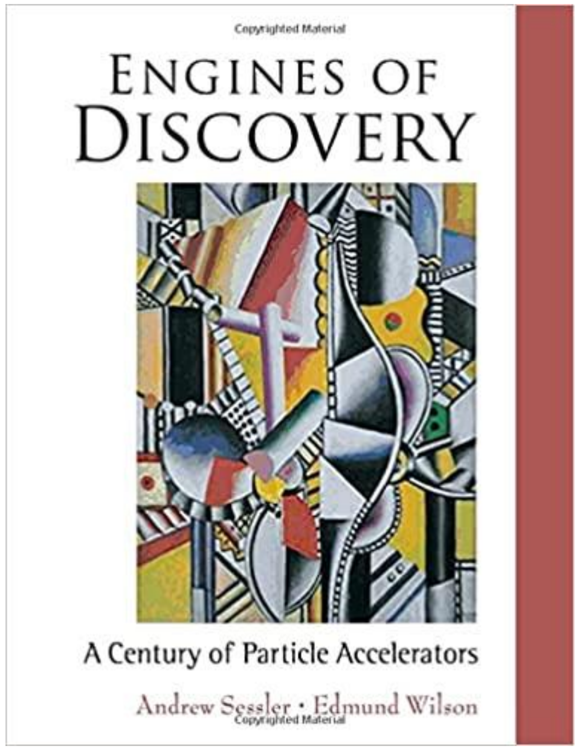
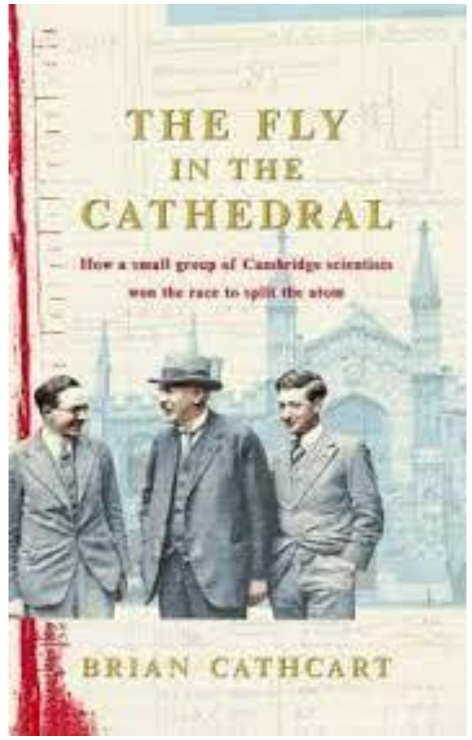
History of Accelerators

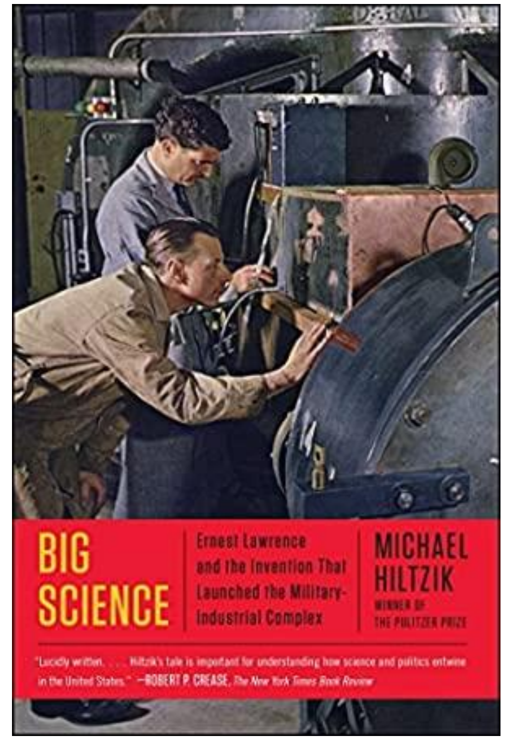
CERN Introductory Accelerator School
Kaunas, 2022

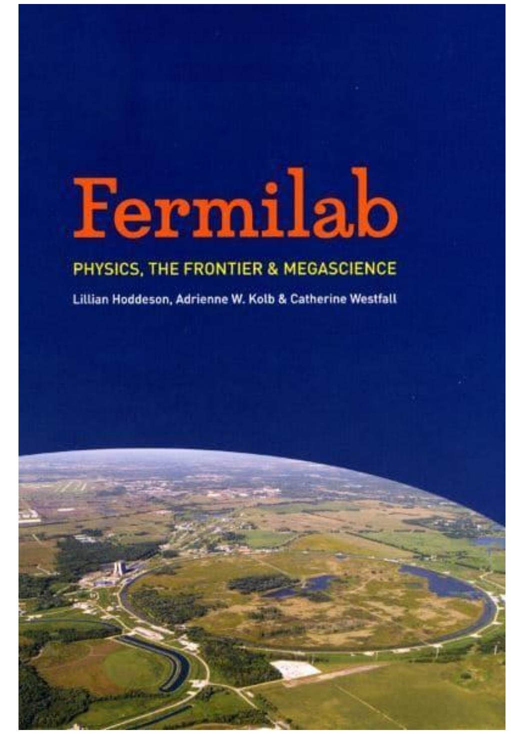
Dr. Suzie Sheehy
University of Melbourne
University of Oxford

Sources and Recommended Books:









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

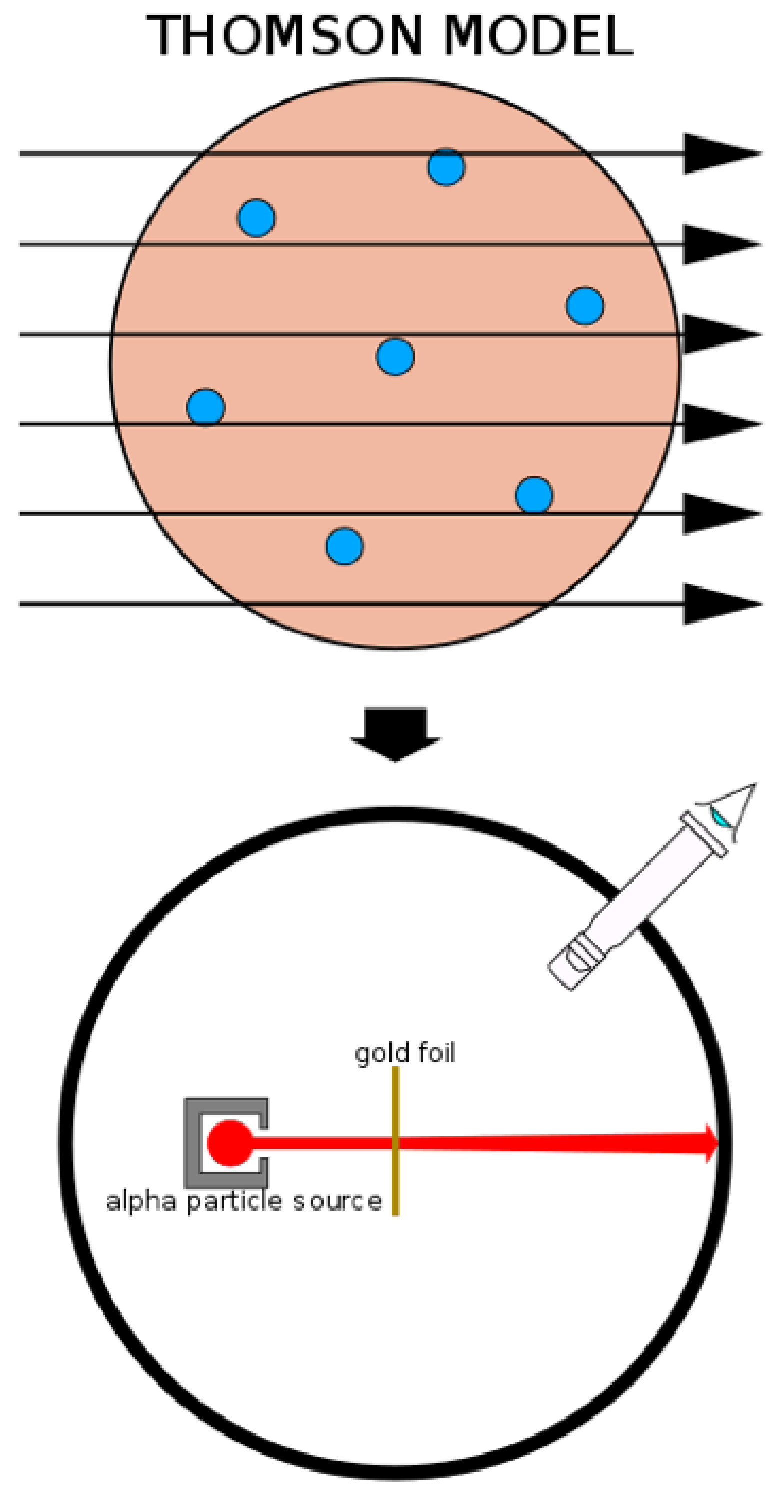
The Matter of Everything: Twelve Experiments that Changed Our World, Suzie Sheehy, 2022

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

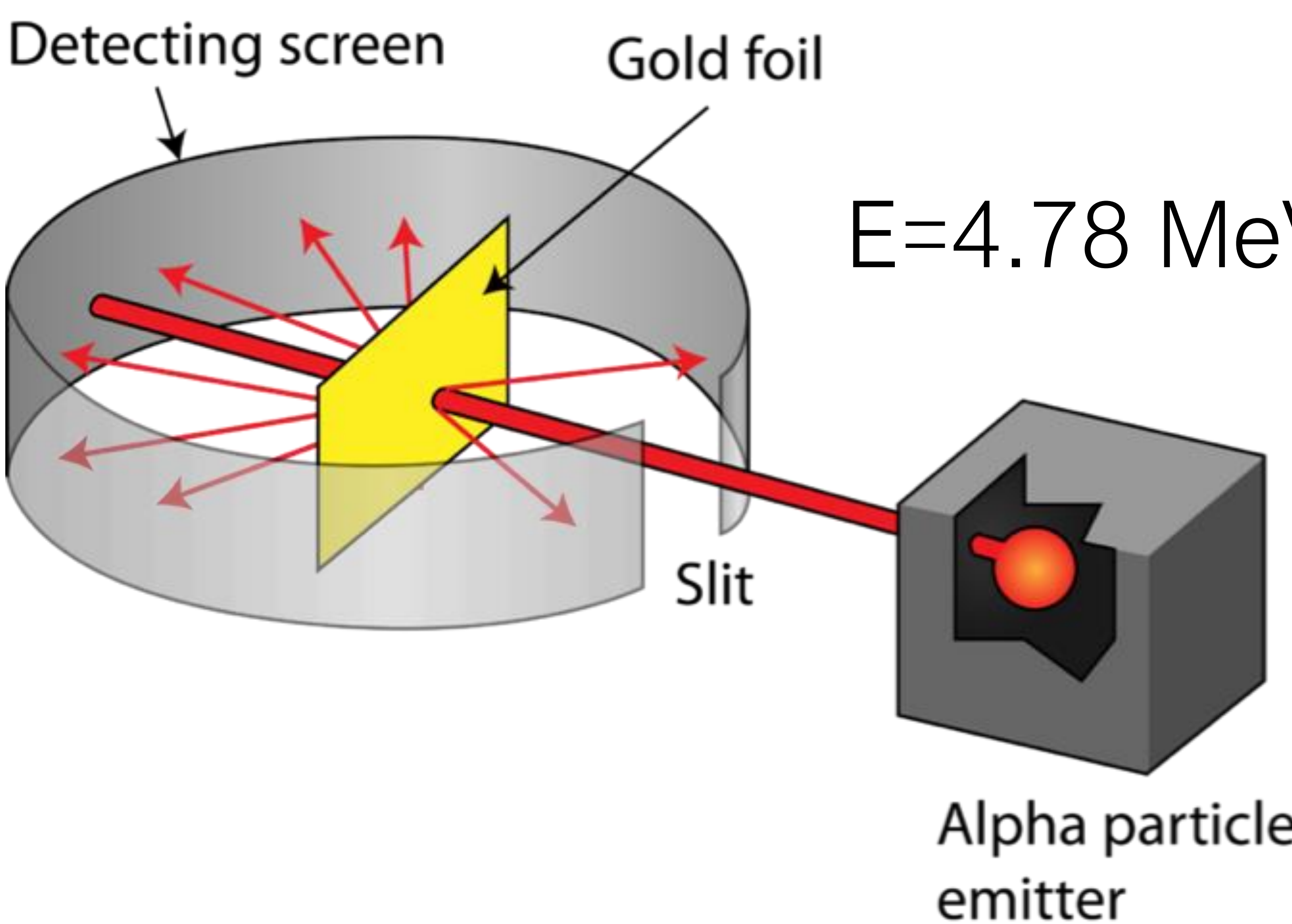
The scientific case for particle accelerators

The early 1900's…

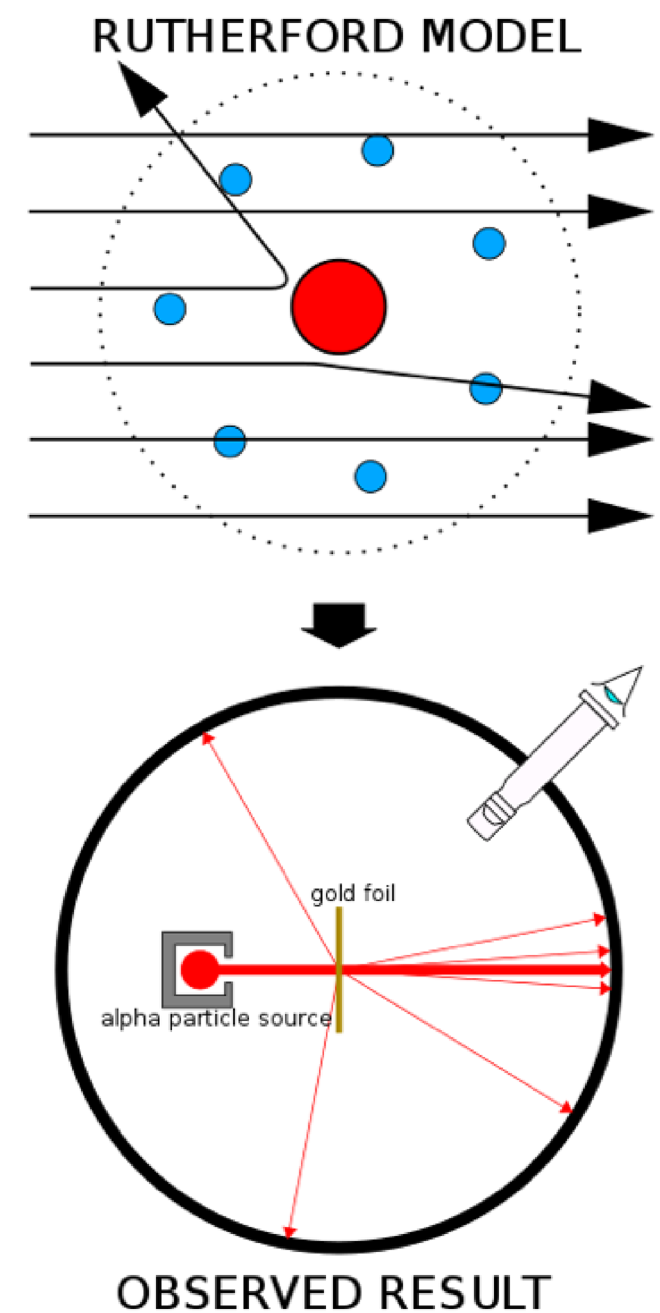


Rutherford* gold foil experiment, 1911

*Actually Ernest Marsden and Hans Geiger

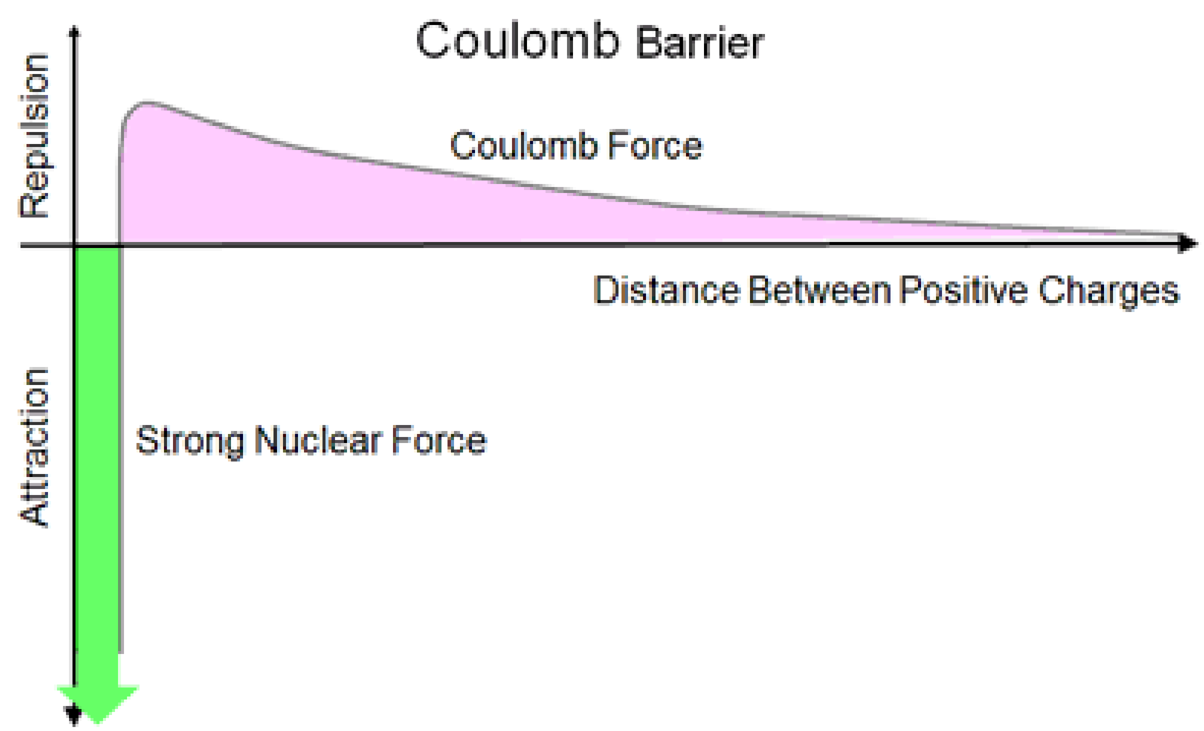


E=4.78 MeV

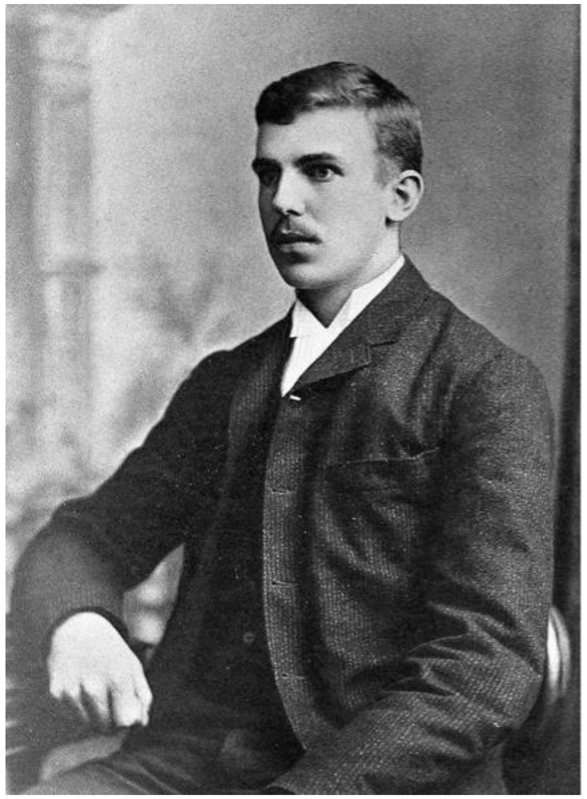


What is the nucleus?

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



Question: what were the limitations of using natural radioactive sources?



"*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

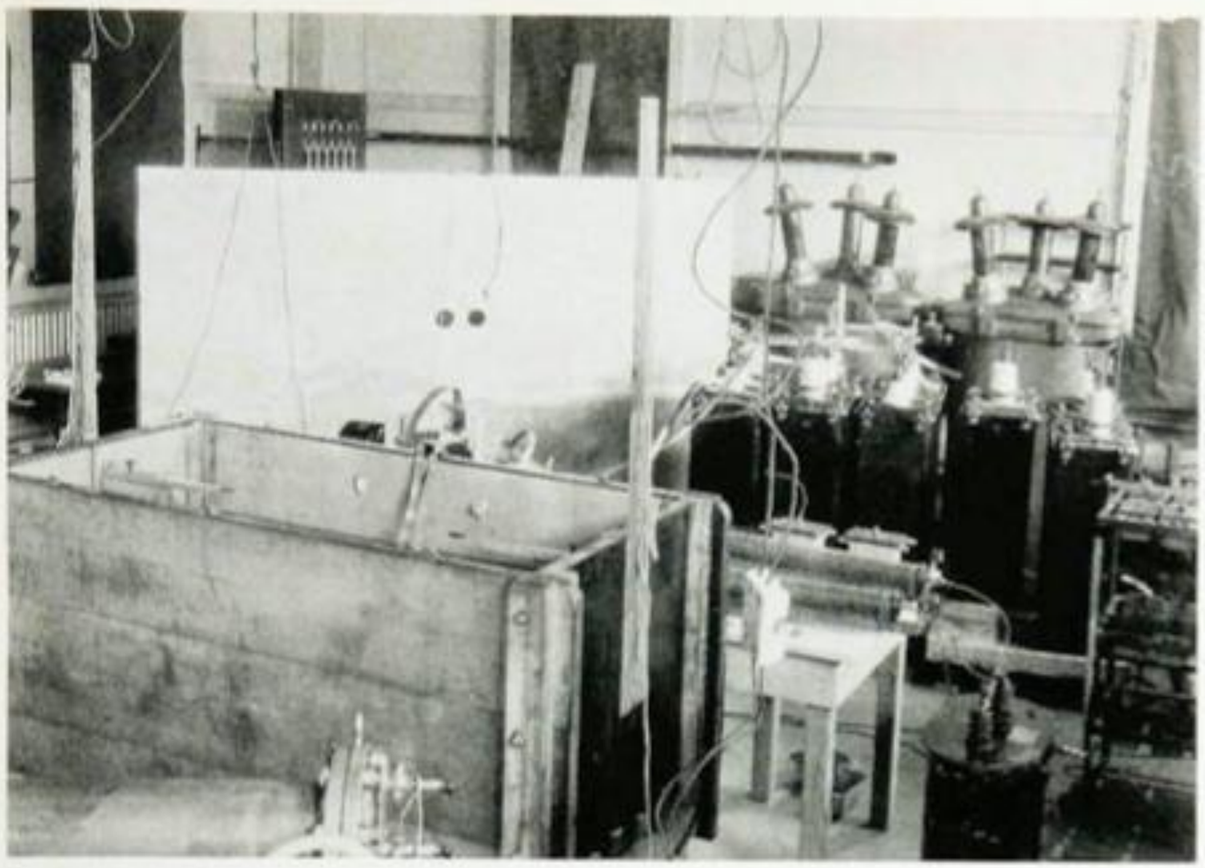
The 1920's


High or Low
The Dirt Must Go
HOOVER
How much easier than straining your arms and back trying to dust up high while you're "balanced" on a step-ladder.
And how much better The Hoover cleans!
PHONE
84


ELECTRIC STYLE SHOW
Electrical
ON DISPLAY DAILY
OTTER TAIL POWER CO.
FEATURING
RUNNING WATER
HOT WATER
COOKING
APPLIANCES
REFRIGERATION
CLEANERS
WASHERS

Attempts at Electrostatic Accelerators

Tesla Coil

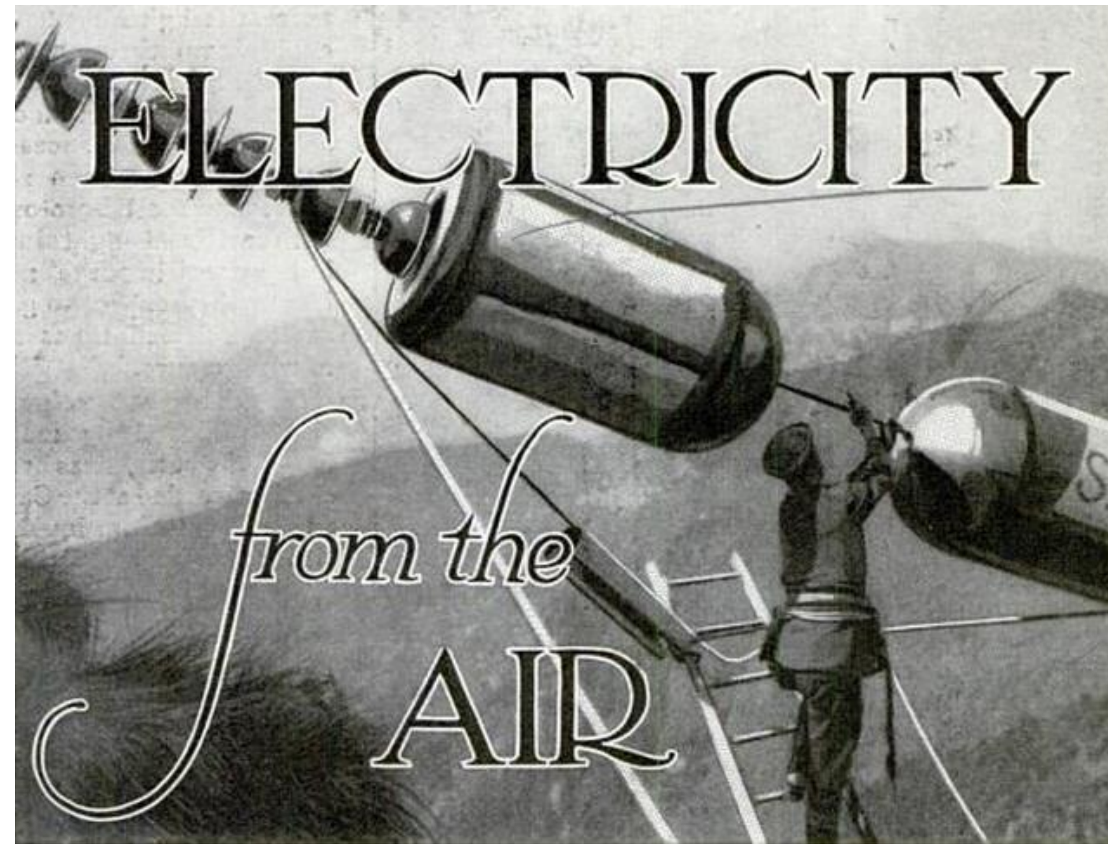


Early version of the Tesla apparatus at the Carnegie Institution's Department of Terrestrial Magnetism in March 1927. By immersing the Tesla coil in a wooden tank filled with oil, Tuve and Gregory Breit succeeded in producing 3 million volts.

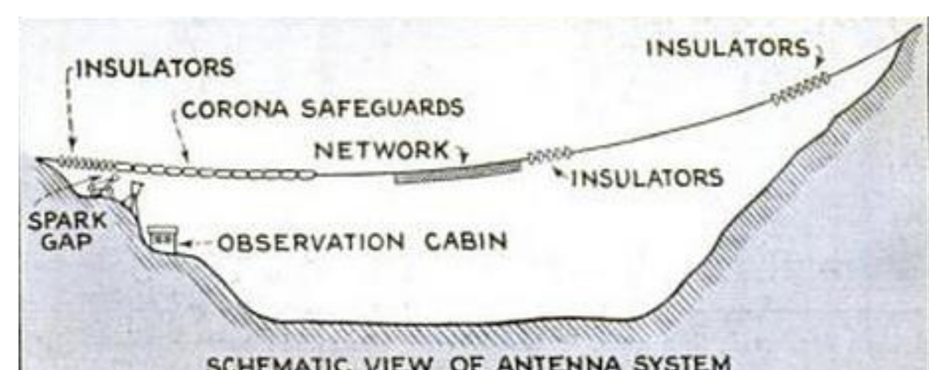
Thomas D. Cornell, Physics Today 41, 1, 57 (1988)

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

Lightning



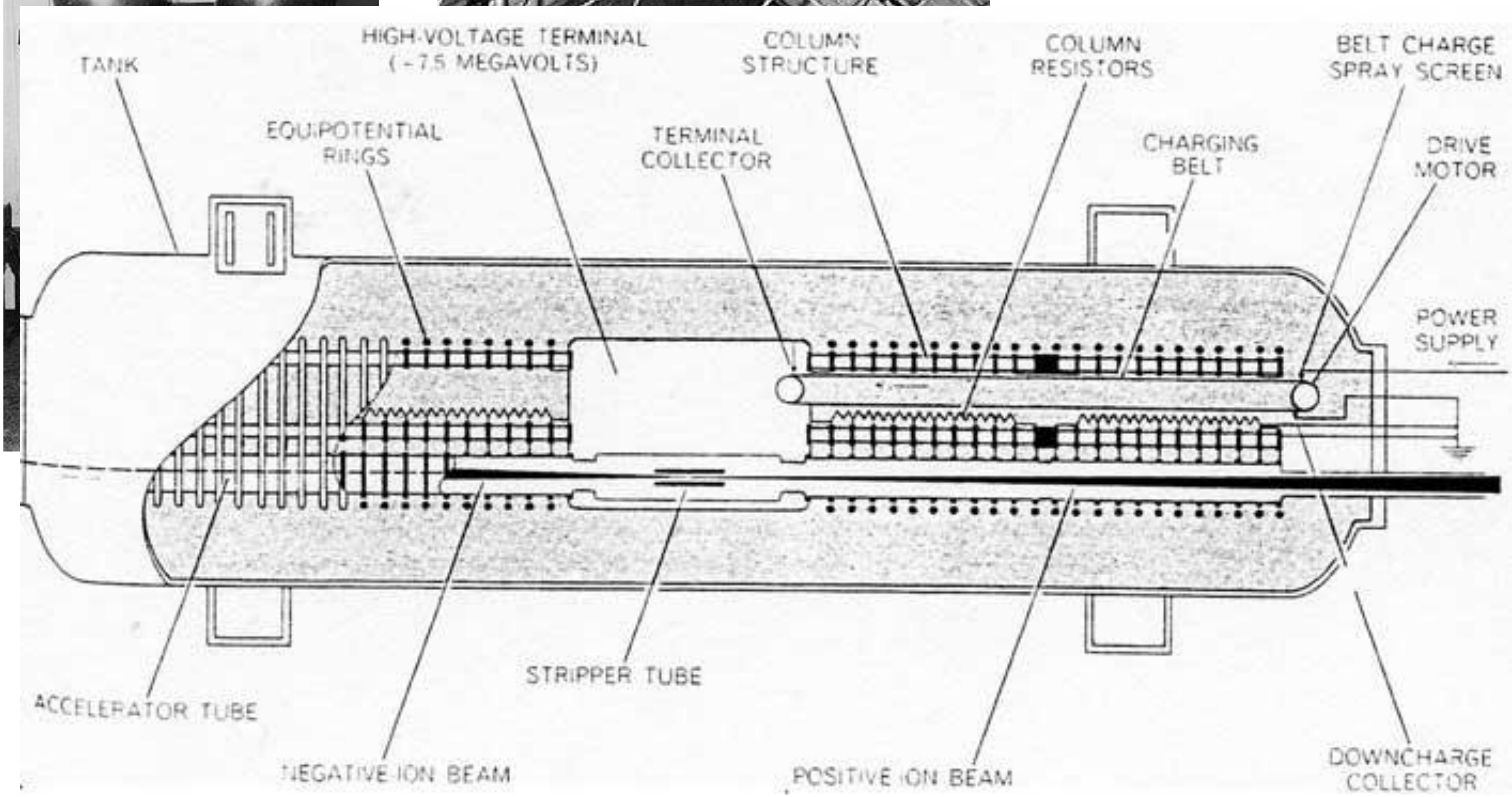
Arno Brasch, Fritz Lange, Kurt Urban, in Italian Alps 1927-28



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

Van de Graaff accelerator

Van de Graaff Generator

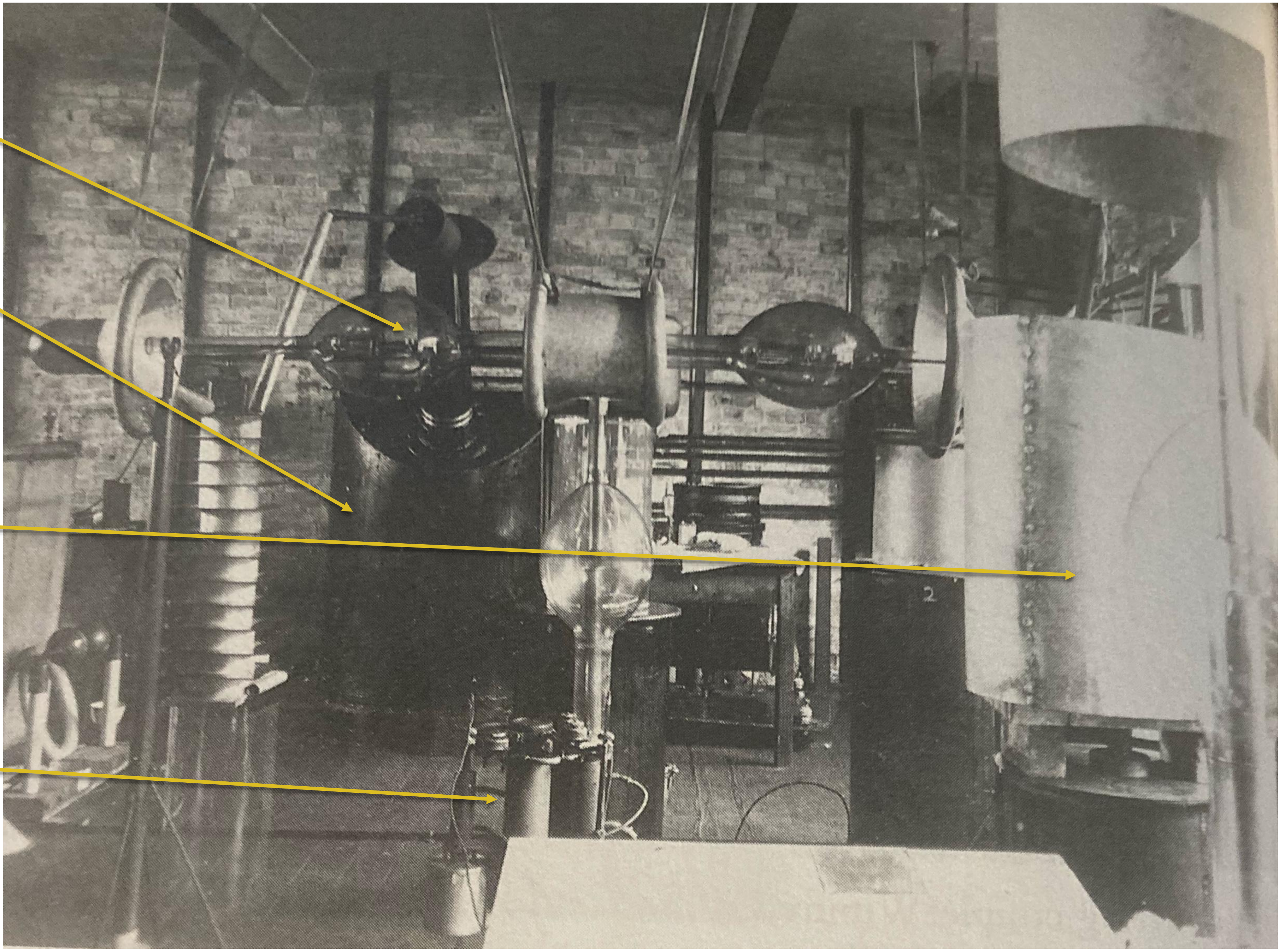


http://chem.ch.huji.ac.il/~eugeniik/history/graaff.html

Gamow changes the game

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

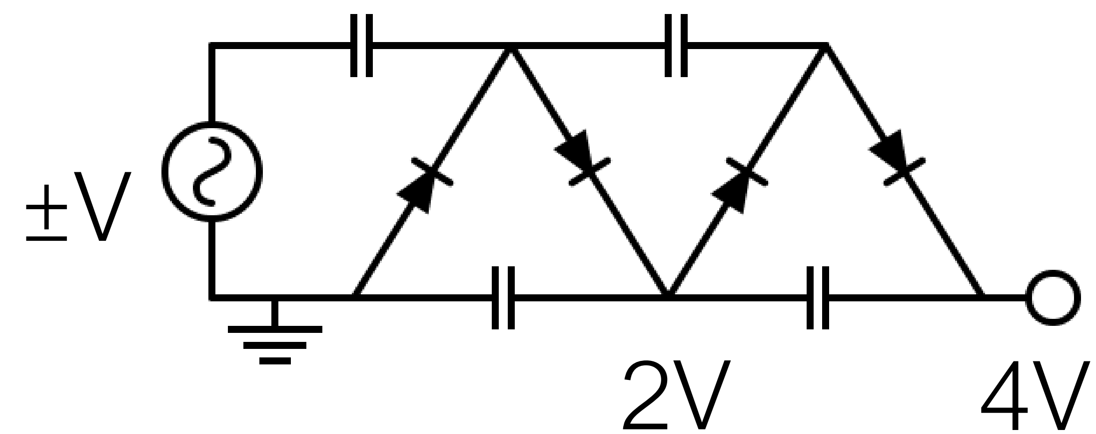
The first accelerator at Cambridge



Cockcroft-Walton accelerator: 1932

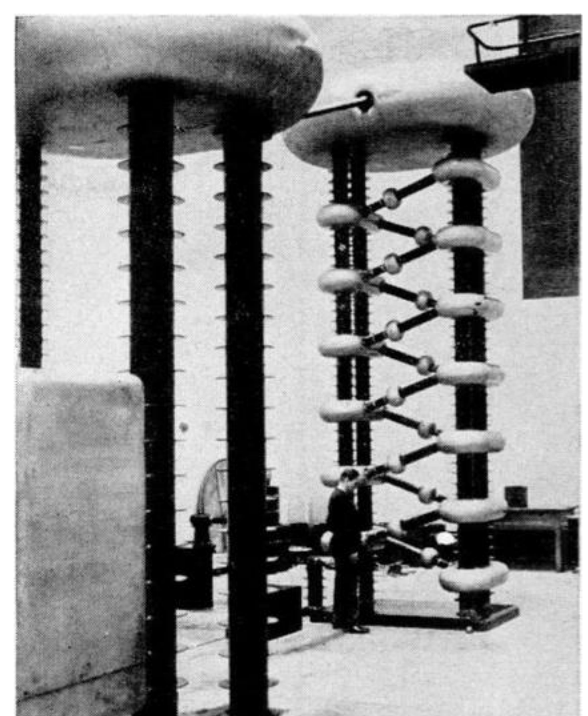
Walton and the machine used to "split the atom"

Cavendish Lab, Cambridge



Voltage multiplier circuit

https://www.youtube.com/watch?v=ep3D_LC2UzU



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

Science context

1932.

TWO CENTS

ATOM TORN APART, YIELDING 60% MORE ENERGY THAN USED

But Two British Scientists Succeed Only Once in Each 10,000,000 Bombarded.

BATTERED WITH PROTONS

Hydrogen Atoms Are Thus Transmuted Into Helium—Conservation Theory Seen Upset.

TESTS MADE FOR 3 YEARS

Dr. J. D. Cockroft and Dr. E. T. S. Walton of Cavendish Laboratory, Cambridge, Explain Work.

Special Cable to THE NEW YORK TIMES.

...May 1.—The atom has

'Forward in God,' ... Given by Hindenb...

By The Associat...

BERLIN, May 1.— ... von Hindenburg to... demic youth this mo... in God!"

The President bo... through a brightly ... torium, where six... ties were holding ... of the German St... Responding to the ... chaplain, the Pres... "I shall contin... strength to help ... upward path. B... too, that youth p... God."

CONGRESS ... TO ADJO...

Pressure of ... Chaos in ... the L...

WATSON ...

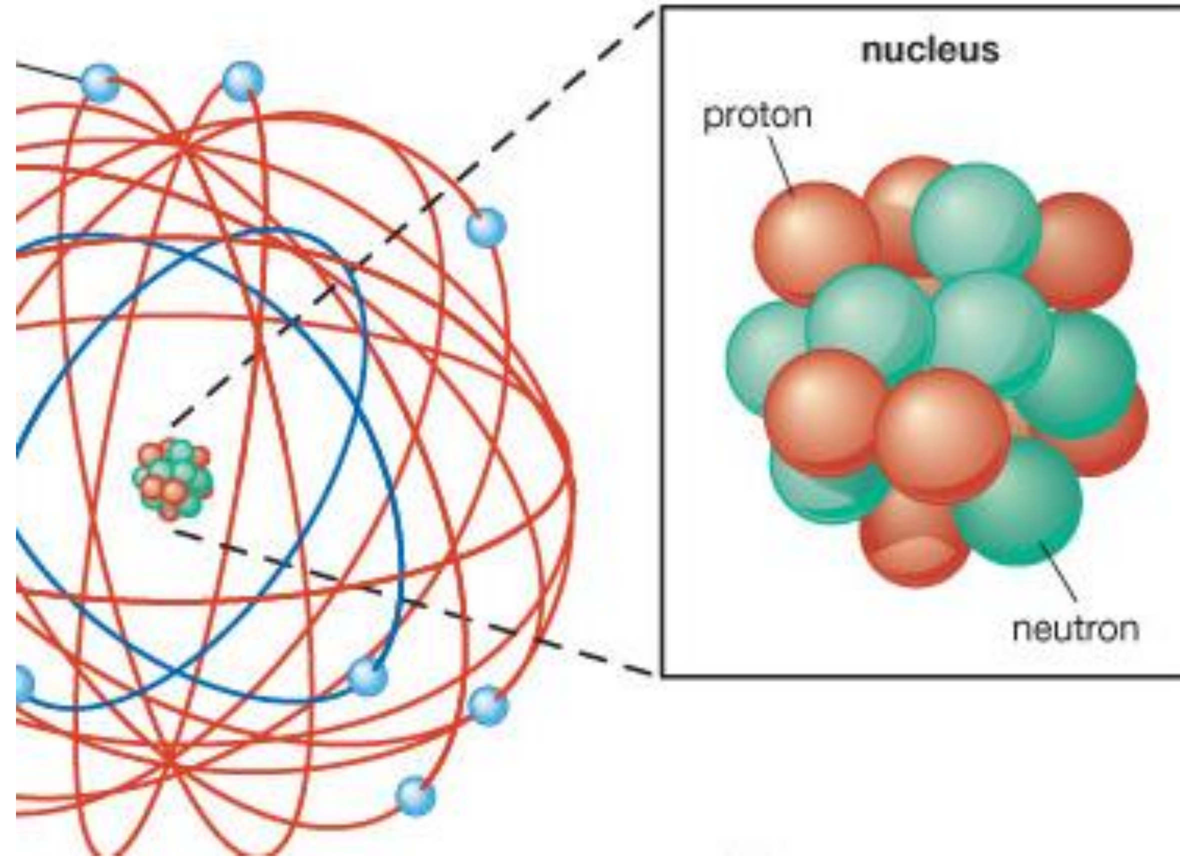
...irds Rule; ...ority Choice

...nventions. In 1924 ...ckwell, pre-conven... manager for William ...osed abolition of the ... Norman E. Mack, ...tteeman from New ...porter of Alfred E. ...d to change the ...ination. In neither ...roposal followed by ... change in the con... because abolition of ...pposed by Southern ...rting McAdoo and in ...mith was assured of ...the delegates by the ...ntion met.

... Governor Roosevelt ... that he will have a ... convention delegates, ...ssibility of an upset ... happen in the Cali... tomorrow, but they ... fearful of a blocking ...r more, of which the ...lged to Smith would ...eus.

...n of some of the most ...pporters of Roosevelt ...n would be made cer... abolition of the two... The Roosevelt leaders ... a majority in the con...

NEW YORK TIMES, May 2, 1932



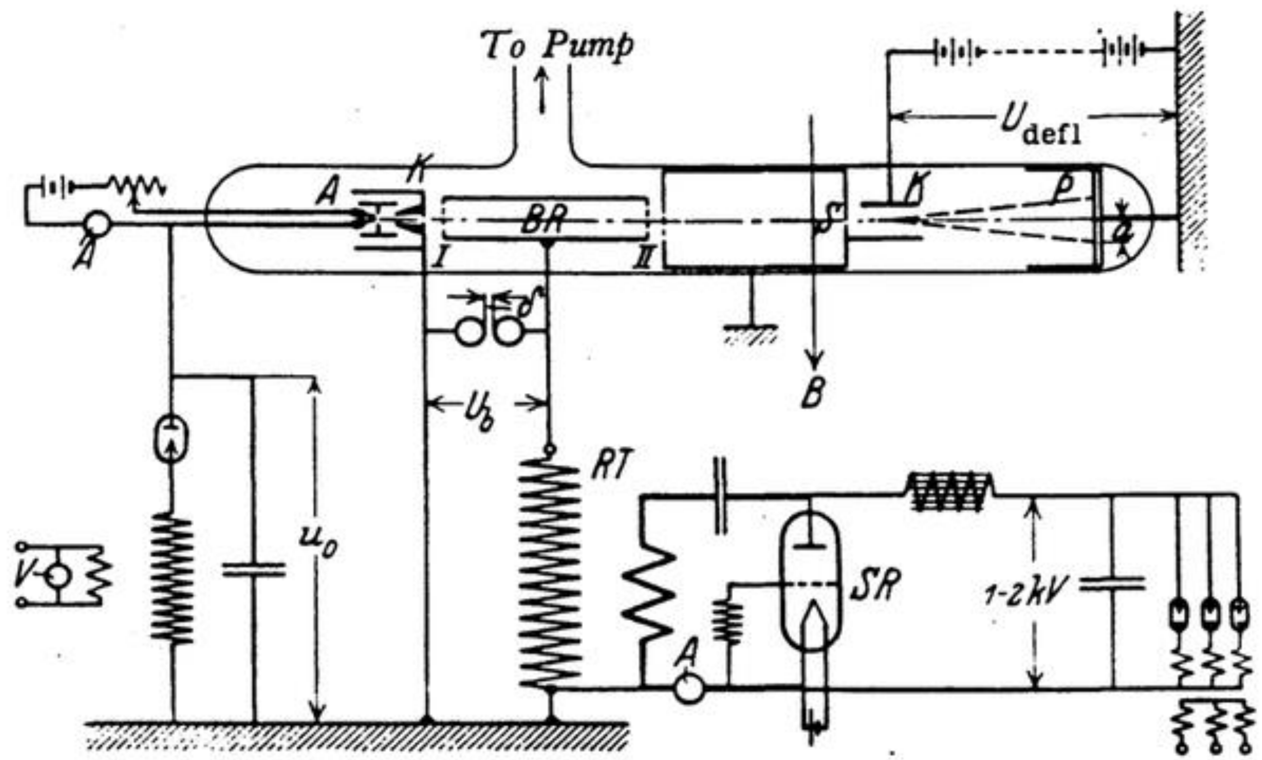
- Image: http://ck12.org.uk

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)

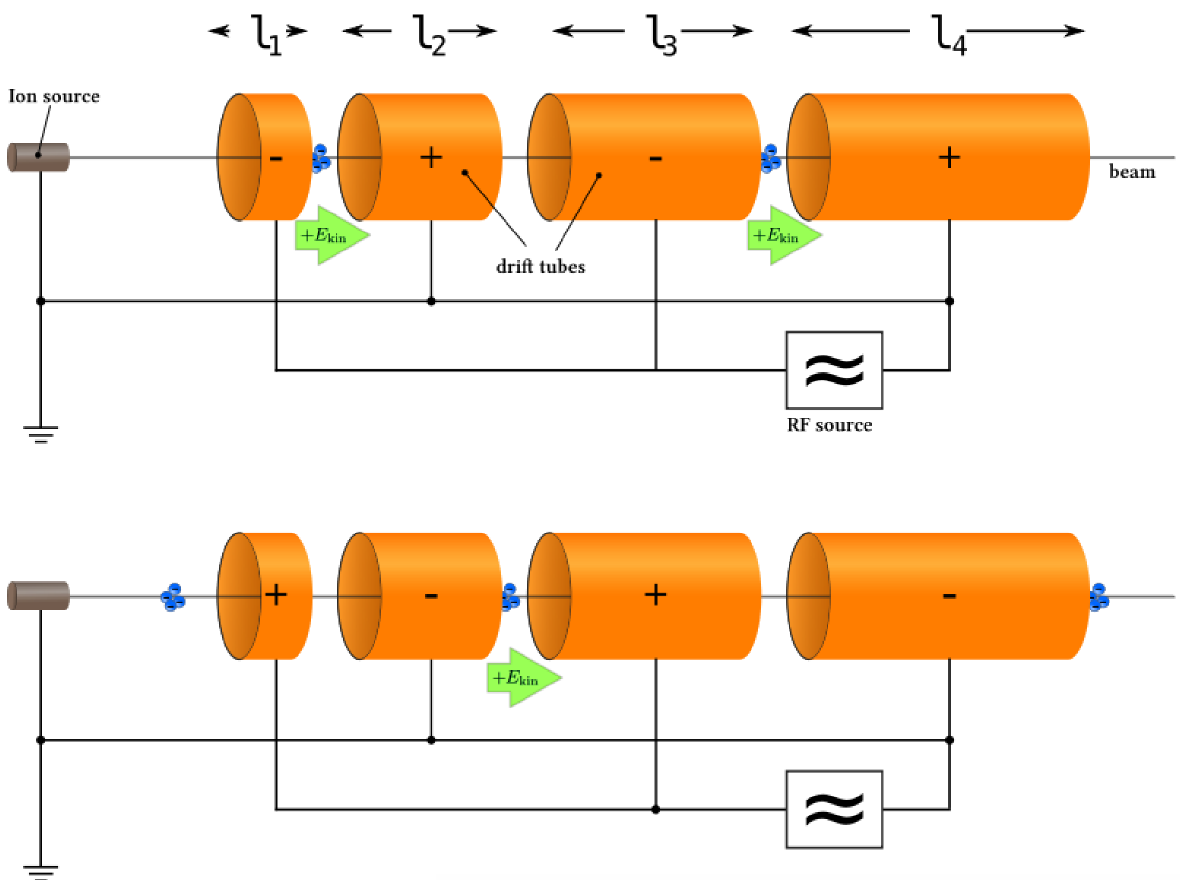


The linear accelerator & it's AC powering circuit

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

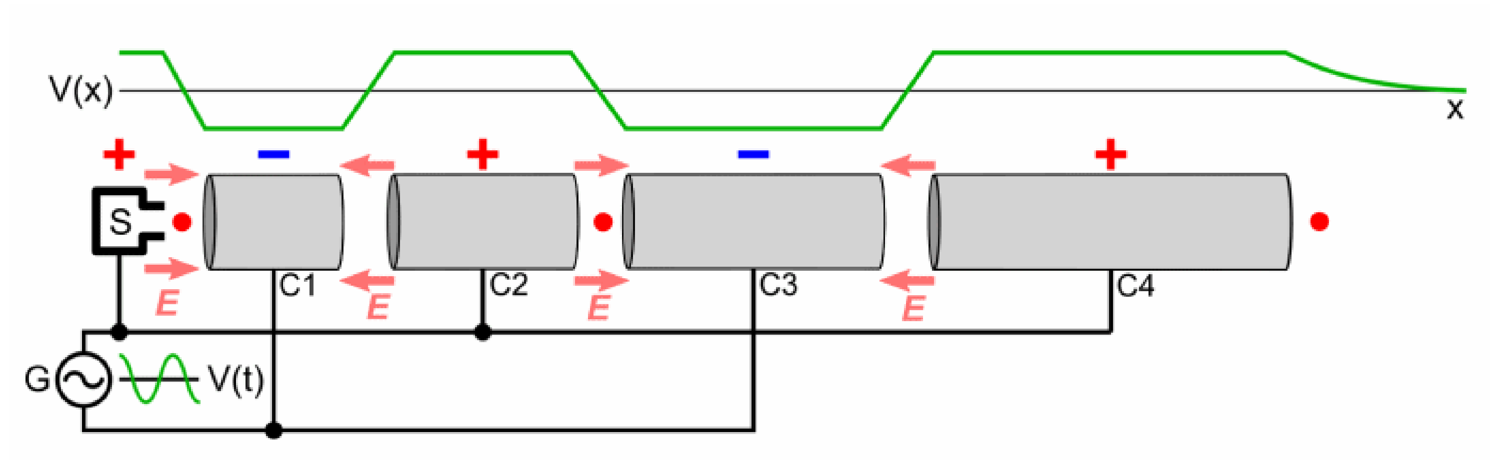
Linear Accelerators (2/3)

- Remember: there is no field inside a conductor



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

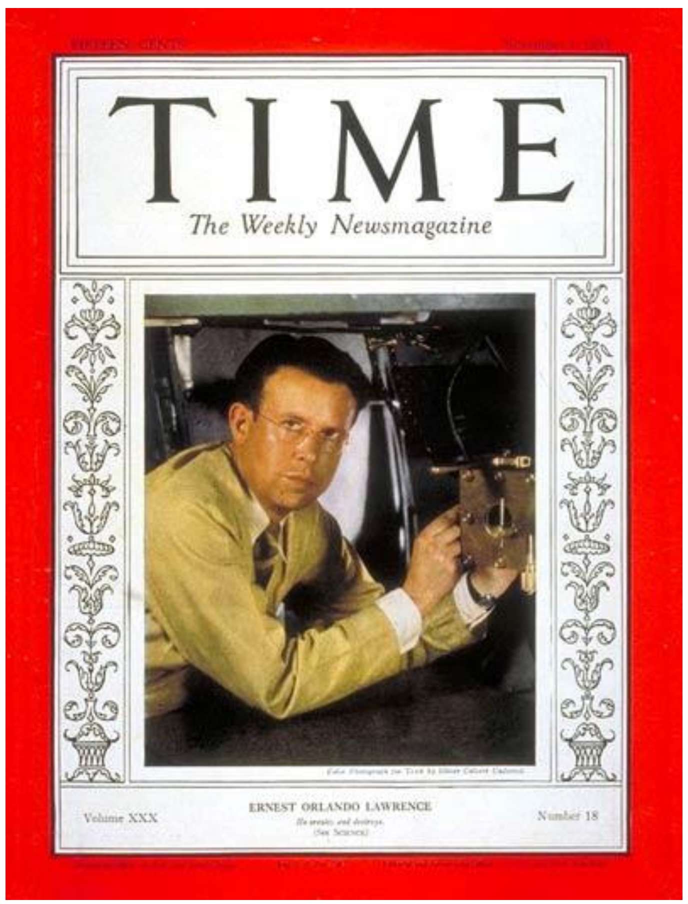
- For high energy, need high frequency RF sources
- Weren't available until after WWII



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


Boyhood friends…
Ernest Lawrence and Merle Tuve

Cyclotrons (1)

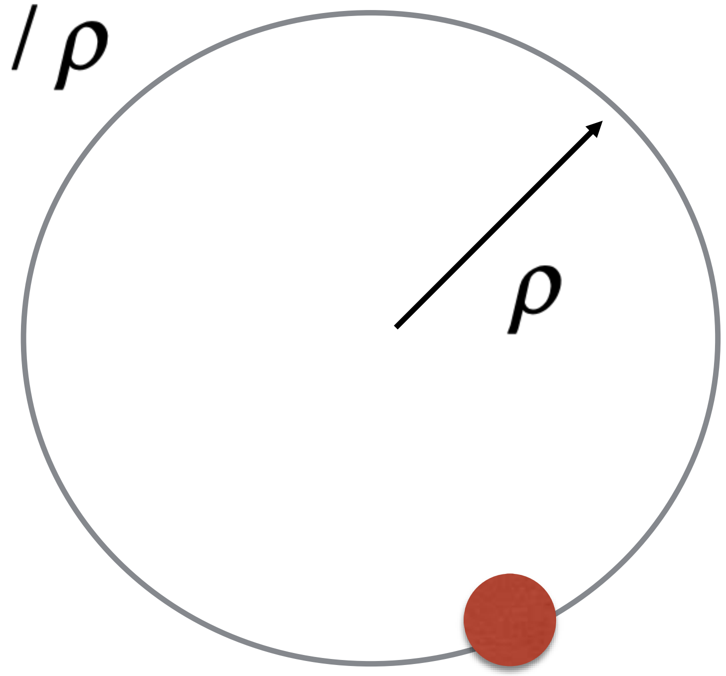


Ernest Orlando Lawrence

Centrifugal force = magnetic force

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

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



Cancelling out rho gives:

$$\omega_0 = qB_z / m$$

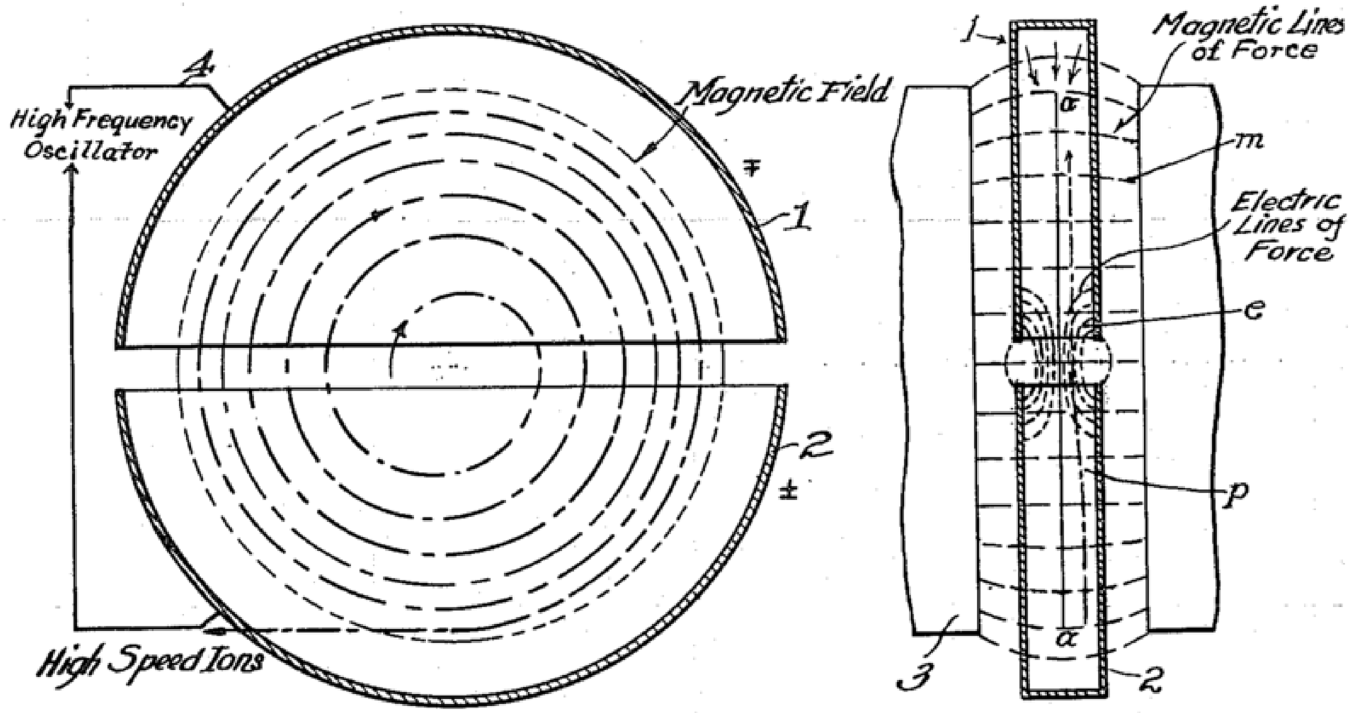
$$\rho = mv / qB_z$$

Lawrence: “R cancels R!”

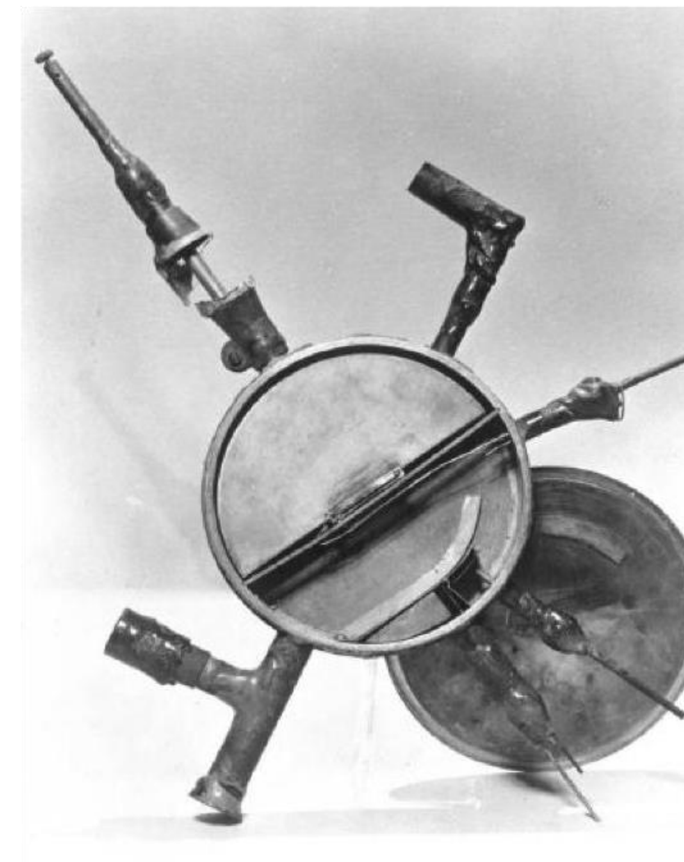
ie. for constant charge q and mass m, and a uniform magnetic field B, the angular frequency is constant. ie. the rf frequency can be constant. The orbit radius is proportional to speed, v.

Q. What is the issue with this statement?

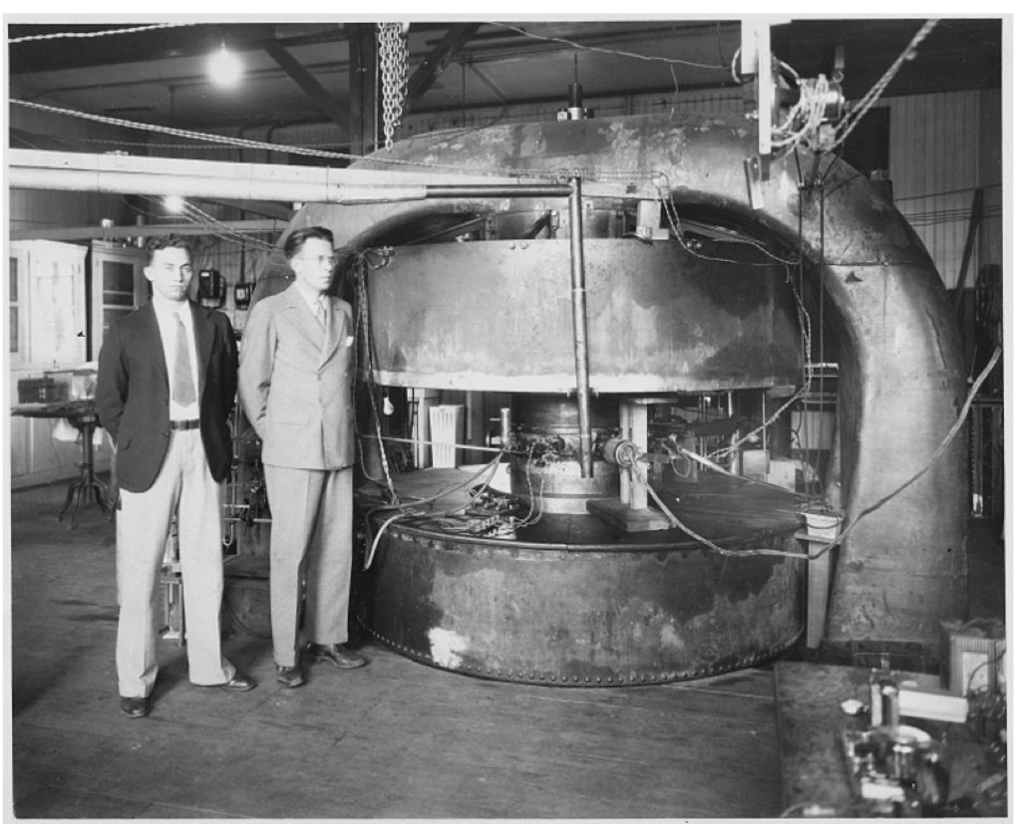
Cyclotrons (2)



The Cyclotron, from E. Lawrence’s 1934 patent



The first cyclotron



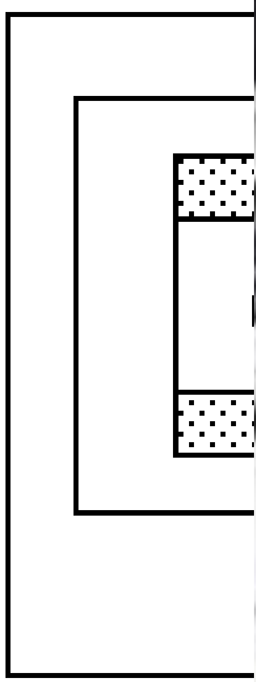
E. Lawrence & M. Stanley Livingston

A creative boom: the 1940s to 1960s

Betatron

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

- Li
- Us
- M
- Ac
  m



tion &

.

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

Ima

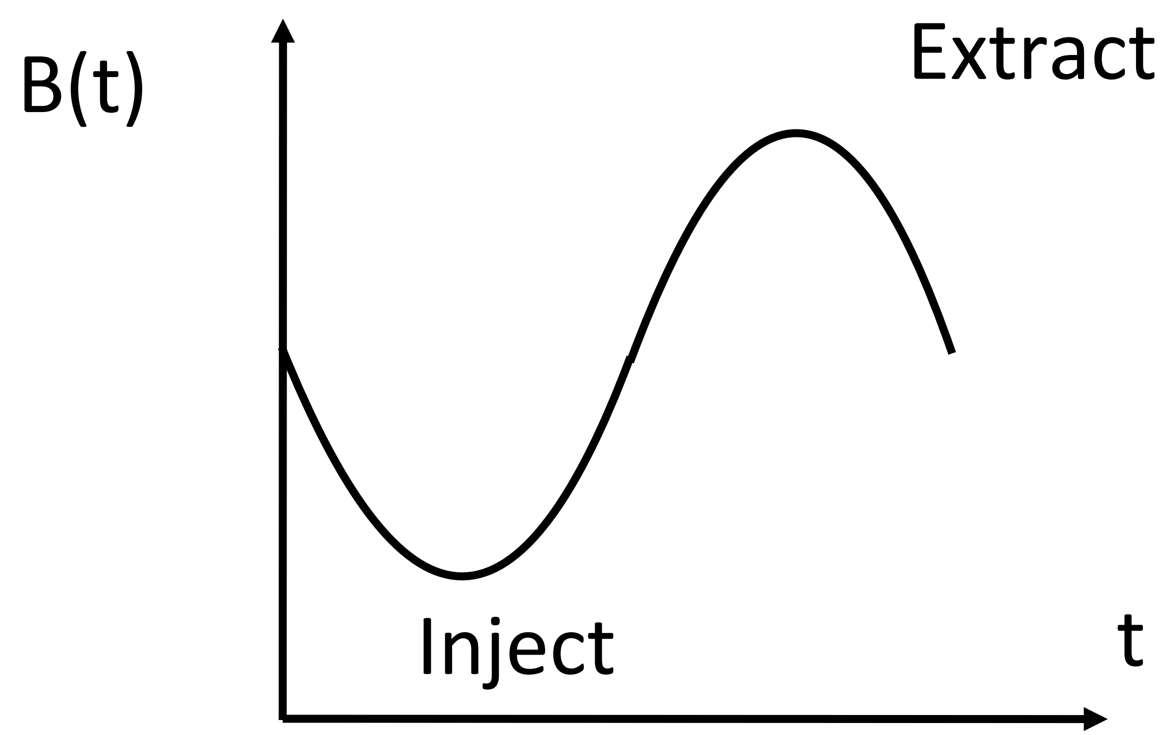
Blewett raises a problem:
do electrons radiate?

- Ivanenko & Pomeranchuk: upper limit to betatron energy around 500MeV! (1944)
- Shwinger 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

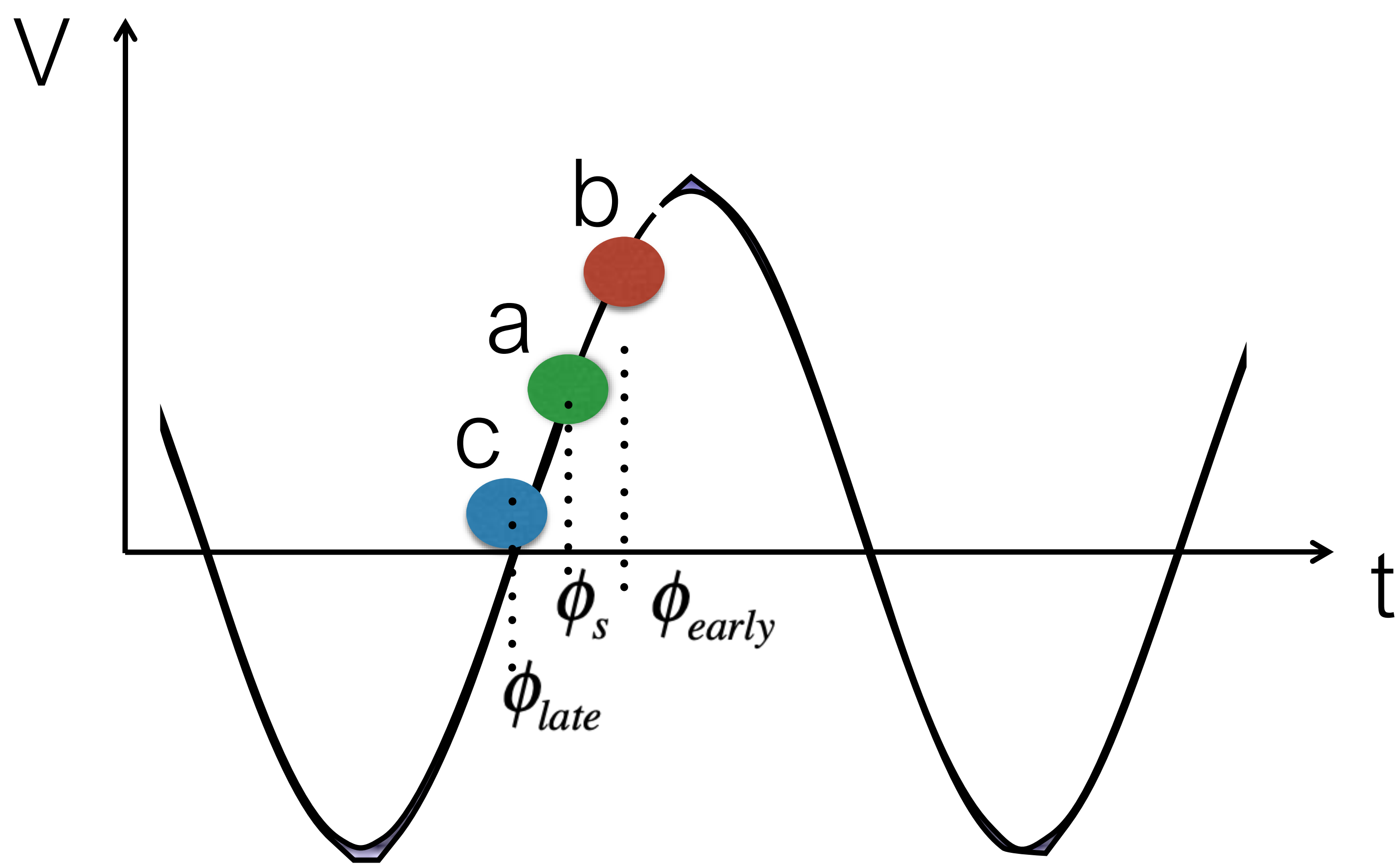
Vladimir Veksler & Ed McMillan

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

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



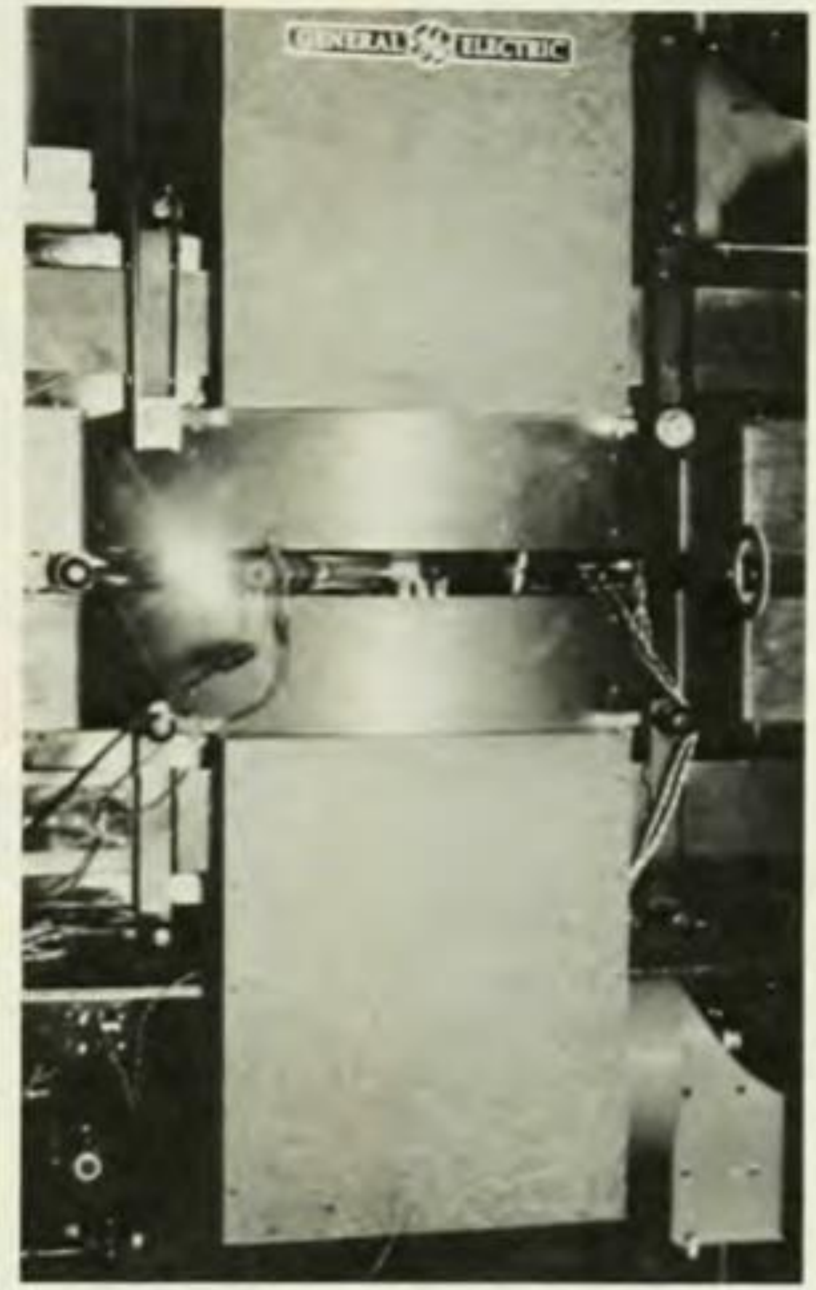
Discovery of Synchrotron Light

GE, 1947

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

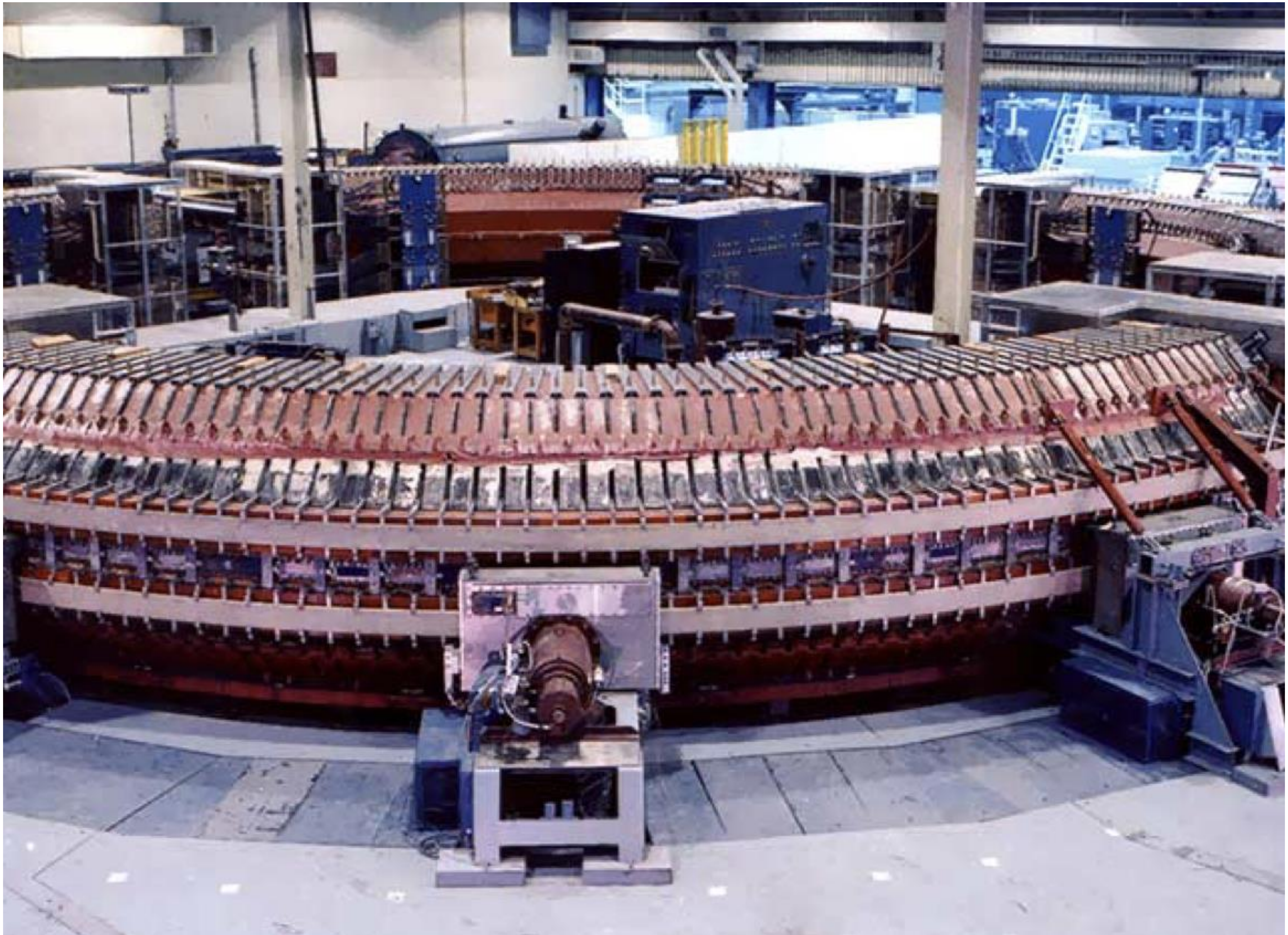
NB. GE team were beaten to ‘first synchrotron’ by a month:

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

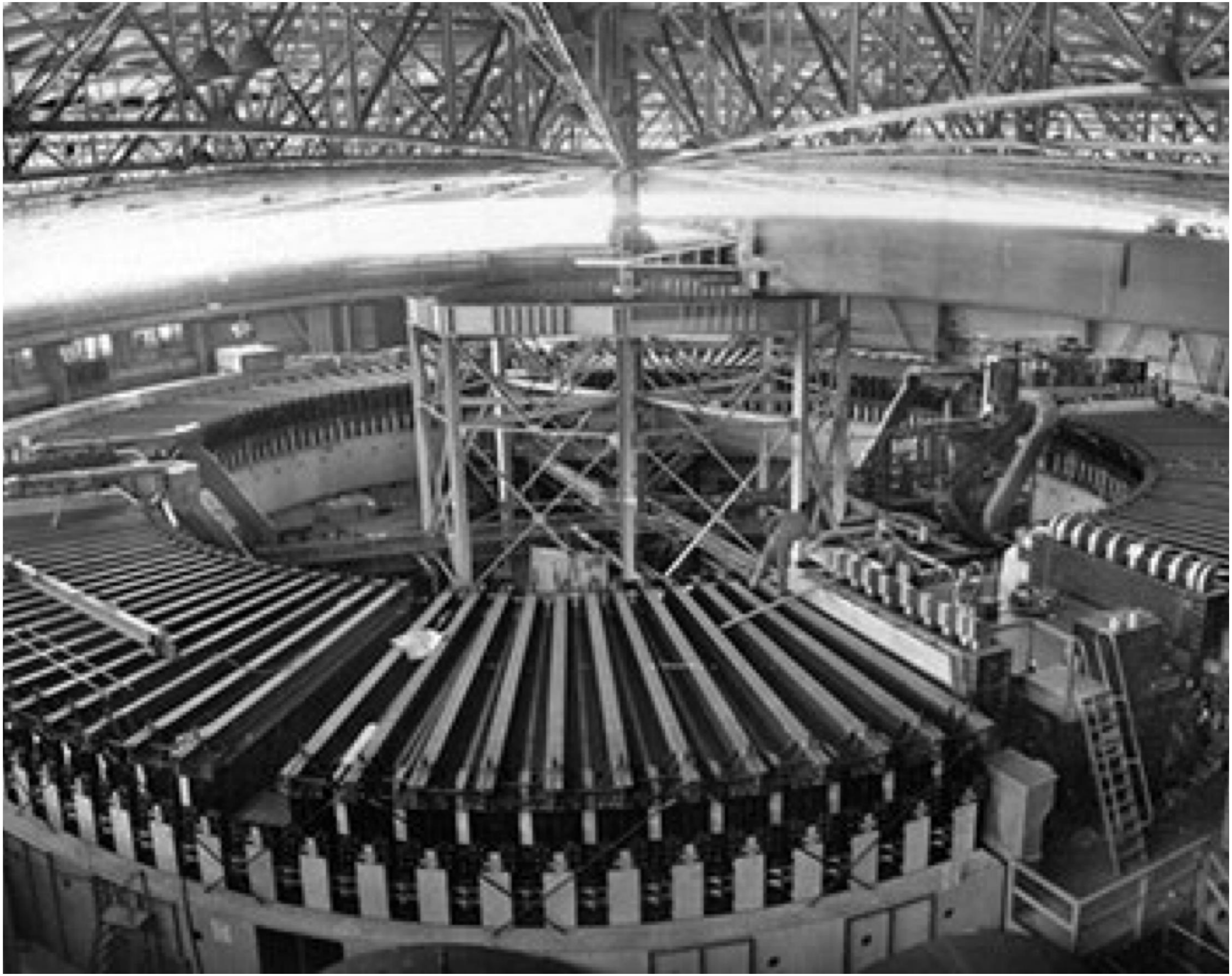


Synchrotron radiation from 70-MeV machine at General Electric Research Laboratory where it was first discovered in 1947.

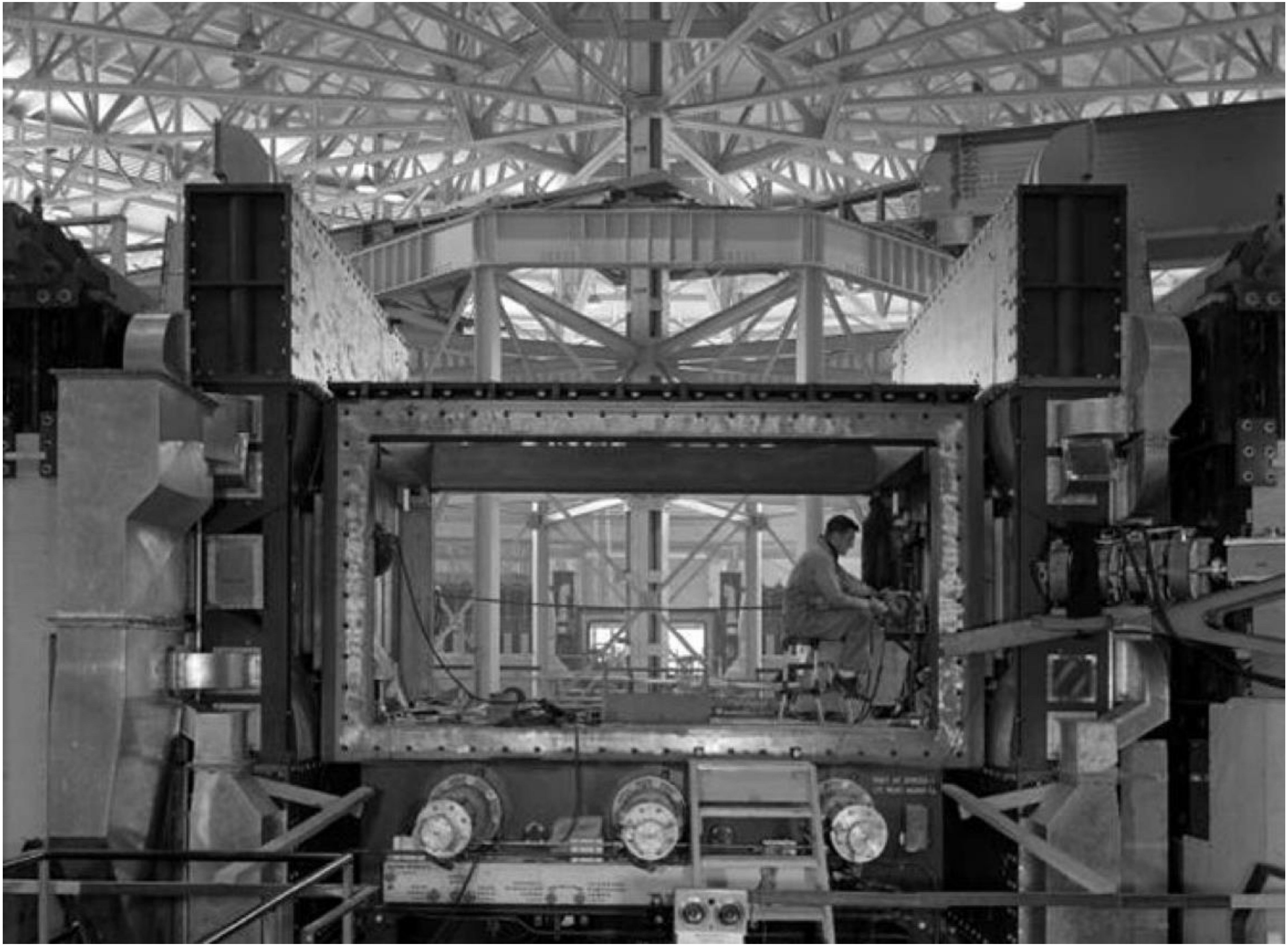
Proton Synchrotrons



The Cosmotron, BNL



The Bevatron, Berkeley: discovered the antiproton



Strong Focusing

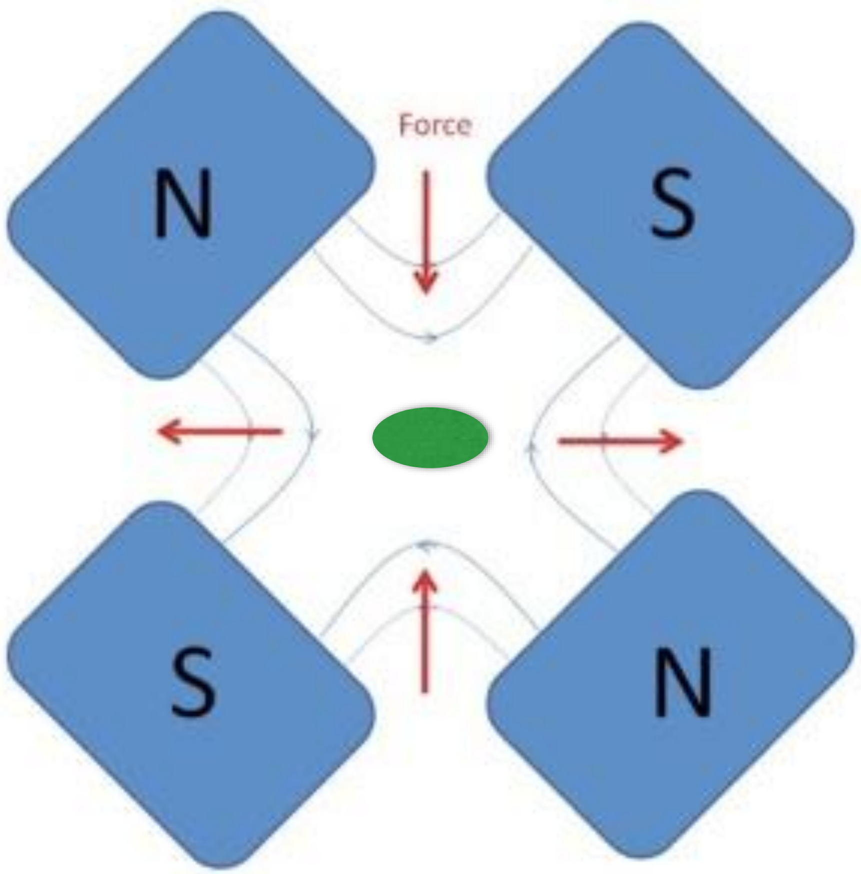
Brookhaven, 1952, Livingston: Can we turn around some Cosmotron magnets?

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



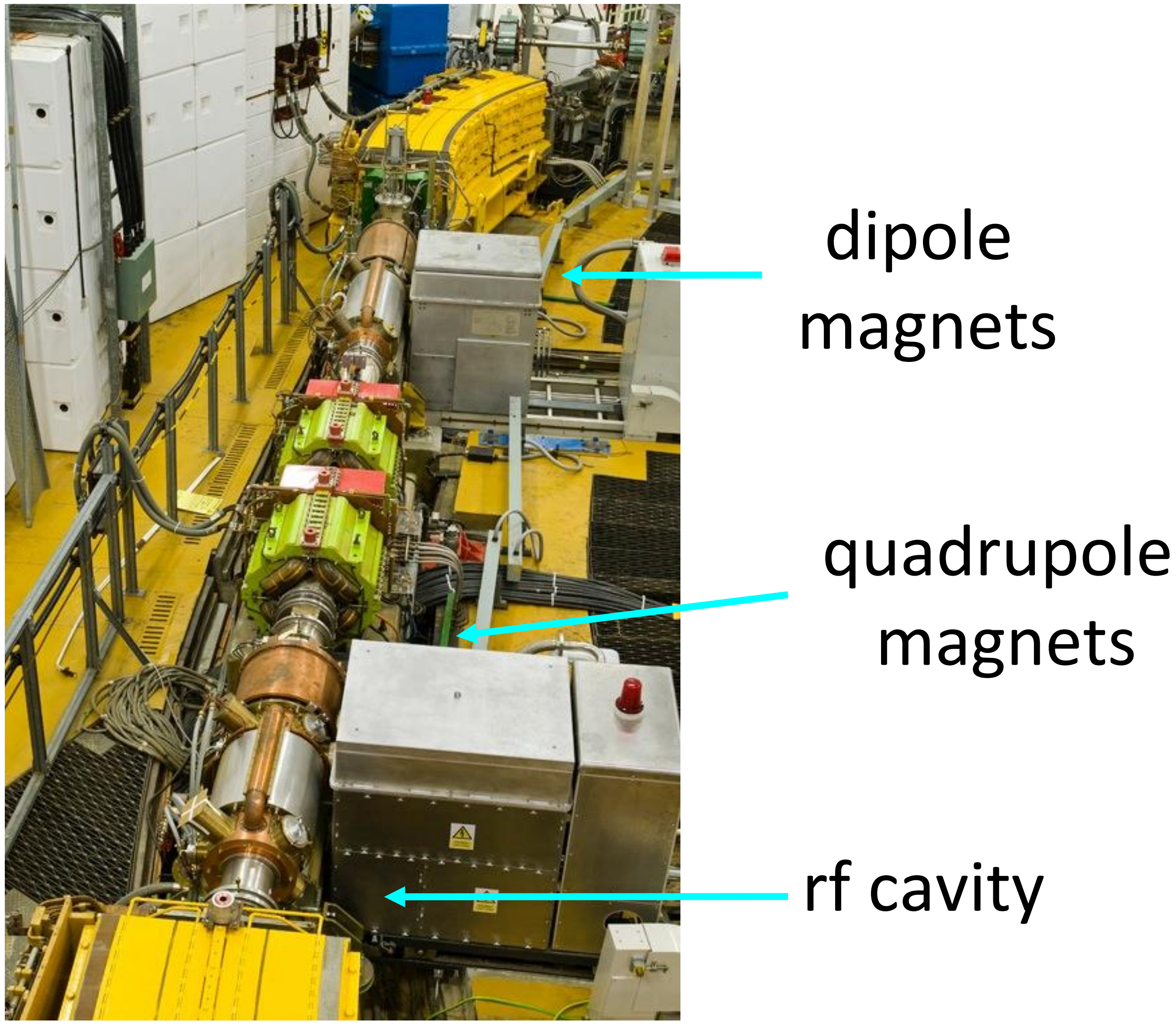


Image courtesy of ISIS, STFC

“What about the Midwest?”
The tale of MURA

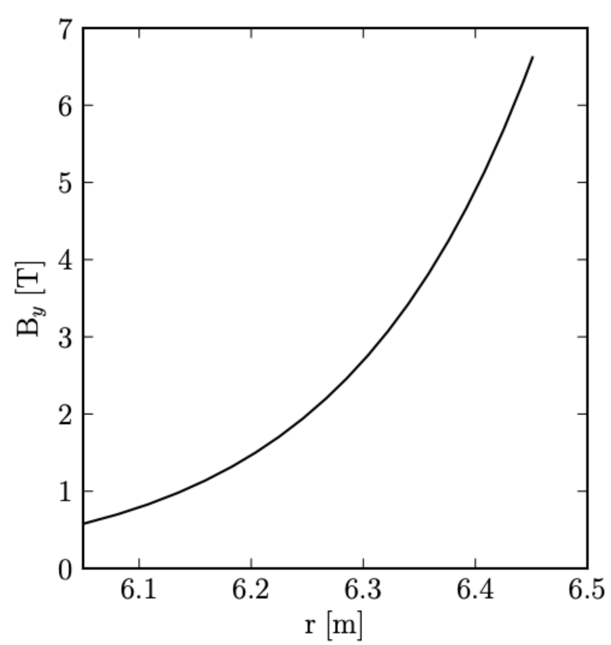
(i) beam stacking,
(ii) Hamiltonian theory of longitudinal motion,
(iii) useful colliding beams (the idea itself is quite old),
(iv) storage rings (independently invented by O'Neill),
(v) spiral-sector geometry used in isochronous cyclotrons,
(vi) lattices with zero-dispersion and low-β sections for 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

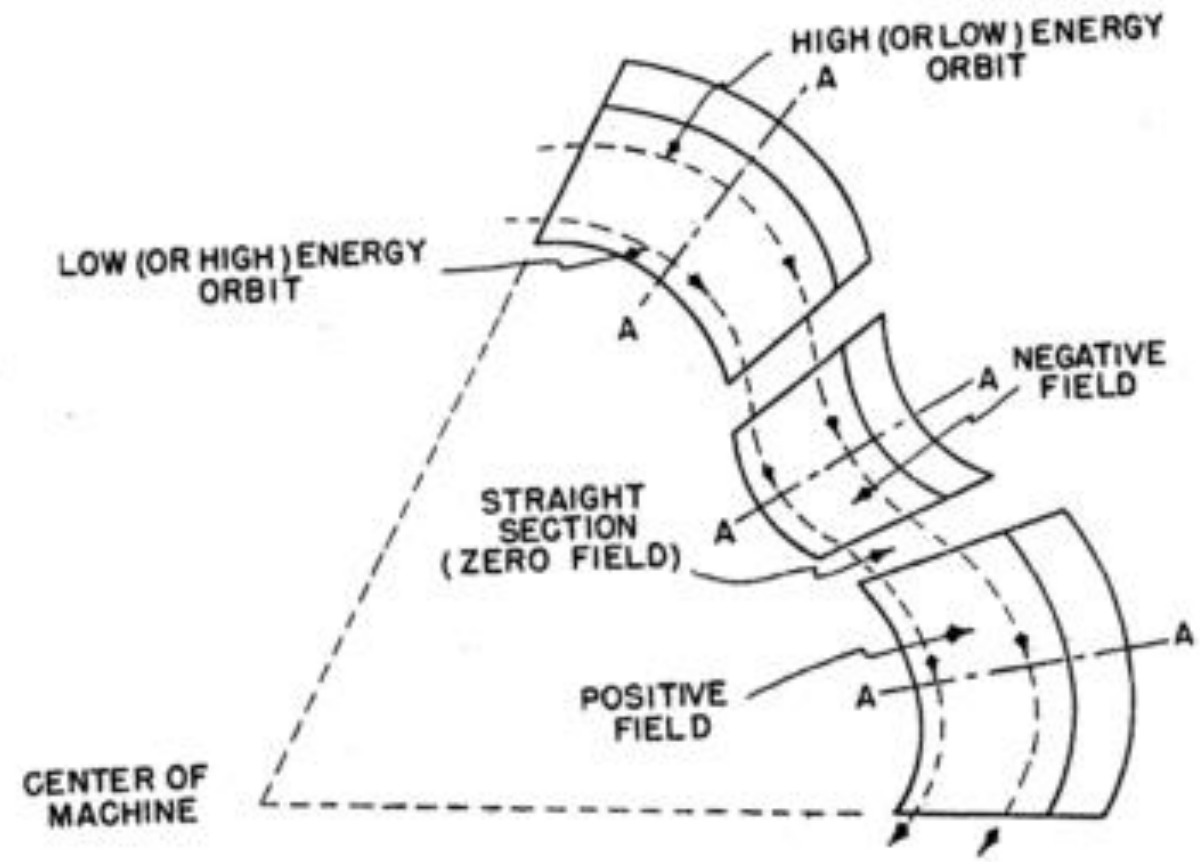
Fixed Field Alternating Gradient Accelerators (FFAs)

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

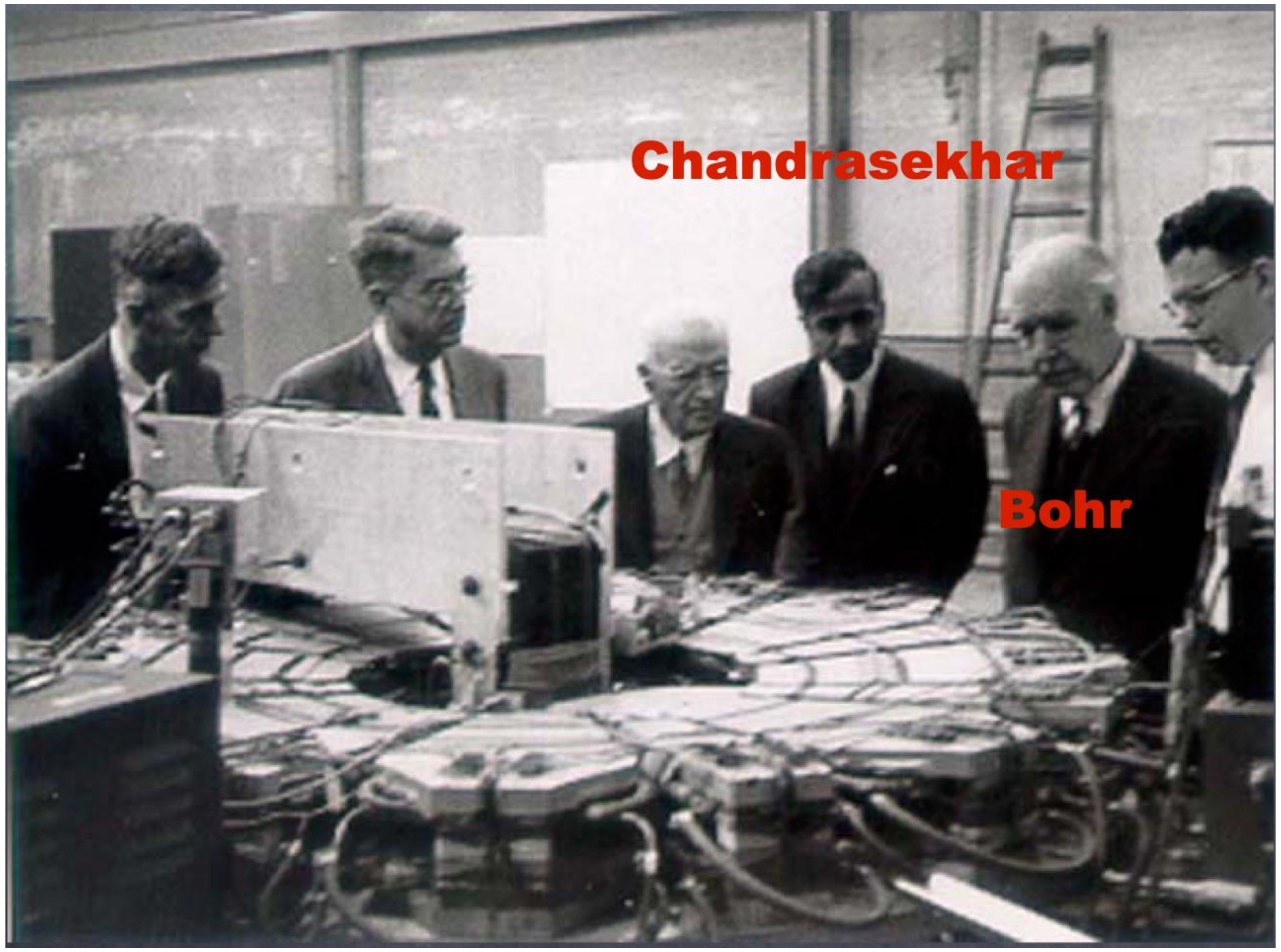
$$B_y = B_0 \left(\frac{r}{r_0} \right)^k F(\theta)$$

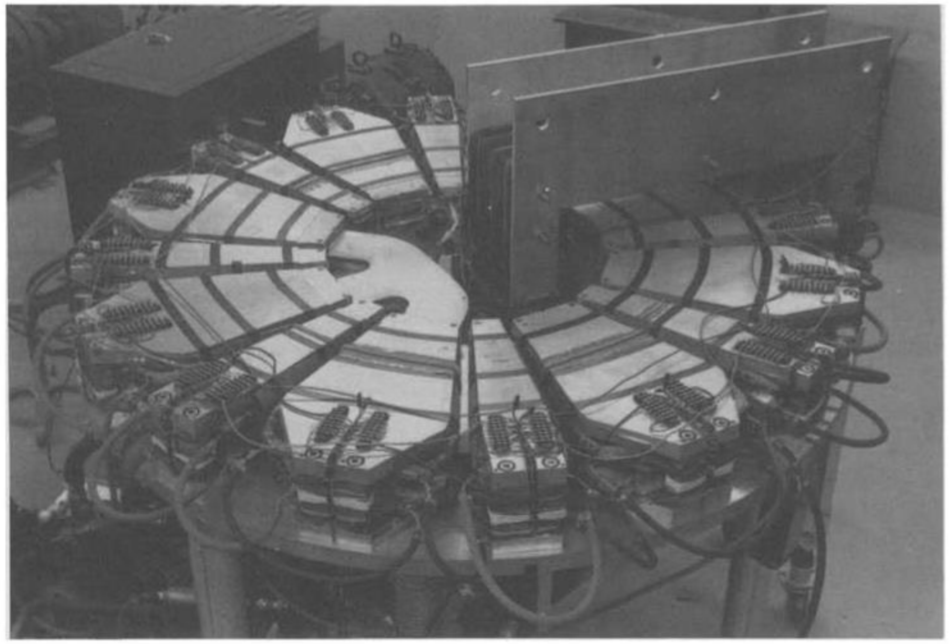


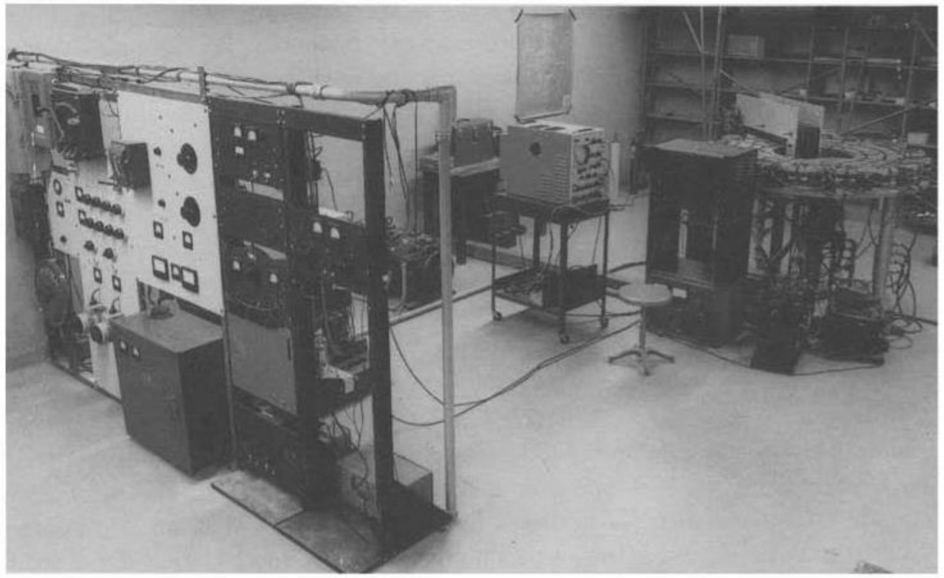


Note that this field profile does NOT satisfy isochronicity

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



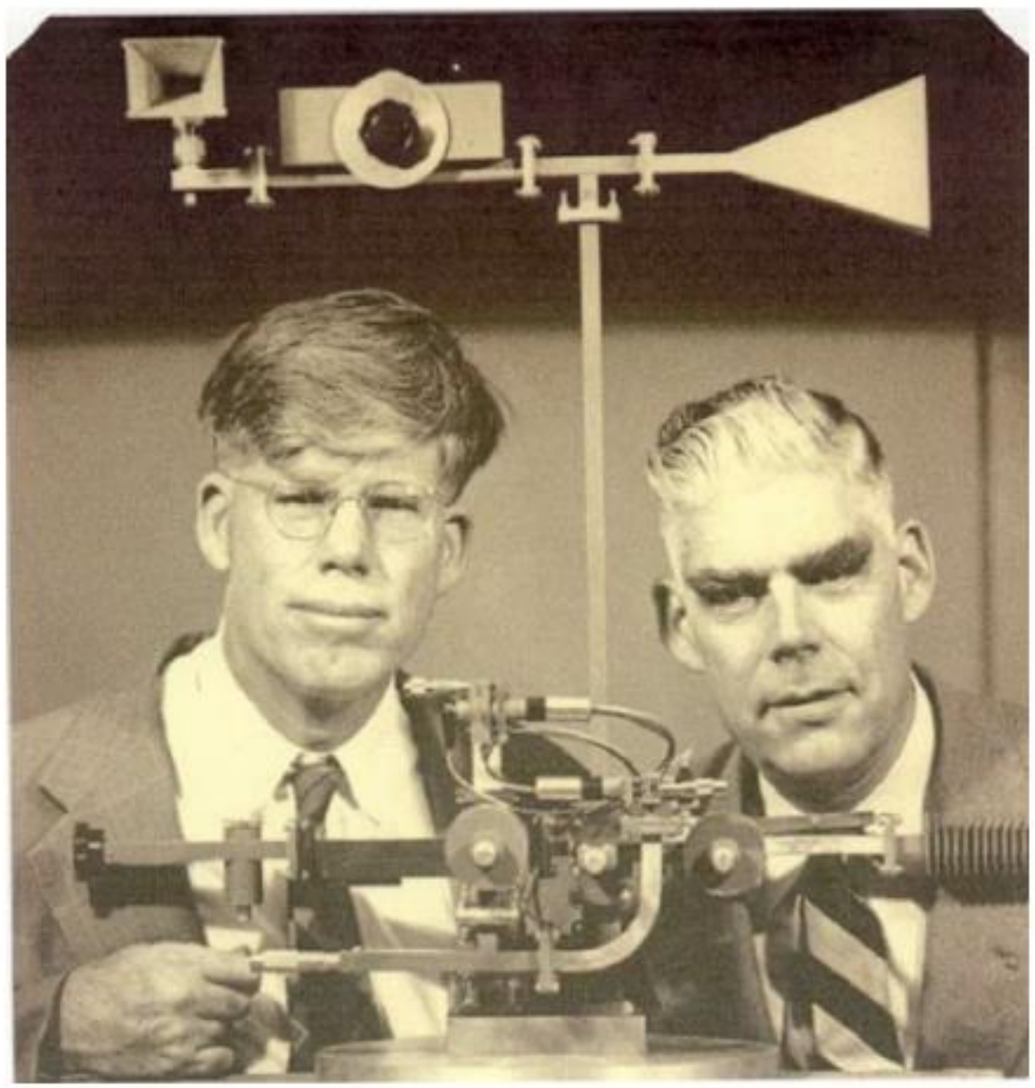




1956

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

LINACs & klystrons: from radar to accelerators



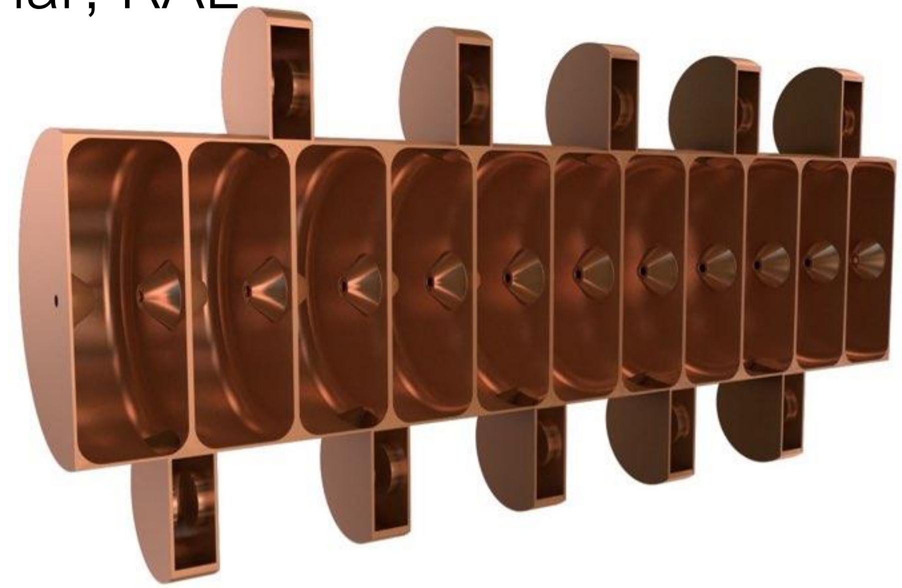
Russ & Sigurd Varian

Bill Hansen & team

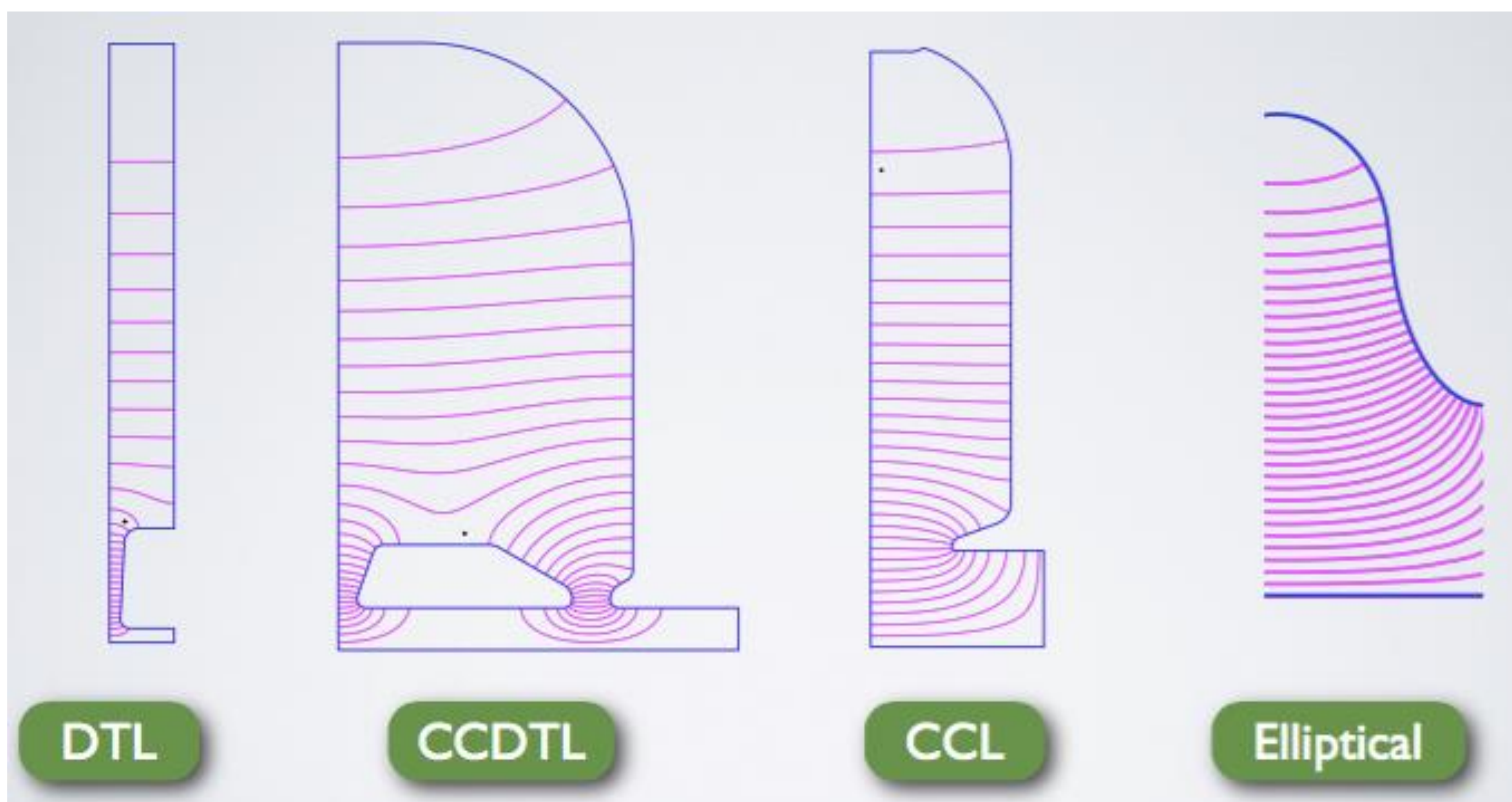
Linac Structures

Images thanks to Ciprian Plostinar, RAL

DTL: Drift Tube Linac



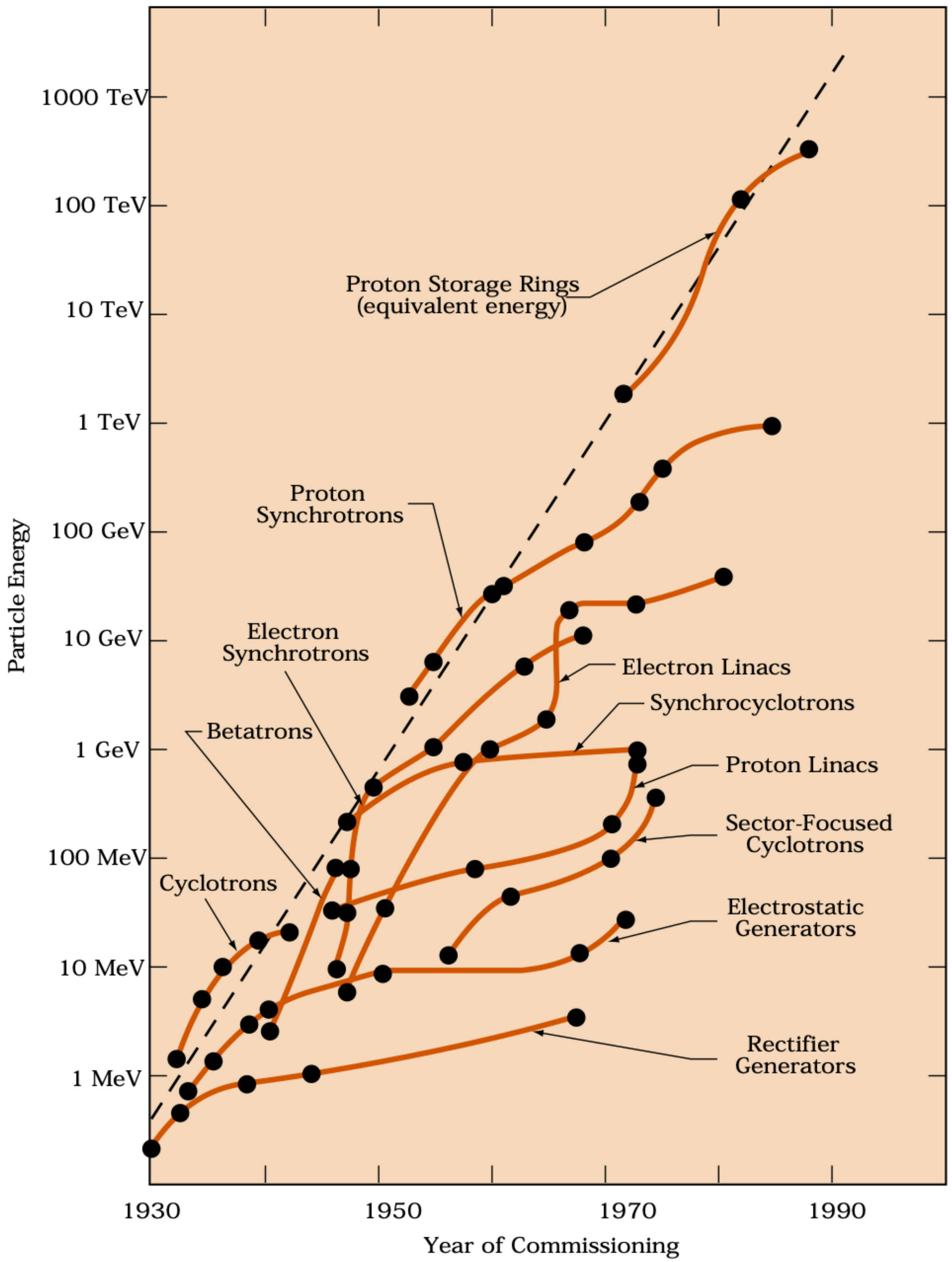
CCL: Coupled Cavity Linac



F. Gerigk, CERN

An established field and a 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

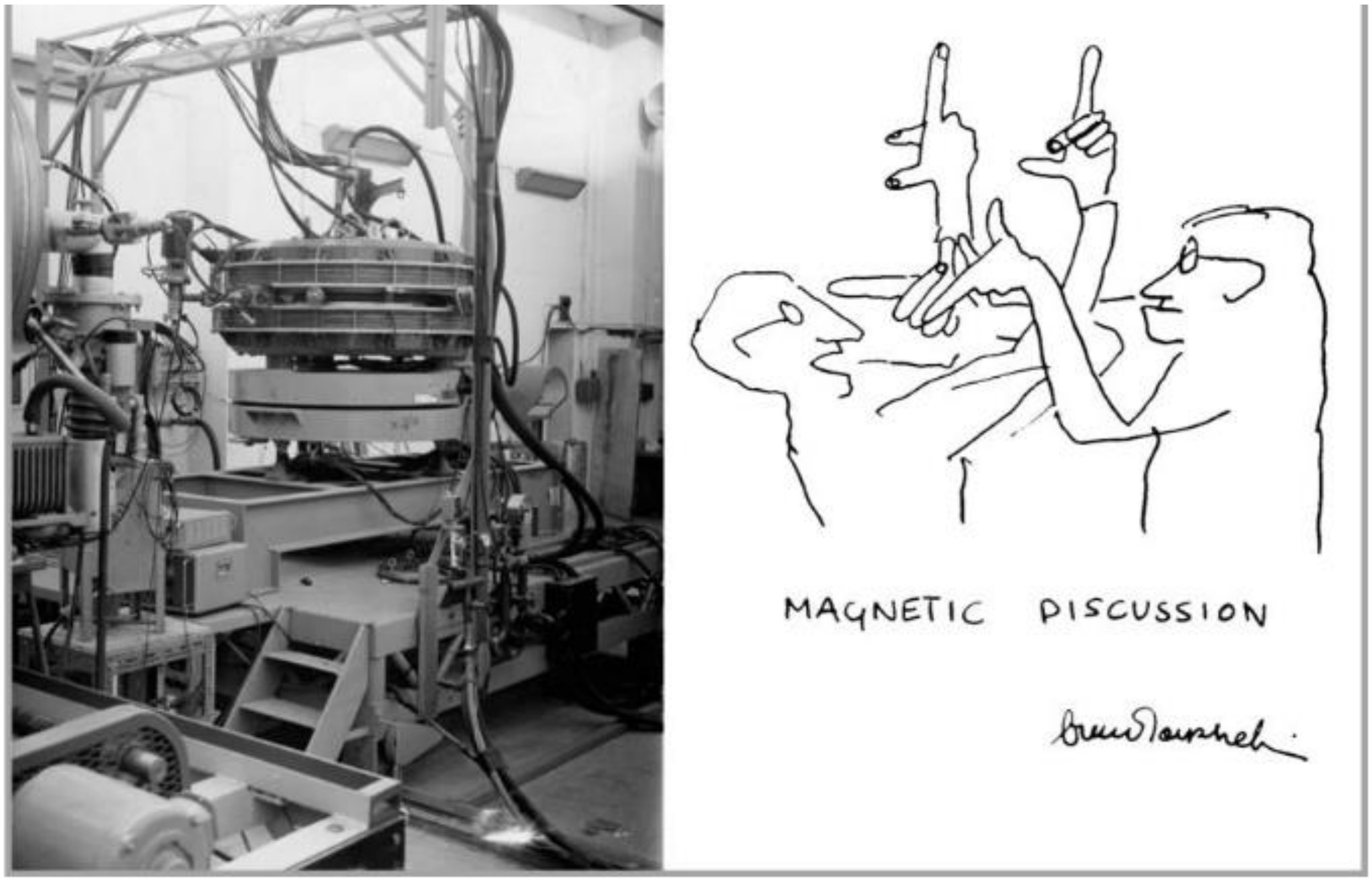
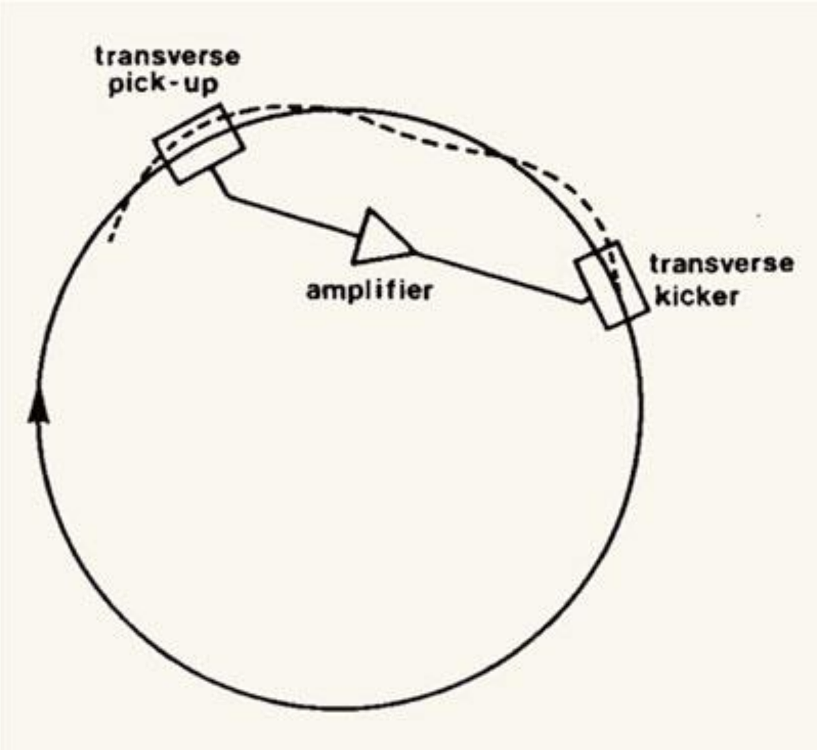


Fig. 2. Left: AdA installed in Salle 500 MeV, Laboratoire de l'Accélérateur Linéaire, Orsay, France, 1963. Right: a drawing by Bruno Touschek reflecting frequent

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

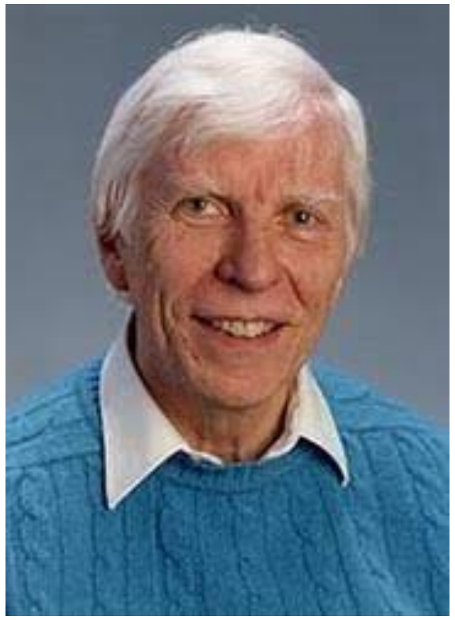
ISR – first hadron collider

1971 to 1984,
CoM energy
62GeV



Also: stochastic cooling invented by Simon Van de Meer

The Tevatron & superconducting magnets



Alvin Tollestrup

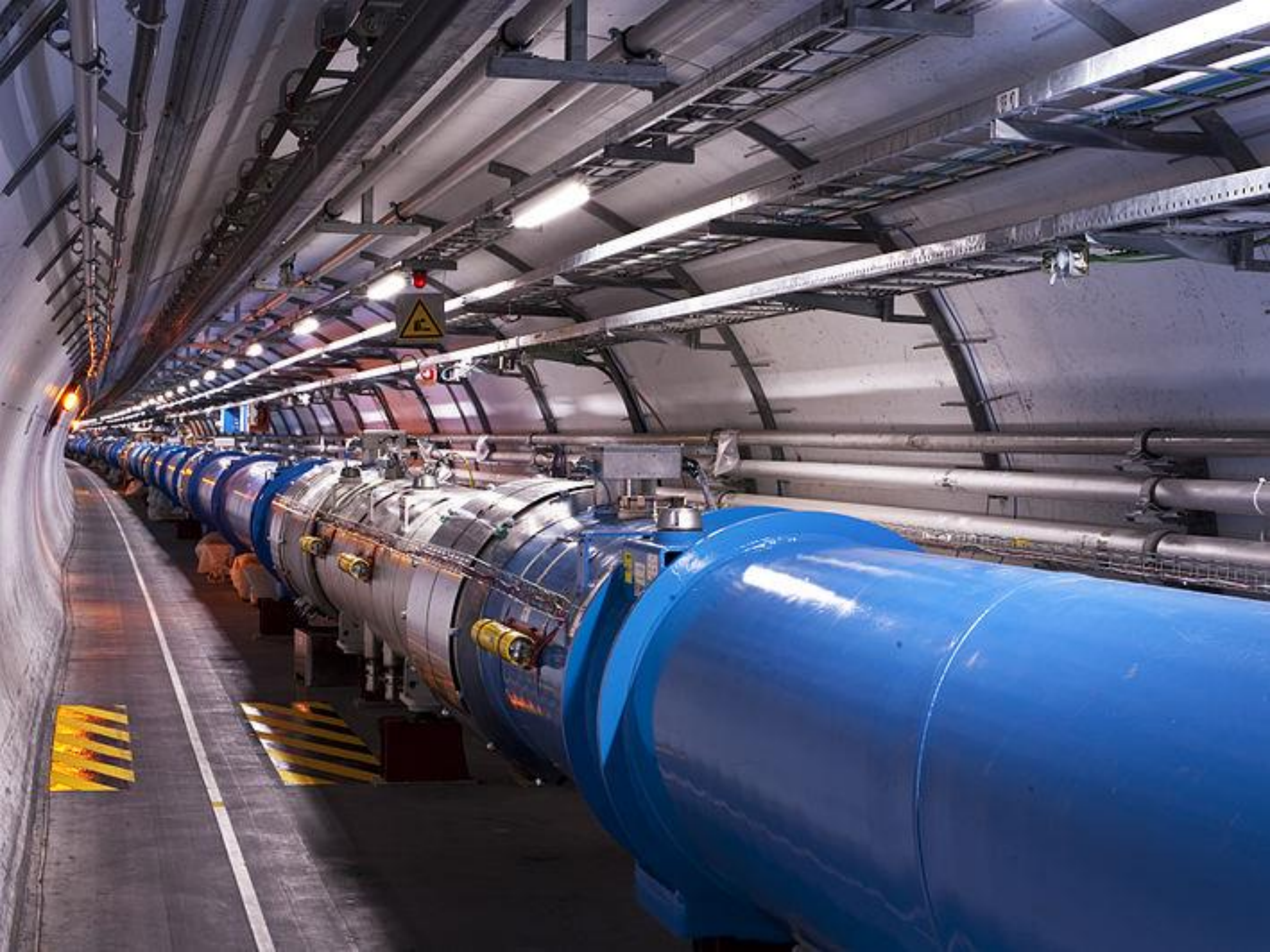
THE TEVATRON ENERGY DOUBLER:
A Superconducting Accelerator

Helen T. Edwards

Fermi National Accelerator Laboratory,[1] 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 (θ and τ) 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/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ 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 Yoichro 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**"

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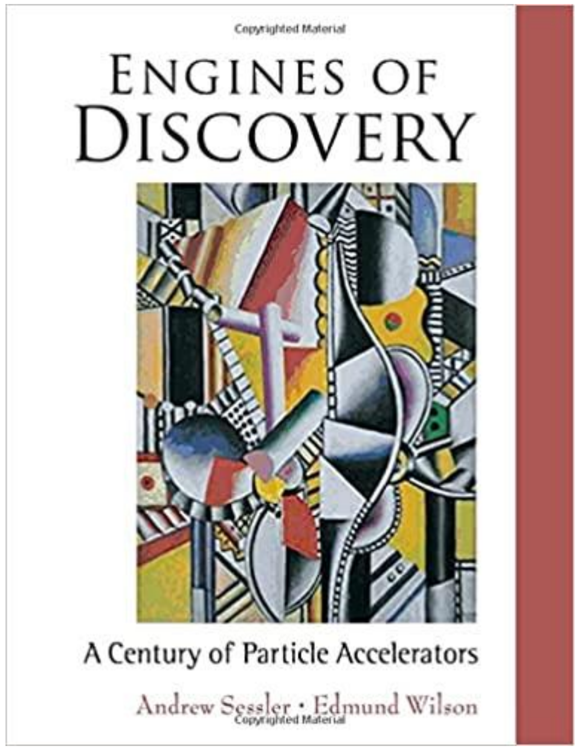
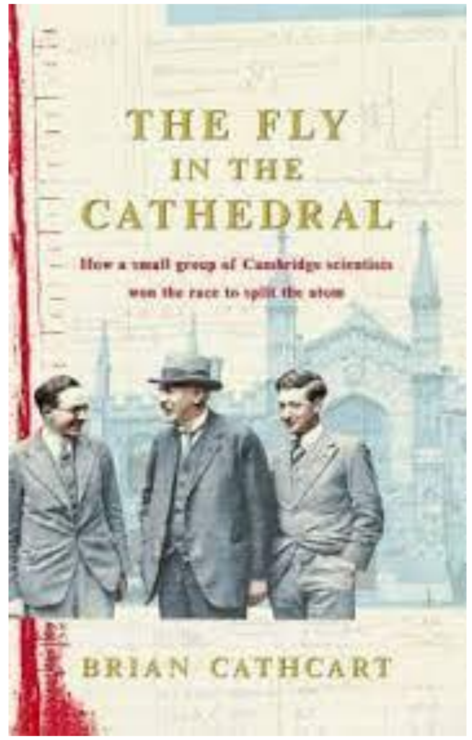
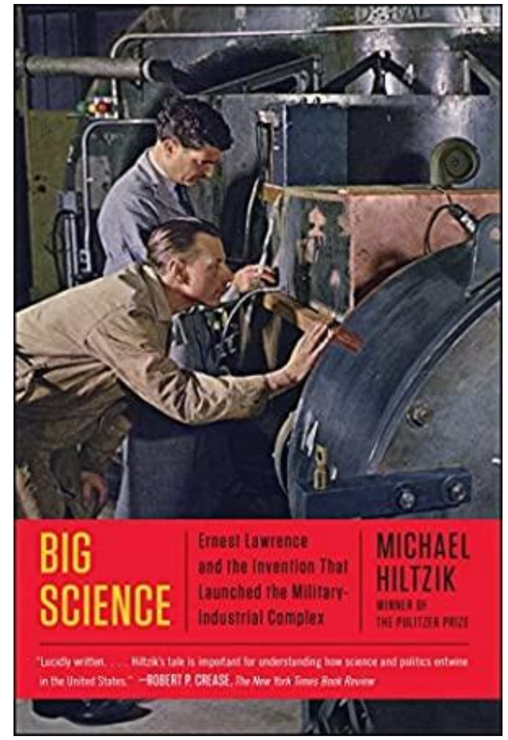
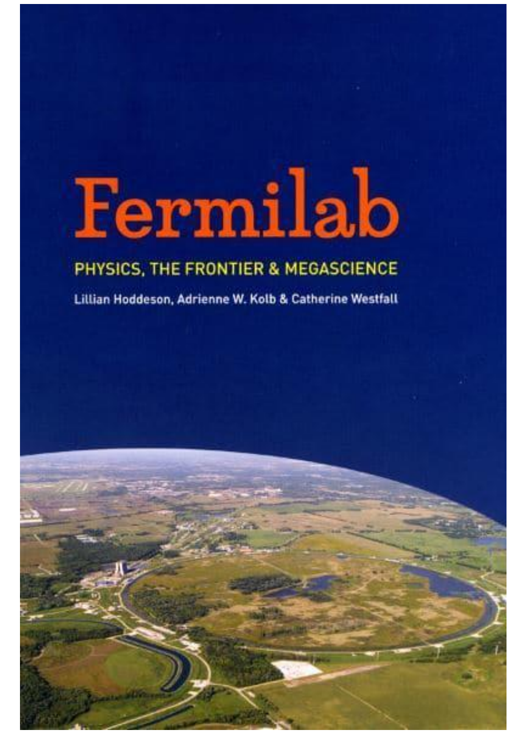
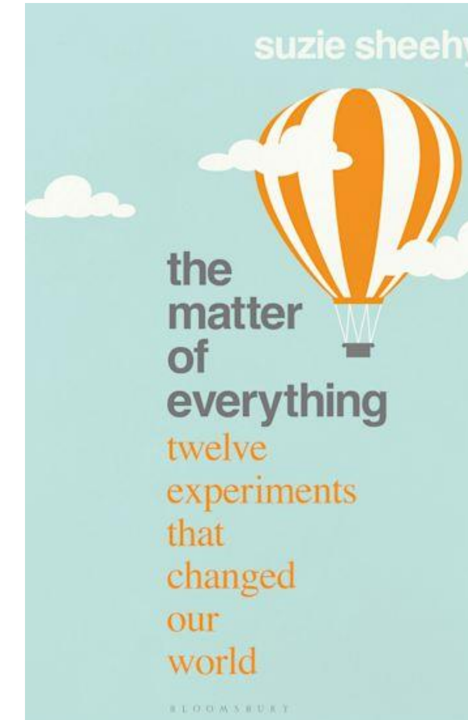
Further Reading:











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

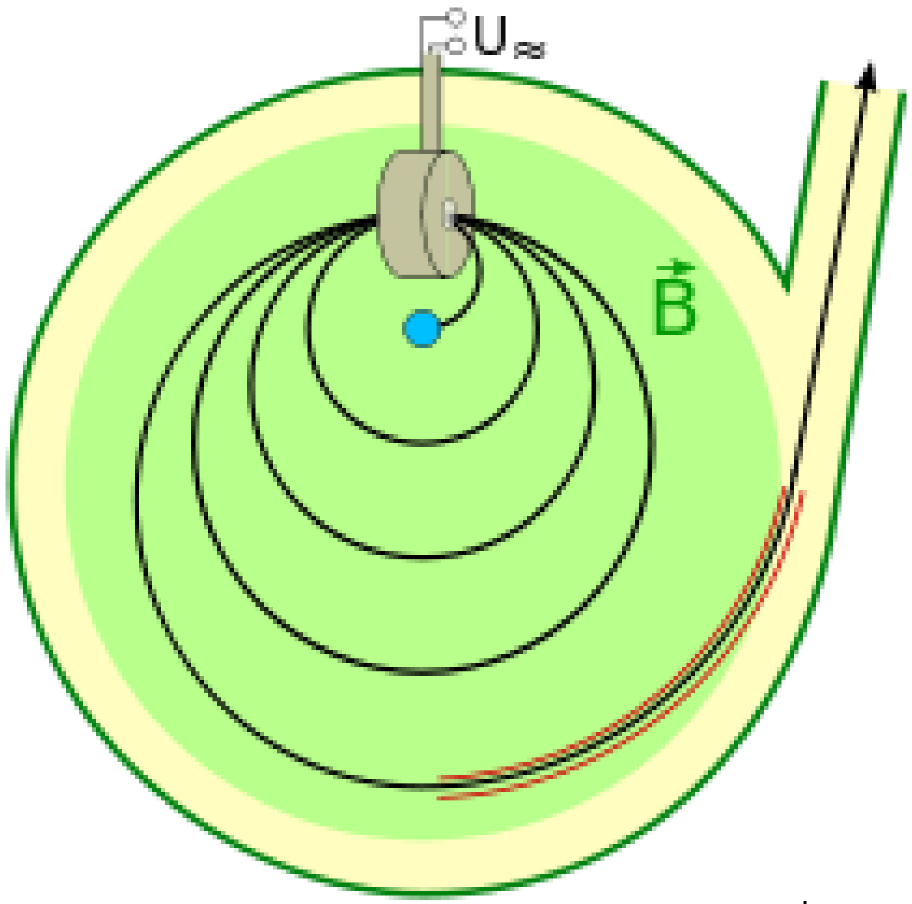
Fermilab Physics, the Frontier, and Megascience, Lillian Hoddeson, Adrienne W. Kolb, Catherine Westfall, 2011

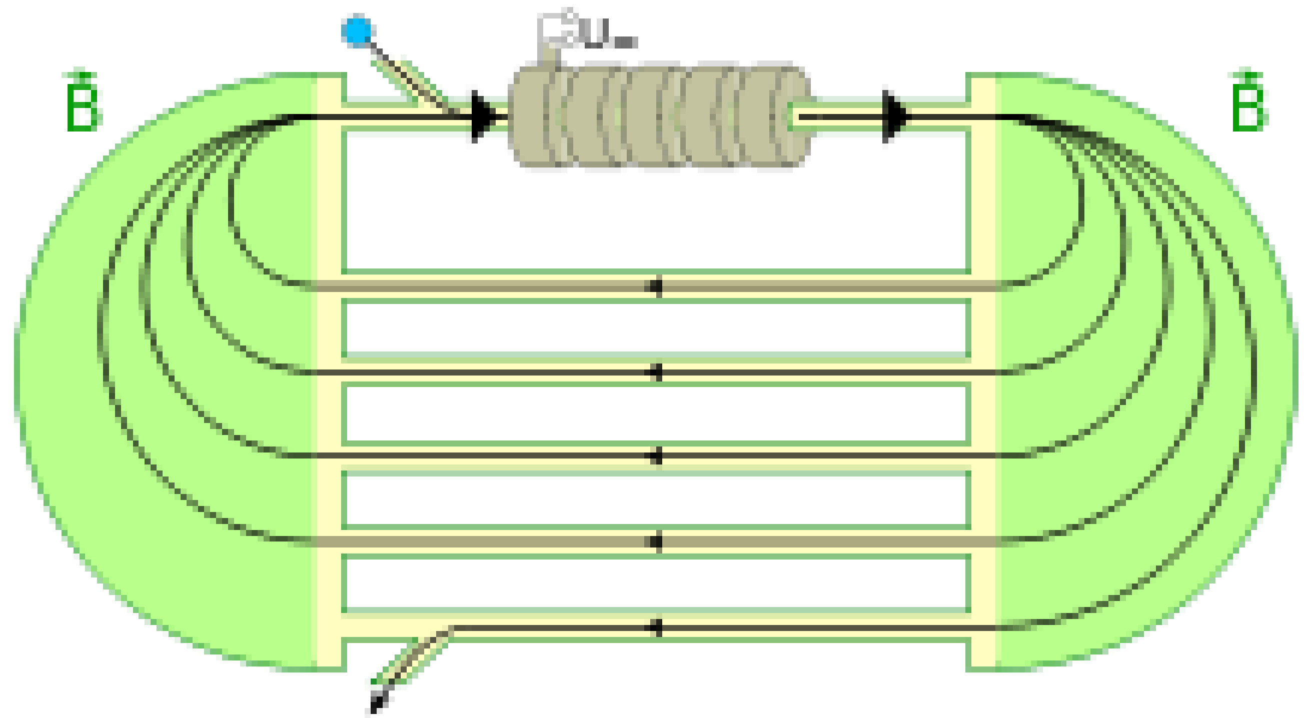
The Matter of Everything: Twelve Experiments that Changed Our World, Suzie Sheehy, 2022

- 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

A few loose ends:

Microtron





Images: wikimedia commons

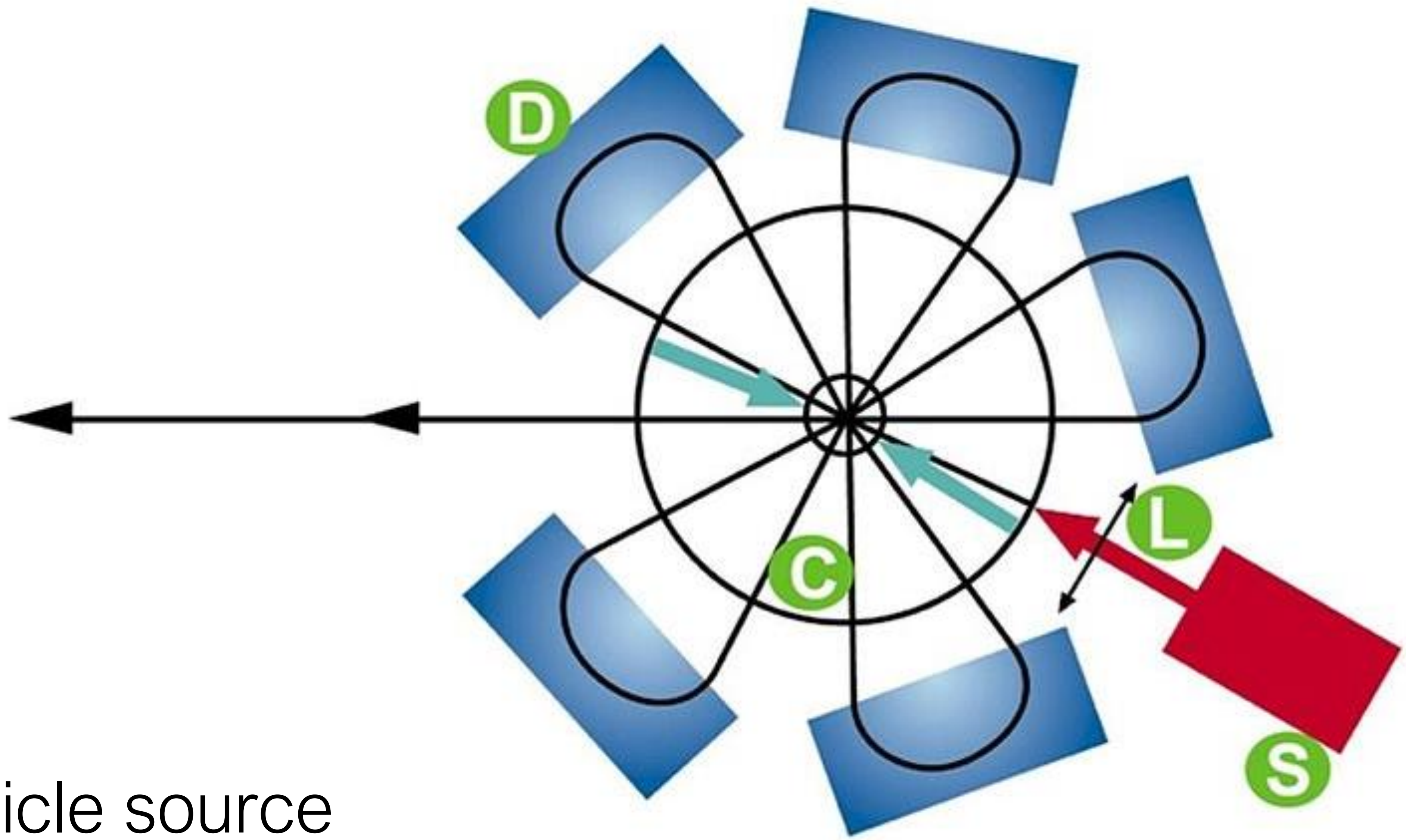
- Uses a linear accelerator structure instead of the dee electrodes of the cyclotron

- Mostly used for electrons as assumes constant frequency RF & B field in the ultra relativistic limit.

Veksler, I. V. (1944). "A New Method of the Acceleration of Relativistic Particles". *Doklady Akad. Nauk SSSR* (in Russian) **43**: 346.

Rhodotron

Invented 1989



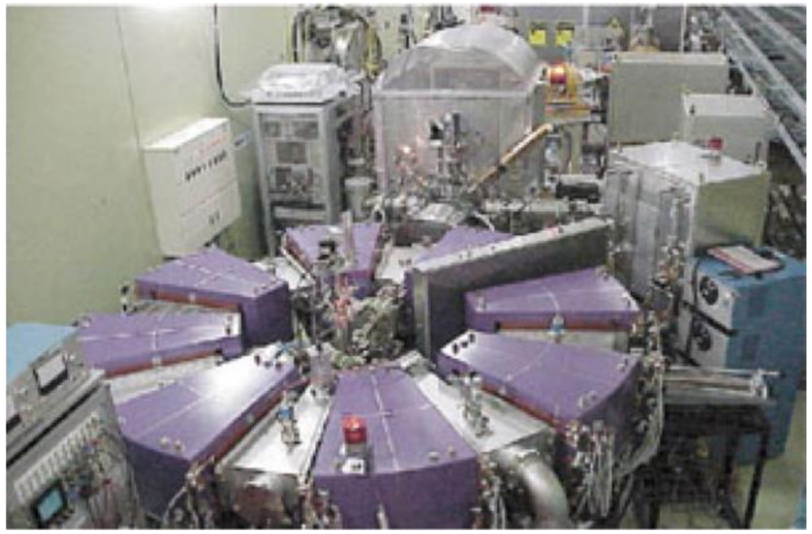
S: particle source
C: coaxial cavity
D: bending magnets
L: focusing lens

Energy gain ~ 1 MeV per crossing

FFAs

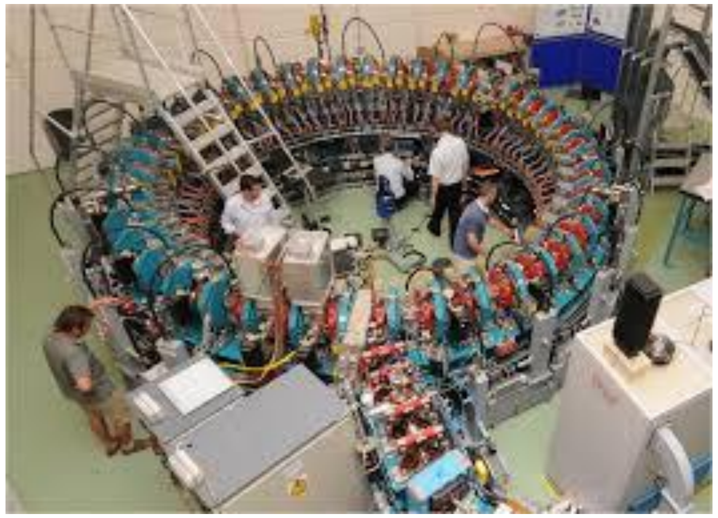
- In the late 90’s and in 2000’s, the FFA idea was re-awakened in Japan,
- Particular focus on hadron FFAs of scaling type
- Recently non-scaling type driven by UK collaboration

Scaling (zero-chromatic)



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

Non-Scaling (chromatic)



EMMA, Daresbury Lab, UK