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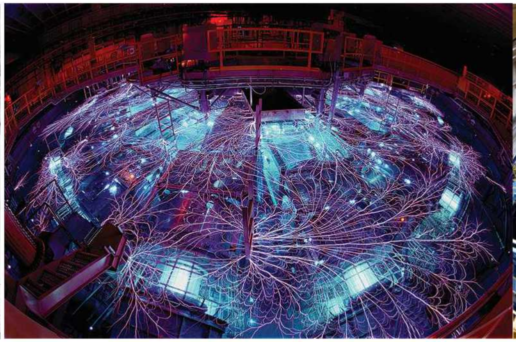

A Brief History of Accelerators in Physics: Dickinson College, April 11, 2019

Jon Custer

Advanced Radiographic Technologies

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Nuclear energy lab

Fossil energy lab

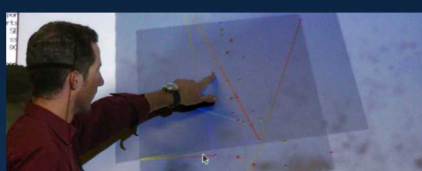
Energy efficiency and renewable energy lab

Fulfilling Our National Security Mission

Modernize the Nuclear Deterrent

Work to Solve Global Security Challenges

Secure America's Energy and Environmental Future



Address National Cyber Security Issues

Deliver Advanced Solutions to Our Military

Overview of Talk

- Radioactivity → Nucleus → Nuclear Physics
- Accelerators required for nuclear physics
  - Basis for all the main accelerators developed in 1928-1931
  - Cockroft & Walton; Van de Graaff
  - Linac, cyclotron
- Accelerators used for much more than nuclear physics
- Pulsed Power accelerators

Why were Accelerators Invented?

On a Diffuse Reflection of the α-Particles.

By H. Geiger, Ph.D., John Harling Fellow, and E. Marsden, Hatfield Scholar, University of Manchester.

Proc. Royal Soc. 82(557) 495-500 (1909)

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* By Professor E. Rutherford, *F.R.S., University of Manchester*.*

Phil. Mag 21(125) 669-688 (1911)

- Ions (α-particles) have been at the heart of understanding the properties of matter since the invention of the atom!
- Natural α sources were quickly deemed insufficient

Where did they get α particles?

- “Radium emanations” were the α source of choice in 1909
- Radium was announced by the Curies in 1898.
- Marie Curie received the Nobel Prize in Chemistry in 1911 (her second after Physics in 1903)
  - First to get 2 Nobel prizes in different fields
    - Who was the other person?
  - Name the 2-time Physics winner and for what discoveries?

Wikipedia

"Radium Emanations"

- Starting with isolated Radium, for each $^{226}_{88}Ra$ decay you rapidly get a variety of α energies
- This, and the similar ^{232}Th decay sequence, provides the helium for party balloons…

Nucleus	Decay
$^{238}_{92}U$	4.5E9 yrs, 4.195 MeV α
$^{234}_{90}Th$	24 days, β^-
$^{234}_{91}Pa$	7 hours, β^-
$^{234}_{92}U$	2.5E5 yrs, 4.773 MeV α
$^{230}_{90}Th$	7.5E4 yrs, 4.684 MeV α
$^{226}_{88}Ra$	1600 yrs, 4.781 MeV α
$^{222}_{86}Rn$	3.8 days, 5.486 MeV α
$^{218}_{84}Po$	3 min, 6.002 MeV α
$^{214}_{82}Pb$	26 minutes, β^-
$^{214}_{83}Bi$	20 minutes, 99.9% β^-
$^{214}_{84}Po$	160 μs, 7.687MeV α
$^{210}_{82}Pb$	21 yrs, β^-
$^{210}_{83}Bi$	5 days, β^-
$^{210}_{84}Po$	5 days, 5.305 MeV α
$^{206}_{82}Pb$	Stable (finally!)

Aside: Induced nuclear reactions

- Geiger and Marsden established elastic recoil of alpha particles
- Rarely, it was noticed that what were thought to be protons could be dislodged from nuclei by alphas
- It was initially assumed that the alpha worked as a billiard ball (spallation)
- Nuclear reactions are discovered

The Ejection of Protons from Nitrogen Nuclei, Photographed by the Wilson Method.

By P. M. S. Blackett, Moseley Research Student of the Royal Society and Fellow of King's College, Cambridge.

(Communicated by Prof. Sir E. Rutherford, F.R.S.—Received December 17, 1924.

About 23,000 photographs have been taken of the tracks of alpha-particles in nitrogen. From 5 to 20 per cent. of oxygen was added to the nitrogen to improve the sharpness of the tracks. The source used was a deposit of Thorium B + C, which gives a complex beam of 8·6 and 5·0 cm. particles, the numbers being known to be in the ratio of 65 to 35. The average number of tracks on each photograph was 18; the tracks of about 270,000 alpha-particles of 8·6 cm. range and 145,000 of 5·0 cm. range have therefore been photographed.

But amongst these normal forks due to elastic collisions, eight have been found of a strikingly different type. Six of them are reproduced on Plate 7. These eight tracks undoubtedly represent the ejection of a proton from a nitrogen nucleus. It was to be expected that a photograph of such an event would show an alpha-ray track branching into three. The ejected proton, the residual nucleus from which it has been ejected, and the alpha-particle itself, might each have been expected to produce a track. These eight forks however branch only into two.

(If you become a grad student, you really can't complain about how tedious your data analysis is…)

Wanted controlled α sources

- Need α particles
  - They are helium ions, so easy to make (plasma source)
  - (Or protons, deuterons, … for exploring nuclear physics fully)
  - Need to accelerate them to MeV energies

- Somebody had to invent high energy accelerators!
  - Cockcroft and Walton, and Van de Graaff
  - Wideröe and Lawrence: Linacs and cyclotrons

- Other accelerators: Pulsed Power Machines and their uses

First Approach

Sandia National Laboratories

Experiments with High Velocity Positive Ions.

By J. D. Cockcroft, Fellow of St. John's College, Cambridge, and E. T. S. Walton, 1851 Overseas Student.

(Communicated by Sir Ernest Rutherford, P.R.S.—Received August 19, 1930.)

[Plate 21a.]

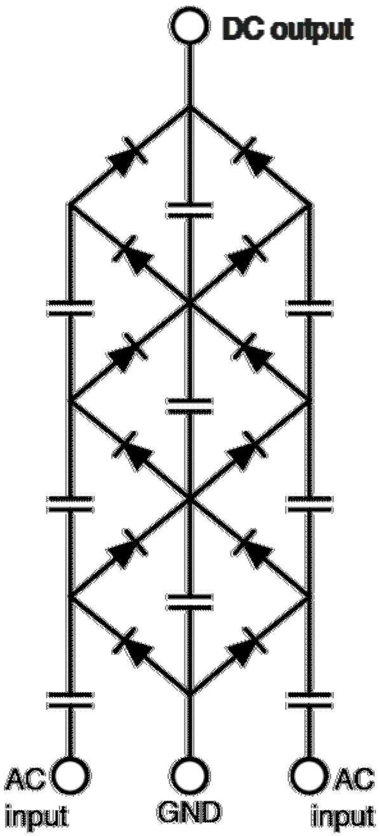
1. *Introduction.*

It would appear to be very important to develop an additional line of attack on problems of the atomic nucleus. The greater part of our information on the structure of the nucleus has come from experiments with α-particles and if we can supplement these with sources of positive ions accelerated by high potentials we should have an experimental weapon which would have many advantages over the α-particle. It would, in the first place, be much greater in intensity than α-particle sources, since one microampere of positive ions is equivalent, so far as numbers of particles is concerned, to 180 grams of radium equivalent. It would in addition have the advantage of being free from penetrating β and γ rays which are a complication in many experiments, whilst the velocity would be variable at will.

Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 129, No. 811 (Nov. 3, 1930), pp. 477-489

The Cockcroft-Walton source

- JD Cockcroft and ETS Walton invented the Cockcroft-Walton high voltage source
- This type is very common for >50kV power supplies (electron microscopes etc.) from, e.g. Glassman



The original apparatus

- Cockcroft and Walton rapidly built and used their high voltage power supply
- Used 2 high-voltage (>300kV) vacuum tube rectifiers (A and B)

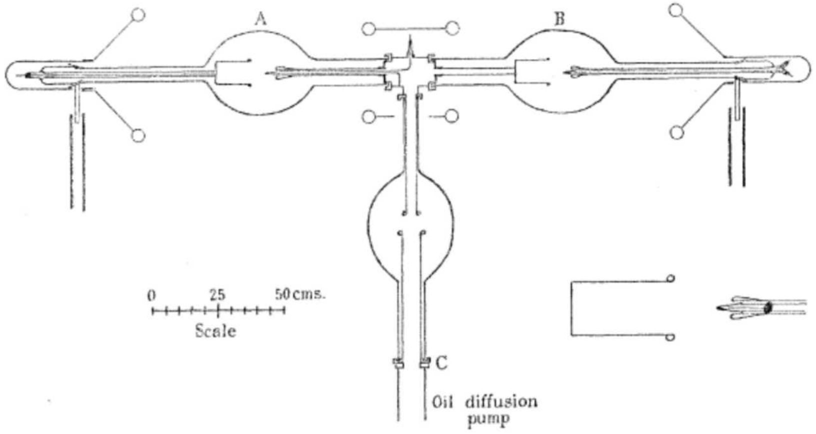
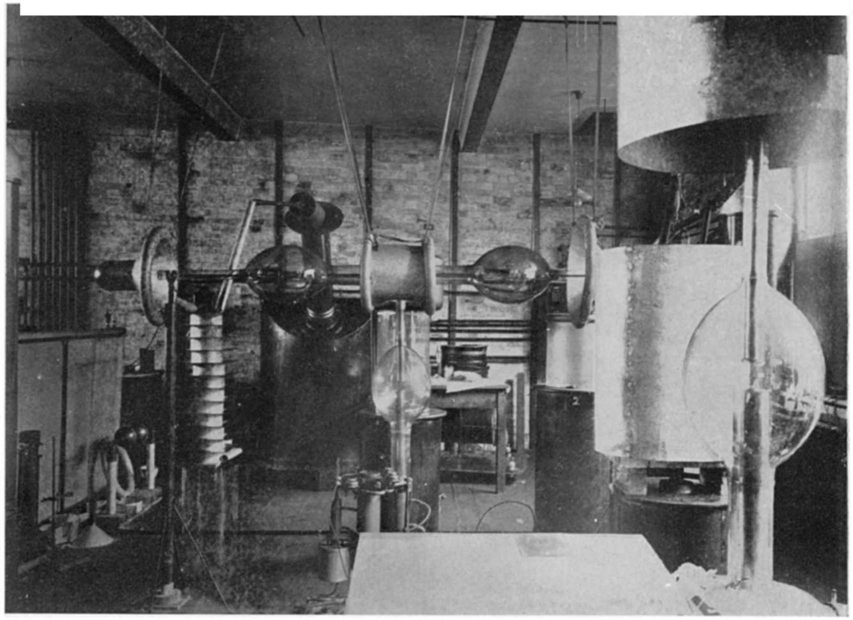


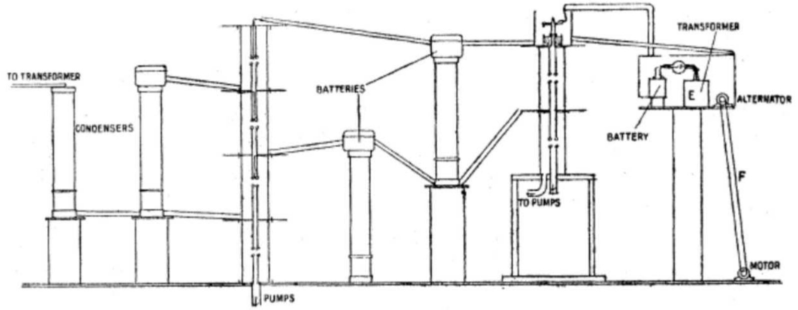
Fig. 4.

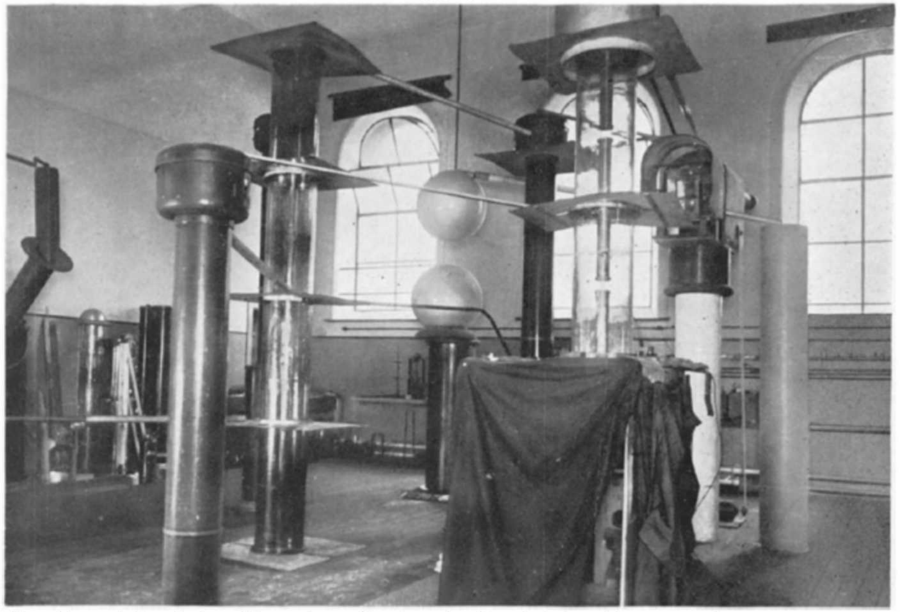


Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 129, No. 811 (Nov. 3, 1930), pp. 477-489

The '800kV' machine:

- The original machine could not generate voltages >600kV
- No unusual reactions were seen
- Answer: make a bigger voltage!
- Redesigned and scaled up to 800kV





Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 136, No. 830 (Jun. 1, 1932), pp. 619-630

Physics: $^7Li + p \rightarrow 2\ ^4He$

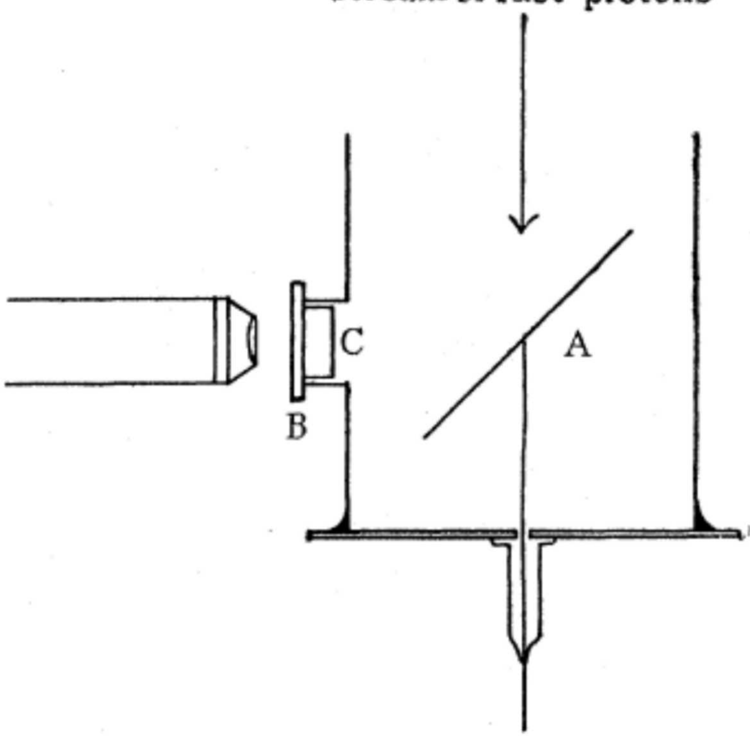


Fig. 1.

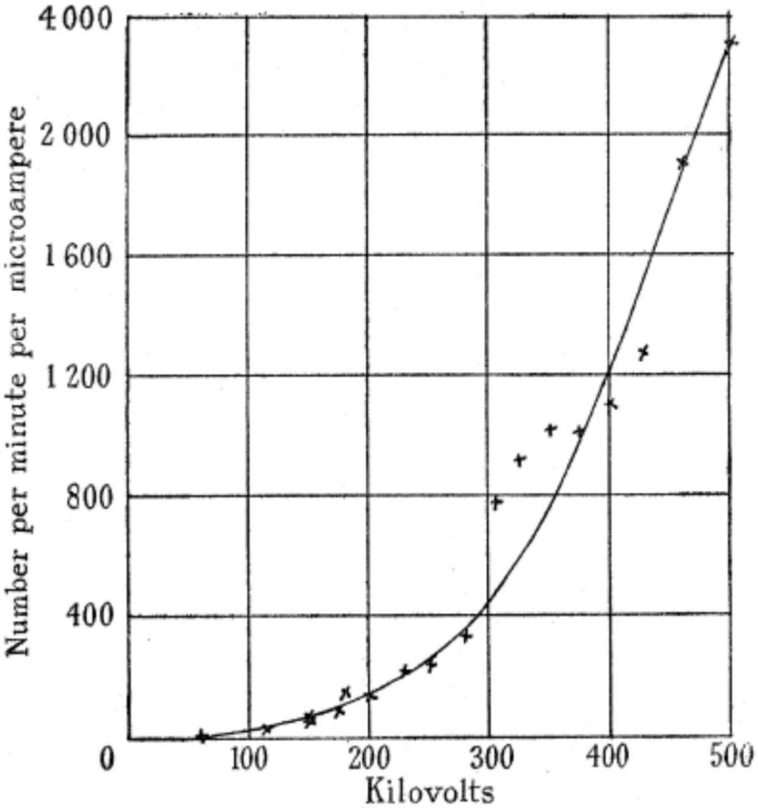
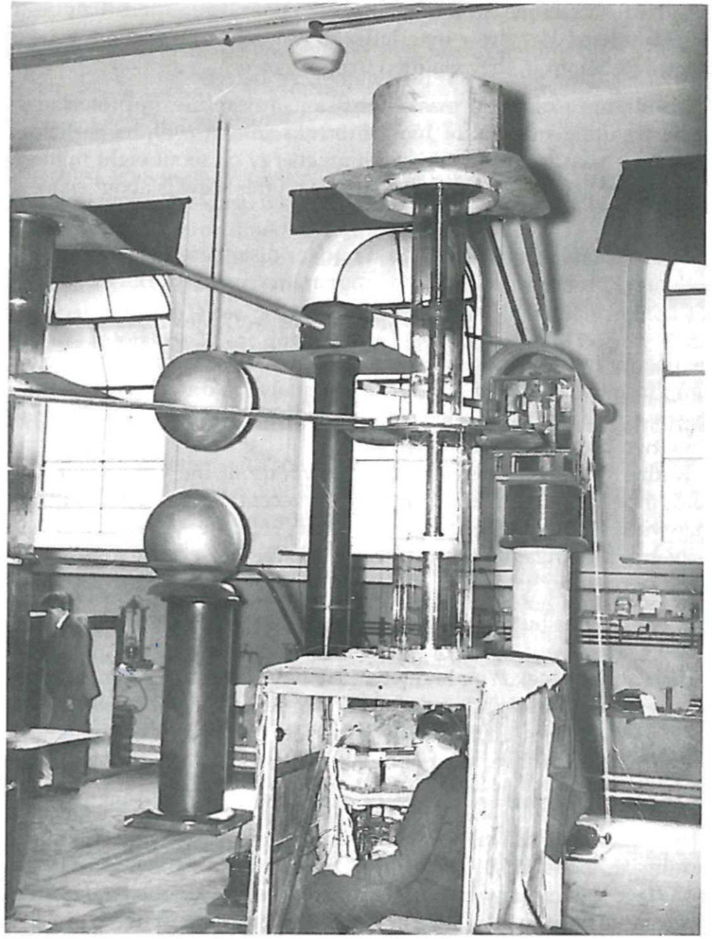


Fig. 4.

J.D. Cockcroft and E.T.S. Walton, Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 137, No. 831 (Jul. 1, 1932), pp. 229-242

How they did the experiment

- Crawl to the box to avoid a lightning bolt
- Sit in the lead-lined box (lined to shield from x-rays)
- Sit in the dark for your eyes to become accustomed
- Count flashes on zinc sulfide screen for <15 minutes
  - Longer and you see things
- Repeat…
- (Today we would get undergraduates to do it)



In Nuclear Transmutation to Nuclear Fission, PF Dahl, CRC Press (2002), from The Cavendish Laboratory

Result: Induced Nuclear Fission

4. *The Interpretation of Results.*

We have already stated that the obvious interpretation of our results is to assume that the lithium isotope of mass 7 captures a proton and that the resulting nucleus of mass 8 breaks up into two α-particles. If momentum is conserved in the process, then each of the α-particles must take up equal amounts of energy, and from the observed range of the α-particles we conclude that an energy of 17·2 million volts would be liberated in this disintegration process. The mass of the Li_7 nucleus from Costa's determination is 7·0104 with a probable error of 0·003. The decrease of mass in the disintegration process is therefore $7{\cdot}0104 + 1{\cdot}0072 - 8{\cdot}0022 = 0{\cdot}0154 \pm 0{\cdot}003$. This is equivalent to an energy liberation of $(14{\cdot}3 \pm 2{\cdot}7) \times 10^6$ volts. We conclude, therefore, that the observed energies of the α-particles are consistent with our hypothesis. An additional test can, however, be applied. If momentum is conserved in the disintegration, the two α-particles must be ejected in practically opposite directions and, therefore, if we arrange two zinc sulphide screens opposite to a small target of lithium as shown in the arrangement of fig. 5, we should observe a large proportion of coincidences in the time of appearance of the scintillations on the two screens. The lithium used in the experiments

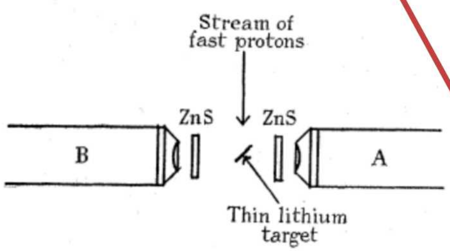


Fig. 5.

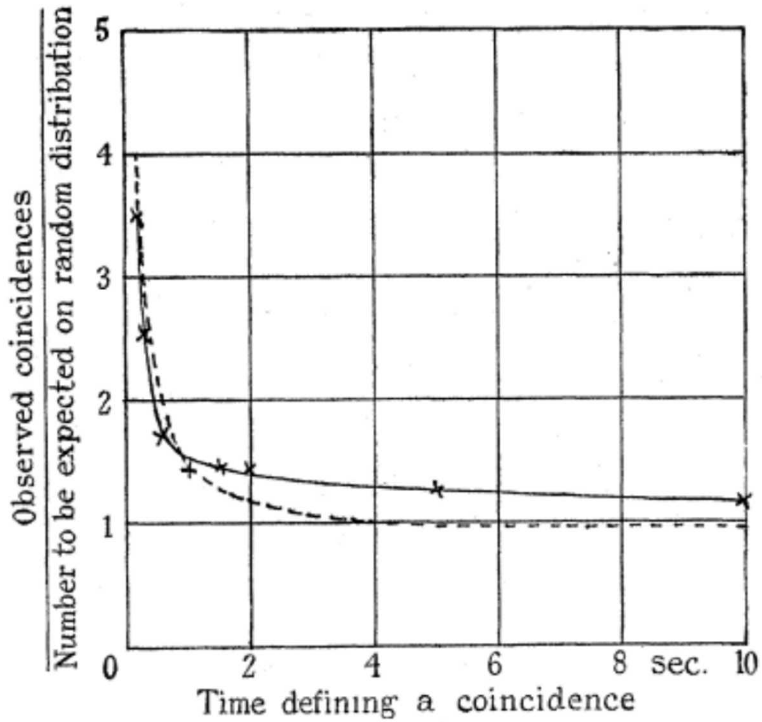
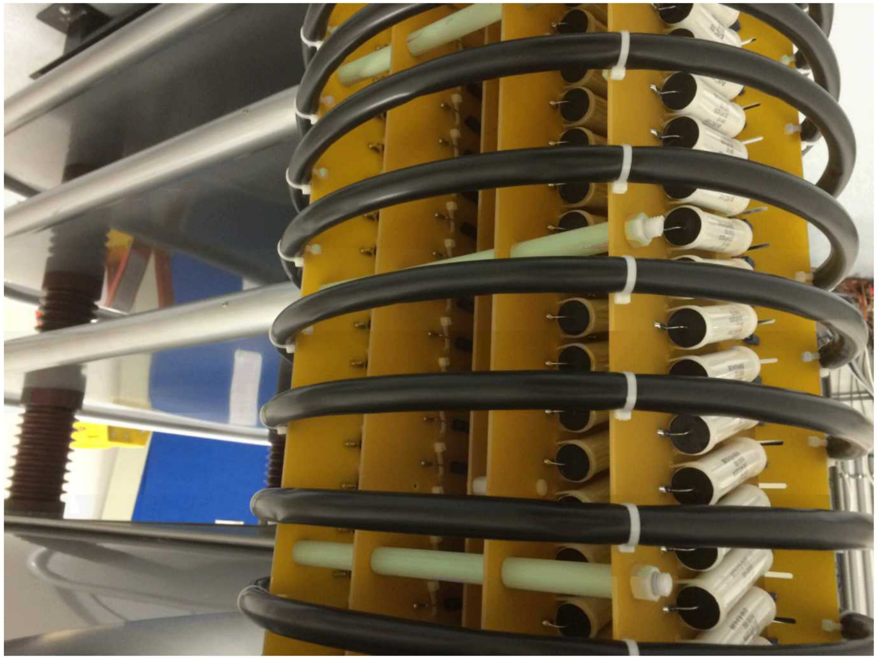


FIG. 6.

Current accepted value: 17.3468MeV

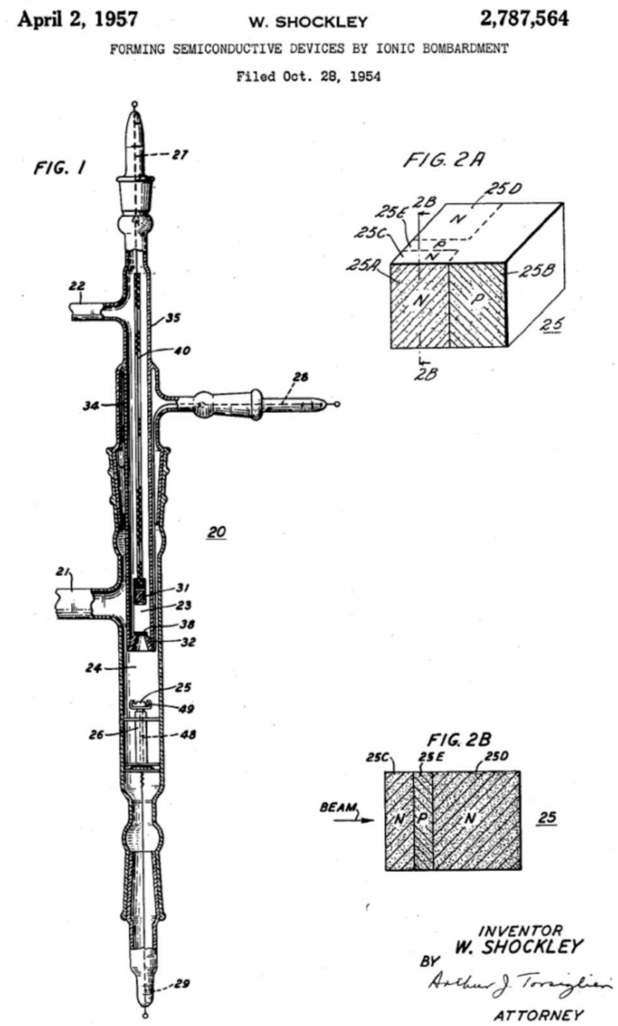
The modern version:

- Parallel 40-stage ladders (350kV)
- COTS components
- Semiconductor diodes much simpler than tubes



Application: Ion Implantion

- William Shockley (AT&T Bell Labs) recognized that you could use an ion accelerator to dope semiconductors and make devices
- Patent expired before ion implant was a major commercial factor
- Ion implantation remains a critical semiconductor manufacturing step



This invention relates to a process for manufacturing semiconductive devices, and to devices fabricated in accordance with this process.

Longer aside:

- Ernest Lawrence, 1941:
  - "In a discussion bearing on the future, the scientist is always in something of a dilemma. On the one hand, he is cautioned to make only very limited prognostications, for he has learned the very limited region of applicability of existing knowledge and the likelihood of error in speculation. On the other hand, he faces the future with eager excitement and curiosity about what is beyond the present frontiers of knowledge, and he is naturally tempted to speculate and indeed to indulge in daydreams."
    - – E.O Lawrence, Science 94 221-225 (September 5, 1941).
  - Beyond the sexism in the comment, lets see how Lawrence did…

Application: Isotope Separation

- Address given at Stanford, June 16, 1941:
  - "Without going into further detail, it is perhaps sufficient to say that there is some evidence now that, if U^{235} could be separated in quantity from the natural mixture of isotopes, a chain reaction could, indeed, be produced. **But herein lies the catch, for there is no practical large-scale way in sight of separating the isotopes of the heavy elements, and certainly it is doubtful if a way will be found**."
    - E.O Lawrence, Science 94 221-225 (September 5, 1941).
    - (Same presentation/paper as last slide)
- November 24, 1941:
  - Inspired by Mark Oliphant, Lawrence dismantles his old cyclotron to use the magnet in a hastily assembled electromagnetic isotope separator.
- December 2, 1941:
  - 18 micrograms of 25% enriched (from 0.72%) U^{235} are produced.

The Calutron:

- An ion beam with energy V (and velocity *v*) is sent into a magnetic field
- Force is $q \cdot v \times B$
- Different mass ions have different velocities
- Different isotopes follow different semicircular orbits
- Capture isotopes in buckets

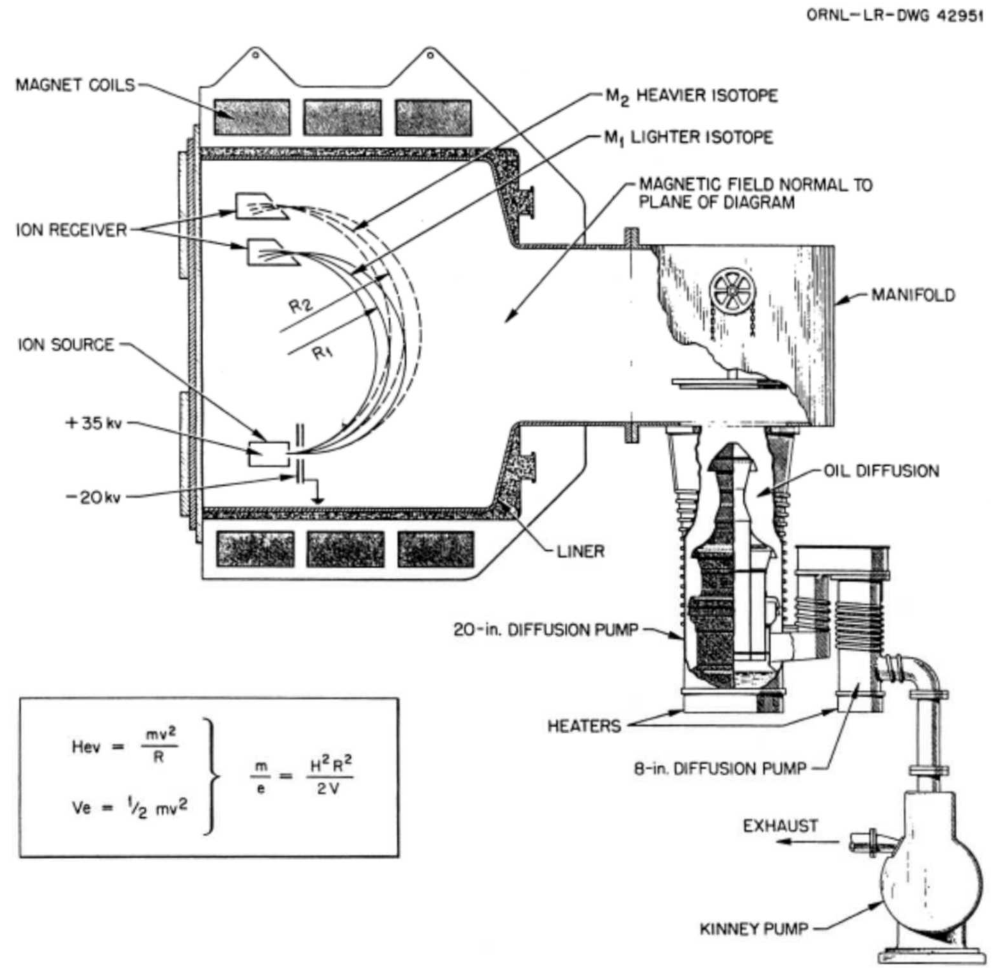
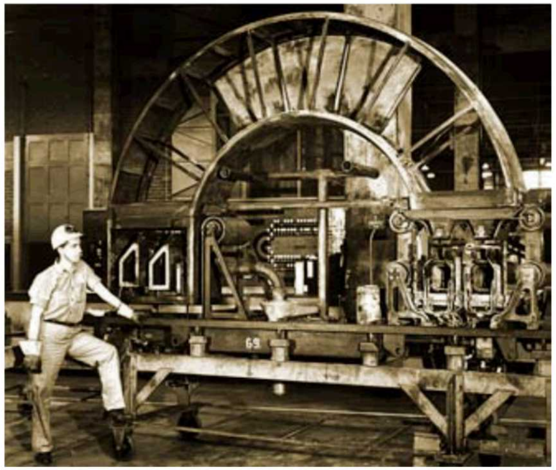


Figure 1. Schematic of second stage, β unit, separator. ORNL Drawing 42951.

Huge industrial enterprise



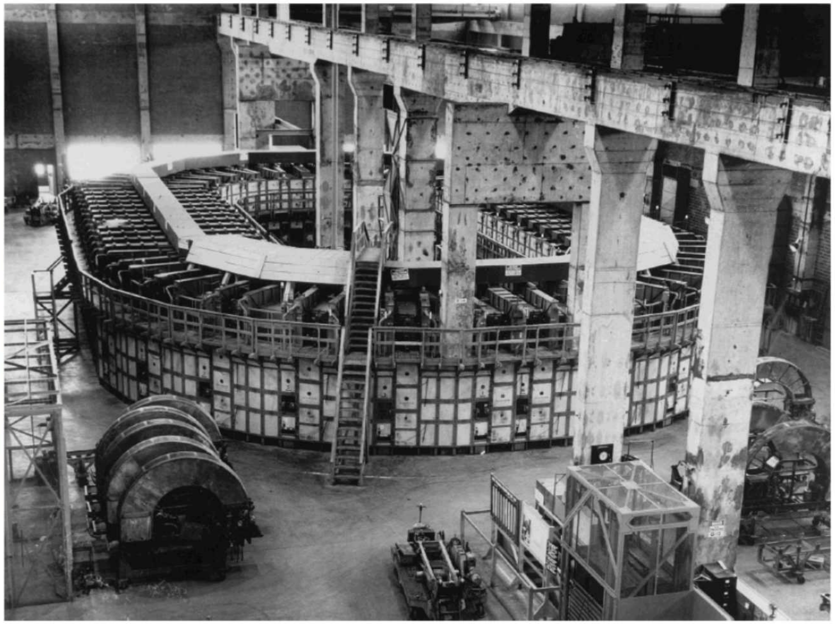


Figure 2. Photograph showing α unit "race track" assembly of calutrons. Photo source: ORD-PRO-2031.

Figure 7. Calutron silver coils before return to U.S. Treasury. Photo source: Y-12 126949.

5000 tons of Ag from the Treasury, worth ~ $1B in current dollars

- 1152 Calutrons of 2 designs installed at Y-12 (near TVA)
- Operational 1944-45
- ~42kg of high enriched U^{235} separated ion-by-ion

2. Van de Graaff Generator

- "It was while at Oxford that Van de Graaff conceived of his belt-charged electrostatic, high voltage generator after reading the 1927 anniversary address on St Andrew's Day by Rutherford to the Royal Society on the need for accelerated subatomic particles"
  - From Nuclear Transmutation to Nuclear Fission, PF Dahl, CRC Press (2002)

- Van de Graaff was at Oxford as a Rhodes Scholar

Robert J. Van de Graaff (1901-1967)

- BS/MS (Mech E.) University of Alabama
- Alabama Power Company (one year)
- Studied at the Sorbonne
- PhD Oxford University 1928 (Rhodes Scholar)
- 1929-31 Princeton University
  - First generator (80kV)
- 1931-1960 MIT
- Directed the High Voltage Radiographic Project at MIT during WWII (X-ray machines)
- Founded High Voltage Engineering in 1946
- APS T. Bonner Prize in Nuclear Physics (1966)

Robert J. Van de Graaff demonstrating his 1.5 MV electrostatic generator to Karl T. Compton in 1931. (from D. Allen Bromley, Nucl. Instr. Method. 122, 1-34 (1974))

THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics

VOL. 43, NO. 3 | FEBRUARY 1, 1933 | SECOND SERIES

The Electrostatic Production of High Voltage for Nuclear Investigations

R. J. VAN DE GRAAFF,* K. T. COMPTON AND L. C. VAN ATTA, *Massachusetts Institute of Technology*

(Received December 20, 1932)

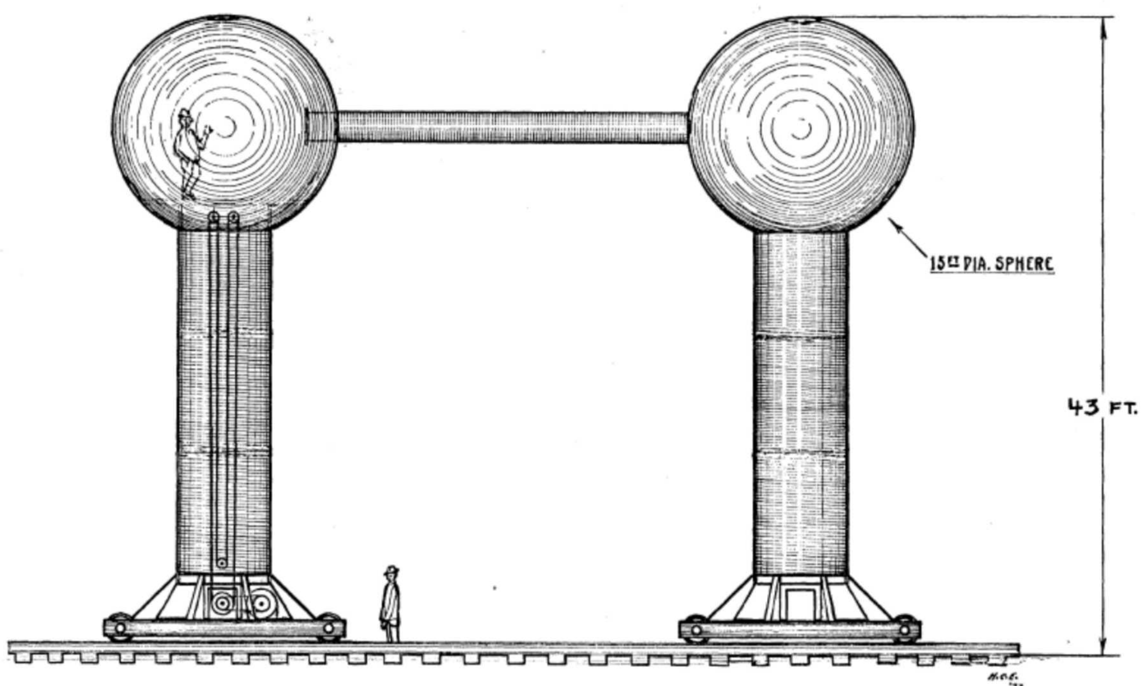


FIG. 4.

Van de Graaff thought big!

MAY 15, 1936 PHYSICAL REVIEW VOLUME 49

The Design, Operation, and Performance of the Round Hill Electrostatic Generator

L. C. VAN ATTA, D. L. NORTHRUP, C. M. VAN ATTA* AND R. J. VAN DE GRAAFF, *Massachusetts Institute of Technology*

(Received March 25, 1936)

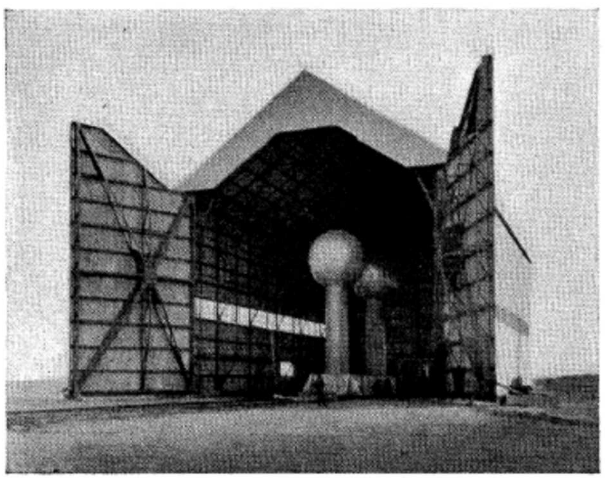
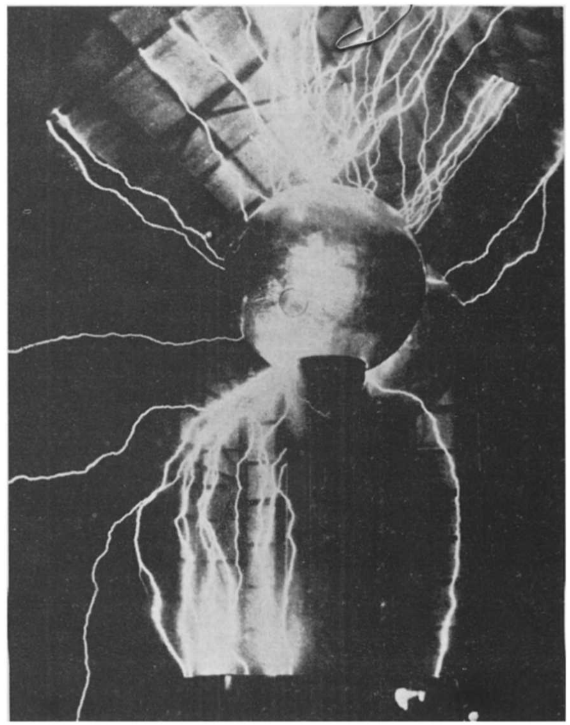
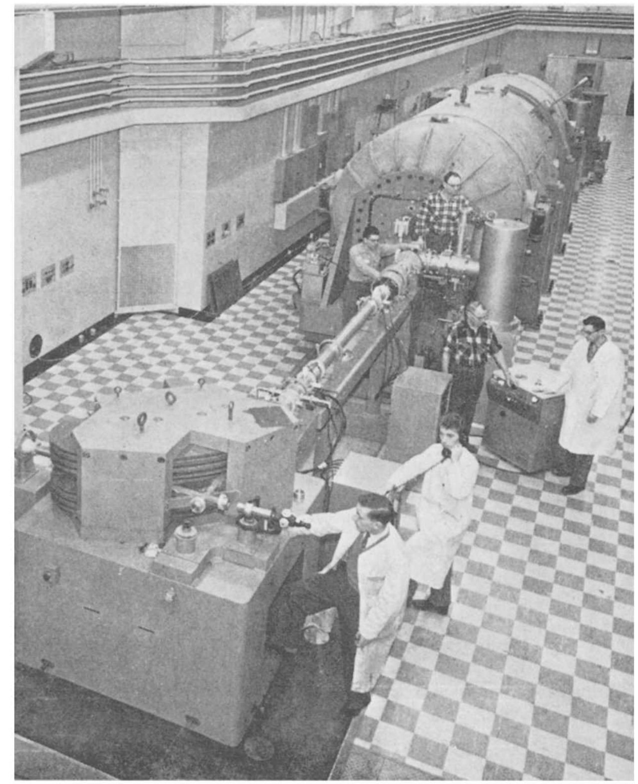


FIG. 1. Electrostatic generator and housing.



Robert J. Van de Graaff's in-air machine reached up to 5.1MV between two spheres. Construction in a large airship hanger resulted in the 'pigeon effect' shown here,



The first HVE EN Tandem at Chalk River, 1958. The High Voltage Engineering Corp. was founded by Robert Van de Graaff in 1946.

Quickly moved to physics labs

Review of Scientific Instruments 9, 398 (1938)

Van de Graaff Generator for General Laboratory Use

J. G. Trump, F. H. Merrill and F. J. Safford
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received August 3, 1938)

Cost

The unit described above was built at a cost of about $325,* which includes all material and all shop time, but does not include the time involved in assembling and adjusting the finished parts. For many experimental and lecture purposes, generators with about the same current capacity but lower voltage rating are needed.

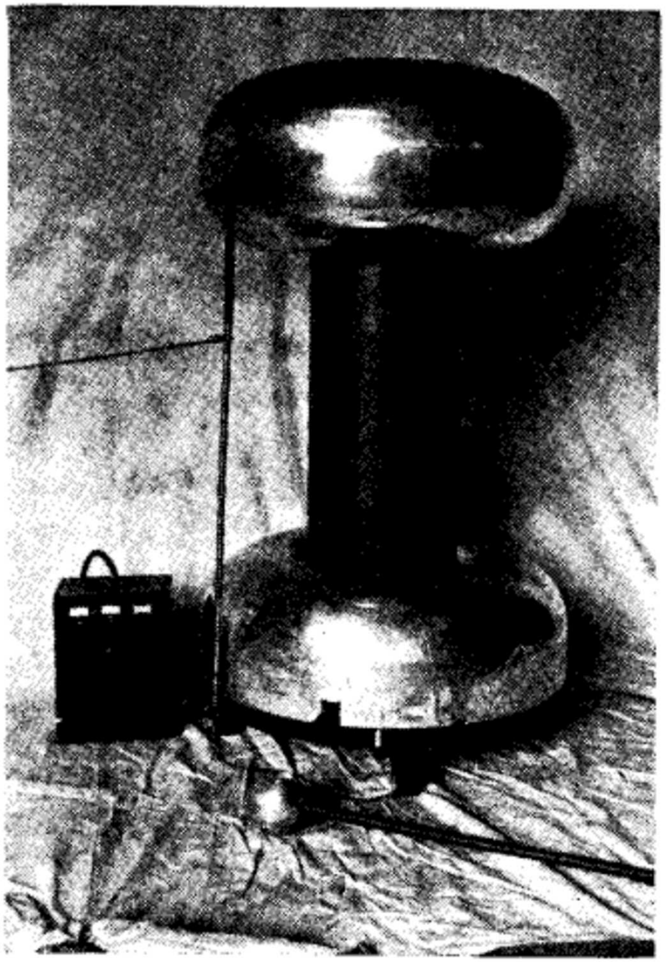


Fig. 4. 500-kv Van de Graaff generator.

4’ 1½” tall, 2’ 6” wide

Modern day versions

- Amazon has a variety of Van de Graaff devices available should you like your very own.

Physics, not prog rock…

350kV, ~$500, 75cm tall

Design of a Million-Volt X-Ray Generator for Cancer Treatment and Research

By J. G. TRUMP AND R. J. VAN DE GRAAFF
Massachusetts Institute of Technology
Cambridge, Massachusetts

602 JOURNAL OF APPLIED PHYSICS

VOLUME 8, SEPTEMBER, 1937

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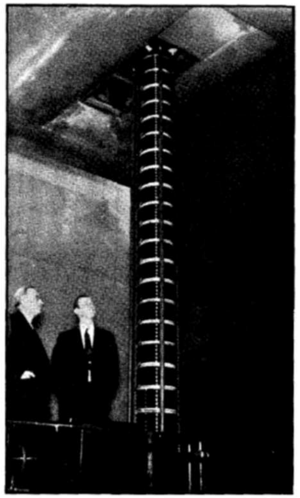


FIG. 2. Cascade type x-ray tube.

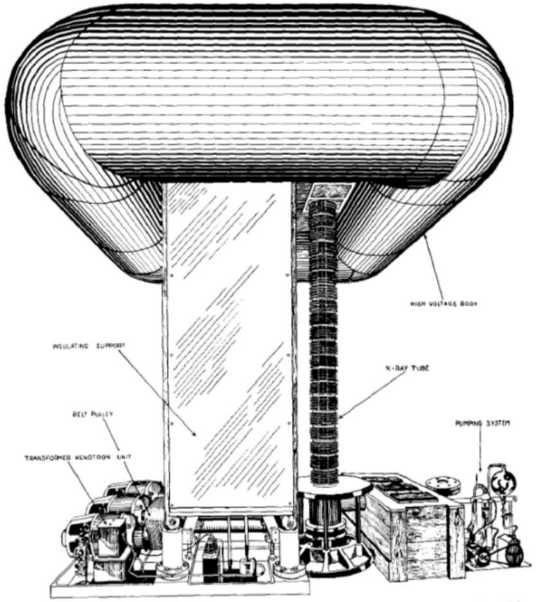


FIG. 1. General arrangement of the million-volt x-ray generator and tube. The bottom cover is shown removed.

FIG. 4. Treatment room which is completely free from high voltage apparatus.

Installed at Huntington Memorial Hospital, Harvard Medical School

3. The path to very high energy

Über ein neues Prinzip zur Herstellung hoher Spannungen[1].

Von

Rolf Wideröe, Berlin.

- Archiv für Electrotechik, 1928
- Rolf Wideröe (1902-1966) was a Norwegian who studied electrical engineering and physics
- Provided the basis for the linac and storage rings

Linac principle:

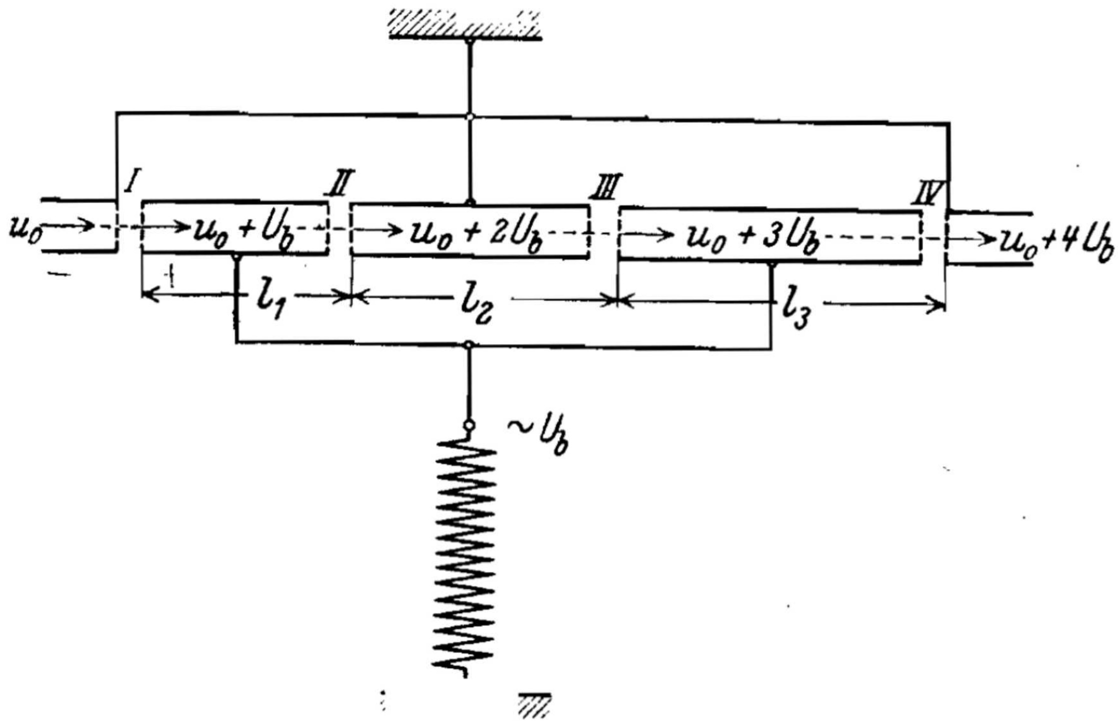


Bild 1. Prinzip der Spannungstransformation mit Potentialfeldern.

- One oscillating voltage source, field-free flight tubes
- Frequency and $l_{1,2,\ldots}$ tuned so that ions/electrons see accelerating potential across each gap

Exploitation of the linac

- Exploitation of the linac principle in the original form would take until post-WWII (beam control issues), but development of the rf power sources occurred earlier
- Such developments were important for radar in WWII (klystron)
- The Varian brothers commercialized many accelerator technologies (including radiation systems for cancer)

A Type of Electrical Resonator

W. W. HANSEN
Stanford University, California

(Received July 17, 1937)*

A High Frequency Amplifier and Oscillator

RUSSELL H. VARIAN
SIGURD F. VARIAN
Stanford University,
Stanford University, California,

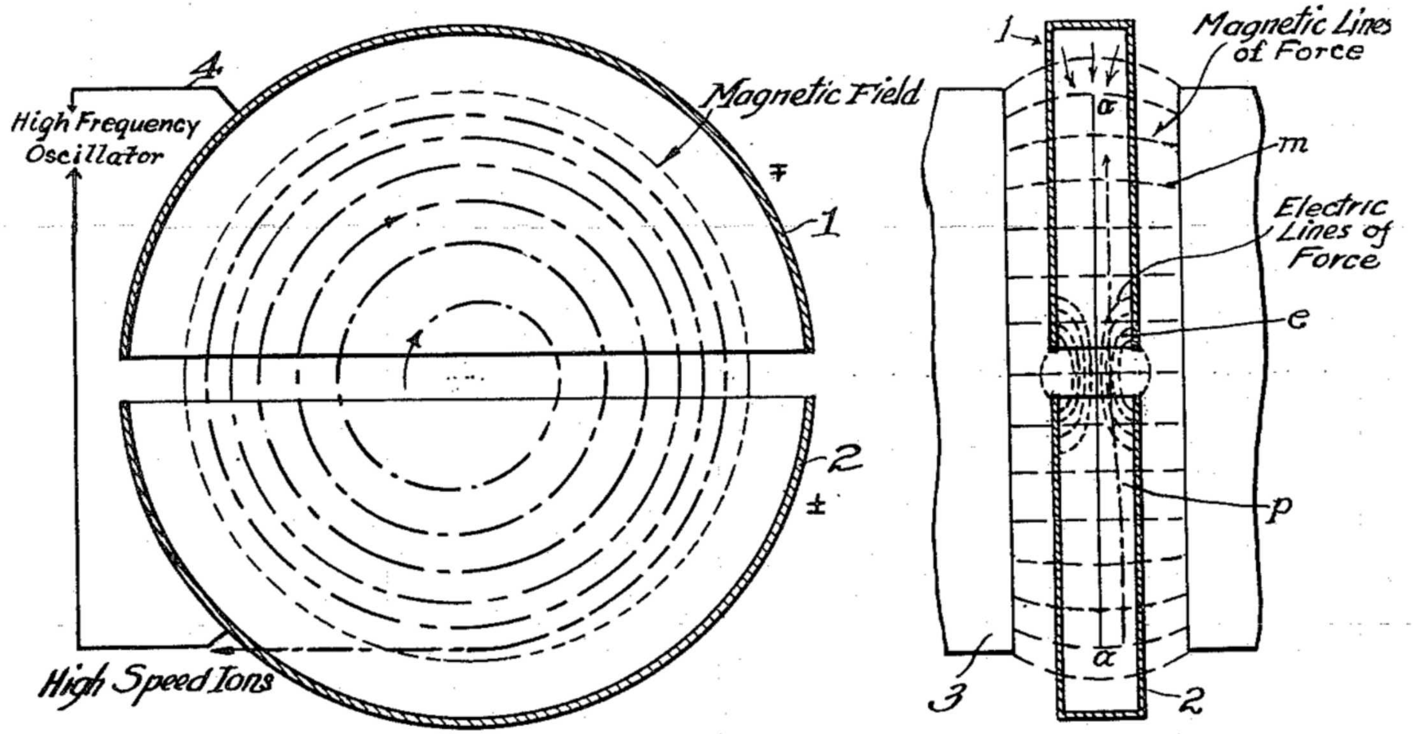
January 6, 1939.

The archetypical linac:

- Stanford Linear Accelerator (SLAC) – 2 miles long
- 50 GeV electrons

4. The Cyclotron

- Lawrence read Wideröe's paper and immediately pictured the cyclotron – one long linac folded around on itself
- Patent in 1934:



Cyclotrons in nuclear physics

- The cyclotron at Berkeley was rapidly put to use:

The Disintegration of Lithium by Swiftly-Moving Protons

We have recently carried through preliminary experiments on the disintegration of lithium by swiftly-moving protons and have obtained results in confirmation of those of the source of high-speed protons, we have bombarded a crystal of lithium fluoride with protons having energies of 360,000, 510,000, and 710,000 volts. Radiations emanating from

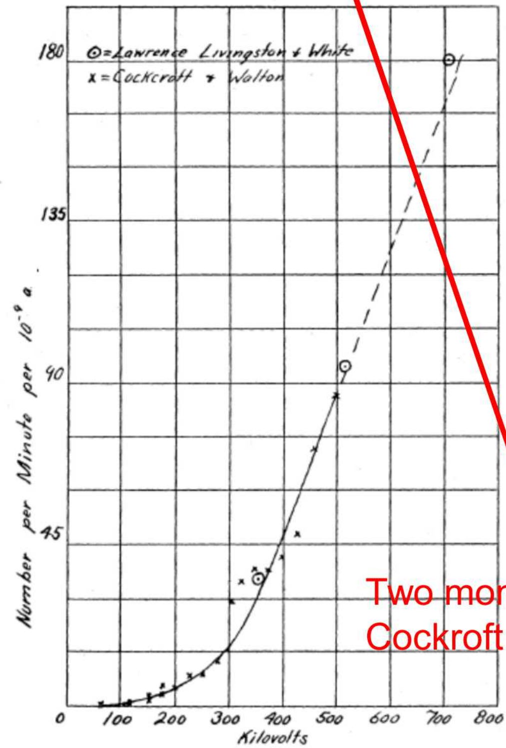


Fig. 1.

Two months after Cockroft and Walton

M. Stanley Livingston
Milton G. White

Radiation Laboratory,
Department of Physics,
University of California.
September 15, 1932.

The Production of High Speed Protons Without the Use of High Voltages

Ernest O. Lawrence
M. Stanley Livingston

University of California,
July 20, 1931.

THE PRODUCTION OF HIGH SPEED LIGHT IONS WITHOUT THE USE OF HIGH VOLTAGES

By Ernest O. Lawrence and M. Stanley Livingston
University of California

(Received February 20, 1932)

The Emission of Protons and Neutrons from Various Targets Bombarded by Three Million Volt Deutons

Ernest O. Lawrence
M. Stanley Livingston

Radiation Laboratory,
Department of Physics,
University of California,
January 3, 1934.

Cyclotrons in Medicine

- Compact cyclotrons are used for a variety of nuclear medicine uses

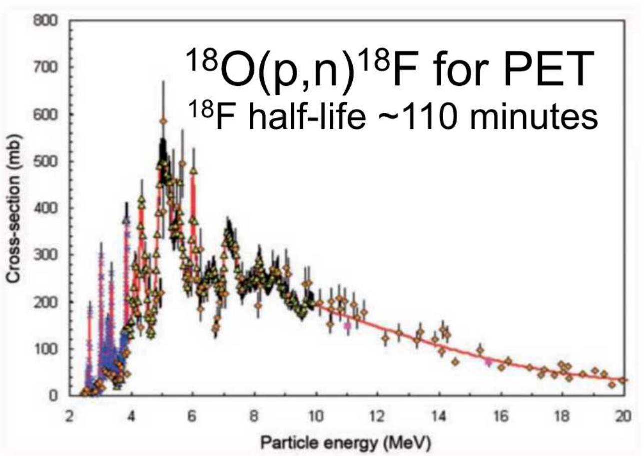
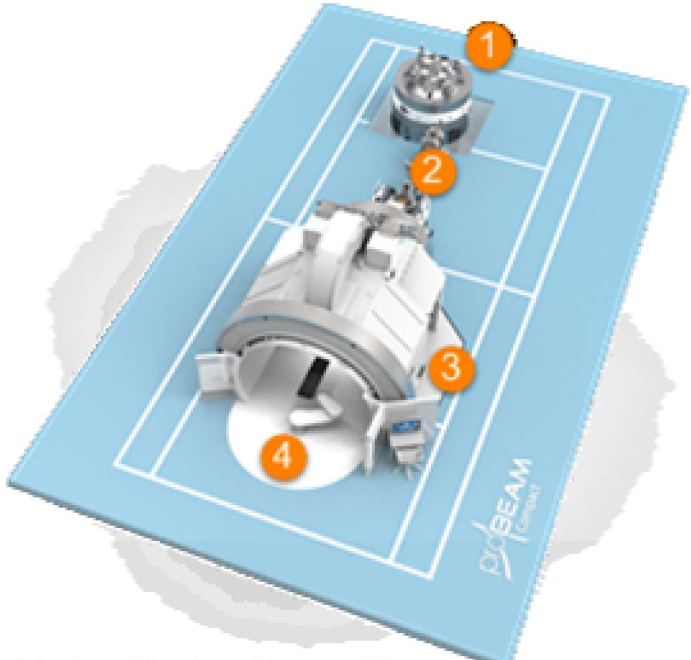


FIG. 4.3. Excitation function for the $^{18}O(p, n)^{18}F$ reaction, illustrating the energy dependence of the cross-section σ.

Cyclotron Produced Radionuclides – IAEA 2008



Varian Proton Beam Therepy

3+4: Linacs/Cyclotrons to Rings:

- CERN - but wait, it isn't linear…
- Bending the beam and running it around and around is easier to scale up than making it longer and longer…
  - Provided you don't lose too much radiation bending the beam
- Operating principles (continued acceleration across gaps) remains essentially the same.

Accelerator Summary:

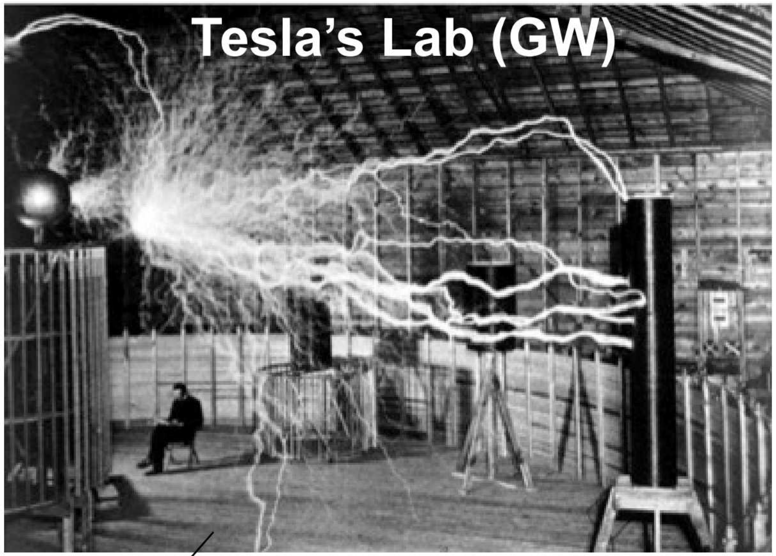
- Within a ~3 year period (1928-1931) all the major accelerator types were invented, all driven by the same desire
- All were quickly used in nuclear physics
  - The linac was somewhat slower, being more difficult technically
- All types, and their descendants, remain in use today
  - Applications extend far beyond nuclear physics

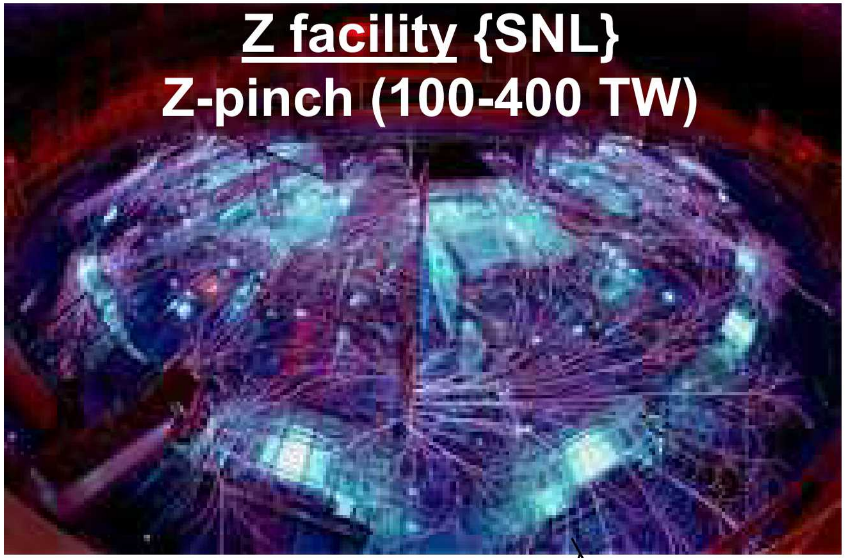
- These accelerate continuous beams of particles or repetitive ‘bunches’ of particles.

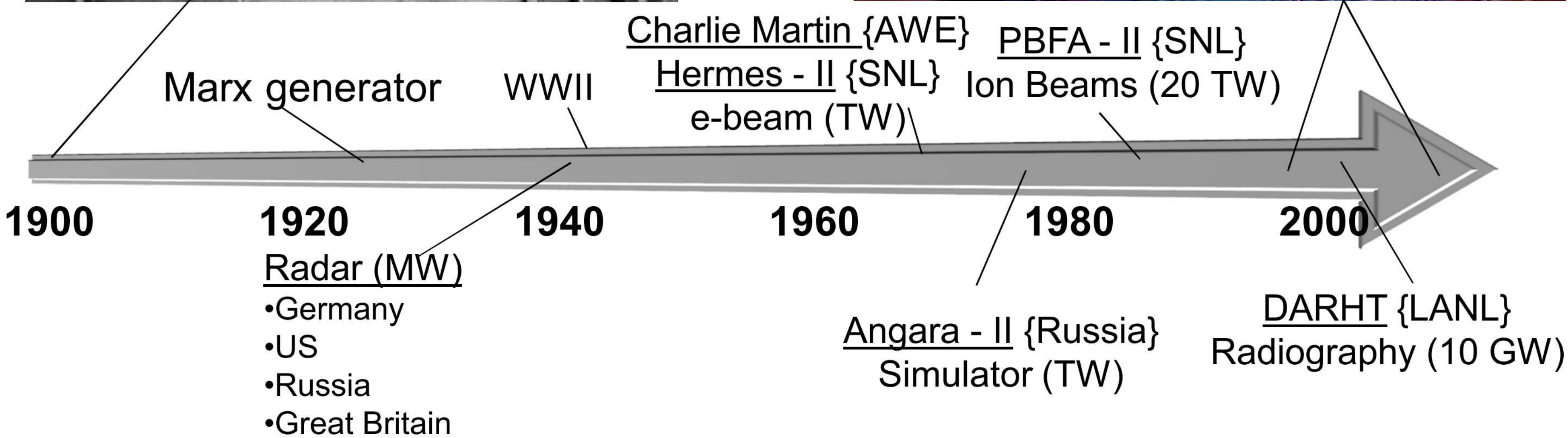
Pulsed Power Machines

- What if you want a whole lot of particles all at once?
- Lots of energy delivered very quickly can create extreme environments in the lab
  - Store energy (Marx bank – 1924)
  - Release quickly
  - Shorten and shape the pulse (transmission lines)
  - Do something interesting with it…

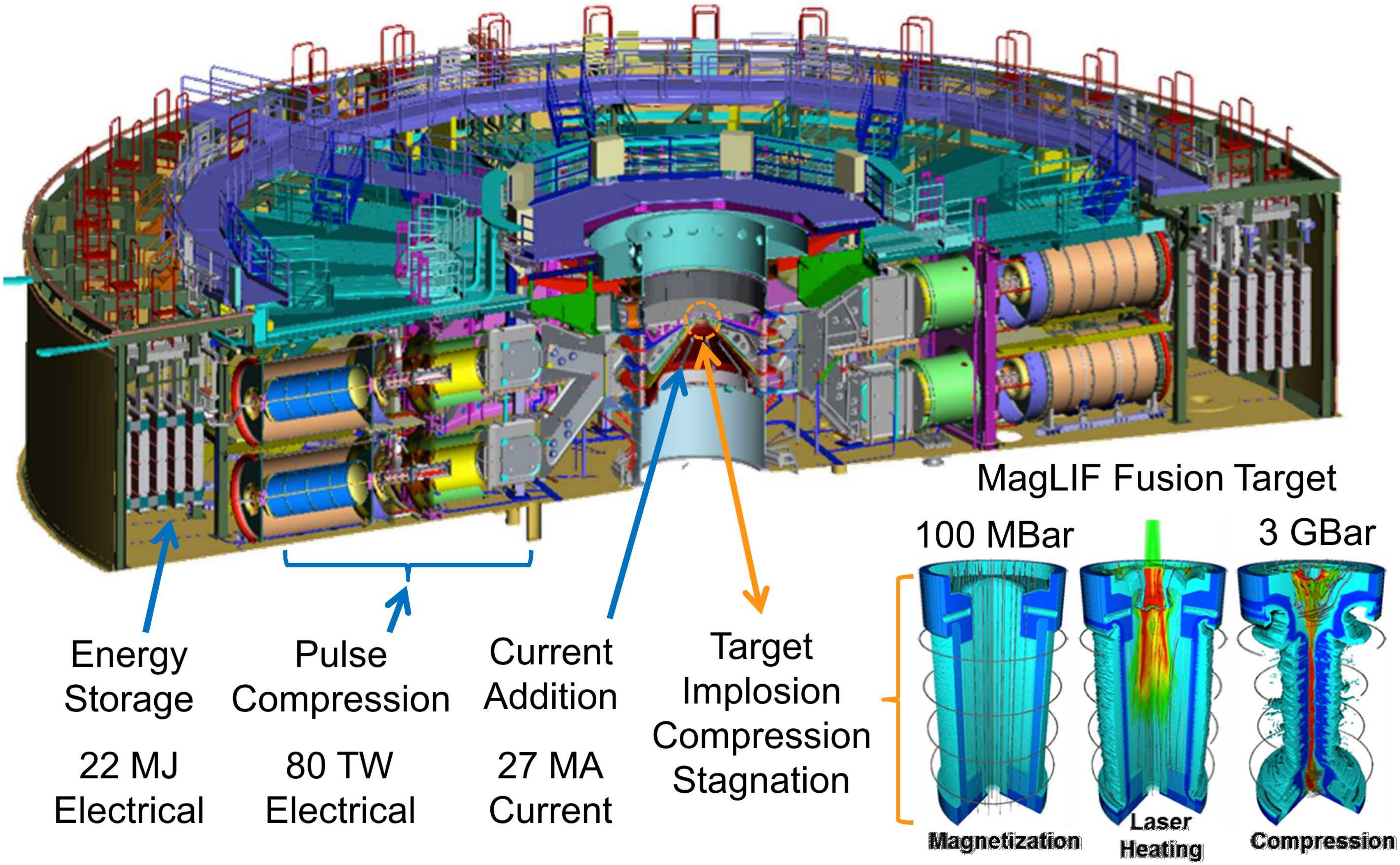
The accumulation and transmission of electromagnetic energy, called “pulsed power”, has been investigated for more than a century







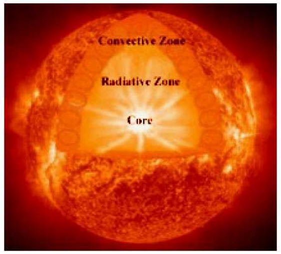
The Z facility compresses energy in space (>10^9 *X*) and time (>10^9 *X*) to generate High Energy Density matter



Each shot from Z carries more than 1,000 times the electricity of a lightning bolt, and is 20,000 times faster.

Five major discoveries in Astrophysics and Planetary Science within the Z Fundamental Science Program

Solar Model

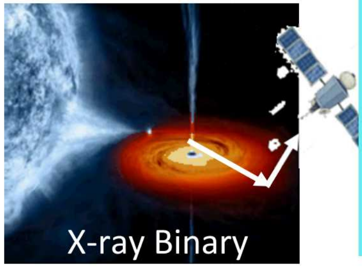


1 µg of stellar interior at R ~ 0.7Rsol

A higher-than-predicted measurement of iron opacity at solar interior temperatures

Jim Bailey, et. al., Nature **517**, 14048 (2015)

Black hole accretion



10^{-3} liters of accretion disk at R ~ 100 – 1000 km from black hole

Benchmark Experiment for Photoionized Plasma Emission from Accretion-Powered X-Ray Sources

G. P. Loisel, J. E. Bailey, et. al., Physical Review Letters **119**, 075001 (2017)

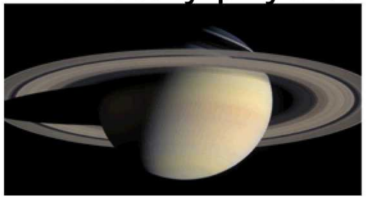
White dwarf photosphere

~0.1 liters of white dwarf photosphere

Laboratory Measurements of White Dwarf Photospheric Lines: HB

Ross Falcon, et. al., The Astrophysical Journal **806** (2015)

Planetary physics



Implications for understanding Jupiter, Saturn, and thousands of exoplanets

Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium

Marcus D. Knudson, Michael Desjarlais, et. al., Science **348**, 1455 (2015).

Impact vaporization of planetesimal cores in the late stages of planet formation

Richard D. Kraus, Seth Root, et. al., Nature Geoscience, DOI:10.1038/NGEO2369 (2015)

Summary

- Accelerators have been a major part of physics
  - Nuclear Physics
  - Particle Physics
  - Extreme Environments

- All the ingredients were created in the 1920's and 30's

- Accelerators derived from physics research are still important
  - Radar
  - Semiconductors
  - Medicine