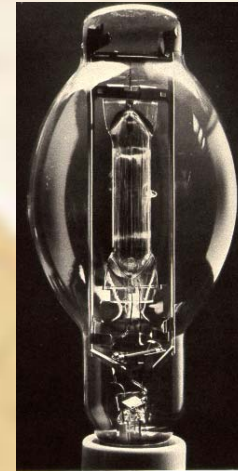


Benjamin Franklin and Future Science

From Lightning to Lighting: Physics and Technology Discharged from Franklin's Kite Experiment

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American Vacuum Society
53rd International Symposium & Exhibition
November 16, 2006

1726 - 1745

Franklin Established Himself as a Printer in Philadelphia

- Prior to 1744, Franklin conducted scientific observations and investigations on effects heat absorption, earthquakes, comets, northern lights, lunar eclipses, paths of storms and invented the “Pennsylvania” stove.
- Franklin had a particular interest in Fire Safety:
 - 1730 - Fire destroyed Fishbourn’s Wharf and surrounding homes;
 - 1733 - He Published articles in the Pennsylvania Gazette on the failings of fire fighting and prevention in Philadelphia and in 1735 on licensing Chimney Sweeps and forming a fire company like those he had observed in Boston;
 - December 1736 - Helped found Union Fire Company in Philadelphia;
 - April 1752 - Helped establish the Philadelphia Contributionship, an insurance company for the victims of fires.



Contributionship
Fire Mark
placed on homes
protected by their
insurance

March 1747: “during the months past, had little leisure for any thing else”

- 1744 Philadelphia - Franklin attended an electrical demonstration by Dr. Spencer, sparking his interest in the subject.
- 1745 - He received an “electrical tube” from Peter Collinson and begins an intense investigation of electricity.

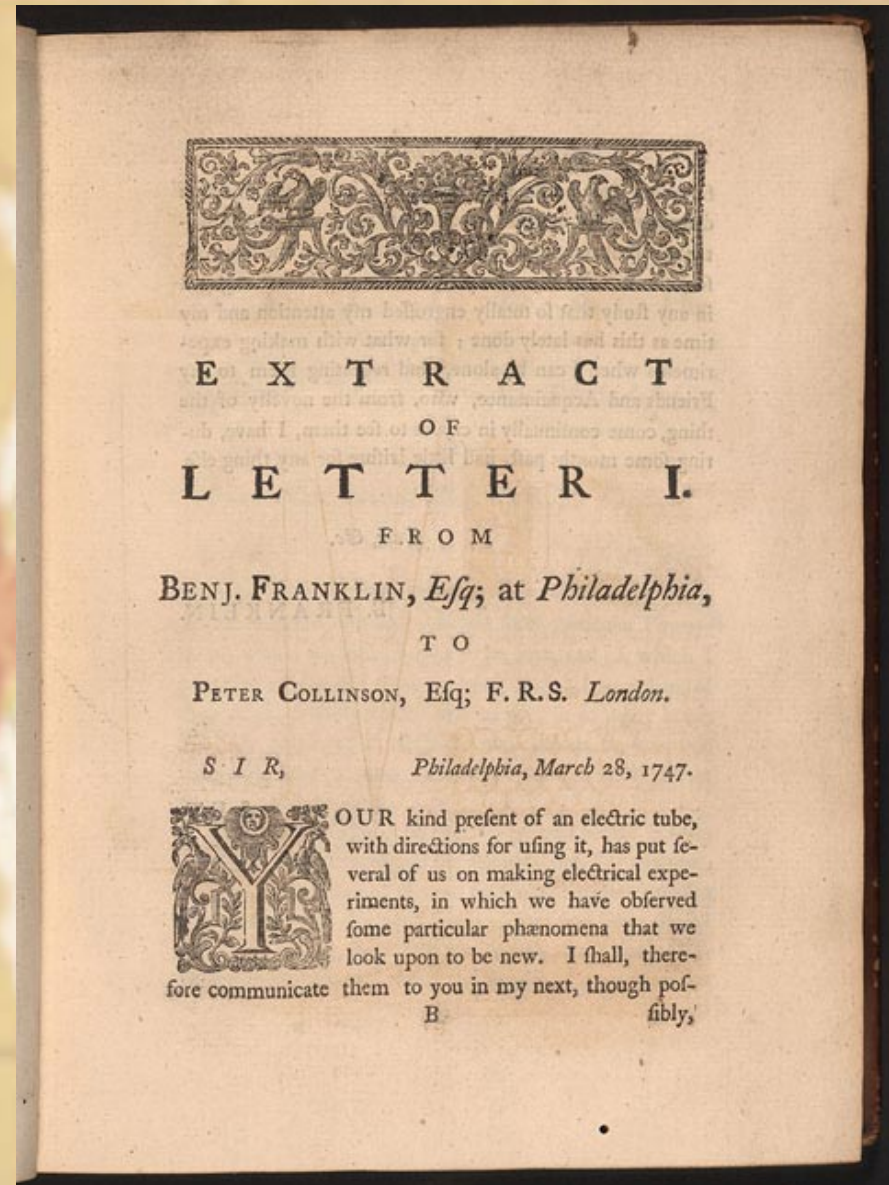


Static Electricity Tube circa 1747

- 28 March, 1747 - Short thank you letter to Collinson:
 - “we have observed some particular phenomena that we look upon to be new”
 - “For my own part, I never was before engaged in any such study that so totally engrossed my attention and my time”

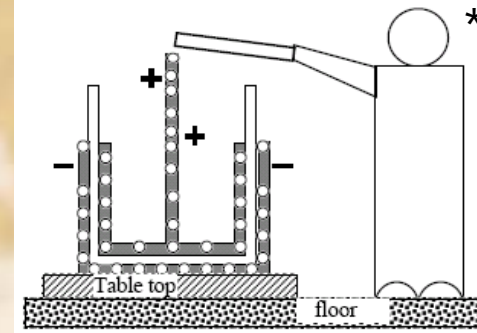
11 July 1747 - Letter to Collinson:

- Describes his demonstration experiments on the “wonderful effect of pointed bodies, both, drawing off and throwing off the electrical fire”
- Discusses gain or loss of “electric fire” or “electric fluid”
- Introduces terminology for positive & negative, plus & minus;



1747 - 1748: Continued Experimentation

- September 1747 - Leyden Jar Experiments & Observations:
 - “I cannot forbear adding a few observations on M. Muschenbroek’s wonderful bottle”
 - Describes insulators as “electric” materials and conductors as “non-electric” materials
- 1748 - Describes
 - A flat plate capacitor
 - Two forms of electrostatic motors
 - An assembled **battery** of Leyden jars



Battery of Leyden Jars
circa 1760-1769

29 April 1749 - Letter to Collinson

Postulates Lightning as a Very Large Electrical Spark

- Alludes to conservation of charge:
 - “Friction between a non-electric (conductor) and an electric (insulator) *per se* will produce electric fire, not by creating, but collecting it, for it is equally diffused in our walls, floors, earth, and the whole mass of common matter.”
- Postulates on how thunderclouds become charged
 - “The ocean is a compound of water, a non-electric, and salt, an electric.”
 - “When there is friction ... electrical fire is ... plainly visible in the night ... in the stern and wake of every sailing vessel, ... every surf and spray, ... in storms the whole sea seems on fire.”
- “if two gun-barrels electrified will strike at two inches distance and make a loud snap, to what a great distance may ten thousand acres of electrified cloud strike to give its fire, and how loud must be that crack?”

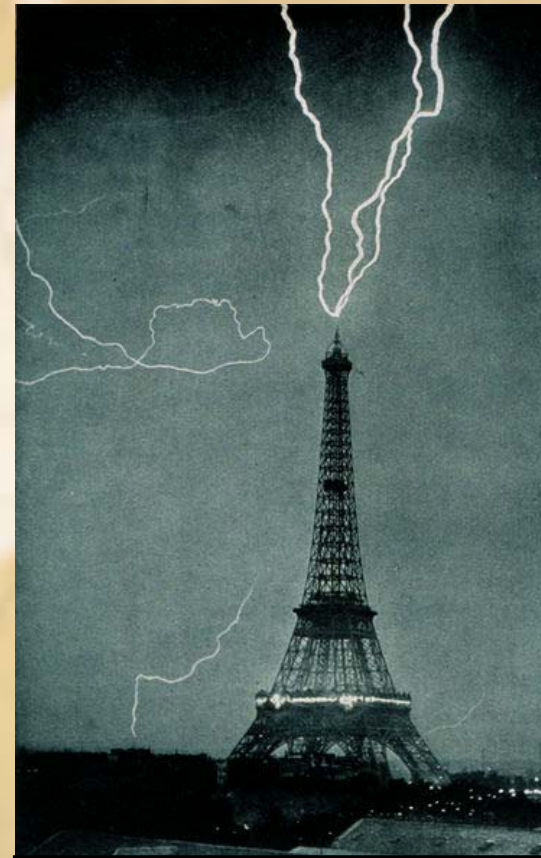
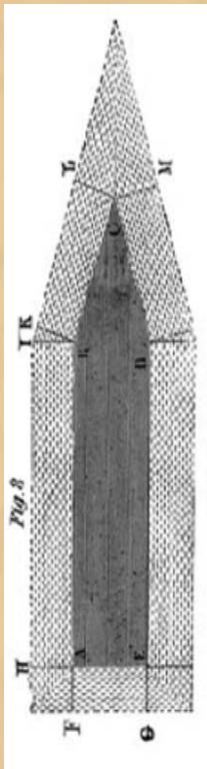


St. Elmo's Fire: Low T plasma caused by atmospheric electrical potential differences which exceed the dielectric breakdown value of air ($\sim 3 \text{ MV/m}$)

29 July 1750: Sends to Collins:

Opinions and Conjectures concerning the Properties and Effects of the Electrical Matter, and the Means of Preserving Buildings, Ships, &c., from Lightning, arising from Experiments & Observations made in Philadelphia, 1749

- Having already established the concept of individual electrical particles, he now discusses “mutual repulsion” and introduces concepts related to field intensity for flat and pointed surfaces.
- Concluding: “I say, if these things are so, may not the knowledge of this power of points be of use to mankind in preserving houses, churches, ships, &c., from the stroke of lightning, by directing us to fix on the highest parts of those edifices upright rods of iron made sharp as a needle”



June 3, 1902: M.G. Loppe

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.

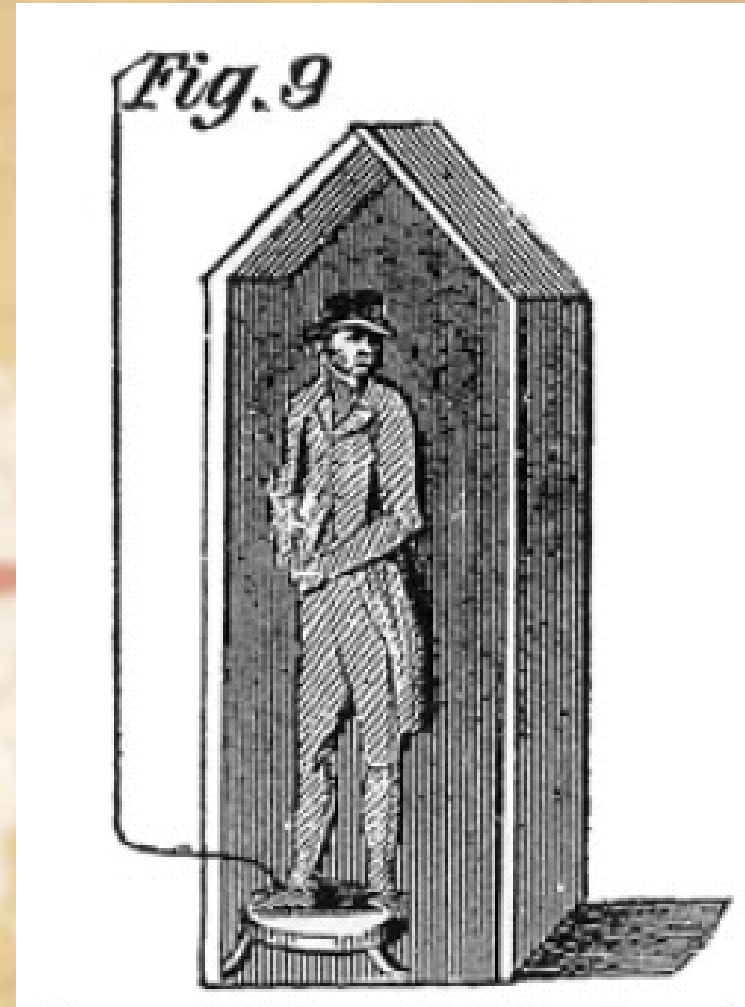


Figure from J. Bigelow, *Works of Benjamin Franklin*, Vol II, p200, 1904

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

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

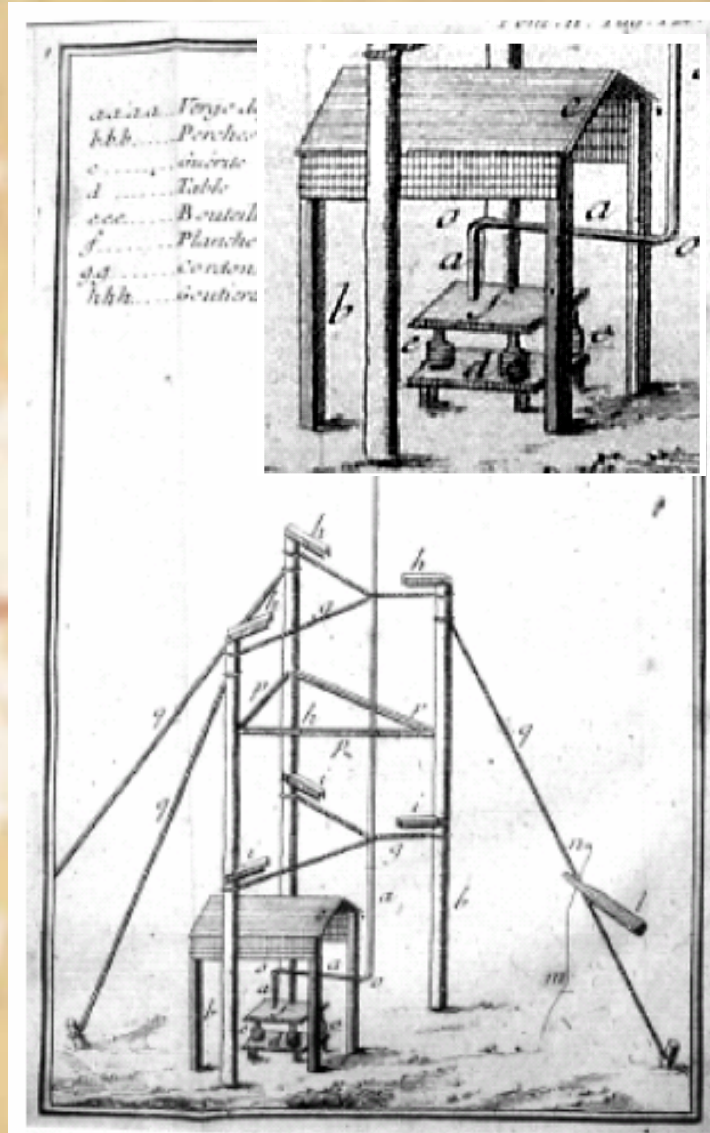
- Consisting of cedar cross with a silk handkerchief, so better to withstand a storm's high winds;
- A sharp wire extending about a foot above the top tip of the kite;
- A key tied to the kite string by a silk thread;
- He stood inside of a door or window to prevent the silk thread from becoming wet 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

The “Philadelphia” Experiments: Marly la Ville, France, 28 May, 1752

- At the direction of His Majesty, M. D’Alibard placed upon an electrical body a pointed bar of iron, about one inch in diameter and of forty foot high.
- “Coiffier, a retired soldier, whom I put in charge of the observations ... having heard a strong clap of thunder, runs immediately to the machine,” and extracts “small bright sparks and hears it crackling”
- To confirm his observations, Coiffier sends speedily for the Prior.
- “the parishioners seeing their parish priest hurry, imagine that the poor Coiffier has killed himself by the thunder”
- “The results of all the tests and observations that I relate ... is that the matter of thunder is incontestably the same as that of electricity.”



From R. A. Morse, Franklin and Electrostatics,

Georg Wilhelm Richmann*

- Richmann, a Baltic scientist and member of the Imperial Academy of Science and M. Sokolaw his assistant, attempted an experiment similar to D'Alibard's;
- Richmann mounted an iron bar atop his house bent and insulated so as to allow observation of the electrical sparks from the convenience of his living space.
- Unfortunately, this prevented him from observing the severity of the approaching storm.
- Reported in Franklin's Pennsylvania Gazette:
"The Professor judging ... that the Tempest was at a great Distance, assured M. Sokolaw that there was no Danger, but that there might be at the Approach. Richmann stood about a Foot from the Bar, attentively observing the Needle. Soon after, Sokolaw saw, the Machine being untouched, a Globe of blue and whitish Fire, about four inches Diameter, dart from the Bar against M. Richmann's Forehead, who fell backwards without the least Outcry. This was succeeded by an Explosion like that of a small Cannon which also threw M. Sokolaw on the Floor"

DEATH OF A SCIENTIST:

Killed August 6, 1753

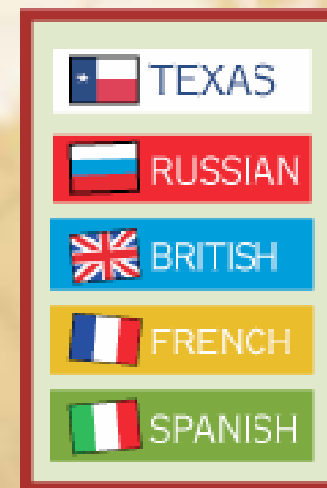
St. Petersburg, Russia



* Source: Today in Science History

WHAT IF:

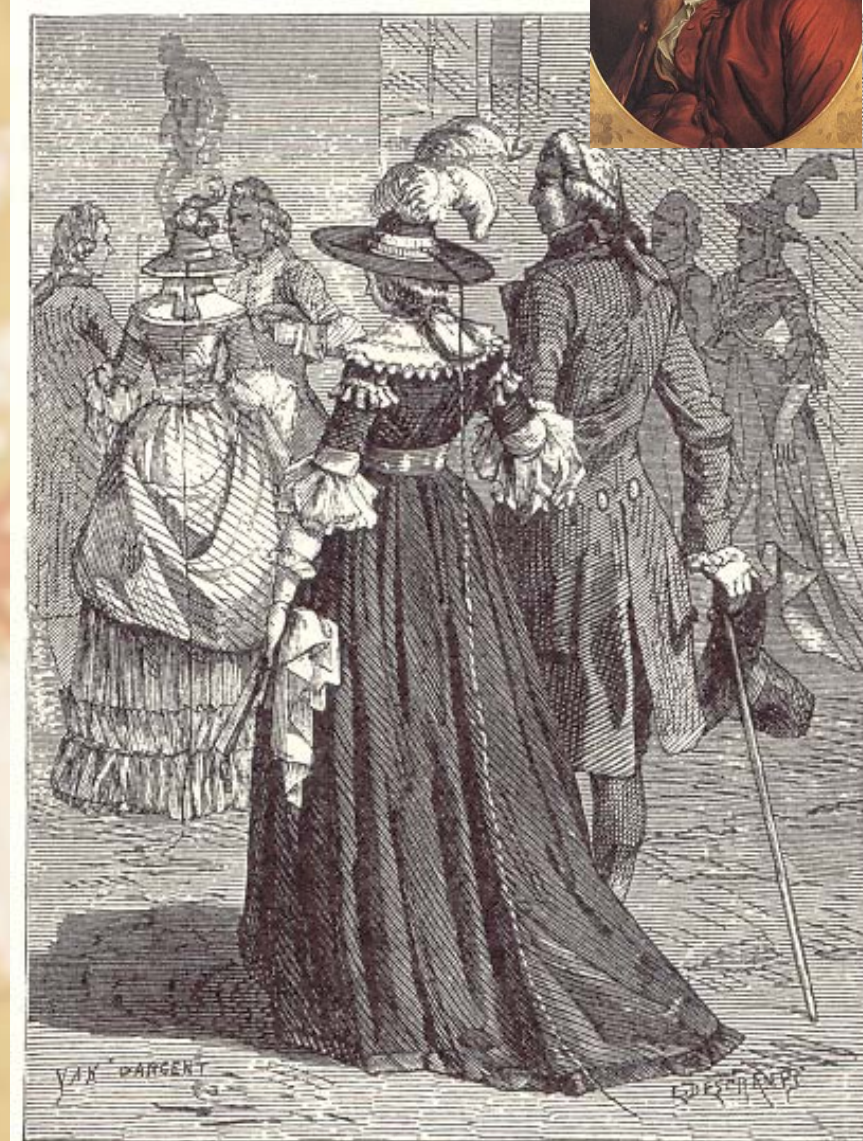
Ben Franklin had been killed by lightning during his experiment?



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.

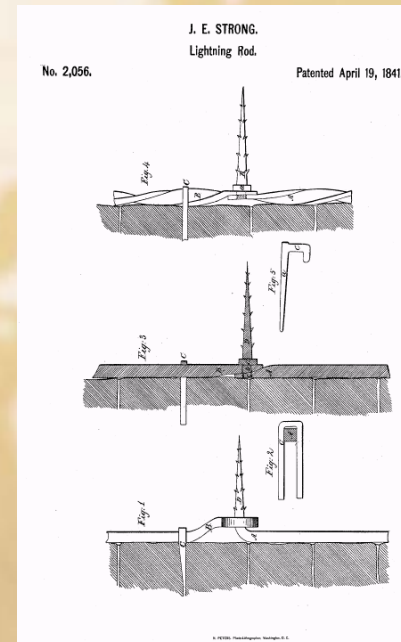


Lightning Rod Refinement & Deployment:

- In the summer & fall of 1752, Franklin attaches the first lightning rod to the roof of his home in Philadelphia to collect data;
- Shortly thereafter, lightning rods are placed on the spires of the Pennsylvania State House (Independence Hall) and the Academy of Philadelphia (University of Pennsylvania);
- Franklin did not patent any of his inventions. Instead, he published advice on lightning protection in Poor Richard's Almanac for 1753;
- His autobiography reads:
“As we enjoy great advantages from the inventions of others, we should be glad of an opportunity to serve others by any invention of ours; and this we should do freely and generously.”
- Nonetheless, the US Patent and Trademark Office was established in 1790;
 - It lists 328 patents related to lightning rods and protectors.
 - The oldest from 1841;
 - Inventor: Justin Strong of Boston MA,
 - Patent # 2056 covers improved mounting clamps for maintaining “Lightning Rod” electrical connections.

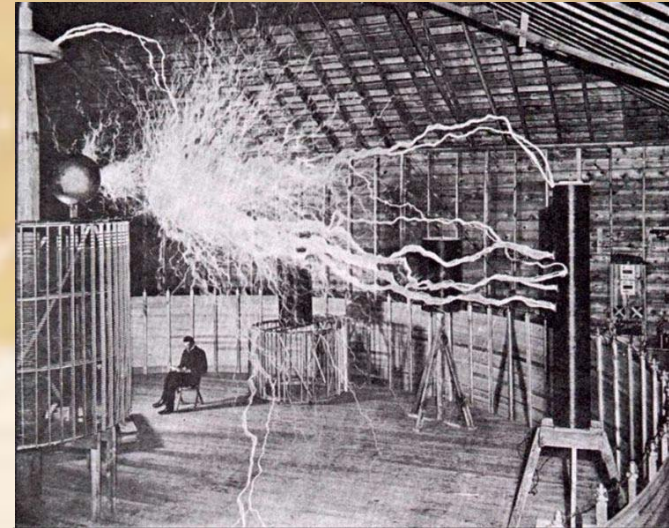


1756 Lightning Rod
(slightly used)



History of Electricity & Light

- 1752 – Franklin's Kite Experiment
- 1785 – Coulomb relates electric force to charge
- 1793 – Volta invents the battery
- 1801 – Davy invents the arc lamp
- 1813 – Gauss formulates divergence theorem
- 1825 – Ampere publishes work on magnetism
- 1826 – Ohm publishes 'Ohm's law'
- 1837 – Faraday discovers dielectric constants
- 1840 – de la Rue invents the vacuum tube light bulb
- 1841 – Joule shows electrical energy conservation
- 1855 – Maxwell publishes his equations
- 1880 – Edison patents long-lasting light bulb
- 1887 – Tesla investigates Bremsstrahlung radiation
- 1893 – Tesla displays fluorescent light at the World's Fair
- 1895 – Rontgen discovers X-rays
- 1897 – Thomson discovers the electron
(~150 years after Franklin's experiments)
- 1901 – Hewitt demonstrates mercury-vapor lamp
- 1926 – Germer invents modern fluorescent lamp



TESLA'S Lightning & Lighting:

MV potentials, arcs ~135ft long
Wireless lighting discharges (below)



Source: Nikola Tesla publicity photos circa 1900

Rocket Triggered Lightning^{*}

Researchers routinely trigger lightning strikes
using small rockets with thin trailing wires



*** University of Florida Lightning Research Group**

Drs. M. Uman and V. Rakov, Co-Directors; www.lightning.ece.ufl.edu

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



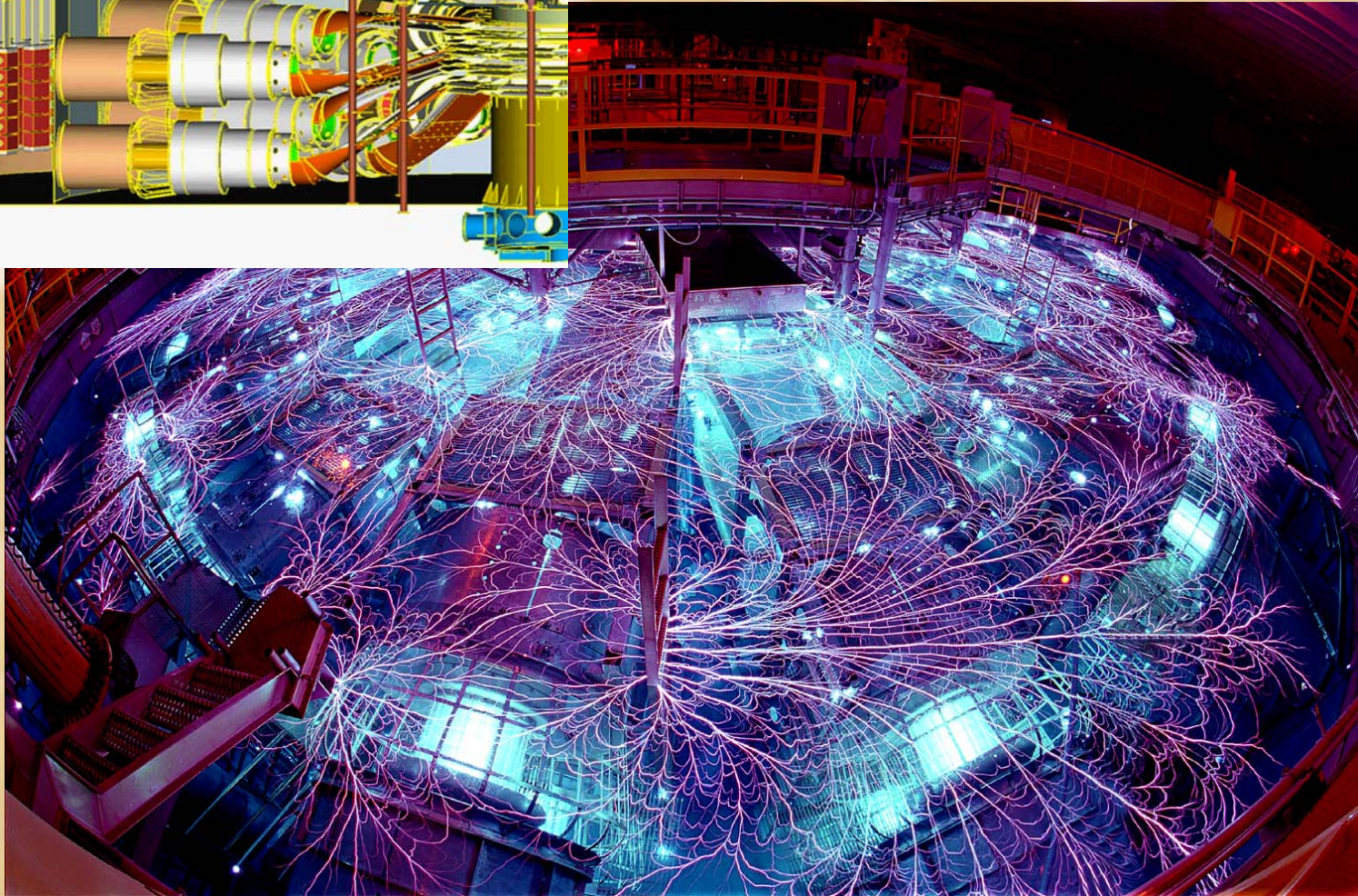
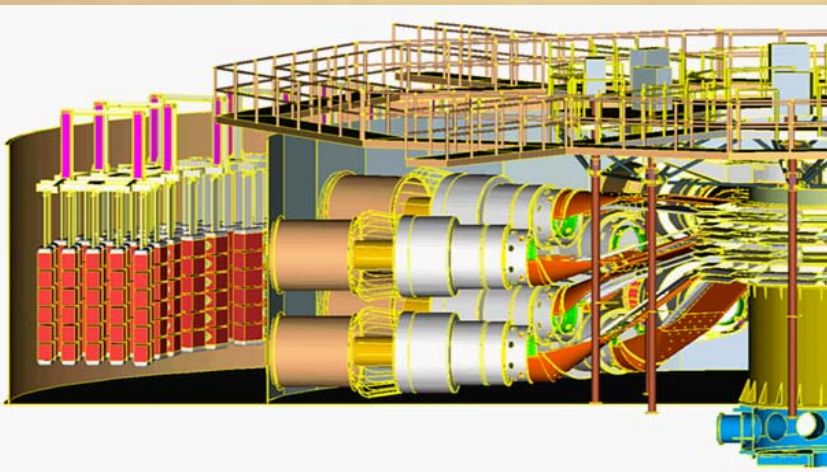
Sandia's Z-Machine

FUSION POWER:

Marx Capacitors: ~11.4 MJ

Delivers: ~20 MA in 100ns

Power: ~200 TW



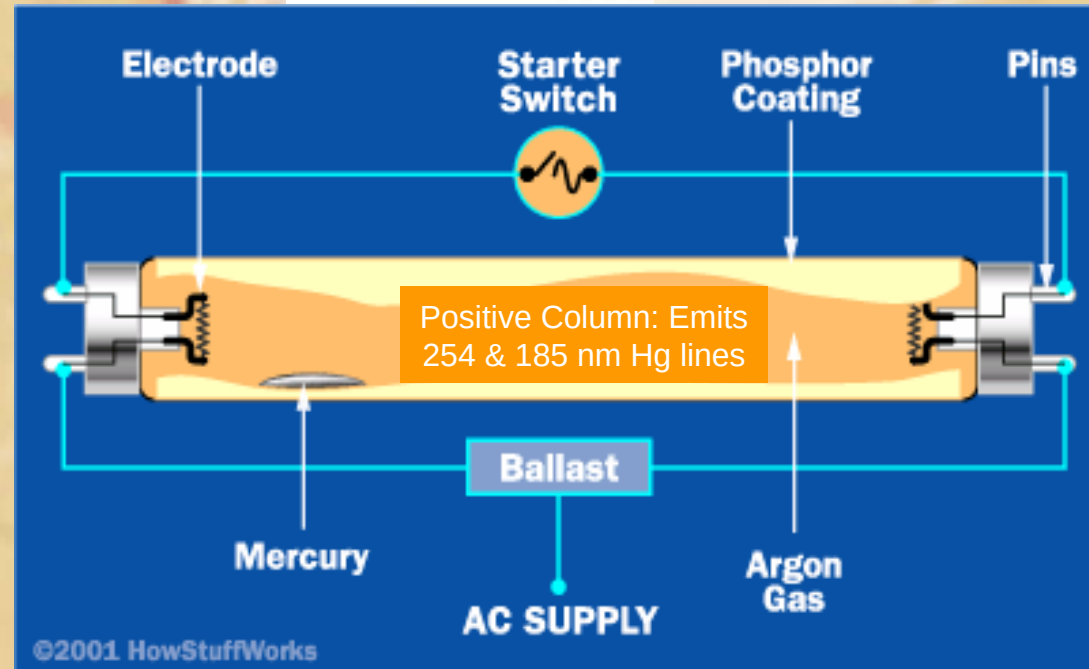
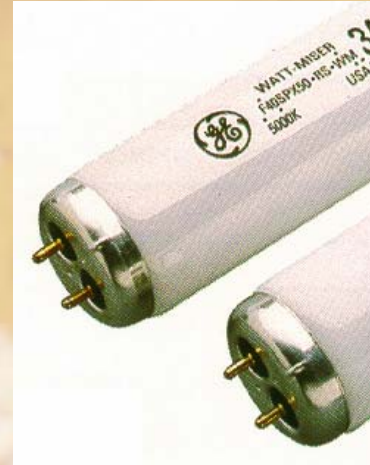
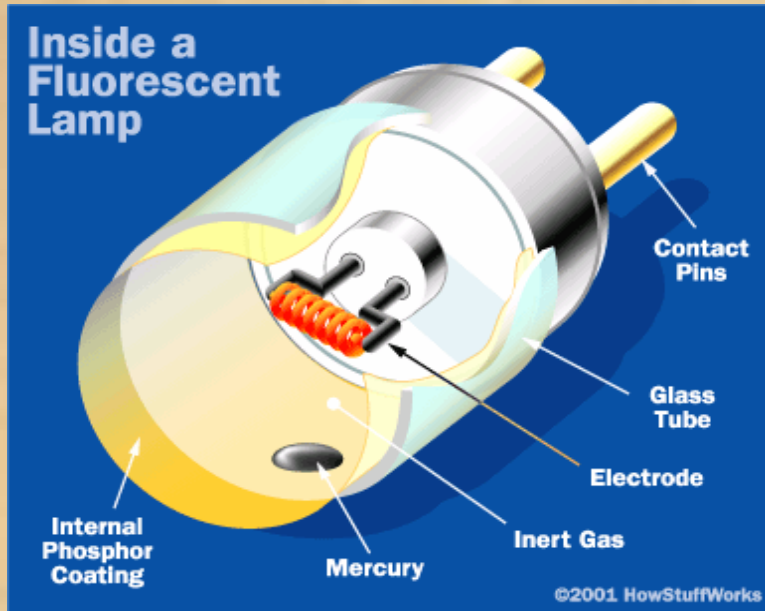
Source: Sandia National Lab

“And then there was light”: The Earth at Night



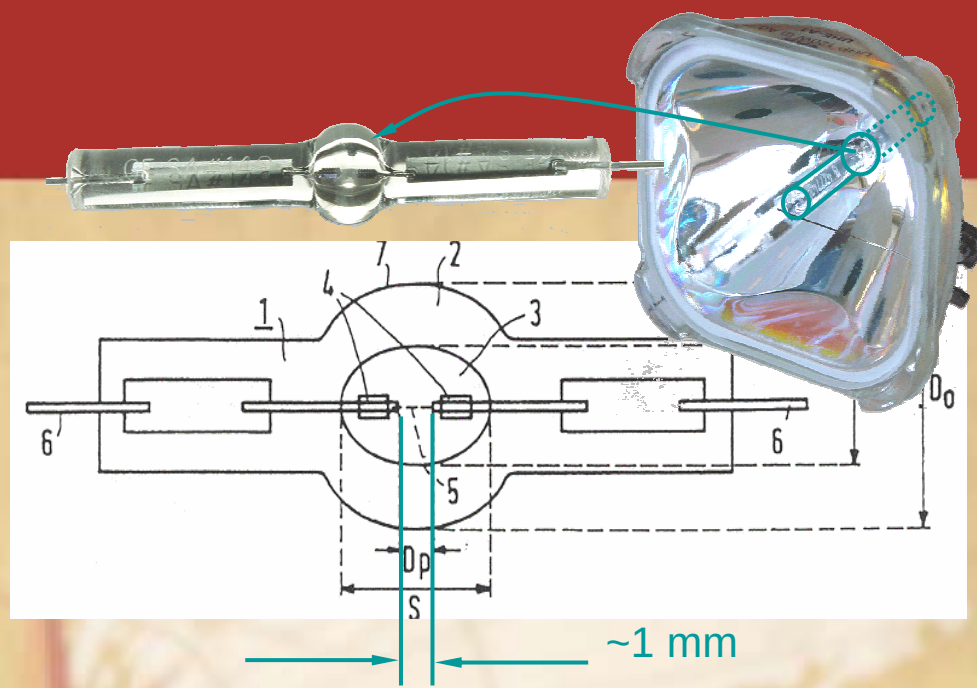
- 1.7 TW = Average Electrical Power Consumption of the World in 2001[#]
- ~1 TW (978 GW) = U.S. Electrical Power Generation in 2005*
 - 39% Gas, 32% Coal, 10% Nuclear, 10% Hydro, 6% petroleum, 2.2% Renewables*
 - ~20% for lighting⁺;
- John Waymouth, from Sylvania Lighting, estimated that in the visible range (400-700 nm) the earth's color temperature would appear to be 1000 - 2000 K.
- Overall, the earth radiates in the IR with blackbody temperature of around 300 K.
- Any intelligent life form sophisticated enough to see us would immediately recognize this non-equilibrium radiation pattern as a sign of intelligent life on our planet.

Fluorescent Lamps



- Inert Gas with Hg
- 0.1 - 10 torr Ag
- 5 - 15 mtorr Hg
- 170 - 200 mA
- 100 - 675 V

Mercury Vapor Lamps



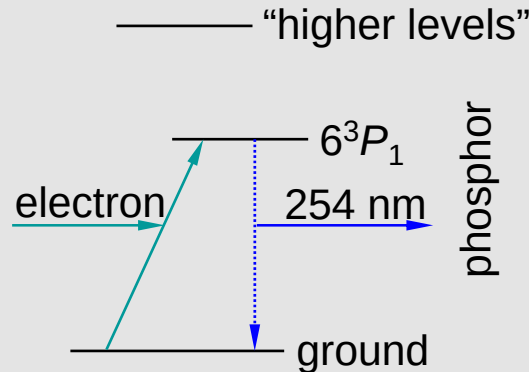
Low-Pressure Mercury

few torr Ar

few mtorr Hg

$n_e \sim 10^{11} \text{ cm}^{-3}$

$T_e \sim 1 \text{ eV}$, $T_g \sim 300 \text{ K}$



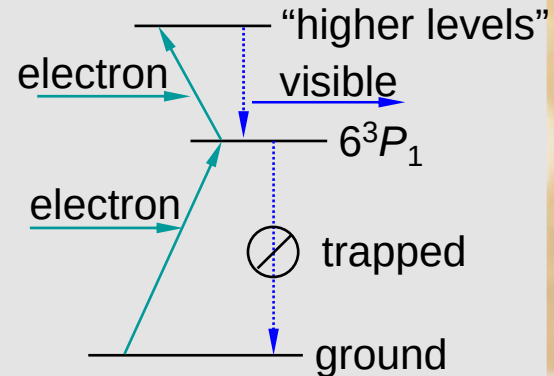
Mercury Projection Lamps

~100 watts;

>150 atm Hg;

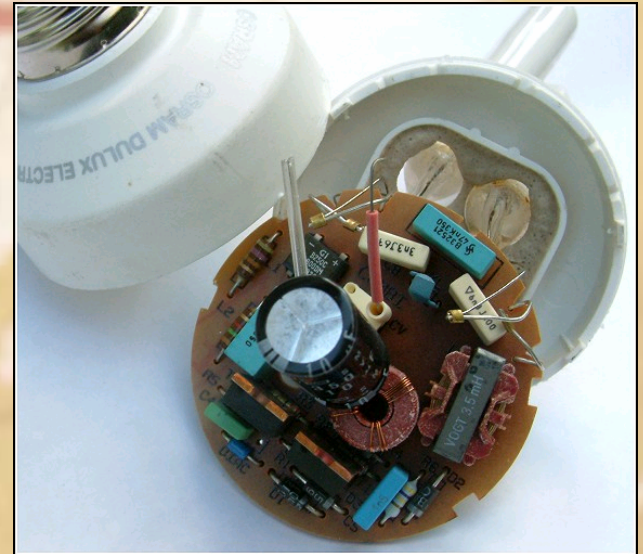
$T_{\text{WALL}} > 900^\circ\text{C}$;

$T_{\text{MAX}} > 1125^\circ\text{C}$



Compact Florescent Lamps (CFLs)

- CFLs compared to traditional incandescent bulbs:
 - Use 1/3 the energy
 - Last 10x longer
 - Generate 30% of the heat
 - Can prevent 450 lbs of greenhouse gas emissions over lifetime
 - Can save over \$30 in power costs over lifetime
- If every American home replaced one bulb with a CFL
 - It would save enough energy to light an additional 2.5 million homes
 - It would reduce greenhouse gas emissions by the equivalent of 800,000 cars



Large Screen Plasma TVs



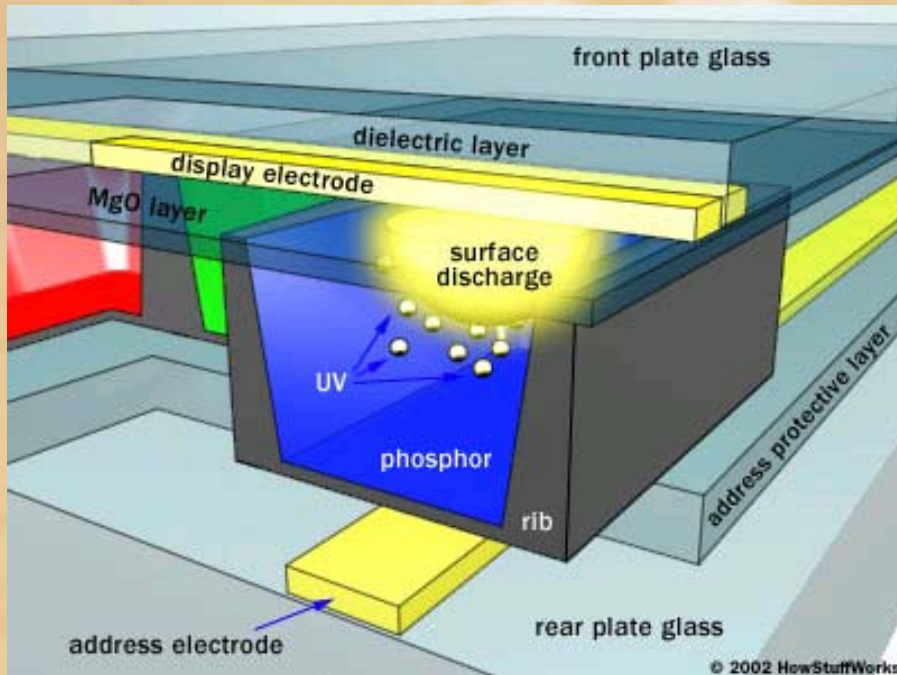
SUPER SIZED TVS:

- 103" diagonal HDTV available from Panasonic for \$70K
- Power consumption: 800 W (65" model)



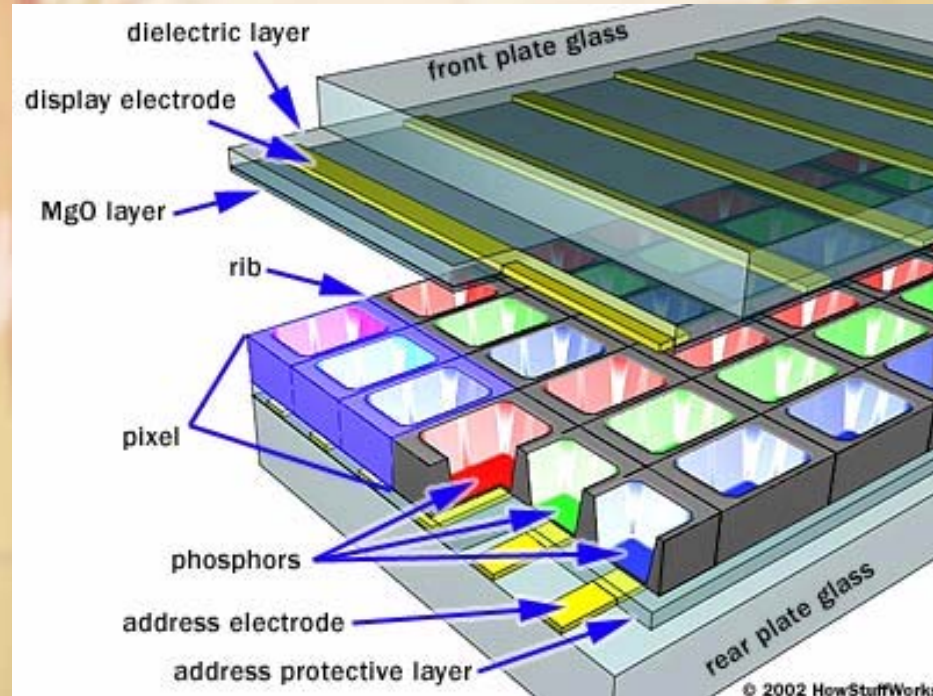
Sources: Panasonic and Samsung

Plasma TVs

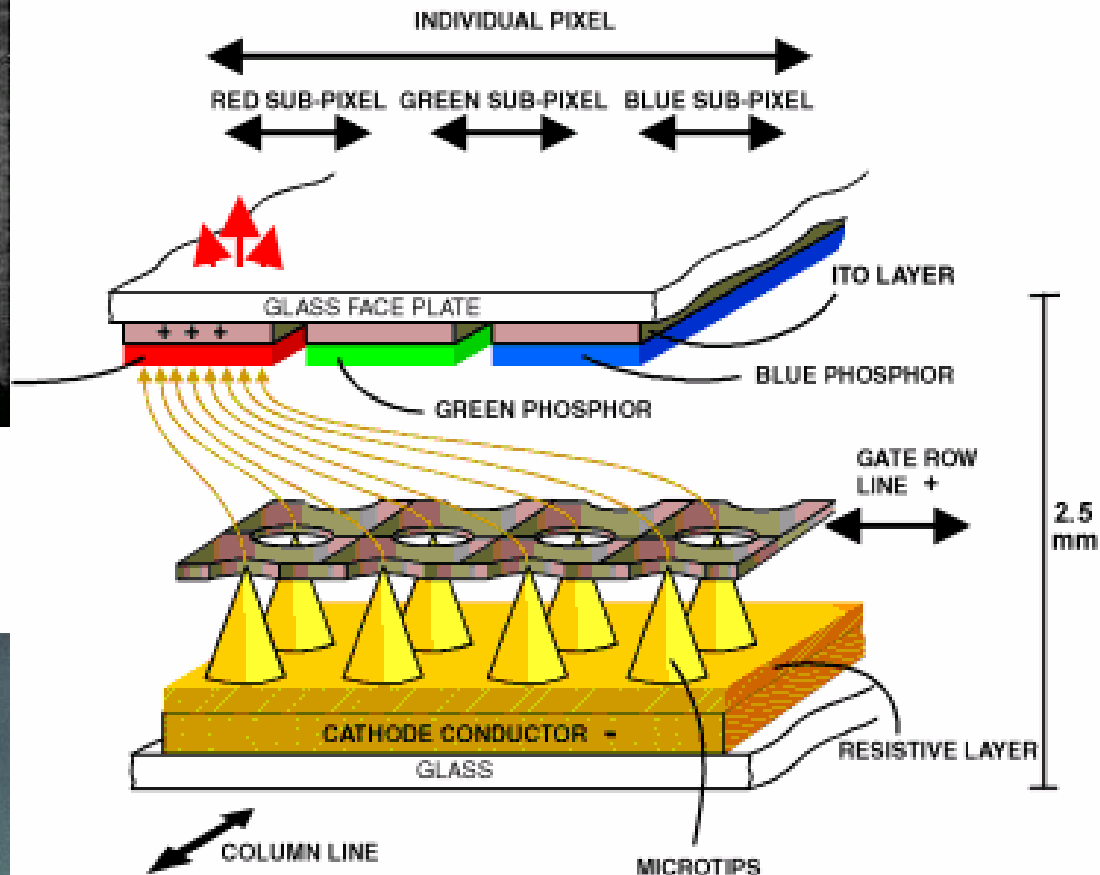
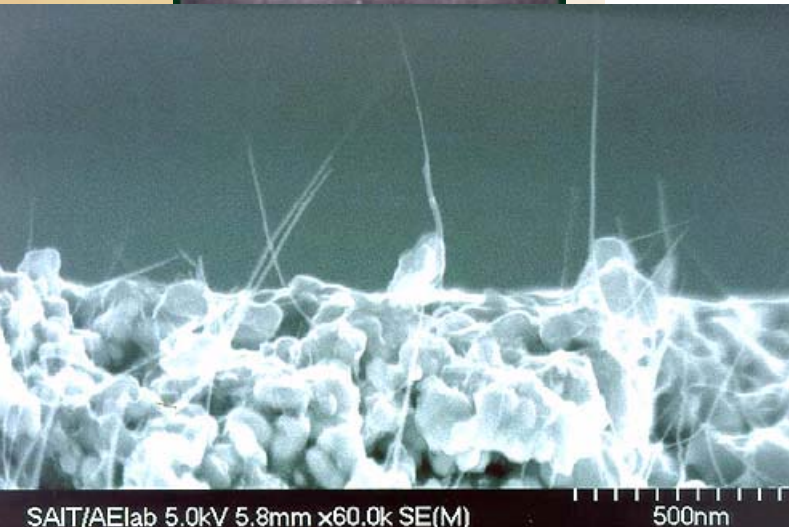
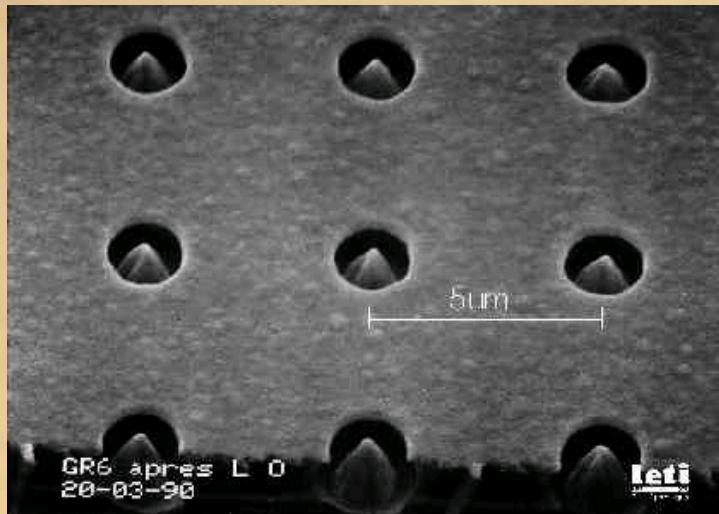


Operational Parameters:

- 100 - 200 V AC driven at 50 kHz
- Simple inert gas Penning discharges, typically: few % Xe generating VUV photons for RGB phosphor stimulation;
- Micro-discharge durations of $\sim 10\text{-}20$ ns
- An RGB micro-cell triad forms each pixel;
- MgO insulating surface stores charge and provides secondary electron emissions



Field Emission Displays: Throwing Off Electrical Fire



MINI LIGHTNING RODS:

~0.5 μm holes; 1.2 μm tall cones;
~100 V potential

Sources: AIP, ITRI

Micro-damage Due To Electro-Static Discharges (ESD)

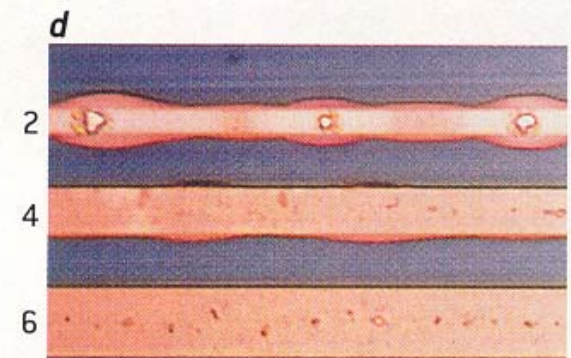
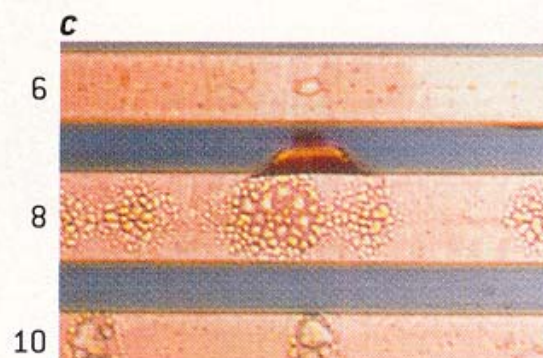
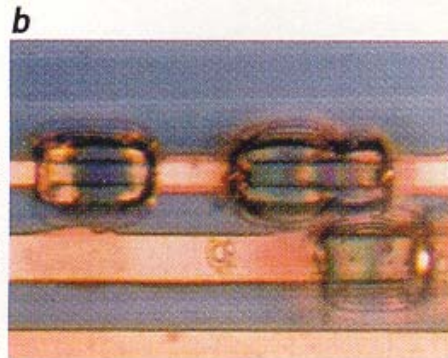
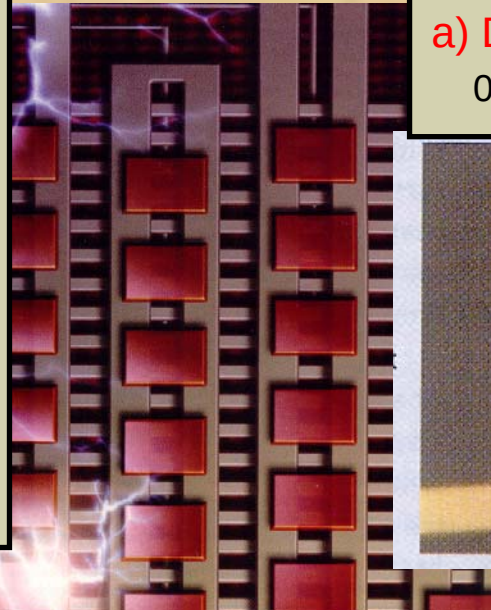
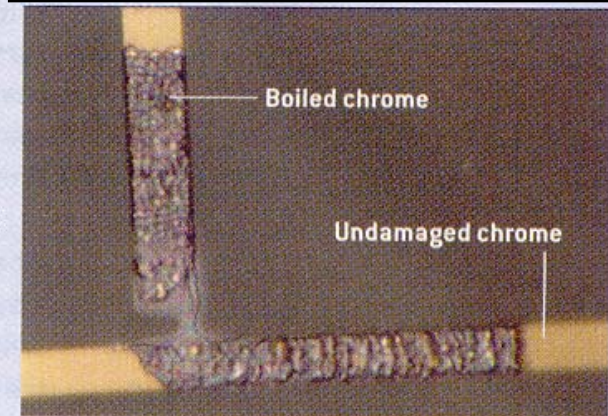
ESD can have potentials of 1–10 keV

Damage includes:

- Changed feature patterns due to photomask damage;
- Thermal breakdown - Internal temperatures can exceed 1500 C;
- Dielectric breakdown;
- Avalanche currents;
- Electro-current restrictions.

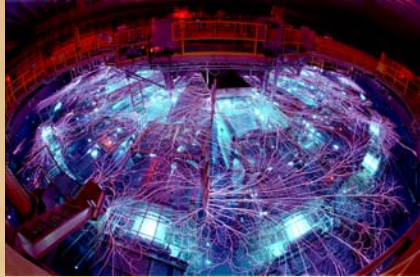
a) Damaged Chrome Reticles

0.25 um feature sizes

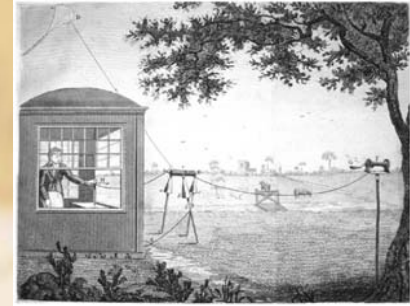


Copper interconnect heating can cause: b) Insulator cracking; c) blistering & evaporation of the copper; d) Cu extrusion through tantalum sidewalls (occurs at >3,017 C)

We Are the Beneficiaries of the Wonderful Science & Technology Discharged From Ben Franklin's Electrical & Lightning Experiments



Battery of Leyden Jars
circa 1760-1769



References & Selected Reading:

- *Benjamin Franklin: An American Life*; Walter Isaacson, Simon & Schuster, 2004
- Benjamin Franklin Tercentenary
- *Franklin and Electrostatics - Ben Franklin as my Lab Partner*; Robert A. Morse, Developed at the Wright Center for Innovative Science Teaching, Tufts University, 2004
- J. Bigelow, *Works of Benjamin Franklin*, Vol II, p200, 1904
- University of Florida Lightning Research Group; Drs. M. Uman and V. Rakov, Co-Directors; www.lightning.ece.ufl.edu
- National Oceanic & Atmospheric Administration (NOAA)
- *Lightning Rods for Nanoelectronics*, Steve Voldman, Scientific American, 2002
- [http://en.wikipedia.org/wiki/Orders_of_magnitude_\(power\)](http://en.wikipedia.org/wiki/Orders_of_magnitude_(power))
- DOE Energy Information Administration, Report: DOE/EIA 0348-2005
- Sandia National Labs
- GE Lighting

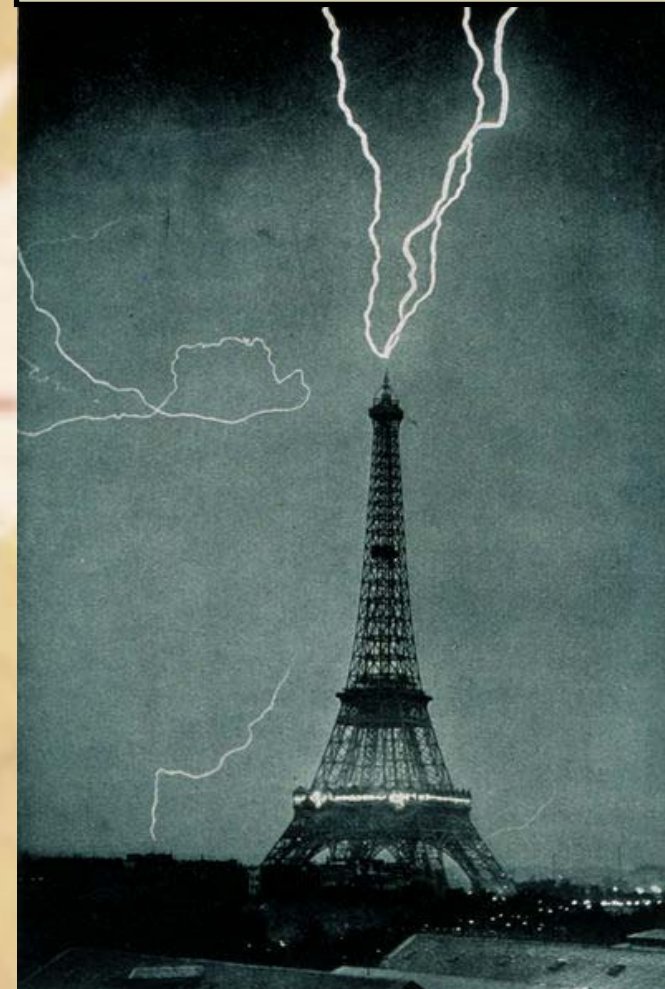
29 April 1749

Postulates Lightning as a Very Large Electrical Spark

AMONG FIRST PHOTOS:

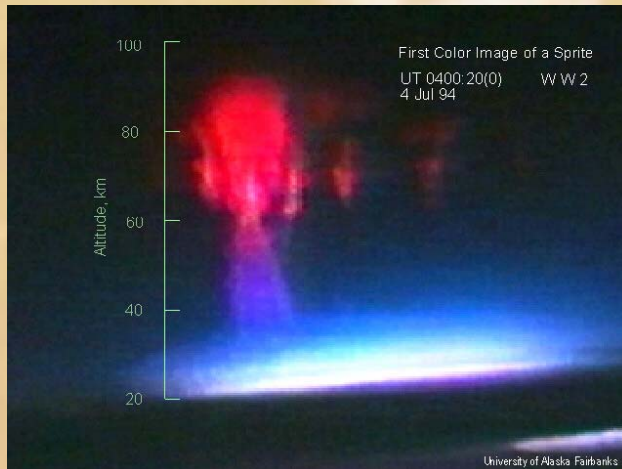
Taken June 3, 1902

By M.G. Loppe

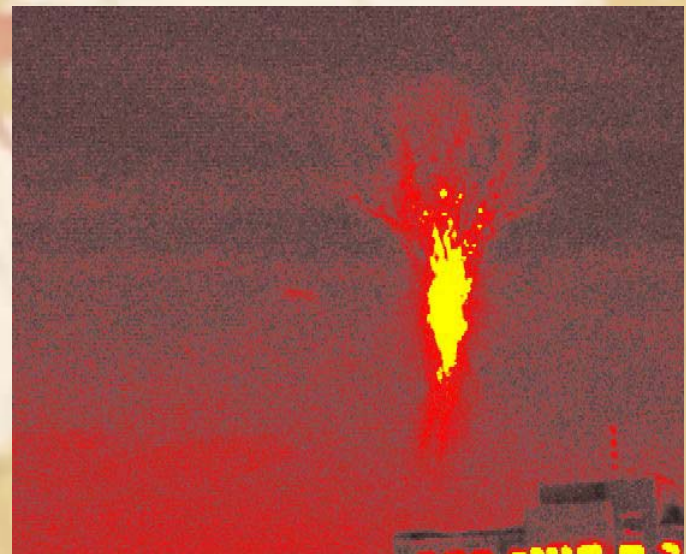
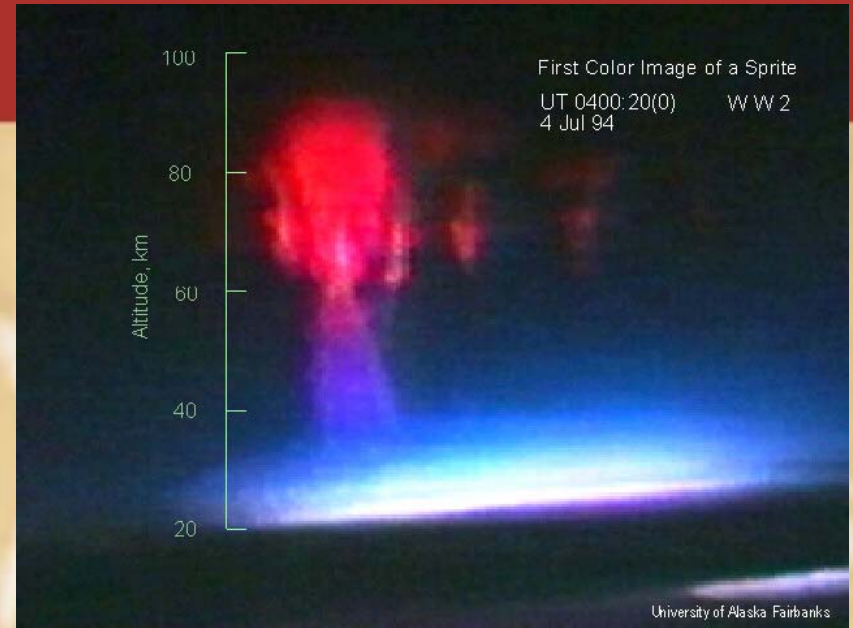


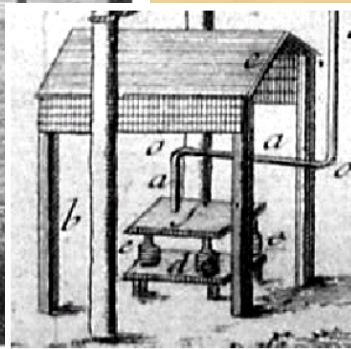
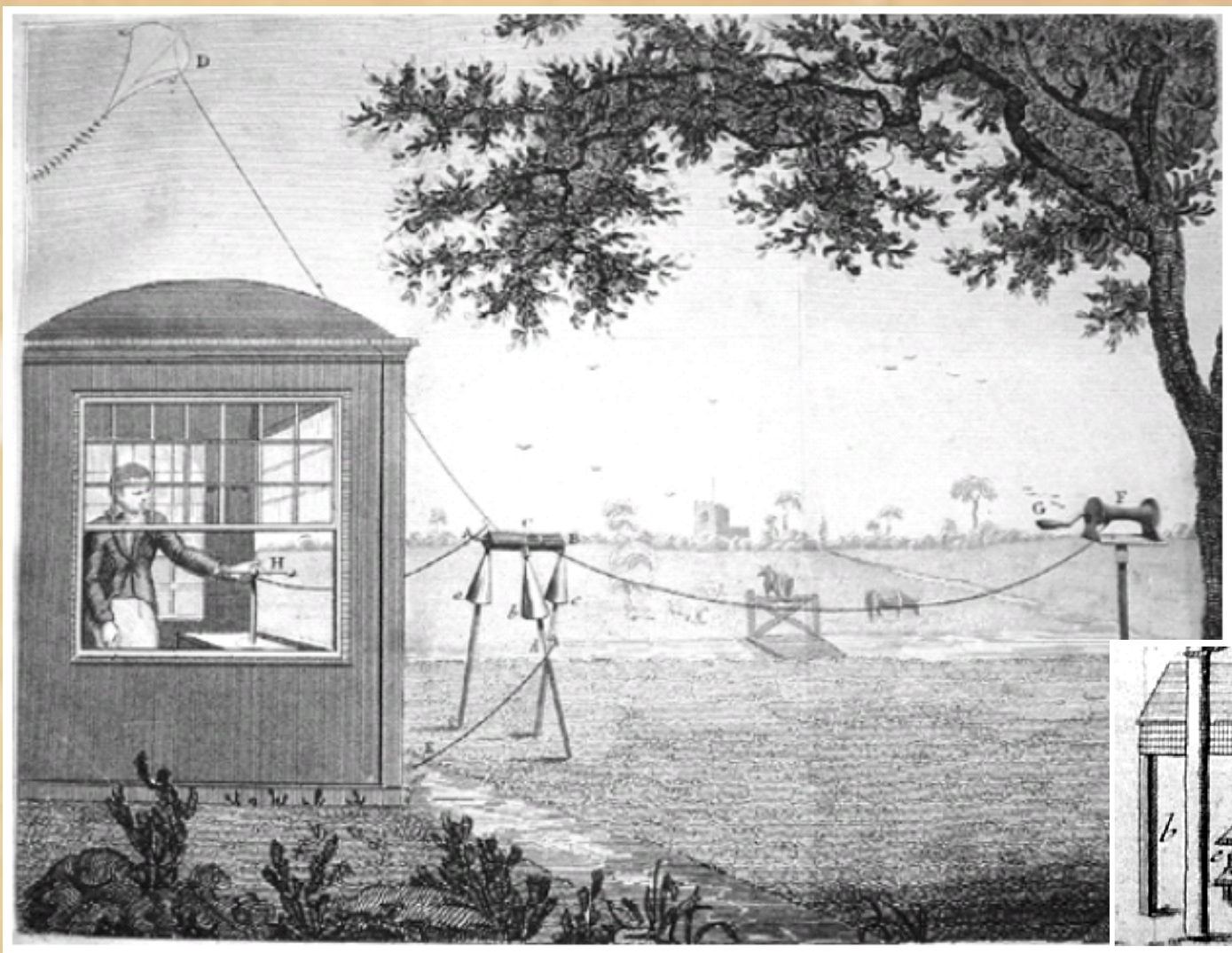
Sprites (upward lightning)

First Image (left) taken
4 July, 1994



Upward Lightning



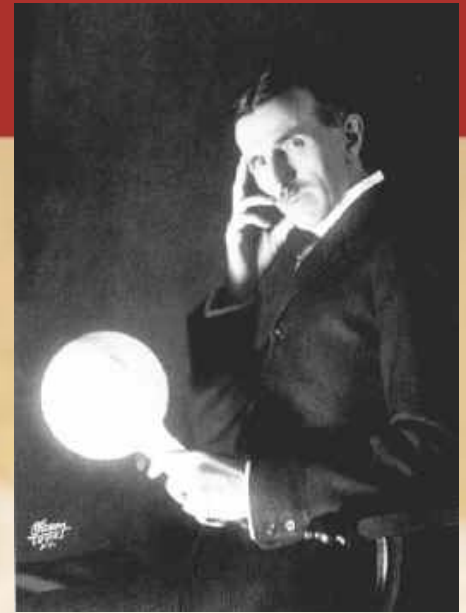


Sources: ?????

Nikola Tesla's Phosphor Bulb

"My project was retarded by laws of nature. The world was not prepared for it. It was too far ahead of time. But the same laws will prevail in the end and make it a triumphal success" ~ Tesla on the failure of his "world wireless" project in 1919

In the 1890's, Tesla developed a wireless light bulb, a glass bulb with a phosphor coating and filled with rarefied gas that was powered by a Tesla coil. Despite the increased efficiency of the bulb, Edison's Incandescent bulbs remained more popular and recognized. Tesla, as seen in the photos above, was never shy about demonstrating these phosphor bulbs for dramatic effect.



Lightning Rod Chronology

- Pointed rod used to draw electricity from the sky thus preventing lightning strikes proposed in letter to Collinson July 1750
- Letter published in a collection by Collinson in April 1751 as a pamphlet titled "Experiments and Observations on Electricity, Made at Philadelphia in America."
- First experiment using a lightning rod performed by D'Alibard under the direction of Comte de Buffon in Marly-la-Ville France in May 1752
- Results of experiment presented to Academie des Sciences by D'Alibard and De Lor three days later, they acknowledge that they were following the description laid out in Franklin's letters
- Franklin attaches the first lightning rod to the roof of his home in Philadelphia to collect data
- Summer or Fall 1752 lightning rods are placed on the spires of the Pennsylvania State House (Independence Hall) and the Academy of Philadelphia (University of Pennsylvania)
- Late fall 1752 Franklin published advice on lightning protection in Poor Richard's Almanac for 1753
- Georg Wilhelm Richmann dies during experiment with lightning rod in St. Petersburg in August 1753, the incident is used to argue against lightning rods by many of Franklin's detractors
- Spring 1761 Franklin receives several reports of lightning rods that portions of have melted or evaporated as a result of discharge. He refines the rod by suggesting a more extensive grounding system and a larger conductor to prevent these powerful discharges from spreading towards the foundations of the houses being protected.
- Republishes "Experiments" in 1769 with modifications to the lightning rod including larger dimensions and the suggestion that painted steel be used in place of gilt iron

First page of
Franklin's
"Experiments and
Observations"



Lightning Rod
1756

Lightning Caused Fires

- Starts ~10,000 forest fires each year, costing \$100M
- From 1991-1995 there were:
 - 30,190 house fires
 - \$175M in annual losses
- % of facility fires caused by lightning:
 - Lumberyards = 18%
 - Churches = 30%
 - Petroleum storage = 61%
 - Power grid outages = 30%



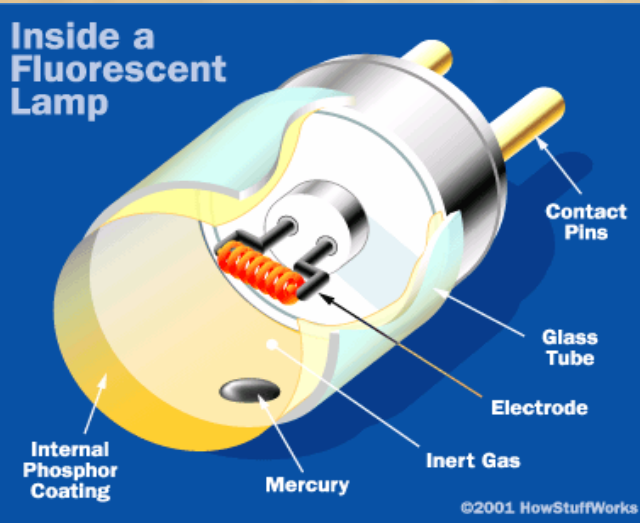
Fluorescent Lamps

PLASMA COLUMNS:

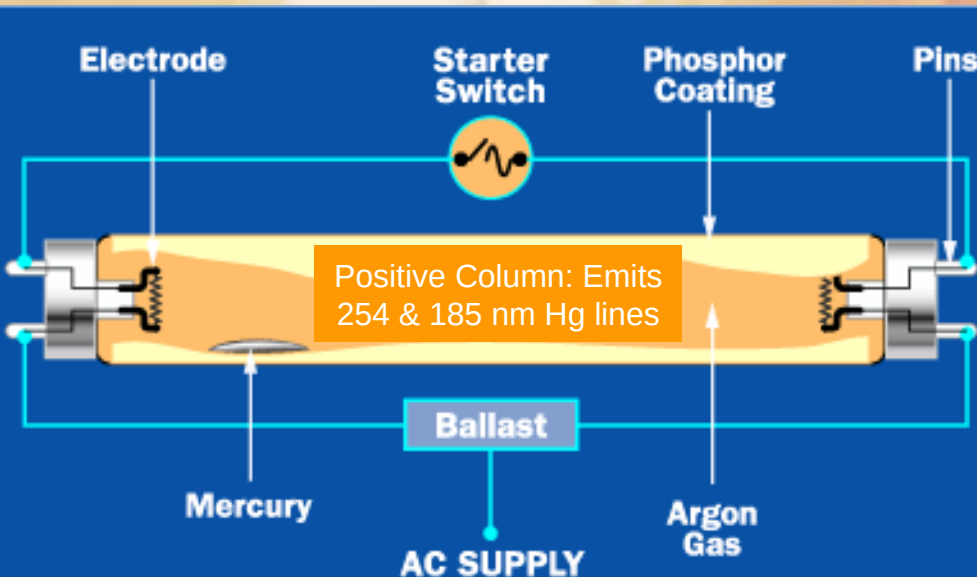
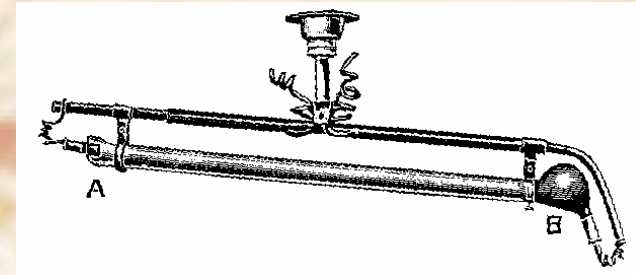
0.3% atms (Argon)

~60 lumens / watt

Inside a Fluorescent Lamp

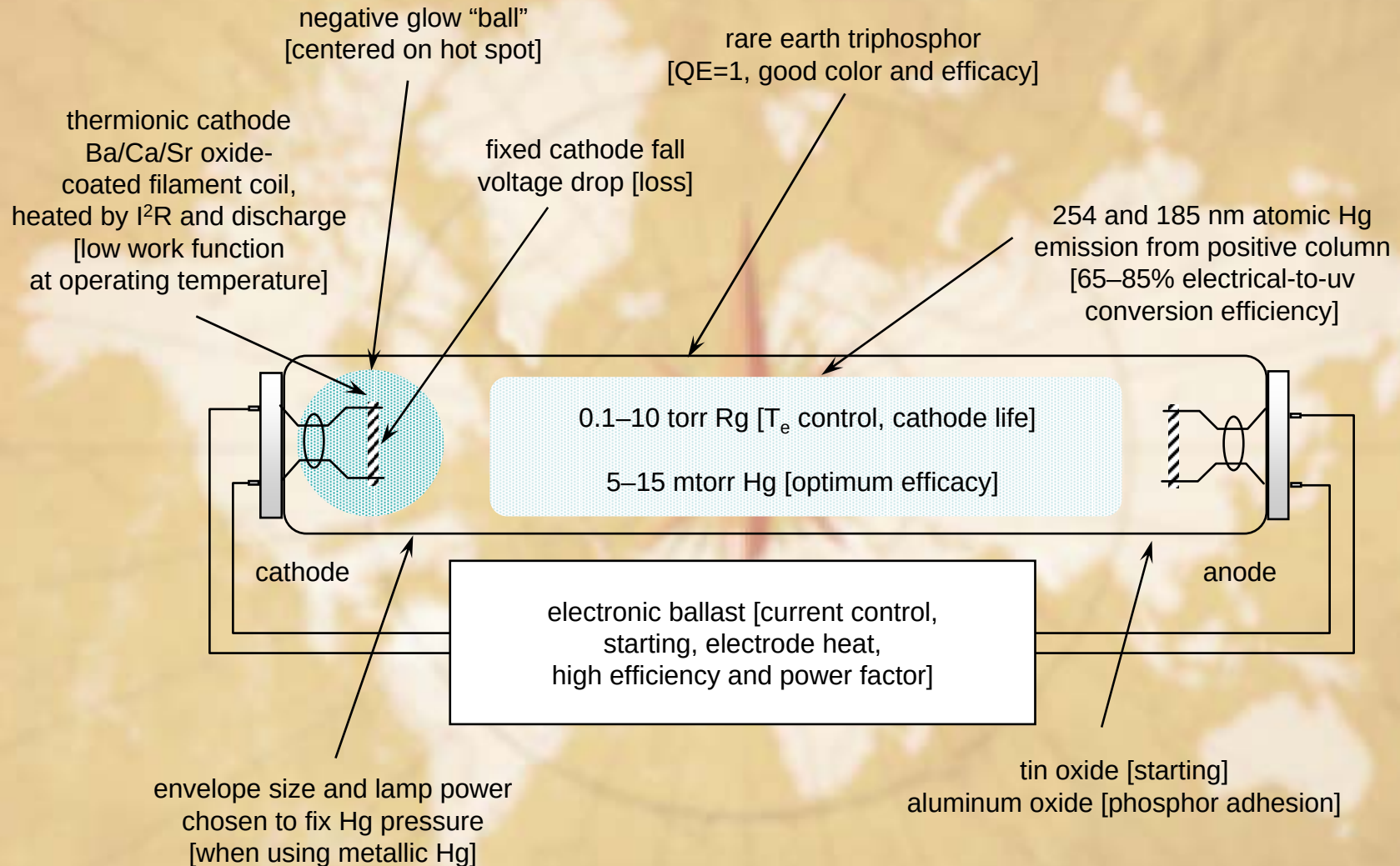


Inert Gas with Hg
0.1 - 10 torr Ag
5 - 15 mtorr Hg
170-200 mA
100-675 V



Lamp Type	Operating Current (mA)	Starting Voltage (V)
F4T5	170	108
F96T8	200	675

Fluorescent Bulb Anatomy



Sodium Lamps

Edit this:???? RELATIVELY NEW:
HPS introduced in 1965

low-pressure sodium

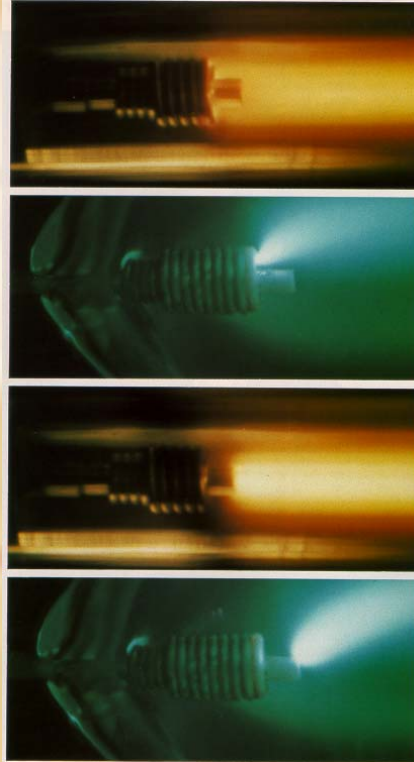
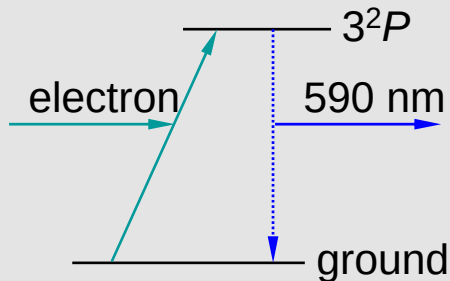
1 - 5 torr Ne

1 - 5 mtorr Na

$n_e \sim 10^{12} \text{ cm}^{-3}$

$T_e \sim 1 \text{ eV}$, $T_g \sim 500 \text{ K}$

———— “higher levels”



high-pressure sodium

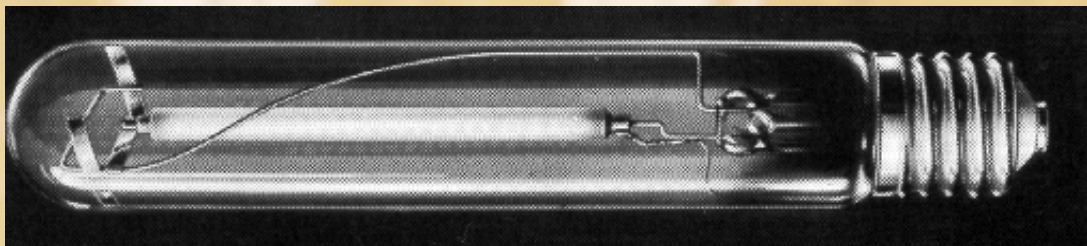
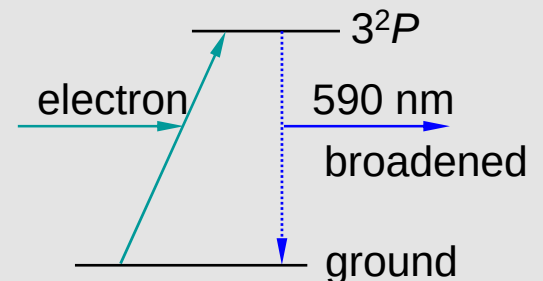
0.5 atm Hg (380 torr)

0.1 atm Na (76 torr)

$n_e \sim 10^{14} \text{ cm}^{-3}$

$T_e \sim T_g \sim 0.3 \text{ eV}$

———— “higher levels”



Source: GE

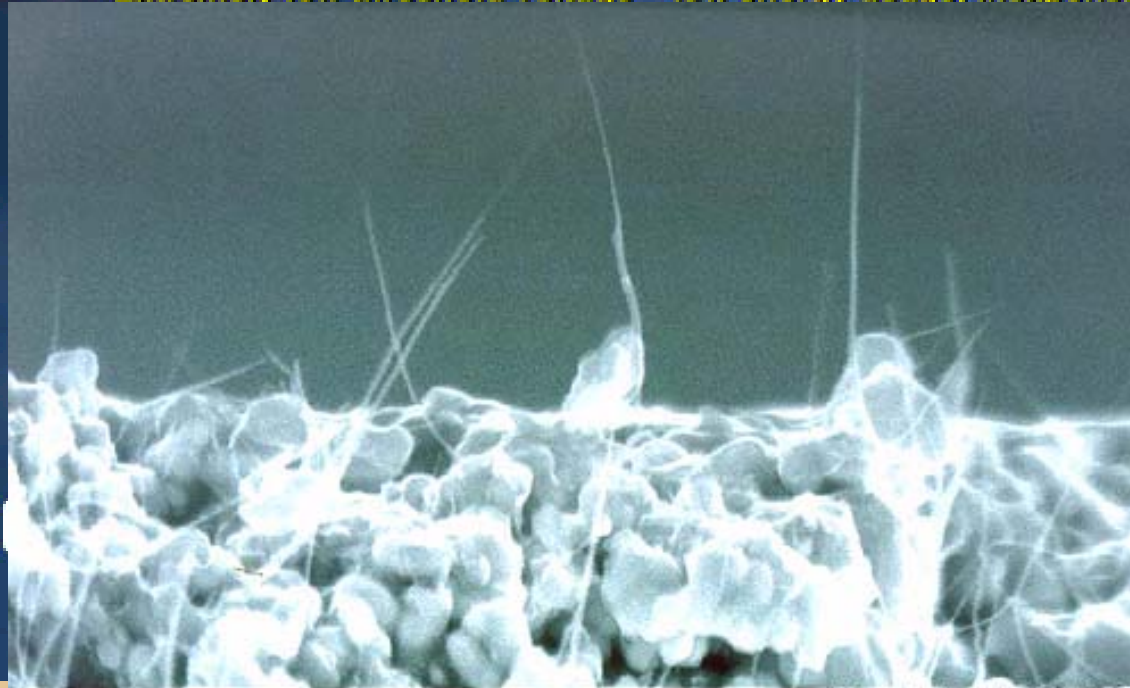
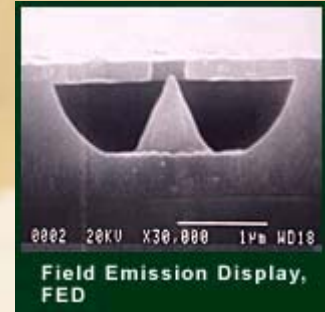
Field Emission Display Principles

???????:

?????????

Cutting Edge: SDNT Field Emission Displays

- Flat panel display, LCD backlighting, other electron devices
- Early market for SWNT
 - 2004 38" SWNT FED prototype
 - Expected launch 2006-2007
- **SDNT Advantages**
 - **SDNT size and conductivity make them the ideal field emitter**
 - **Easy to manufacture = low cost**
 - **Extremely high redundancy = high durability**
 - **Extremely low threshold voltage = low energy usage, inexpensive electronics**



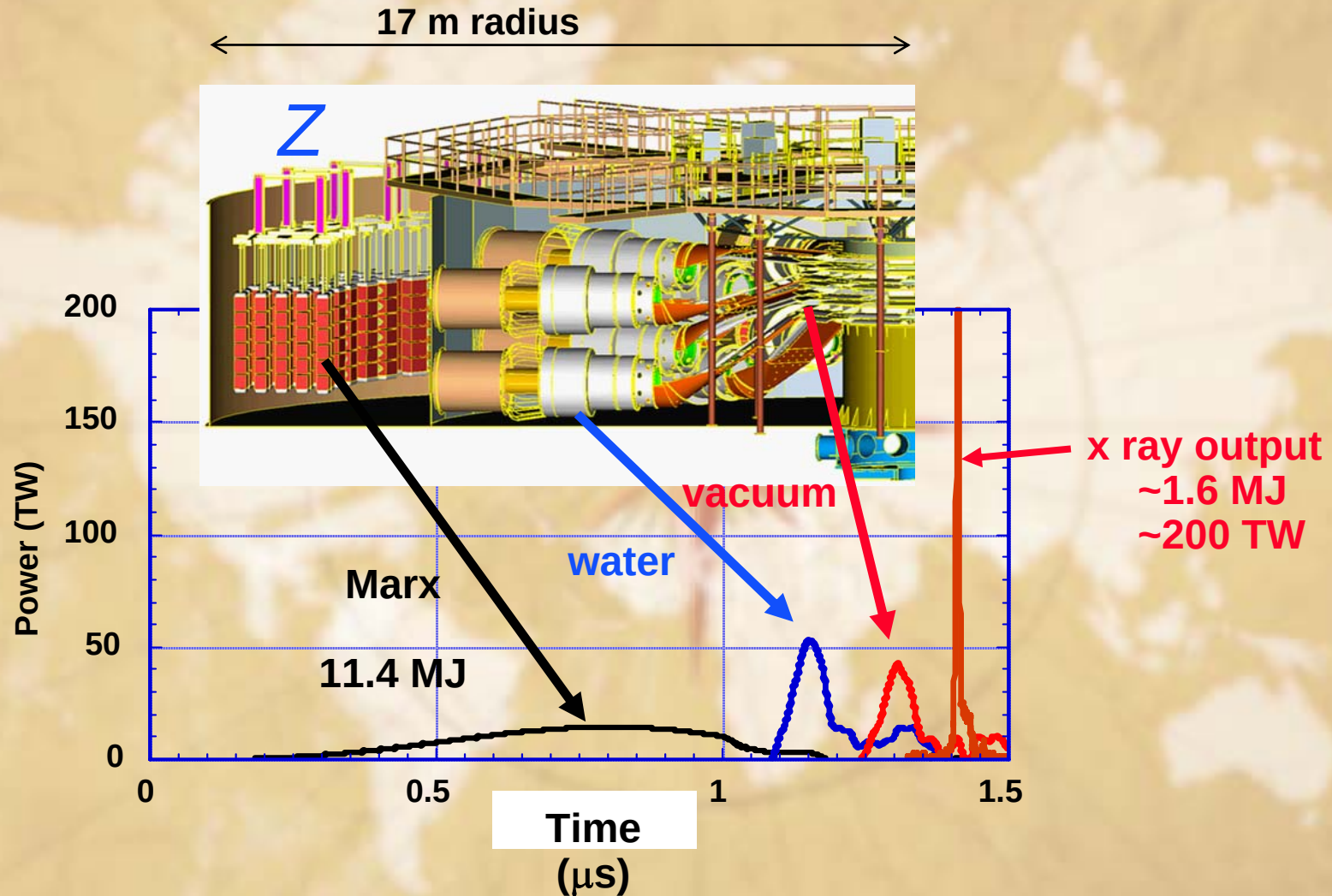
Vacuum

Sandia NL's Z-Machine

ENERGY CONVERSION:

Electrical $\rightarrow$ X-ray

15% efficiency



Source: Sandia National Lab

Sandia NL's Z-Machine

EM Radiation

Laser intensity: $3 \times 10^{15} \text{ W/cm}^2$

T_{rad} : 400 eV

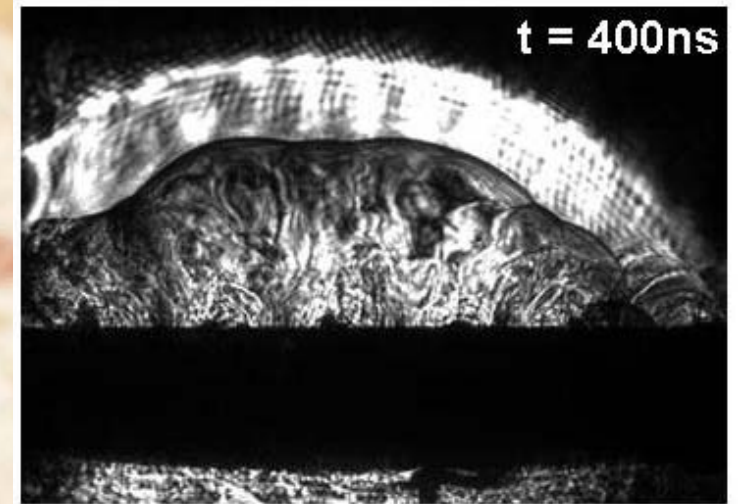
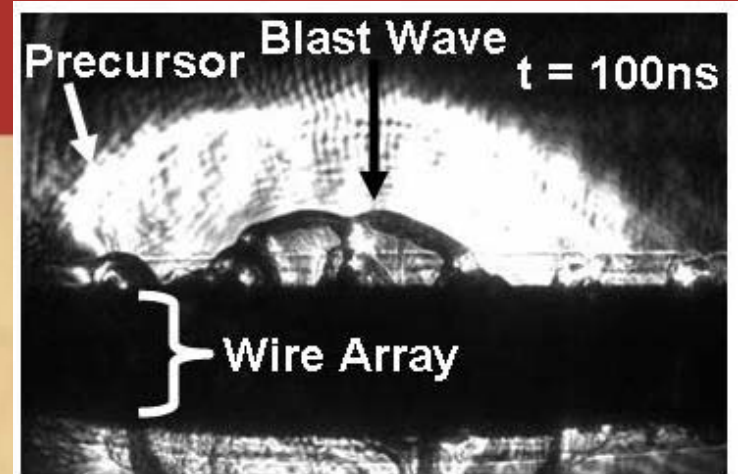
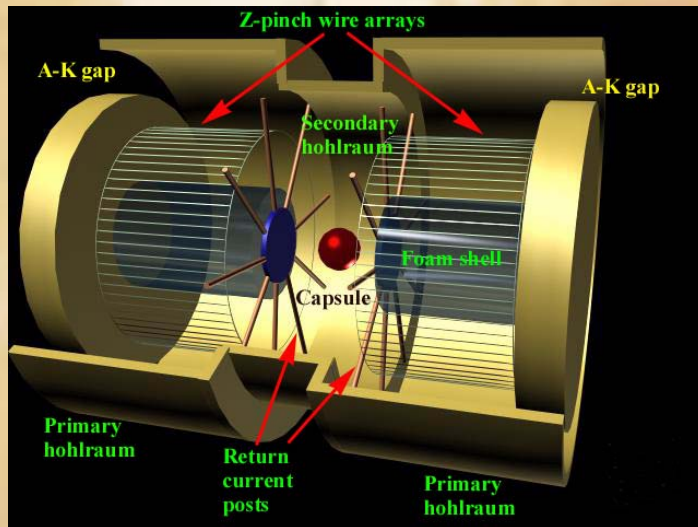
E-field strength: $1.5 \times 10^{11} \text{ V/m}$

B-field strength: 500 T

Ablation pressure:

1 μ laser: $4 \times 10^{12} \text{ W/cm}^2$

Radiation: 75 eV

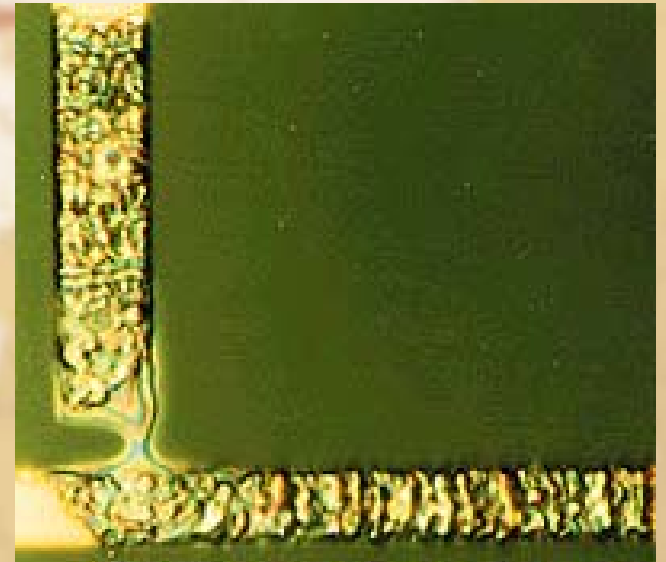
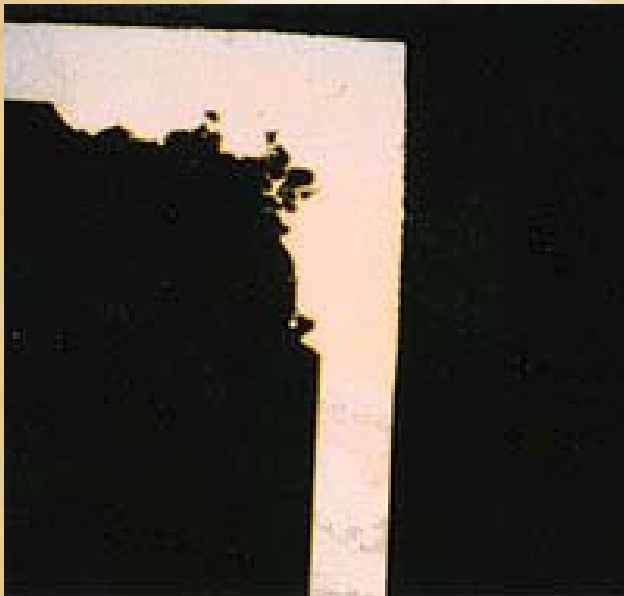
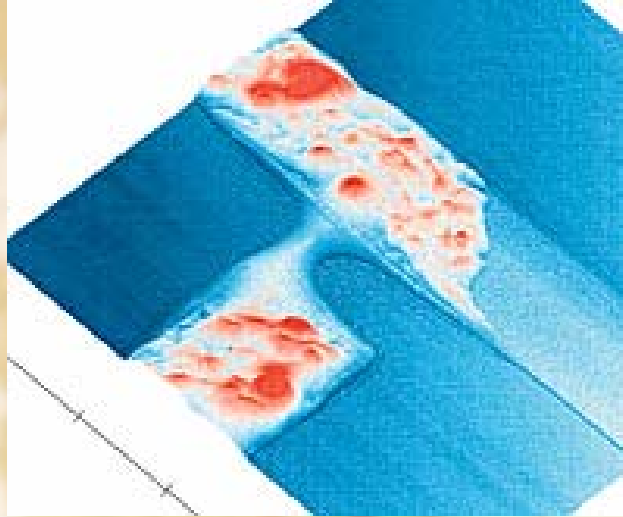


ESD Induced Defects

CHROME RETICLES:

0.25 um feature sizes

ESD causes erosion at corners



Source: Micromagazine