

# Low Temperature Plasmas:

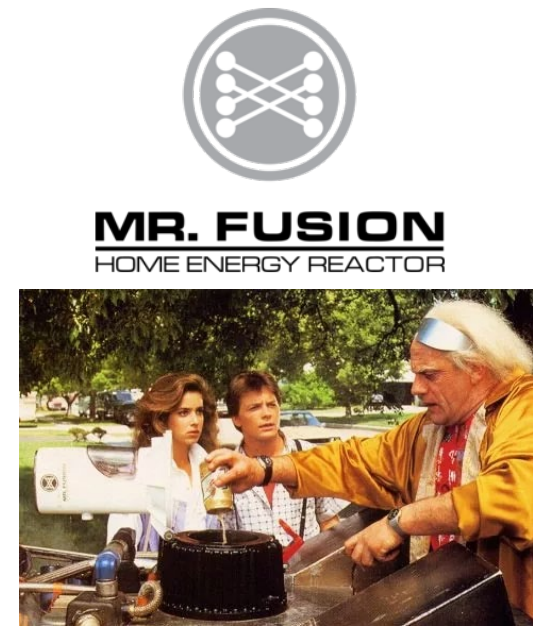
**Lessons from Yesterday, Breakthroughs of Today  
& Visions of the Future**

**Jose L. Lopez, Ph.D.**

**Department of Physics  
Laboratory of Electrophysics & Atmospheric Plasmas (LEAP)  
South Orange, New Jersey (USA)**



# How I became interested in Science, Physics, and Plasmas...



**Fr. Mark Payne, O.S.B. (1952-2016)**  
Physics Teacher at St. Benedict's Prep



Department of Physics

# How I pursued my interest in Science, Physics, and Plasmas...



 **Saint Peter's**  
UNIVERSITY  
The Jesuit University of New Jersey

Jersey City, NJ



Bethlehem, PA

**Jose - Summer '99 NSF Physics Research Experience for Undergraduates (REU) @ Lehigh University**



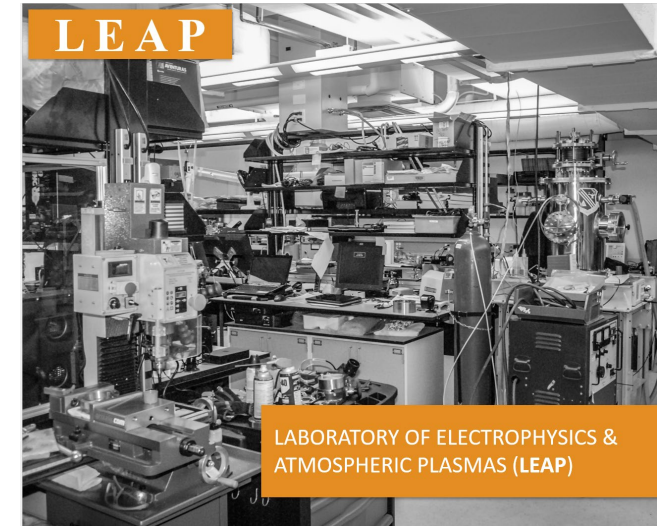
Hoboken, NJ



Department of Physics

# Dr. Jose L. Lopez, Ph.D.

**Director of University Research  
Professor of Physics / Plasma Physicist  
Seton Hall University  
Department of Physics  
Laboratory of Electrophysics & Atmospheric Plasmas (LEAP)**

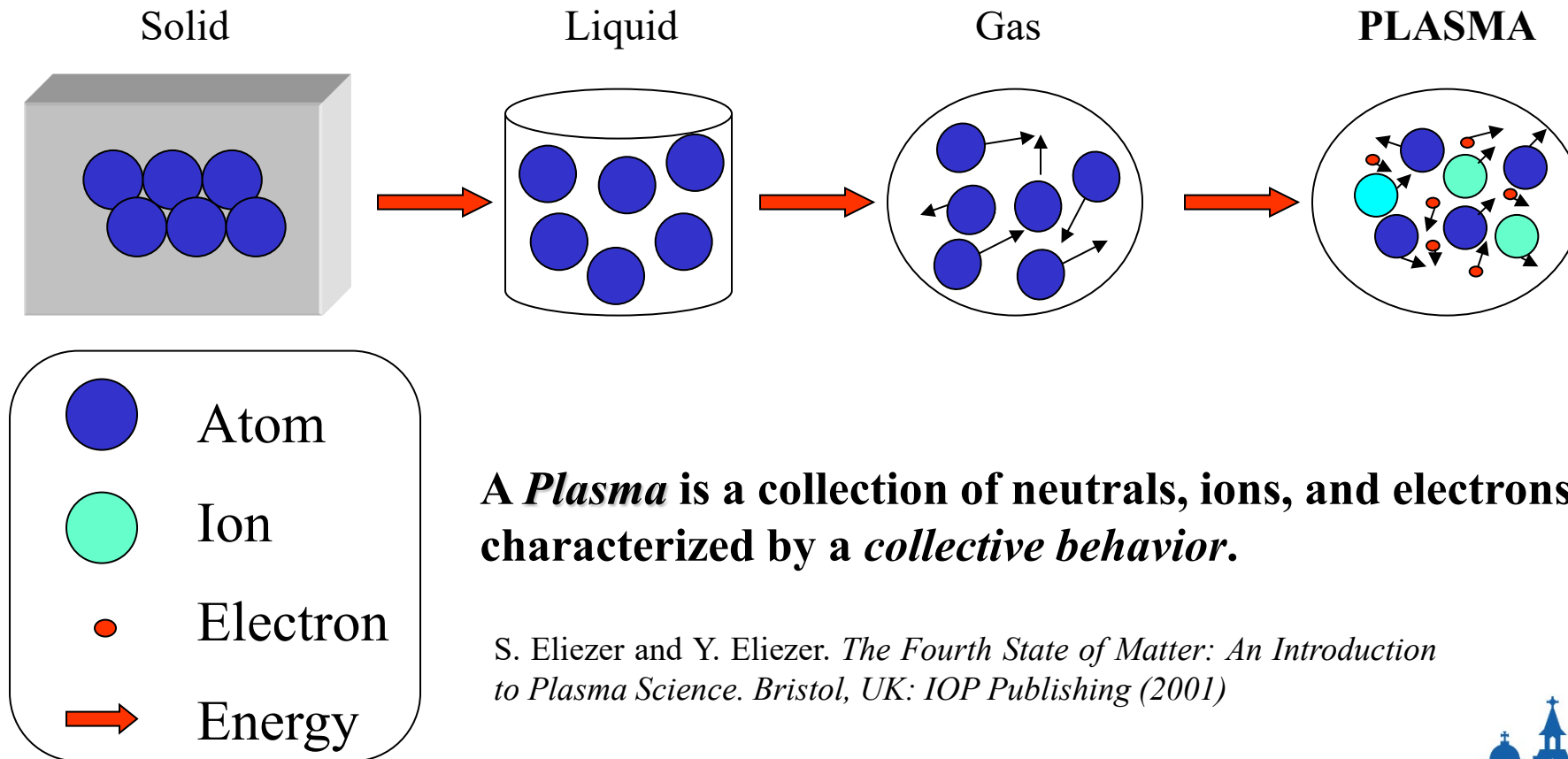


**&  
'Former' - Program Director of Plasma Physics  
Division of Physics  
Mathematical and Physical Sciences (MPS) Directorate  
National Science Foundation  
Alexandria, VA**



# What is a Plasma?

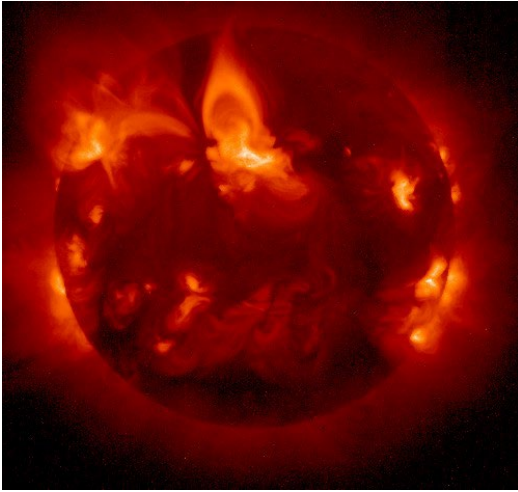
**The *Plasma* state is ‘The Fourth State of Matter’ (99%)**



**A *Plasma* is a collection of neutrals, ions, and electrons characterized by a *collective behavior*.**

S. Eliezer and Y. Eliezer. *The Fourth State of Matter: An Introduction to Plasma Science*. Bristol, UK: IOP Publishing (2001)

# Plasmas in Nature



The Sun



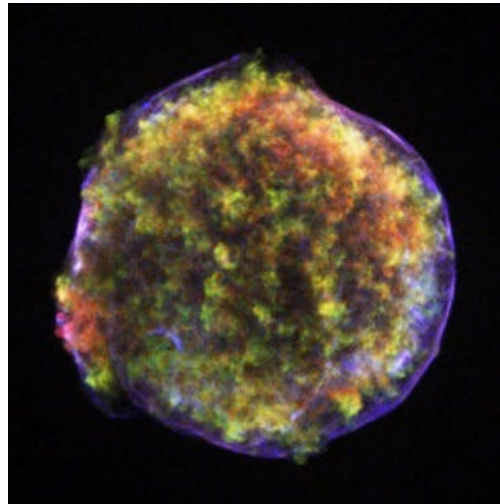
Aurora



Lightning

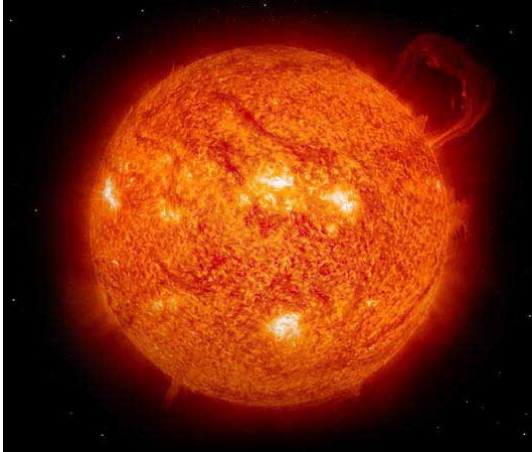


The Comet



Supernova

# Plasmas are everywhere!!!



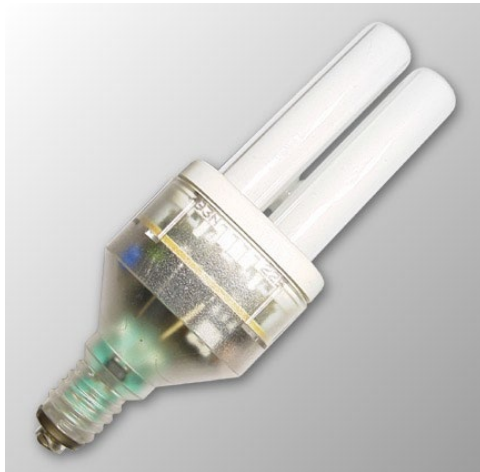
**Sun**



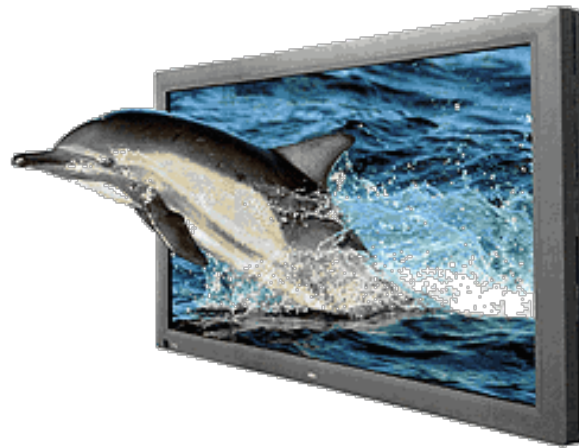
**Aurora Borealis (Northern Lights)**



**Lightning**



**Fluorescent Lamps**



**Plasma Display Televisions**



**Ozone (O<sub>3</sub>) generators**

# Two Types of plasmas

## High-temperature plasmas or Hot (Thermal) plasmas

$$T_{\text{ion}} \approx T_{\text{electron}} \geq 10^7 \text{ K } (\approx 10,000,000 \text{ }^\circ\text{C})$$

Examples: fusion plasmas like the Sun and stars

$$T_{\text{ion}} \approx T_{\text{electron}} \approx T_{\text{gas}} \leq 2 \times 10^4 \text{ K } (\approx 10,000 \text{ }^\circ\text{C})$$

Examples: arc plasma or lightning at atmospheric pressure

## Low-temperature plasmas or Cold (Non-thermal) Plasmas

$$T_{\text{ion}} \approx T_{\text{gas}} \approx 300 \text{ K } (\approx \text{room temperature } \approx 20 \text{ }^\circ\text{C})$$

$$T_{\text{ion}} \ll T_{\text{electron}} \leq 10^5 \text{ K } (\approx 100,000 \text{ }^\circ\text{C})$$

Examples: low-pressure glow discharge like a fluorescent lamp or comet tails

**high-pressure** cold plasma like an auora or ozone generator system



# Low Temperature Plasma (LTP)

## Low-temperature plasmas or Cold (Non-thermal) Plasmas

$$T_{\text{ion}} \approx T_{\text{gas}} \approx 300 \text{ K } (\approx \text{room temperature } \approx 20 \text{ }^\circ\text{C})$$

$$T_{\text{ion}} \ll T_{\text{electron}} \leq 10^5 \text{ K } (\approx 100,000 \text{ }^\circ\text{C})$$

**High pressure** LTPs range from:

- › 0.1 atm ( $\approx$  0.1 bar / 100 Torr / 13 kPa)
- › 1 atm ( $\approx$  1 bar / 760 Torr / 100 kPa)
- › 3 atm ( $\approx$  3 bar / 2,000 Torr / 270 kPa)



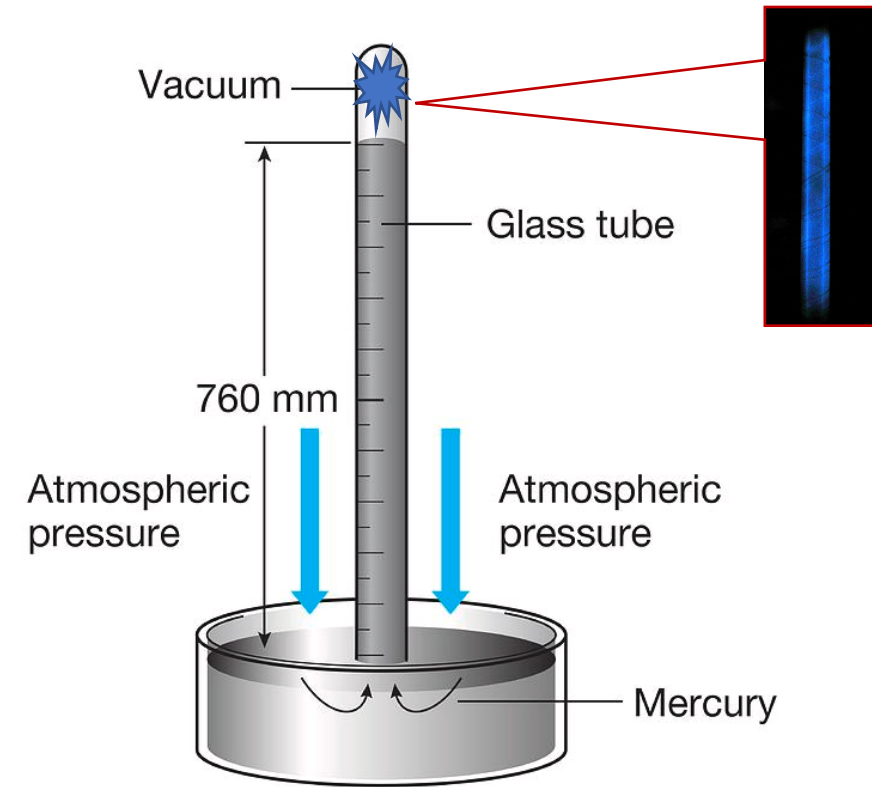
# The first observation of LTP by Jean Piccard



Jean (Félix) Piccard (July 21, 1620 – July 12, 1682) was a French astronomer and Catholic priest.

The first person to accurately measure the circumference of the earth. Around 1670!

Observed in his barometer tube glowing light that were produced when mercury atoms rubbed against the barometer's glass wall. i.e. first documented observation a *low temperature plasma*.



Mercury barometer

# The scientific study of electricity

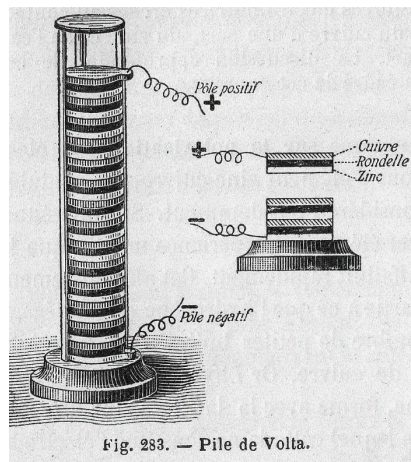
In 1752, Benjamin Franklin ‘discovers’ electricity!



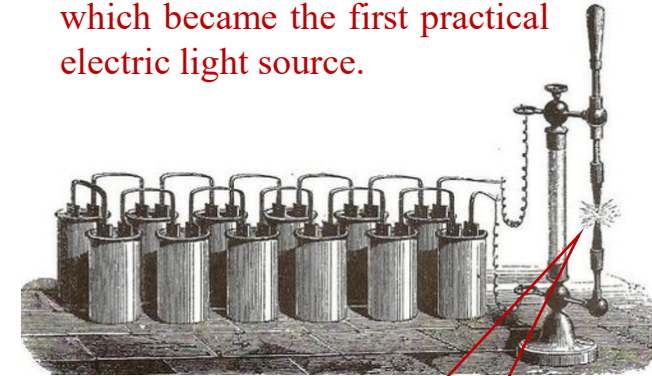
Although Benjamin Franklin (1706–1790) or now known as Mr. \$100 didn't discover electricity, he coined most of the words we use today to describe it such as positive and negative charge, conductor, and battery.



In 1800, Alessandro Volta (1745-1827) invents the battery



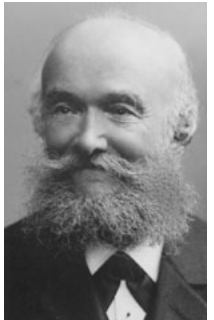
Arc Lamp is invented in 1809 by Humphry Davy (1778-1892) which became the first practical electric light source.



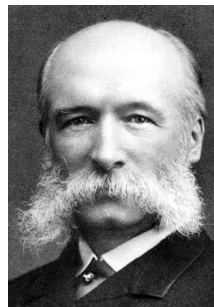
# The development of 'scientific' vacuum pumps



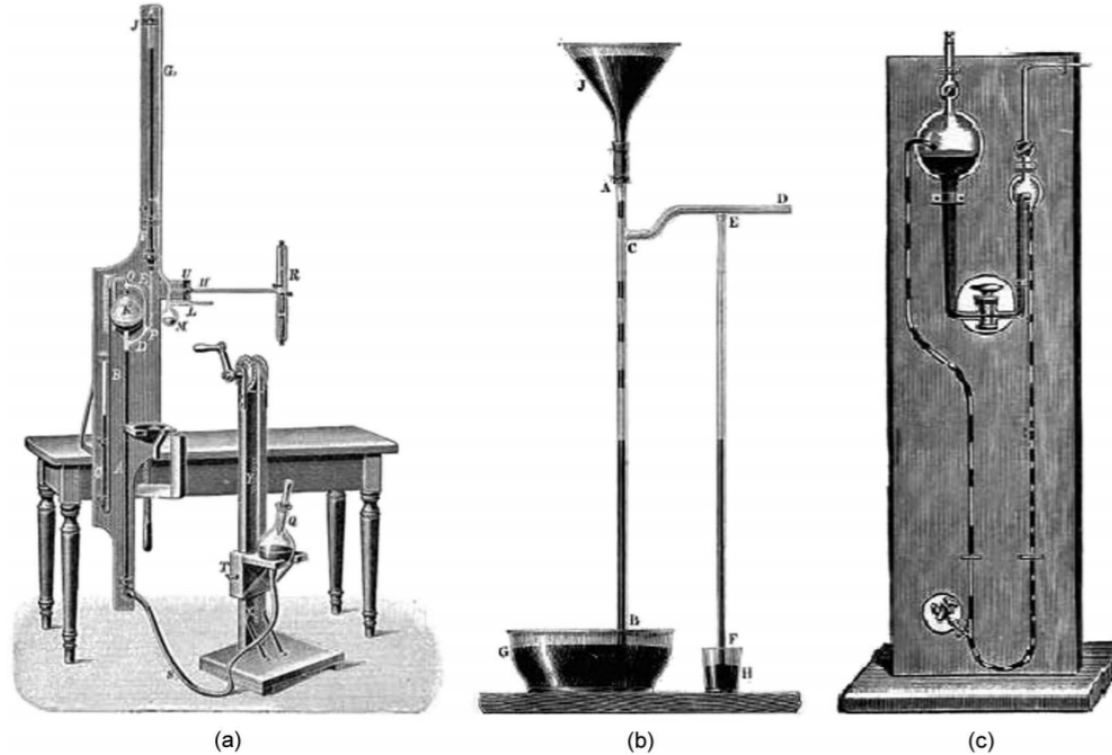
Heinrich Geissler (1814-1879)



August Toepler (1836-1912)



Hermann Sprengel (1834-1906)

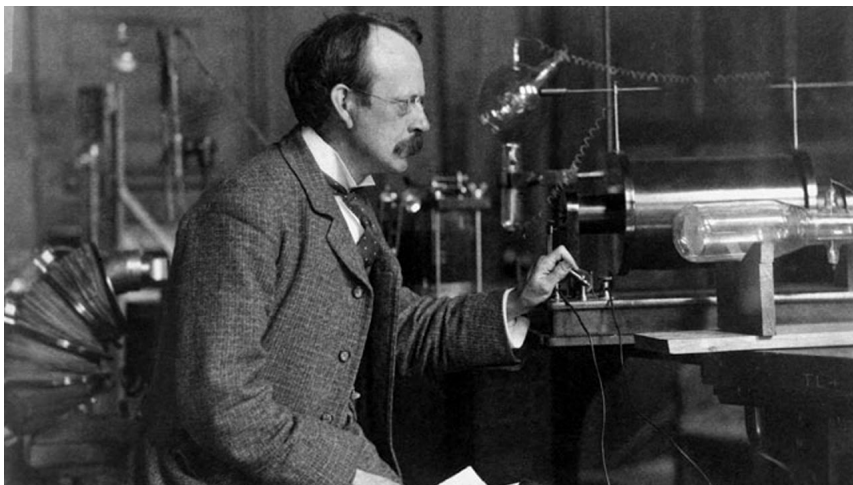
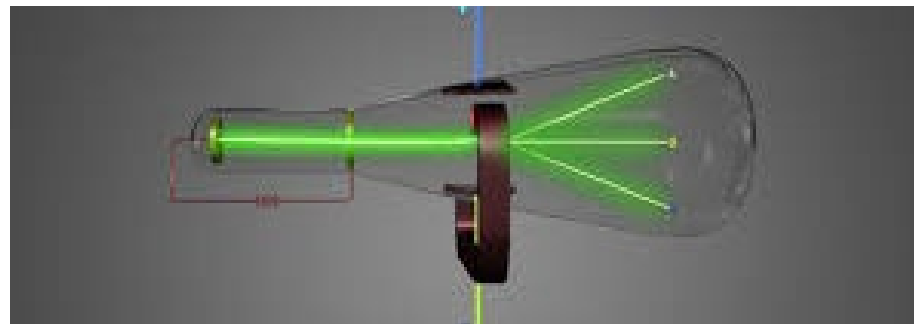
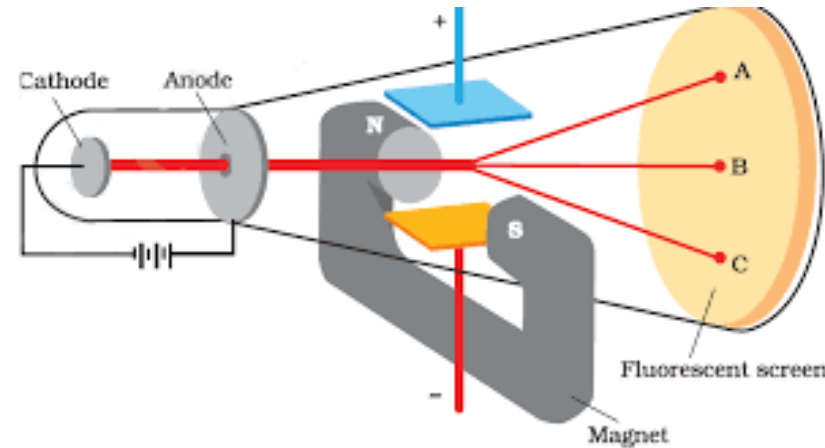
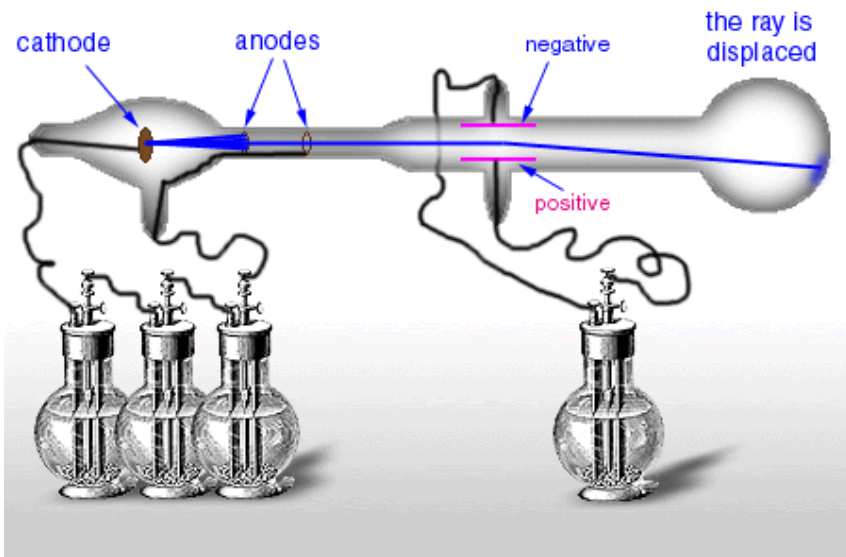


Schematics of the Geissler vacuum pump. (a) Toepler's pump. (b) Original Sprengel's pump. (c) Self-recycling Sprengel's pump.

**The significance of these vacuum pumps is that they were able to create vacuum of much less than 1 mTorr or 13 mPa or  $13 \times 10^{-6}$  Atm / Bar.**

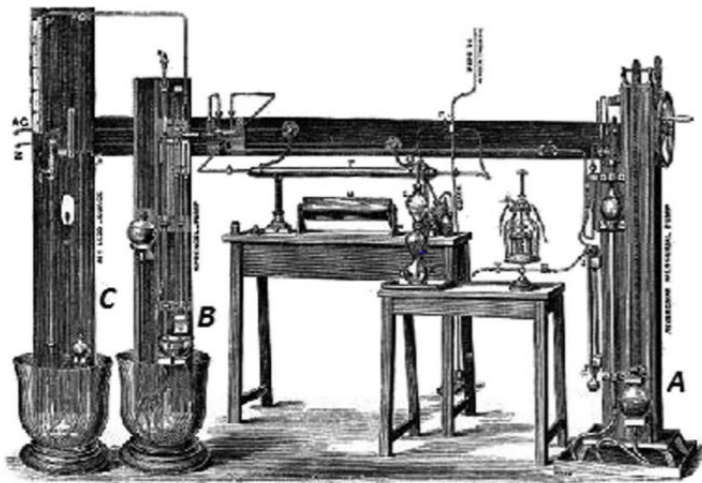


# The discovery of the 'electron'

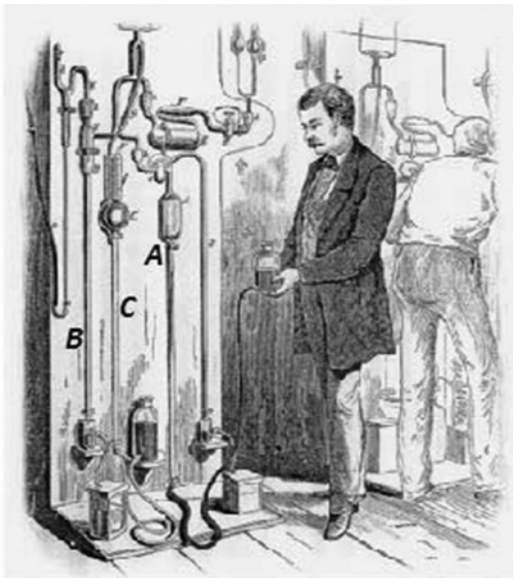
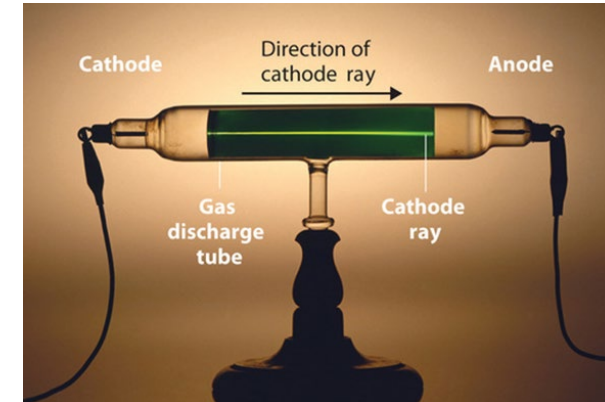


In 1897, Joseph John (J.J.) Thomson (1856-1940) discovers the 'electron' subatomic particle at the Cavendish Laboratory at the University of Cambridge, UK.

# The development of 'scientific' and 'industrial' vacuum pumps



As shown on the left, a circa 1880s research laboratory scale vacuum pump system with a combination of (A) Geissler's pump, (B) Sprengel's pump, and (C) McLeod's gauge. Such vacuum pumps were used to evacuate borosilicate glass chambers to study gas discharges leading to the what were known as Cathode Ray Tubes (CRT) as seen to the right side.

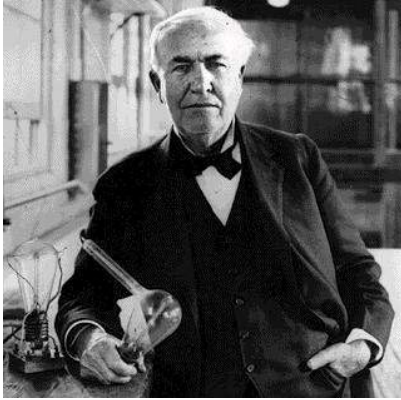


A schematic of an industrial-scale vacuum system (right) used in Thomas's Edison's incandescent light bulb production. Edison inspecting one of his light bulbs.

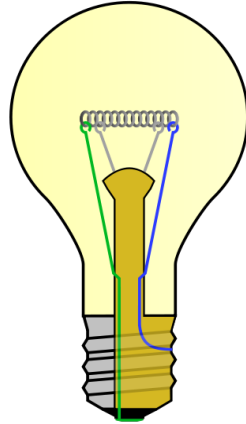


**Reference:** Simón Reif-Acherman. *Heinrich Geissler: Pioneer of Electrical Science and Vacuum Technology*. Proceedings of the IEEE. Vol. 103, No. 9, September 2015.

# Plasma Lighting Technology



**Thomas Edison**



**Incandescent Light Bulb**



**Daniel McFarlan Moore**



**Fluorescent Lamps**



**Compact fluorescent bulb**



**Birthplace of the Fluorescent Light Bulb: Edison (Menlo Park) / West Orange, NJ**

# The birthplace of Plasma Science



**Irving Langmuir**

## Birth of Plasma Science

**Birthplace: Hoboken, New Jersey**

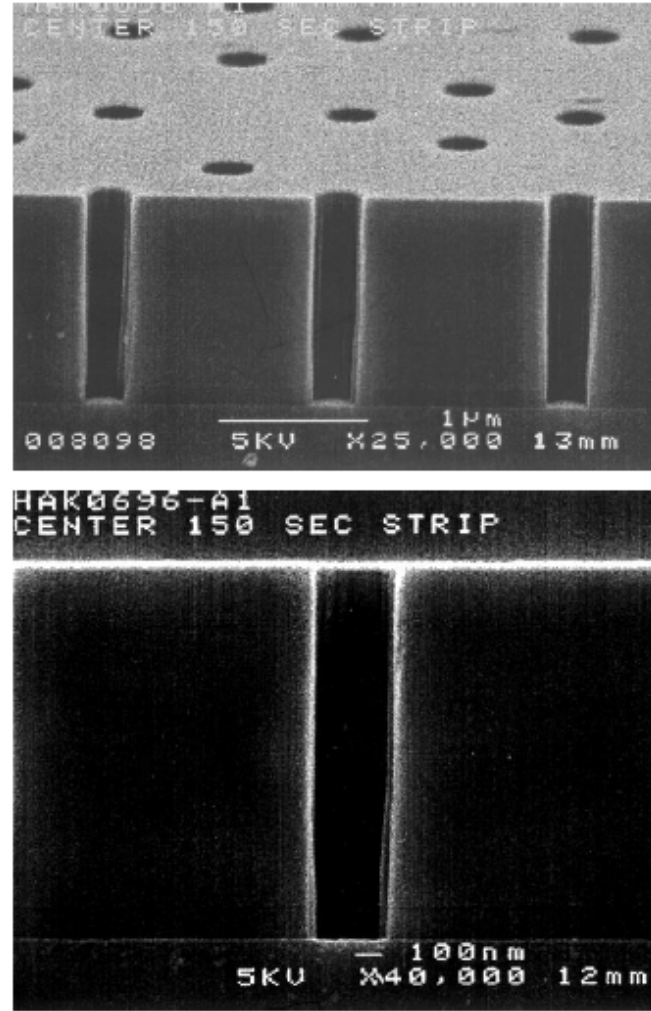
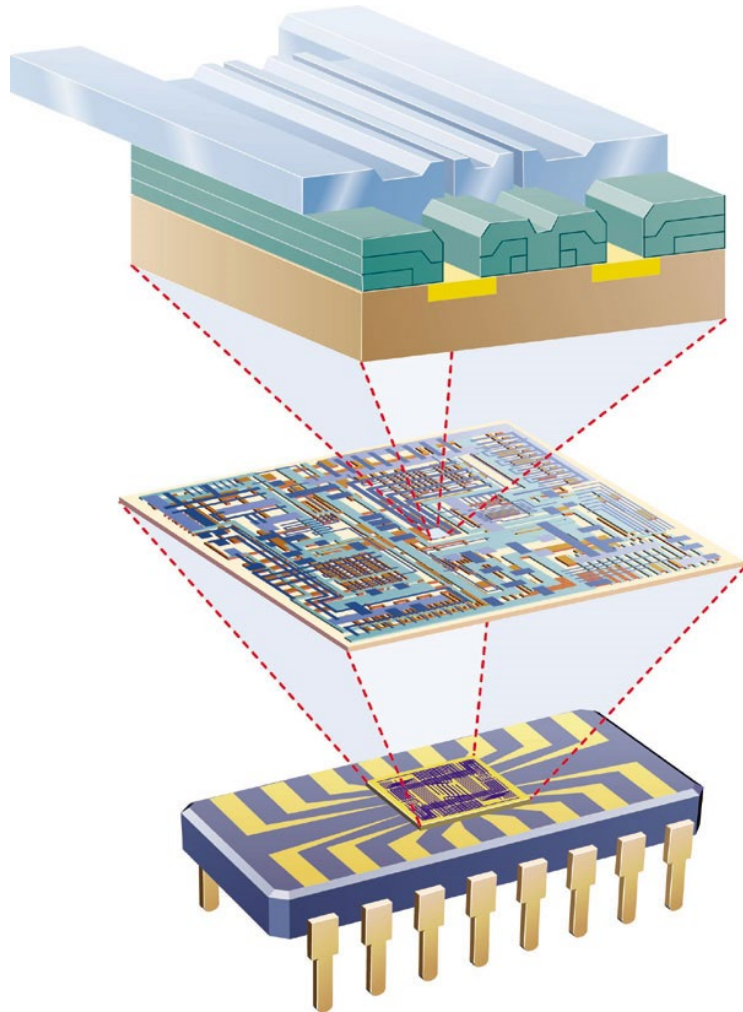


Irving Langmuir was one of the first scientists to work on plasmas and the first to refer to this 4<sup>th</sup> state of matter as *plasmas* in 1927, because his perceived descriptive similarity to blood plasma.



# Plasma Enhanced Technology

Microchip fabrication with plasmas.



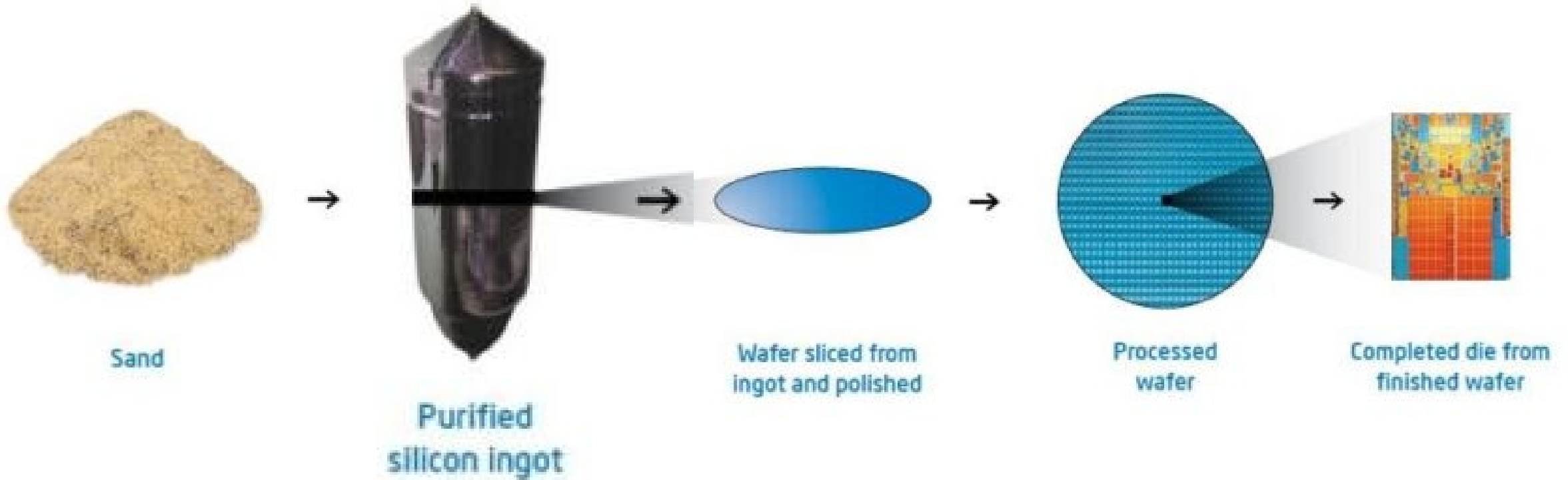
Straight holes like these can be etched with plasmas.

A small section of a memory chip.



**Birthplace of solid-state microelectronics: Bell Laboratories, Murray Hill, NJ**

# Semiconductors: The New Foundation of Modern Life



# The Invisible Infrastructure of the 21st Century

## Semiconductors: The New Foundation of Modern Life

- Semiconductors now play the role steel, electricity, and petroleum once played in earlier eras: they quietly power every major system of modern civilization.
- From smartphones and satellites to medical imaging and autonomous vehicles, chips form the hidden backbone of global technological capability.
- The modern digital economy—AI, data centers, cloud computing—rests entirely on the ability to manipulate electrons in exquisitely engineered materials.



# Why Semiconductors Matter More Than Ever

## A Pillar of National Competitiveness

- Nations now view semiconductor capability the way they once viewed oil reserves or industrial steel output.
- Chip manufacturing determines national strength across:
  - AI & Machine Learning
  - Advanced Communications (5G/6G)
  - Quantum and High-Performance Computing
  - Renewable and Smart Energy Systems
  - Defense, Security, and Space Technologies



## A Global “Materials Arms Race”

- Leadership is no longer just about making chips—it is about mastering the materials science behind them.



# Behind Every Chip Lies a Materials Revolution

## Semiconductors Are Not Just Electronics—They Are Materials Systems

- ✓ A modern chip contains trillions of precisely positioned atoms.
- ✓ Its performance depends on:
  - crystal quality
  - dopant distribution
  - interface chemistry
  - defect management
  - nanoscale plasma-assisted processing
- ✓ Every breakthrough in computing starts as a breakthrough in materials physics.



# The Hidden Scientific Race

## Design • Understand • Control

Behind every transistor geometry, memory architecture, or energy-efficient device lies a deeper competition:

### ✓ Designing new electronic materials

- Wide-bandgap semiconductors
- 2D materials (graphene, MoS<sub>2</sub>)
- Ferroelectrics, neuromorphic oxides
- Photonic and quantum materials

### ✓ Understanding their fundamental behavior

- Electron transport at the atomic scale
- Defect physics and excitonic processes
- Plasma-materials interactions (where your expertise powerfully connects)

### ✓ Controlling fabrication at the nanoscale *is all about plasma control*

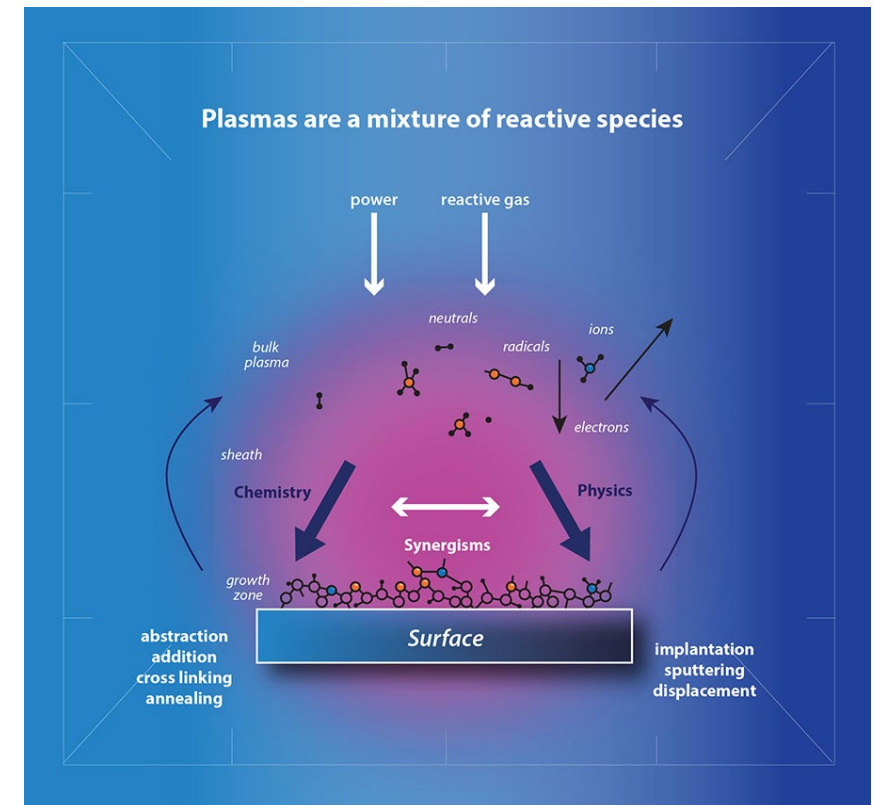
- Plasma etching
- Atomic layer deposition
- Extreme UV lithography
- Ultra-fast pulsed plasmas for next-generation interfaces



# Plasma Science: The Unseen Engine of Semiconductor Fabrication

Nearly every step in chip manufacturing depends on **low-temperature plasma physics**, including:

- Pattern transfer
  - Thin-film deposition
  - Surface activation
  - 3D nanostructure fabrication
- 
- ✓ The industry's most advanced features (sub-5 nm structures) are not possible without the precision of plasma-based processes.
  - ✓ Plasma-enabled materials engineering is now a decisive factor in the global semiconductor race.



# Why Materials Matter: The Future Depends on Them

Technologies shaped by breakthroughs in materials science:

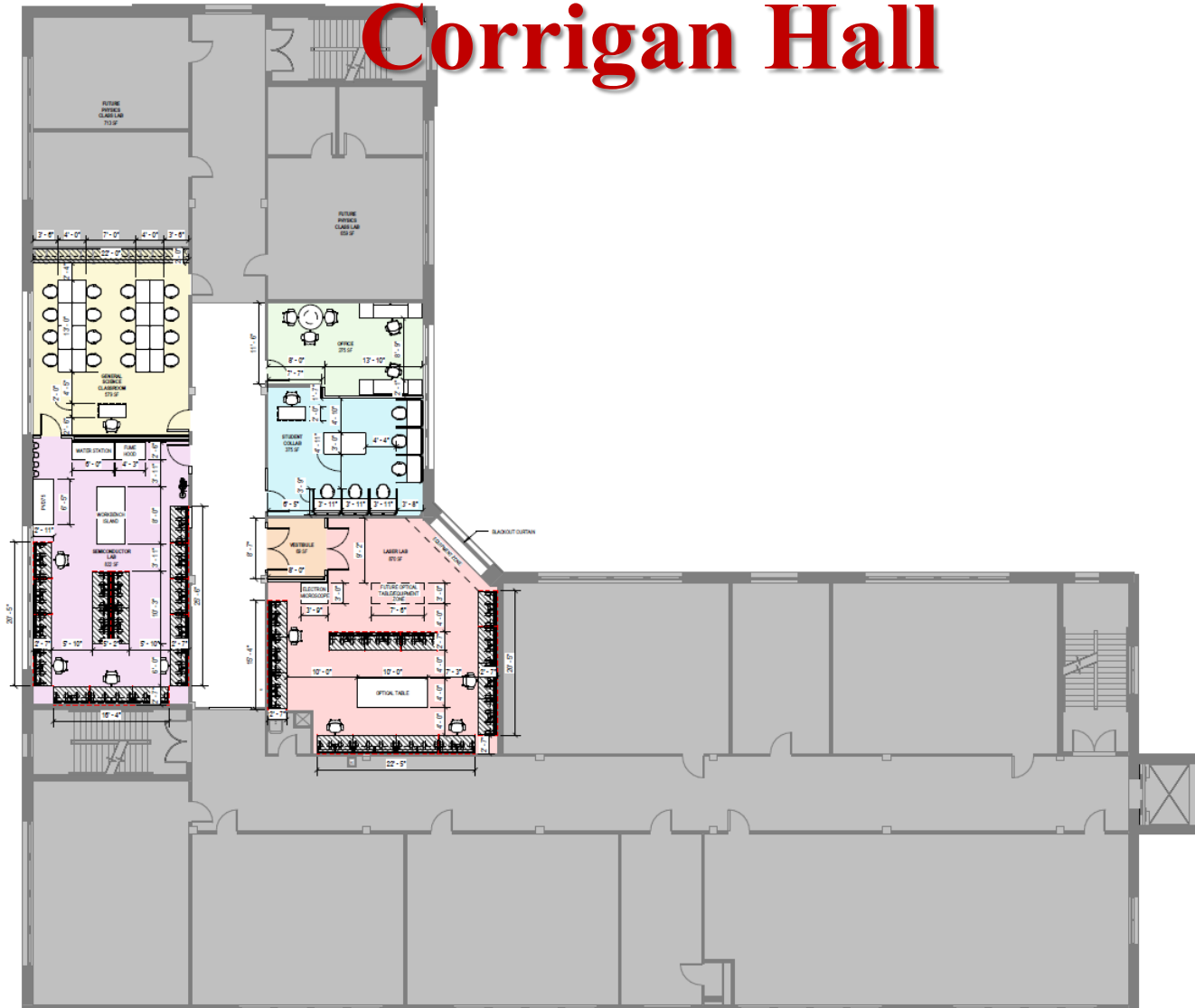
- Quantum computing
- AI accelerators
- Efficient power electronics for EVs and clean energy
- Secure communications and sensing
- High-speed photonics
- Biomedical diagnostics and environmental monitoring



**The next great leaps in technology will come not from software alone, but from the materials that make computation possible**

# SHU Applied Physics & Engineering Laboratories –

## Corrigan Hall



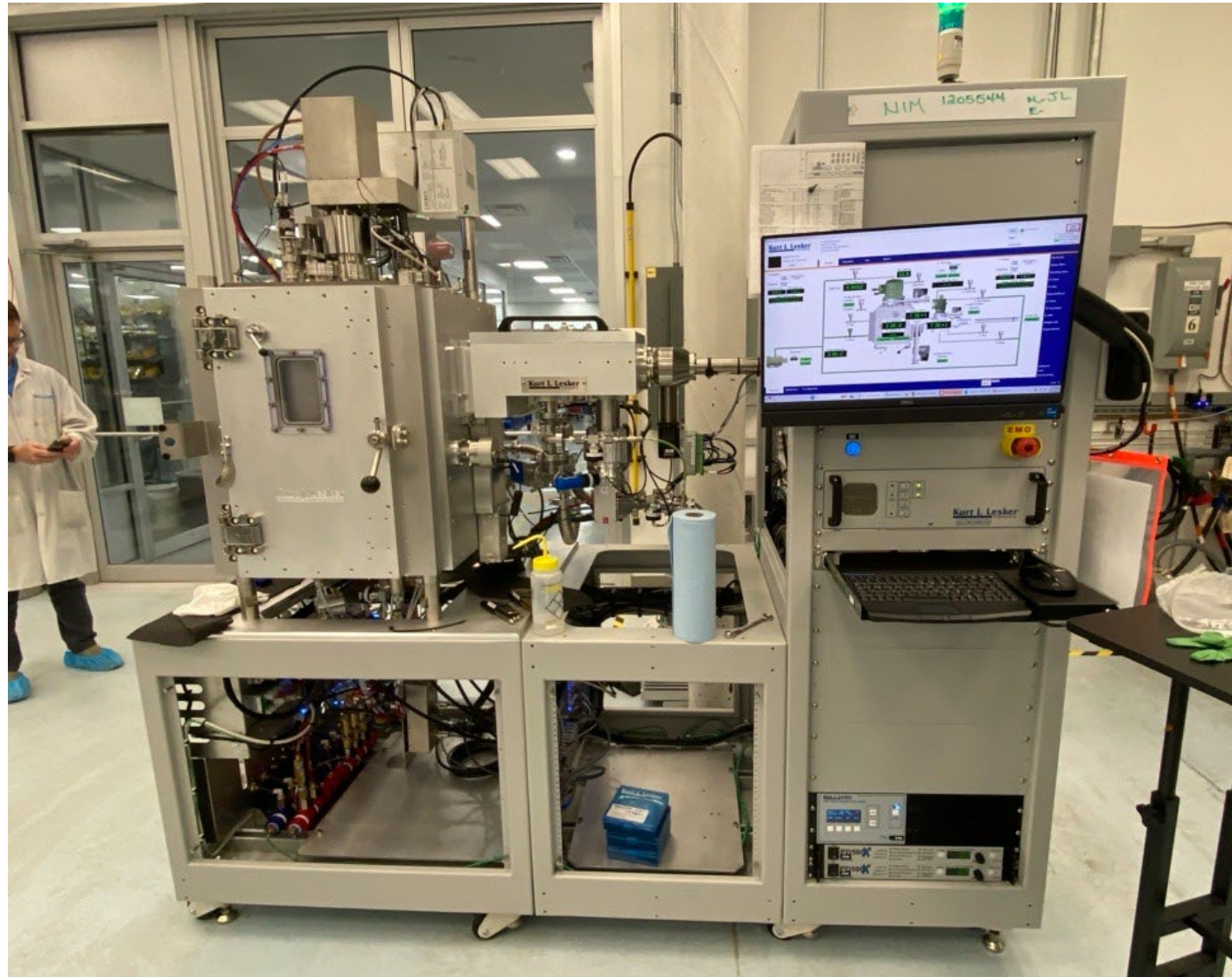
# Corrigan Hall Physics Laboratories



**Coming online: September 2026**

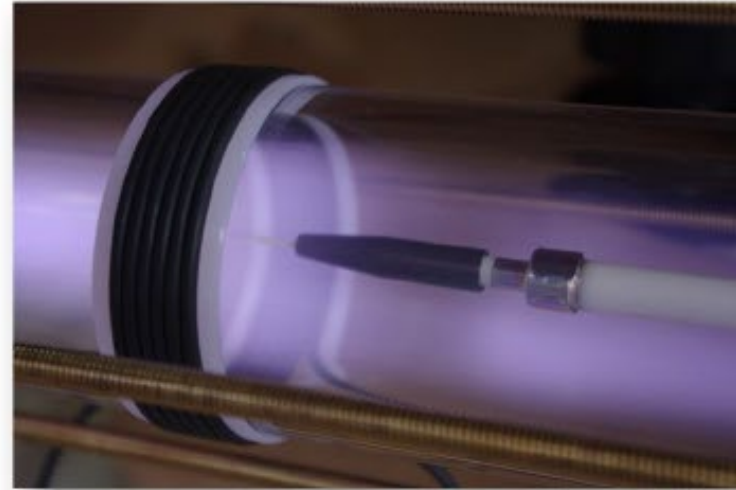


# Semiconductor Lab - Plasma processing system



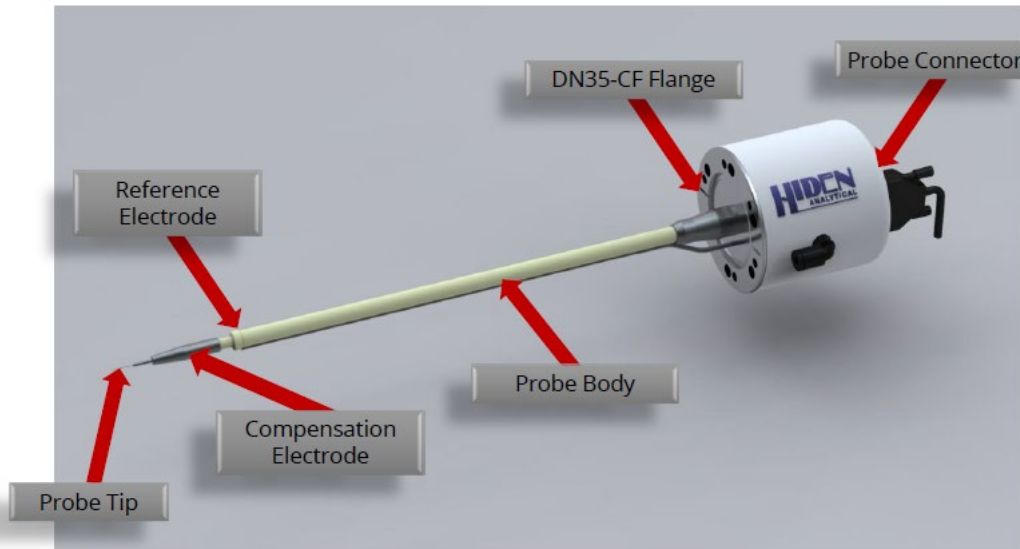
# Langmuir Probe

- Floating Potential,  $V_f$
- Plasma Potential,  $V_p$ .
- Electron Energy Distribution Function, EEDF.
- Debye length,  $\lambda_D$ .
- Ion Flux,  $\Gamma_i$
- Electron Temperature,  $T_e$ , up to 10 eV.
- Orbital motion Limited (OML) and Allen Boy Reynolds (ABR)
- Ion density,  $N_i$ , and electron density,  $N_e$ , over the range  $10^{14}$ - $10^{19}$   $\text{m}^{-3}$



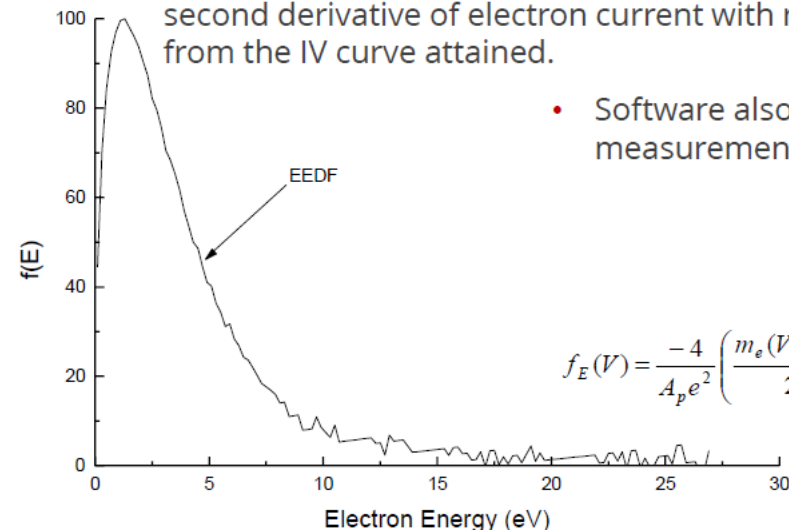
# Langmuir Probe

## Configuration



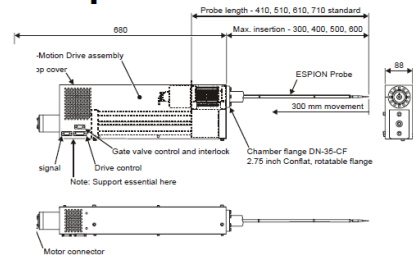
## Electron Energy Distribution Function, EEDF

- EEDF is determined by the **Druyvestyn** method, using the second derivative of electron current with respect to voltage from the IV curve attained.
- Software also provides additional measurements of:  $T_e$ ,  $N_e$  and  $EE$ .



$$f_E(V) = \frac{-4}{A_p e^2} \left( \frac{m_e (V_p - V)}{2e} \right)^{1/2} \frac{d^2 I_e(V)}{dV^2}$$

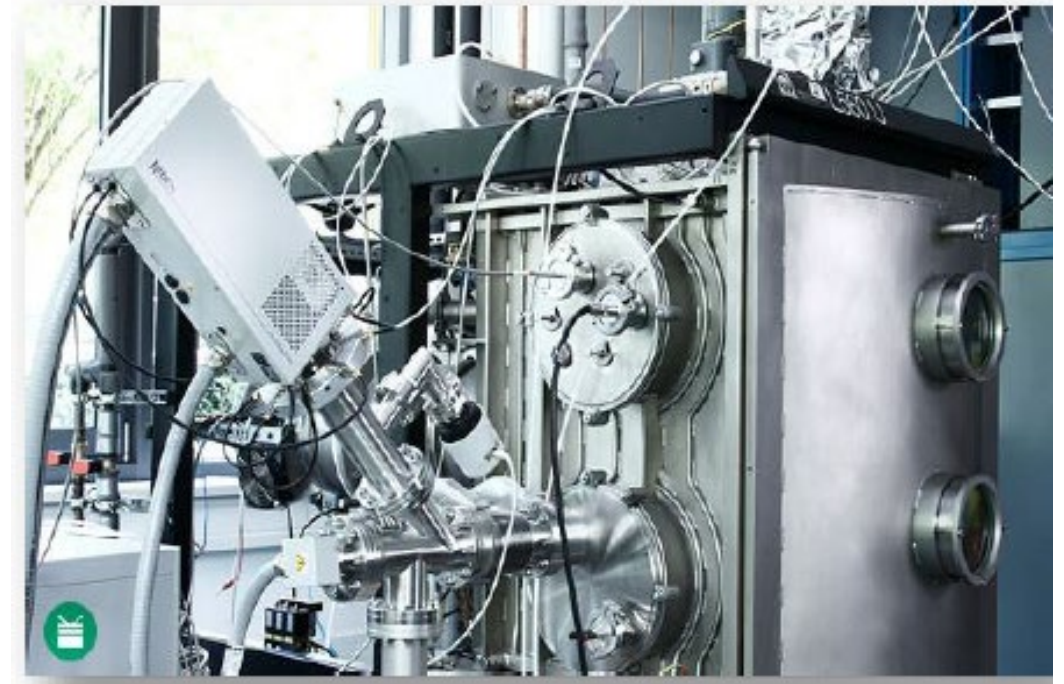
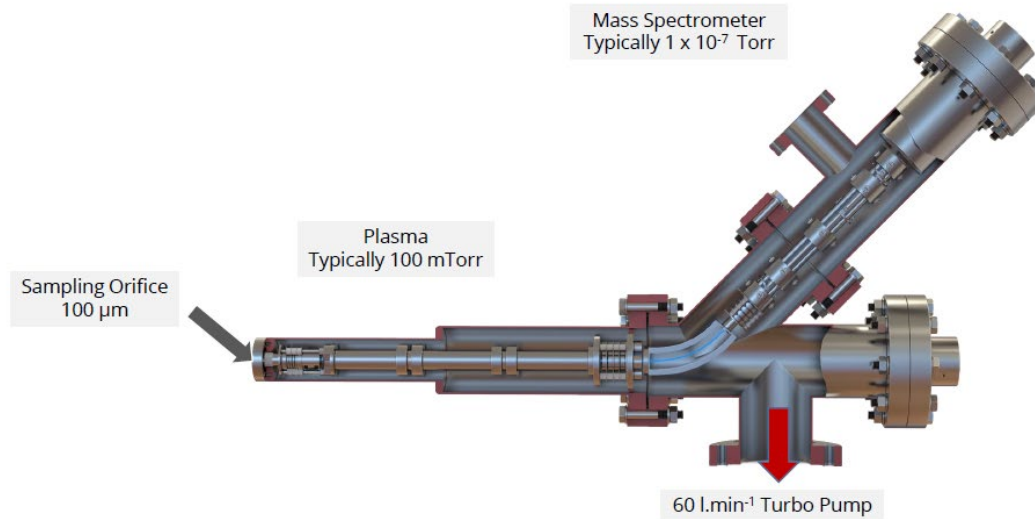
## Custom Options



### Automatic Z-Drive

- Stroke 300-900 mm
- Speed 12.7-25.0 mms<sup>-1</sup>
- Manual option available

# Energy & Mass Analyzer



- Sub PPM detection of plasma ions, neutrals and radicals.
- Ion Energy Analysis, 0-100 eV and 0-1000 eV energy range versions are available.
- Positive and Negative Ion Analysis.
- Neutral and Radical Species Detection.
- Electron attachment ionisation mode for the study of electro-negative radicals.
- Mass range options: 20, 50, 200, 300, 510, 1000, 2500 or 5000 amu.
- A standard TTL signal gating input is included for time resolved studies.

# The 'Physics' Message

- ✓ Semiconductors are the infrastructure.
- ✓ Materials science is the enabler.
- ✓ **Plasma physics is the accelerator.**
- ✓ The individuals that understand and groups control advanced materials will set the technological direction of the next century.

The **CHIPS and Science Act of 2022** is a landmark U.S. federal law enacted to revitalize domestic semiconductor manufacturing, secure critical technology supply chains, and bolster long-term scientific research. It authorizes approximately \$280 billion in total spending over 10 years.



# LEAP

LABORATORY OF ELECTROPHYSICS & ATMOSPHERIC PLASMAS (LEAP)



WHAT GREAT MINDS CAN DO

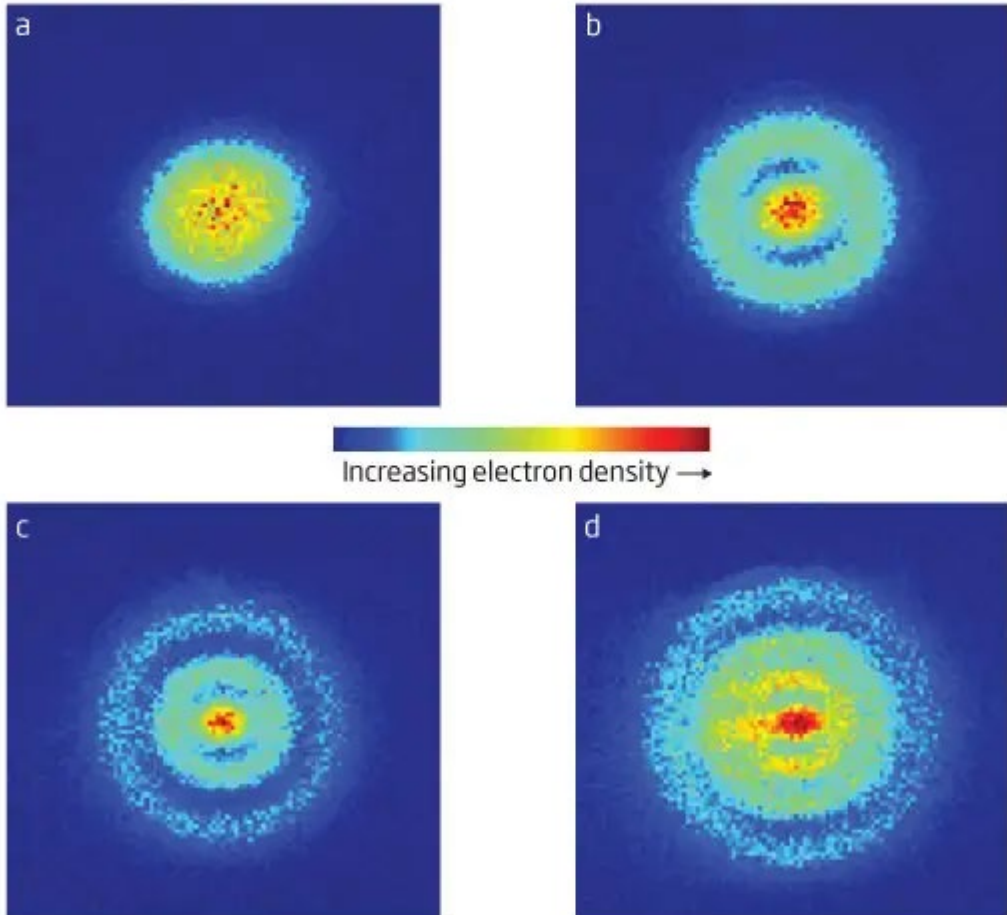
Department of Physics

# The Electron

## An atom undressed

©NewScientist

Electrons have quantum properties so can be in many places at once, making it hard to image atoms. By combining snapshots of many electrons at once, hydrogen atoms have now been imaged at four energy levels (increasing from a to d)

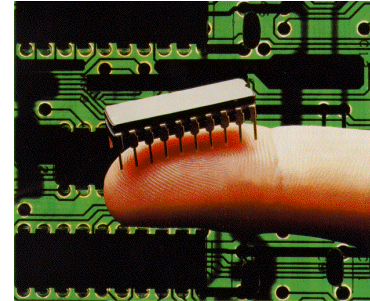
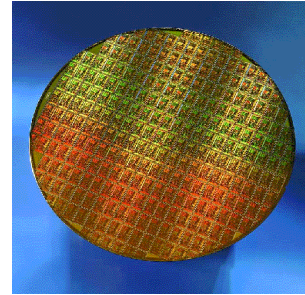


“Every modern technology rests on the ability to manipulate electrons.”

# Plasmas are easier to generate at low pressures

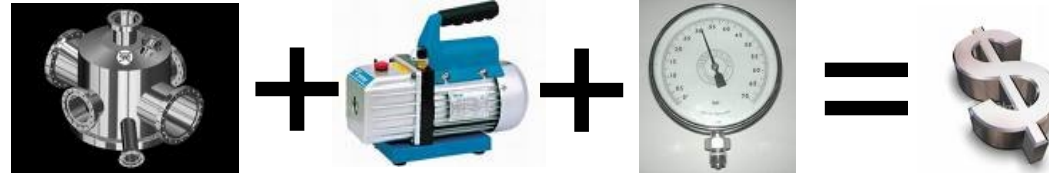
## Low pressure plasmas (1 mTorr ~ a few Torr)

- are well understood
- are used extensively nowadays  
(e.g. in semiconductor industry for computer chips manufacturing)



However, to generate low pressure plasmas:

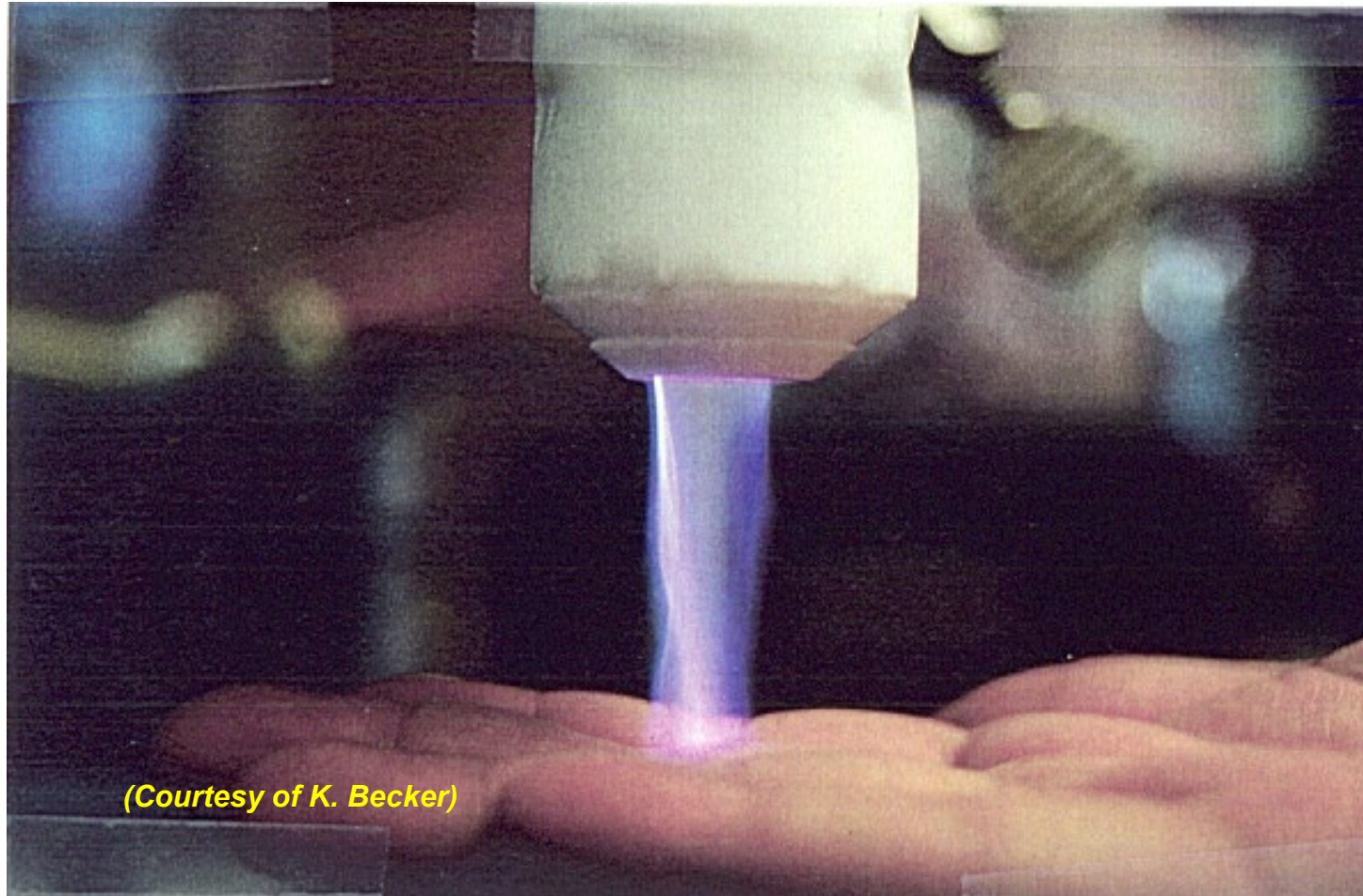
- vacuum chambers
- expensive vacuum pumps
- pressure monitoring and pressure control devices



***Generate Plasmas at Atmospheric (or higher) Pressure!!!***

# Atmospheric Cold Plasmas

Erich Kunhardt & Kurt Becker



**An Atmospheric Pressure Plasma Generated with a  
Capillary-Plasma-Electrode Discharge**

# Two Types of plasmas

## High-temperature plasmas or Hot (Thermal) plasmas



Sun



Electric spark

$$T_{\text{ion}} \approx T_{\text{electron}} \geq 10^7 \text{ K } (\approx 10,000,000 \text{ } ^\circ\text{C})$$

Examples: fusion plasmas like the Sun and stars

$$T_{\text{ion}} \approx T_{\text{electron}} \approx T_{\text{gas}} \leq 2 \times 10^4 \text{ K } (\approx 10,000 \text{ } ^\circ\text{C})$$

Examples: arc plasma or lightning at normal pressure

## Low-temperature plasmas or Cold (Non-thermal) Plasmas



Aurora Borealis



Compact  
Fluorescent bulb

$$T_{\text{ion}} \approx T_{\text{gas}} \approx 300 \text{ K } (\approx \text{room temperature } \approx 20 \text{ } ^\circ\text{C})$$

$$T_{\text{ion}} \ll T_{\text{electron}} \leq 10^5 \text{ K } (\approx 100,000 \text{ } ^\circ\text{C})$$

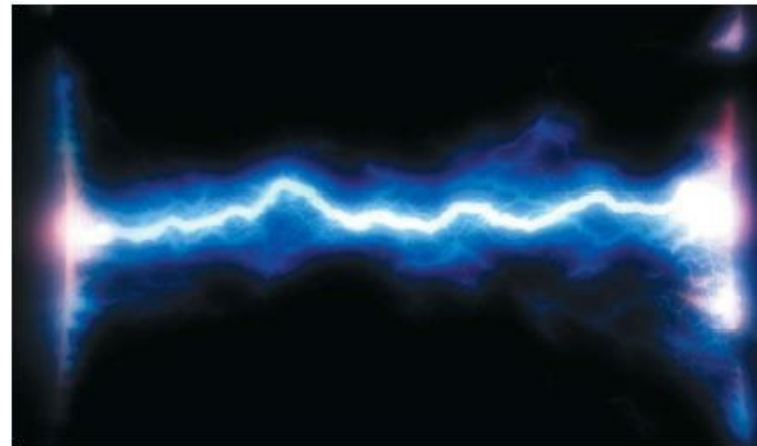
Examples: low-pressure glow discharge like a fluorescent lamp or comet tails  
high-pressure cold plasma like an auora or ozone generator system

# What happens at air pressure?

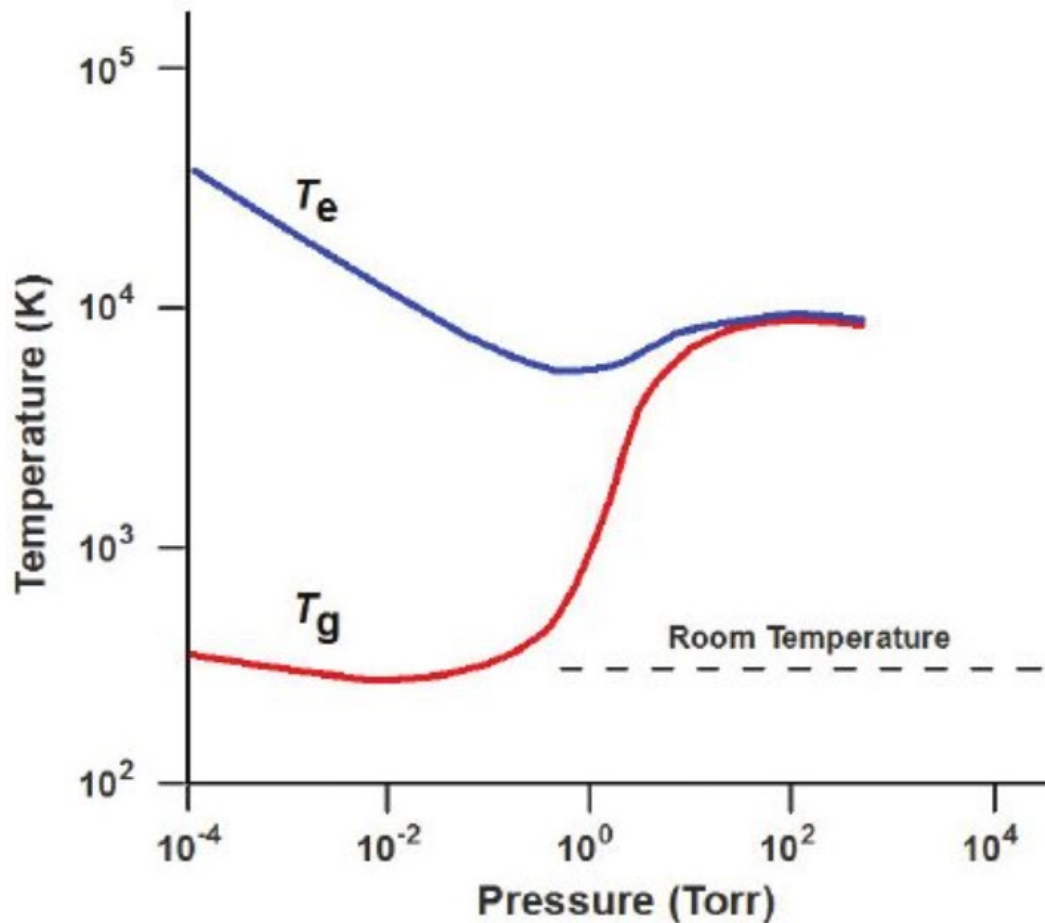
- No vacuum is involved
- Difficult to generate and sustain
- Run into some challenges such as glow to *arc* transition – Non controllable

**Arc Discharge:** thermal plasma

- It's hot and detrimental
- Gas temperature can reach as high as  $2 \times 10^4$  K
- Low voltage drop at cathode
- High cathode current density



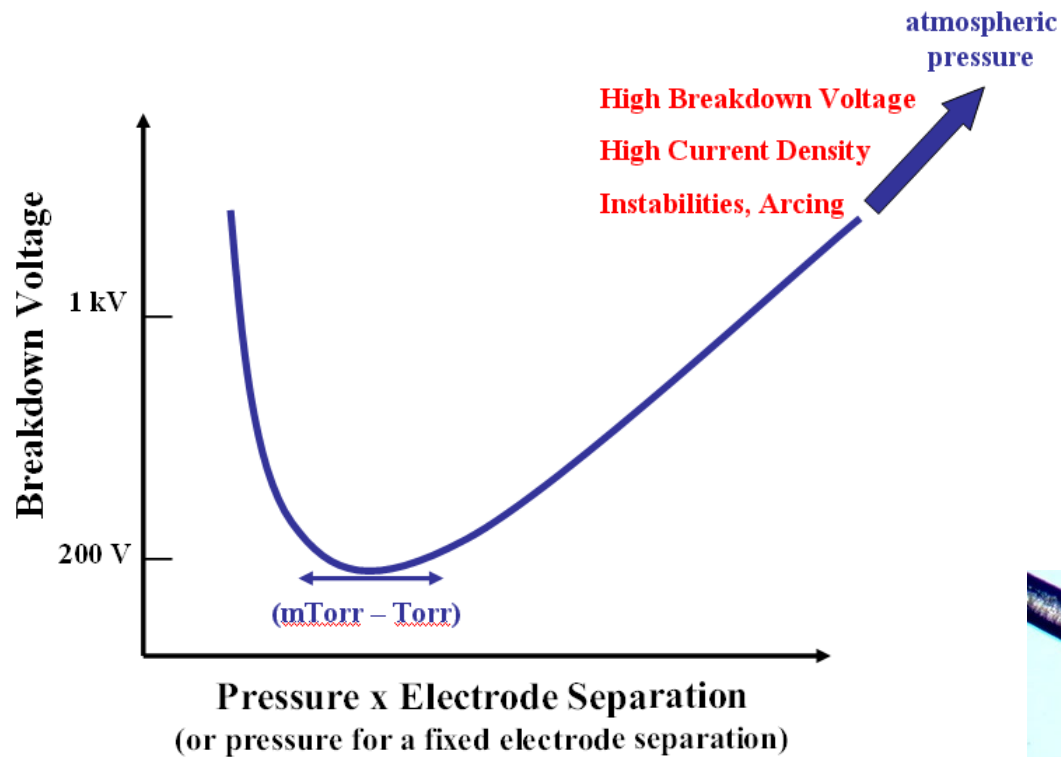
# Low-Temperature Plasmas



Electron temperatures ( $T_e$ ) and gas temperatures ( $T_g$ ) versus pressure for a glow discharge.

Low temperature plasmas will limit the gas (heavy particles i.e. ions, atoms, molecules, dust, etc.) temperature to room temperature.

# High Pressure (atmospheric) plasmas



**Paschen Breakdown Curve**

Stabilization of high-pressure plasmas: “pd scaling”: “p”  $\uparrow$ , so “d”  $\downarrow$  to keep breakdown voltage low and minimize instabilities after breakdown -

## Microplasmas

Dimension: a few millimeter down to and below **100  $\mu\text{m}$**



Human Hair: 60 – 100  $\mu\text{m}$

# Plasma physics of high pressure LTPs

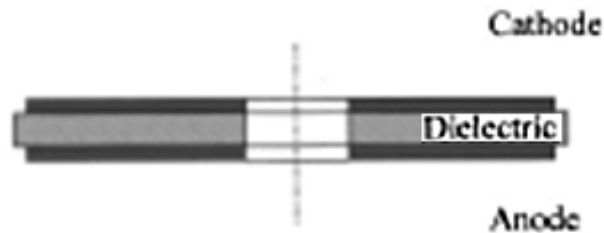
**Micro-confinement:** Gas heating occurs in the plasma volume, and the energy is carried away by thermal diffusion/convection to the outside. If the plasma has a small volume and a relatively large surface, gas heating is limited.

**Dielectric Barrier Discharges (DBD):** These plasmas are typically created between metal plates, which are covered by a thin layer of dielectric or highly resistive material. The dielectric layer plays an important role in suppressing the current: the cathode/anode layer is charged by incoming positive ions/electrons, which reduces the electric field and hinders charge transport towards the electrode. DBD also has a large surface-to-volume ratio, which promotes diffusion losses and maintains a low gas temperature.

**Transient (pulsed) plasmas:** *In atmospheric plasmas, for efficient gas heating at least 100-1000 collisions are necessary. Thus, if the plasma duration is shorter than  $10^{-6} - 10^{-5}$  s, gas heating is limited. A corona discharge might be grouped here. However, overall for practical purposes such plasma has to be operated in a repetitive mode, e.g., in trains of microsecond pulses with millisecond intervals or more recently due to fast compact HV pulsed power there are nanoseconds duration pulses.*



# Micro Hollow Cathode Discharge (MHCD)



← Sandwich Structure:  
Electrode – Dielectric - Electrode

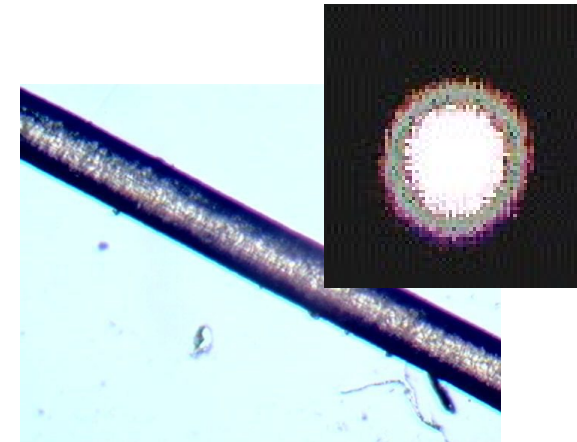
Critical dimensions at atmospheric pressure (static operation):

$d$ :  $< 500 \mu\text{m}$

$D$ :  $10 - 300 \mu\text{m}$

(assuming at room temperature)

Most of the experimental studies are in rare gases and rare gas halide mixtures, with an increasing interest on atmospheric pressure air .



Human Hair:  $60 - 100 \mu\text{m}$

## Reference:

Plasma Sources Sci. Technol. **6** (1997) 468–477. Printed in the UK

PII: S0963-0252(97)86592-9

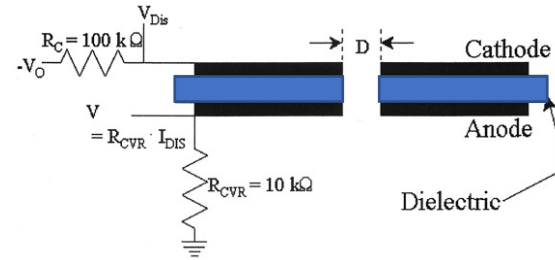
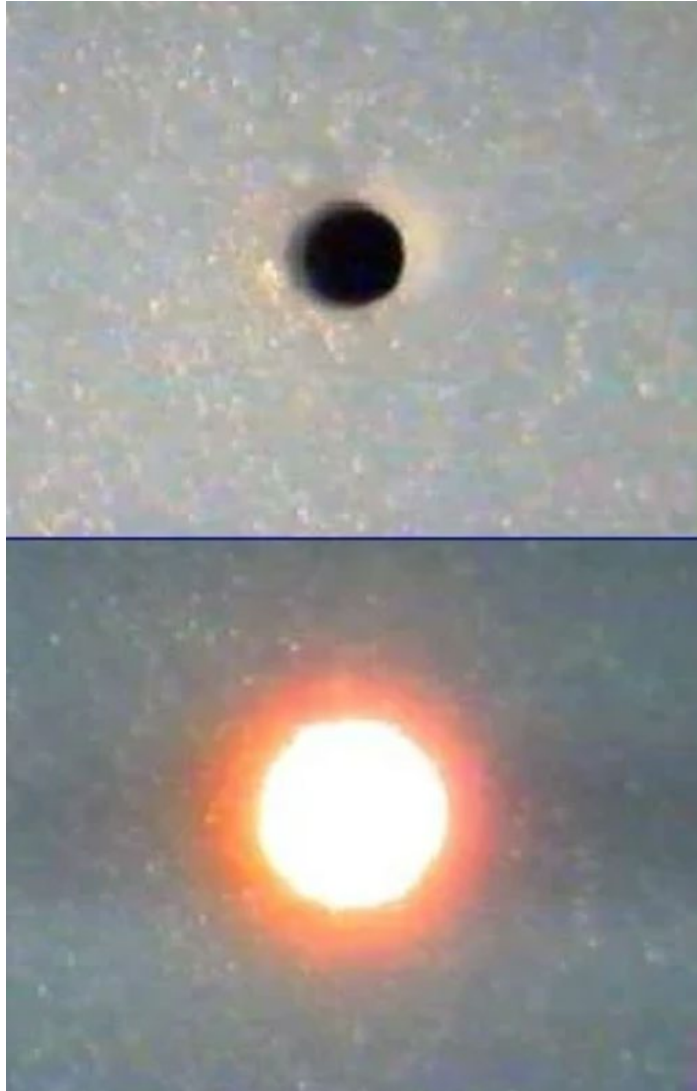
## High-pressure hollow cathode discharges

Karl H Schoenbach, Ahmed El-Habachi, Wenhui Shi and Marco Ciocca

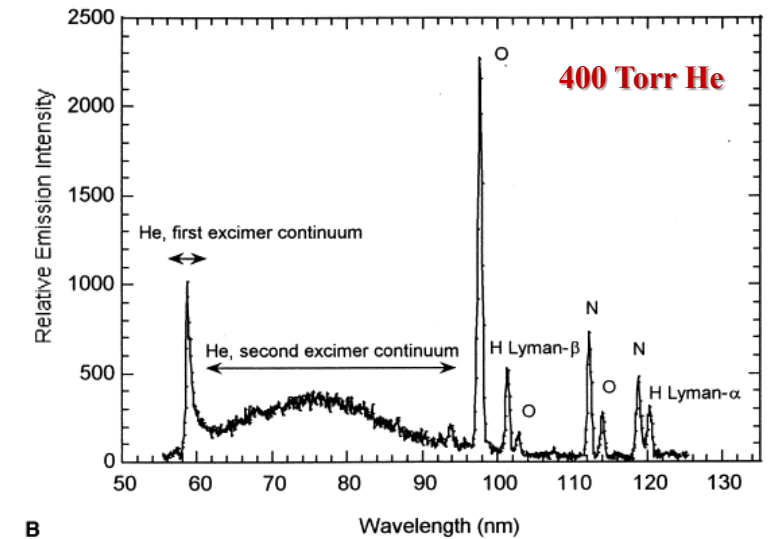
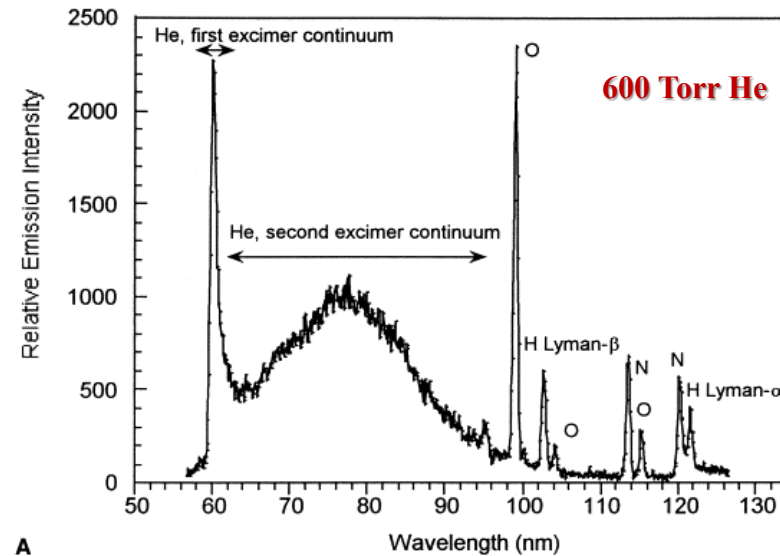
Physical Electronics Research Institute, Old Dominion University, Norfolk, VA 23529, USA



# Micro Hollow Cathode Discharge (MHCD)



Schematic diagram of the microhollow cathode discharge device and the electric circuit used in the present experiments. The cathode material is molybdenum, and the dielectric is mica.

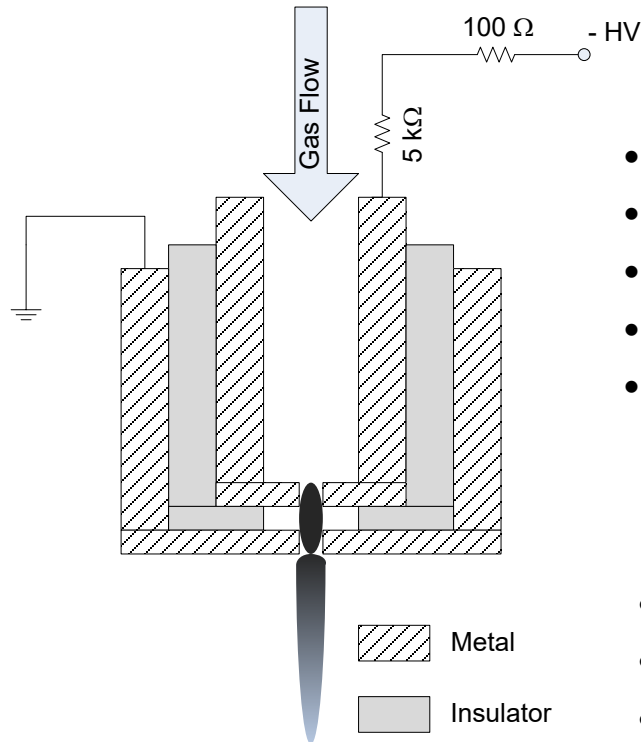


(A) Emission spectrum from a MHCD plasma in 600 Torr He with trace impurities of  $H_2$ ,  $N_2$ , and  $O_2$ . The first and second  $He_2^*$  excimer-emission continua have been marked. Also indicated are several O, N, and H atomic line emissions (see text for further details). (B) Same as (A) for a He pressure of 400 Torr.

**Reference:** P. Kurunczi, J. Lopez, H Shah, K Becker. *Excimer formation in high-pressure microhollow cathode discharge plasmas in helium initiated by low-energy electron collisions*. International Journal of Mass Spectrometry 205 (1-3), 277-283

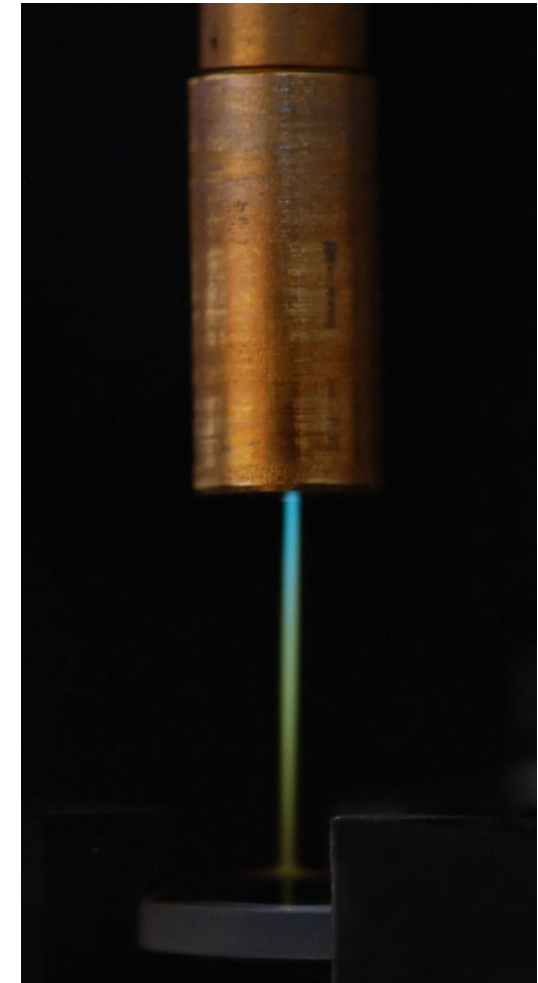


# MHCD Plasma Micro Jet

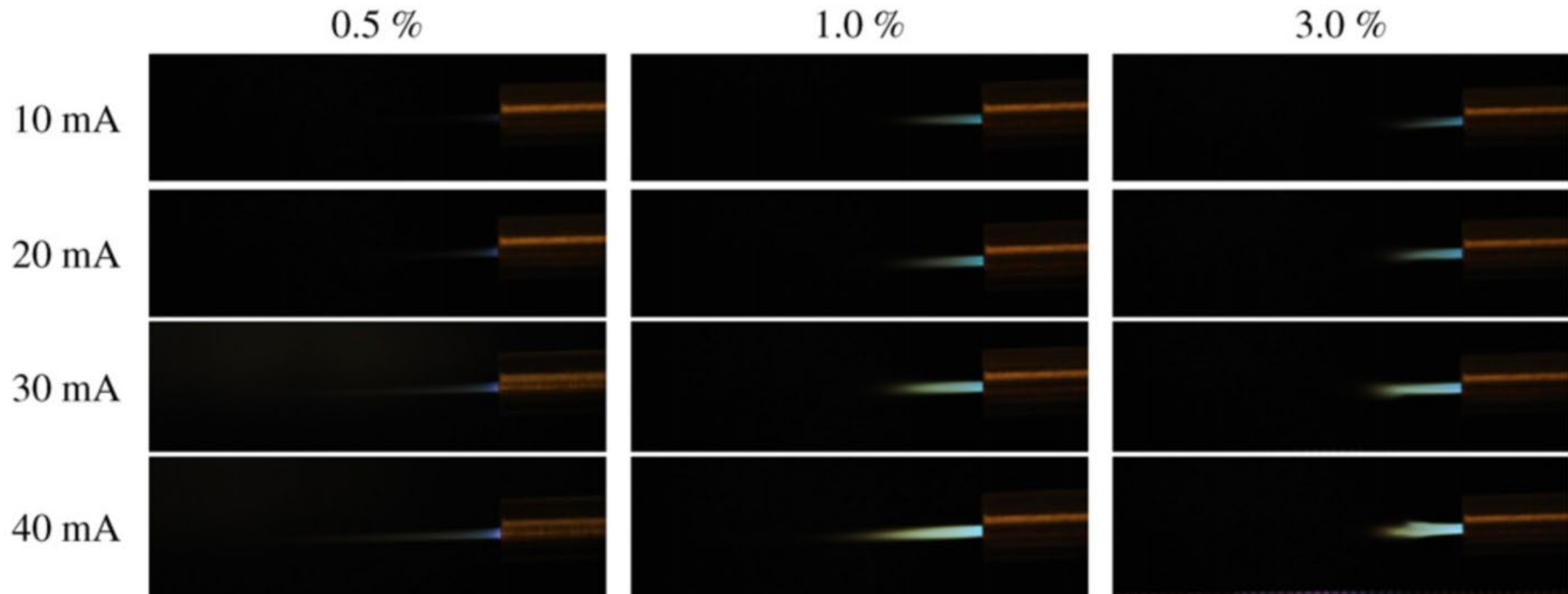


- Dimensions of the device are:
- Opening: 0.8 mm in diameter
- Separation: 0.5 mm
- Depth of exit opening: 1 mm
- Electrode material: copper

- Dimension of the plasma jet are
- ~ 800  $\mu\text{m}$  in diameter
- 8 -10 mm in length
- Flow rate: 2-3 SLM of He or dry air
- Power consumption: 8 W (400 VDC, 20 mA)

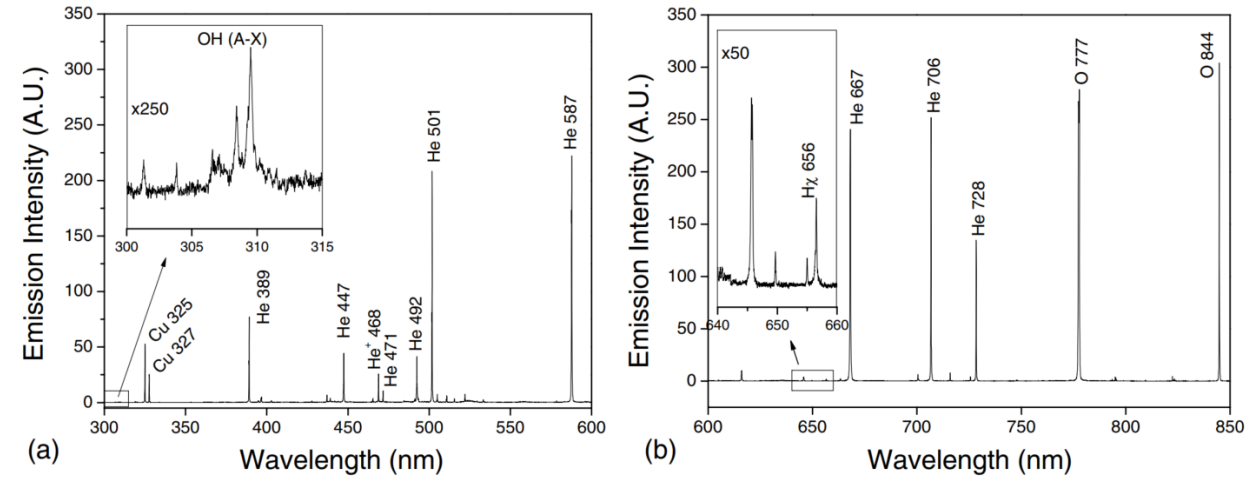
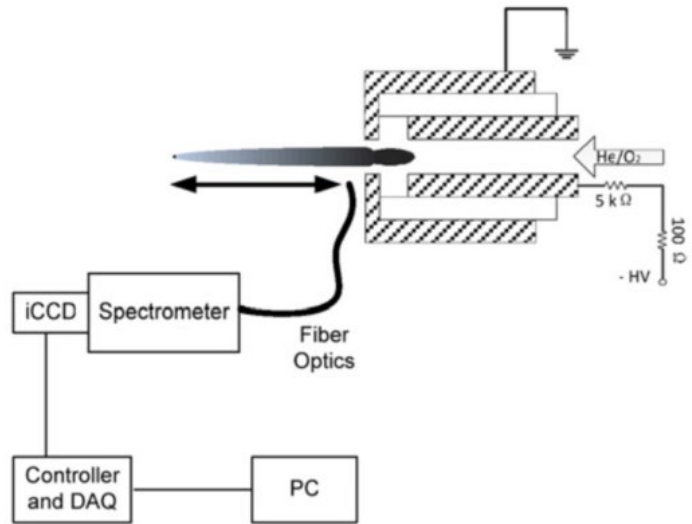


# MHCD Plasma Micro Jet

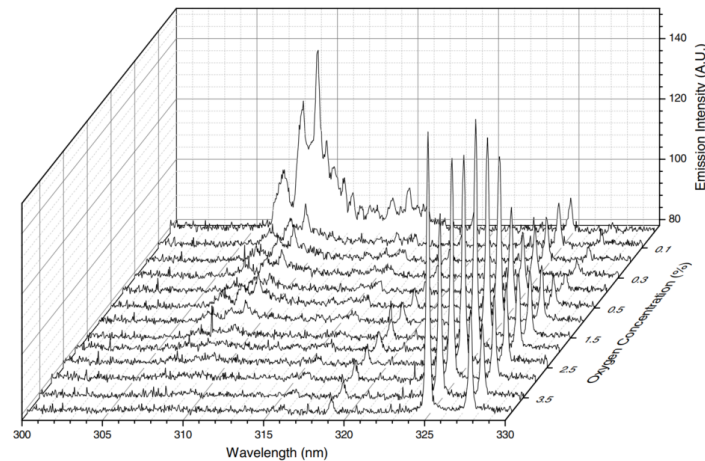


**Figure 2.** Pictures of the PMJ at O<sub>2</sub>% of 0.5%, 1% and 3%, and discharge current 10 mA, 20 mA, 30 mA and 40 mA.

# MHCD Plasma Micro Jet



**Figure 6.** End-on emission spectra of the PMJ from (a) 300–600 nm and (b) 600–850 nm (with He and 2% O<sub>2</sub> as working gas at a flow rate of 2 slm and a discharge current of 30 mA).



**Figure 8.** Optical emission spectra in 300–330 nm region showing emissions from OH (306–309 nm) and Cu (325 and 327 nm)

## Reference:

IOP PUBLISHING  
Plasma Sources Sci. Technol. **21** (2012) 034018 (10pp)

PLASMA SOURCES SCIENCE AND TECHNOLOGY  
doi:10.1088/0963-0252/21/3/034018

## A dc non-thermal atmospheric-pressure plasma microjet

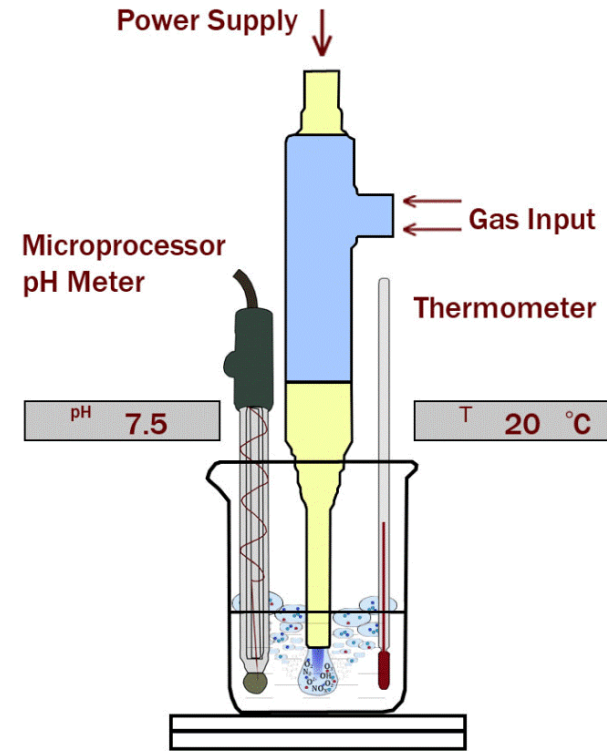
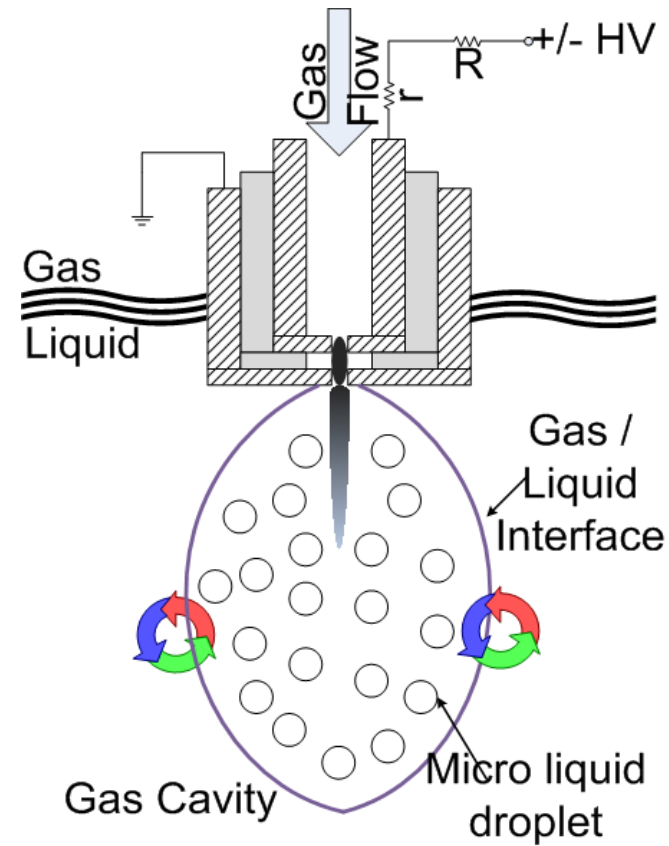
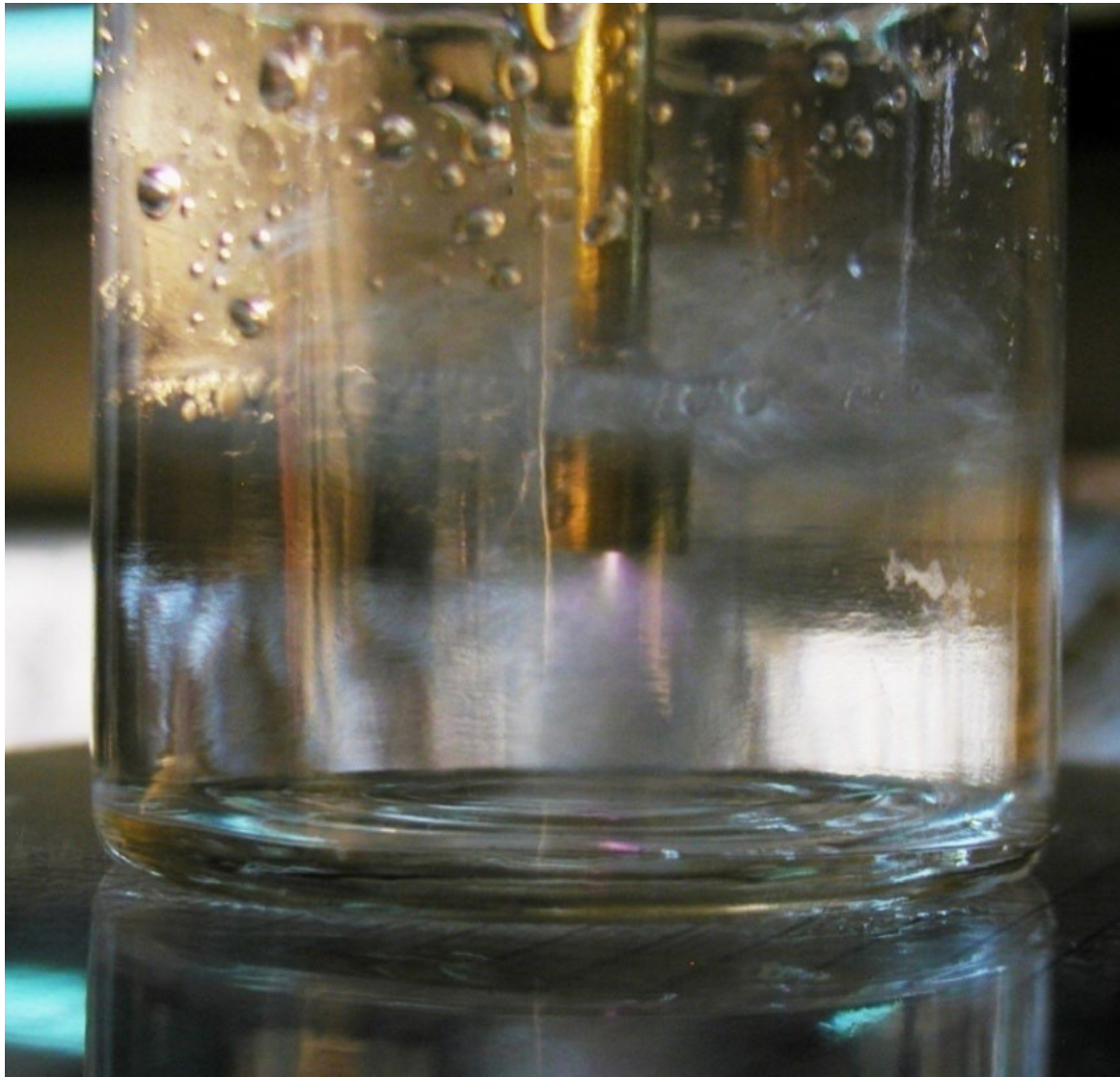
WeiDong Zhu<sup>1</sup> and Jose L Lopez<sup>2</sup>

<sup>1</sup> Department of Applied Science and Technology, St. Peter's College, Jersey City, NJ, USA

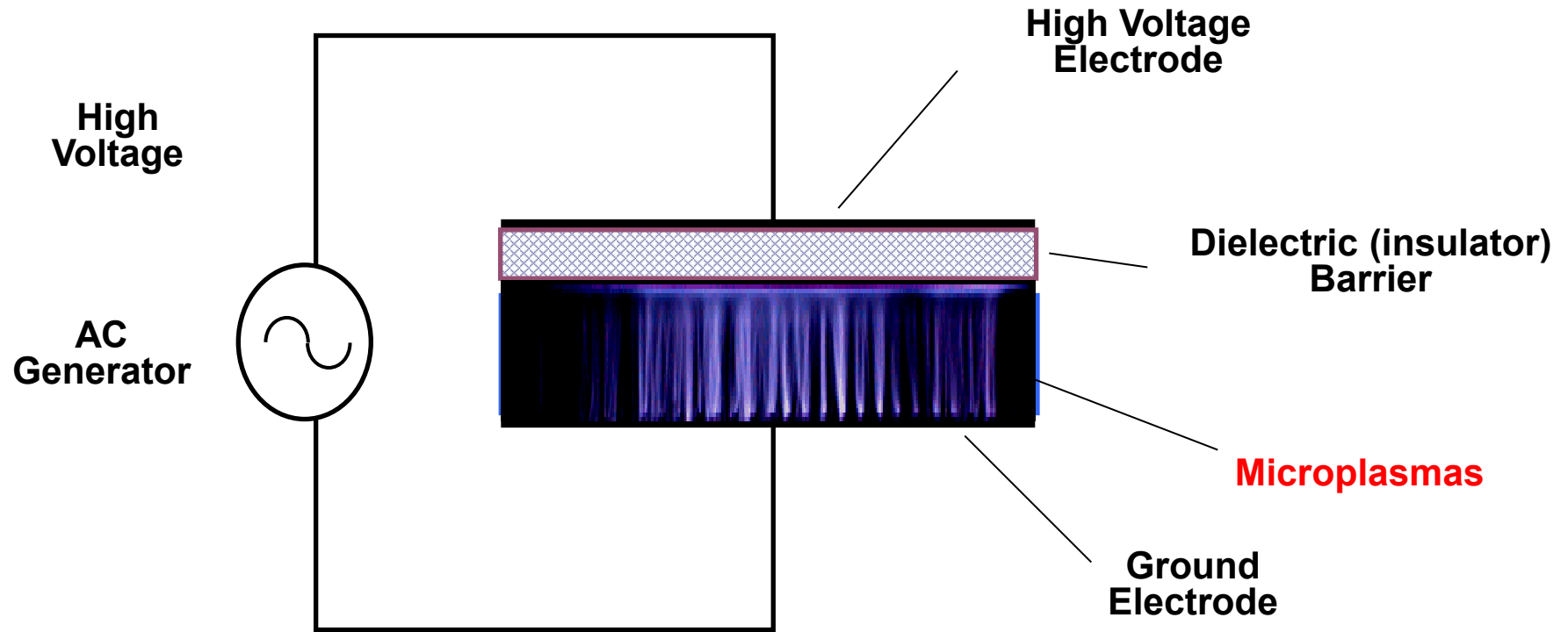
<sup>2</sup> Department of Physics, Seton Hall University, South Orange, NJ, USA



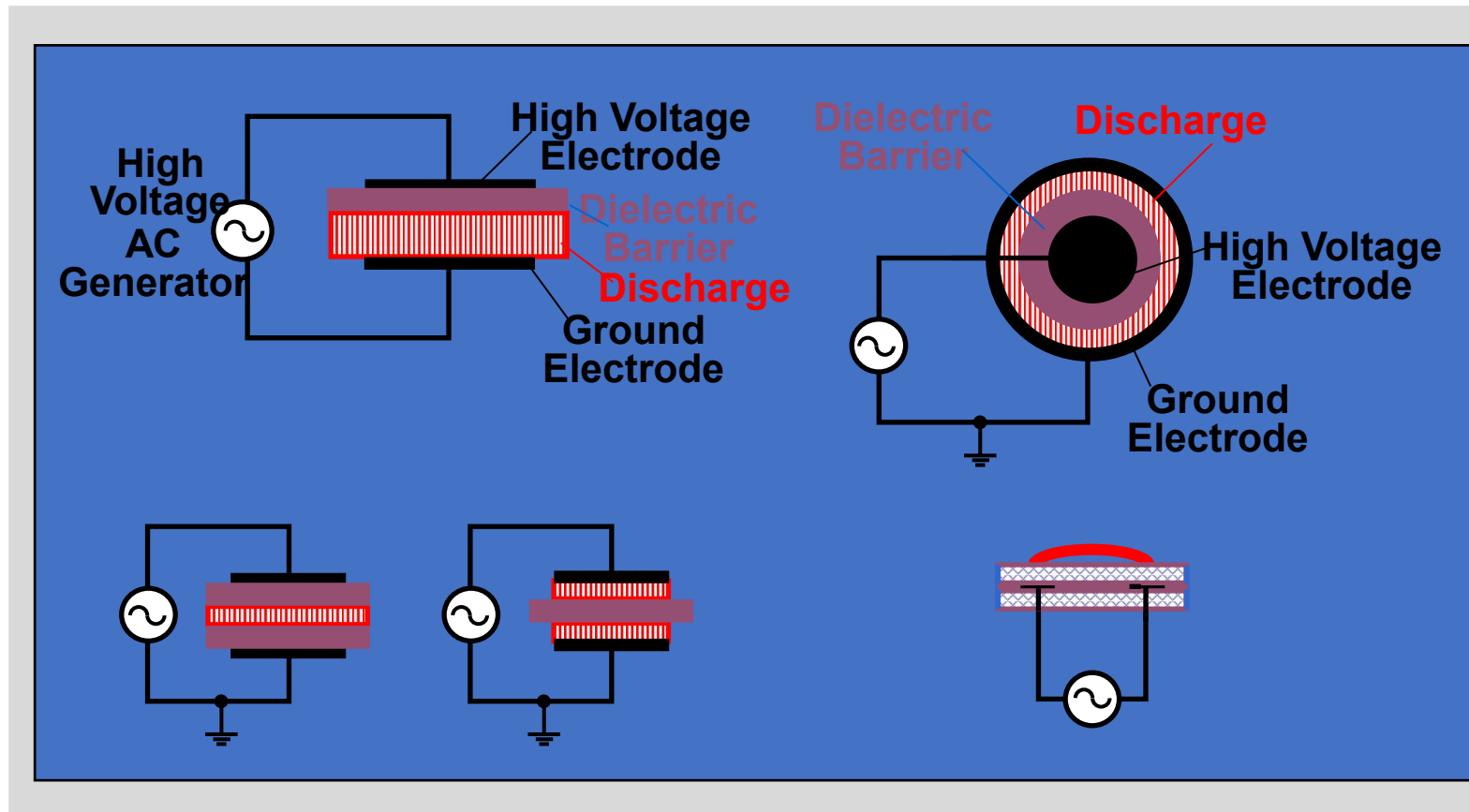
# MHCD Micro Jet Inside Water



# Dielectric Barrier Discharge (DBD)



# Dielectric Barrier Discharge



H.E. Wagner, R. Brandenburg, et. al. 'The barrier discharge: basic properties and applications to surface treatment'. *Vacuum*. 71 p417-436 (2003).

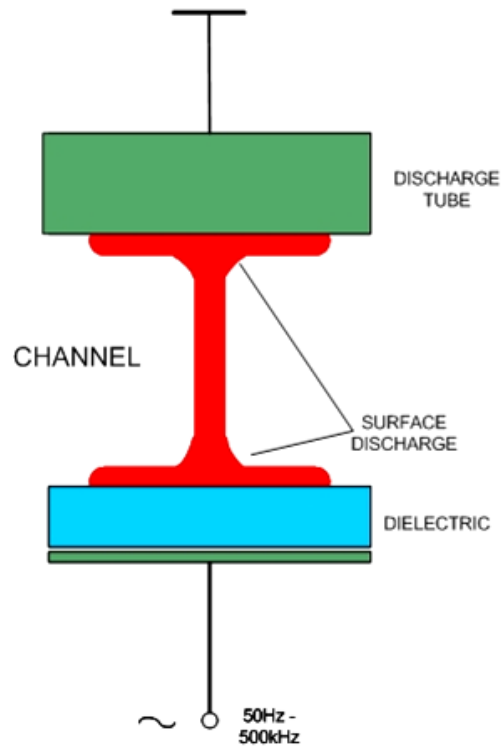
# Role of the Dielectric (Insulator)

The dielectric is the key for the proper functioning of the plasmas.

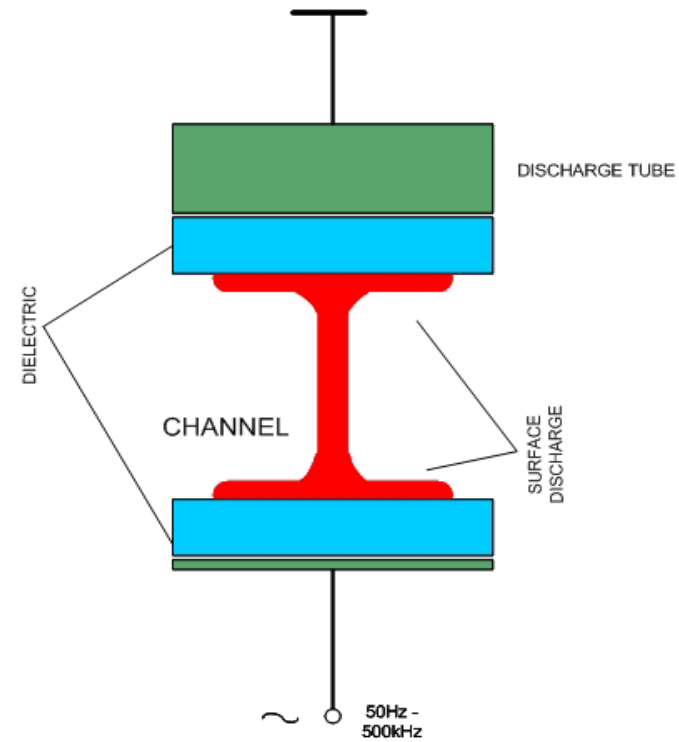
Serves two functions:

1. Limits the amount of charge transported by a single microplasma
2. Distributes the microplasmas over the entire electrode surface area

# Single and double DBD

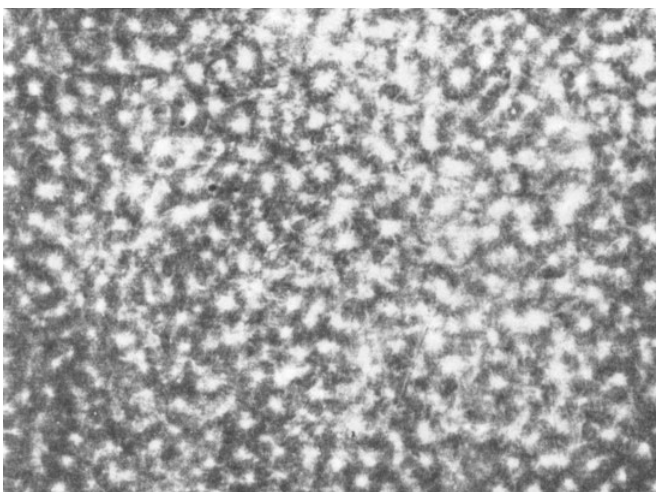
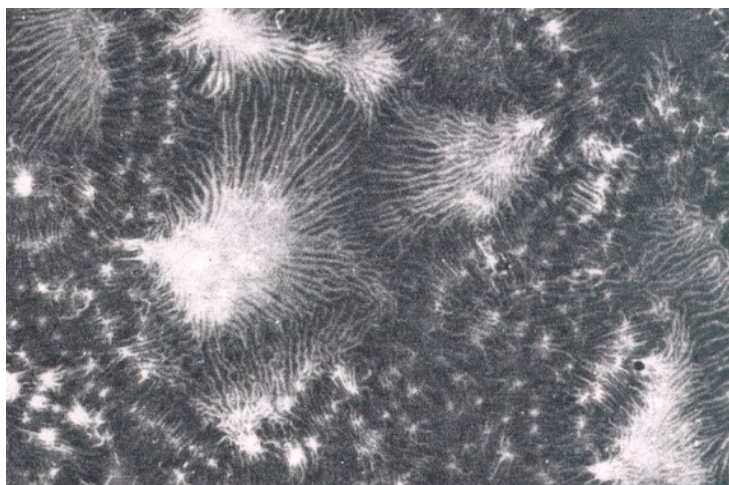
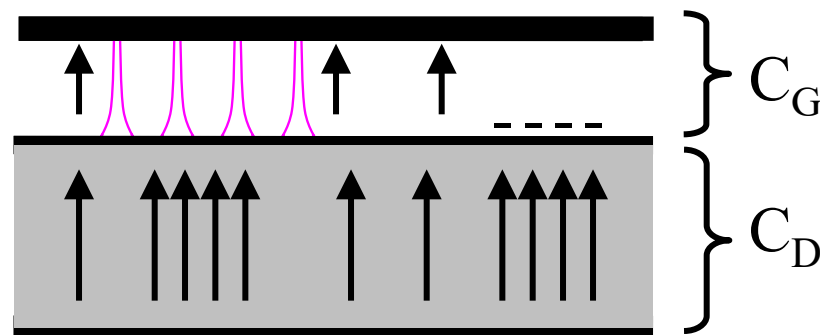
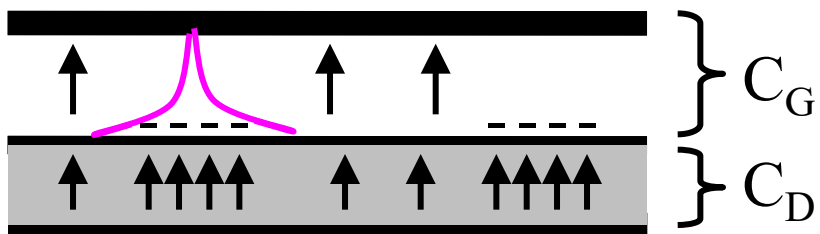


Single dielectric



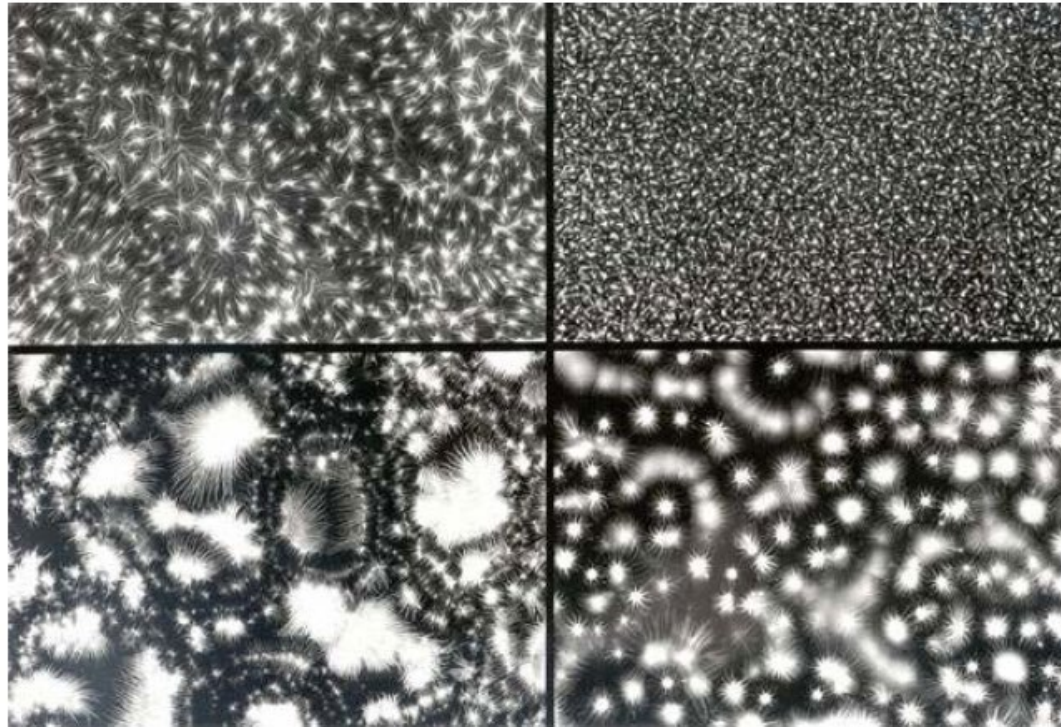
Double dielectric

# Principals of DBD Microplasmas



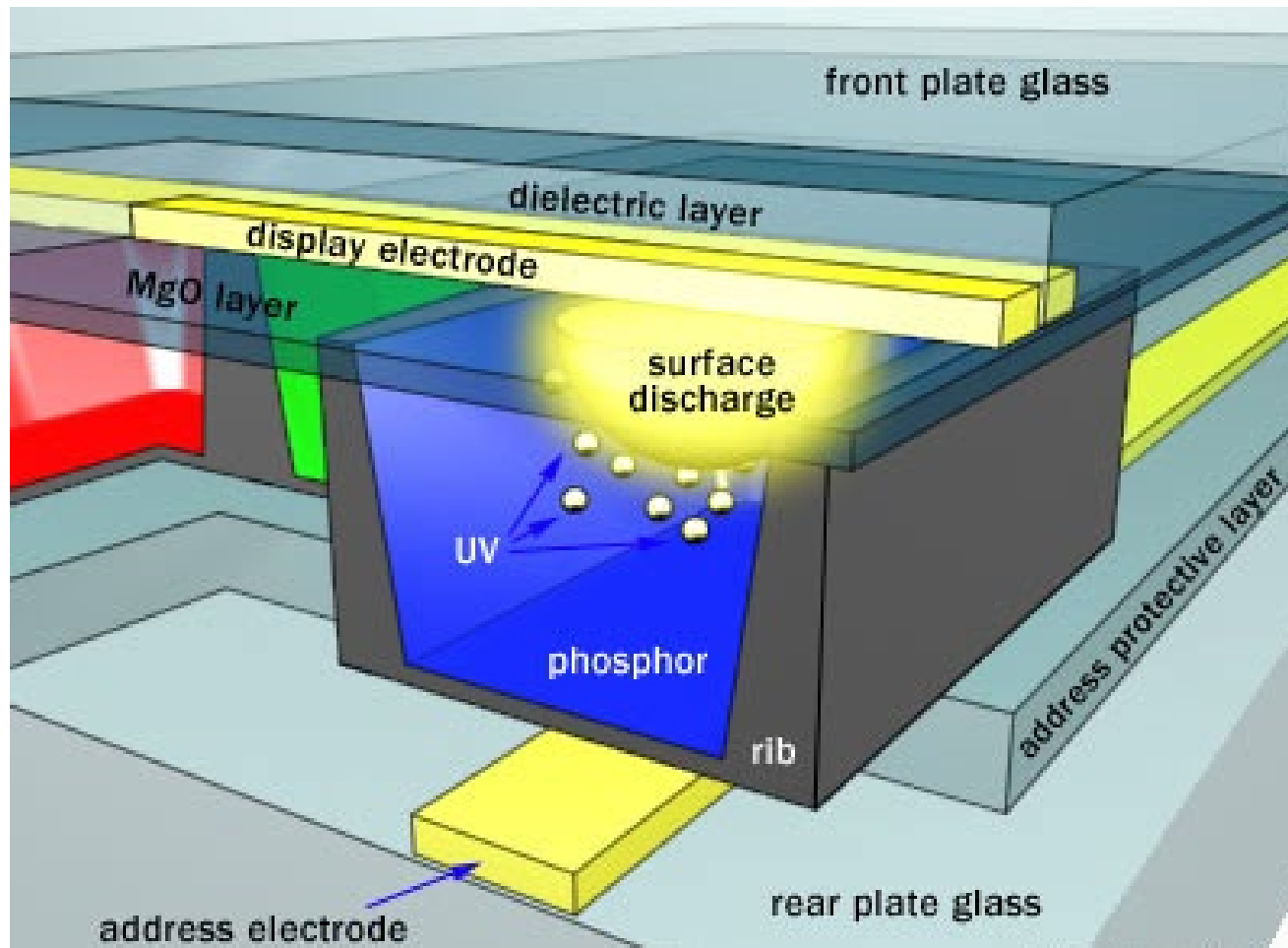
# Principals of DBD Microplasmas

Four Different Gap Widths

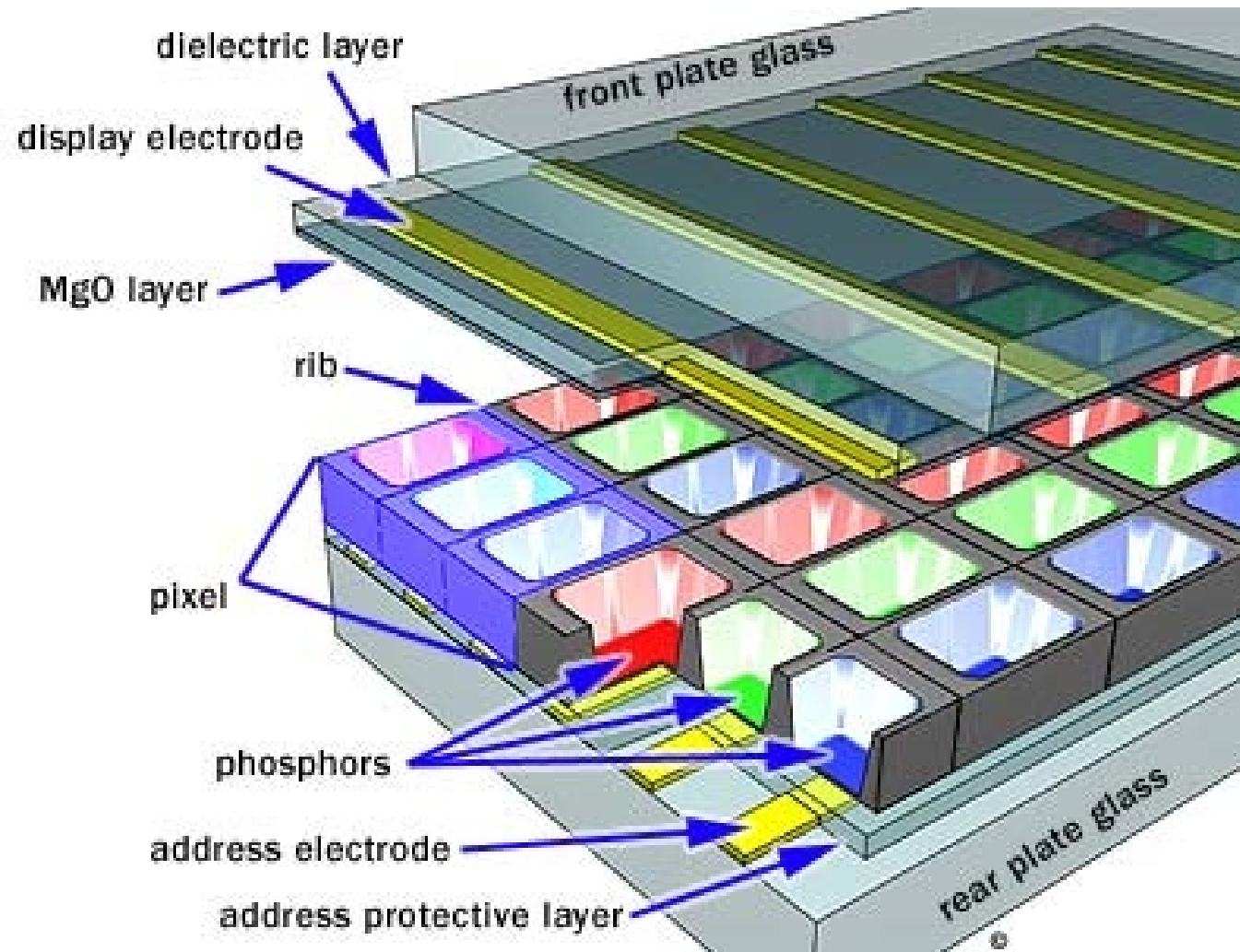


B. Eliasson and U. Kogelschatz. *IEEE Trans Plasma Sci.* 19(2) p309 (1991)

# DBD - How A Plasma Display Works!



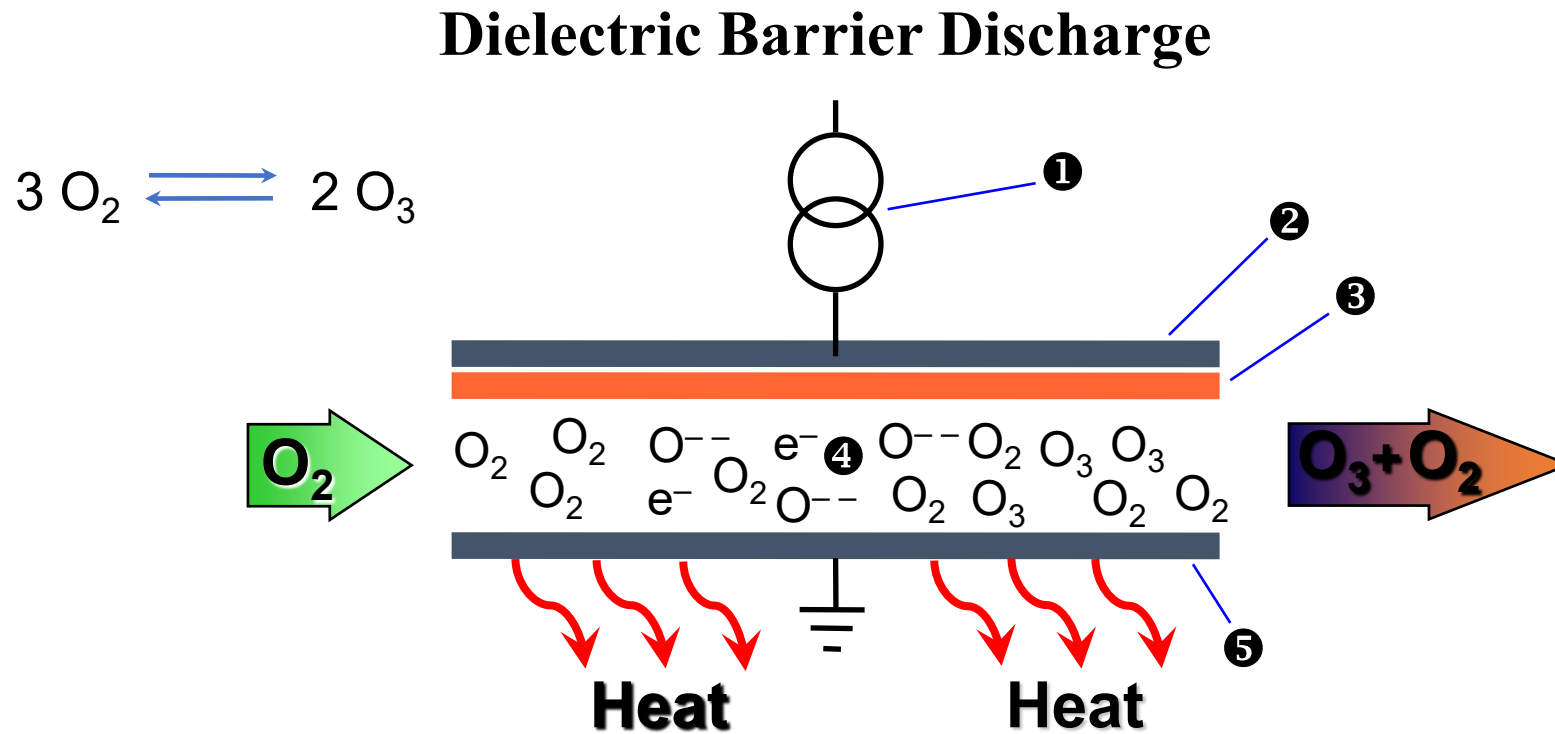
# How A Plasma Display Work!



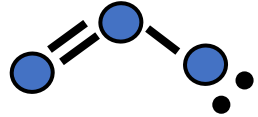
# Plasma Displays



# Ozone Generator



# Properties of Ozone (O<sub>3</sub>)

- Tri-atomic form of oxygen. 
- Most powerful commercial oxidizing agent
- Unstable - must be generated and used onsite
- Limited solubility in water, but more so than oxygen
- Leaves a dissolved residual which ultimately converts back to oxygen

# Ozone Water Treatment



## **Bubble Diffusion**

**Easy to use**

**Low energy usage**

**Mass transfer  
efficiencies to  $> 90\%$**

# Environmental and Water Remediation with Plasma Technologies



Intelligent Gap System



**5000 kg/day of ozone**

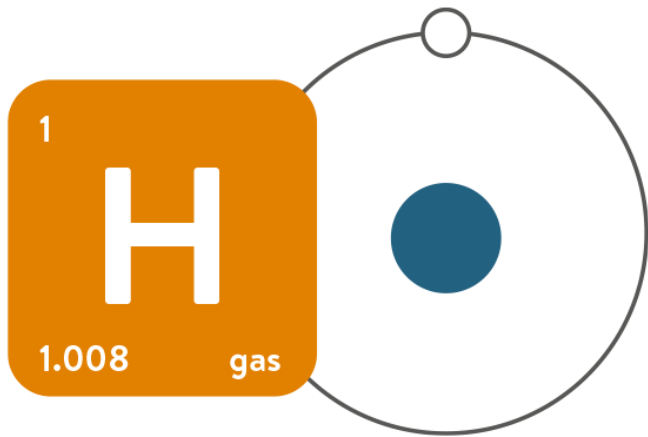
Guido Vezzu, Jose L Lopez, Alfred Freilich, Kurt H Becker. *Optimization of large-scale ozone generators*. IEEE Transactions on Plasma Science. Vol. 37, Issue 6, pp. 890-896 (2009).

Jose L Lopez. *Progress in Large-Scale Ozone Generation*. **Complex Plasmas: Scientific challenges and Technological Opportunities**. Editors – Michael Bonitz, Jose Lopez, Kurt Becker, Hauke Thomsen. Chp 13, pp. 427-453, Springer Publishing (2014).



# Hydrogen (H<sub>2</sub>) to make energy

## WHAT IS HYDROGEN?



### **LIGHTEST AND MOST ABUNDANT**

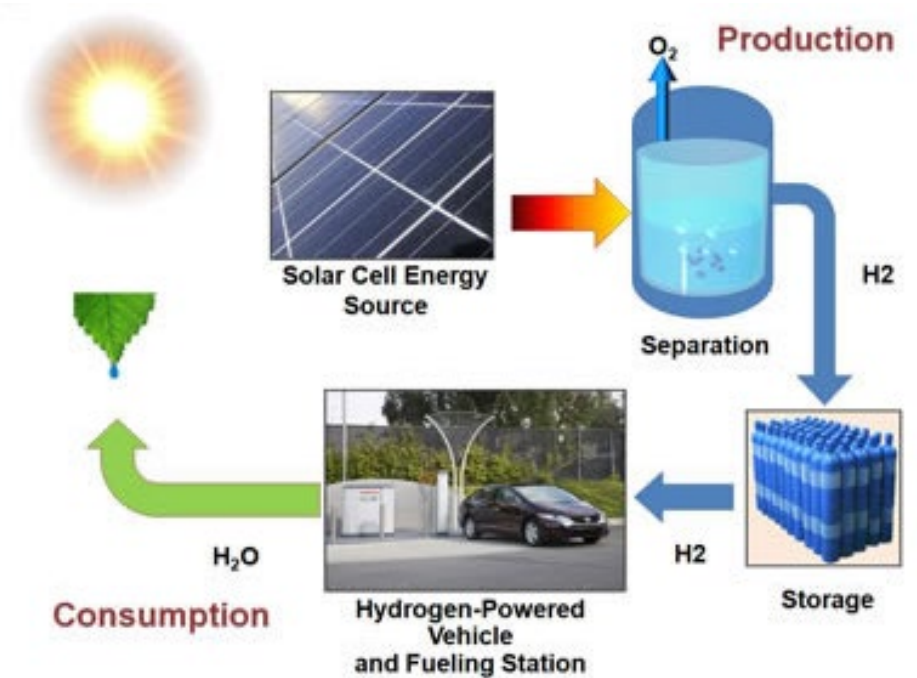
Hydrogen is the first element in the periodic table. It is the lightest, most abundant and one of the oldest chemical elements in the universe.

### **NEVER ALONE**

On Earth, hydrogen is found in more complex molecules, such as water or hydrocarbons. To be used in its pure form, it has to be extracted.

### **FUEL OF STARS**

Hydrogen fuels stars through nuclear fusion reaction. This creates energy and all the other chemical elements which are found on Earth.



# H<sub>2</sub> in combination with Electric Fuel Cell

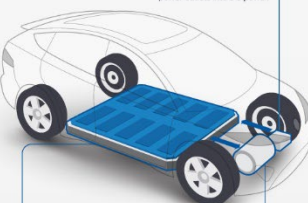
E

## Lithium Ion BATTERY vs Hydrogen FUEL CELL

### Electric Vehicles

**BEVs contain a large battery to store electricity.**

**Onboard charger**  
Converts AC electricity from power outlets into DC power.



**Electric motor**  
Propels the car using energy from the battery.

**Lithium-ion battery**  
Lithium ions create an electrical current by moving between the negative (anode) and positive (cathode) electrodes.

Cathode	Liquid Electrolyte	Anode
Lithium ions	Charging	→
←	Discharging	←

The longest-range BEV is the 2022 Lucid Air Dream Edition, which has an EPA rating of 505 miles.

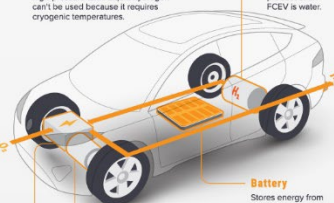
The longest-range FCEV is the 2022 Toyota Mirai XLE, which has an EPA rating of 402 miles.

Source: U.S. Department of Energy

**FCEVs use a hydrogen fuel cell to create electricity. This requires a tank to store hydrogen gas.**

**Fuel tank**  
Hydrogen gas is stored in a high-pressure tank. Liquid hydrogen can't be used because it requires cryogenic temperatures.

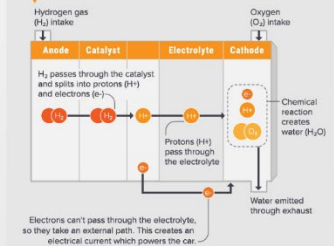
**Exhaust**  
The only waste product of an FCEV is water.



**Battery**  
Stores energy from regenerative braking.

**Electric motor**  
Propels the car using energy produced by the fuel cell stack.

**Fuel cell stack**  
The fuel cell combines hydrogen and oxygen to generate electricity.



Hydrogen gas (H<sub>2</sub>) intake

Oxygen (O<sub>2</sub>) intake

**Anode** | **Catalyst** | **Electrolyte** | **Cathode**

H<sub>2</sub> passes through the catalyst and splits into protons (H<sup>+</sup>) and electrons (e<sup>-</sup>).

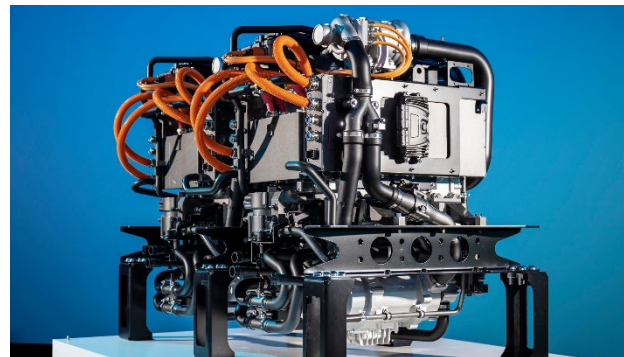
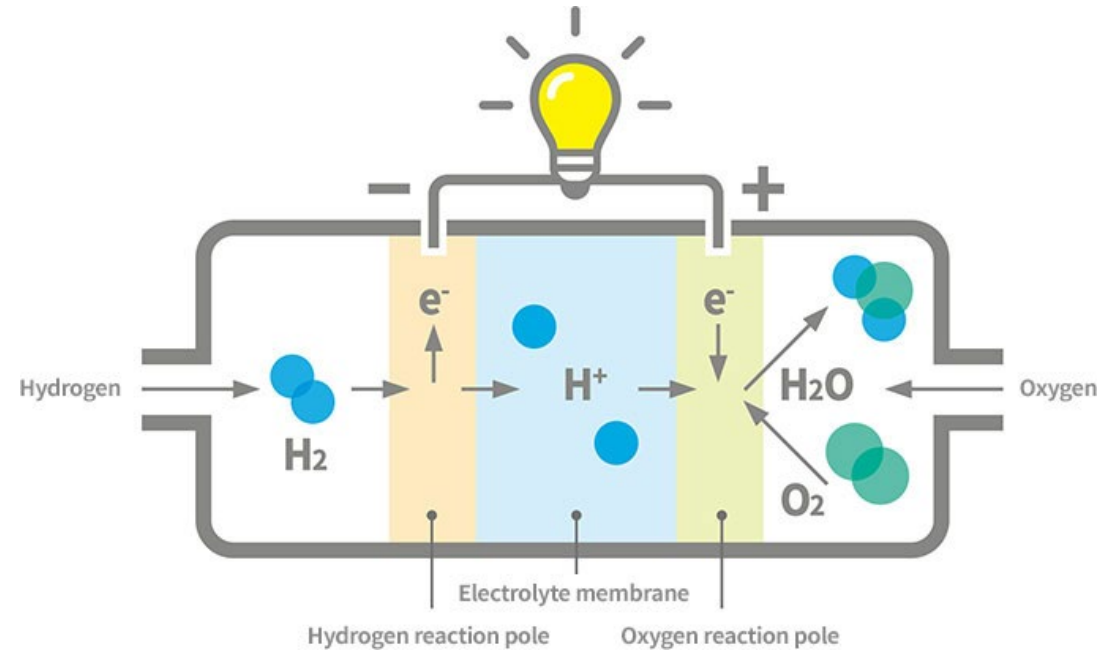
Protons (H<sup>+</sup>) pass through the electrolyte.

Chemical reaction creates water (H<sub>2</sub>O).

Water emitted through exhaust.

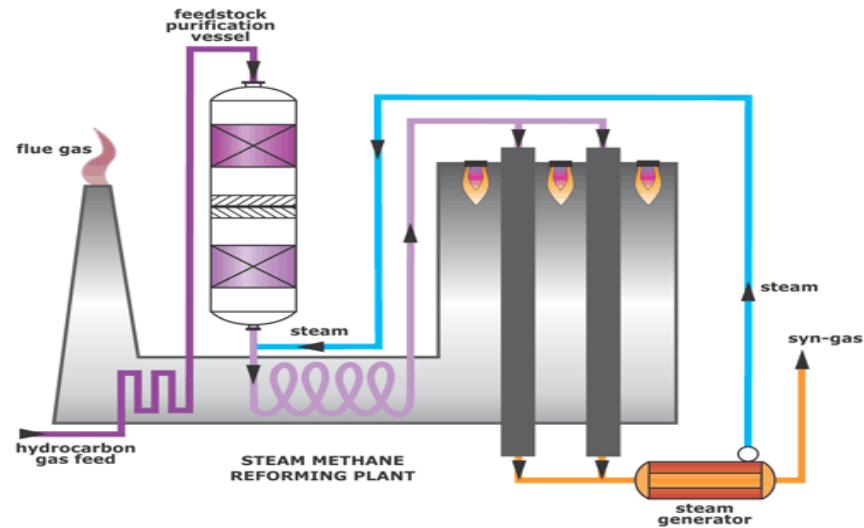
Electrons can't pass through the electrolyte, so they take an external path. This creates an electrical current which powers the car.

ELEMENTS VISUALCAPITALIST.COM



# Large-scale Hydrogen (H<sub>2</sub>) Production

## Steam Methane Reforming



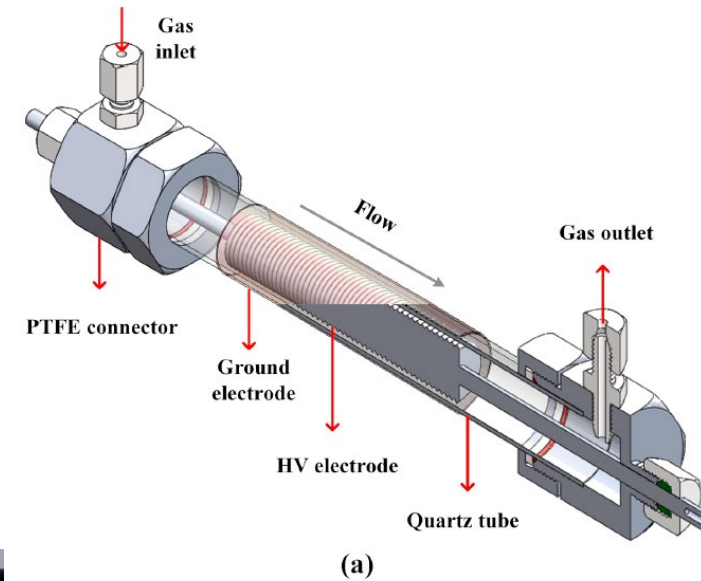
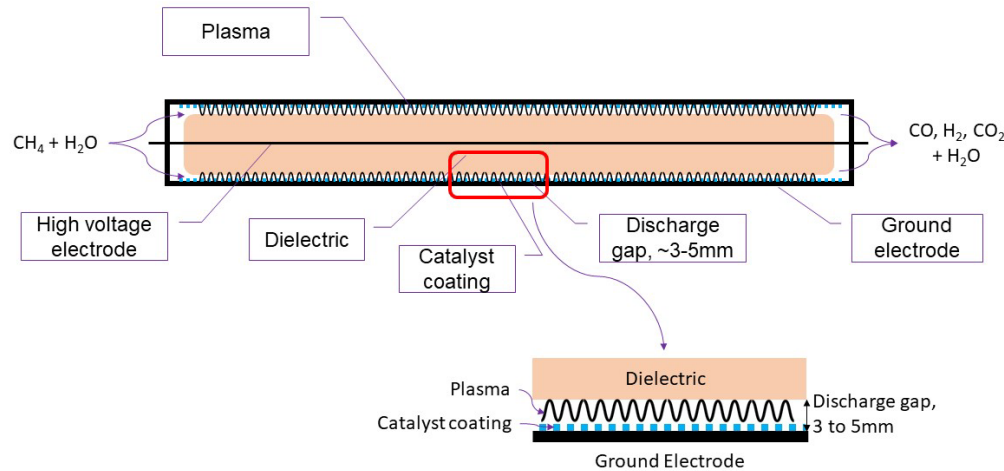
©2009 AirScience Technologies Inc.

Production of H<sub>2</sub> at these facilities is about \$1.25 per kg



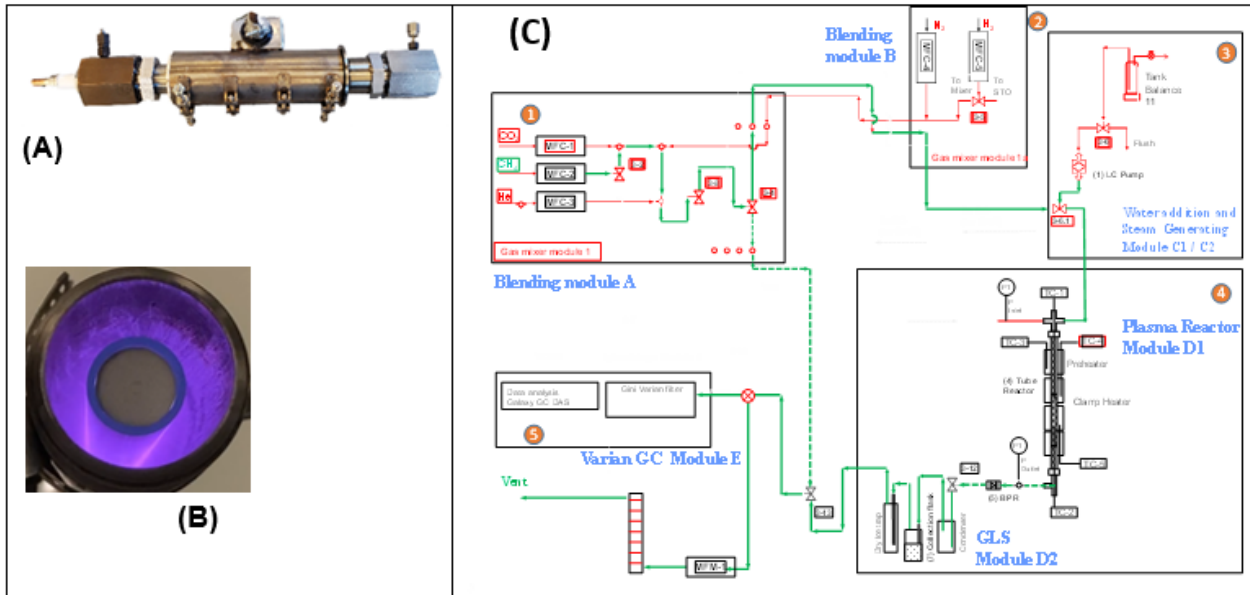
# Small-scale H<sub>2</sub> production

## Cold Plasma-Catalysis for H<sub>2</sub> Production

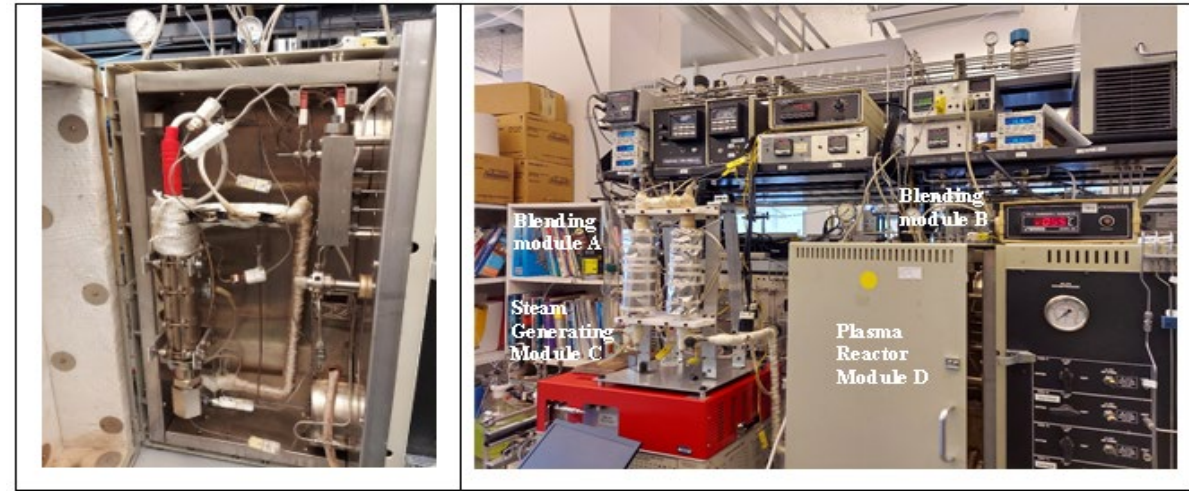


5 kg/day H<sub>2</sub> production rate

# Cold Plasma-Catalysis for H<sub>2</sub> Production system



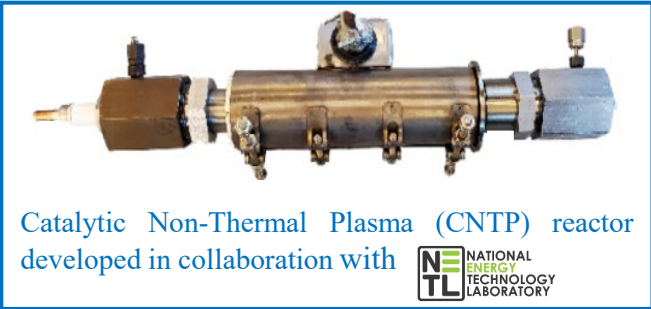
**Figure 1.** Methane reforming reactor system, re-configured for an on-line GC monitoring of the reaction in progress. The image on the left is the plasma assisted thermo-catalytic tube reactor (A) and an image of the plasma generated in the inner space of the tube (B). The image on the right (C) is the schematic of the methane reforming system.



**Figure 2.** Image of the reactor tube assembly installed within the oven (LEFT) and the view of the five modules (A-E) as described in Figure 1C (RIGHT).

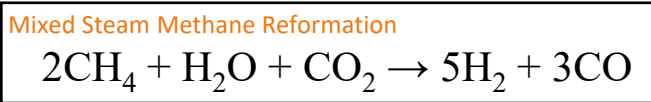
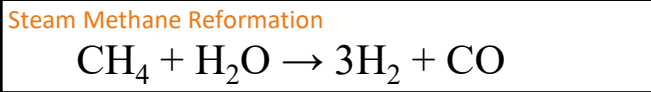
- The ReforMax<sup>®</sup> 300 catalyst is Ni/Ca/Al<sub>2</sub>O<sub>3</sub> based catalyst that was provided to us by the chemical manufacturing company, Clariant Specialty Chemicals, as preformed 10-hole cylindrical shapes.

# Steam Methane Reformation with CNTP reactor to generate Syngas



**Table 1.** Syngas synthesis by thermo-catalytic conversion of methane and steam with & w/out plasma discharge. Ratio of H<sub>2</sub>O/Methane is 4:1, methane residency time is 6s, catalyst charge (Clariant Reformax 330) = 20 cc. Electrical power supply voltage for plasma operation is 15 kV at a set frequency of 10 kHz.

Operational Parameters				Efficiency Parameters			
H <sub>2</sub> O/CH <sub>4</sub>	Temp	CH <sub>4</sub> Res Time	Plasma Voltage		CH <sub>4</sub> Conversion, %	H <sub>2</sub> Selectivity, %	CO Selectivity, %
Mol/mol	°C	s	V				
4.0	460	6	15,000	No Plasma	32.8	96.9	1.7
				Plasma 15.0kV	48.7	92.9	5.1

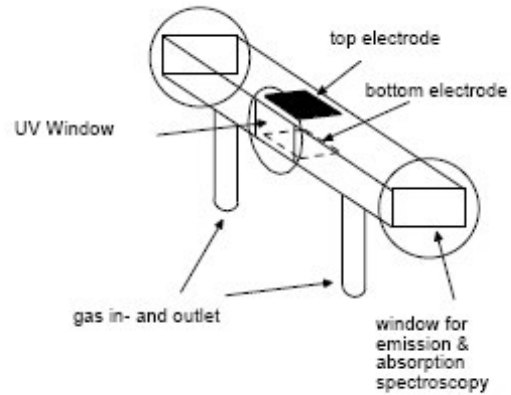


Operational Parameters				Efficiency Parameters			
H <sub>2</sub> O/CH <sub>4</sub>	Temp	CH <sub>4</sub> Res Time	Plasma Voltage		CH <sub>4</sub> Conversion, %	H <sub>2</sub> Selectivity, %	CO Selectivity, %
Mol/mol	°C	s	V				
4.0	460	6	15,000	No Plasma	33.1	95.7	1.8
				CO <sub>2</sub> feed ON, NO Plasma	29.0	94.9	3.2
				CO <sub>2</sub> feed ON Plasma 15 kV	42.3	93.1	7.3

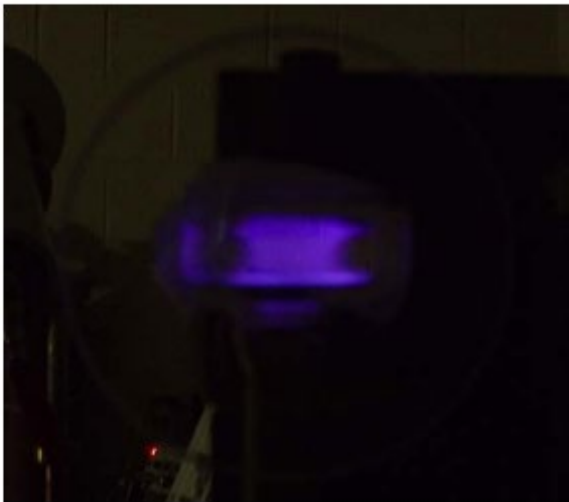
**Table 2.** Mixed process for Syngas production by thermo-catalytic conversion of CO<sub>2</sub>, CH<sub>4</sub> and H<sub>2</sub>O with & w/out plasma discharge. Ratio of H<sub>2</sub>O/CH<sub>4</sub> is 4:1, ratio of CO<sub>2</sub> /CH<sub>4</sub> = 1:2, residence time is 6s, and catalyst charge (Clariant Reformax 330) = 20 cc. Electrical power supply voltage for plasma operation is 15kV at a set frequency of 10 kHz.



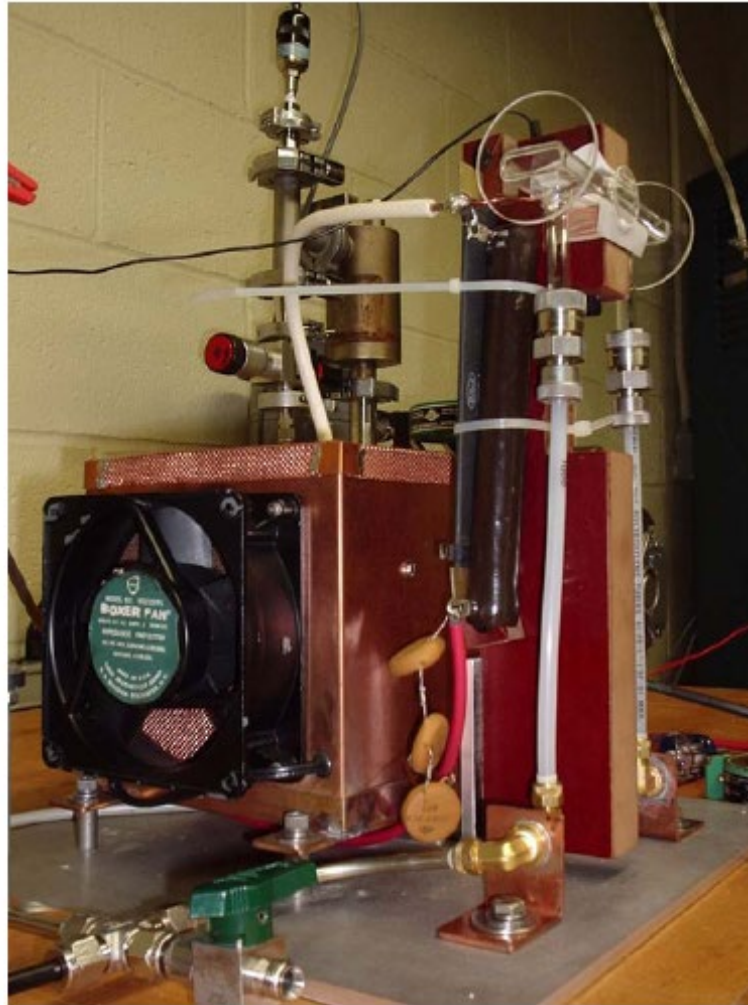
# Pulsed DC Homogeneous DBD



The Dielectric Barrier Discharge (DBD) cell.



A typical plasma in pure nitrogen environment.



Side view of the DBD cell experiment with the fast high voltage transistor switch connected to the bottom electrode.

# Low Temperature plasma jets: DBD-like scheme

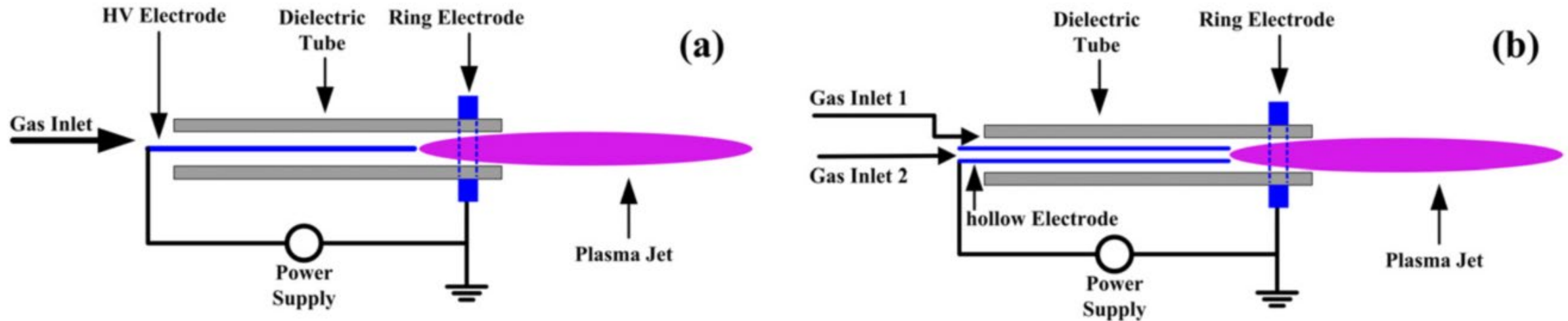


Figure 3. Schematic of a DBD-like plasma jet.

## On atmospheric-pressure non-equilibrium plasma jets and plasma bullets

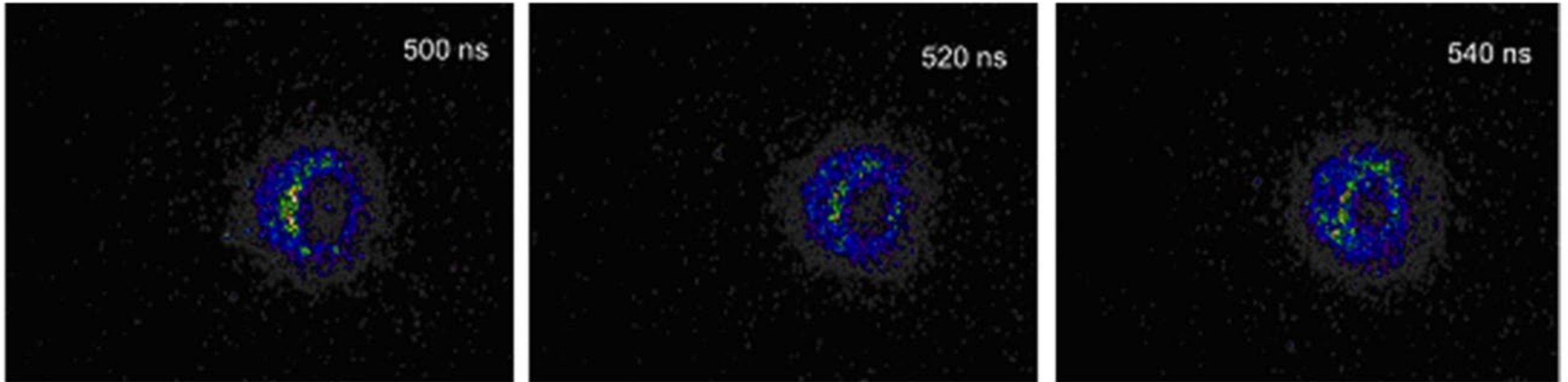
X Lu<sup>1,4</sup>, M Laroussi<sup>2</sup> and V Puech<sup>3</sup>

<sup>1</sup> State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, Hubei 430074, People's Republic of China

<sup>2</sup> Laser & Plasma Engineering Institute, Old Dominion University, Norfolk, VA, USA

<sup>3</sup> Laboratoire de Physique des Gaz et des Plasmas, CNRS & Univ. Paris-Sud, Orsay, France

# Plasma Bullets: Donut shape



**Figure 11.** Photographs of bullets illustrating their donut shape [111].

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PLASMA SOURCES SCIENCE AND TECHNOLOGY

Plasma Sources Sci. Technol. 21 (2012) 034005 (17pp)

doi:10.1088/0963-0252/21/3/034005

## On atmospheric-pressure non-equilibrium plasma jets and plasma bullets

X Lu<sup>1,4</sup>, M Laroussi<sup>2</sup> and V Puech<sup>3</sup>

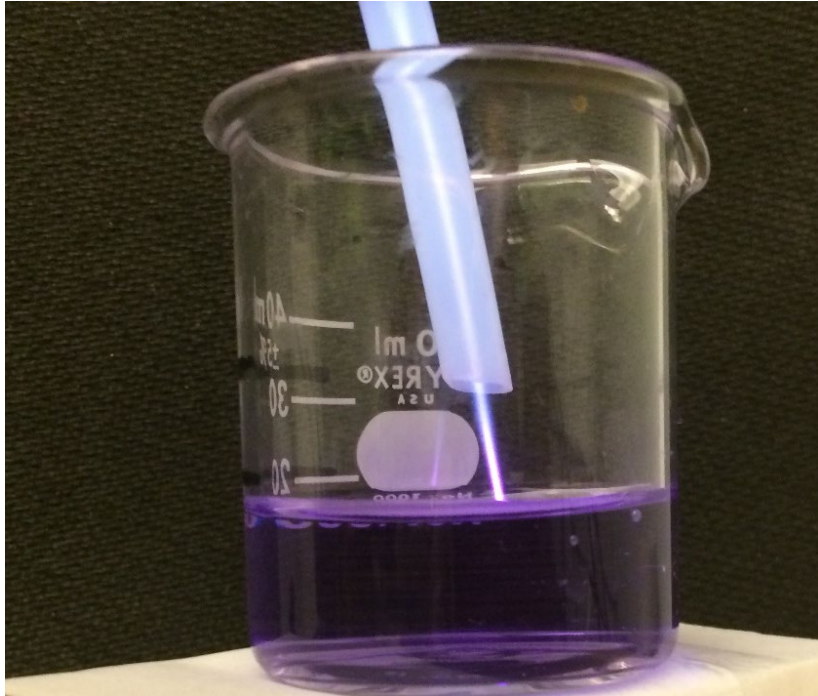
<sup>1</sup> State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, Hubei 430074, People's Republic of China

<sup>2</sup> Laser & Plasma Engineering Institute, Old Dominion University, Norfolk, VA, USA

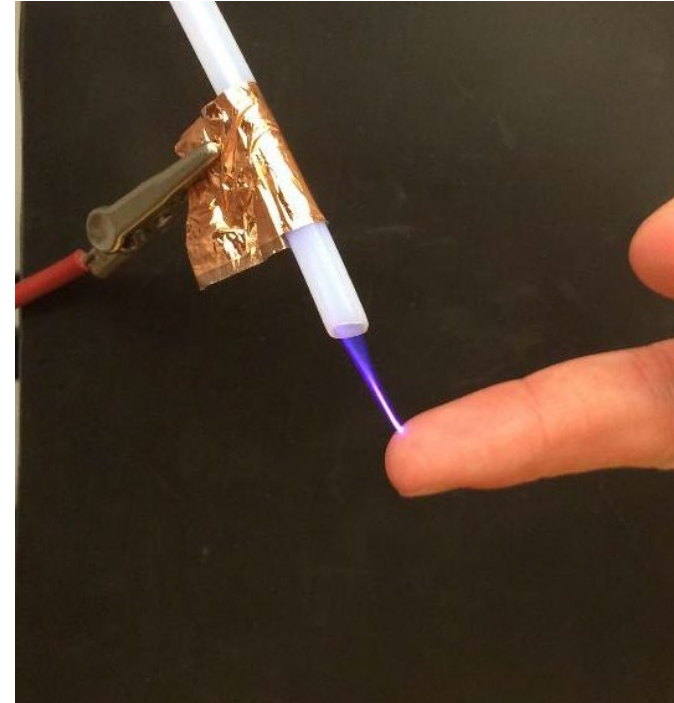
<sup>3</sup> Laboratoire de Physique des Gaz et des Plasmas, CNRS & Univ. Paris-Sud, Orsay, France



# Our Version of the Atmospheric Pressure Plasma Jet



Interaction with aqueous environments



Interaction with organic surfaces

# Our Version of Atmospheric Pressure Plasma Jet

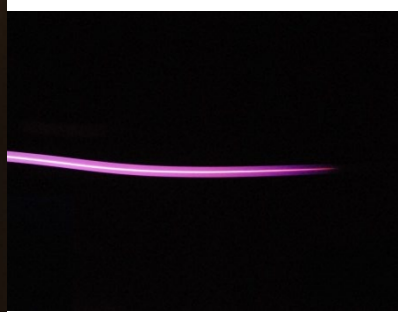
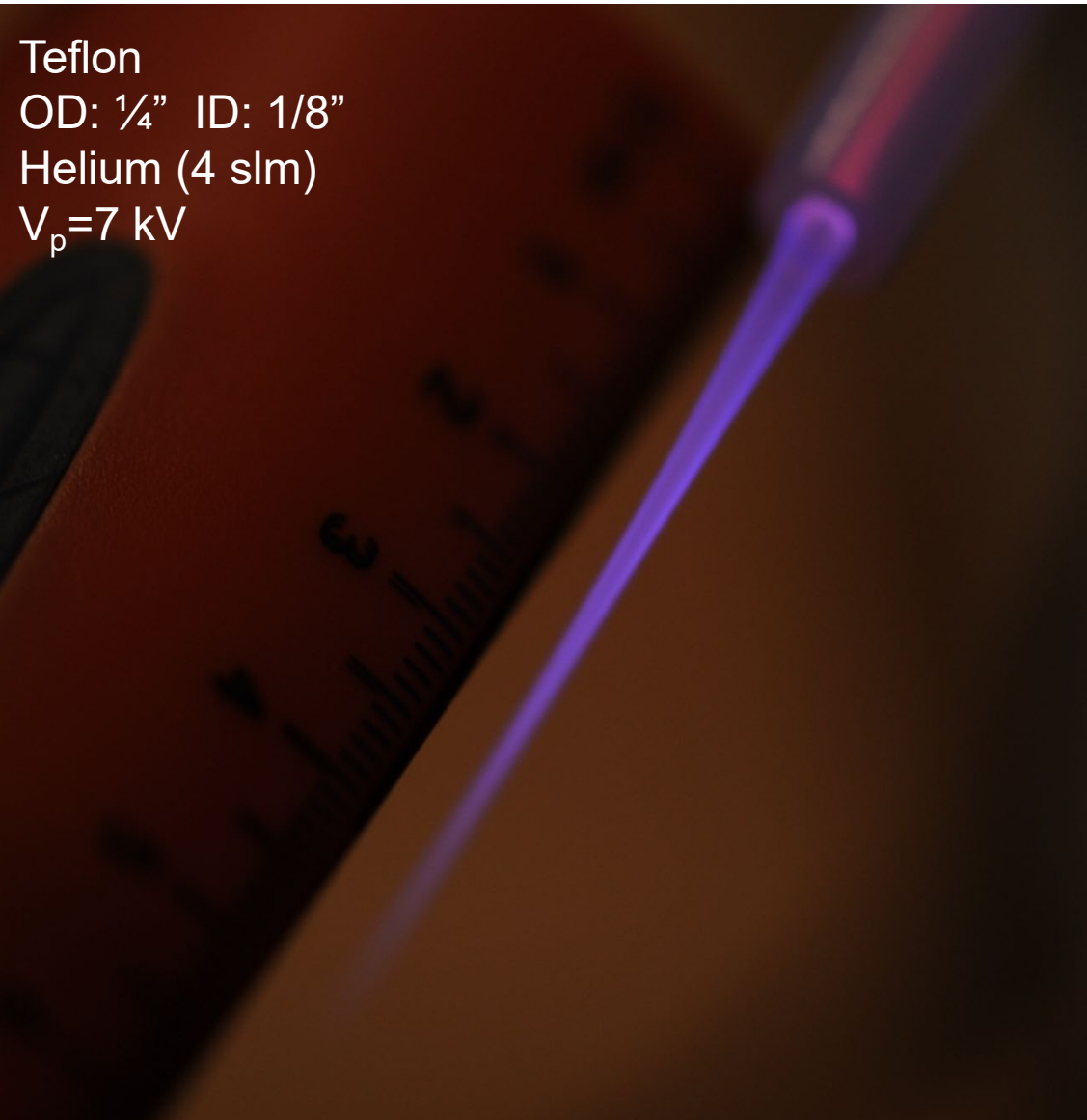
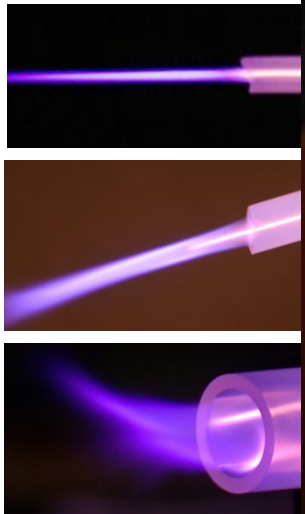
We couldn't



Teflon  
OD: 1/4" ID: 1/8"  
Helium (4 slm)  
 $V_p = 7$  kV

glass, Teflon, Peek  
D: 0.0625-0.5")  
Tape (1" wide  
6%),  
5%)

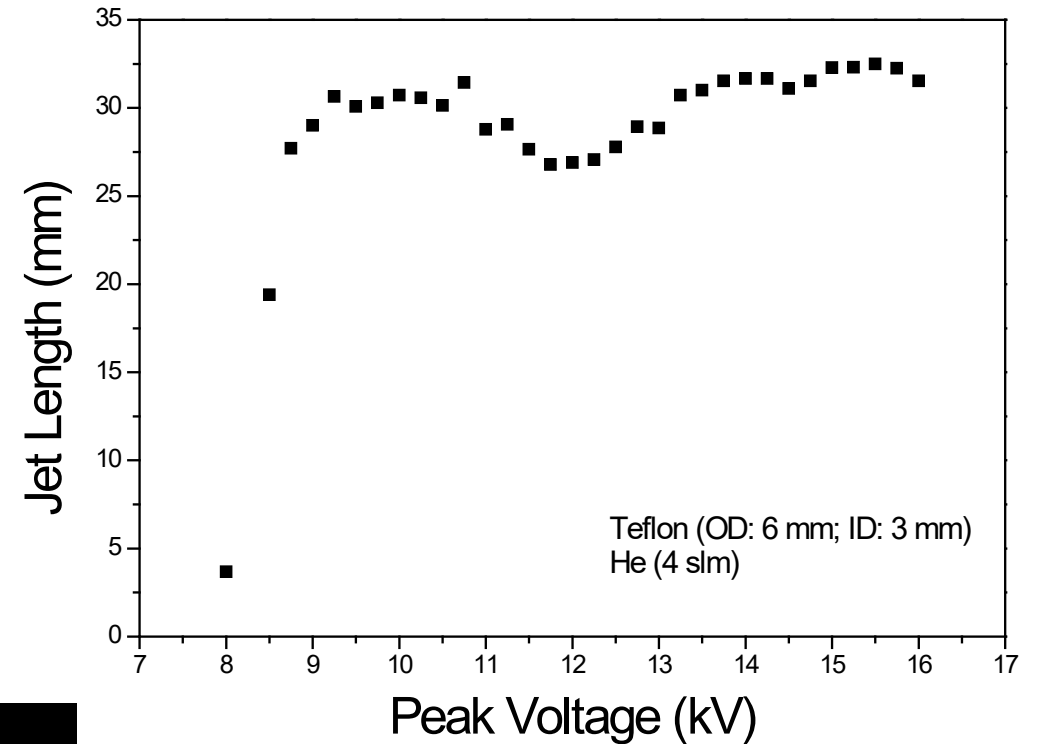
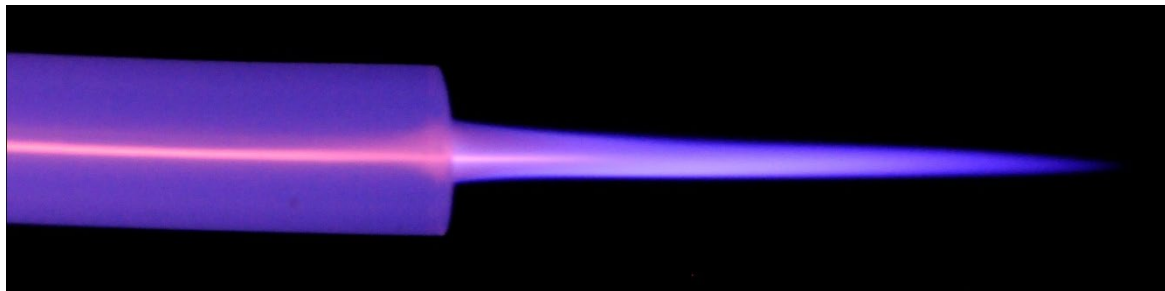
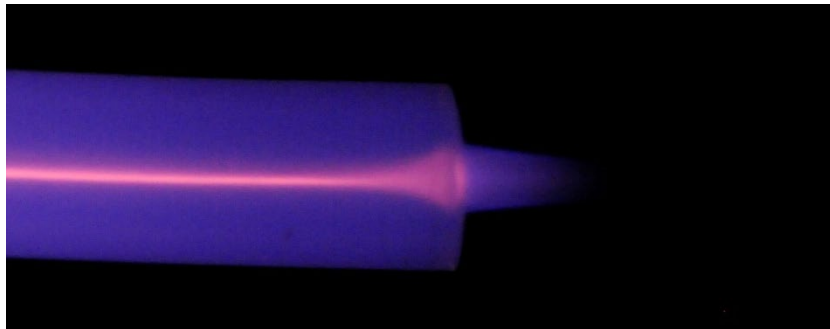
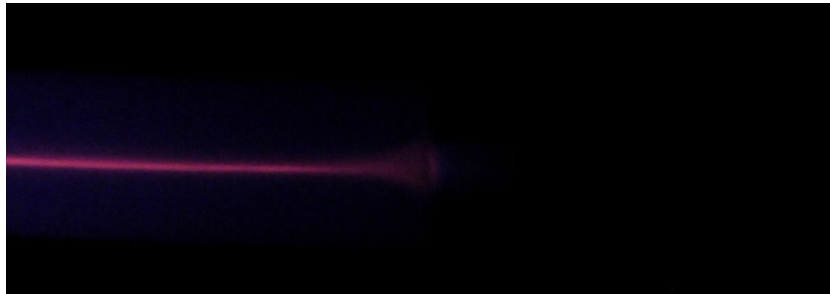
15 kV



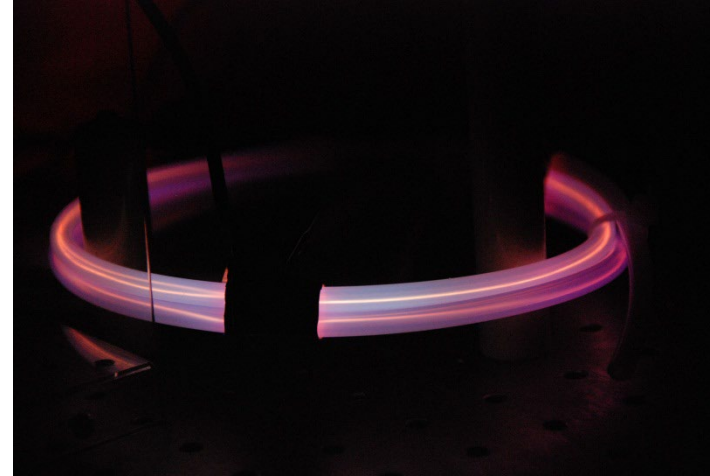
and downstream



# Jet Length vs. applied voltage

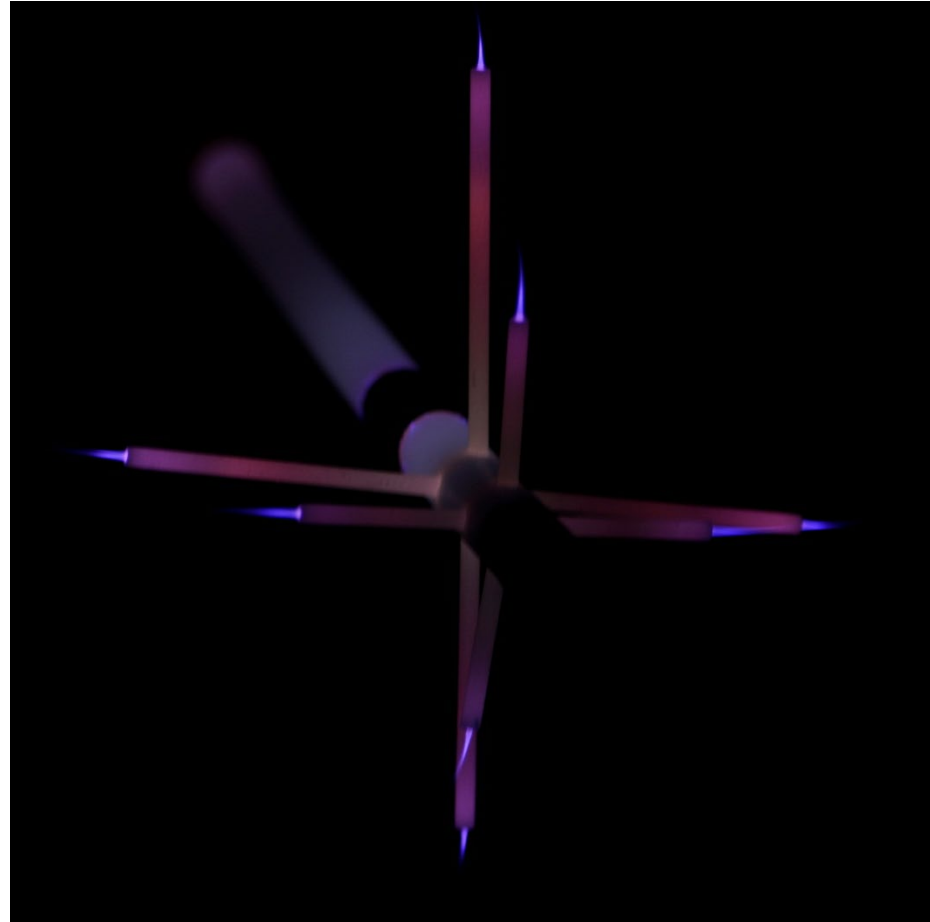
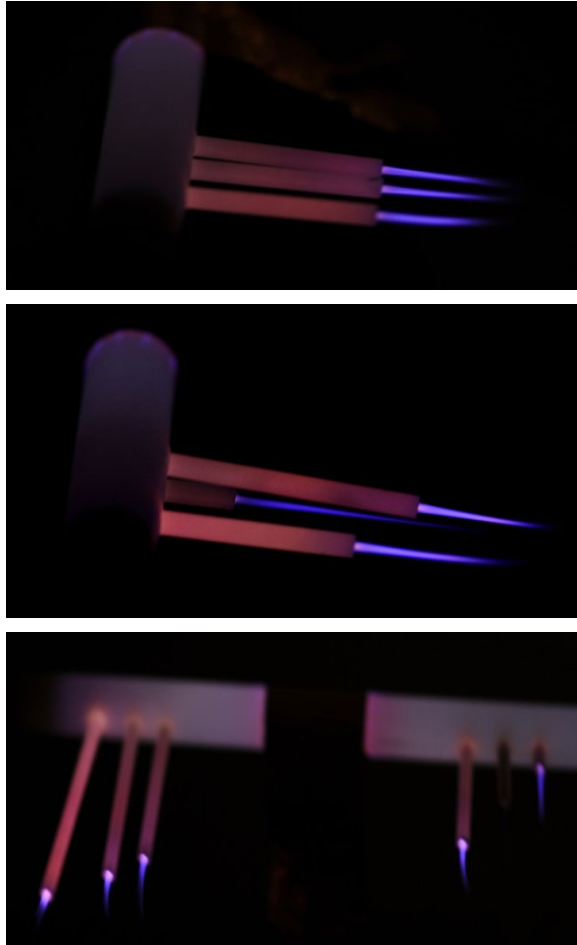


# Plasma in a Curved Teflon Tubing

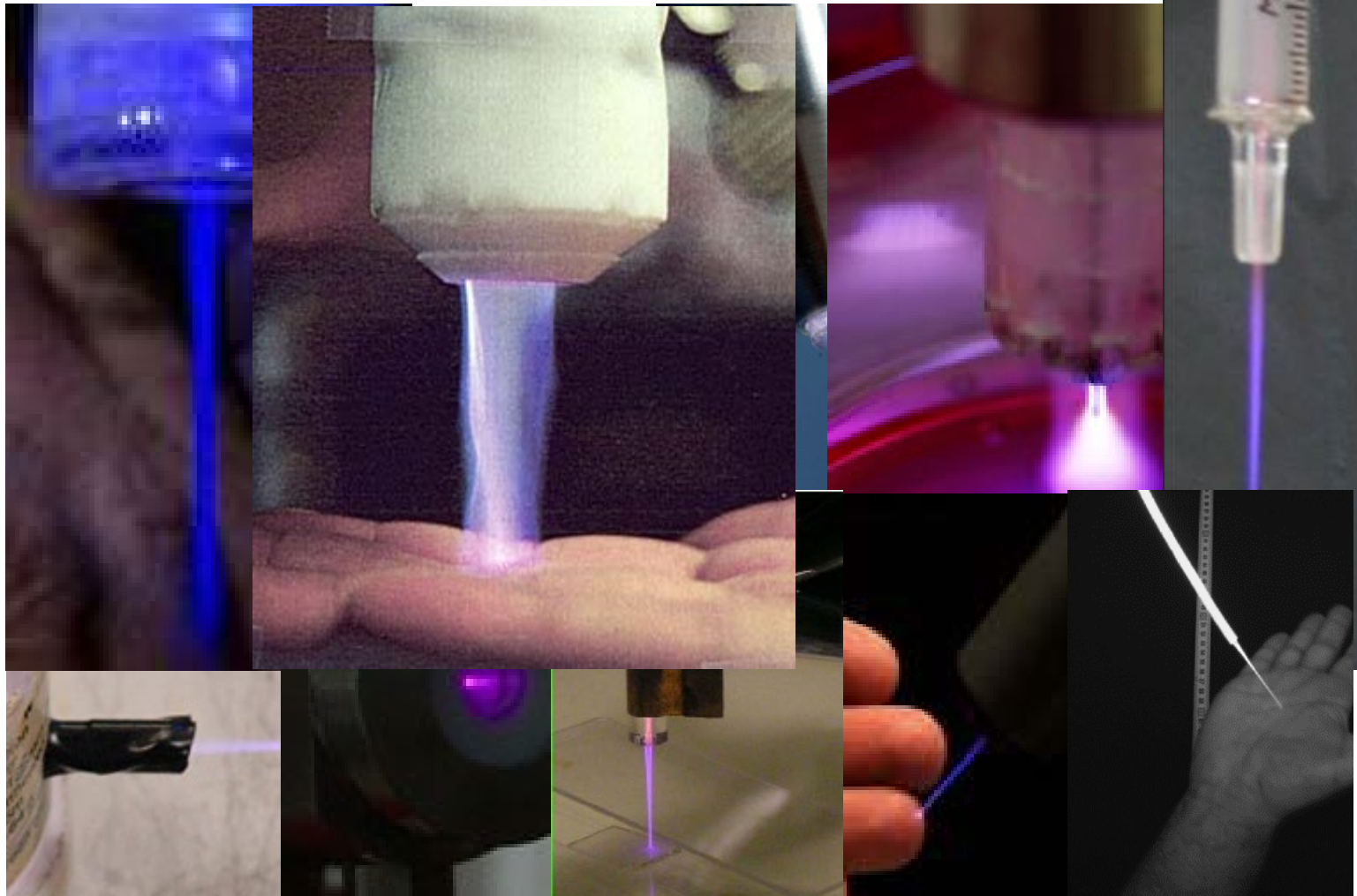


Distance the streamer can travel inside the insulating tubing depends on applied voltage, location of the powered electrode, type of working gas.

# Further Extension of these Plasma Jets



# A Brief Collection of Atmospheric Pressure Plasma Jets (APPJ)



Gases used: Helium, Argon... or mixed with reactive gases ( $O_2$ ,  $CH_4$ ...)  
AC, pulsed DC, rf or microwave

# 3D printed Atmospheric Pressure Plasma Jet reactors



Gerald J. Buonopane, Cosimo Antonacci, & Jose L. Lopez. *Effect of cold plasma processing on botanicals and their essential oils.* Plasma Medicine. Vol 6, Issue 3-4 (2016).



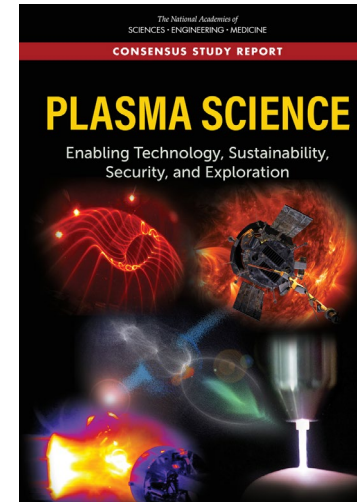
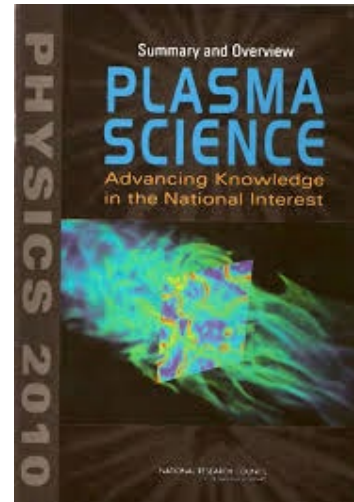
# Plasmas enable lots of technologies

Plasmas in the kitchen. Plasmas and the technologies they enable are pervasive in our everyday life. Each one of us touches or is touched by plasma-enabled technologies every day.

*Plasma Science: Advancing Knowledge in the National Interest.* Plasma 2010 Committee, Plasma Science Committee, National Research Council. ISBN: 0-309-10944-2, 280 pages, (2010)



- |  |  |   |
|--|--|---|
| 01—Plasma TV                                   | 09—Plasma-aided combustion                           | 16—Plasma-treated polymers                            |
| 02—Plasma-coated jet turbine blades            | 10—Plasma muffler                                    | 17—Plasma-treated textiles                            |
| 03—Plasma-manufactured LEDs in panel           | 11—Plasma ozone water purification                   | 18—Plasma-treated heart stent                         |
| 04—Diamondlike plasma CVD eyeglass coating     | 12—Plasma-deposited LCD screen                       | 19—Plasma-deposited diffusion barriers for containers |
| 05—Plasma ion-implanted artificial hip         | 13—Plasma-deposited silicon for solar cells          | 20—Plasma-sputtered window glazing                    |
| 06—Plasma laser-cut cloth                      | 14—Plasma-processed microelectronics                 | 21—Compact fluorescent plasma lamp                    |
| 07—Plasma HID headlamps                        | 15—Plasma-sterilization in pharmaceutical production |   |
| 08—Plasma-produced H <sub>2</sub> in fuel cell |  |   |



Plasma Decadal Reports

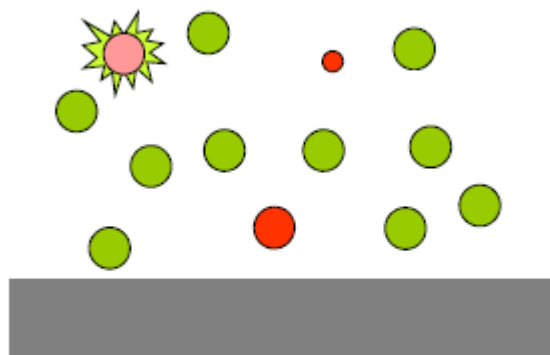


# Surface Effects of Low-Temperature Plasmas

*For instance, if we want to modify the surface of a material (e.g. a silicon wafer)*

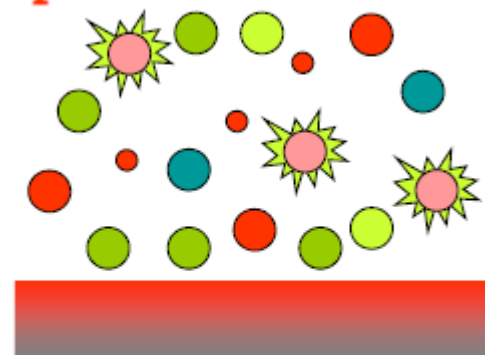
- Molecules
- Excited molecules
- Ions
- Electrons

gas



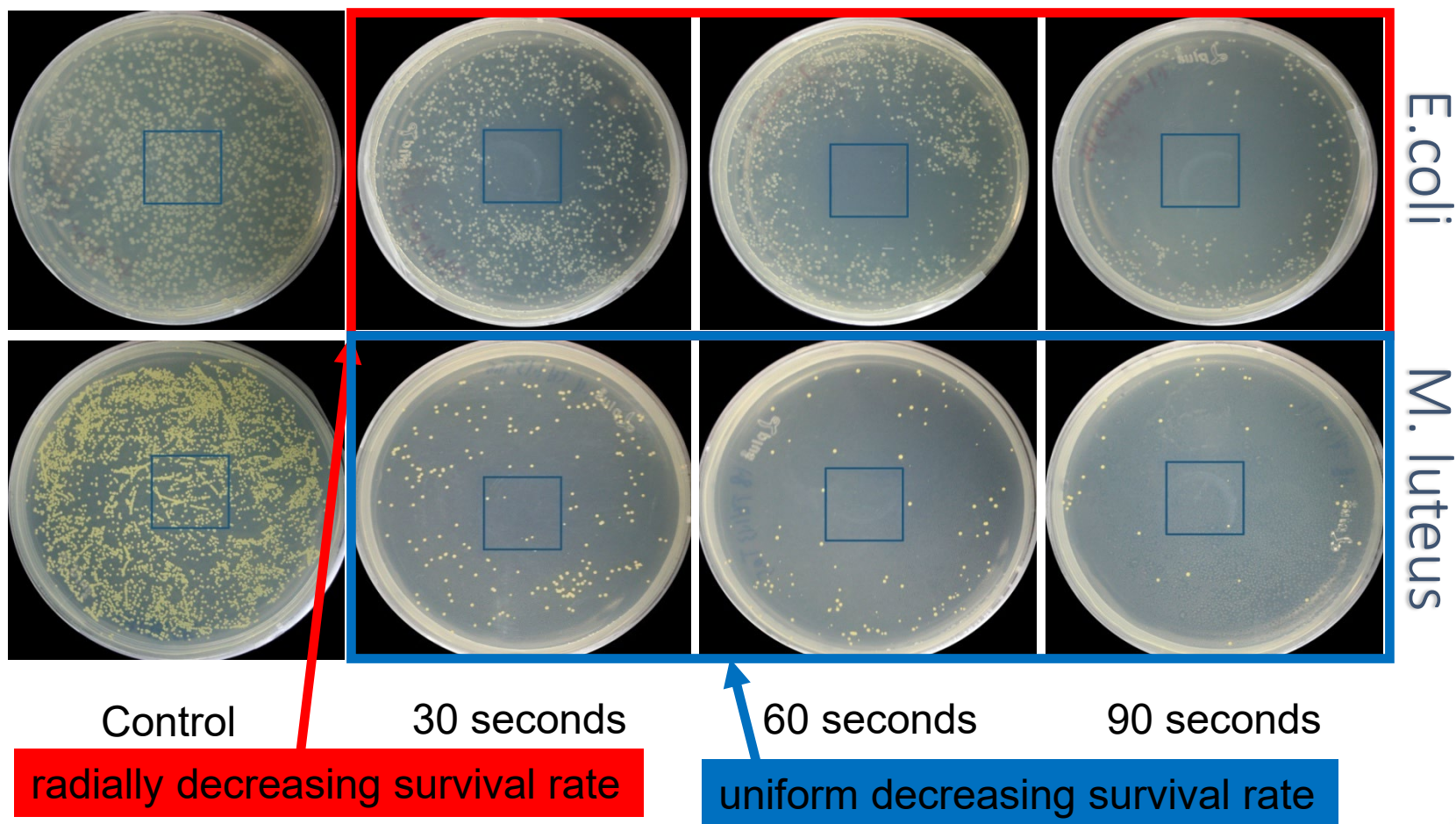
*Small changes at the surface*

plasma



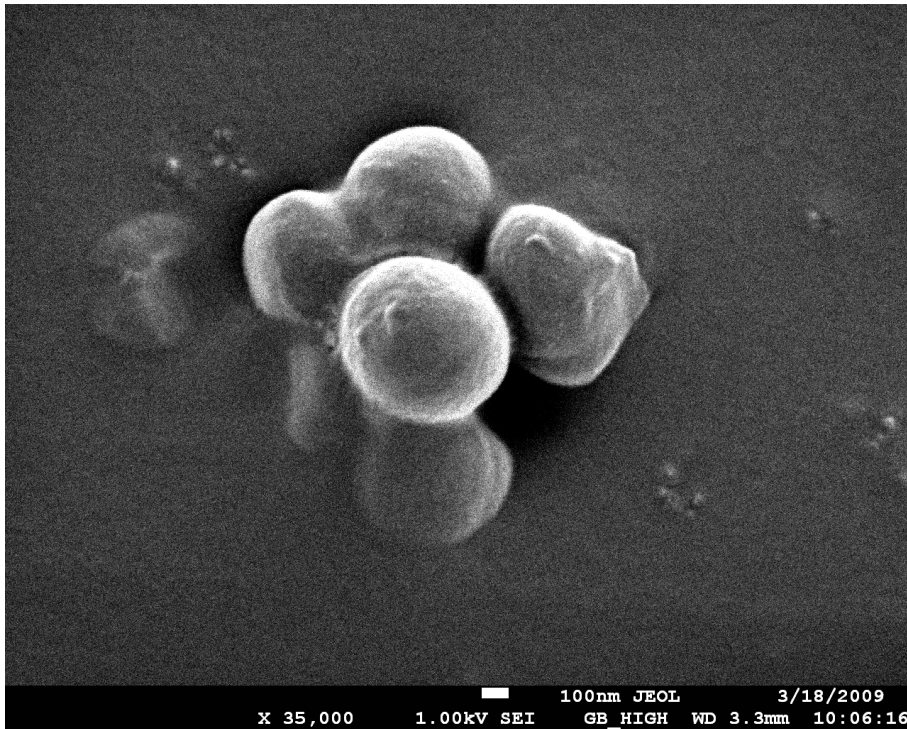
*Energy & reactive species can change the surface*

# Plasma Dose Effect

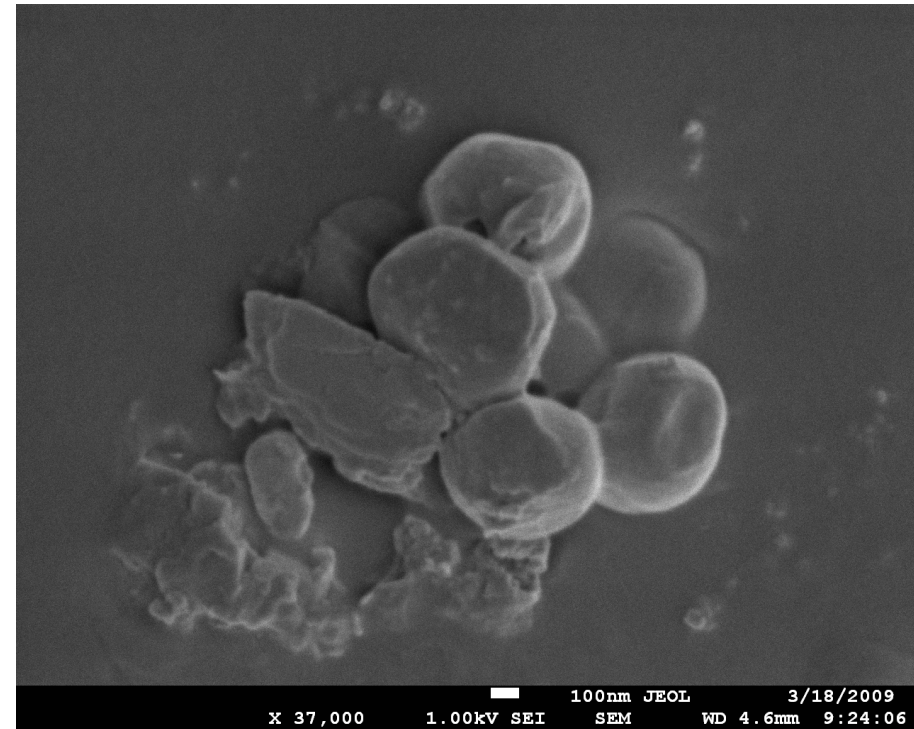


# SEM Pictures of how plasma destroy bacteria

SEM pictures of *S. aureus* before and after PMJ treatment



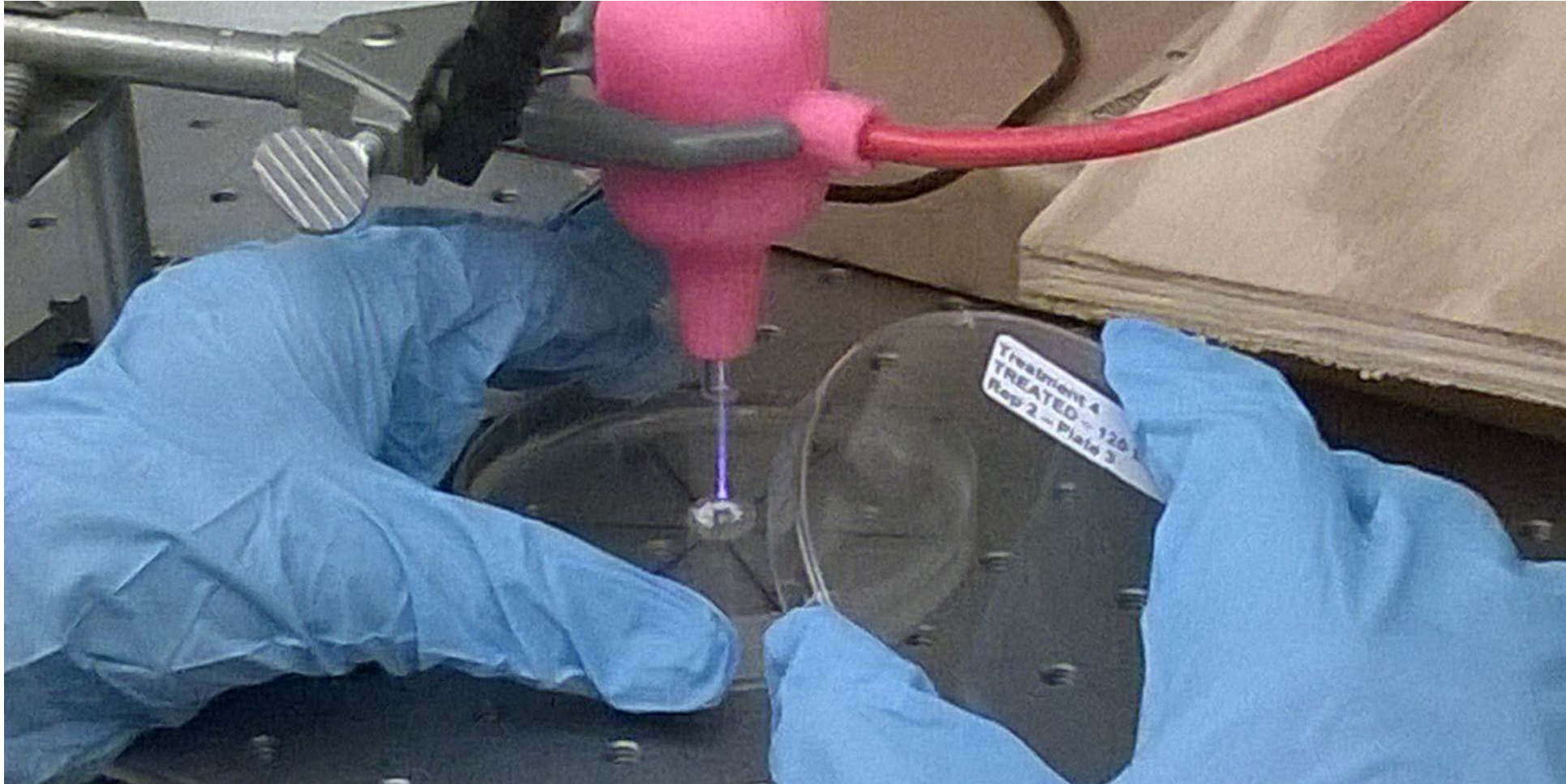
Control



PMJ treatment

SEM of PMJ treated *S. aureus* show clear poration on cell membrane as well as the change of the cell morphology.

# Plasma Treatment of Fungi

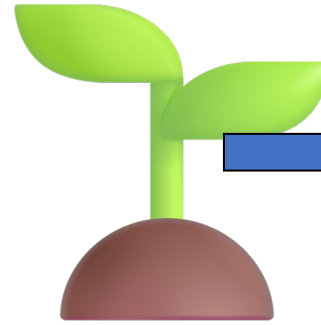


Peng Sun, Yi Sun, Haiyan Wu, Weidong Zhu, Jose L Lopez, Wei Liu, Jue Zhang, Ruoyu Li, Jing Fang. *Atmospheric pressure cold plasma as an antifungal therapy*. Applied Physics Letters. Vol. 98, Issue 2 (2011).



Department of Physics

# Plasma Seed Treatments



Plasma  
Treatment



Measure  
Plants



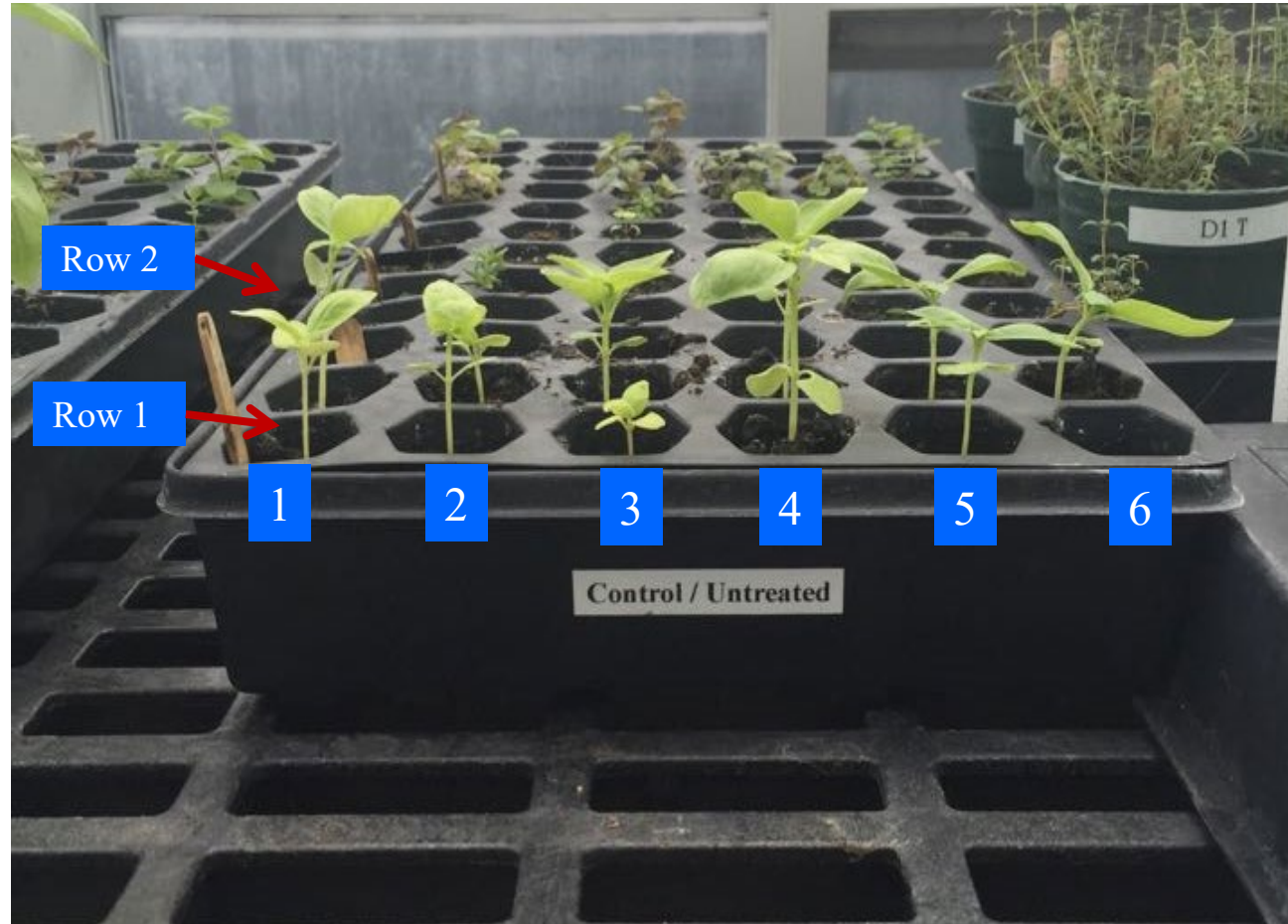
(a)



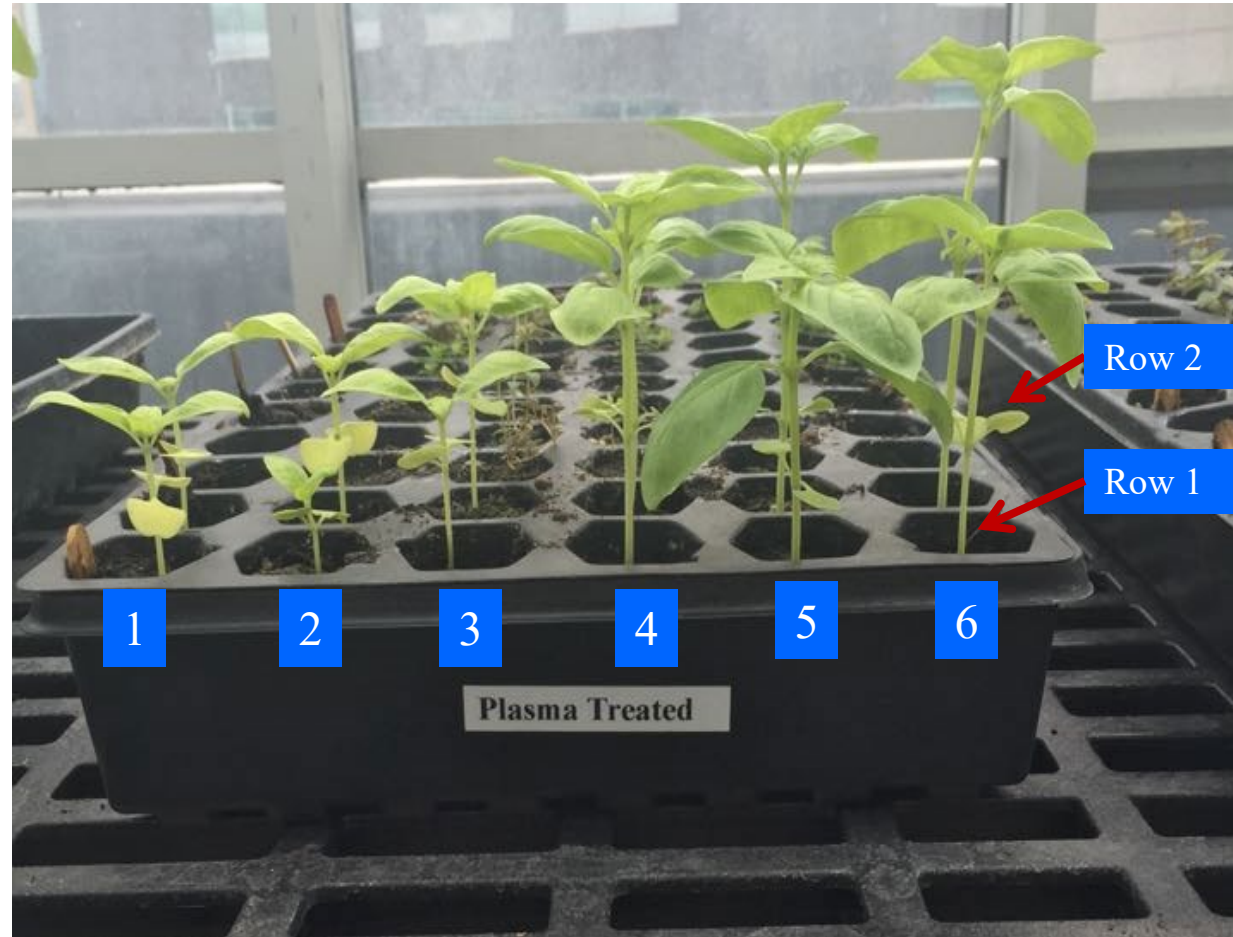
(b)

(a) Side-view of basil seedlings grown from plasma treated seeds (left) and untreated seeds (right). (b) Top-view of basil seedlings grown from plasma treated seeds (left) and untreated seeds (right).

# Untreated (Control) Basil

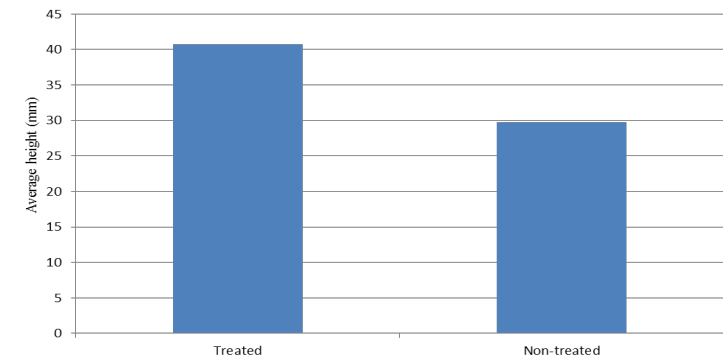


# Plasma Treated Basil



# Basil: Plasma Treated vs. Untreated

Basil plants were plasma treated weekly for 4 weeks. The picture on shows plasma treated on the left and untreated control plants that were all planted on the same day.

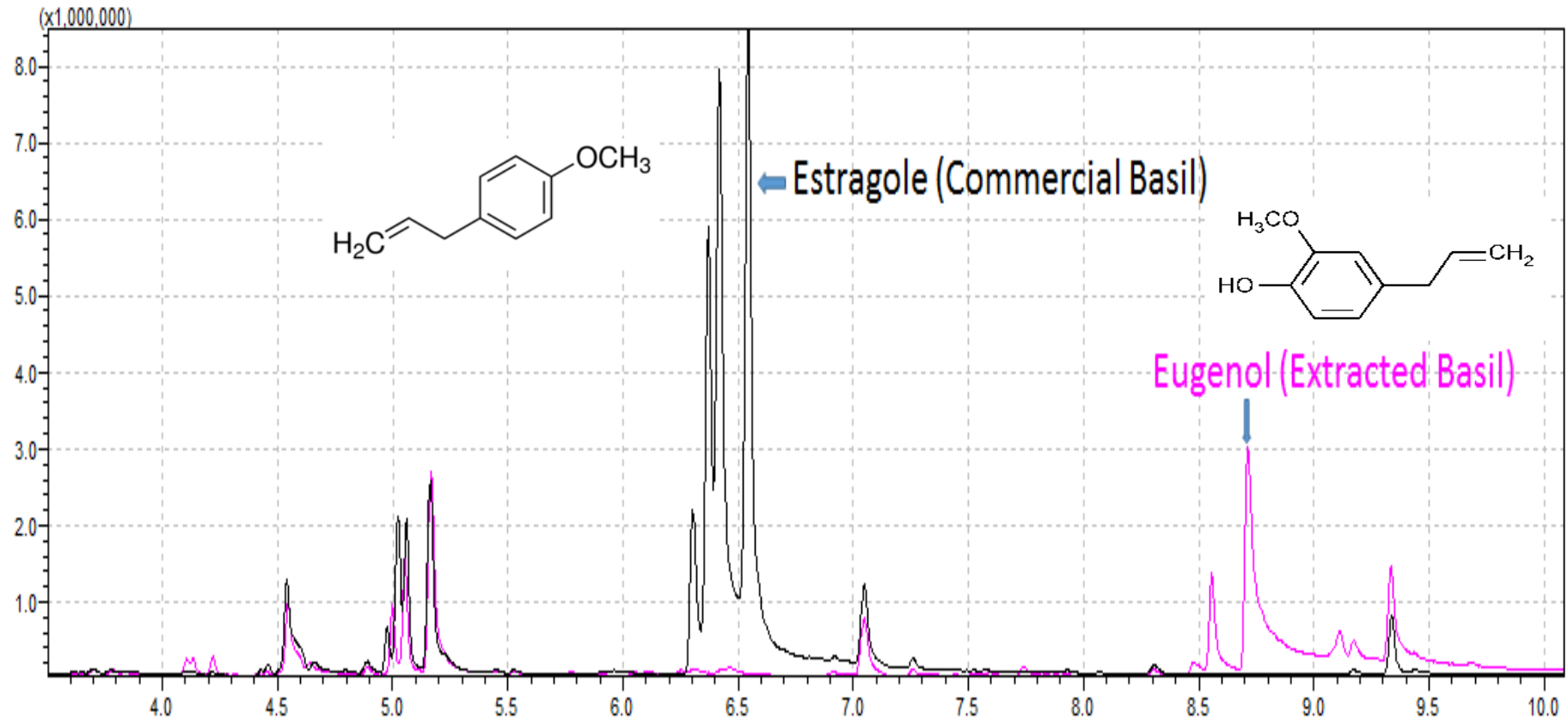


Graph demonstrating average final height of twelve treated and non-treated sweet basil plants after a month of growth from seeds.



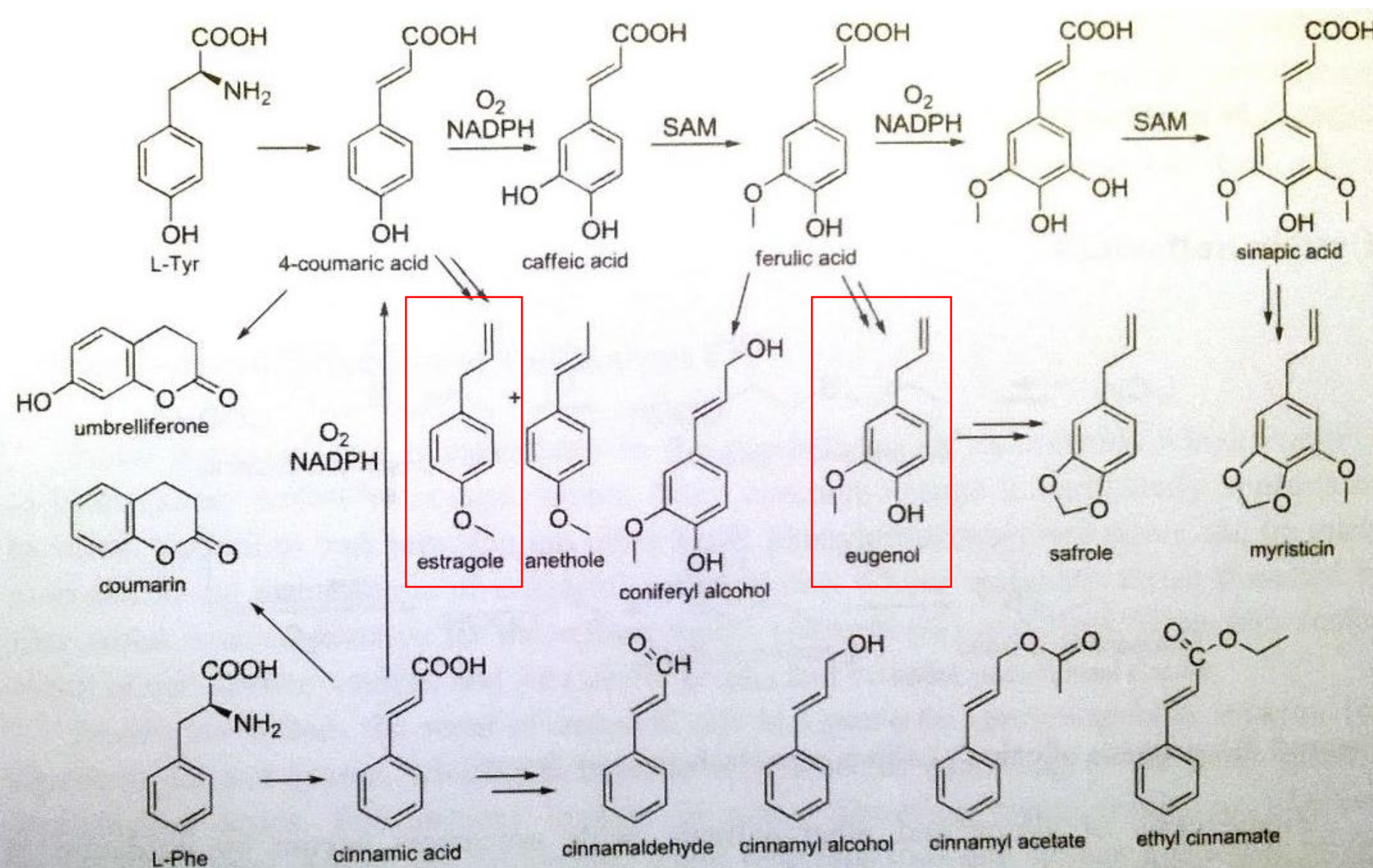
# Gas Chromatogram: Overlay of Commercial Oil and Extracted (T + NT)

Shimadzu GC-MS; Column: RTX-5 MS: 15m X 0.25mm X 0.25 $\mu$ m

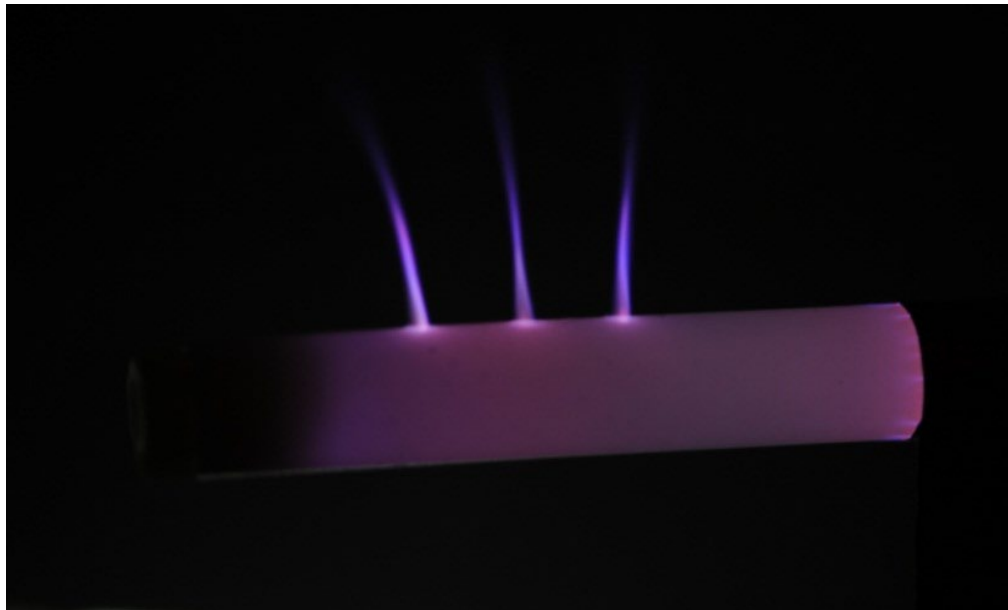
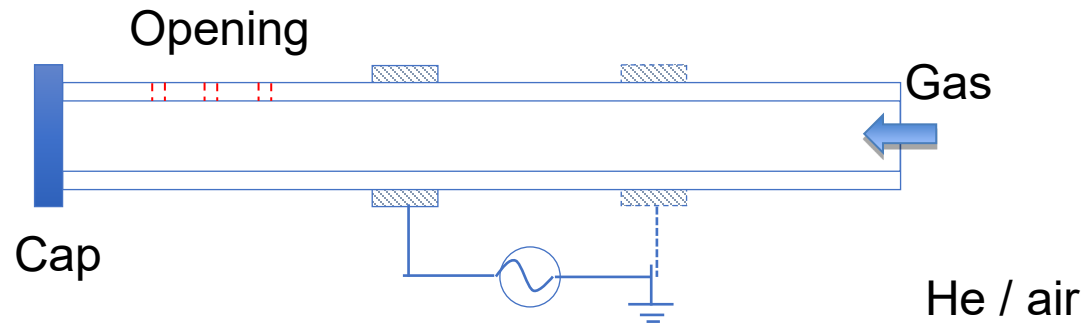


# Biosynthesis of Phenylpropanoids and Phenolic Compounds

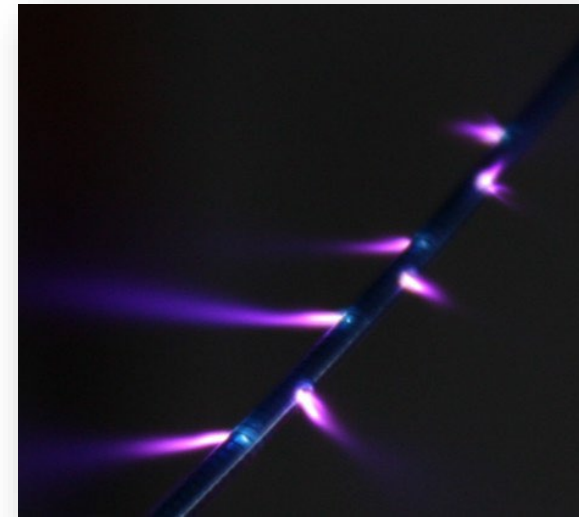
(Valgimigli, 2012)



# Create plasma jets in multiple directions



3-D Arrays!

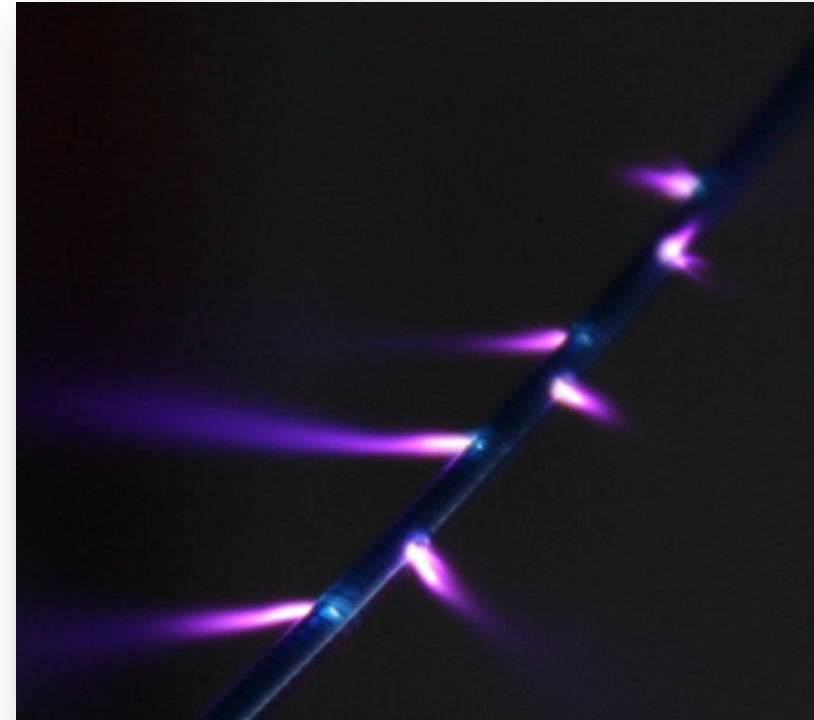


Plasma Jet Array

# Irrigation: Water & Plasma



**Water irrigation** in fields and greenhouses



**Plasma irrigation** for agriculture

# Living tissue sterilization without harm: Recent pig experiments



*Courtesy: Drexel Plasma Institute*

# Hemostasis and coagulation in Hairless mice, not immunocompromised (SKH<sub>1</sub>)

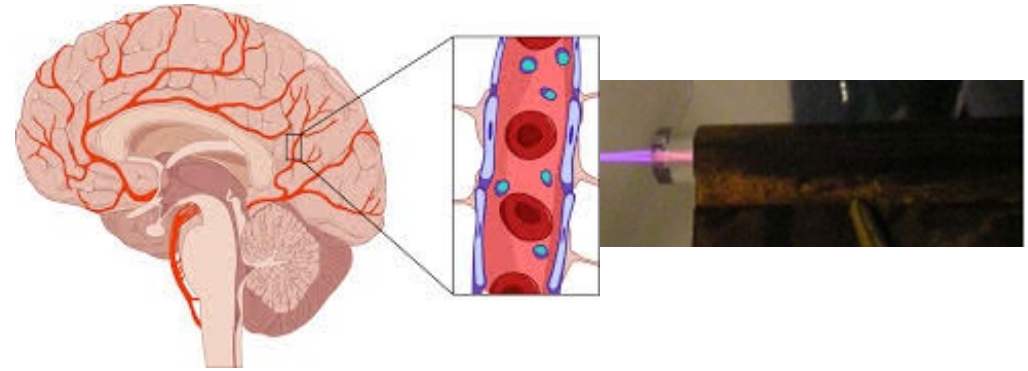
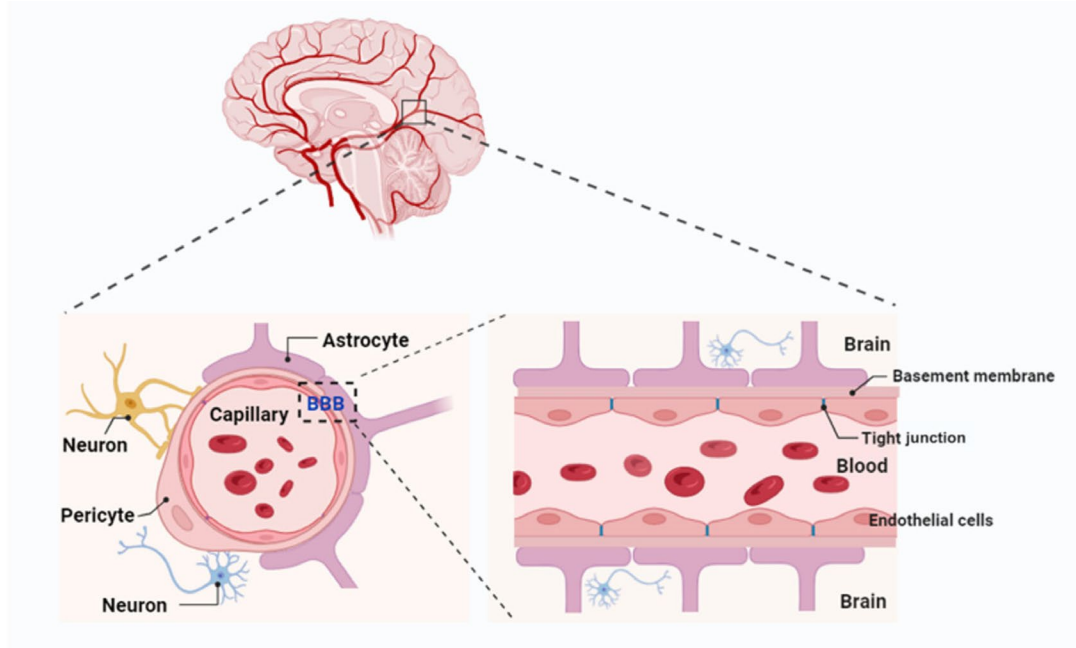


Saphenous vein cut: without plasma animal continues to bleed for 10-20 minutes.

15 seconds of FE-DBD clots the blood and seals the vessel without damaging tissue, preventing additional bleeding.

*Courtesy: Drexel Plasma Institute*

# Regeneration of the Blood-Brain-Barrier



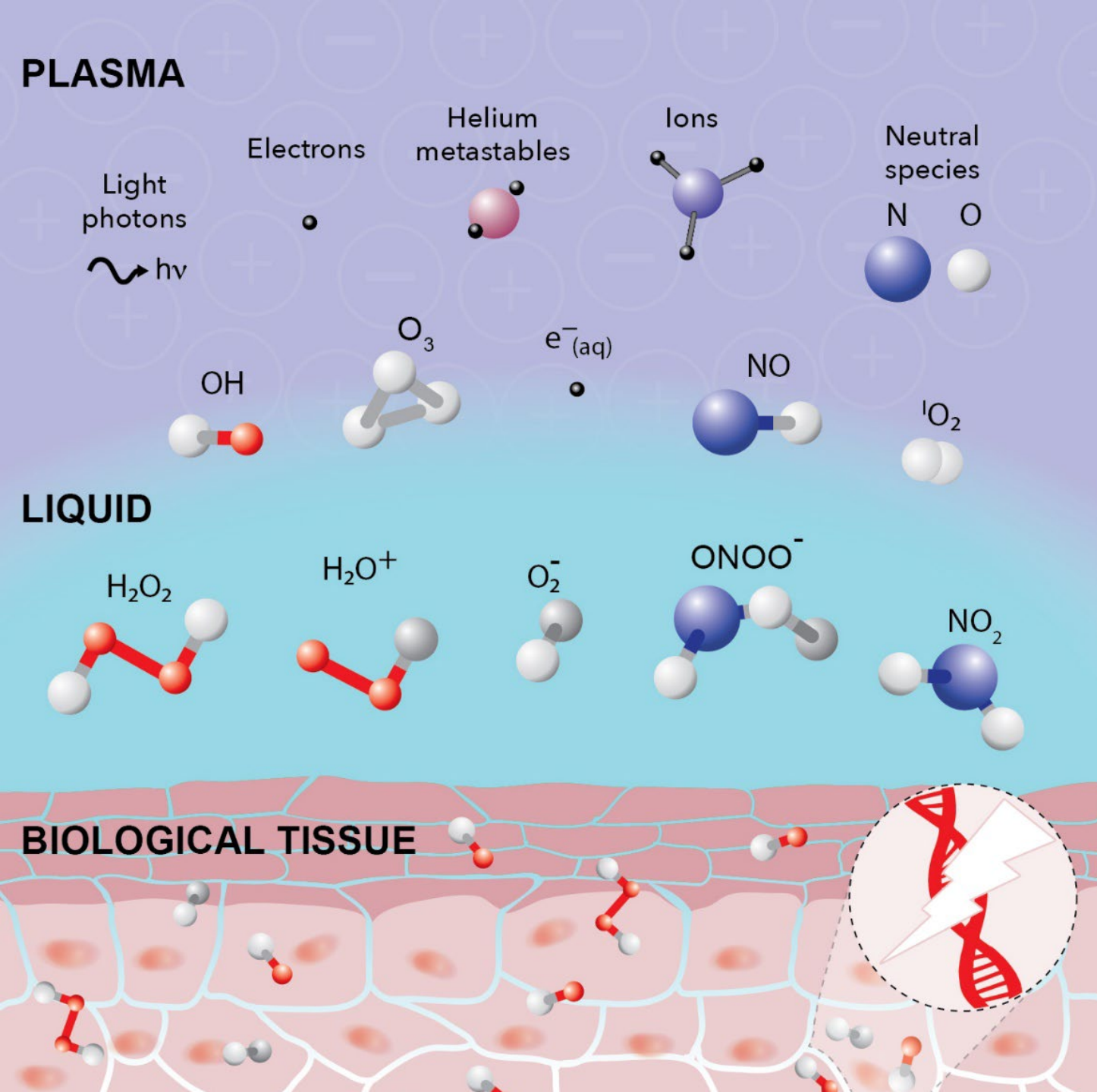
**Institute of NeuroImmune Pharmacology (INIP)**



Sulie L. Chang, Ph.D.  
Professor and Director of INIP

The blood-brain barrier (BBB) is a highly selective semi-permeable border that separates the circulating blood from the brain's extracellular fluid. It acts as a "gatekeeper," protecting the central nervous system (CNS) from toxins, pathogens, and inflammation while allowing essential nutrients and gases to pass through.





## Plasma interaction with biological materials?

- ✓ Many unanswered questions as to the role of plasma in the biological interactions with biological materials.
- ✓ What are the plasmas doing to the live biological materials?
- ✓ Can plasma sources be tailored to better control interactions with biological materials?

# Star Trek's Dermal Regenerator



On *Star Trek*, the dermal regenerator is a hand-held device that instantly heals cuts and burns without leaving a scar. It's used not just for injuries, but also for quick healing after surgery, making for a very speedy recovery.

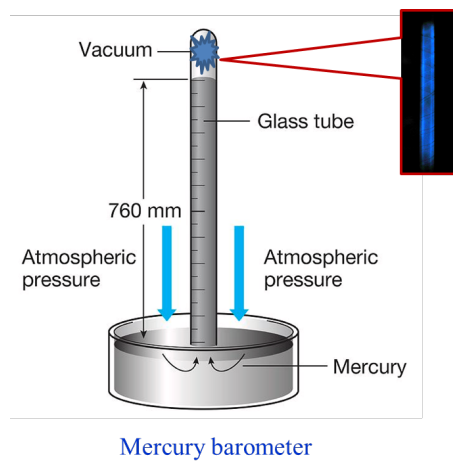
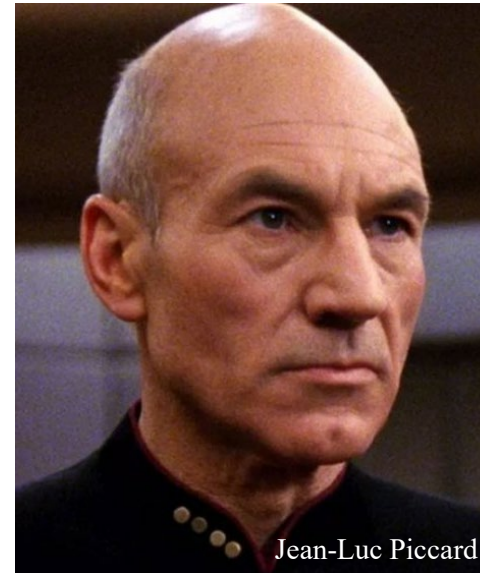


# Star Trek's Dermal Regenerator



Video clip reference:  
*Star Trek: Picard* (Episode #1 - Remembrance)

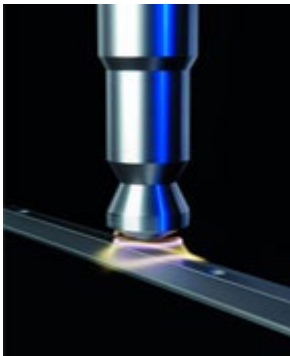
# What plasma technologies will the future bring???



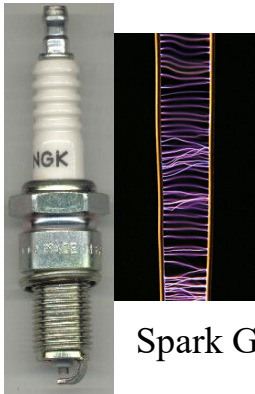
# Many, many Innovative Technologies due to LTPs...



Lasers



Plasma Surface Treatment



Spark Gap



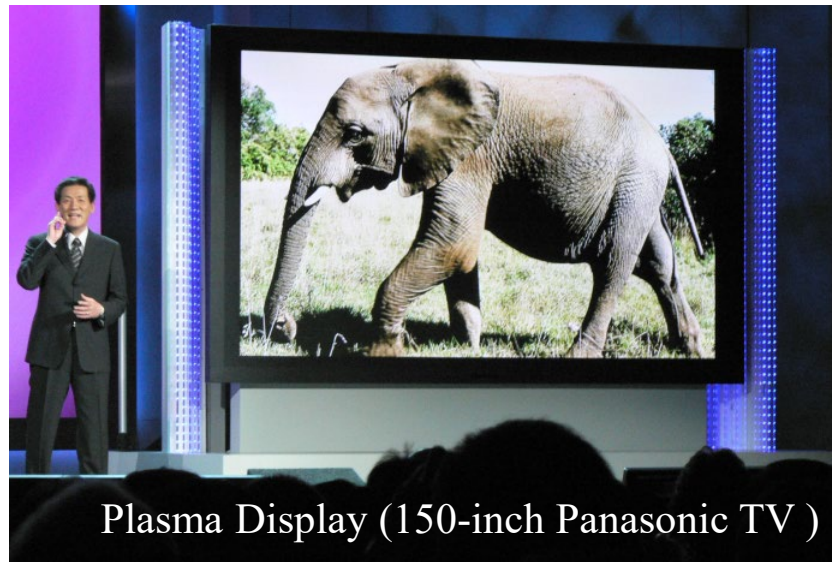
Ozone generator



High Intensity Plasma Arc Lamp



Fluorescent Lamp

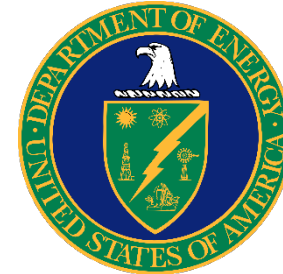
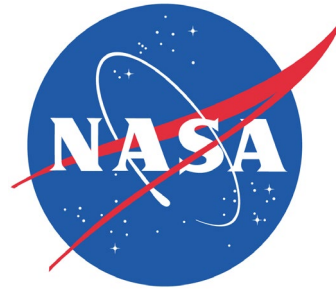


Plasma Display (150-inch Panasonic TV )



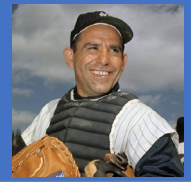
# Acknowledgements

## Funding Partners:



# The future ain't what it used to be...

....Yogi Berra



# Masters of Science (M.S.) in Applied Physics & Engineering



[www.shu.edu/physics](http://www.shu.edu/physics)

## Two M.S. in Applied Physics & Engineering Degree Tracks:

1. Course track (33 credits) for educators / doctoral degree (Ed.D.) and business tracks (M.B.A)
2. Master's Thesis (30 credits) for R&D research or scientific research doctoral degree (Ph.D.)

## Research Areas:

1. Plasma Physics - Science & Technology
2. Condensed Matter / Complex Matter Physics
3. Biophysics & Environmental Physics
4. Environmental Systems & Technologies



**SETON HALL UNIVERSITY**

# *Thank You!*



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