
2. $n = 0$ the field is uniform
3. $n > 0$ the field decreases with r



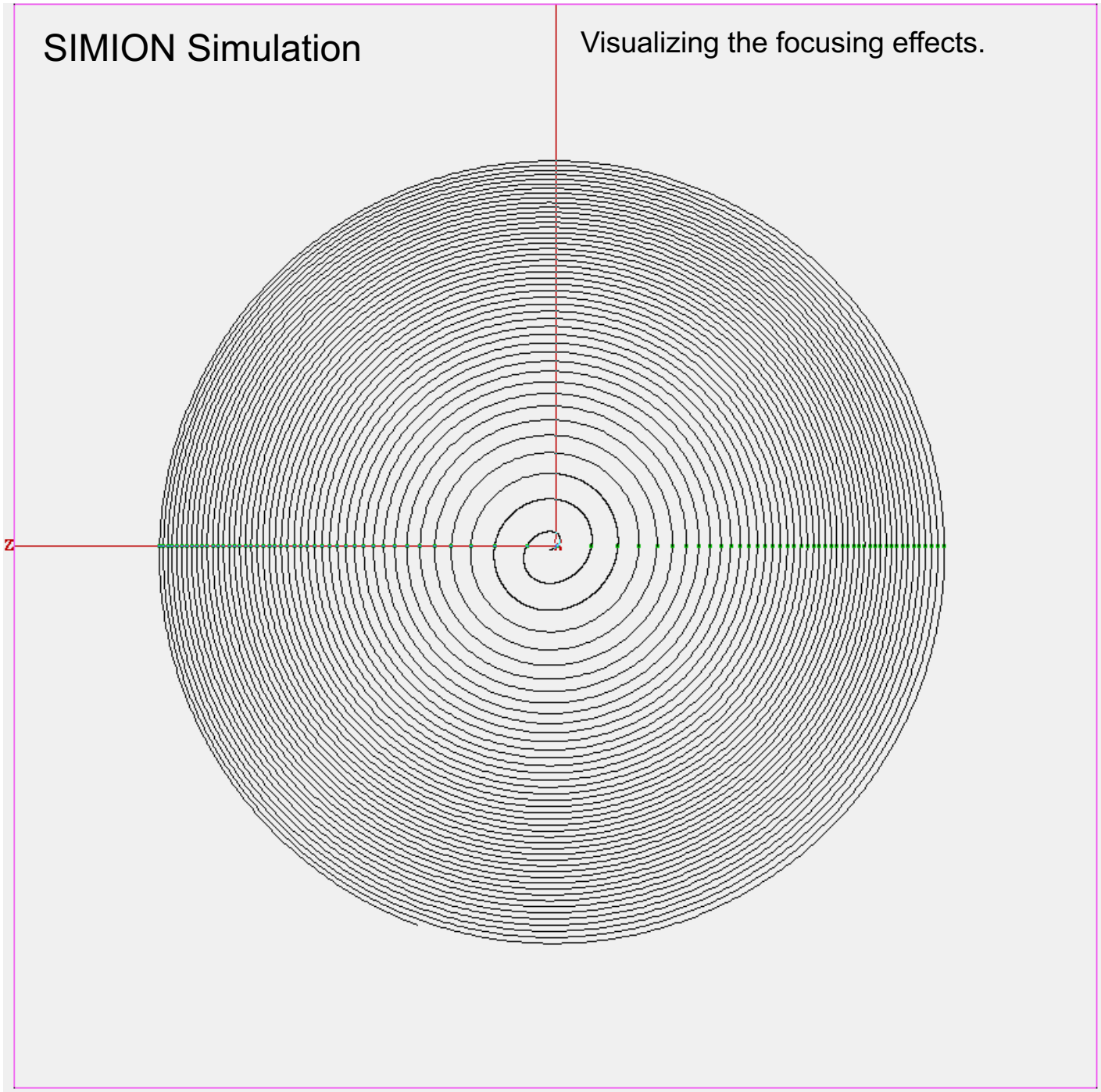
$n = 0$ $n < 0$ $n > 0$

Example Weak Focusing Field Index Profile



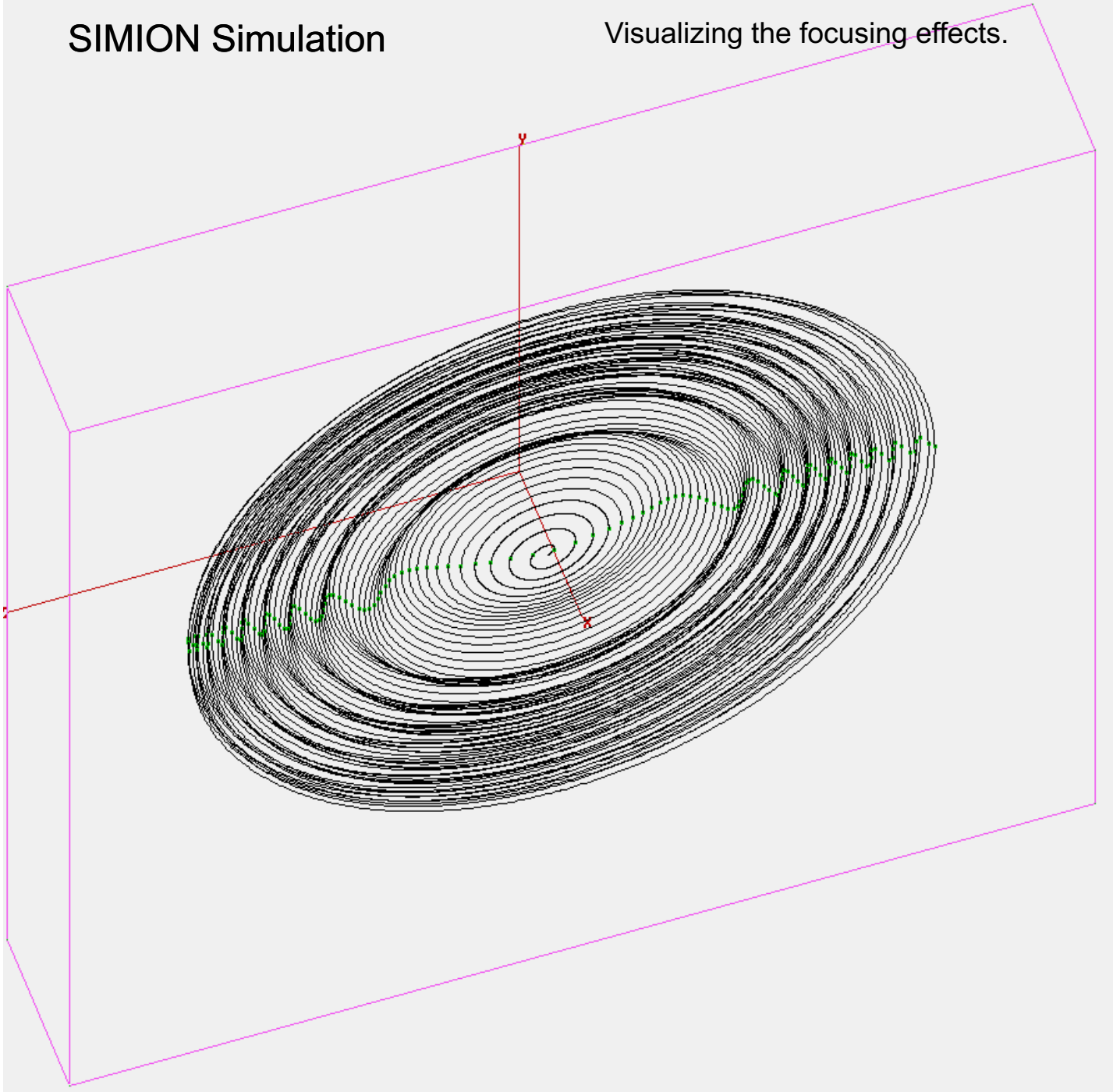
SIMION Simulation

Visualizing the focusing effects.



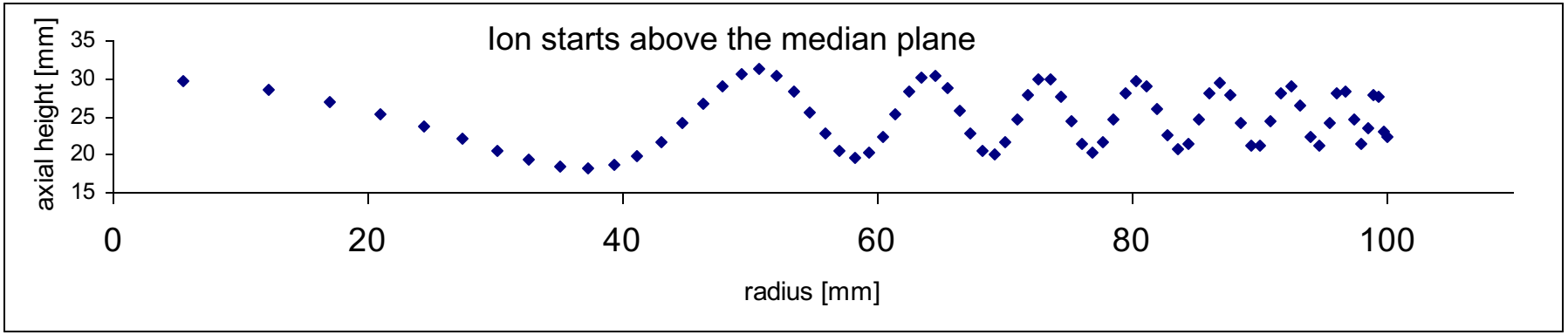
SIMION Simulation

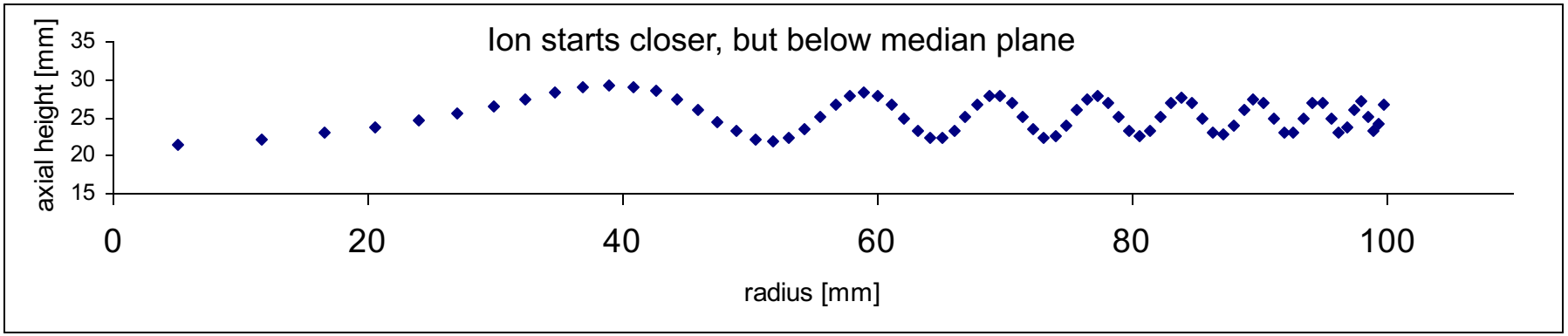
Visualizing the focusing effects.

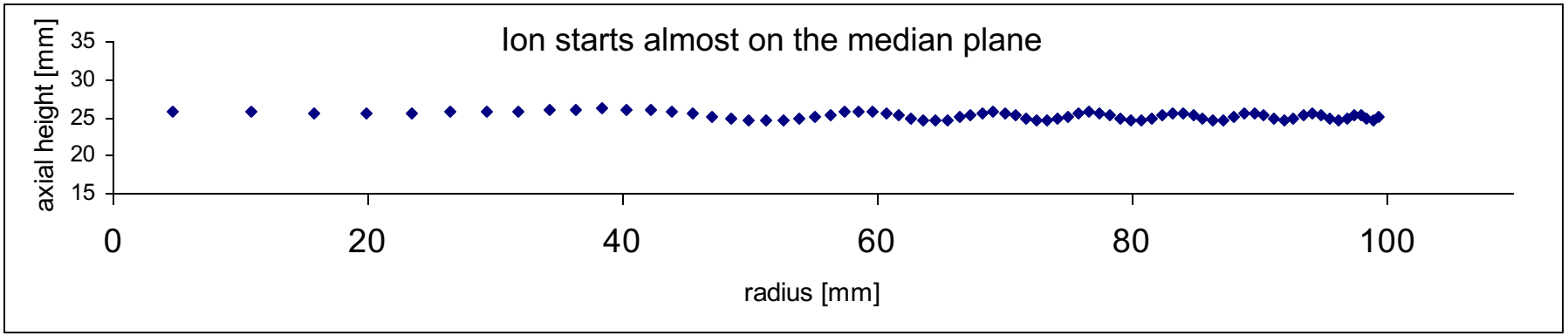


SIMION Simulation

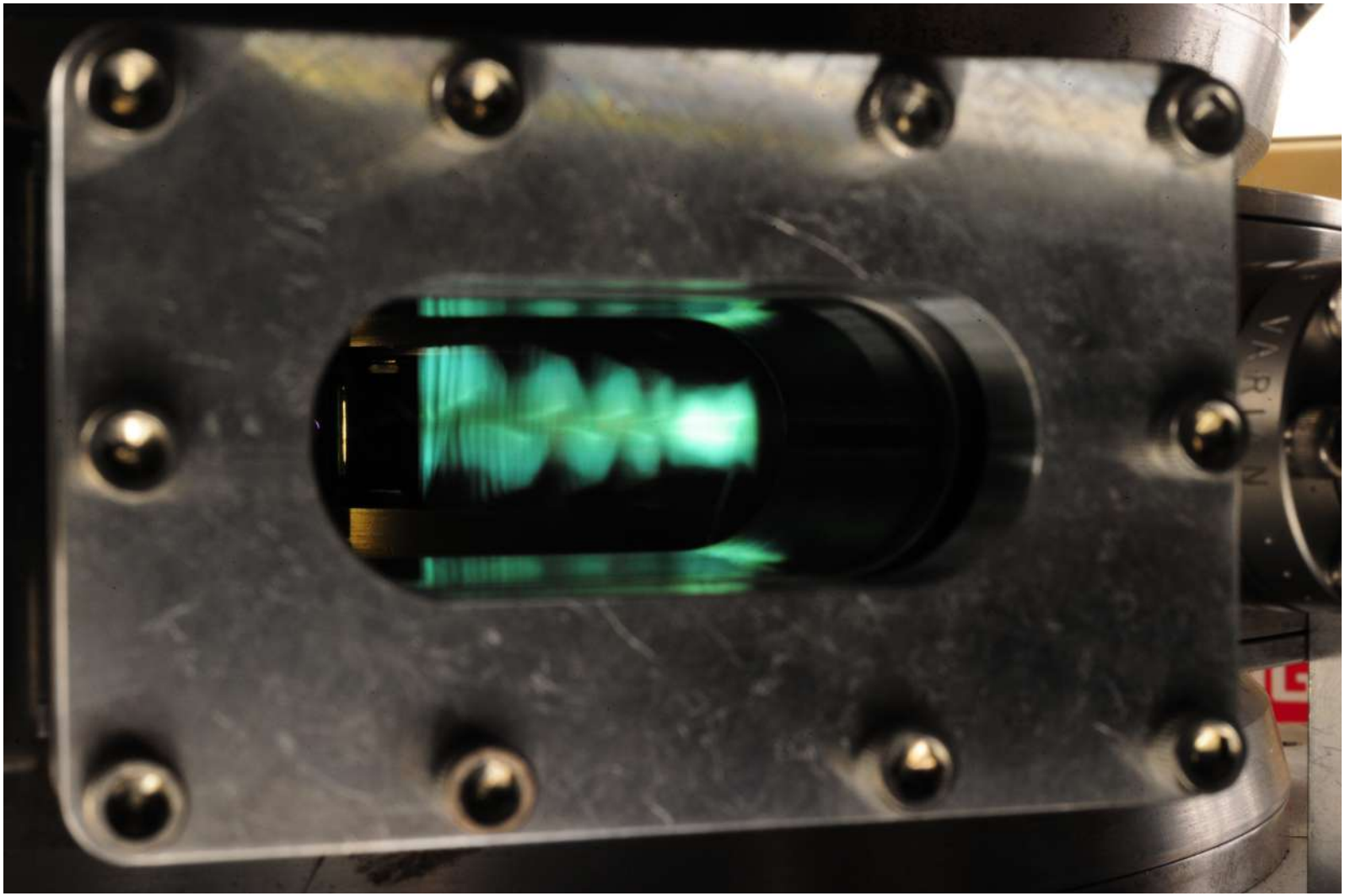
Three Examples visualizing the focusing effects.







My Cyclotron now at UMD



Opportunity for UMD to have biggest educational Cyclotron

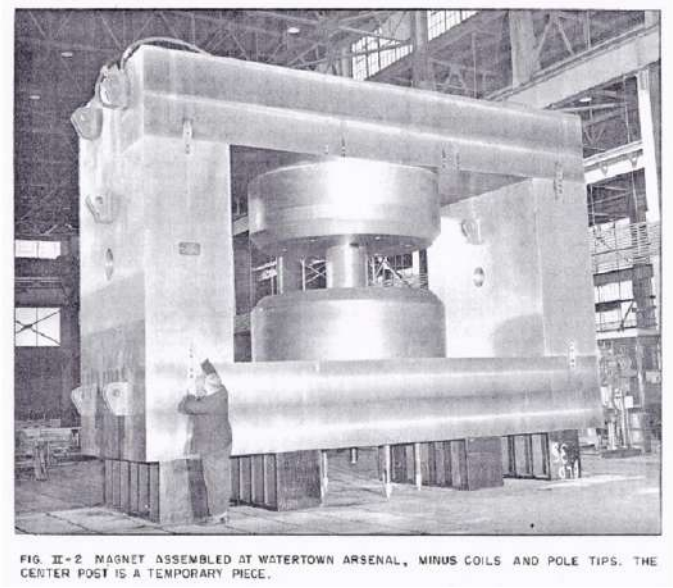
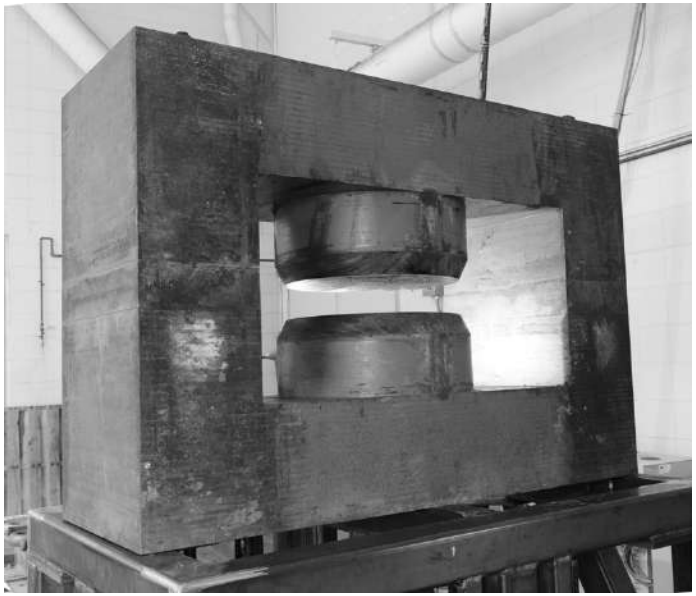


FIG. II-2 MAGNET ASSEMBLED AT WATERTOWN ARSENAL, MINUS COILS AND POLE TIPS. THE CENTER POST IS A TEMPORARY PIECE.



- 19.5” diameter poles
- 1.5 Tesla
- 40 kW
- 12,000 lbs

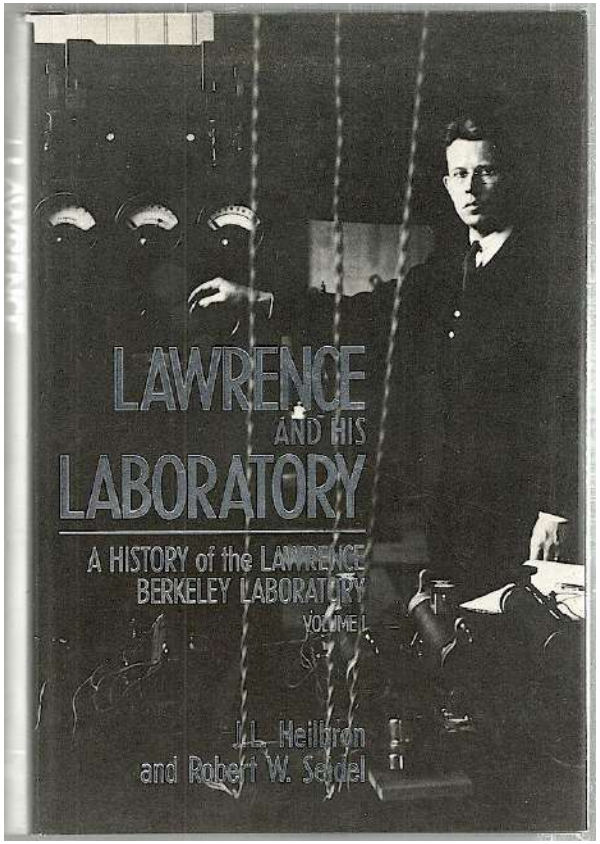
<u>Research Opportunity</u>

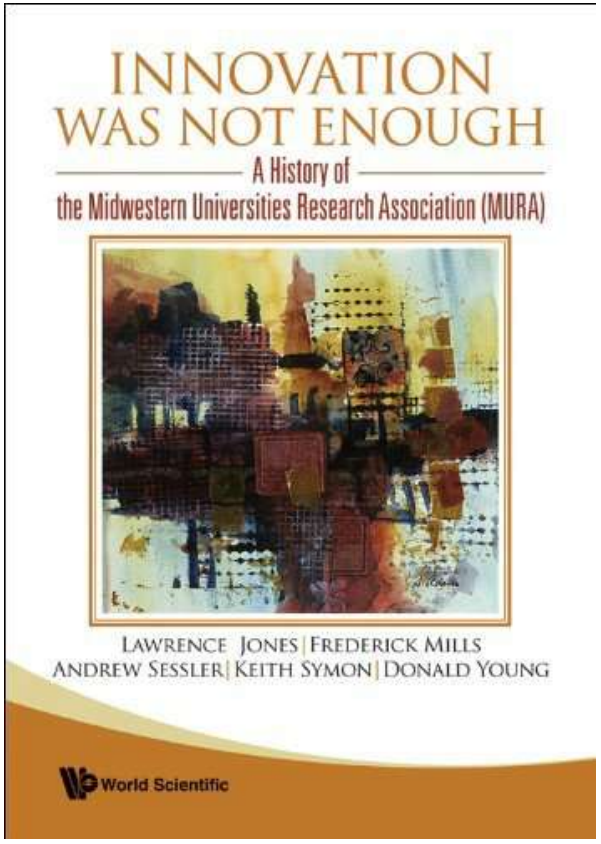
- Extracted beam
- Intensity studies

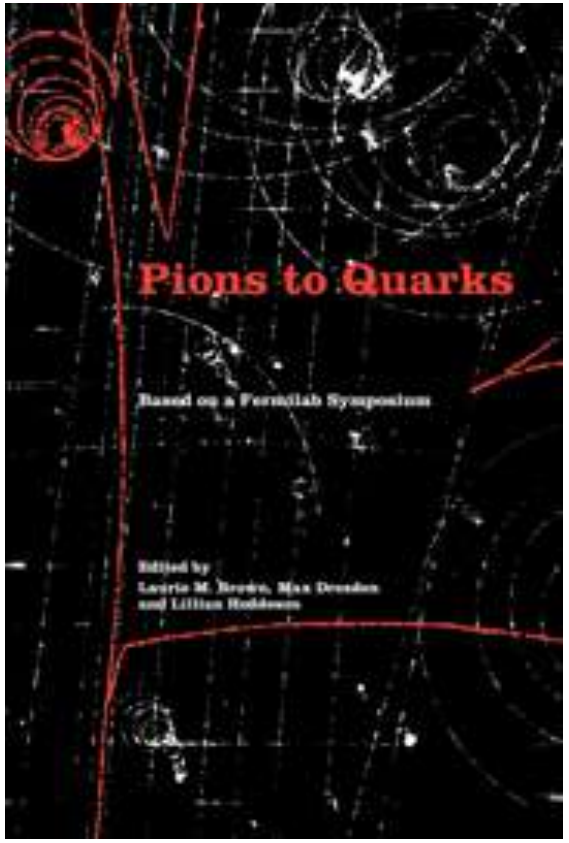
Designing…

- Pole tips [&]
- Chamber
- Pumping system
- RF system
- Control System

Further Reading







Further Viewing

Mightiest Atom Smasher
https://www.youtube.com/watch?v=2BbWbsMSGRc

EOL demonstrates the cyclotron:
https://www.youtube.com/watch?v=cutKuFxeXmQ

EOL talks about the evolution of the cyclotron
https://www.youtube.com/watch?v=8tJrJ9dSLFg

Impact of Nobel Prize on EOL
https://www.youtube.com/watch?v=9gcz-NULeF0

Atoms Old and New – Life & Times of EOL
https://www.youtube.com/watch?v=zx09bH5XSXY

In the Heart of CERN
https://www.youtube.com/watch?v=wgxpicikNEg

RR Wilson Story (FNAL VMS Archives),
- Un Certain Regard's humaniste de l'age atomique,
- A Life of Courage and Creativity
- Water to the Ropes

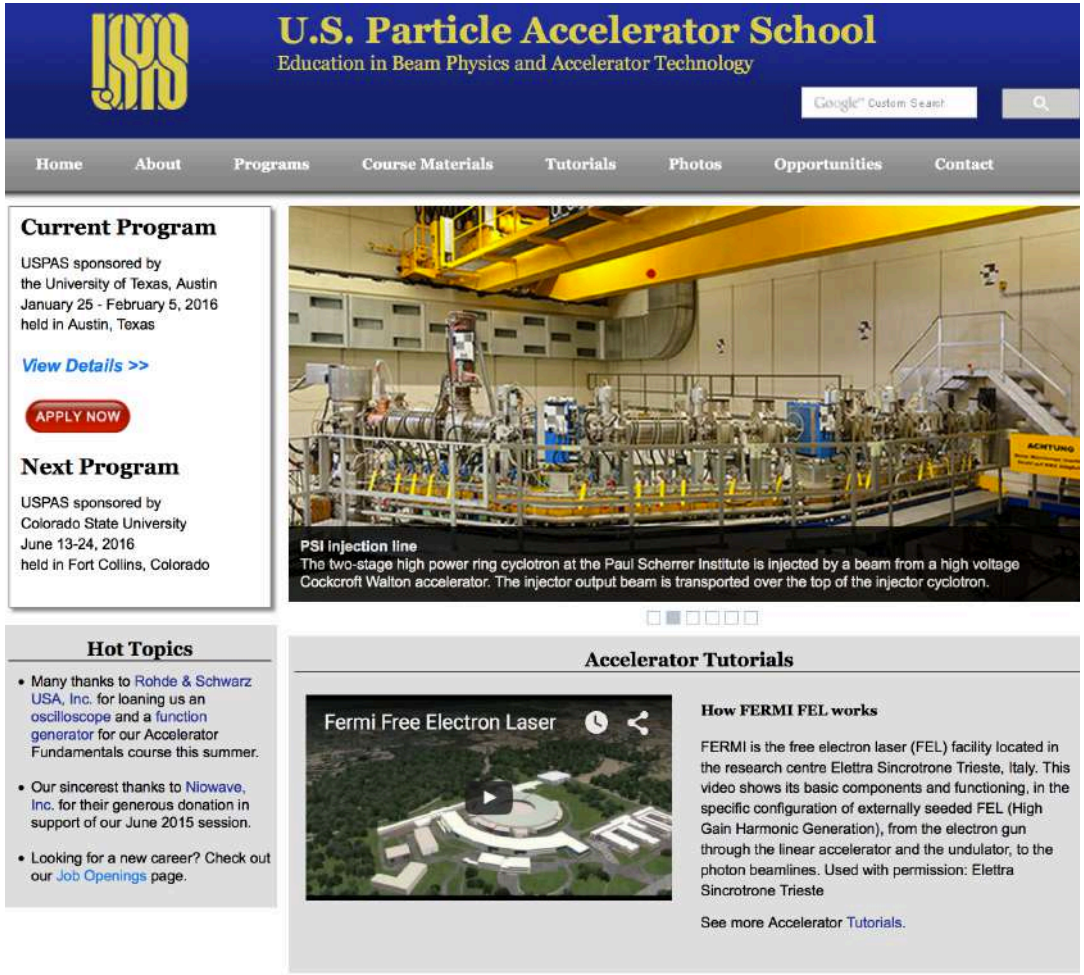
https://vms.fnal.gov/asset/detail?recid=1946874

The Worlds Within – SLAC movie
https://www.youtube.com/watch?v=9I4GxICAcBs&feature=emb_logo

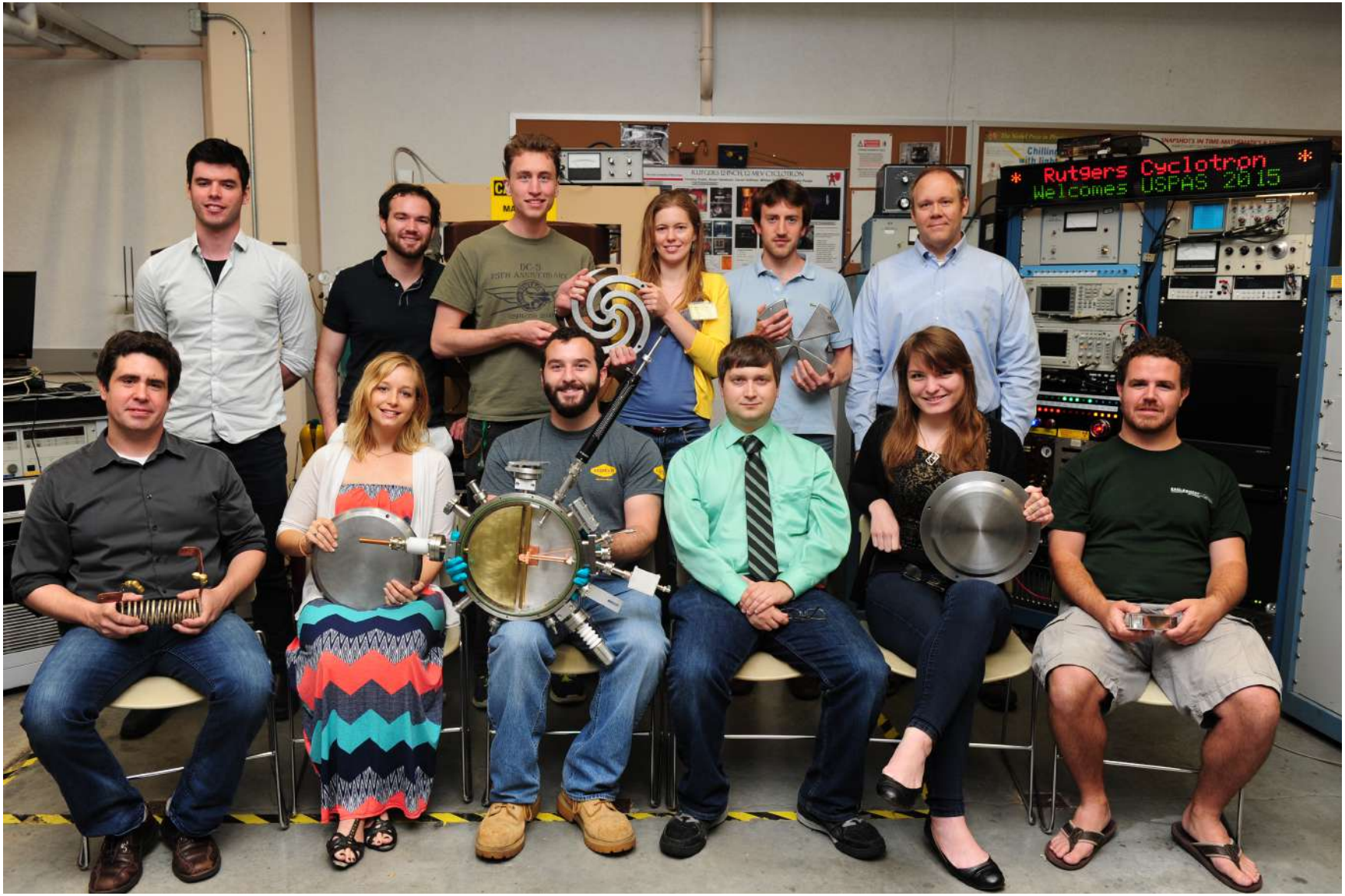
USPAS

Are you interested in Accelerator Physics ?

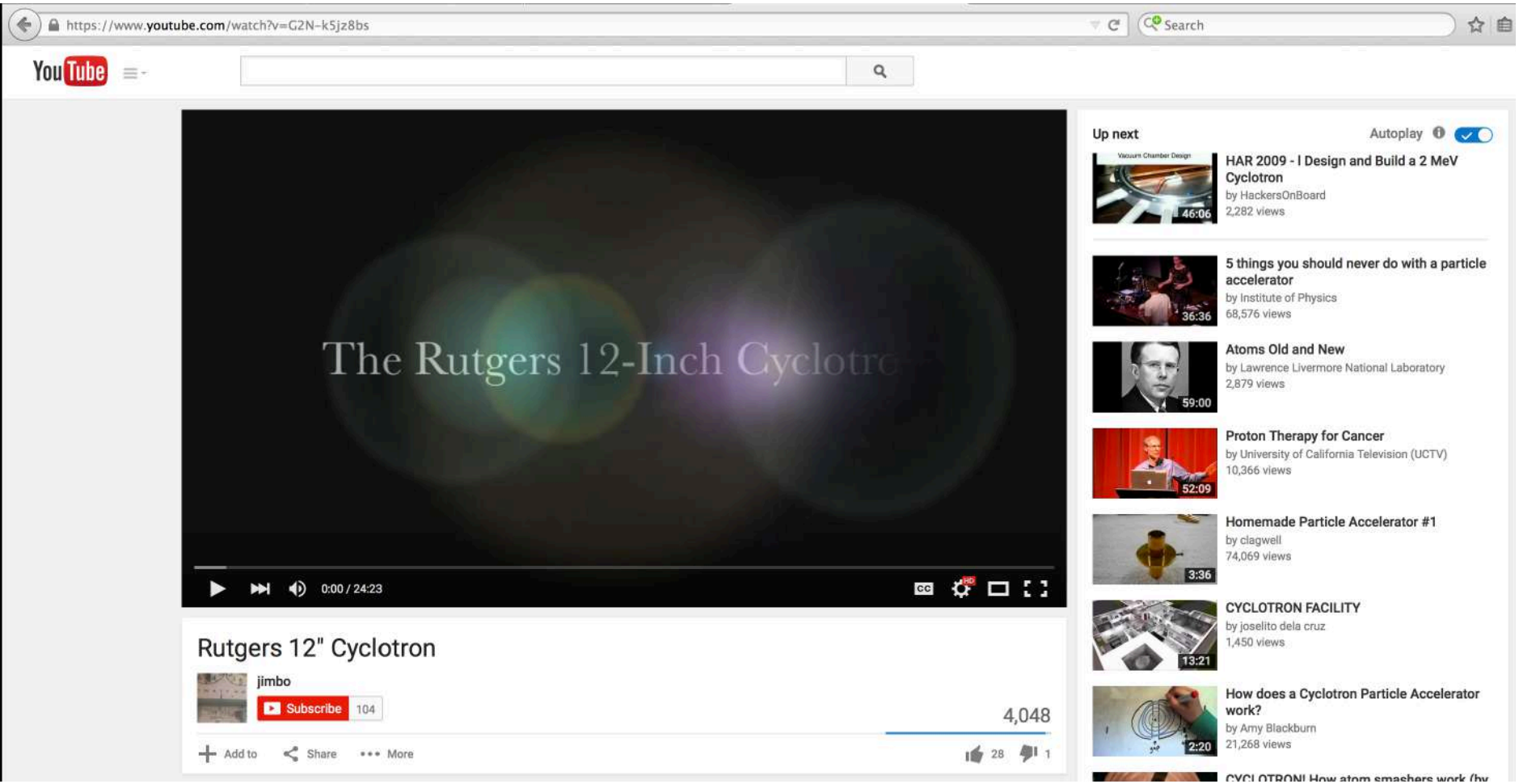
Then go to the United States Particle Accelerator School !



USPAS 2015 SUMMER @ RUTGERS



Take a tour of the Rutgers Cyclotron on YouTube



Take a tour of the Rutgers Cyclotron in Chem Nuke

END