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Image © STFC Alan Ford

Image © STFC

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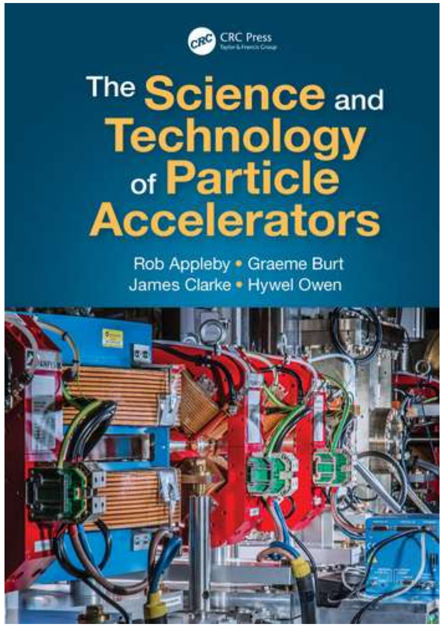
'Particle accelerators are built for the sole purpose of endowing nuclear particles with large quantities of kinetic energy' – John Livingood

CI-ACC-101.1
Particle Accelerators – History and Principles

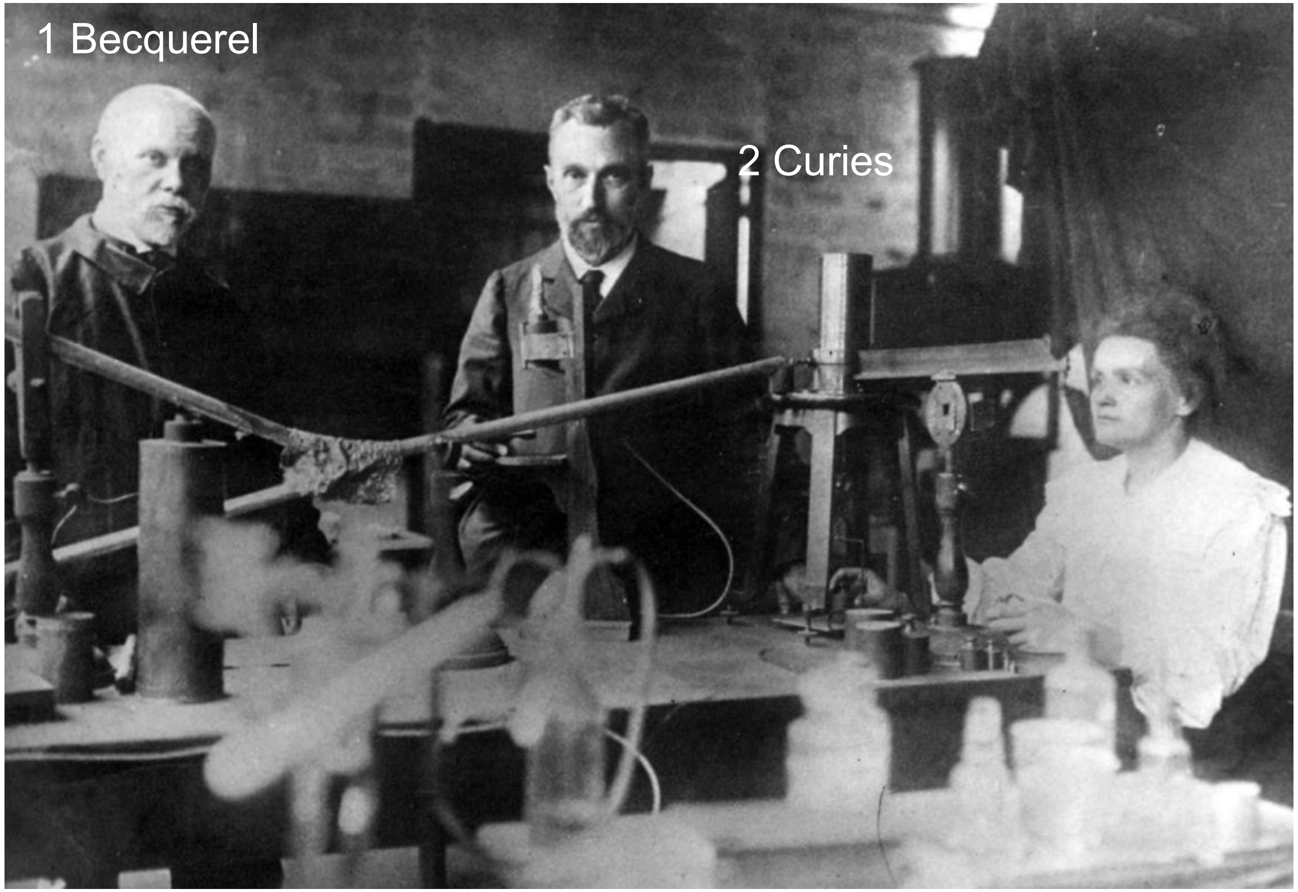
Hywel Owen, UKRI-STFC-ASTEC-AP
Accelerator Science and Technology Centre
hywel.owen@stfc.ac.uk, @hywelowen

13th October 2025
Cockcroft Institute Lecture Series



https://www.amazon.co.uk/Science-Technology-Particle-Accelerators/dp/1138499870

Radioactivity: Becquerel + 2 Curies



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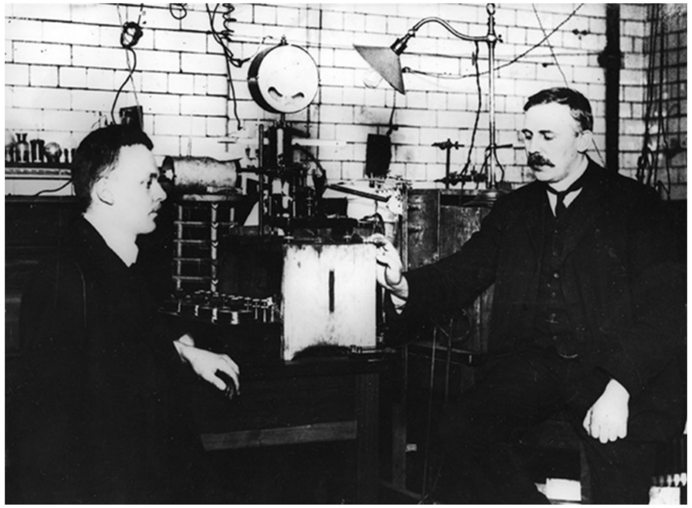
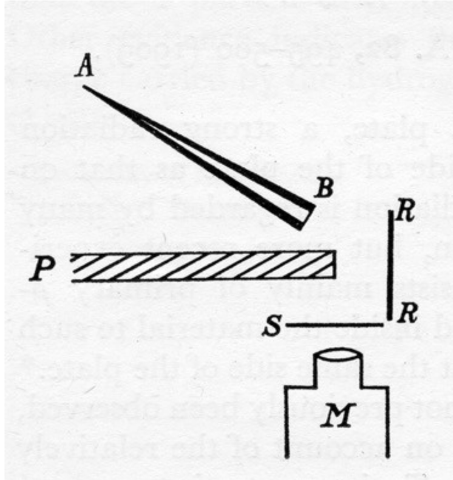
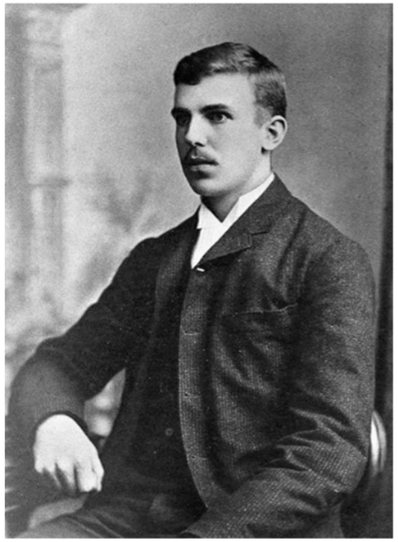
Splitting the atom - Manchester







"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"

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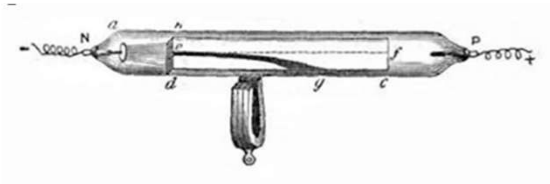
William Crookes

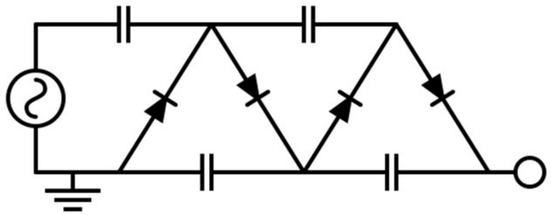


$$\vec{F} = q\vec{\mathrm{E}} + q\vec{v} \times \vec{\mathrm{B}}$$

Walton, Rutherford, Cockcroft

Walton and the machine used to "split the atom"

- In 1928, George Gamow proposed that alpha particles could tunnel through the nuclear energy barrier. John Cockcroft saw Gamow give a lecture in January 1929 at the Cavendish laboratory (Cambridge), and realised that voltages of only a few hundred keV could deliver nuclear transmutations, rather than the many MeV they previously thought was needed.
- Rutherford agreed with Cockcroft's calculations, and convinced Walton to abandon his linear accelerator idea. Using a £1000 university grant they bought a 300 kV transformer which they then rectified to DC. A small beam of low-energy protons was then accelerated downwards to 280 keV and into some light targets (Li and Be). However, this didn't work.
- Cockcroft invented a voltage multiplier to obtain up to 700 keV, which was enough. The atom was split, making alpha particles that Walton observed while sitting in the lower observation cabin.



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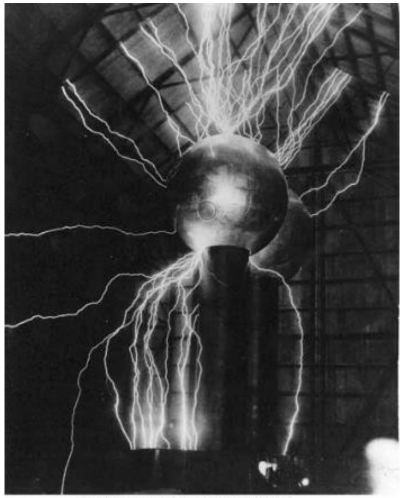
DC Acceleration

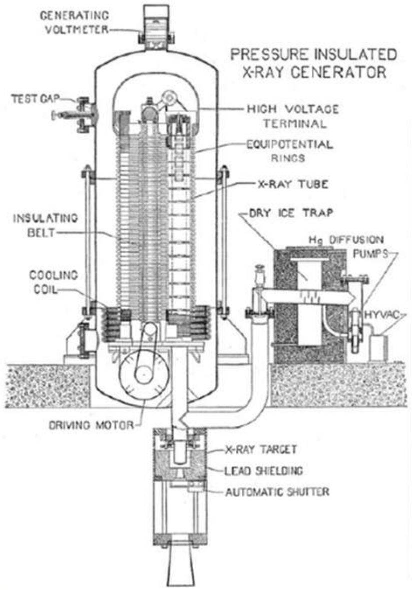
Cockcroft-Walton
Li + p → He + He

Walton and the machine used to "split the atom"



MIT Round Hill Van de Graaff

Robert Van de Graaff's Patent



ORNL Tandem VdG

Birmingham dynamitron
3 MeV, 1 mA protons

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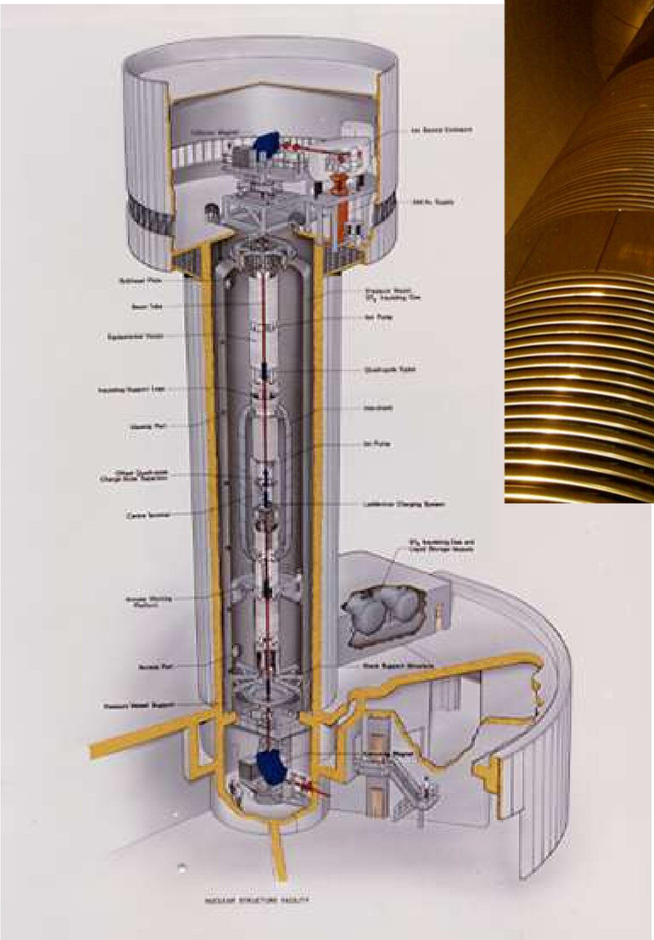
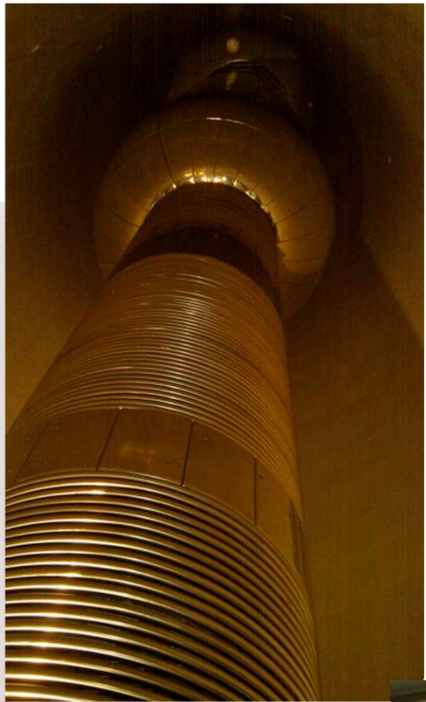
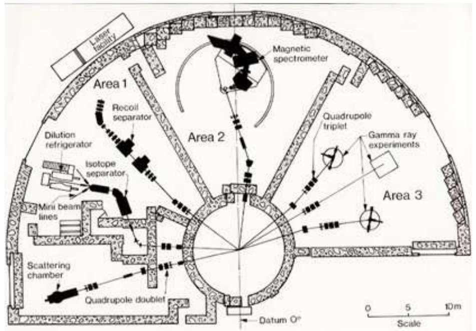
Daresbury VdG





NSF: 20 MV Van de Graaff



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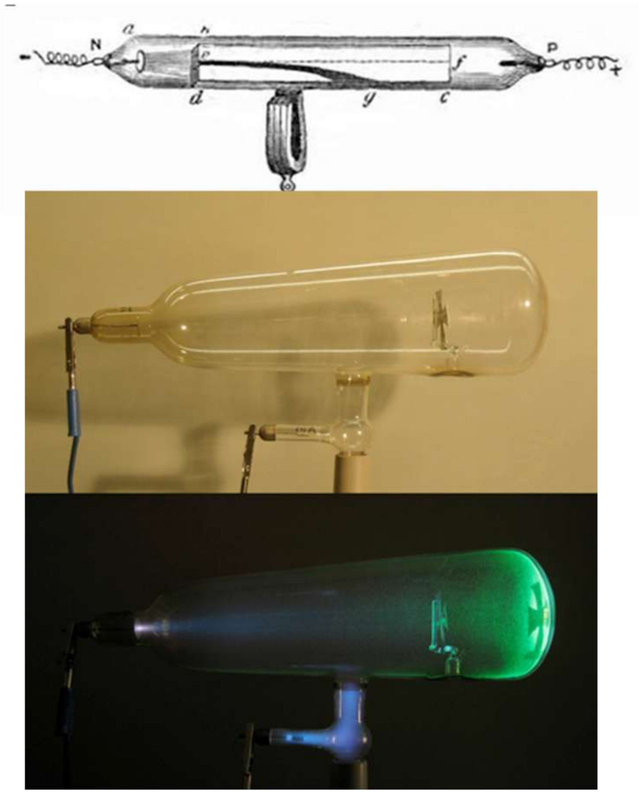
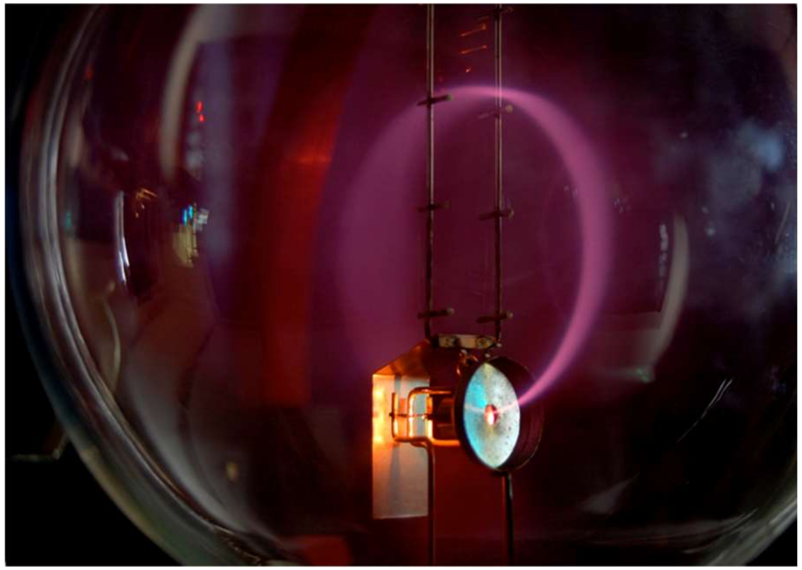
Lorentz Force – the fundamental equation for accelerators

$$\mathbf{F} = e\mathbf{E} + e\mathbf{v} \times \mathbf{B}$$





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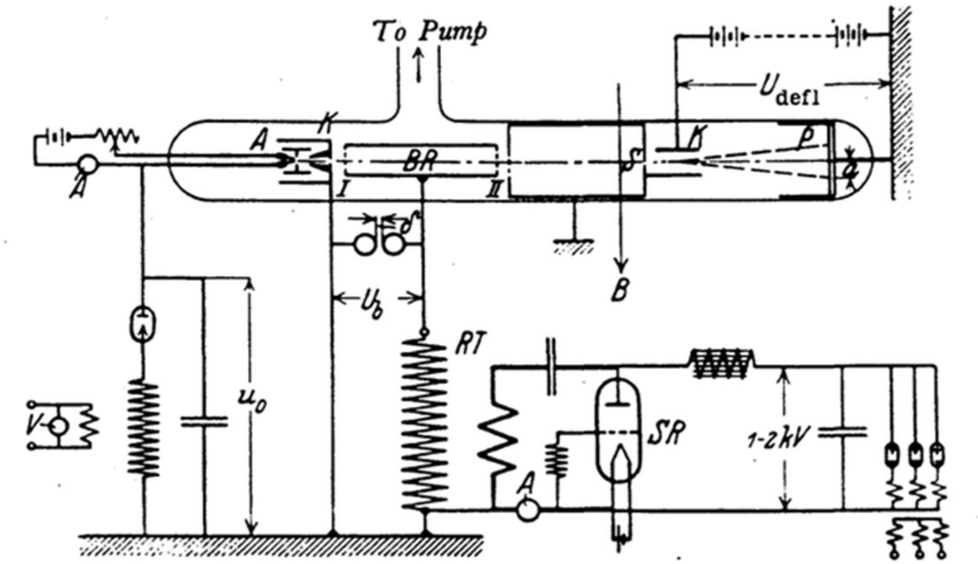
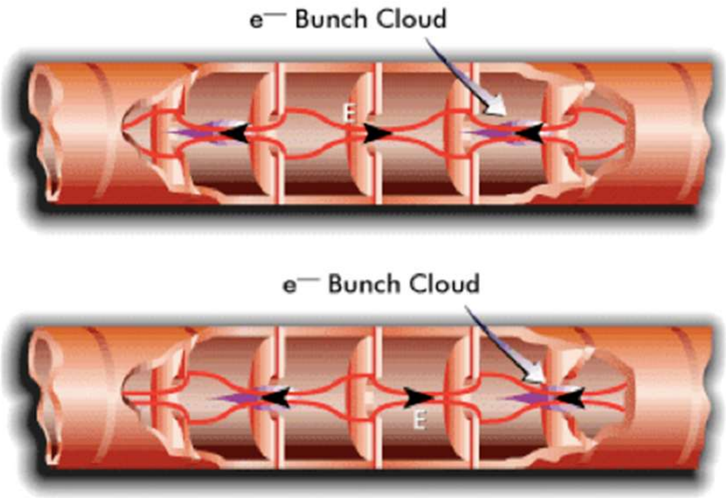
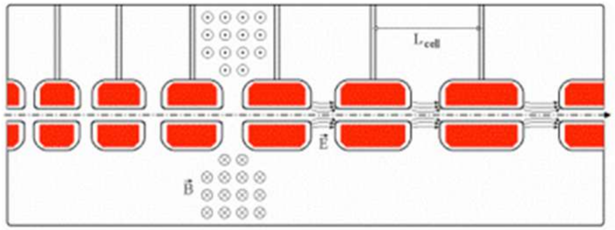
Rolf Wideroe’s Linac



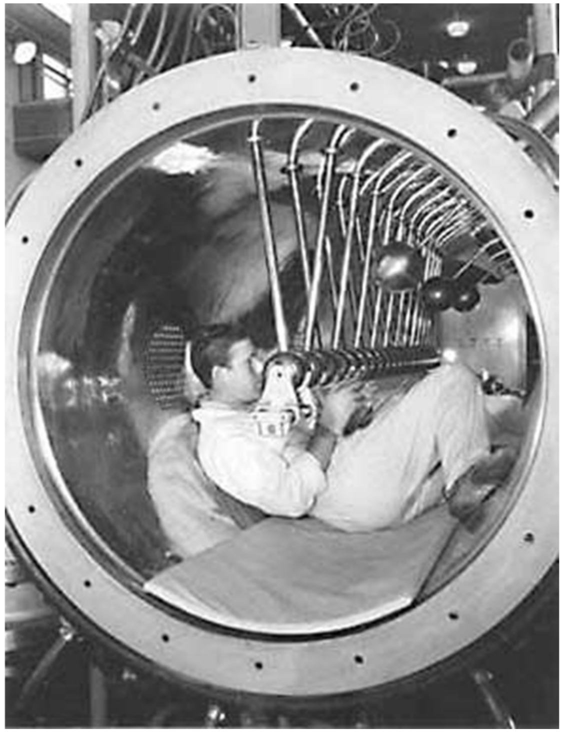
Replica of original linac, at National Physical Laboratory



1/20,000,000,000 second later
(notice how far the bunches have moved)



Alvarez structure
(with drift tubes)



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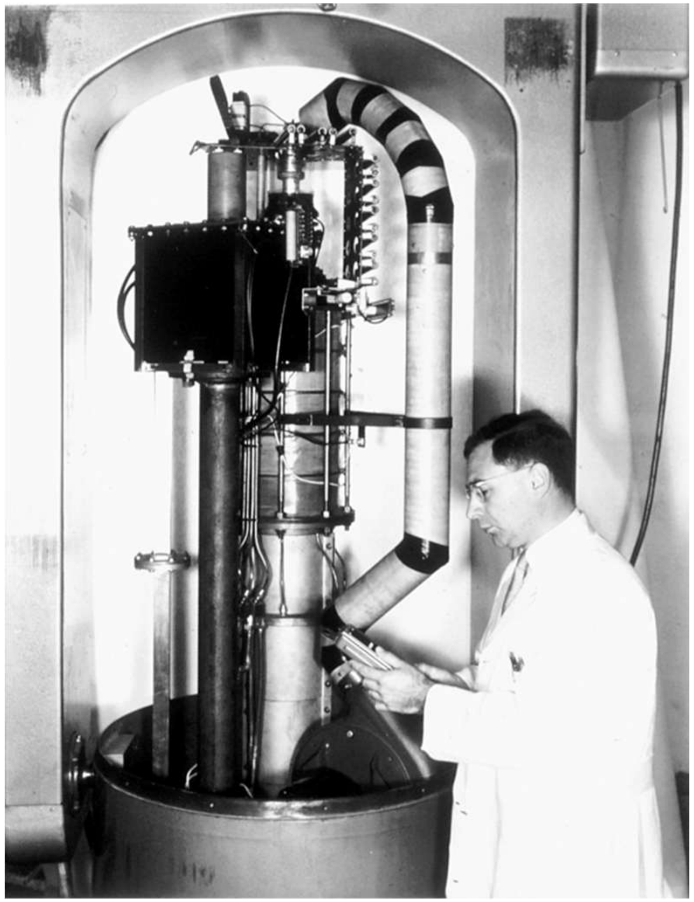
Bill Hansen and the 1 MeV Linac, 1947 (6 MeV)

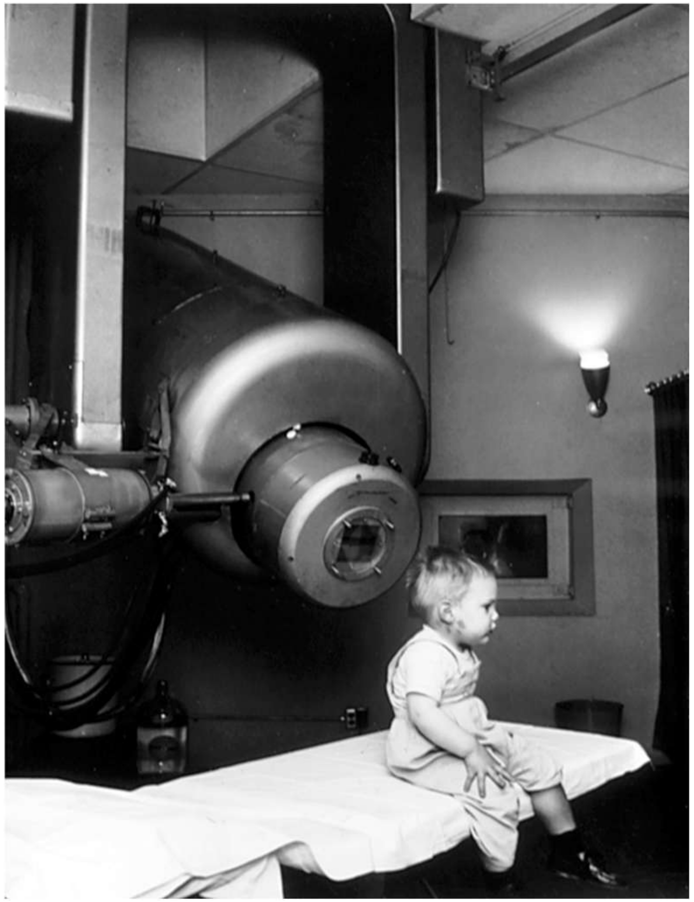
Proposed the cavity resonator for acceleration
https://www.youtube.com/watch?v=jMv77iqsQIY

Strongly involved in the invention of the klystron:
https://patents.google.com/patent/US2269456A/en
https://doi.org/10.1063/1.1710371
https://patents.google.com/patent/US2242275A/en

(beware of beryllium)



Harry Kaplan
Radiotherapy pioneer



Gordon Isaacs, 1957
The first external-beam radiotherapy patient

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Chadwick apparatus – discovery of the neutron

Chadwick and Cockcroft,
At Daresbury 20th Oct 1966

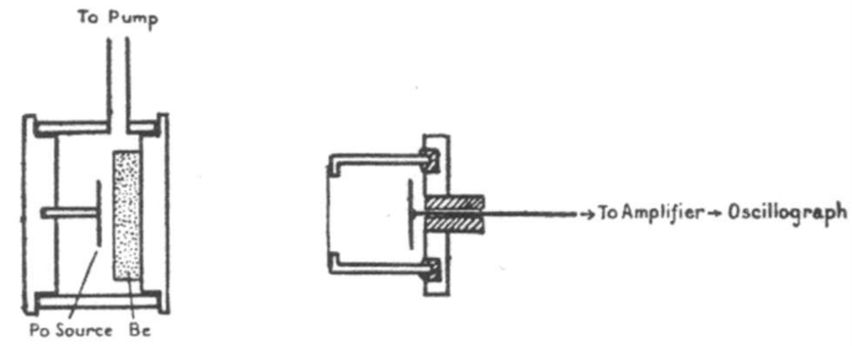

Fig. 1.

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James Chadwick and Leslie Groves

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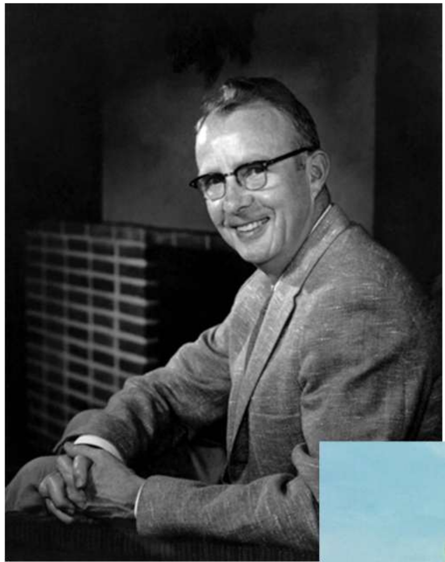
Louis Alvarez



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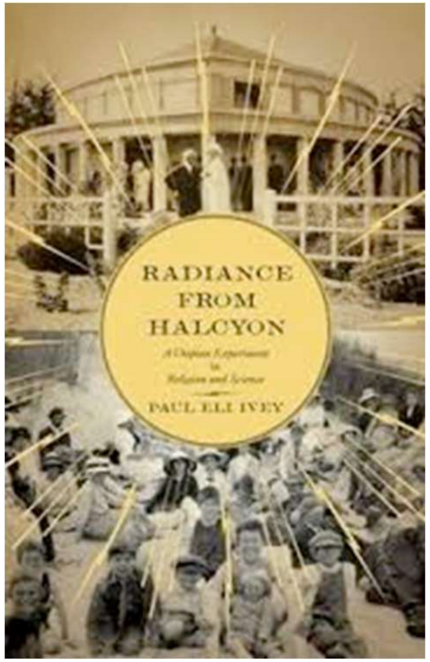
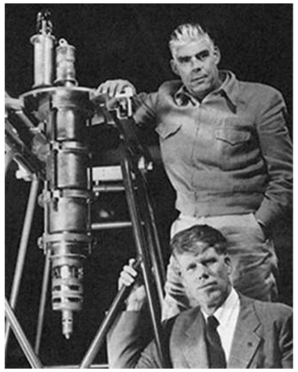
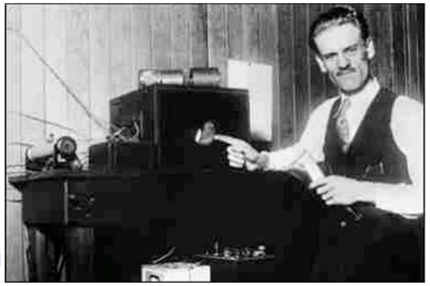
Radiance from Halcyon





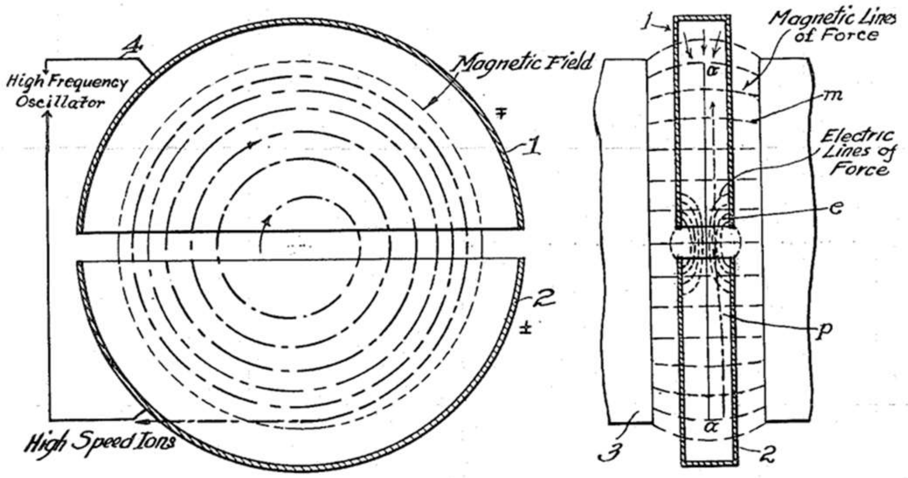
1937

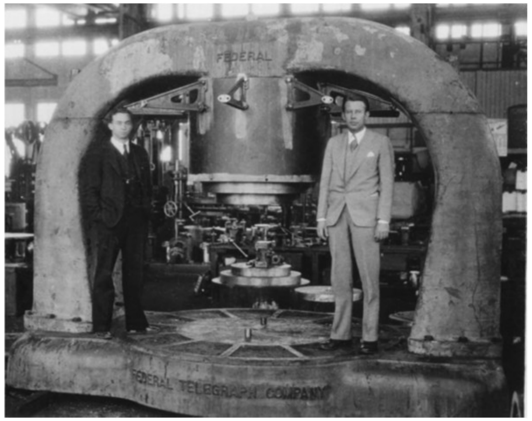


Round and round we go... Cyclotrons (protons)

Ernest O. Lawrence,
Milton Livingston

$$f = \frac{qB}{2\pi\gamma m_0}$$





'Lawrence got his Nobel Prize. I just got a PhD.'
(but in 8 months)

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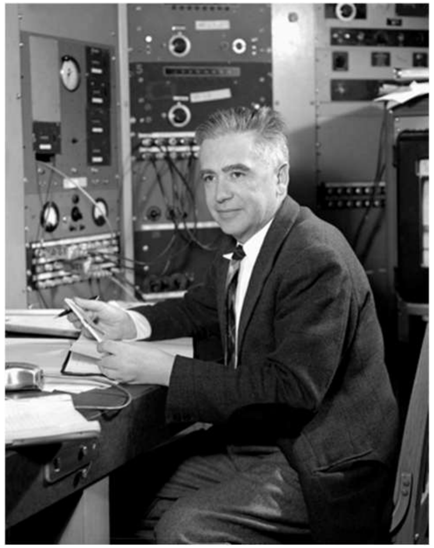
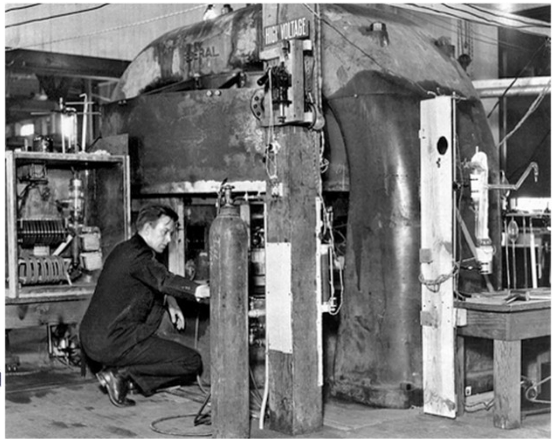
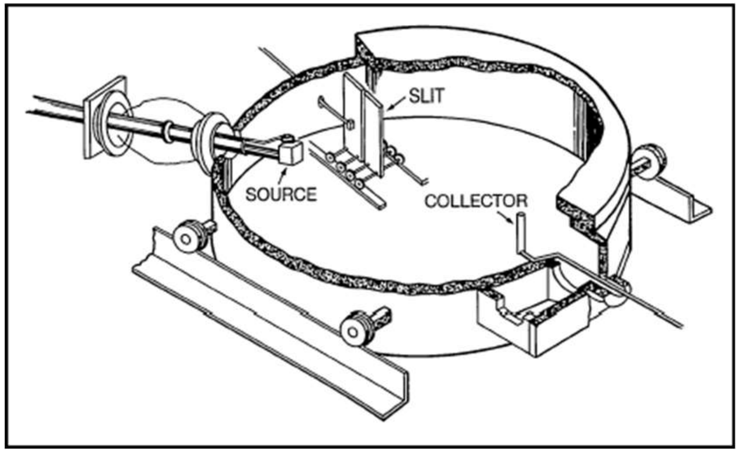
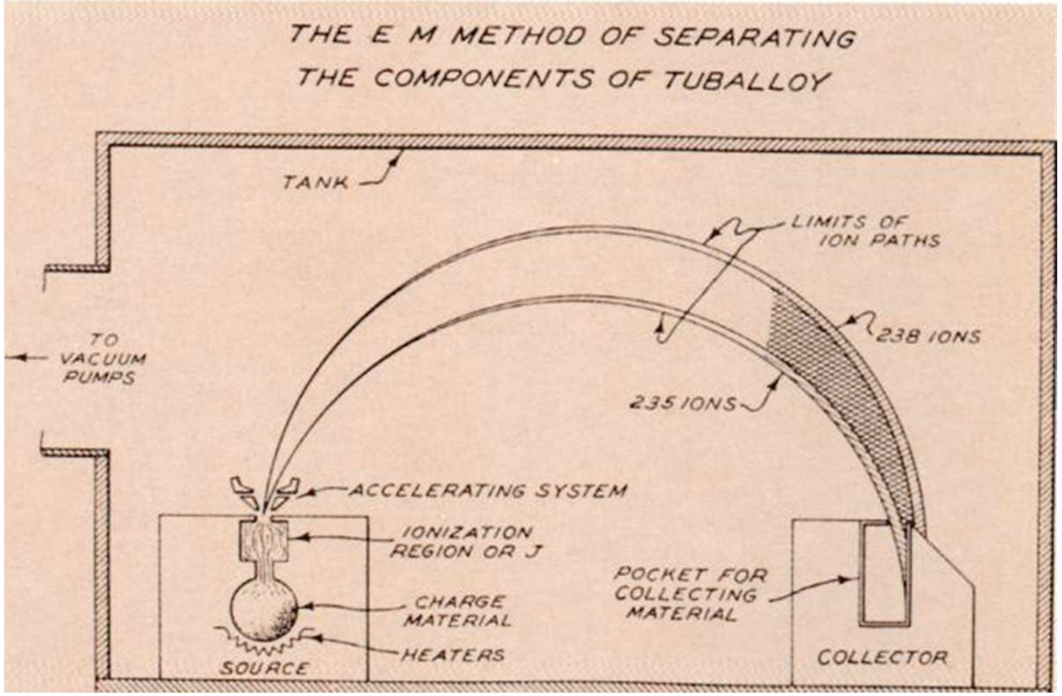
Emilio Segrè and the 37-inch cyclotron deflector foil



‘In February 1937 I received a letter from Lawrence containing more radioactive stuff. In particular, it contained a molybdenum foil that had been part of the cyclotron's deflector. I suspected at once that it might contain element 43. The simple reason was that deuteron bombardment of molybdenum should give isotopes of element 43 through well-established nuclear reactions. My sample, the molybdenum deflector lip, had certainly been intensely bombarded with deuterons, and I noted that one of its faces was much more radioactive than the other. I then dissolved only the material of the active face, in this way achieving a first important concentration of the activity. ‘






THE E M METHOD OF SEPARATING
THE COMPONENTS OF TUBALLOY
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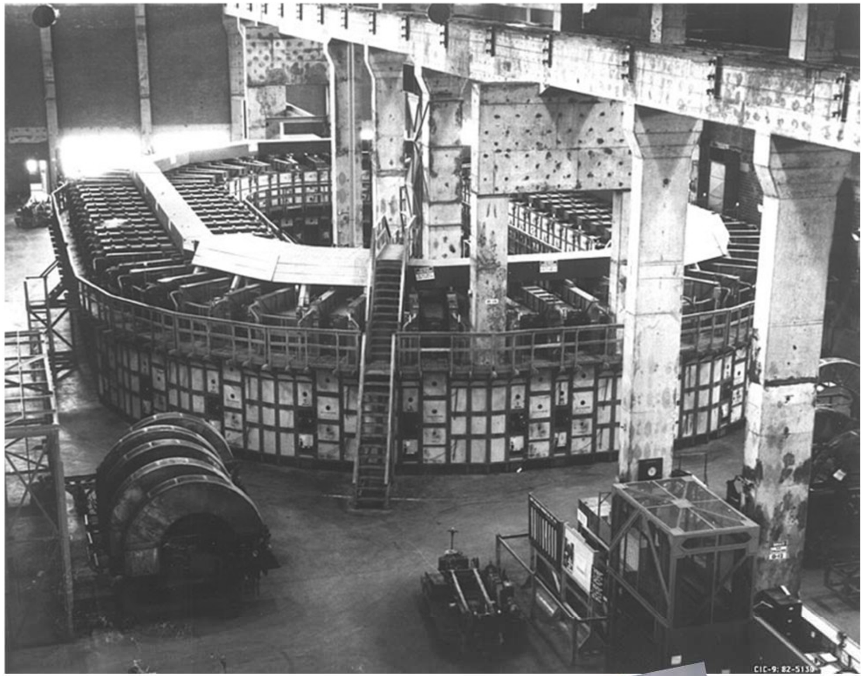

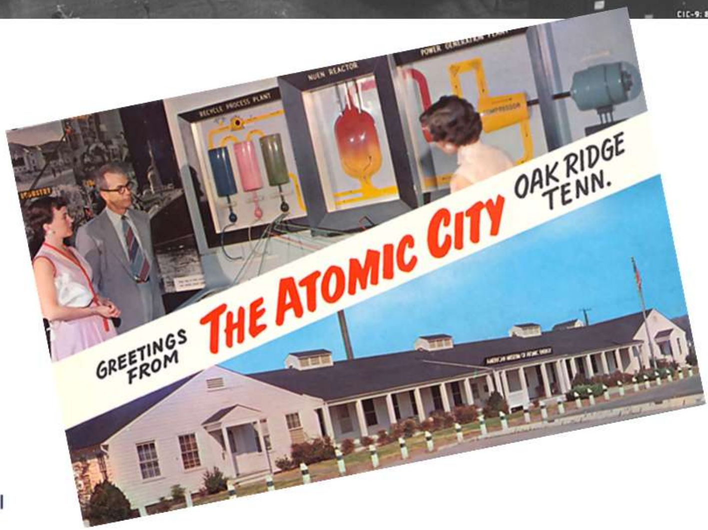

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Arthur Dooley: ‘Splitting the Atom’ (1974)

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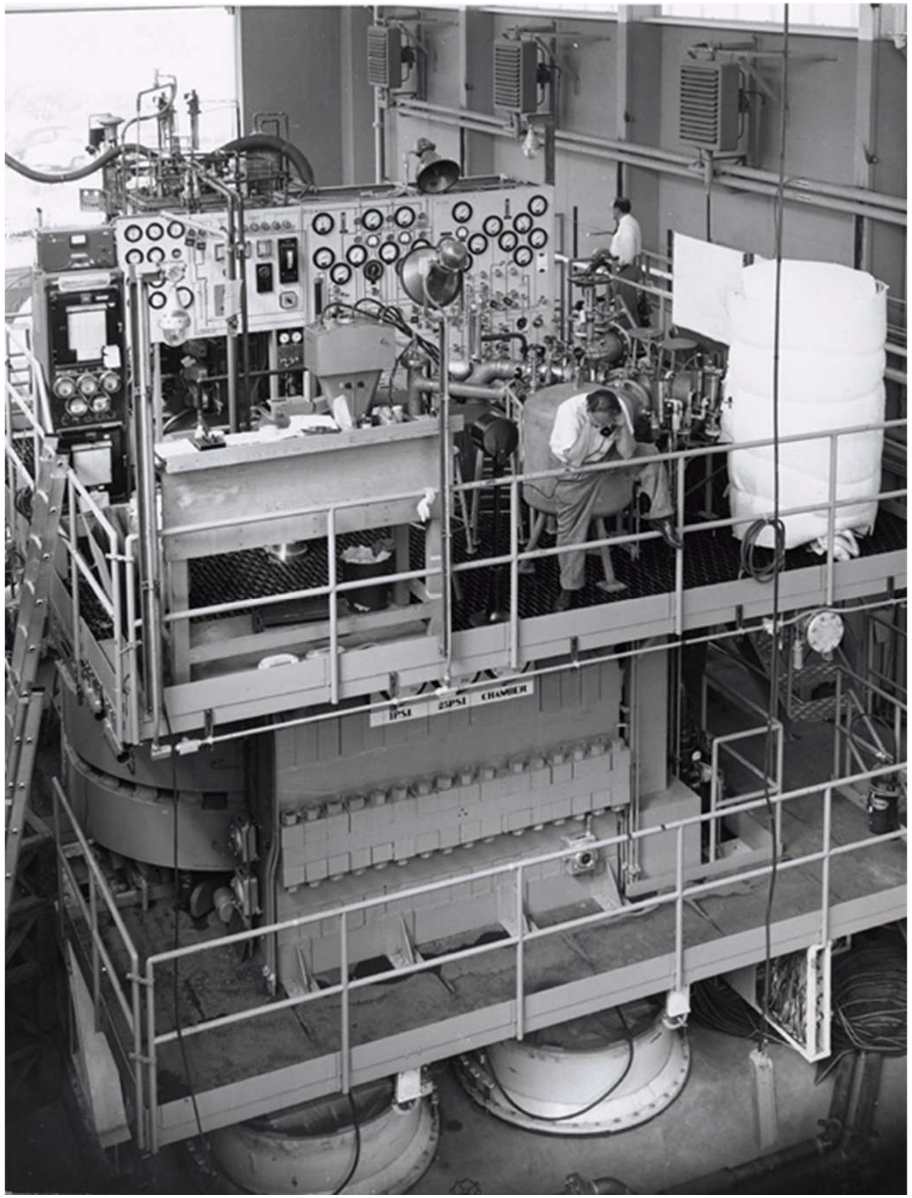
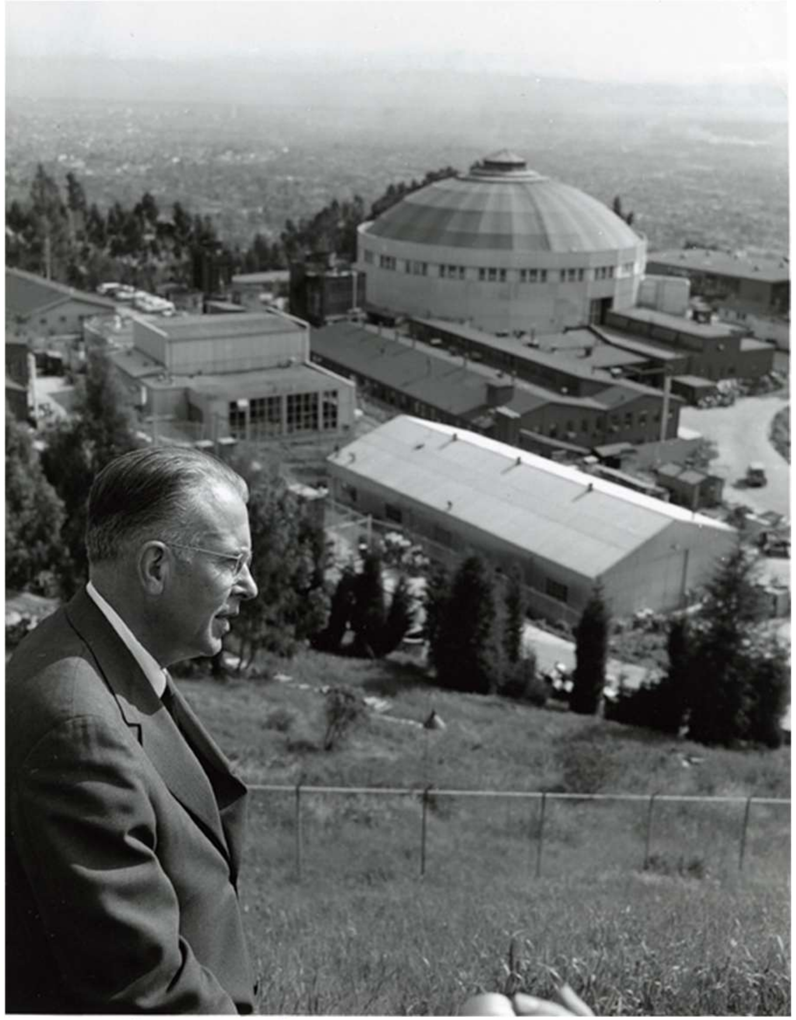
Liverpool 37” cyclotron, 20 MeV, 1939

60-inch cyclotron

20 MeV, 1939

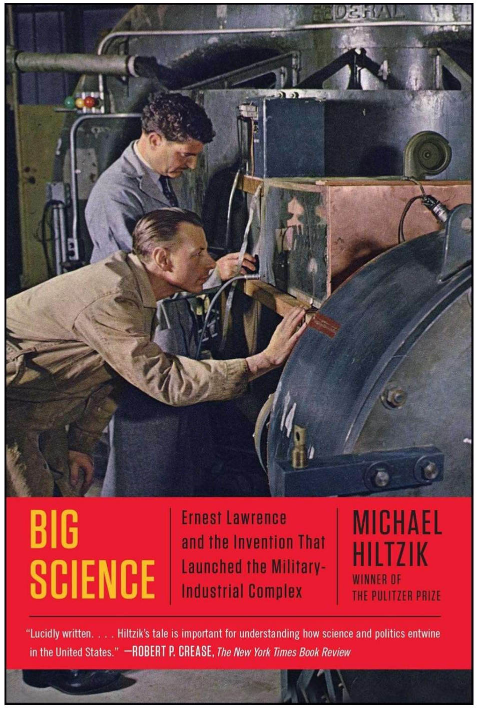


‘Big Science’ and Ernest Lawrence

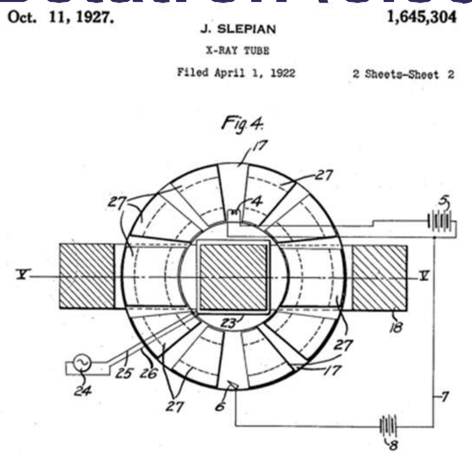


- LANL
- LLNL – Lawrence Livermore
- LBNL – Lawrence Berkeley
- Oak Ridge (Calutron)

https://www.amazon.co.uk/Big-Science-Lawrence-Invention-Military-Industrial-ebook/dp/B010GW025O?s=books



The Betatron (electrons)



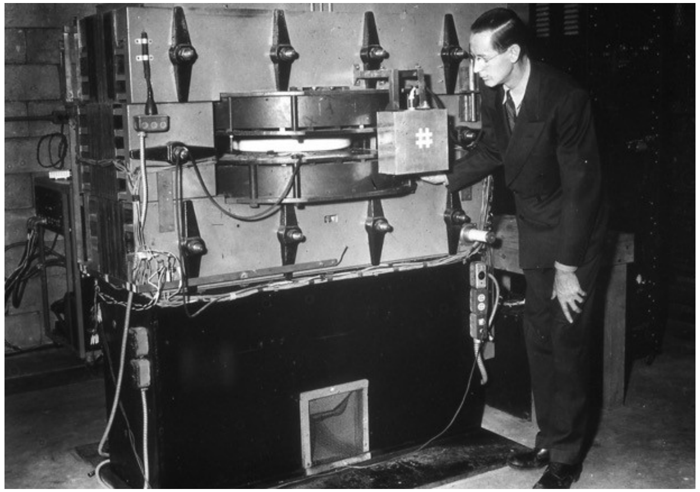
Slepian, 1922
Wideroe, 1928
Kerst, 1940

FIG. 14 Diagram of betatron magnet pole tips and vacuum chamber, showing orbit location and the central core supplying flux linkage for acceleration. (From M. S. Livingston and J. P. Blewett, "Particle Accelerators," 1962. Reprinted by permission of McGraw-Hill Book Company.)

Meanwhile, Kerst returned to the University of Illinois to build first an 80-MeV "model" (*61*) and ultimately a 300-MeV betatron (*62*) which was the largest and probably the last of this line.

It seems clear that the complete stability theory of Kerst and Serber and the careful and thorough magnet design calculations of Kerst were the reason for Kerst's success in the rapid development of the betatron. Orbital stability requires spatial focusing for particles which deviate in direction from the equilibrium orbit. Such stability will occur in a radially decreasing magnetic field, such as would be specified by a radial variation:

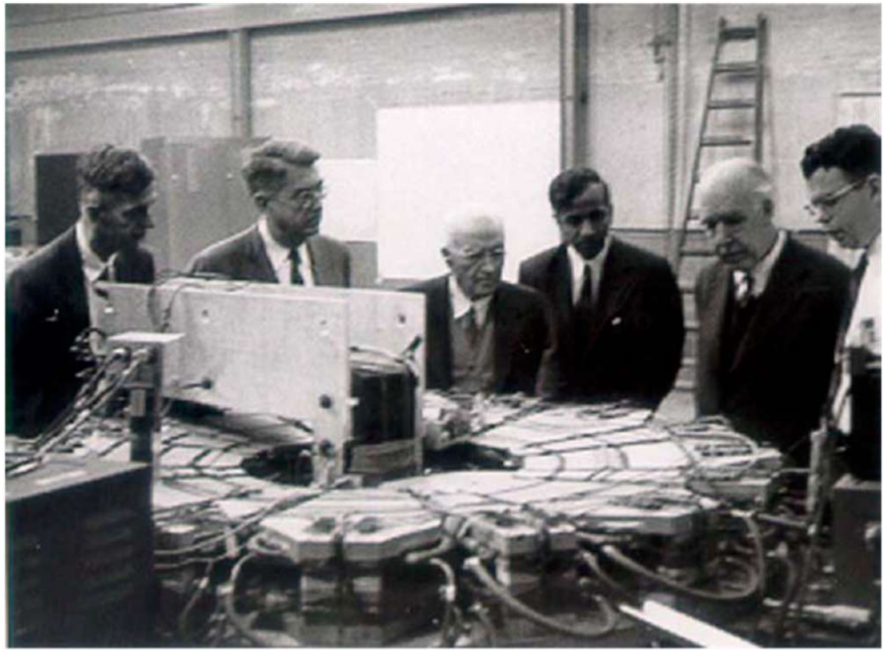
2 MeV betatron, Donald Kerst

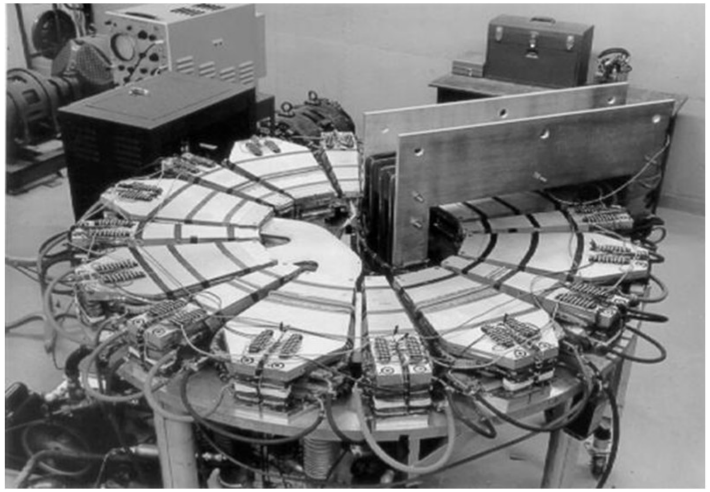


22 MeV betatron

Electron Betatrons...

Electron FFAG, with Chandrasekhar and Bohr





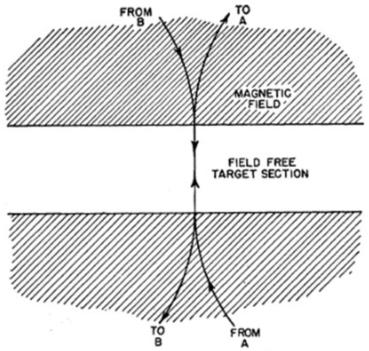


FIG. 1. The target straight section. B and A can be adjacent or concentric fixed-field alternating-gradient accelerators.

Kerst proposed in 1956 to have colliding beams:
https://doi.org/10.1103/PhysRev.102.590

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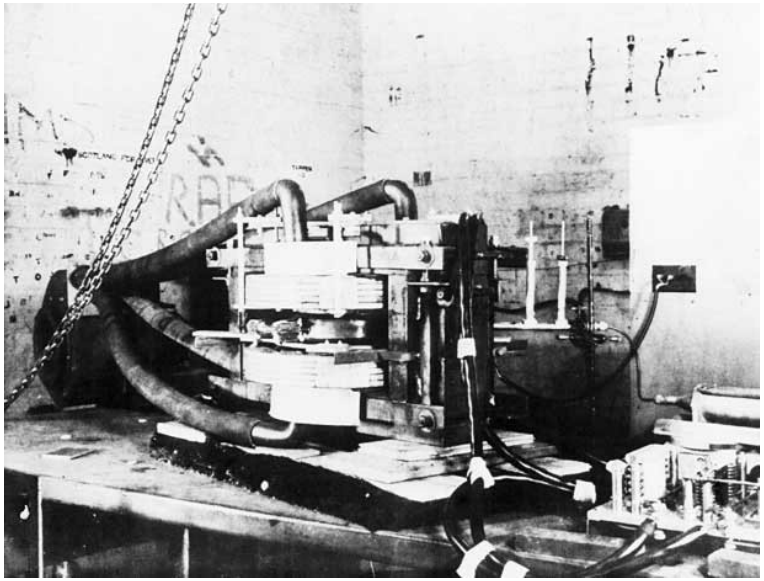
The earliest synchrotrons



Goward & Barnes's original e-synchrotron
(converted from betatron)
Woolwich Arsenal, London, 1946

See historical memoir by Herbert Pollock:
https://doi.org/10.1119/1.13289

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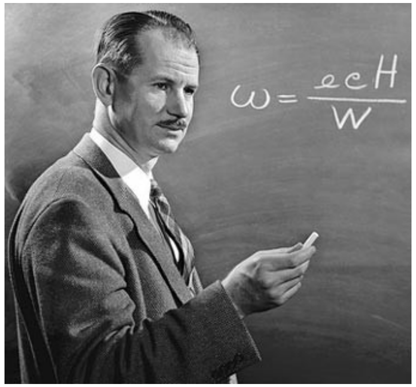
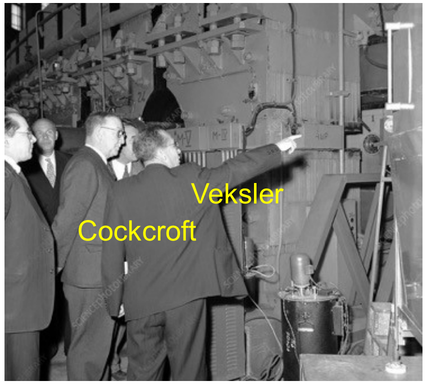
Phase stability

Marcus Oliphant



Ed McMillan



Vladimir Veksler

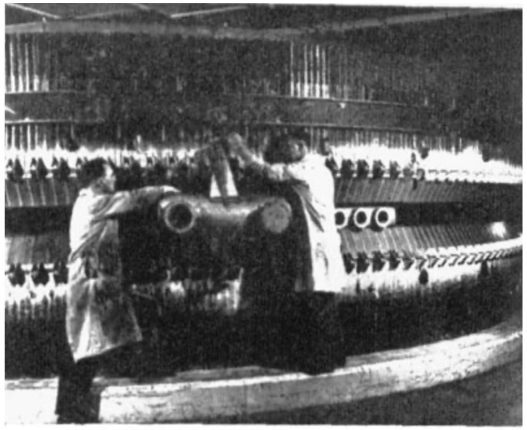


Fig. 12. Birmingham synchrotron magnet with a section of the vacuum chamber and portion of the pumping manifold in place

First planned proton synchrotron
1.3 GeV Birmingham, 1953

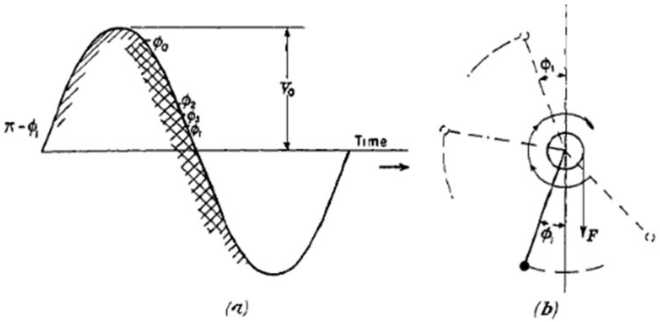
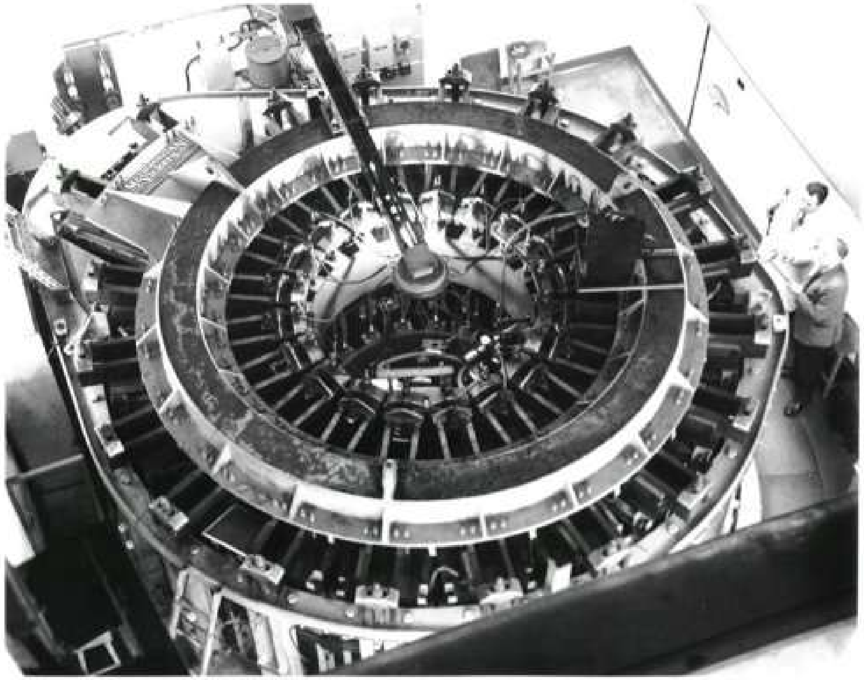


Figure 1. (a) Accelerating voltage amplitude to illustrate phase oscillations (b) Pendulum analogue.

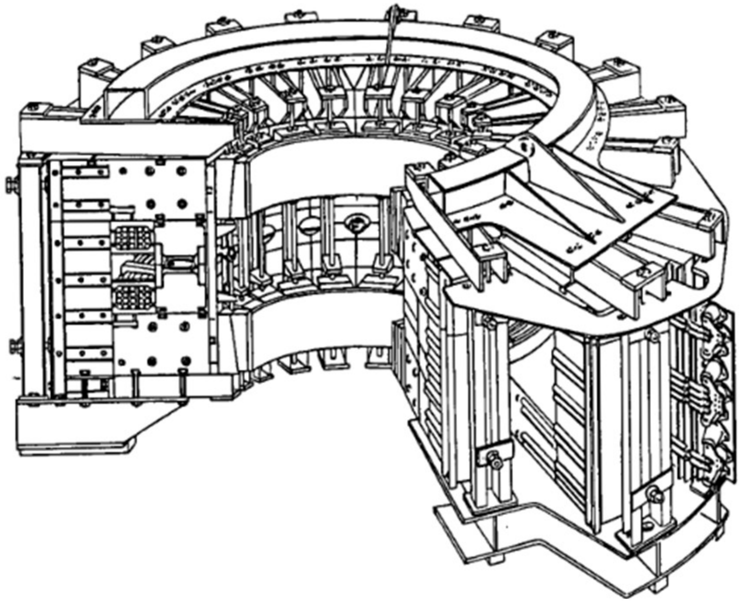
Synchrophasotron, Dubna, 1957

https://iopscience.iop.org/article/10.1088/0959-5309/59/4/314
https://iopscience.iop.org/article/10.1088/0959-5309/59/4/315

Glasgow 340 MeV e- Synchrotron (1954)



https://doi.org/10.1038/176666a0



https://epubs.stfc.ac.uk/work/26728

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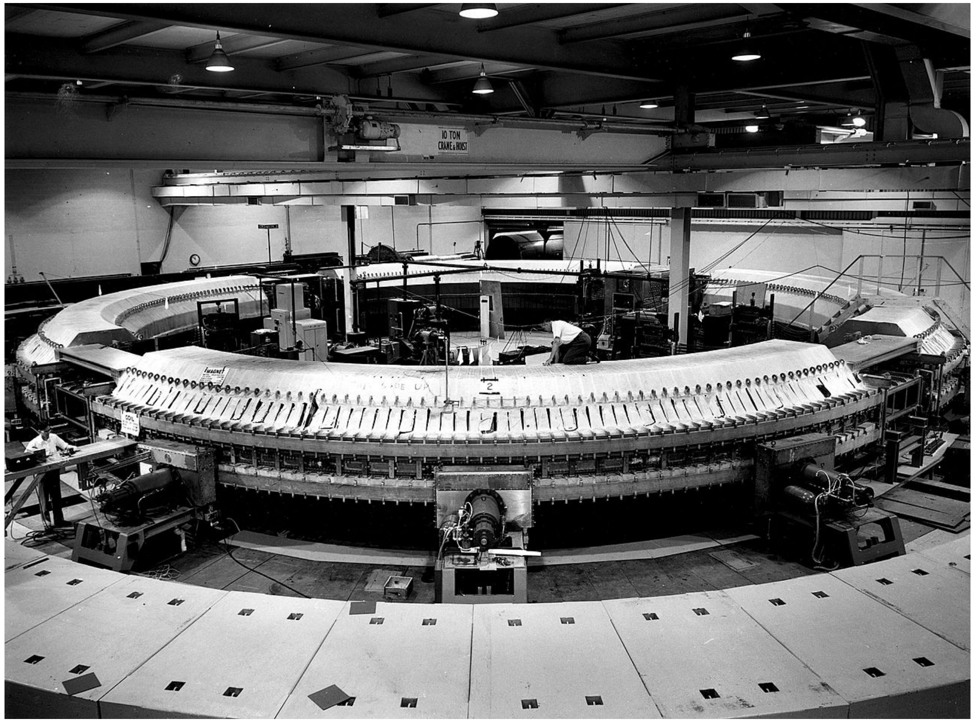
Cosmotron – first GeV proton accelerator, 1953 (3 GeV)



Also, 1st extracted beam

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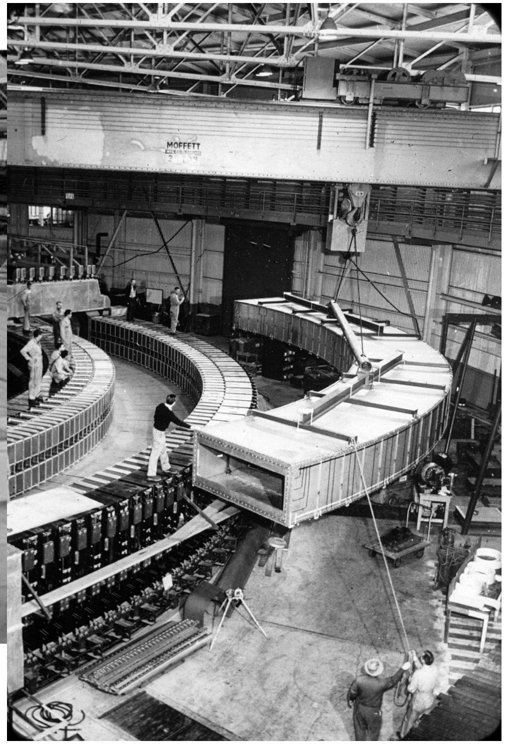
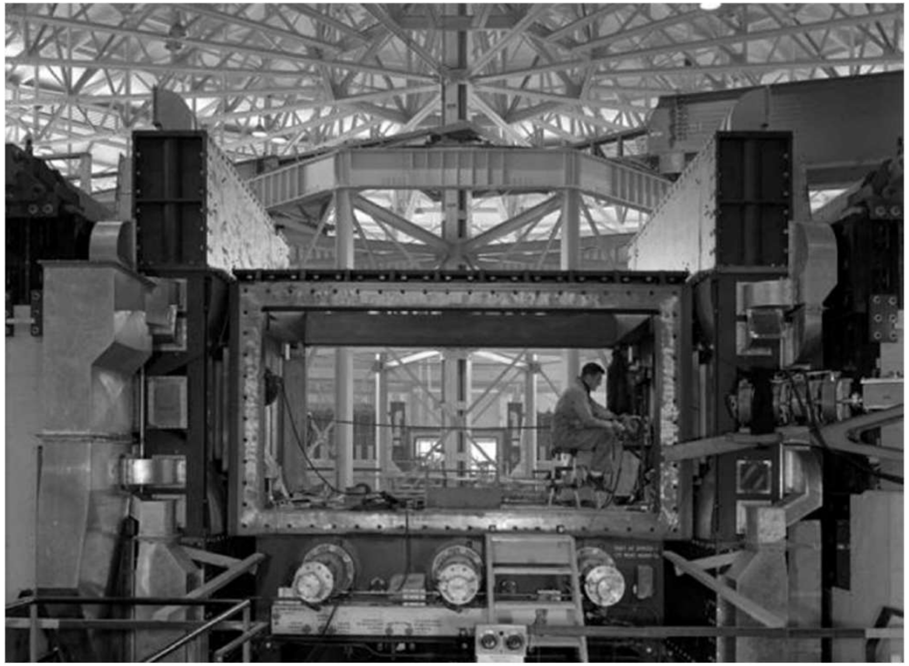
The Bevatron (6 GeV): a Large Weak-Focusing Synchrotron (1954)

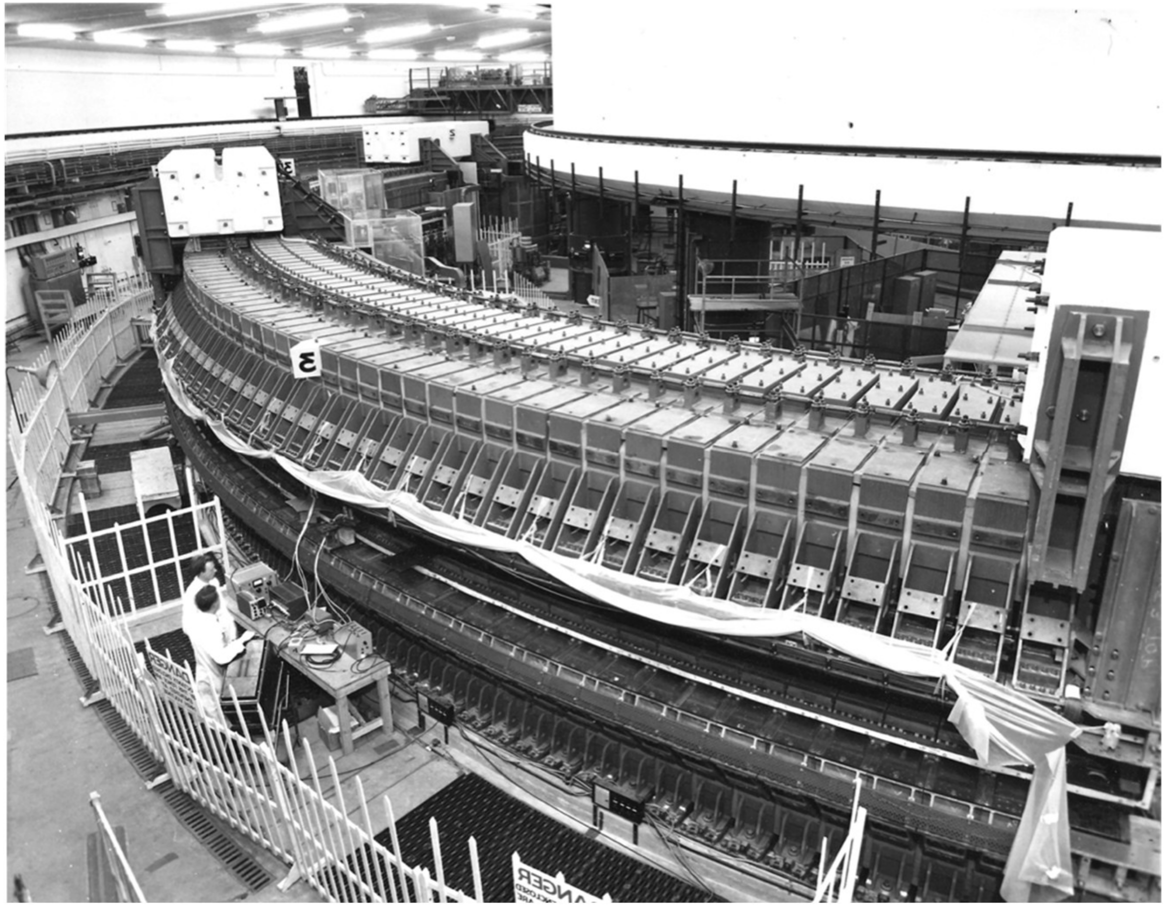
(Ed McMillan on the left)





Discovered the antiproton (Chamberlain, 1955)

NIMROD (RAL, UK): p+, 7 GeV, 1960



Before Daresbury, 1964

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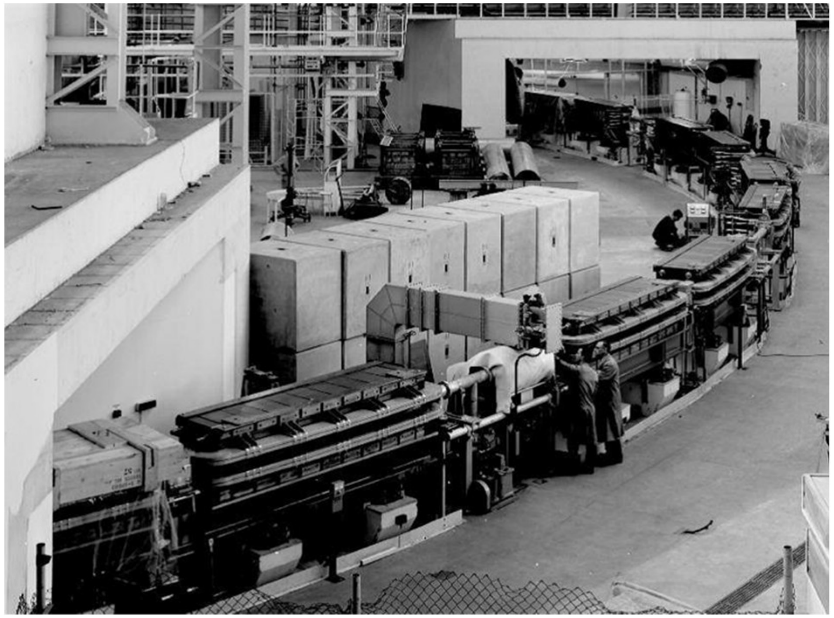
NINA at Daresbury Laboratory; e-, 5 GeV, 1966



The founding of Daresbury

ATOM LAB. IS A 'WORLD-BEATER'

Startling—but safe

DARESBURY may soon become a famous centre for atomic research. The £3,500,000 nuclear physics laboratory to be built there—if planning permission is granted—will keep Britain in the forefront of world developments.

Director of the project, Professor A. W. Merrison, of Liverpool University, said this week that the Russians, America and West Germany had similar projects.

The laboratory will be a Mecca for research physicists from many British universities, although Liverpool, Manchester and Glasgow are the chief sponsors.

After investigation of several sites, Professor Merrison has already applied for planning permission, and he will give details to representatives of the County Planning Department, and Runcorn Rural Council (Daresbury is in its area), at a meeting on Thursday.

The sandstone at Daresbury was found suitable by boring as a steady base for the delicate instruments of the "lab".

Villagers' fears that a dangerous "atom factory" was to be built, are groundless, Professor Merrison revealed.

The 4,000 electron-volt synchrotron, enclosed in a 200 feet diameter concrete shell, which will be the heart of the laboratory, will be harmless.

No atom[illegible]action

"There will [illegible] no question of atomic reaction. [illegible]s is an electrical machine for speeding electrons to high velocity," he said.

"This will enable us to examine the fundamental structure of matter on a *millionth* of the atomic scale."

The scientists will be able to examine the *twenty millionth millionth* part of an inch.

The accelerator will probe the behaviour of the tiniest particles known to science by speeding up the same kind of electron beam which throws the picture on a TV set.

Although this is a research project, the possible findings could be the basis for great future developments—in space travel, for example.

The project was authorised by the Ministry of Science in July. If planning permission is granted, building will start next spring, and completion is envisaged after five years, although the laboratory would be in operation before that.

There would eventually be a staff of 250; local people would be employed.

Professor Merrison, 38, is a Londoner, but has been at Liverpool for some years. Earlier he studied in Geneva.

Strong Focusing

Ernest Courant, Milton Livingston, Hartland Snyder, John Blewett
1952
https://doi.org/10.1103/PhysRev.88.1190
https://doi.org/10.1103/PhysRev.88.1197

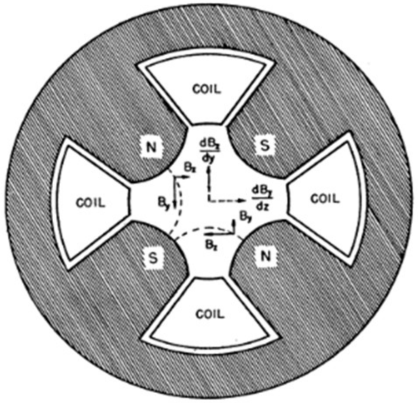
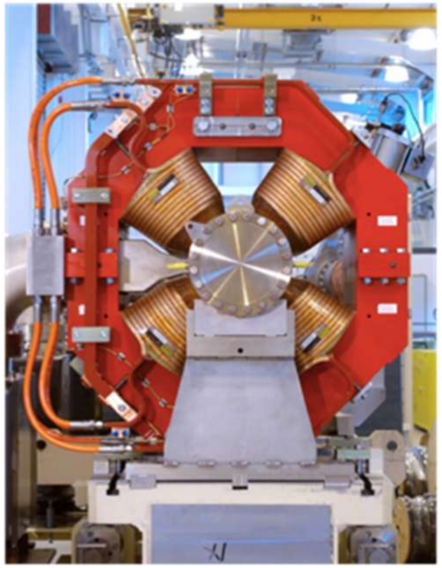
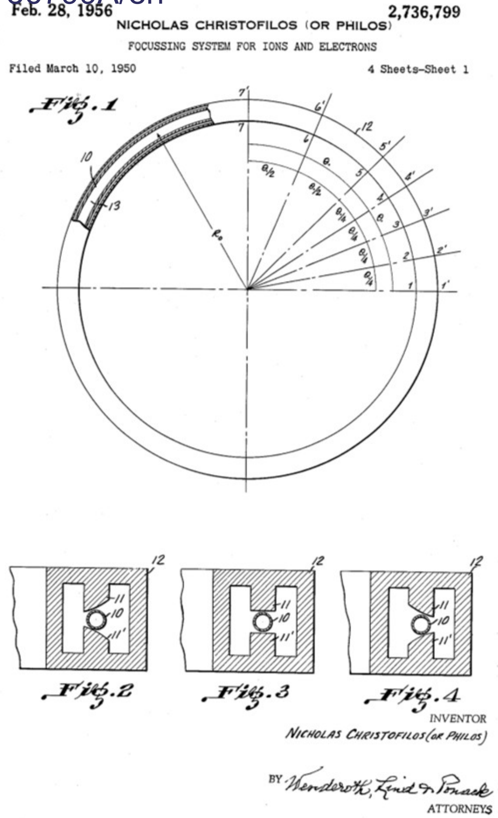


FIG. 9. Cross section of a 4-pole magnet with hyperbolic pole faces to produce uniform and equal field gradients dB_z/dy and dB_y/dz.



Patent application filed 1950
Granted 1956
https://patents.google.com/patent/US2736799A/en



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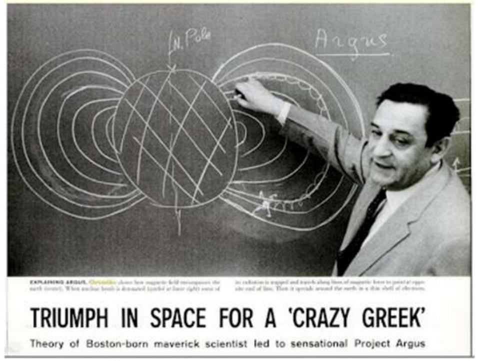
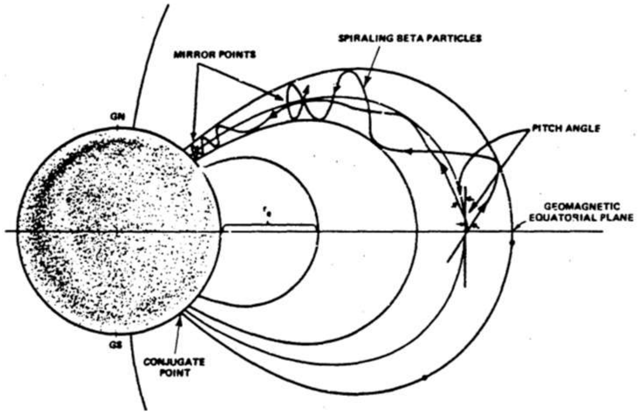
Daresbury Laboratory

Nick Christofilos, and Particles in Space

Starfish Prime (1.4 MT) a.k.a. the 'Rainbow Bomb'
- knocked out Ariel 1, the first British satellite, and Telstar 1, the first TV satellite

..turning the Earth into a giant particle accelerator, to knock out incoming nuclear weapo





Electrons in the few mev range are lost by scattering without appreciable energy loss. In this case the lifetime is

$$T = 1.7 \cdot 10^6 \frac{\psi \gamma^2}{N_0} \sqrt{\frac{h}{r_0}} \quad \text{days} \qquad (4)$$

For the following parameters

$$(r_0/h)^{1/2} = 8 \qquad N_0 = 10^4$$
$$\psi = 1.5 \text{ (latitude } 45°) \qquad \gamma = 3$$
$$T = 2.86 \text{ days}$$

These results pointed toward a convenient source of a large quantity of electrons, namely, to an A-bomb. This source is so plentiful that even one megaton of fission would create an electron layer so dense as to constitute a radiation hazard in outer space. To illustrate this I cite the following example: one megaton of fission yields 10^{26} fissions, approximately. If we assume that 4 electrons per fission are above 1 mev energy and half will be trapped in the earth's field we derive the number of trapped electrons, namely, $2 \cdot 10^{26}$. Then let us assume that these will be spread in a volume in outer space equal to the earth's volume, or 10^{27} cm.^{3} The resulting electron density is 0.2 electron/cm.^{3} The flux against any surface exposed to the electrons is

https://www.pnas.org/doi/abs/10.1073/pnas.45.8.1144

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Digging the first foundations for CERN, May 1954

First proposed by Louis de Broglie in 1949

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Daresbury Laboratory

https://home.cern/news/news/cern/cern-celebrates-60-years-science-and-peace
https://inis.iaea.org/collection/NCLCollectionStore/_Public/46/027/46027043.pdf

Scien
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ADA – the first electron/positron storage ring

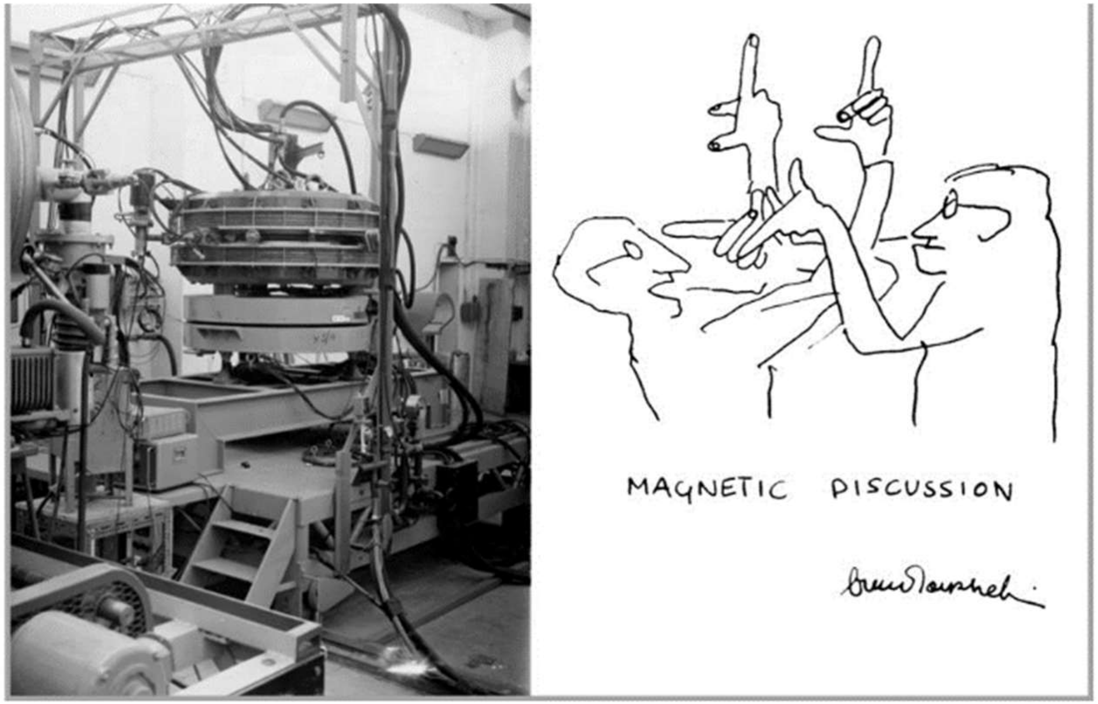
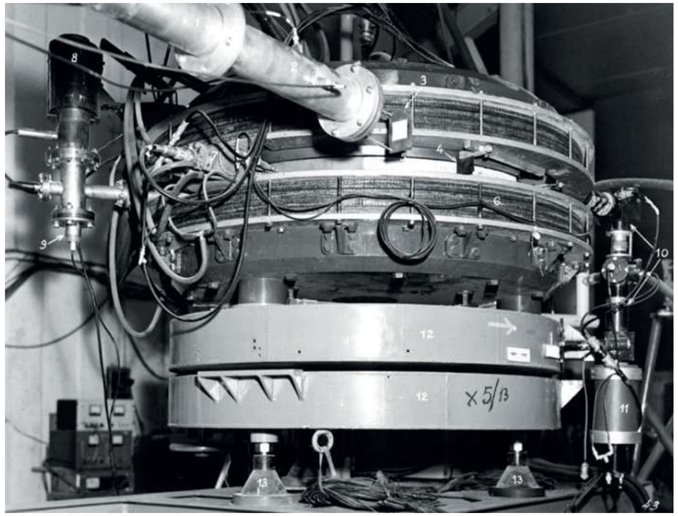
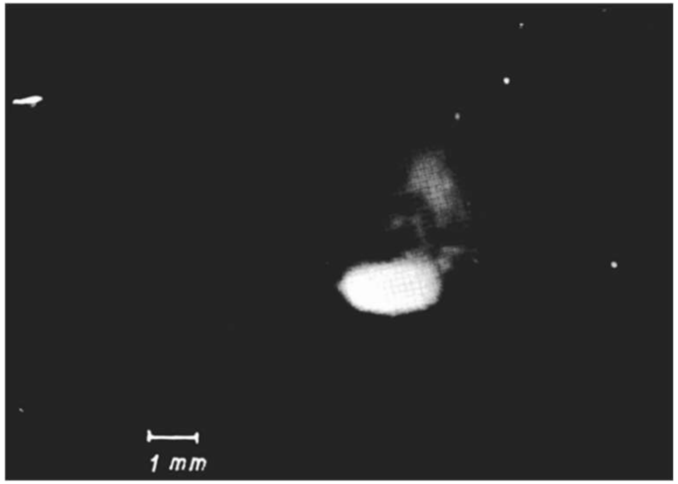


Fig. 2. Left: AdA installed in Salle 500 MeV, Laboratoire de l'Accélérateur Linéaire, Orsay, France, 1963. Right: a drawing by Bruno Touschek reflecting frequent

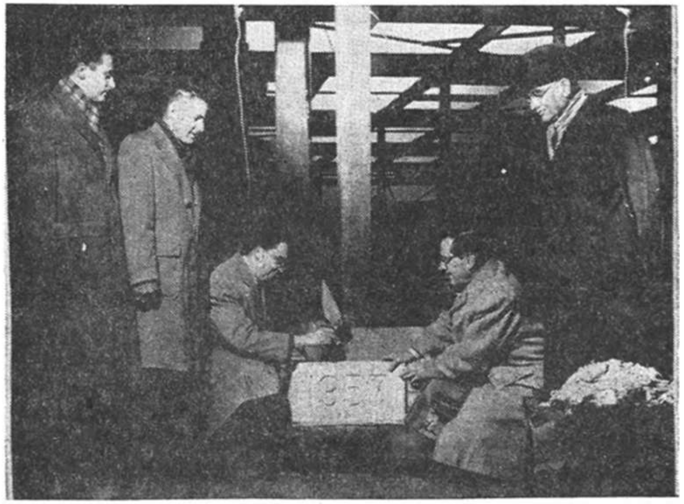




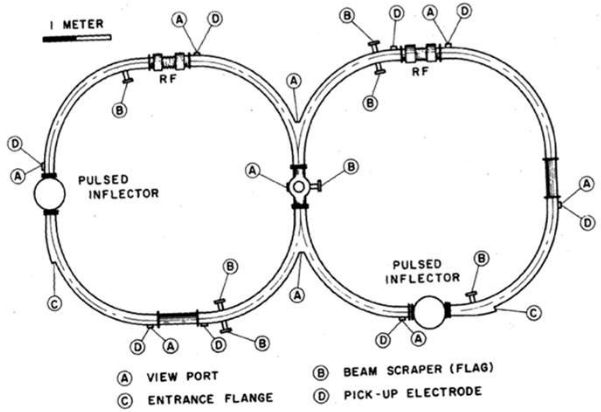
Storage Ring Colliders (1963)

https://journals.aps.org/pr/abstract/10.1103/PhysRev.102.1418
https://www.jstor.org/stable/1710761

Cornerstone of Accelerator Is Laid

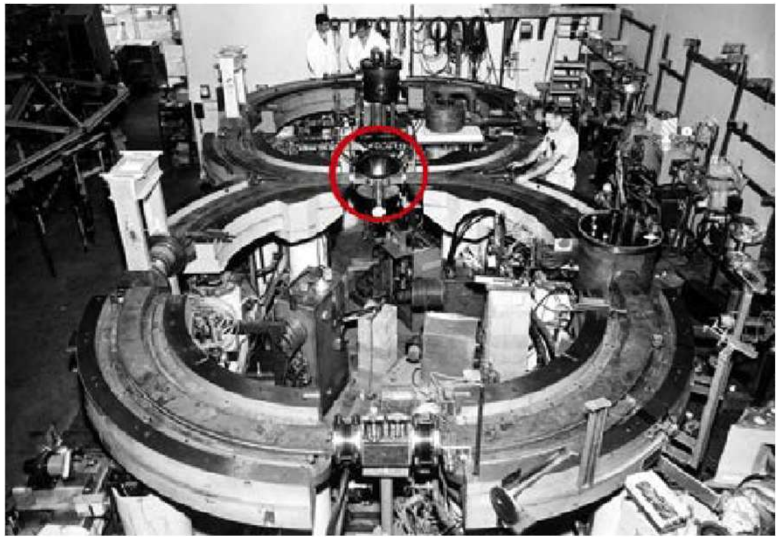


FORRESTAL: Milton G. White, director of the Princeton-Penn accelerator, lays cornerstone. Also (l. to r.), designers Gerald K. O'Neil and Frank G. Shoemaker, AEC's Enzi DeRenzis, Alan G. Shenstone '14.



Princeton-Stanford Experiment

Gerard Kitchen O'Neill



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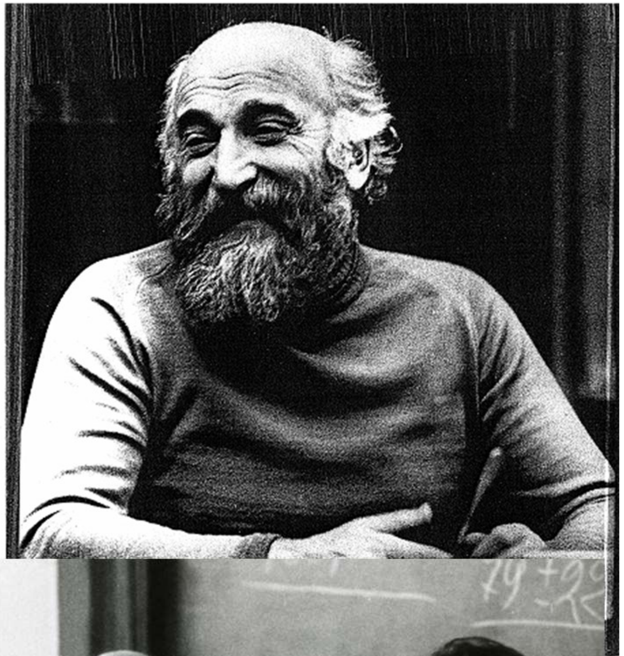
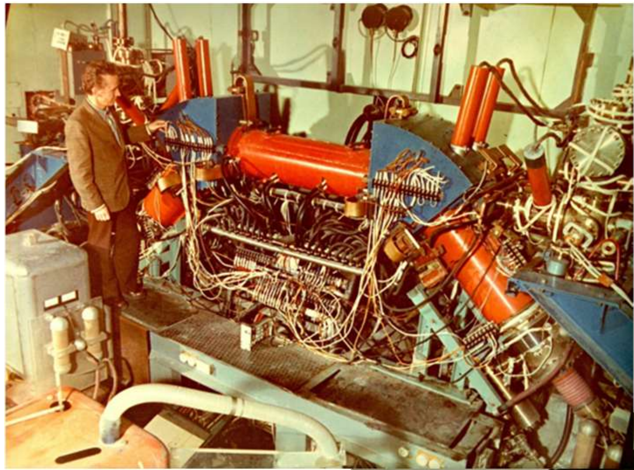
Gersh Budker

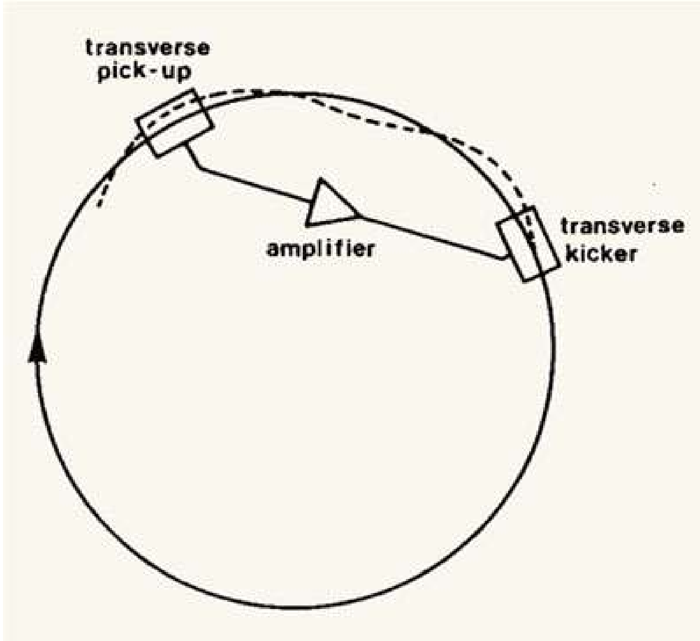


with Boris Chirikov



Invented electron cooling
Founded INP Novosibirsk

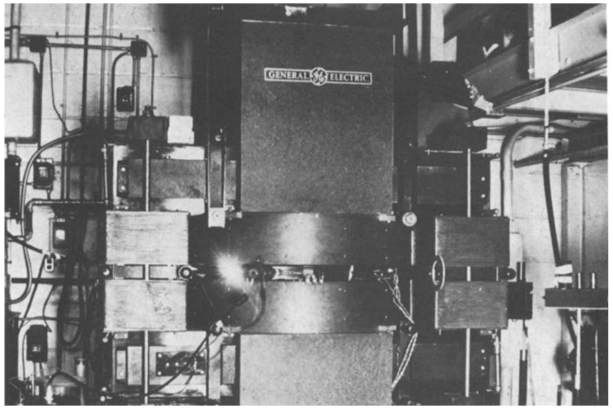
Stochastic Cooling; Simon van der Meer (1970s)



https://cds.cern.ch/record/312939?ln=en

Synchrotron Radiation

Floyd Haber was the first person to observe artificial synchrotron radiation
(you can see synchrotron radiation each night if you look up)



'If the accelerator tube of the 100-MeV betatron at Schenectady had not been opaque, the visual observation would probably have been made three years earlier by Westendorp or Blewett soon after the publication of your letter to the Physical Review (Phys. Rev. 65:343, 1944). Unfortunately they were not able to see through the silvered wall of the betatron donut.'

Radiation from Electrons in a Synchrotron

F. R. Elder, A. M. Gurewitsch, R. V. Langmuir, and H. C. Pollock
Research Laboratory, General Electric Company, Schenectady, New York
May 7, 1947

HIGH energy electrons which are subjected to large accelerations normal to their velocity should radiate electromagnetic energy.[1-4] The radiation from electrons in a betatron or synchrotron should be emitted in a narrow cone tangent to the electron orbit, and its spectrum should extend into the visible region. This radiation has now been observed visually in the General Electric 70-Mev synchrotron.[5] This machine has an electron orbit radius of 29.3 cm and a peak magnetic field of 8100 gausses. The radiation is seen as a small spot of brilliant white light by an observer looking into the vacuum tube tangent to the orbit and toward the approaching electrons. The light is quite bright when the x-ray output of the machine at 70 Mev is 50 roentgens per minute at one meter from the target and can still be observed in daylight at outputs as low as 0.1 roentgen.

https://doi.org/10.1103/PhysRev.71.829.5

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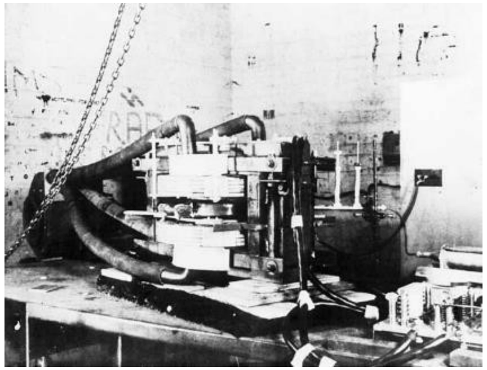
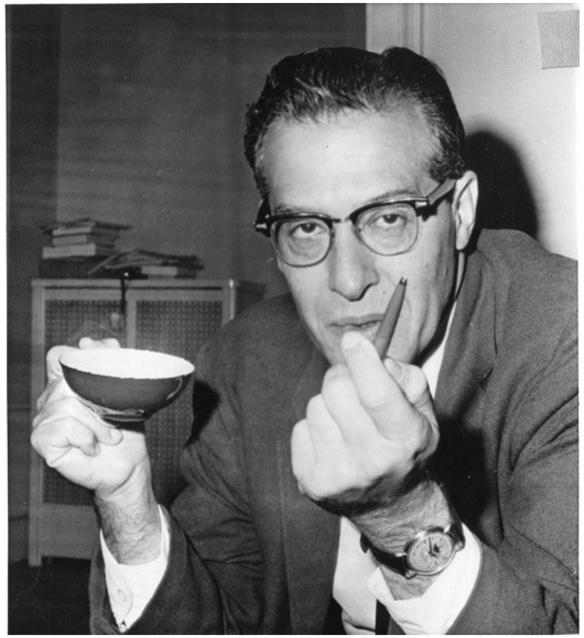
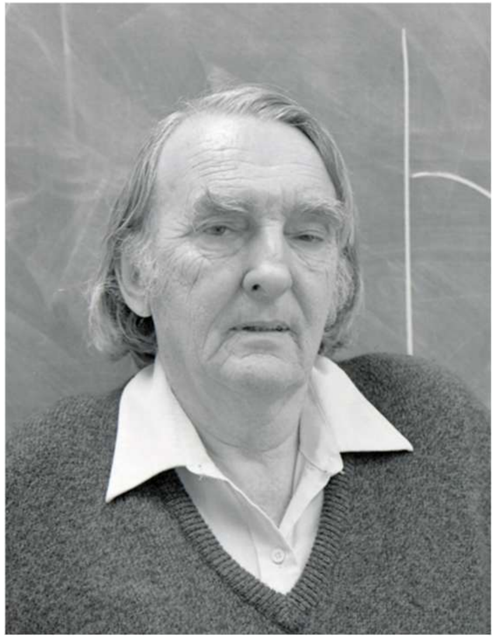


Goward's original synchrotron
(converted from betatron)
Woolwich Arsenal, London

The DIAMOND synchrotron: 561.6m, 3 GeV electrons
(RAL, Oxfordshire)
Designed here at Daresbury!

Julian Schwinger and Matthew Sands





'My laboratory is my ballpoint pen'

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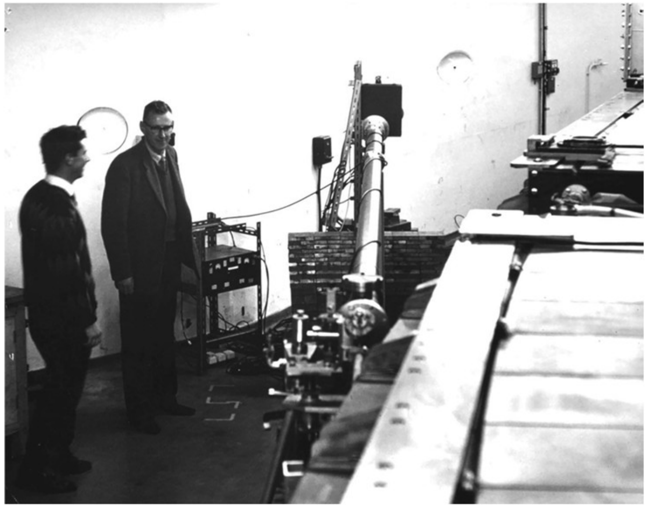
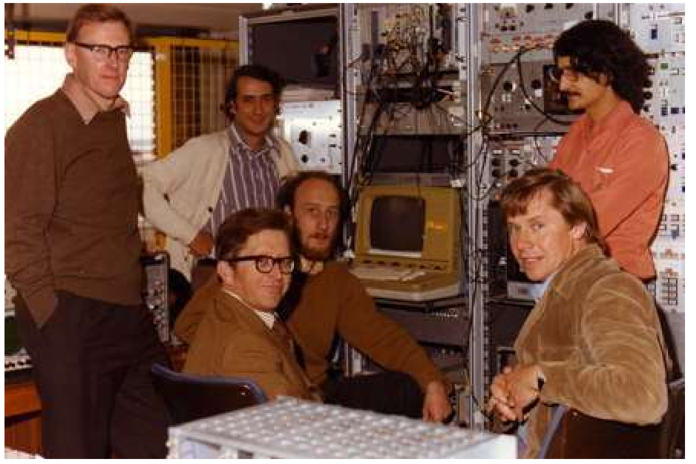
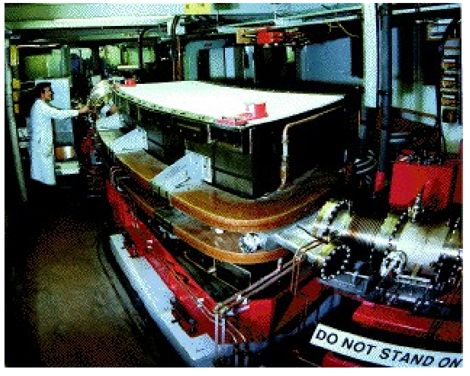
The first X-ray beamline – Daresbury, 1970s



First X-Ray Beamline on NINA



The original synchrotron radiation gang



SRS, Daresbury (1980-2008): world's 1st X-ray facility

Outside DL Building A

Science and Technology Facilities Council
Daresbury Laboratory

Achromats

Renate Chasman
Phys. Perspect. 10 (2008) 438

1. Introduction

The most important factor for synchrotron radiation users is the brilliance which is mainly determined by the cross section of the beam and given by the square root of the emittance multiplied with the betatron function.

The emittance ε of a beam in a storage ring is determined by the balance of two competing processes: the quantum excitation by the emission of synchrotron radiation and the acceleration of the particles within the rf cavities. The formulae for calculating the emittance of a storage ring and other related parameters are summarized in table 1.

The emittance scales in general with the square of the energy and the third power of the bending magnet's deflection angle. The optics influences the emittance

For the case in fig. 1b a minimum of β and η in the centre of the magnet is required with $\beta_{\min} = L/(\sqrt{15})$ and $\eta_{\min} = L^2/(24\rho)$:

$$\varepsilon_b = C_q \gamma_0^2 \frac{1}{J_x} \phi^3 \frac{1}{3 \times 4\sqrt{12}} . \qquad (2)$$

ϕ if the bending angle of the dipole, the other symbols are explained in table 1 [3–5].

The second expression is smaller than the first one by a factor of three. Hence to reach the lowest emittance, a storage ring should have a lattice which provides a shape of the horizontal betatron and dispersion functions as represented in fig. 1b in all dipole magnets. However, other design considerations forbid this. A light source includes undulators and wigglers and at the position of these insertion devices, in the long straight sections, the dispersion has to be zero. This