Introduction of Accelerator

History

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Motivation

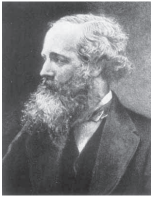
The first motivation was from Ernest Rutherford who desired to produce nuclear reactions with accelerated nucleons.

For many decades the motivation was to get to ever higher beam energies. At the same time, and especially when colliding beams became important, there was a desire to get to ever higher beam current.

In the last three decades there has been motivation from the many applications of accelerators, such as producing X-ray beams, medical needs, ion implantation, spallation sources, and on and on.

Prehistory

- 1883 Maxwell equations



$$\nabla \cdot \vec{B} = 0$$
$$\nabla \cdot \vec{D} = \rho$$
$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{J}$$
$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$

When they were first written, these equations were meant to be not much more than phenomenological. Maxwell probably did not realize how rich and deep his equations would turn out to be, influencing several generations of physics to come.

- It was the first of the unified theories to be realized.
- Its Lorentz invariance property laid the foundation to the special theory of relativity.
- Its gauge invariance property led to the Yang-Mills theory, the electro-weak theory, and the standard model of particle physics.

Prehistory (cont.)

- 1887 Hertz E&M wave.
- 1890-1930 cathode ray tubes are the first accelerators
- 1911 Rutherford -particle beam experiment
- 1912 Schott's synchrotron radiation classical analysis. 1946 Schwinger's synchrotron raditation quantum analysis

The beginning

The years around 1930 can be marked as the starting point of the accelerator era. Lord Ernest Rutherford can be regarded as the first person to push the development of particle accelerators.

- 1923 Wiederoe, betatron principle,
- 1928 Wiederoe, rf linac, 50 kV potassium ions
- 1930 Cockcroft & Walton, 400 kV rectifier high voltage
- 1931 Van de Graff, electrostatic charging device
- 1932 Lawrence 1.25 MeV cyclotron

The evolution

- 1939 klystrons, Hansen and Varian brothers
- 1940 Kerst betatron 2.3 MeV
- 1941 betatron stability principle, Kerst & Serber
- 1945 phase stability principle, McMillan & Veksler
- 1948 Alvarez 32 MeV drift tube proton linac
- 1952 strong focusing principle, Christofilos, Courant, Snyder, Livingston

Phase stability and strong focusing principles marked a revolutionary period and the beginning of modern era of accelerator physics.

The evolution

- 1958 Christofilos induction linac
- 1960 first electron storage ring collider, Touschek
- 1966 electron cooling, Budker
- 1966 SLAC linac
- 1969 first proton storage ring ISR
- 1970 RFQ, Kapchinskij & Teplyakov
- 1972 stochastic cooling, Van de Meer
- 1985 first linear collider SLC

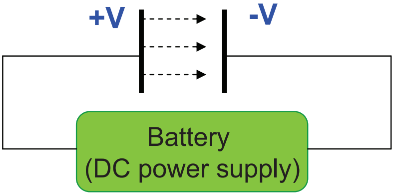
Mechanism of Particle Acceleration

DC voltage acceleration (developed in 1930s)
- Voltage multiplier cascade (Cascade accelerators, Cockcroft and Walton)
- Electrostatic generator (Van de Graaff accelerators)

Resonance acceleration (Gustaf Ising, Sweden, first proposed it in 1924)
- Radio-frequency (RF) Linear accelerators
  (Rolf Wideröe, Norway, built the first linac using an RF accelerating field)
- Radio-frequency quadrupole (RFQ)
  (first proposed by I.M. Kapchinski and V.A. Teplyakov in 1970)
- Cyclic accelerators
  Cyclotron (first one built in 1931)
  Microtron (first proposed in 1944 by V. Veksler and J. Schwinger)
  Synchrocyclotron (first proposed in 1945 by E. McMillan and V. Veksler)
  synchrotron

Magnetic induction acceleration
- Betatron (reinvented & built in 1940 by Donald Kerst, but the concept was formulated by R. Wideröe in 1928)
- Induction linac (invented by N.C. Christofilos in 1950s)

DC voltage acceleration:
(DC electric field)



Magnetic induction acceleration:
(Faraday's Law of Induction)

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\oint \vec{E} \cdot d\vec{\ell} = -\int \dot{\vec{B}} \cdot d\vec{S}$$

Resonance acceleration:
(AC electric field)

$$\Delta W = e\Delta V$$

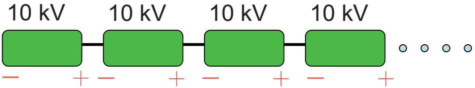
$$\Delta V = V_0 \sin(\omega_{rf} t + \phi)$$

Electrostatic Accelerator

using DC electric field to accelerate charged particles, the gain in the kinetic energy is: ***K*= qV**

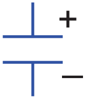
Voltage gain $\Delta V \leqq$ 10 kV

Method 1)



Connecting several accelerating structures in succession each is charged by high voltage power supply (10 kV max.)

Method 2)

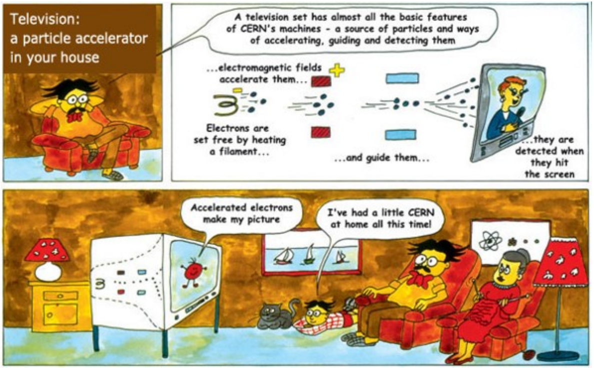


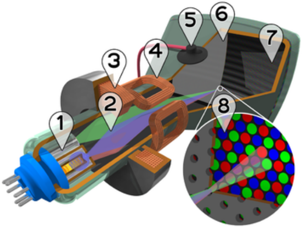
Charging up several high voltage capacitors, each to the maximum voltage available, then we discharge those capacitors all in series

➔ Cockcroft-Walton accelerator, it can reach few MeV

Method 3) Van de Graaff accelerator, it can reach ~ 10 MeV, invented in 1930's➔deposit charge on a moving belt (insulating material) driven by a motor. The belt carries the charge to a large sphere continuously. A very huge charge (high voltage) is built up on the sphere. →The physical size and expense are the limitation

Cathode ray tube

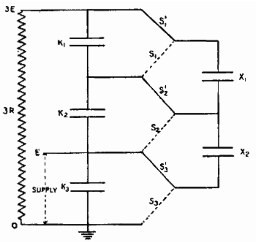




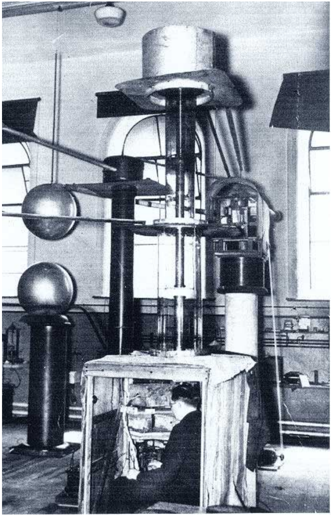
1. Three Electron guns (for red, green, and blue phosphor dots)
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection
6. Mask for separating beams for red, green, and blue part of displayed image
7. Phosphor layer with red, green, and blue zones
8. Close-up of the phosphor-coated inner side of the screen

The Cockcroft-Walton Accelerator

John Cockcroft, Ernest Rutherford, and E.T.S. Walton.



Schematic of Cockcroft and Walton's voltage multiplier. Opening and closing the switches S transfers charge from capacitor K3 through the capacitors X up to K1.



Cockcroft-Walton accelerator installation at the Cavendish Laboratory in Cambridge, England.

The Cockcroft-Walton Accelerator (cont.)

•The Cockcroft-Walton generator can convert AC or raise a low DC voltage to a much higher DC voltage level. It is used to provide higher DC electric fields for particle acceleration.

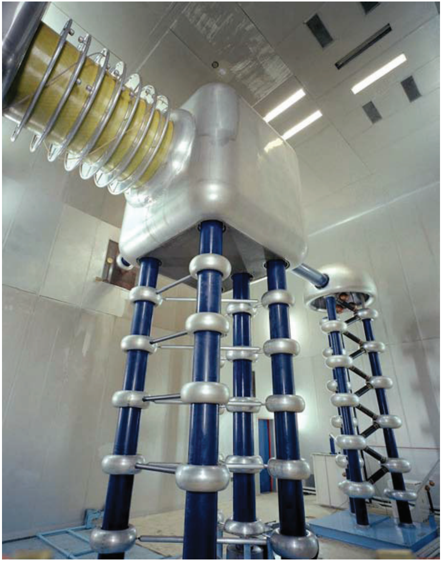
•It is based on the principles of **voltage multiplying circuit**. A voltage multiplier can step up a relatively low voltage to an extremely high value. This technique is different from the transformer. It does not require the heavy core and use only capacitors and rectifiers (diodes).

•The voltage potential achieved by the first Cockcroft-Walton voltage multiplier is 700 kV with a voltage variation within few percent. Positive ions of hydrogen with a beam current of the order of 10 μA being obtained (protons of 710 keV).

•This is the first accelerator to demonstrate disintegration of atomic nuclei by artificially accelerated particles! They induced the nucear reaction:

$$Li + p \rightarrow 2He$$

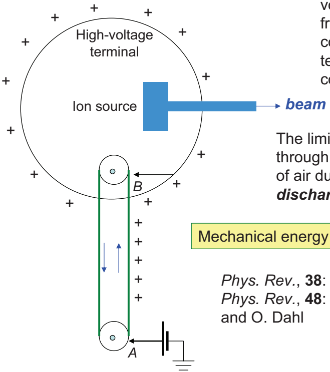
Cockcroft and Walton were honored by receiving the Nobel Prize in 1951.



The Cockcroft-Walton pre-accelerator, built in the late 1960s, at the National Accelerator Laboratory in Batavia, Illinois. This very large and expensive installation provided the voltage for the first tiny step in the acceleration of protons to energies of hundreds of GeV.

The Van de Graaff Generator

Belt-charged Electrostatic Generator (invented by R.J. Van de Graaff)



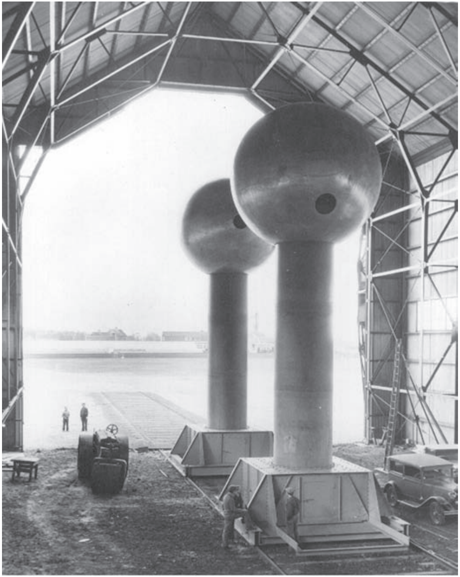
Charge is sprayed from a sharp tip at ***A*** on a moving belt (insulating material). The belt carries the charge to the high-voltage terminal, where it is removed from the belt at ***B*** (a sharp tip connected to the outer conductor of terminal) and transfers to the outer conductor of terminal.

The limiting factors: leakage of charge through the insulating supports, breakdown of air due to the moisture (***corona discharge***: near sharp points or edges)

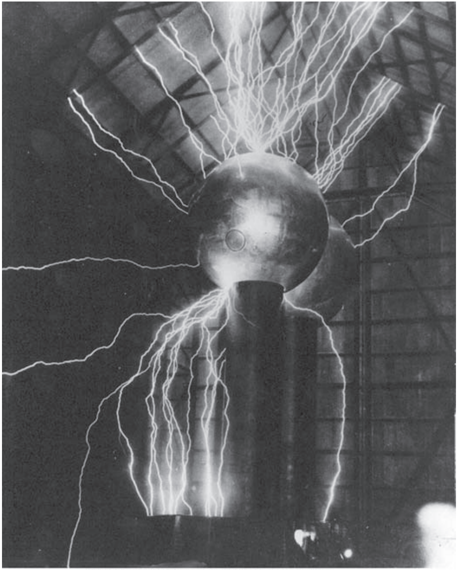
Mechanical energy (motor) ➔ Electrical potential energy

Phys. Rev., **38**: 1919 (1931), R.J. Van de Graaff
Phys. Rev., **48**: 315 (1935), M.A. Tuve, L.R. Hafstad, and O. Dahl

The Van de Graaff Generator (cont.)



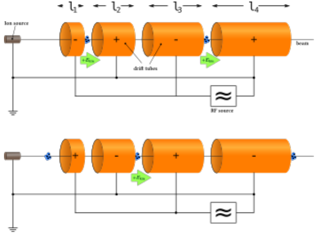
THE GENERATOR IN THE HANGAR AT ROUND HILL



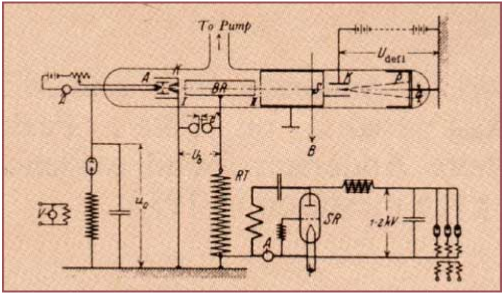
AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)

The Early Linear Accelerator

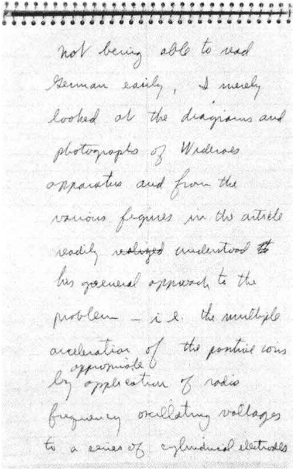
Rolf Wideröe as a young man.



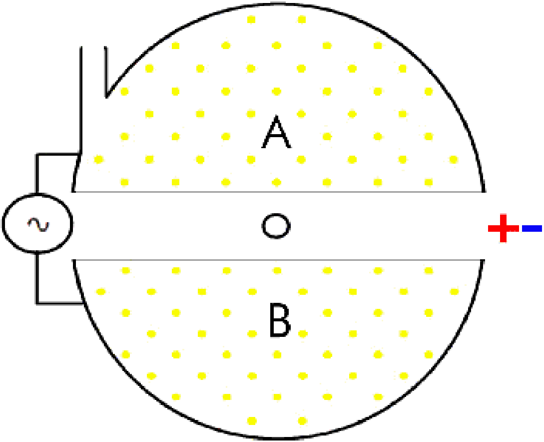
Sketch of the Ising/Widerøe linear accelerator concept, employing oscillating fields (1928)



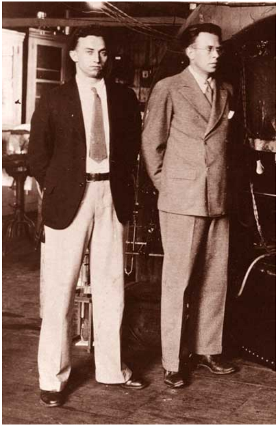
Rolf Wideröe's diagrams describing a method for accelerating ions inspired Ernest Lawrence's invention of the cyclotron.


not being able to read German easily, I merely looked at the diagrams and photographs of Wideroes apparatus and from the various figures in the article readily ~~realized~~ understood ~~the~~ his general approach to the problem — i.e. the multiple acceleration of the positive ions by approximate application of radio frequency oscillating voltages to a series of cylindrical electrodes

Lawrence's notes on Wideröe's paper.



The Cyclotron (cont.)

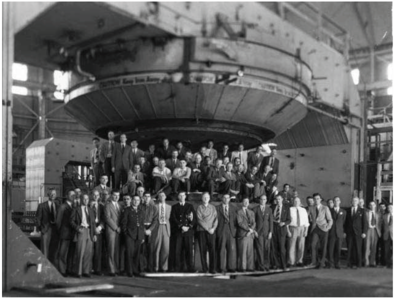


Lawrence and Livingston around 1933.

The first successful cyclotron, the 4.5-inch model built by Lawrence and Livingston.

Lawrence received the Nobel Prize in 1939.

The Largest Cyclotron by Lawrence

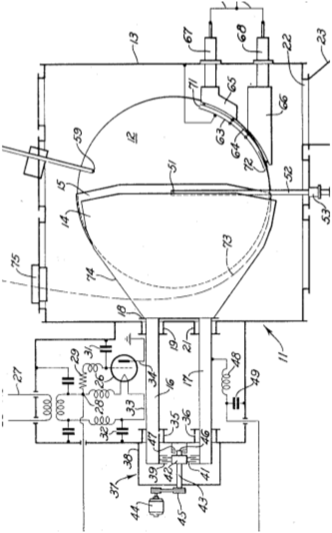


The 184 inch cyclotron built at Univ. of California, Berkeley

[Ref.]: Photography Gallery of Lawrence Berkeley National Laboratory,
http://cso.lbl.gov/photo/gallery/

SynchroCyclotron

A synchrocyclotron is a special type of cyclotron, patented by Edwin McMillan, in which the frequency of the driving RF electric field is varied to compensate for relativistic effects as the particles' velocity begins to approach the speed of light. This is in contrast to the classical cyclotron, where this frequency is constant.

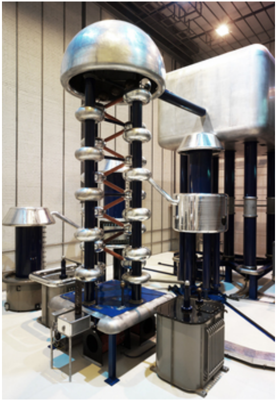


Sketch of a synchrocyclotron from McMillan's patent.

The PSI proton accelerator

Protons are accelerated in three steps:

1. A Cockroft-Walton accelerator, which also contains the proton source, is used as the first stage from which protons are fed into Injector II.
2. Injector II, a smaller ring cyclotron. (72MeV)
3. The core of this facility is the large ring cyclotron with a diameter of approximately 15 metres, in which protons are accelerated to their terminal speed of almost 80% of the speed of light (equivalent to a kinetic energy of 590 MeV).

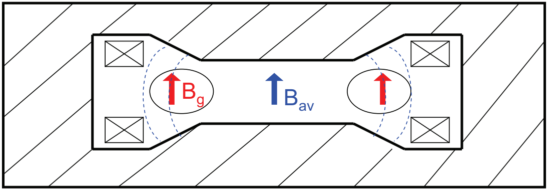


The PSI Cockroft-Walton accelerator – the first stage of the proton accelerator facility.

The magnets are coloured turquoise and the four acceleration cavities dark grey.

Magnetic induction acceleration

Betatron



- Donald Kerst and Robert Serber reinvented R. Wideröe's ***beam transformer*** idea and renamed it as betatron. The success is due to their detailed orbit stability analysis and careful magnet design by D. Kerst.
- In the betatron, a time varying magnetic field produces an electric field that accelerates electrons. Although the betatron has a circular geometry similar to the cyclotron, it's a pulsed machine and the particle orbit does not spiral out.
- It's the first circular accelerator to operate at a constant orbit radius

Phys. Rev., **58**: 841 (1940), D.W. Kerst
Phys. Rev., **60**: 47 (1941), D.W. Kerst
Phys. Rev., **60**: 53 (1941), D.W. Kerst and R. Serber

Betatron

Donald Kerst and the first betatron (2.3 MeV electrons) he built in Univ. of Illinois in 1940. The betatron had been used by the ***Manhattan Project*** to determine basic properties of thorium, uranium, and plutonium.

[Ref.] http://www.physics.uiuc.edu/history/Timeline/1940s.html

A modern compact betatron, commercially available. The compact betatron is used as a portable x-ray source for the detection of flaws in metal, such as steel beams, ship hulls, pressure vessels, bridges, etc.

[Ref.] http://www.globalxray.com/betatron_photo.html

Betatron Principle

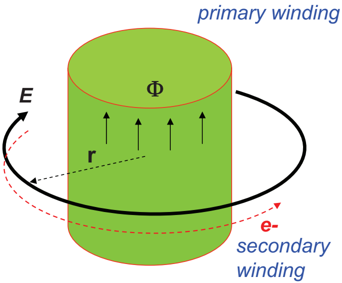
The centripetal force,

$$\frac{1}{r} = \frac{eB_g}{P} \qquad (1.6)$$

The electromagnetic induction,

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\partial \vec{\Phi}}{\partial t}$$

$$E = \frac{\dot{\Phi}}{2\pi r} \qquad (1.7)$$



For constant orbit radius: $-\frac{1}{r^2}\frac{dr}{dt} = 0$ (1.8)

The magnetic flux enclosed by the radius *r* is: $\Phi = \pi r^2 B_{av}$ (1.9)

Those conditions result in the ***betatron principle*** given by R. Wideröe in 1928,

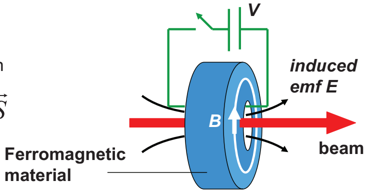
$$B_g = \frac{1}{2} B_{av} \qquad (1.10)$$

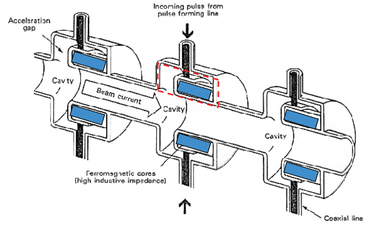
Induction linac

Induction Linac

Faraday's Law of Induction

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\partial}{\partial t} \int \vec{B} \cdot d\vec{S}$$





Cutaway sketch of three induction modules

[Ref.] http://hif.lbl.gov/engineering/ind_module_summary.html

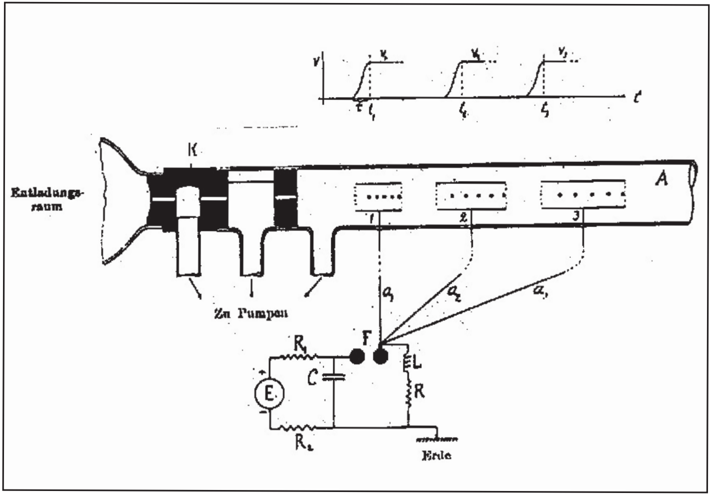
The Flash X-Ray Facility (FXR), a linear-induction electron beam accelerator built in 1982, at **Lawrence Livermore National Laboratory**, California, USA. It is used to study the detonation process (implosion) of nuclear weapons.

[Ref.] http://www.llnl.gov/str/April02/April50th.html

Nichola C. Christofilos, the inventor of the induction linac (1950s) and the principle of strong focusing.

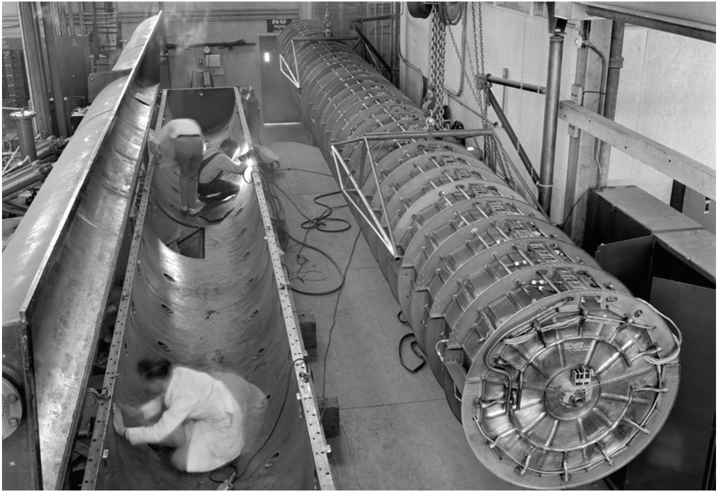
Christofilos

[Ref.] http://www.mlahanas.de/Greeks/new/Christofilos.htm



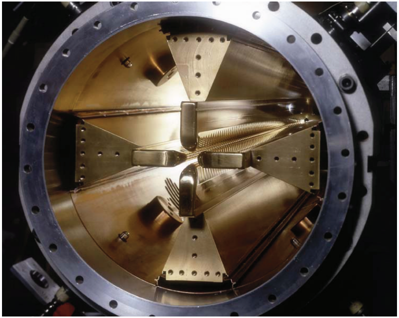
A drawing, from Ising's original paper of 1924, showing his idea for an RF accelerator. Later Wideroe was able to turn this idea into reality, demonstrating RF acceleration for the first time and opening the door to all modern accelerators.

Protron Linac - Drift Tube Linac



An accelerating tank of the first Alvarez linac, built just after WWII. Since that time many similar linacs have been built all around the world.

Protron Linac - Radio Frequency Quadrupole (RFQ)

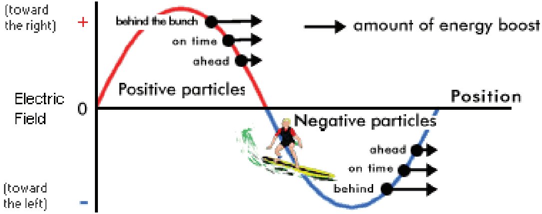


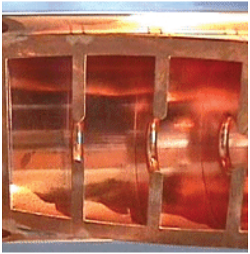
The inside of a Radio Frequency Quadrupole. The RFQ has generally replaced the very large Cockcroft-Waltons as the first stage of injectors into synchrotrons.

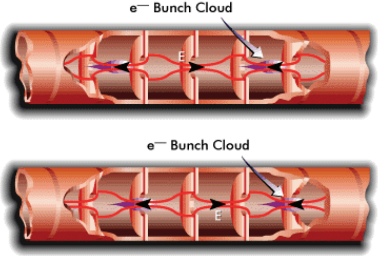
Invented in the Soviet Union by Teplyakov and Kapachinskii in 1970, the Radio Frequency Quadrupole linac (RFQ) was brought to the attention of Western physicists by Joe Manca at Los Alamos. The first RFQ, a "proof of principle"device built at Los Alamos, was small but highly successful.

Electron Linac (disk loaded structure)

Electron Linac (disk loaded structure)







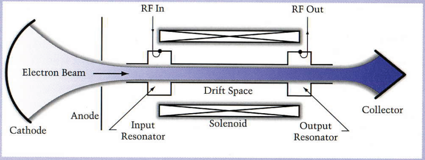
1/20,000,000,000 second later
(notice how far the bunches have moved)

[Ref.] http://www.slac.stanford.edu

The klystron

High power microwave amplifier:

Klystron Amplifier Principle



Basic klystron arrangement.

THE PRINCIPLE OF THE KLYSTRON AMPLIFIER is shown in the figure above. A heated cathode emits a continuous electron beam of relatively low density. The beam is accelerated and at the same time focused by an electrostatic anode before entering an input resonator that is fed by a low power input signal. There the beam receives a velocity modulation that depends on the input signal. This dependence makes the klystron an amplifier, as opposed to an oscillator. This is critical because it allows control of the multiple klystrons needed in an accelerator. After a drift space, where the beam is focused magnetically, the originally continuous beam is bunched which corresponds to a large rf current. It enters the output resonator where it loses energy to an external load (usually the accelerator). The leftover beam with a strongly reduced kinetic energy is dumped into the collector. The klystron as described would be fully operational, but it would have low efficiency and low gain. High power klystrons have additional idling resonators between the input and output resonators to improve the bunching process.

[Ref.] ***Beam Line, Vol.28 (1998), published by SLAC***

Synchrotron

Cyclotron and betatron are both limited by the relativistic effect

Particles not synchronized with the accelerating voltage as their energy increase.

E.M. McMillan @ Univ. California, USA
V. Veksler @ U.S.S.R.

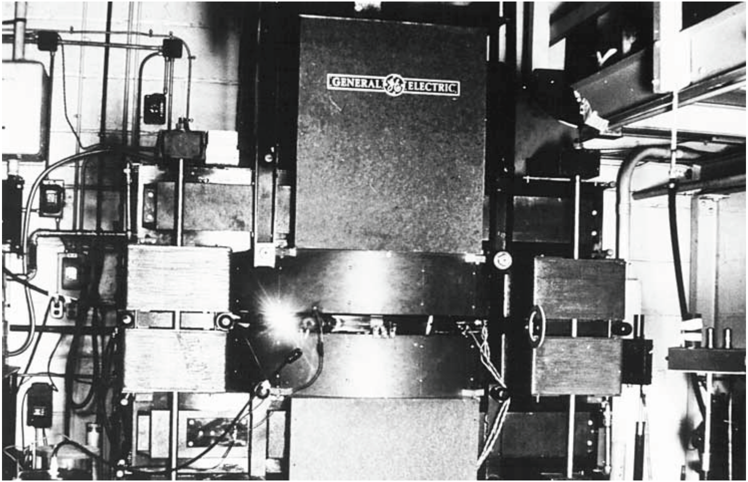
→ Discovered the principle of ***phase stability***

both solved this synchronism problem independently in 1945.
Their solutions were:

1) When the particle energy increases, we can slow down the accelerating voltage, i.e. the accelerating voltage is frequency modulated (decreasing f_{RF}) → ***synchrocyclotron***
2) The guiding magnetic field be increased in strength as the beam gains energy (the orbit radius kept constant) ⇦ see Eq.(1.5)

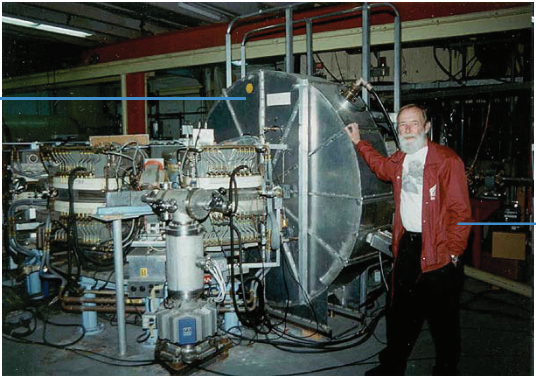
→ ***The idea of the electron synchrotron!***

- *J. of Phys.*, U.S.S.R., **9**: 153 (1945), V. Veksler
- *Phys. Rev.*, **68**: 143 (1945), E.M. McMillan

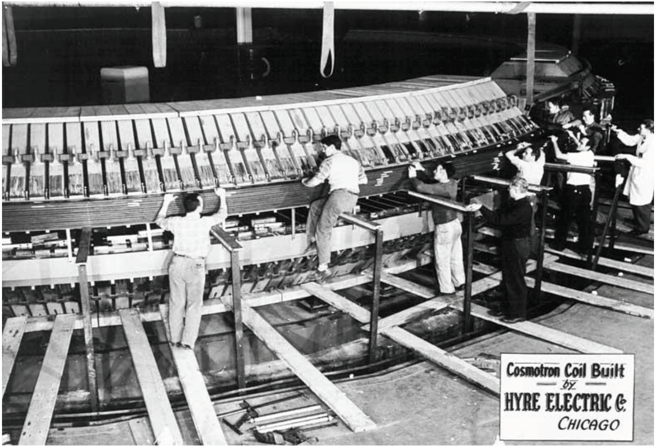


The 300 MeV electron synchrotron built at General Electric Co. in 1940s. The photograph shows the synchrotron radiation emitted from the accelerator.

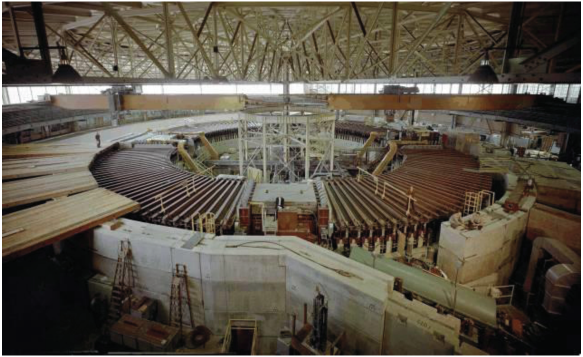
The first dedicated synchrotron light source, became operational for users on August 7, 1968. The circulating beam current was 1.4 mA. 240 MeV e- storage ring (Tantalus), U. of Wisconsin- Madison.



[Ref.] http://www.src.wisc.edu/about/erowe.htm
[Ref.] G. Margaritondo, *“The evolution of a dedicated synchrotron light source”,* Physics Today (May 2008), p.37.



The 3 GeV Cosmotron was the first proton synchrotron to be brought into operation.



Overview of the Berkeley Bevatron during its construction in the early 1950s. One can just see the man on the left.

Strong Focusing

The invention of strong focusing, in the early 1950's, by Ernie Courant, Hartland Snyder and Stan Livingston, revolutionized accelerator design in that it allowed small apertures (unlike the Bevatron whose aperture was large enough to contain a jeep, with its windshield down).

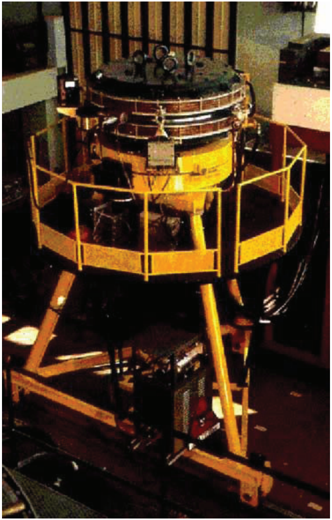
The concept was independently discovered by Nick Christofilos.

An example of strong focusing synchrotron

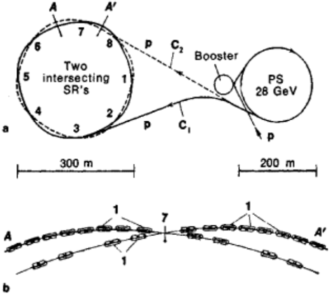
Early Colliders

In the 1950's a number of places, MURA, Novosibirsk, CERN, Stanford, Frascati, and Orsay, developed the technology of colliding beams. Bruno Touschek, Gersh Budker and Don Kerst were the people who made this happen.

Colliders are now the devices employed to reach the highest energies.



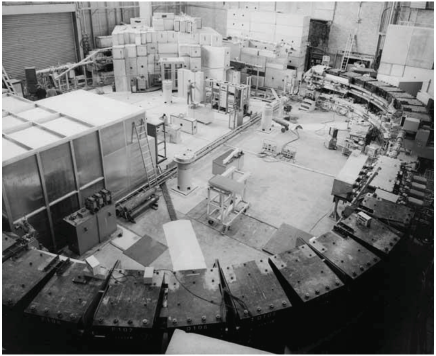
The first electron-positron storage ring, AdA. (About 1960) Built and operated at Frascati, Italy and later moved to take advantage of a more powerful source of positrons in France.



The first proton-proton collider, the CERN Intersecting Storage Rings (ISR), during the 1970’s. One can see the massive rings and one of the intersection points.

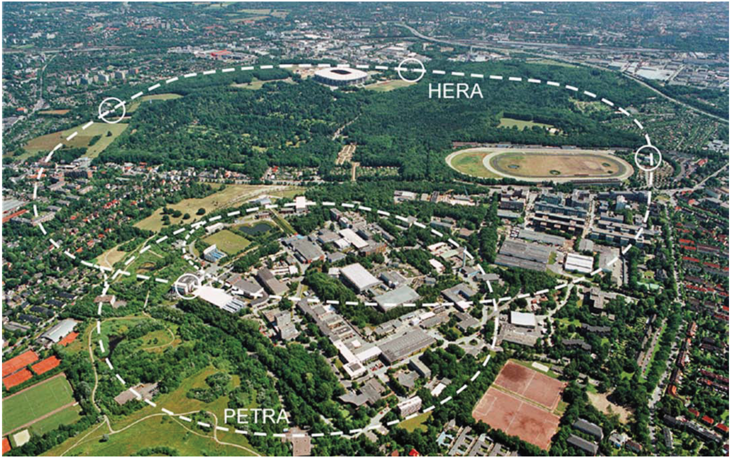
Proton-Antiproton Colliders

It was the invention of stochastic cooling, by van de Meer, that made proton-anti-proton colliders possible.



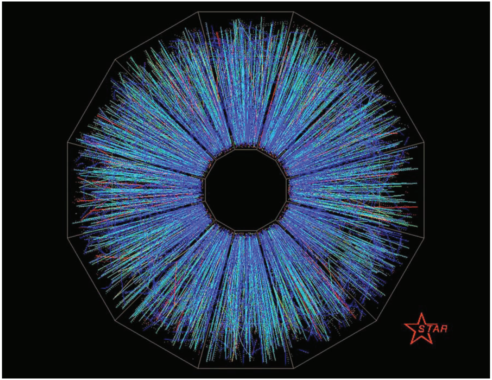
In 1977 the magnets of the "g-2" experiment were modified and used to build the proton-antiproton storage ring: ICE (the Initial Cooling Experiment). The ring verified the stochastic cooling method, and allowed CERN to discover the W and Z.

Electron-protron collider



An aerial view of DESY in the city of Hamburg.

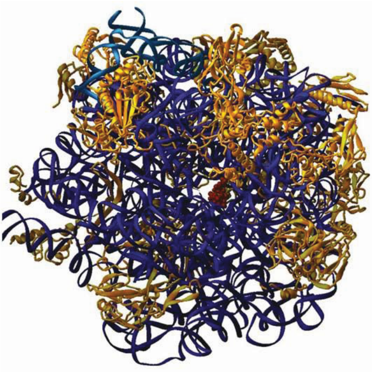
Heavy-Ion Colliders



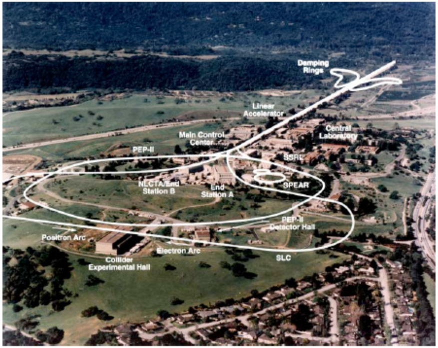
The Relativistic Heavy Ion Collider, RHIC, at Brookhaven National Laboratory, has been used to study nuclear matter under extreme conditions of very high density and very high temperature similar to the conditions in the original Big Bang. Here we see the result of a collision of a nucleus of gold with a nucleus of gold. The temperature, in a collision, rises to 2 trillion degrees Kelvin and as many as 10,000 particles are born in the resulting fireball.

Synchrotron X-Ray Sources

At first (about 1970's), accelerators built for high-energy physics were used parasitically, but soon machines were specially built for this important application. There are more than 50 synchrotron radiation facilities in the world. In the US there are machines in Brookhaven (NSLS), Argonne (APS), SLAC: SPEAR and the LCLS, and at LBL (ALS).



This intricate structure of a complex protein molecule structure has been determined by reconstructing scattered synchrotron radiation.

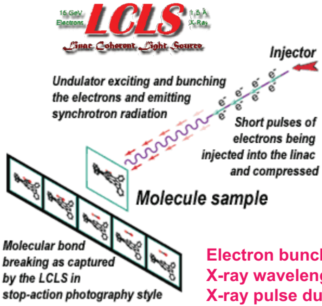


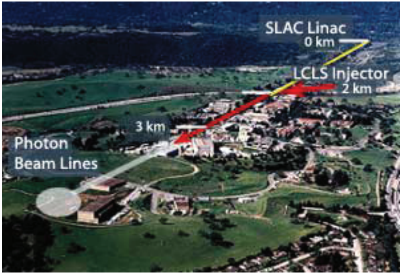
T he SLAC site showing its two-mile long linear accelerator, the two arms of the SLC linear collider, and the large ring of PEP II. This is where the LCLS is being located.

Linear Coherent Light Source

Forth Generation Light Source (X-ray FEL)

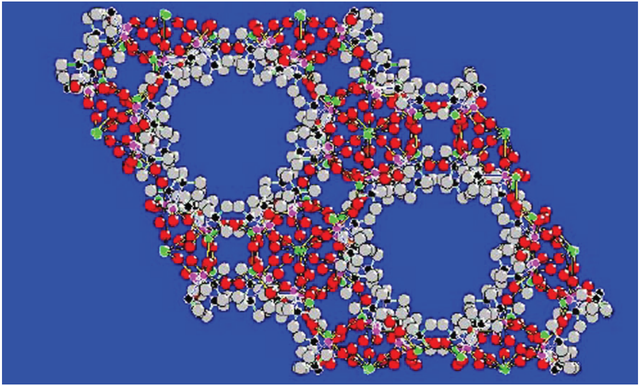
FEL: free electron laser





http://www-ssrl.slac.stanford.edu/lcls/

Electron bunch length: 0.023 mm, 15 GeV electron beam
X-ray wavelength: 0.15 – 1.5 nm
X-ray pulse duration: 100 femtosecond – 100 attosecond



A picture taken at the British neutron facility ISIS showing a hybrid microporous organic-inorganic solid. Neutron diffraction is particular in its sensitivity to light elements such as hydrogen, deuterium, carbon, nitrogen and oxygen, and thus provides an ideal tool for structural studies of such materials. Synchrotron radiation, on the other hand, is sensitive to heavy elements, so the two approaches are complementary.

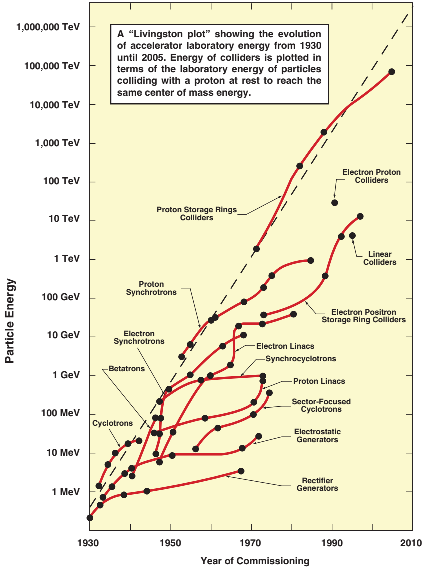
Summary

- The field started for nuclear physics in the 1930s. Made a transition to high energy physics in the 1960-70s.
- Accelerator size grew rapidly from 4-in prototype cyclotron (1930) to 7 TeV LHC. Energy increased 5×10^6 times, while accelerator size increased 5×10^4 times.
- Cost grew rapidly also, although cost per GeV is decreasing.
- Technology evolved. Several accelerator principles and ingenious ideas invented. Several generations of accelerators built.

Summary (Cont.)

- Livingston chart
  12 orders of magnitudes
  over 70 years.

A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.



Summary (Cont.)

- Since 1980s, there has been rapid growth of other accelerator applications. Rapid technology growth is continuing. American Physical Society established a new Beam Physics Division in 1985. It has 1200 members out of 40000 in APS. Other physical societies in Europe, Japan, and Mainland China took similar steps.
- The field is rapidly evolving and growing.

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