Microplasmas:

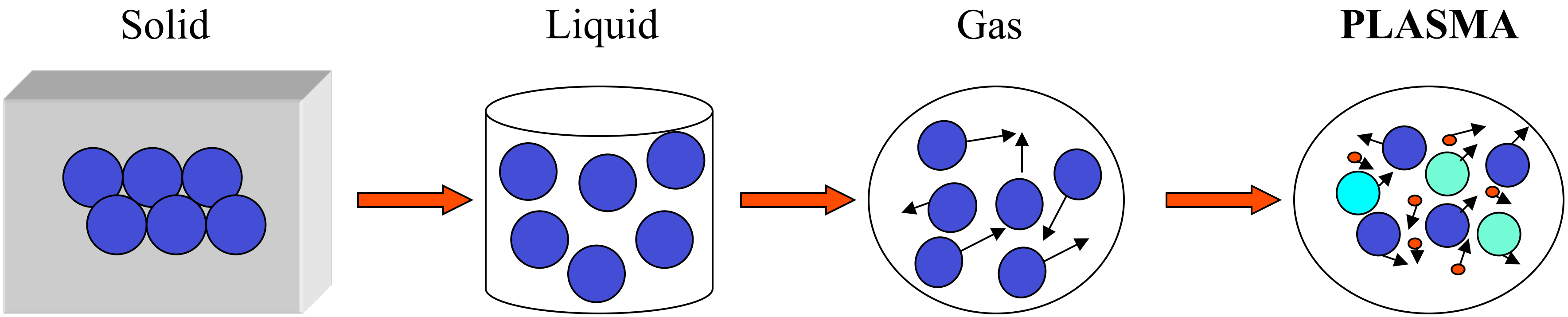
The Little Plasmas that Matter!

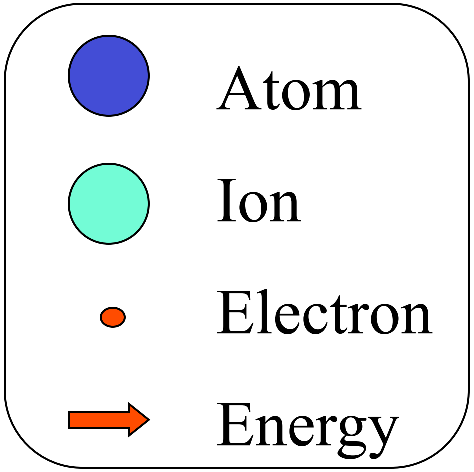
Jose L. Lopez, PhD

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

What is a Plasma?

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



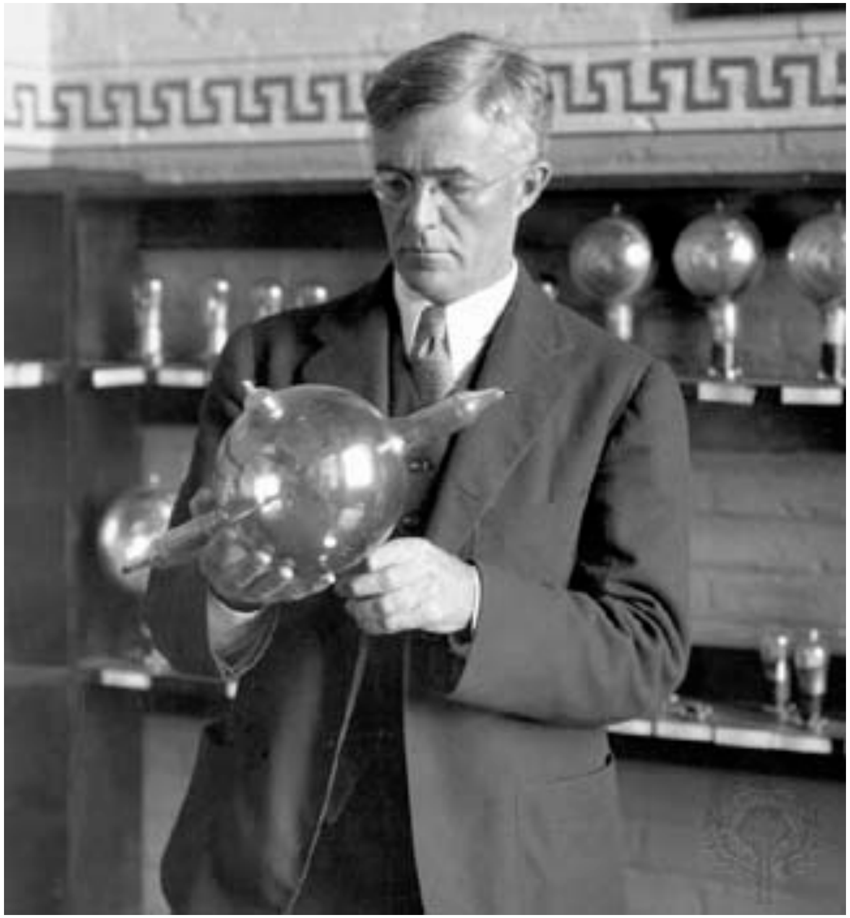


A *Plasma* is a collection of neutrals, ions, and electrons characterized by a *collective behavior*.

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

Where is Seton Hall?

New Jersey – The birth place of Plasma Science



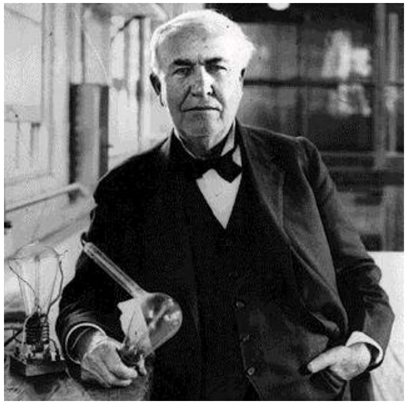
Irving Langmuir

Birth of Plasma Science

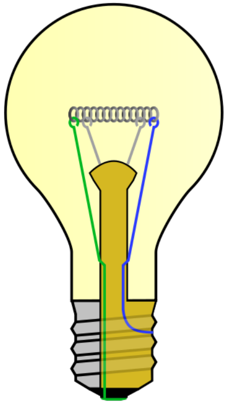
Birthplace: Hoboken, New Jersey

Irving Langmuir was one of the first scientists to work on plasmas and the first to refer to this 4th state of matter as ***plasmas***, because their similarity to blood plasma

Plasma Lighting Technology



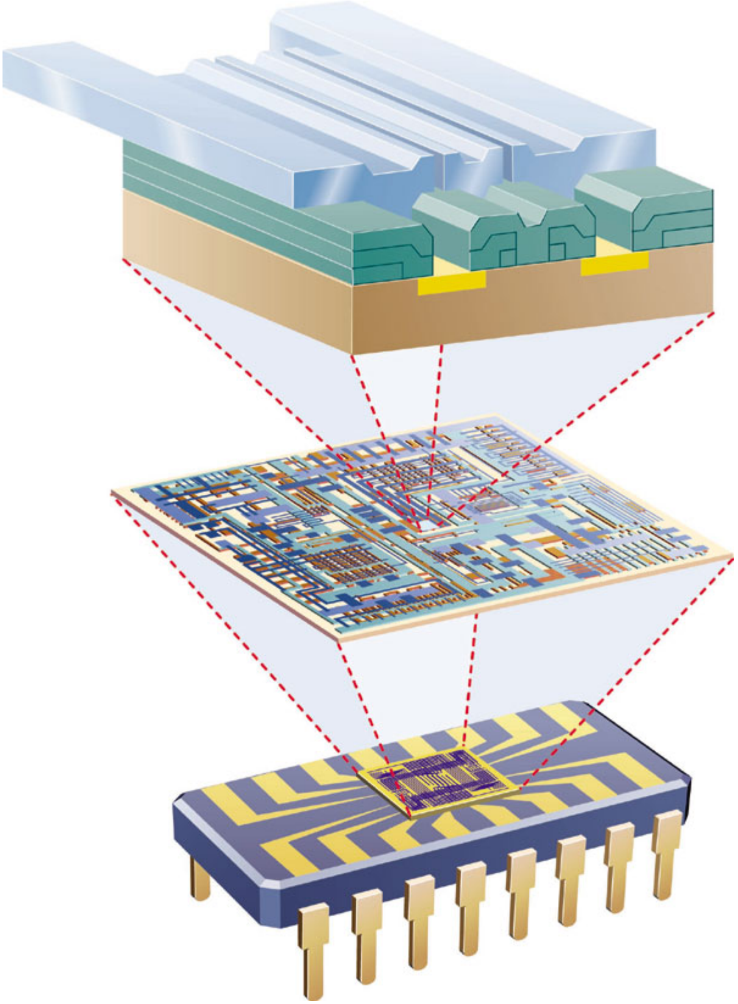
Thomas Edison

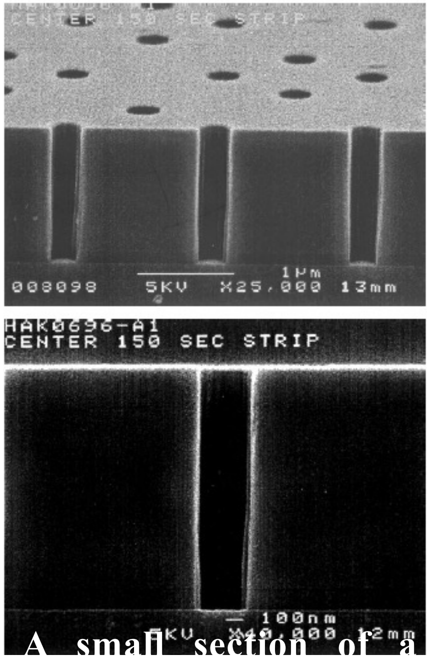


Daniel McFarlan Moore

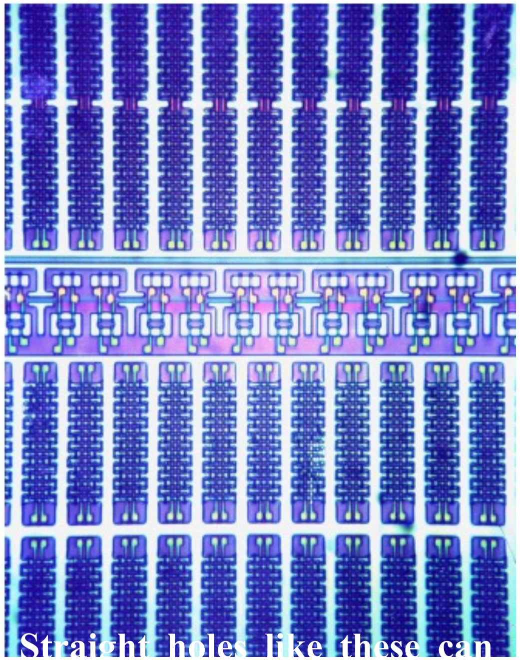
Birthplace of the Fluorescent Light Bulb: Edison (Menlo Park) / West Orange, NJ

Plasma Enhanced Technology





A small section of a



Straight holes like these can

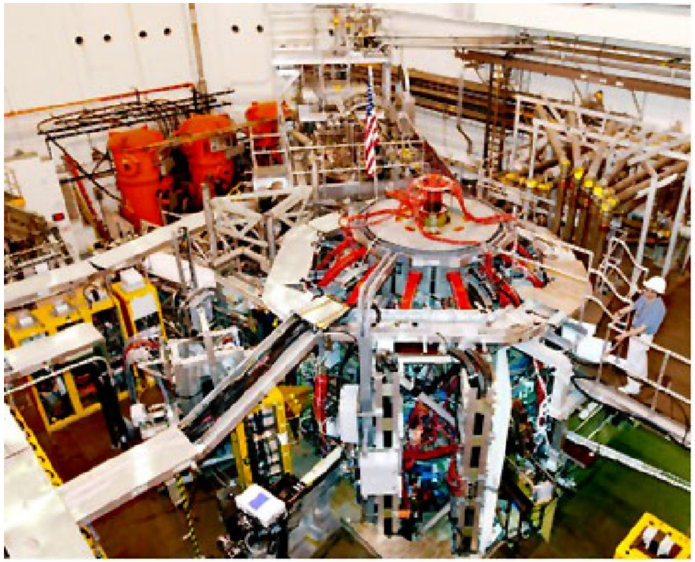
Birthplace of solid-state microelectronics: Bell Laboratories, Murray Hill, NJ

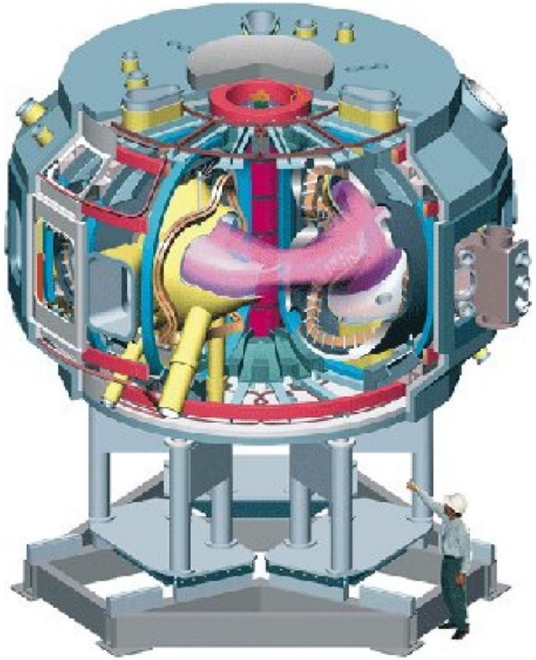
PPPL
PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

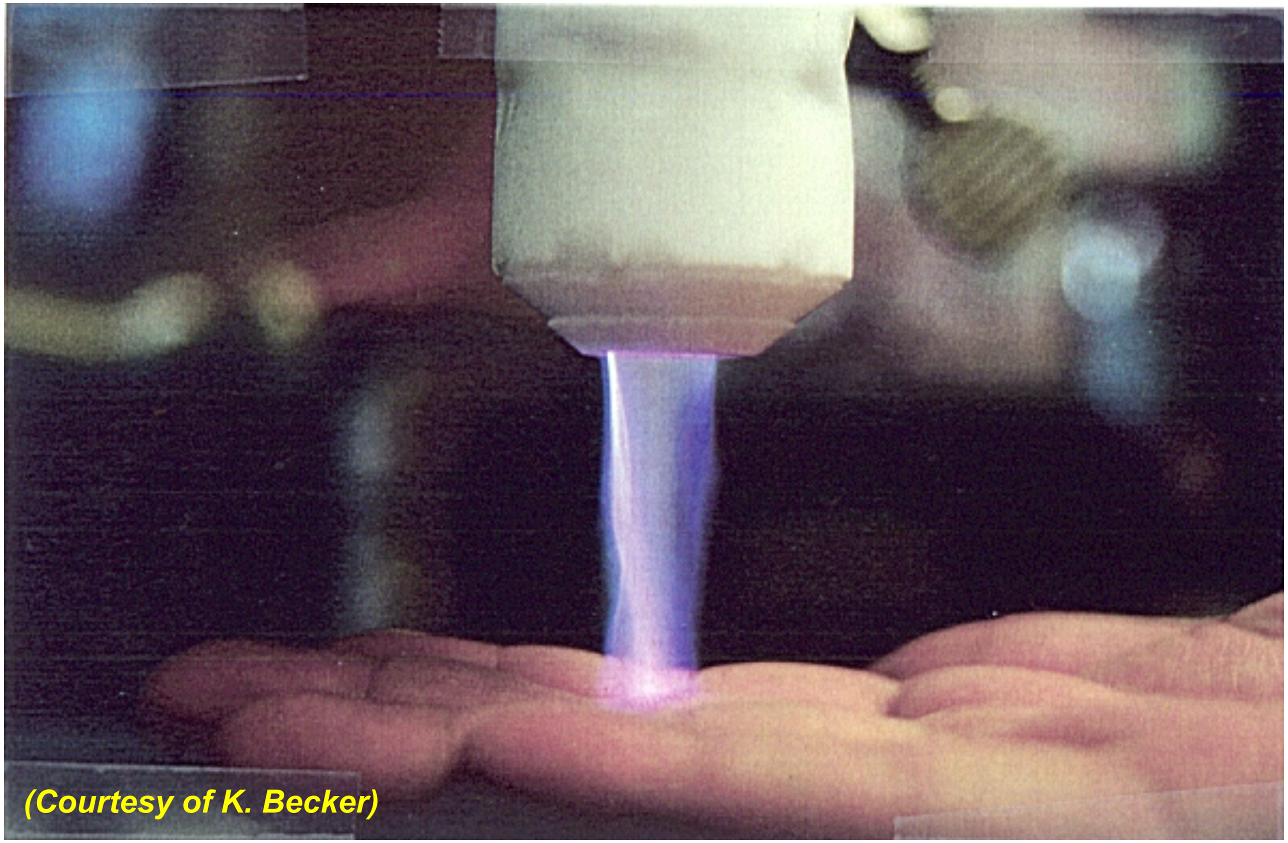
U.S. DEPARTMENT OF ENERGY

The U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL) is a collaborative national center for plasma and fusion science. Its primary mission is to develop the scientific understanding and the key innovations which will lead to an attractive fusion energy source. Associated missions include conducting world-class research along the broad frontier of plasma science and technology, and providing the highest quality of scientific education.



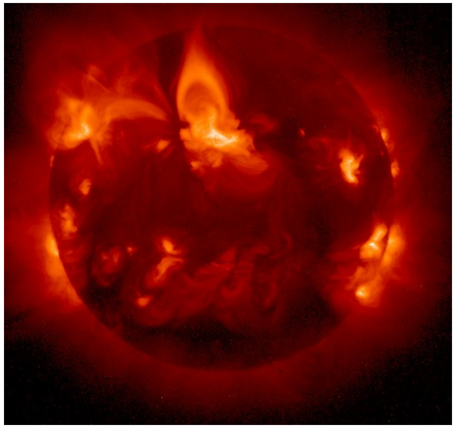


National Spherical Torus Experiment (NSTX)


(Courtesy of K. Becker)

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

Plasmas in Nature

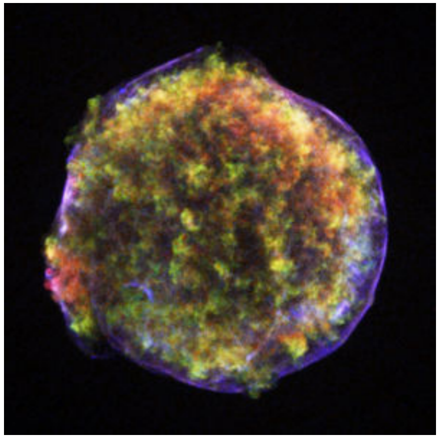


The Sun

Aurora

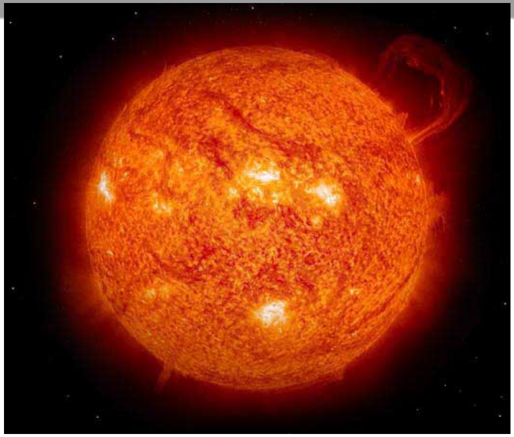
Lightning

The Comet



Supernova

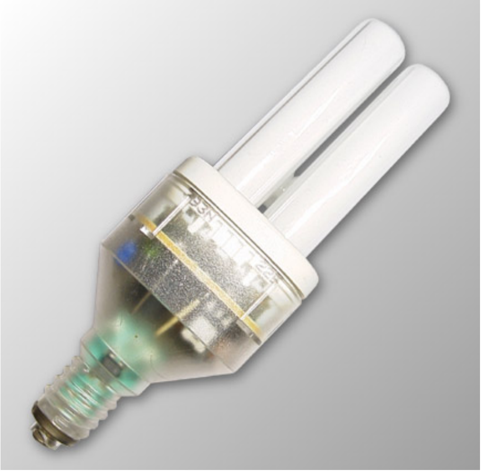
Plasmas are everywhere!!!



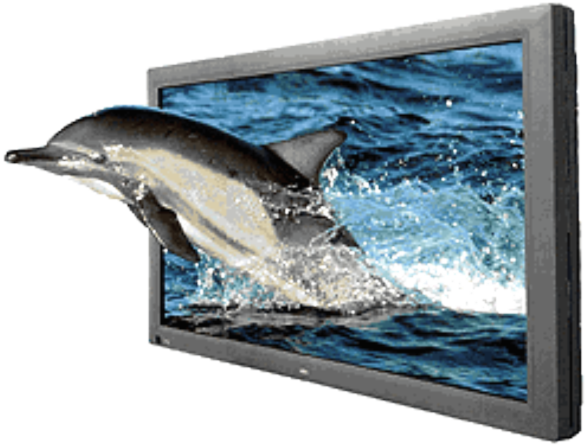
Sun

Aurora Borealis (Northern Lights)

Lightning



Fluorescent Lamps



Plasma Display Televisions

Plasmas 101

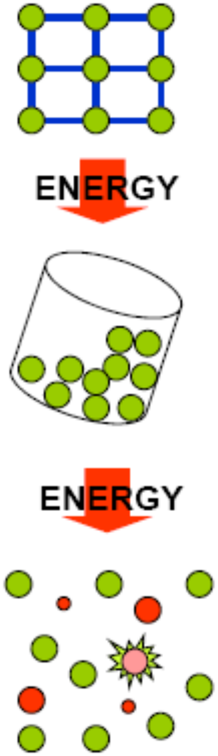
Solid, Liquid, Gas and …Plasma

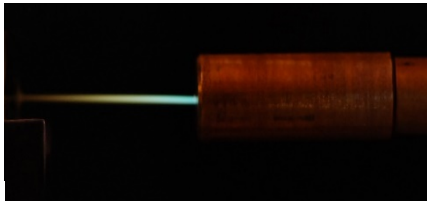
-The 4th State of Matter

SOLID
- Molecules fixed in lattice
- Electrons bound to molecules or lattice

LIQUID
- Molecule bonds are flexible
- Electrons close to molecules

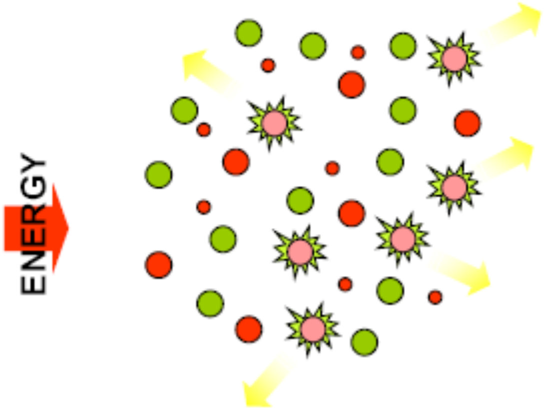
GAS
- Molecules free to move
- Few electrons and ions that are free to move
- Some excited molecules are present





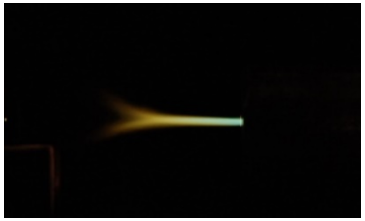
- 🟢 Molecules
- ✷ Excited molecules
- 🔴 Ions
- • Electrons

PLASMA
- Molecules free to move
- Many electrons, ions and excited molecules, all free to move
- often accompanied by light



>99% in Universe

The Eventful Plasma World

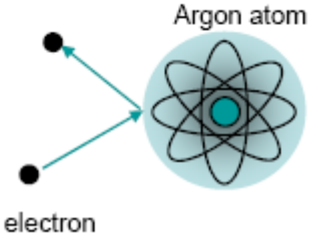


Collisions in a plasma

● Molecules
✸ Excited molecules
● Ions
• Electrons

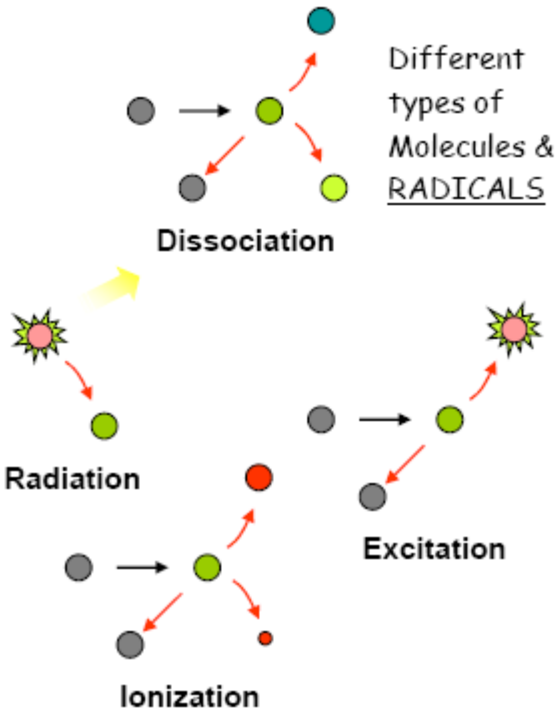
Elastic collisions

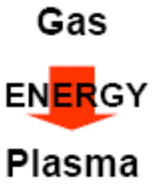
Elastic collision are frequent in gases
No energy exchange



essentially no exchange of energy ($m_{Ar} >> m_e$)

Inelastic collisions





Therefore more and stronger collisions
leading to more

ionization,
excitation,
dissociation and
radiation

Two Types of plasmas

High-temperature plasmas (Hot Plasmas)

$T_i \approx T_e \geq 10^7$ K

e.g., fusion plasmas

$T_i \approx T_e \approx T_g \leq 2 \times 10^4$ K

e.g. arc plasma at normal pressure

Low-temperature plasmas (Cold Plasmas)

$T_i \approx T_g \approx 300$ K

$T_i << T_e \leq 10^5$ K

e.g. low-pressure glow discharge

high-pressure cold plasma

Hot vs. Cold Plasmas

Thermal vs. Non-Thermal Plasmas

The plasma components (electrons, ions, neutrals) are characterized by energy distribution functions or alternatively by an "average" energy or temperature (T_e, T_i, T_n) – not quite correct, only true for Maxwell-Boltzmann distributions !!!

Electrons in general have more complicated energy distributions !!!

Thermal Plasma: $T_e \approx T_i \approx T_n$ (a few thousand Kelvin for e.g. torches to $>10^6$ Kelvin for e.g. fusion plasmas)

Non-Thermal Plasma: $T_e >> T_i, T_n$ with $T_i \approx T_n$

- high electron temperature (10,000 – 50,000 K)
- low gas temperatures (300 – 1,500 K)
- "high-temperature chemistry" at low ambient temperatures

(through dissociation and ionization & vibrational non-equilibrium)

Low-Temperature (“Cold”) Plasmas [Non-equilibrium, Non-Thermal]

→ $T_e >> T_i, T_n$ with $T_i \approx T_n$ ←

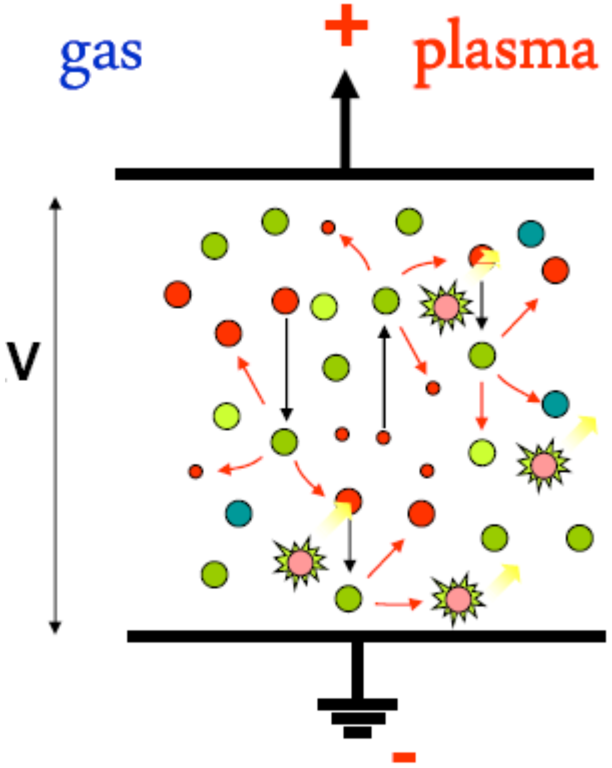
- High “electron temperature” (10,000 – 100,000 K)
  - ❖ T_e from 0.5 eV to 10 eV
  - ❖ Often highly non-Maxwellian EEDF; “bulk” and “beam” electrons
- Low gas temperature (350 – 2,500 K)
- “High-temperature chemistry” at low ambient temperatures
  - ❖ Electron-driven ionization and dissociation (in molecular plasmas) create reactive radicals
  - ❖ Electron interactions (in molecular plasmas) create a vibrational non-equilibrium

How do we make plasmas?

Supply Energy!!
e.g. Heat transfer, radiation, electric power…

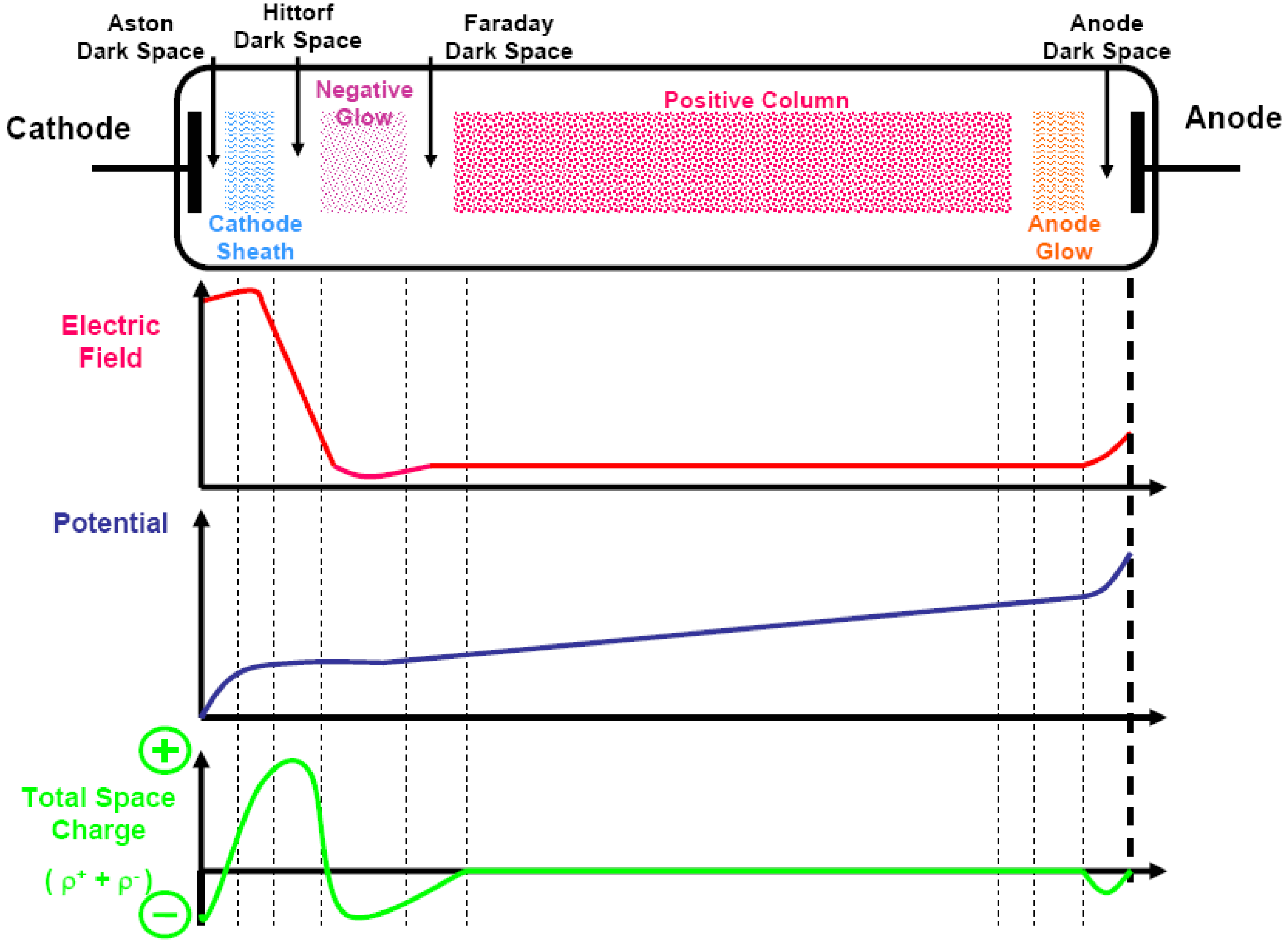
For many plasma applications, an Electric Field is applied to a gaseous environment

Plasma or Gaseous Discharge

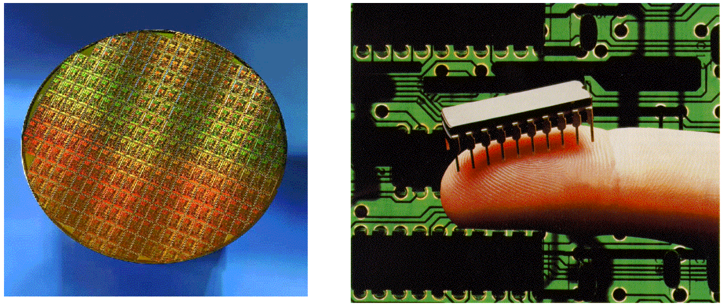


- ● Molecules
- ✸ Excited molecules
- ● Ions
- • Electrons

Low-Pressure Glow Discharge Plasmas



Plasmas are easier to be generated at low pressures

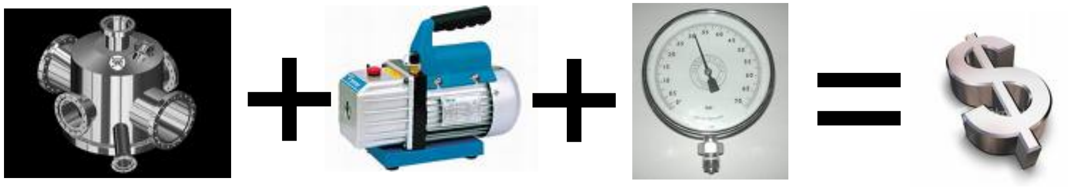


Low pressure plasmas

(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 Pressure!!

What happens at air pressure?

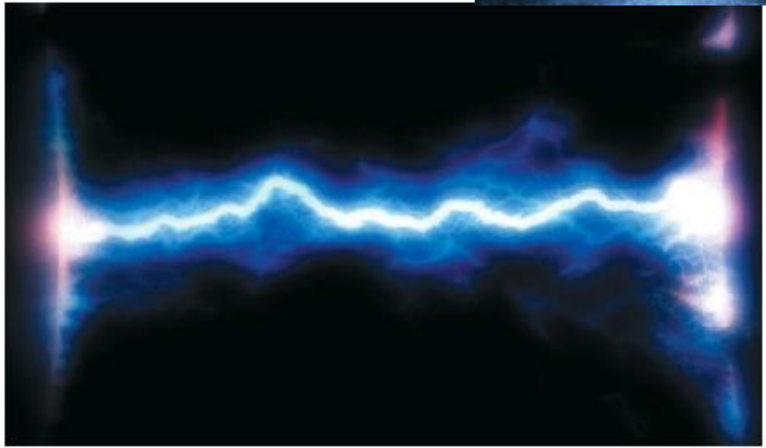
- No vacuum is involved
- Difficult to generate and sustain
- Run into some challenges such as glow to ***arc*** transition – Non controllable

Arc Discharge: thermal plasma

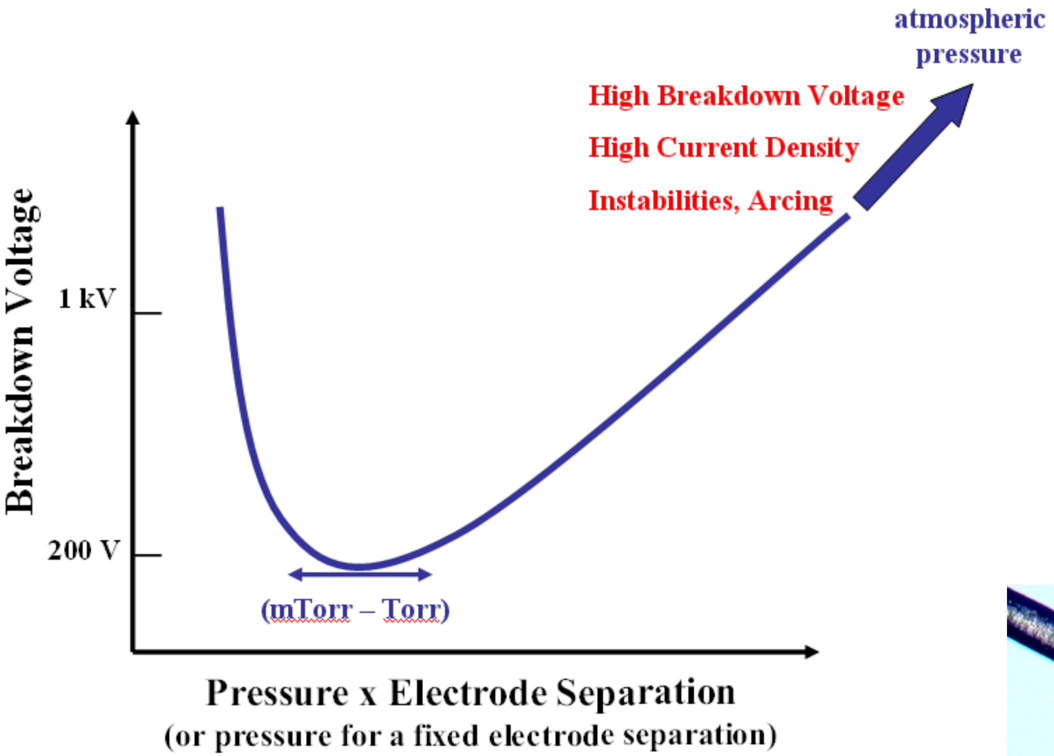
-It's hot and detrimental

-Gas temperature can reach as high as 2×10^4 K

- Low voltage drop at cathode
- High cathode current density



High Pressure Microplasmas



Paschen Breakdown Curve

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

Microplasmas

Dimension: a few millimeter down to and below **100 μm**

Human Hair: 60 – 100 μm

How do we solve this problem?

Transient (pulsed) plasmas: *In atmospheric* plasmas, *for efficient gas heating at least 100-1000 colli*sions are necessary. Thus, if the plasma duration is shorter than 10^{-6} – 10^{-5} s, *gas* heating is limited. Of course, for practical purposes such plasma has to be operated in a repetitive mode, e.g., in trains of microsecond pulses with millisecond intervals.

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: 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.

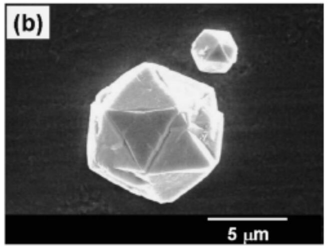
Advantages of Microplasmas

- Low-cost of implementation
- System flexibility
- Atmospheric pressure operation
- High densities and high reaction rates
- Fast and efficient processes
- Easy to generate and sustain for a variety of gas mixtures
- Glow-like and diffuse
- Non-equilibrium ($T_e > T_g$) *to thermal*
- Unique chemistry

… a new realm of plasma science

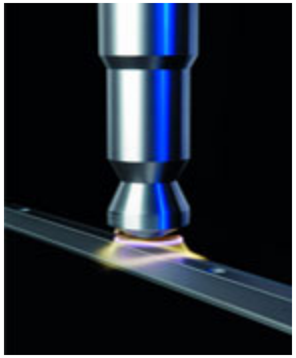
What can we do with it?

Material Synthesis



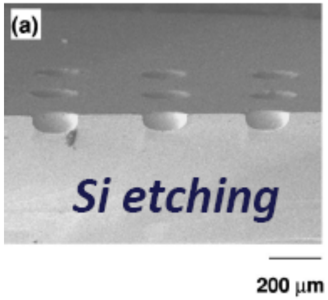
Plasma display

Surface Treatment



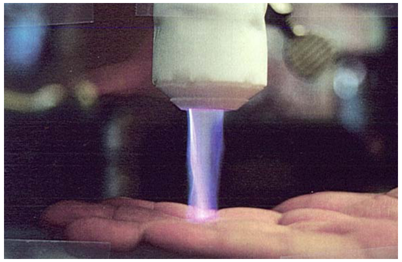
Lighting

Material processing

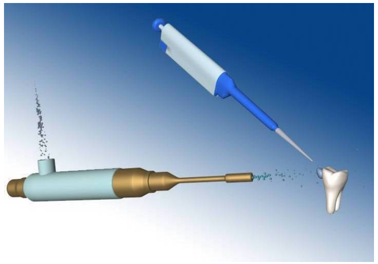


Ozone generation for water cleaning

Bio-application

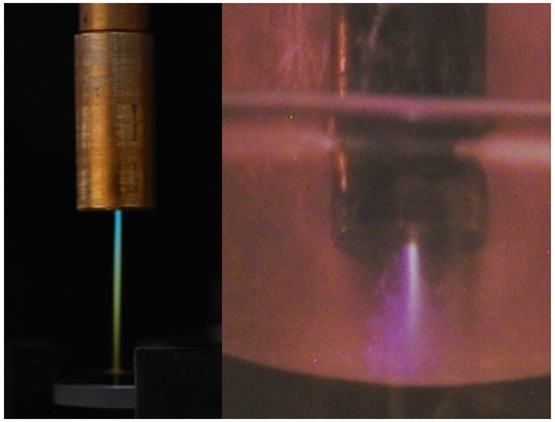


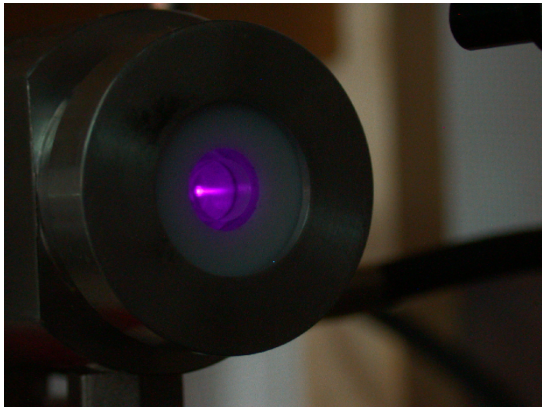
Dental application

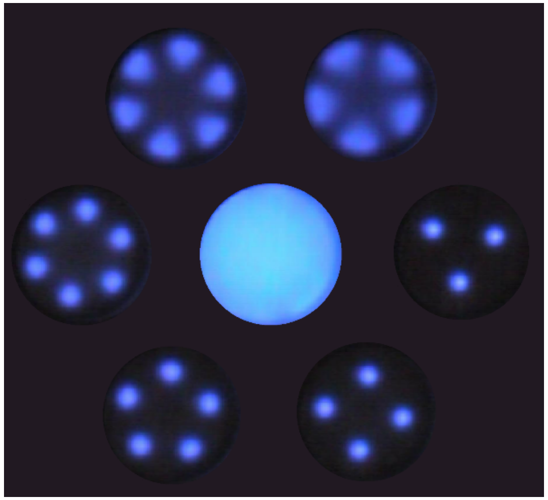


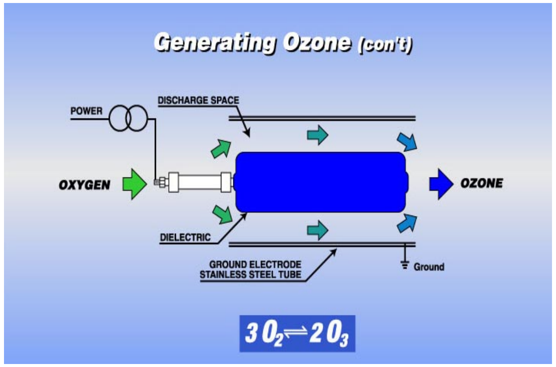
and Many more…

Some examples…





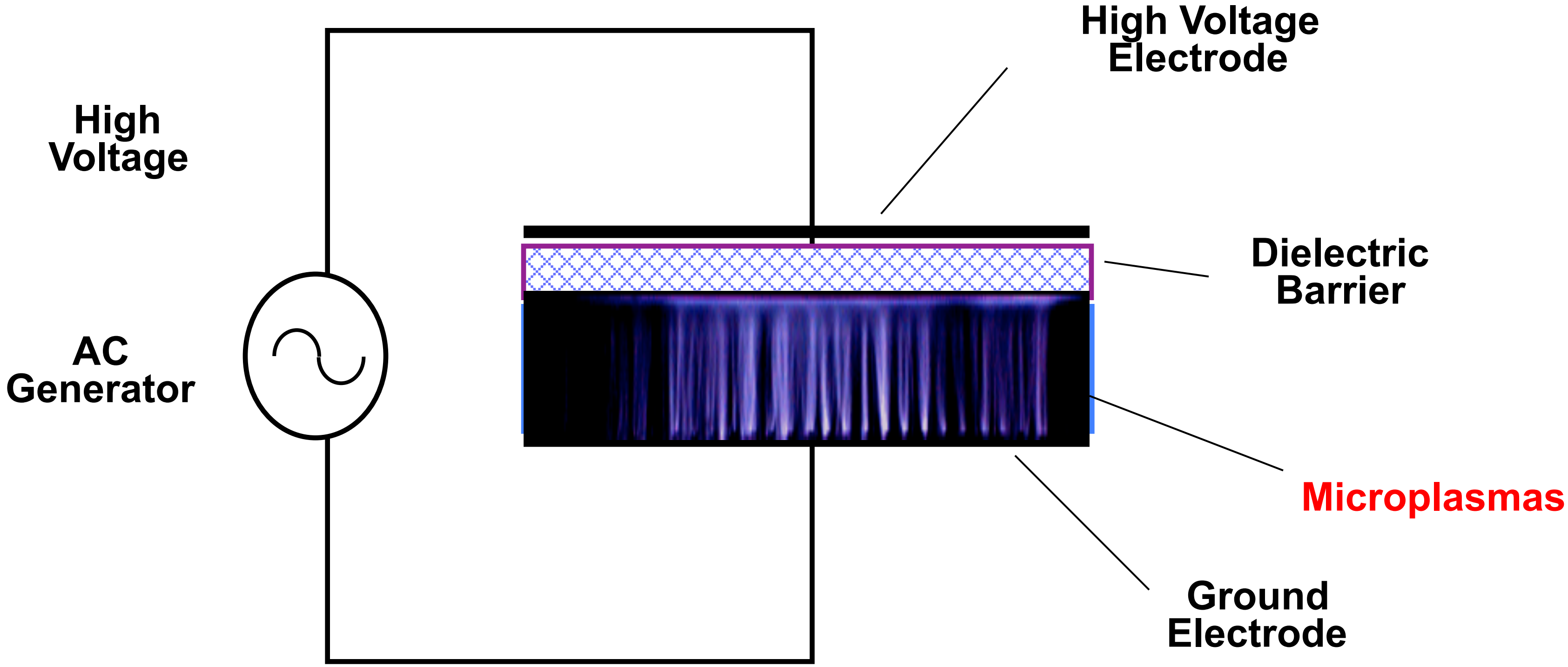




Generating Ozone (con't)

$3O_2 \rightleftharpoons 2O_3$

Atmospheric Pressure Cold Plasma



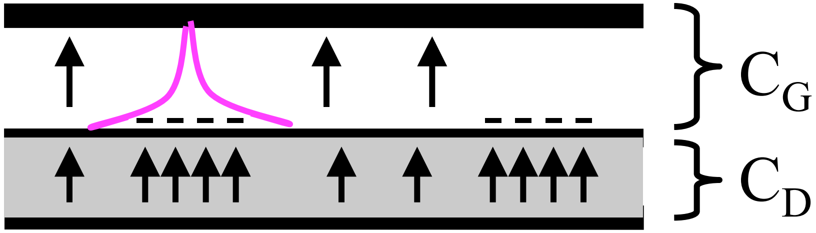
Role of the Dielectric (Insulator)

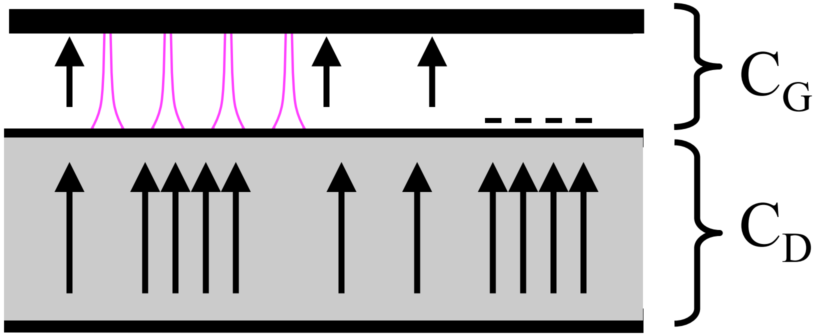
The dielectric is the key for the proper functioning of the discharge.

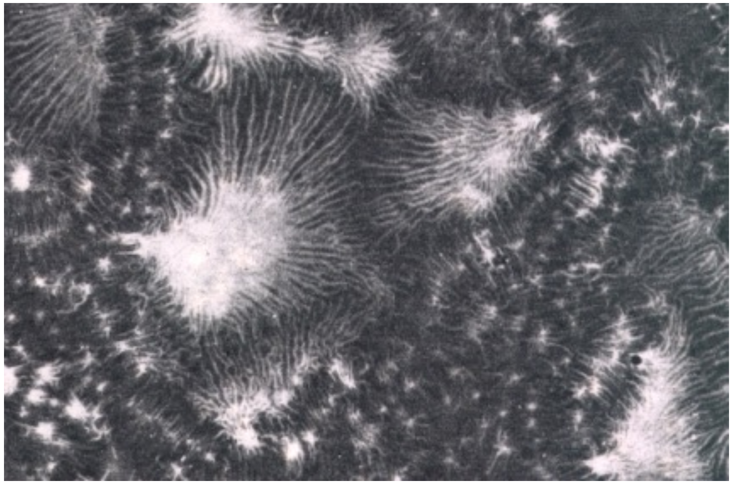
Serves two functions:

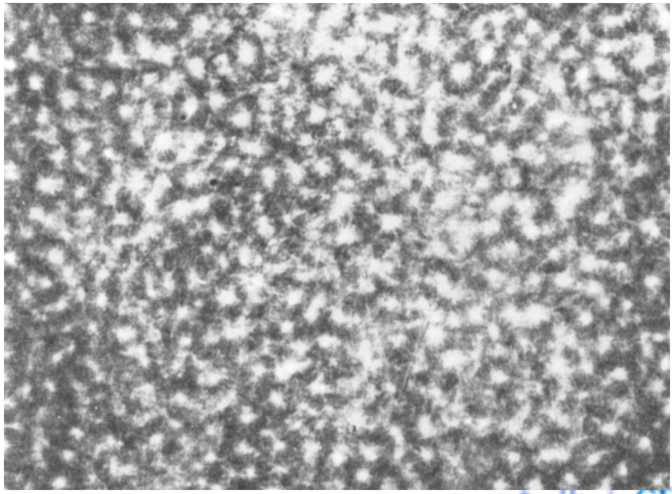
1. Limits the amount of charge transported by a single microplasma
2. Distributes the microplasmas over the entire electrode surface area

Principals of DBD Microplasmas



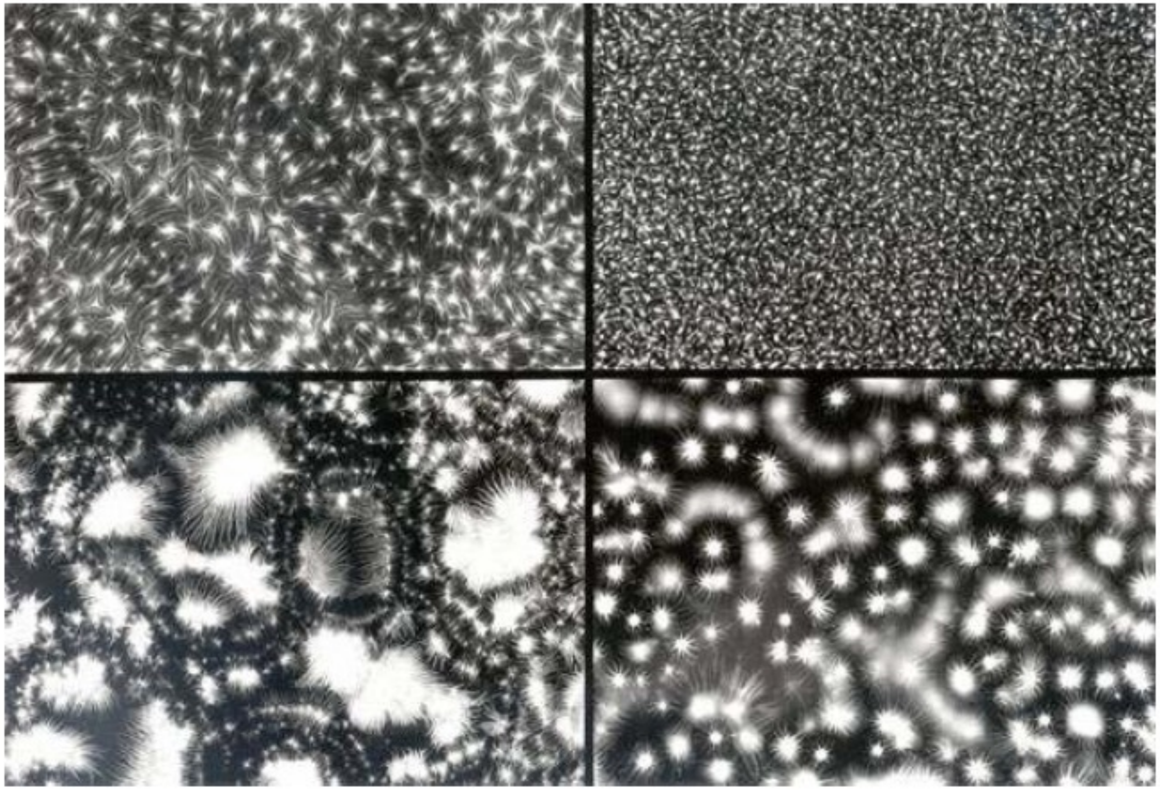






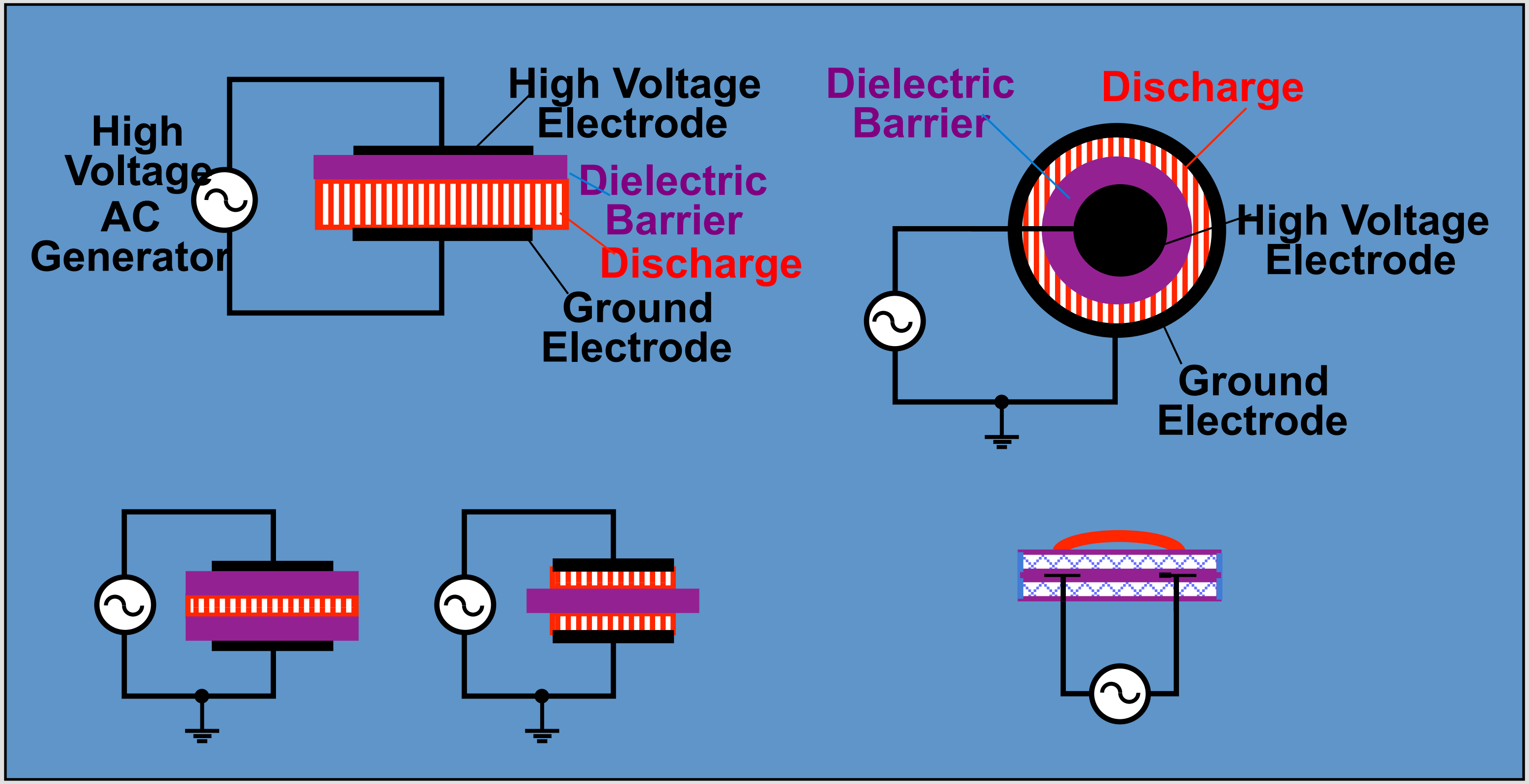
Principals of DBD Microplasmas

Four Different Gap Widths



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

Dielectric Barrier Discharge

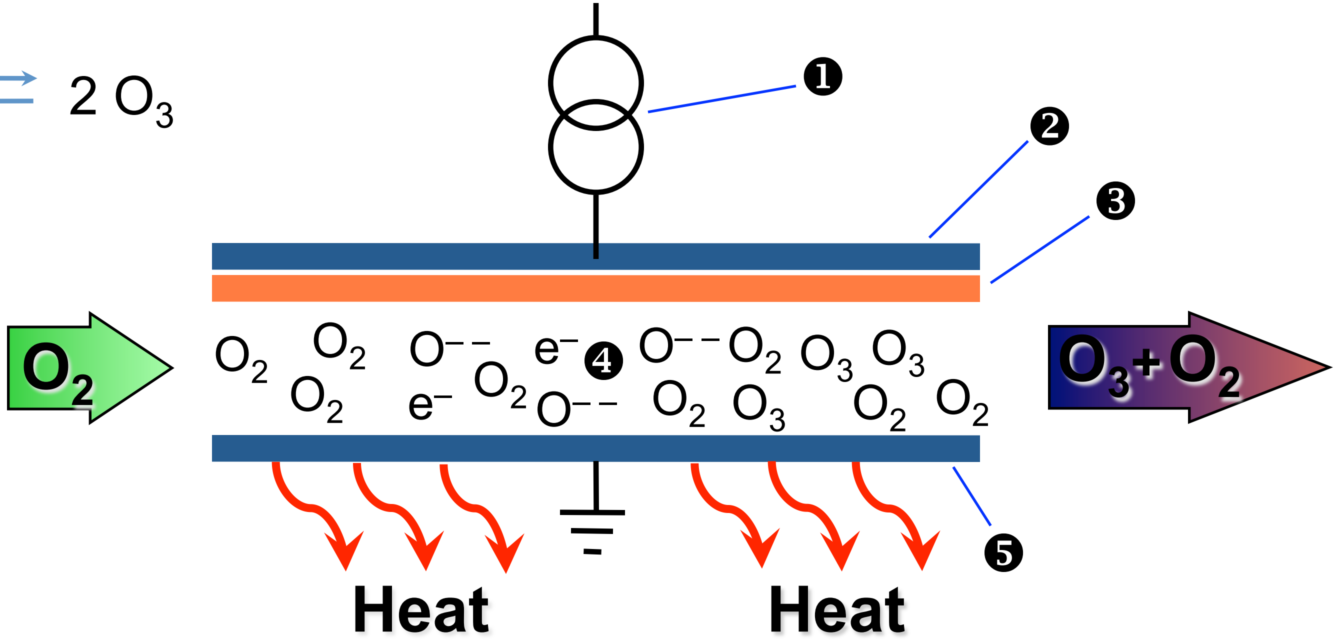


H.E. Wagner, R. Brandenburg, et. al. ‘The barrier discharge: basic properties and applications to surface treatment’. *Vacuum.* 71 p417-436 (2003).

Ozone Generator

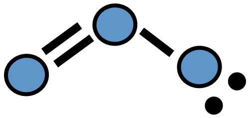
Dielectric Barrier Discharge

$3\,O_2 \rightleftharpoons 2\,O_3$



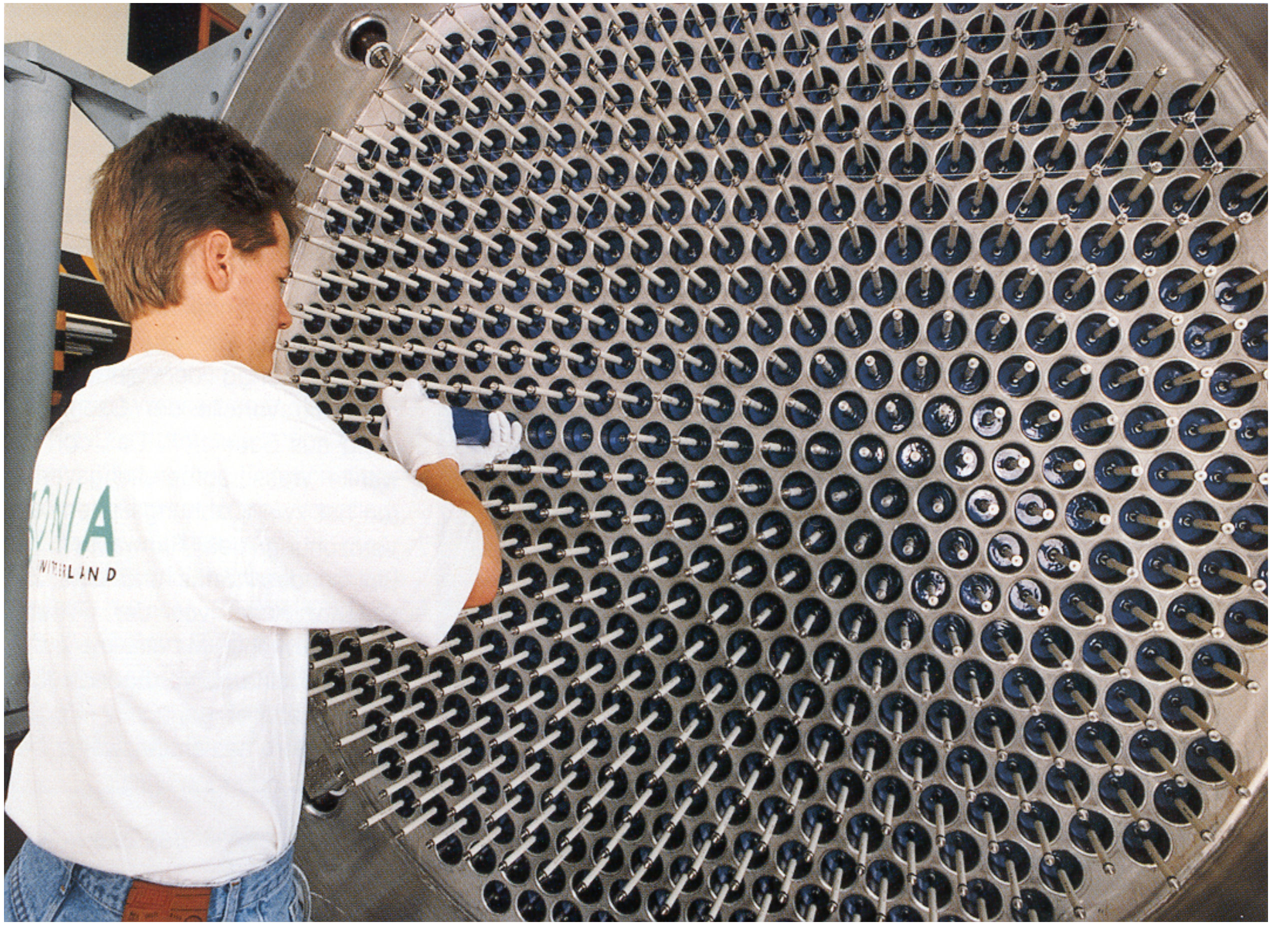
Properties of Ozone (O_3)

- 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

Ozonia Advanced Technology Ozone Generator



Ozone Water Treatment

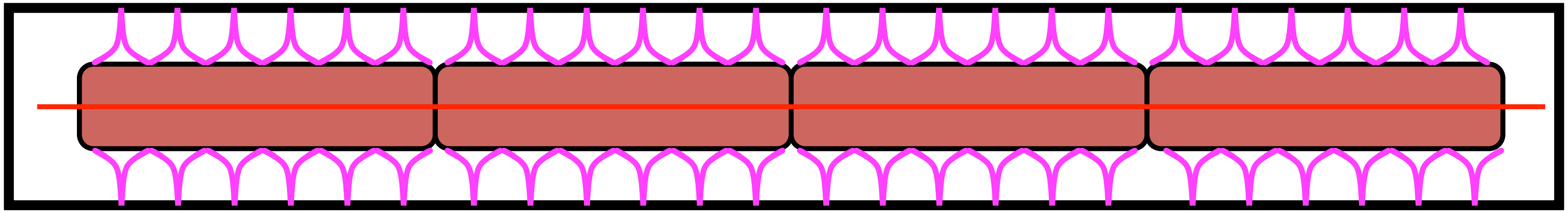
Bubble Diffusion

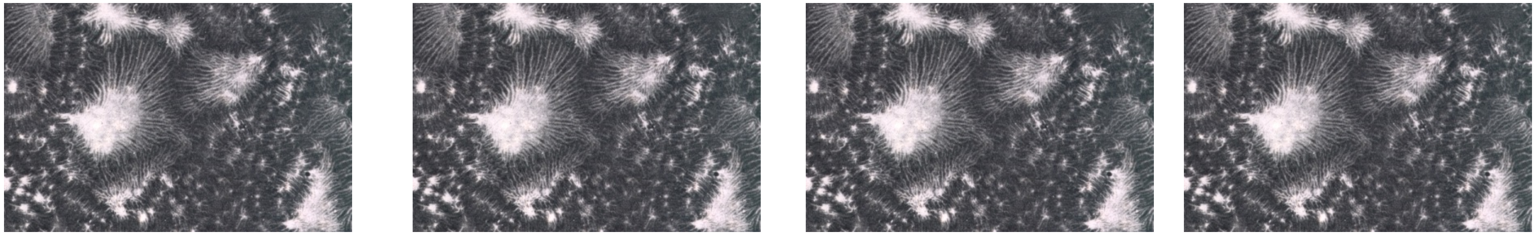
Easy to use

Low energy usage

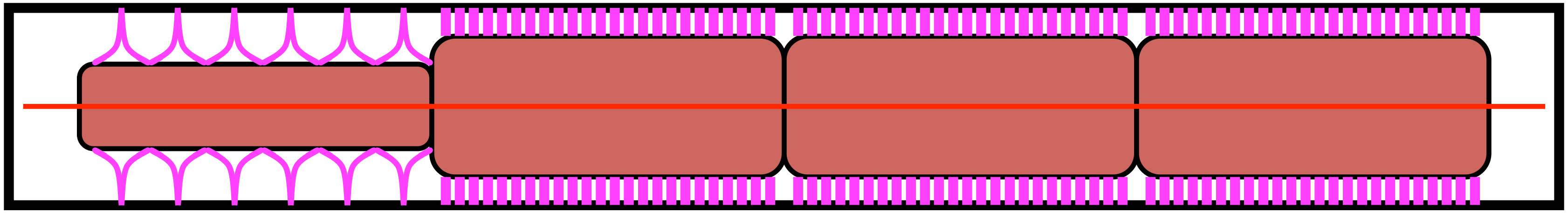
Mass transfer efficiencies to > 90%

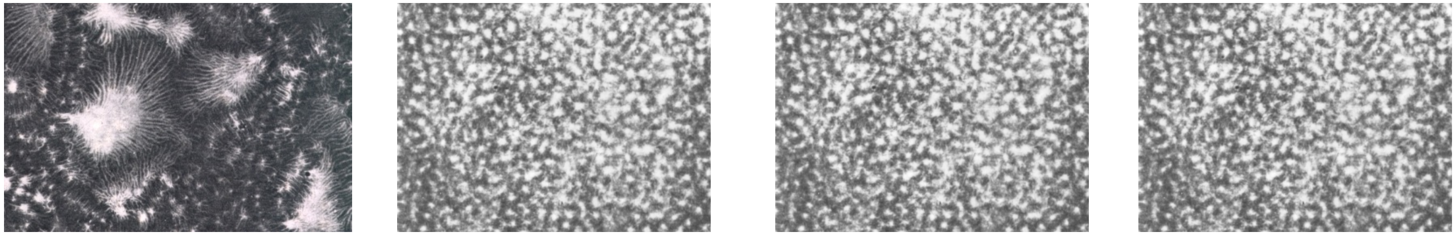
Reference (Traditional) Arrangement



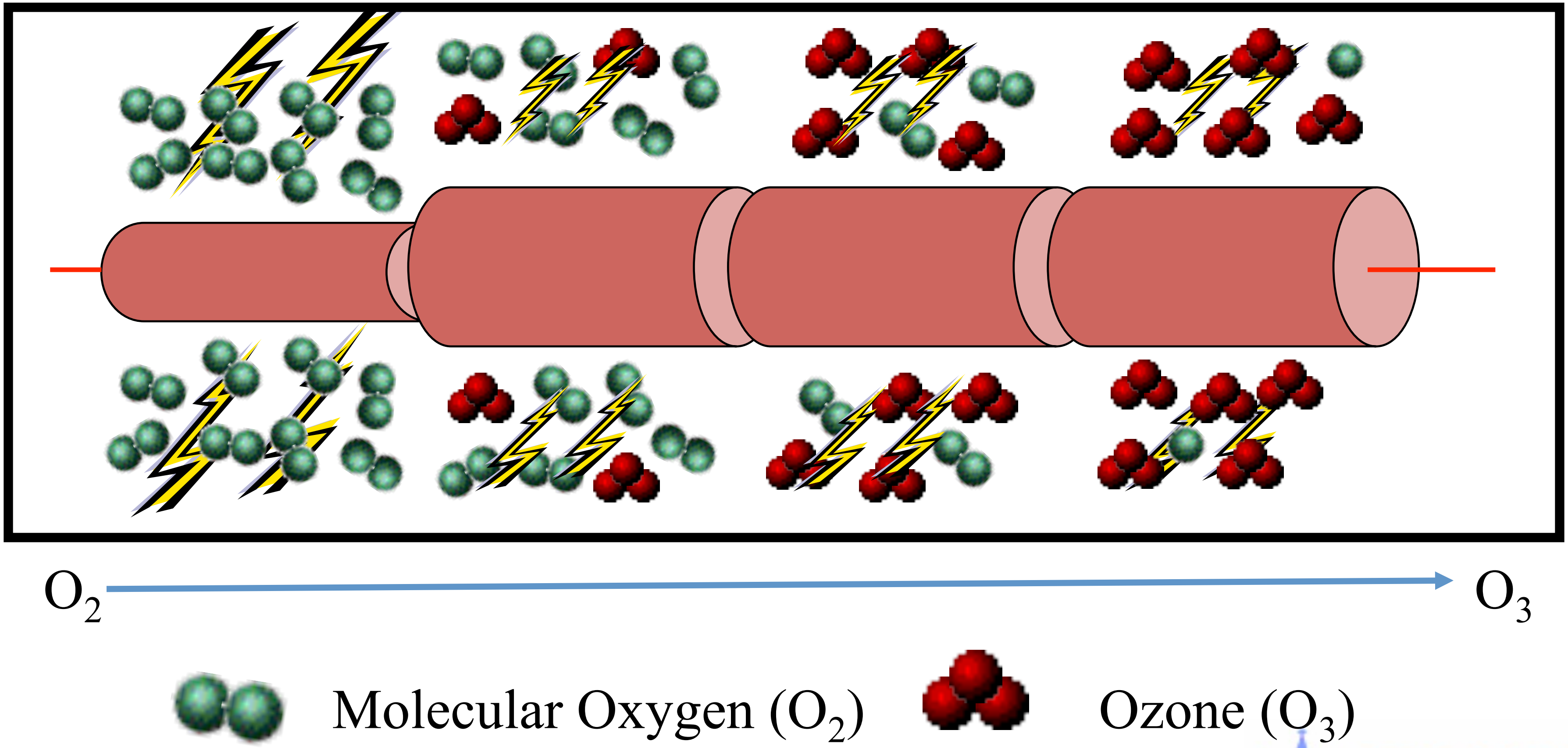


Optimized Arrangement





Intelligent Gap System (IGS)



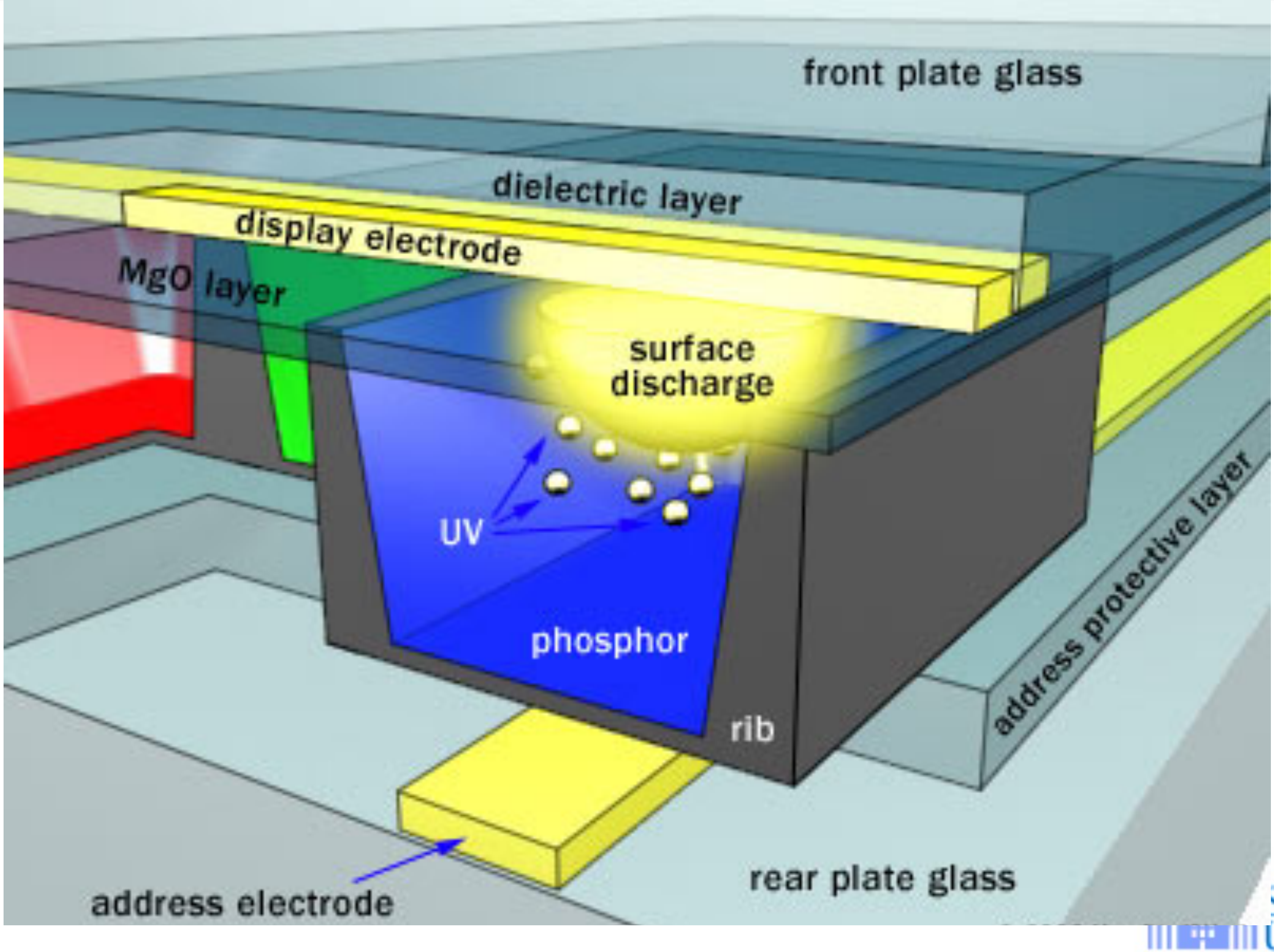
Molecular Oxygen (O_2)

Ozone (O_3)

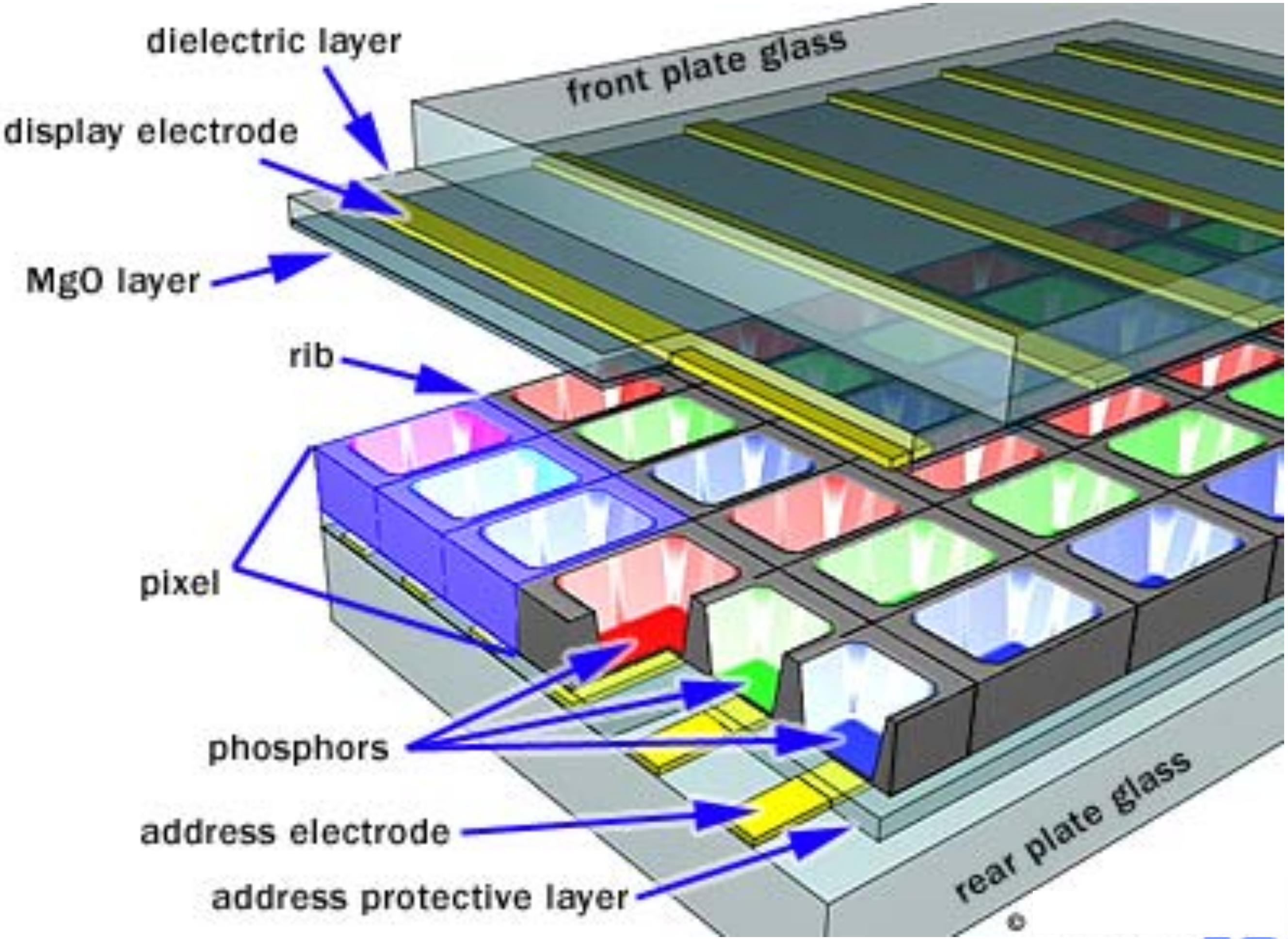
Degrémont Technologies – Ozonia Intelligent Gap System

Degremont Technologies
suez

How A Plasma Display Works!



How A Plasma Display Work!



Plasma Display Televisions

Applications of High-Pressure Microplasmas: Light Sources, Photonics, Sensors

Excimer and other non-coherent VUV/UV light sources

  - efficiency
  - intensity
  - wavelength selectivity and control; monochromaticity
  - lifetime and stability
  - arrays

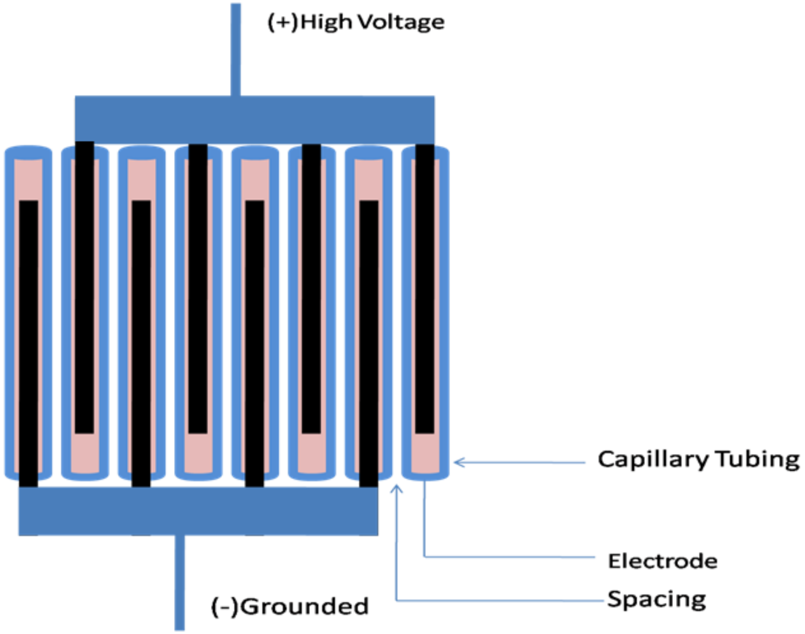
Photonic devices

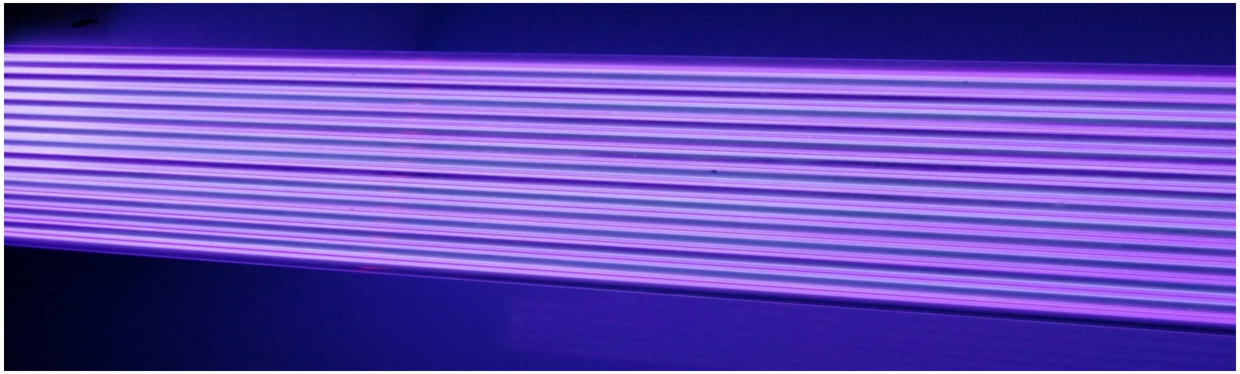
- semiconductor devices
  - photodetectors
  - flexible devices and arrays
  - devices approaching cellular dimensions
  - nano-devices

Sensors

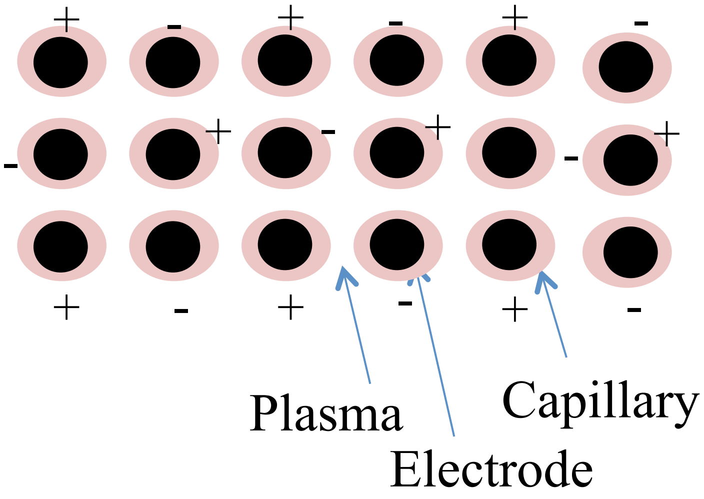
  - sensor for chemical and biological agents
  - sensor for explosives

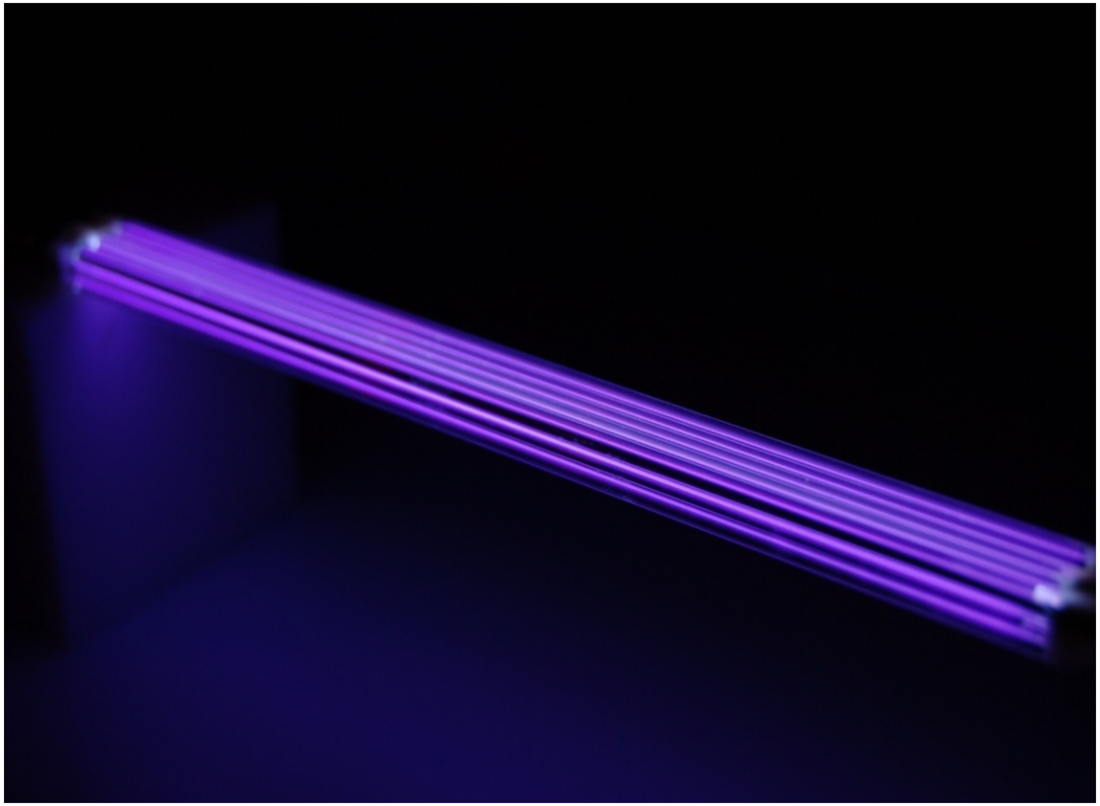
Capillary Dielectric Barrier Discharge



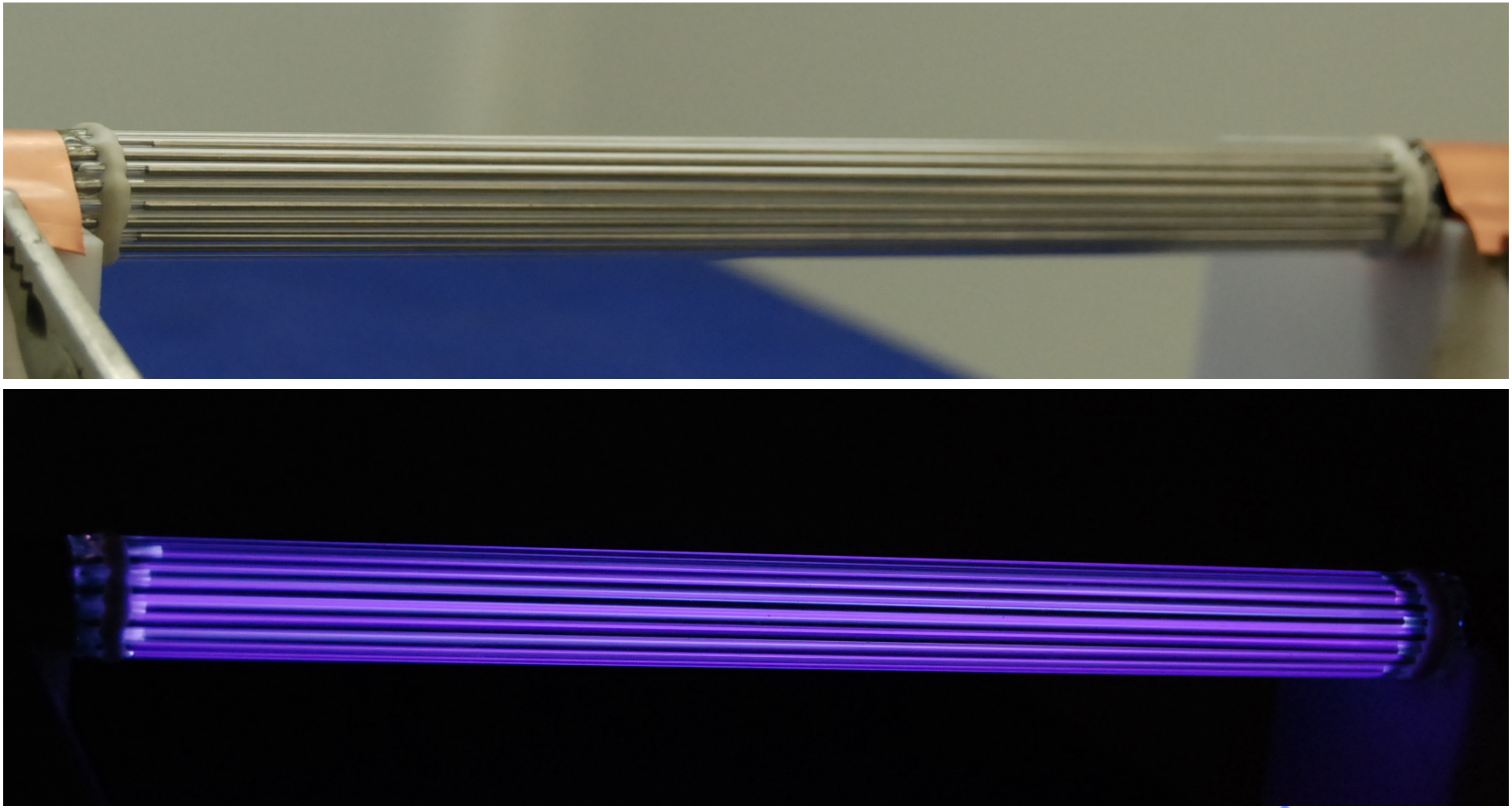


3-D Expansion

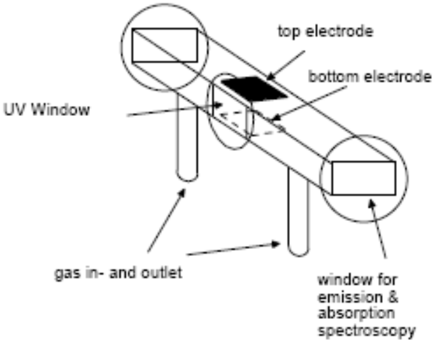




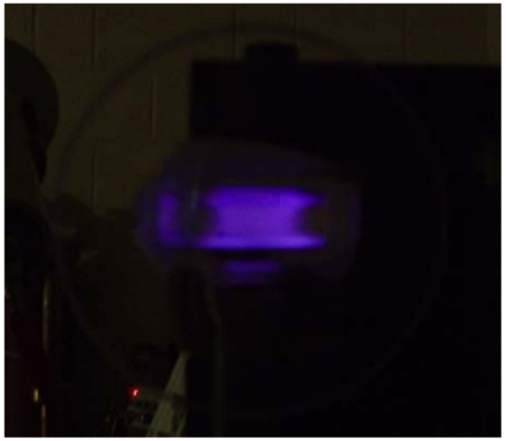
Cylindrical Arrangement



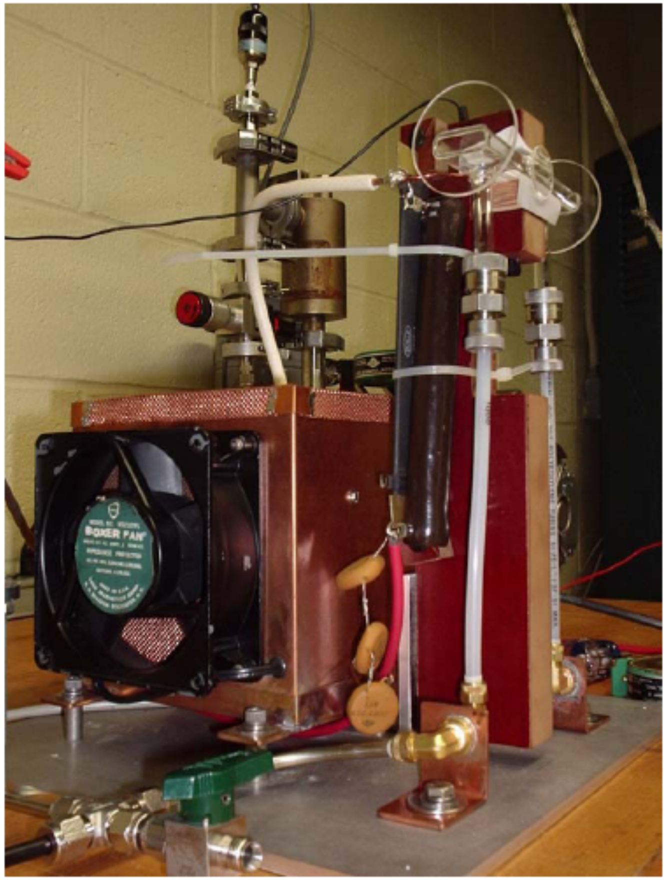
Pulsed DC Homogeneous DBD



The Dielectric Barrier Discharge (DBD) cell.

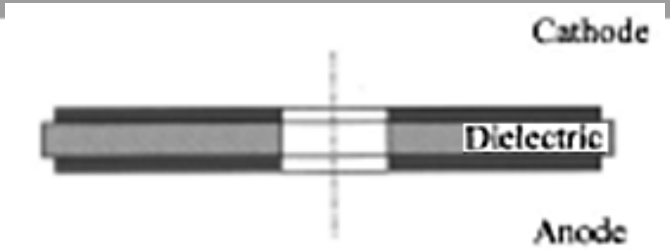


A typical plasma in pure nitrogen environment.



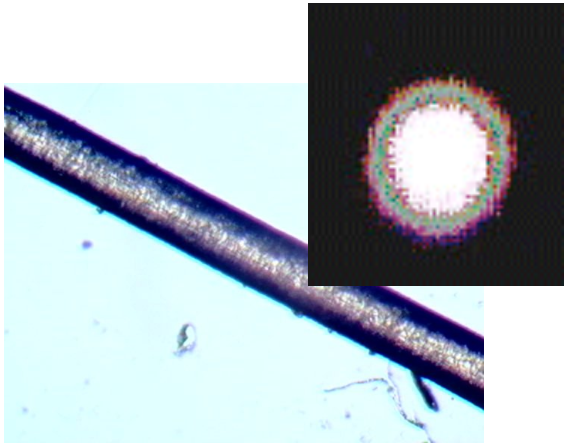
Side view of the DBD cell experiment with the fast high voltage transistor switch connected to the bottom electrode.

Micro Hollow Cathode Discharge (MHCD)



Sandwich Structure:
Electrode – Dielectric - Electrode

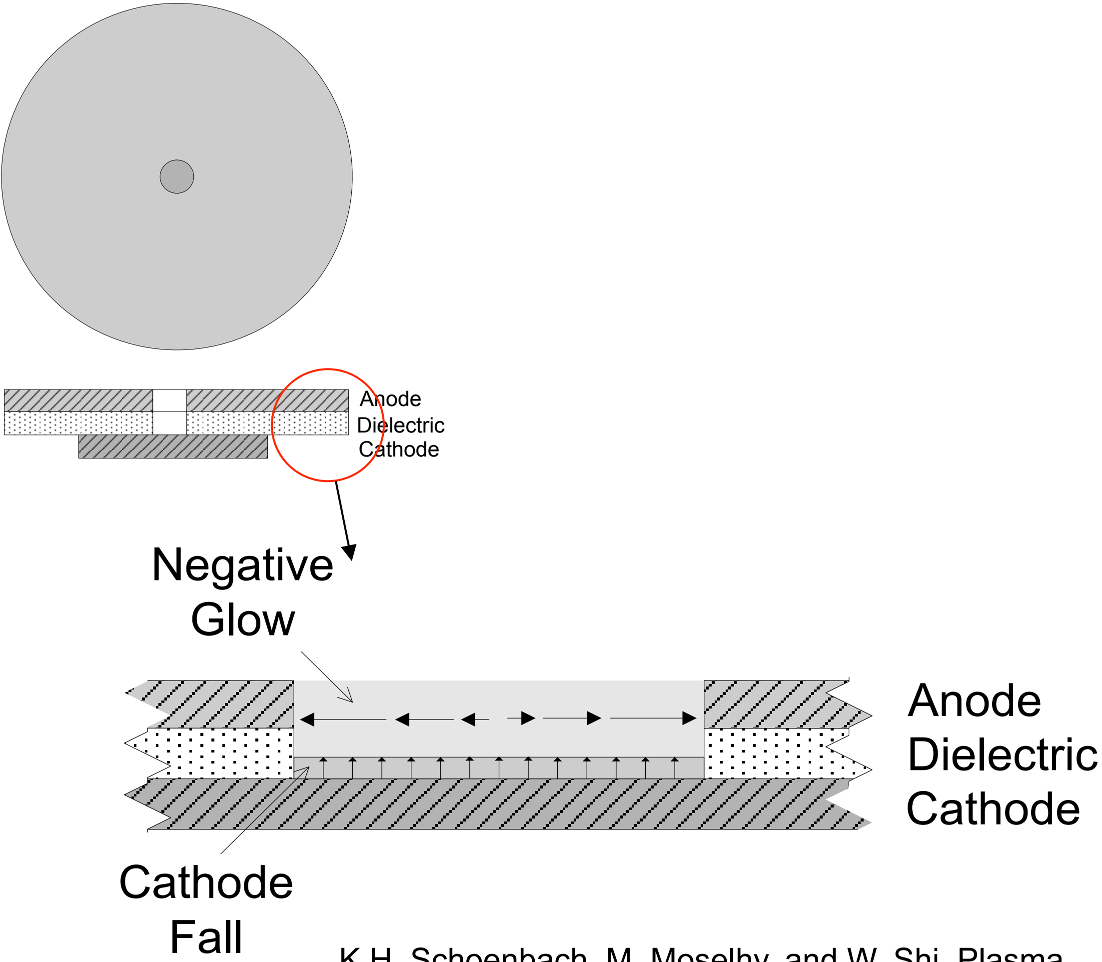
Critical dimensions at atmospheric pressure (static operation):
d: <500 μm
D: 10 – 300 μm
(assuming at room temperature)



Human Hair: 60 – 100 μm

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

Cathode Boundary Layer Discharges (CBLD)



K.H. Schoenbach, M. Moselhy, and W. Shi, Plasma Sources Scie. Technol. 13, 177 (2004)

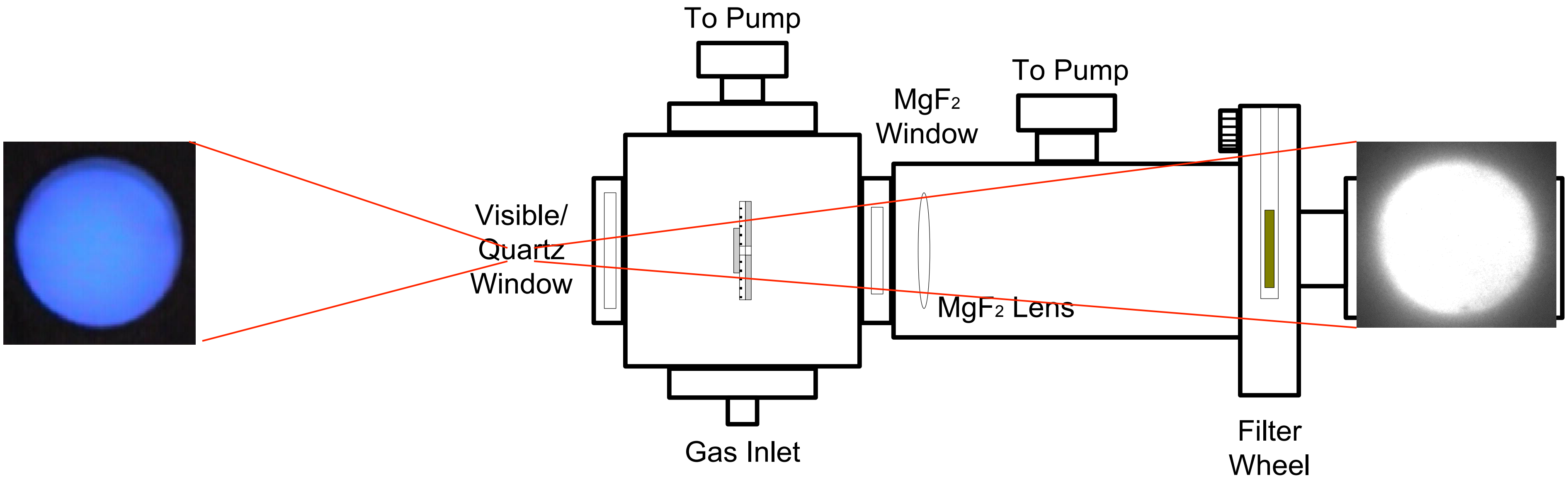
Materials:

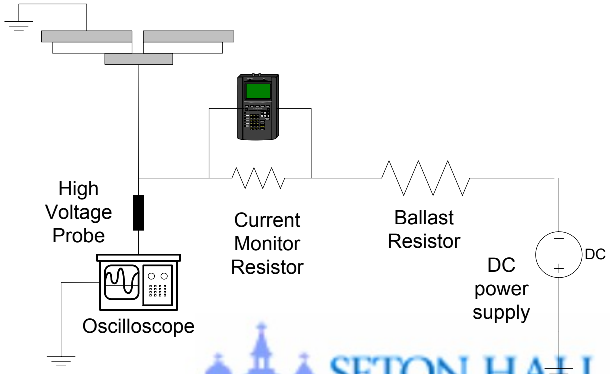
Electrodes: Molybdenum
Dielectric: Alumina

Dimensions:

Electrode Thickness: 100 μm to 250 μm
Dielectric Thickness: 100 μm to 250 μm
Opening Diameter: 300 μm to 4.5 mm

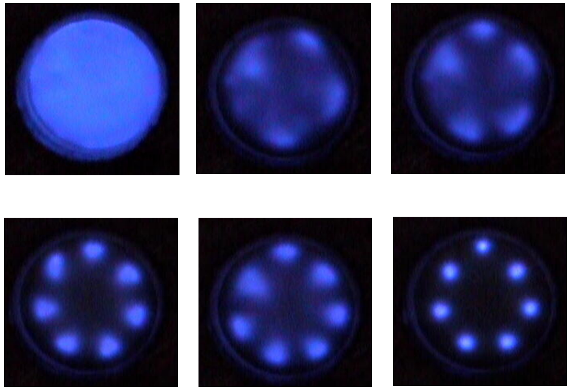
Visible imaging



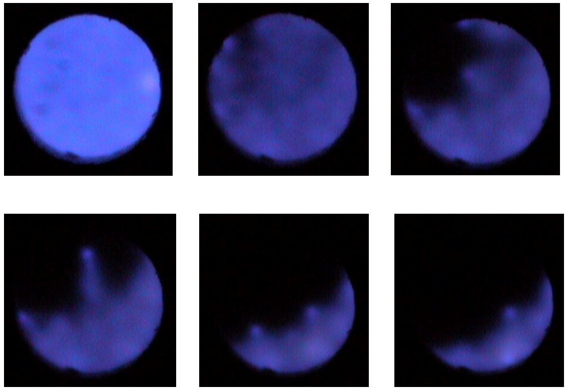


- Gas: Xenon (Scientific grade)
- Spectral filter: 170 nm with FWHM of 26.8 nm
- Sample: Either mechanically assembled at Old Dominion University or plasma sprayed at University of Minnesota

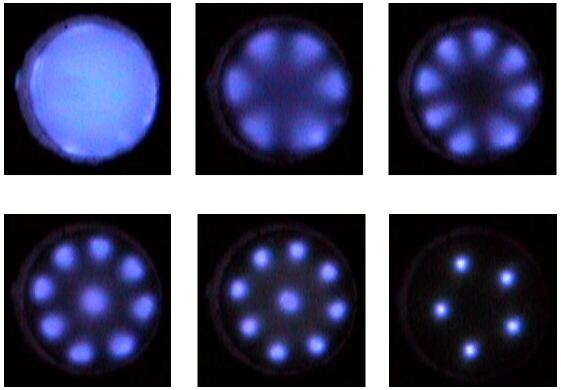
Self-organization on different cathode materials



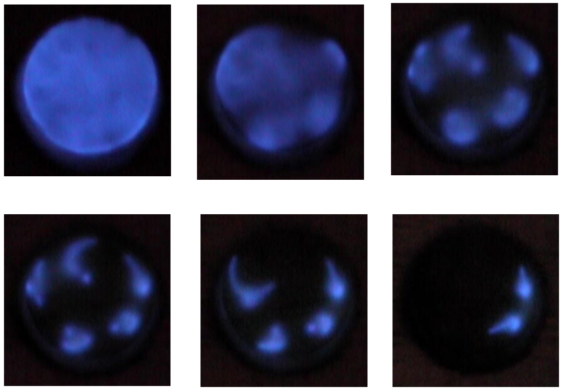
Titanium



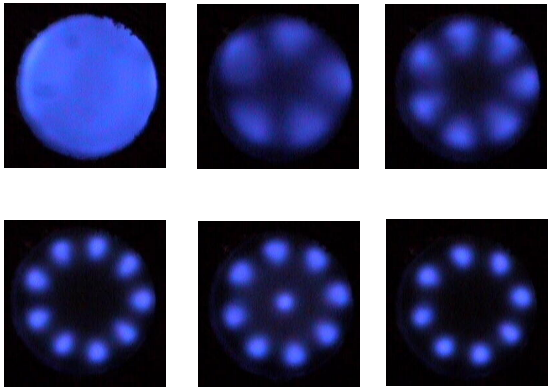
Aluminum



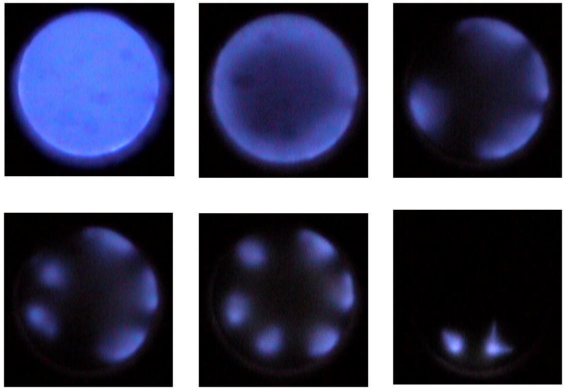
Molybdenum



Hafnium



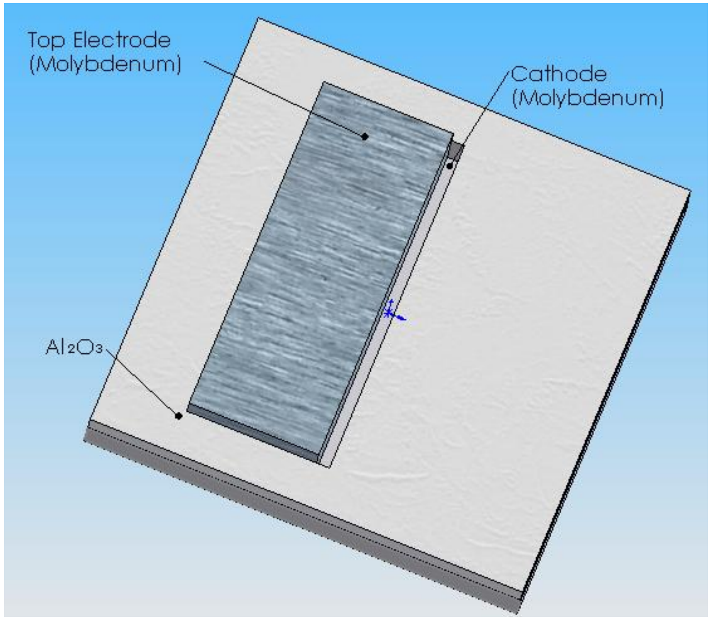
Tungsten

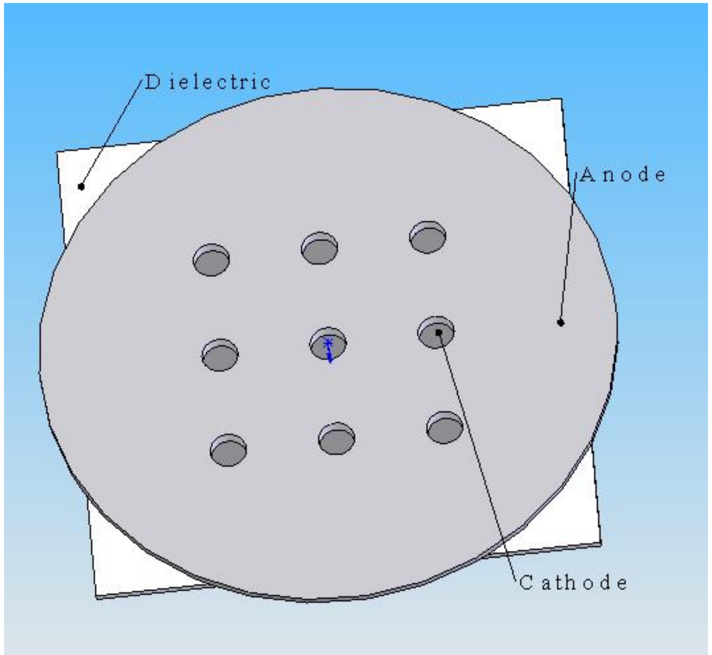


Silver

Up Scaling

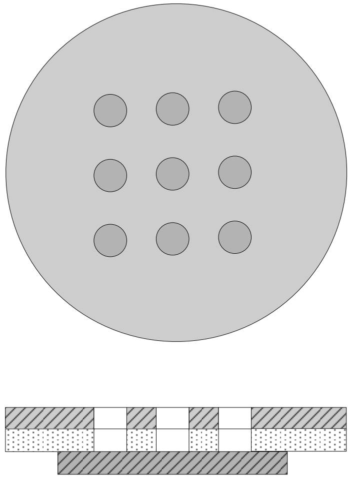
Maintain the sandwich structure and scale up in one direction
– ***Micro-slit structure***



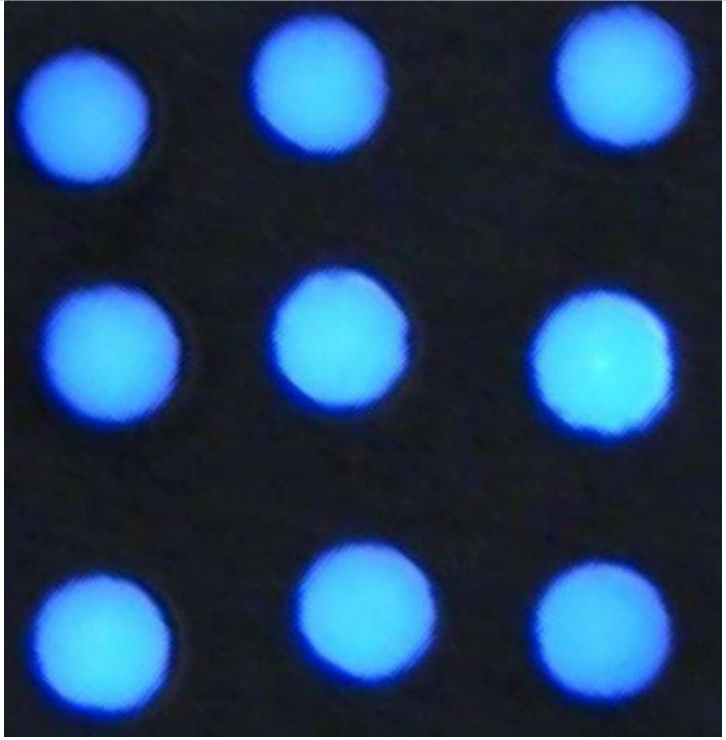


Parallel operation of multiple openings – ***Multi-CBL structure***

Parallel operation without individual ballast

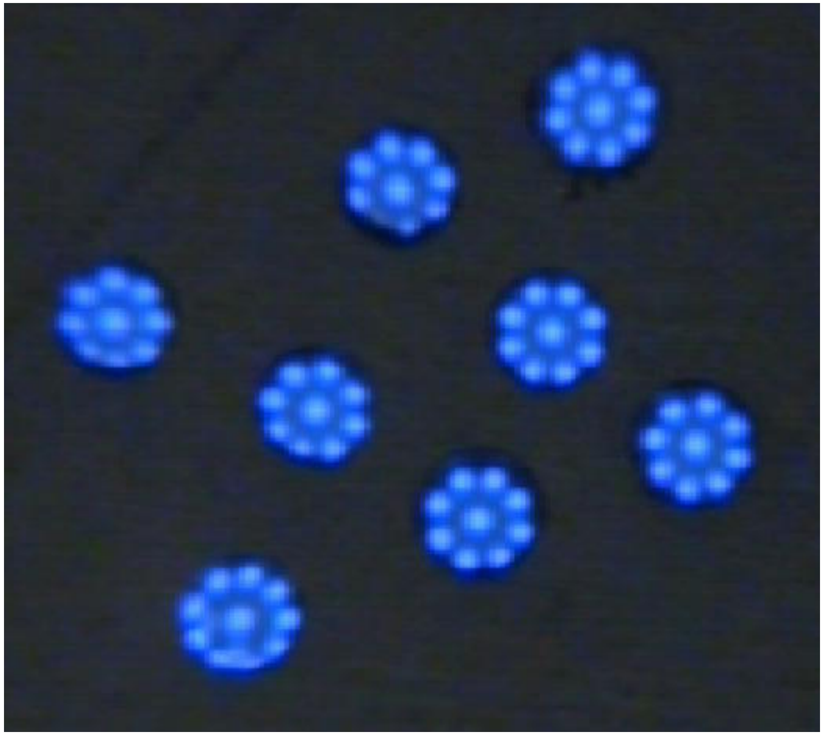


- Cathode: Mo ~0.25 mm thick
- Dielectric: Al_2O_3 ~0.25 mm thick
- Anode: Mo ~0.25 mm thick
- Hole diameter: ~0.75 mm
- Center to center distance: ~1.5 mm

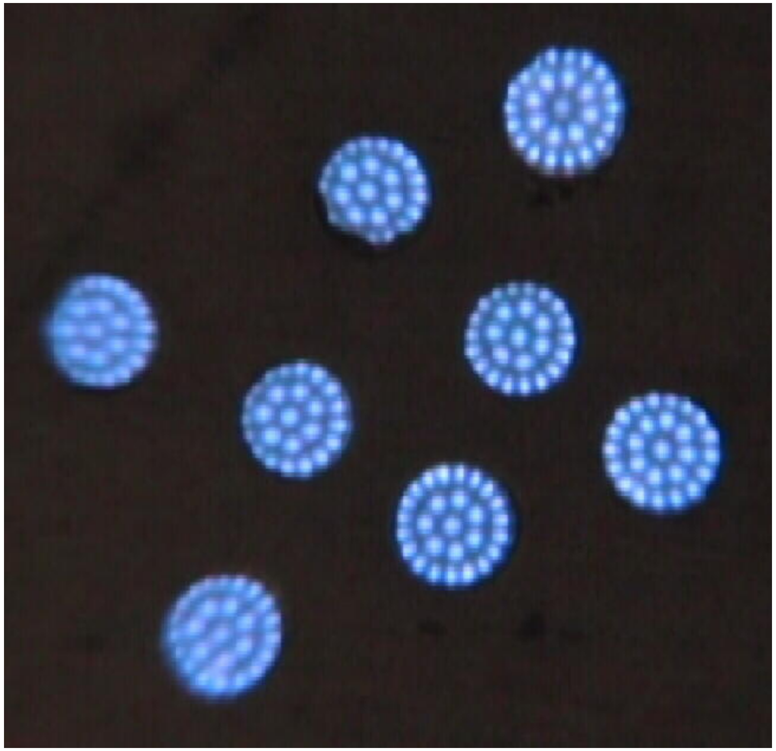


Visible Picture of parallel operation of 9 holes
(Operating gas: xenon (scientific grade)
Base pressure: ~1 mTorr; Working pressure: 200 Torr
Cathode voltage: -398 V; Discharge current: 6 mA)

Self-organization

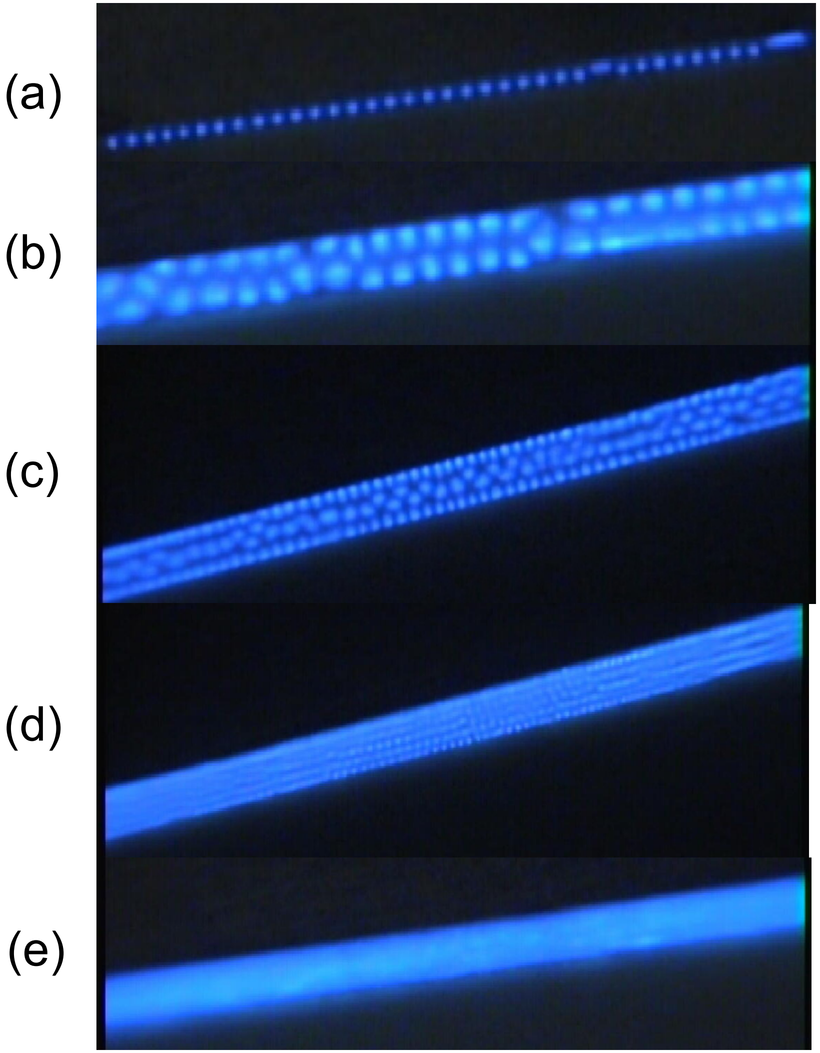


Xenon (100 Torr)



Xenon (250 Torr)
(ignition assisted with mechanical switch)

More on Self Organization

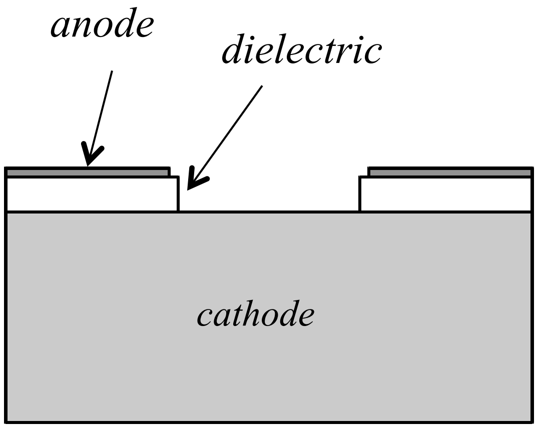


Self-organization (Visible images) of a micro-slit CBL discharge:

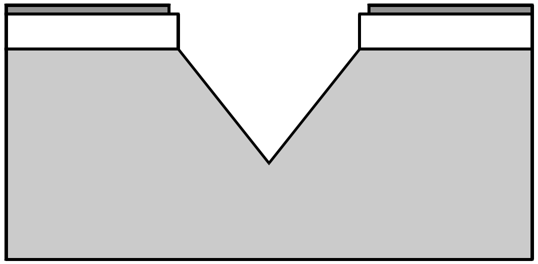
(a) 50 Torr;
(b) 150 Torr;
(c) 245 Torr;
(d) 354 Torr and
(e) homogeneous discharge at 100 Torr (249V and 4 mA)

(The images are at different magnification for a better demonstration purpose)

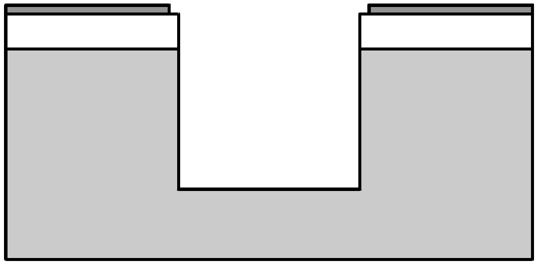
Si MICROCAVITY DEVICE STRUCTURES



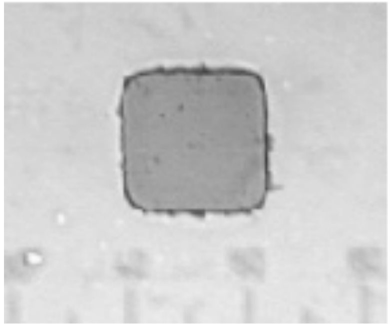
Planar Si Electrode

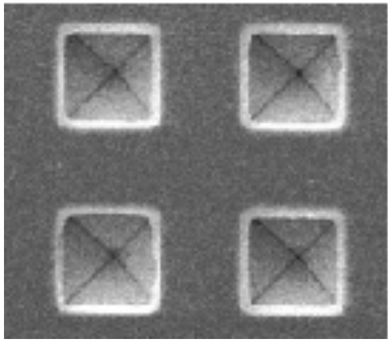


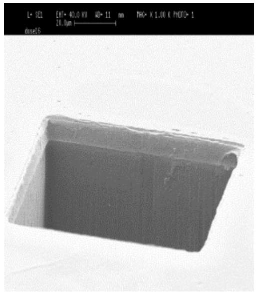
Inverted Pyramidal Electrode



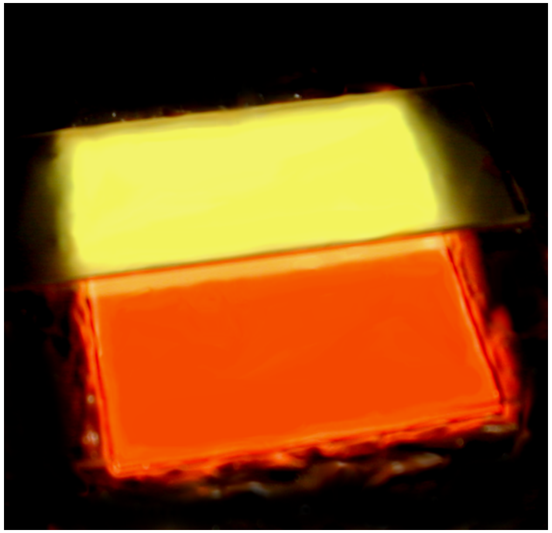
DRIE Electrode



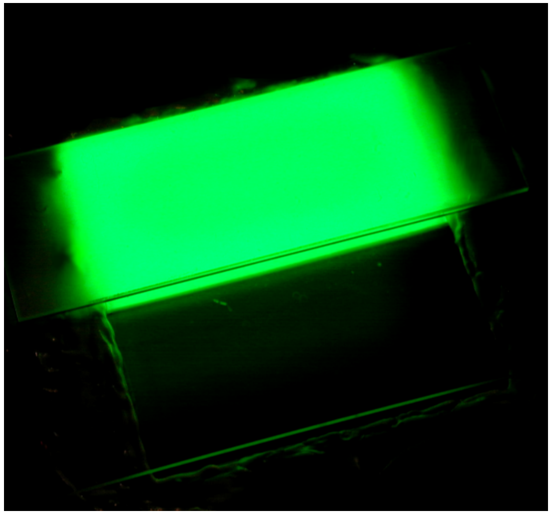




EXCITATION OF A GREEN PHOSPHOR ($Mn:Zn_2SiO_4$)

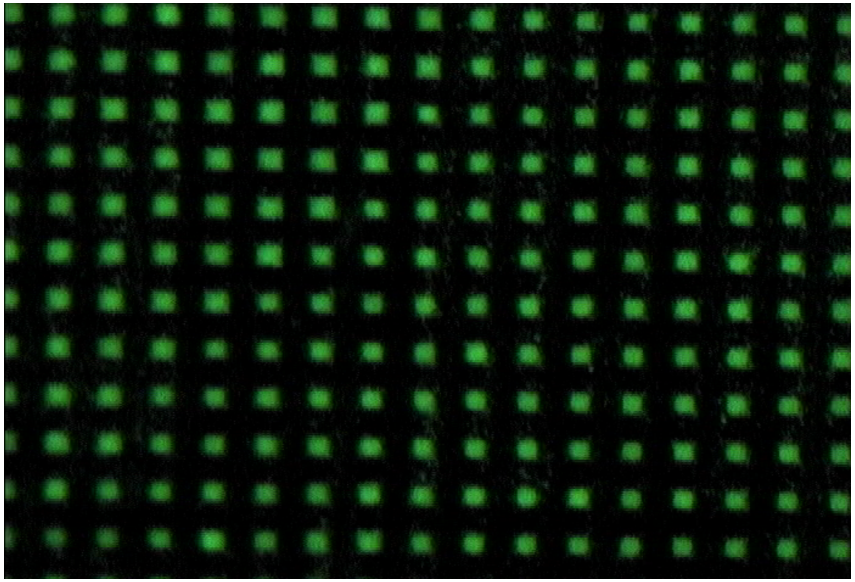


Ne



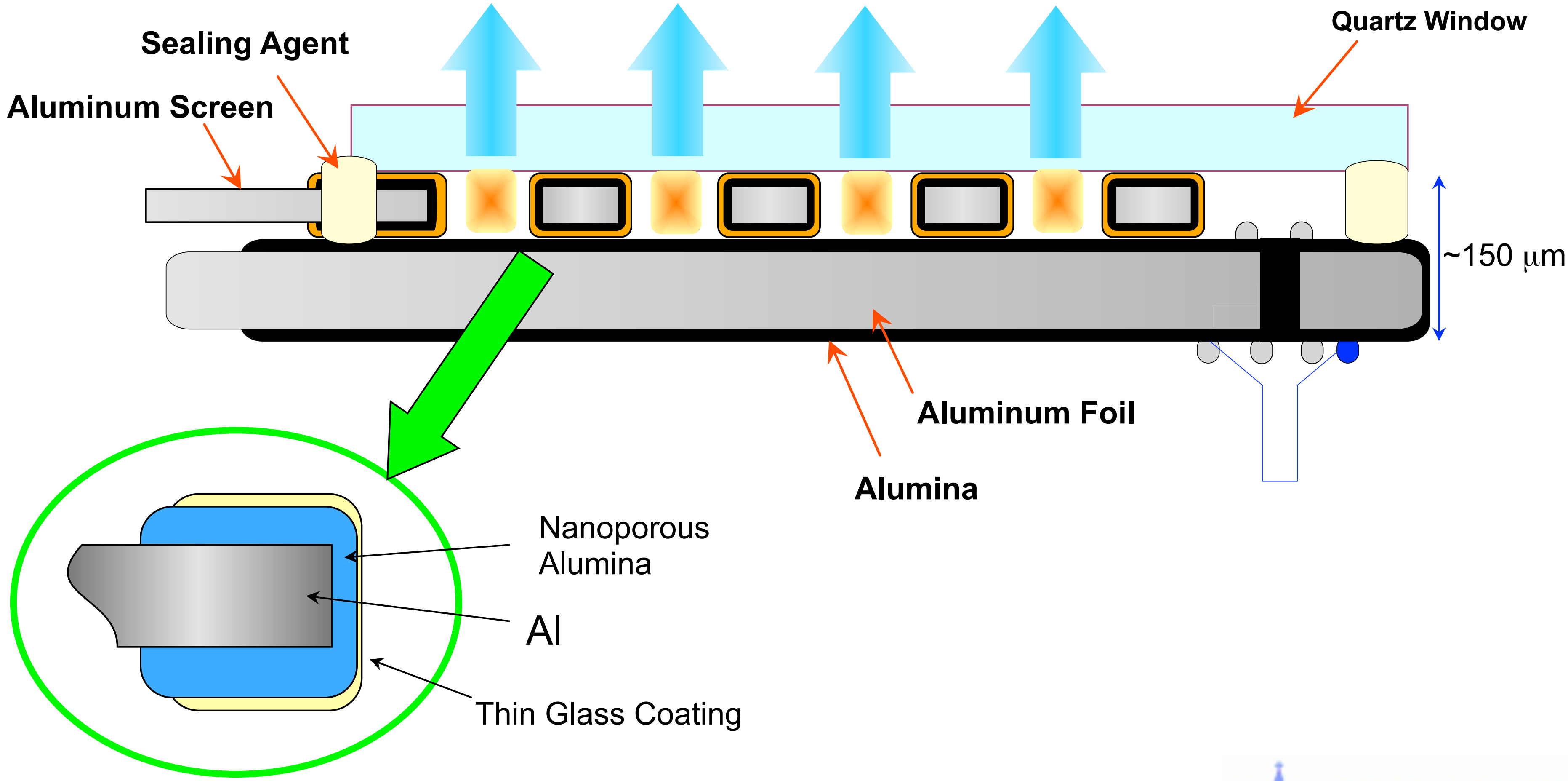
50% Xe/Ne

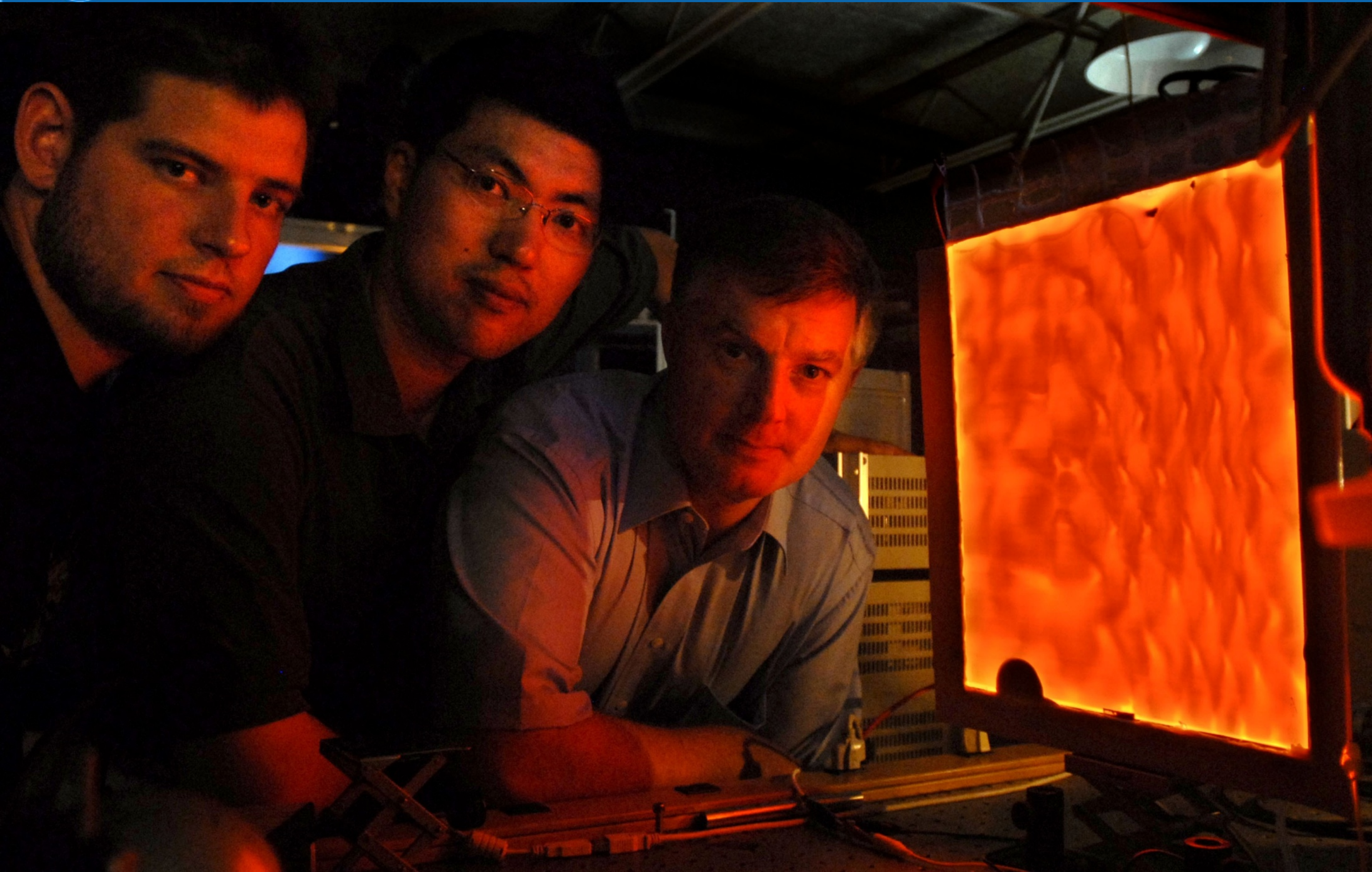
PHOSPHOR EMBEDDED MICROCAVITY



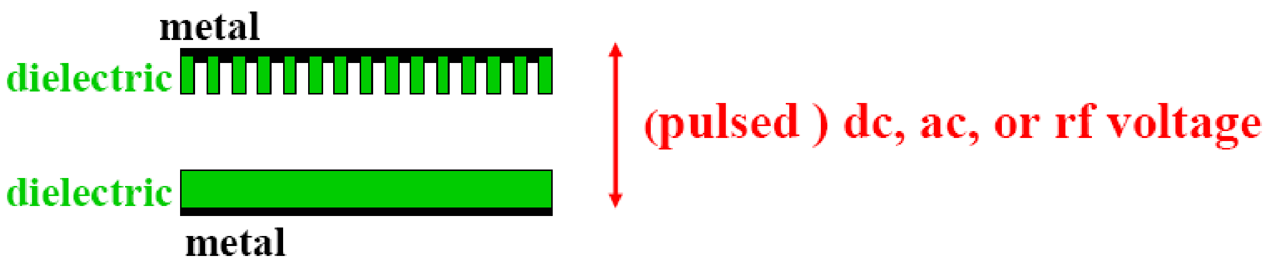
10 % Xe/Ne, 700 Torr

Microdischarge Array Flat Lamp : Basic Design

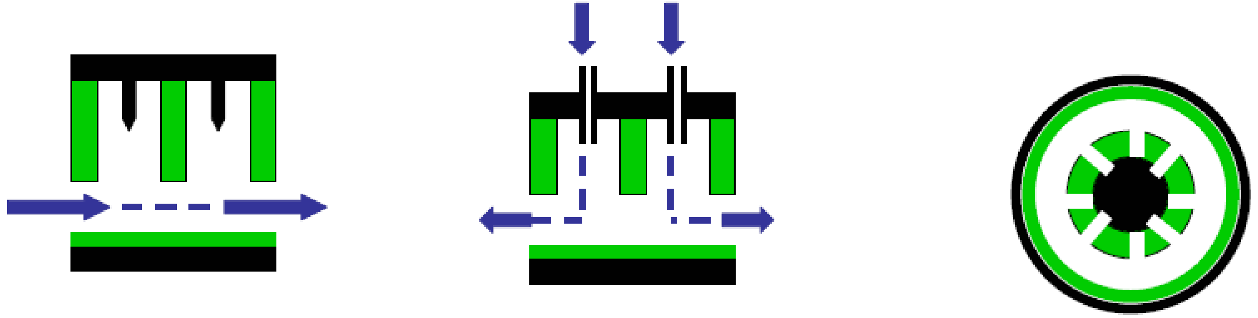




Capillary Plasma Electrode (CPE)



Capillary Plasma Electrode (CPE) Realizations



Solid Pin Electrodes

(Cross Flow)

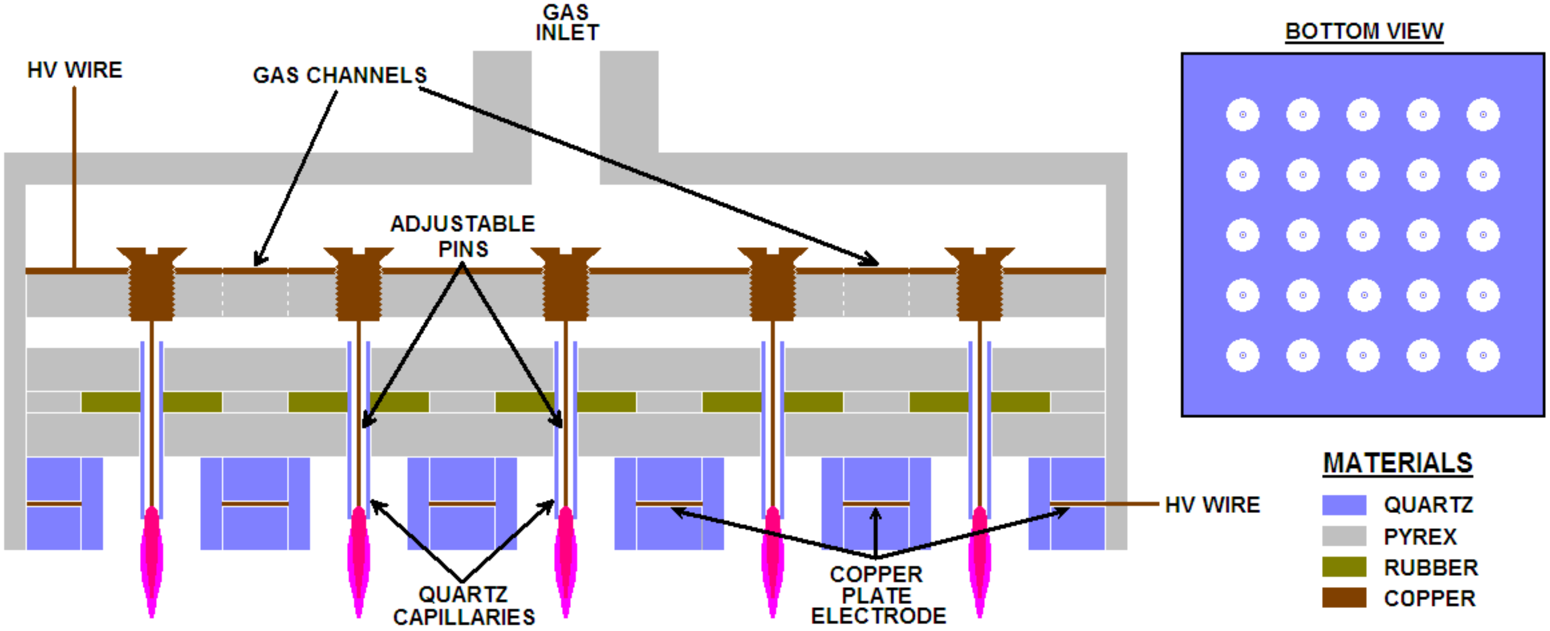
Hollow Pin Electrodes

(Flow-Through)

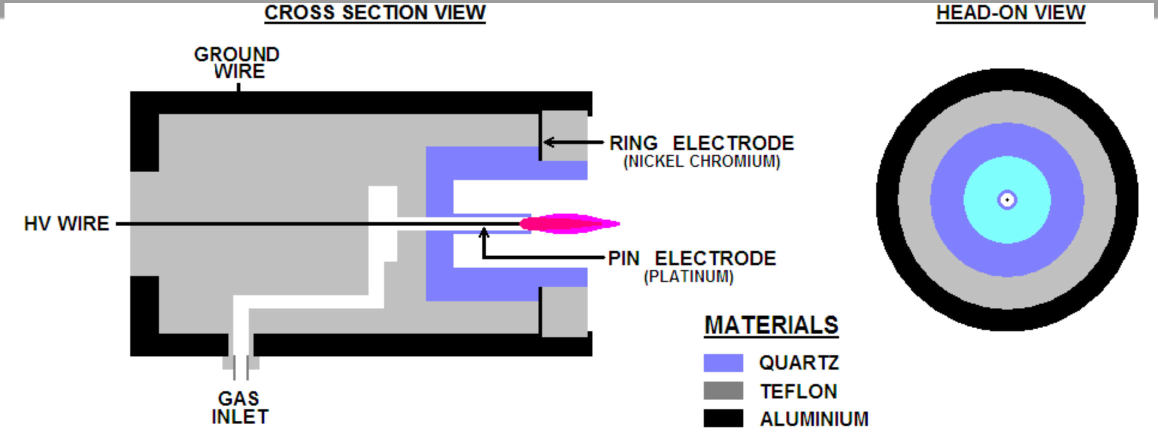
Cylindrical Electrodes

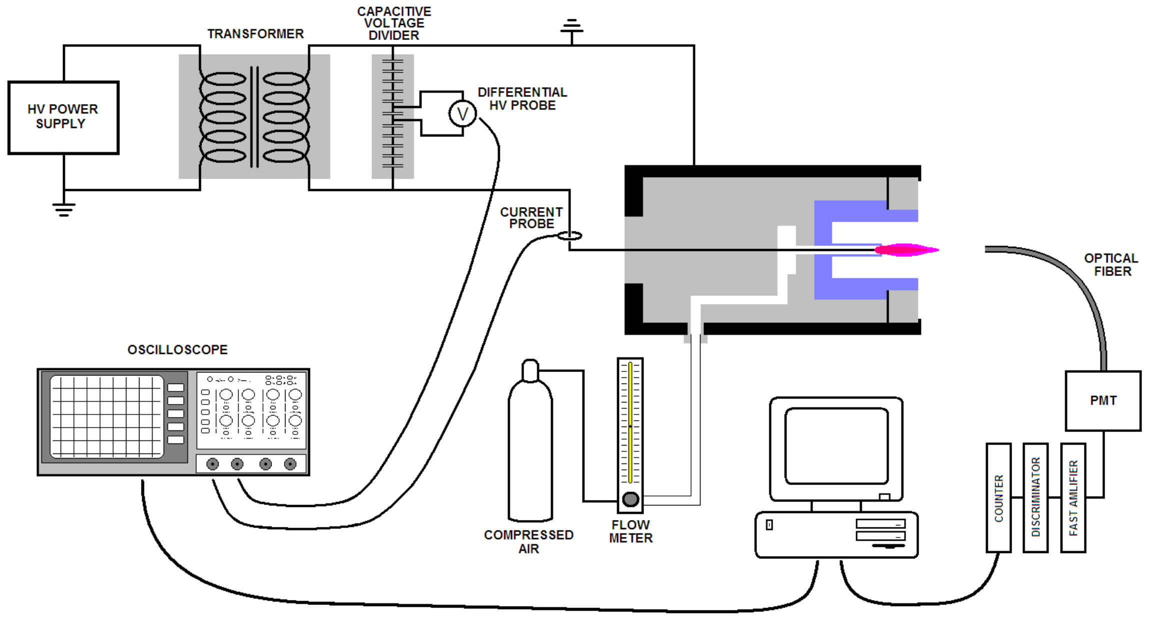
(Longitudinal Flow)

Multi-Capillary Plasma Electrode

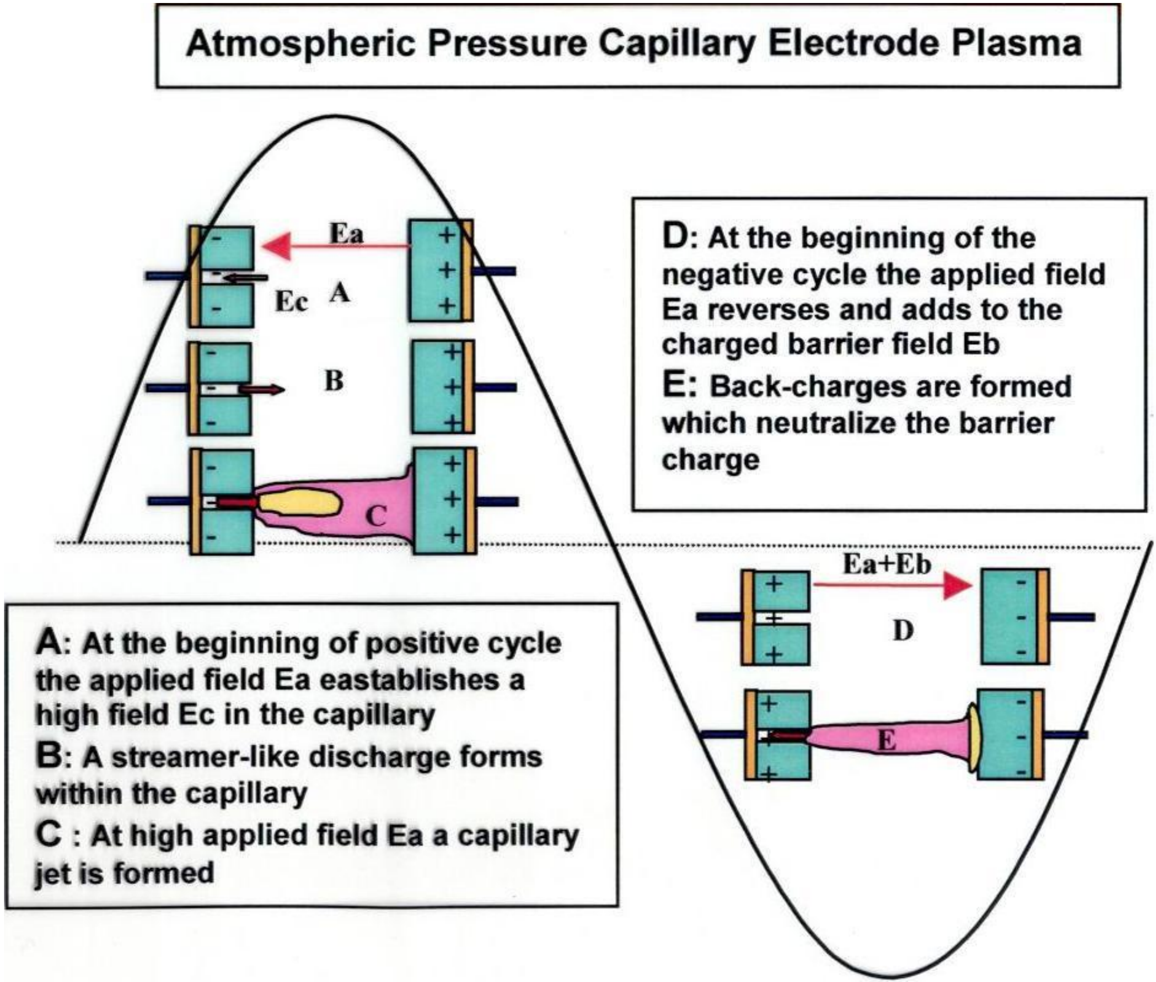


1 Capillary Plasma Electrode





Capillary Plasma Electrode - Operation



Atmospheric Pressure Capillary Electrode Plasma

D: At the beginning of the negative cycle the applied field Ea reverses and adds to the charged barrier field Eb

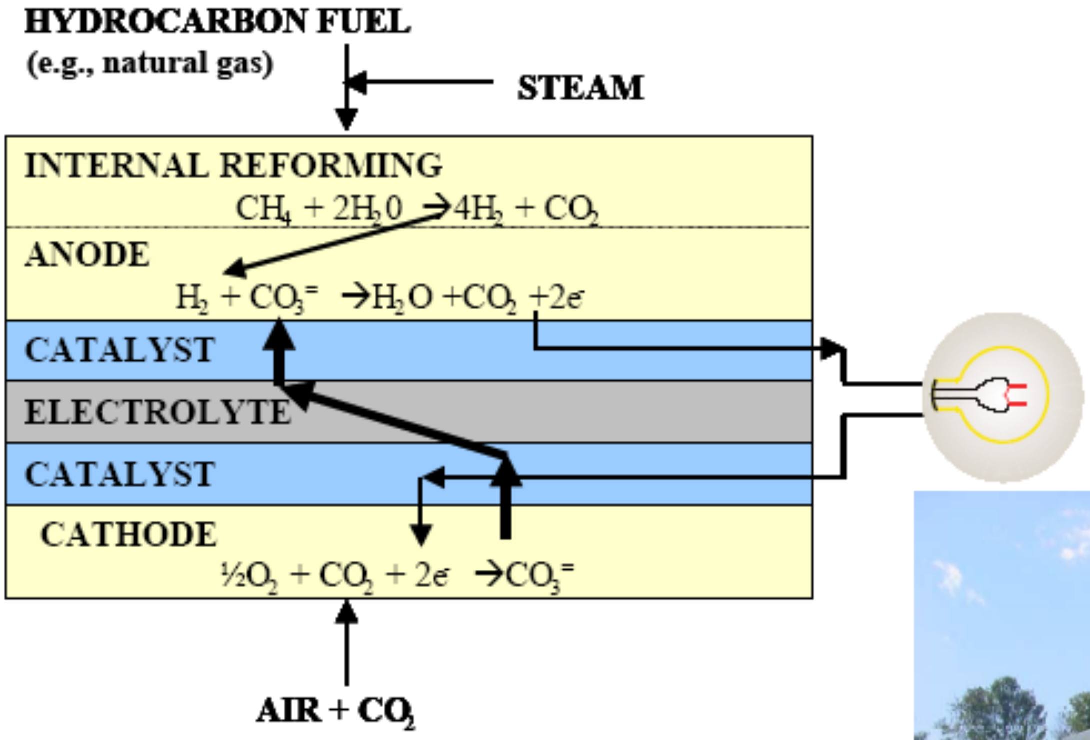
E: Back-charges are formed which neutralize the barrier charge

A: At the beginning of positive cycle the applied field Ea eastablishes a high field Ec in the capillary

B: A streamer-like discharge forms within the capillary

C : At high applied field Ea a capillary jet is formed

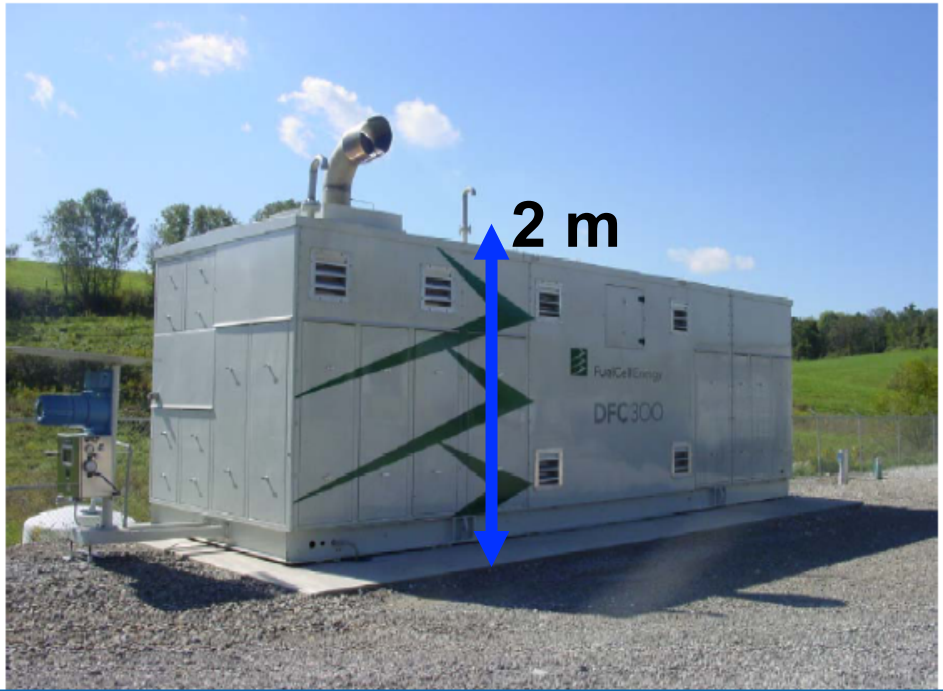
Low-T Plasmas for Fuel Cell Systems



Solid Oxide Fuel Cell Chemistry

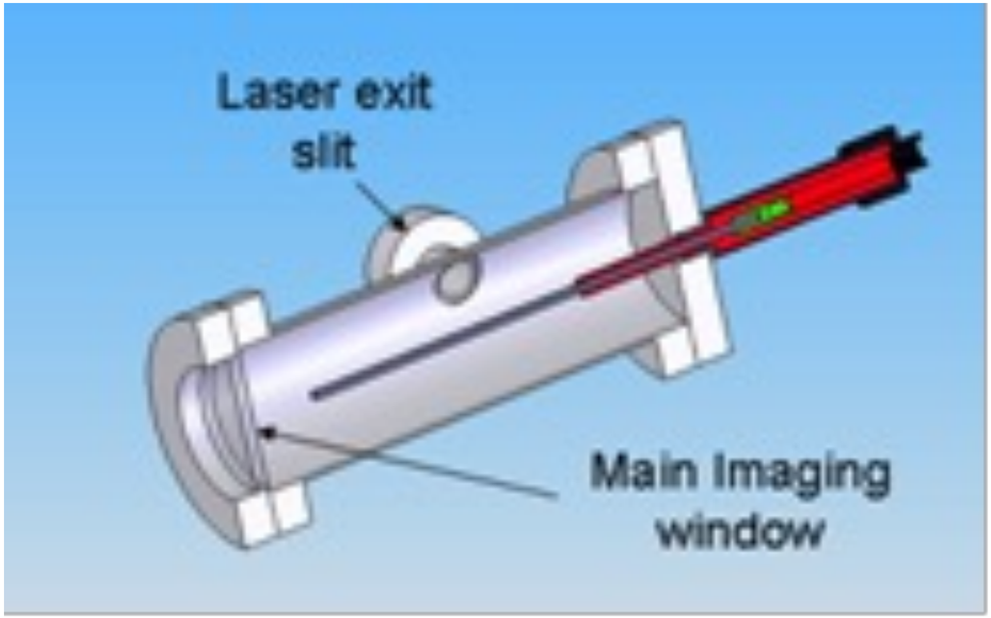
Idea:

Use low-T plasma to generate hydrocarbon feed gas for cell



300 kW Fuel Cell

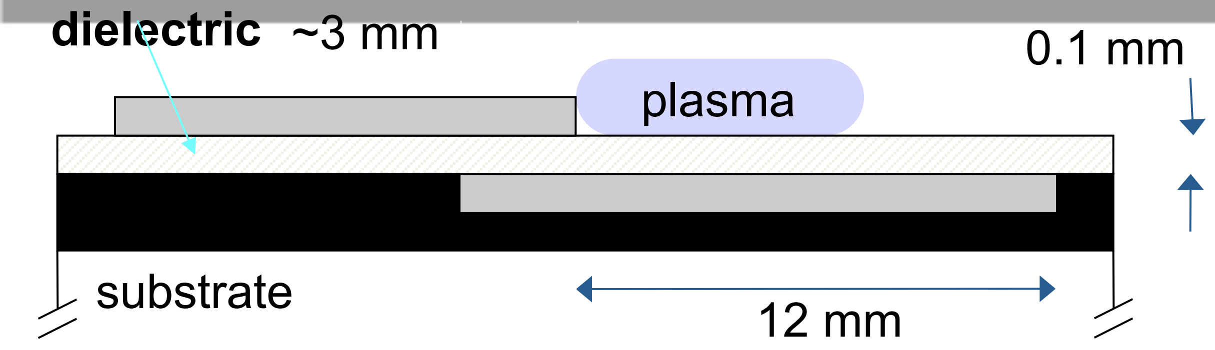
Microplasma-Assisted Combustion

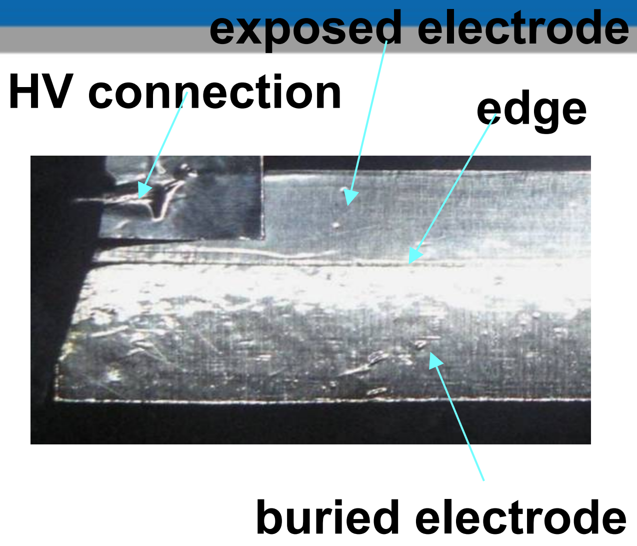


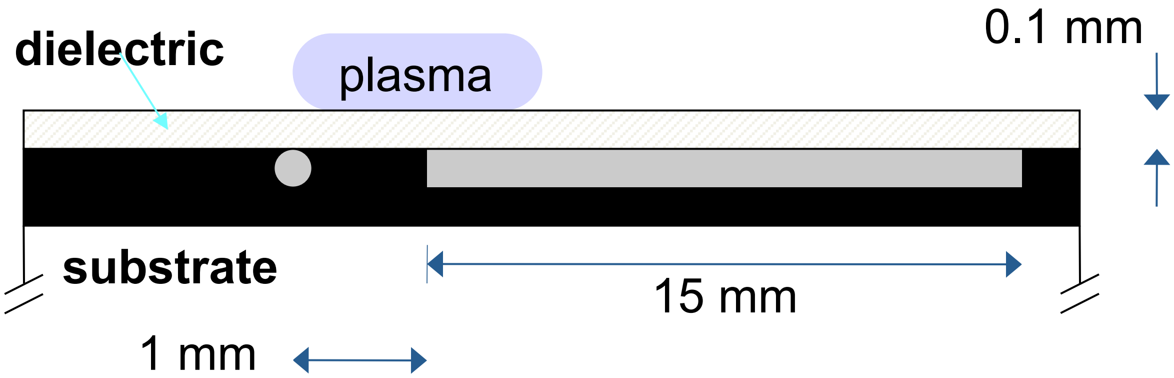
(Courtesy of M. Gundersen – USC)

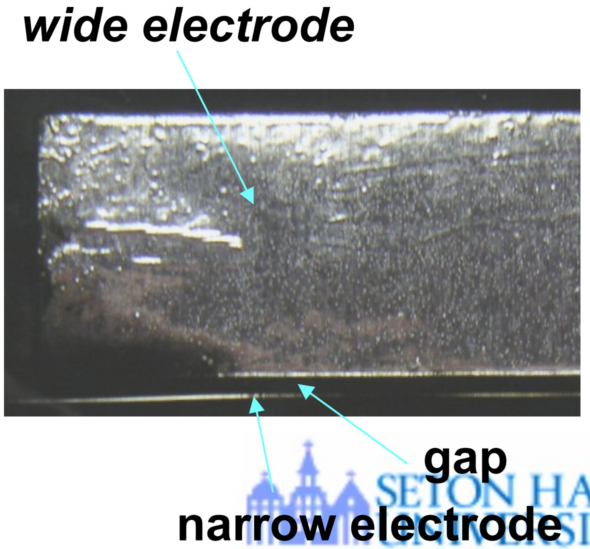
USC static reactor for studies of pulsed plasma induced ignition

Plasma-Aero Experimental System
University of Wisconsin (Madison) - Noah Hershkowitz



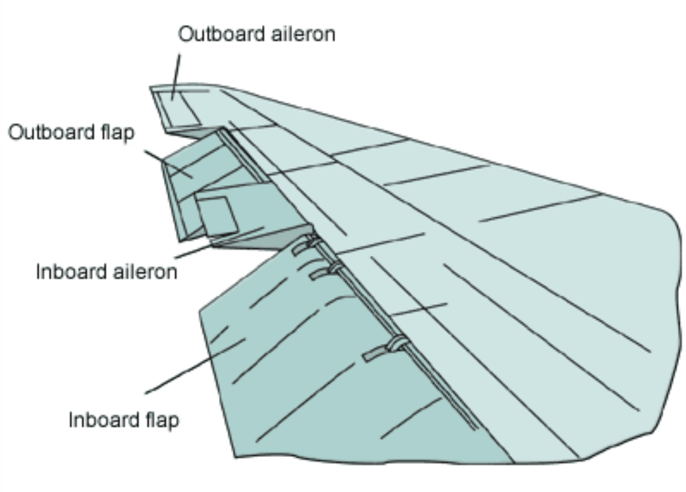


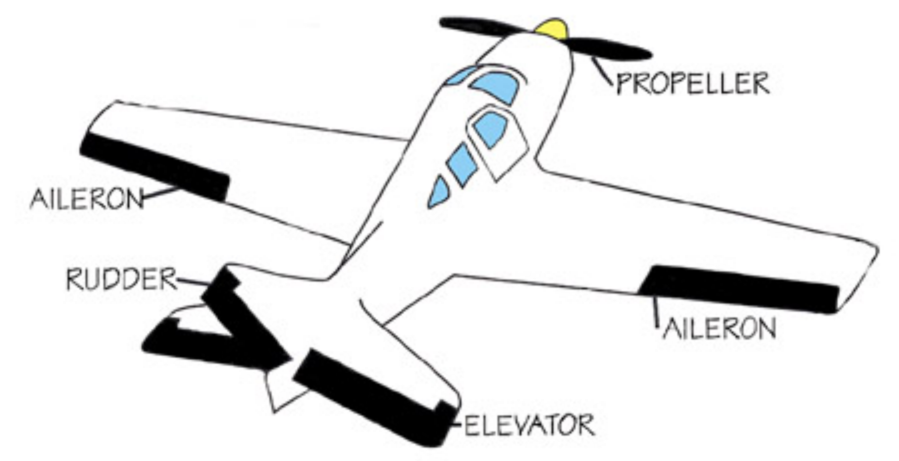


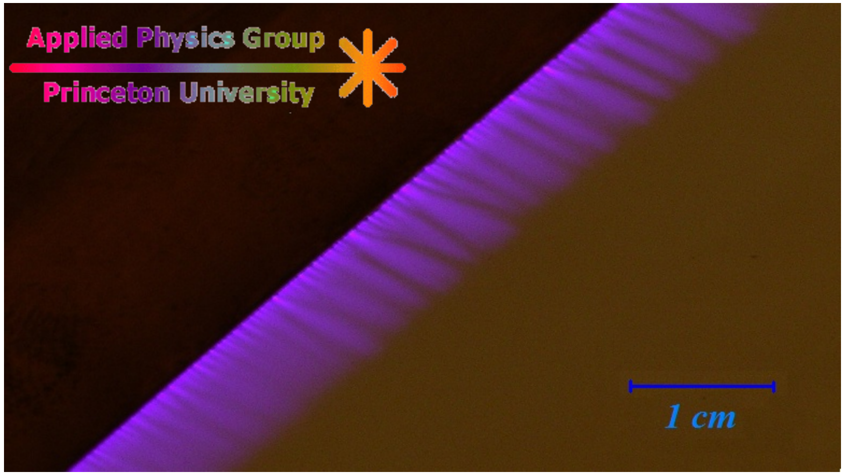


- **Planar electrodes are 0.08 mm aluminum tape**
- **Wire electrode is 0.38 mm diameter copper wire**
- **Dielectric layer is 0.1 mm polyethylene, $\varepsilon \approx 3.2\,\varepsilon_0$**

Plasma Actuators – The future of Flying!?!







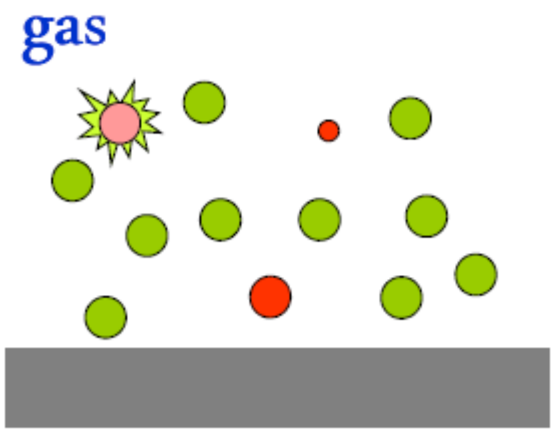
Plasma Actuators – The future of Flying!?!

Wing-less planes!!!

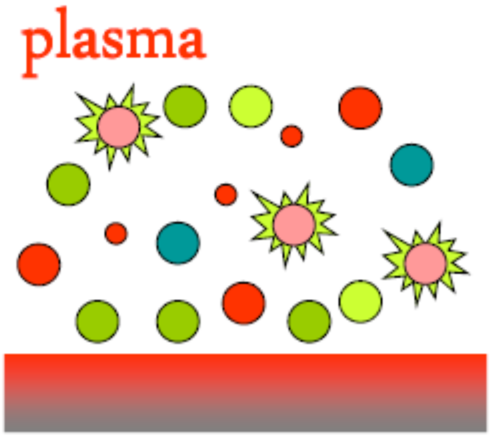
Surface Effects of Microplasmas

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

- 🟢 Molecules
- ✹ Excited molecules
- 🔴 Ions
- • Electrons



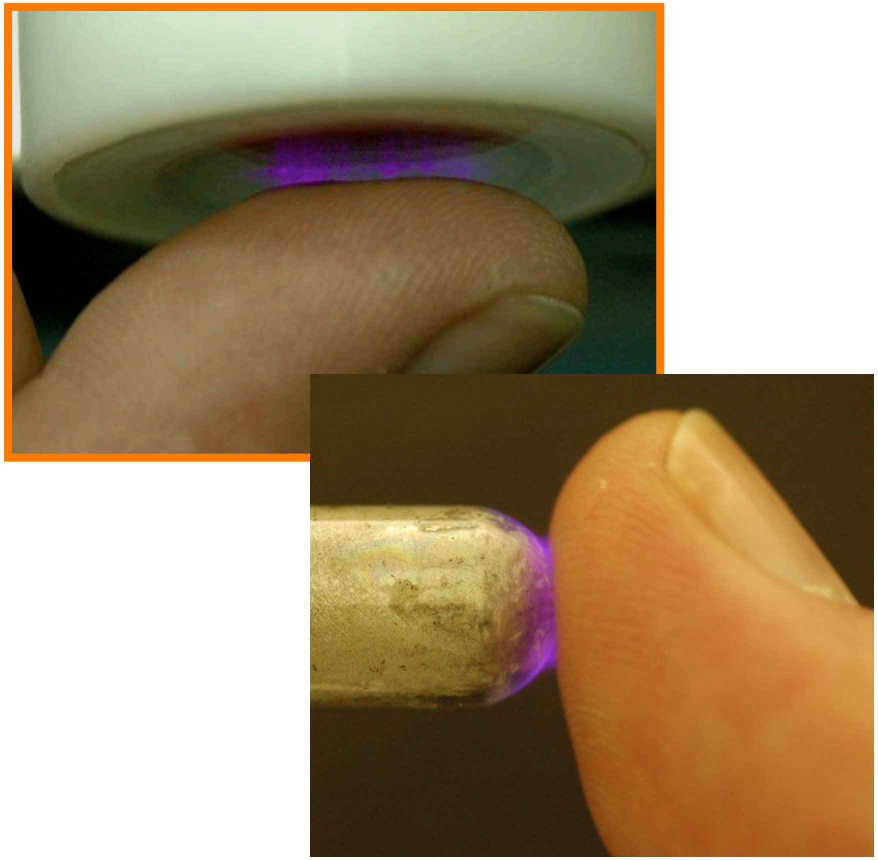
Small changes at the surface



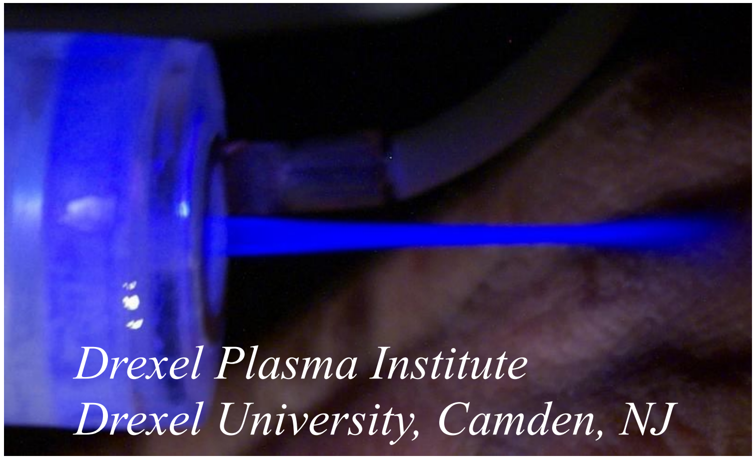
Energy & reactive species can change the surface

Plasma Application in Medicine

Direct Plasma – Charges on Tissue, Produced In Air or Oxygen

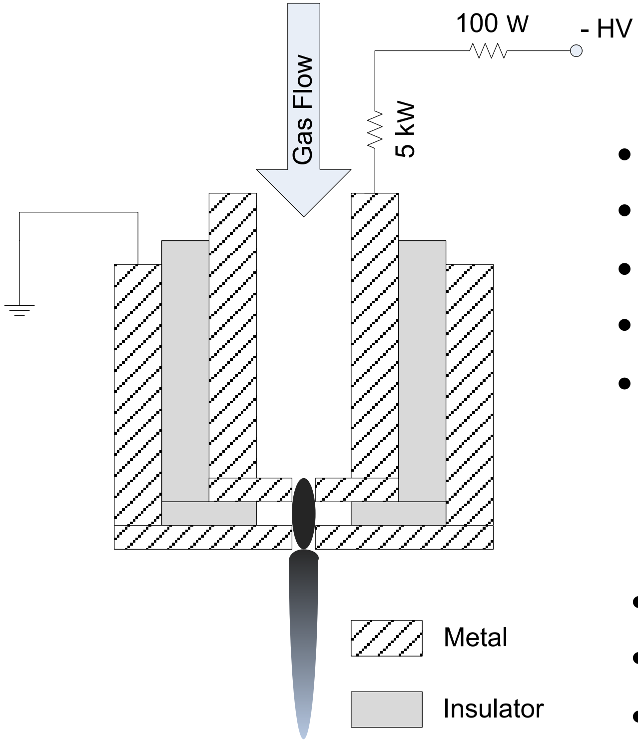


Indirect Plasma – Jet, Often NOT in OXYGEN



Drexel Plasma Institute
Drexel University, Camden, NJ

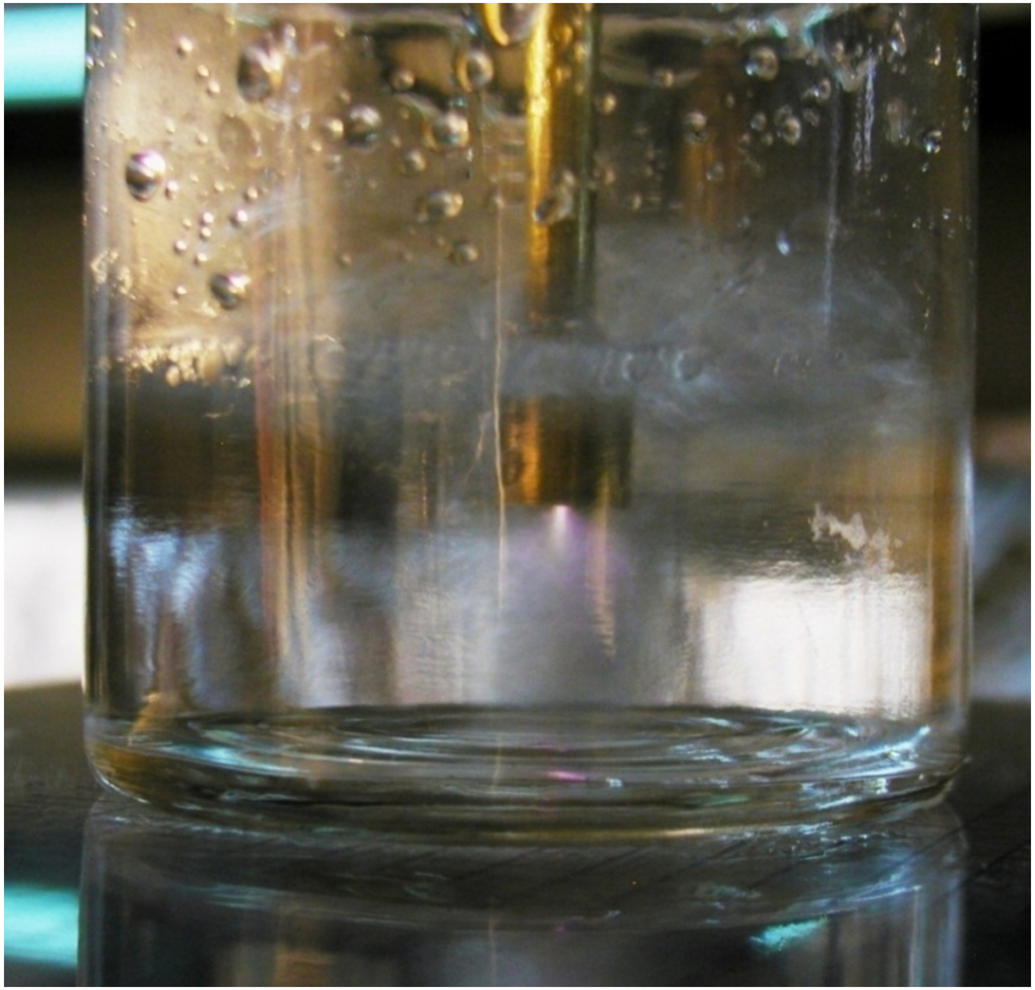
DC MHCD Plasma Micro Jet

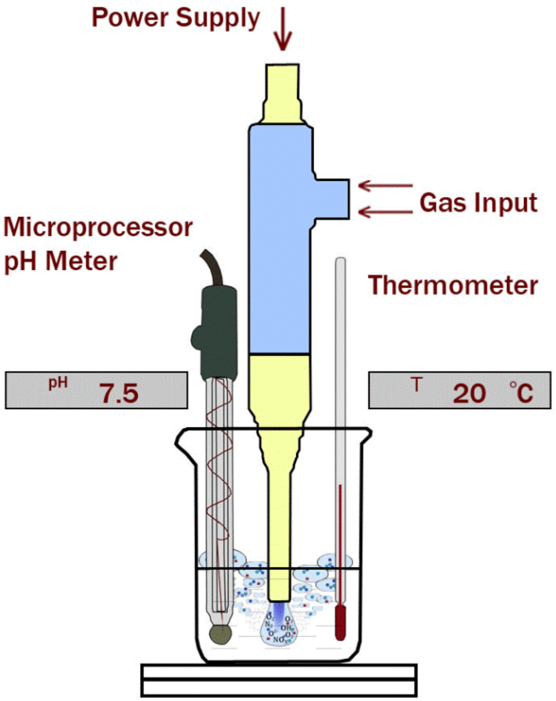


- Dimensions of the device are:
- Opening: 0.8 mm in diameter
- Separation: 0.5 mm
- Depth of exit opening: 1 mm
- Electrode material: copper

- Dimension of the plasma jet are
- ~ 800 μm in diameter
- 8 -10 mm in length
- Flow rate: 2-3 SLM
- Power consumption: 8 W (400 VDC, 20 mA)

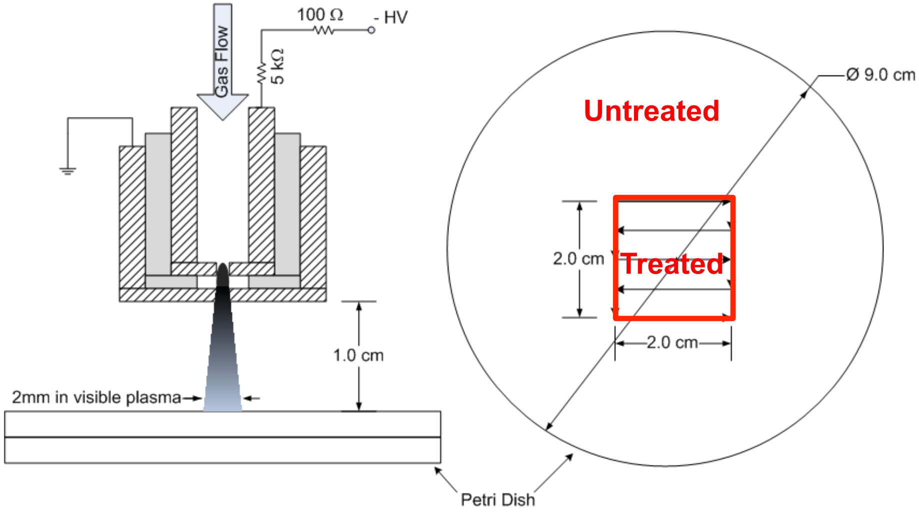
Plasma Micro Jet Inside Water





Inactivation of Bacteria

Experimental Set-up



	Bacteria	Gram stain
A	**Escherichia coli**	**Negative**
B	**Staphylococcus aureus**	**Positive**
C	**Micrococcus luteus**	**Positive**
D	**Bacillus megaterium**	**Positive**
E	**Bacillus subtilis**	**Positive**
F	**Bacillus natto**	**Positive**

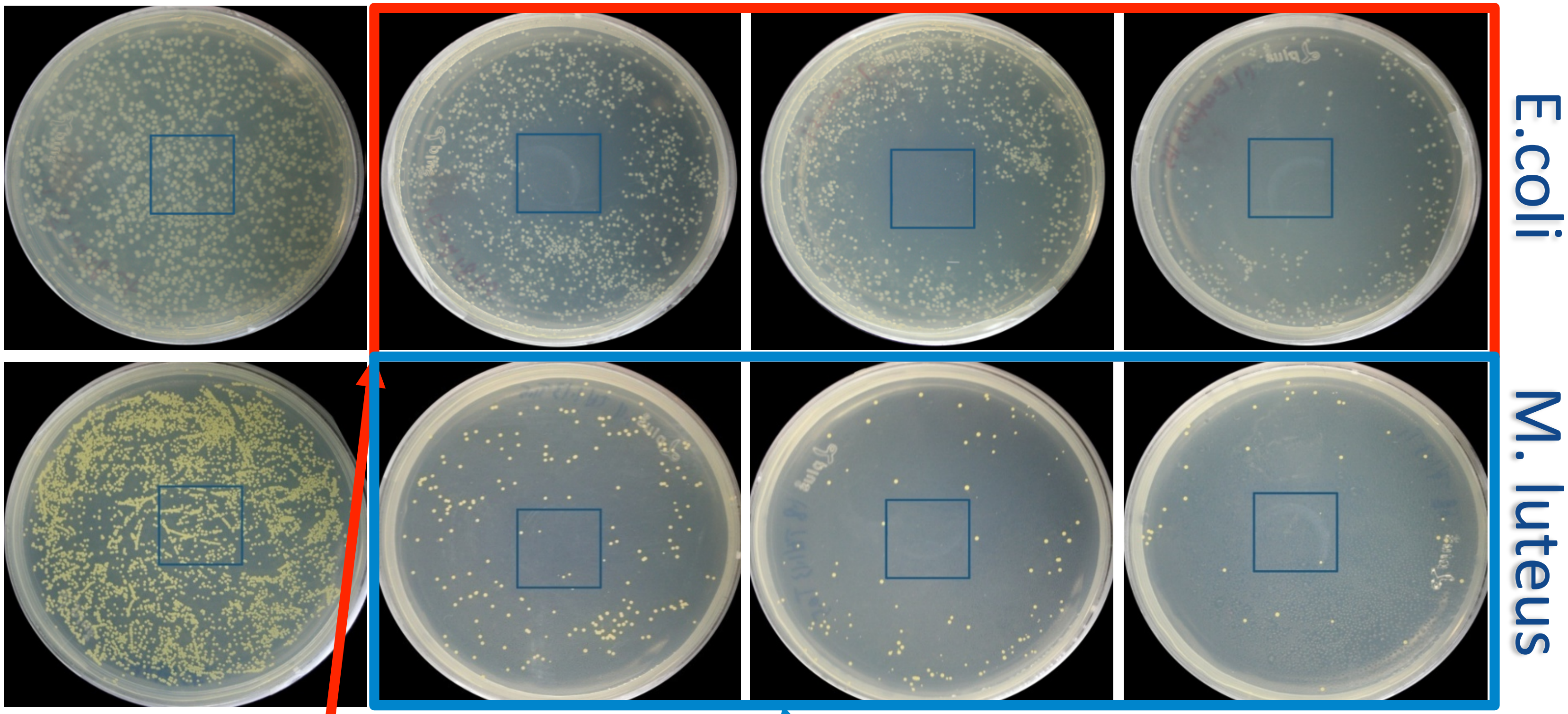
Spore Forming

List of bacteria cultures studied

Experimental Procedure

Total path length: 120 mm
Moving speed: 4 mm/s
Time per path: 30 s
Total treatment time: 30s / 60s / 90 s
Area exposure/path: < 1 s (visible plasma),~10 s (radical exposure)

Plasma Dose Effect



Control

30 seconds

60 seconds

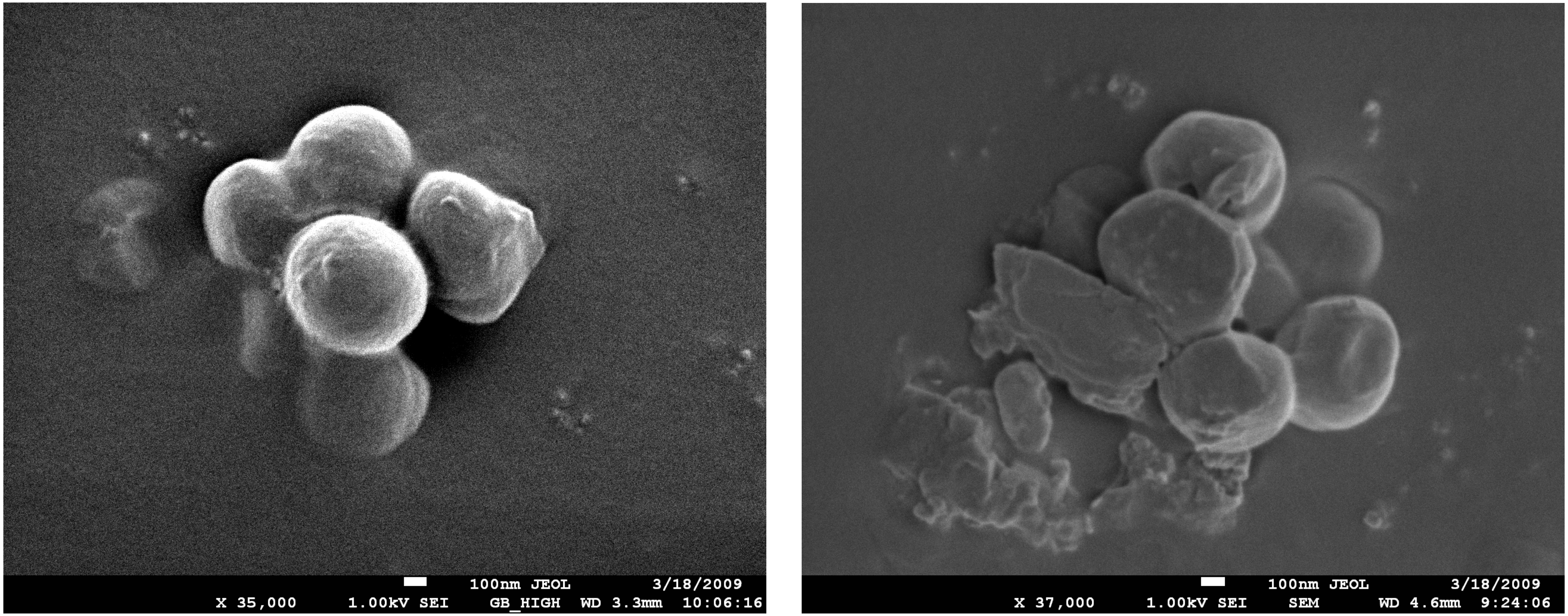
90 seconds

radially decreasing survival rate

uniform decreasing survival rate

SEM Pictures

SEM pictures of S. aureus before and after PMJ treatment



Control

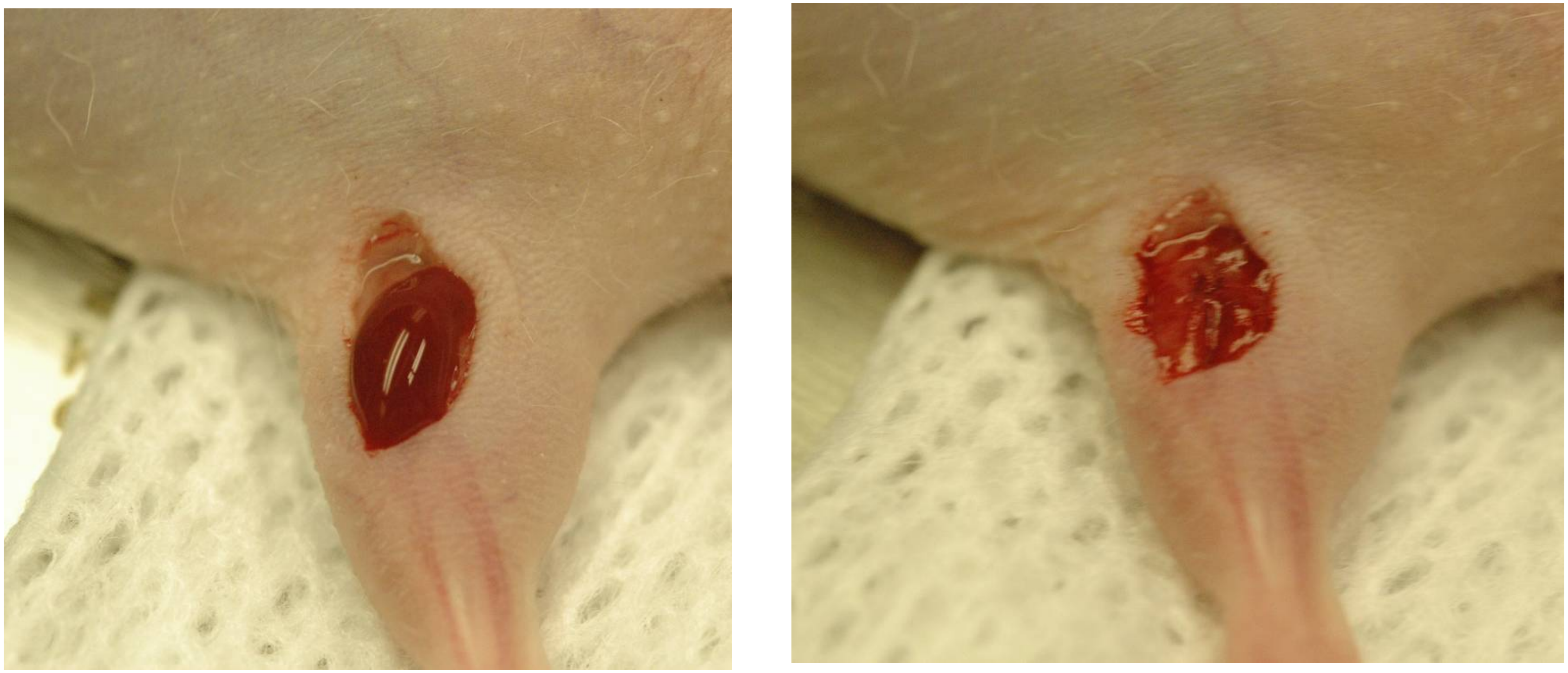
PMJ treatment

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

Living tissue sterilization without harm: Recent pig experiments

Courtesy: Drexel Plasma Institute

Hemostasis and coagulation in Hairless mice, not immunocompromised (SKH$_1$)

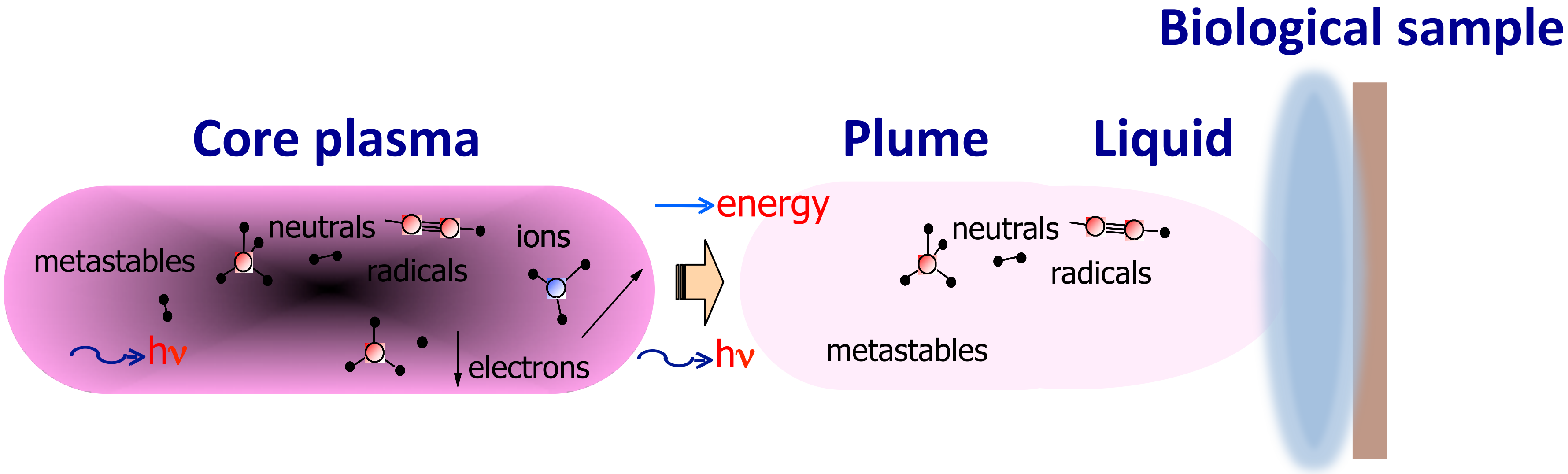


Saphenous vein cut: without plasma animal continues to bleed for 10-20 minutes.

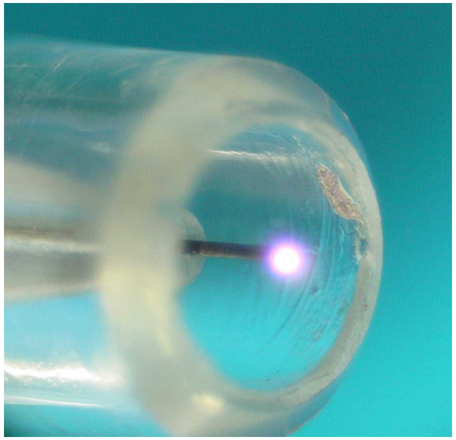
15 seconds of FE-DBD clots the blood and seals the vessel <u>without damaging tissue</u>, preventing additional bleeding.

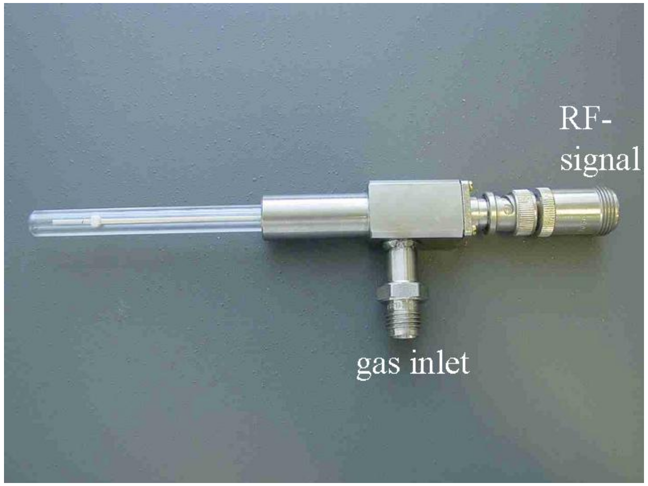
Courtesy: Drexel Plasma Institute

Biological Mechanisms: Plasma Interference into Natural Intracellular Biochemistry



Dental Application



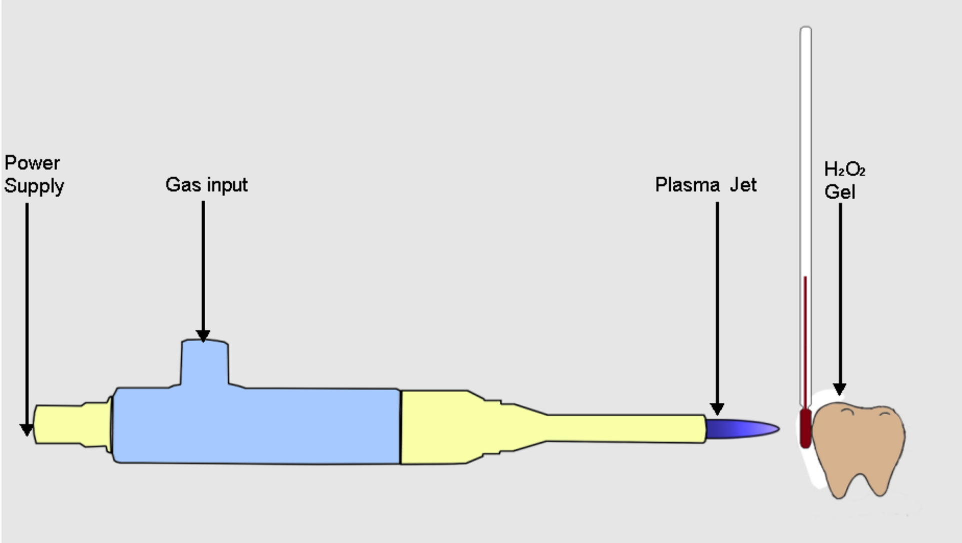


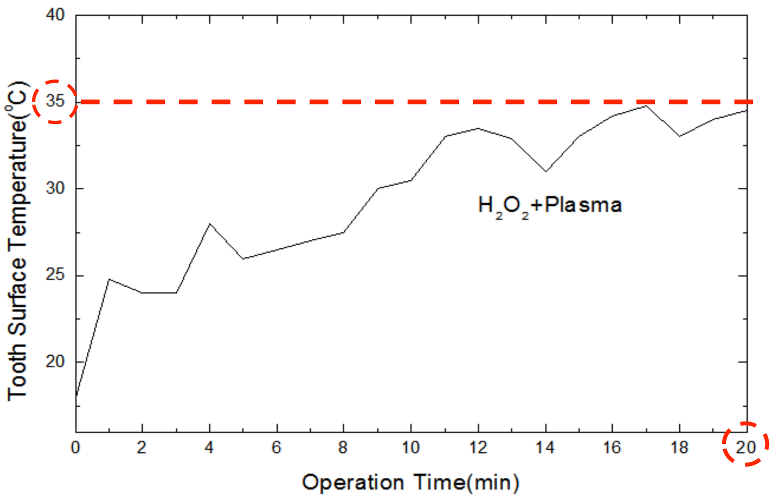
Cleaning of Dental Cavities

Other Applications

- Bio Decontamination
- Sterilization of Medical Instruments and Wounds

Teeth Whitening with non-thermal plasma





- The plasma jet did not heat tooth surface over **37 degrees**.
- Heating the tooth over **42 degrees** can causes severe damages to the nerves inside a tooth.

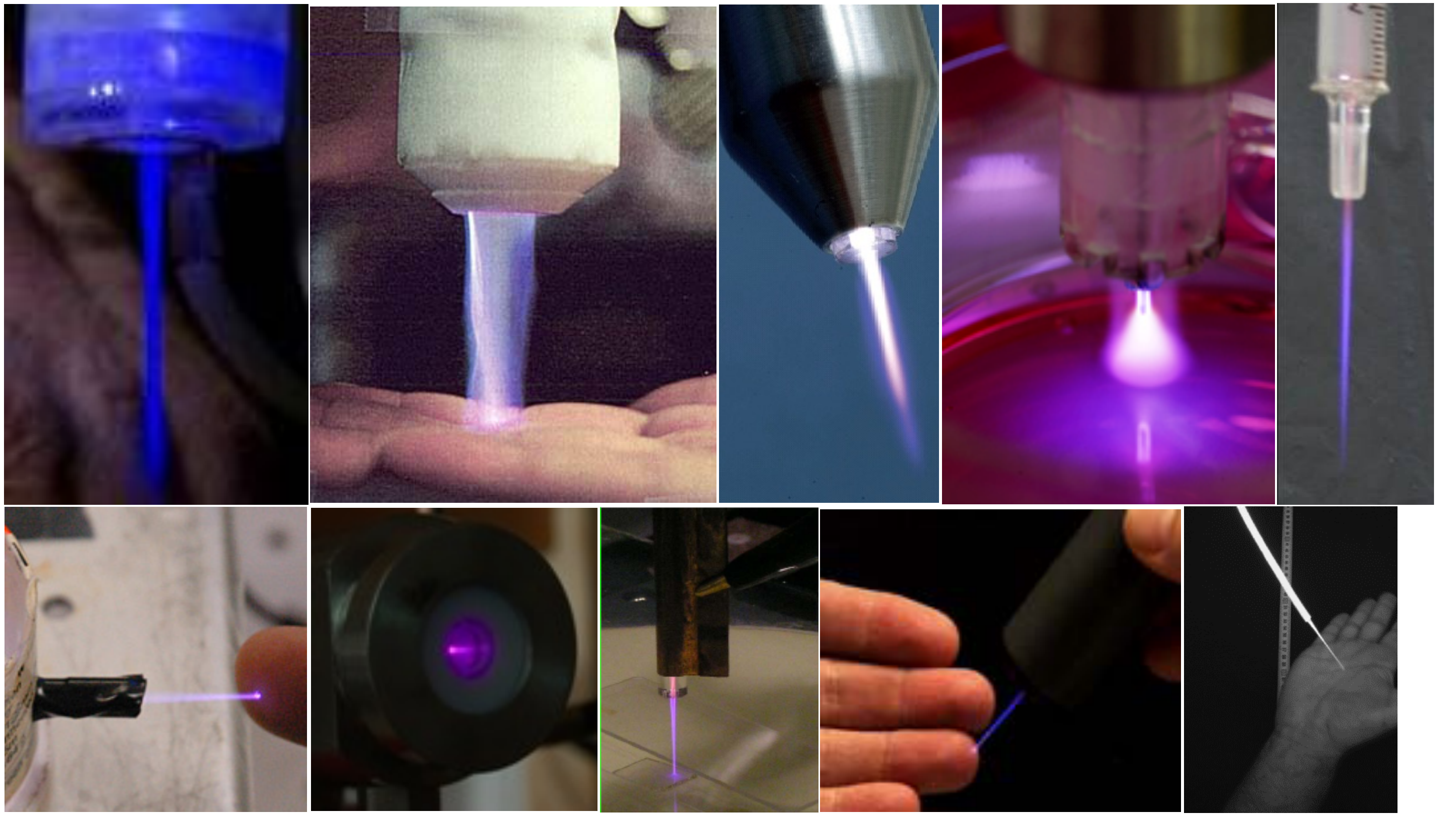
“No thermal-damages”

Teeth Whitening with non-thermal plasma

H_2O_2 before 20min **H_2O_2 after**

Plasma+H_2O_2 before 20min **Plasma+H_2O_2 after**

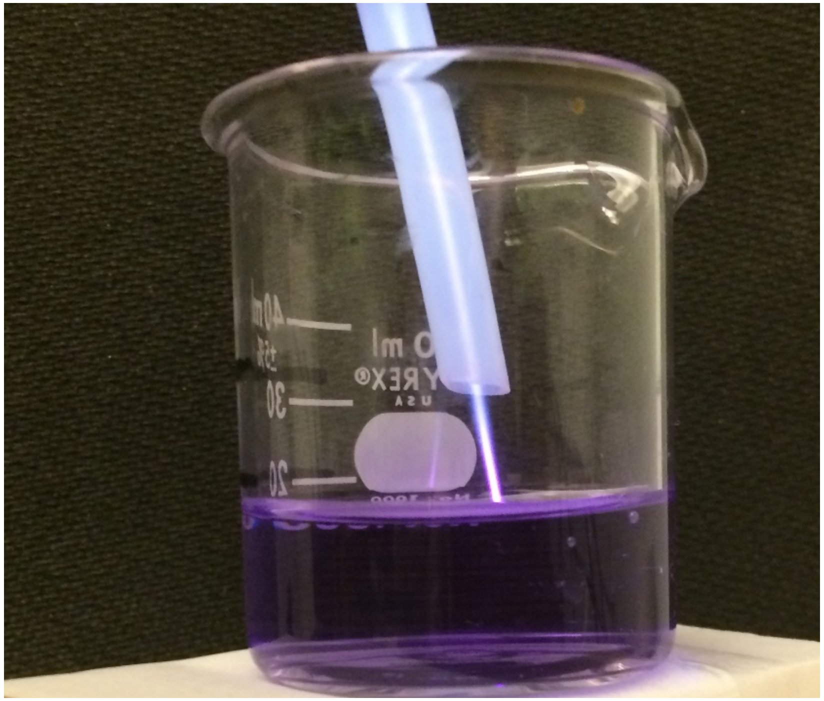
A Brief Collection of Atmospheric Pressure Plasma Jets (APPJ)



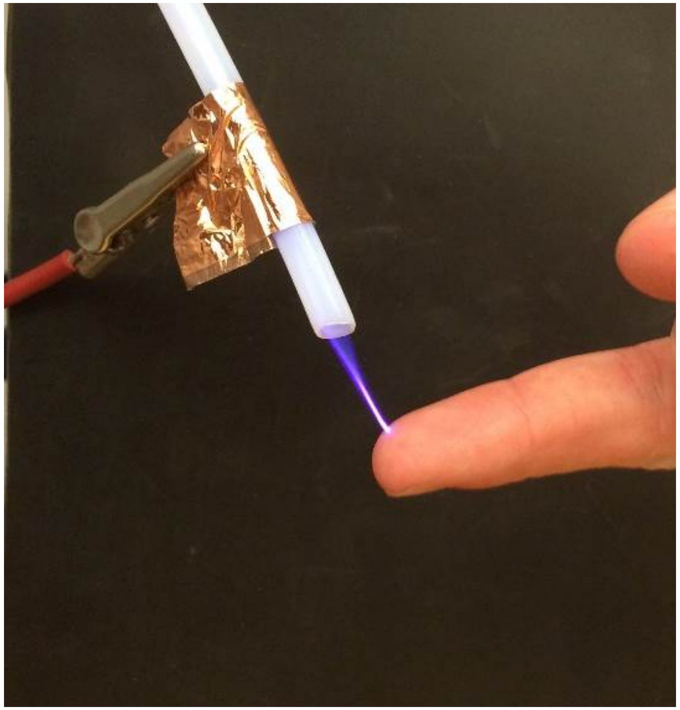
Gases used: Helium, Argon… or mixed with reactive gases (O_2, CH_4…)

AC, pulsed DC, rf or microwave

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 resist to try it out…

- Tubing material: Glass, Teflon, Peek

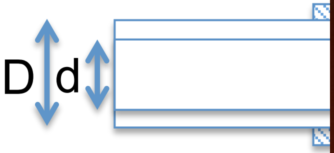
, D: 0.0625-0.5”)

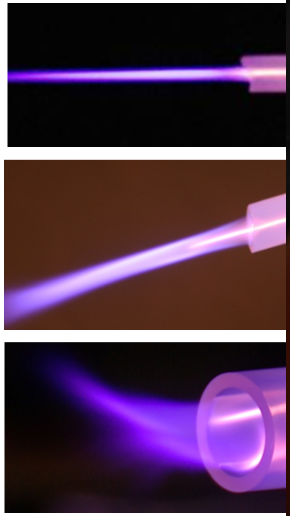
Tape (1” wide)

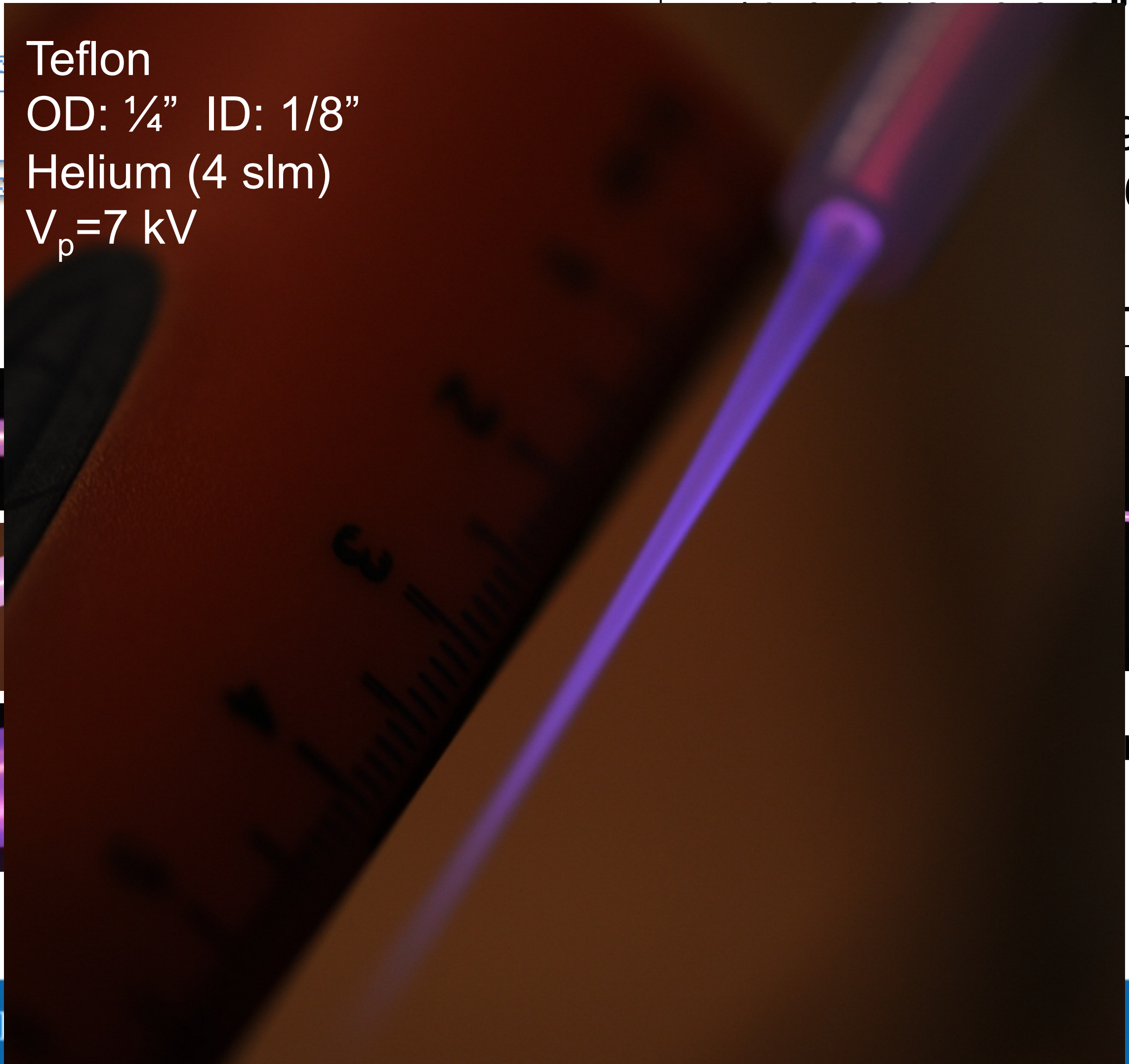
96%),

6%)

-15 kV



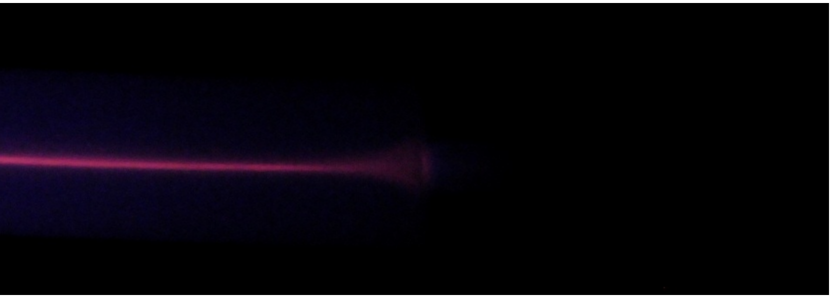


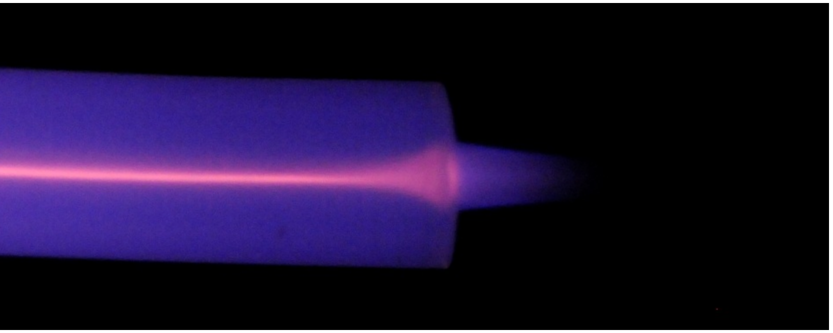


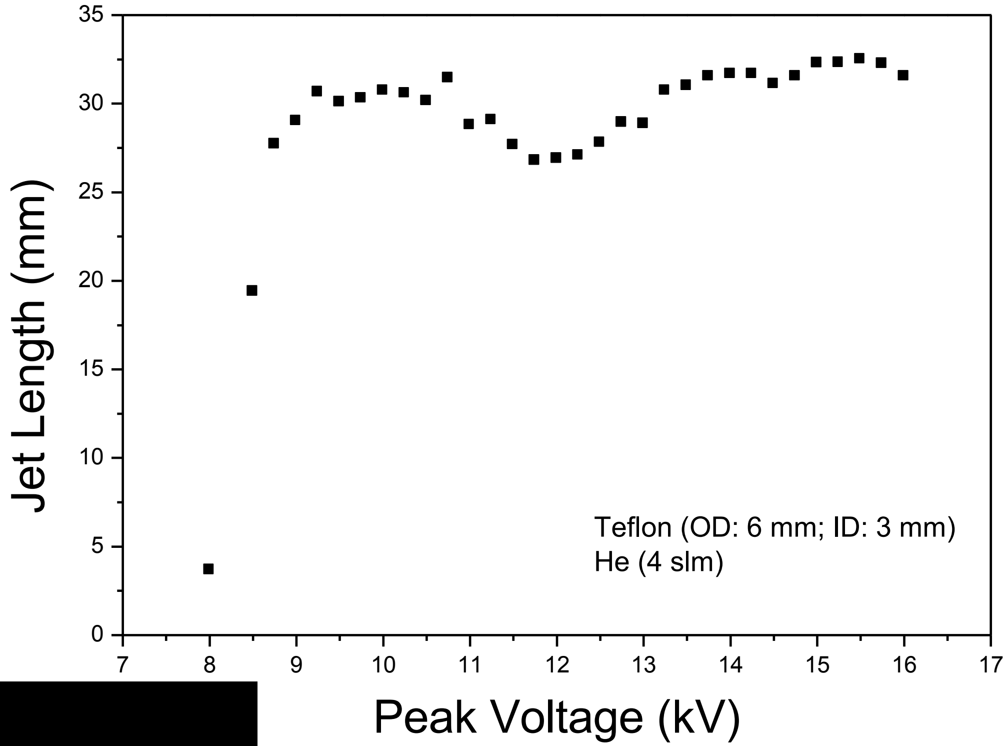
Teflon
OD: ¼” ID: 1/8”
Helium (4 slm)
V_p=7 kV

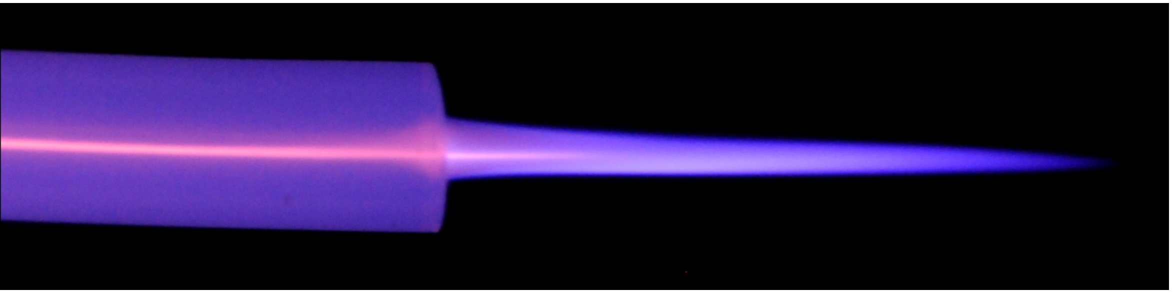
nd downstream

Jet Length vs. applied voltage

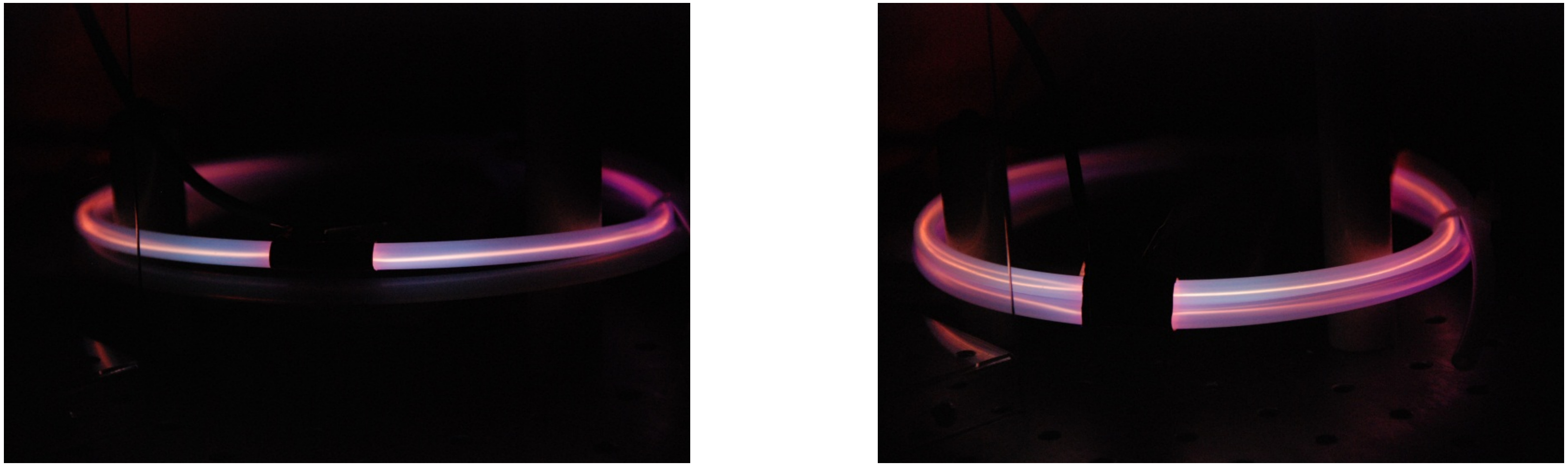






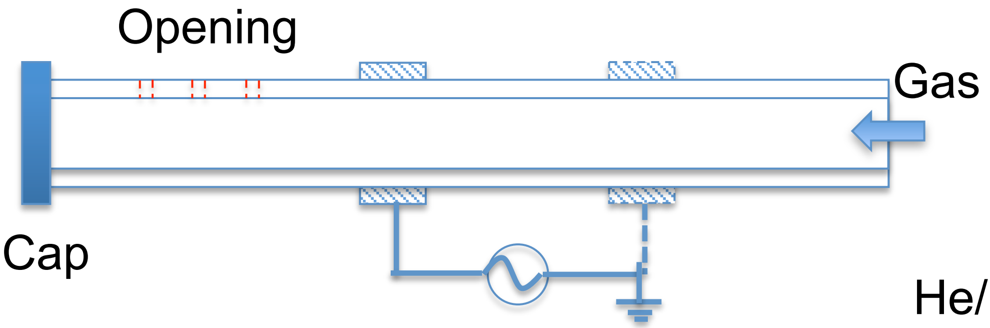


Plasma in a Curved Teflon Tubing

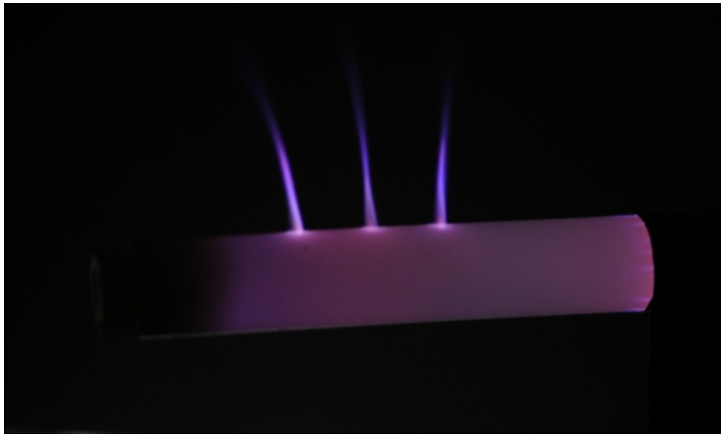


Distance the streamer can travel inside the insulating tubing depends on applied voltage, location of the powered electrode, type of working gas.

Move plasma jets in multiple directions



He/O_2 (2%)

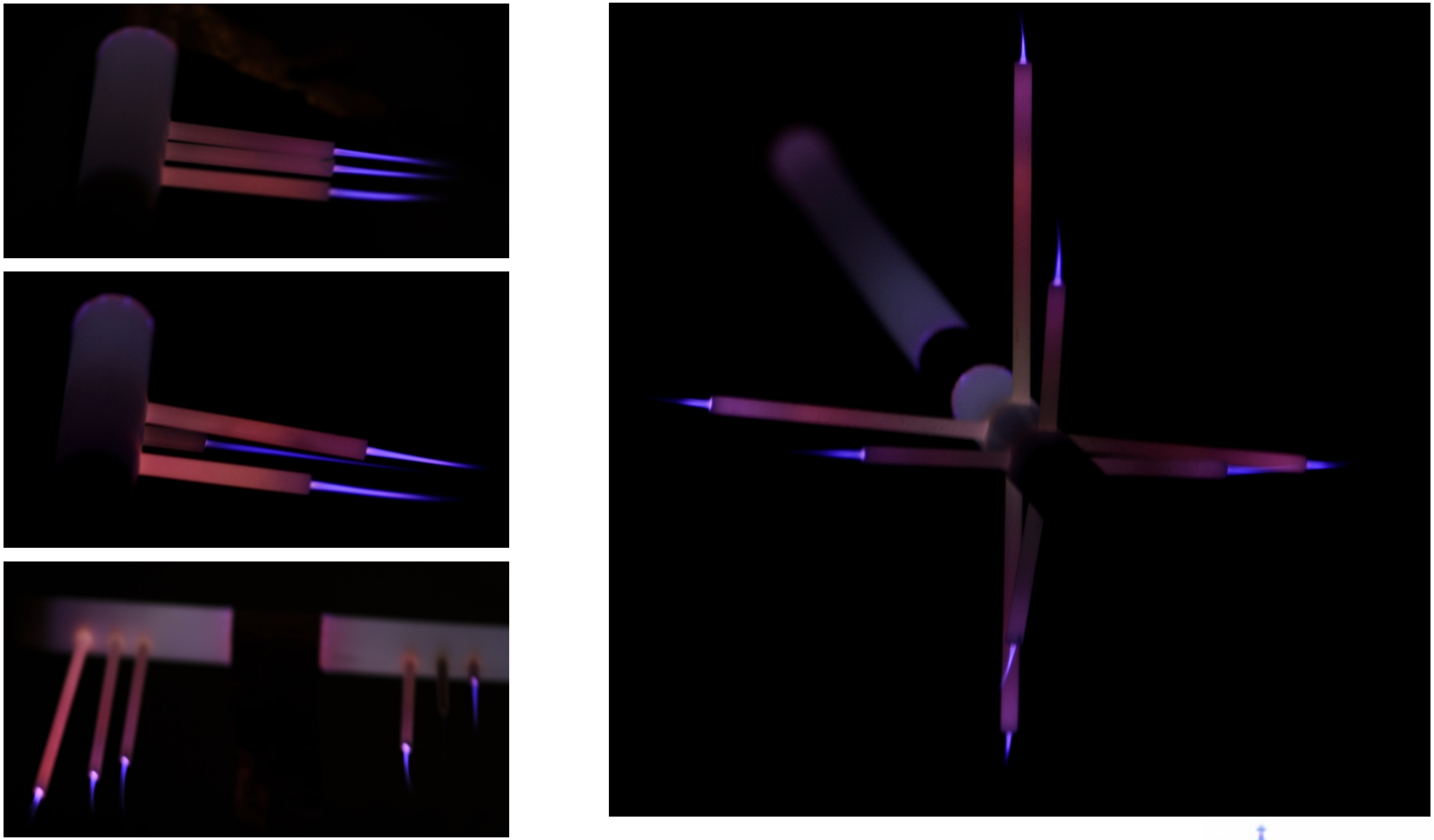


Pure helium (8 slm);
Teflon tube (OD=½”; ID=¼”)
3 holes (diameter: 1/16”) on side wall

3-D Arrays!

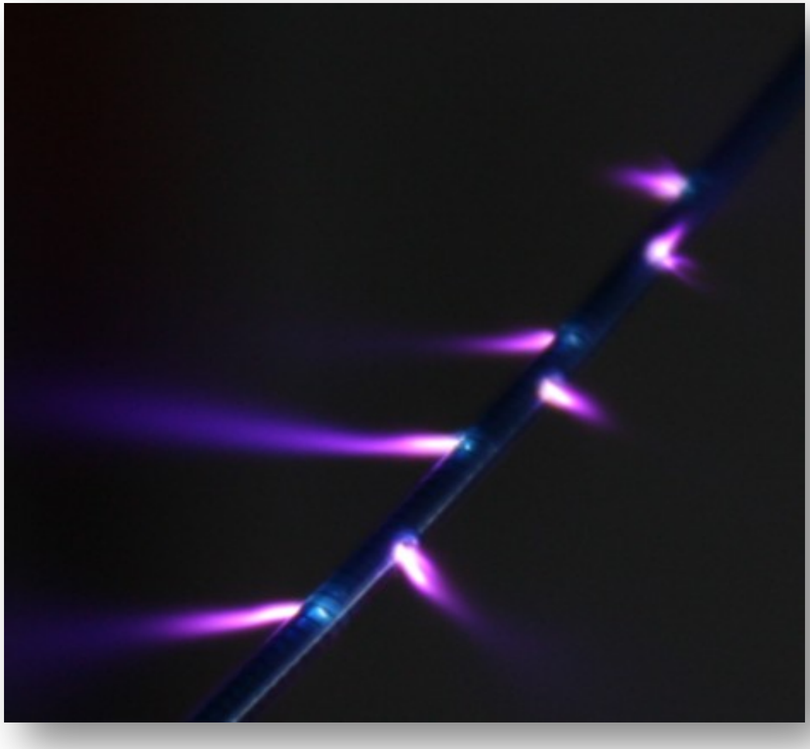
Plasma Jet Array

Further Extension of these Plasma Jets



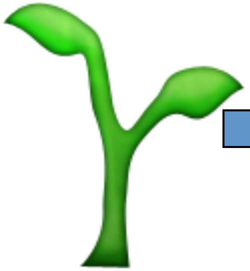
Irrigation: Water & Plasma

Water irrigation in fields and greenhouses



Plasma irrigation for agriculture

Plasma Processing: Experimental Plan



Plasma Treatment

Measure Plants

Harvest

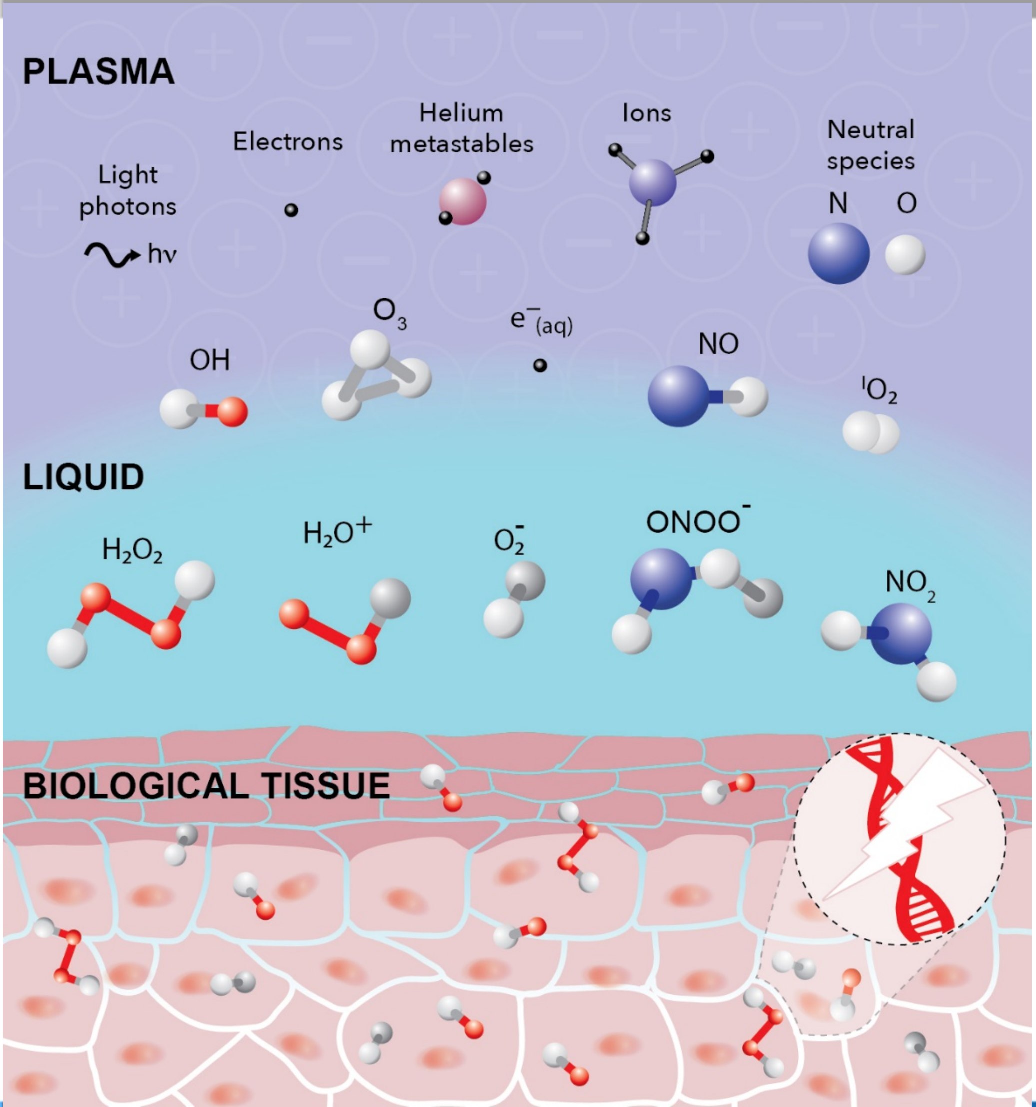
Distillation

Antioxidant Testing

GC-MS

Basil: Plasma Treated vs. Untreated

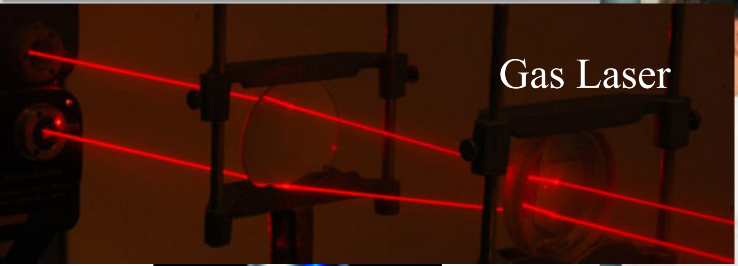
Microplasma interaction with biological materials???



Many unanswered questions as to the role of plasma in the biological interactions with biological materials.

- ➢ What are the microplasmas doing to the live biological materials?
- ➢ Can microplasma sources be tailored to better control interactions with biological materials?

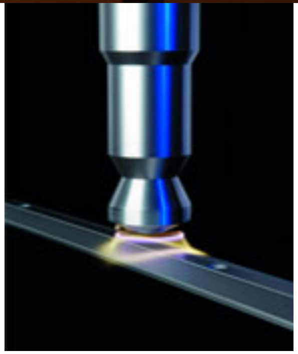
Many, many Innovative Technologies…



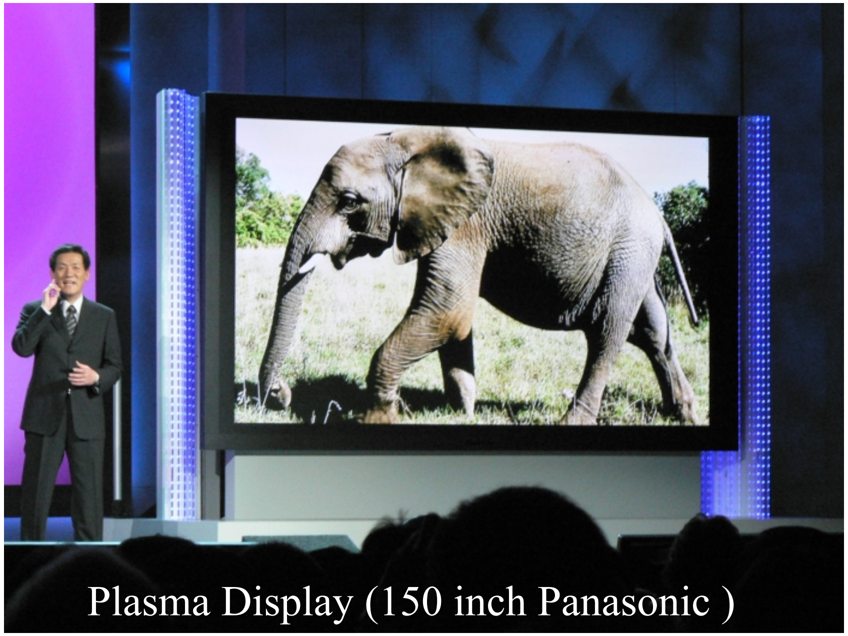
Gas Laser

Ozone generator

High Intensity
Plasma Arc Lamp

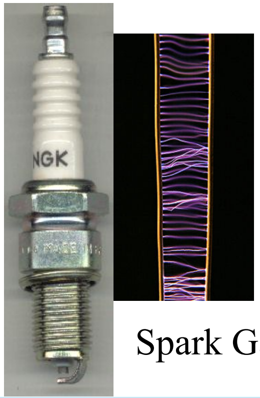


Plasma Surface Treatment



Plasma Display (150 inch Panasonic)

Fluorescent Lamp



Spark Gap

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Seton Hall University – May 11-14, 2015

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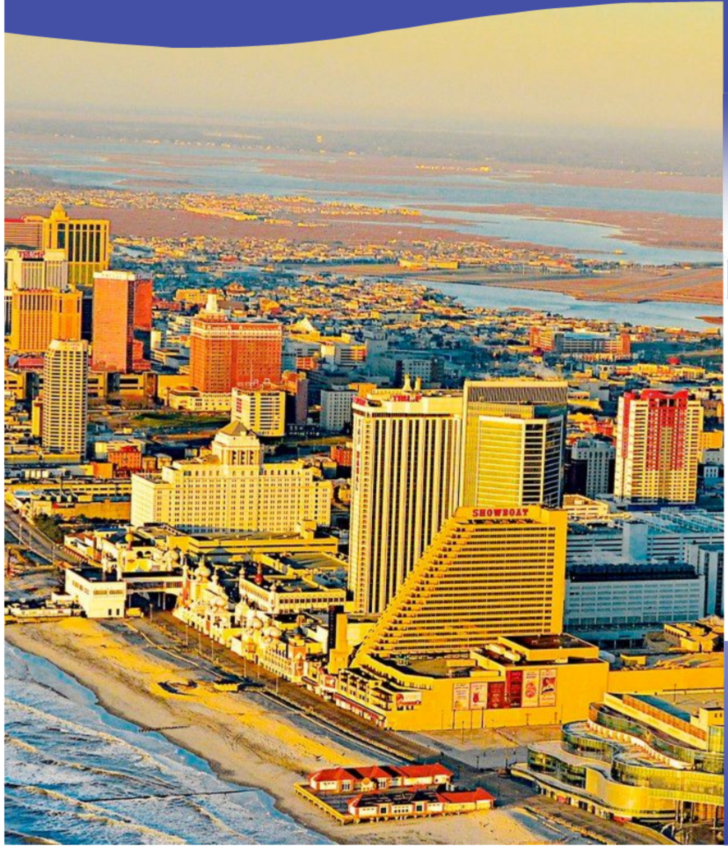

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The future ain't what it used to be...

….Yogi Berra

Questions???

Thank You!

Prof. Jose L. Lopez, PhD
Department of Physics
Laboratory of Electrophysics & Atmospheric Plasmas (LEAP)

Telephone: (973) 761-9057
Email: jose.lopez1@shu.edu

Website: *www.shu.edu/academics/artsci/**physics**/*