Vacuum Technology and the Birth of Electronics

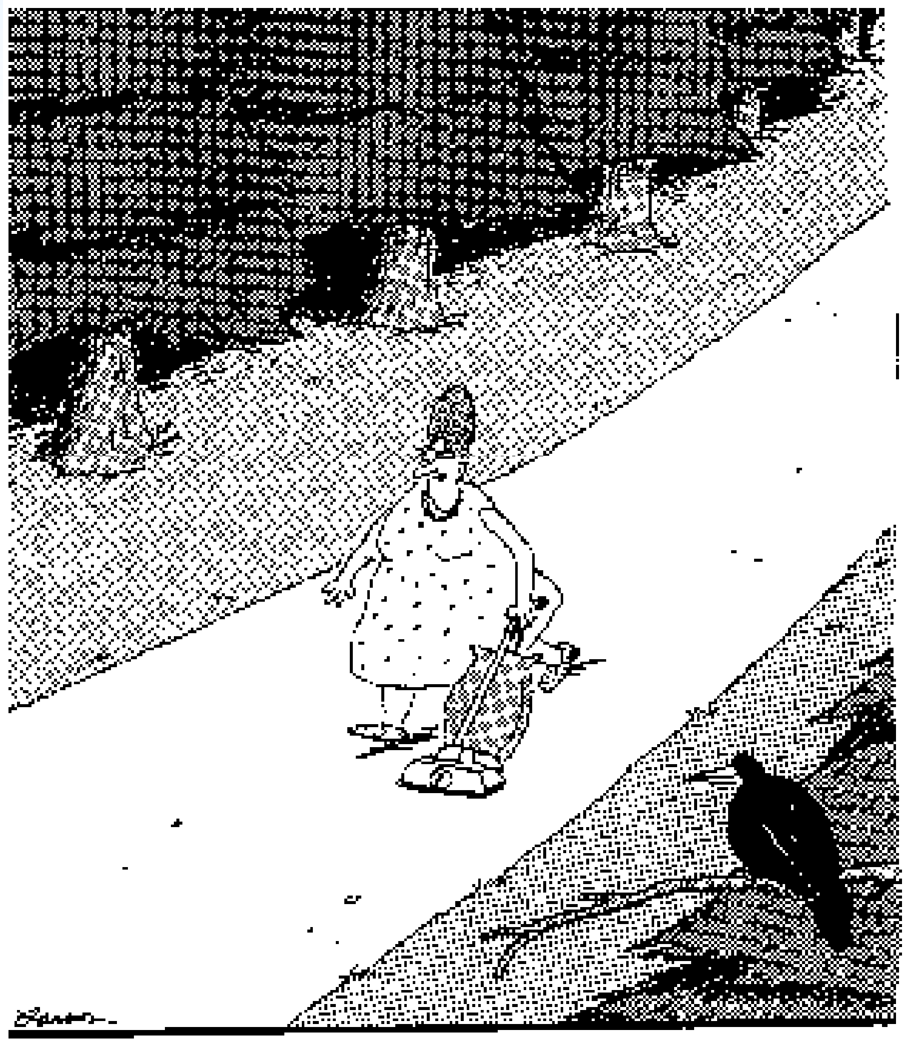
- or -

How Almost Nothing Changed the World

Steve Hansen KB1TCE

Pen Bay ARC

Gotta Start with a Joke



The woods were dark and foreboding, and Alice sensed that sinister eyes were watching her every step. Worst of all, she knew that Nature abhorred a vacuum.

Overview

The results of vacuum technology are everywhere:

All semiconductors
Displays
Imaging devices
Glass coatings of all sorts
Wear coatings on cutting tools
Decorative films
Particle accelerators
X-ray systems
Manufacture of high purity metal alloys (VIM/VAR)
MEMS devices
Space simulation chambers
Vacuum Tubes (of course)
Biological films
The chrome on your plastic faucet or bumper
Freeze dried food ……

Vacuum Ranges

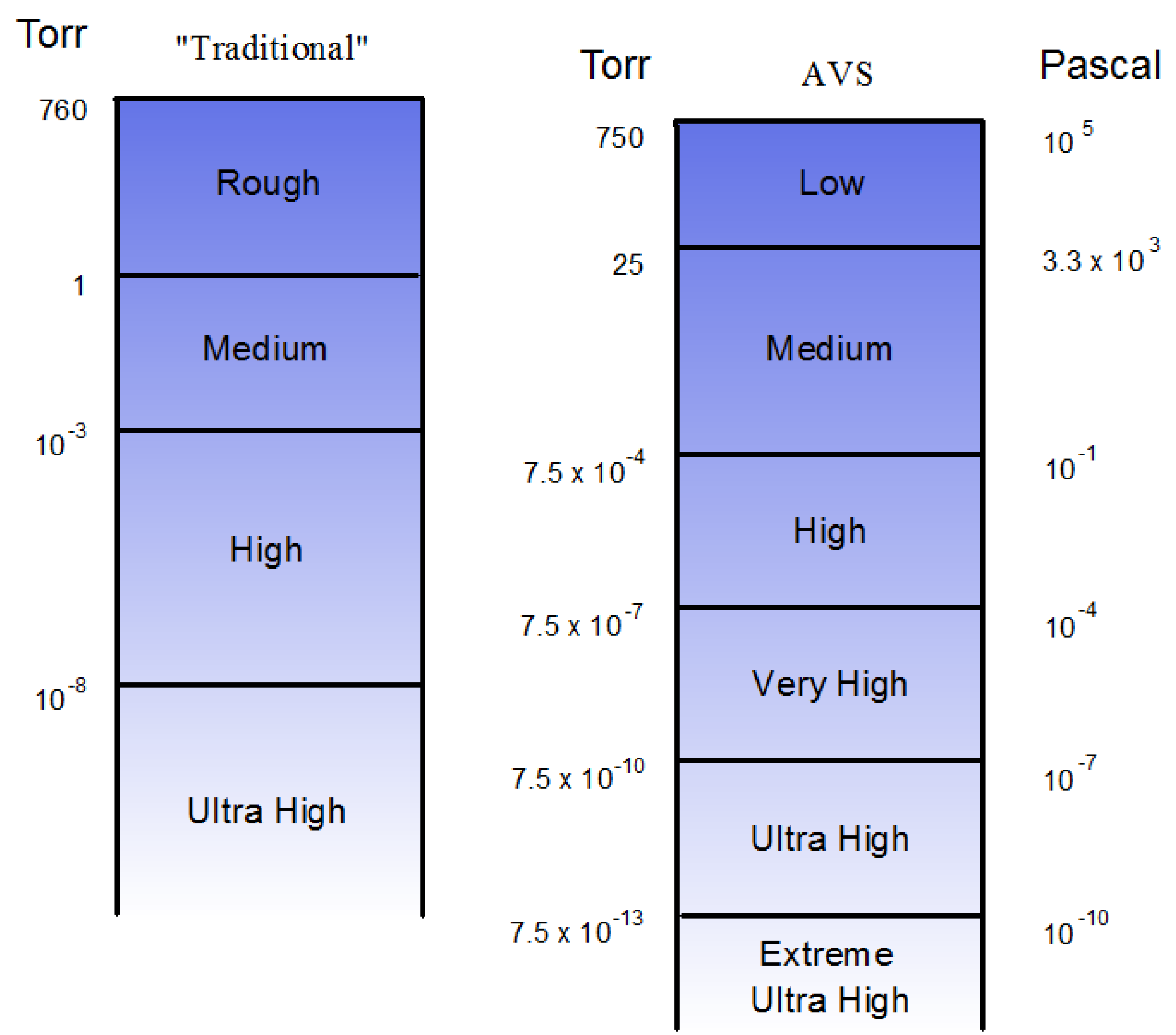


Illustration courtesy of MKS Instruments

Some Properties of Vacuum

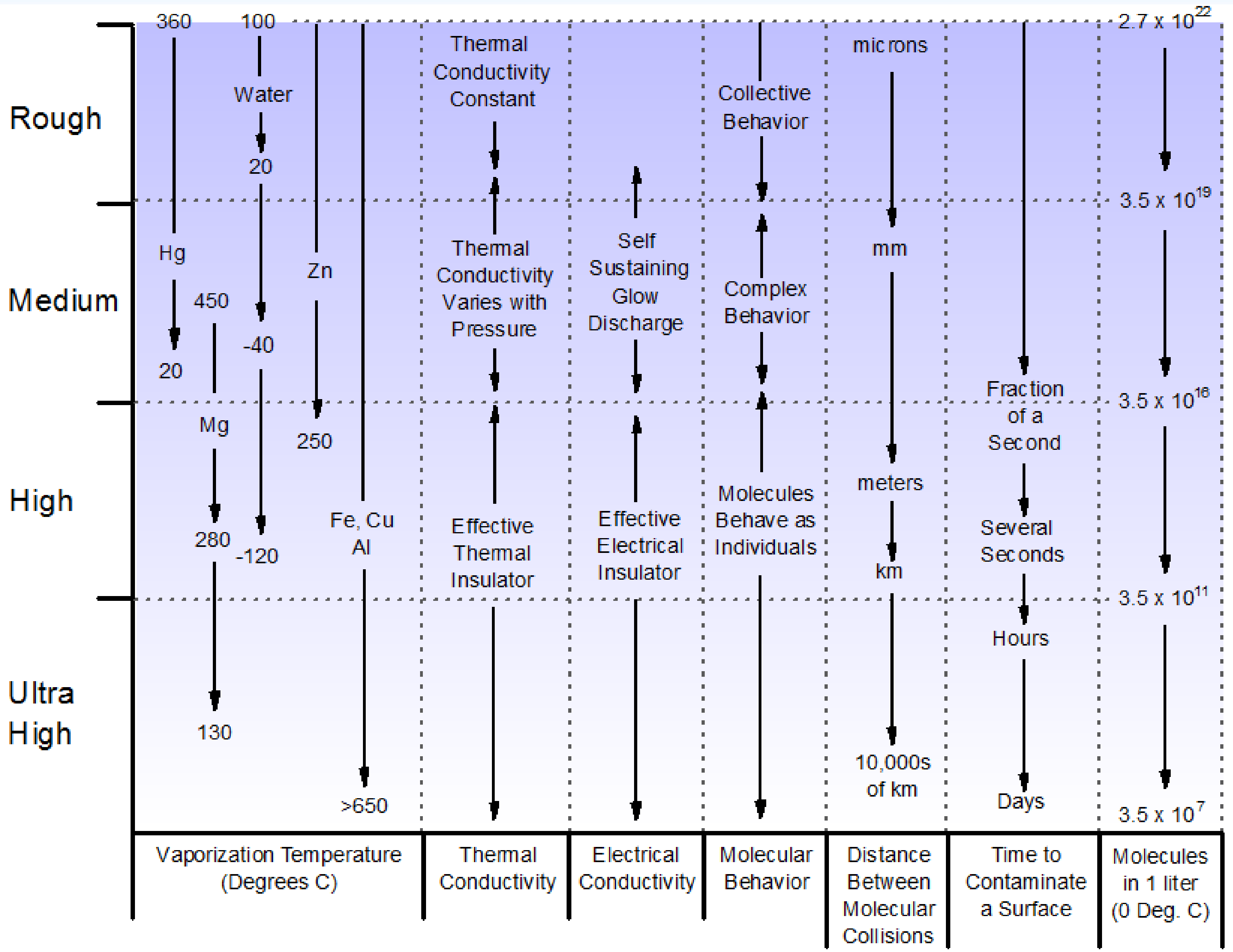
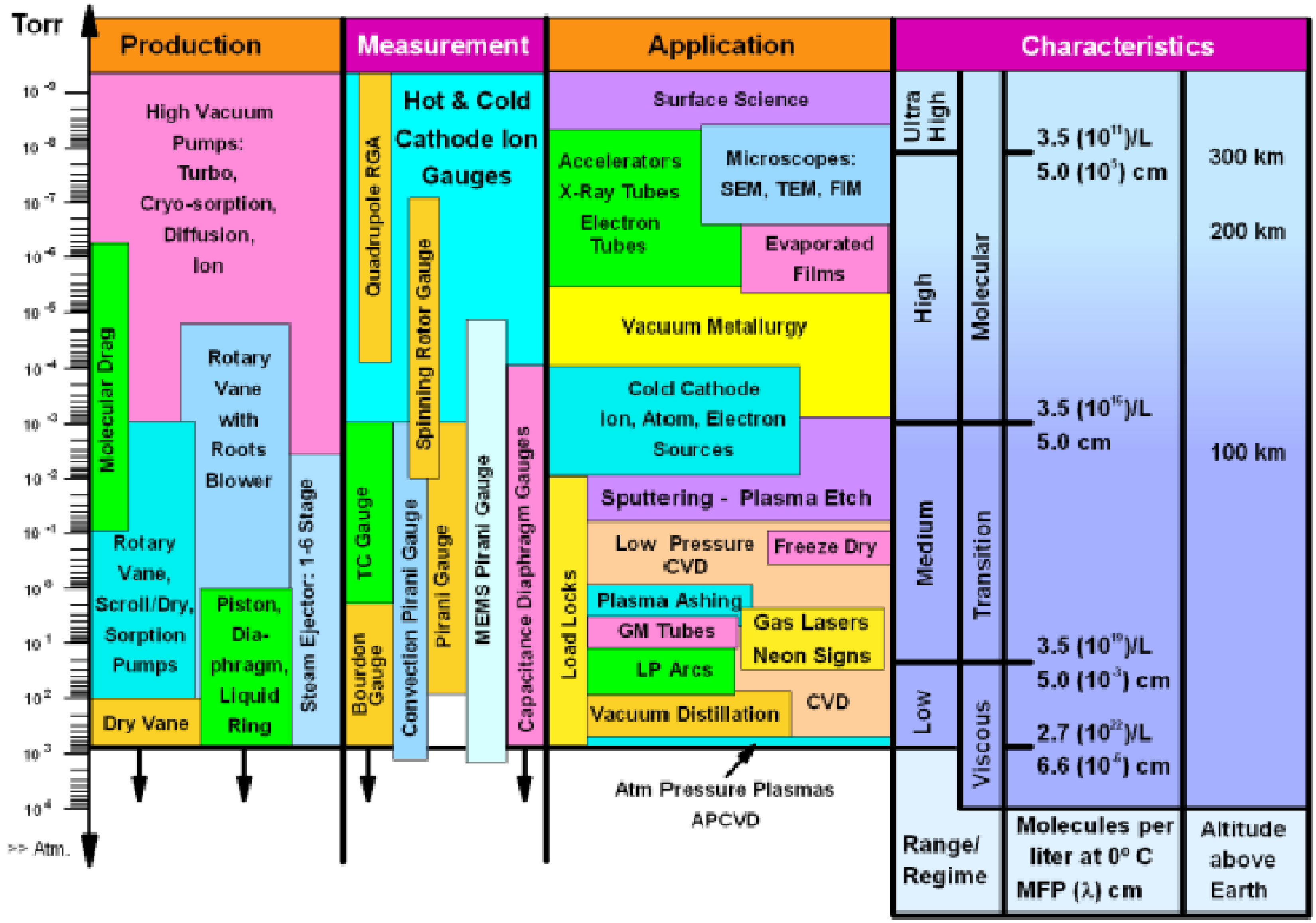


Illustration courtesy of MKS Instruments

Making, Measuring & Using Vacuum



Evolution of Vacuum Related Technology

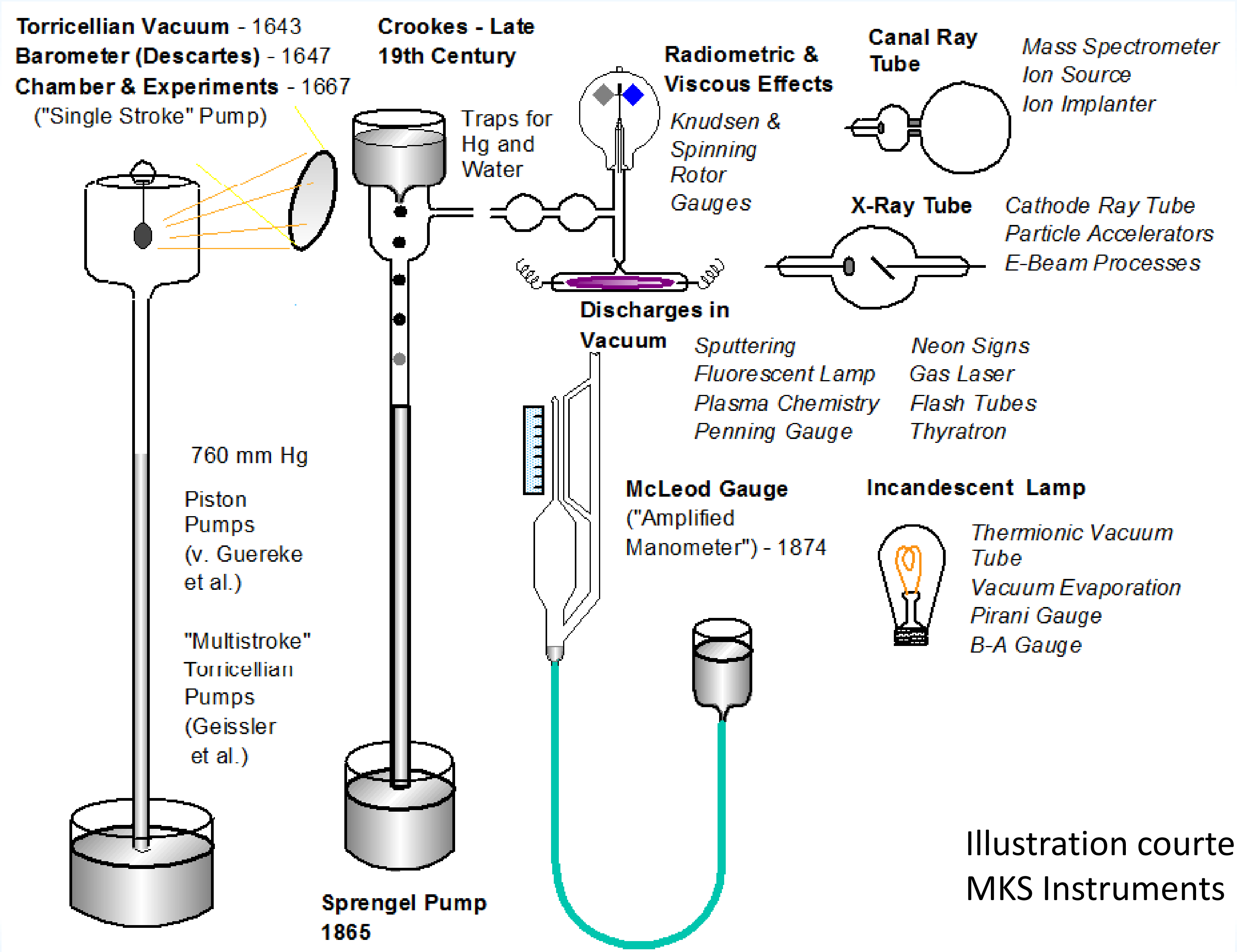
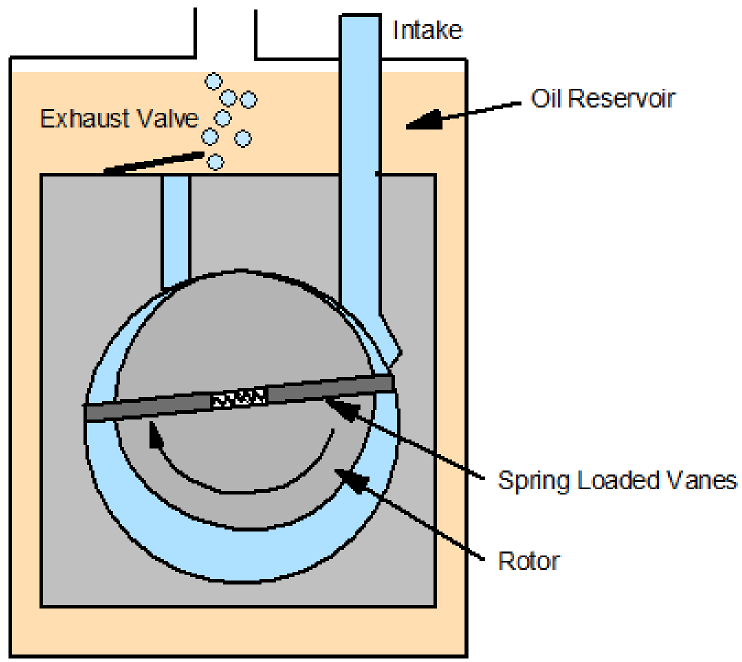
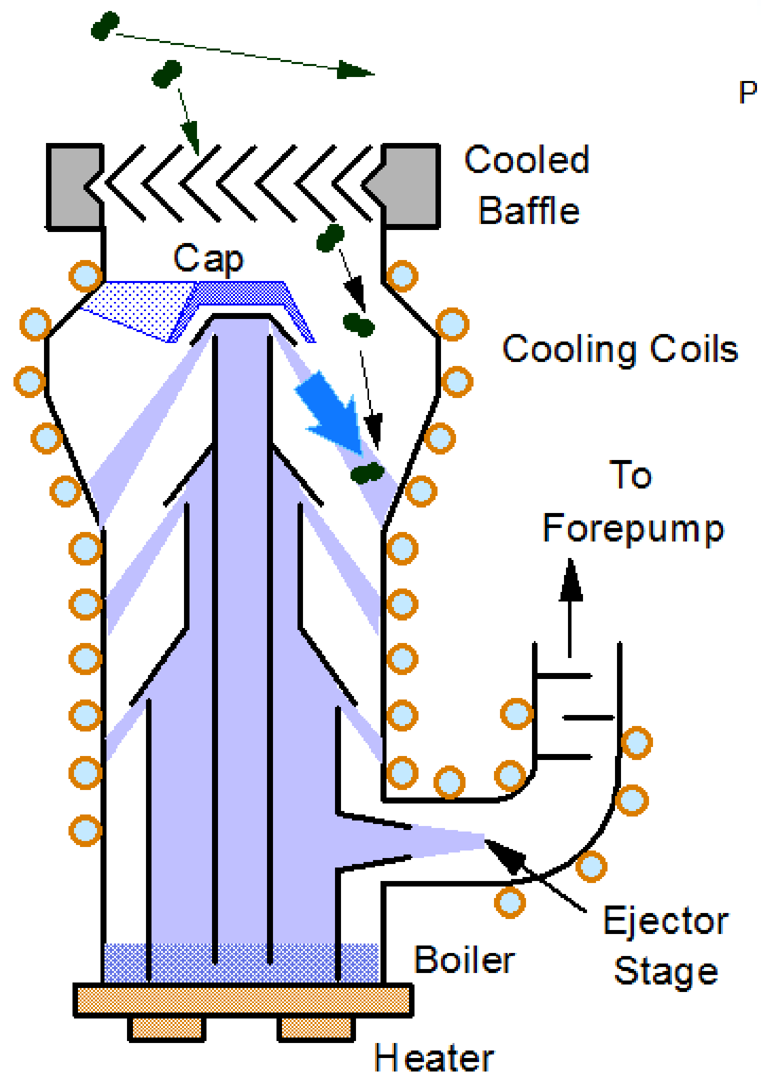


Illustration courtesy of MKS Instruments

The Pumping Revolution





Oil-Sealed Rotary Vane Pump: Gaede 1910 - Displacement

Diffusion Pump: Langmuir 1916 - Momentum Transfer

Illustration courtesy of MKS Instruments

Electron Tube Manufacturing

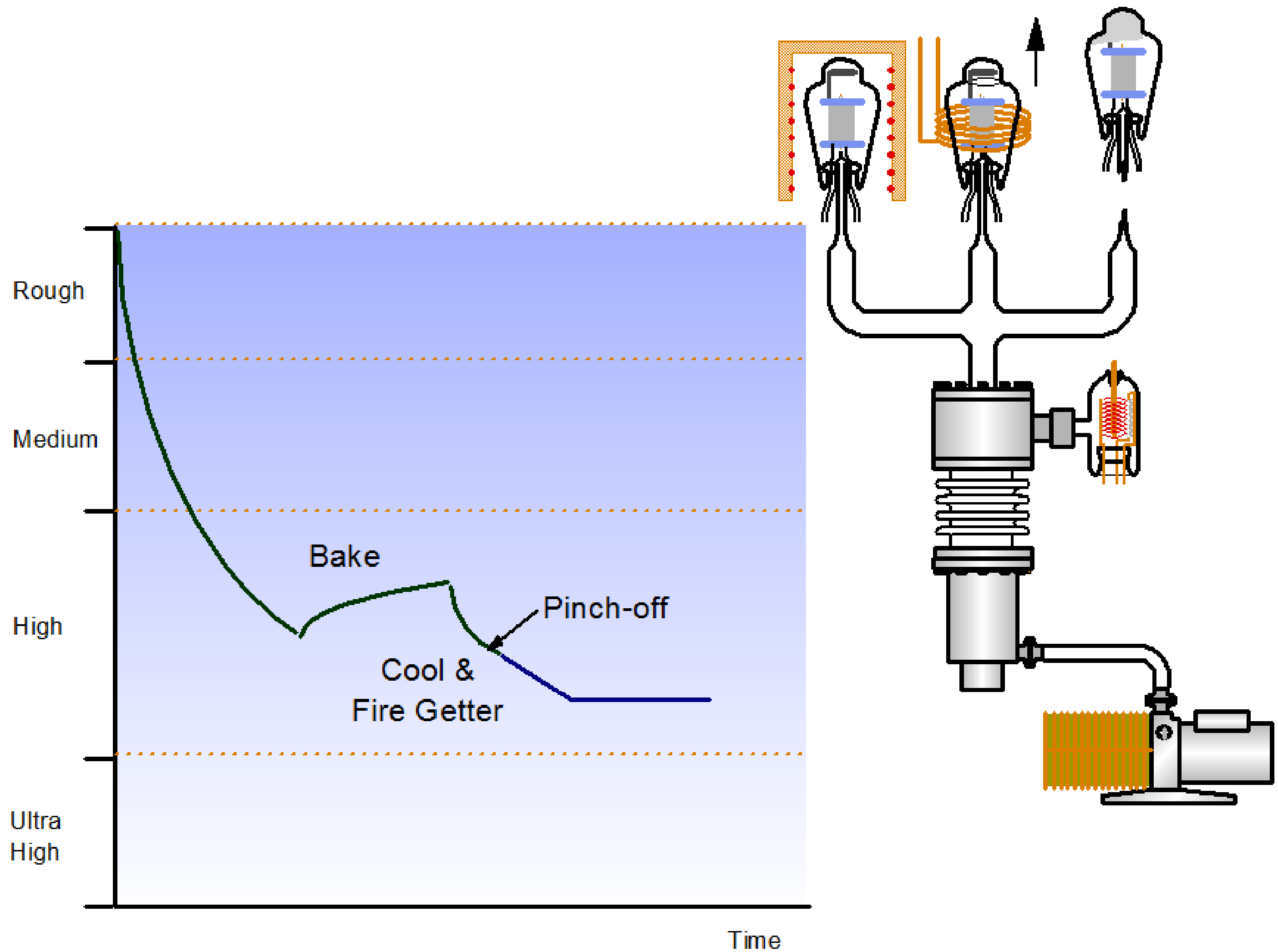


Illustration courtesy of MKS Instruments

John Strong's Chamber for Aluminizing the 36" Mt. Wilson Mirror

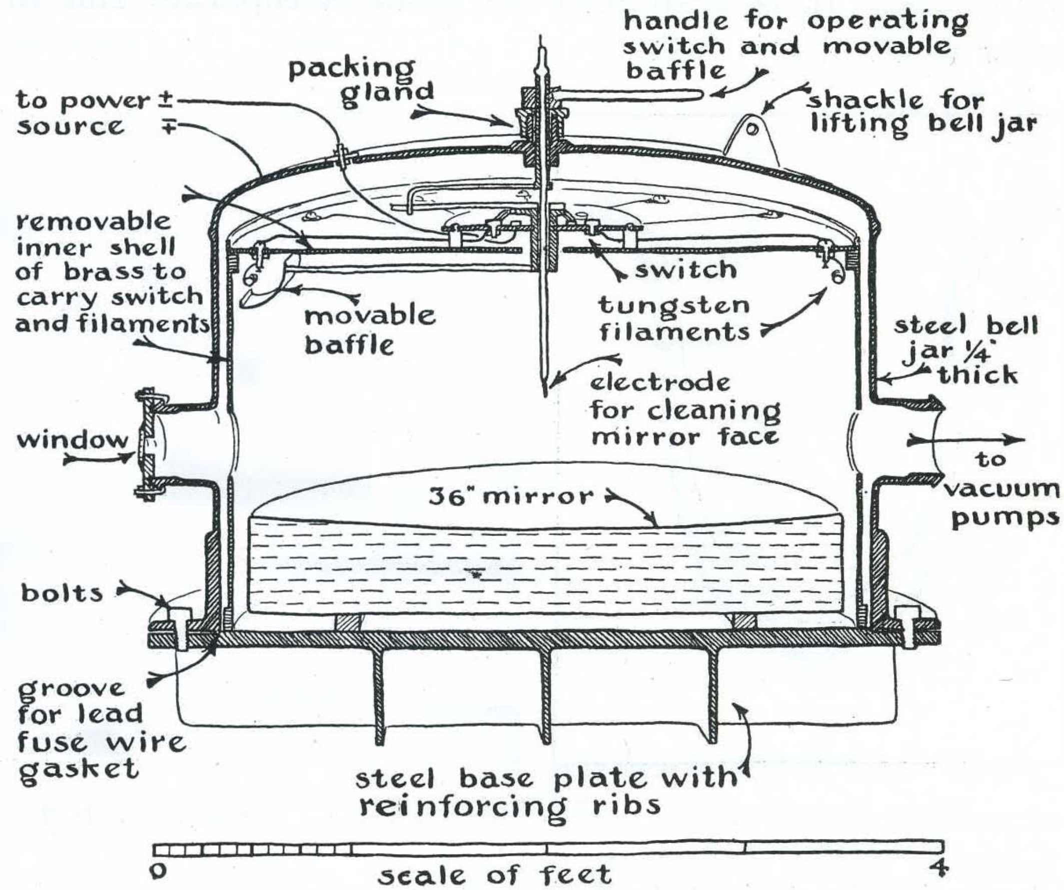
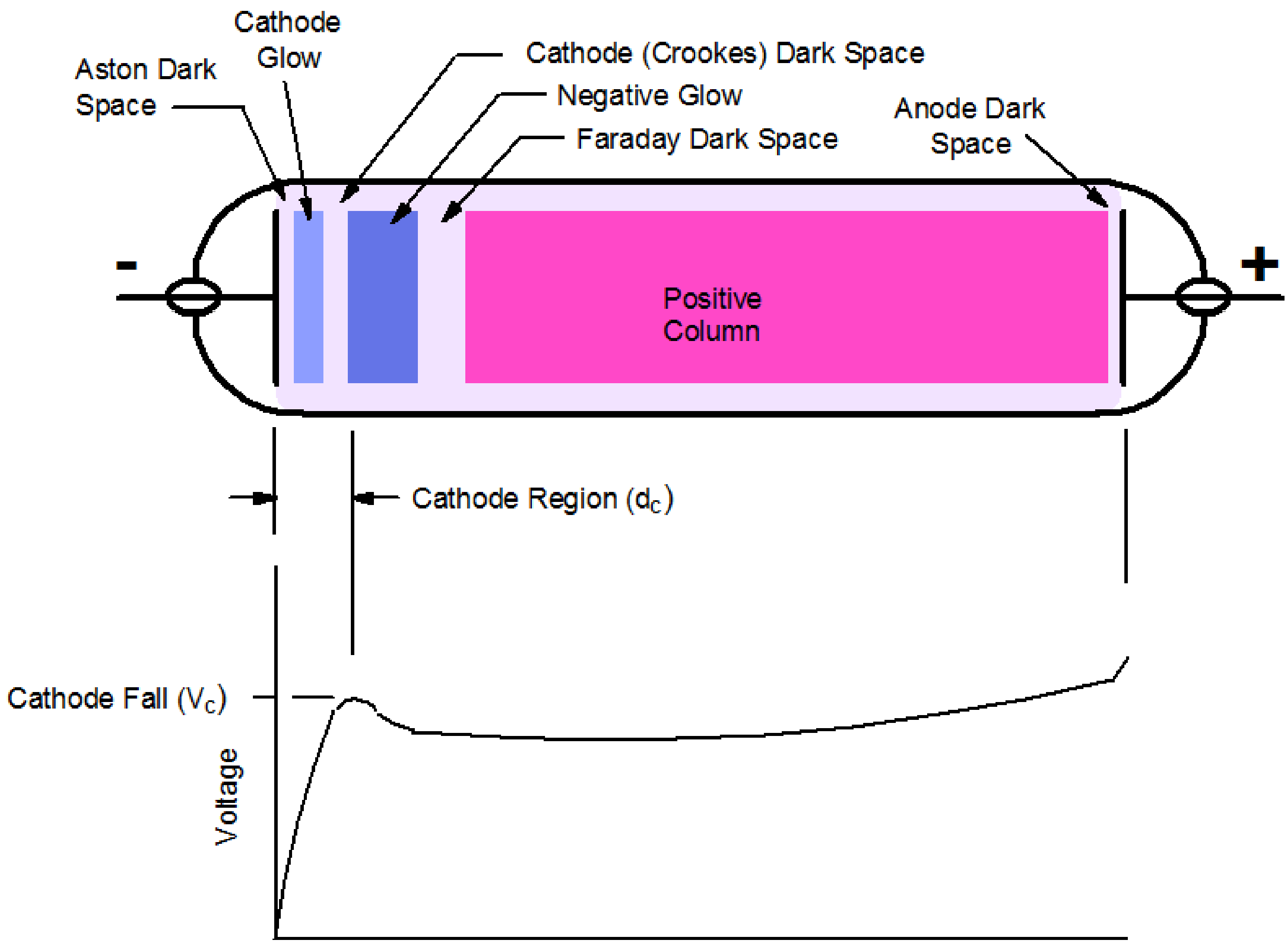
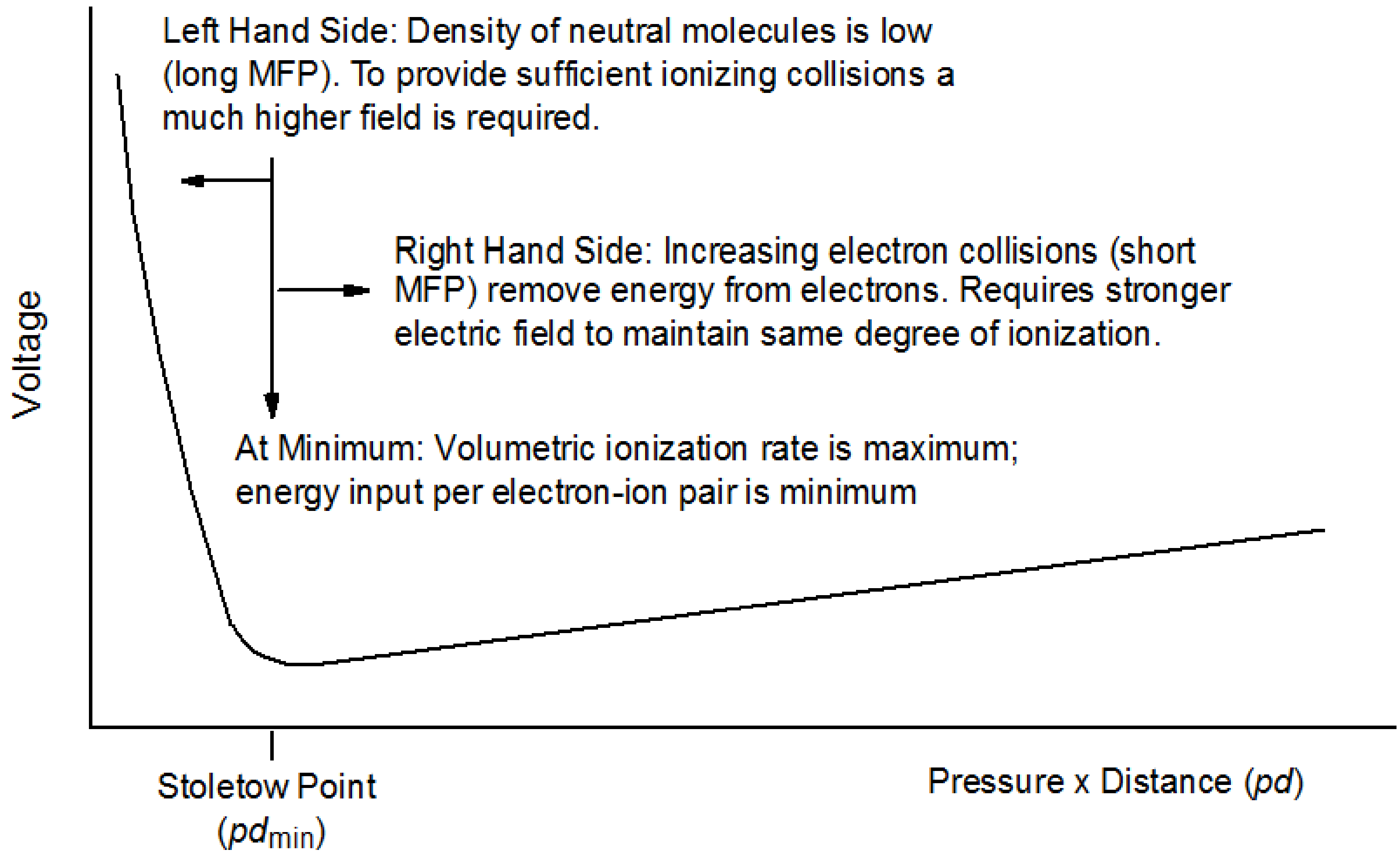


Illustration from John Strong, *Procedures in Experimental Physics*, 1938

Some Plasma Physics before the Demo

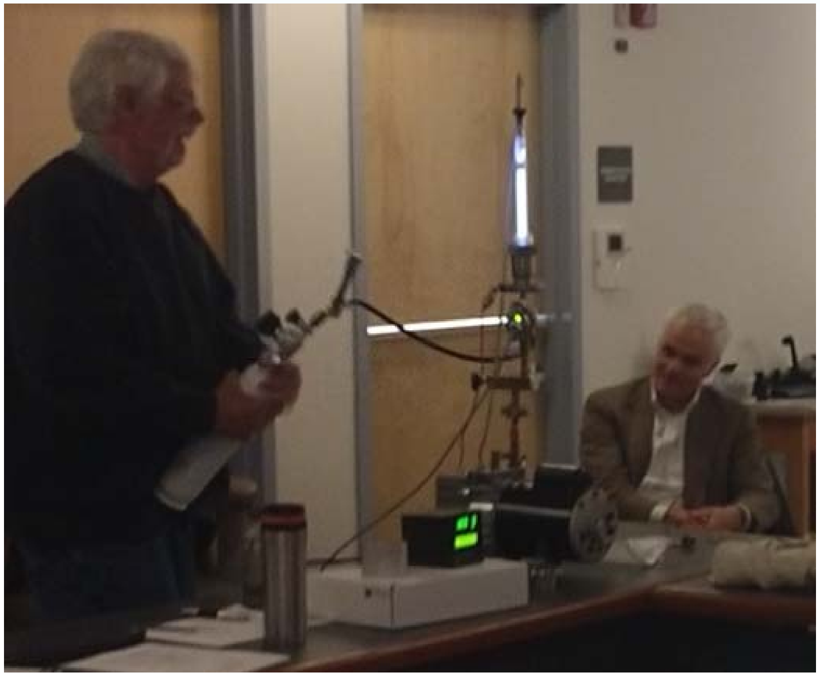


The Paschen Curve



Photos from the Demo

- Courtesy of KB1DBL -



Left: Glow discharge at low pressure (<1 Torr) showing white color associated with water vapor, the dominant residual gas.

Immediate Right: Glow discharge <<1 Torr just before discharge “goes dark” and gas becomes non-conductive.

Right: Tube backfilled with neon.

Photos from the Demo

- Courtesy of KB1DBL -

Phosphor screen illuminated by electron beam produced by negative electrode.

Pressure <0.1 Torr.

Related videos:

Electron beam formation in a glow discharge – http://belljar.net/video/ebeam.html

Hittorf (detour) tube illustrating Pachen's Law – http://belljar.net/video/hittorf.html

Sputtering – W.R. Grove 1852

A glow discharge is established between a metallic cathode and substrate. Gas ions impinge on the target and dislodge metal atoms which then, by recoil, travel to the substrate.

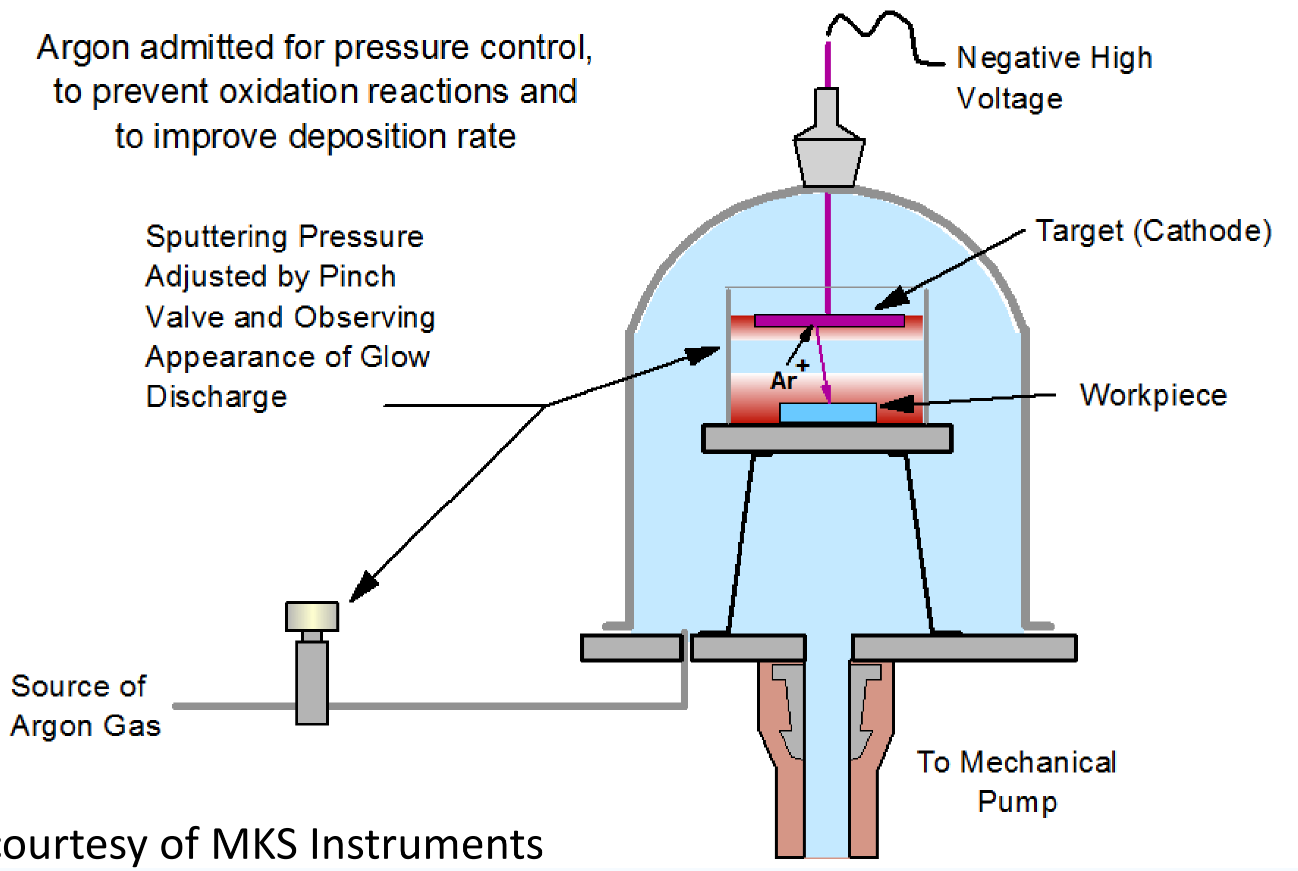
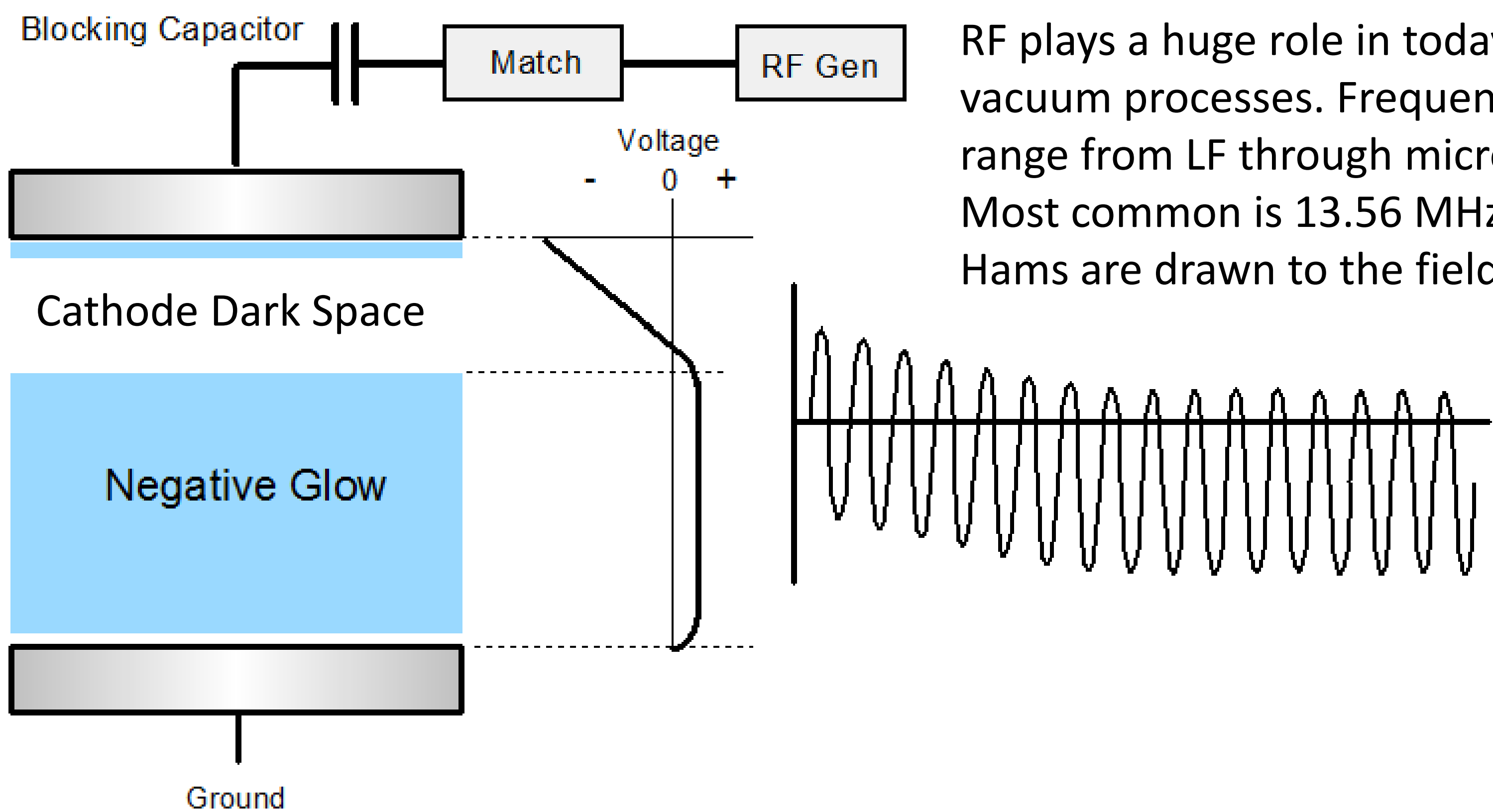


Illustration courtesy of MKS Instruments

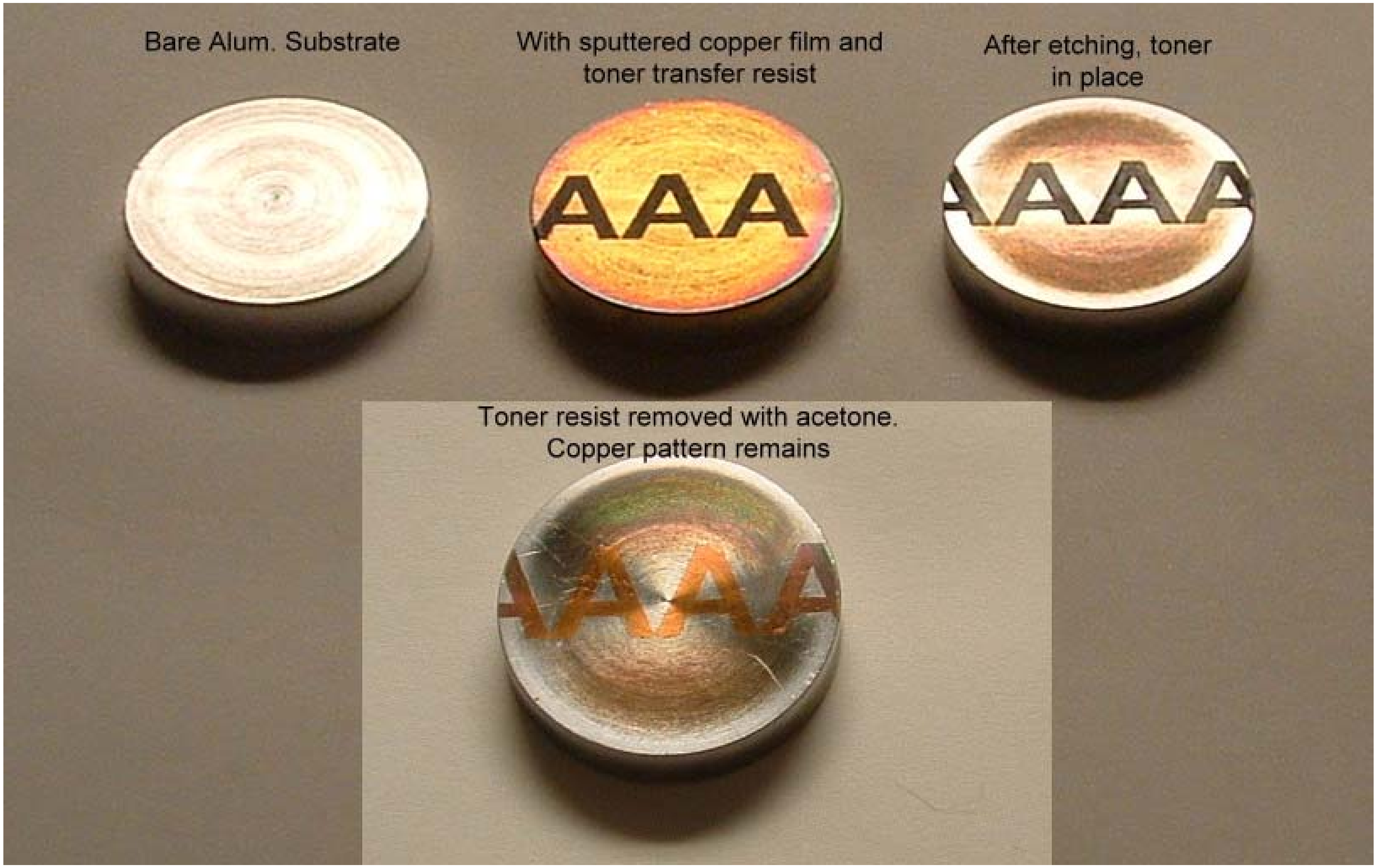
RF Sputtering



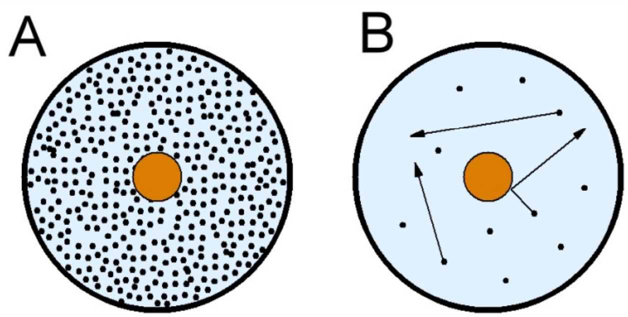
RF plays a huge role in today's vacuum processes. Frequencies range from LF through microwave. Most common is 13.56 MHz. Hams are drawn to the field.

The plasma ions have a lower mobility than the electrons. The electrons disproportionately accumulate on the target electrode, driving it negative.

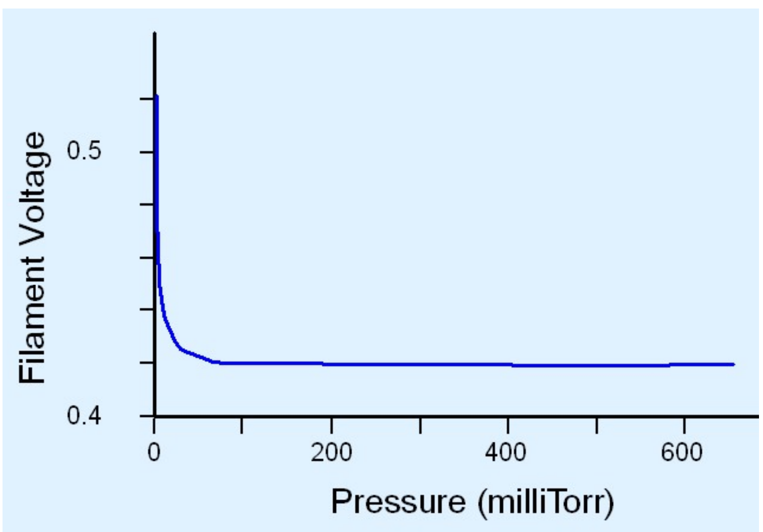
Sputtering & Ion Milling (Reverse Sputtering)



The Pirani Thermal Conductivity Gauge

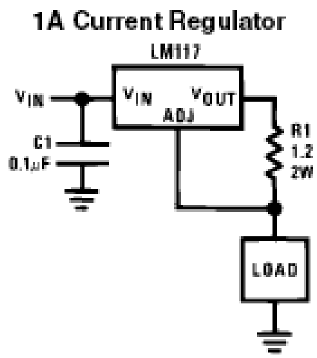


A – High pressure, frequent collisions by Molecules on a heated filament
B – Low pressure, many molecules miss colliding with the filament

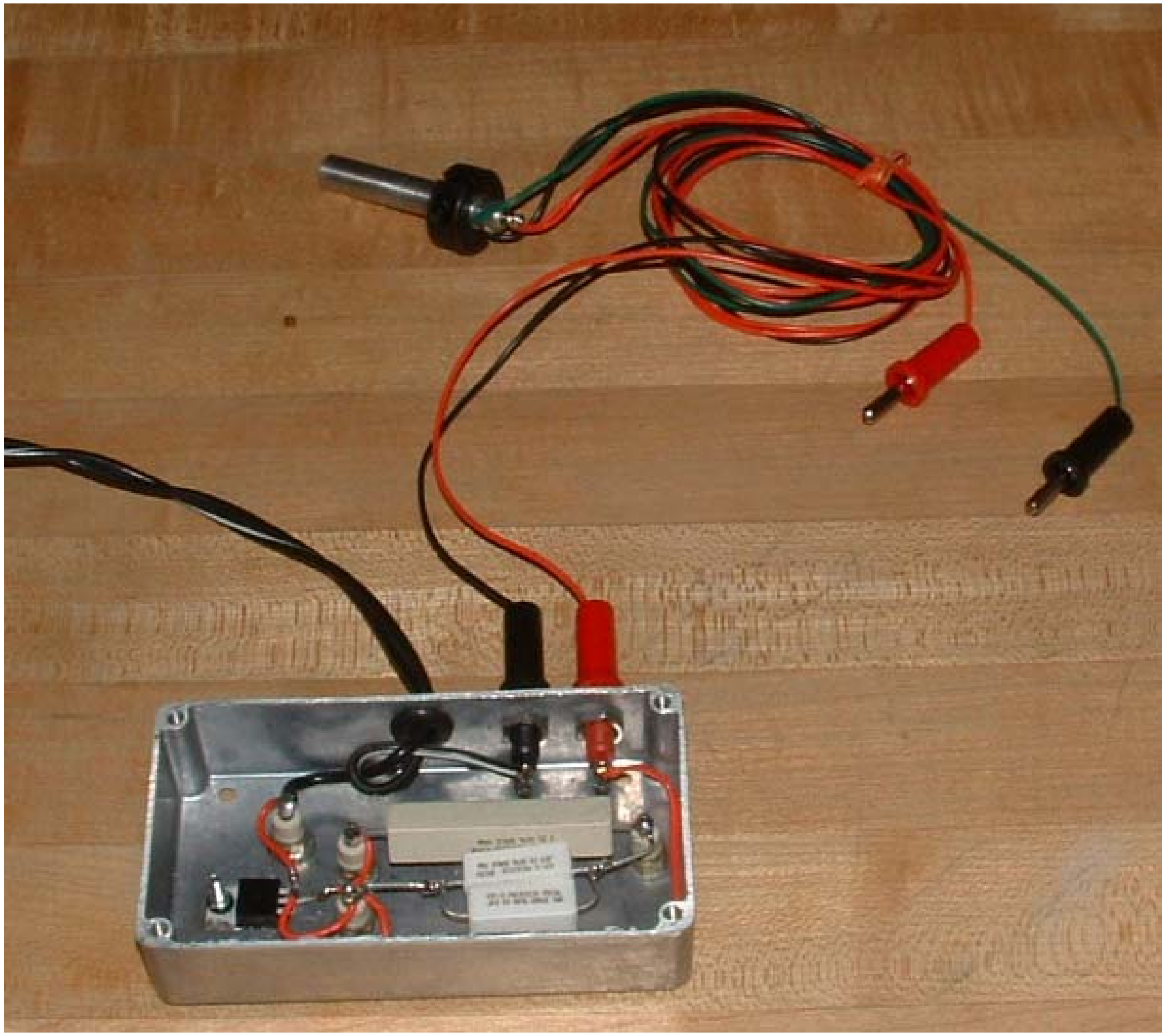


With a constant current through the filament, the voltage across the filament is constant through the viscous flow regime, begins to increase in transition flow, eventually becoming linear.
Sensitivity is lost in molecular flow.
Useful range typically 10 Torr down to 10 milliTorr.
MEMS gauges have a much wider range.

Simple Glow Plug Pirani Gauge



1 amp constant current, measure voltage across the filament. Kelvin contact configuration to avoid errors.



Measuring the Diameter of a Gas Molecule with a Model Engine Glow Plug

$$\lambda = \frac{1}{\sqrt{2}\,\pi d_0^2 n}$$

Based on when the mean free path λ becomes greater than the diameter of the filament

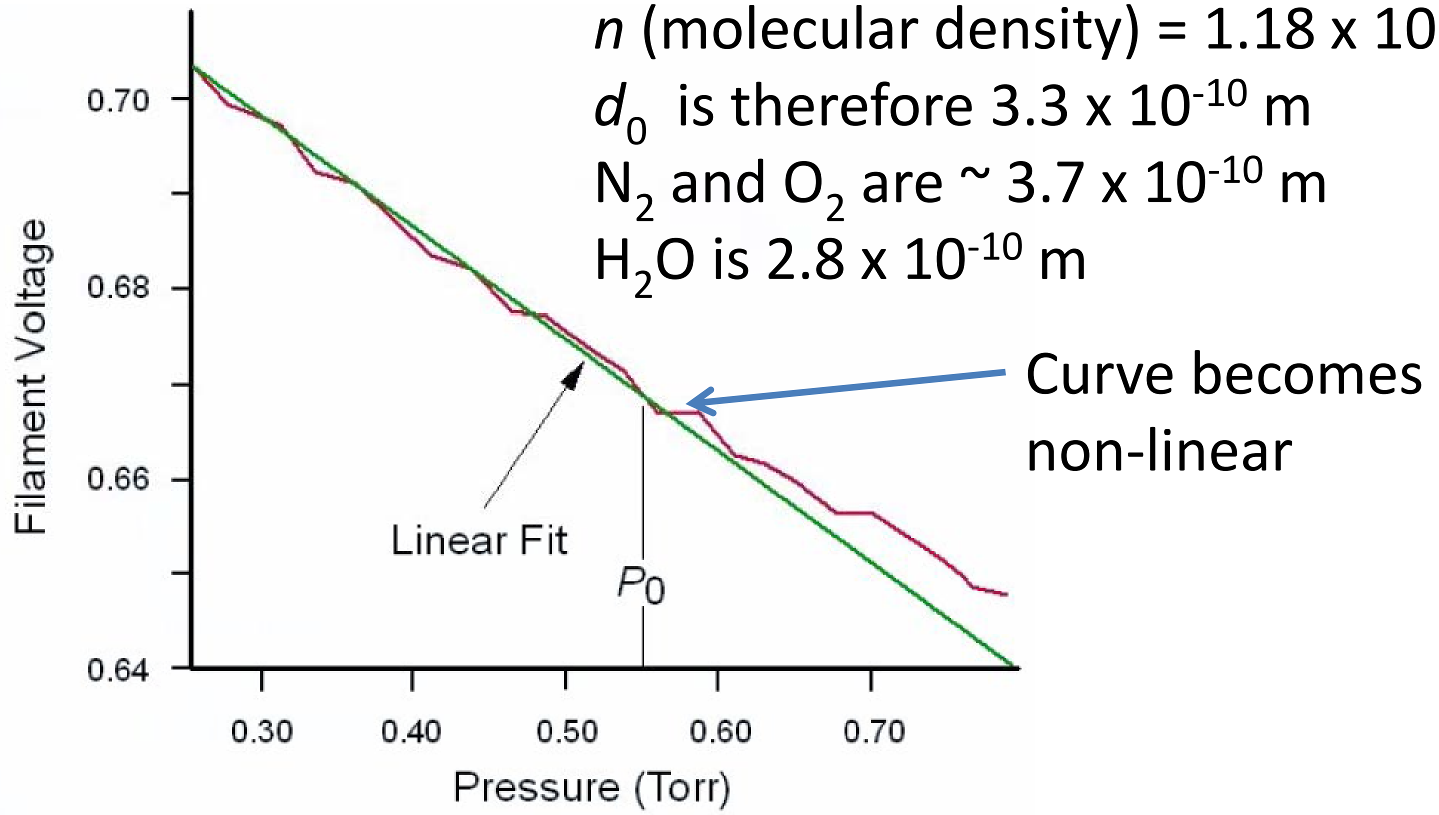
λ (dia. of filament) = 114 μ or 1.14×10^{-4} m

n (molecular density) = 1.18×10^{22} at 0.55 Torr

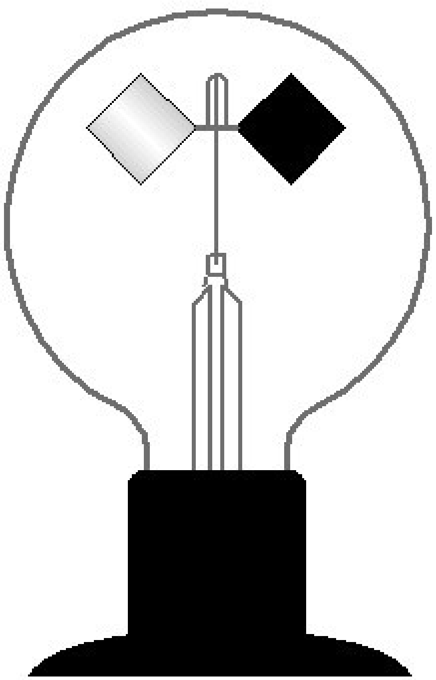
d_0 is therefore 3.3×10^{-10} m

N_2 and O_2 are ~ 3.7×10^{-10} m

H_2O is 2.8×10^{-10} m



Weird Stuff in Vacuum: Thermal Transpiration



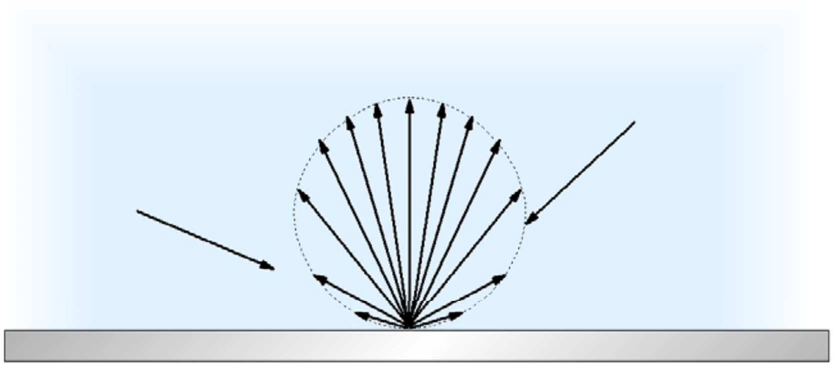
Sir William Crookes invented the radiometer in 1873. He thought that it would show the force of light particles reflecting from the shiny side.

He was wrong. It went the other way.

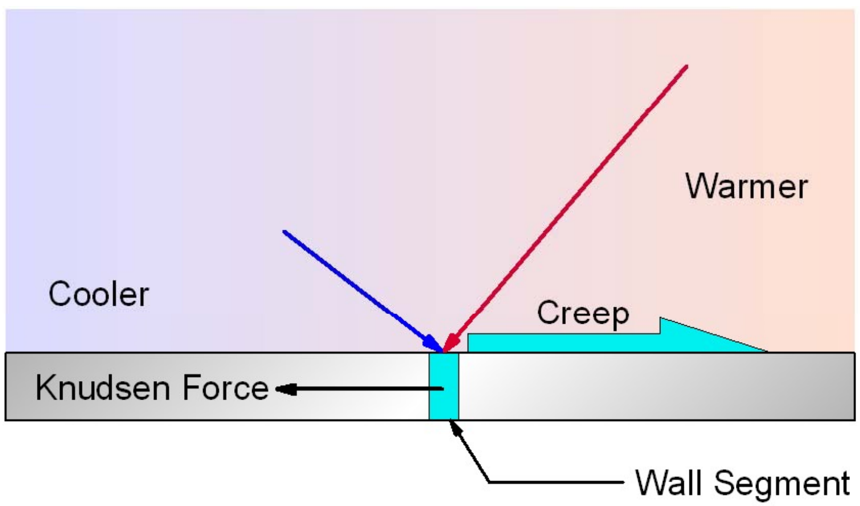
Radiometer vendors often explain the effect as due to molecules recoiling from the dark (warmer) side. Or outgassing from the lampblack. Wrong on both counts.

The effect is due to thermal transpiration, an effect discovered independently by Reynolds and Maxwell in 1879.

Weird Stuff in Vacuum: Thermal Transpiration

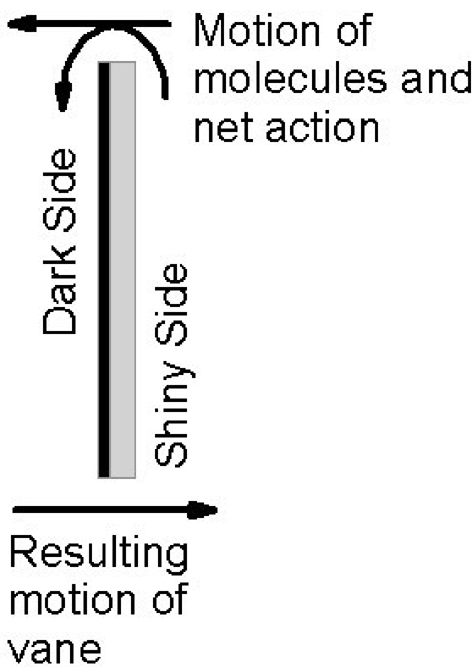


In medium/high vacuum, at uniform temperature, molecules impinging on a surface stick and then release (at some point) following a cosine distribution. They "forget" where they came from.



A molecule from a hot region will have a higher velocity than one from a cold region.
When a "hot" molecule hits a cool surface it will emerge with a lower energy.
The result is a transfer of momentum resulting in what's called the Knudsen force.
Walls usually don't move. This results In creep, a net movement of molecules to the warmer area along the surface.

Weird Stuff in Vacuum: Thermal Transpiration



If one volume or surface is at a higher temperature than the other and the pressure is low enough for the gas to be in transition or molecular flow, there will be a pressure difference between the two areas.

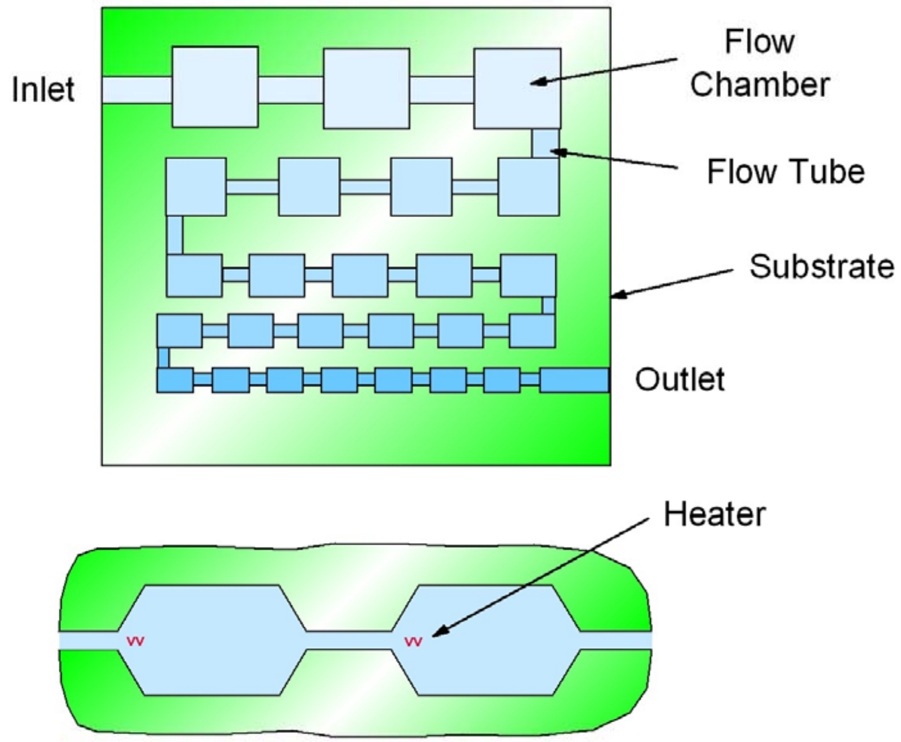
The gas in the volume or surface at the higher temperature will be at the higher pressure.

This means that there is a flow of molecules from the cooler area to the warmer. The result is the pressure rise in the warm area.

The effect is important when connecting, for example, a room temperature gauge to a hot vacuum chamber and the pressure is below 1 Torr.

Why is the optimum operating pressure of a radiometer around 40-50 mTorr?

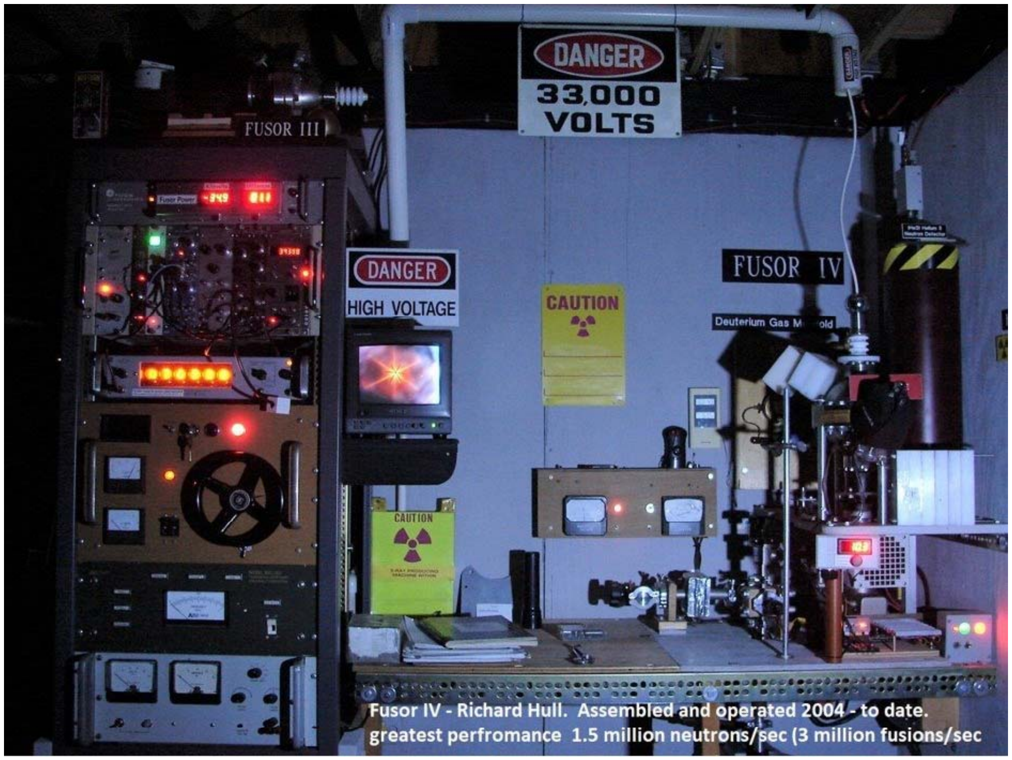
Practical Application: Thermal Transpiration (Knudsen) Pump

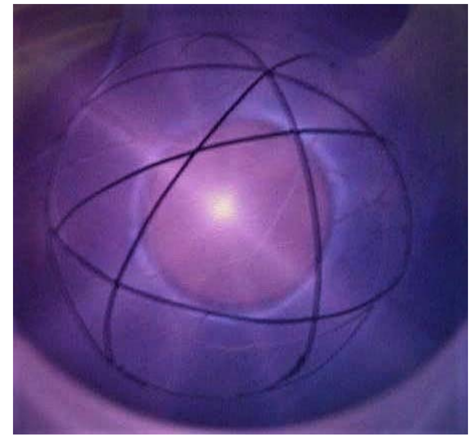


Portion of MEMS transpiration pump by Young (1999) . Effective pumping speed approx. 4.4×10^{-4} std. cc/minute (around 10^{15} molecules/sec). Heaters maintain 100 K difference between stages.

Application would be MEMS analytical instruments.

The Other Side of Philo Farnsworth: The Farnsworth-Hirsch Fusor

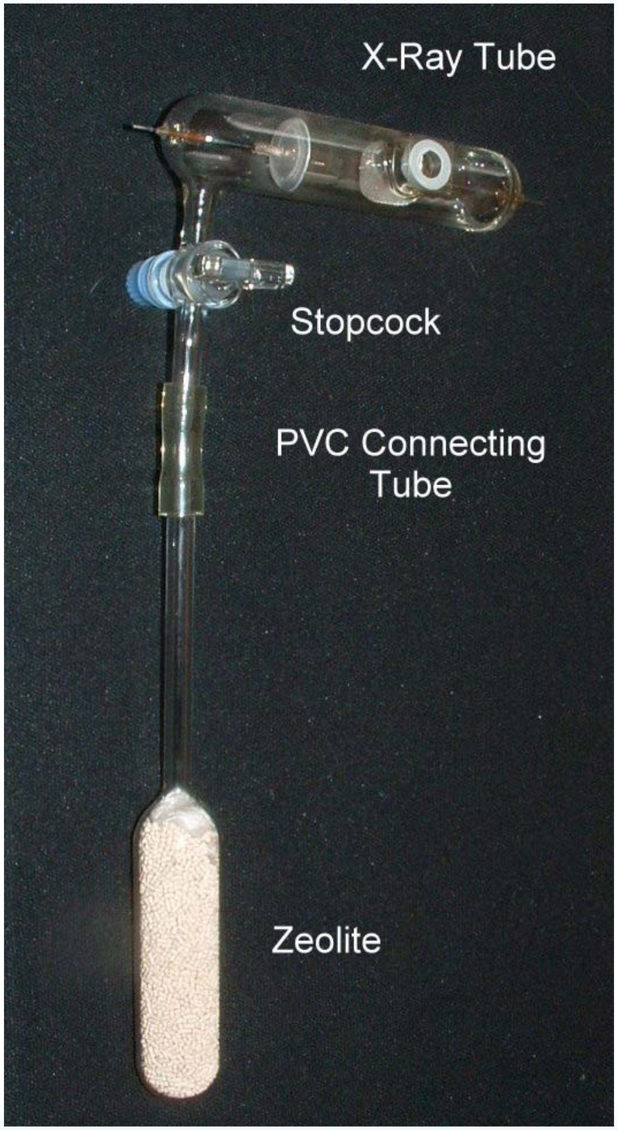




Above: Confined deuterium ions within the fusor's negative grid. **Left:** Richard Hull's lab in Richmond, VA.

Developed by Farnsworth in the 1950s and improved by Hirsch in the 1960s, the fusor uses inertial electrostatic confinement (IEC) to create the conditions within a negative grid to fuse deuterium ions. Typical bias voltages are in the range of 30-70 kV. While his fusor did not achieve break even, it is a useful source of neutrons and there is a large group of amateurs that are doing nuclear fusion in their homes.

A Sorption Pumped X-Ray Tube



Zeolite is a ceramic molecular sieve. It has a very large surface area and is used as a pump that has an operating range from atmosphere to about 1 milliTorr.

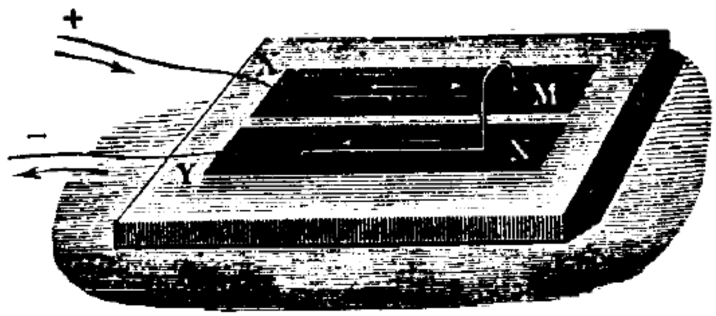
The vessel with zeolite is baked and then attached to the x-ray tube. The zeolite Is then immersed in liquid nitrogen.

Gas molecules will be adsorbed on the surface of the zeolite pellets. It is effective for all gas species with the exception of the noble gases.

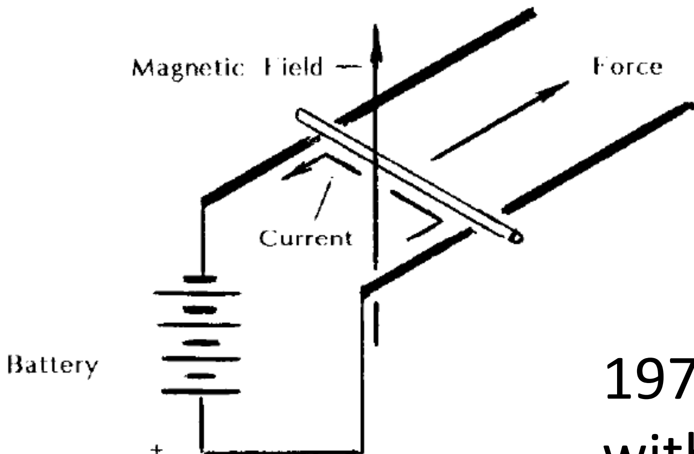
This device was made by George Schmermund, an amateur living in CA.

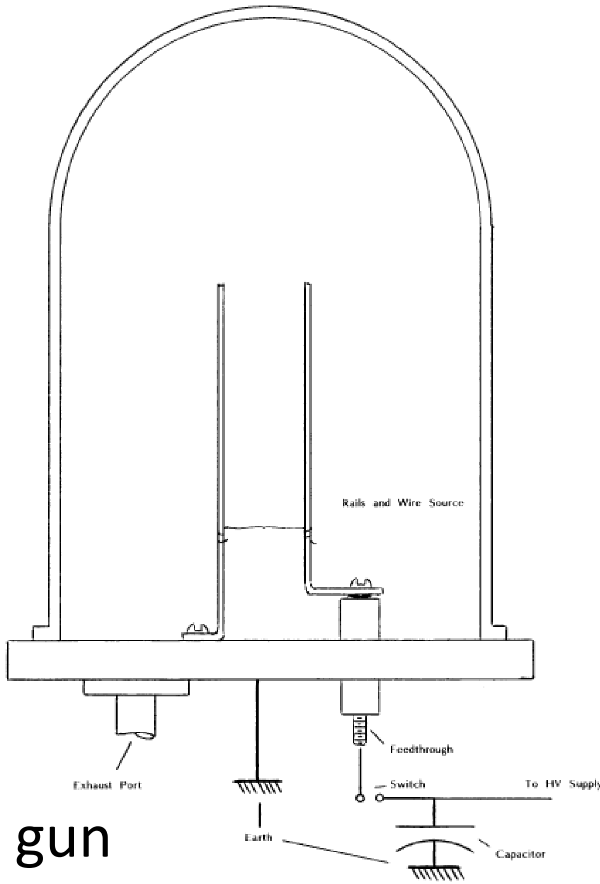
Some of Steve’s Favorite Things

Rail Guns, Coaxial Plasma Accelerators and the Dense Plasma Focus



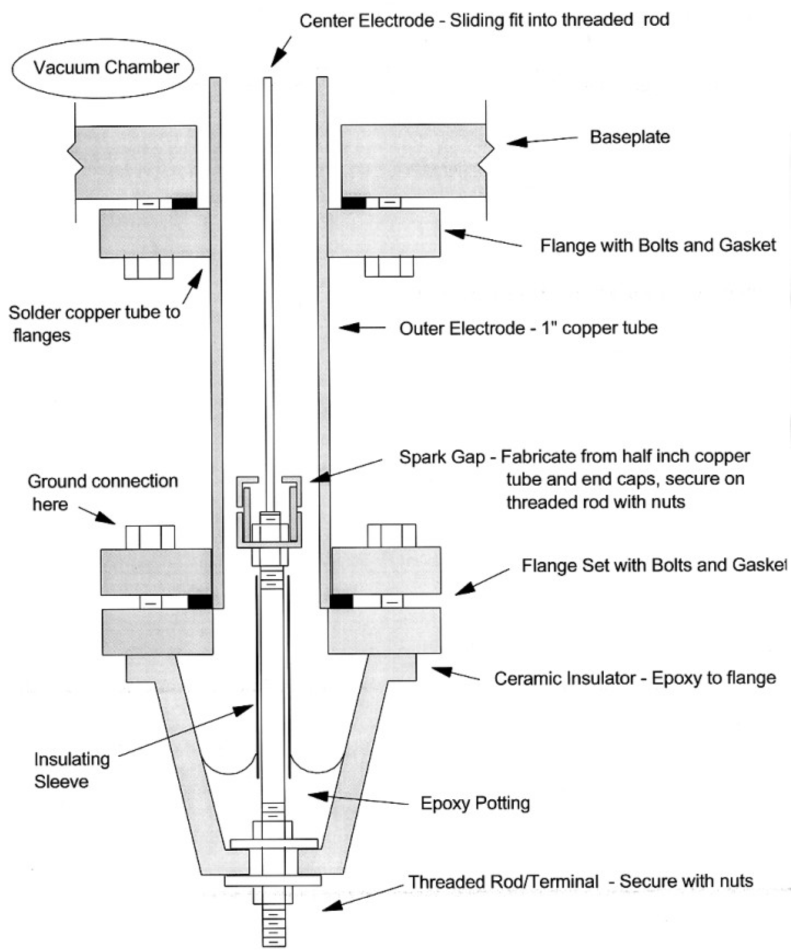
Ampére's experiment





1970 - Plasma rail gun
with exploding
wire source

Rail Guns, Coaxial Plasma Accelerators and the Dense Plasma Focus



1974 – Coaxial Accelerator

Typical operating parameters:

Pressure: 200 mTorr

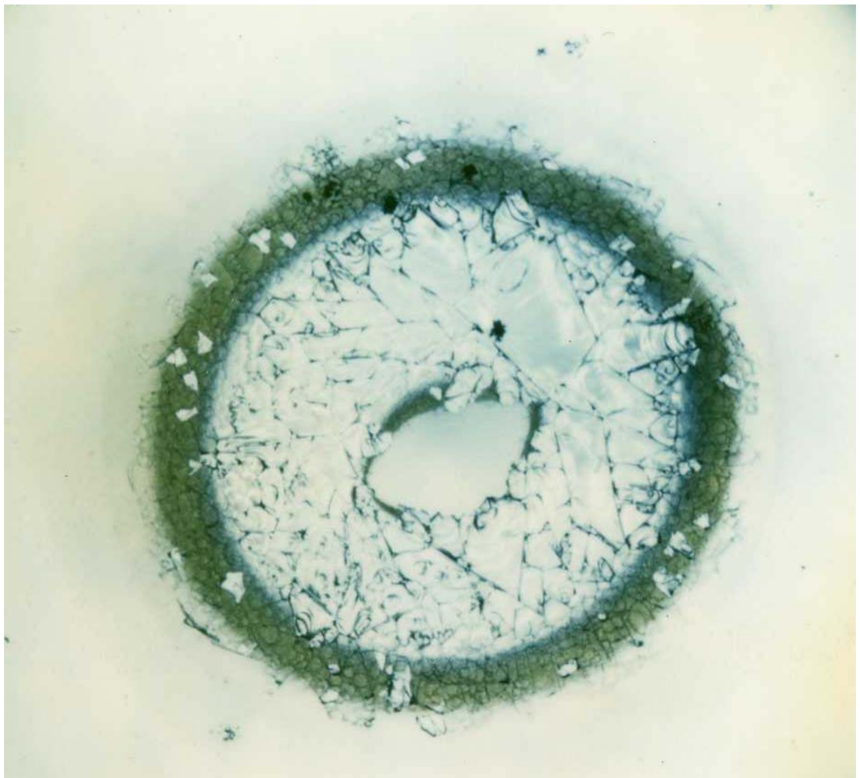
240 μF at 2 kV (480 J)

Pulse duration ~1 μs

Plasma temp. >10,000 K

Beam velocity $>10^5$ m/s

Rail Guns, Coaxial Plasma Accelerators and the Dense Plasma Focus



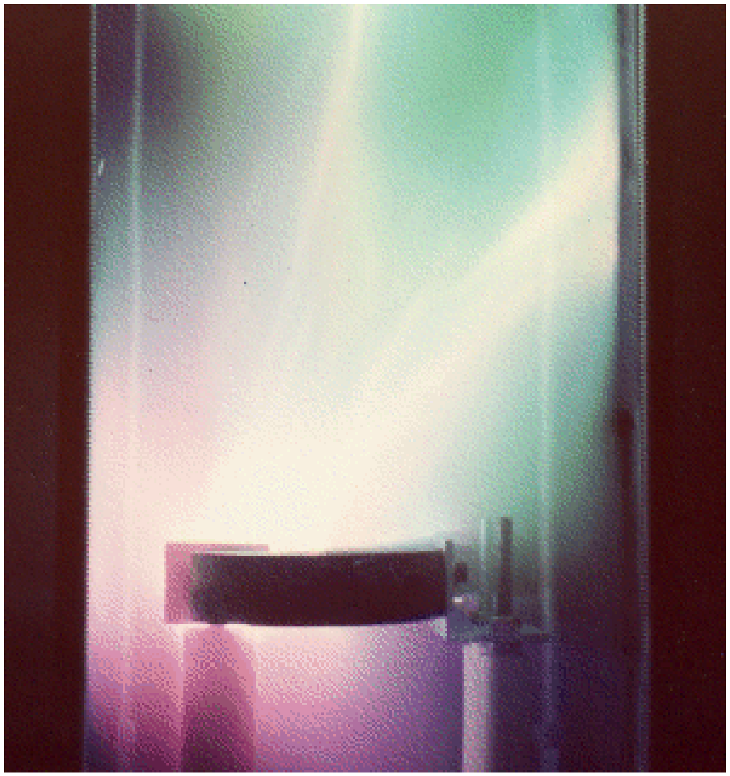
Glass target at muzzle end of coaxial plasma gun:

Clear center is shadow of inner 1/8” diameter electrode

Fracture area around electrode

Copper deposit in focus region

Rail Guns, Coaxial Plasma Accelerators and the Dense Plasma Focus



Beam through 3 kG magnet which bends the ion trajectories according to charge and mass

Separated species are ionized copper.

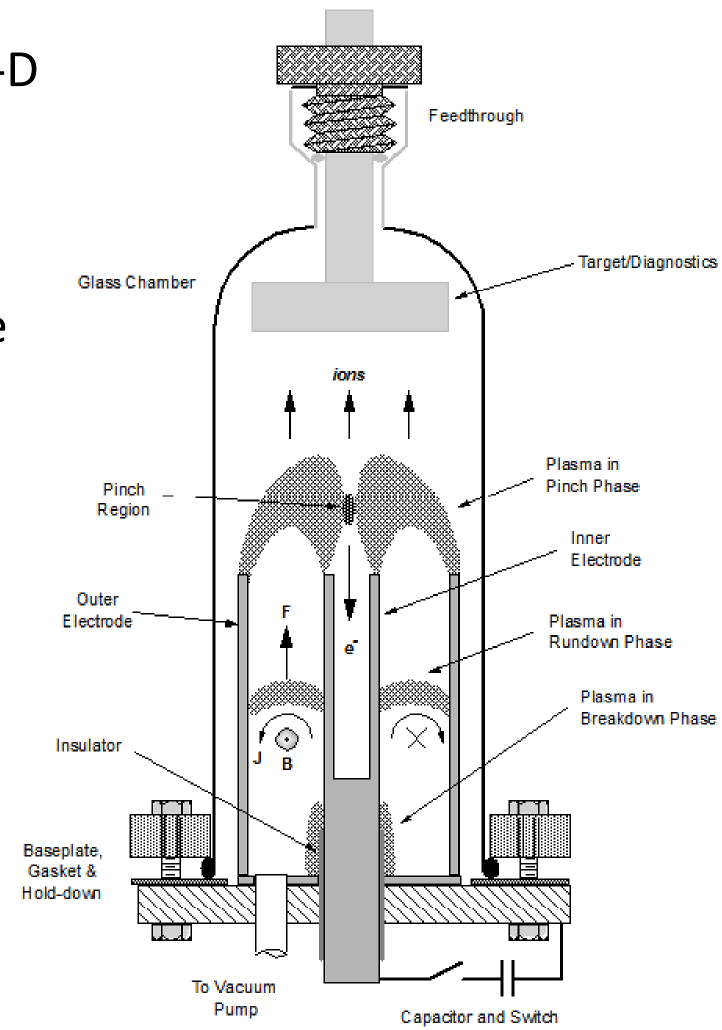
Rail Guns, Coaxial Plasma Accelerators and the Dense Plasma Focus

DPF generally used to study nuclear fusion (D-D reaction). Also a source of intense x-rays.

Produces a very small (hot, dense) plasma pinch region adjacent to the end of the device

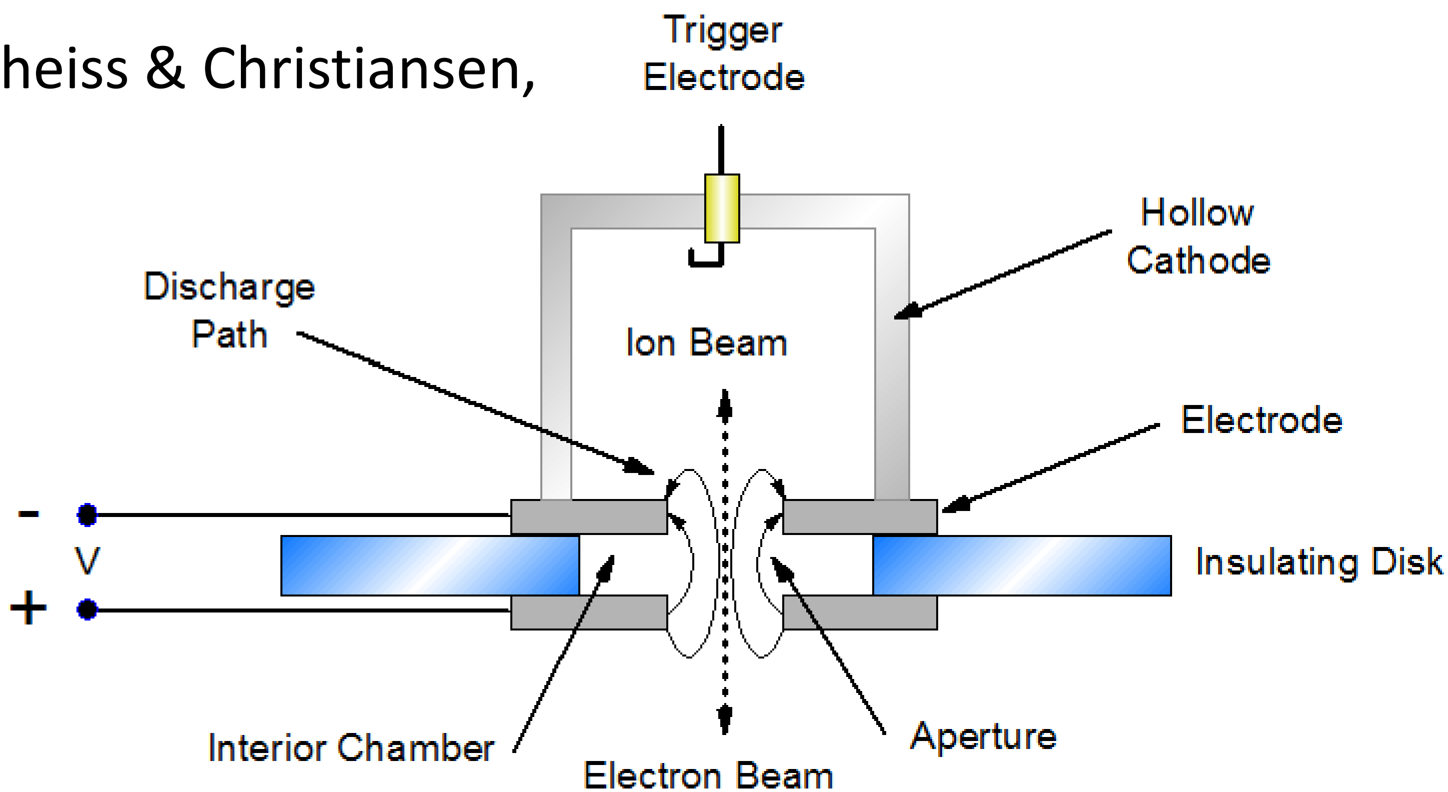
Inductance reduced to minimal levels to produce nanosecond-order pulses

Energy levels typically 2-5 kJ, temperatures in excess of 100 kilo K



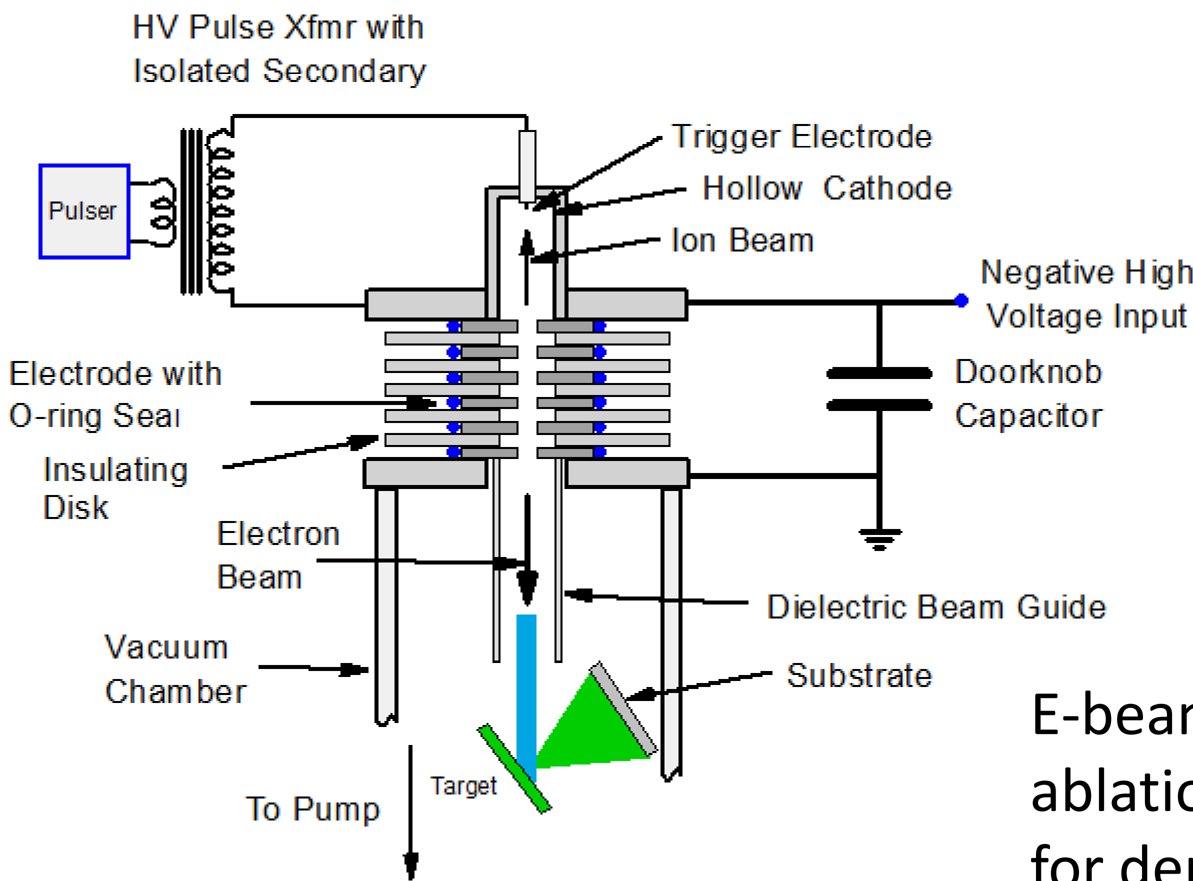
Pseudospark Electron Source

Schultheiss & Christiansen, 1978



Not a spark, not a glow discharge but a unique pinched, very fast (sub micro-second scale), intense, pulsed linear discharge.
Used as a beam source, for microwave generation (up to terahertz) and as an x-ray and EUV light source.

Pseudospark Electron Source



E-beam ablation source for deposition

Typical operating voltage range: 10 to 50 kV
Electron beam currents in excess of 100 A

Getting into Vacuum

1950s: Heroic effort

1960s-’80s: Grim determination

Vacuum projects in Scientific American (F.B. Lee and others), improvised equipment used to make particle accelerators and lasers

1990s: Serious DIY

More vacuum featured in Scientific American (Kendall, Hansen, Schmermund)

2000 to Present: Reasonable threshold for the dedicated experimenter

Good sources of information available, commercial quality hardware at reasonable prices on ebay. Still a niche activity for the hobbyist.

Further Reading

Amateur vacuum web site - belljar.net

Guides to Vacuum Technology in “Vacuum Technology & Coating” - vtcmag.com
Start with April 2012; June & July 2015; June 2019; August & September 2019

Vacuum Science & Technology Timeline: 1500 -2007
American Vacuum Society
avs.org/About/History/Vacuum-Science-and-Technology-Timeline
Be sure to look at January 1992