Progress and Prospects in the Generation of High Voltages

Electric fields across the vacuum

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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
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

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

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spark length (inches)</th>
<th>Voltage (kilovolts)</th>
<th>Energy (joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass rod (Franklin 1747)</td>
<td>1</td>
<td>5</td>
<td>.000006</td>
</tr>
<tr>
<td>Globe (Franklin 1750)</td>
<td>2</td>
<td>10</td>
<td>.0008</td>
</tr>
<tr>
<td>with gun barrel</td>
<td></td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>with Leyden jar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylinder (Nairne 1773)</td>
<td>14</td>
<td>30</td>
<td>0.2</td>
</tr>
<tr>
<td>with prime conductor</td>
<td></td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>with Leyden jar</td>
<td></td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>with 64 jars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate (van Marum 1785/90)</td>
<td>24</td>
<td>80</td>
<td>0.6</td>
</tr>
<tr>
<td>with prime conductor</td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>with Leyden jar</td>
<td></td>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>with 100 jars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storm cloud</td>
<td></td>
<td></td>
<td>50000000</td>
</tr>
</tbody>
</table>

*Elements of Early Modern Physics, J. L. Heilbron*
Early vacuum pumps
Mechanical air pumps (O. von Guericke, 1640)
“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.”

Progress of vacuum technology in Franklin’s day

• For research and for demonstration, every respectable “cabinet” of the late 18\textsuperscript{th} 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 1/600 atm

• “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.**

<table>
<thead>
<tr>
<th>Electrical appearances exhibited</th>
<th>Degree of exhaustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light began first to appear in flashe</td>
<td>5</td>
</tr>
<tr>
<td>Light appeared the whole length of the tube</td>
<td>8</td>
</tr>
<tr>
<td>Tube was filled with an uniform body of pale light</td>
<td>74</td>
</tr>
<tr>
<td>The tube was filled with a uniform body of pale light</td>
<td>269</td>
</tr>
</tbody>
</table>

*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
- Battery
- Rhumkorff coils
- 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)
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

**Technology link from Franklin’s time to ours:**
Electrostatic machines and crude vacuum pumps → particle accelerators

**Science link from Franklin’s time to ours:**
“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 cyclotron
(1.2 MeV, H⁺)
(1932)
Evolution of Accelerators

Livingston, 1960 and numerous updates
Accelerators, the current generation

CERN, showing the LEP/LHC ring
Accelerators, the current generation, cont.

LHC starting up in 2007 (1.5 TeV)

LEP 1989-1999
(100 GeV)
Bigger sparks in the vacuum

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 (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

World Record! (Cornell / KEK)

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.

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?”

From those reports:
* Laser intensities > 10^{19} \text{ 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
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