



# History of Accelerators

CERN Introductory Accelerator School  
Geneva, 2021

Dr. Suzie Sheehy

Senior Lecturer, University of Melbourne

Royal Society University Research Fellow, University of Oxford

# Outline

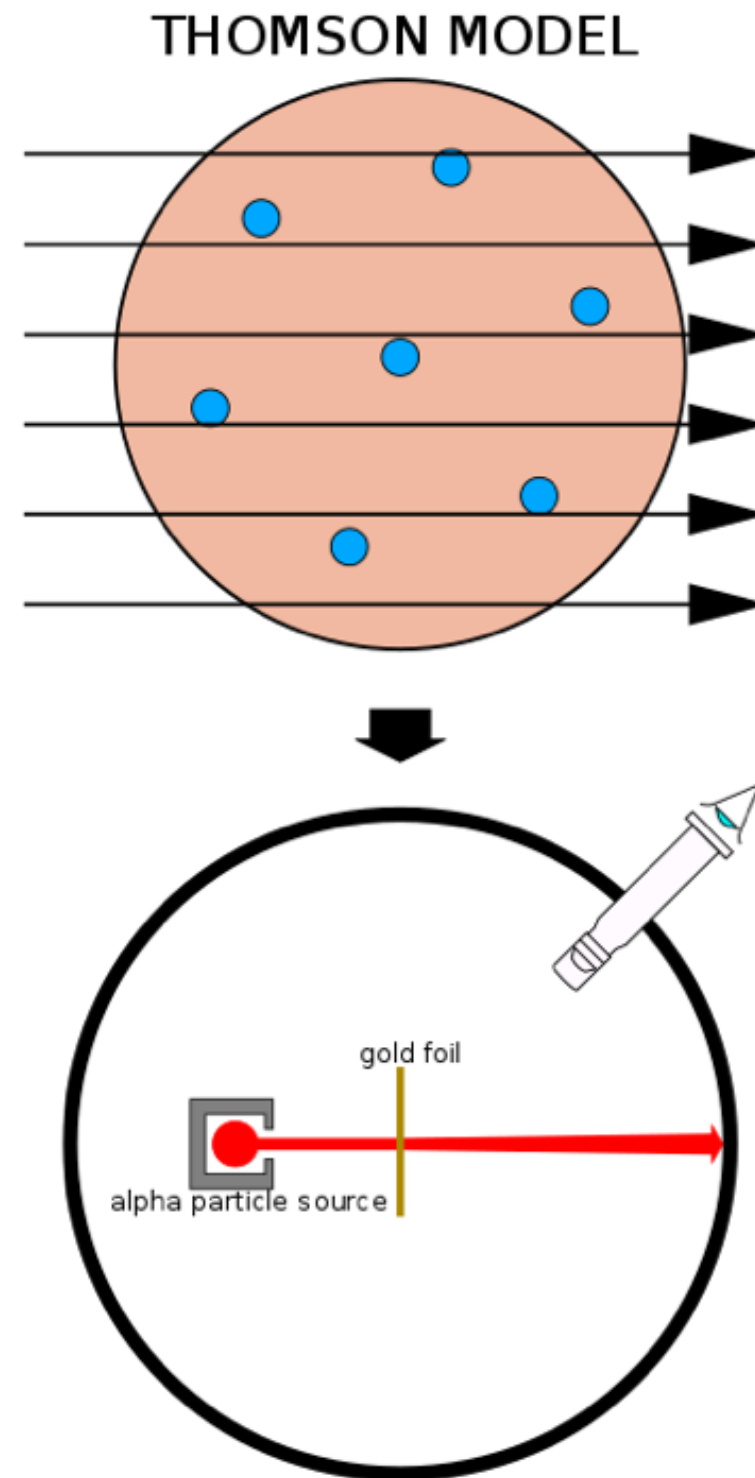
- **The scientific case for particle accelerators**
- **The early days: the first accelerators up to 1930s**
  - Electrostatic accelerators, Cyclotron, early LINACs
- **A creative boom: the 1940s to 1960s**
  - Betatron, Synchrotron, FFAs
- **An established field and powerful tool: 1970s to today**
  - LINACs, superconducting technology, colliders and advances
- **A few loose ends:**
  - The microtron, rhodotron

# **The scientific case for particle accelerators**

# The early 1900's...

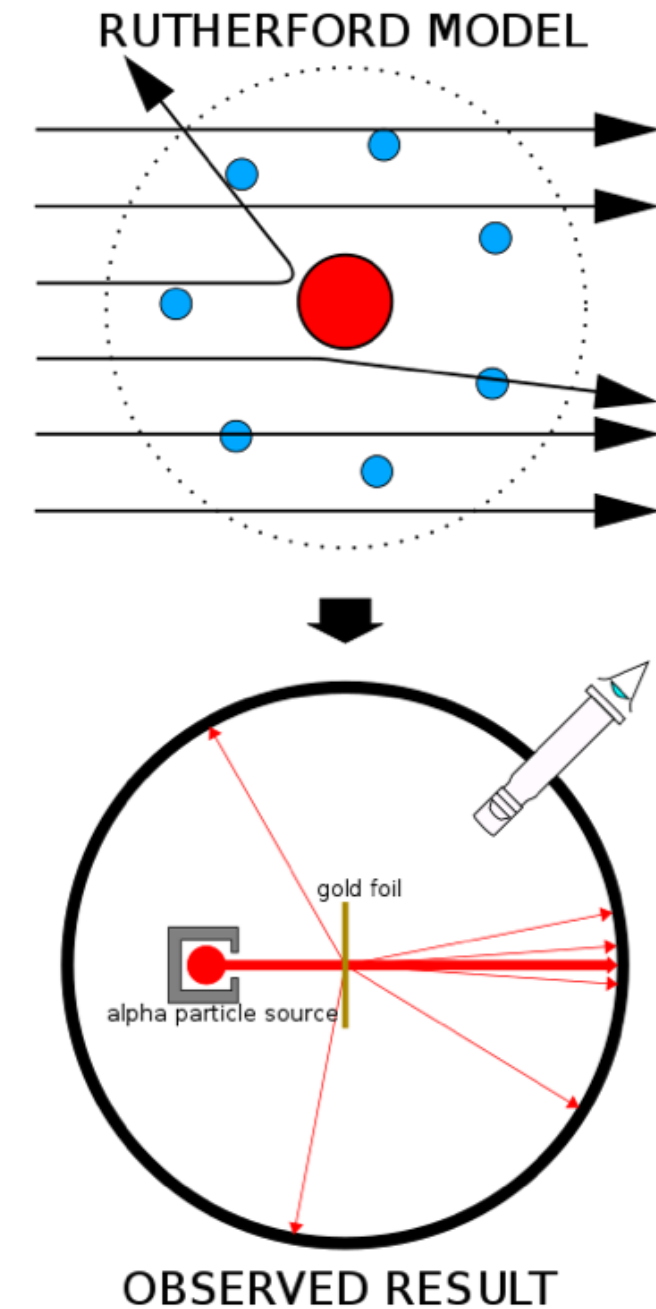
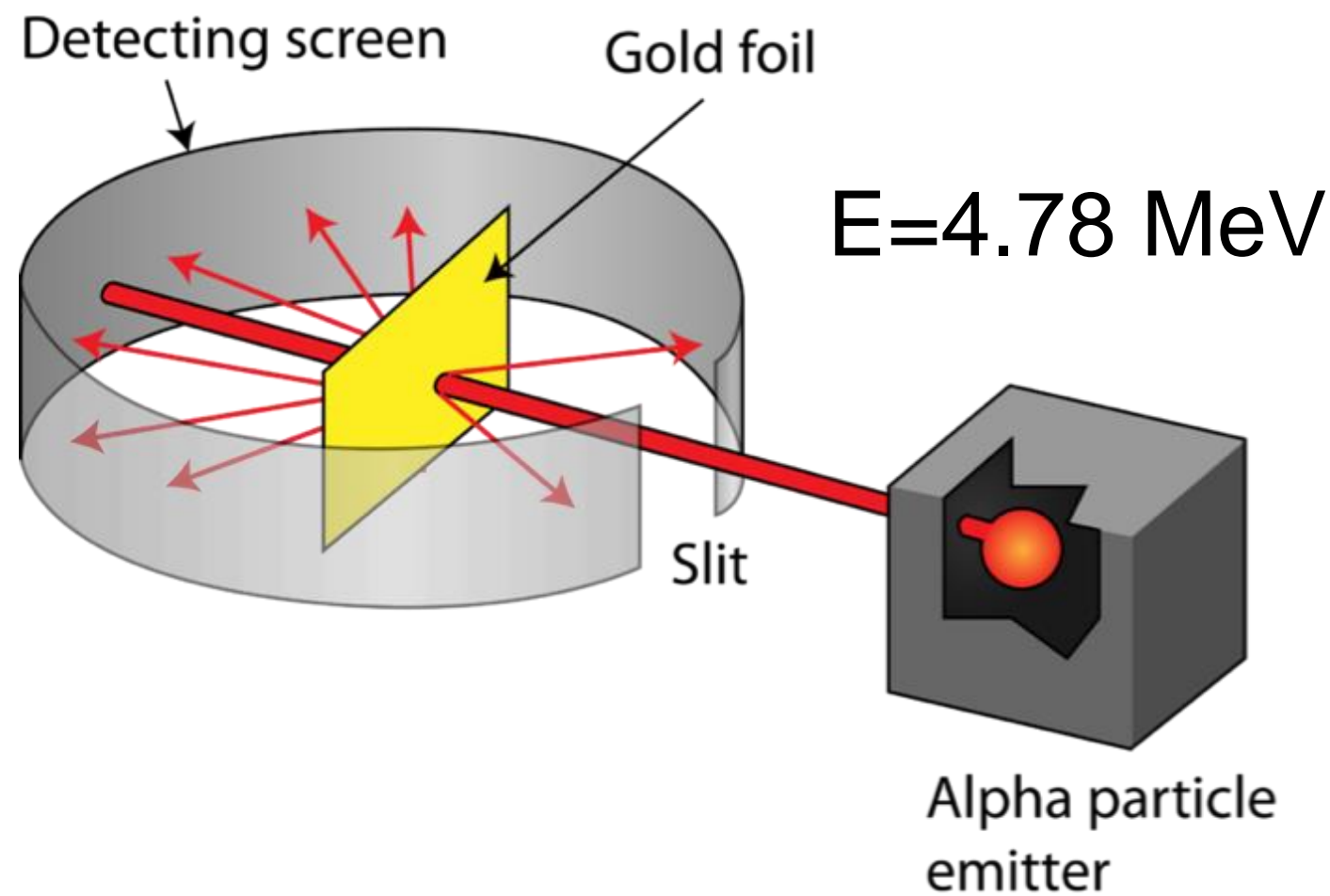


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scientific multimedia



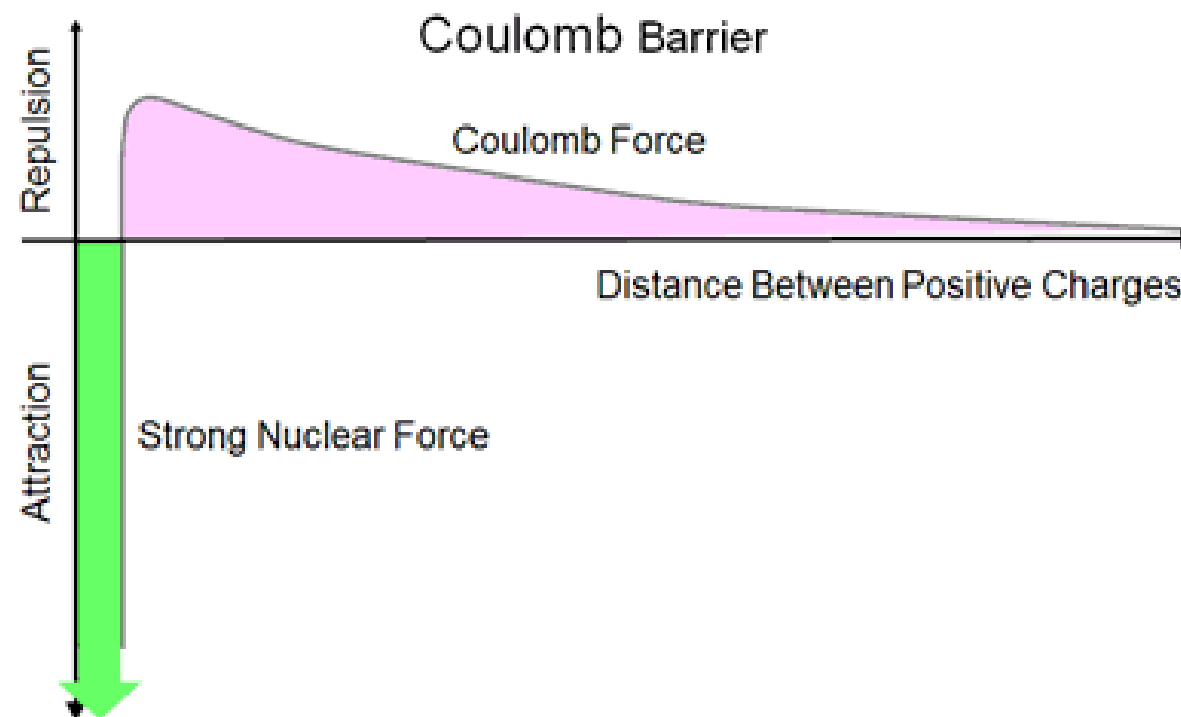
# Rutherford\* gold foil experiment, 1911

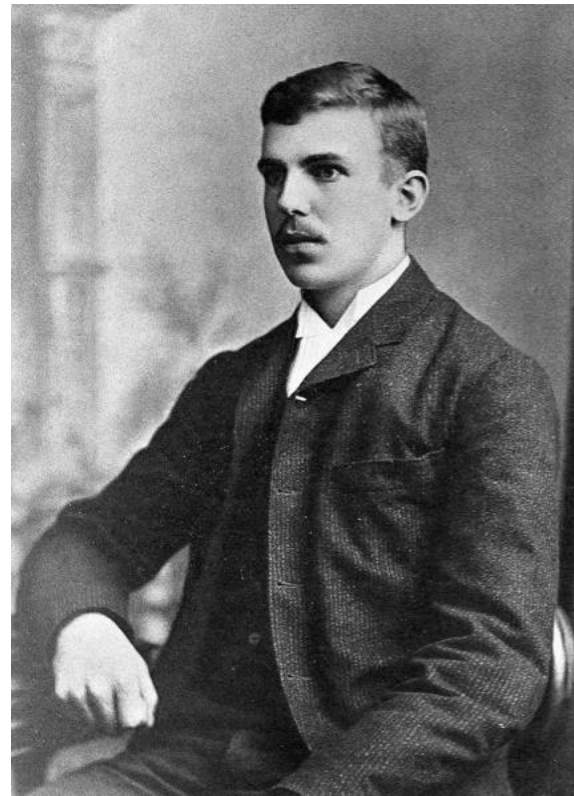
\*Actually Ernest Marsden and Hans Geiger



# What is the nucleus?

- What is inside? (protons/neutrons not known)
- How is it held together?
- Why don't electrons spiral in? (N. Bohr solved this w. QM)





*“it has long been my ambition to have available for study a  
copious supply of atoms and electrons which have an individual  
energy far transcending that of the alpha- and beta-particles from  
radioactive bodies”*

Ernest Rutherford  
Address to the Royal Society, 1927

**The early days: the first  
accelerators up to 1930s**

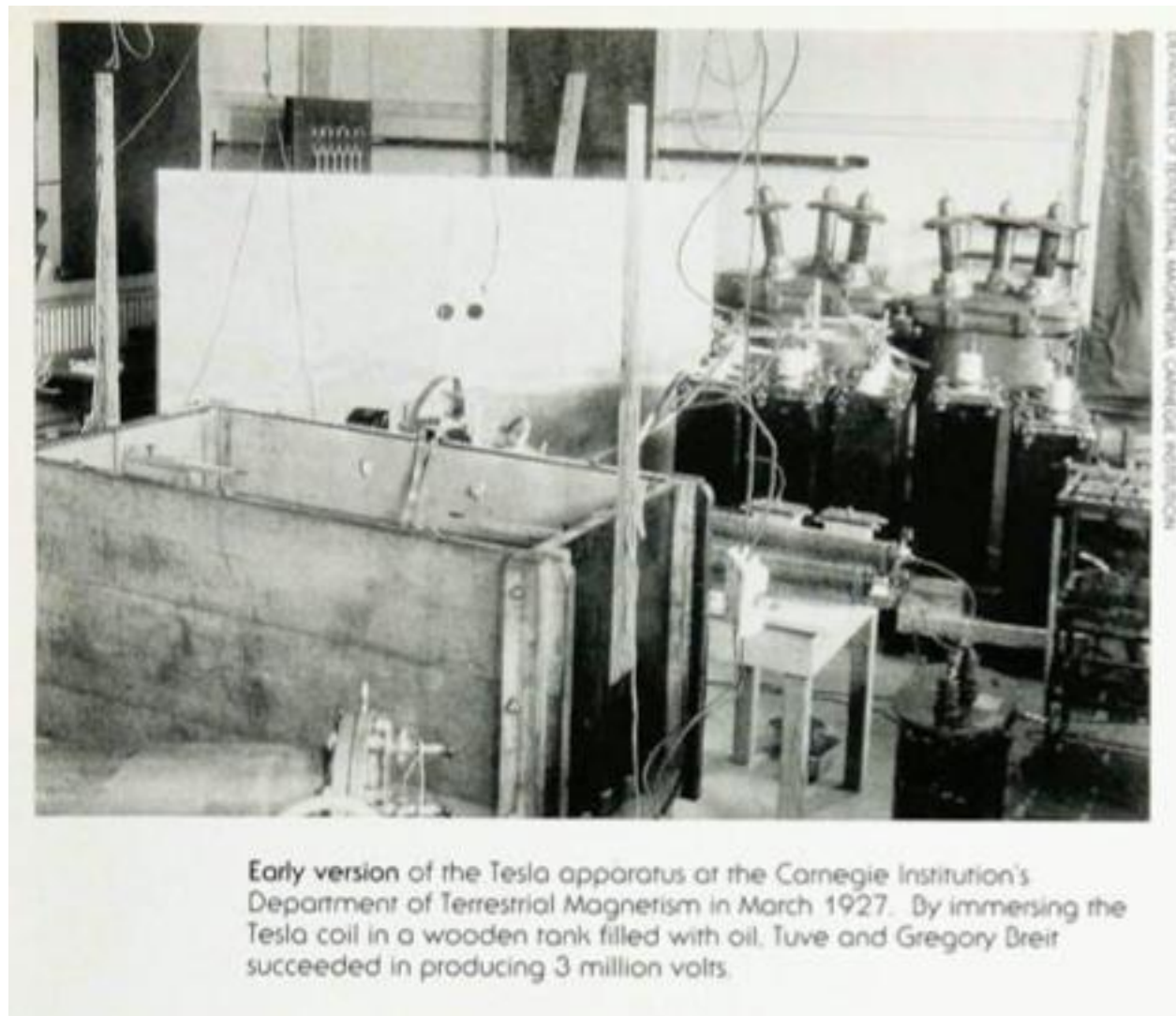


# The 1920's



# Attempts at Electrostatic Accelerators

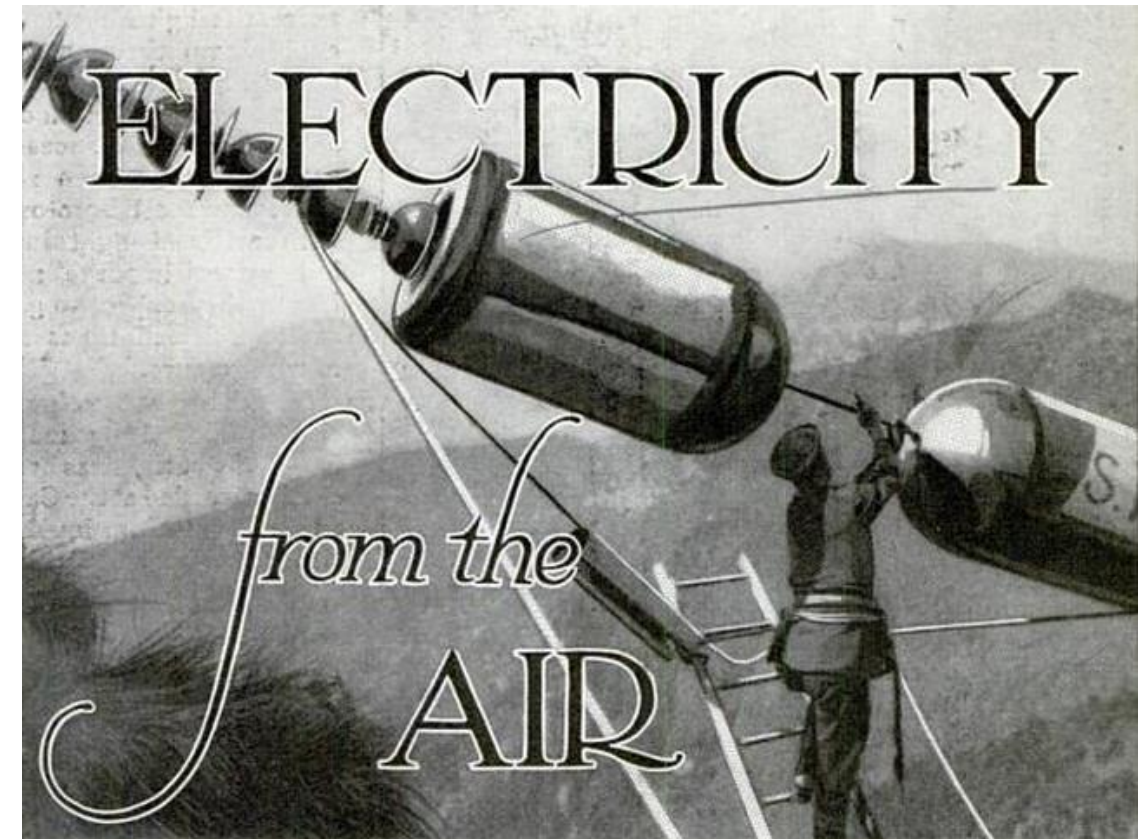
## Tesla Coil



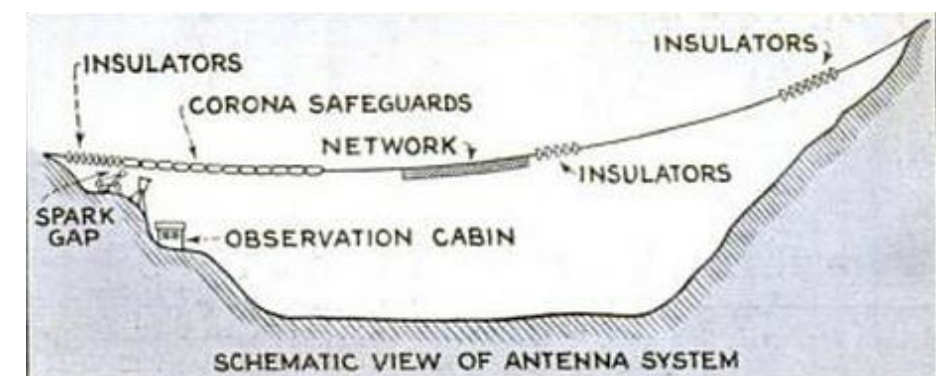
Thomas D. Cornell, Physics Today 41, 1, 57 (1988)

Merle Tuve – Carnegie –  
3MV Tesla Coil. Allibone  
also at Cambridge.

## Lightning



Arno Brasch, Fritz Lange, Kurt  
Urban, in Italian Alps 1927-28



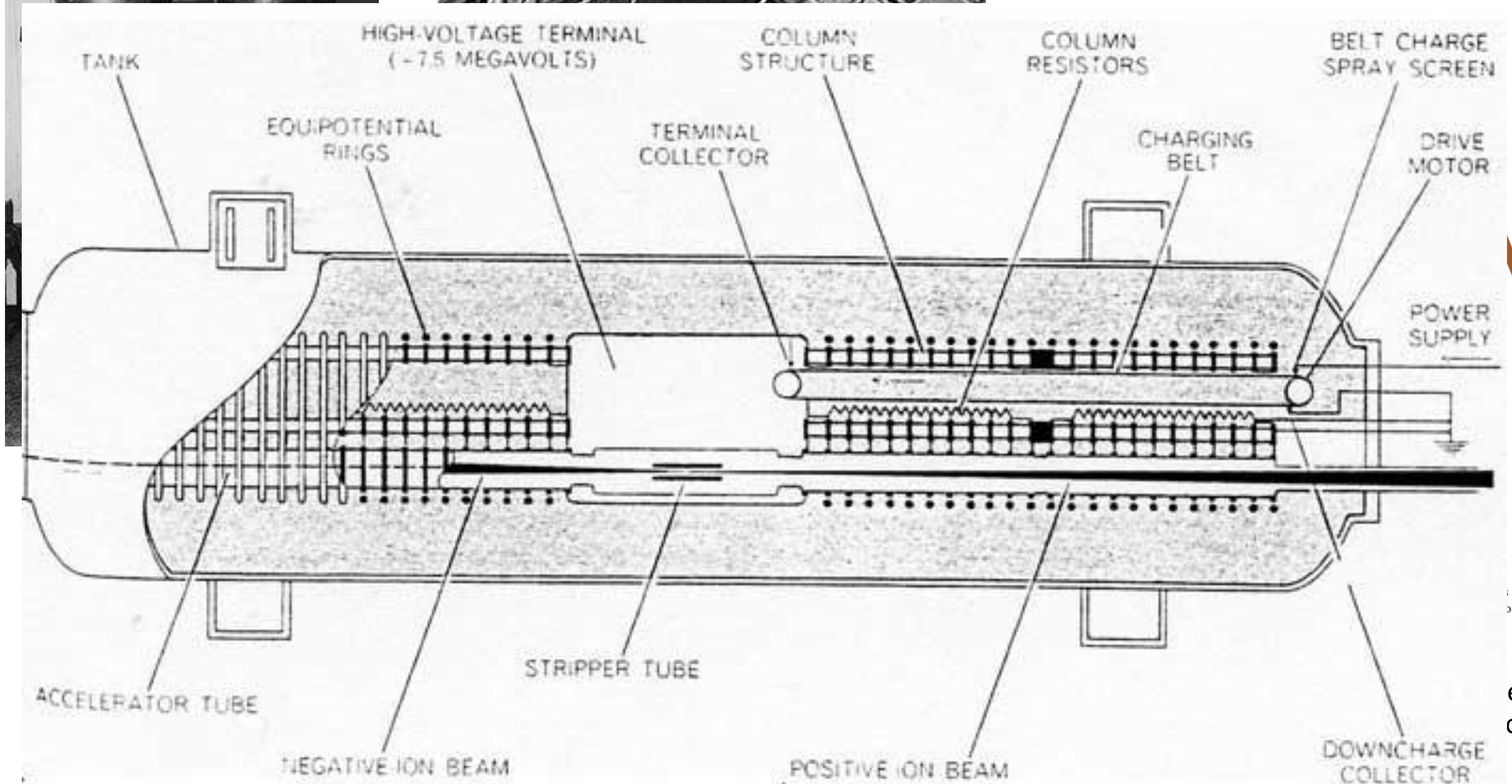
<http://lateralscience.blogspot.com/2012/10/alpine-air-to-produce-30-million-volts.html?m=0>



# Van de Graaff accelerator



## Van de Graaff Generator



<http://chem.ch.huji.ac.il/~eugeniik/history/graff.html>

# Gamow changes the game

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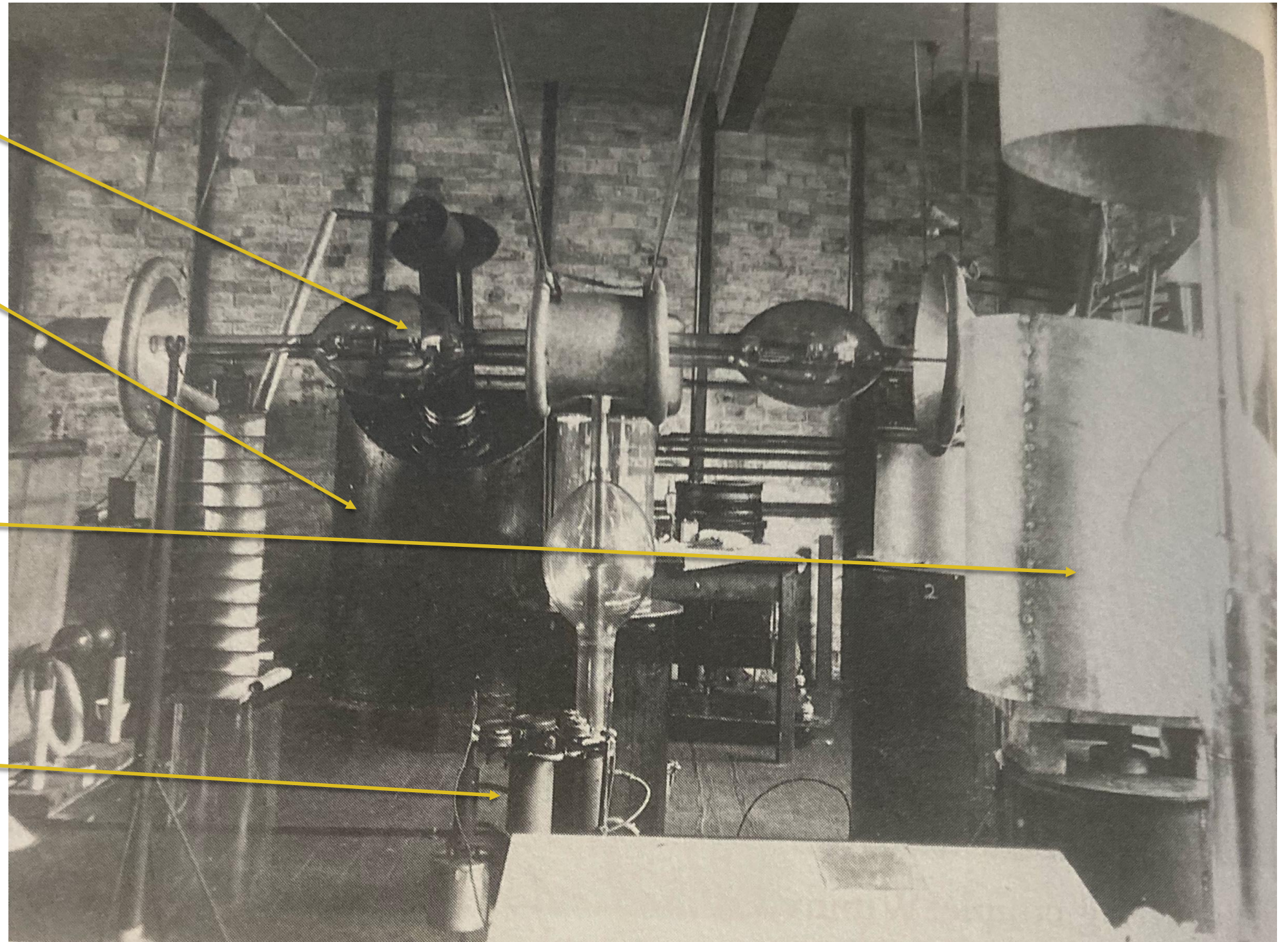
- George Gamow arrives at Cambridge, UK, 1929 armed with two plots
- Predicts  $< 1\text{MeV}$  and as low as  $200\text{ keV}$  sufficient based on quantum tunnelling
- John Cockcroft pushes ahead





# The first accelerator at Cambridge

Rectifier  
Transformer  
Acceleration  
tube  
Burch pump



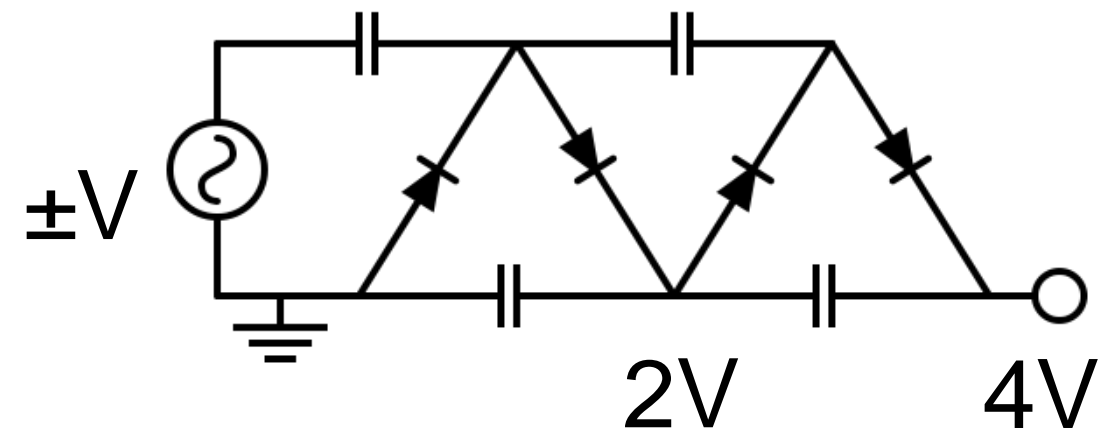


# Cockcroft-Walton accelerator: 1932



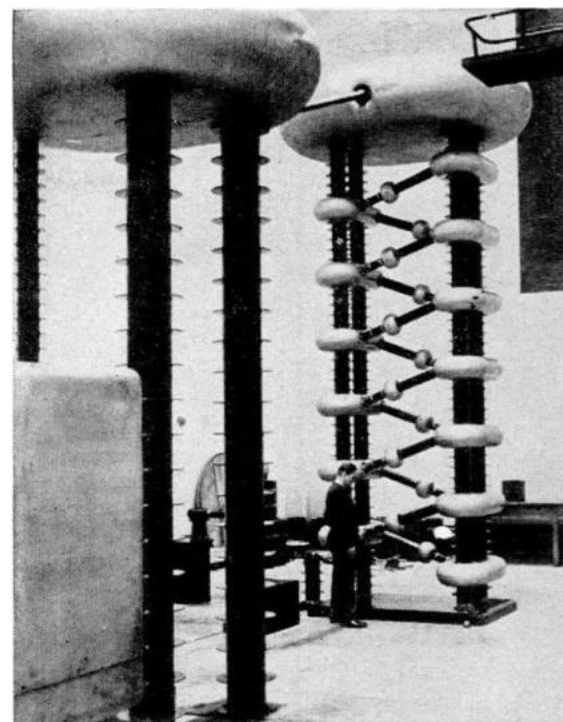
Walton and the machine used to "split the atom"

Cavendish Lab, Cambridge



Voltage multiplier circuit

[https://www.youtube.com/watch?v=ep3D\\_LC2UzU](https://www.youtube.com/watch?v=ep3D_LC2UzU)



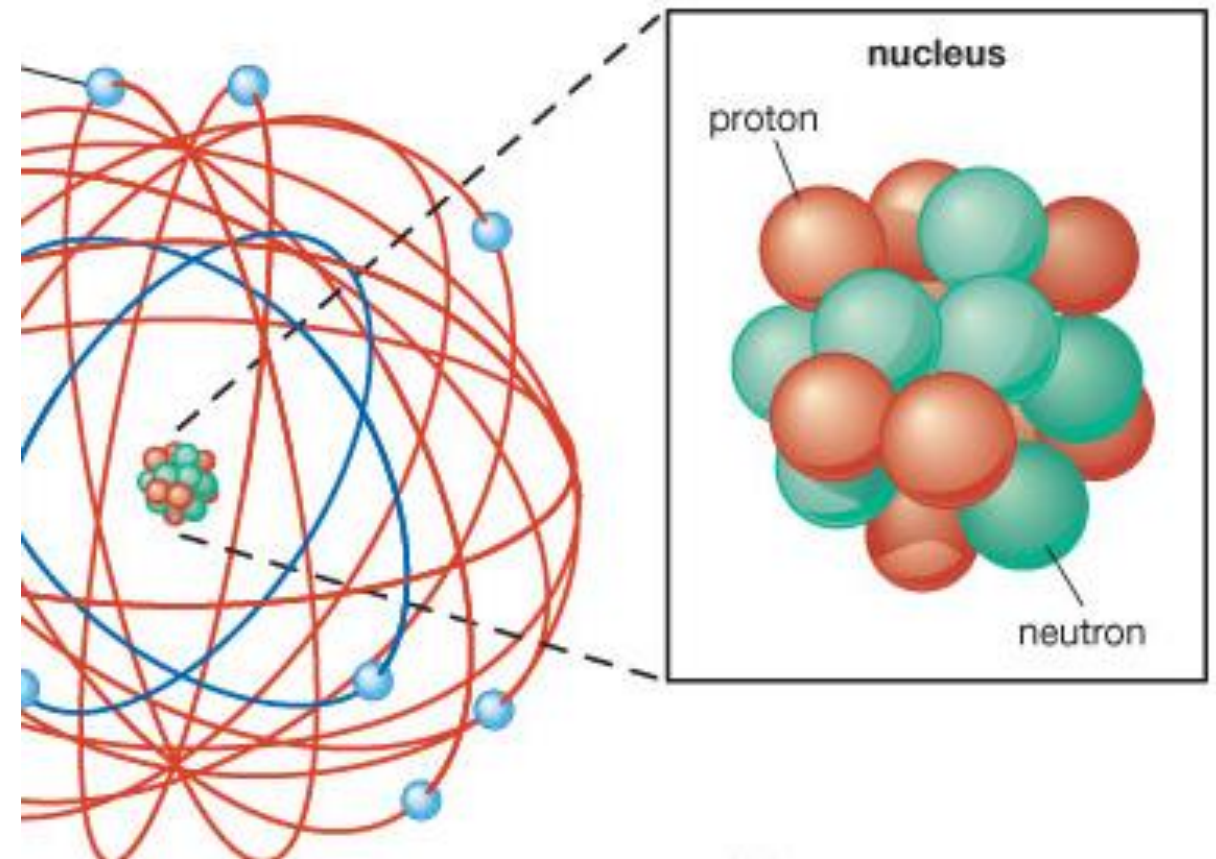
1.2 MV 6 stage Cockcroft-Walton accelerator at Clarendon Lab, Oxford University in 1948.



# Science context



NEW YORK TIMES, May 2, 1932



• Image: <http://ck12.org.uk>

Proton: 1909(?) Rutherford

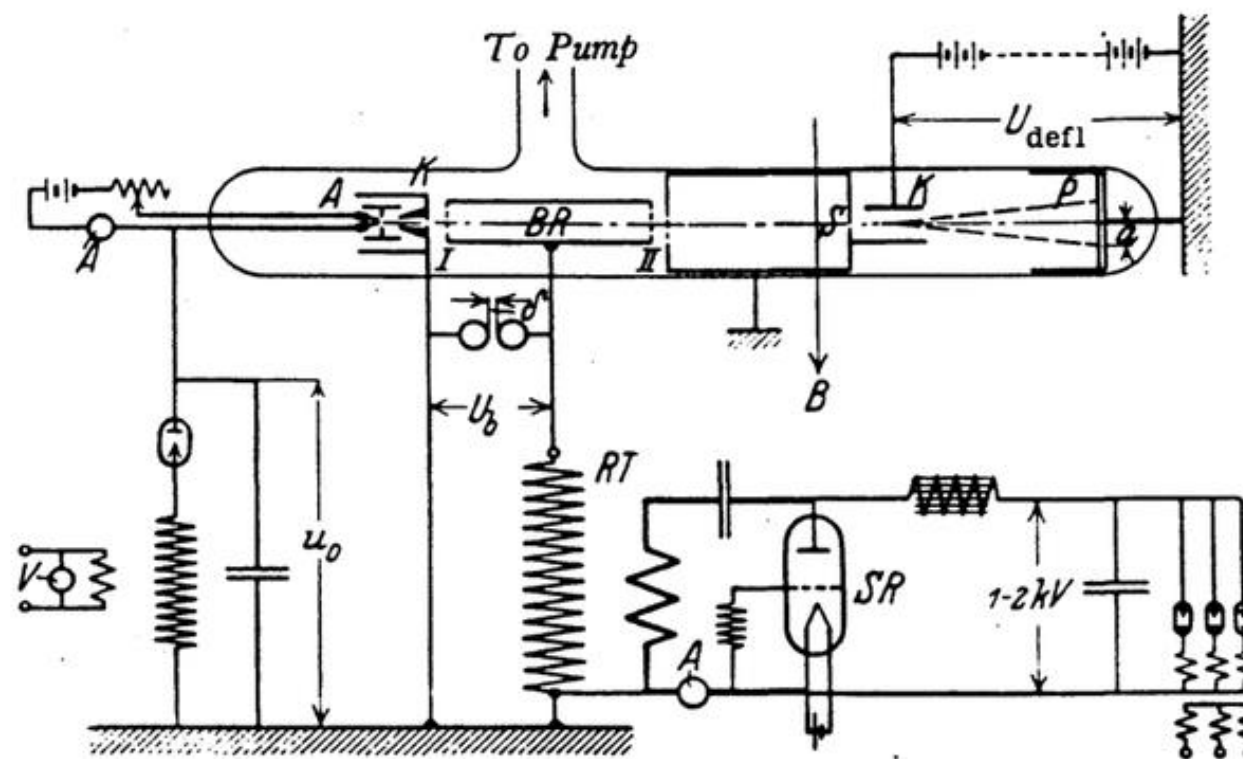
Neutron: 1932, Chadwick

Splitting the atom was  
announced at same meeting!

# We missed one...

## Linear Accelerators (very early)

- Rolf Widerøe, 1924
- His PhD thesis was to realise a single drift tube with 2 gaps. 25kV, 1MHz AC voltage produced a 50keV kinetic energy beam.
- First resonant accelerator (patented)



The linear accelerator & it's AC powering circuit

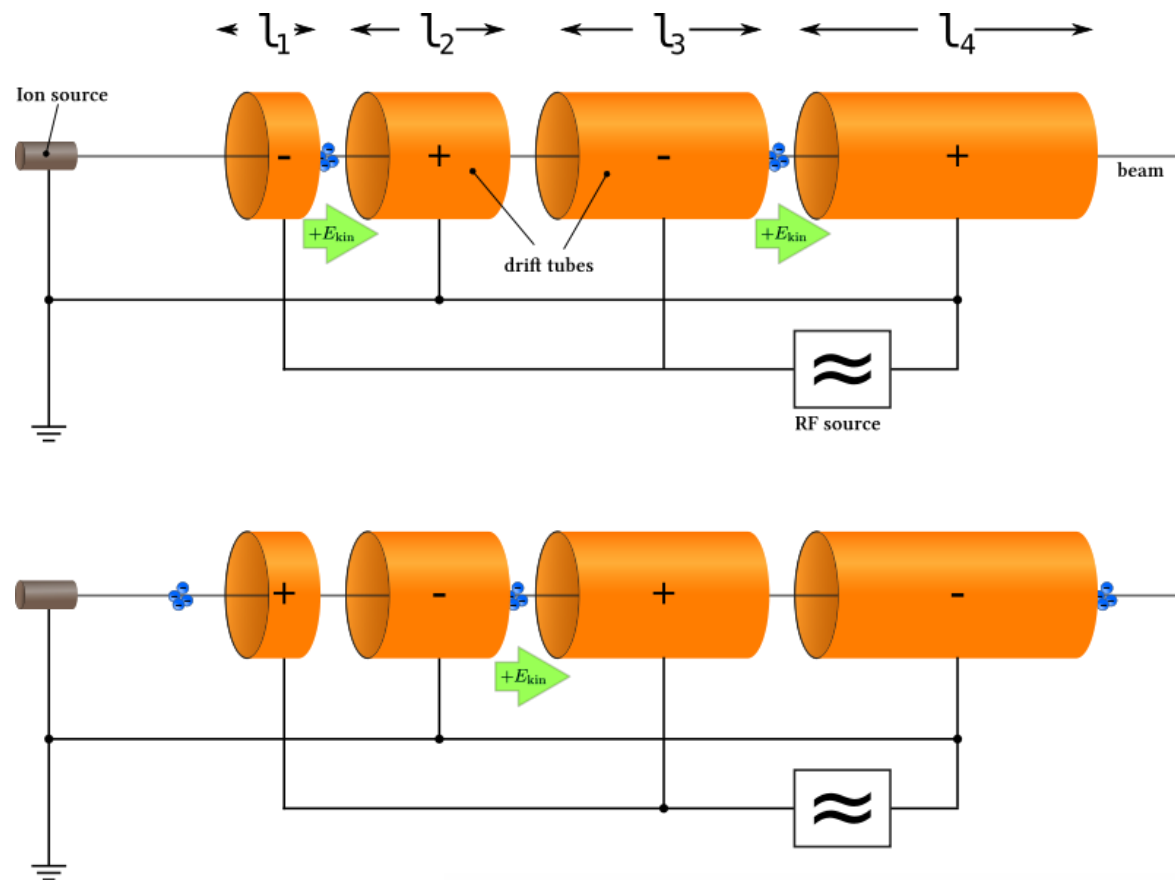
Historical note: He was influenced by Gustav Ising's work, which was never realised in practise as Ising didn't use an AC source.

Ising, Gustav. *Arkiv Fuer Matematik, Astronomi Och Fysik* 18 (4), 1928



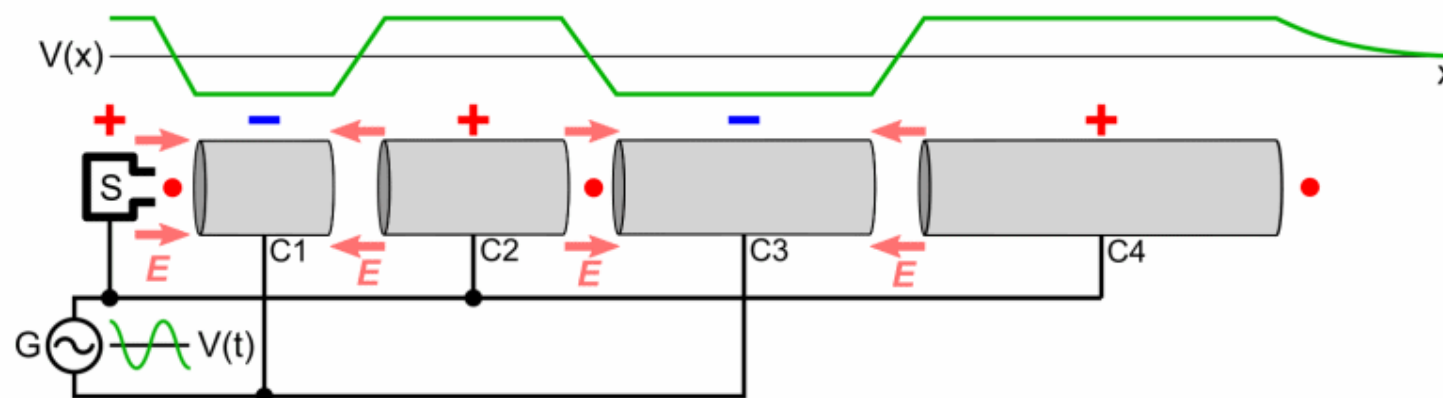
# Linear Accelerators (2/3)

- Remember: there is no field inside a conductor



$$l = \beta \lambda_{rf} / 2 = v / 2 f_{rf}$$

- For high energy, need high frequency RF sources
- Weren't available until after WWII



But Wideroe's idea was not quite an RF cavity, Alvarez introduced that...



Boyhood  
friends...  
Ernest  
Lawrence  
and  
Merle  
Tuve

# Cyclotrons (1)

Centrifugal force = magnetic force

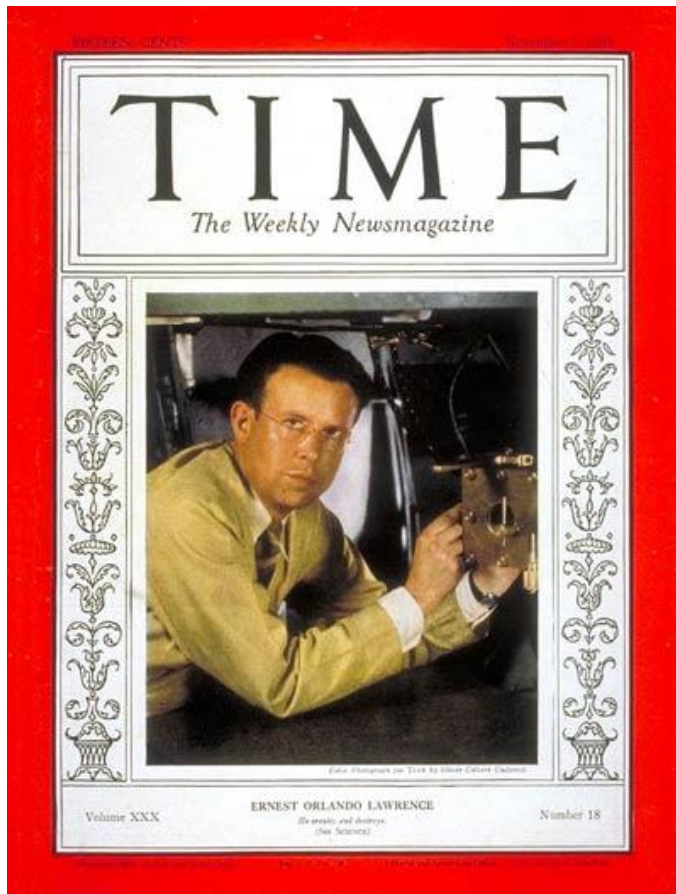
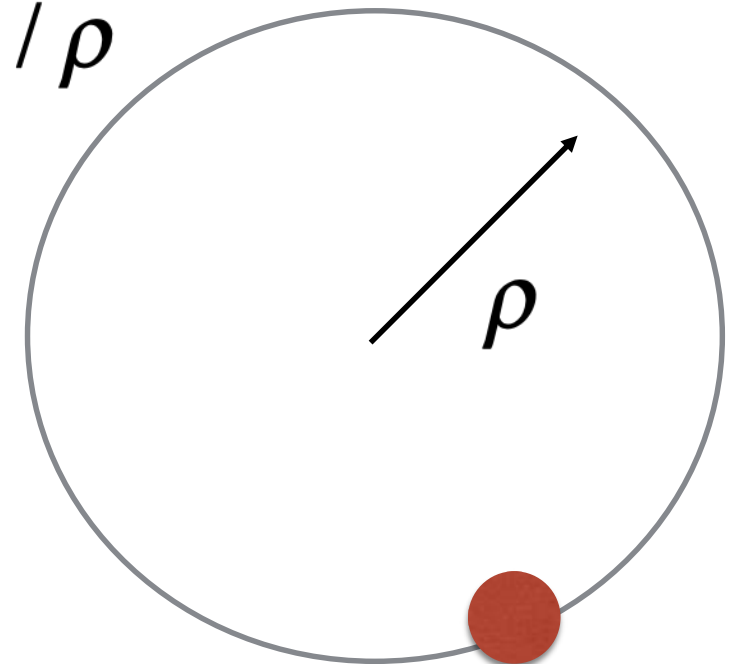
$$\frac{mv_{\theta}^2}{\rho} = qv_{\theta}B_z$$

Revolution frequency  $\omega_0 = v_{\theta} / \rho$

*Lawrence: “R cancels R!”*  
Cancelling out rho gives:

$$\omega_0 = qB_z / m$$

$$\rho = mv / qB_z$$

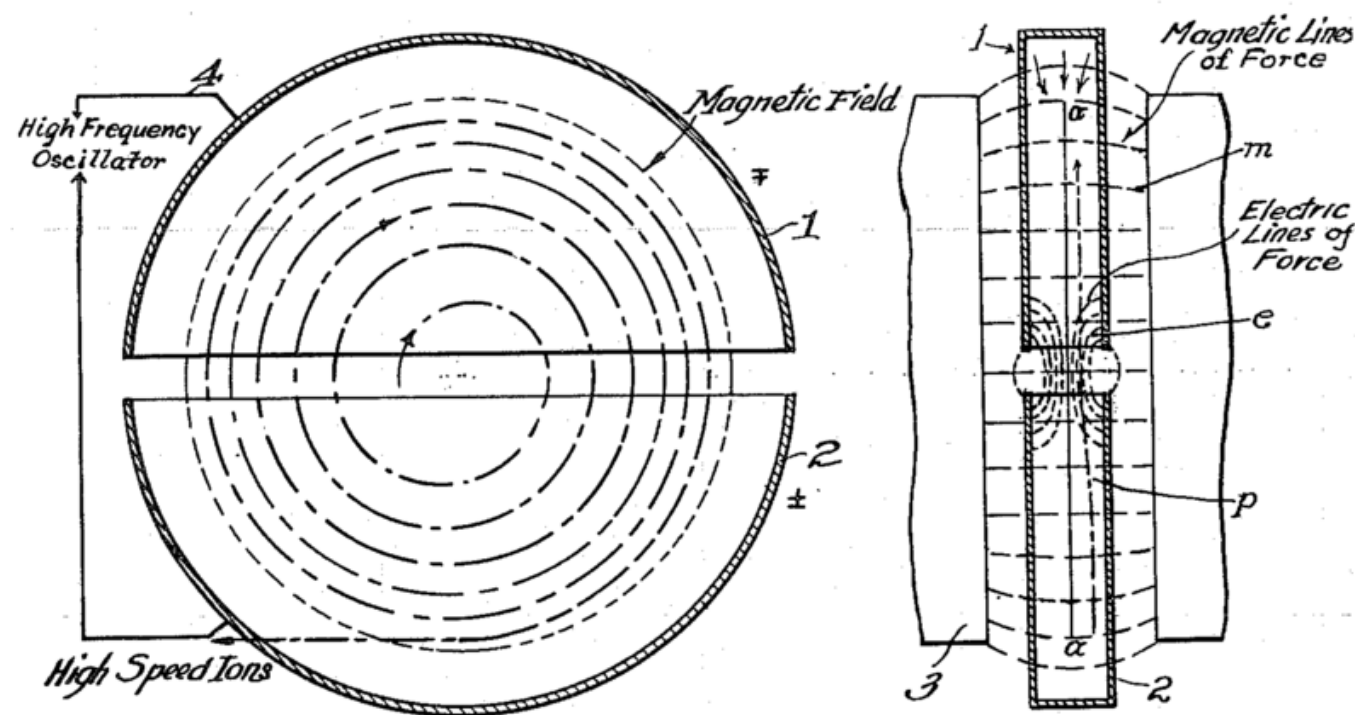


Ernest Orlando Lawrence

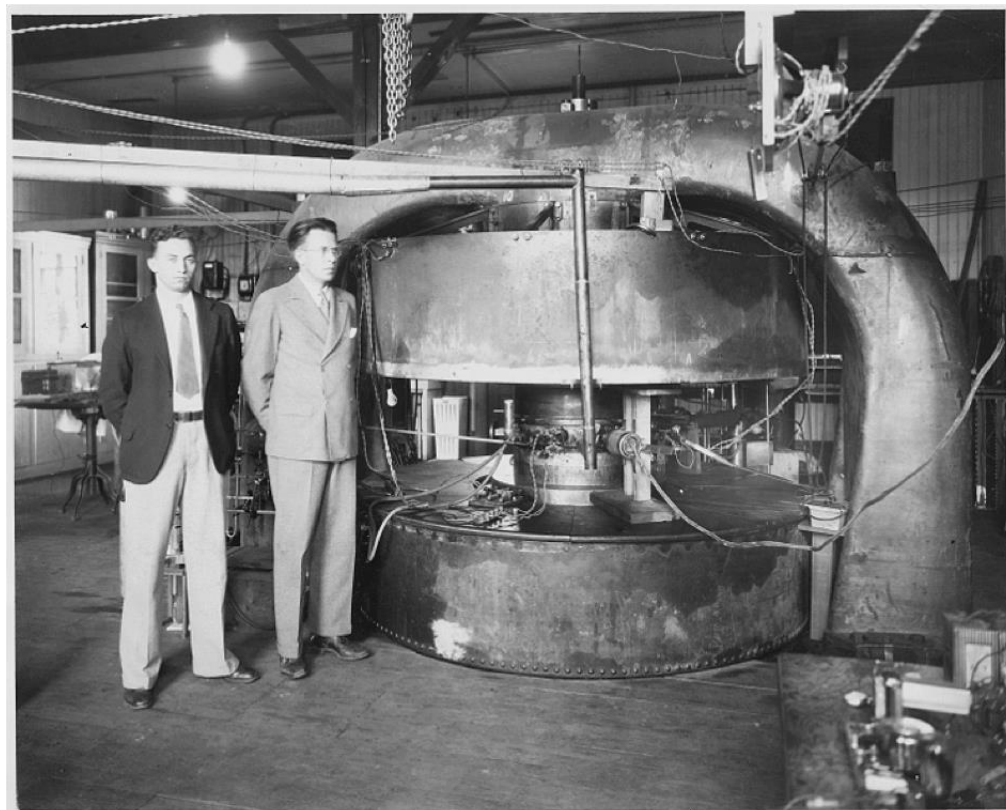
ie. for constant charge  $q$  and mass  $m$ , and a uniform magnetic field  $B$ , the angular frequency is constant. ie. the rf frequency can be constant. The orbit radius is proportional to speed,  $v$ .

Q. What is the issue with this statement?

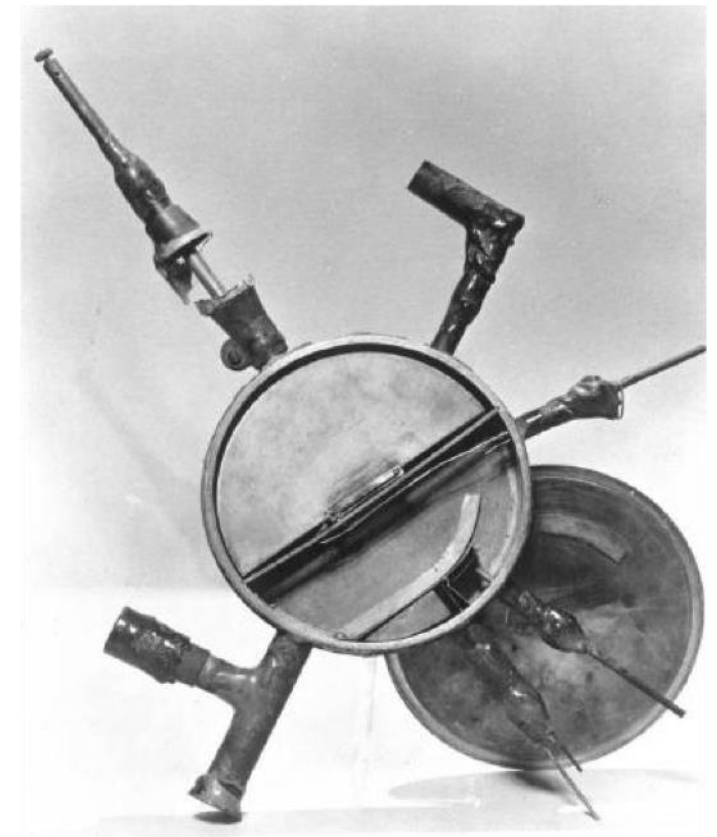
# Cyclotrons (2)



The Cyclotron, from E. Lawrence's 1934 patent



E. Lawrence & M. Stanley Livingston



The first cyclotron

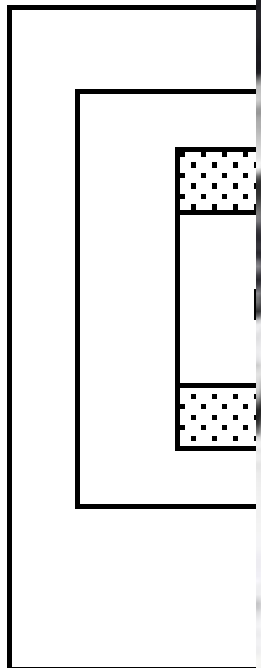
# **A creative boom: the 1940s to 1960s**



# Betatron

D.W. Kerst, Phys. Rev. 58, 841 (1940)

- Li
- Us
- M
- Ac  
m



Image

uction

...

$$= \frac{\bar{B}}{2}$$

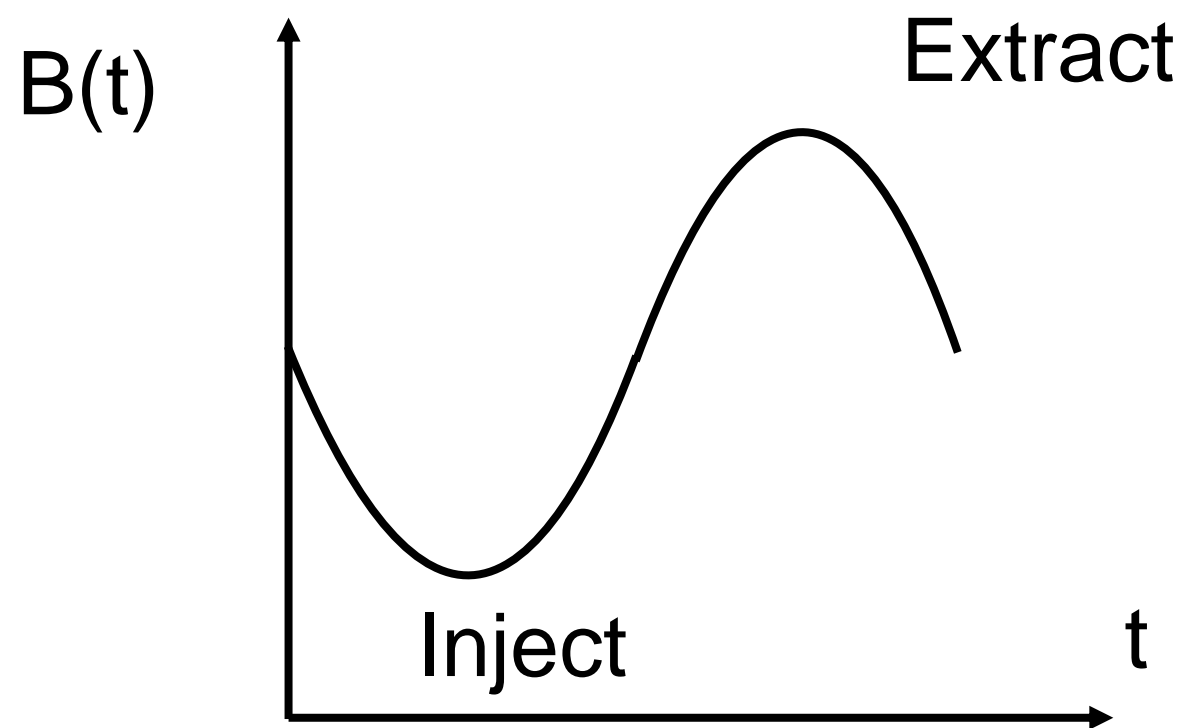
## Blewett raises a problem: do electrons radiate?

- Ivanenko & Pomeranchuk: upper limit to betatron energy around 500MeV! (1944)
- Schwinger also predicted radiation (1945)
- Opposing views: electrons in wires don't radiate?

GE team searched in the radio spectrum... found nothing?

# Synchrotrons

*“Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field ... which would be varied in such a way that the radius of curvature remains constant as the particles gain energy through successive accelerations”* - Marcus Oliphant, 1943



Typical synchrotron magnet cycle



# Synchrotrons - Phase stability

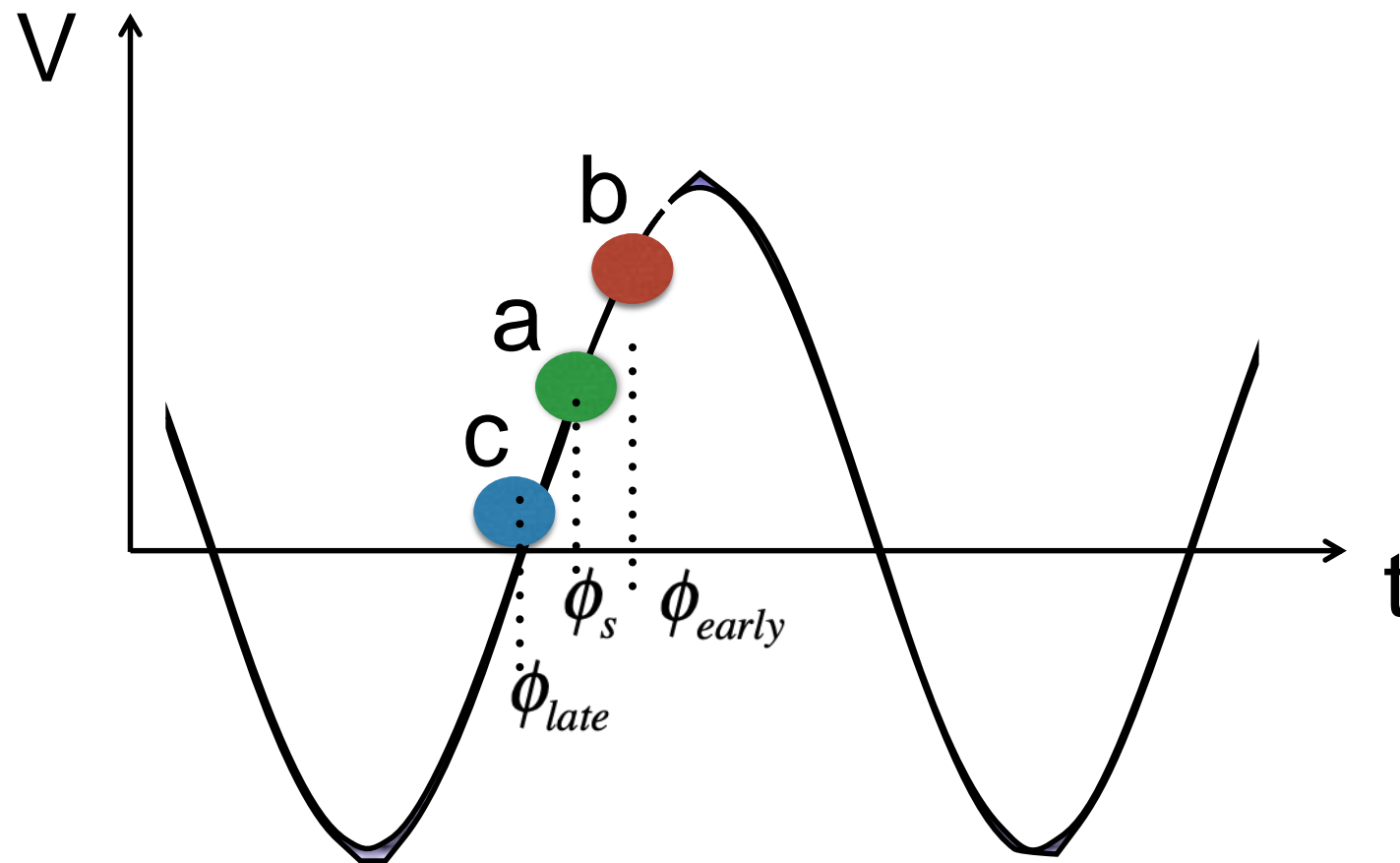
Vladimir Veksler & Ed McMillan

a - synchronous

b - arrives early, sees higher voltage, goes to larger orbit -> arrives later next time

c - arrives late, sees lower voltage, goes to smaller orbit -> arrives earlier next time

$$V = V_0 \sin(2\pi f_a + \phi_s)$$



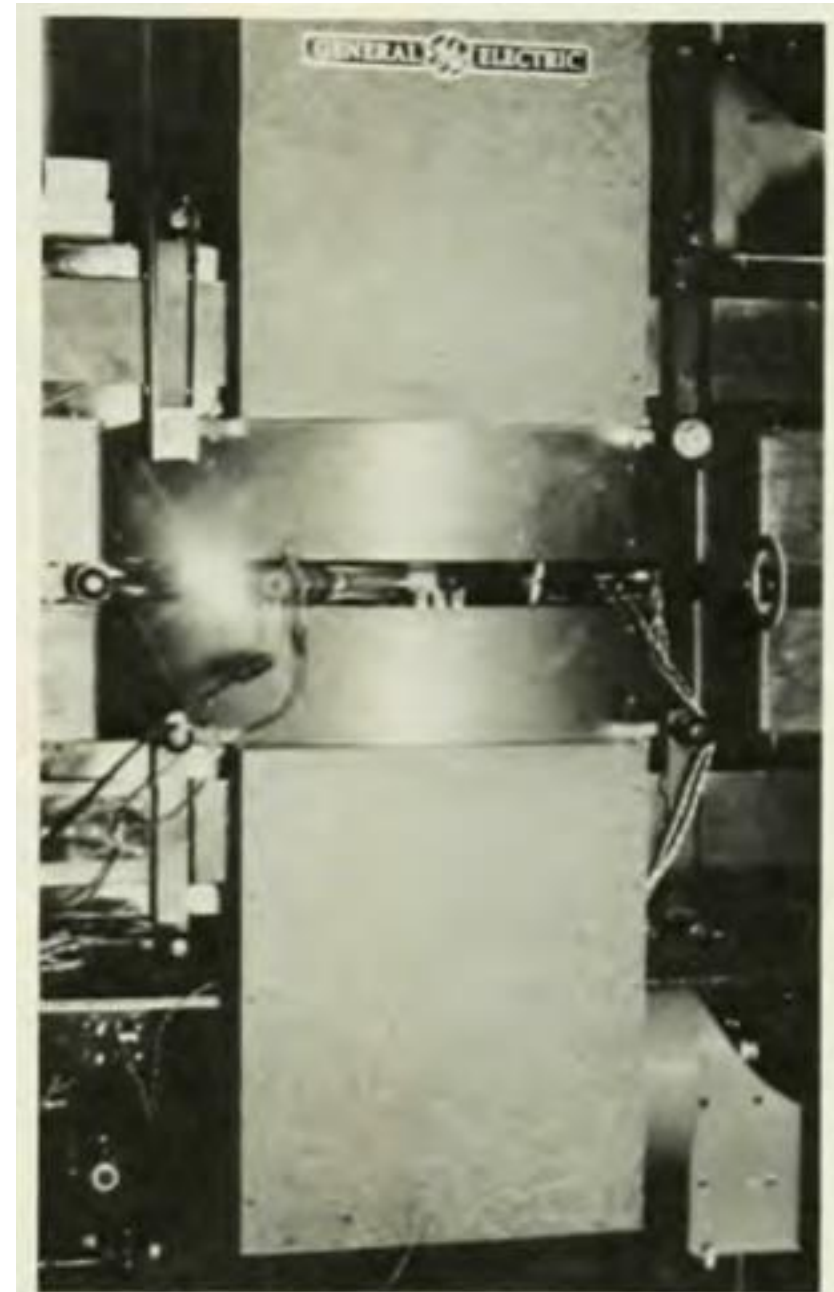
# Discovery of Synchrotron Light

GE, 1947

Astrophysical relevance:  
majority of radio sources in the  
universe emit via synchrotron  
processes!

NB. GE team were beaten to 'first  
synchrotron' by a month:

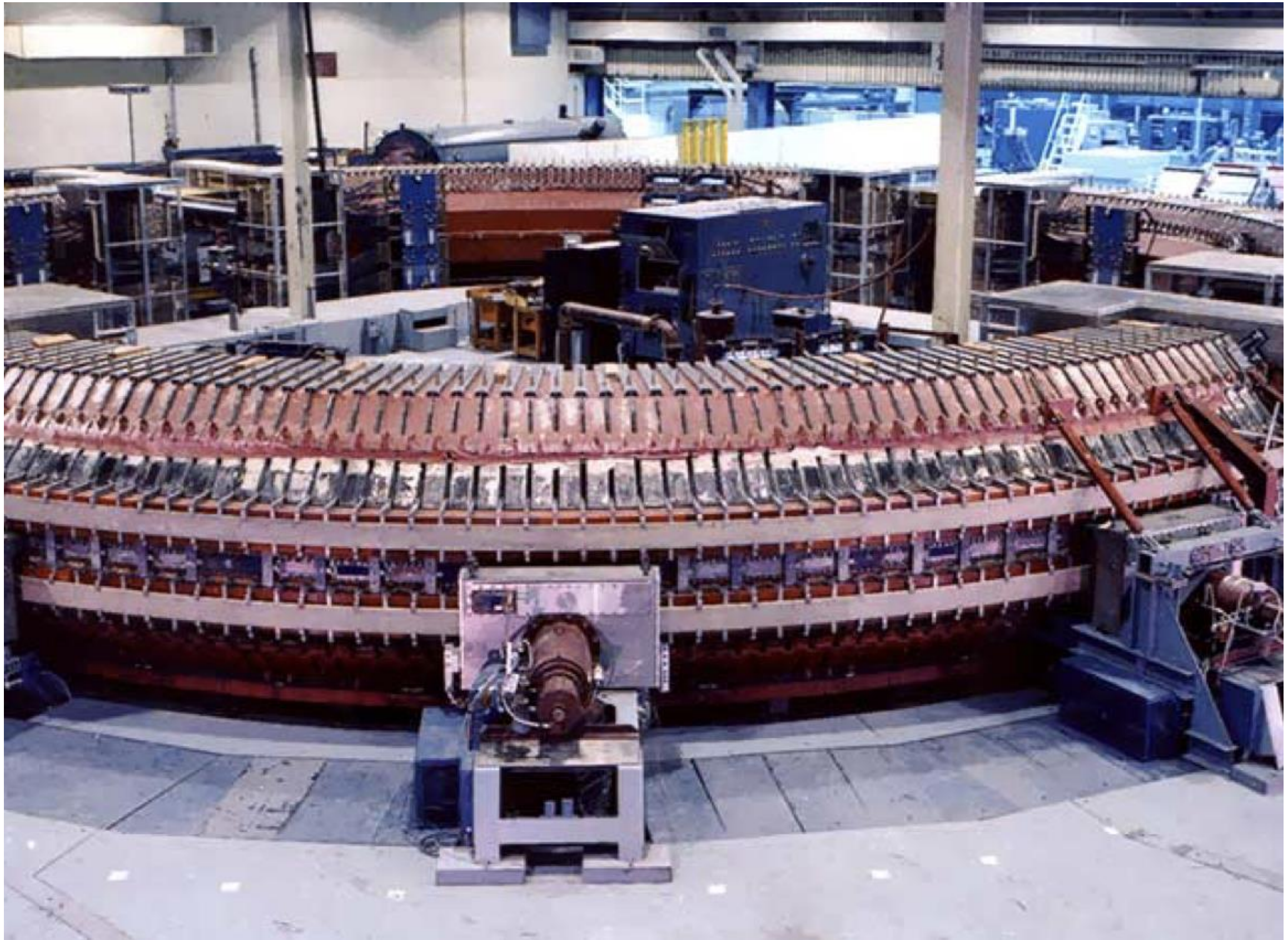
Goward and Barnes (UK) converted a  
small betatron into an 8 MeV electron  
synchrotron



Synchrotron radiation from 70-MeV machine  
at General Electric Research Laboratory  
where it was first discovered in 1947.



# Proton Synchrotrons

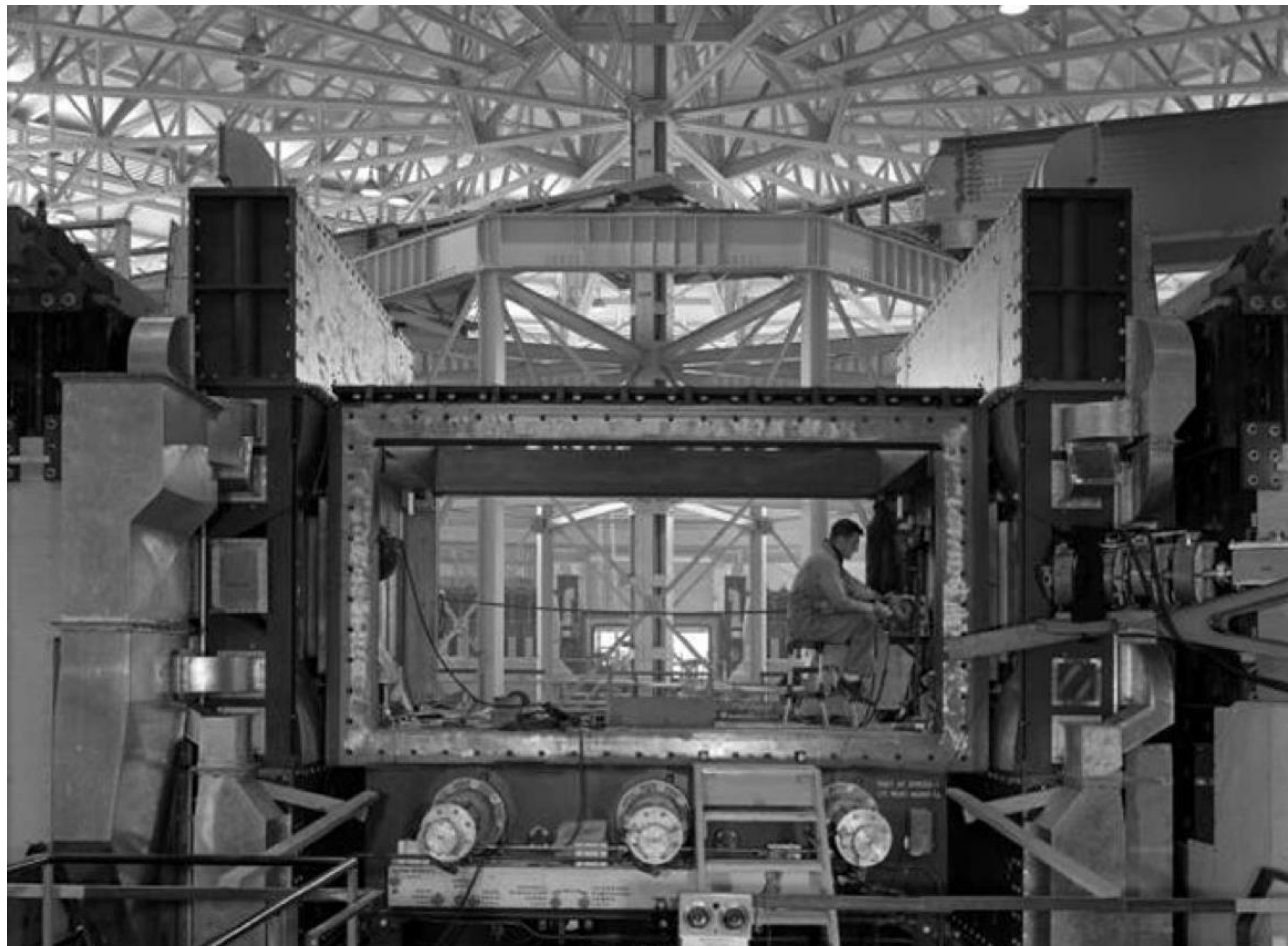


The Cosmotron, BNL





The Bevatron, Berkeley: discovered the antiproton





# Strong Focusing

Brookhaven, 1952, Livingston: Can we turn around some Cosmotron magnets?



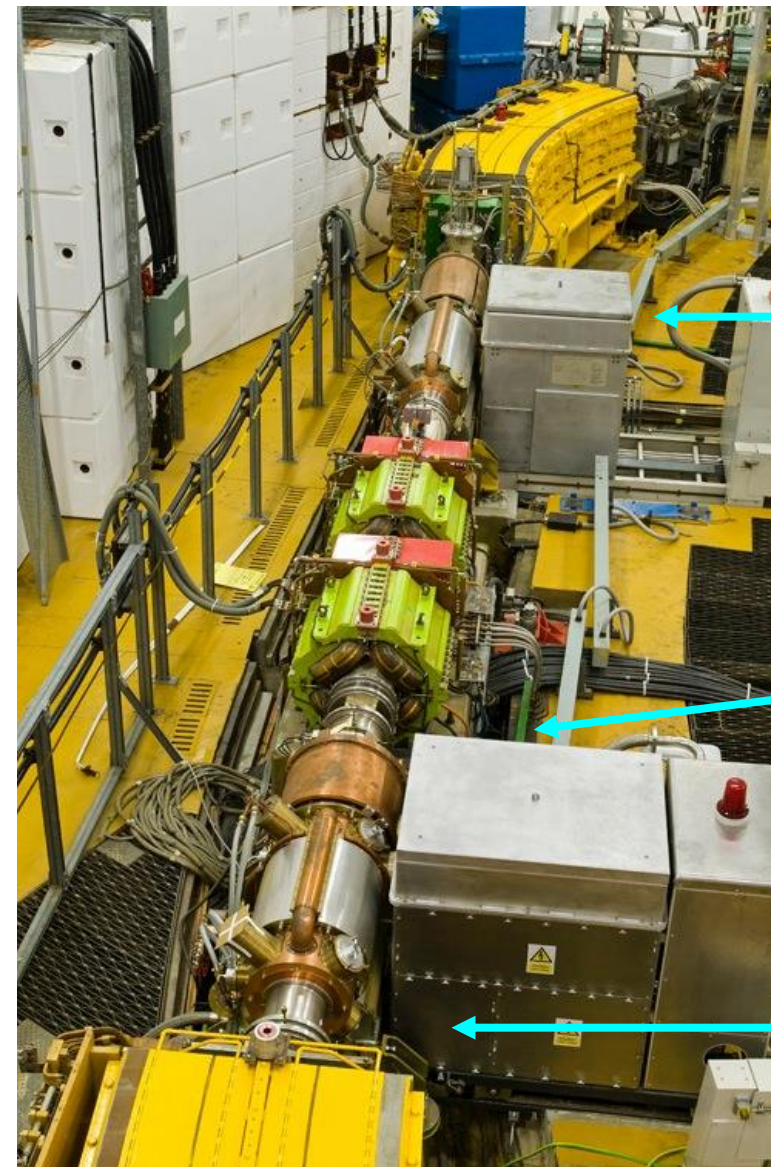
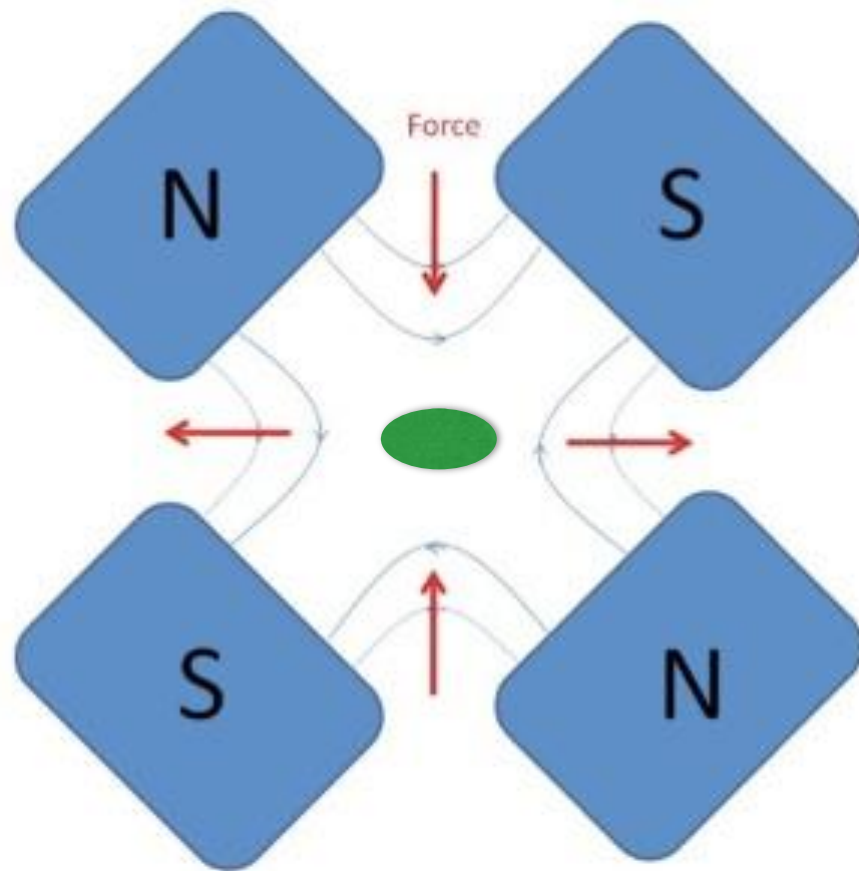
It turned out Nikolas Christophilos (Greek engineer) had got there first and patented the idea: they later hired him.



FIG. 27. E. D. Courant, M. S. Livingston, H. S. Snyder, and J. P. Blewett demonstrating the relative cross sections of the cosmotron magnet and a speculative alternating-gradient magnet of very large gradient.

E. Courant & H. Snyder worked out the theory...

# Strong Focusing Synchrotrons



dipole magnets

quadrupole magnets

rf cavity

*Image courtesy of ISIS, STFC*

# “What about the Midwest?”

## The tale of MURA

- (i) beam stacking,
- (ii) Hamiltonian theory of longitudinal motion,
- (iii) useful colliding beams (the idea itself is quite old),
- (iv) storage rings (independently invented by O'Neill),
- (v) spiral-sector geometry used in isochronous cyclotrons,
- (vi) lattices with zero-dispersion and low- $\beta$  sections for colliding beams,
- (vii) multiturn injection into a strong-focusing lattice,
- (viii) first calculations of the effects of nonlinear forces in accelerators,
- (ix) first space-charge calculations including effects of the beam surroundings,
- (x) first experimental measurement of space-charge effects,
- (xi) theory of negative-mass and other collective instabilities and correction systems,
- (xii) the use of digital computation in design of orbits, magnets, and rf structures,
- (xiii) proof of the existence of chaos in digital computation, and
- (xiv) synchrotron-radiation rings

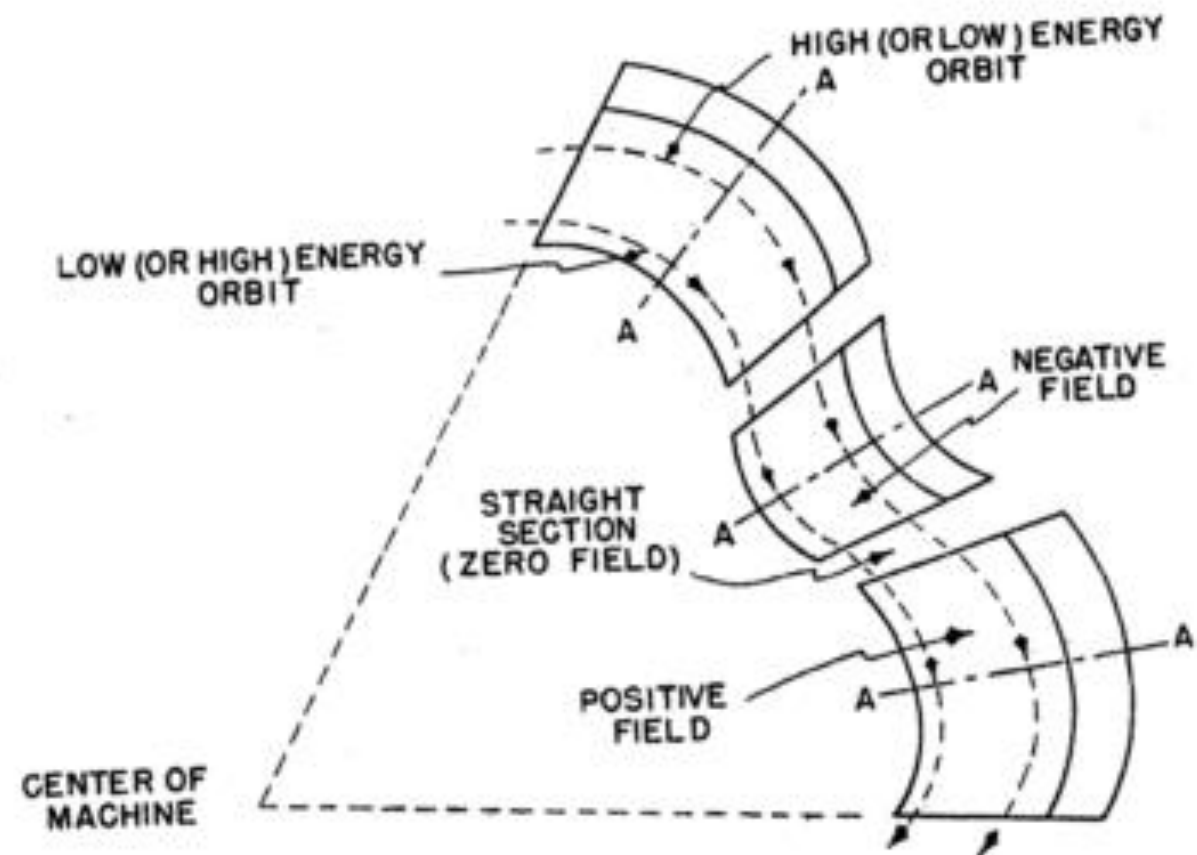
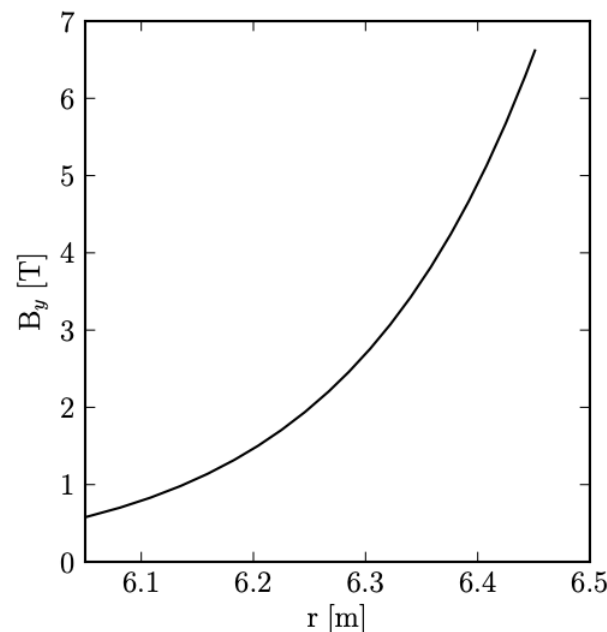


# Fixed Field Alternating Gradient Accelerators (FFAs)

Formerly 'FFAG'

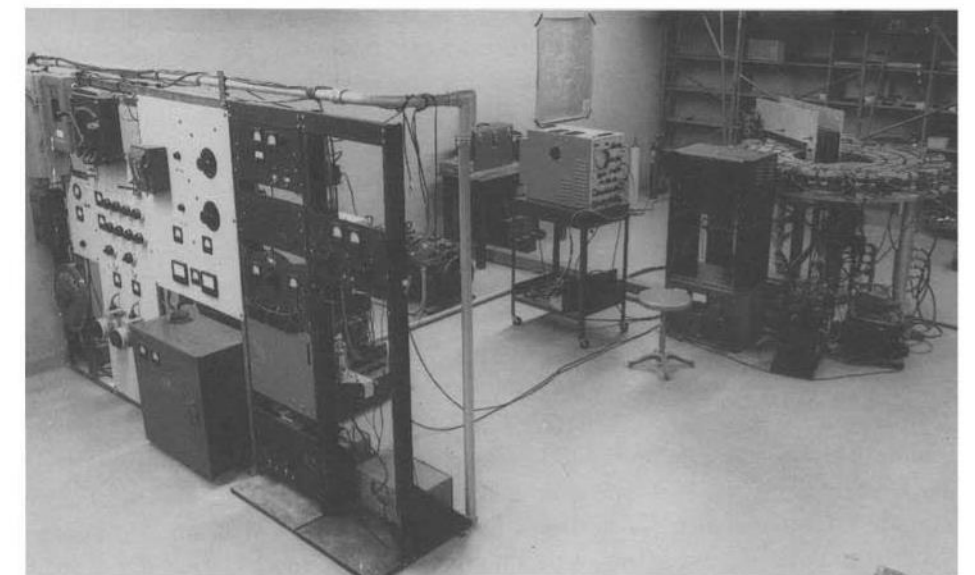
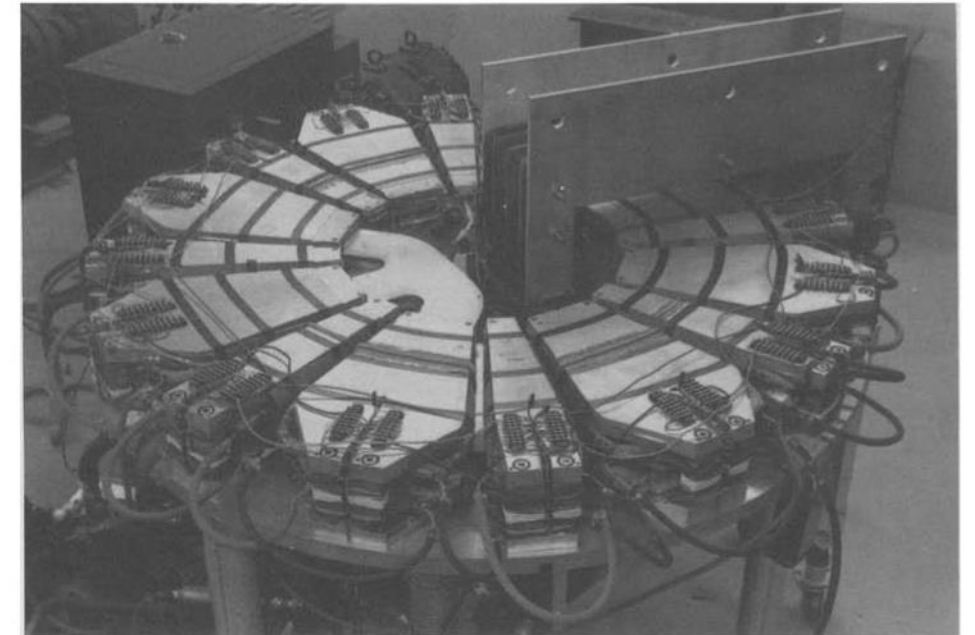
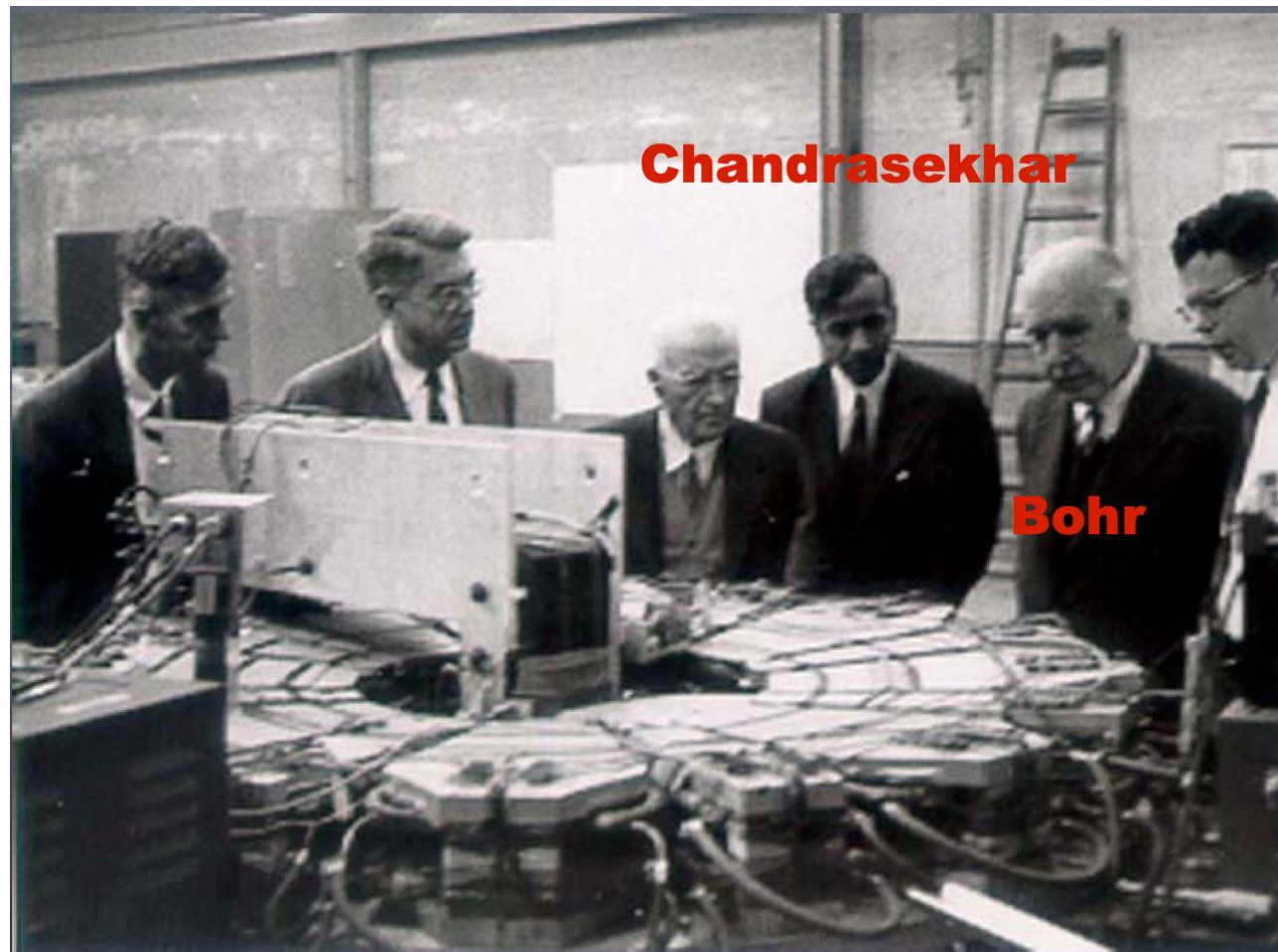
- If the field profile is of a particular form, we call this type of FFA\* a 'scaling' type
- Alternating magnets have opposite bending fields
- Beam moves radially with energy

$$B_y = B_0 \left( \frac{r}{r_0} \right)^k F(\theta)$$



Note that this field profile does NOT satisfy isochronicity

$$\omega = \frac{eB}{m\gamma} \neq \text{const.}$$

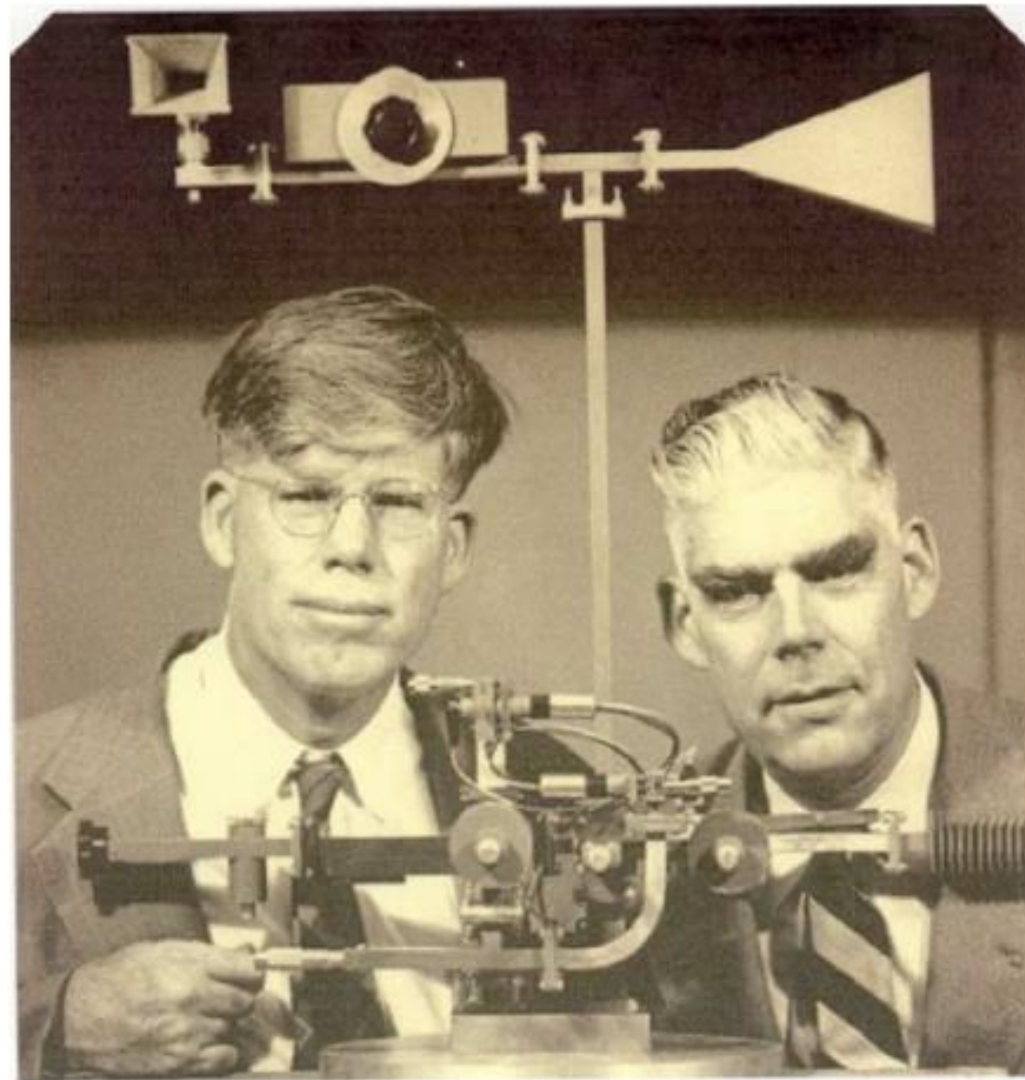


1956

- L. W. Jones, AIP Conference Proceedings, 237, 1 (1991)



# LINACs & klystrons: from radar to accelerators



Russ & Sigurd Varian



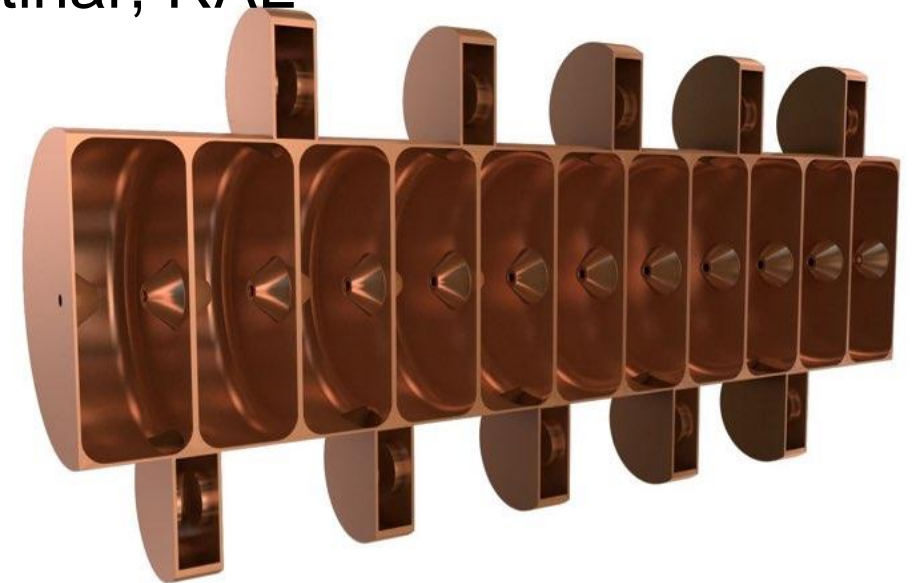
Bill Hansen & team

# Linac Structures

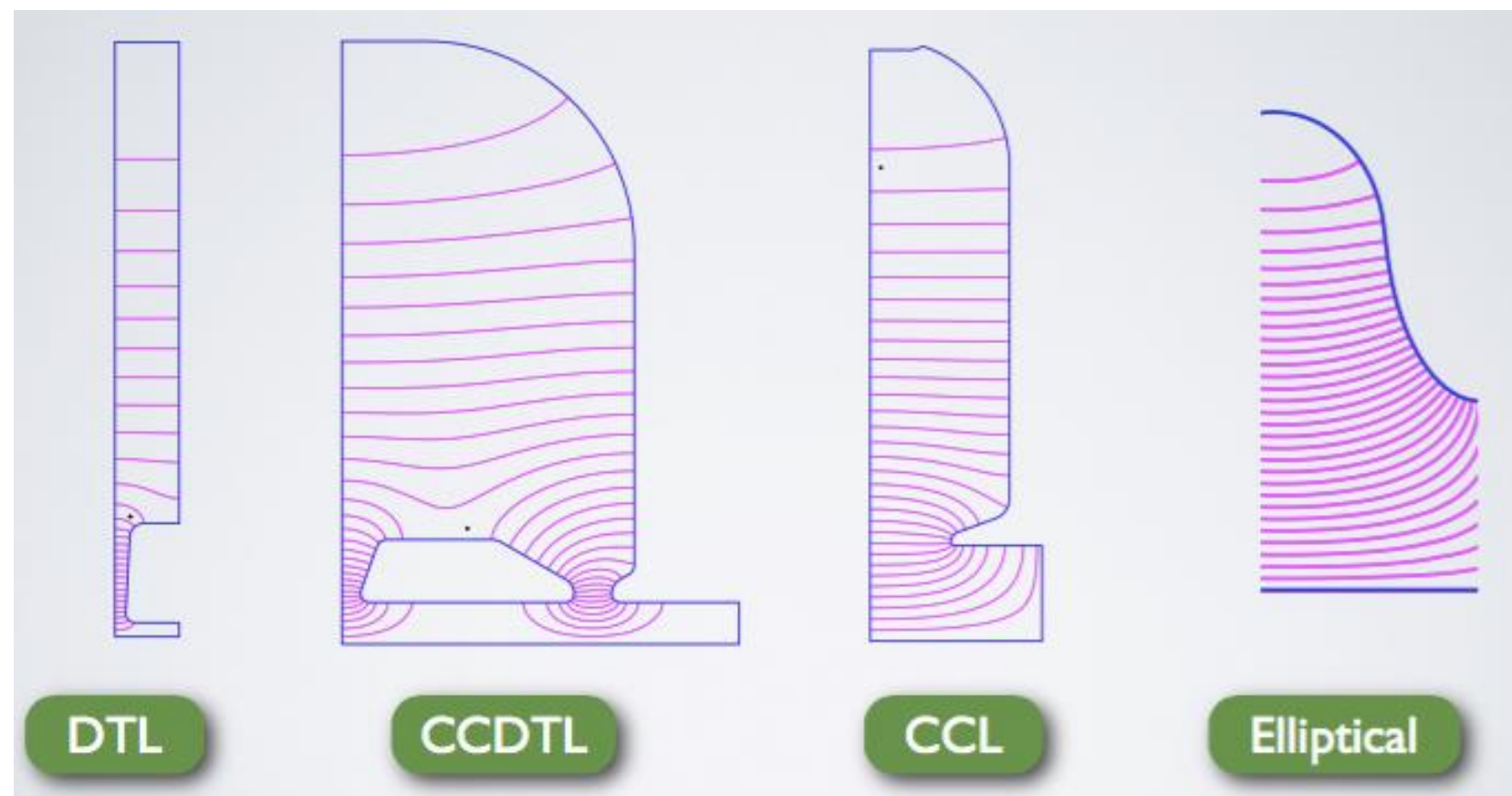
Images thanks to Ciprian Plostinar, RAL



DTL: Drift Tube Linac



CCL: Coupled Cavity Linac



**An established field  
and powerful tool:  
1970s to today**

# ‘Livingston plot’

M. Stanley Livingston:

advances in accelerator technology  
increase in energy record by **a factor  
of 10 every six years.**

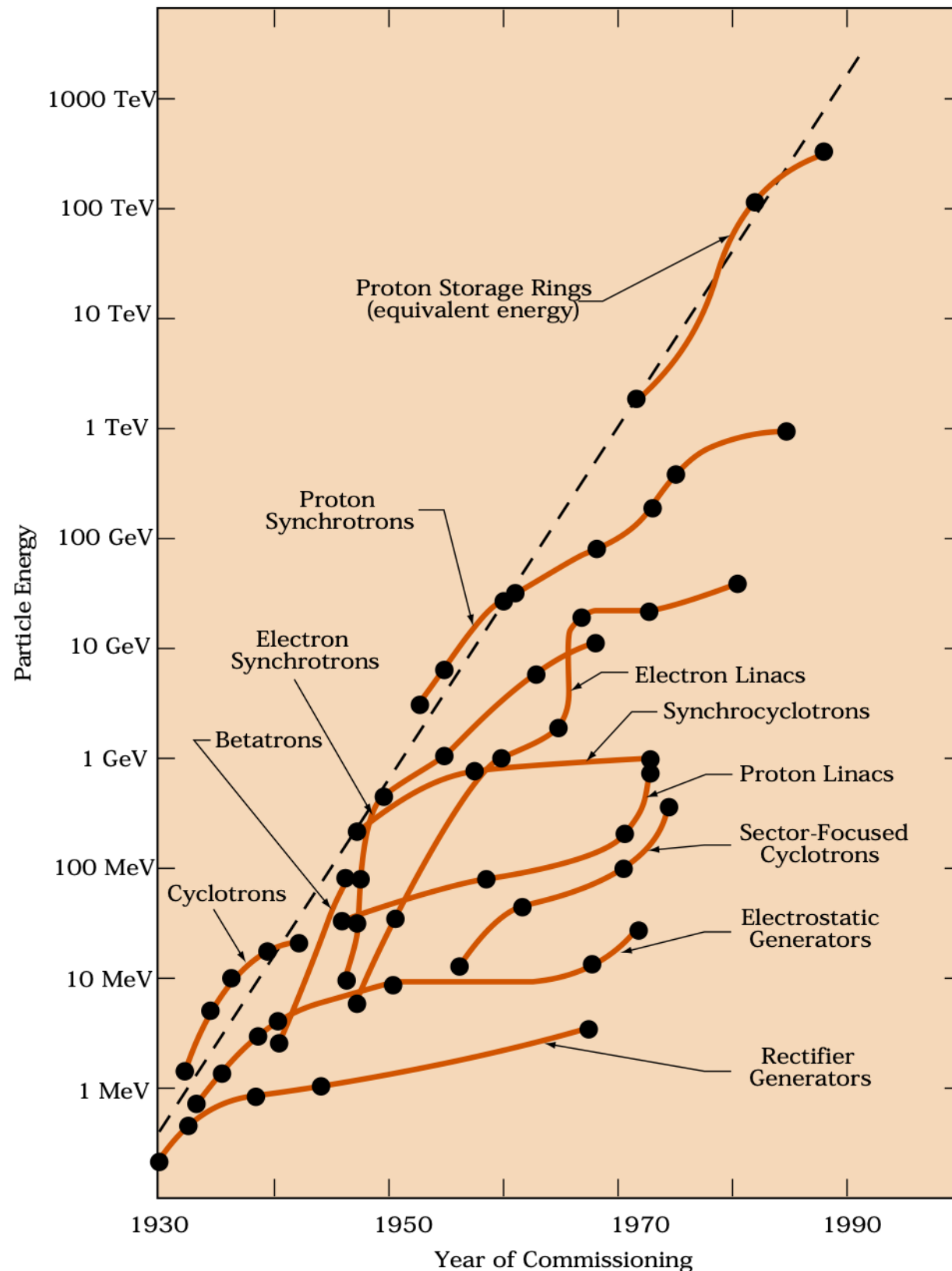


Image: <http://www.slac.stanford.edu/pubs/beamline/27/1/27-1-panofsky.pdf>



# Colliders

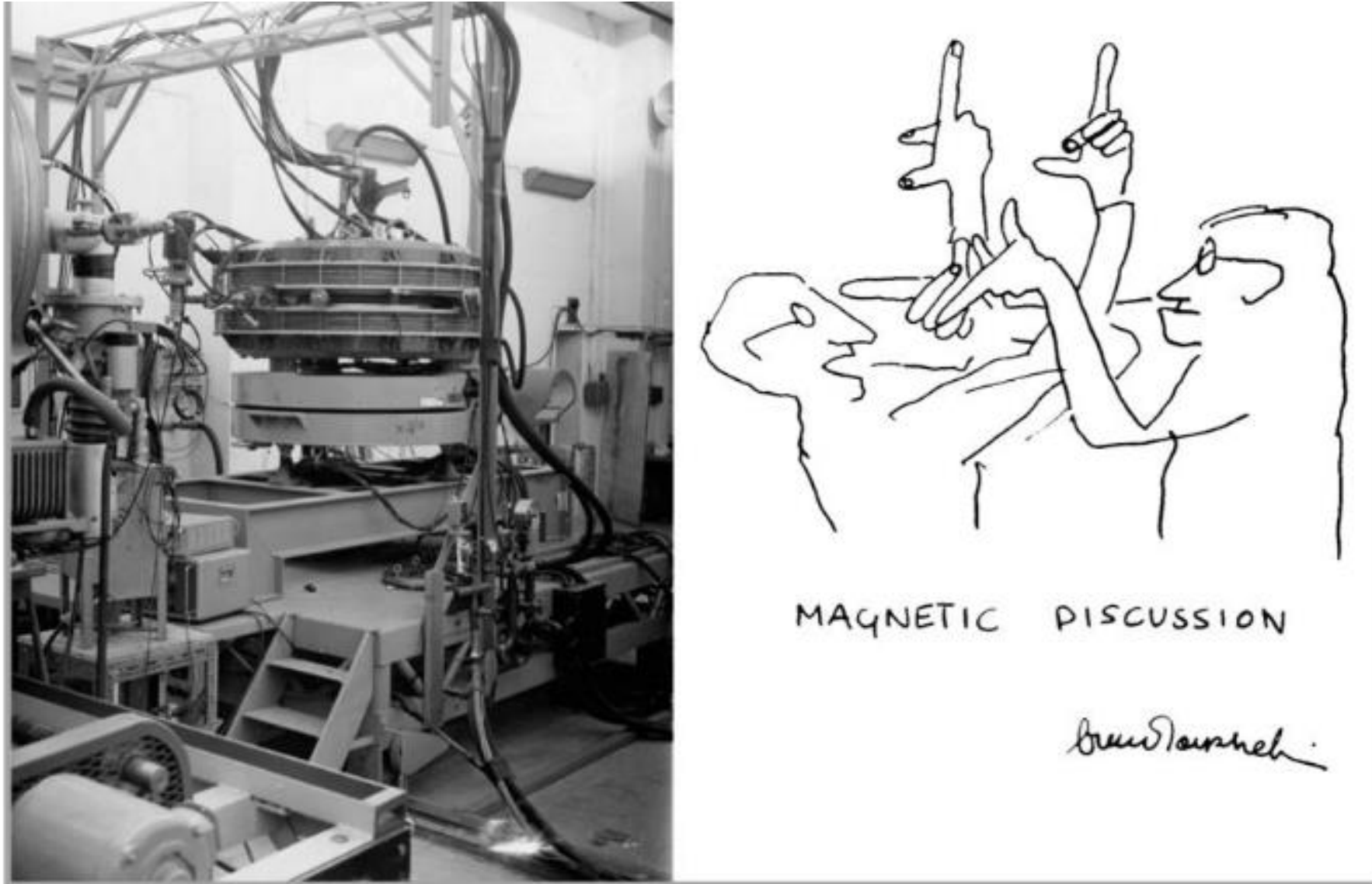
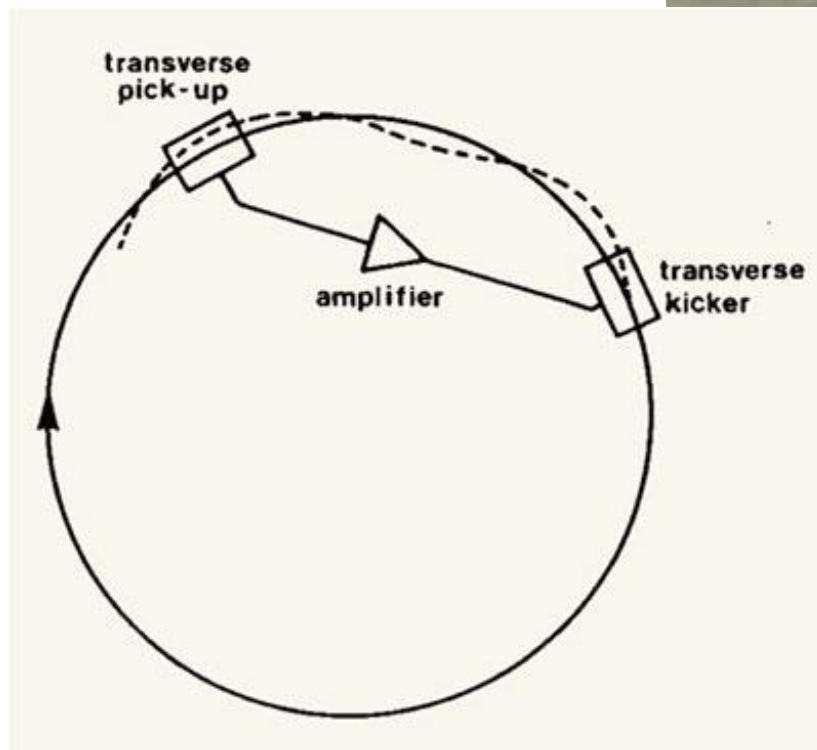


Fig. 2. Left: AdA installed in Salle 500 MeV, Laboratoire de l'Accélérateur Linéaire, Orsay, France. 1963. Right: a drawing by Bruno Touschek reflecting frequent

From: G. Pancheri, L. Bonolis, in History of Particle Colliders,  
IOP History of Physics Group, 2018

# ISR – first hadron collider

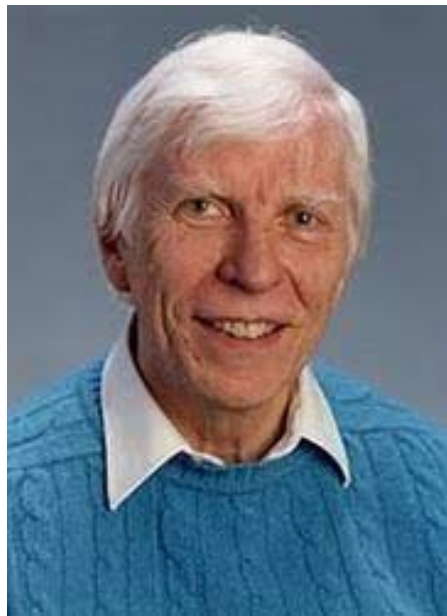
1971 to 1984,  
CoM energy  
62GeV



Also: stochastic cooling invented by Simon Van de Meer



# The Tevatron & superconducting magnets



Alvin Tollestrup

## THE TEVATRON ENERGY DOUBLER: A Superconducting Accelerator

*Helen T. Edwards*

Fermi National Accelerator Laboratory,<sup>1</sup> Batavia, Illinois 60510

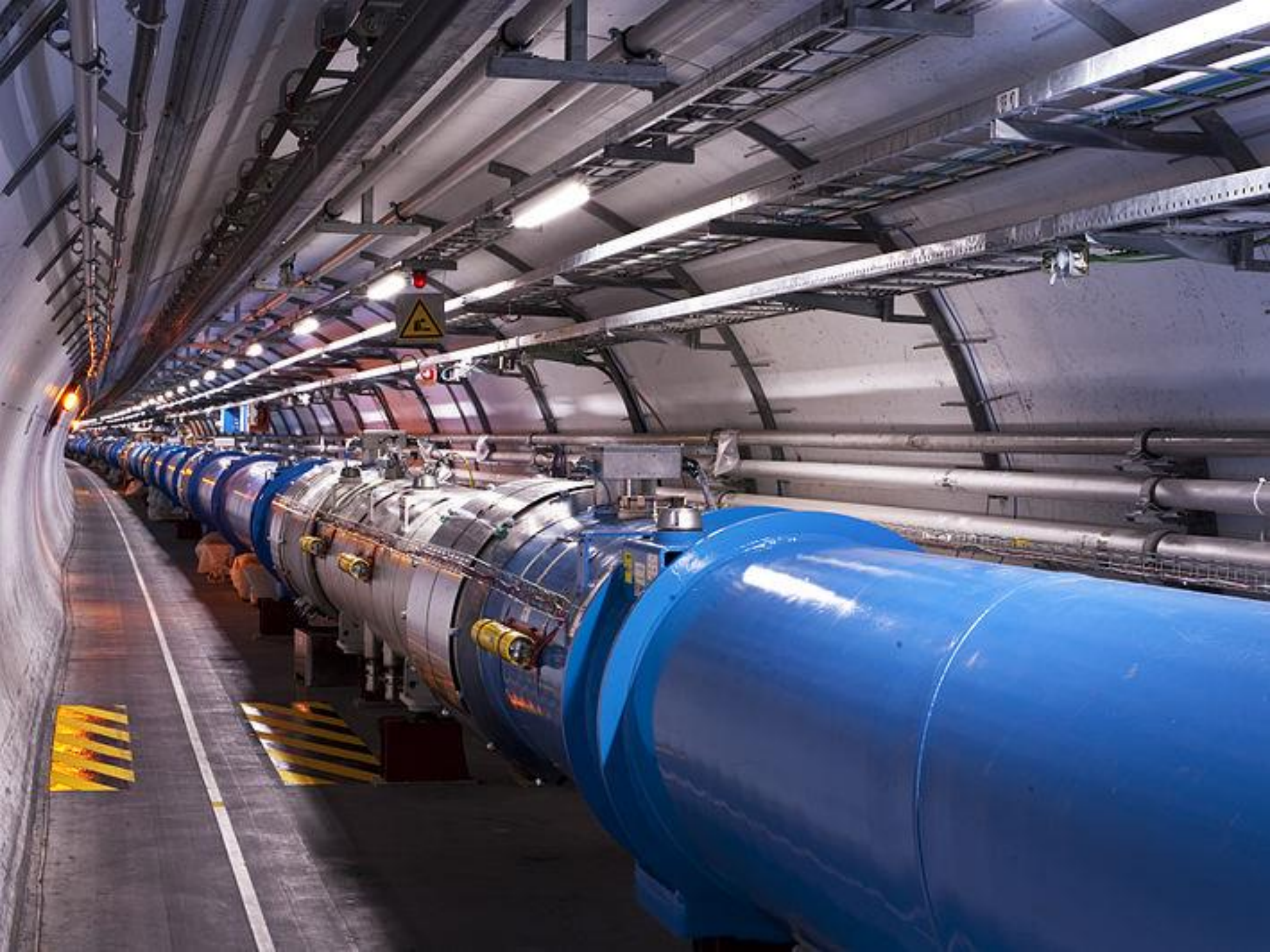


Helen Edwards



“Tevatron”= 1 TeV beam energy







# Accelerators: Nobel-winning pursuit

“28% of the research in physics between 1939 and 2009 has been influenced by accelerator science and that on average accelerator science contributed to a Nobel Prize for Physics every 2.9 years”\*



\*Haussecker, E.F., Chao, A.W. The Influence of Accelerator Science on Physics Research. *Phys. Perspect.* **13**, 146 (2011).

## 25 Nobel Prizes in Physics that had direct contribution from accelerators

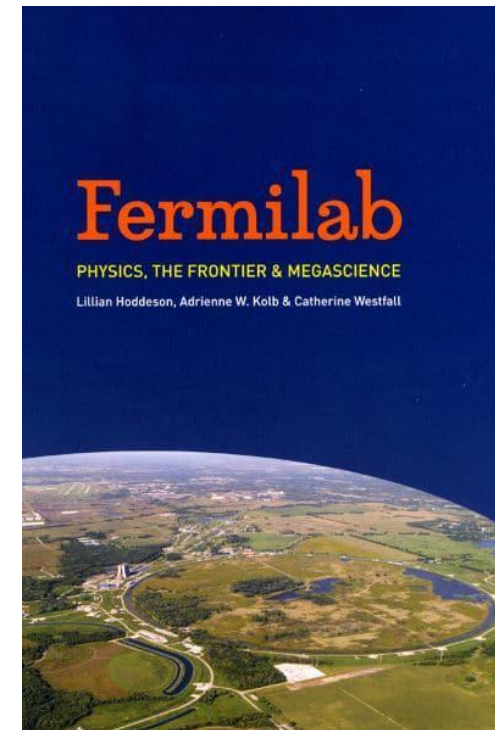
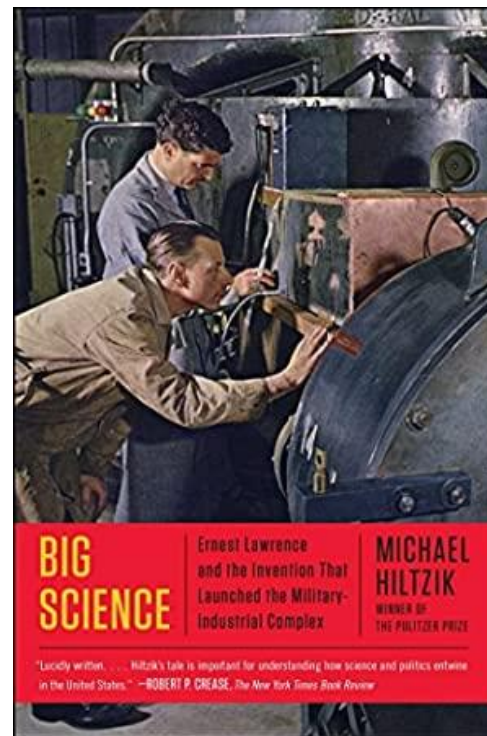
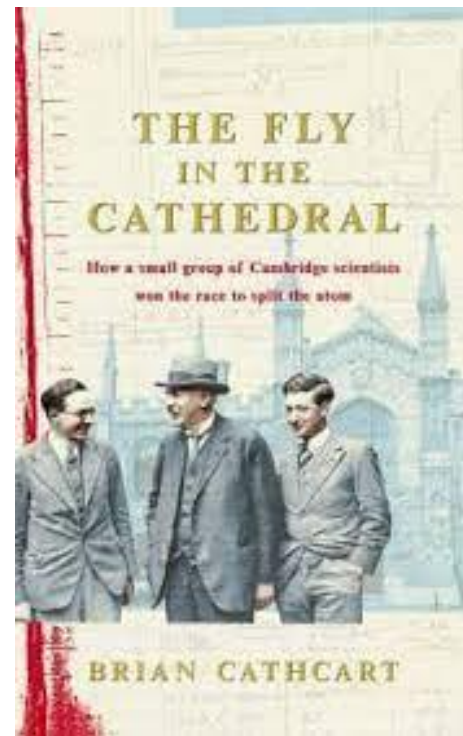
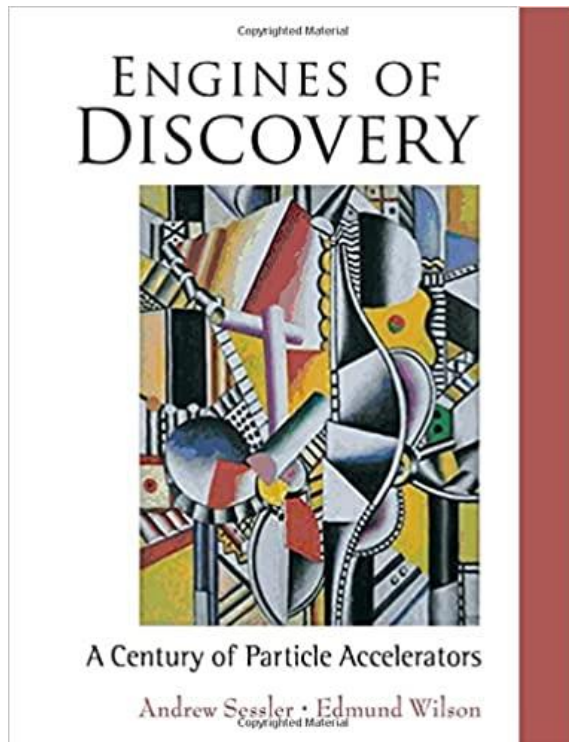
Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons ( $\theta$ and $\tau$ ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the $J/\Psi$ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the $J/\Psi$ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].

1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa and Yoichiro Nambu	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

**2013:** François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at **CERN's Large Hadron Collider**"



# Further Reading:



*Engines of Discovery,*  
Andy Sessler, Edmund (Ted) Wilson, 2014

*The Fly in the Cathedral,* Brian Cathcart, 2004

*Big Science: Ernest Lawrence and the Invention that Launched the Military-Industrial Complex,* Michael Hiltzik, 2016

*Fermilab Physics, the Frontier, and Megascience,* Lillian Hoddeson, Adrienne W. Kolb, Catherine Westfall, 2011

*The Matter of Everything: Twelve Experiments that Changed Our World,* Suzie Sheehy, 2022

- Betatrons:  
<http://web.mit.edu/course/22/22.09/ClassHandouts/Charged%20Particle%20Accel/CHAP11.PDF>
- FFA history: K. R. Symon, 'The Mura Days'  
<https://accelconf.web.cern.ch/accelconf/p03/PAPERS/WOPA003.PDF>

My contact details:

[suzie.sheehy@physics.ox.ac.uk](mailto:suzie.sheehy@physics.ox.ac.uk)

[suzie.Sheehy@unimelb.edu.au](mailto:suzie.Sheehy@unimelb.edu.au)

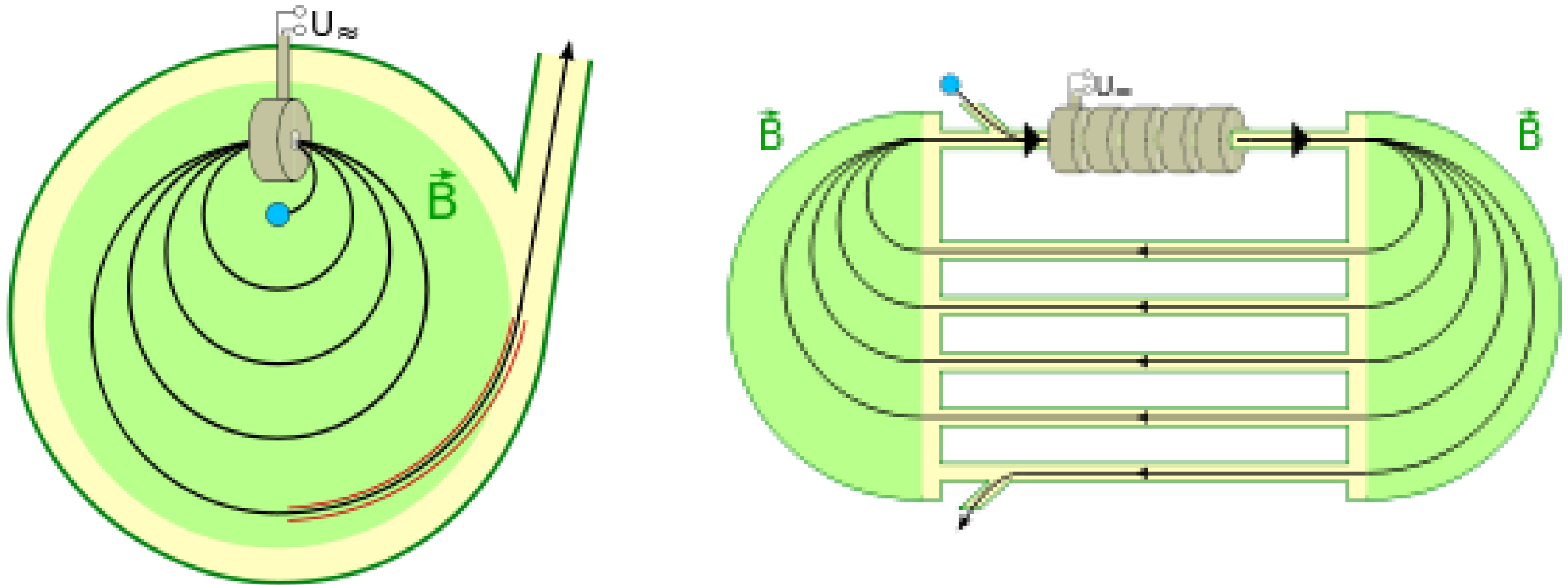
Twitter: @suziesheehy

[www.suziesheehy.com](http://www.suziesheehy.com)

**A few loose ends:**



# Microtron

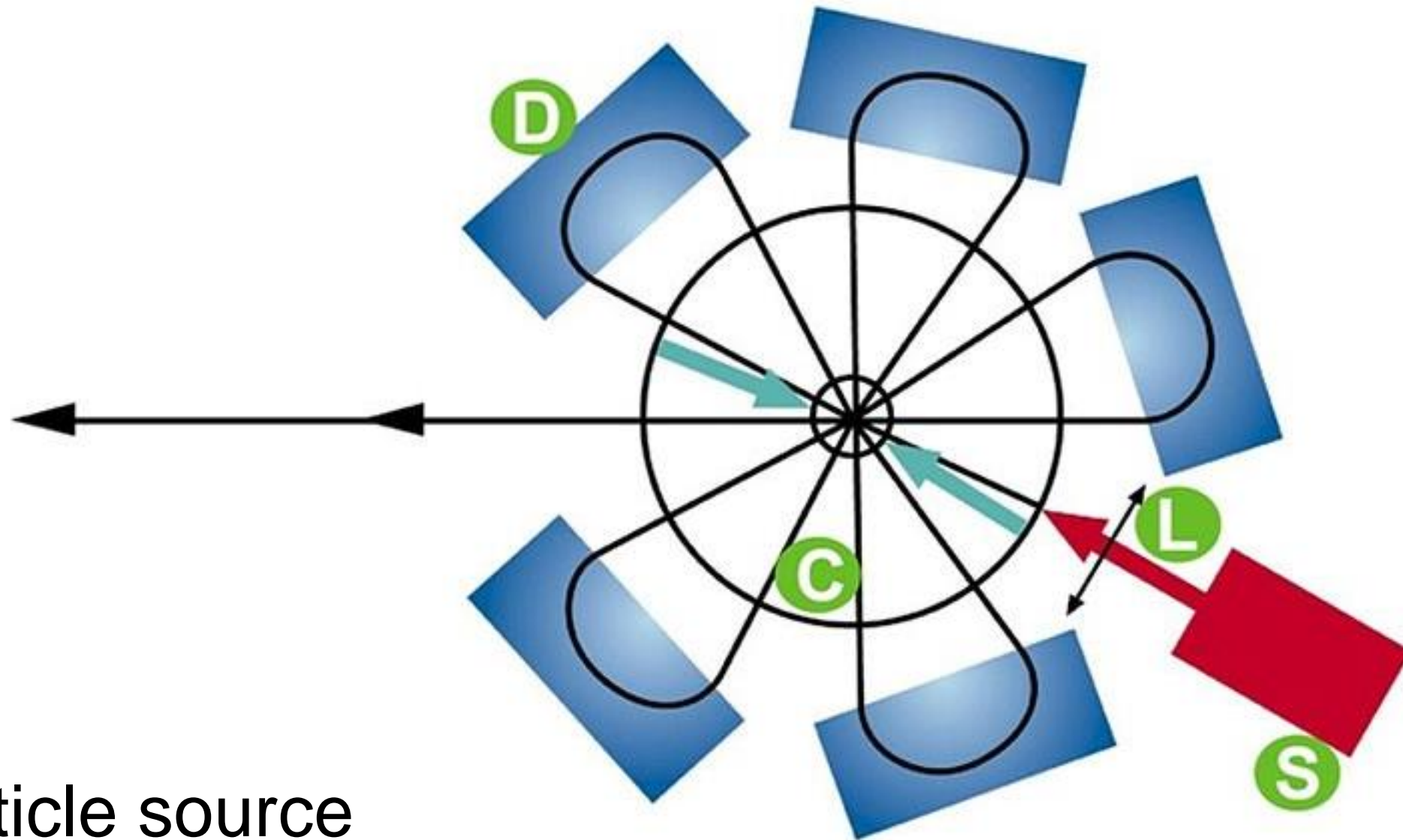


Images: wikipedia commons

- Uses a linear accelerator structure instead of the dee electrodes of the cyclotron
- Mostly used for electrons as assumes constant frequency RF & B field in the ultra relativistic limit.

# Rhodotron

Invented 1989



S: particle source

C: coaxial cavity

D: bending magnets

L: focusing lens

Energy gain  $\sim 1$  MeV per crossing

# FFAs

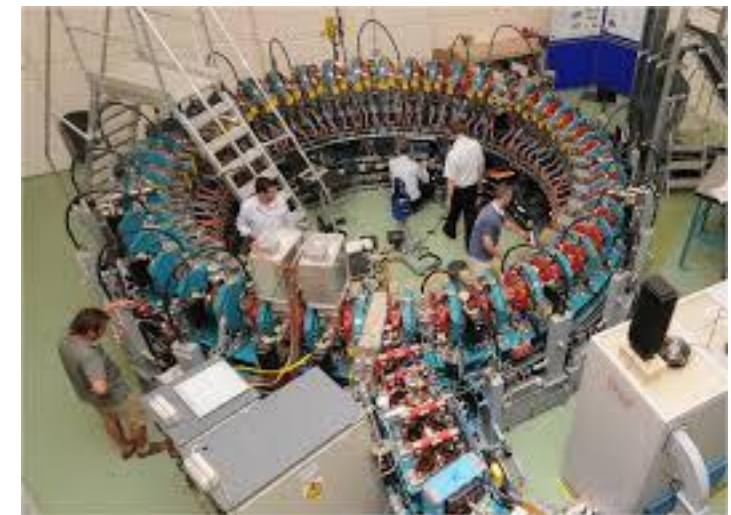
- In the late 90's and in 2000's, the FFA idea was re-awakened in Japan,
- Particular focus on hadron FFAs of scaling type
- Recently non-scaling type driven by UK collaboration

Scaling (zero-chromatic)



Proof of Principle machine built in 1999 at KEK, demonstrated 1kHz rep. rate

Non-Scaling (chromatic)



EMMA, Daresbury Lab, UK