HISTORY OF PARTICLE ACCELERATORS

Lecture 1
January 2014

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What about the name accelerator?

- **Special relativity says that for an electron**

Energy	1 MeV	→		1 GeV
$\beta = v/c$	0.95	0.99	0.999	0.999 999 9
$\gamma = m/m_0$	3	7	22	2000

- **Yes, the speed increases, but not as spectacularly as the mass. In fact, it would be more correct to speak of the mass or better the momentum (*mv*) increasing.**

- **Ginzton, Hansen and Kennedy* suggested**

"Ponderator" or "Mass Agrandiser",

but this did not become fashionable and we are left with 'Accelerator'.

*** Rev. Sci. Instr., Vol.19, No.2, Feb. 1948.**

Pre-accelerator era

During the 1800s, prior to the era of accelerators, physics experimentation was very popular with the general public who often built their own equipment.

HOW TO MAKE A WIMSHURST MACHINE. 95

centre of the diameter of the semicircle. Two similar ½-in. holes are also to be put through the centres of the wider extremities of these standards, at 33 ins. up from the shoulders of the tenon. From

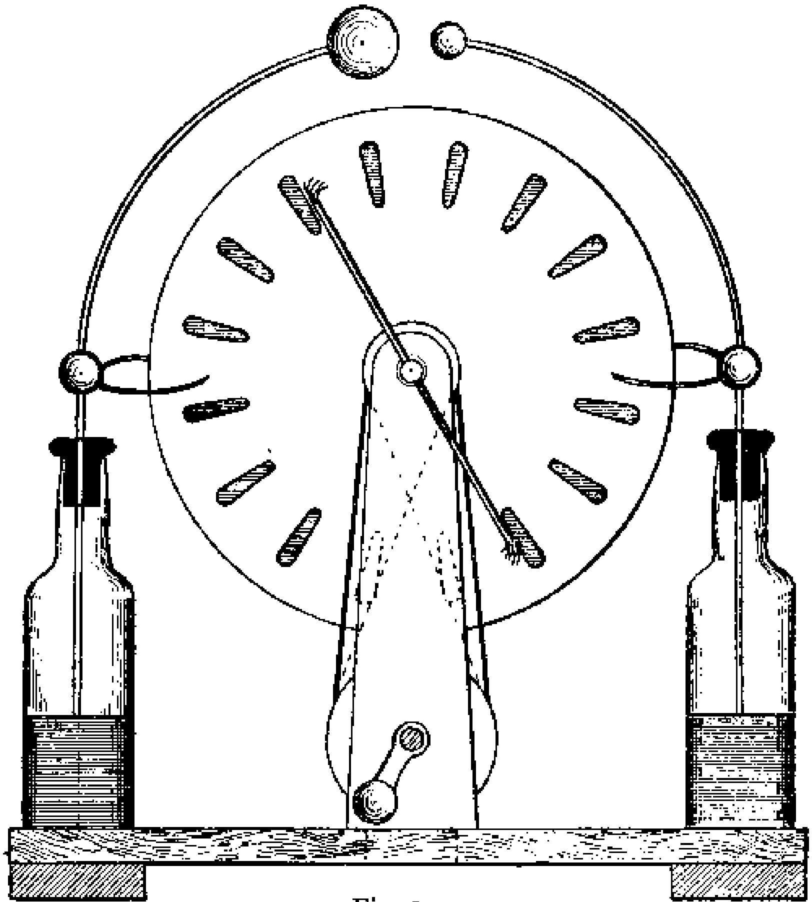
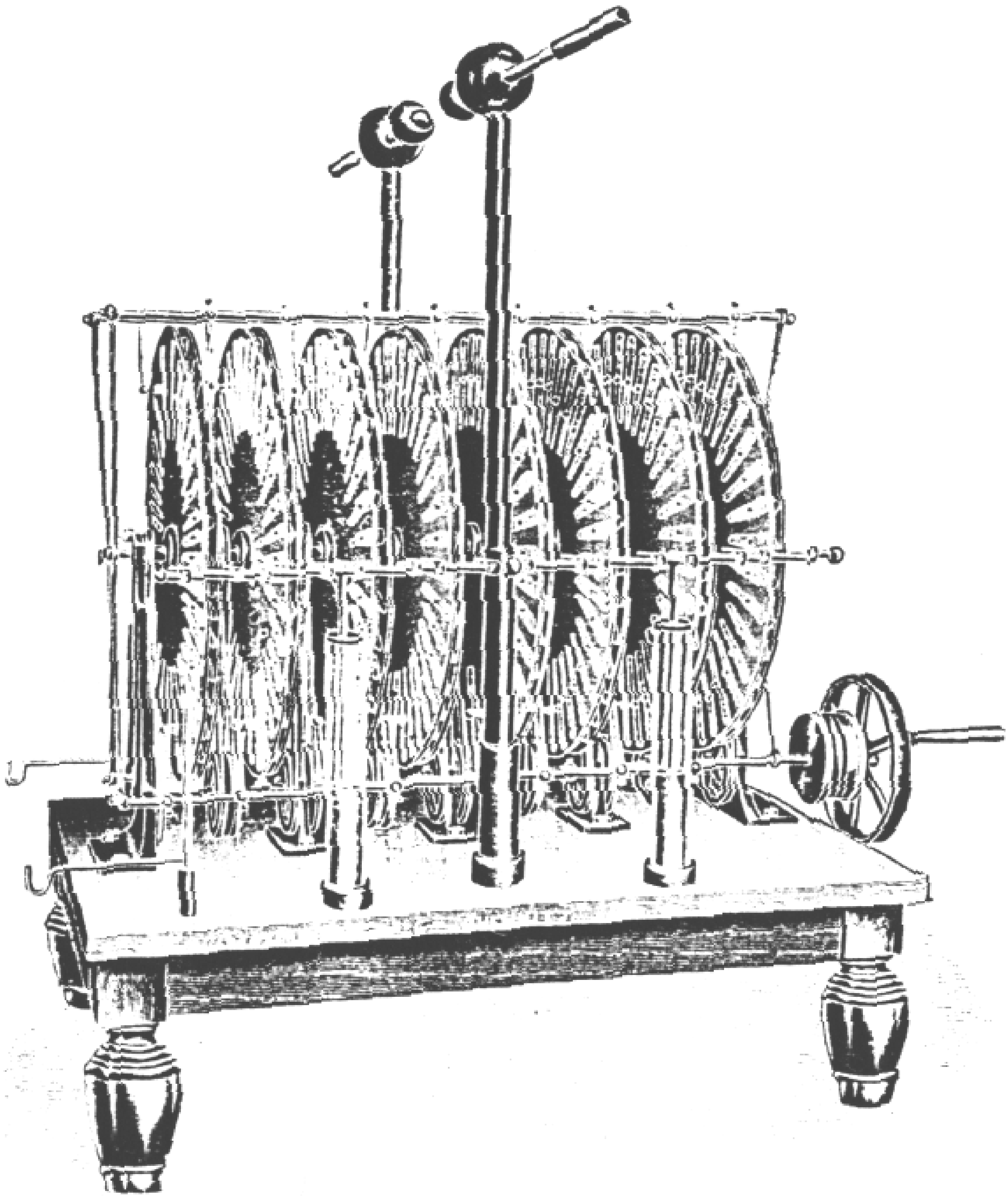


Fig. 1.

GUILBERT PITMAN
Cecil Court, St. Martin's Lane, W.C.
1903

A commercial Wimshurst-type machine



The main history line

- In 1906, Rutherford bombards a mica sheet with natural alphas of a few MeV and monitors the scattering.
- In 1919 Rutherford induces a nuclear reaction with natural alphas.

…Rutherford believes that he needs a controllable source of many MeV to continue his research on the nucleus. This is far beyond the electrostatic machines then existing, but

…in 1928 Gamov predicts quantum 'tunneling' and perhaps 500 keV would suffice ???

…and so the first accelerator was built for physics research:

- 1928 Cockcroft & Walton start designing an 800 keV generator encouraged by Rutherford.
- 1932 the generator reaches 700 keV and Cockcroft & Walton split the lithium atom with only 400 keV protons. They received the Nobel Prize in 1951.

The players

- **Ernest Rutherford:**

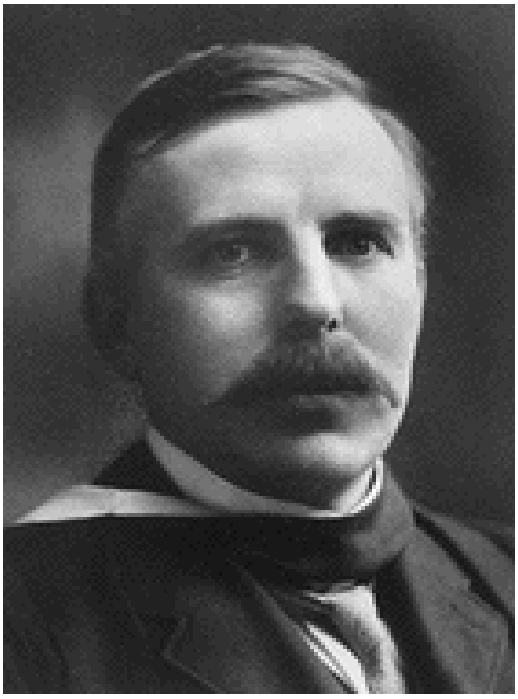
  Born 30/8/1871, in Nelson, New Zealand.

  Died 1937.

  Professor of physics at McGill University, Montréal (1898-1907).

  Professor of physics at University of Manchester, UK (1907-1919).

  Professor of experimental physics and Director of the Cavendish Laboratory, University of Cambridge.



- **Sir John Douglas Cockcroft:**

  Born 27/5/1897, Todmorden, UK.

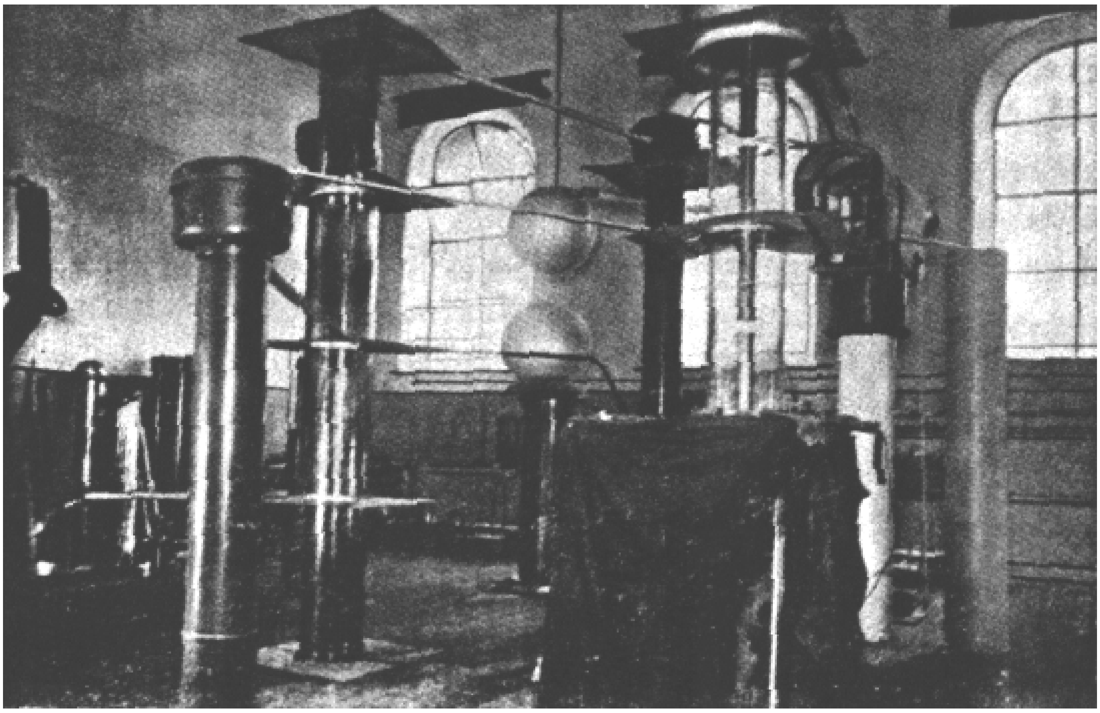
  Died 1967.

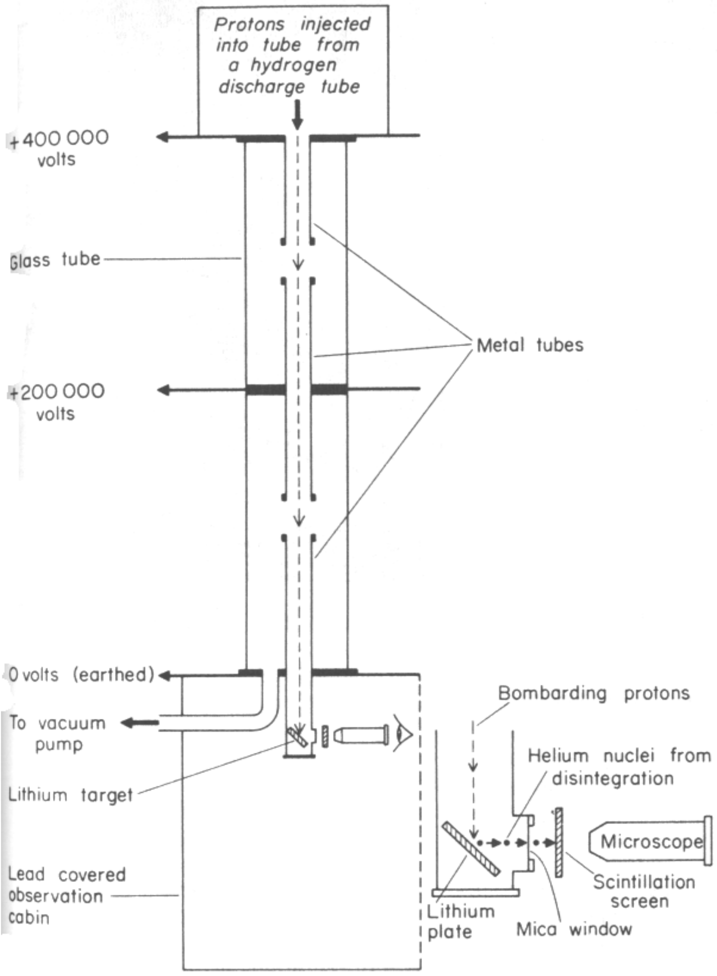
- **Ernest Thomas Sinton Walton:**

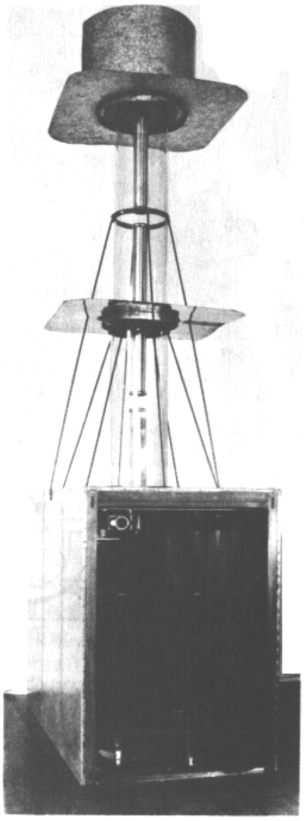
  Born 6/10/1903, Ireland.

  Died 25/6/1995.

Cockcroft & Walton's generator

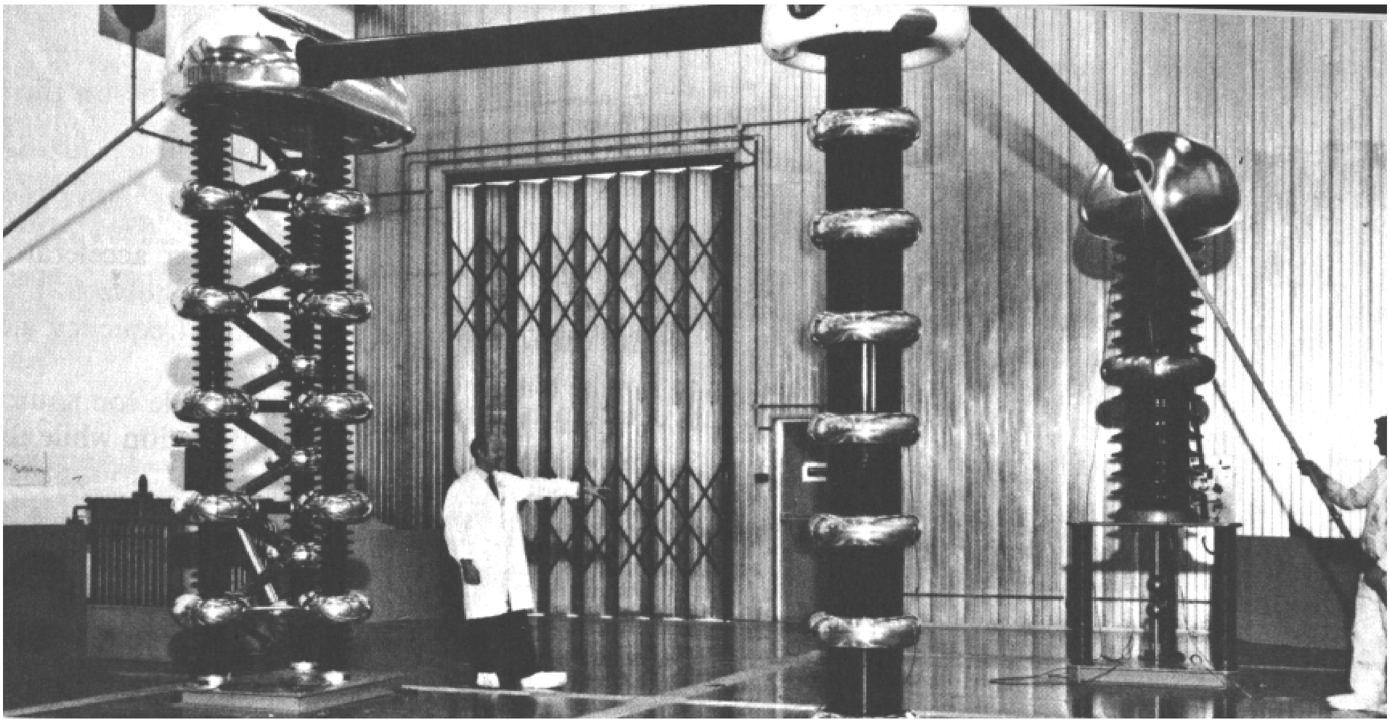


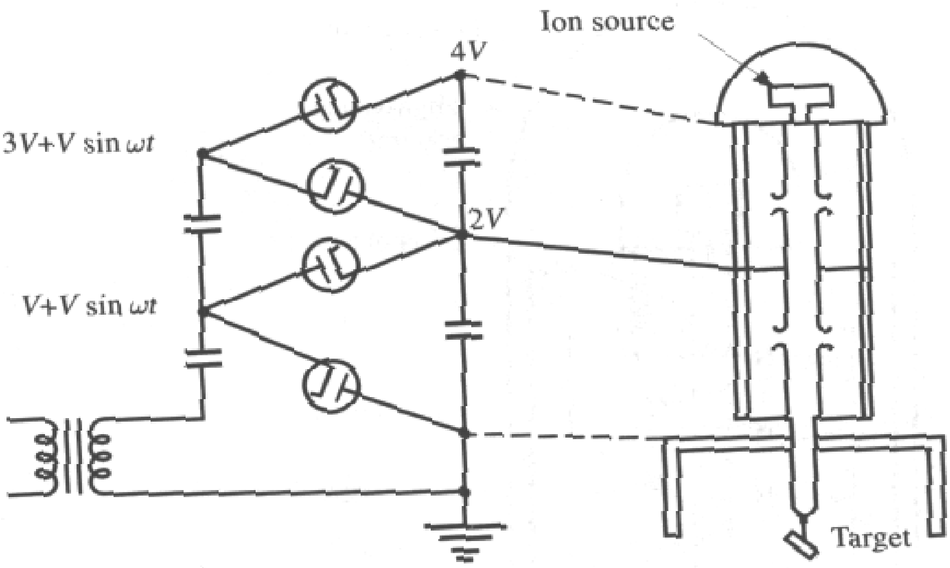




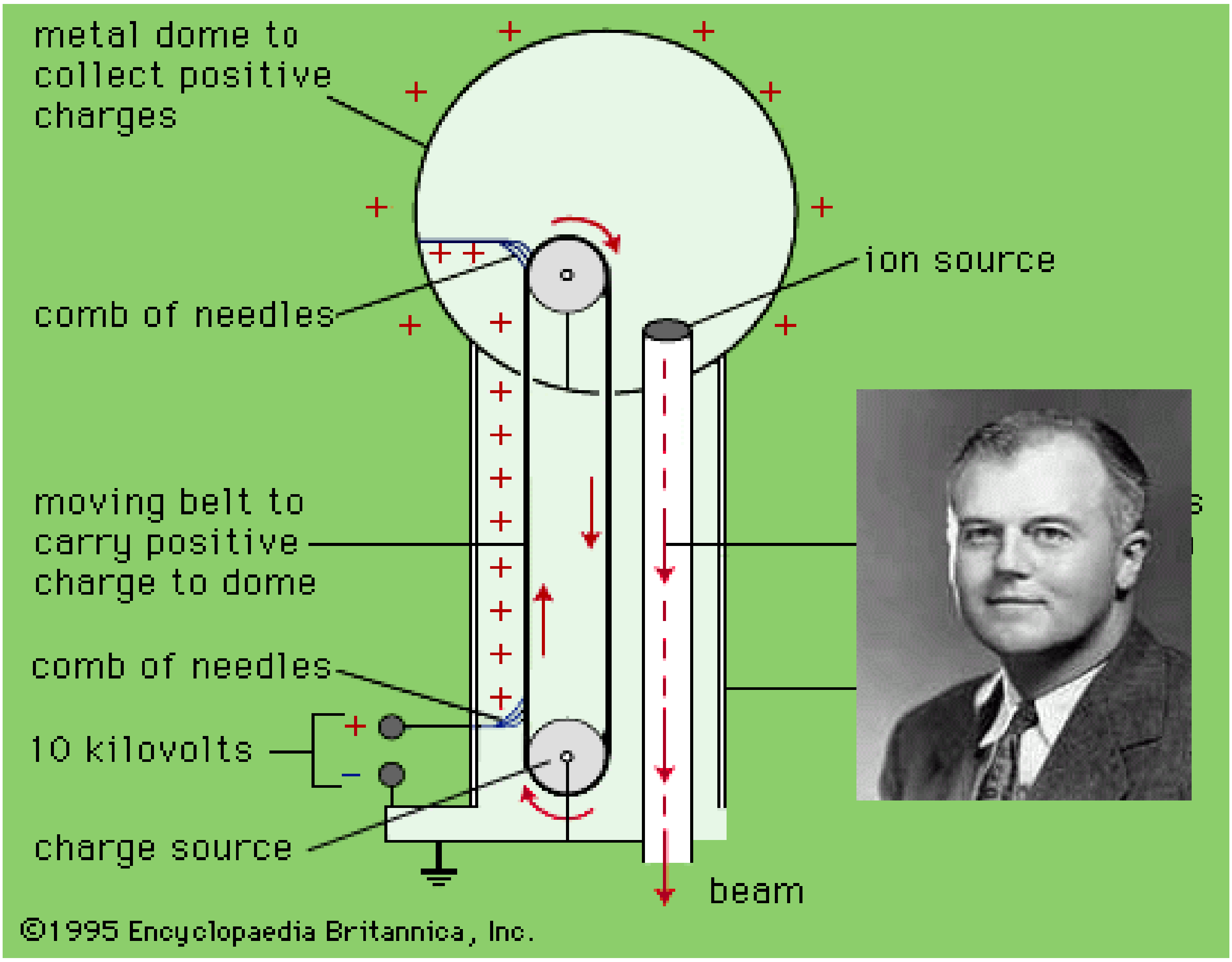
Cockcroft-Walton generators became standard equipment

The Cockcroft-Walton generator that served the 7 GeV NIMROD synchrotron at Rutherford laboratory.





Van de Graaff, a competitor



DC voltage generator:

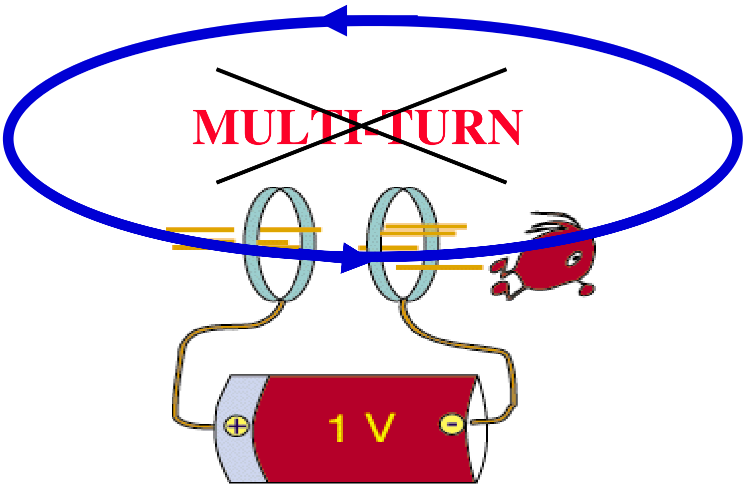
Van de Graaff was an American Rhodes scholar in Oxford, UK in 1928 when he became aware of the need for a high-voltage generator. His first machine reached 1.5 MV in Princeton, USA, in the early 1930s.

These generators typically operate at 10 MV and provide stable low-momentum spread beams.

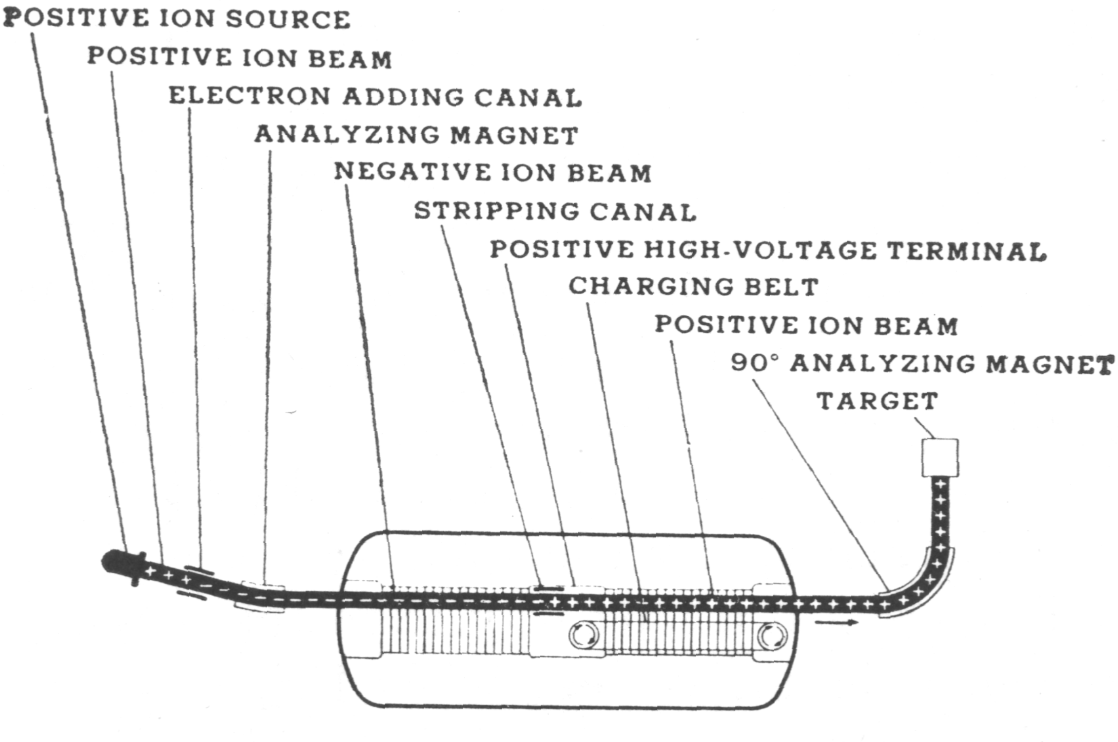
[Robert Van de Graaff 1901-1967]

Tandem

- DC generators produce conservative fields and the voltage can only be used once for acceleration.



- The Tandem van de Graaff is a clever to trick to use the voltage twice.



TWO-STAGE TANDEM ACCELERATOR

A second history line

❖ Theory and proof-of-principle:

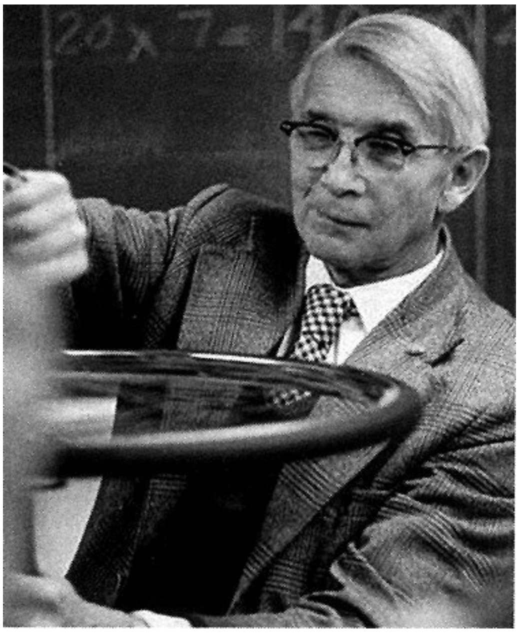
- ❖ **1924 Ising proposes time-varying fields across drift tubes. <u>This is a 'true' accelerator that can achieve energies above that given by the highest voltage in the system.</u>**
- ❖ **1928 Wideröe demonstrates Ising's principle with a 1 MHz, 25 kV oscillator to make 50 keV potassium ions; <u>the first linac</u>.**

❖ And on to a practical device:

- ❖ **1929 Lawrence, inspired by Wideröe and Ising, conceives <u>the cyclotron; a 'coiled' linac</u>.**
- ❖ **1931 Livingston demonstrates the cyclotron by accelerating hydrogen ions to 80 keV.**
- ❖ **1932 Lawrence's cyclotron produces 1.25 MeV protons and he also splits the atom just a few weeks after Cockcroft & Walton. Lawrence received the Nobel Prize in 1939.**

The players

- **Gustaf Ising:**



- **Rolf Wideröe:**

  Born 11/7/1902 in Oslo, Norway.

  Died 1996.

  Also contributed to the fields of power lines and cancer therapy.

- **Ernest Orlando Lawrence:**

  Born 8/8/1901 in South Dakota, USA. Third generation Norwegian.

  Died 27/8/1958.

The first 'true' accelerator

–50–

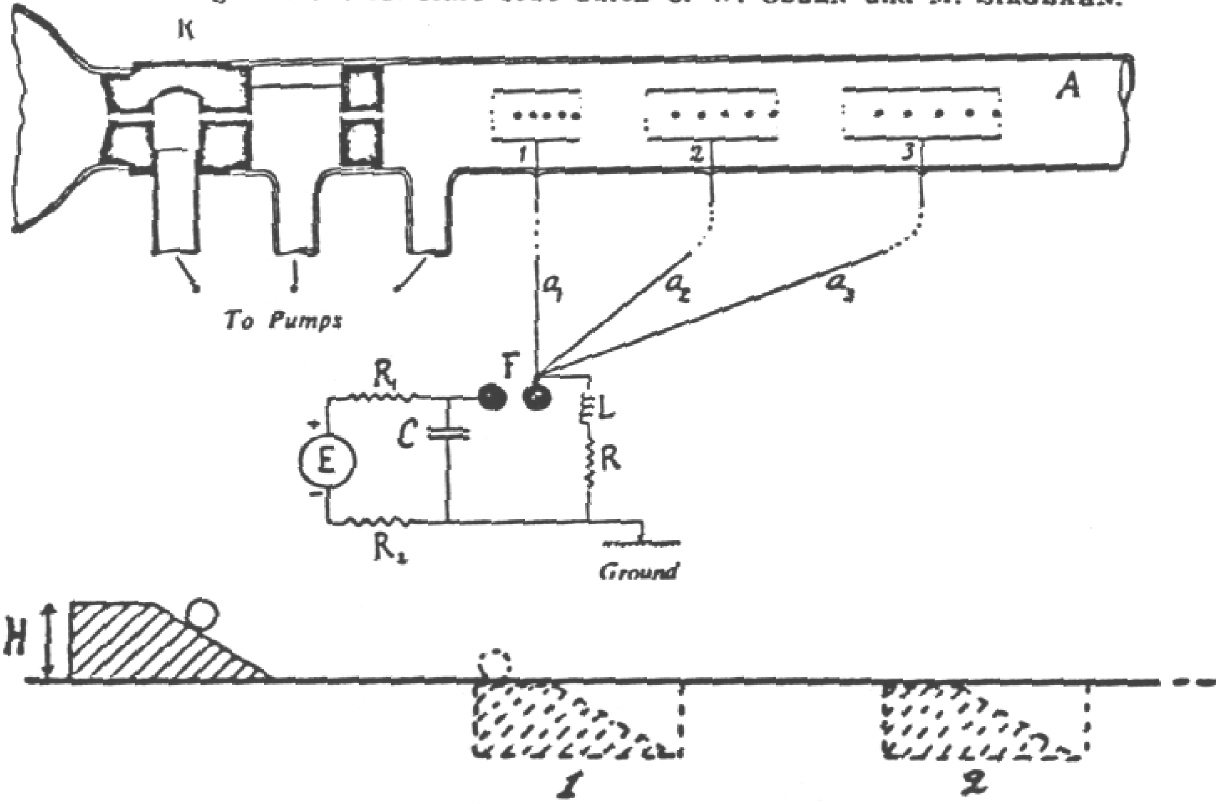
Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl.

Von

GUSTAF ISING.

Mit 2 Figuren im Texte.

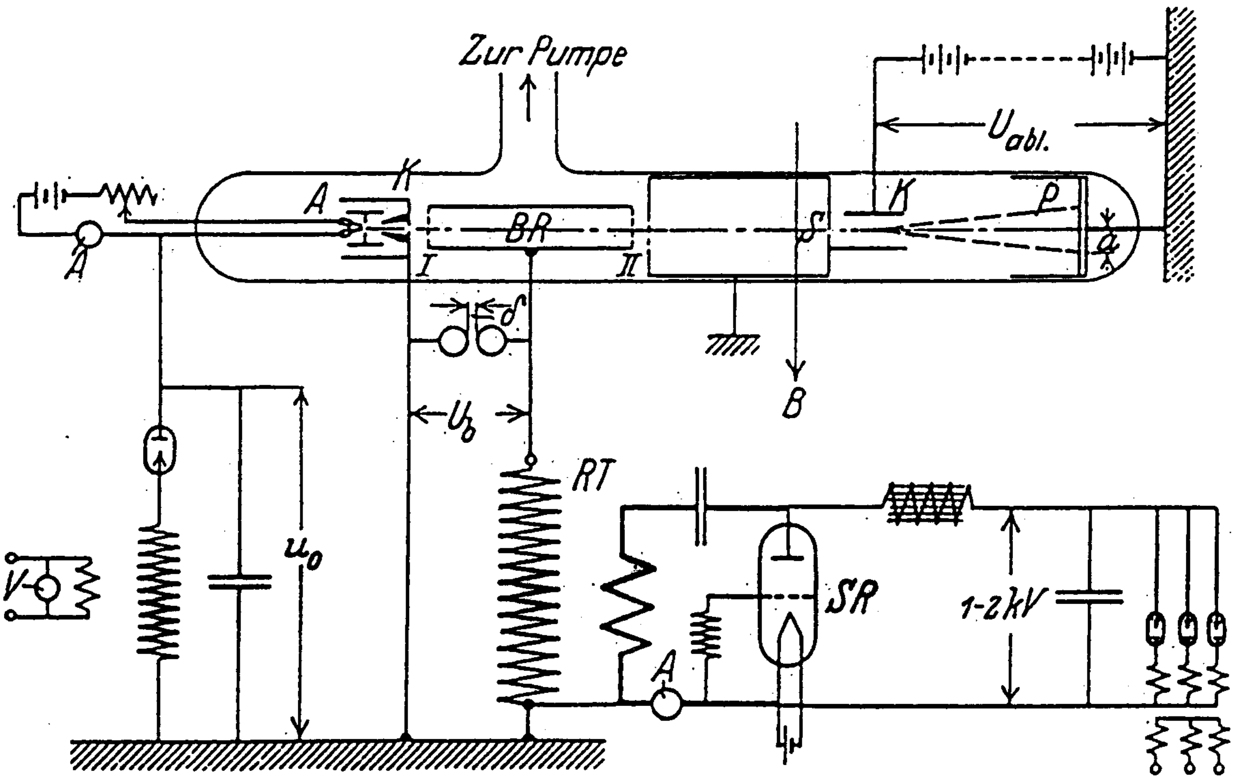
Mitgeteilt am 12. März 1924 durch C. W. OSEEN und M. SIEGBAHN.



- This principle is used in almost all of today's accelerators. The ions can reach energies above the highest voltage in the system.

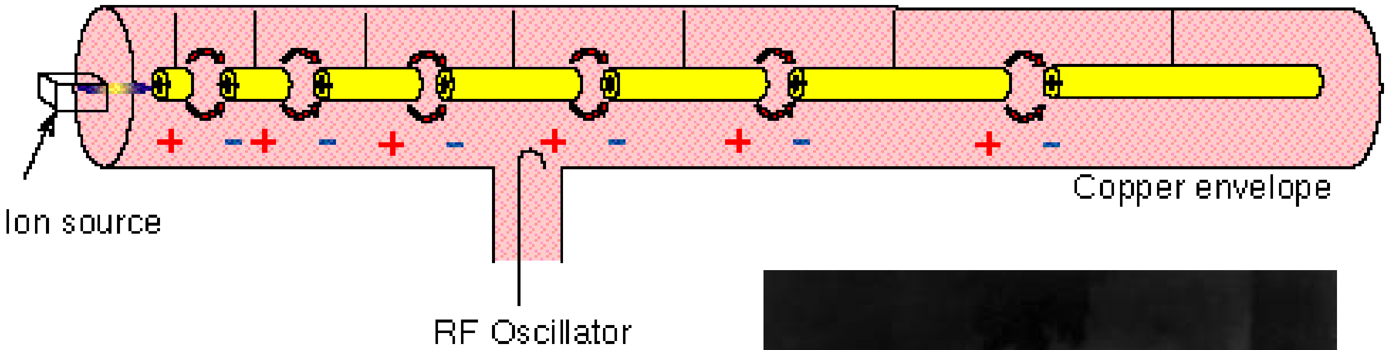
Wideröe's Linac

- Wideröe's first linac 1928



Alvarez Linac

- Alvarez linac – the first practical linac 32 MeV at Berkeley 1946:
  - Particle gains energy at each gap.
  - Drift tube lengths follow increasing velocity.
  - The periodicity becomes regular as $v \Rightarrow c$.
  - His choice of 200 MHz became a *de facto* standard for many decades.

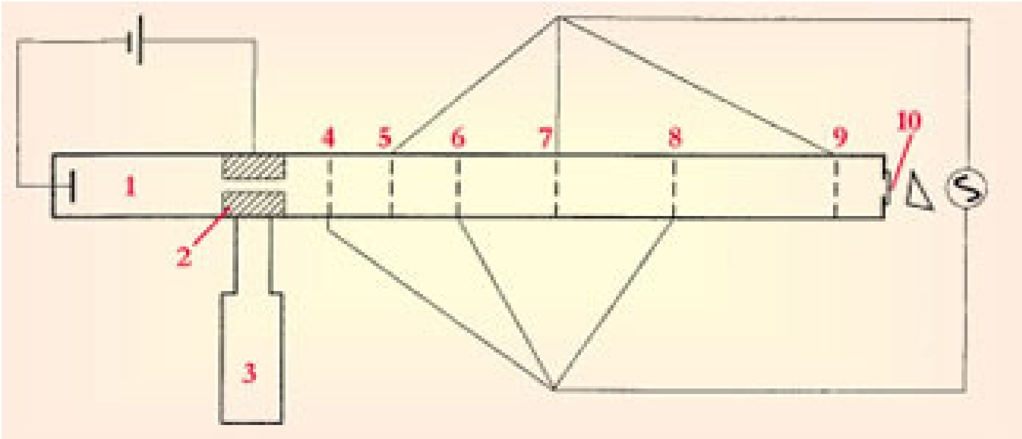


- Luis W. Alvarez was born in San Francisco, Calif., on 13/6/1911.

  Died 1/9/1988.

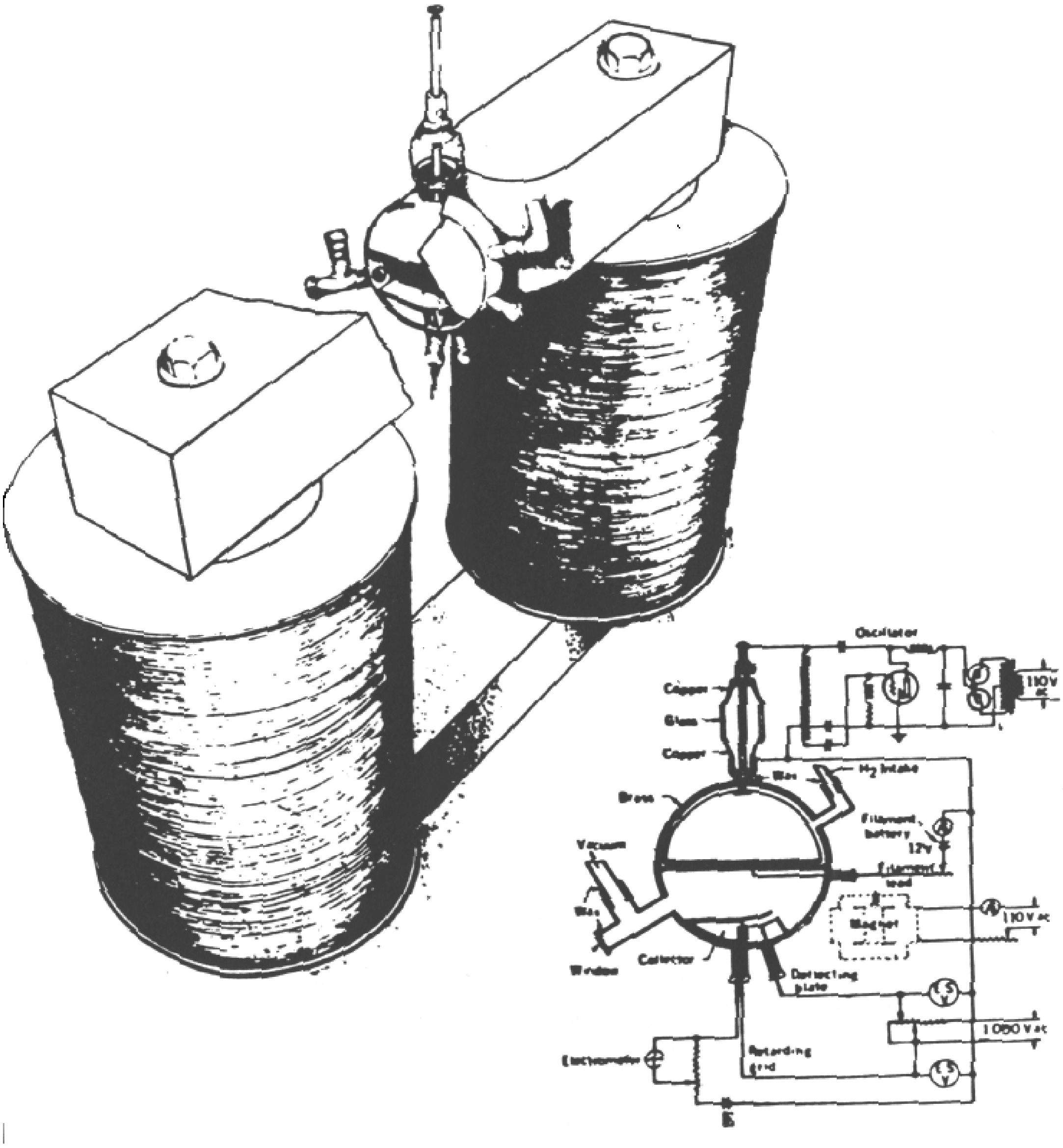
  He received the Nobel physics prize in 1968.

Leo Szilard was too late

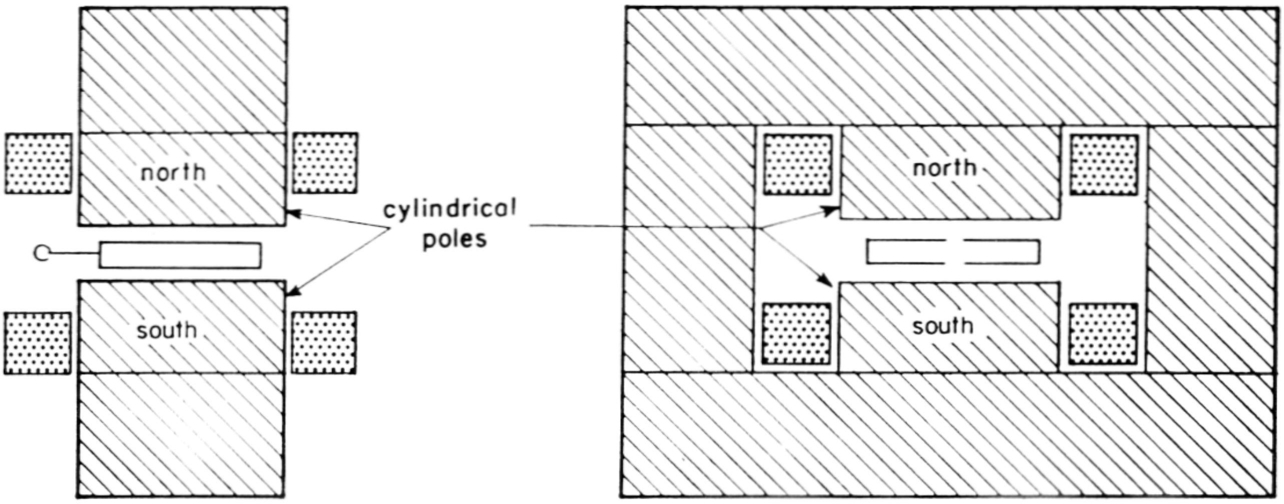


- The first accelerator proposed by L. Szilard was a linac, appearing in a German patent application entitled "Acceleration of Corpuscles" and filed on 17 December 1928. The Figure shows the proposed layout. Though Szilard writes of "canal rays" in the patent application, he also refers to "corpuscles, e.g. ions or electrons." Considering the low-frequency RF sources available in those days, an apparatus of modest length would have worked only for rather heavy ions.
- Leo Szilard was a professional inventor. He dropped the above patent perhaps because of 'prior art' by Ising.

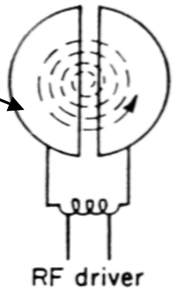
Livingston's demonstration cyclotron



Cyclotron



Electrodes, known as 'Dees'



Centripetal force

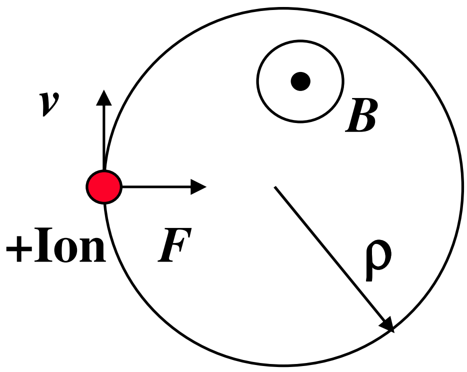
$$F = evB = \frac{mv^2}{\rho}$$

Constant revolution frequency

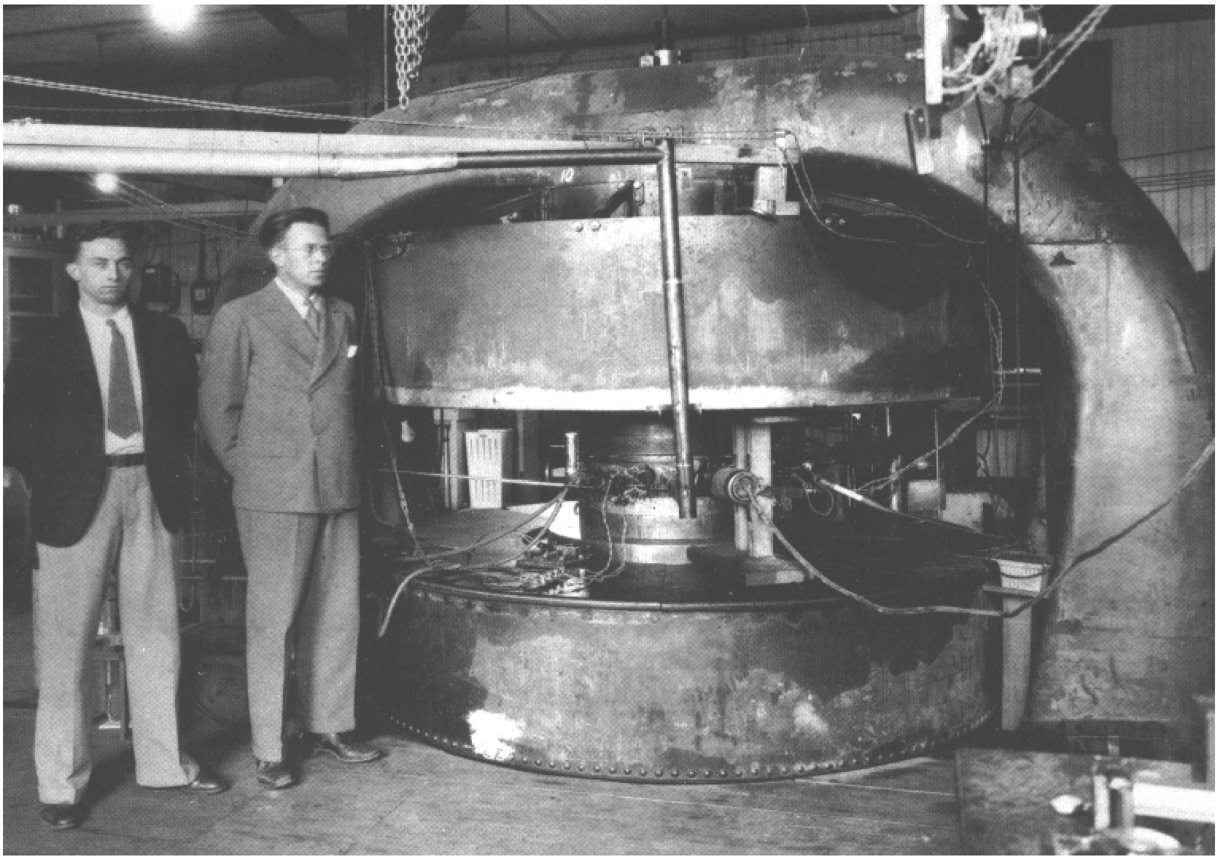
$$f_{rev} = \frac{v}{2\pi\rho} = \frac{v}{2\pi}\frac{eB}{mv} = \frac{eB}{2\pi m}$$

Radius of gyration

$$\rho = \frac{mv}{eB}$$



One of Lawrence's cyclotrons

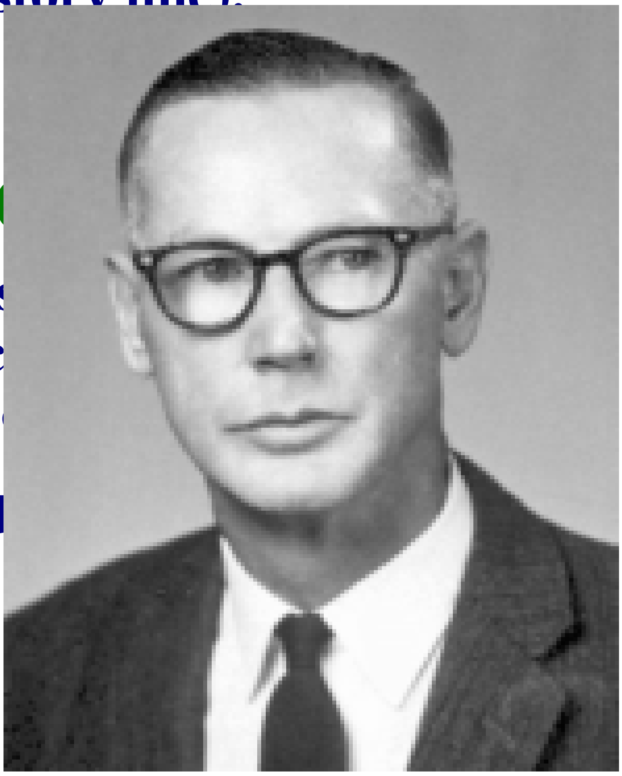


Stanley Livingston and Ernest O. Lawrence (left to right) beside the 27 inch cyclotron at Berkeley circa 1933. The peculiar shape of the magnet's yoke arises from its conversion from a Poulson arc generator of RF current, formerly used in radio communication.

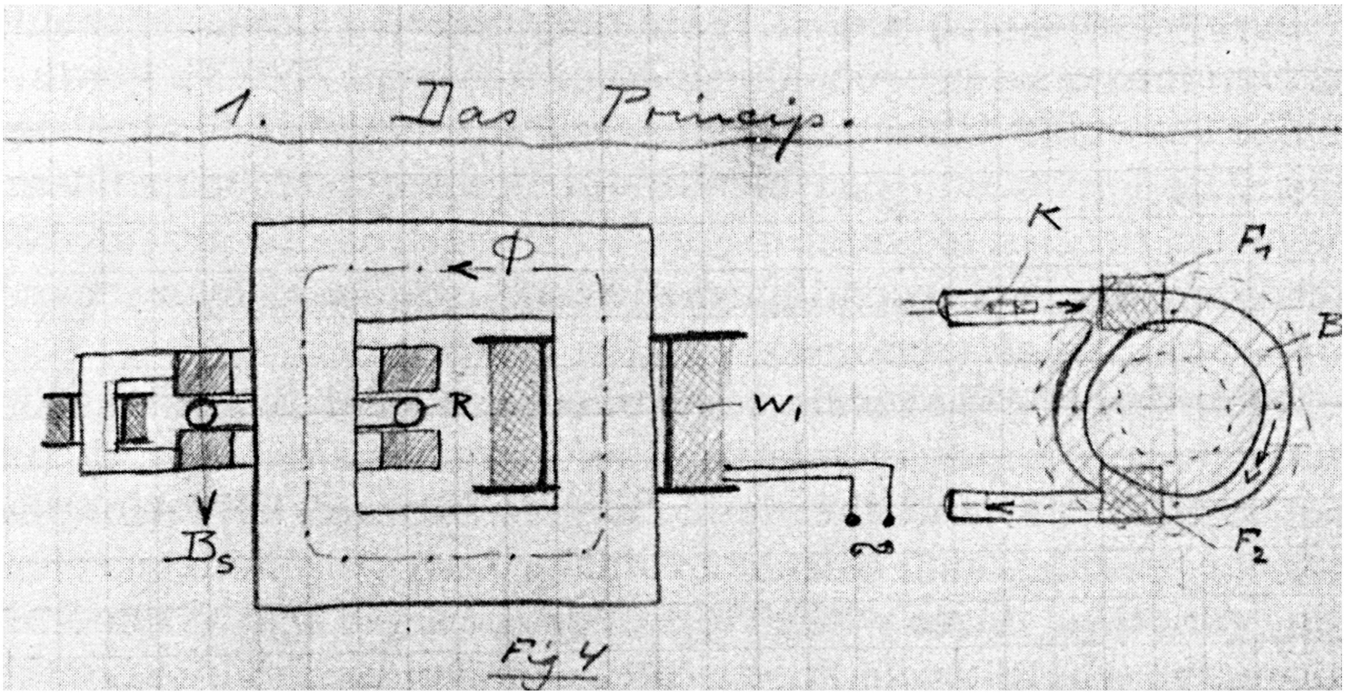
And another history line, but fainter

- **Also the birth of a 'true' accelerator:**
  - **1923 Wideröe, a young Norwegian Ph.D. student draws in his laboratory notebook the design of the betatron with the well-known 2-to-1 rule. Two years later he adds the condition for radial stability, but does not publish.**
  - **1927 in Aachen, Wideröe makes a model betatron, but it does not work. Discouraged he changes course and builds the world's first linac (see previous history line).**

- **All is quiet until 194**
  - **1940 Kerst re-invent**
    the first working mac
    electrons (University
  - **1950 Kerst also build**
    betatron (300 MeV).



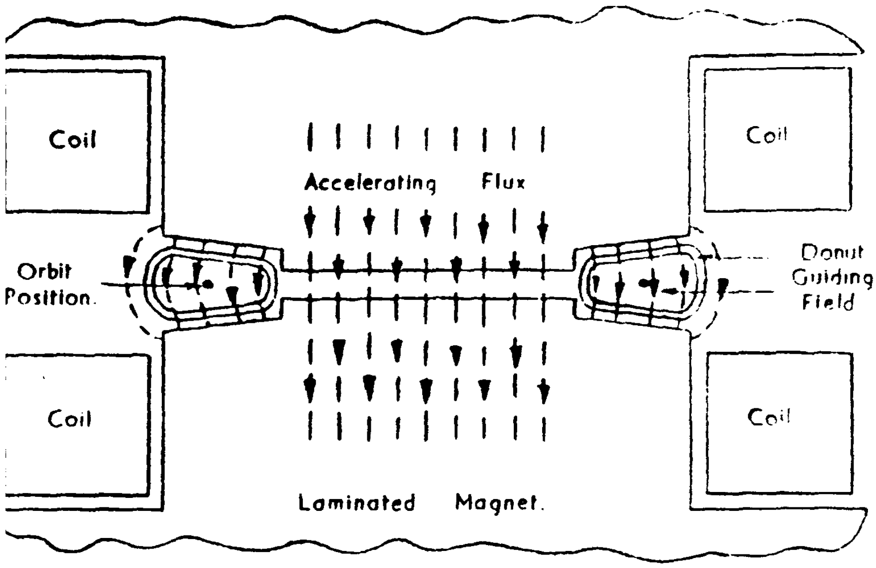
Wideröe's betatron

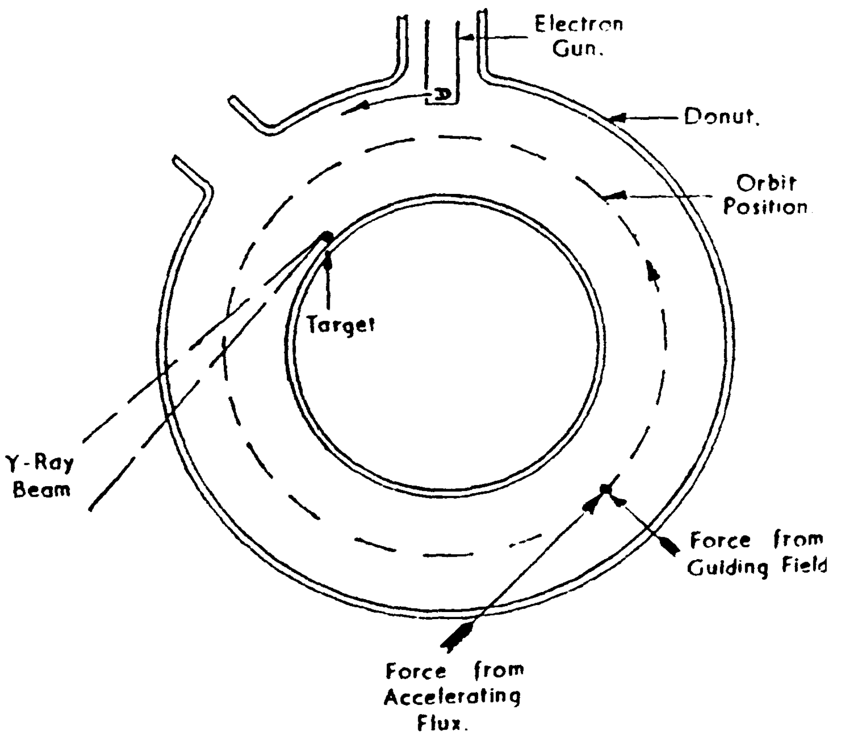


Continuous acceleration – betatron:

Wideröe called this device a "strahlung transformator" because the beam effectively forms the secondary winding on a transformer. The above diagram is taken from his unpublished notebook (1923). This device is insensitive to relativistic effects and is therefore ideal for accelerating electrons. It is also robust and simple. The idea re-surfaced in 1940 with Kerst and Serber, who wrote a paper describing the beam oscillations. Subsequently the term 'betatron oscillation' was adopted for these oscillations in all devices.

Betatron


Coil
Coil
Coil
Coil
Accelerating Flux
Orbit Position.
Donut Guiding Field
Laminated Magnet.


Electron Gun.
Donut.
Orbit Position
Target
γ-Ray Beam
Force from Guiding Field
Force from Accelerating Flux.

Classification by Maxwell

- **Accelerators must use electric fields to transfer energy to/from an ion, because the force exerted by a magnetic field is always perpendicular to the motion.**

- **Mathematically speaking, the force exerted on an ion is:**

$$\boldsymbol{F} = e\boldsymbol{E} + e(\boldsymbol{v} \times \boldsymbol{B})$$

so that the rate at which work can be done on the ion is:

$$\boldsymbol{F} \cdot \boldsymbol{v} = e\boldsymbol{E} \cdot \boldsymbol{v} + e(\boldsymbol{v} \times \boldsymbol{B}) \cdot \boldsymbol{v}$$

but $(\boldsymbol{v} \times \boldsymbol{B}) \cdot \boldsymbol{v} = 0.$

- **Each 'history line' can be classified according to how the electric field is generated and used.**

Use of the electric field

$$E = -\nabla\phi - \partial A/\partial t$$

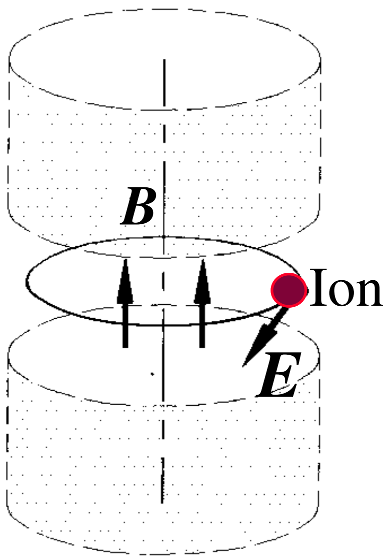
Acceleration by DC voltages:

- **Cockcroft & Walton rectifier generator**
- **Van de Graaff electrostatic generator**
- **Tandem electrostatic accelerator**

Acceleration by time-varying fields:

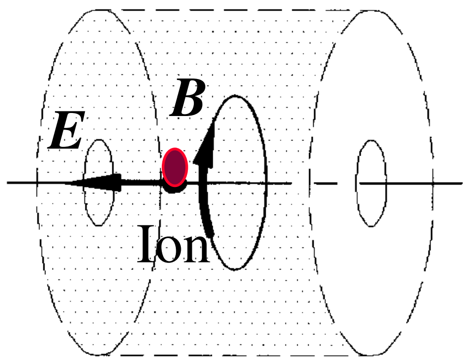
$$\nabla \times E = -\partial B/\partial t$$

'Betatron' or 'unbunched' acceleration



'Resonant' or 'bunched' acceleration

- **Linear accelerator (linac).**
- **Synchrotron.**
- **Cyclotron ('coiled' linac).**



Status in 1940

- **Three acceleration methods had been discovered:**
  - **DC voltage (e.g. Cockcroft and Walton),**
  - **'Resonant/bunched' acceleration (e.g. cyclotron)**
  - **'Betatron/unbunched' acceleration.**

- **Try to think of other possibilities for accelerating ions. ***

- **Progress now turns to applying these basic concepts more efficiently and to improving the technology.**

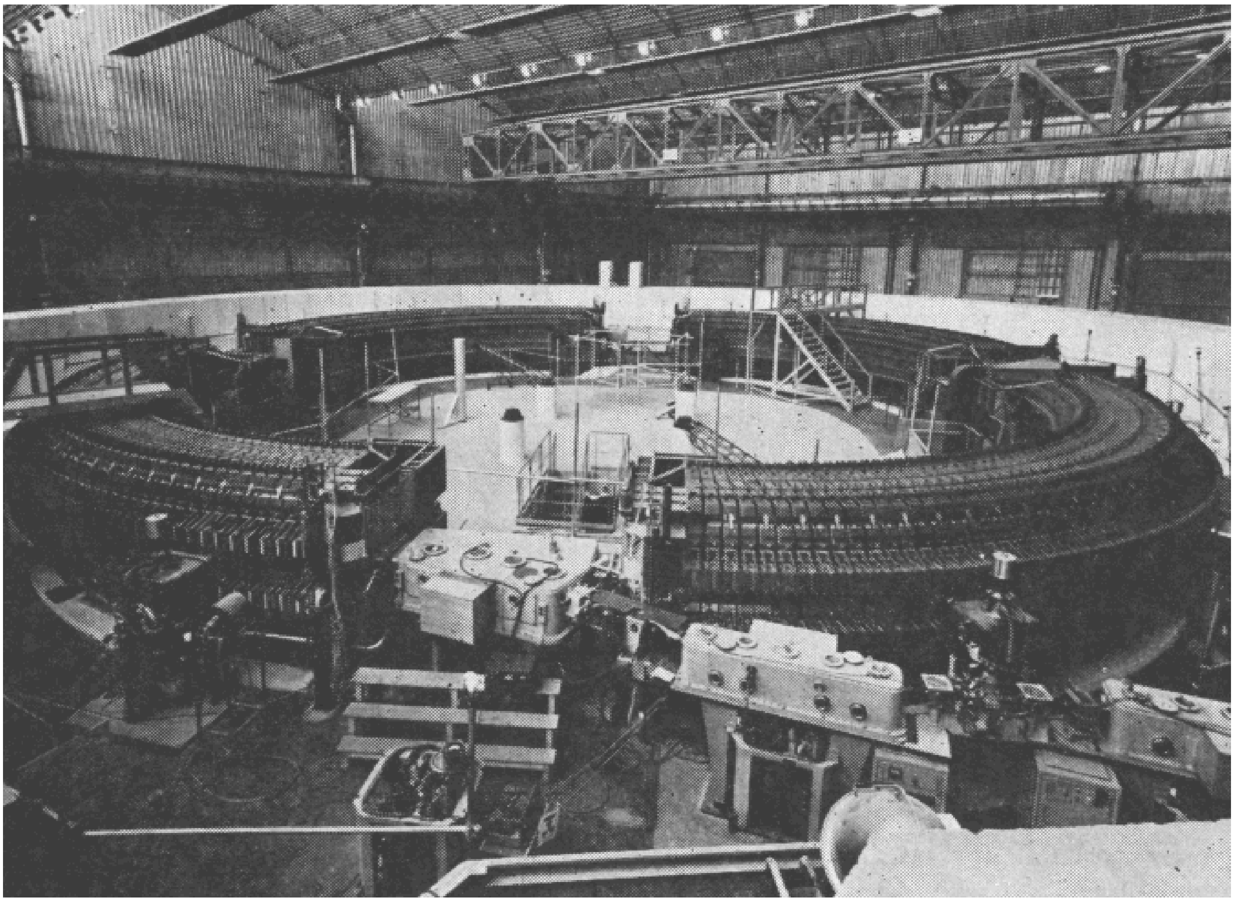
*** This is an important question for the future.**

After 1940 in a nutshell…

- **1943 Once again, Wideröe is a pioneer and patents <u>colliding beams</u> (pub. 1953).**
- **1944 McMillan and Veksler independently propose <u>synchronous acceleration with phase stability</u>. They use an electron synchrotron as example.**
- **1946 Goward and Barnes are first to make the synchrotron work in the UK.**
- **1947 Oliphant and Hyde start a 1 GeV machine in Birmingham, UK, but an American group overtakes them and is first with the 3 GeV Cosmotron at BNL.**
- **1952 Christofilos, and Courant, Livingston and Snyder independently invent <u>strong focusing</u>. CERN immediately drops its design for a weak-focusing, 10 GeV FFAG in favour of a strong-focusing, 28 GeV synchrotron.**
- **1956 MURA, US proposes <u>particle stacking to increase beam intensity</u>, opening the way for circular colliders.**

Trick Question: Why did McMillan receive the Nobel Prize and not Veksler?

An early synchrotron



3 GeV proton synchrotron 'Saturne' at Saclay (commissioned 1958). A Van de Graaff injector lies out of view front-right.

This is a so-called weak-focusing machine. Note the characteristic long curved dipole magnets with only small drift spaces for tasks such as injection and extraction.

More progress…

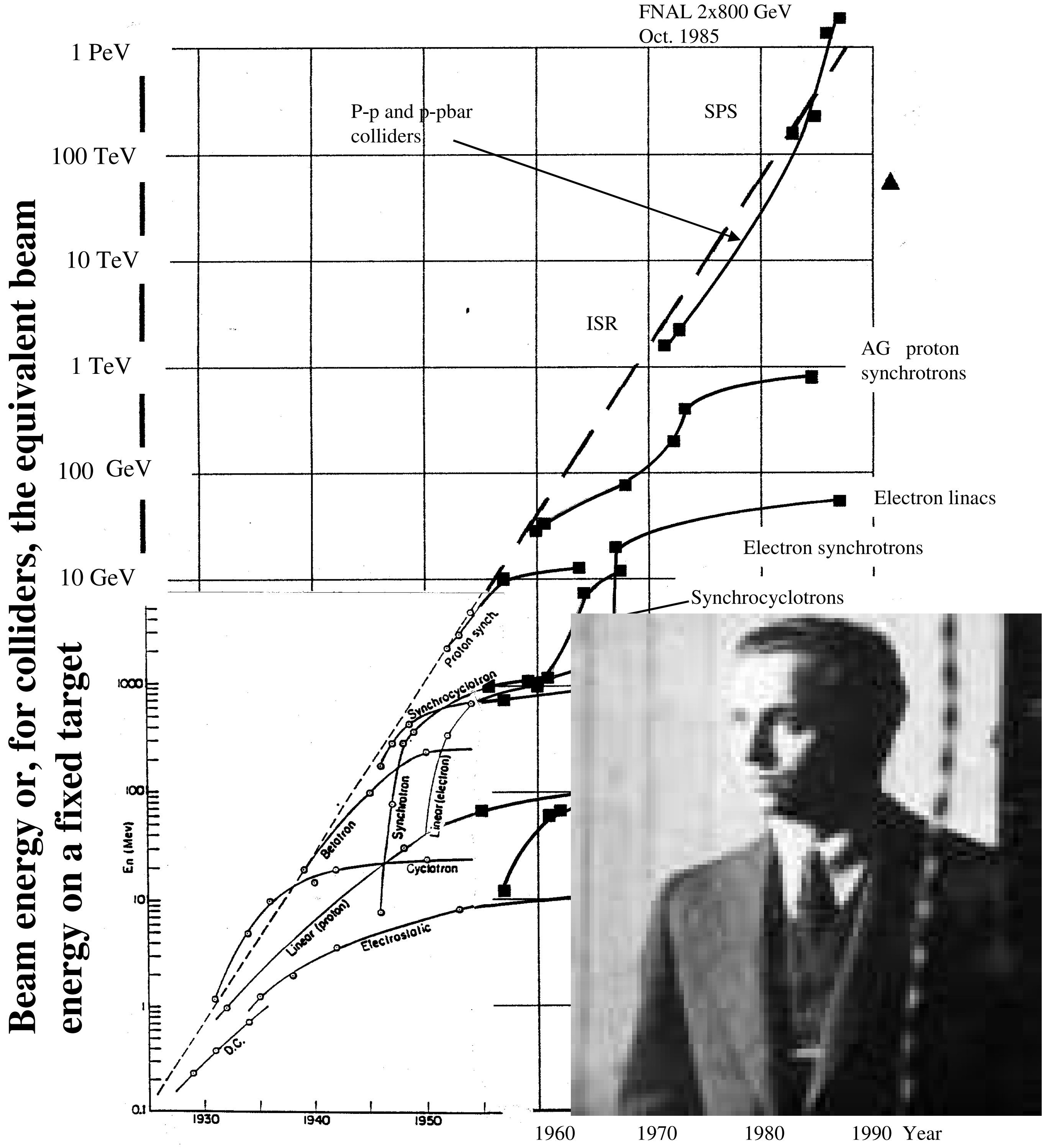
- 1956 Tigner proposes linear colliders for high-energy electron machines.
- 1961 AdA, an electron-positron storage ring is built in Frascati, Italy. This is the first single-ring, particle-antiparticle collider (first operated in Orsay, France).
- 1966 Budker and Skrinsky propose electron cooling.
- 1970 Kapchinski & Teplyakov propose the RFQ (radiofrequency quadrupole).
- 1971 CERN operates the ISR, the first proton-proton, intersecting-ring collider.
- 1971 Blewett proposes superconducting magne in LHC.
- 1972 van der Meer inv cooling opening the way particle-antiparticle col
- 1978 The CERN ISR o superconducting magne used in a synchrotron r industrially built.

And more…

- 1982 CERN converts its SPS to a single-ring proton-antiproton collider.
- 1984 C. Rubbia and S
receive the Nobel physic
discoveries.

- 1989 CERN starts LI
highest energy electron-
- 1991 HERA at DESY
major facility for collidi
electrons or positrons.
- 1995 CERN runs superconducting rf cavities in LEP for physics.
- 1999 RHIC at BNL becomes the world facility for colliding ions.
- 2008 CERN switches on LHC, the world's highest energy proton-proton collider (superconducting, twin-bore dipoles), but an electrical fault delays running until end of 2009.
- 2012 the Higgs is discovered at LHC.
- 20?? CERN has plans for a TeV linear collider, CLIC.

Livingston chart



Bottom left corner, Milton Stanley Livingston's original chart from his book "High energy accelerators" 1954.

Classification of accelerators

- **DC voltage generators:**
  - **Cockcroft Walton generator.**
  - **Van de Graaff.**
  - **Tandem.**
- **Unbunched/continuous acceleration:**
  - **Betatron.**
  - **Betatron core.**
- **Bunched/resonant acceleration:**
  - **RFQ.**
  - **Linac.**
  - **Cyclotron, synchrocyclotron.**
  - **Microtron.**
  - **FFAG (Fixed Field Alternating Gradient).**
  - **Synchrotron.**
- **Colliders:**
  - **Circular (single-ring, particle v anti-particle and intersecting-rings, particle v particle).**
  - **Linear.**
- **Other classifications:**
  - **Weak/strong focusing.**
  - **Normal/superconducting magnets & cavities.**

In the beginning there was HEP

but more money now passes through non-HEP applications…

- **Accelerator applications:**
  - **Synchrotron light sources.**
  - **Spallation sources.**
  - **Isotope production.**
  - **Radiography.**
  - **Cancer therapy.**
  - **Ion implantation and surface metallurgy.**
  - **Sterilisation.**
  - **…**
- **Proposed accelerator applications:**
  - **Inertial fusion drivers.**
  - **Nuclear incinerators.**
  - **Rocket motors for space.**
  - **…**
- **Spin-offs from HEP and accelerators:**
  - **PET, NMR and CAT scanners.**
  - **Pixelated detectors for K-edge subtraction imaging.**
  - **Superconducting wires, cables and devices.**
  - **Large-scale UHV systems.**
  - **Large-scale cryogenic systems.**
  - **……..**

Where to next?

- **Today's accelerators are nearing practical limits. What can be done?**
  - **1982 ECFA held the first workshop of a series on advanced accelerating techniques; 'Challenge of Ultra-high Energies", New College, Oxford, UK.**
  - **The goal was a new acceleration technique capable of PeV energies at a reasonable cost.**
- **Four essential ingredients are:**
  - **A new acceleration mechanism.**
  - **Transverse stability.**
  - **Longitudinal (phase) stability.**
  - **Stability against collective effects.**
- **The candidates were:**
  - **Plasma-beat-wave accelerator.**
  - **Wake-field accelerator.**
  - **Lasers with gratings.**
  - **Lasers on dense bunches.**
  - **But the search is still on.**
- **How far is beyond?**
  - **The CERN LHC will operate at 2×7 TeV.**
  - **The cosmic ray spectrum is expected to extend up to the Planck energy (1.22×10^{28} eV), but cosmic rays above 5×10^{7} TeV from sources beyond 1.5 $\times 10^{8}$ light-years will be absorbed by photons of the microwave background (GZK cut-off).**

Miscellaneous

- **Questions on accelerator history ?:**

  E.M. McMillan shared the Nobel Prize with G.T. Seaborg for their discoveries in chemistry of transuranium elements, NOT for the synchrotron.

  'Ernest Rutherford' was registered at birth as 'Earnest Rutherford'. The mistake by the Registrar was not noticed at the time.

  The missing prize: Rutherford received the 1908 Nobel Prize in chemistry for his investigations into radioactive substances. Some say he should have had a second prize in physics.

- **Other possibilities for acceleration?:**

  One practical example is 'collective acceleration' as applied in the 'Electron-ring accelerator' where positive ions are trapped in the negative potential well at the centre of a ring of electrons, which are being accelerated along the axis of the ring. The potential well drags the ions along giving them energy.