Ernest Rutherford and the Accelerator: "A Million Volts in a Soapbox"

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Outline

- Rutherford's call for inventing accelerators ("million volts in a soap box")
- Newton, Franklin and Jefferson: Notable prefiguring of Rutherford's call
- Rutherfords's discovery: The atomic nucleus and a new experimental method (scattering)
- A century of particle accelerators

Rutherford's call for inventing accelerators

1911 – Rutherford discovered the atom's nucleus

- Revolutionized study of the submicroscopic realm
- Established method of making inferences from particle scattering

1927 – Anniversary Address of the President of the Royal Society

- Expressed a long-standing "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" available from natural sources so as to "open up an extraordinarily interesting field of investigation."

Rutherford's wish:
"A million volts in a soapbox"

Spurred the invention of the particle accelerator, leading to:

- Rich fundamental understanding of matter
- Rich understanding of astrophysical phenomena
- Extraordinary range of particle-accelerator technologies and applications

From Newton, Jefferson & Franklin to Rutherford's call for inventing accelerators

Isaac Newton, 1717, foreseeing something like quarks and the nuclear strong force:

"There are agents in Nature able to make the particles of bodies stick together by very strong attractions. And it is the business of Experimental Philosophy to find them out. The smallest particles of matter may cohere by the strongest attractions."

From Query 31, *Opticks*

Newton in a 1702 portrait by Godfrey Kneller

From Newton, Jefferson & Franklin to Rutherford's call for inventing accelerators

THOMAS JEFFERSON
President of the United States. —

Thomas Jefferson, 1788, lamenting that his (and Franklin's) era was "an age too soon" for what he called the "chemistry" of "minute" particles:

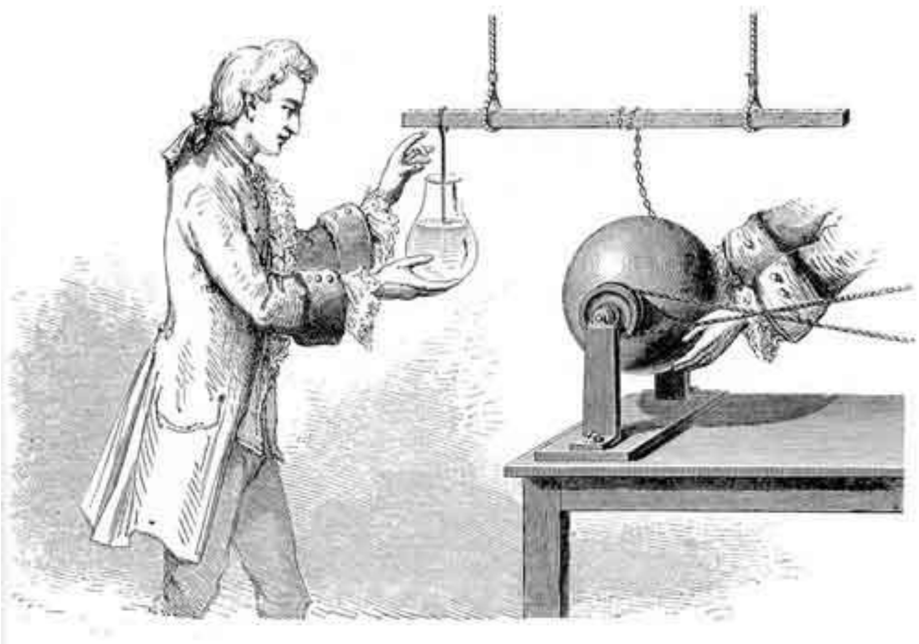
"Art has not yet invented sufficient aids, to enable such subtle bodies to make a well defined impression on organs as blunt as ours. …[Chemistry is] among the most useful of sciences…[but still] a mere embryon. Its principles are contested; experiments seem contradictory; their subjects are so minute as to escape our sense; and their result too fallacious to satisfy the mind. It is probably an age too soon… ."

Paris, 1788

Franklin's era *not* "an age too soon" for modeling nature's awesome forces

"The confirmations that lightning is an electrical discharge was perhaps the most dramatic and far-reaching finding of 18th century science. Above all, it showed that human-made microcosms might mimic cosmic phenomena. With an electrical machine and Leyden jar, for example, the scientists created, in miniature, lightning in the laboratory. The ability to model nature's most awesome forces had obvious implications for enhancing elite Enlightenment ideology… ."

From *Draw the Lightning Down: Benjamin Franklin and Electrical Technology in the Age of Enlightenment*, Michael Brian Schiffer



First-generation electrical sources:

Electrostatic machines and Leyden jars

Technology link from Franklin’s day to Rutherford’s:

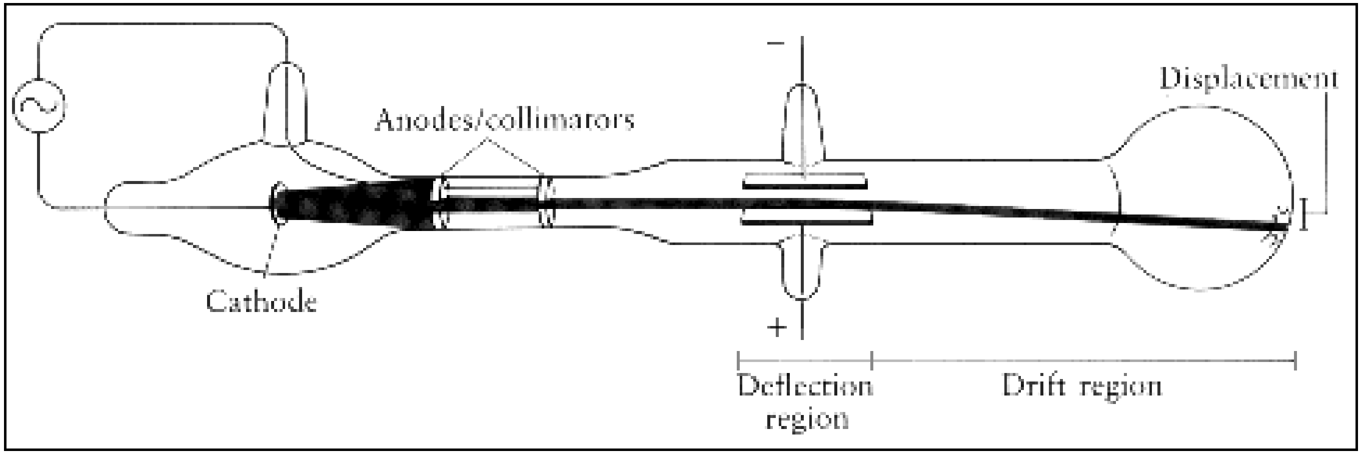
Electrostatic machines and crude vacuum pumps ⟶ particle accelerators

Science link from Franklin’s time to Rutherford’s:

“The ability to model nature’s most awesome forces.”

Accelerators pre-1900

The Thomson and Roentgen tubes were electron and ion accelerators at the kV range

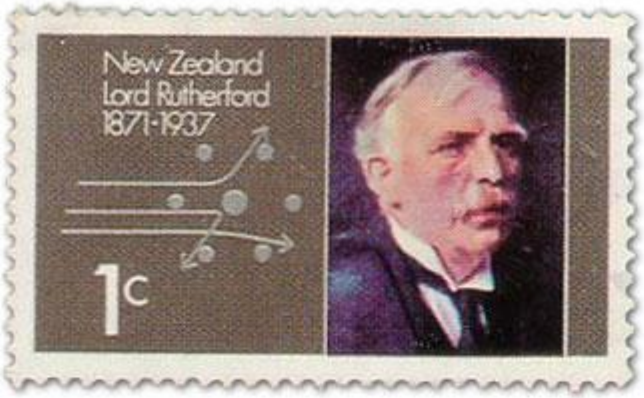


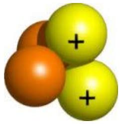
Rutherford's experiments discovered the nucleus and his later Nobel winning work on radiochemistry used naturally emitted radioactivity as MeV accelerators.

An accelerator for Rutherford

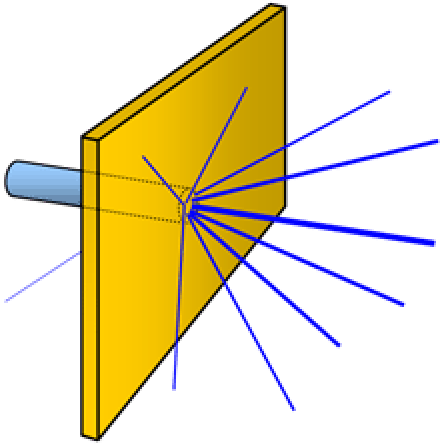
The discovery of the "point-like" atomic nucleus

- Marsden and Rutherford, Manchester 1909





Alpha particles: probe



Ultra thin gold foil: target

MeV from an atomic nucleus

$\sim 10^{14}$ MV/m!

Manchester: The discovery of the "point-like" atomic nucleus

PhD student Ernest Marsden told Rutherford of the strange scattering of alpha particles by gold leaf and later recalled a feeling:

"…something like that of a cat delivering a choice mouse to his mistress."

(from Rutherford Memorial Lecture, Royal Society London, 1954)

"…quite the most memorable event that ever happened to me in my whole life."

Ernest Rutherford, 1909
then Professor of Physics at Manchester University

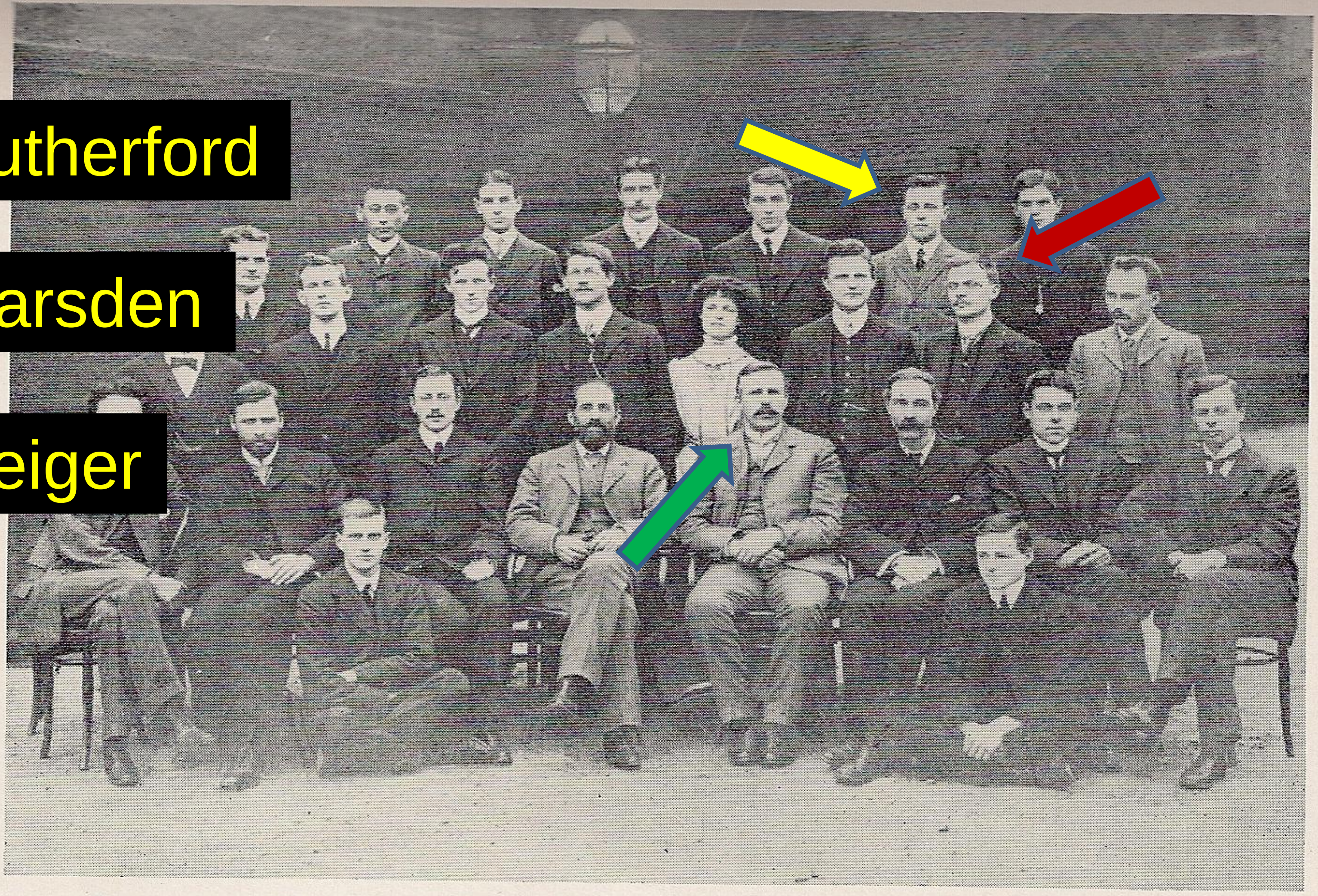
Rutherford sought "information of great value"

- Why a positively charged, massive, nucleus and negatively charged, light, electron cloud?
- Are nuclei and electrons fundamental? If not, do they have substructure?
- What new physics is beyond the Periodic Table?
- Why are some atoms radioactive?
- Are there new particles and forces at play in atoms?

Rutherford

Marsden

Geiger



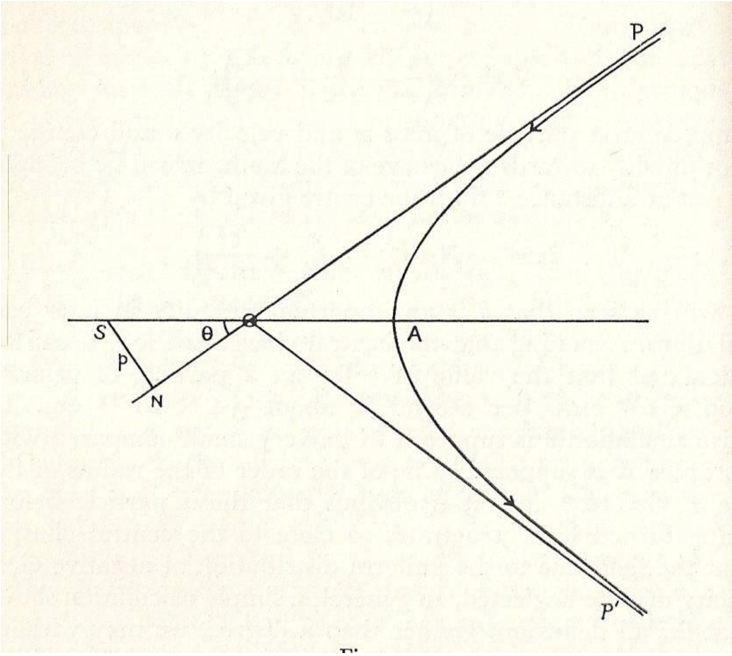
STAFF AND RESEARCH STUDENTS OF MANCHESTER UNIVERSITY PHYSICS DEPARTMENT, 1910

W. Eccles S. Kinoshita R. Rossi W. Kay G. N. Antonoff E. Marsden W. C. Lantsberry
F. W. Whaley H. C. Greenwood W. Wilson W. Borodowsky Miss M. White E. J. Evans H. Geiger T. Tuomikoski
S. Russ H. Stansfield H. Bateman Prof. Schuster Prof. Rutherford R. Beattie J. N. Pring W. Makower
R. E. Slade W. A. Harwood

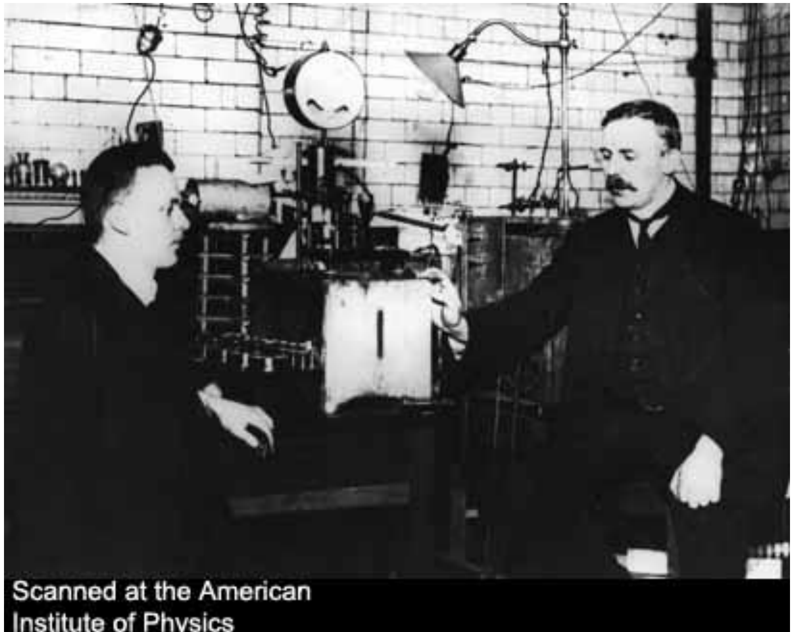
(J.B. Birks, ed., Rutherford at Manchester, 1962)

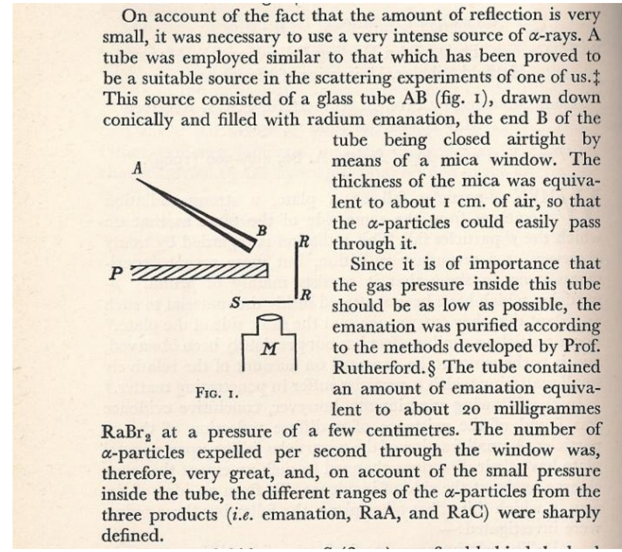
Rutherford's Nuclear Timeline

- 1908-1910 Geiger & Marsden study scattering of alpha particles
- 1910/11 Rutherford considers a nucleus of positive or negative charge, settles on positive
- 1913 Geiger & Marsden publish "On the Laws of Deflexion of Particles through Large Angles"
- "…the deflexions are the result of an intimate encounter of an α particle with … the central concentrated charge…"



(J.B. Birks, ed., Rutherford at Manchester, 1962)



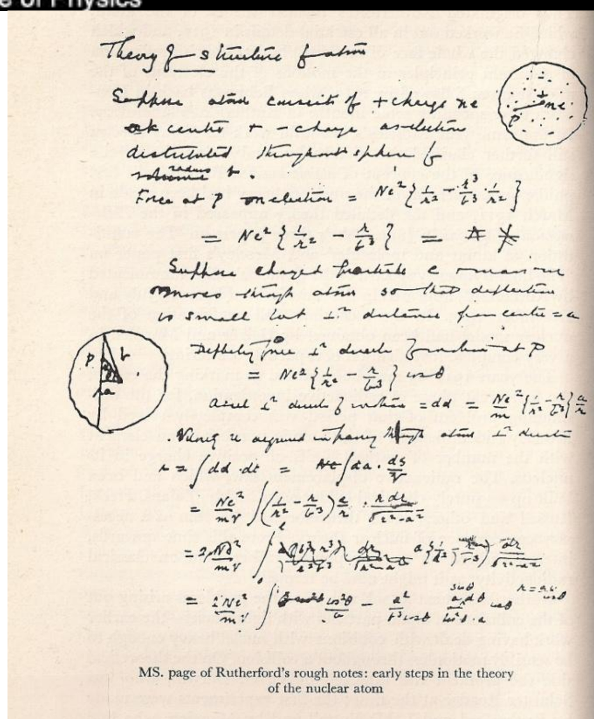


On account of the fact that the amount of reflection is very small, it was necessary to use a very intense source of α-rays. A tube was employed similar to that which has been proved to be a suitable source in the scattering experiments of one of us.‡ This source consisted of a glass tube AB (fig. 1), drawn down conically and filled with radium emanation, the end B of the tube being closed airtight by means of a mica window. The thickness of the mica was equivalent to about 1 cm. of air, so that the α-particles could easily pass through it.

Since it is of importance that the gas pressure inside this tube should be as low as possible, the emanation was purified according to the methods developed by Prof. Rutherford.§ The tube contained an amount of emanation equivalent to about 20 milligrammes $RaBr_2$ at a pressure of a few centimetres. The number of α-particles expelled per second through the window was, therefore, very great, and, on account of the small pressure inside the tube, the different ranges of the α-particles from the three products (*i.e.* emanation, RaA, and RaC) were sharply defined.

FIG. 1.

("On a Diffuse Reflection of the α-Particles," Proceedings of the Royal Society, 1909)

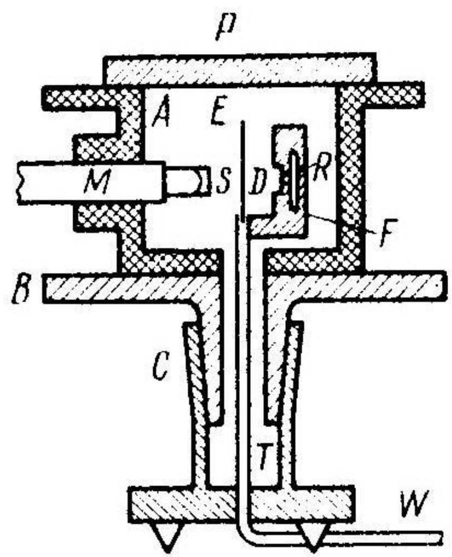


Theory of structure of atom

Suppose atom consists of + charge ne at centre & – charge as electrons distributed throughout sphere of radius b.

MS. page of Rutherford's rough notes: early steps in the theory of the nuclear atom

(J.B. Birks, ed., *Rutherford at Manchester*, 1962)



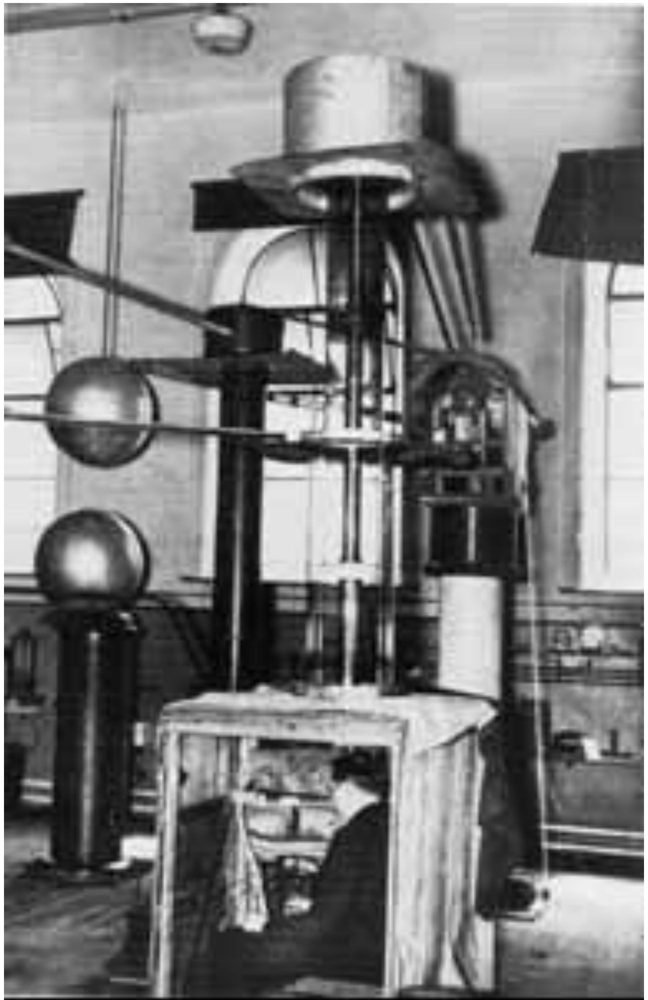
(*Philosophical Magazine*, 1913)

Particle Physics in Rutherford's Labs

- Until 1920s, Rutherford and his students used natural sources of radioactivity as the source of alpha particles
- Teams in the Cavendish Lab after Rutherford took over in 1919 used cosmic rays as a source and started building their first "accelerators"

Then came 1932, an *Annus Mirabilis*

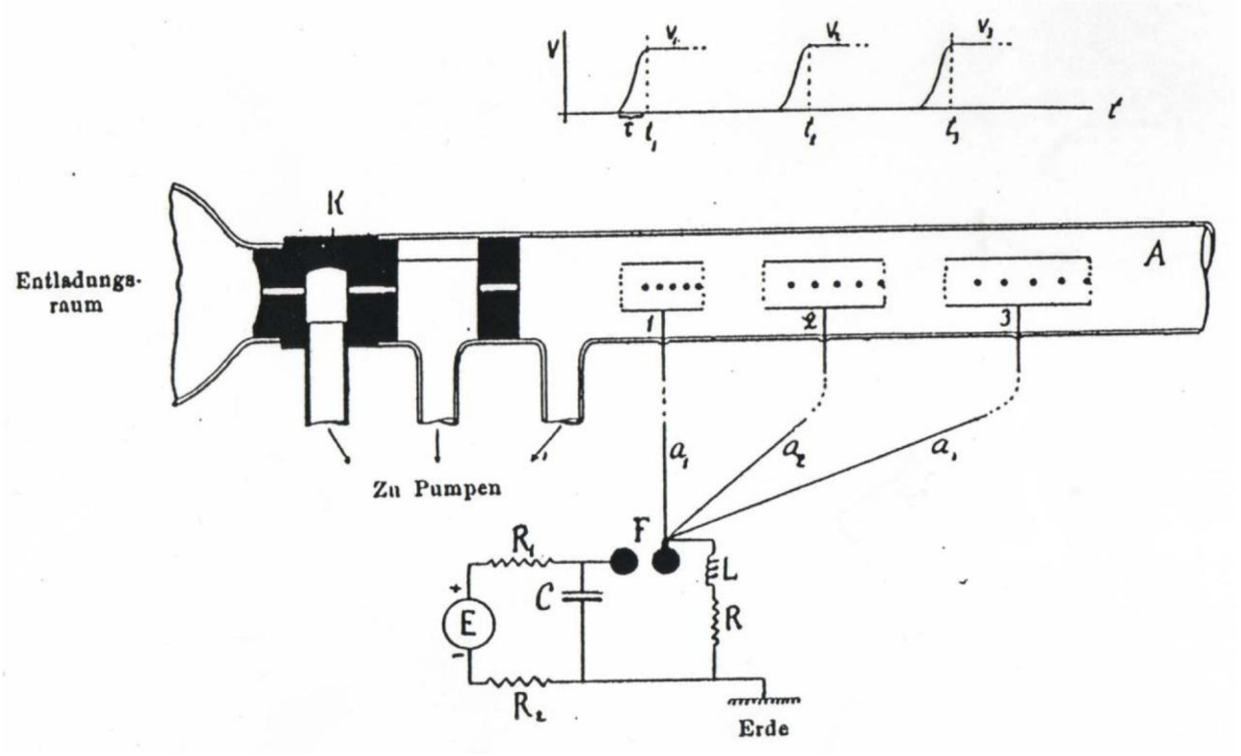
- Cockcroft & Walton build a 500,000 volt proton accelerator
- Chadwick discovers the neutron
- Blackett & Occhiallini independently discover the positron



Scanned at the American Institute of Physics

First generation of accelerators

G. Ising's pioneering RF linear accelerator (1924)



R. Wideroe demonstrated in 1928 with 50 keV K+

First generation of accelerators

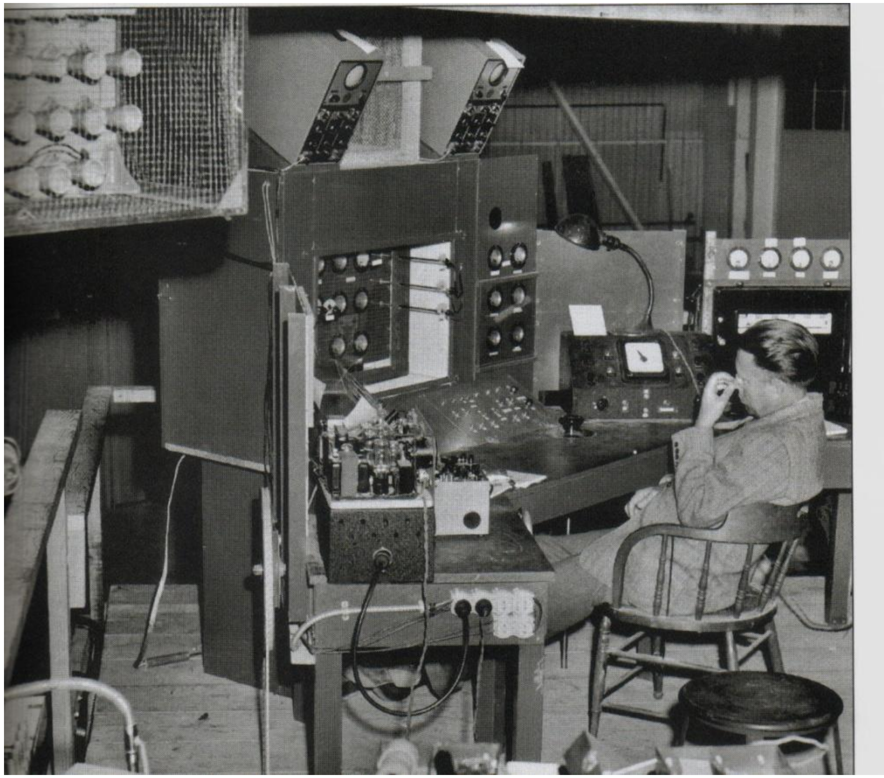
Electrostatic:

Cockcroft-Walton generator

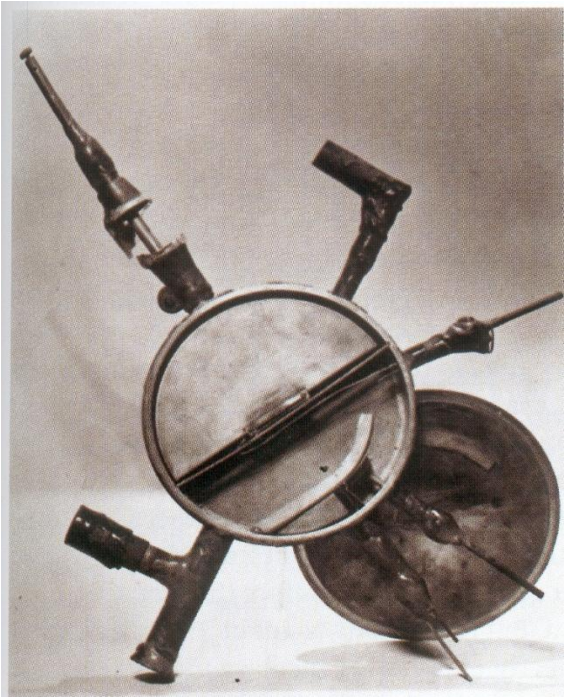
(voltage multiplier)

1932, 400 keV H^+, Li^+

First generation of accelerators



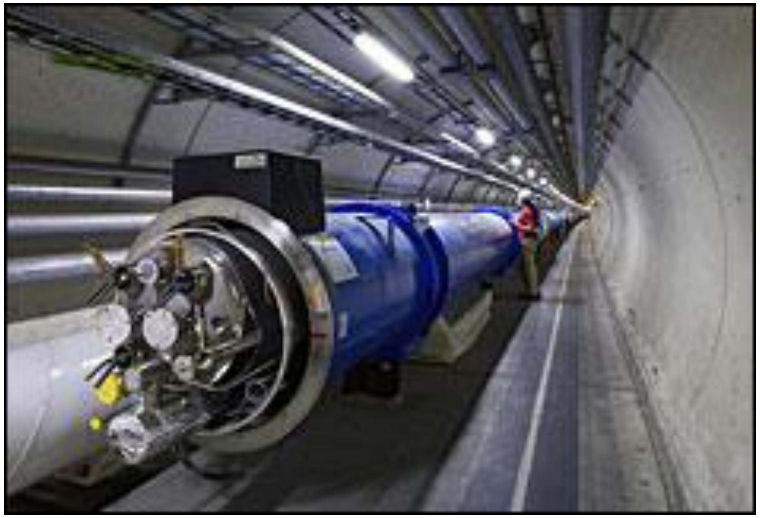
Lawrence's lab at Berkeley



E.O. Lawrence's first cyclotron

1932, 1.2 MeV, H^+

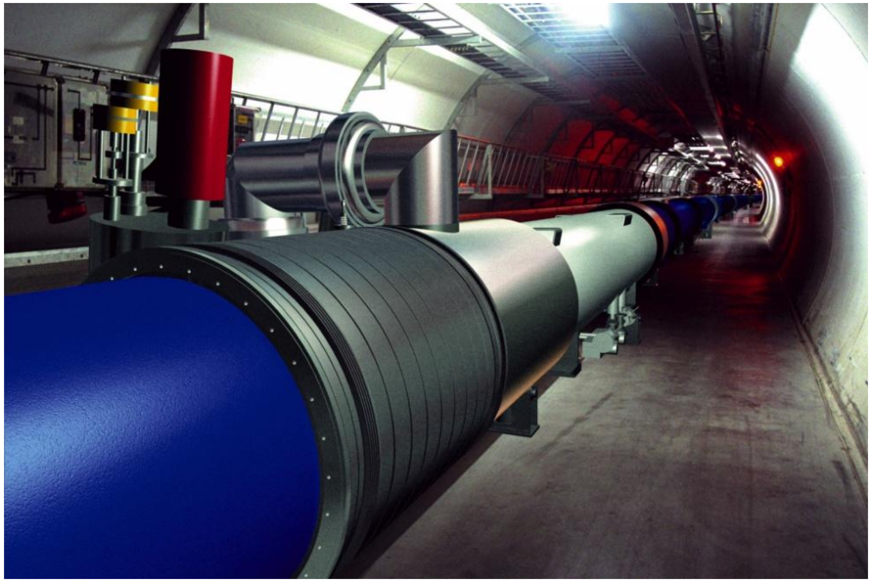
Accelerators, the current generation



CERN, showing the LEP/LHC ring

Accelerators, the current generation

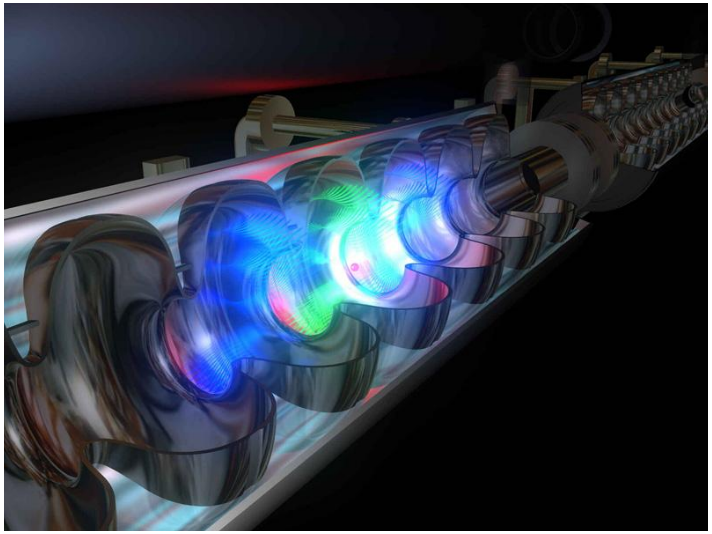
LHC started up in 2009 (1.5 TeV)

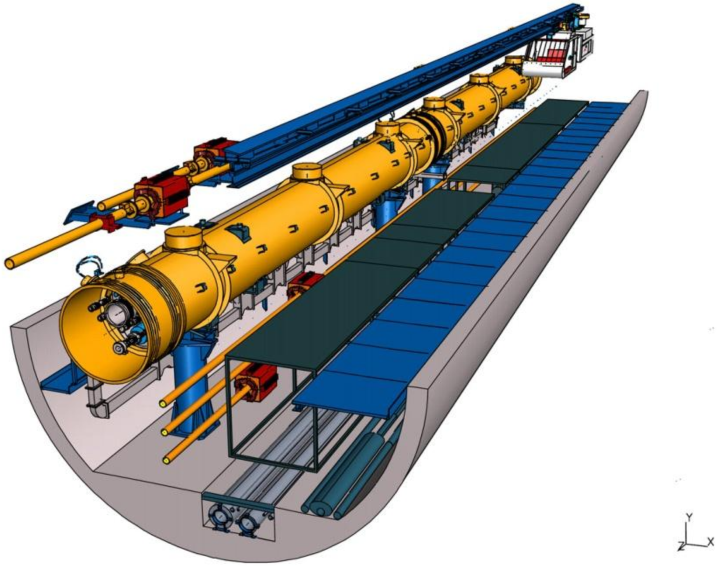


LEP 1989-1999 (100 GeV)

Next generation: Superconducting RF acceleration

SRF acceleration cavities have pushed the state of the art for sustained (cw) fields across an evacuated electrode system

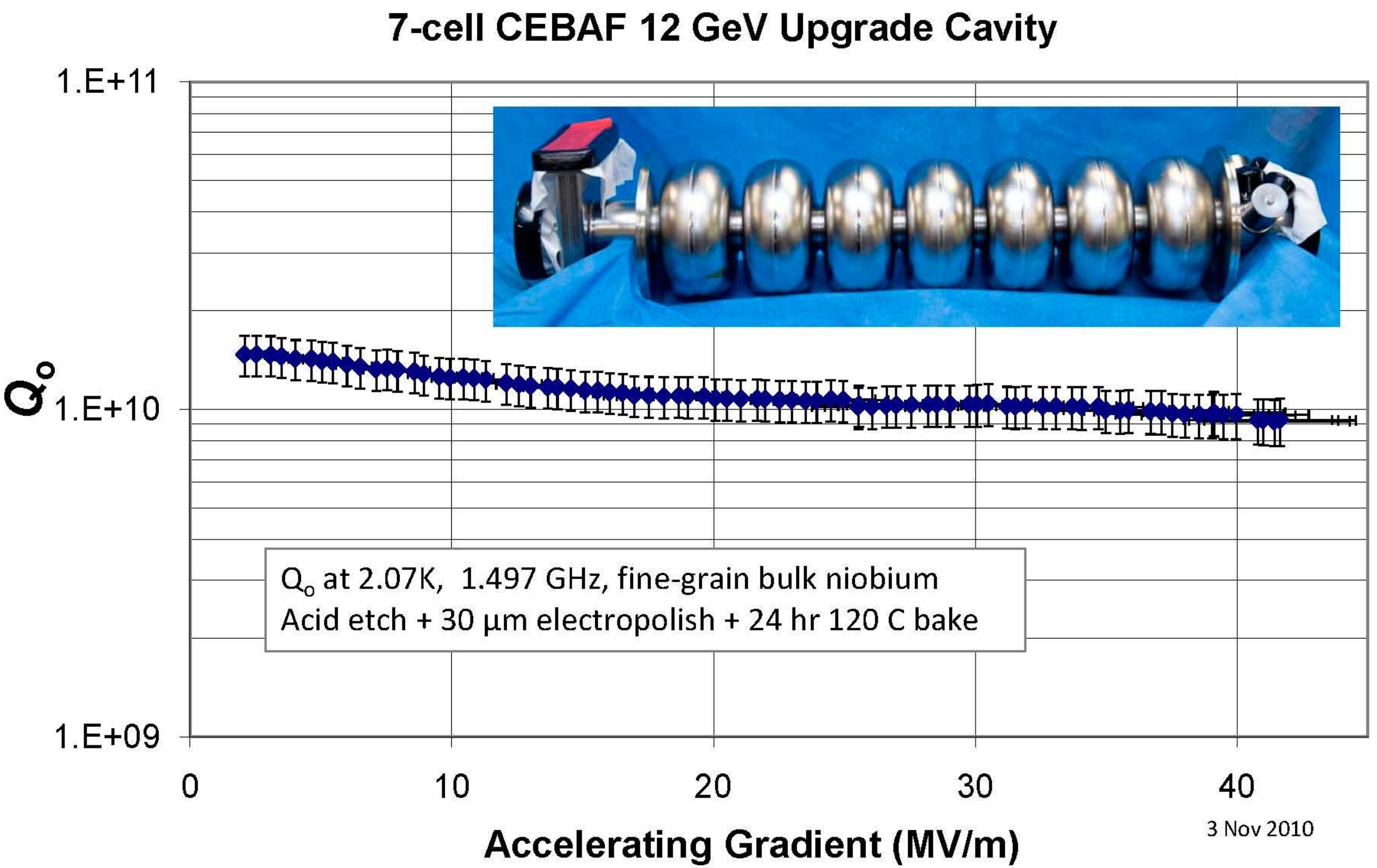




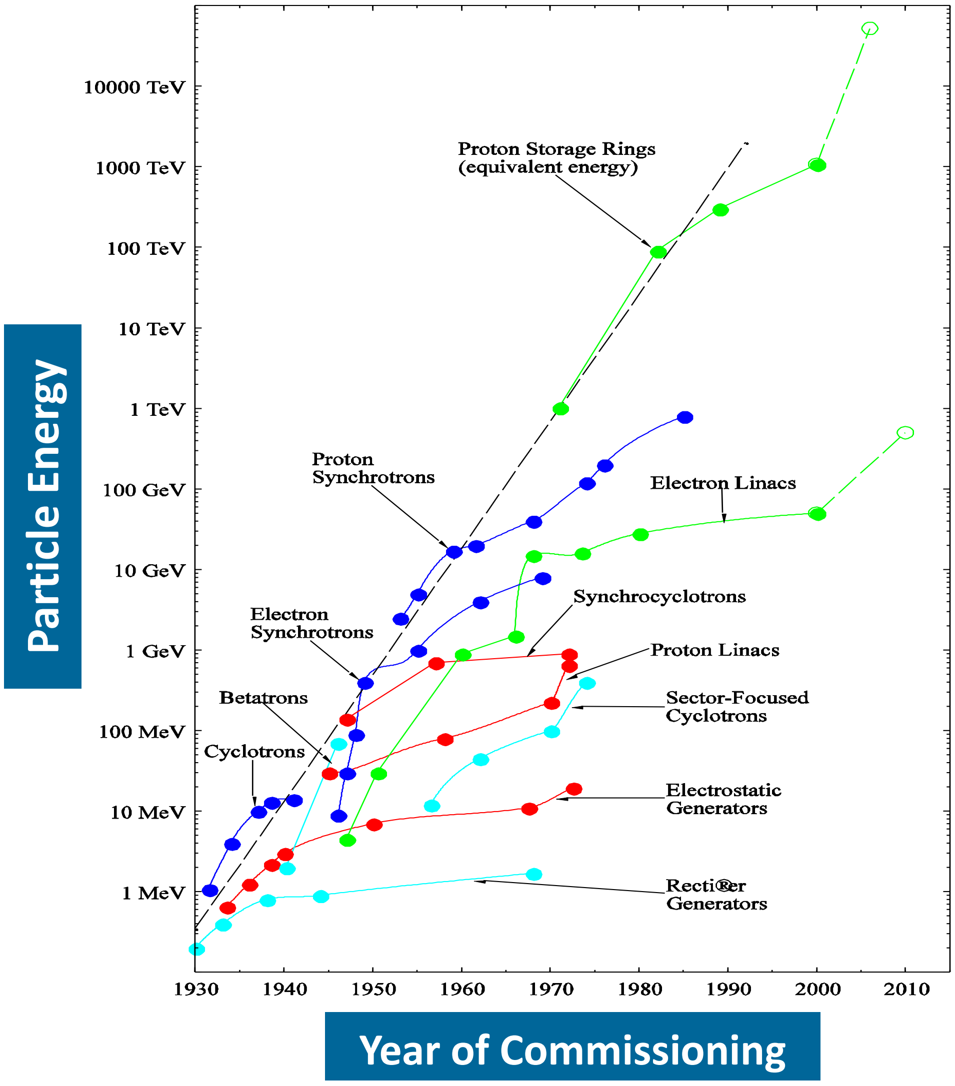
Applications:

- The linear collider at TeV energies (ILC Project)
- High-power (JLab) and short wavelength (x-ray) FELs (DESY and SLAC)

Superconducting RF cavities



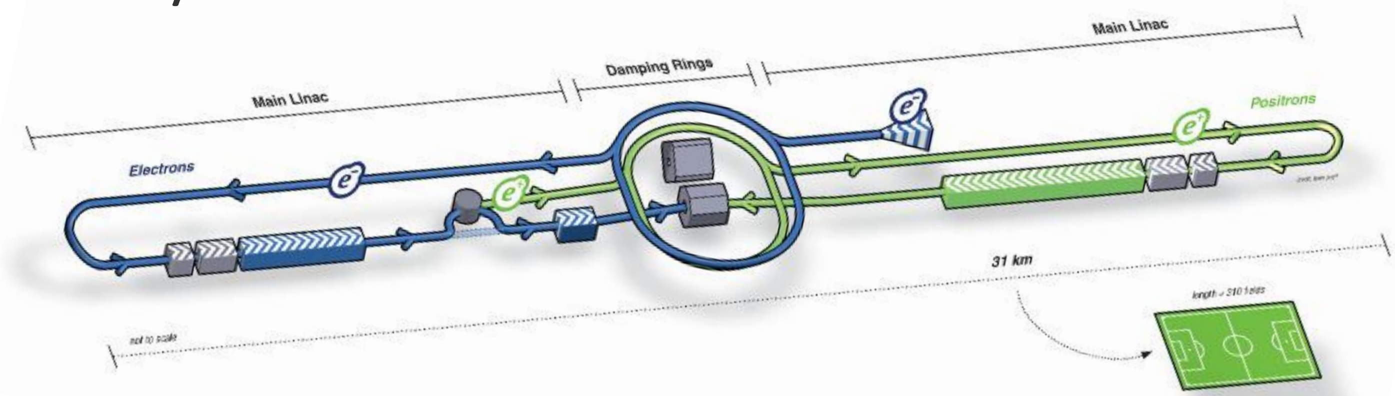
Evolution of accelerators



Livingston, 1960 and numerous updates

Future science:
International Linear Collider (ILC)

To complement/extend LHC's work:



- Energy up to 500 GeV (option for upgrade to 1 TeV)
- 14,000 electron-positron collisions per second
    - Each 5 nm bunch contains 20 billion particles
- 16,000 SRF cavities @ 31.5 MV/m gradient
- Involving nearly 300 laboratories and universities worldwide
    - 700 people working on accelerator design; 900 on detectors

Site not yet decided

Accelerator applications are multiplying

From *Accelerators for America's Future* (DOE; September, 2010):

- 30,000 accelerators operate worldwide
- Products processed, treated or inspected by beams > $500B
- Market for medical and industrial accelerators > $3.5B
  - Growing 10% / year
- Market for ion implantation for digital electronics: $1.5B

In other countries:

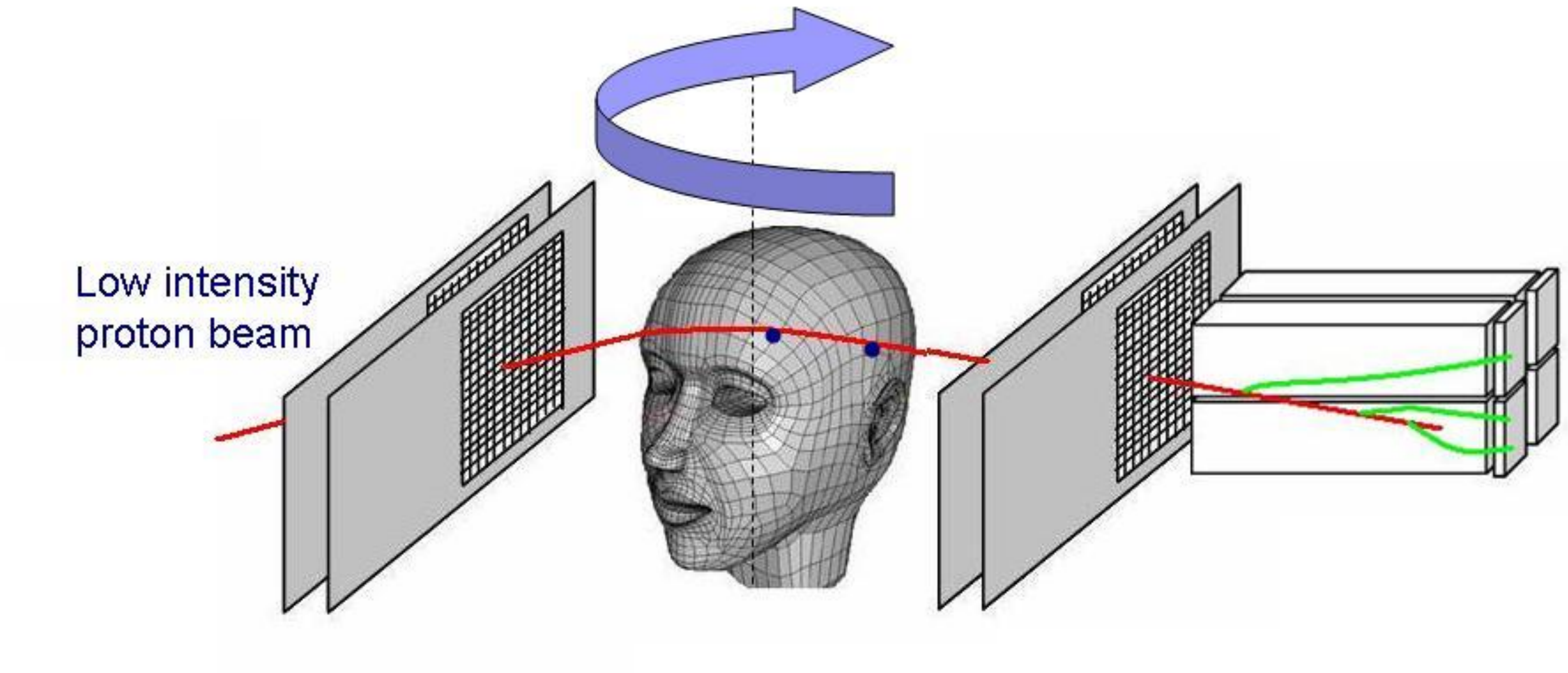
- Belgian accelerator-driven systems demo project: $1.3B
- China & Poland: accelerators turn flue gases into fertilizer
- Korea: industrial-scale water-treatment plant uses e-beams
- Japan & Germany: light-ion beams for cancer treatment

Accelerator applications are multiplying

Judy Jackson, from *Accelerators for America's Future*: A beam of the right particles with the right energy at the right intensity can:

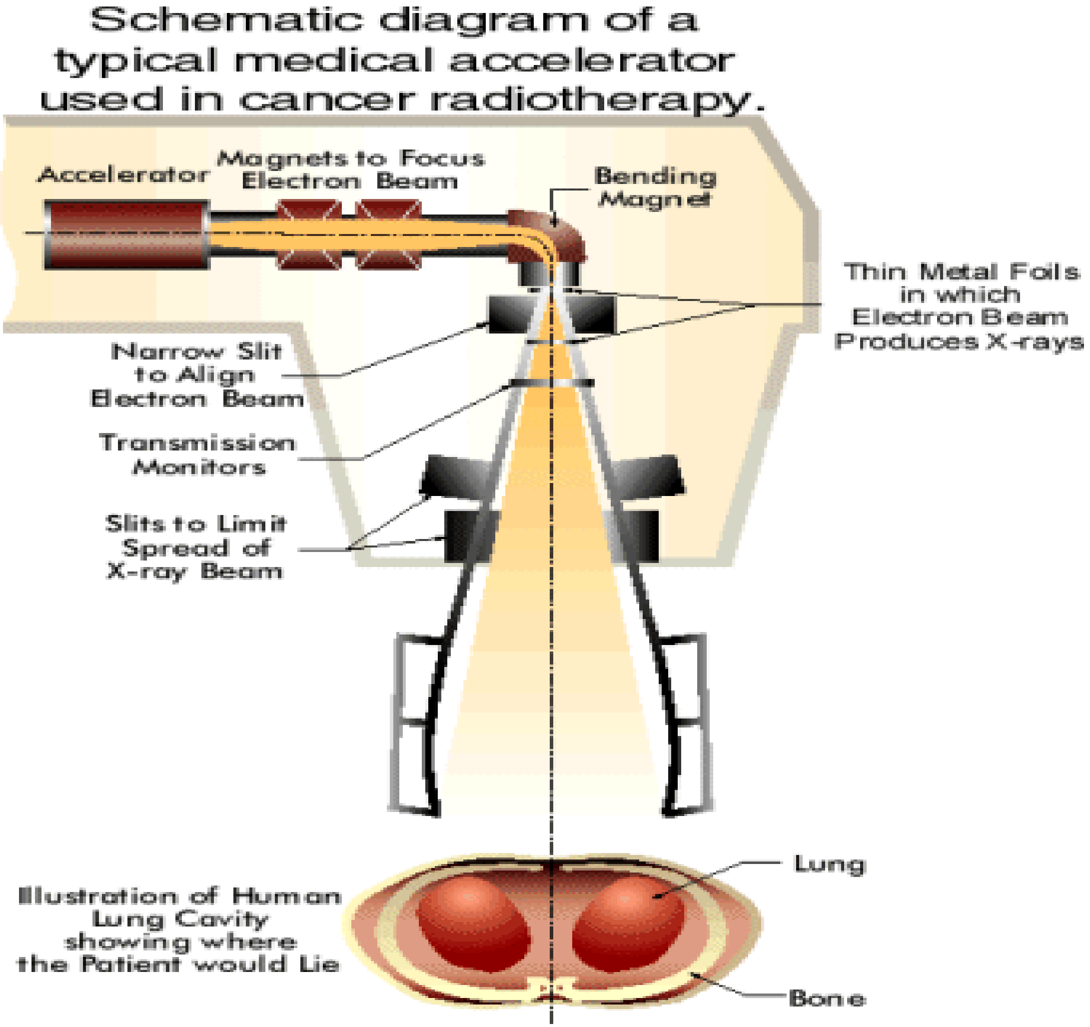
- Shrink a tumor
- Produce cleaner energy
- Spot suspicious cargo
- Make a better radial tire
- Clean up dirty drinking water
- Map a protein
- Study a nuclear explosion
- Design a new drug
- Make a heat resistant automotive cable
- Diagnose a disease
- Reduce nuclear waste
- Detect an art forgery
- Implant ions in a semiconductor
- Prospect for oil
- Date an archaeological find
- Package a Thanksgiving turkey, or
- Discover the secrets of the universe.

Accelerators and medical diagnostics



Medical accelerator for radiotherapy

(Courtesy of the Stanford Linear Accelerator Center)



Accelerators and national security

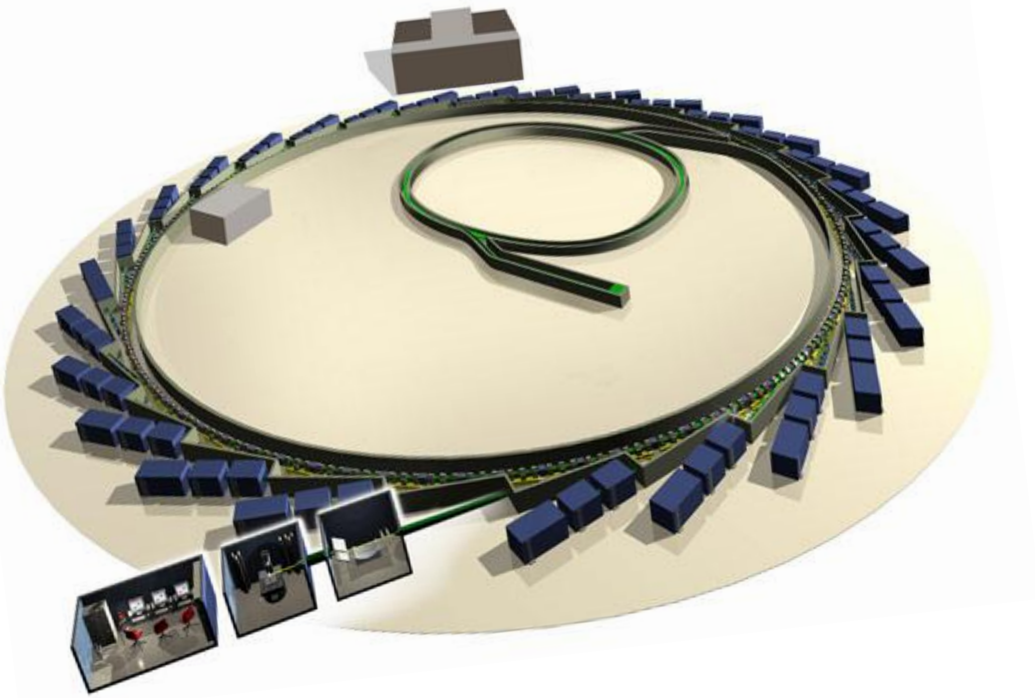
A single ship can bring up to 8000 tractor-trailer-sized cargo containers into an American port.

How can these large steel-walled boxes be inspected to assure safety?

High-density rail cargo imager scans fully loaded trains, tankers and double-stacked cars in a single pass using X-rays.

Beams of light from beams of particles

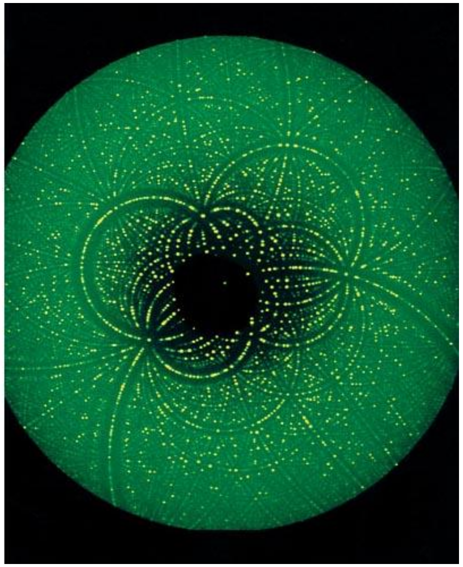
- Accelerator-driven light sources: synchrotrons, free-electron lasers
- Exceptionally intense, tightly focused beams of light
  - X rays & UV (also IR)
- More than 60 facilities in more than 20 countries
- More than 20,000 users worldwide

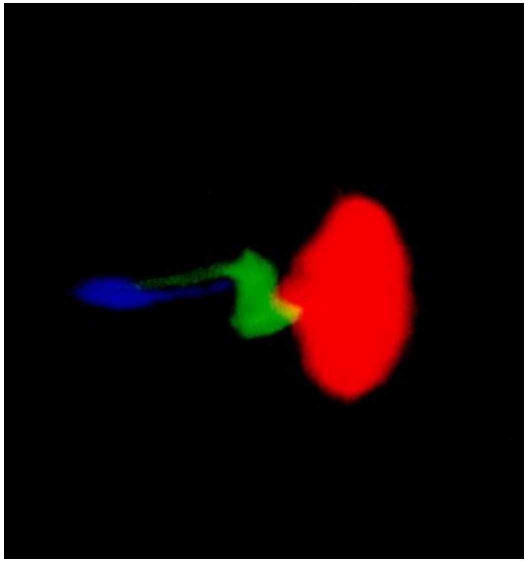


Schematic of Diamond Light Source, showing the components that make up the synchrotron.

(Courtesy of Diamond Light Source)

Accelerator-driven light source applications





Diffraction image of a biomolecule (Source: Max Planck working groups, Hamburg)	Multicolored laser light from the JLab FEL (Source: Jefferson Lab)

Examples of applications: probing the electronic structure of matter; semiconductors; magnetic materials; 3D-biological imaging; protein crystallography; ozone photochemistry; x-ray microscopy of biological samples; chemical reaction dynamics; atomic and molecular physics; optics testing

Accelerators and art

Light source used to study a Shang Dynasty vase

A PIXE measurement with AGLAE on the Saqqara Scribe from the Louvre museum

AGLAE, Accélérateur Grand Louvre d'Analyse Elémentaire in Paris, is the world's only accelerator facility fully dedicated to the study and investigation of works of art. Scientists use it for research on constituent materials.

Rutherford was right: Accelerators matter for physics

(Source: "Influence of Accelerator Science on Physics Research," E. Haussecker, A. Chao)

* Accelerators influenced 28% of physics research 1939-2009
* Accelerators contributed to a Nobel Prize every 2.9 years

1939	Ernest O. Lawrence
1951	John D. Cockcroft and Ernest T.S. Walton
1952	Felix Bloch
1957	Tsung-Dao Lee and Chen Ning Yang
1959	Emilio G. Segrè and Owen Chamberlain
1960	Donald A. Glaser
1961	Robert Hofstadter
1963	Maria Goeppert Mayer
1967	Hans A. Bethe
1968	Luis W. Alvarez
1976	Burton Richter and Samuel C.C. Ting
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg
1980	James W. Cronin and Val L. Fitch
1981	Kai M. Siegbahn
1983	William A. Fowler
1984	Carlo Rubbia and Simon van der Meer
1986	Ernst Ruska
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger
1989	Wolfgang Paul
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor
1992	Georges Charpak
1995	Martin L. Perl
2004	David J. Gross, Frank Wilczek, and H. David Politzer
2008	Makoto Kobayashi and Toshihide Maskawa

International cooperation

SESAME, a synchrotron-light source under construction in Jordan under UNESCO auspices, is closely modeled on CERN. SESAME allows science to advance in the Middle East despite the political unrest among its member nations.

Some 8000 visiting scientists—half of the world's particle physicists—come to **CERN** for their research. They represent 580 universities and 85 nationalities. Allows communication in science between countries that would not otherwise talk to each other.

From plum pudding atom to supersymmetry

*with thanks to Thomas Schulz and Richard Milner from MIT

Rutherford's seminal alpha particle experiments (with Geiger and Marsden) published in May 1911 (*Philosophical Magazine*)

- unveiled the central atomic nucleus
- presented a new mode of exploring the sub-atomic world: scattering experiments

These discoveries launched a century of development and application of particle accelerators

- the energy scale has evolved from 5 MeV (Rutherford) to 5 TeV (LHC)
- distances probed from 10^{-15}m (proton) to 10^{-21}m (LHC)
- enabled fundamental discoveries in particle physics leading to the Standard Model and our knowledge of element formation in the stars
- enabled applications of accelerators to a wide variety of fields (medicine, materials, energy)

The future is just as exciting:

- dark energy
- the nature of mass
- supersymmetry

Acknowledgments

- Greg Good, Director, Center for History of Physics
- Joe Anderson, Director, Niels Bohr Library & Archives
- Liz Dart Caron, Director, Corporate Communications, AIP

"Rutherford's Nuclear World"

Center for History of Physics online exhibit
to debut in the spring of 2011

http://www.aip.org/history/exhibits.html

(Courtesy Edgar Fahs Smith Memorial Collection, Department of Special Collections, University of Pennsylvania Library)