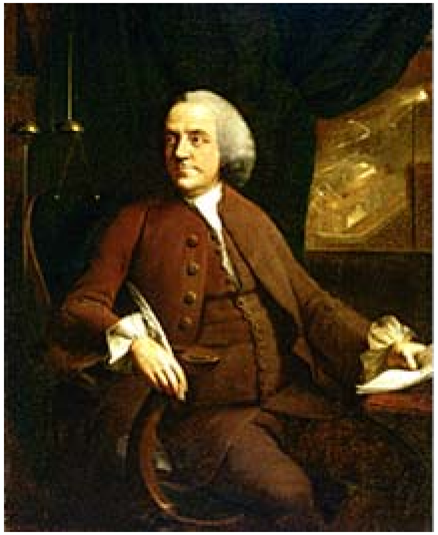
AVS Special Session: Franklin and the Future



Progress and Prospects in the Generation of High Voltages

Electric fields across the vacuum

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November 2006

http://www2.avs.org/benjaminfranklin/

Benjamin Franklin and Future Science

Presentations in Adobe PDF format from a special history session

http://www2.avs.org/benjaminfranklin/

The session also included future-oriented presentations on:

Monolayer Films, from Franklin's Oil-Drop Experiment to Self-Assembled Monolayer Structures, by Geraldine Richmond, a Materials Scientist from the University of Oregon.

The Outlook for Electrophotography, the Best Known Modern Application of Electrostatics, by Lawrence B. Schein, an independent consultant and former Xerox and IBM Research Scientist.

From Lightning to Lighting: Physics and Technology Discharged from Franklin's Kite Experiment, by Robert McGrath, Senior Vice President for research at Ohio State University.

Progress and Prospects in the Generation of High Voltages, by H.F. Dylla, Chief Technology Officer at Thomas Jefferson National Accelerator Facility, Newport News, Virginia.

Benjamin Franklin and Future Science

1. "Franklin: The First Scientific American"

   (see Joyce Chaplin's book)

2. 18th and 19th Century experiments on electricity and vacuum

3. Contemporary physics

Gilbert Stuart's Lansdowne Portrait of George Washington

* Founding father and statesman
* Symbols include oratorical pose, sword

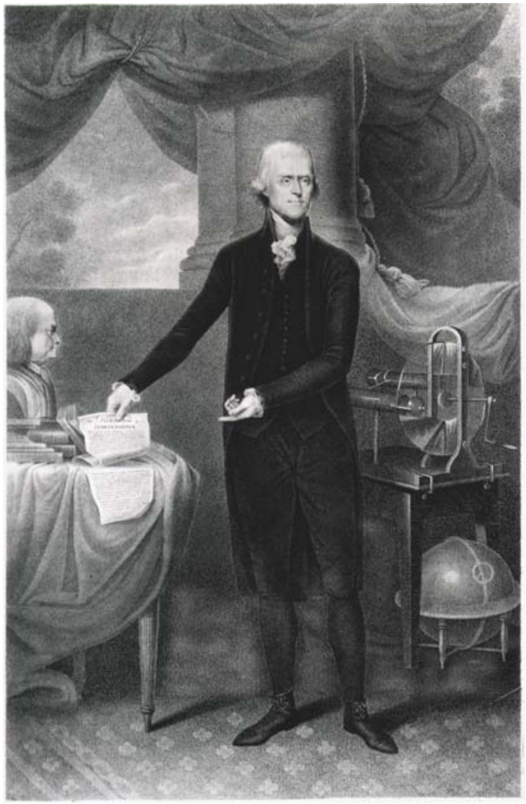
An enterprising engraver devised a Lansdowne Portrait knockoff

* Founding father and statesman of science Thomas Jefferson
* Symbols of science:

-Declaration of Independence (historian Garry Wills: “a scientific paper”)

-Knowledge of the physical world: globe, electrostatic generator

-Bust of founding father and pre-eminent scientist: Benjamin Franklin



THOMAS JEFFERSON
President of the United States. —

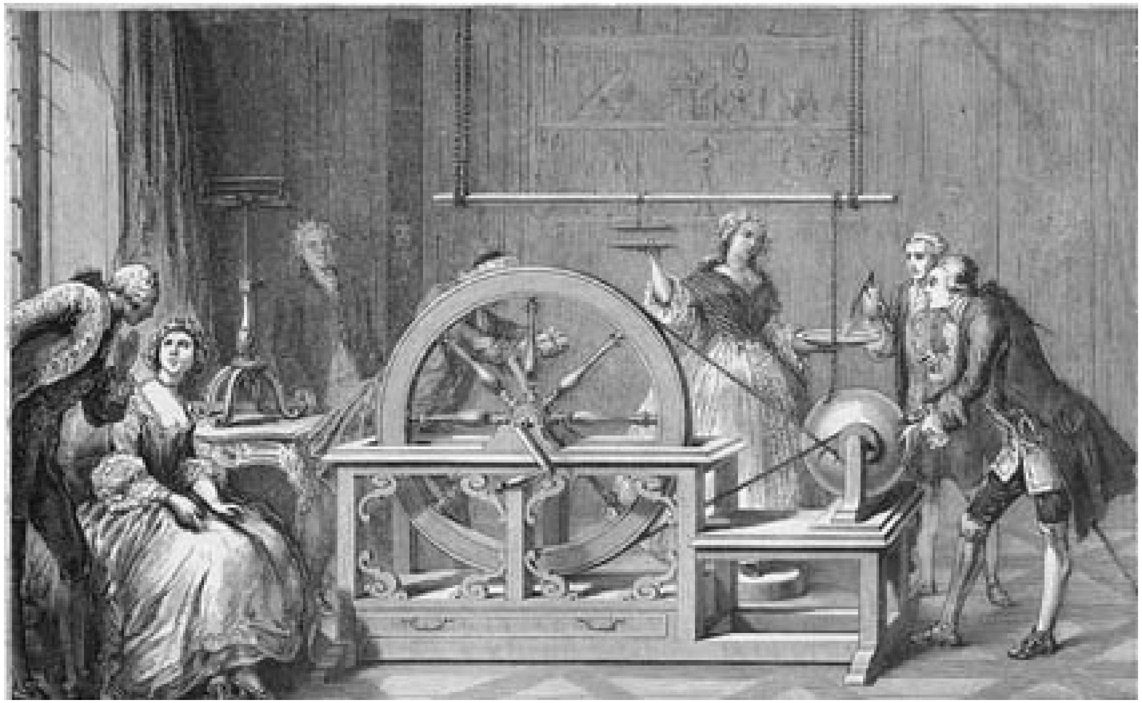
Bust of Franklin beside Ramsden generator

Bakken Museum, Minneapolis

"Electricity was unique among branches of Enlightenment physics in amusing the public, who enjoyed seeing others shocked, and in showing … that science might be useful. **Electricity became the exemplar of physical science during the eighteenth century.**"

Elements of Early Modern Physics, J. L. Heilbron

Demonstration using Nollet glass-globe-style electrical machine



http://www.sparkmuseum.com/FRICTION_HIST.HTM

The primitive glow discharge

Applying electric fields in the primitive vacuum tubes of the 19th century led to many important advances in classical physics

The first hint of the new phenomena:

The glow seen above a Torricelli barometer when the mercury bounced up and down as the barometer was moved.

French Astronomer-

Jean Picard (1676)

Early electrical experiments in rarefied gases

ESPERIENZE
FISICO-MECCANICHE
SOPRA VARJ SOGGETTI
CONTENENTI
Un racconto di diversi stupendi fenomeni
INTORNO
LA LUCE E L' ELETTRICITA'
Producibile dallo strofinamento de' corpi.
con molte altre notabili apparenze
non mai prima osservate.
Colle spiegazioni di tutte le macchine.
OPERA
DI F. HAUKSBEE
DELLA SOCIETA' REGIA
Tradotta dall' Idioma Inglese.

IN FIRENZE. M.DCC.XVI.
Nella Stamperia Di Sua Altezza Reale.
Per Jacopo Guiducci e Santi Franchi.
Con Licenza de' Superiori.

"Physico-Mechanical Experiments on Various Subjects. Containing an Account of Several Surprising Phenomena Touching Light and Electricity"

The earliest experiments on electrical discharges and gases are attributed to Francis Hauksbee between 1705 and 1711.

“Electrical aurora”

- Glass tube produced electrical glow similar to an aurora when:
  - Air pump produced partial vacuum inside
  - Glass rubbed with cloth, or electrodes touched to electrical machine's conductor
- English physicist William Henley used a similar instrument
  - Showed luminescence produced by positive and negative discharges
  - Saw this as proving Franklin's theory of a single electrical fluid

From the Institute and Museum of the History of Science, Florence, Italy

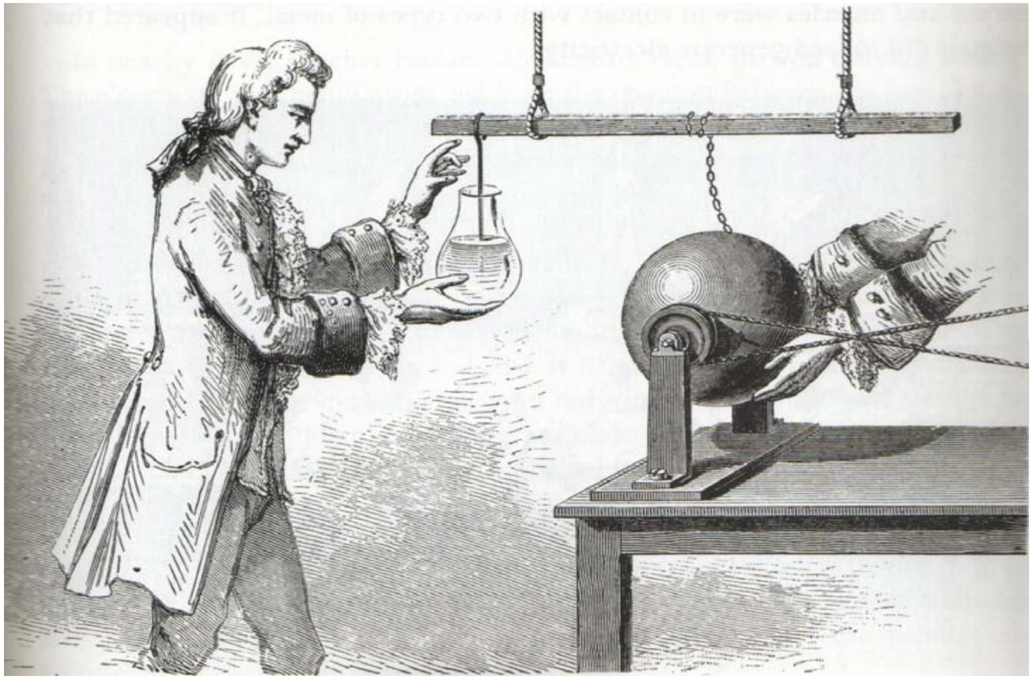
http://brunelleschi.imss.fi.it/museum/esim.asp?c=500183

Technology enablers

Understanding the science of glow discharges required efficient means of producing both electricity and vacuum at will:

First-generation electrical sources:

Electrostatic machines and “Leyden Jars”



The cast: B. Franklin, O. von Guericke, Kleist, Musschenbroek

Electrostatic machine like the one that Franklin and Ebenezer Kinnersley used for experiments and public demonstrations

(Courtesy Benjamin Franklin Tercentenary)

"Your kind present of an electric tube, with directions for using it, has put several of us on making electrical experiments, in which we have observed some particular phenomena that we look upon to be new. I was never before engaged in any study that so totally engrossed my attention and time."

Franklin to the Library Company's British agent, March 28, 1747

Voltage & energy in 18th-century sparks

Instrument	Spark length (inches)	Voltage (kilovolts)	Energy (joules)
Glass rod (Franklin 1747)	1	5	.000006
Globe (Franklin 1750)	2	10	
with gun barrel			.0008
with Leyden jar			0.1
Cylinder (Nairne 1773)	14	30	
with prime conductor			0.2
with Leyden jar			0.9
with 64 jars			58
Plate (van Marum 1785/90)	24	80	
with prime conductor			0.6
with Leyden jar			20
with 100 jars			2000
Storm cloud			5000000

Elements of Early Modern Physics, J. L. Heilbron

29 July 1750
Opinions and Conjectures concerning the Properties and Effects of the Electrical Matter . . .

- Always in need of experimental proof, Franklin proposed an experiment to verify that lightning was a large scale manifestation of the electrical discharges that he had been producing in his lab.

- "On the top of some high tower or steeple, place a kind of sentry-box, big enough to contain a man and an electrical stand. From the middle of the stand let an iron rod rise and pass bending out of the door and then upward twenty or thirty feet …"

- "A man standing on it when such clouds are passing low might be electrified and afford sparks"

- "If any danger to the man be apprehended (though I think there should be none), let him stand on the floor of his box" and draw off sparks from the rod to demonstrate the effects.

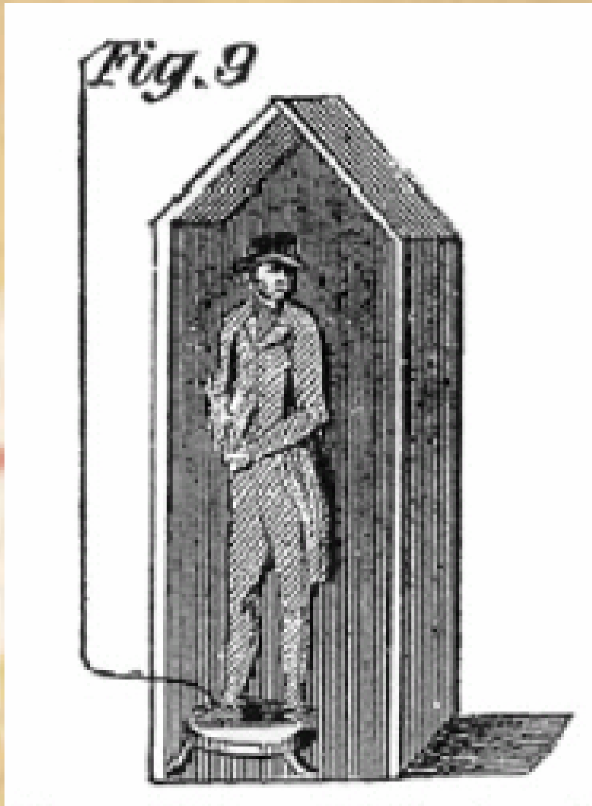


Figure from J. Bigelow, *Works of Benjamin Franklin,* Vol II, p200, 1904

The Kite Experiment: Unable to conveniently execute his original experiment, Franklin devised another:

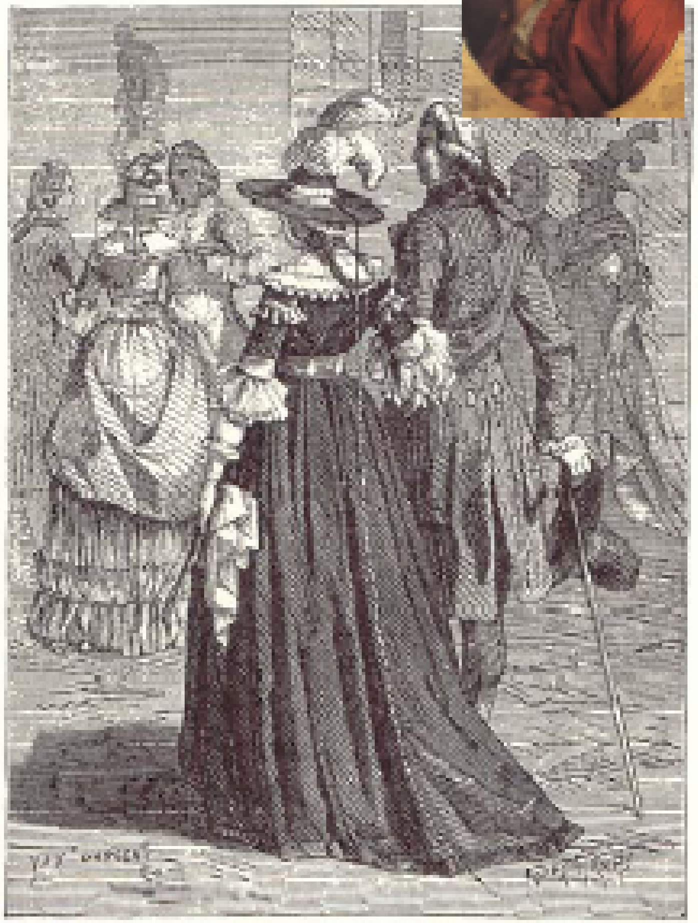
Sometime in June of 1752, he constructed a **kite**

- Consisting of cedar cross with a silk handkerchief, so better to withstand a storm's high winds;
- A sharp wire extending about a foot above the top tip of the kite;
- A key tied to the kite string by a silk threat;
- He stood inside of a door or window to prevent the silk thread from becoming wet and conducting;
- When the rain wetted the silk string of the kite, the "electric fire" was conducted down the string to the key from which Franklin extracted sparks and charged a Leyden Jar.

Sources: Benjamin Franklin Tercentenary

Fortunately: Ben Franklin did survive

- He lived on to become a celebrity in Paris;
- Contributing significantly to science, to high society and to high fashion;
- Importantly too, he secured the services of His Majesty's Navy:
  - The French Fleet defeated the British Fleet at the Battle of the Chesapeake
  - Bottled up Cornwallis at the Siege of Yorktown, VA, which
  - Precipitated the British surrender to George Washington's Continental Army on Oct. 19, 1781;
  - Thereby securing independence for the newly formed United States of America.



Lightning Facts*

- The 'average' negative lighting strike:
  - Consist of up to 12 separate discharges
  - Can be 5 km long
  - Travels at 1/10 speed of light
  - Reaches 50,000 °F / 28,000 °K / 2.4 eV
  - Duration: ~10 - 30 ms
  - ~10 MV Potential Difference
  - 5 C of charge transferred
  - 30 – 50 kA of current
  - 500 MJ of energy
  - Instantaneous Power: ~ 50-500 GW (0.05 - 0.5 TW)

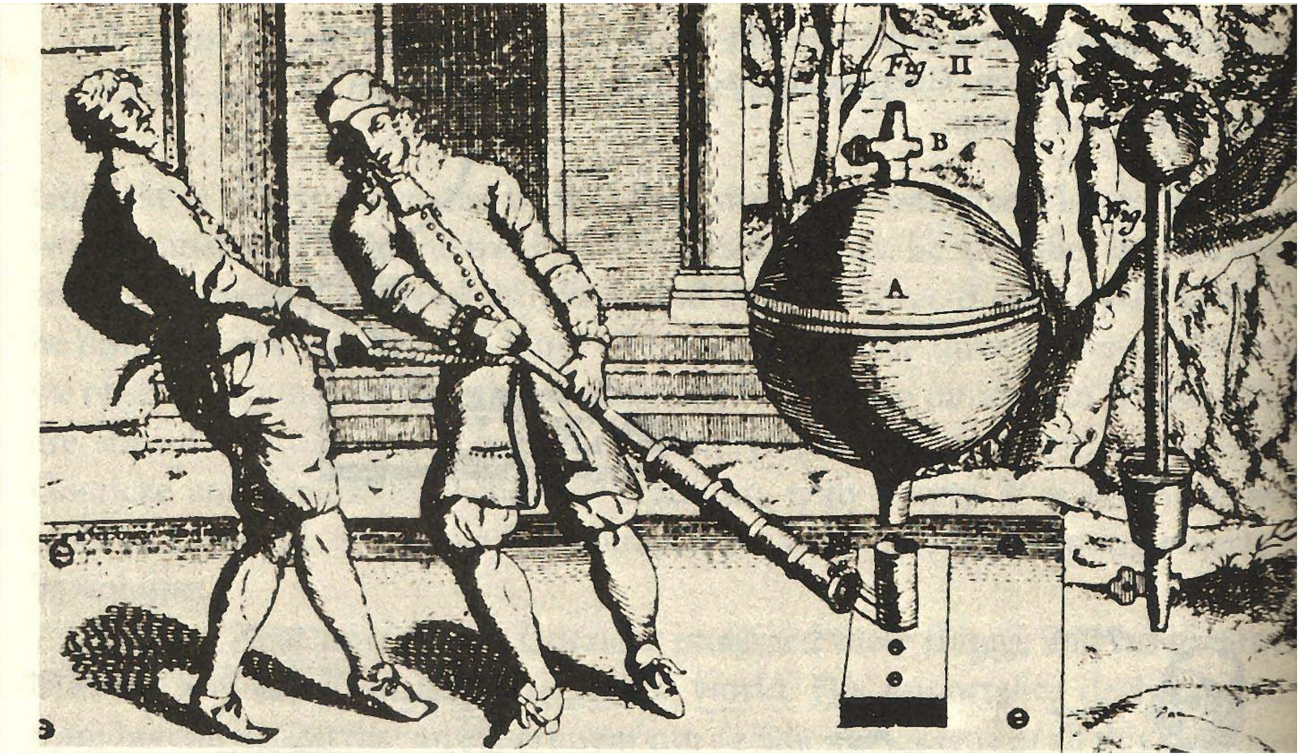
- The 'average' positive lighting strike:
  - (Less than 5% of all strikes)
  - 300 kA of current
  - 1 GV potential difference
  - 300 GJ of energy
  - 300 C of charge transferred
  - Instantaneous Power: ~ 300 TW (> 20 X global power consumption rate)

AMONG FIRST PHOTOS:
Taken by M.G. Loppe; June 3, 1902

* Source: National Oceanic & Atmospheric Administration (NOAA)

Early vacuum pumps

Mechanical air pumps (O. von Guericke, 1640)



From "Electrical experiments made in order to determine the non-conducting power of a perfect vacuum, &c.":

"It is surprising to observe, how readily an exhausted tube is charged with electricity. … Upon the slightest excitation the electric fluid will accumulate at the sealed end, and be discharged through the inside in the form of a spark …" .

"By this means I have had a spark 42 inches long, and, had I been provided with a proper tube, I do not doubt but that I might have had a spark of four times that length."

William Morgan, *Philosophical Transactions of the Royal Society of London*, Vol. 75, 1785.

Progress of vacuum technology in Franklin's day

- For research and for demonstration, every respectable "cabinet" of the late 18th century included not only an electrical machine, but an air pump
- Air pumps' power increased dramatically after 1750
  - Midcentury: probably 1/40 or at best 1/50 atm
  - Midcentury: Smeaton, perhaps 1/80 atm (leather fittings, alchol/water mixture)
  - 1770s: 1/165 atm
  - 1770s: Nairne: advertised improvement of Smeaton, 1/300 to 1/600atm

- "These improvements enabled physicists to investigate, among other matters, the vexed question whether vacuum conducts or insulates."

(Data and quotation: *Elements of Early Modern Physics*, J. L. Heilbron)

Excerpts from “An Account of some experiments made with an air-pump on Mr. Smeaton’s principle; together with some experiments with a common air-pump,” by Edward Nairne, F. R. S.:

“I was now therefore desirous of seeing what appearance the electric matter would exhibit in these different rarified media. For this purpose I had a glass tube made, of an inch bore, and four feet and a half in length. … The brass cap at [the] extremity of the tube [was] placed so as to be in contact with the prime conductor of an electrical machine.”

EXPERIMENT LVIII.

Electrical appearances exhibited	Degree of exhaustion
Light began first to appear in flashe	5
Light appeared the whole length of the tube	8
Tube was filled with an uniform body of pale light	74
The tube was filled with a uniform body of pale light	269

Philosophical Transactions of the Royal Society of London 67 (1777) 614–648.

Double-acting pneumatic air pump, 1750–1770
(Courtesy Benjamin Franklin Tercentenary)

"On the Electrical Phenomena Exhibited in Vacuo"
Sir Humphry Davy, 1822

"Electric and magnetic repulsions and attractions took place in the mercurial vacuum, as in air;—a circumstance which shows, says Sir Humphry, that they are not dependent upon elastic ponderable matter, and points them out as primary causes of other electrical phenomena.

From an abstract composed by the Royal Society for
Sir Humphry Davy's 1822 *Philosophical Transactions* paper
"On the Electrical Phenomena Exhibited in Vacuo."

Second-generation electrical sources

Induction coil

Rhumkorff coils

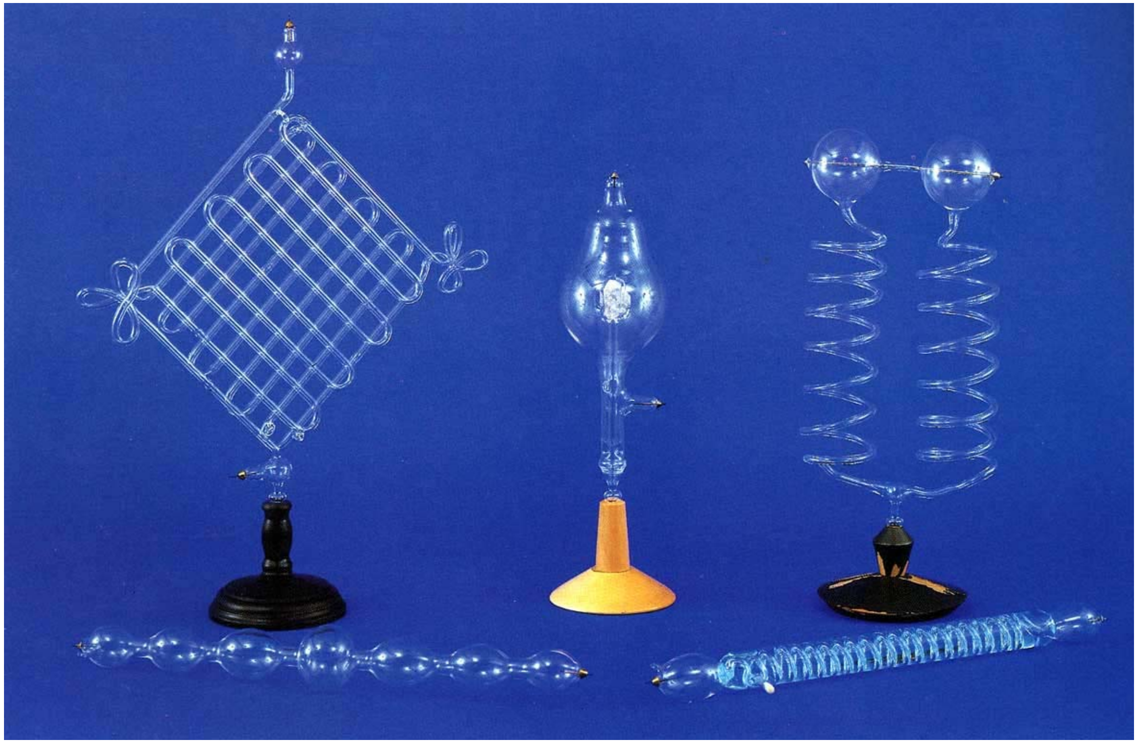
Battery

Voltaic piles

The spark across the vacuum

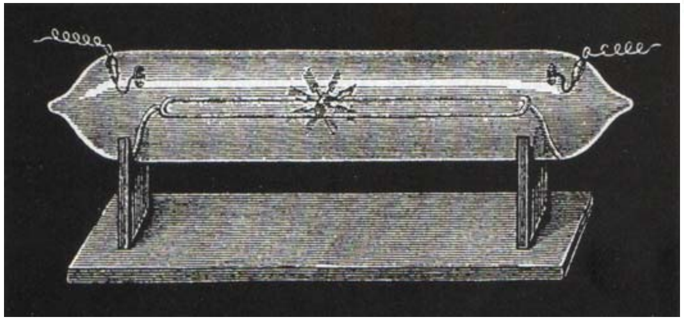
Combining these two primitive technologies unlocked many mysteries of the glow discharge:

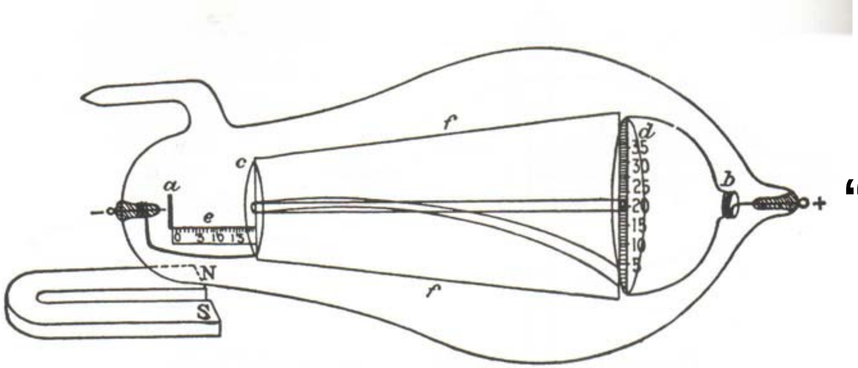
Crookes' and Geissler's tubes



What the glow discharge taught us by 1900

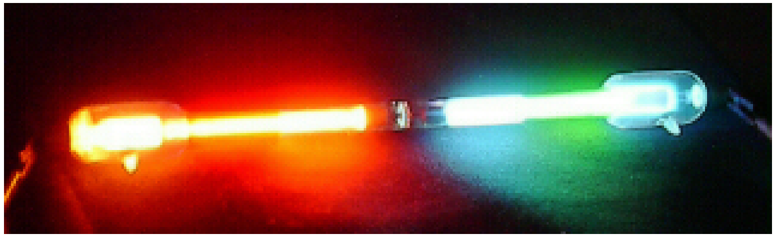
Mechanical and heat energy are carried by the "kanal rays"



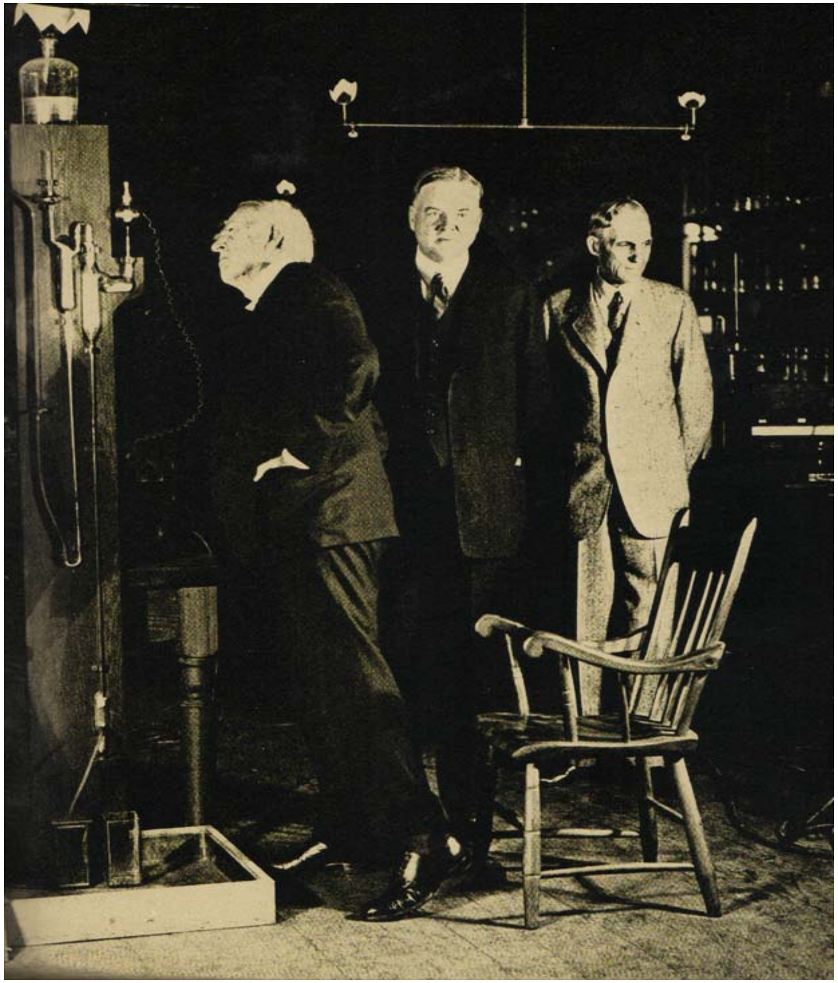


"Rays" are bent by magnetic fields

Different gases emit different colors of light



Edison’s pump for the first lamps



Mercury drop pump

Geissler/Sprengel pump used and modified by Thomas Edison

The dawn of modern physics

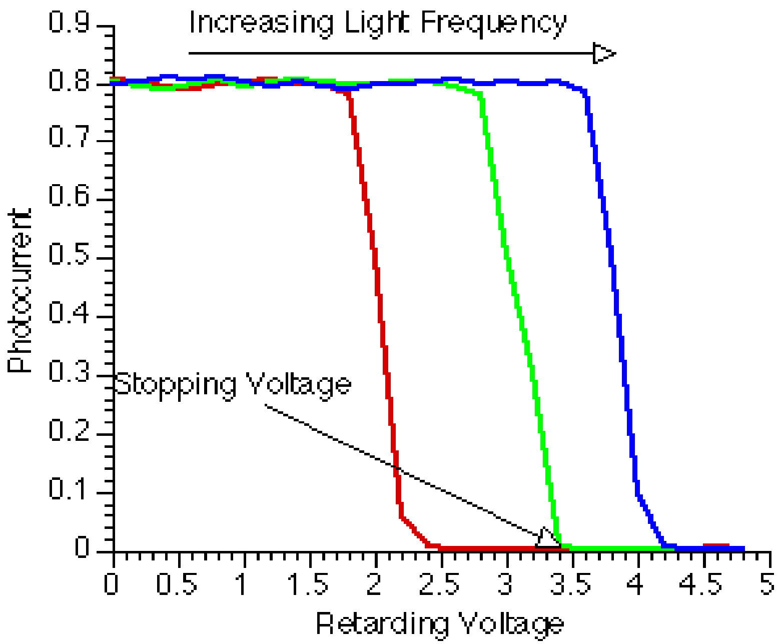
The physics we learned from the glow discharge:

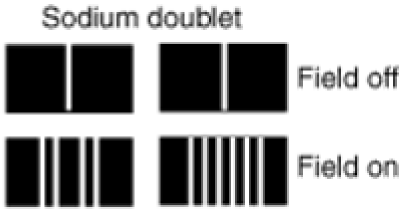
The first observed sub-atomic particles (electrons and nucleons)

Energetic radiation (x-rays)

Physical measurements which heralded the birth of quantum mechanics

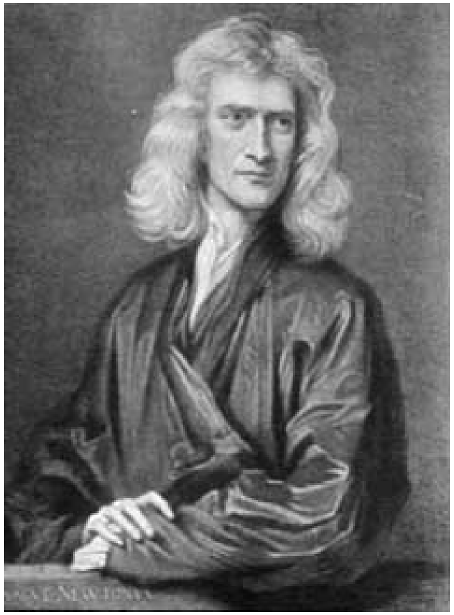
The photoelectric effect:





Atomic spectra observed in high magnetic and electric fields

Franklin believed in the particle theory of matter

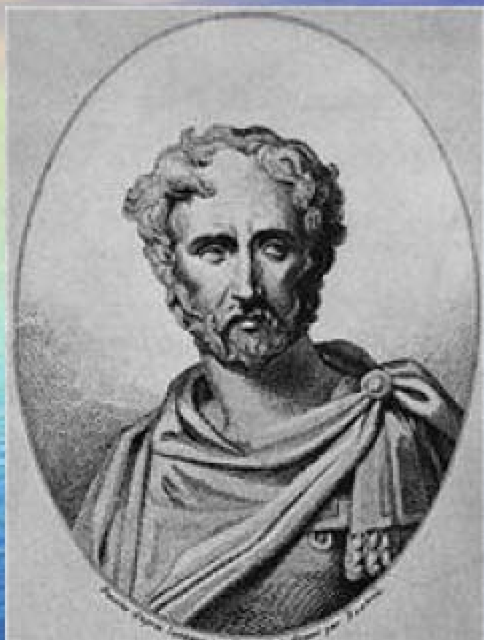


- "There are agents in Nature able to make the particles of bodies stick together by very strong attractions. And it is the business of Experimental Philosophy to find them out. The smallest particles of matter may cohere by the strongest attractions."

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

- *** Franklin's "Of the stilling of waves by means of oil" → precursor of monolayer film science?**
  - Read to the Royal Society: William Brownrigg, June 2, 1774
  - Published: *Philosophical Transactions* 64 (1774) 445–460
  - "Monolayer Films, from Franklin's Oil-Drop Experiment to Self-Assembled Monolayer Structures," G. Richmond, U. Oregon (VT-ThM3)

Inspiration from:



- Writings of Pliny the Elder
  (AD 23-79)

- Observations during his travels that ships in back have smoother sailing than in front.

- Ship captain: "The cooks have, I suppose, been just emptying their greasy water through the scuppers, which has greased the sides of those ships a little."

Experiments on a pond at Clapham

"I fetched out a cruet of oil and dropped a little of it on the water. I saw it spread itself with surprising swiftness upon the surface… Though not more than a teaspoonful, produced an instant calm over a space several yards square which spread amazingly and extended itself gradually till it reached the lee side, making all that quarter of the pond, perhaps half an acre, as smooth as a looking glass."

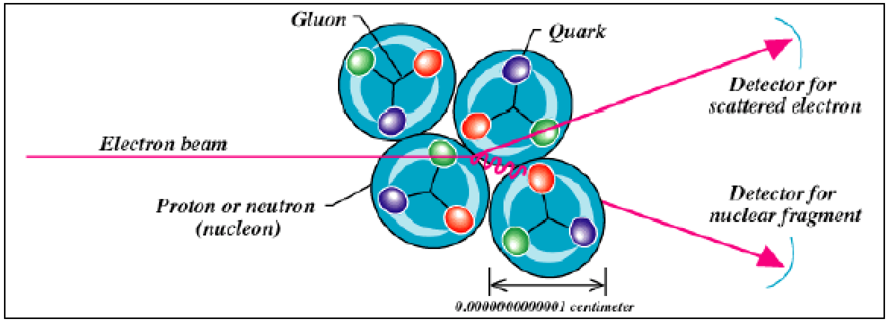
"After this I contrived to take with me, whenever I went into the country, a little oil in the upper hollow joint of my bamboo cane, with which I might repeat the experiment and I found it constantly to succeed."

Franklin's era was "an age too soon" for 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 senses; and their result too fallacious to satisfy the mind. It is probably an age too soon … ."

Thomas Jefferson writing from Paris, 1788

Long before particle physics and accelerators, Thomas Jefferson had inklings of something like the research that nuclear physics labs like JLab now conduct—and Benjamin Franklin advanced the "arts" of vacuum and high voltage.



Not "an age too soon" for modeling nature's awesome forces

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

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

<u>Technology link from Franklin's time to ours</u>:

Electrostatic machines and crude vacuum pumps → particle accelerators

<u>Science link from Franklin's time to ours</u>:

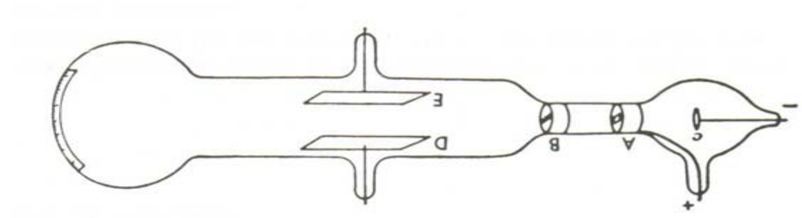
"The ability to model nature's most awesome forces."

From millivolts to teravolts

The primitive “Thomson Tube” has evolved to teravolt accelerators used to probe sub-nuclear to stellar dimensions and timescales

Accelerators at the turn of the last century:

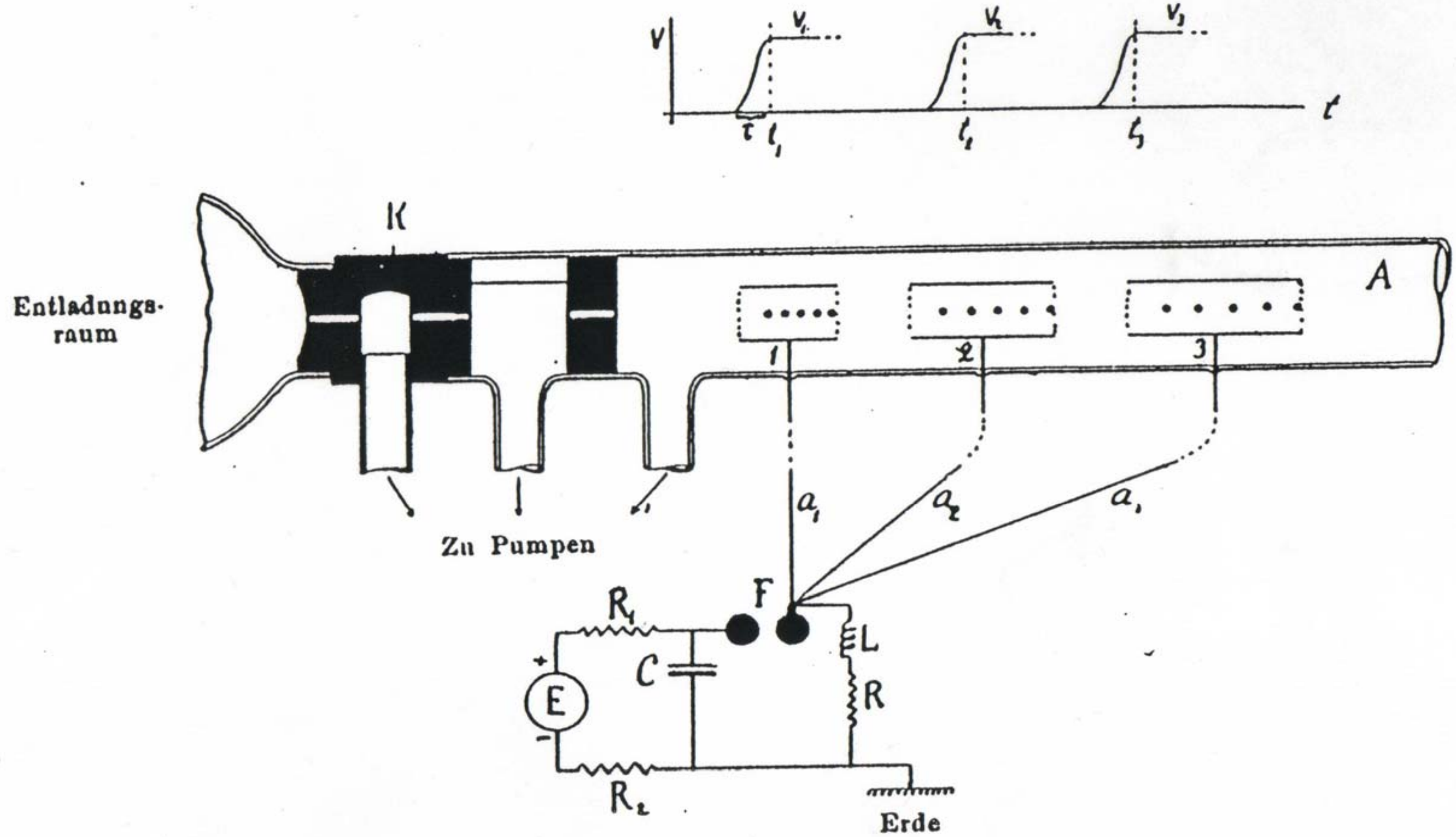
- **The Thomson and Roentgen tubes were electron and ion accelerators at the kV range**



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

First generation of accelerators

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

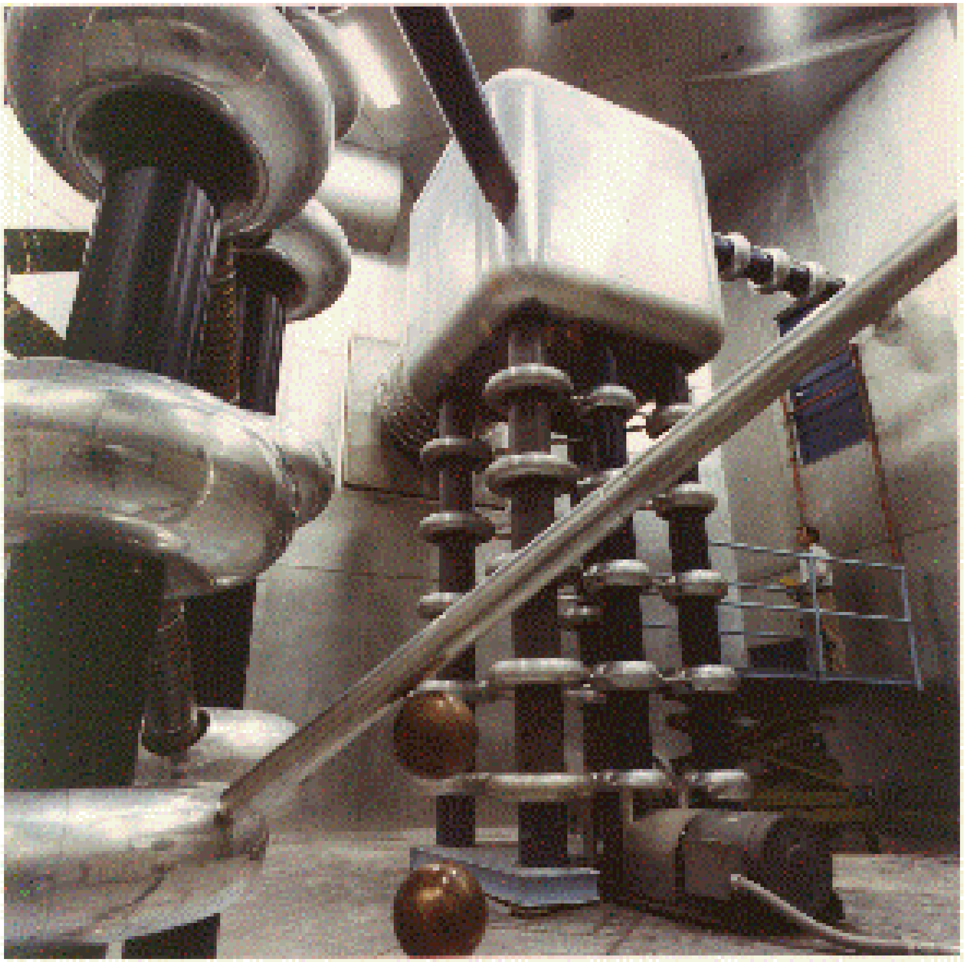


R. Wideroe demonstrated device in 1928 with 50 keV K+

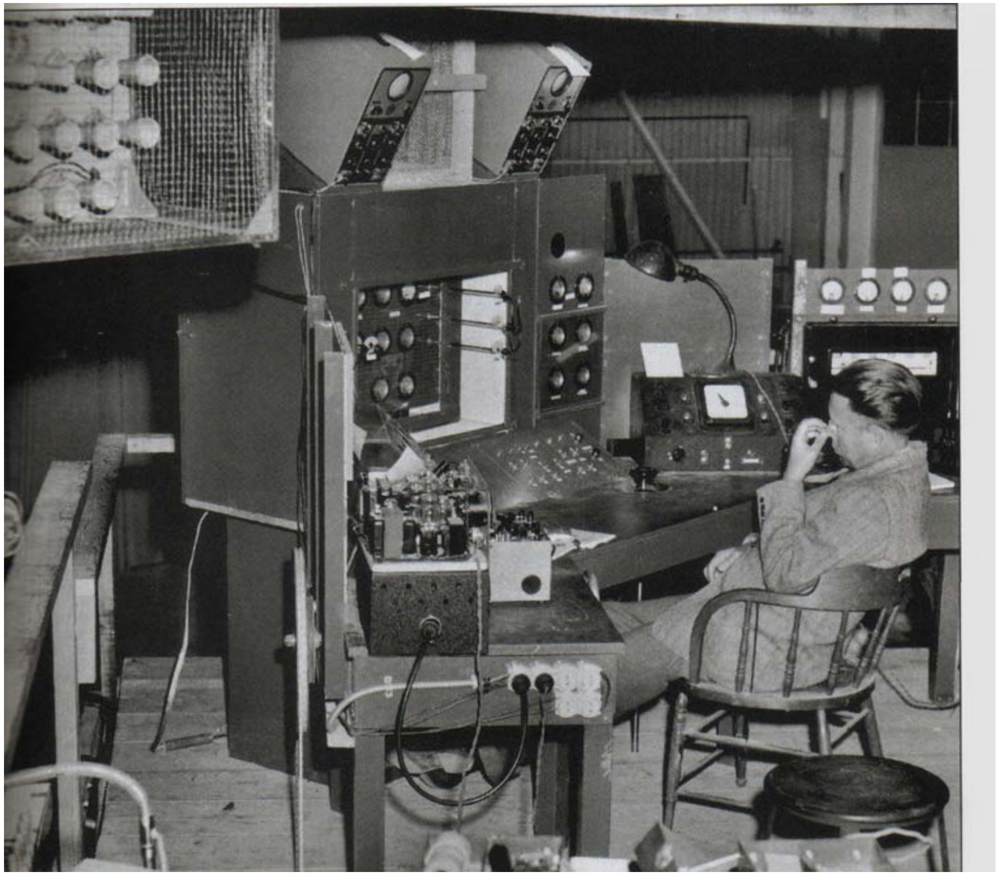
First generation of accelerators

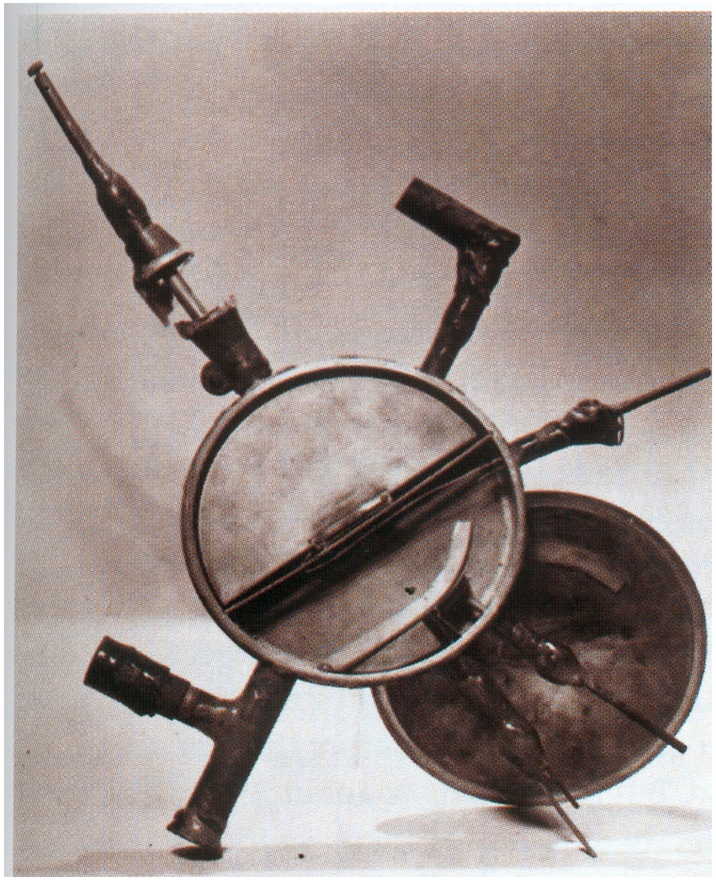
Electrostatic: Cockcroft-Walton generator (voltage multiplier)

(1932, 400 keV H+- Li+)



First generation of accelerators, cont.

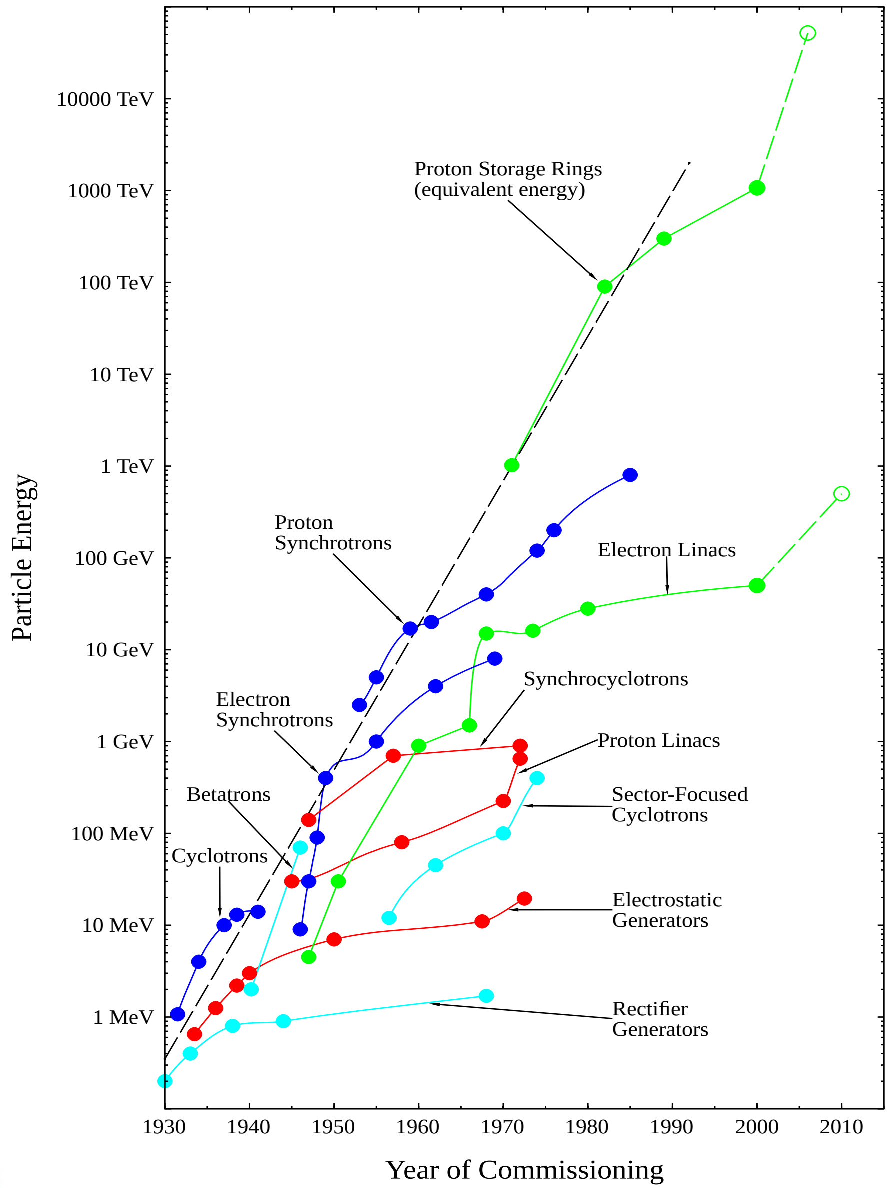




E. O. Lawrence's first cylcotron
(1.2 MeV, H^+)
(1932)

(LBNL)

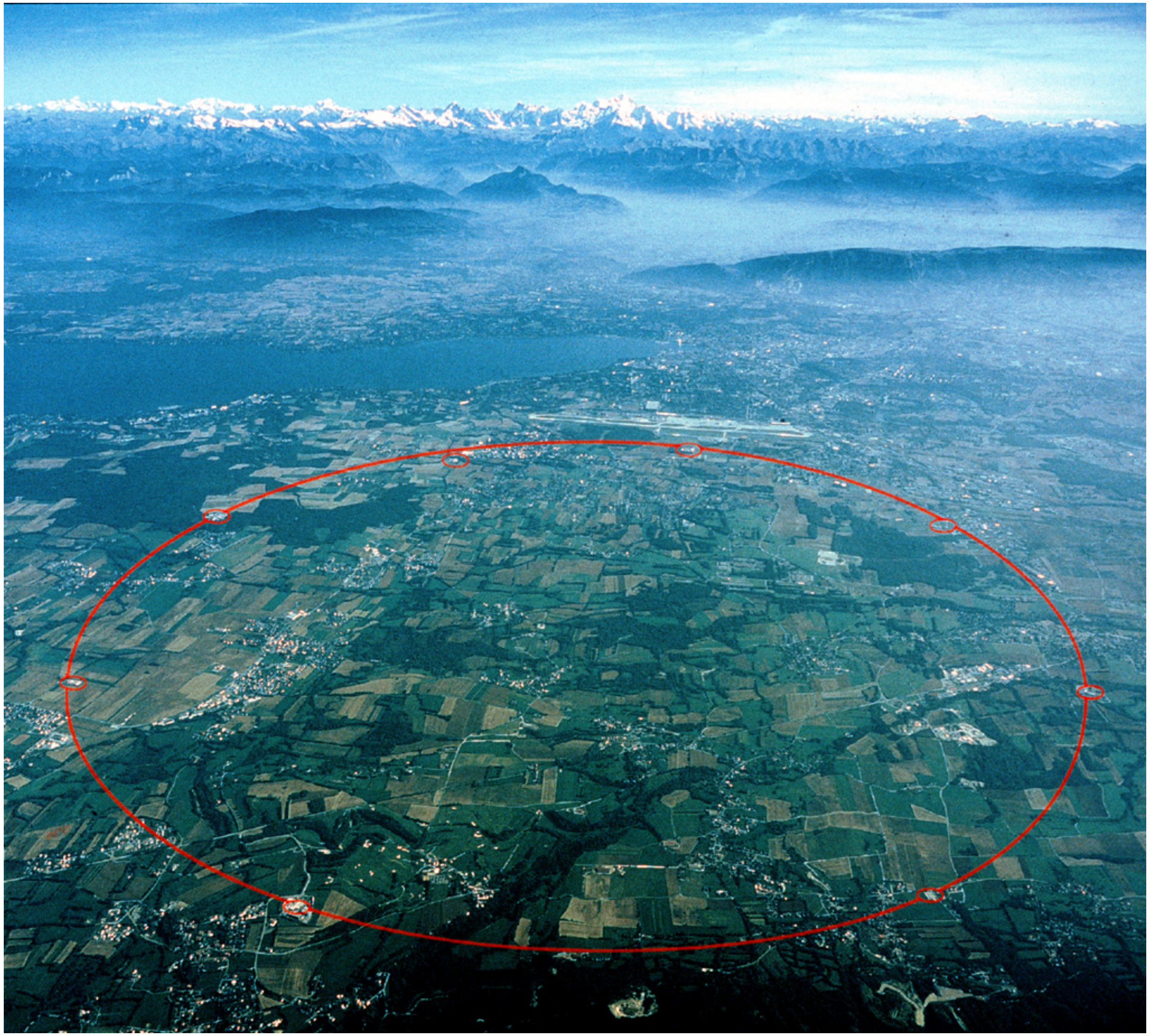
Evolution of Accelerators



Livingston, 1960 and numerous updates

Accelerators, the current generation

CERN, showing the LEP/LHC ring

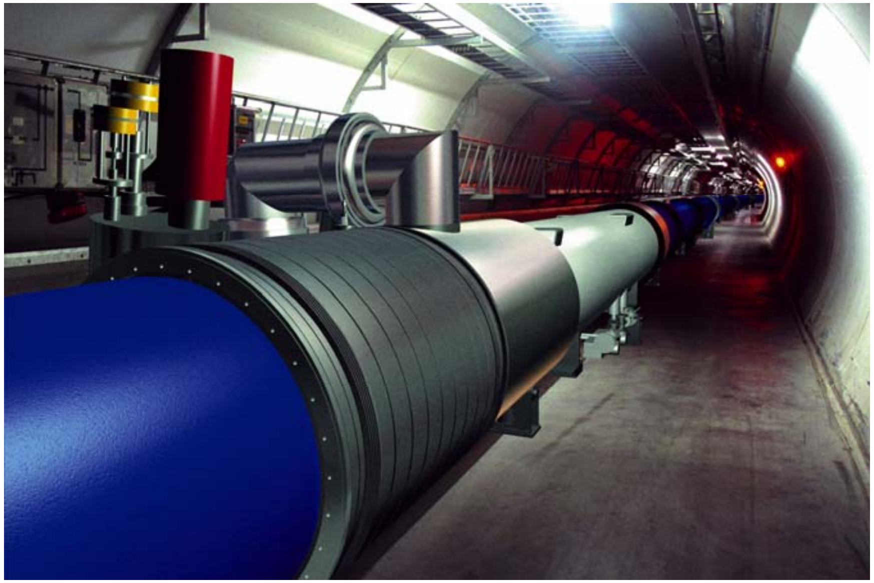


(CERN)

Accelerators, the current generation, cont.

(CERN)

LEP 1989-1999
(100 GeV)

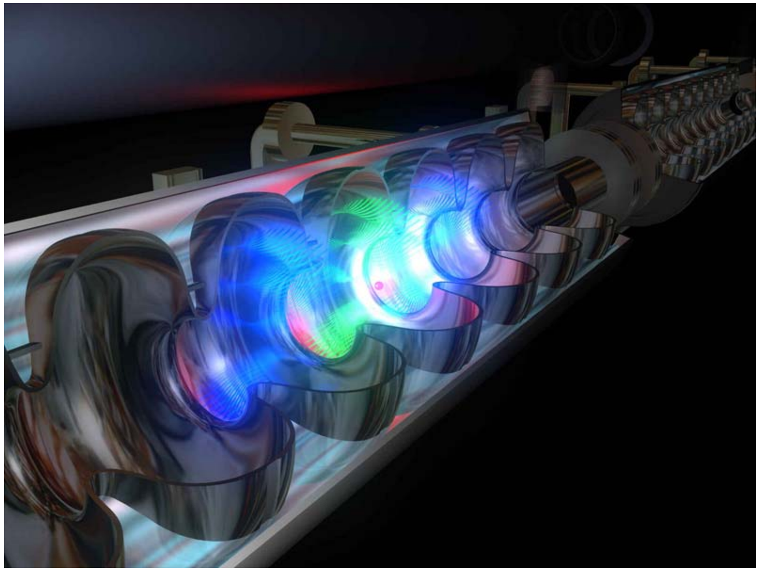


(CERN)

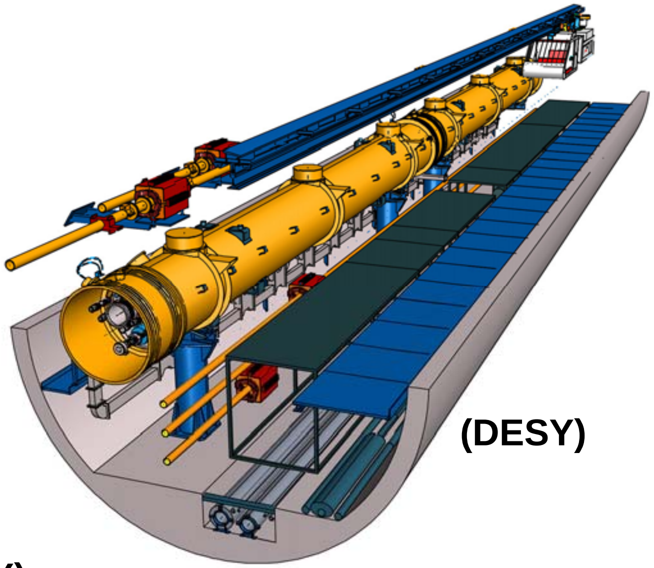
LHC starting up in 2007 (7 TeV)

Bigger sparks in the vacuum

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



(DESY)



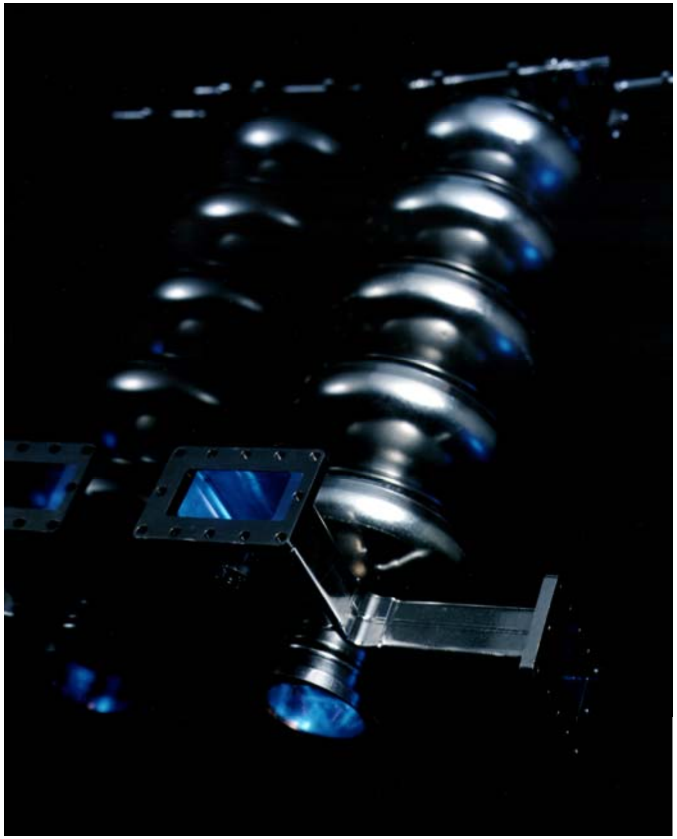
(DESY)

Applications:

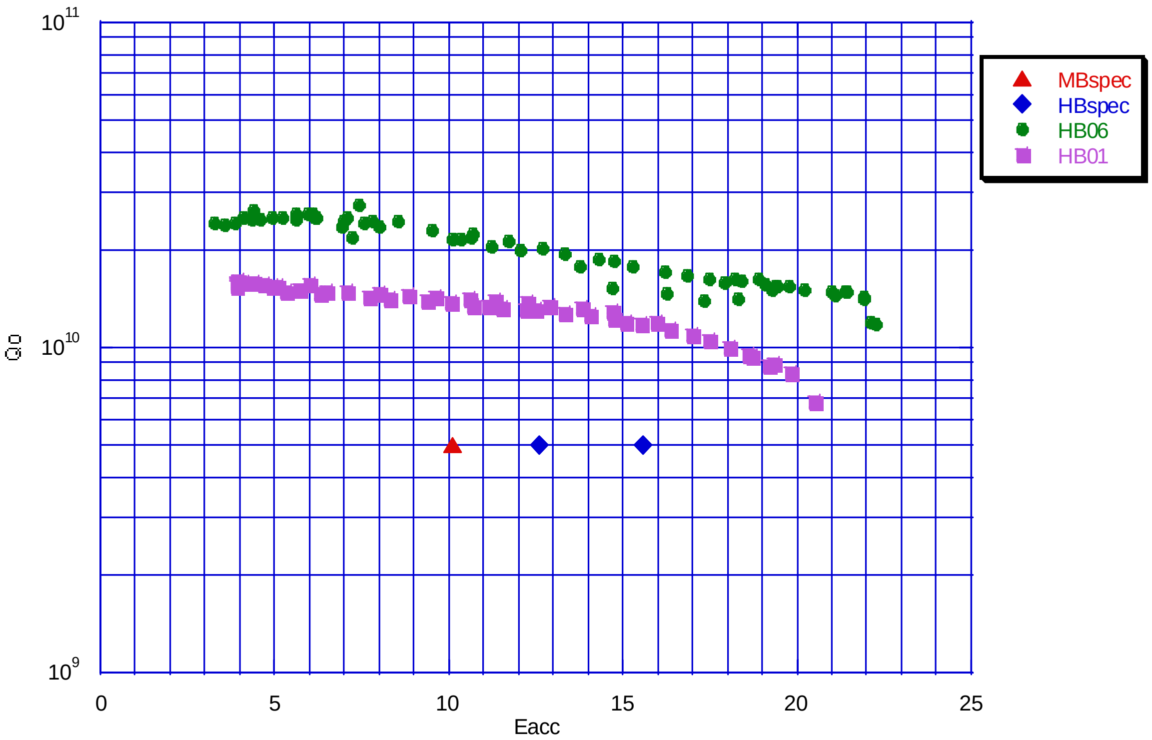
- **The linear collider at TeV energies (TESLA Project)**
- **High-power (JLab) and short wavelength (x-ray) FELs**

(DESY and SLAC)

Superconducting RF cavities



1.5 GHz from JLab



Cavity *Q* vs. accelerating gradient (MV/m)
805 MHz cavities for the SNS

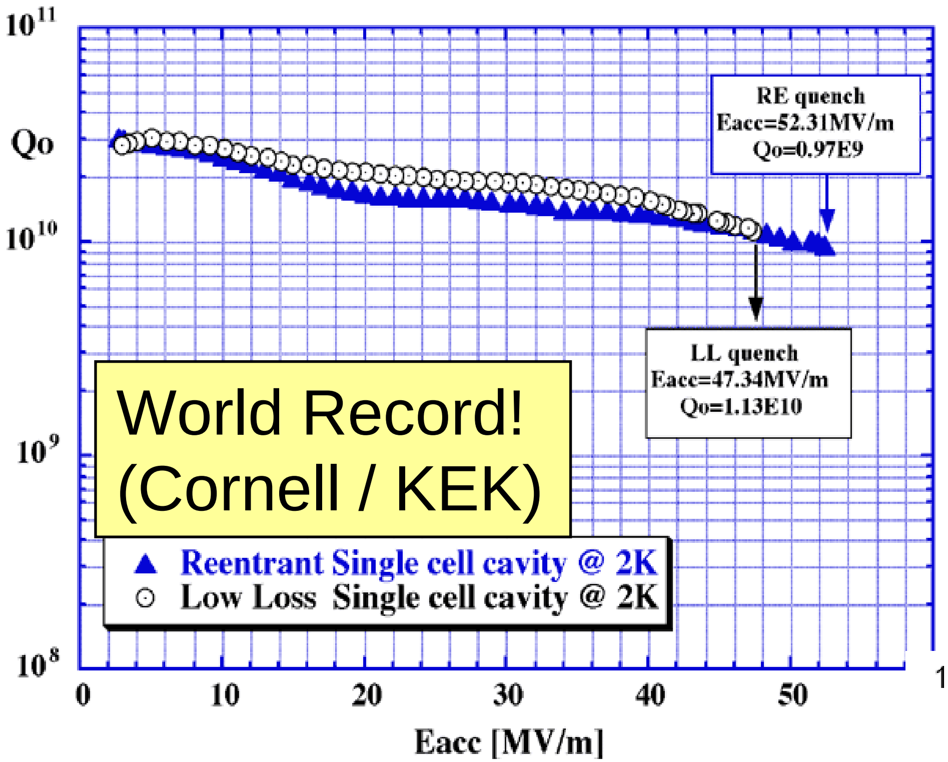
Future science: International Linear Collider (ILC)

- Electron-positron collision energy 500–1000 GeV

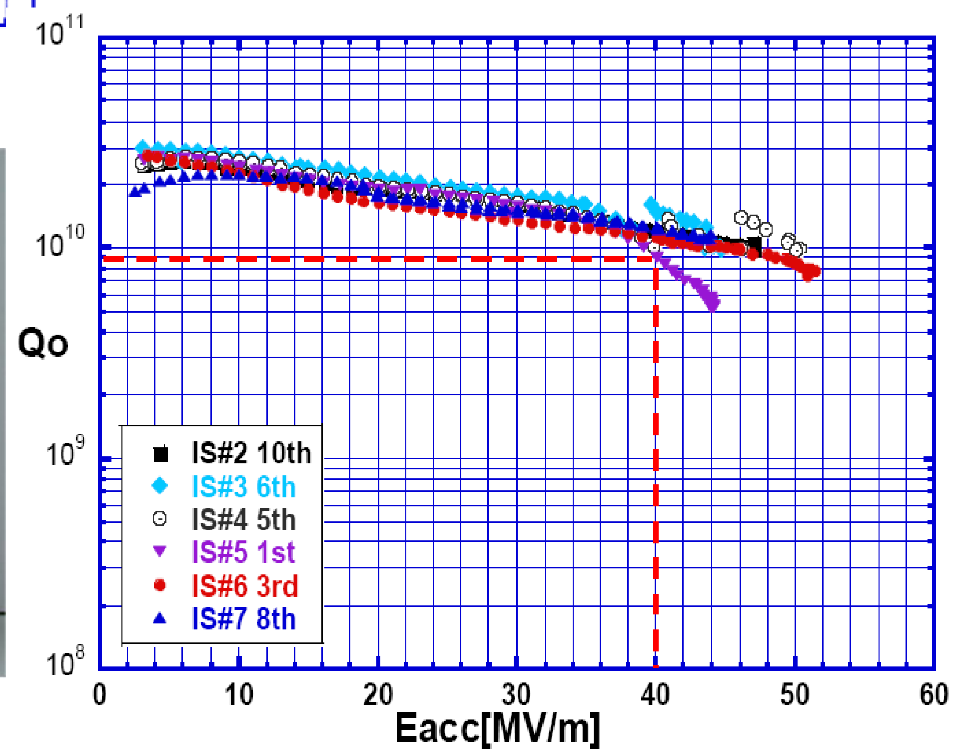
- “Warm” (normal conducting) technology was capable:
  100 MV/m for short time

- “Cold” (superconducting) technology was chosen:
  50 MV/m for CW

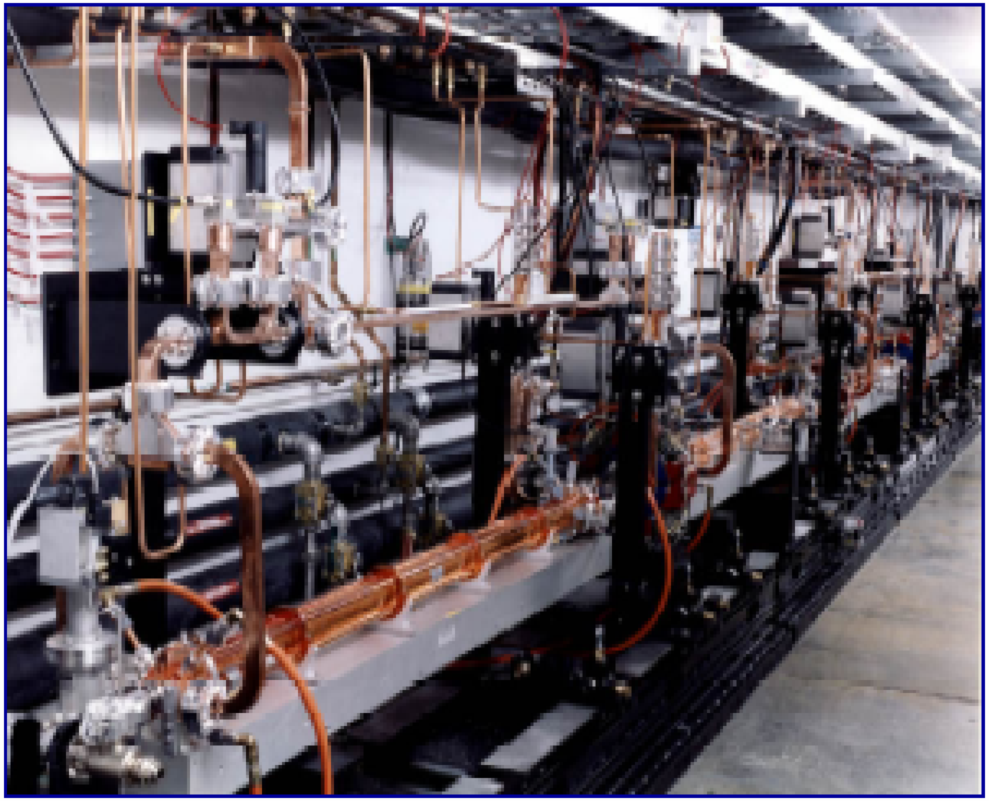
Single-Cells: Other Shapes



Several cavities achieved more than 45 MV/m at high Q! (KEK)



The Test Accelerator at SLAC



The NLCTA with 1.8 m accelerator structures (1997).

Accelerating gradient 40 MV/m (unloaded) with good wake-field control and energy spread.

Demonstrated ability to reach 500 GeV cms.

Ref: D. Burke, International Technology Recommendation Panel Report April 26-27, 2004, SLAC, http://www-project.slac.stanford.edu/lc/ITRP/

The Future: Laser-based particle accelerators?

"The recent publication of three **high-profile reports** on the use of laser-based accelerators to produce high-energy quasi-monoenergetic electron beams of unprecedented quality heralds a new age of high-energy physics. … [M]ultifunctional desktop accelerators have a wealth of potential applications … ."

"News and Views: Desktop accelerators: Going up?"
Nature Physics 2, 11–12 (2006), Ken Ledingham.

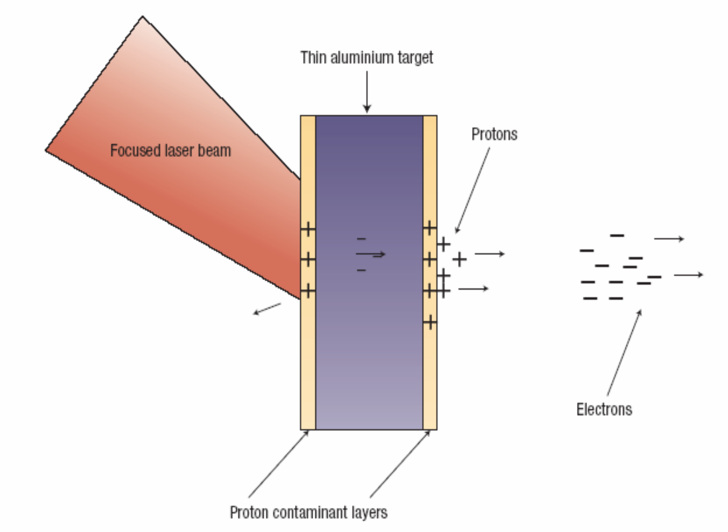
From those reports:

* Laser intensities > 10^{19} W/cm^2 for electron, proton beams & gamma rays

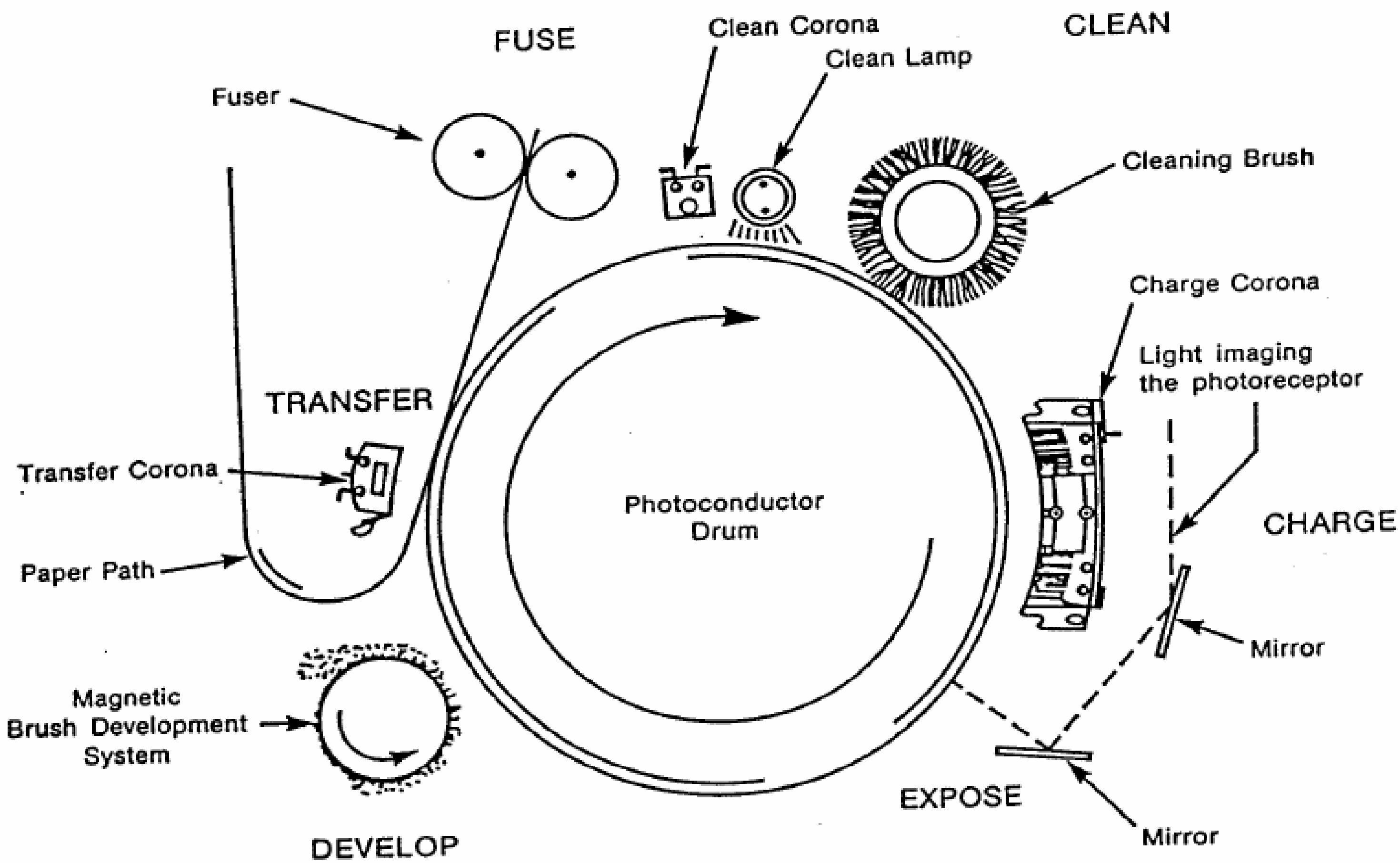
"Monoenergetic beams of relativistic electrons from intense laser–plasma interactions,"
S. P. D. Mangles et al., *Nature* 431, 535–538

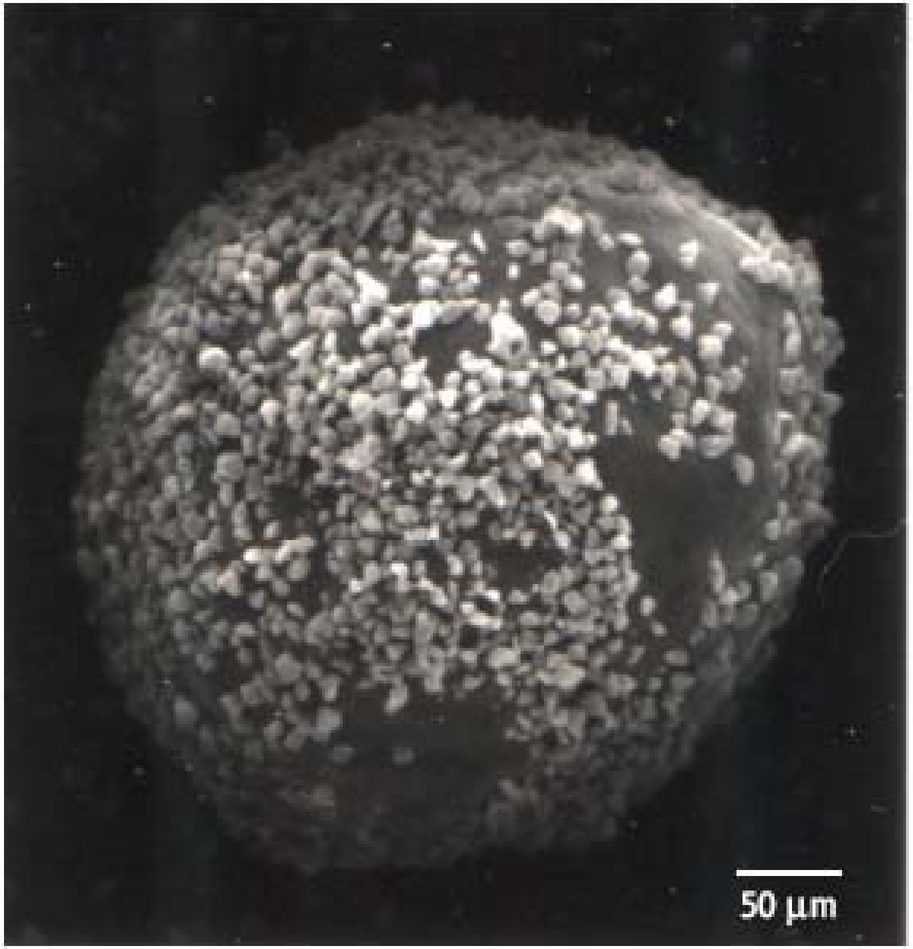
* Hundreds of GV/m[1] — thousands of times greater than conventional RF

"High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding,"
C. G. R. Geddes et al., *Nature* 431, 538–541



Electrophotographic Process





Extreme closeup. A scanning electron micrograph of 10-µm toner particles on a 200-µm carrier particle used in electrophotography. Detailed understanding of how these particles become electrostatically charged and the resultant adhesive force have improved the imaging technology

Summing up

- Founding fathers' legacies include science
  - Strong interest in science's enabling tools
  - Deep curiosity -- knowledge for its own sake
  - Practical search for useful knowledge
- Franklin-era electrical machines and air pumps increased in power, but only barely began to be used together
  - Desideratum for historians: To what extent did Franklin himself investigate electric fields across the vacuum?
- What was learned from electric fields across the vacuum has led to modern physics

Useful References

- *The First Scientific American: Benjamin Franklin and the Pursuit of Genius*, Joyce Chaplin (Basic Books, 2006)
- *Elements of Early Modern Physics*, J. L. Heilbron (University of California Press, 1982)
- *Draw the Lightning Down: Benjamin Franklin and Electrical Technology in the Age of Enlightenment*, Michael Brian Schiffer (University of California Press, 2003)
- Benjamin Franklin Tercentenary

  http://www.benfranklin300.org/
- Institute and Museum of the History of Science, Florence, Italy

  http://brunelleschi.imss.fi.it/museum
- Franklin and His Friends: Portraying the Man of Science in 18th-Century America

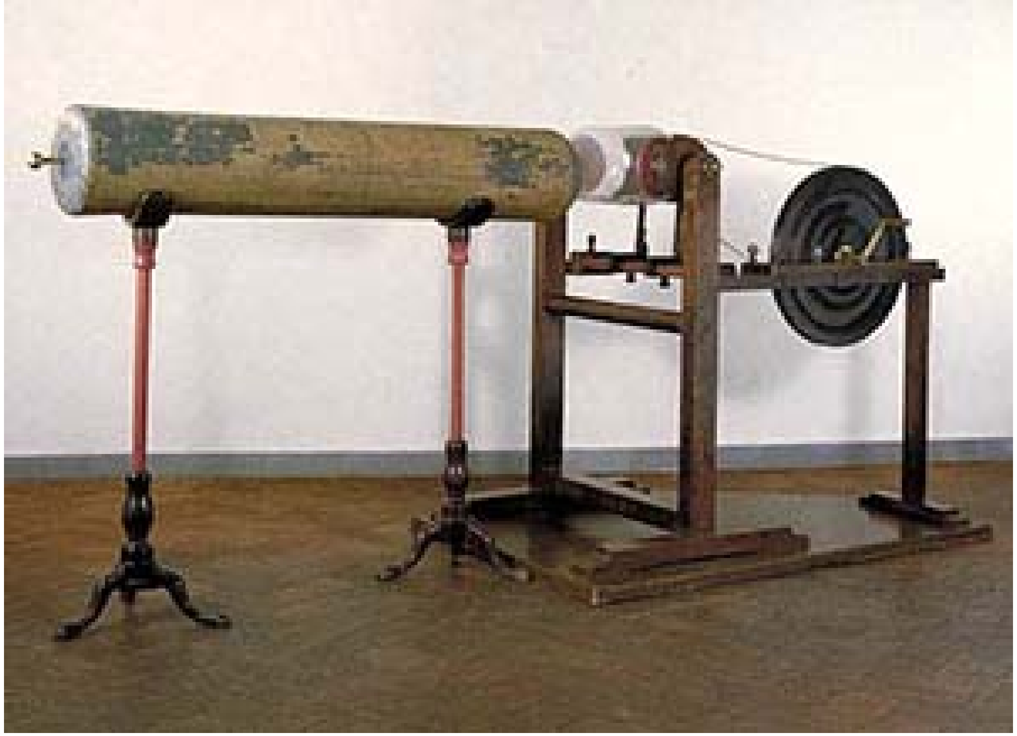
  http://www.npg.si.edu/exh/franklin/

Backups

Electrical apparatus designed by Franklin in the 1740s

(Courtesy Benjamin Franklin Tercentenary)

Edward Nairne's large cylinder frictional electrical machine and prime conductor, 1773



Institute and Museum of the
History of Science, Florence, Italy

High voltage ca. 1840

William George Armstrong's hydro-electric machine, 1840

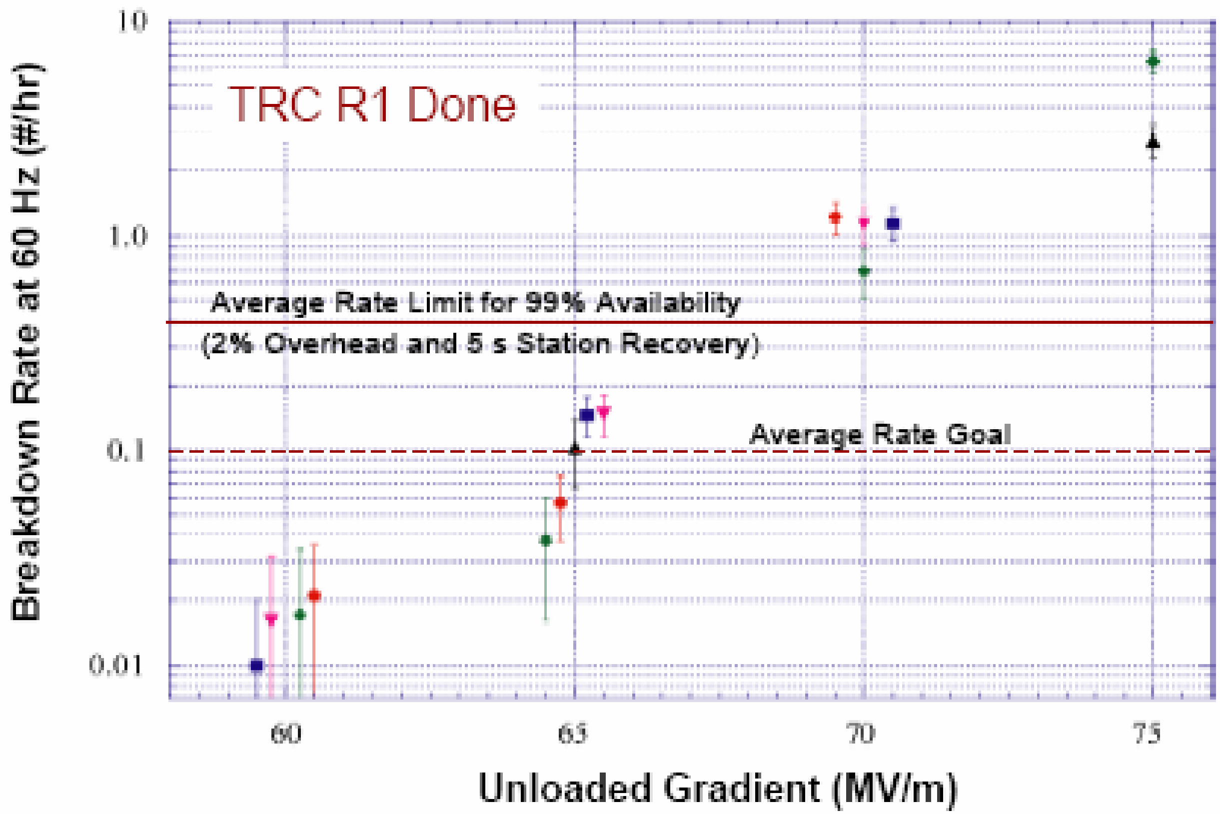
"[W]ater drops in the jets of steam became electrically charged because of friction with the wooden walls of the nozzles. This system was the largest source of high-voltage static electricity at that time. However, it caused a rapid increase in the humidity of the room where it operated, making electrostatic experiments difficult to perform."

Photo and text: Institute and Museum of the History of Science, Florence, Italy

“To control these effects, we need to know how charging occurs and how electrostatic forces behave. Surprisingly, although electrostatic charging is well known, it remains among the most poorly understood areas of solid-state physics. Several recent studies have improved our insights into electrostatic charging and adhesion, which in turn may foster advances in the near future that could influence multibillion-dollar industries.”

Science 15 June 2007: Vol. 316. no. 5831, pp. 1572 – 1573
Perspectives, APPLIED PHYSICS:
Recent Progress and Continuing Puzzles in Electrostatics
L. B. Schein*

High Gradient Performance of Five Recent Structures



Ref: D. Burke, International Technology Recommendation Panel Report, April 26-27, 2004, SLAC, http://www-project.slac.stanford.edu/lc/ITRP/