Low Temperature Plasmas :

Generation & Sustainment

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What is a Plasma?

A *Plasma* is <u>more</u> than a collection of neutrals, ions, and electrons!

What characterizes a plasma (i.e. low temperature plasma)?

1. **Quasi-neutral state of existence**
2. **Collective behavior due to Coulomb forces**
3. **Energy distribution (T_e is high, not T_i and T_g)**
4. **Collisional and radiative processes**

Two types of plasmas

High-temperature plasmas or Hot (Thermal) 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 or Cold (Non-thermal Plasmas)

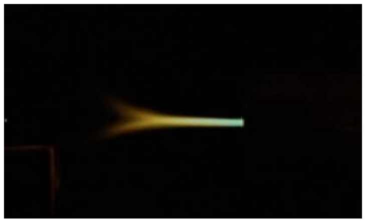
$T_i \approx T_g \approx 300$ K

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

e.g. low-pressure glow discharge

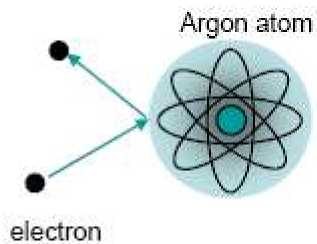
high-pressure cold plasma

Collisions generate & sustain the plasma



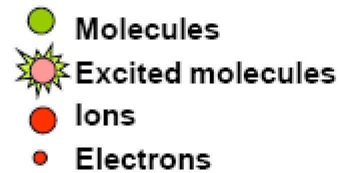
Elastic collisions

Elastic collision are frequent in gases
No energy exchange

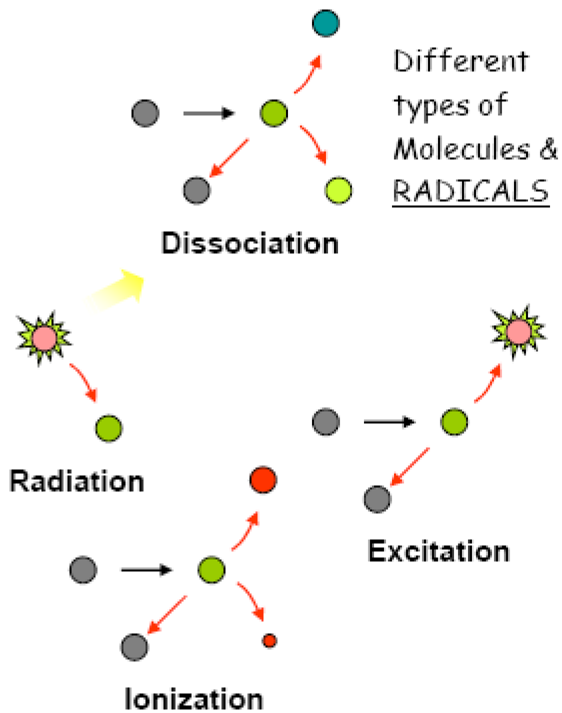


essentially no exchange of energy ($m_{Ar} >> m_e$)

Collisions in plasmas



Inelastic collisions



Gas

ENERGY

Plasma

Therefore more and stronger collisions leading to more

ionization,
excitation,
dissociation and
radiation

Plasma generation

A plasma is generated by supplying energy to a volume of gas to produce pairs of electrons and ions (charge carriers).

- most commonly electrical energy is supplied

Low temperature plasmas are usually excited and sustained electrically by applying

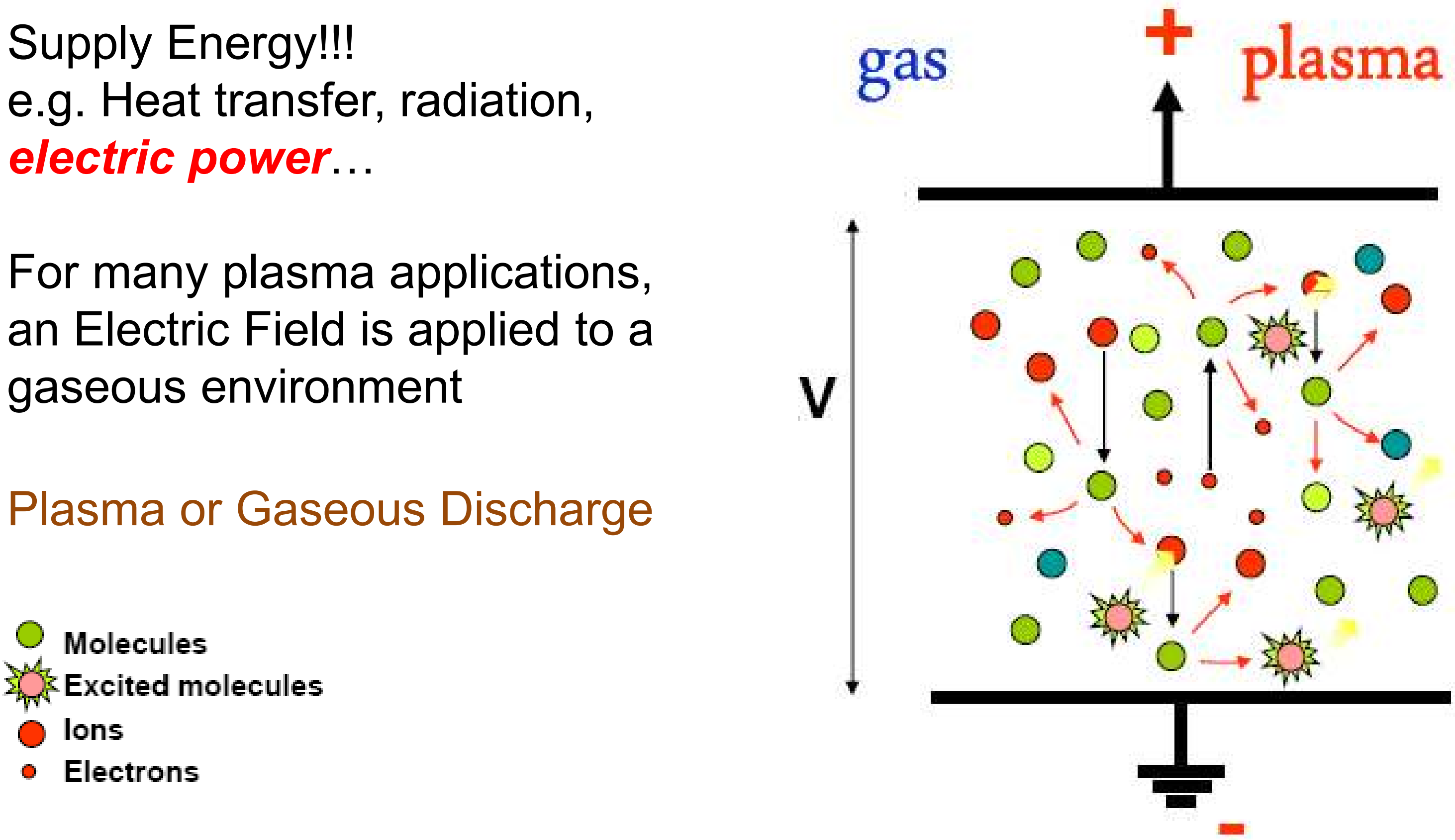
- Alternating Current (AC) power
- Radio Frequency (RF) power
- Microwave (MW) power
- Direct Current (DC) power
  - Pulsed DC power

How do we make plasmas?

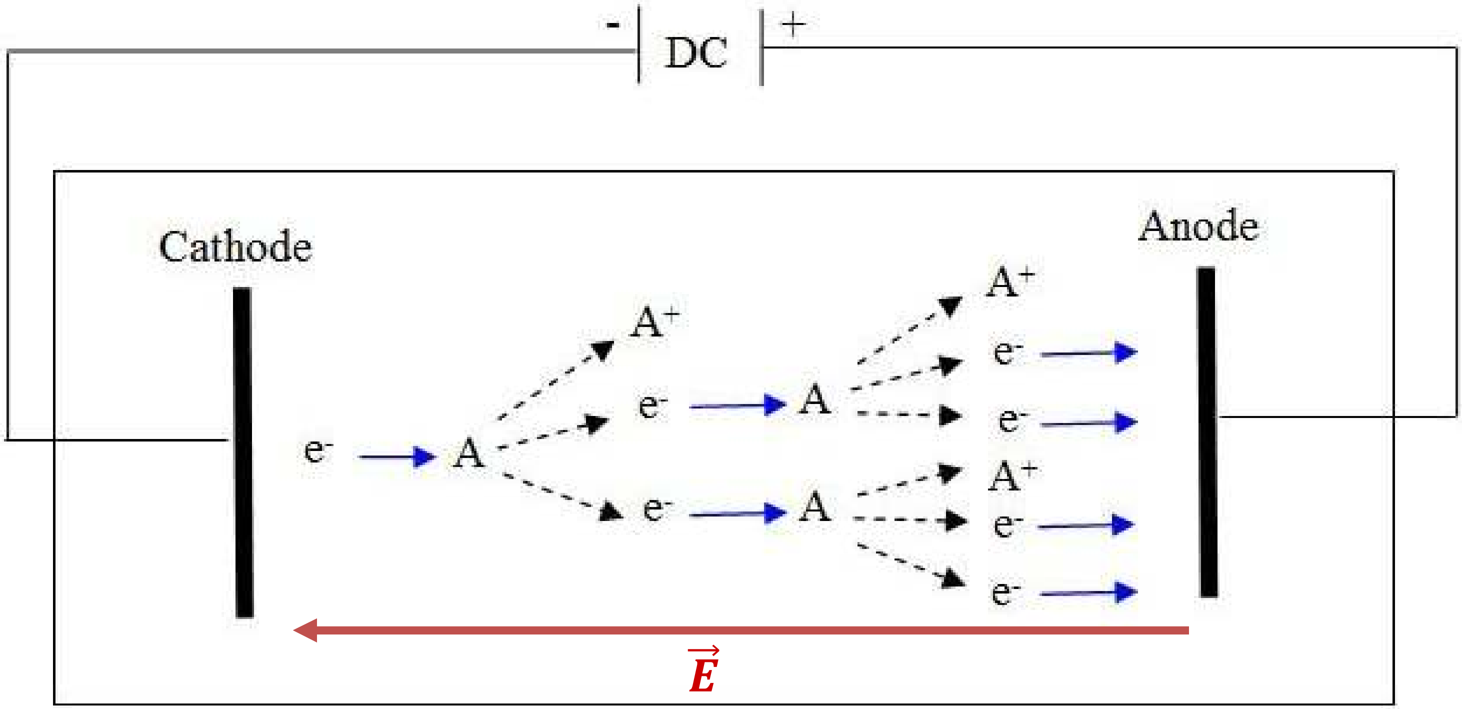
Supply Energy!!!
e.g. Heat transfer, radiation, ***electric power***…

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

Plasma or Gaseous Discharge

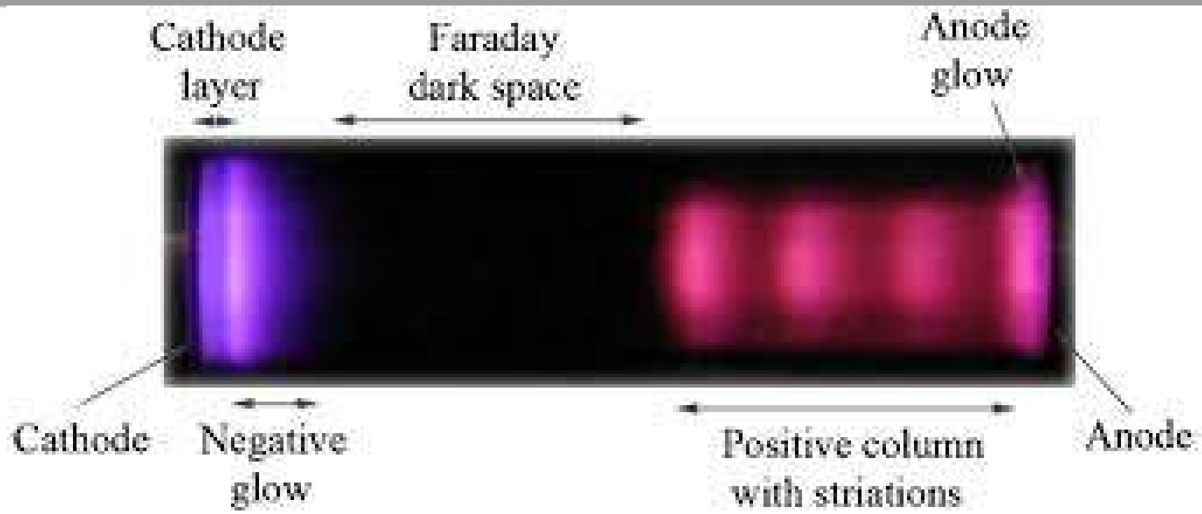


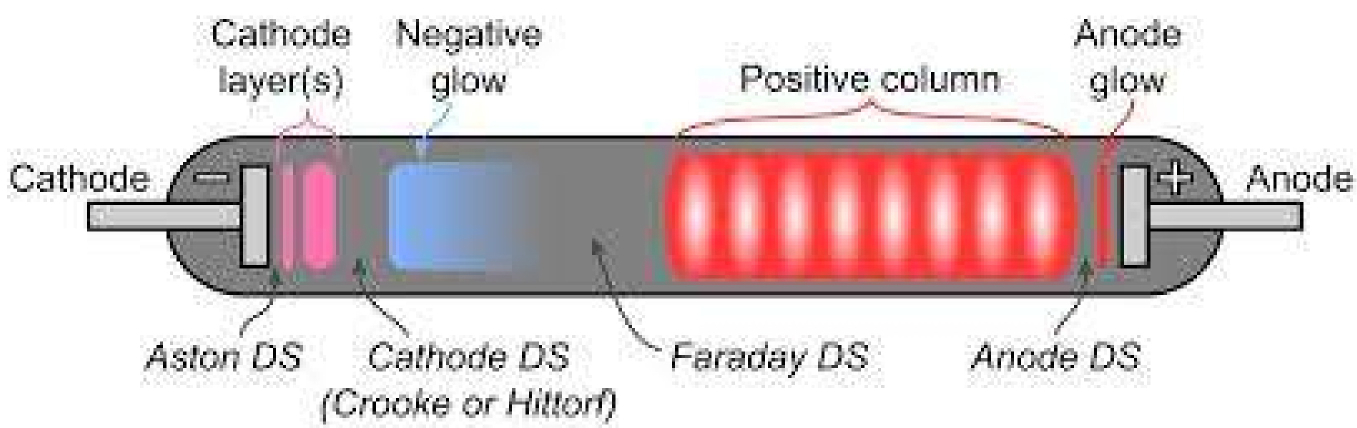
DC Glow Plasma



A - neutrals
A+ - ions
e- - electrons
Accelerating force
Reaction path

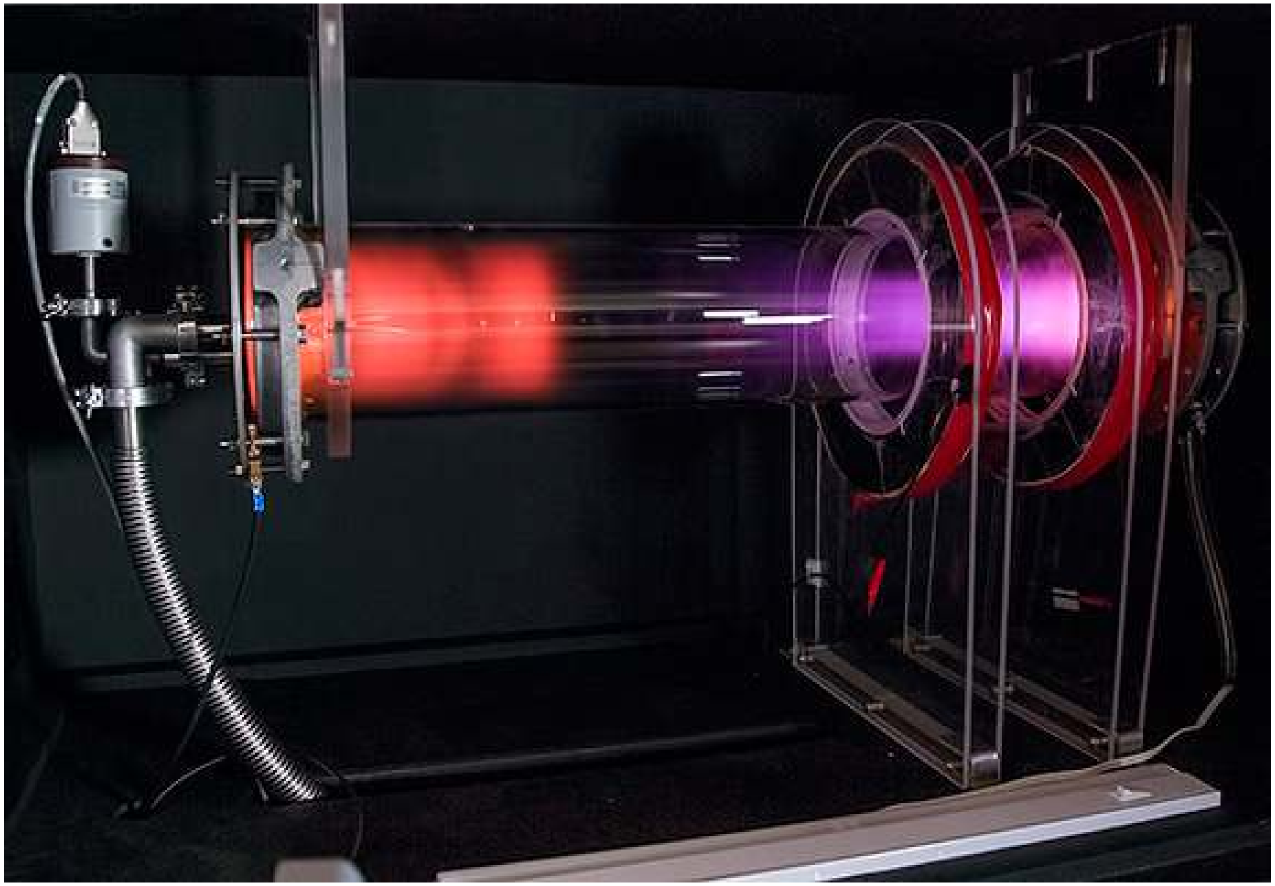
DC Glow Plasma





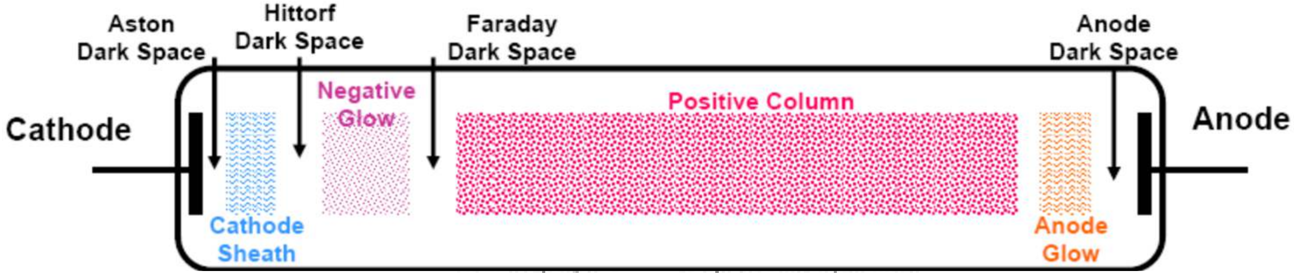
Reference: J.T. Gudmundsson & A. Hecimovic. *Foundations of DC plasma sources.* **Plasma Sources Science and Technology**, Volume 26, Number 12 (2017)

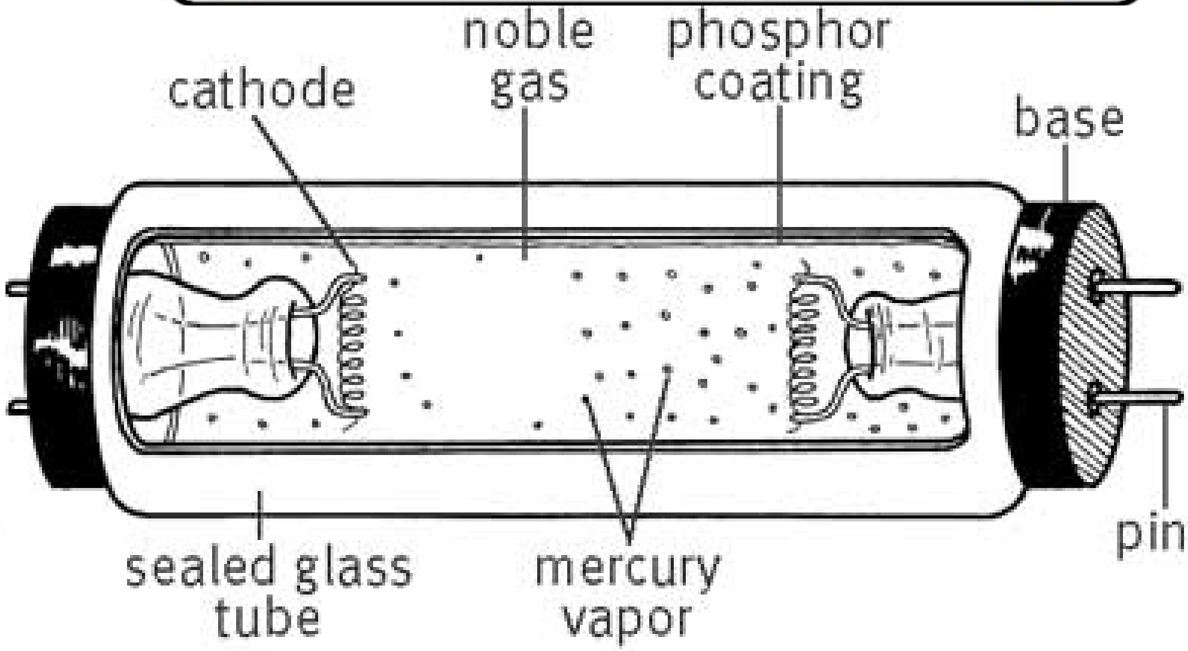
PPPL's Remote Glow Discharge Experiment (RGDX)



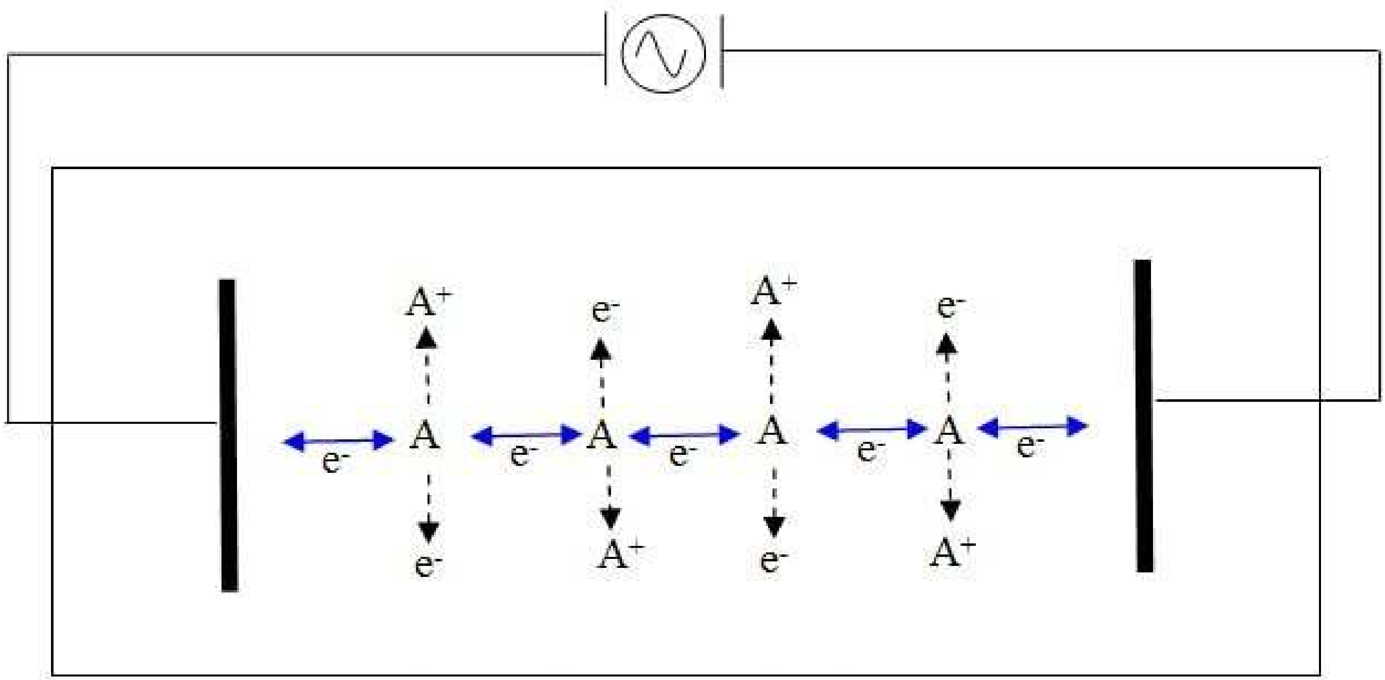
https://www.pppl.gov/RGDX

Low-Pressure Glow Discharge Plasmas





Capacitively coupled plasma

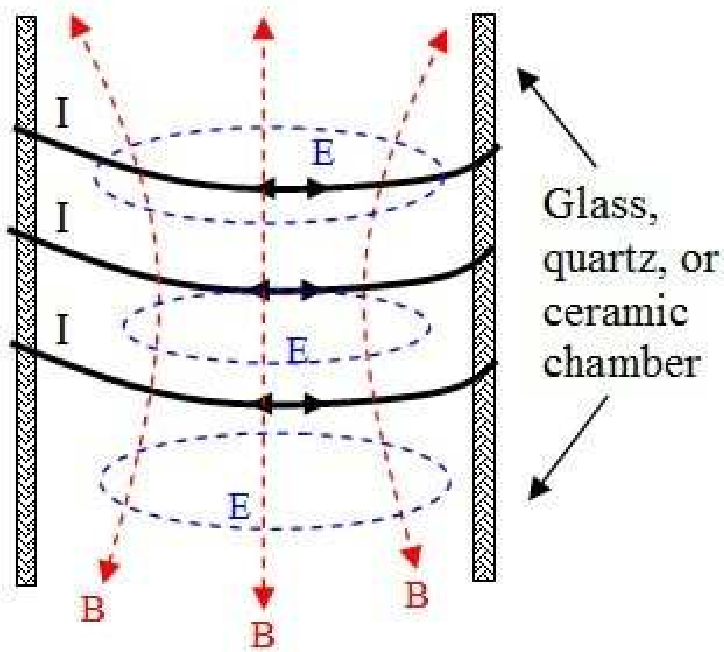


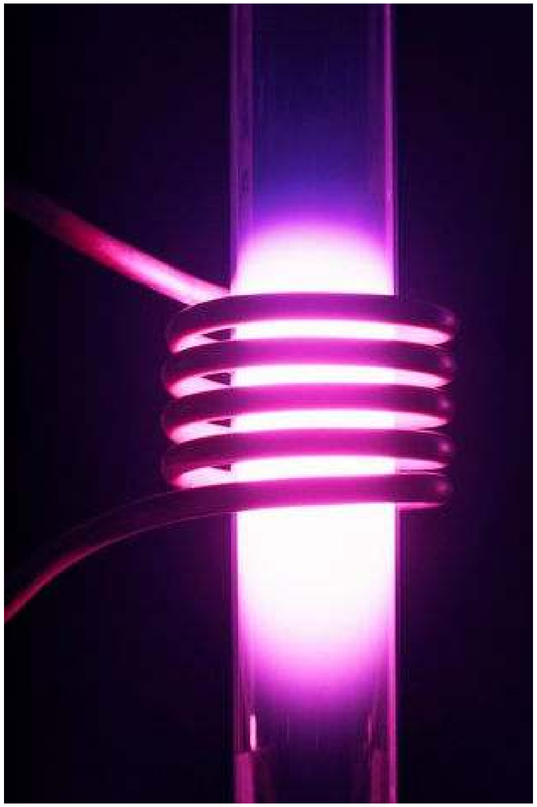
A - neutrals   A+ - neutrals   e- - electrons

↔ Oscillating force   - - - -▶ Reaction path

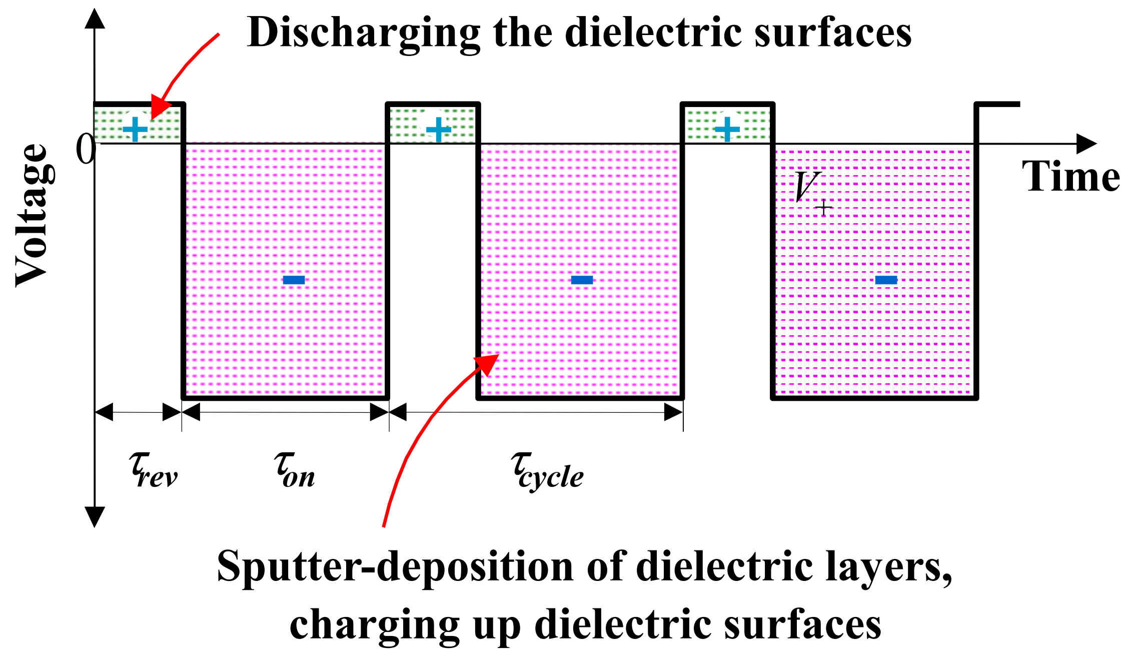
Inductively Coupled Plasma

Frequency range: 10s kHz - 10s of MHz range





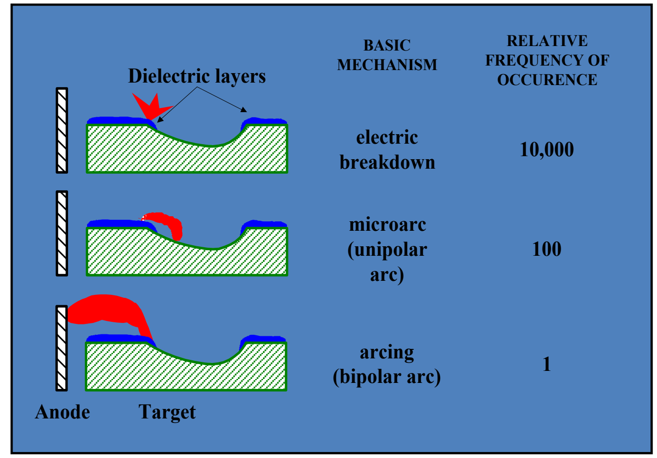
Pulsed DC generated plasmas



- During operation with pulsed DC the potential on the dielectric (target) is periodically modulated, at a pulsing frequency *f*, typically between 1 to 350 kHz.
- For a certain *reverse time*, τ_{rev} or *off time* at the beginning of each pulse, a positive reverse voltage is applied
  - this phase typically accounts for 10-50% of the pulse
- The remaining phase or *on time*, τ_{on} accounts for 50-90% of each pulse.

Pulsed DC generated plasmas

- The primary reason in the development and establishing of pulsed DC was the suppression of arcs at the target during reactive deposition.

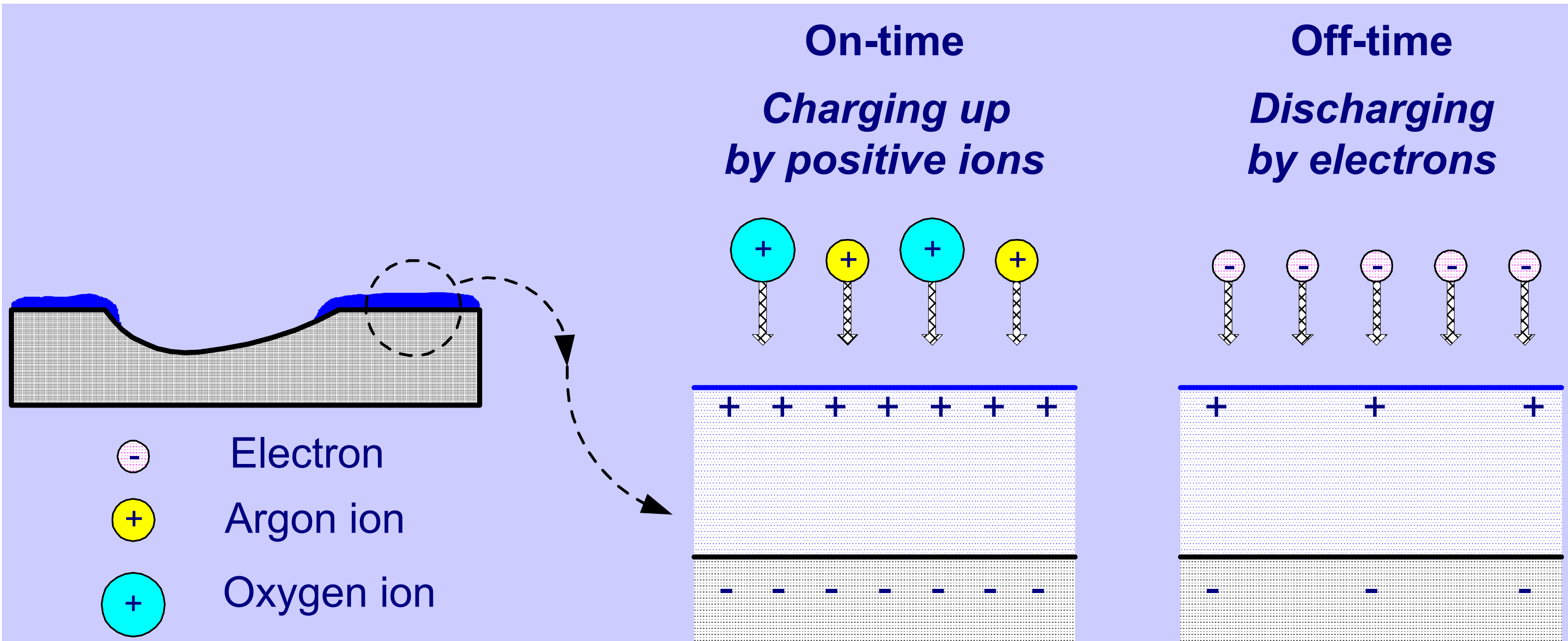


- Research indicates that pulsing the discharge modulates the intrinsic plasma parameters.

- One of the most important parameters influencing the quality of deposited films is the energy of ions impinging on growing films.
  - Studies have shown a dependency of film properties on the selected pulsing frequency and reverse times.

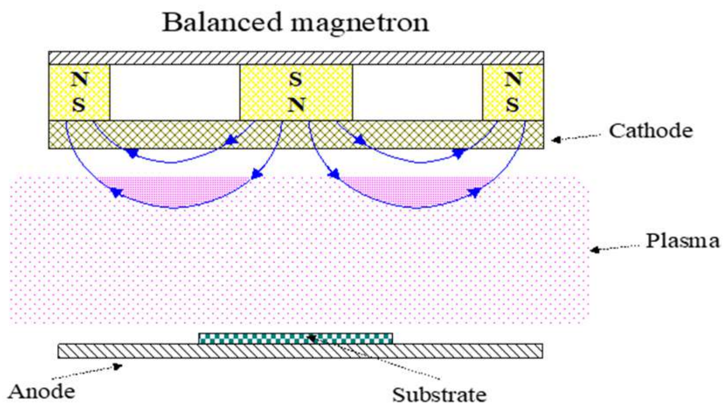
Pulsed DC generated plasmas

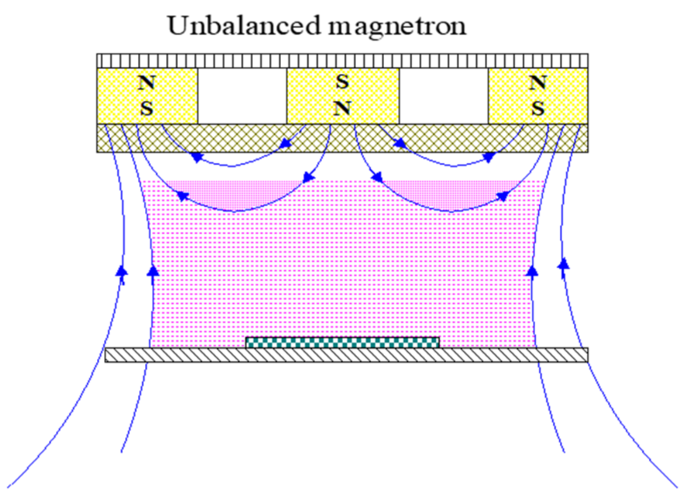
Charging up and discharging the dielectric surfaces



When no arcing regime is maintained, discharging during each off-time is complete

Magnetron Introduction





Balanced Magnetron

- one pole is positioned at the central axis of the target and the other pole is placed around the outer edge of the target forming closed or balanced field lines.
- In the balanced magnetron, the dense plasma is constrained near the target racetrack (~60 mm from the target surface)

Unbalanced Magnetron

- outer magnets are stronger than ones in the center.
- some of the field lines from the edge magnets cannot be balanced by the center ones and have to be closed on themselves then causing the field lines to come down to the substrate
- Electrons move down to the substrate along these field lines with ions coming together as required by global plasma neutrality.
- higher ion flux onto the substrate compared to the balanced magnetrons.

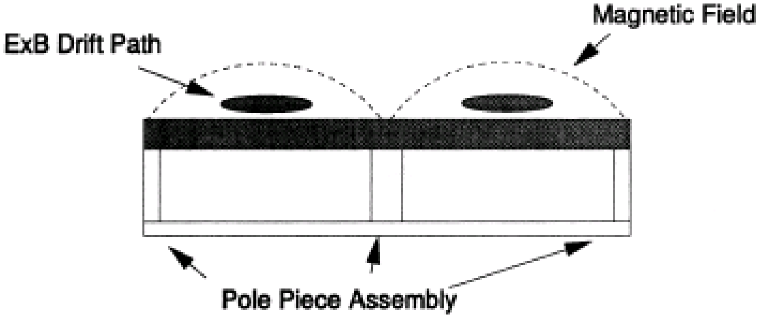
Pulsed DC Unbalanced Planar Magnetron

- Secondary electrons move in a direction perpendicular to both the electric and magnetic field.

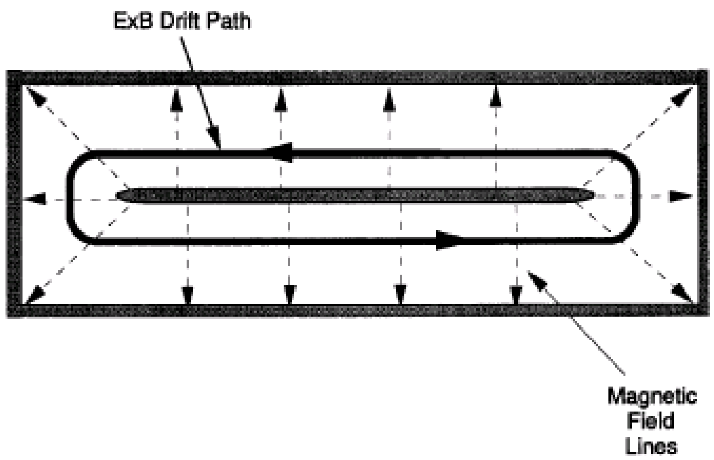
- the **E×B** drift causes electrons to move parallel to the cathode surface in a direction 90 degrees away from the magnetic field.

- Secondary electrons lose their kinetic energy due to collisions with gas atoms (ionization) or with other electrons (electron heating), and the net result is an extremely dense plasma in this drift ring

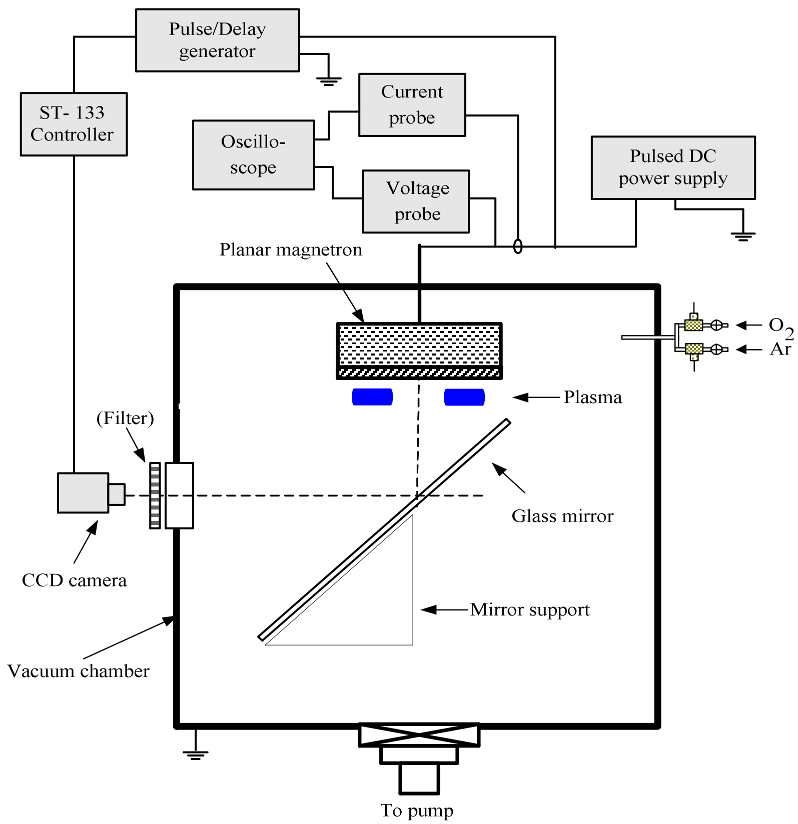
- Ions in the drift region have a high probability of hitting the cathode. This results in even more production of secondary electrons and eventually very dense plasma

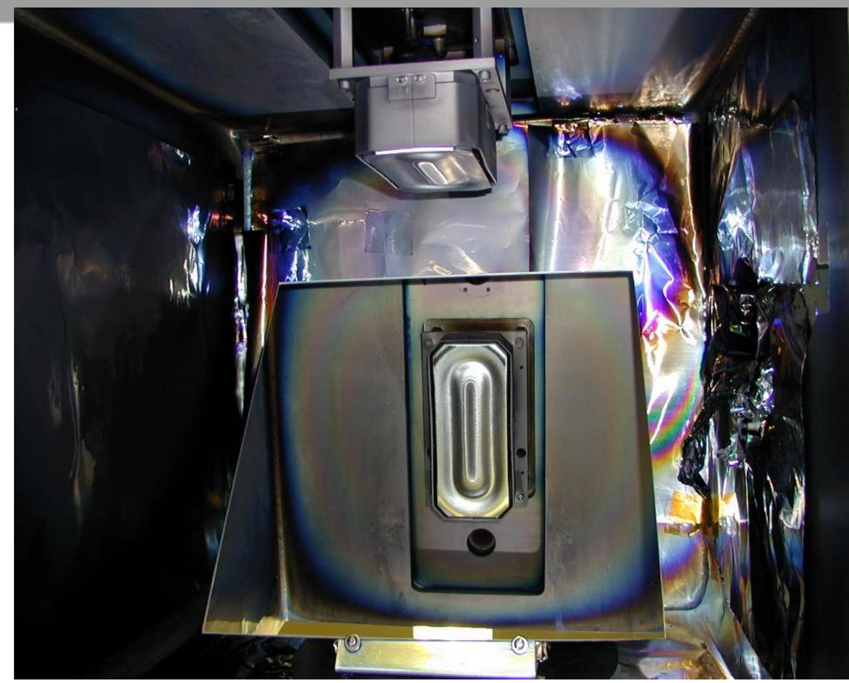


Top view



Pulsed DC Unbalanced Planar Magnetron

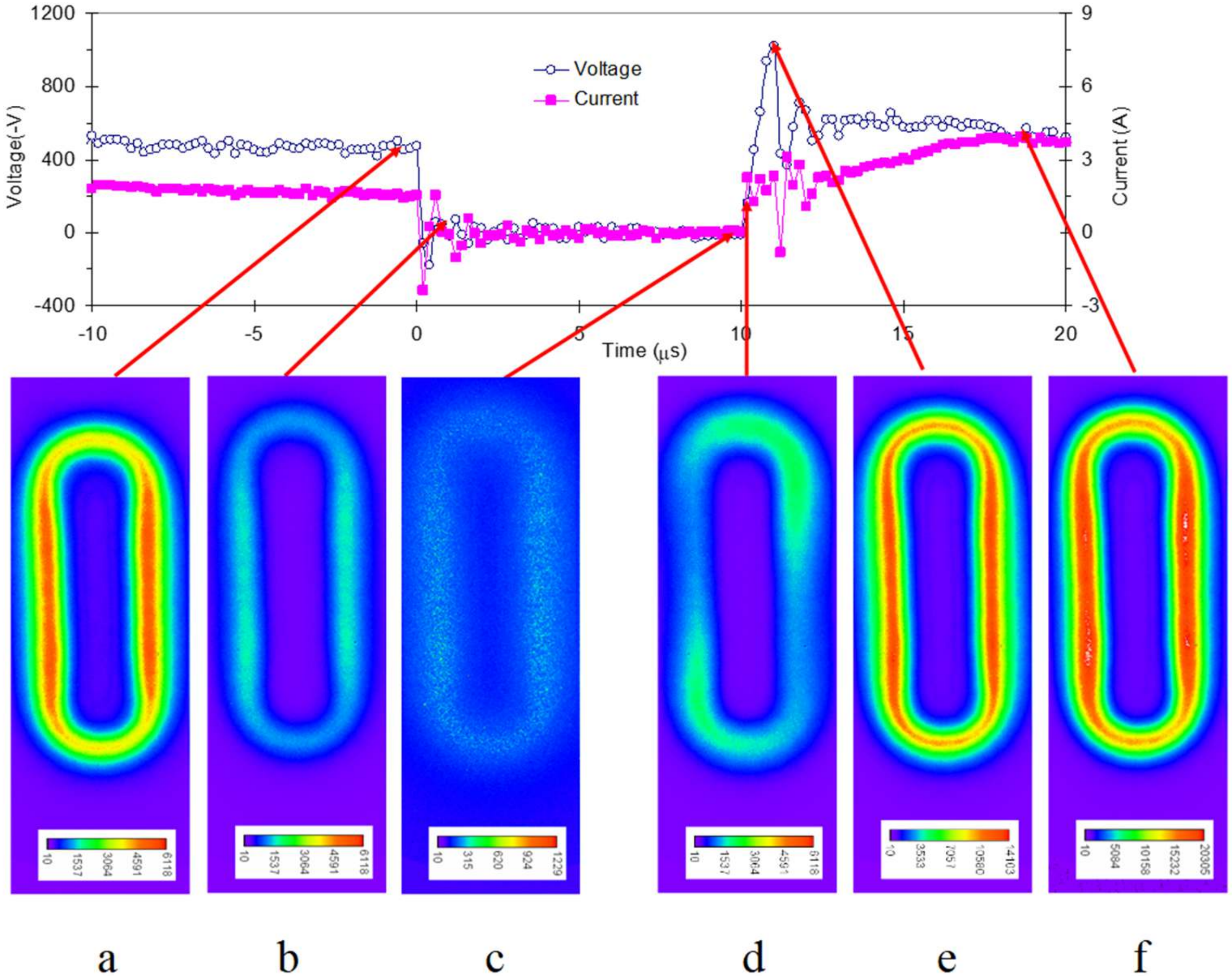




Picture of inside the vacuum chamber with the magnetron and it's reflection in the mirror.

Planar rectangular HRC-873 magnetron with a Ti target (3.5" × 8")
Base pressure 6 × 10^{-6} Torr
Working atmosphere: Ar/O_2 mixture at a gas flow ratio of 1:1 and a pressure of 9 mTorr

Time-Resolved Plasma Emission Images



Images taken
Power=1 kW
f = 20 kHz
τ_{off} = 10 μs

Plasma distribution at the beginning of the on-time is different than during the rest of the cycle.

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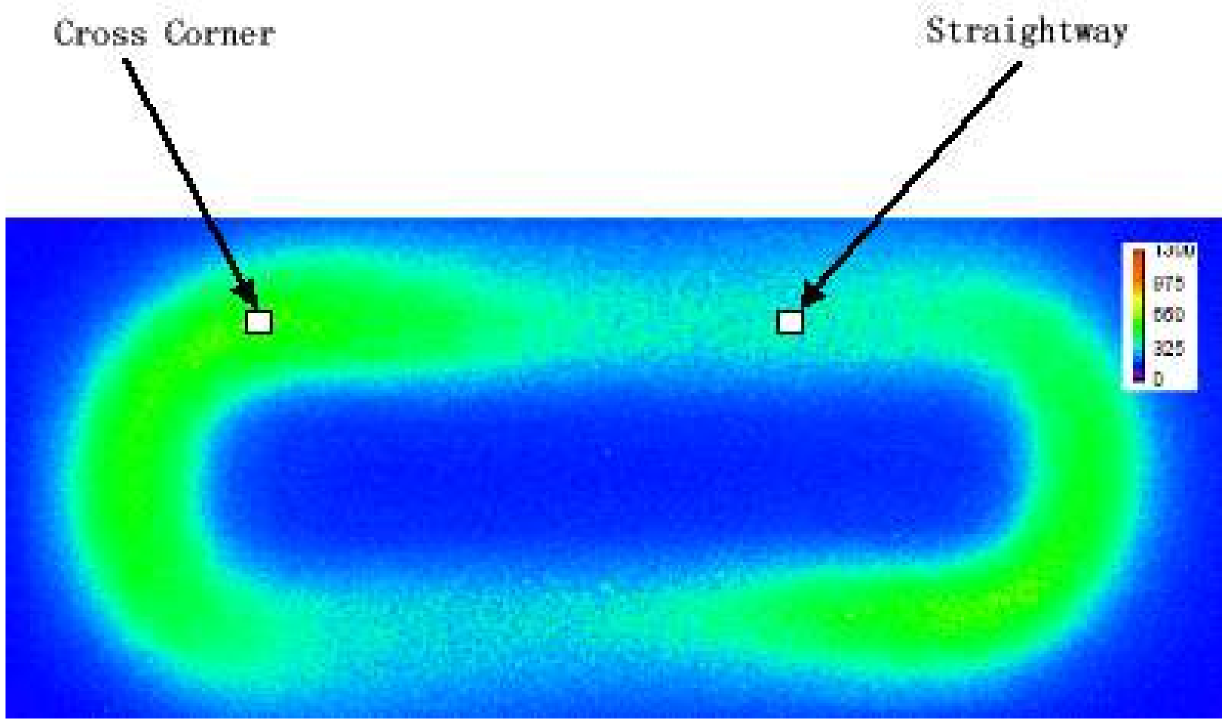
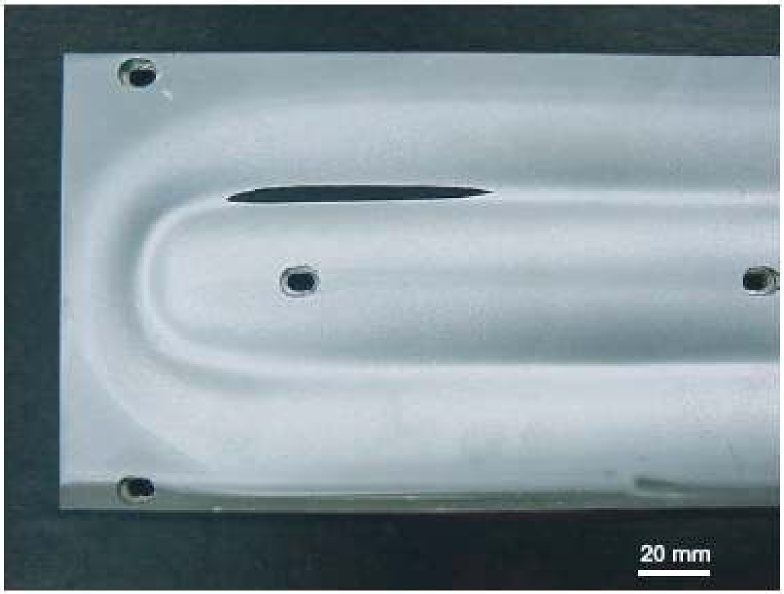
Cross-corner effect in planar rectangular magnetrons

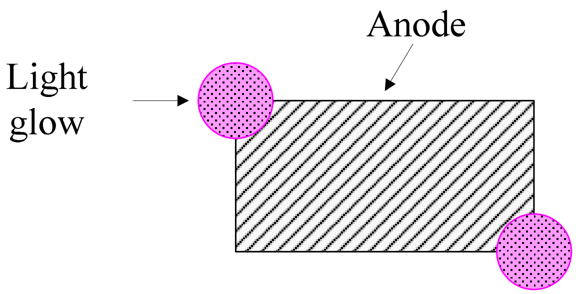


An image of the Ti target magnetron plasma racetrack taken approximately 0.2 μs after the start of the on-time. Notice the cross-corner effect is clearly present at the opposing edges of the plasma racetrack.

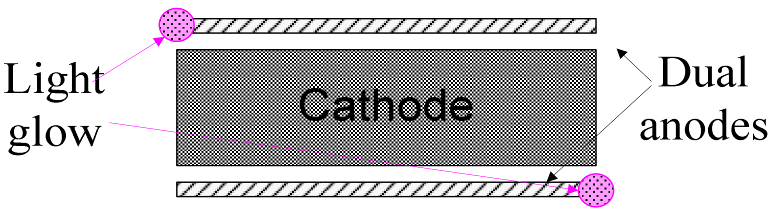
Cross-corner effect in planar rectangular magnetrons



Eroded rectangular target sputtered with a conventional magnetron cathode, showing faster etching in the upper left corner area.

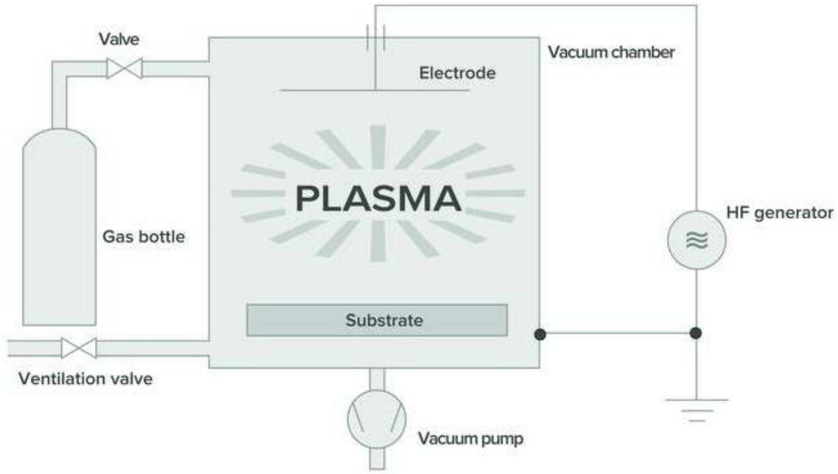


Glow in opposite corners of a flat anode placed under a rectangular magnetron

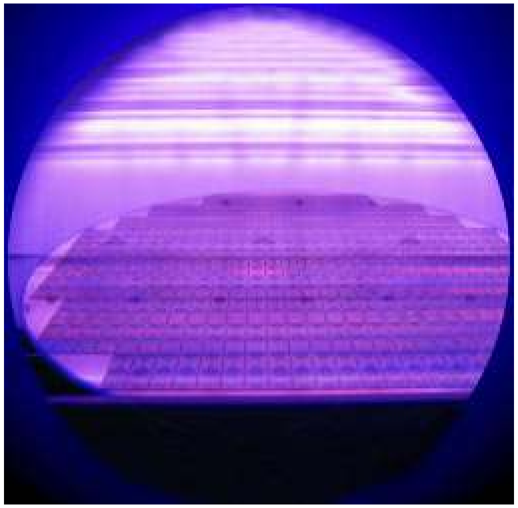


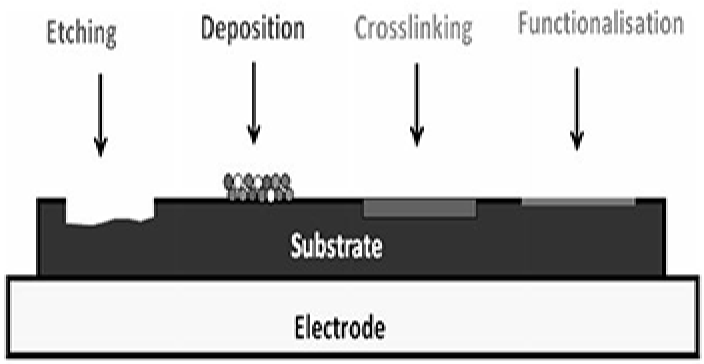
Glow in opposite corners of dual anodes placed on the sides of a rectangular magnetron

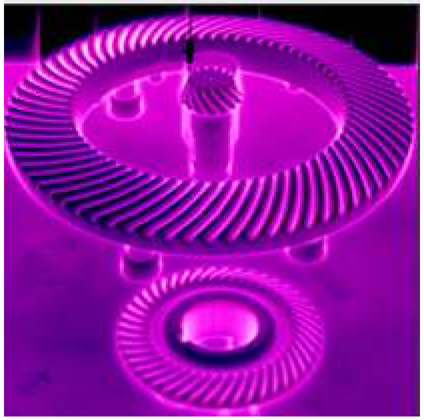
Low-Pressure, Low-Temperature Plasma Processing



Plasma processing of silicon for semiconductor manufacturing.







Plasma processing to harden or coat materials.

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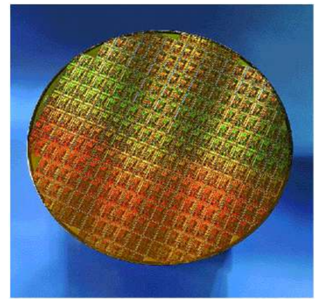
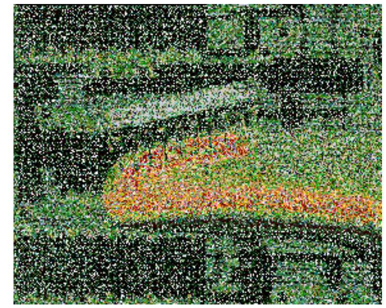
Plasmas are easier to be generated at low pressures

Low pressure plasmas
(1 mTorr ~ a few Torr)

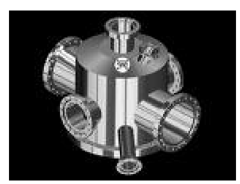
- are well understood
- are used extensively nowadays (e.g. in semiconductor industry for computer chips manufacturing)





However, to generate low pressure plasmas:

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

 +  +  = 

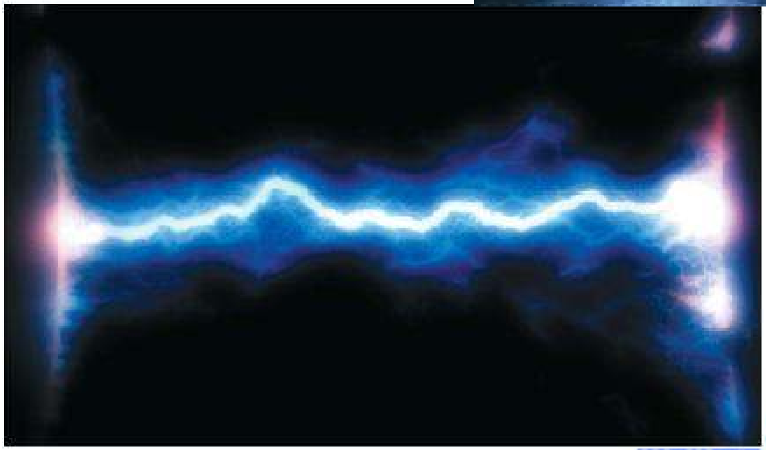
Generate Plasmas at Atmospheric Pressure!!

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 $2x10^4$ K
- Low voltage drop at cathode
- High cathode current density



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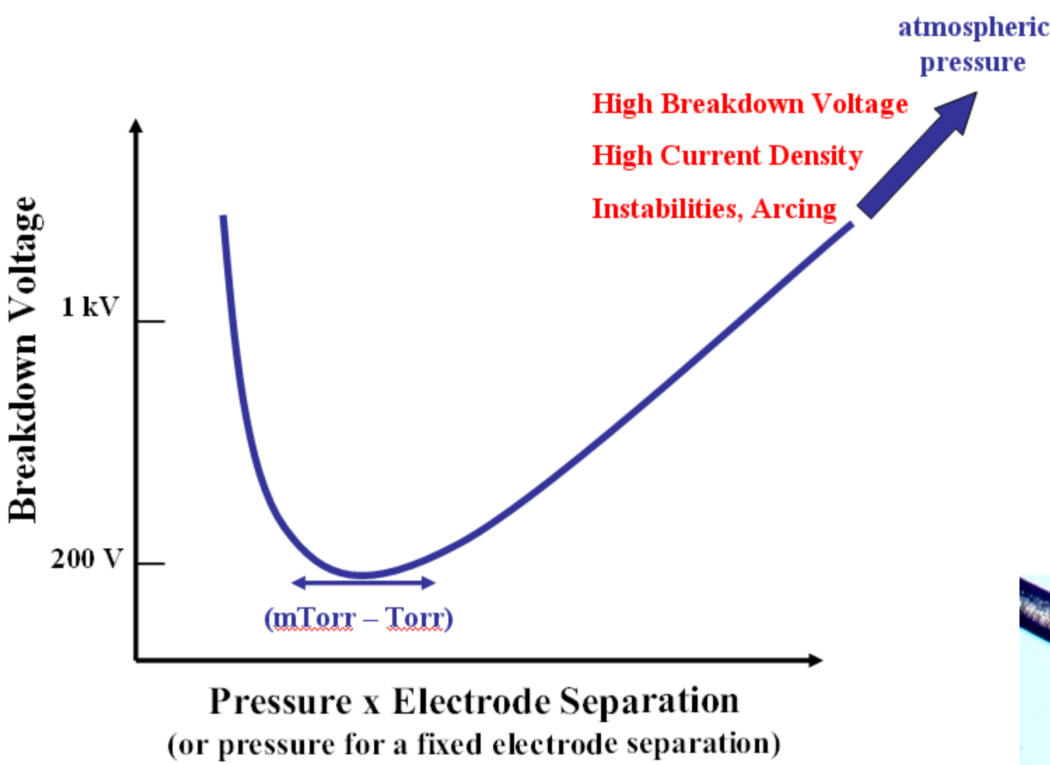
Atmospheric (or higher) Pressure: Microplasmas



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 create stable atmospheric pressure, low temperature plasmas?

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.

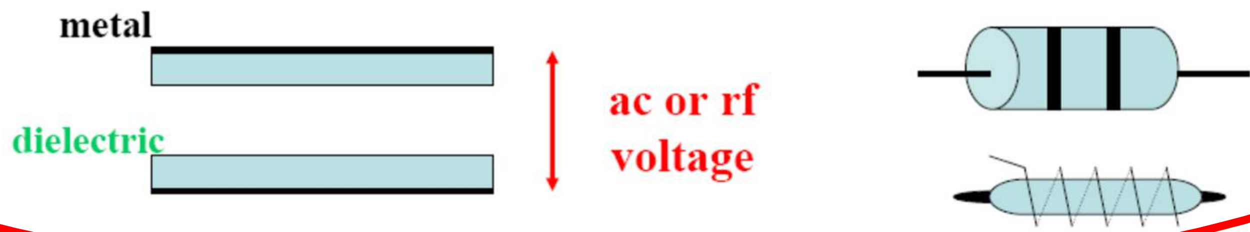
Micro-confinement: Gas heating occurs in the plasma volume, and the energy is carried away by thermal diffusion/convection to the outside. If the plasma has a small volume and a relatively large surface, gas heating is limited.

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.

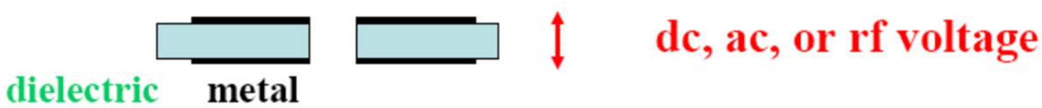
a.k.a **Microplasmas**

Some High Pressure microplasma reactors

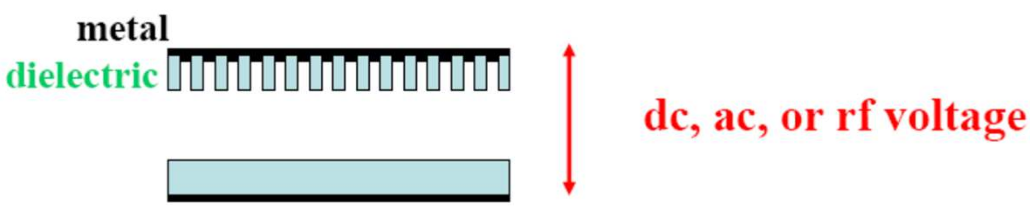
Dielectric barrier discharge configurations



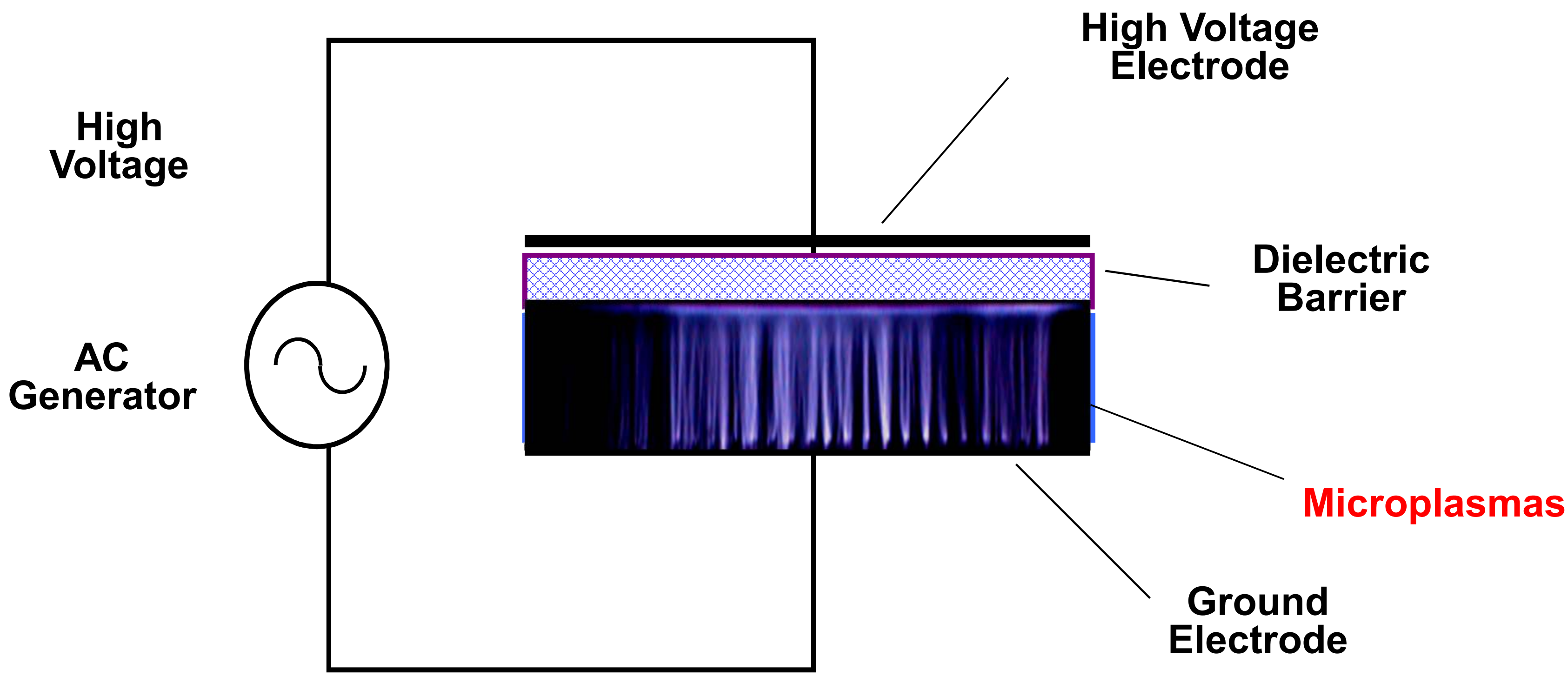
Microhollow cathode discharge configuration



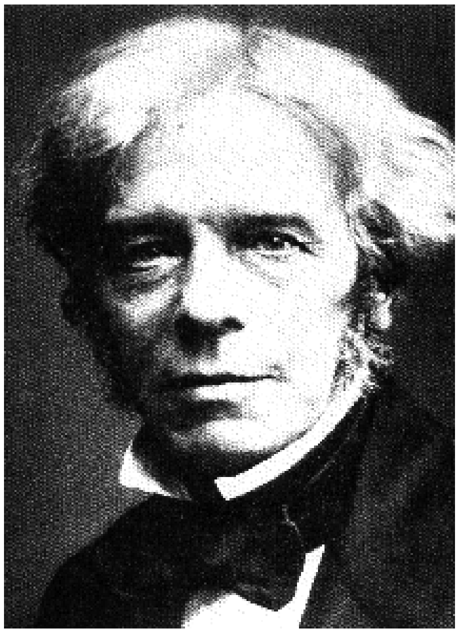
Capillary plasma electrode discharge configuration



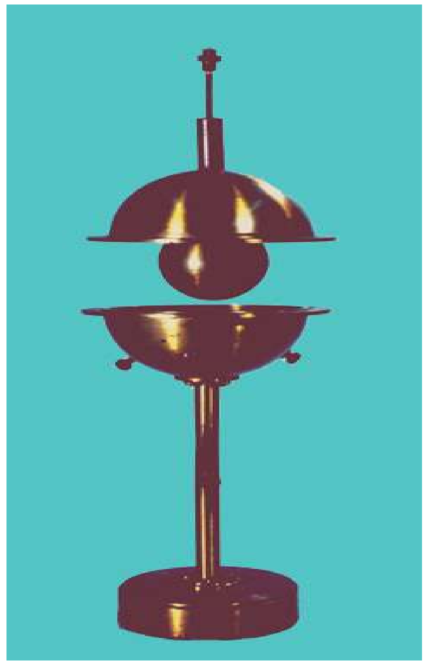
Atmospheric Pressure Cold Plasma



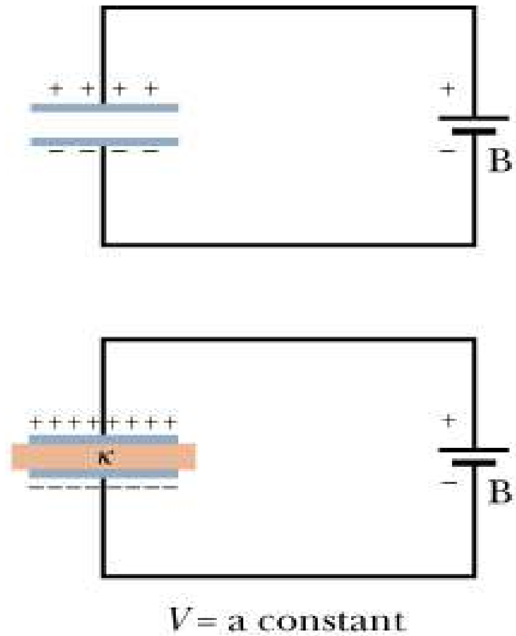
Faraday's Dielectric Capacitors



Michael Faraday (1781 – 1867)

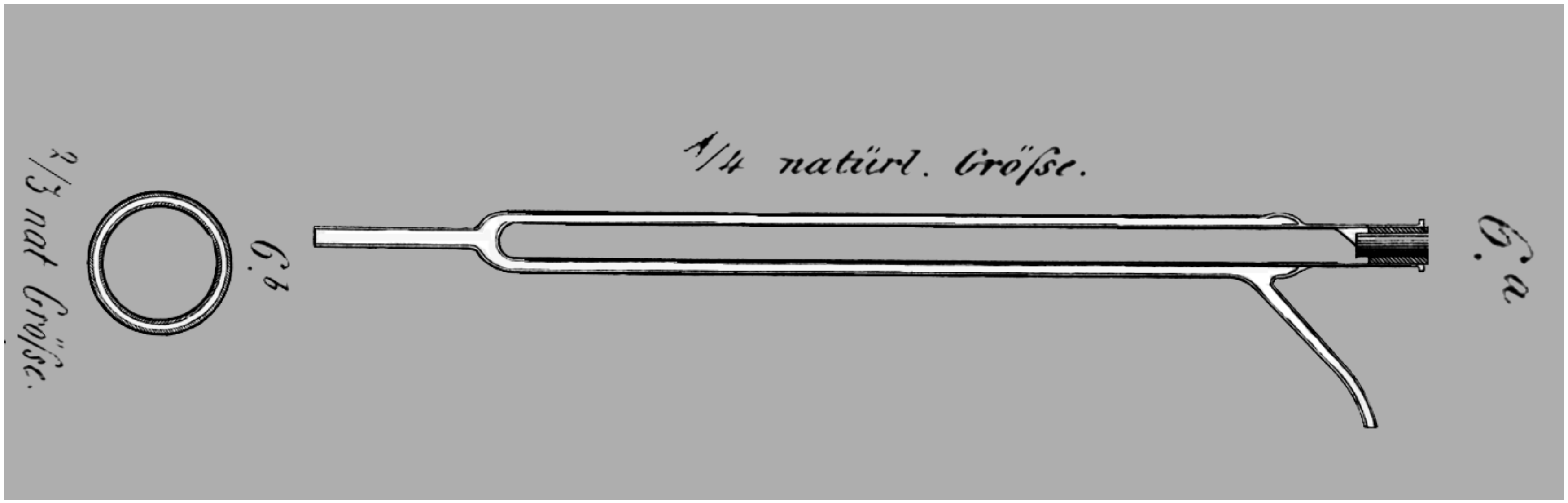


Faraday's Dielectric Capacitor
(circa 1837)



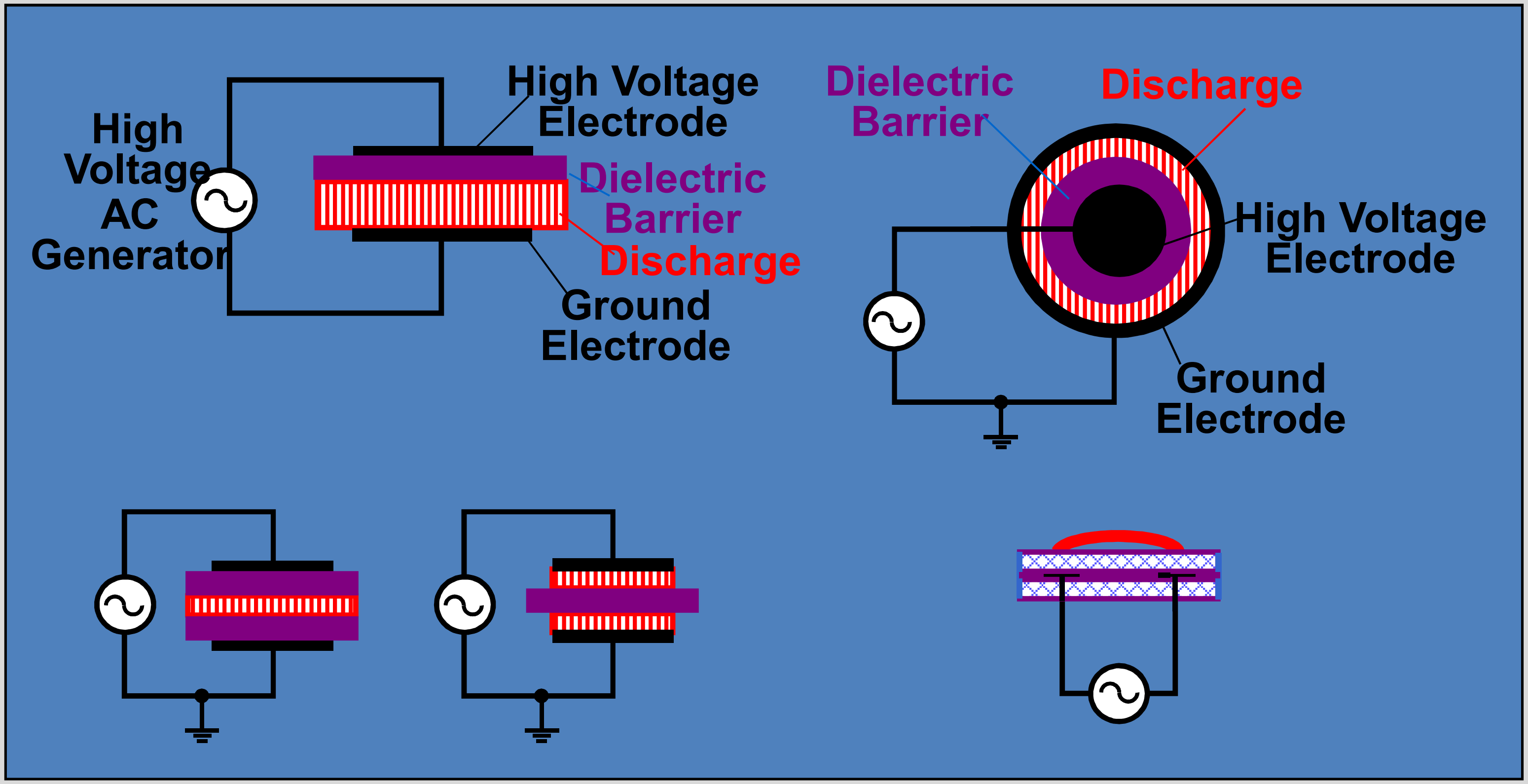
Capacitance INCREASED!

Historical Ozone Tube of W. Siemens (1857)



Werner v. Siemens
Poggendorf's Annalen der Chemie und Physik 102, 66 (1857)
"Ozone Production in an Atmospheric-Pressure Dielectric Barrier Discharge"

Dielectric Barrier Discharge



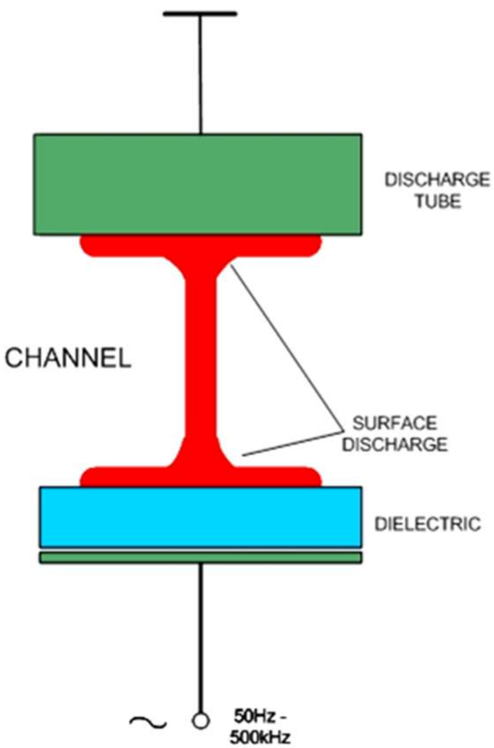
H.E. Wagner, R. Brandenburg, et. al. 'The barrier discharge: basic properties and applications to surface treatment'. *Vacuum*. 71 p417-436 (2003).

Typical operational conditions of barrier discharges

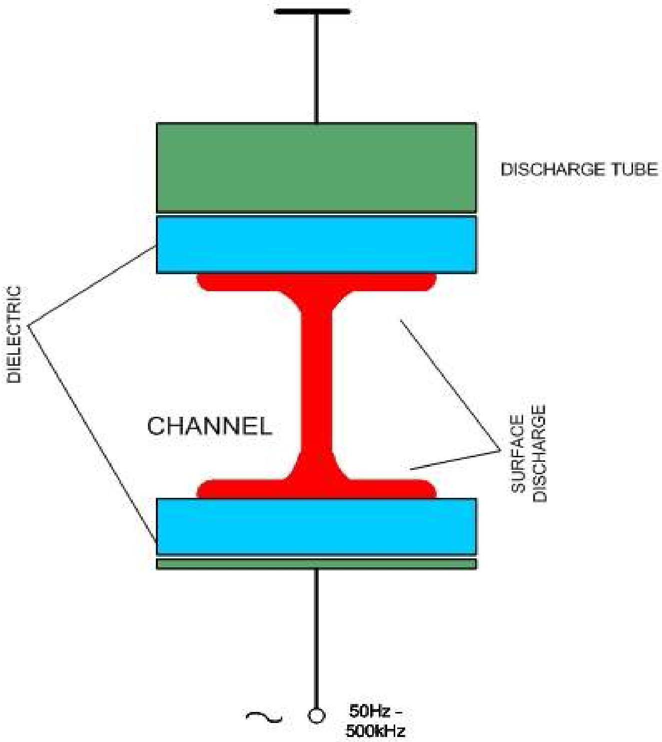
Electric field strength E of first breakdown	≈150 Td (p = 1bar, T=300 K)
Voltage V_{pp}	3–20 kV
Repetition frequency f	50 Hz–30 kHz
Pressure p	1–3 bar
Gap distance g	0.2–5mm
Dielectric material thickness d	0.5–2mm
Relative dielectric permittivity ε_r	5–10 (glass)

B. Eliasson and U. Kogelschatz. *IEEE Transactions Plasma Science*. Vol. 19 Issue 6, 1063-1077 (1991)

Single and double DBD



Single dielectric



Double dielectric

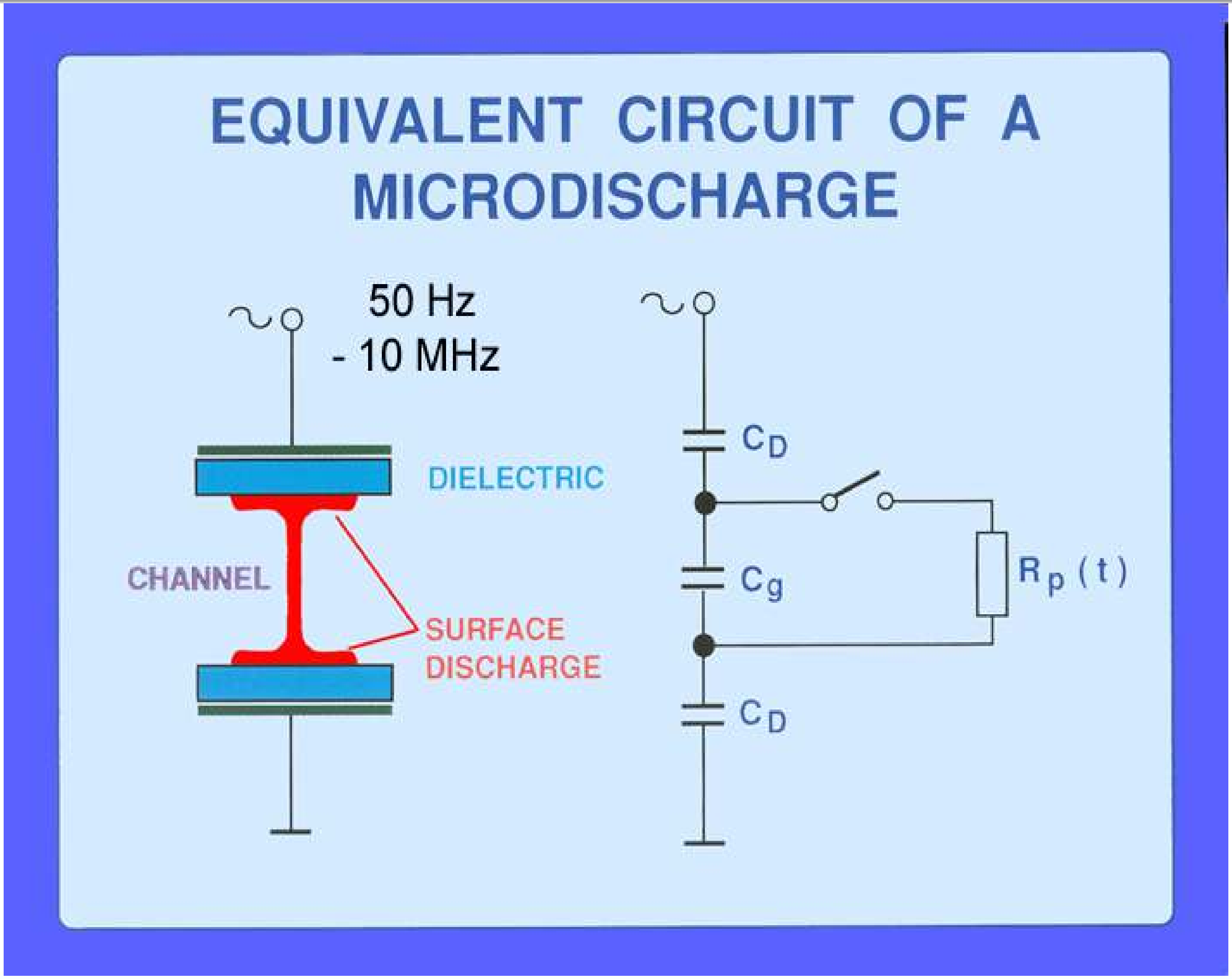
Role of the Dielectric (Insulator)

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

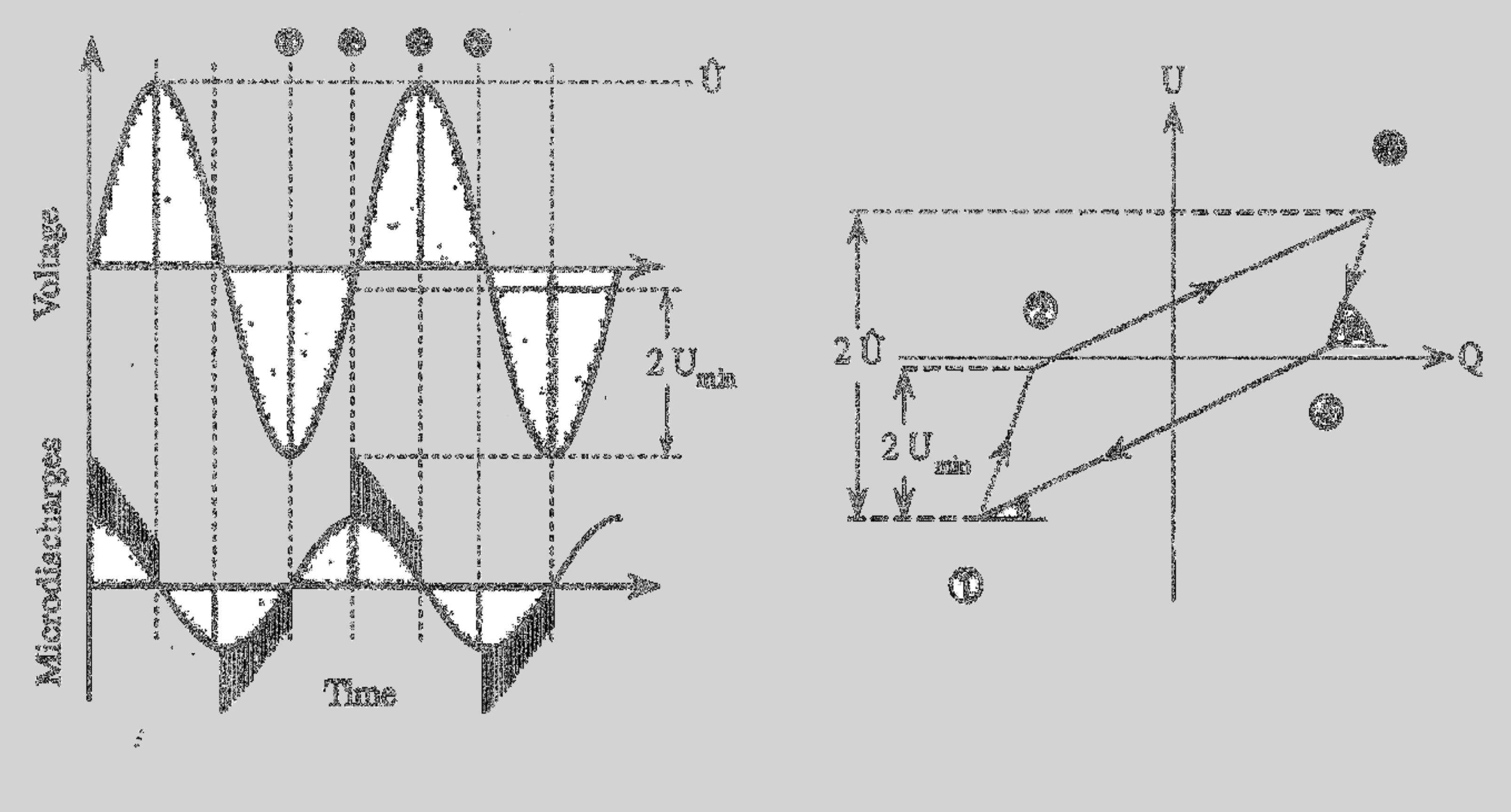
Serves two functions:

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

Equivalent Circuit of a Microdischarge



Microdischarge Activity and U-Q Lissajous Figure

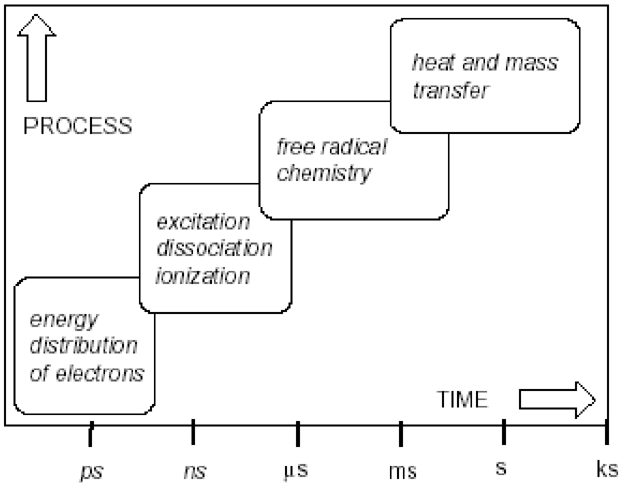


B. Eliasson and U. Kogelschatz. *IEEE Transactions Plasma Science*. Vol. 19 Issue 6, 1063-1077 (1991)

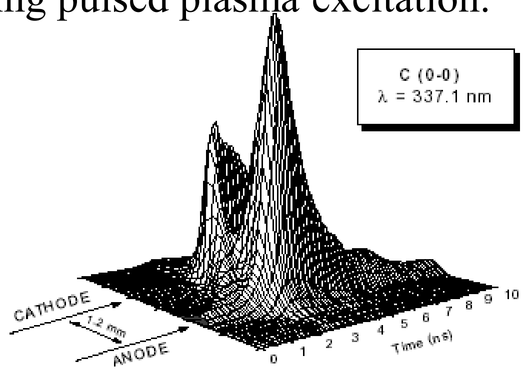
Fundamental Operation of the Dielectric Barrier Discharge

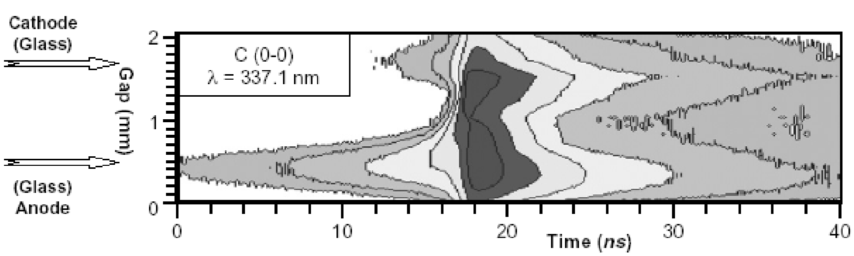
- Many of relevant plasma processes that are of importance to achieving our goal occur on time scales that allow us to study them.

- Optical emission spectroscopic studies will allow us to determine the temporal and spatial development of important plasma species such as radicals (OH, NO, various oxygen radicals) with high time resolution (less than 10 ns) and a spatial resolution on the scale of mm in the plasma volume following pulsed plasma excitation.



Time scale of the relevant processes of the DBD.





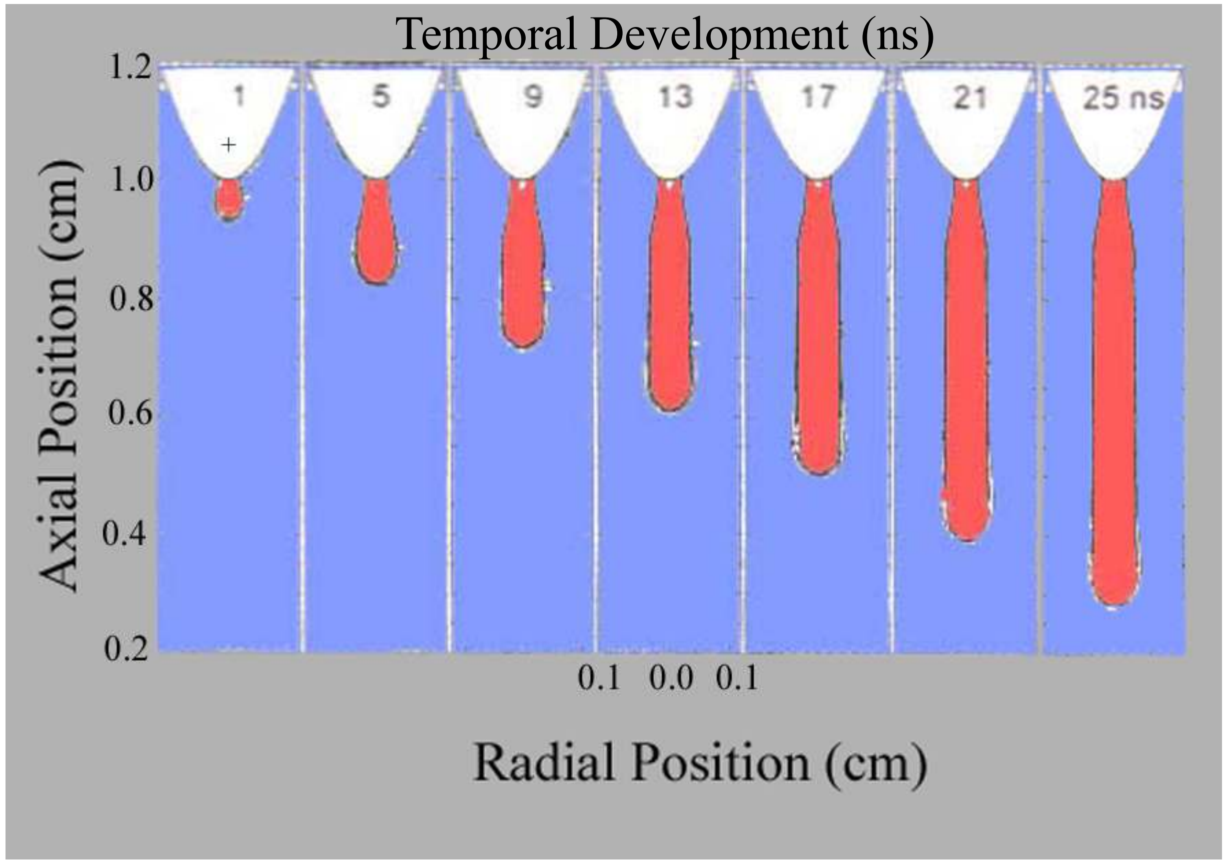
H.E. Wagner, R. Brandenburg, et. al. 'The barrier discharge: basic properties and applications to surface treatment'. *Vacuum.* 71: 417-436 (2003).

Fundamental Operation of the DBD

Electron Density

Outer Contour Line
$n_e = 10^{10}$ cm^{-3}

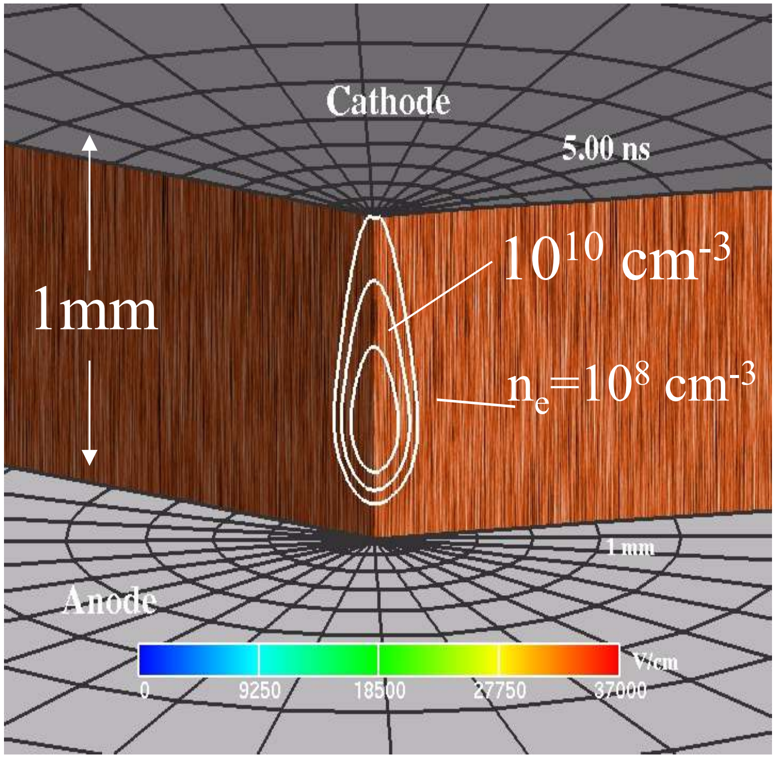
Inner Contour Line
$n_e = 10^{14}$ cm^{-3}



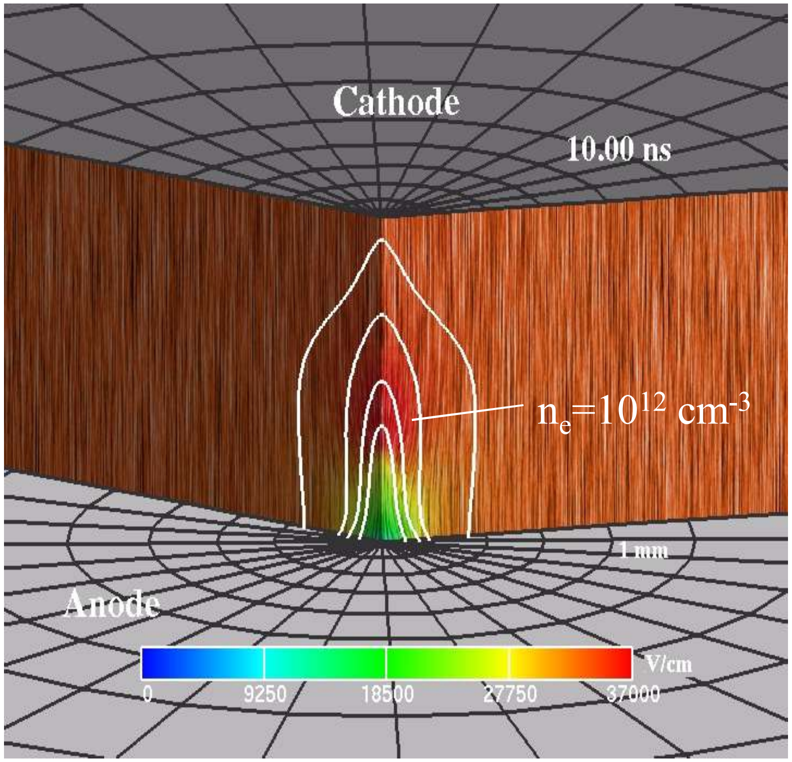
Streamer Propagation in 1 bar Air
A.A. Kulikovsky, IEEE Trans. Plasma Sci. **25** 439-446 (1997).

Numerical Results of Microdischarge Formation in Dielectric Barrier Discharges

Starting Phase of a Microdischarge (1 bar: 20% CO_2 / 80% H_2)



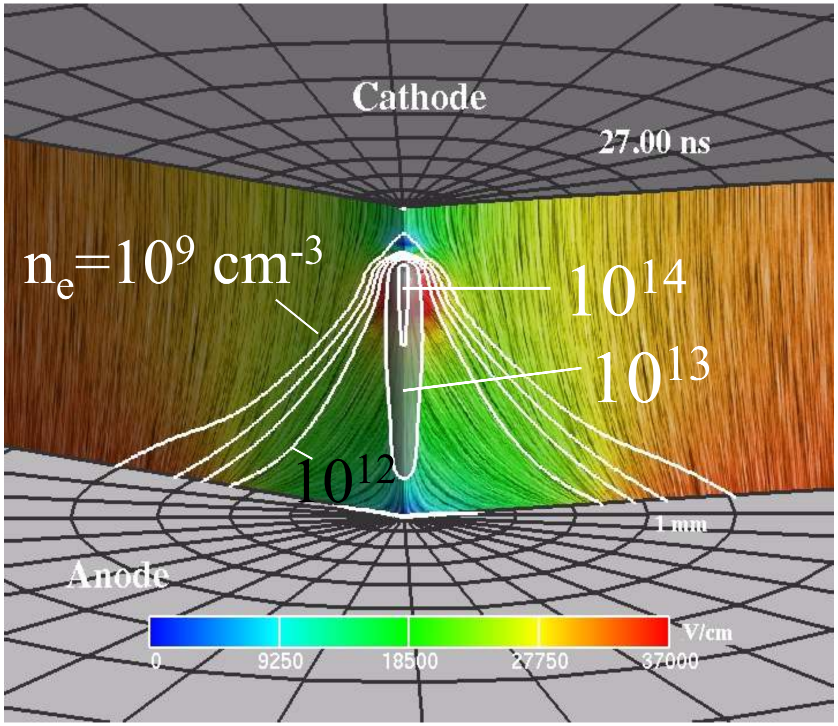
An electron avalanche propagates towards the anode



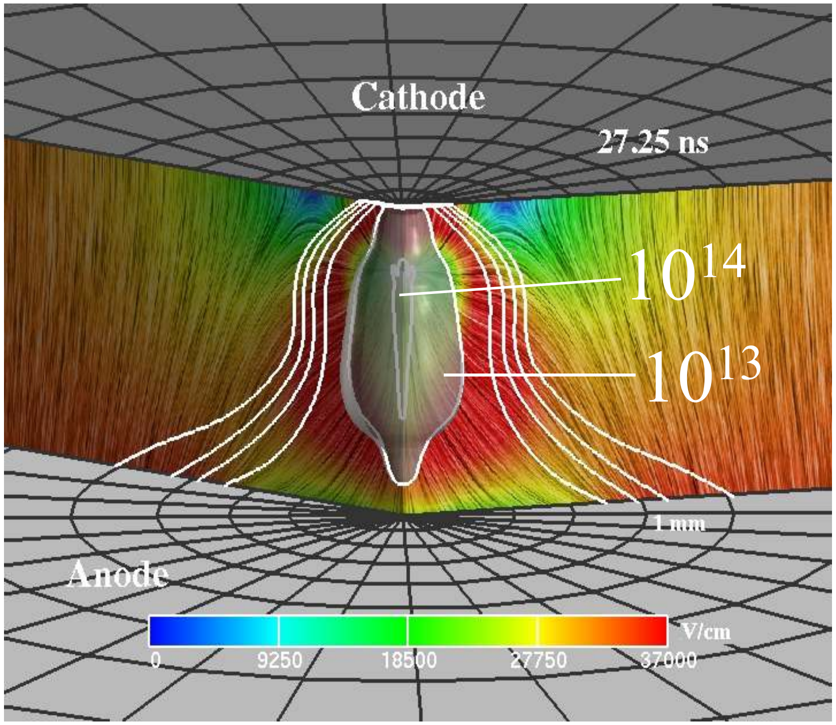
Reverse propagation towards the cathode

Numerical Results of Microdischarge Formation in Dielectric Barrier Discharges

Cathode Layer Formation



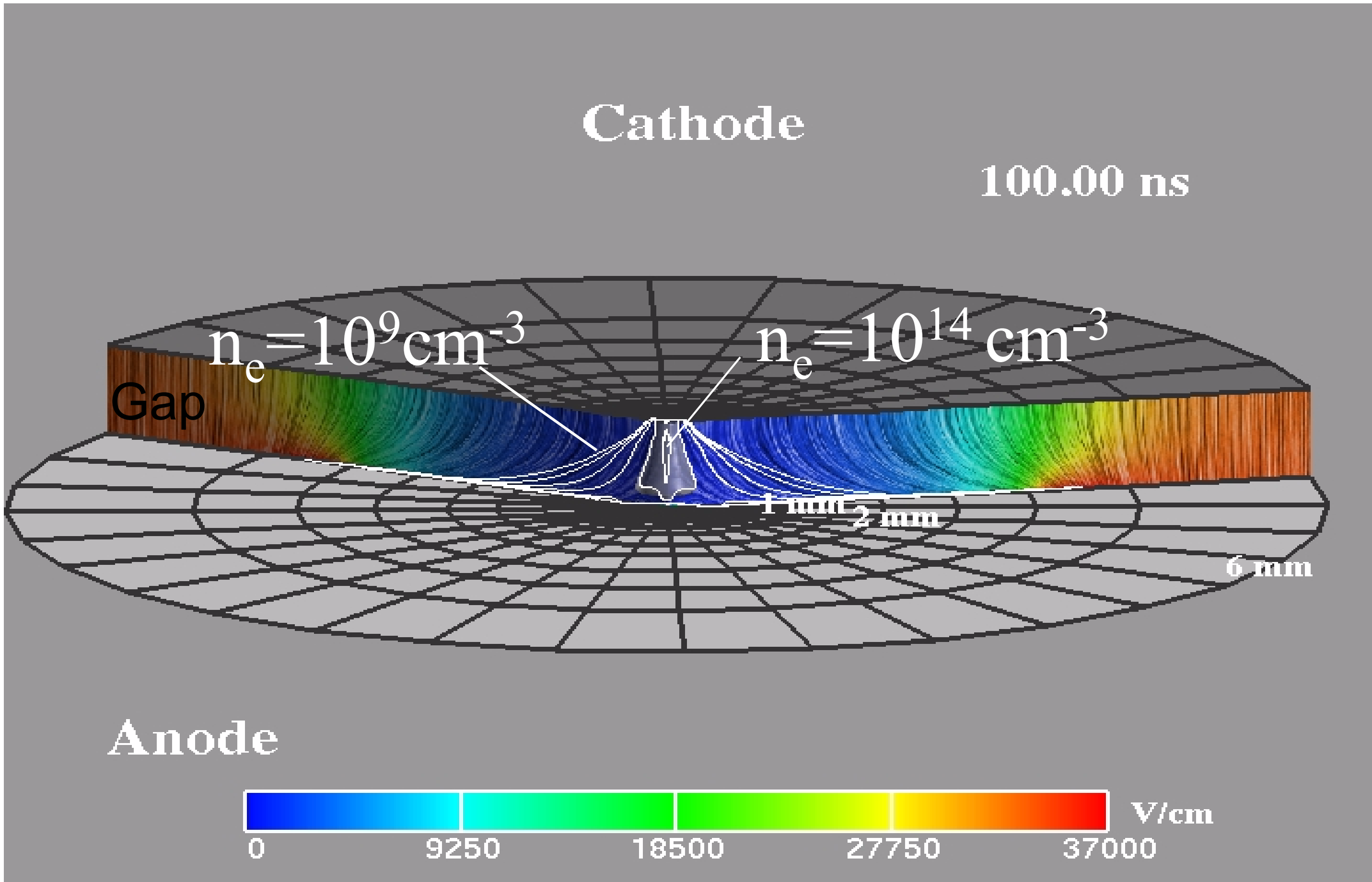
Just before the peak of the total current



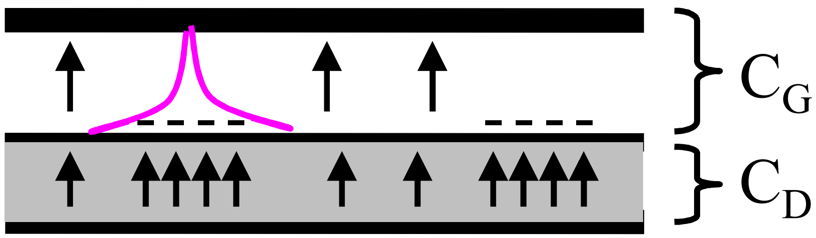
Peak current

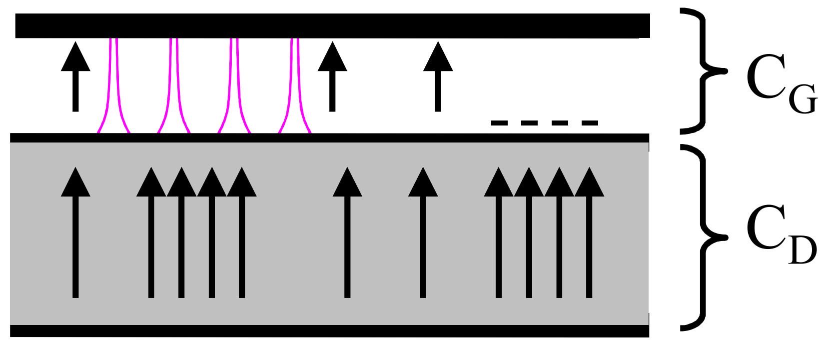
Numerical Results of Microdischarge Formation in Dielectric Barrier Discharges

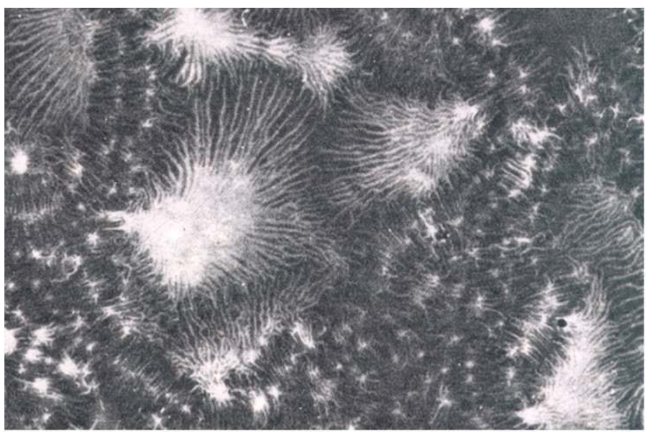
Local Field Collapse in Area Defined by Surface Discharge

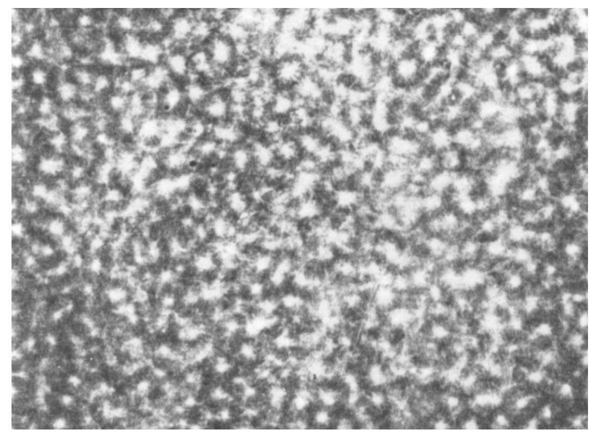


Principals of DBD Microplasmas



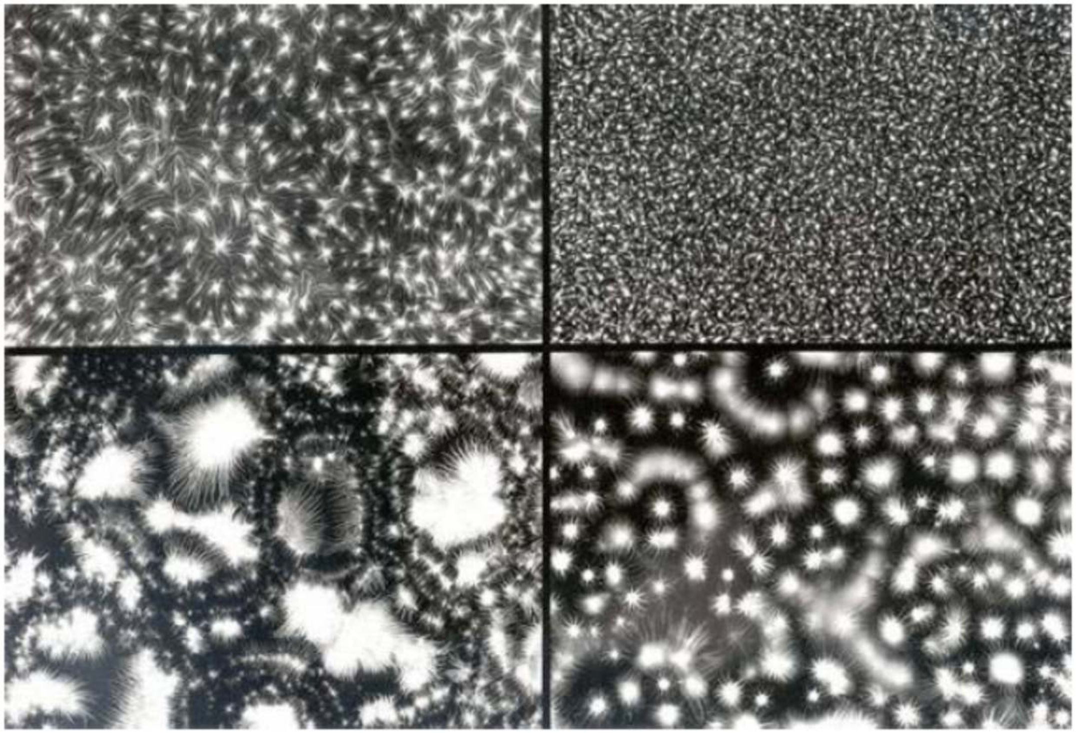






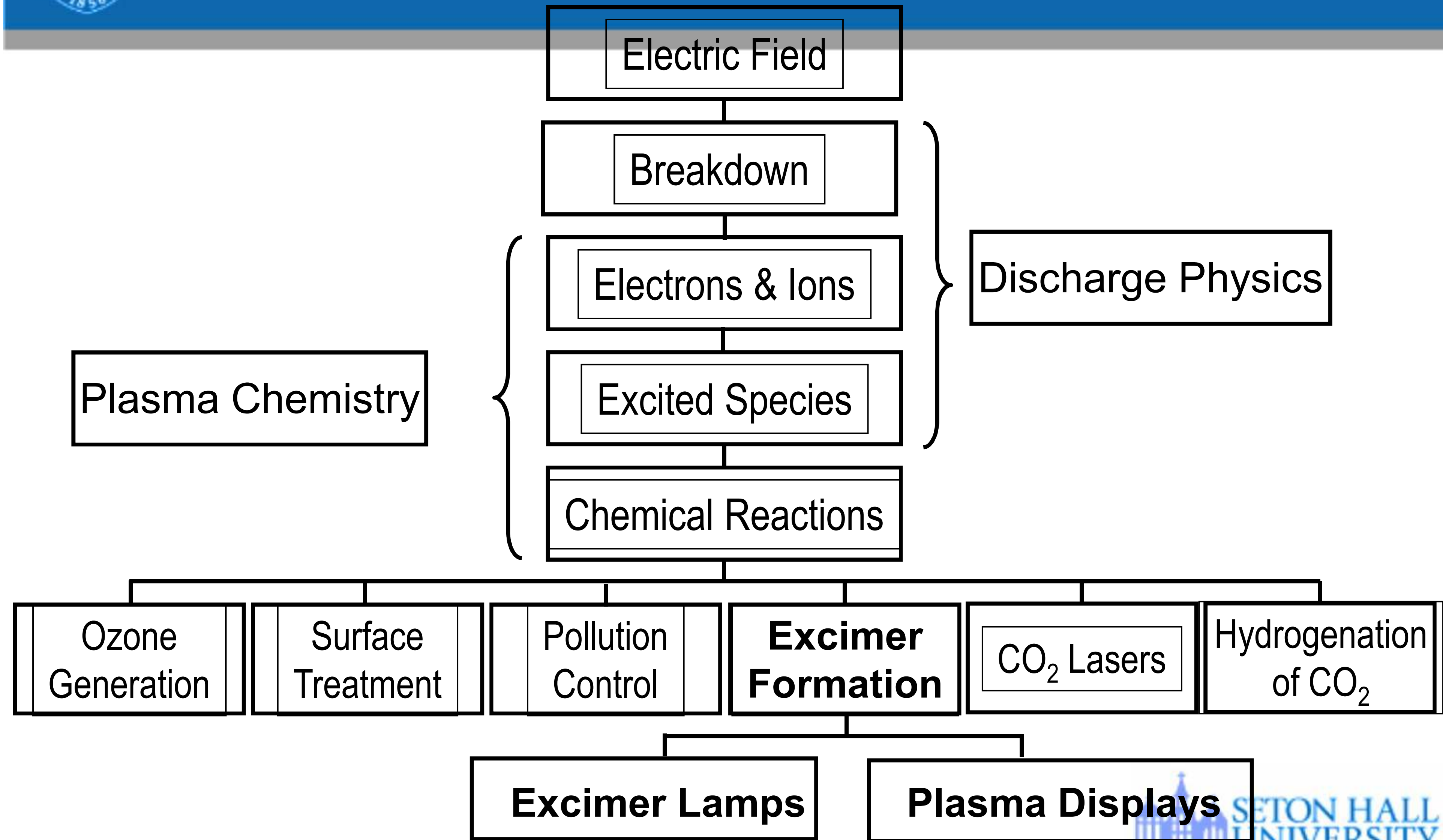
Principals of DBD Microplasmas

Four Different Gap Widths

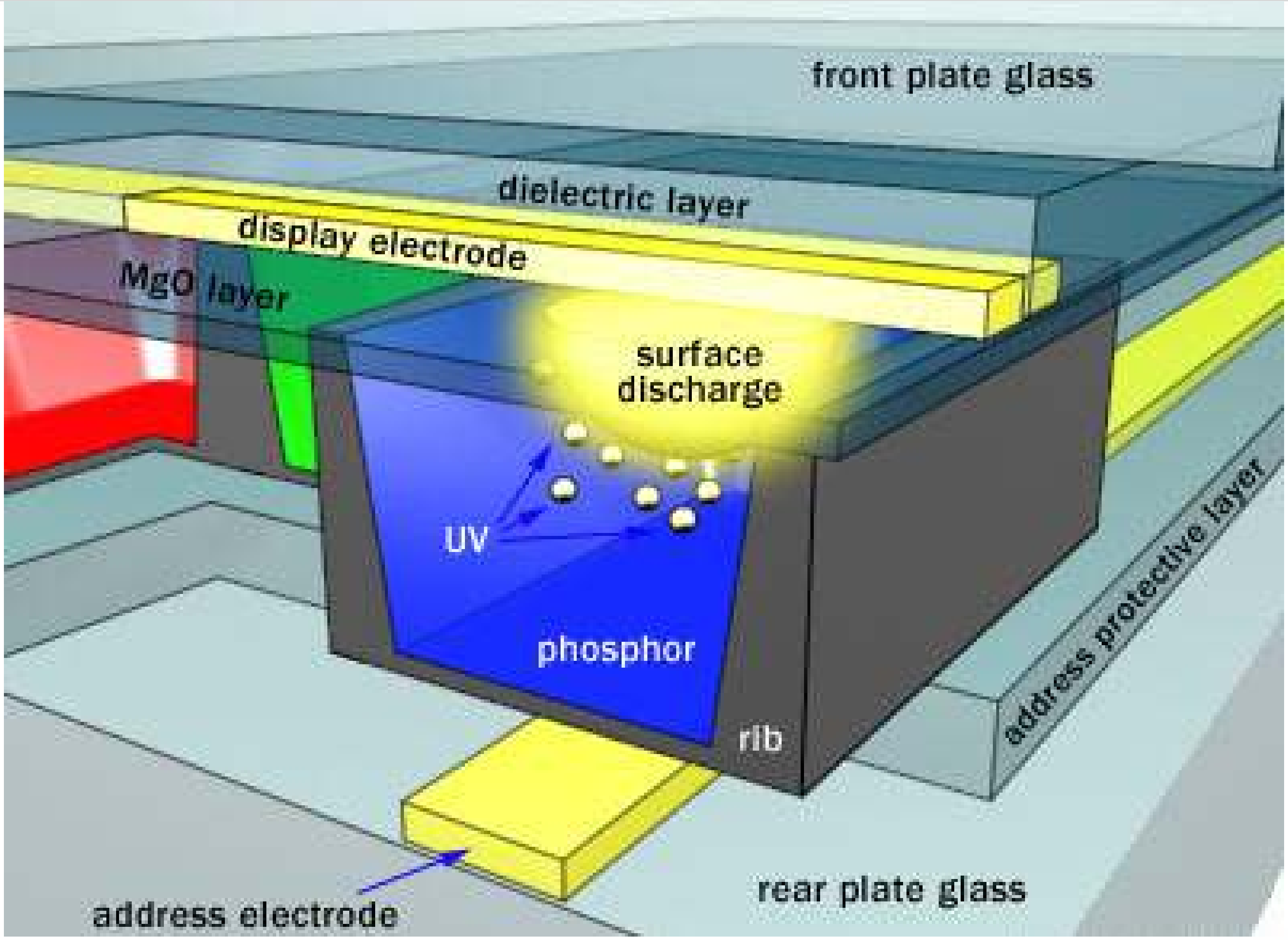


B. Eliasson and U. Kogelschatz. *IEEE Trans Plasma Sci*. 19(2) p309 (1991)

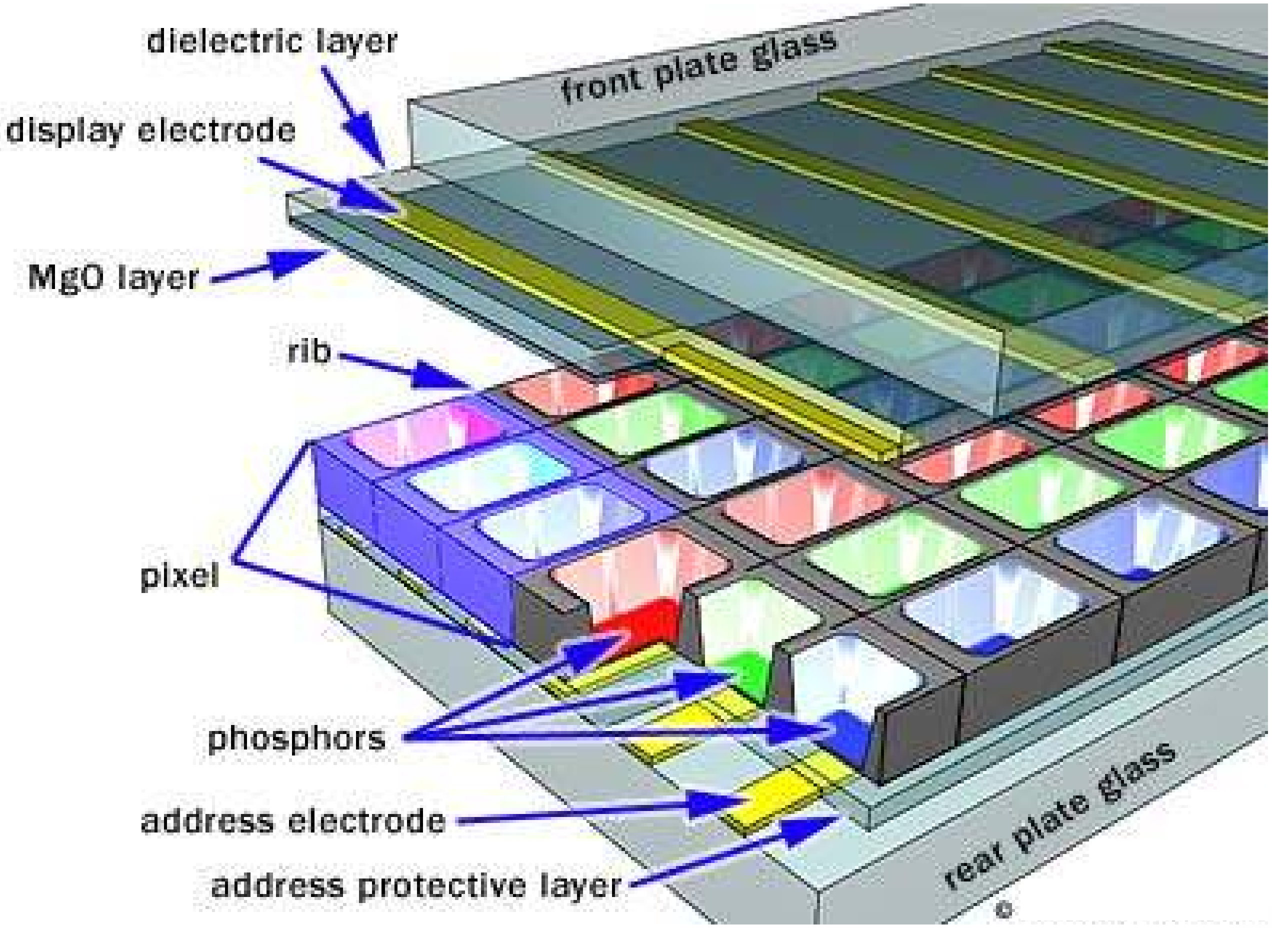
Dielectric Barrier Discharge (DBD)



How A Plasma Display Works!



How A Plasma Display Work!

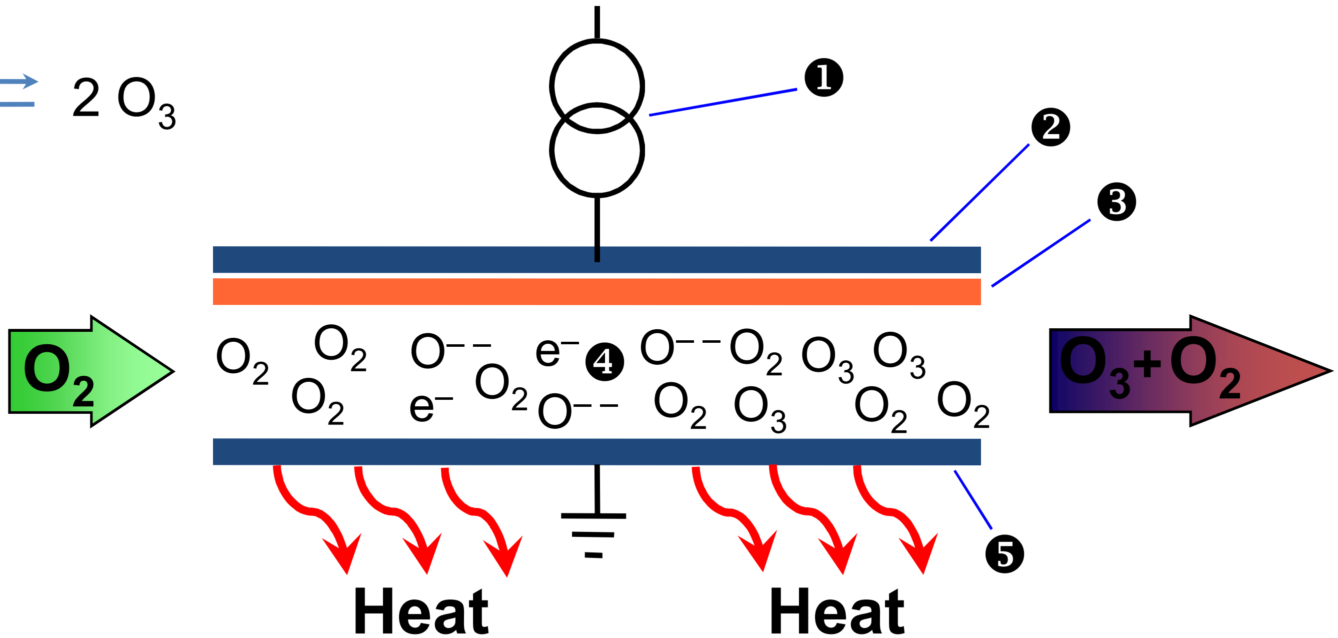


Plasma Display Televisions

Ozone Generator

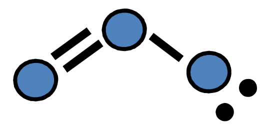
Dielectric Barrier Discharge

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



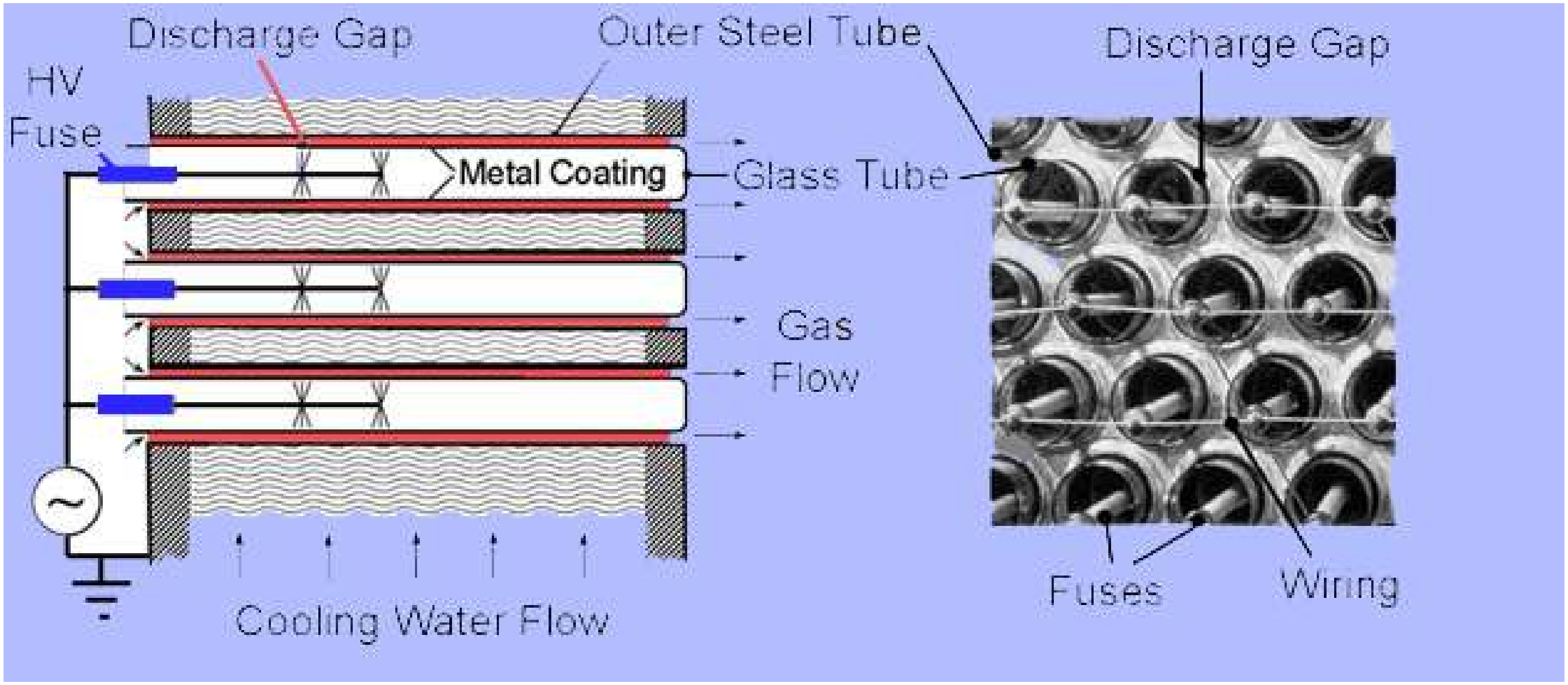
Properties of Ozone (O_3)

- 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

Discharge Tubes in Ozone Generators

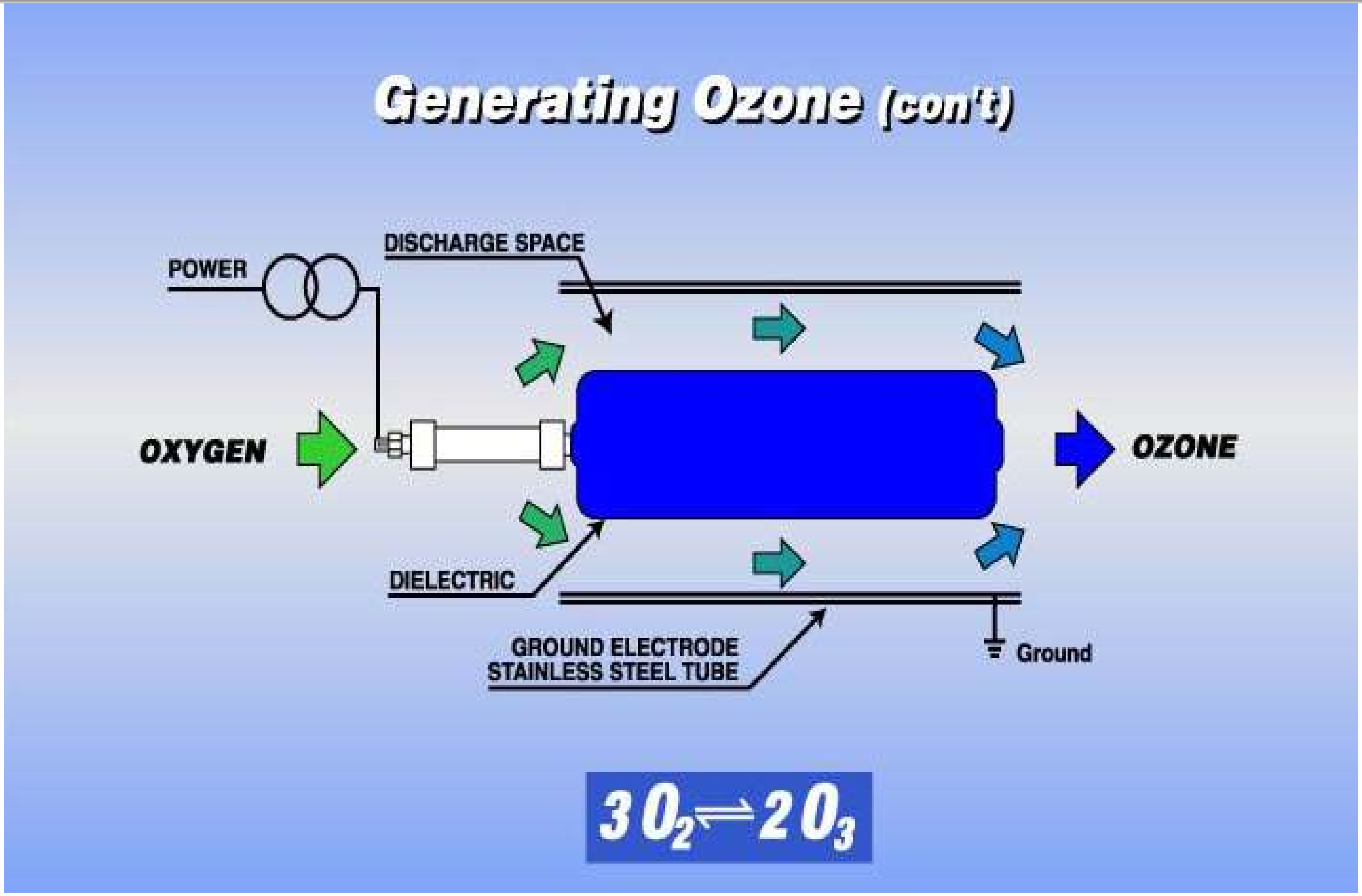


Traditional

Ozone Generator

with Glass Tubes

Generation of Ozone



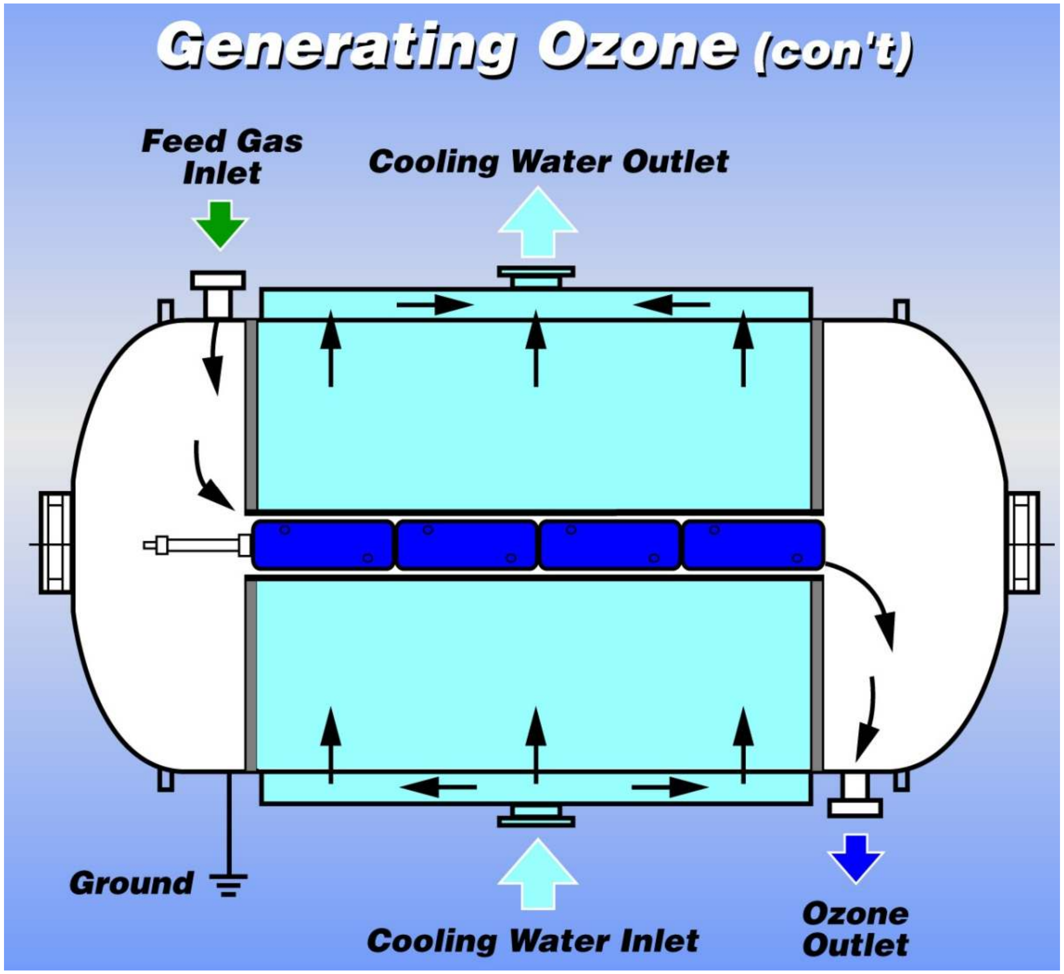
Generation of Ozone

Advantages of Enamel Dielectrics

Proven, Patented Design

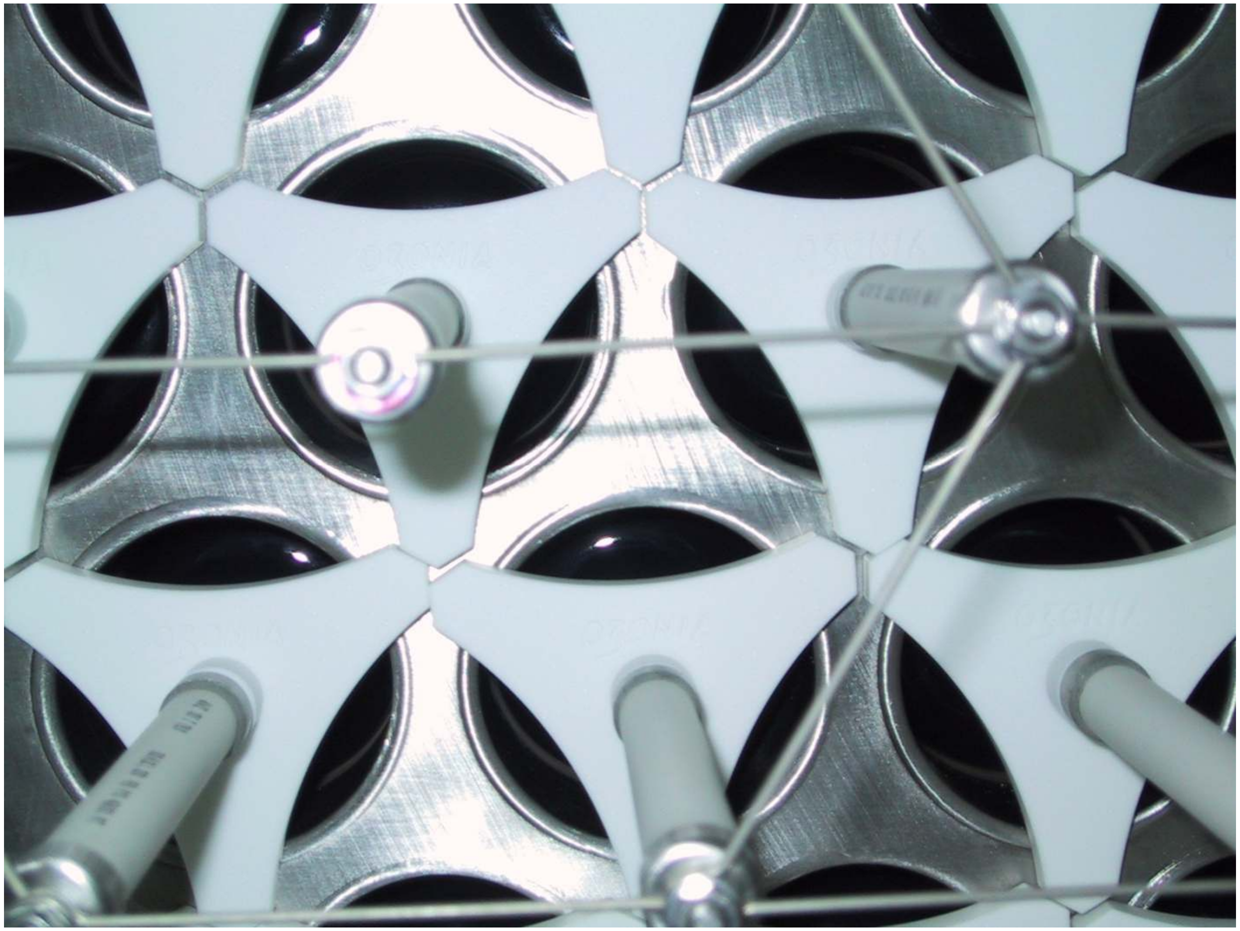
- Simplicity
- Single Dielectric Component
  - Reduced number of Dielectrics
- Safety
  - Lower operating voltage (< 4000 V)
- Reliabilty
  - Fused Dielectrics ensure continuous production
- ***Lowest Power Consumption – Operational Savings!***

Modern Ozone Generator



Ozonia Advanced Technology Ozone Generator

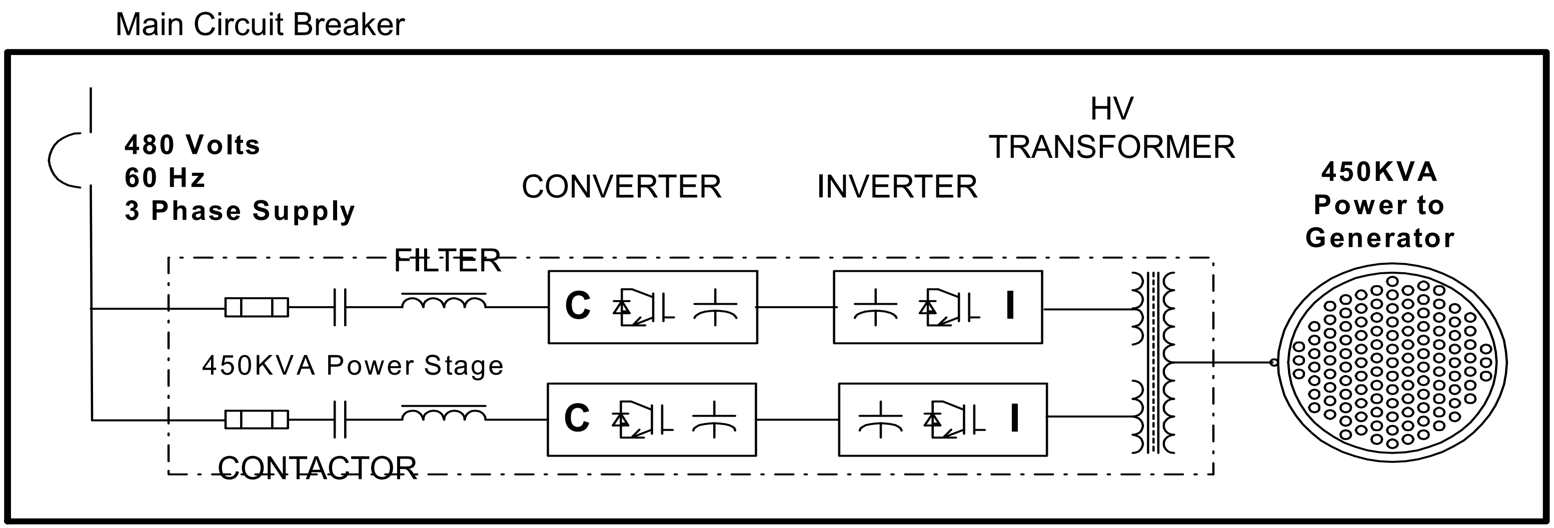
Generation of Ozone



Generation of Ozone

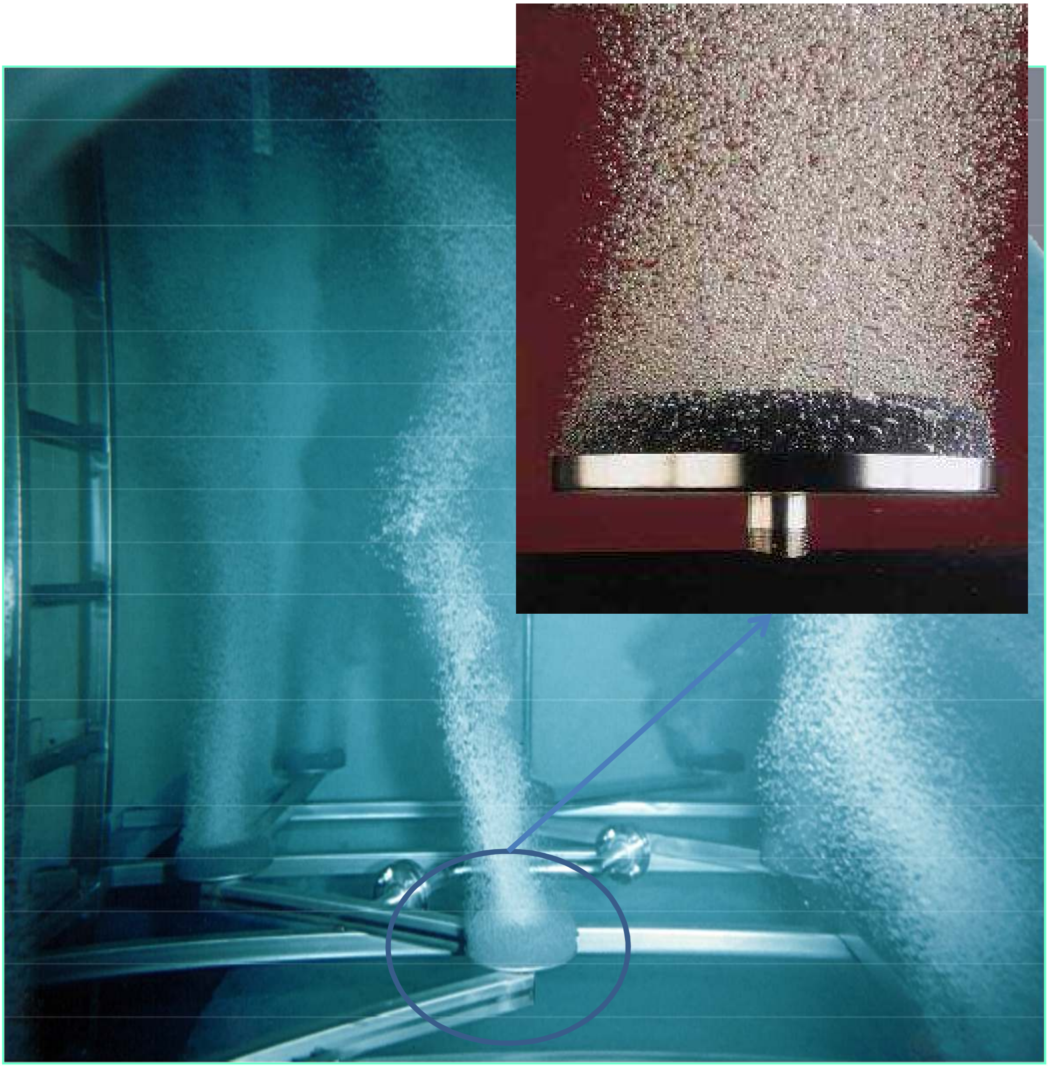
Power Supply Unit

IGBT Inverter Circuit



- **Latest in Power Semiconductor Technology, Modular Design**
- **Utilizes IGBT's (Insulated Gate Bi-Polar Transistors) Converter and Inverter Components**

Ozone Water Treatment



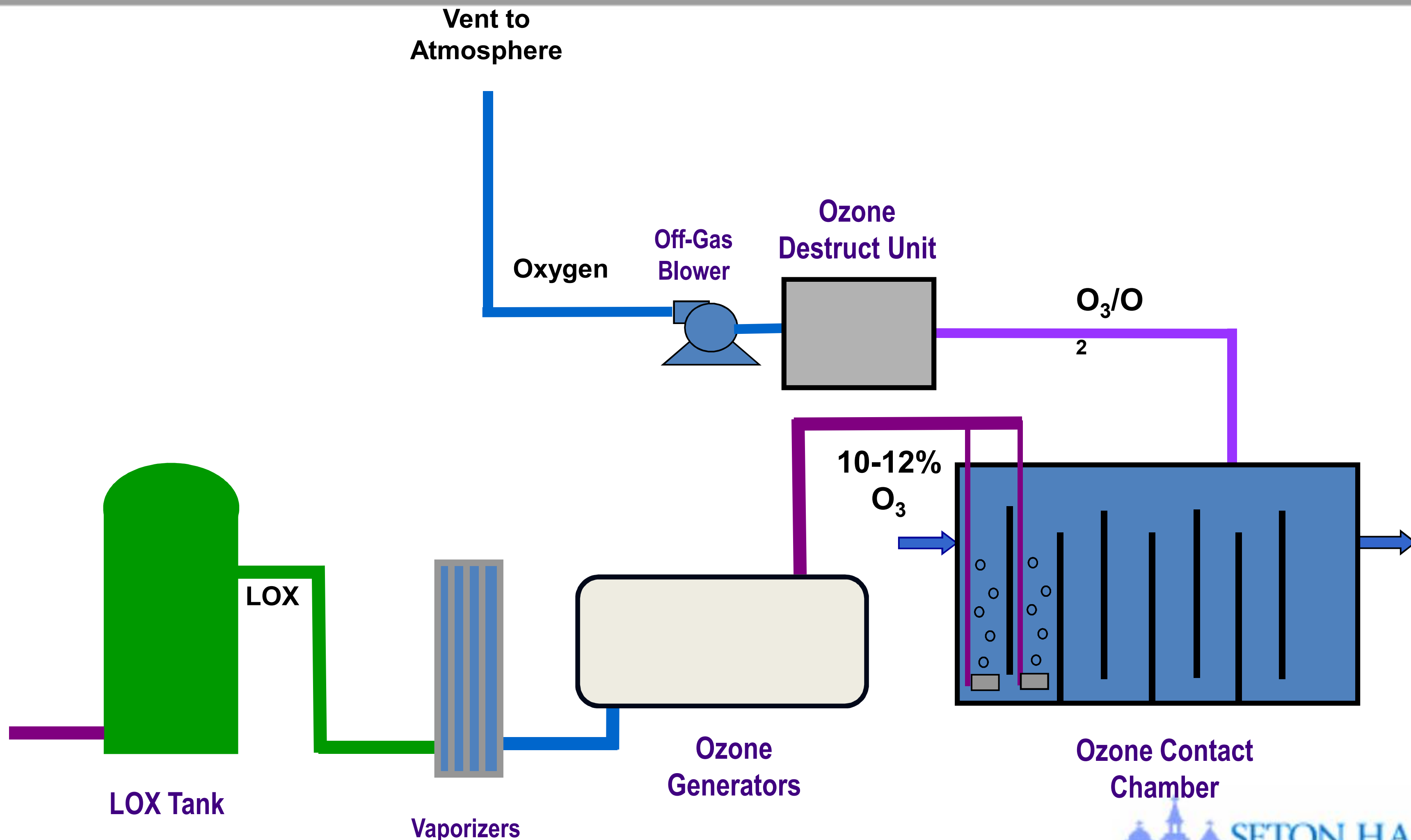
Bubble Diffusion

Easy to use

Low energy usage

Mass transfer efficiencies to > 90%

Ozone Process Flow Diagram



Municipal Ozone Installations

Key Ozonia Installations (Partial List)

Ozonia Installations	Ozone Plant Size [lb/day]	Start-Up Date
Los Angeles, CA	**10,000**	**1986**
Fairfax, VA – Corbalis	**9,000**	**2003**
MWD, CA – Mills	**9,000**	**2003**
Fairfax Co., VA – Griffith	**9,000**	**2004**
MWD, CA – Jensen	**18,750**	**2005**
Indianapolis, IN – *Belmont AWT*	***12,000***	***2007***
Indianapolis, IN – *Southport AWT*	***12,000***	***2007***
MWD, CA – Diemer	***13,400***	***2008***
MWD, CA – Weymouth	***13,400***	***2009***

Ozonia North America - Potable Water Summary

Total Number of Installations: 90

Total Installed Production: > 265,000 lbs/day

Ozone Water Treatment

MWD Mills WTP - California

3 x 3,000 lbs/day of ozone

How do you optimize an ozone generator?

Scientific Approach

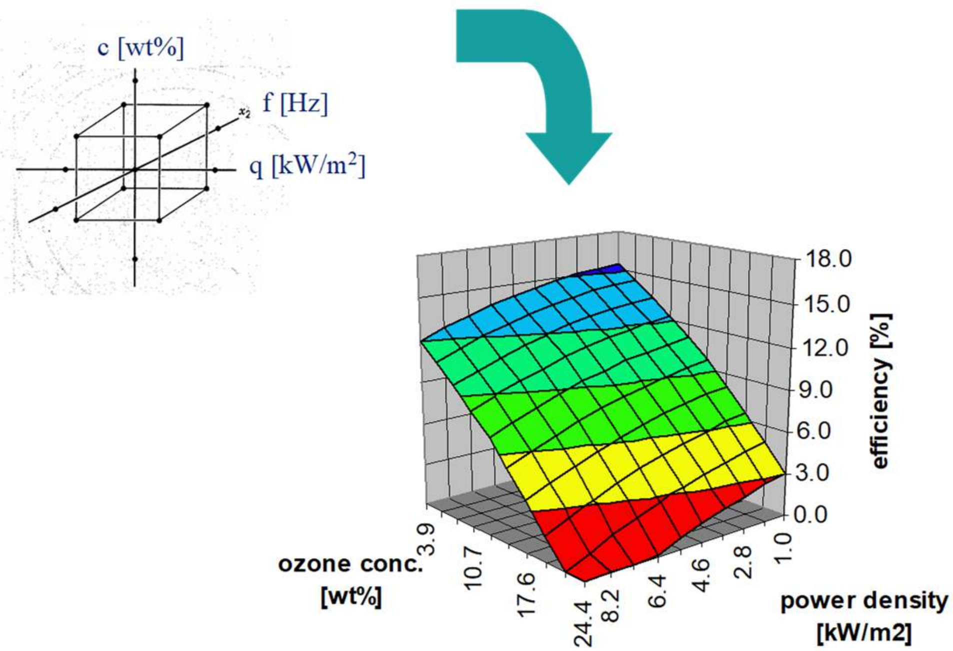
Theoretical

$$P = \alpha \cdot 4f \sum_{i=1}^{n} C_{D,i} \frac{1}{1+\beta_i} U_{min,i}\left(U_{peak} - U_{min,i}\right) \quad [kW]$$

where

i	:	i^{th} slice
n	:	amount of slices per cylinder []
Upeak	:	peak voltage [V]
Umin,i	:	minimum voltage i^{th} slice [V]
f	:	frequency [Hz]
$C_{D,i}$	:	capacitance of dielectrics i^{th} slice [F]
α	:	adjustable parameter [0,∞]
β_i	:	$C_{G,i}/C_{D,i}$ []

Experimental



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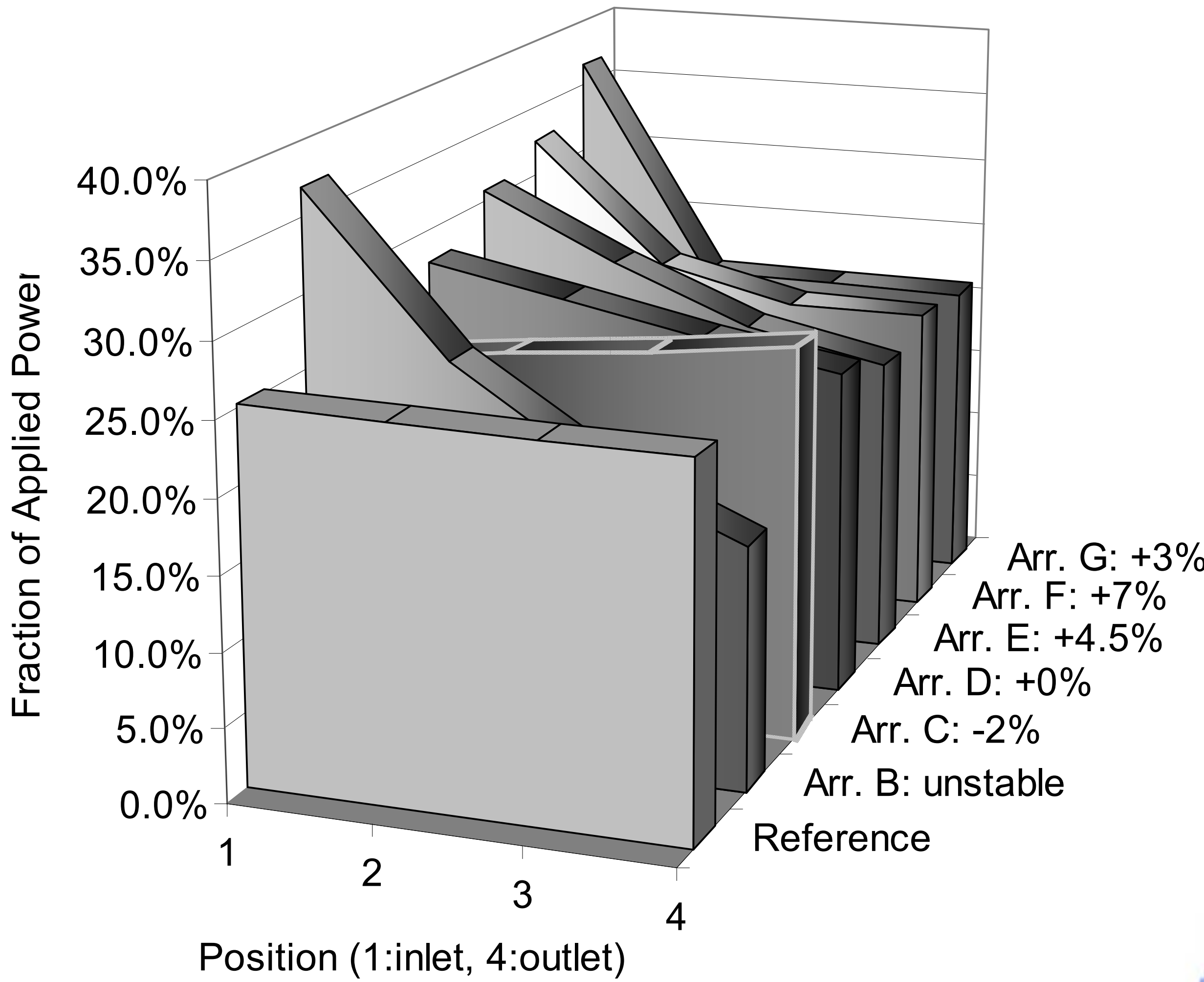
Impact of Power Induction

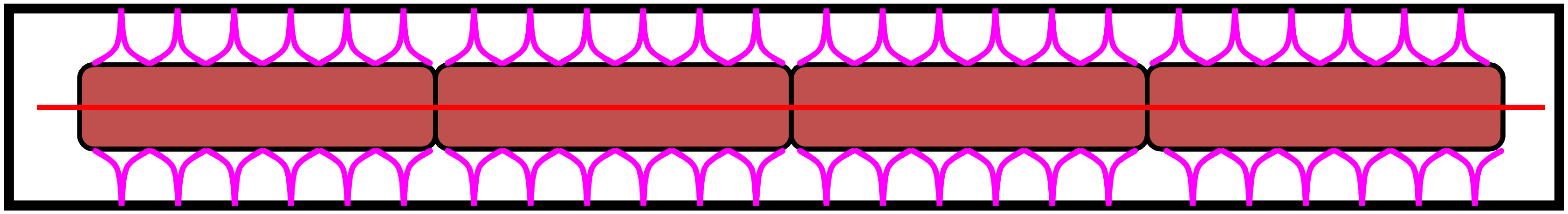


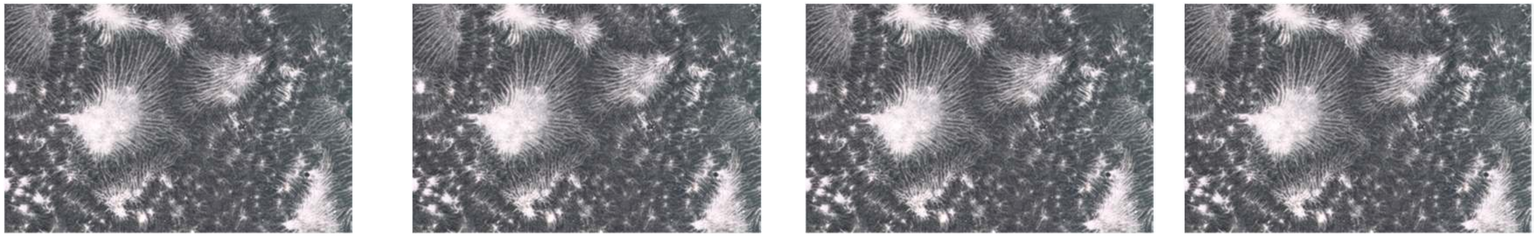
Experimental Test Rig

Experimental Test Rig

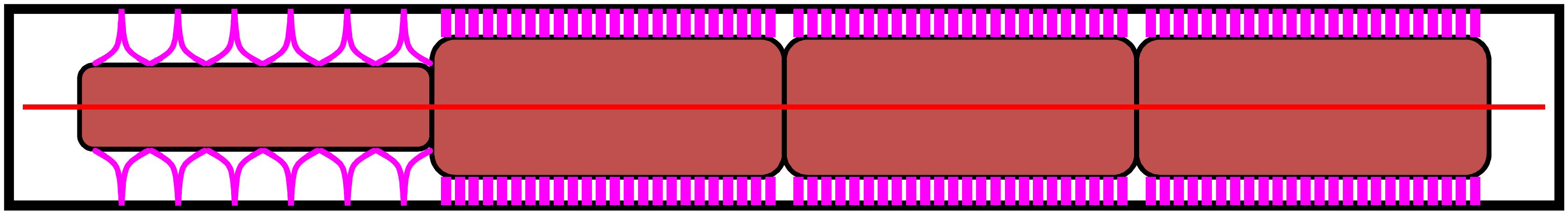
Outer grounded electrode (left picture) and the dielectric covered inner electrodes (right).

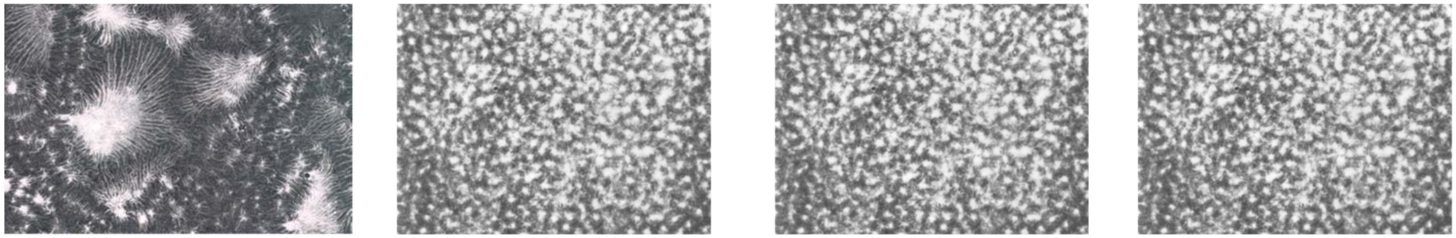
Reference (Traditional) Arrangement



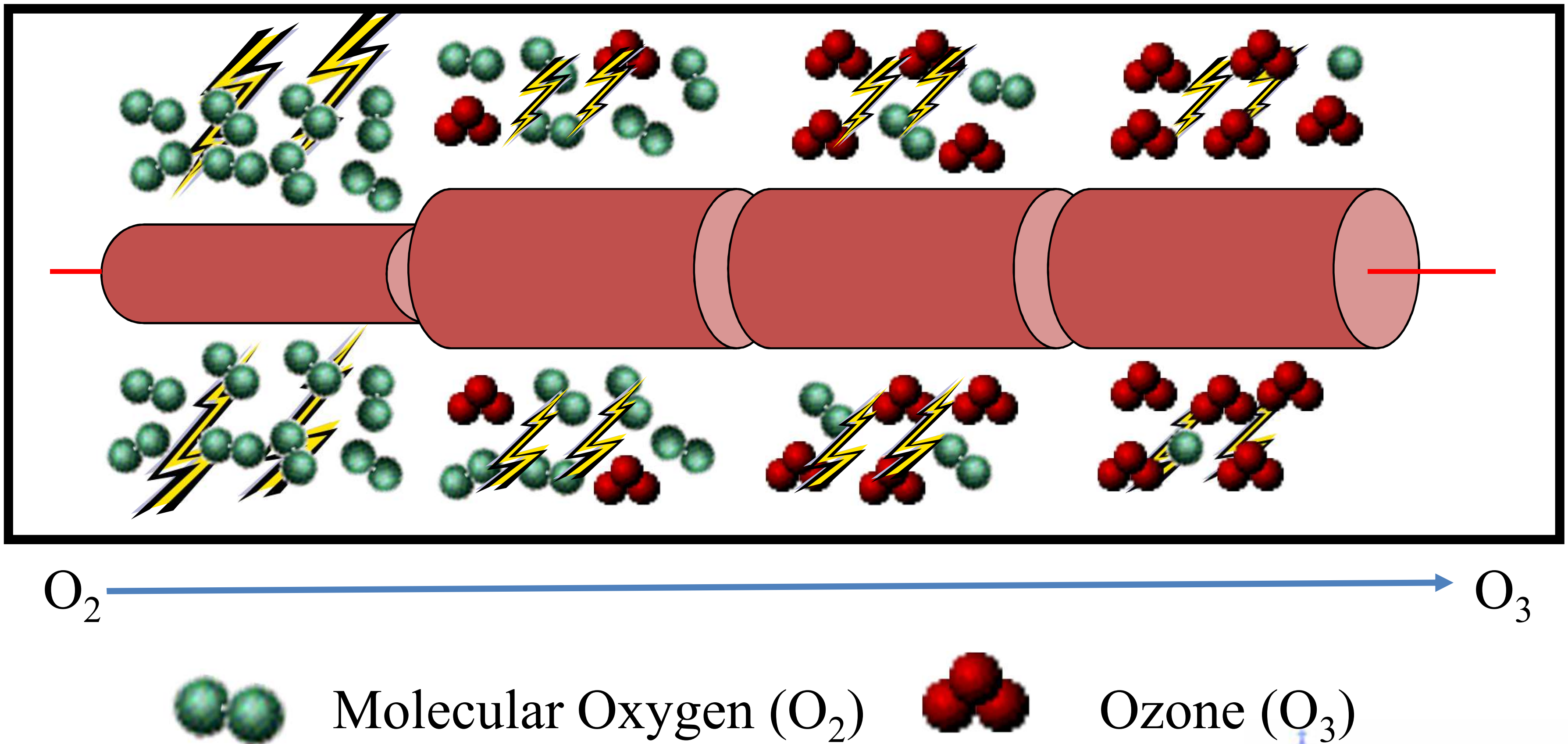


Optimized Arrangement





Intelligent Gap System (IGS)



Degrémont Technologies – Ozonia Intelligent Gap System

Degremont Technologies
SUEZ

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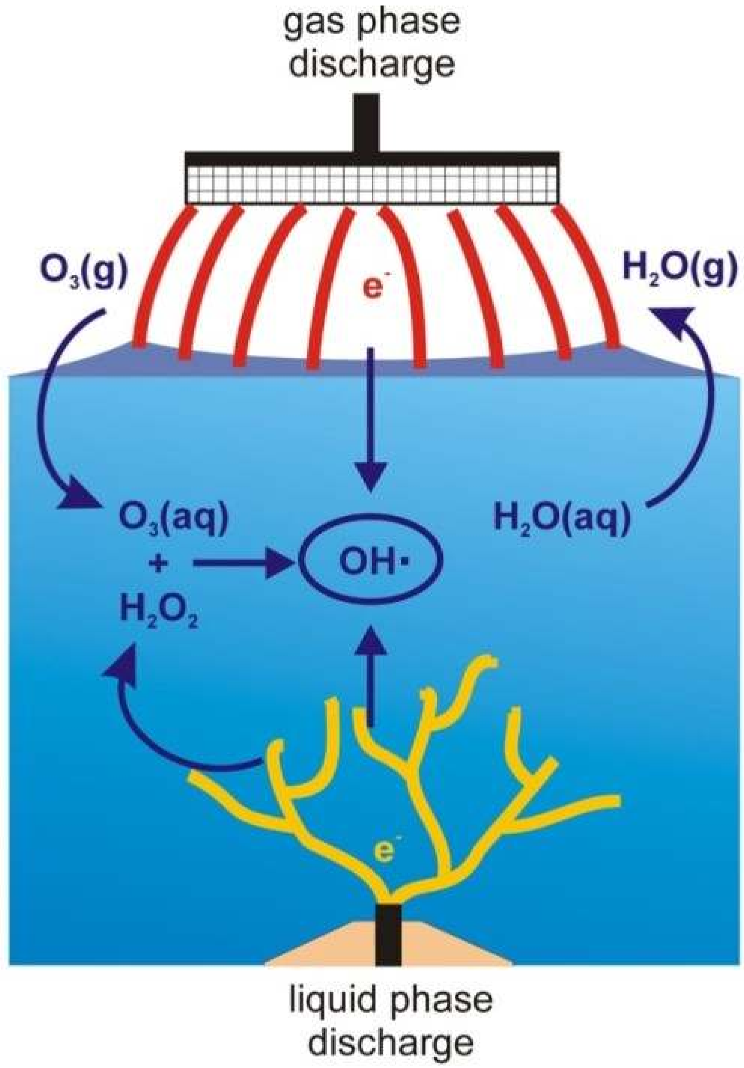
Plasma Discharges in Water



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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

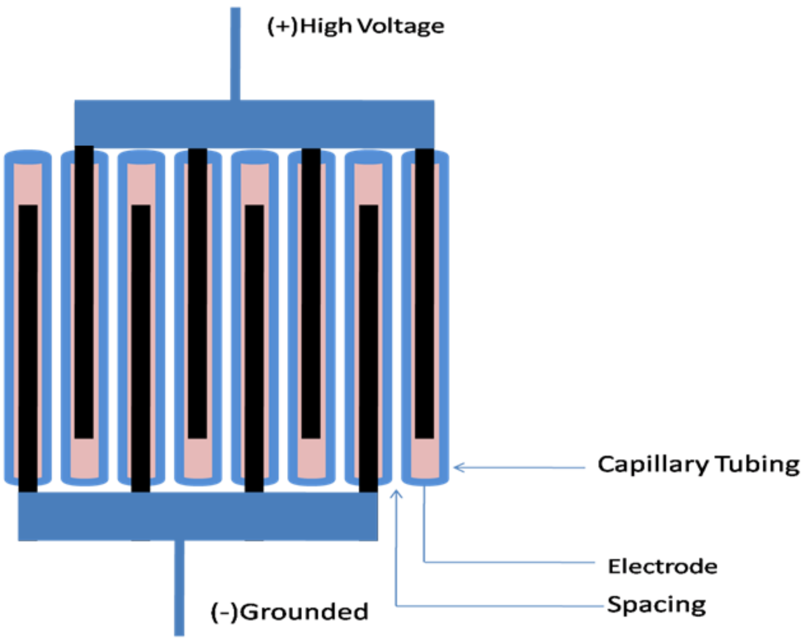
Photonic devices

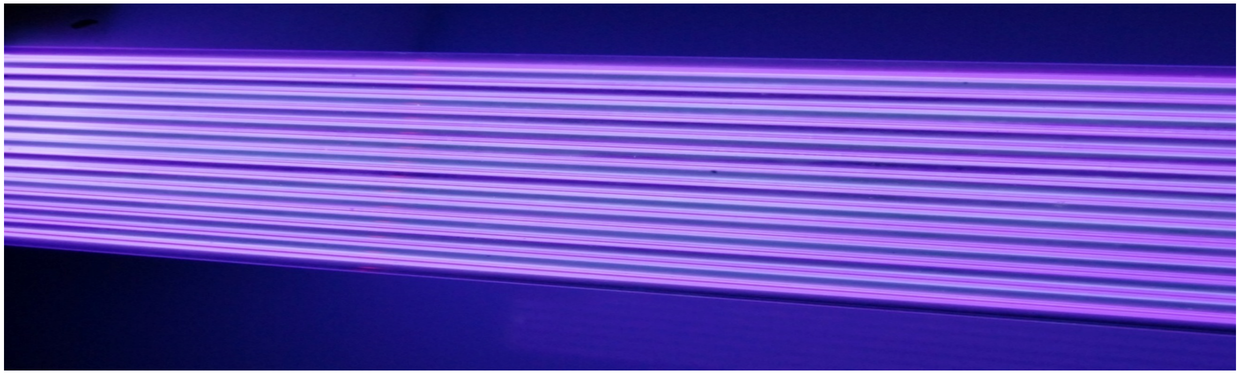
- semiconductor devices
    - photodetectors
    - flexible devices and arrays
    - devices approaching cellular dimensions
    - nano-devices

Sensors

- sensor for chemical and biological agents
- sensor for explosives

Capillary Dielectric Barrier Discharge





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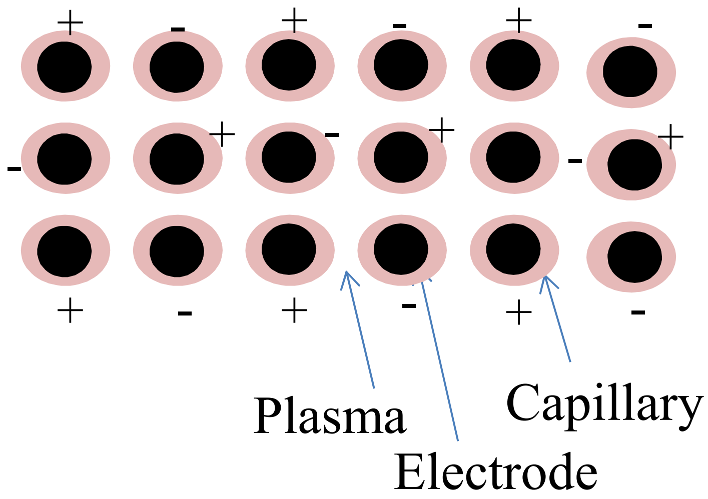
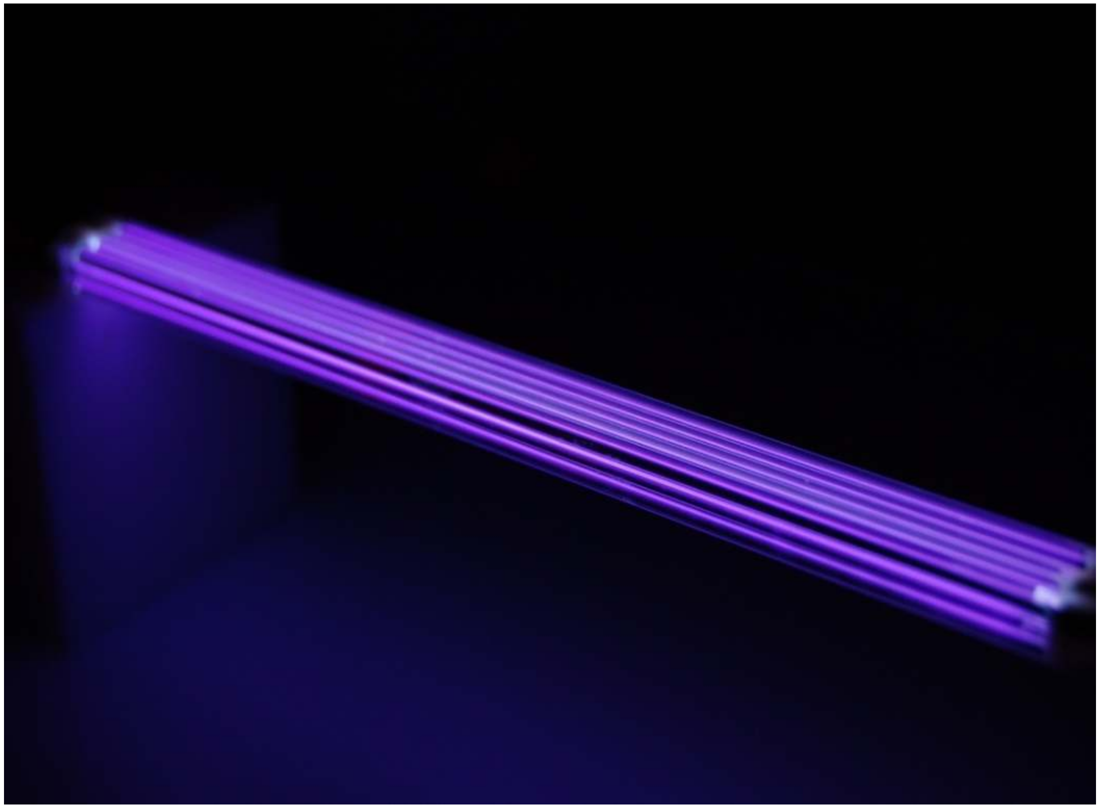
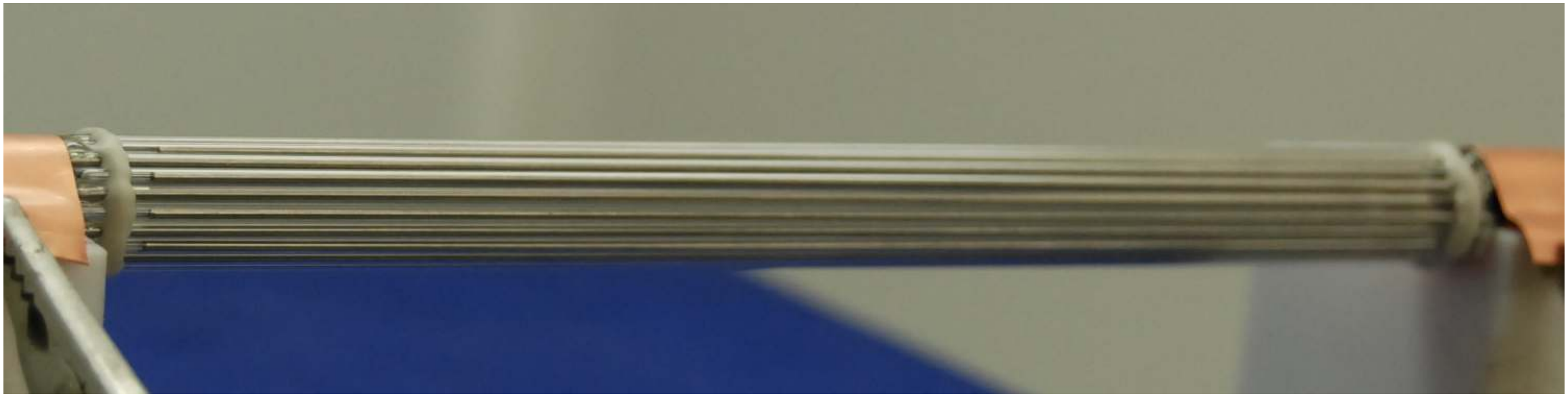
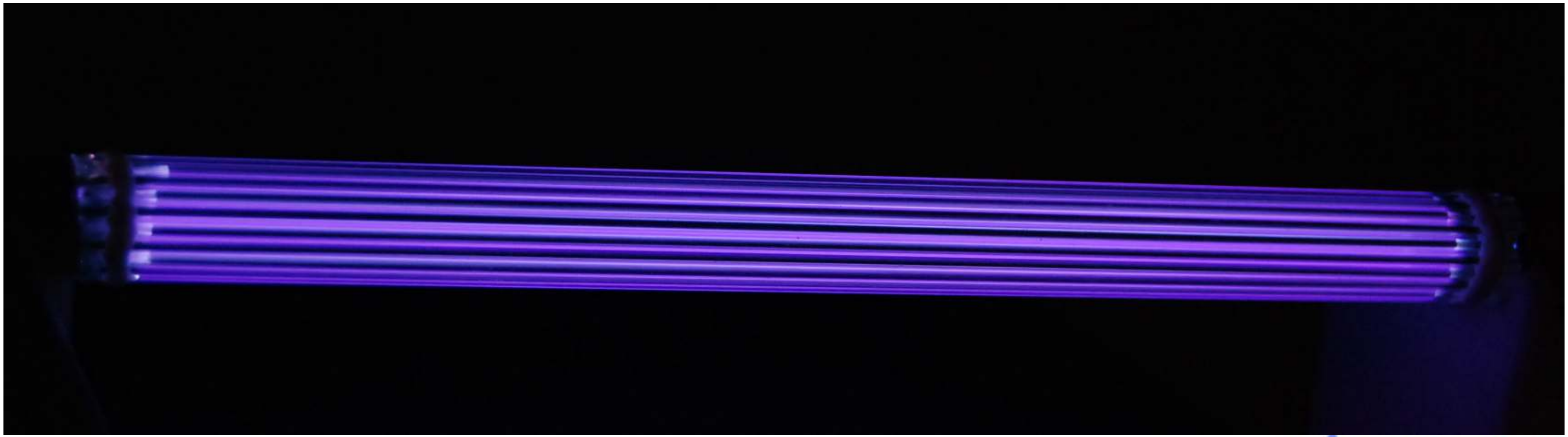
3-D Expansion



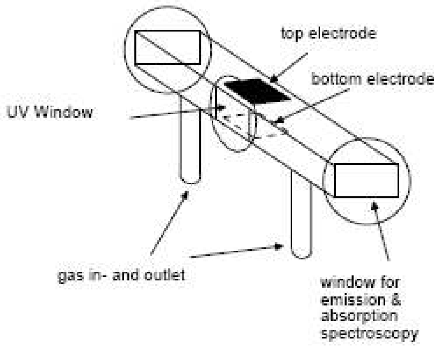


Cylindrical Arrangement

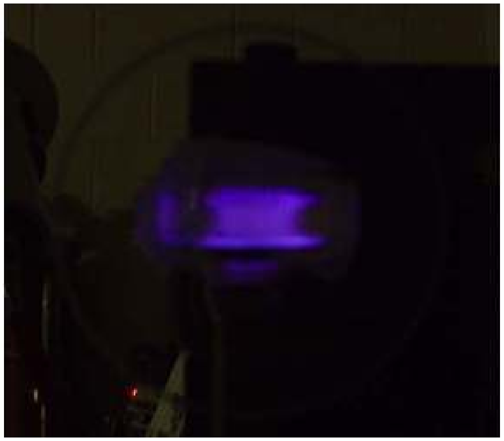




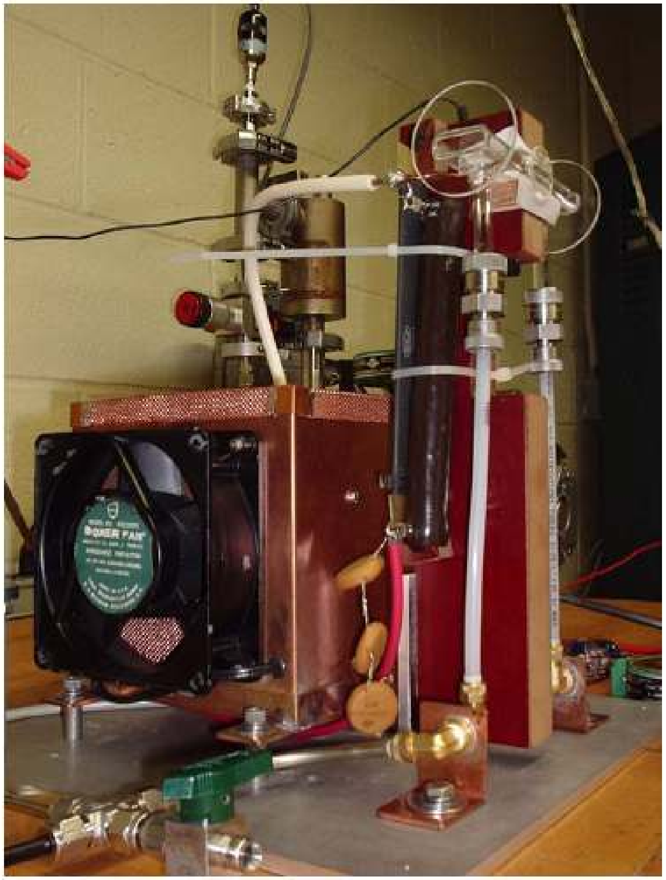
Pulsed DC Homogeneous DBD



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.

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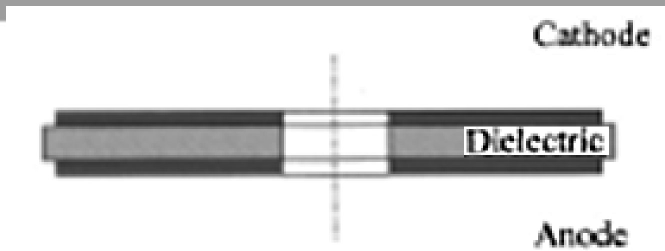
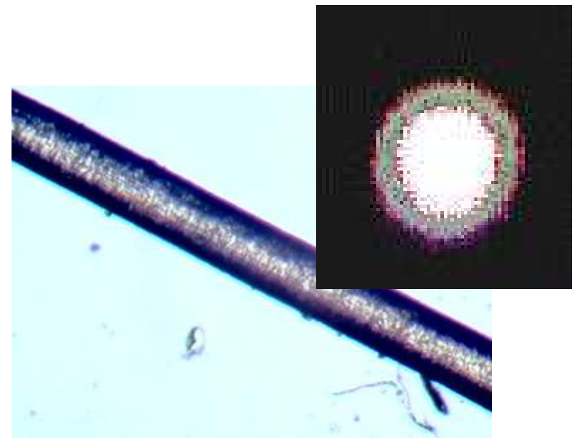
Micro Hollow Cathode Discharge (MHCD)



Sandwich Structure:
Electrode – Dielectric - Electrode

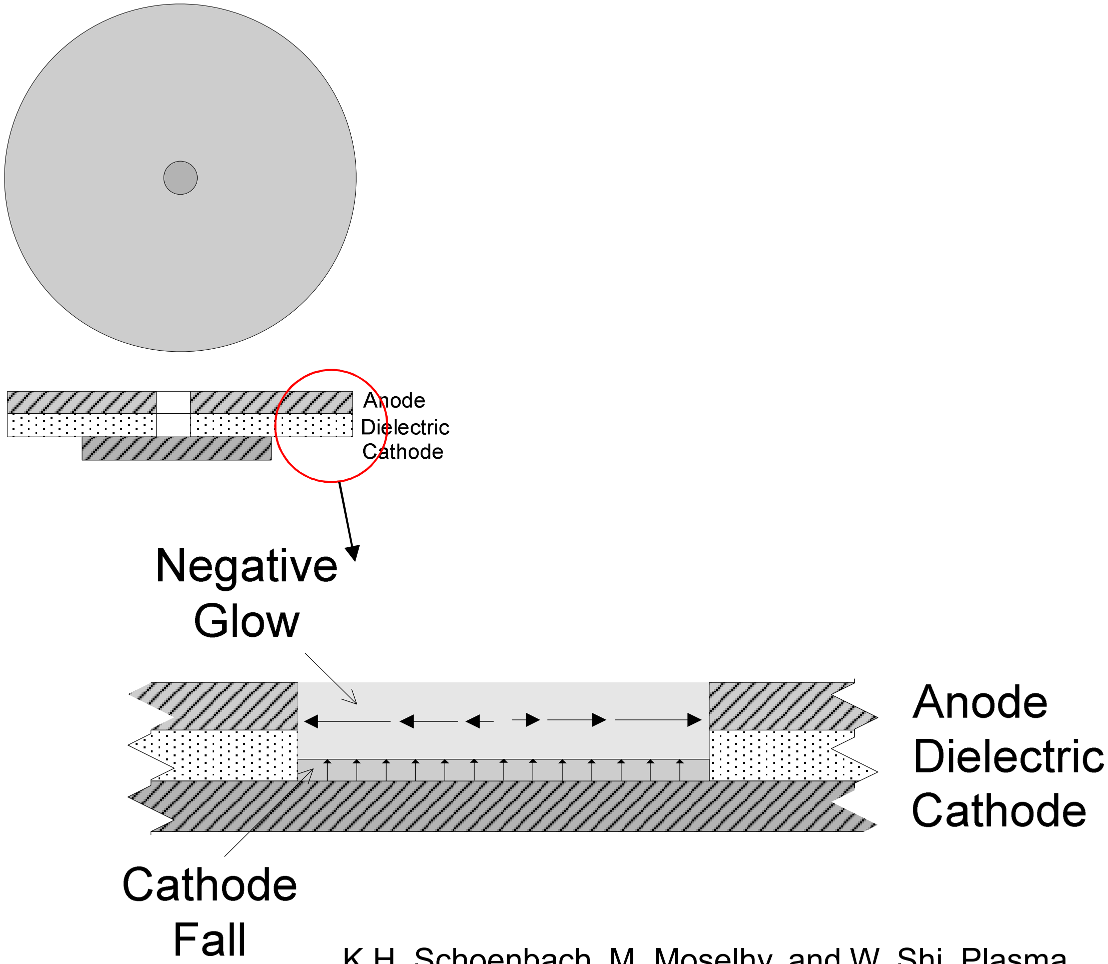
Critical dimensions at atmospheric pressure (static operation):
d: <500 μm
D: 10 – 300 μm
(assuming at room temperature)



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)

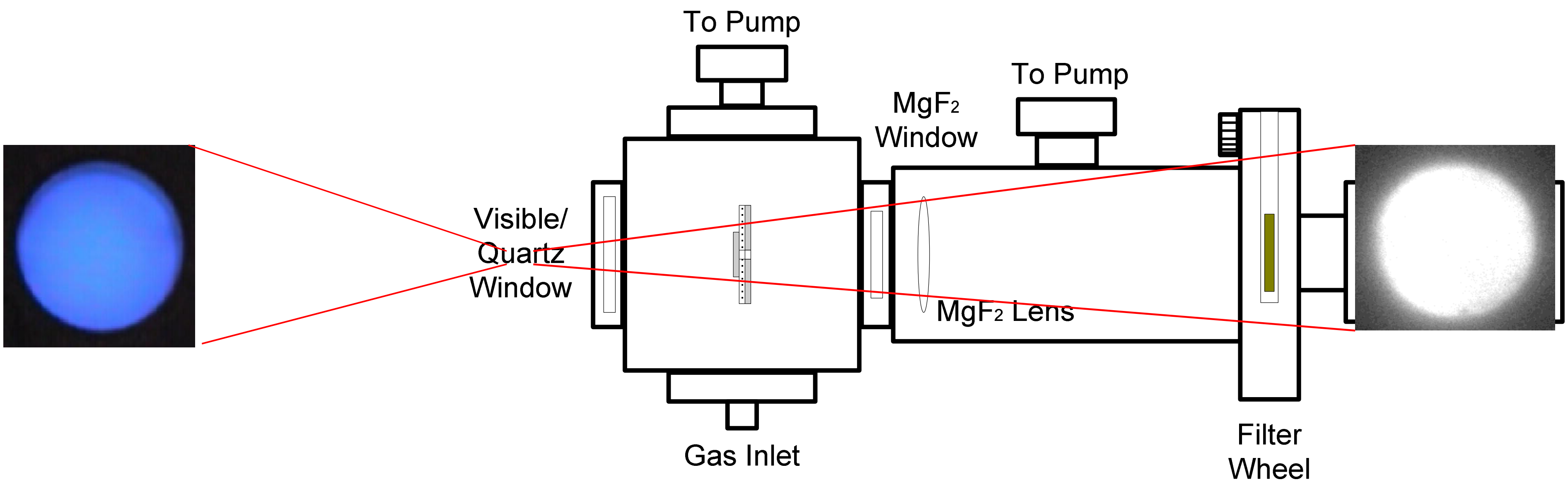
Materials:

Electrodes: Molybdenum
Dielectric: Alumina

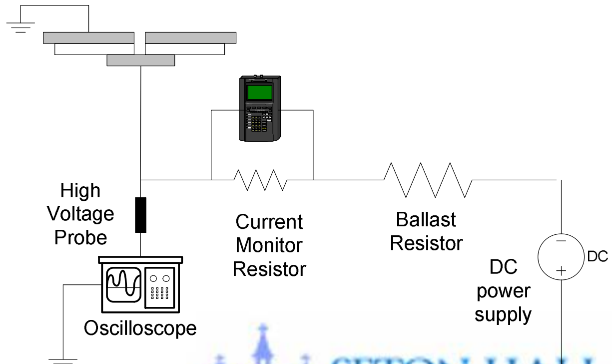
Dimensions:

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

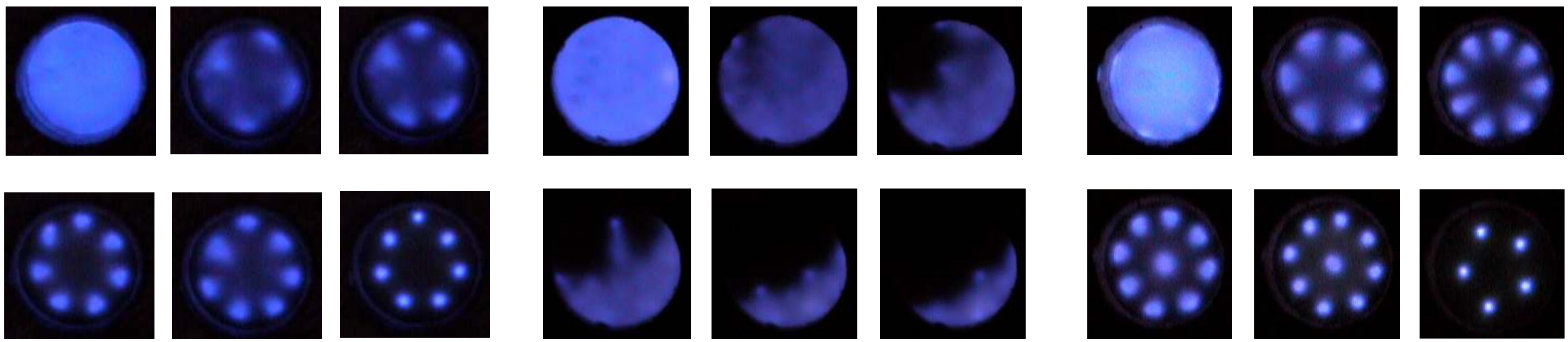
Visible imaging



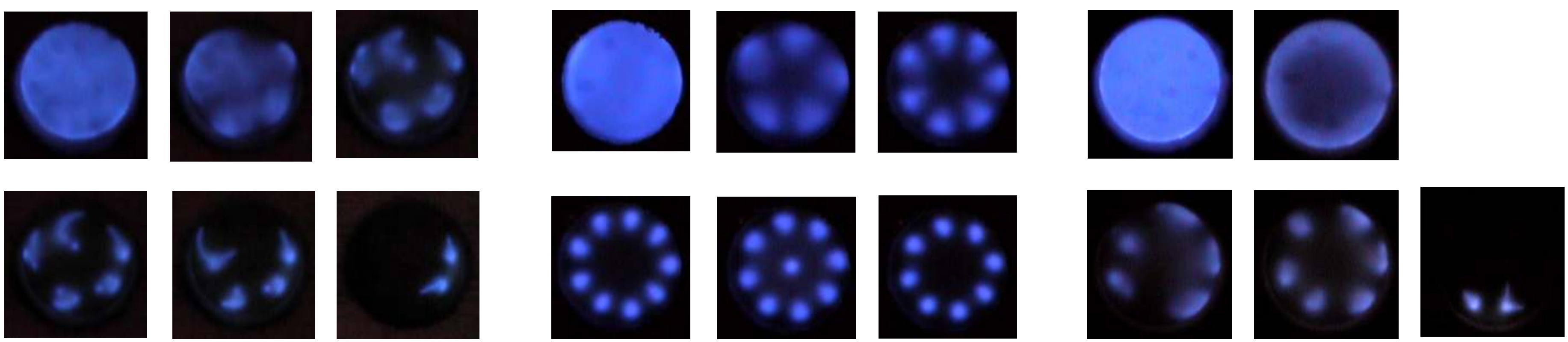
- Gas: Xenon (Scientific grade)
- Spectral filter: 170 nm with FWHM of 26.8 nm
- Sample: Either mechanically assembled at Old Dominion University or plasma sprayed at University of Minnesota



Self-organization on different cathode materials



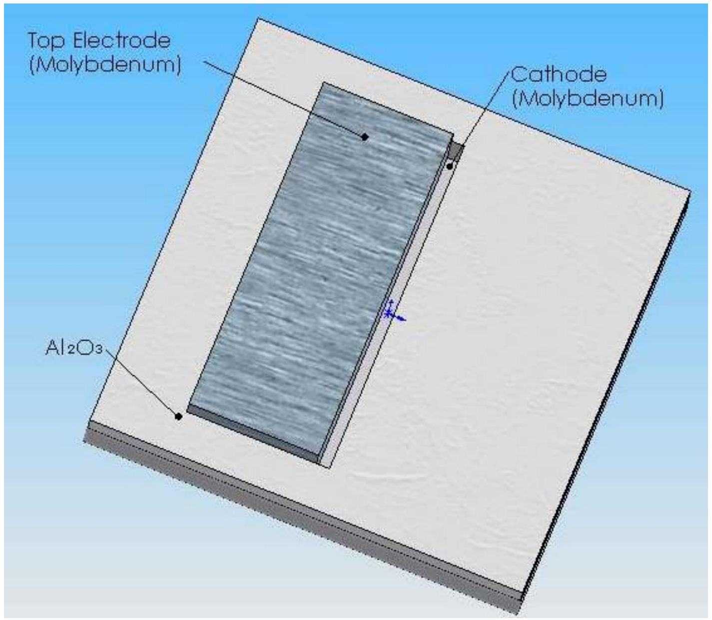
Titanium Aluminum Molybdenum

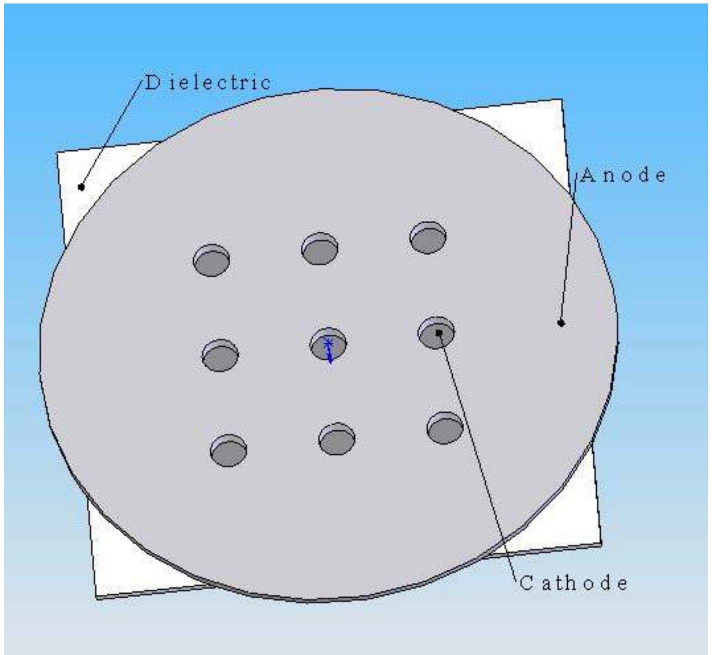


Hafnium Tungsten Silver

Up Scaling

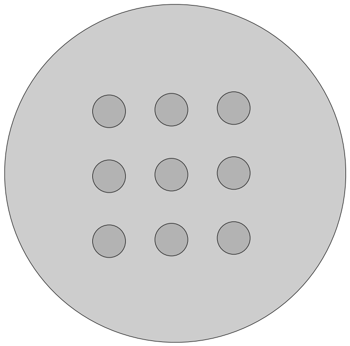
Maintain the sandwich structure and scale up in one direction
– ***Micro-slit structure***

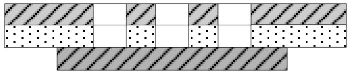




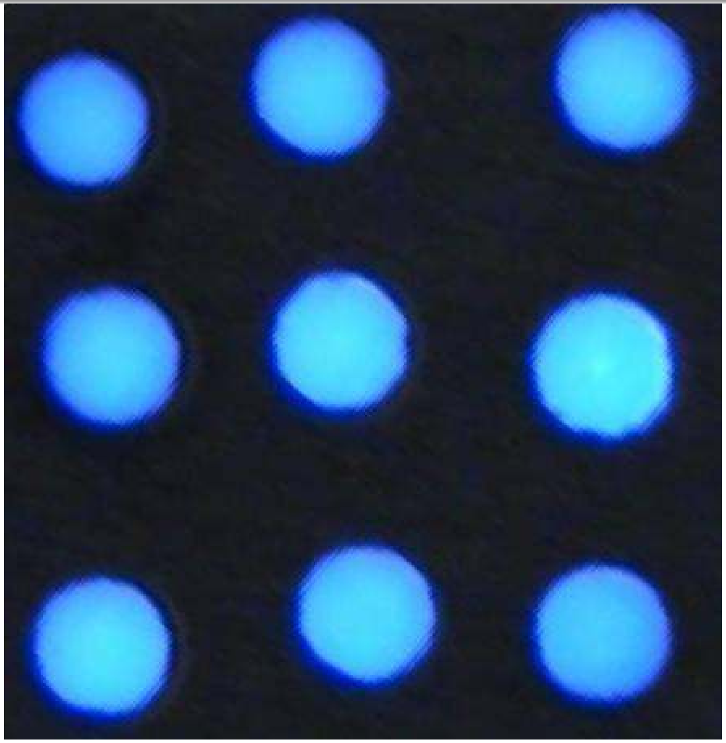
Parallel operation of multiple openings – ***Multi-CBL structure***

Parallel operation without individual ballast



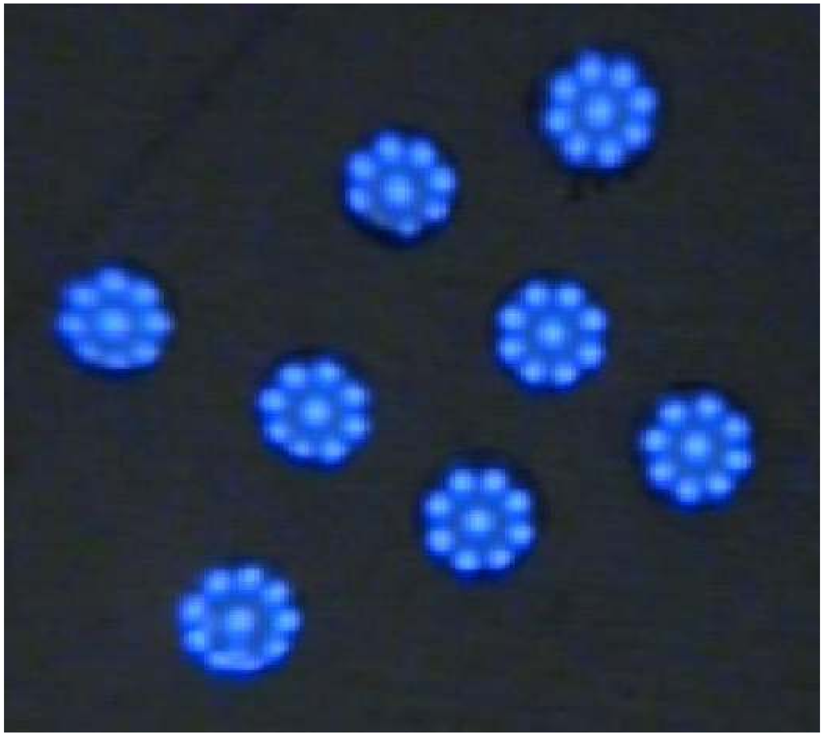


- Cathode: Mo ~0.25 mm thick
- Dielectric: Al_2O_3 ~0.25 mm thick
- Anode: Mo ~0.25 mm thick
- Hole diameter: ~0.75 mm
- Center to center distance: ~1.5 mm

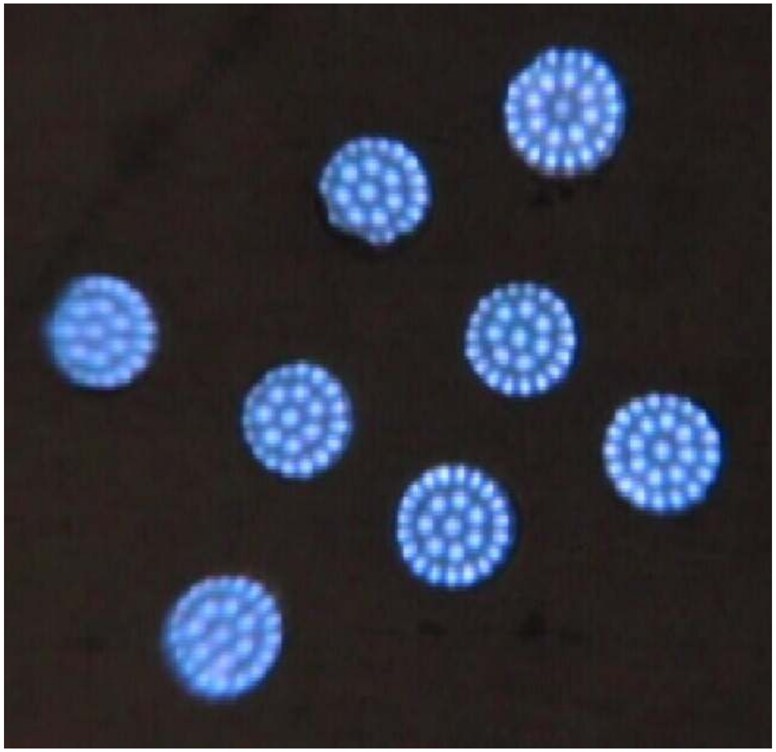


Visible Picture of parallel operation of 9 holes
(Operating gas: xenon (scientific grade)
Base pressure: ~1 mTorr; Working pressure: 200 Torr
Cathode voltage: -398 V; Discharge current: 6 mA)

Self-organization



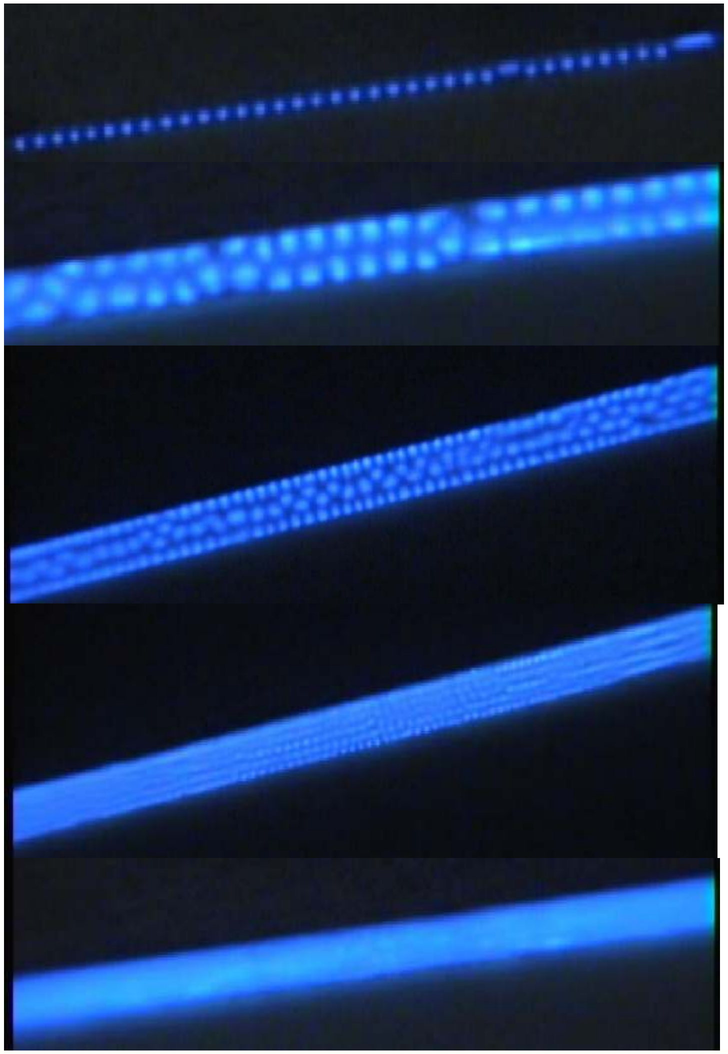
Xenon (100 Torr)



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

More on Self Organization

(a)
(b)
(c)
(d)
(e)

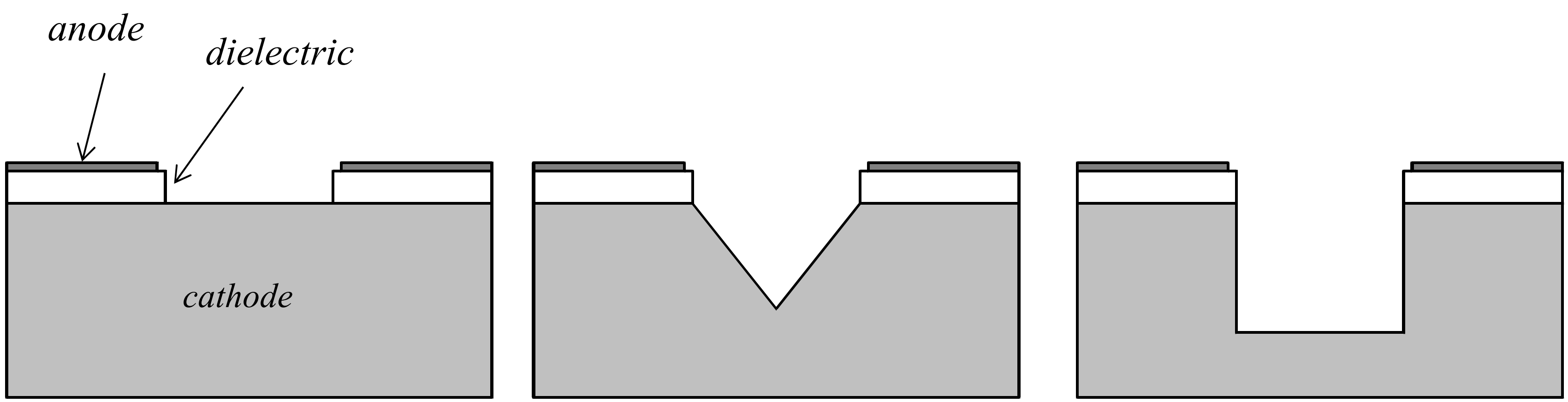


Self-organization (Visible images) of a micro-slit CBL discharge:

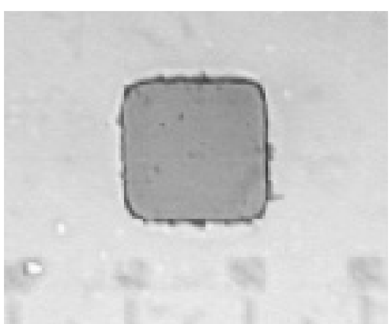
(a) 50 Torr;
(b) 150 Torr;
(c) 245 Torr;
(d) 354 Torr and
(e) homogeneous discharge at 100 Torr (249V and 4 mA)

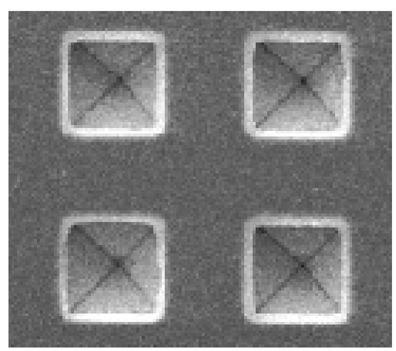
(The images are at different magnification for a better demonstration purpose)

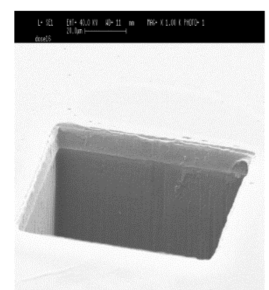
Si MICROCAVITY DEVICE STRUCTURES



Planar Si Electrode *Inverted Pyramidal Electrode* *DRIE Electrode*





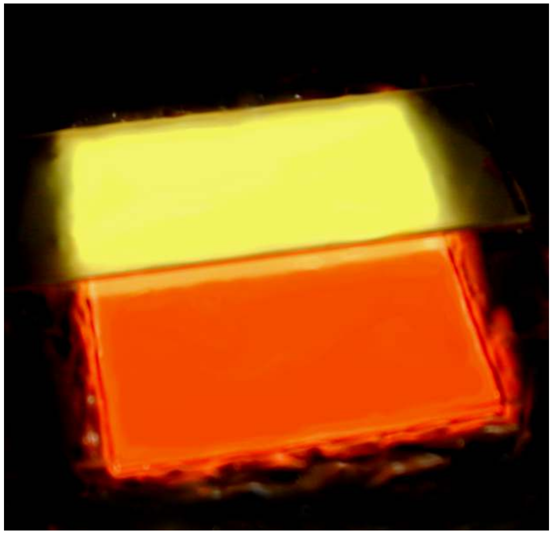


EXCITATION OF A GREEN PHOSPHOR ($Mn:Zn_2SiO_4$)

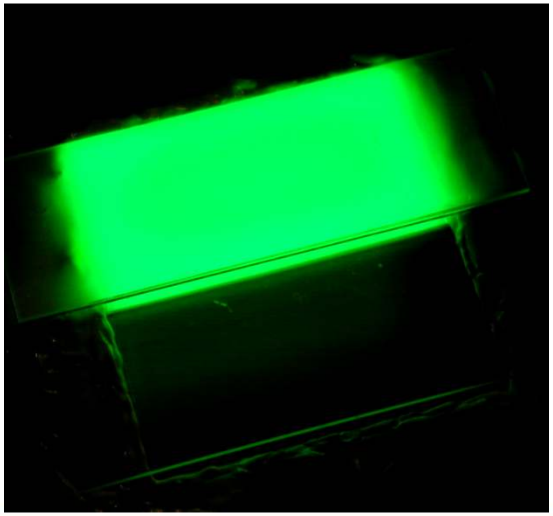
University of Illinois
Laboratory for Optical Physics and Engineering

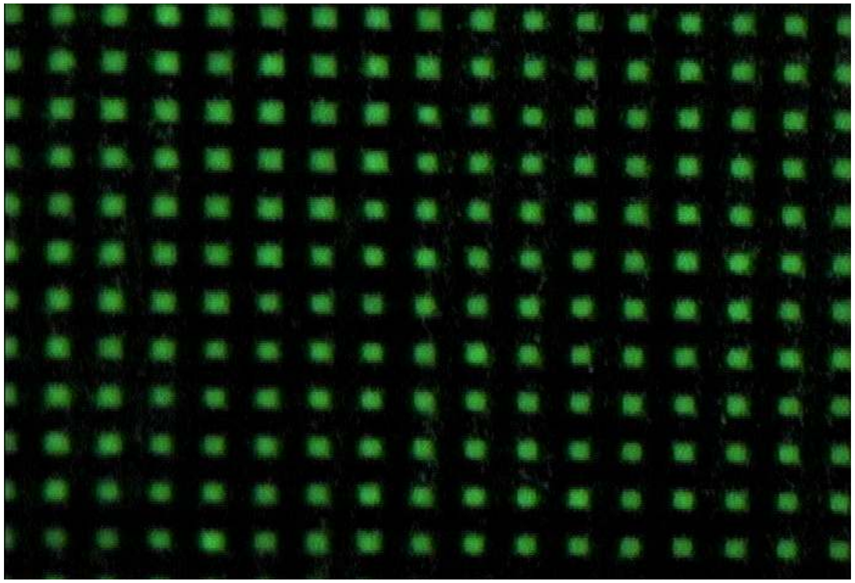
PHOSPHOR EMBEDDED MICROCAVITY

Ne



50% Xe/Ne





10 % Xe/Ne, 700 Torr

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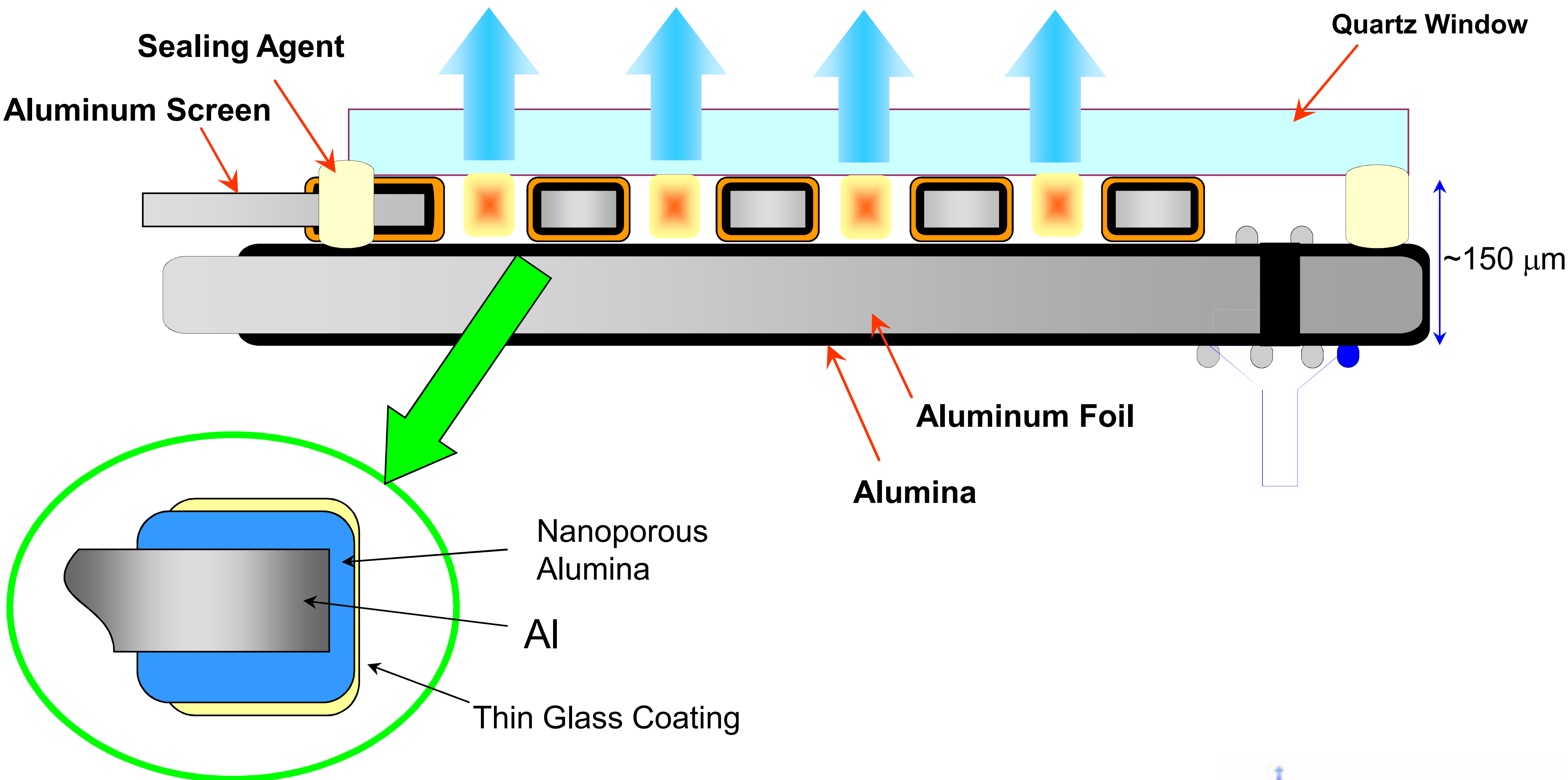
Microdischarge Array Flat Lamp : Basic Design



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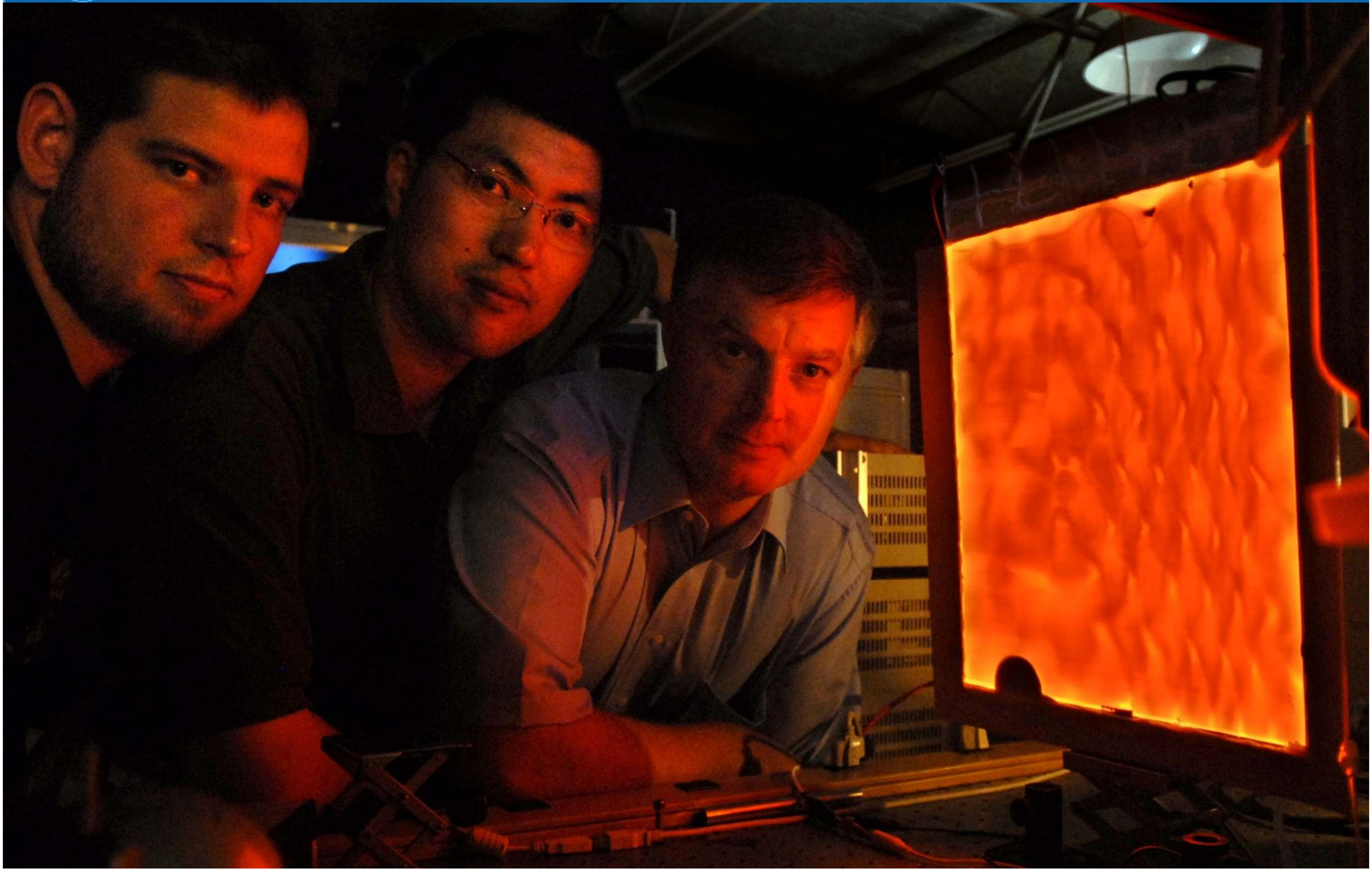
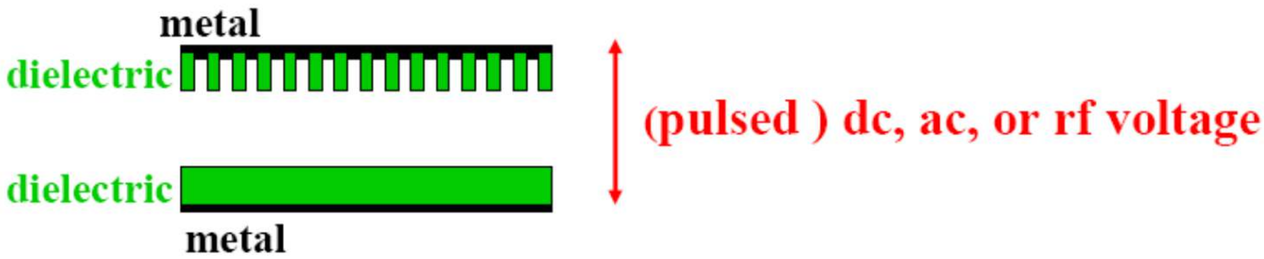
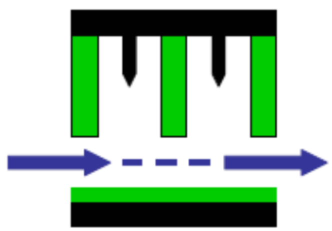


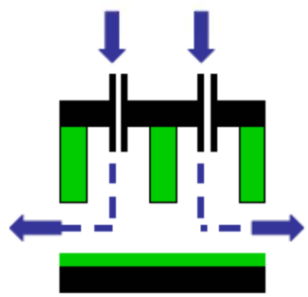
Capillary Plasma Electrode (CPE)



<u>Capillary Plasma Electrode (CPE) Realizations</u>



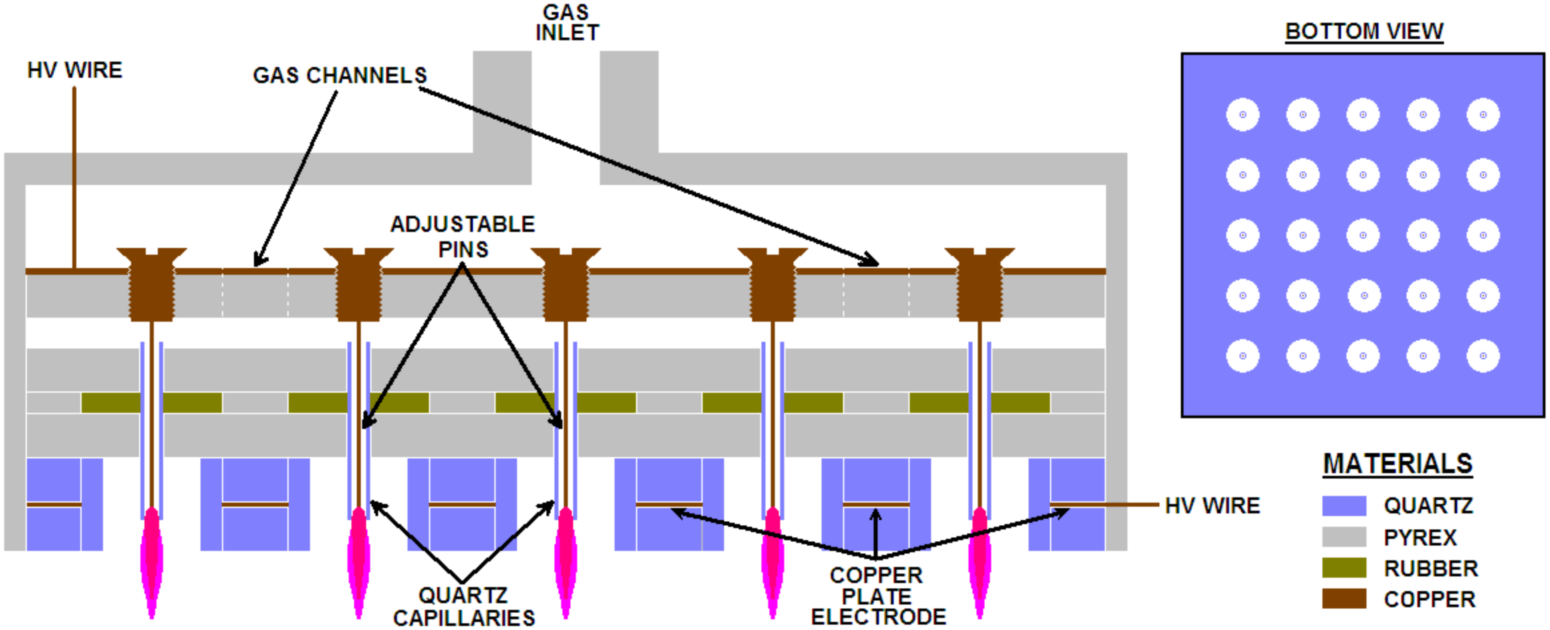
Solid Pin Electrodes
(Cross Flow)

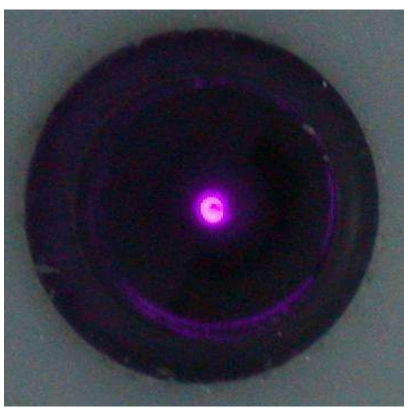


Hollow Pin Electrodes
(Flow-Through)

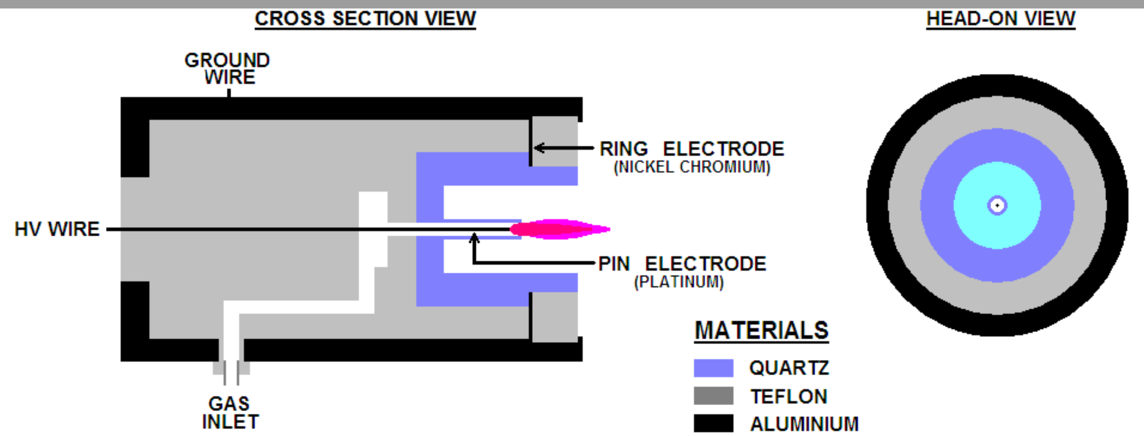
Cylindrical Electrodes
(Longitudinal Flow)

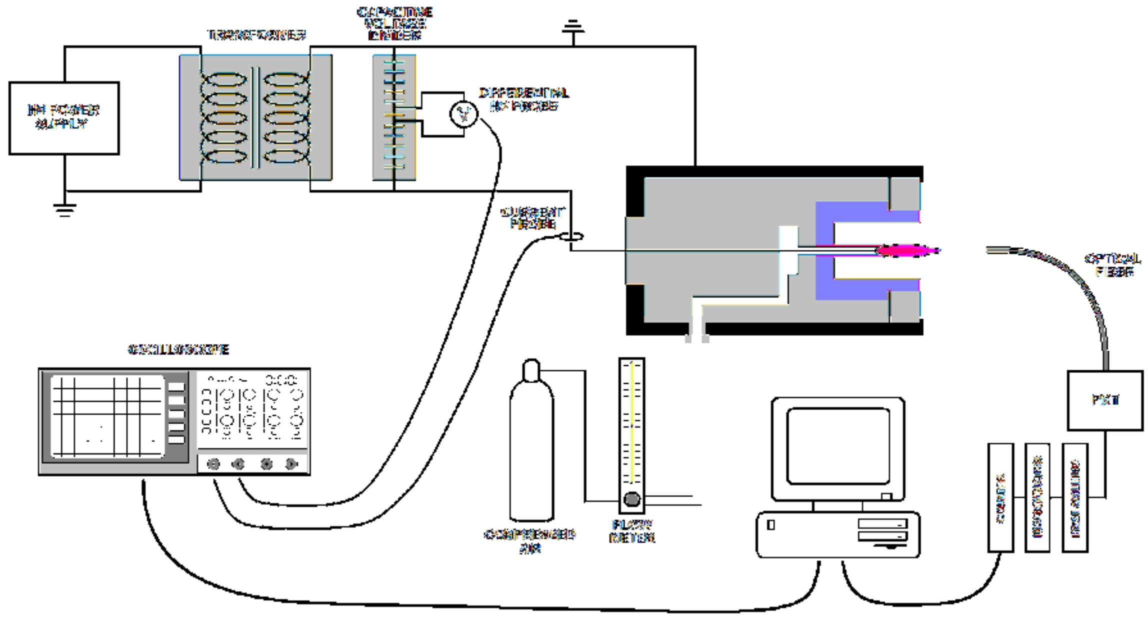
Multi-Capillary Plasma Electrode



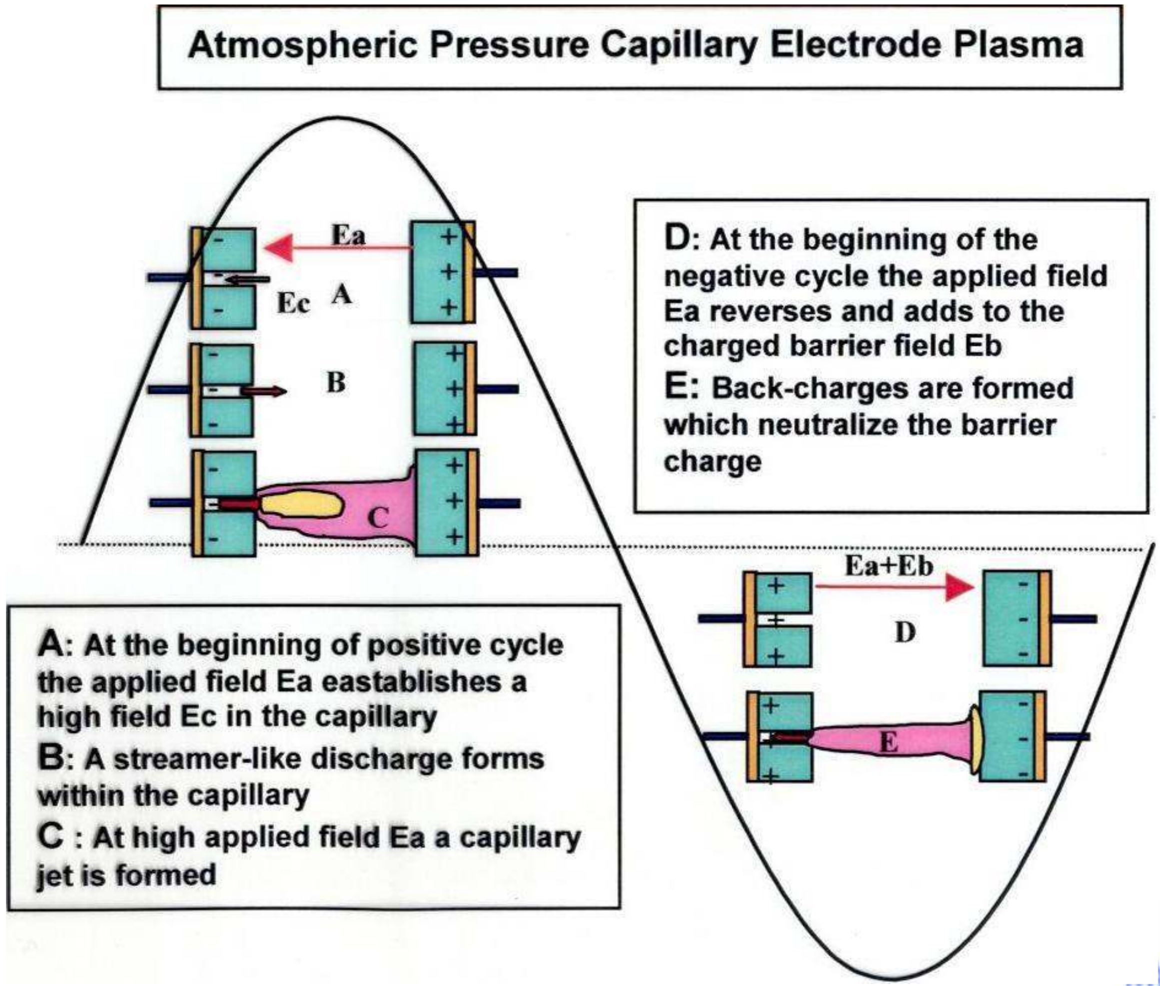


1 Capillary Plasma Electrode

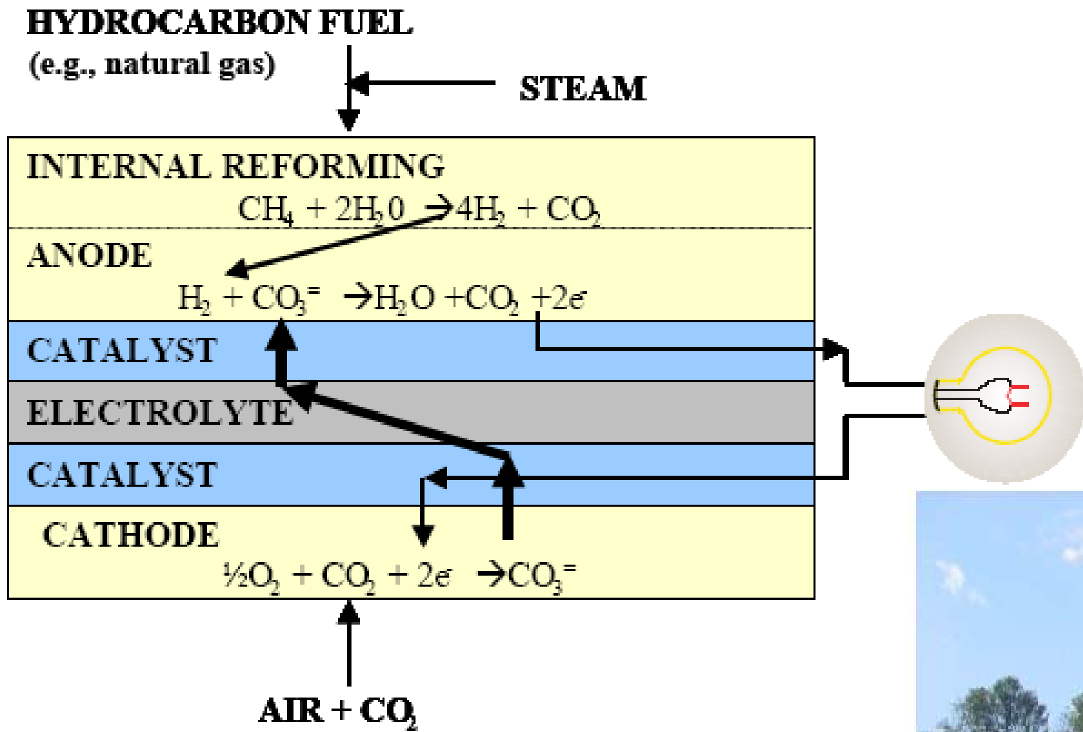




Capillary Plasma Electrode - Operation

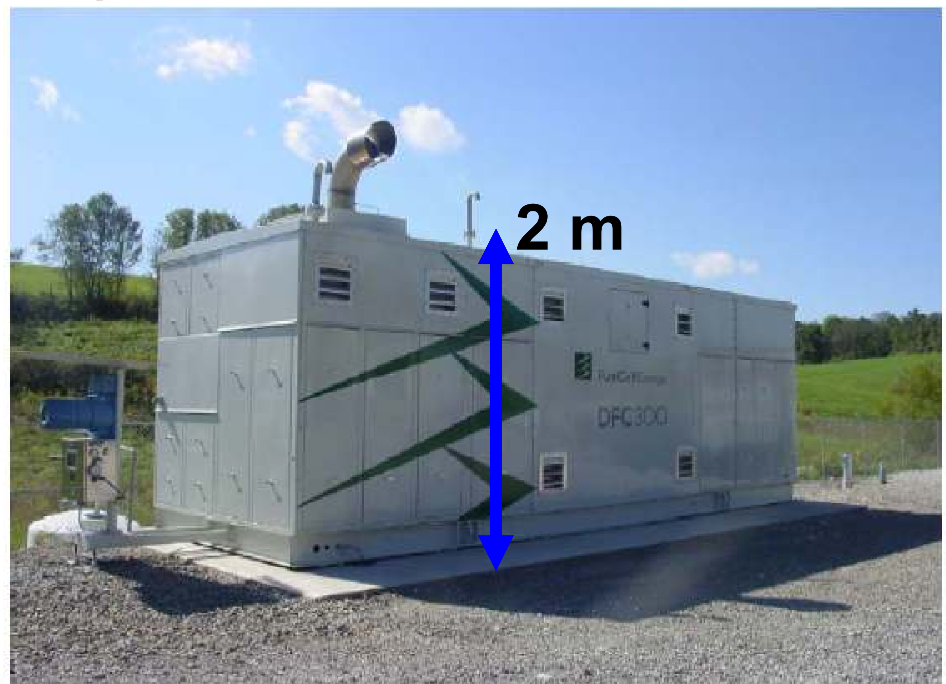


Low-T Plasmas for Fuel Cell Systems



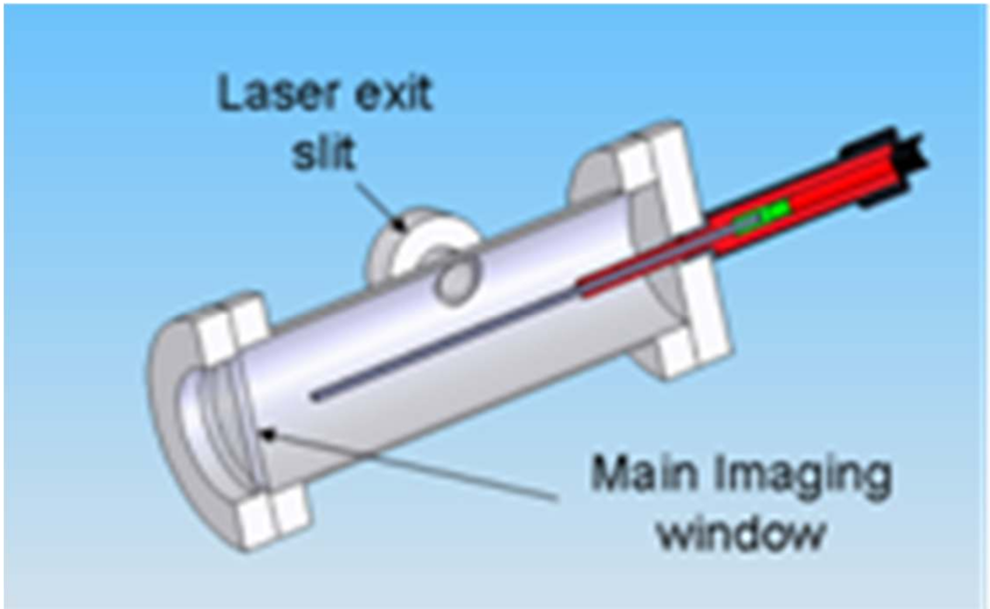
Solid Oxide Fuel Cell Chemistry

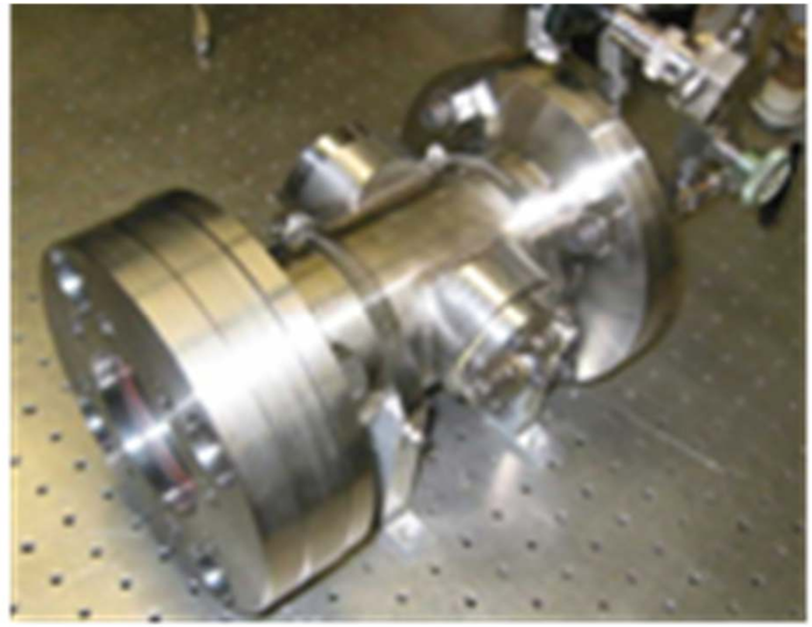
Idea:
Use low-T plasma to generate hydrocarbon feed gas for cell



300 kW Fuel Cell

Microplasma-Assisted Combustion

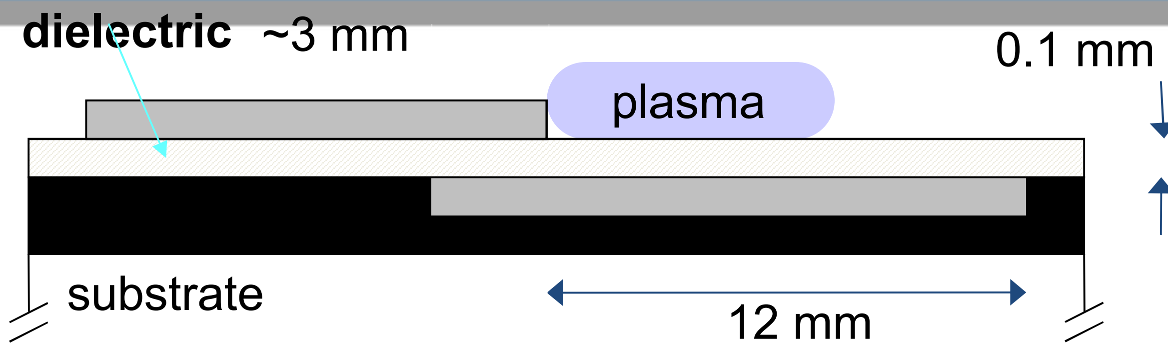


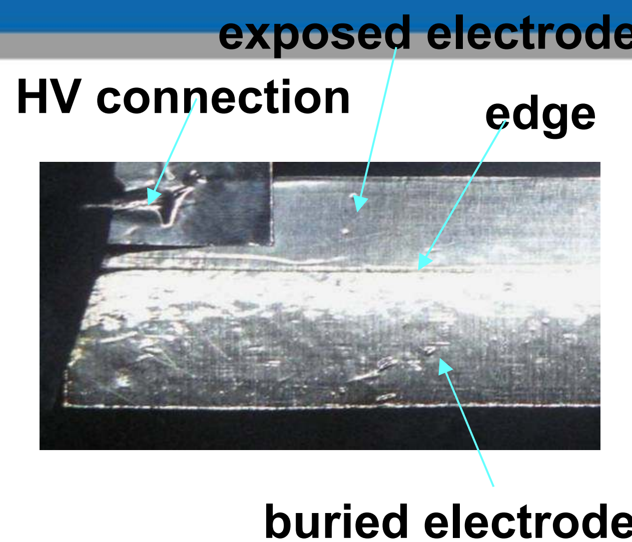


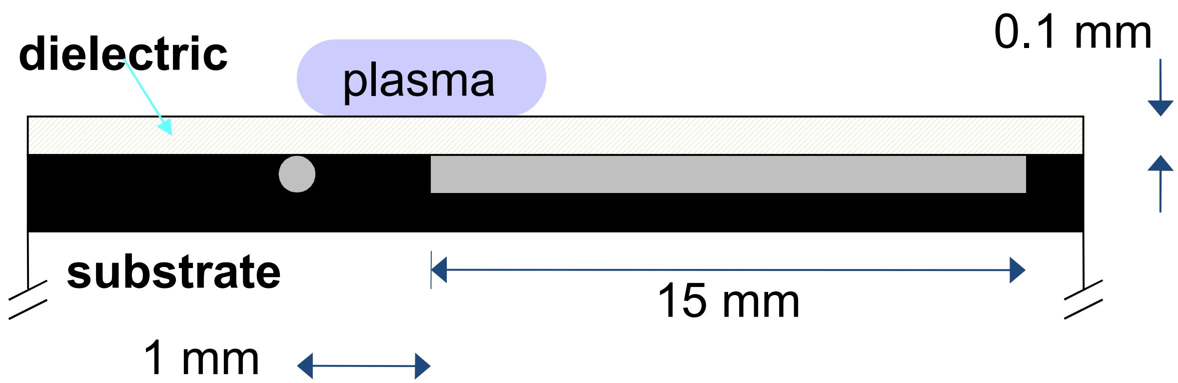
(Courtesy of M. Gundersen – USC)

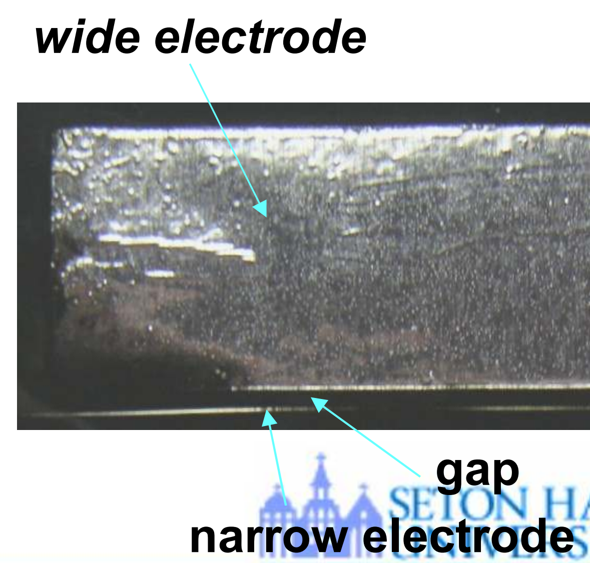
USC static reactor for studies of pulsed plasma induced ignition

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



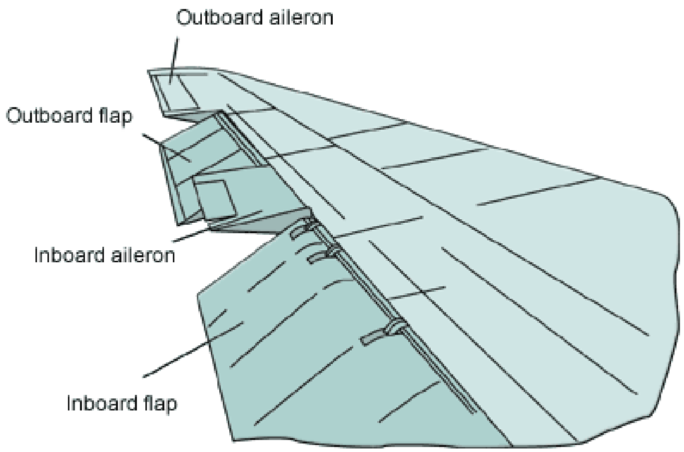


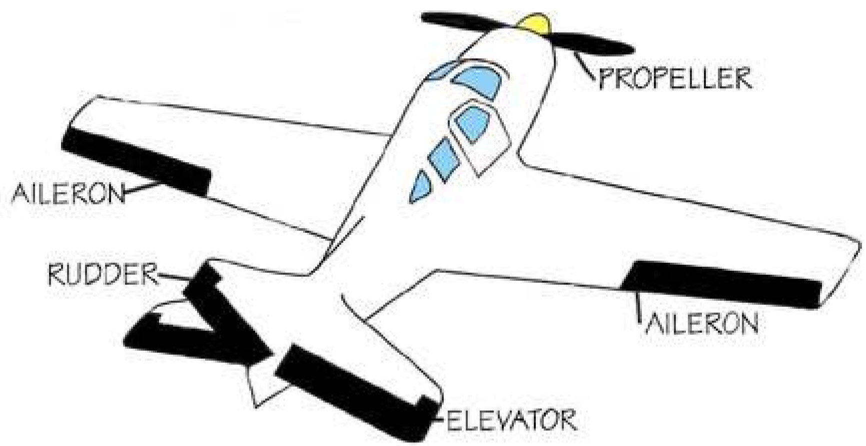


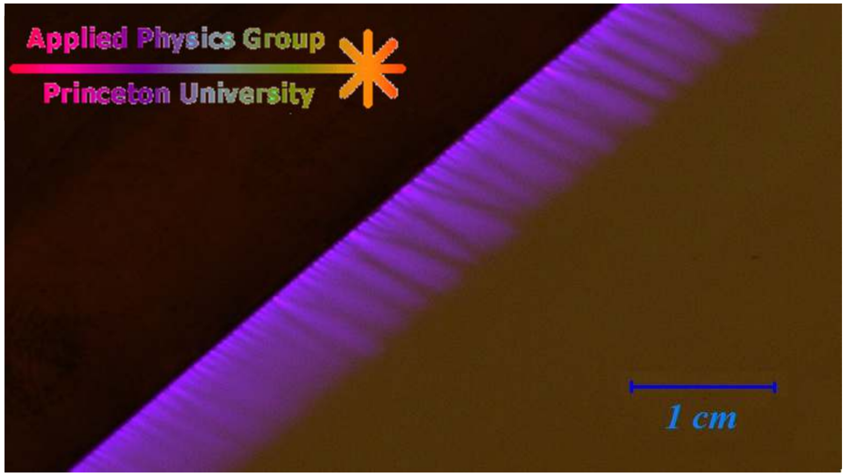


- **Planar electrodes are 0.08 mm aluminum tape**
- **Wire electrode is 0.38 mm diameter copper wire**
- **Dielectric layer is 0.1 mm polyethylene, $\varepsilon \approx 3.2\,\varepsilon_0$**

Plasma Actuators – The future of Flying!?!





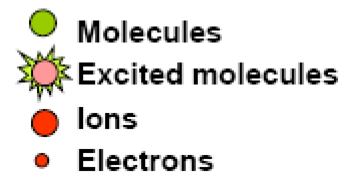


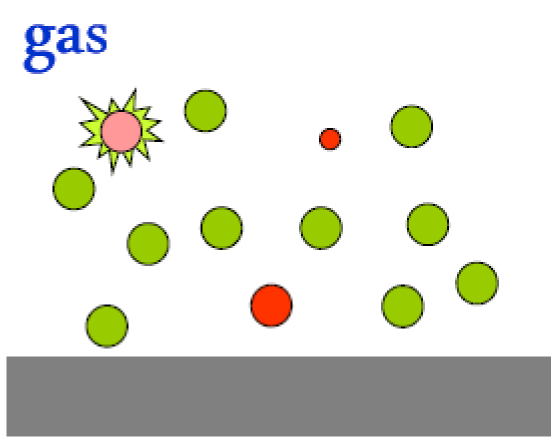
Plasma Actuators – The future of Flying!?!

Wing-less planes!!!

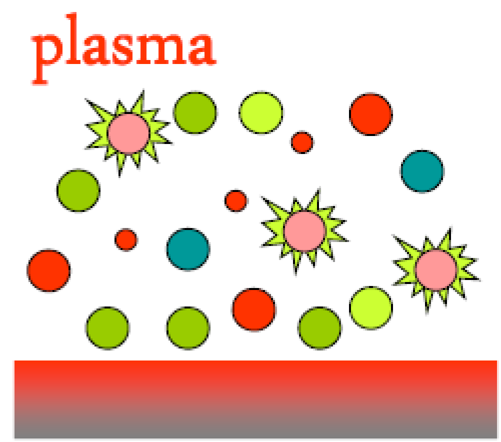
Surface Effects of Microplasmas

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





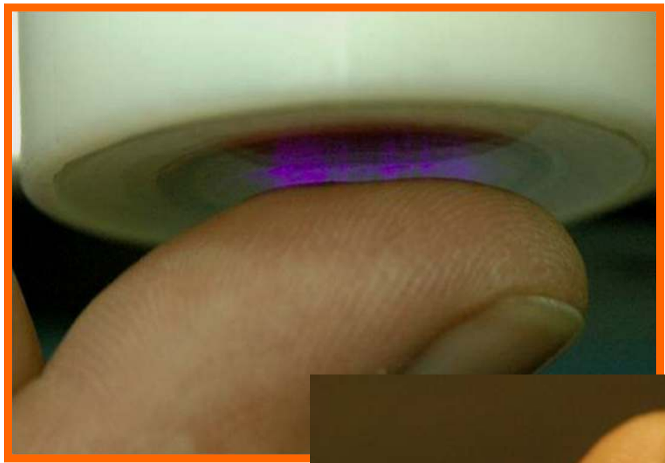
Small changes at the surface

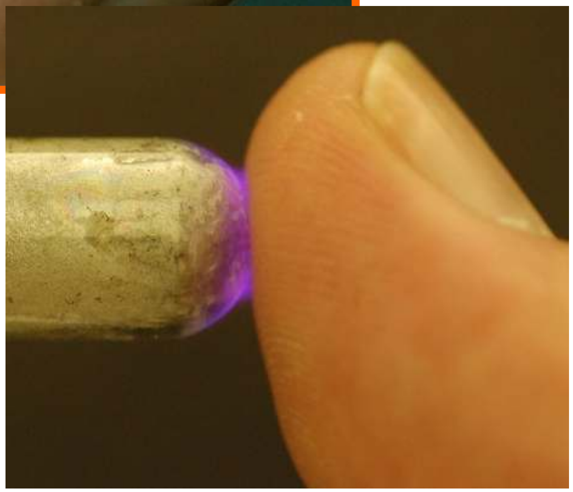


Energy & reactive species can change the surface

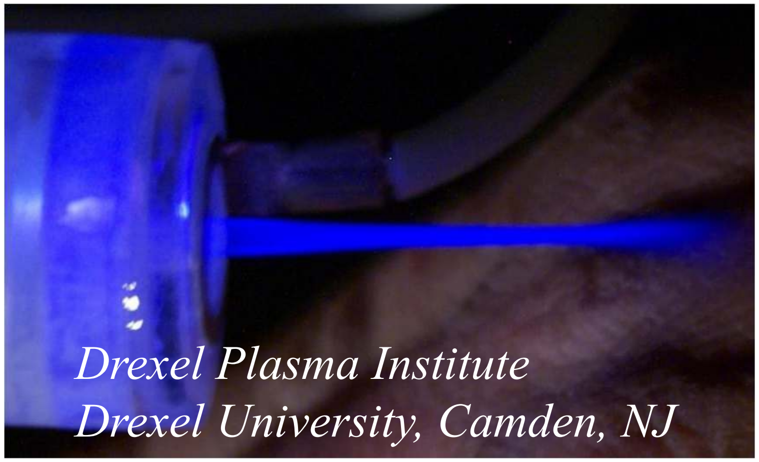
Plasma Application in Medicine

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





Indirect Plasma – Jet, Often NOT in OXYGEN



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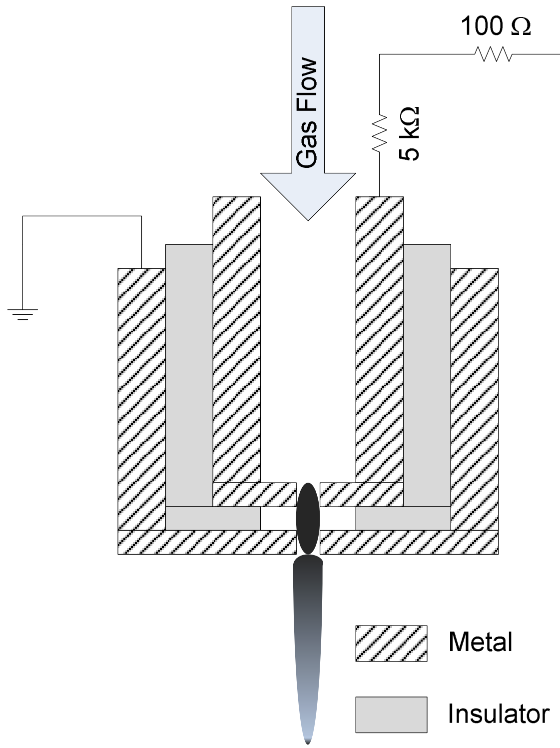
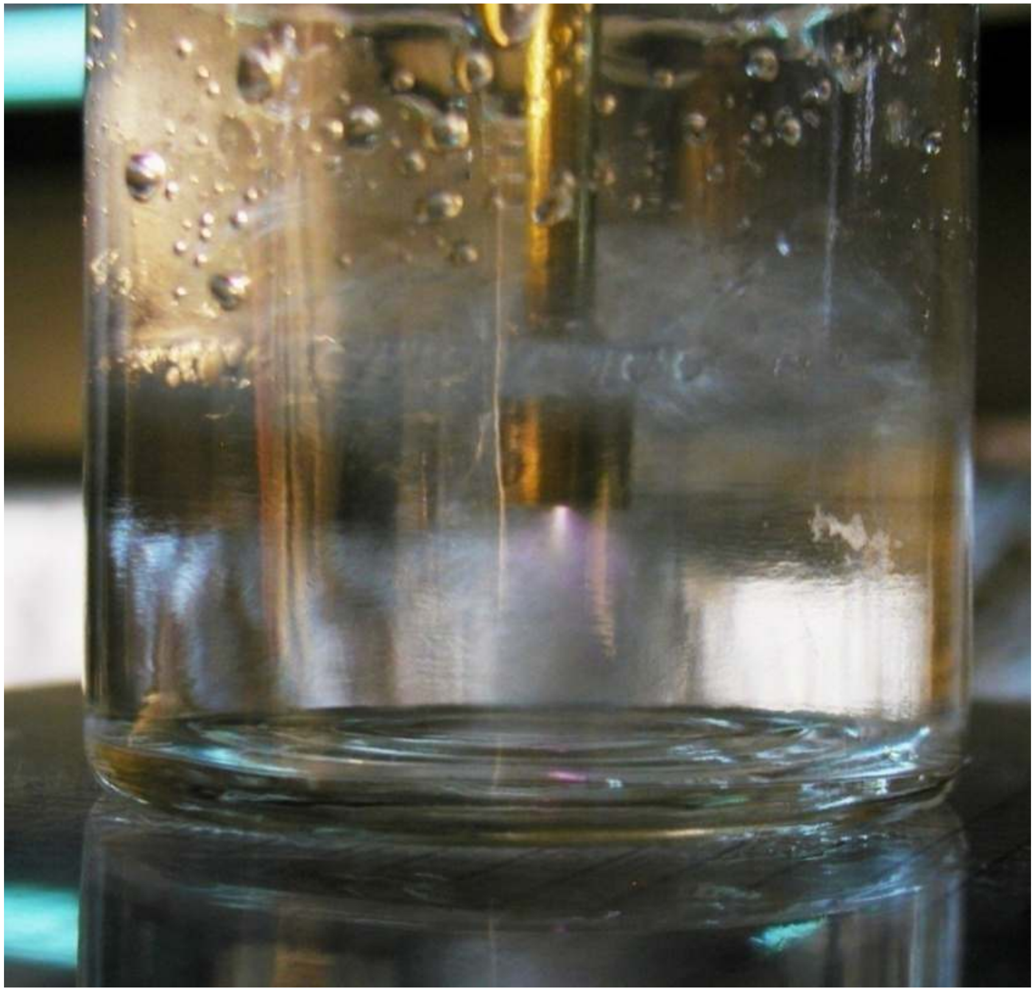
DC MHCD Plasma Micro Jet

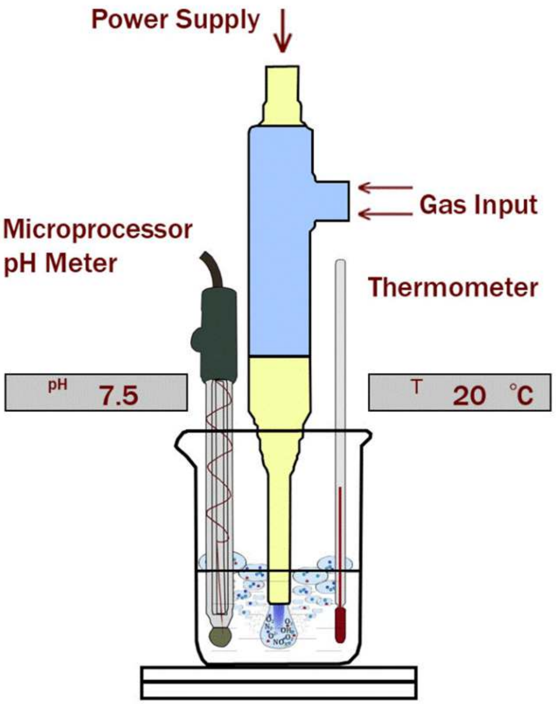


- Dimensions of the device are:
- Opening: 0.8 mm in diameter
- Separation: 0.5 mm
- Depth of exit opening: 1 mm
- Electrode material: copper

- 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)

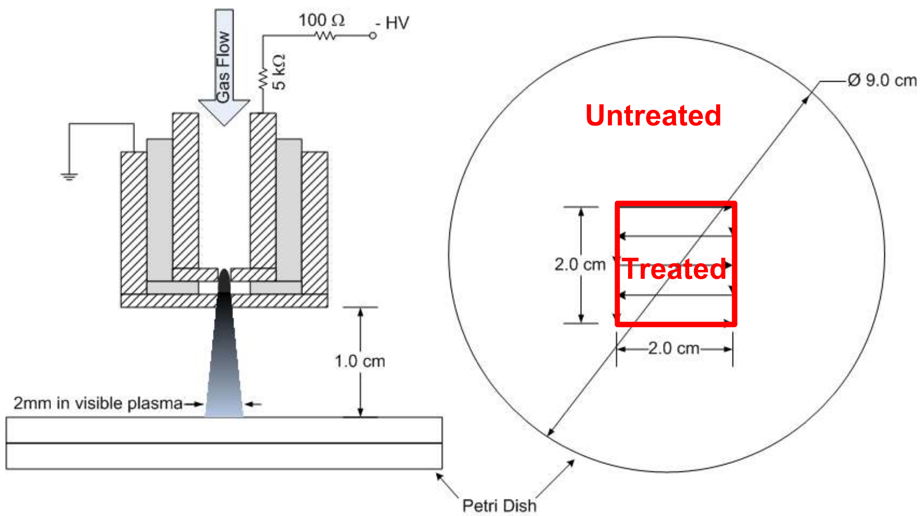
Plasma Micro Jet Inside Water





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

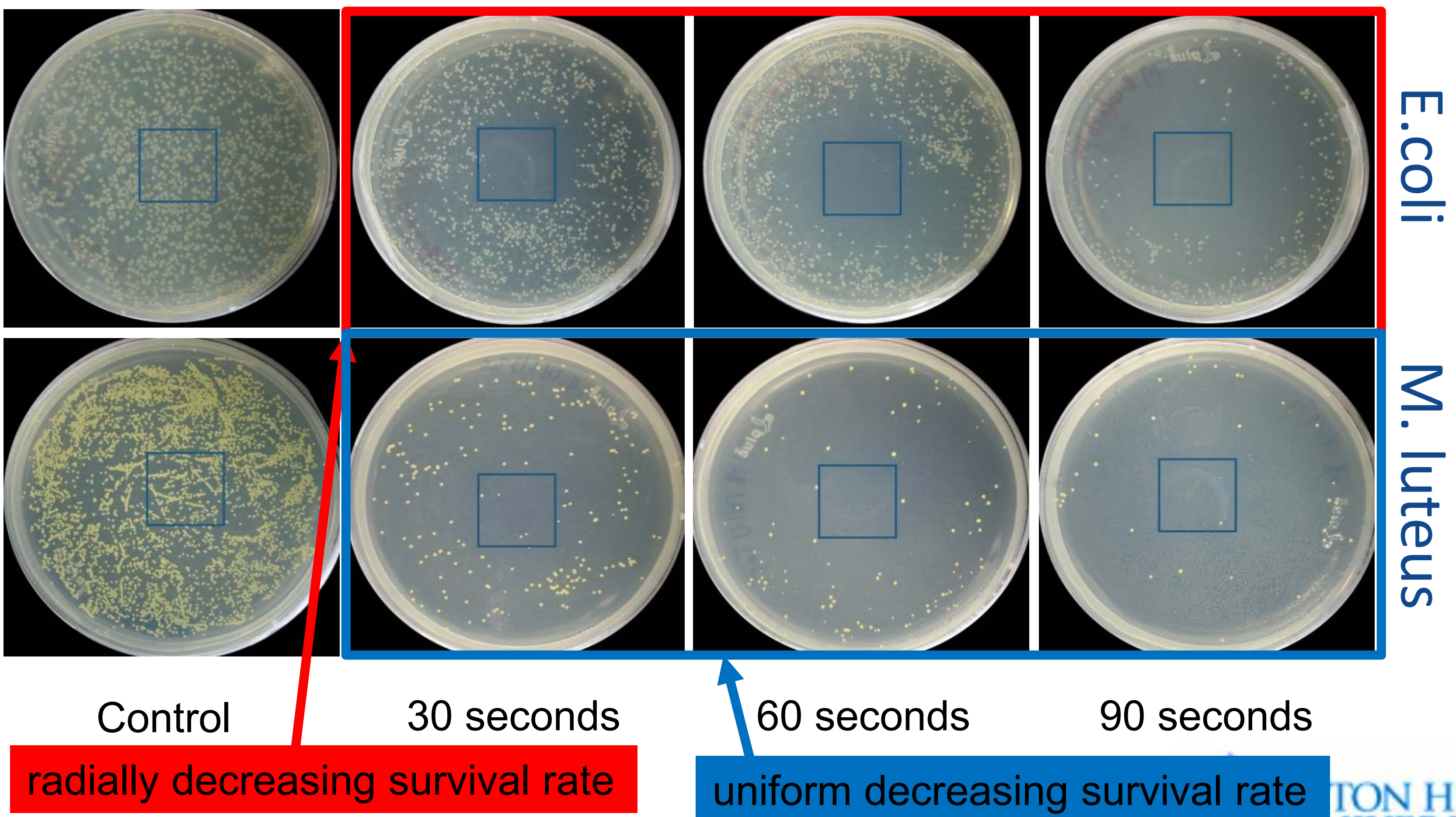
Spore Forming

List of bacteria cultures studied

Experimental Procedure

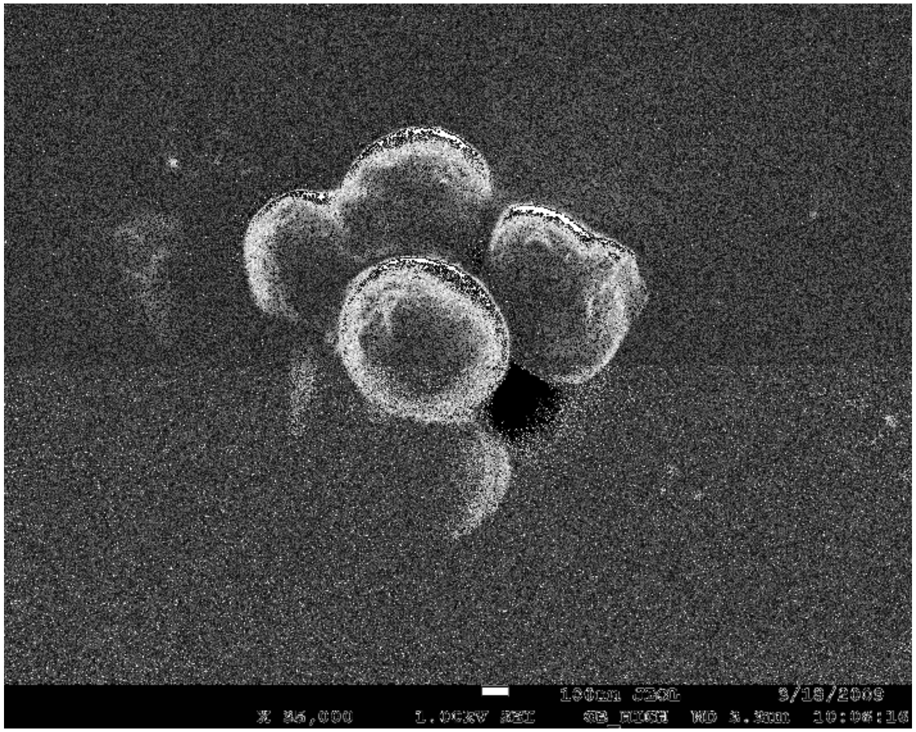
Total path length: 120 mm
Moving speed: 4 mm/s
Time per path: 30 s
Total treatment time: 30s / 60s / 90 s
Area exposure/path: < 1 s (visible plasma),~10 s (radical exposure)

Plasma Dose Effect

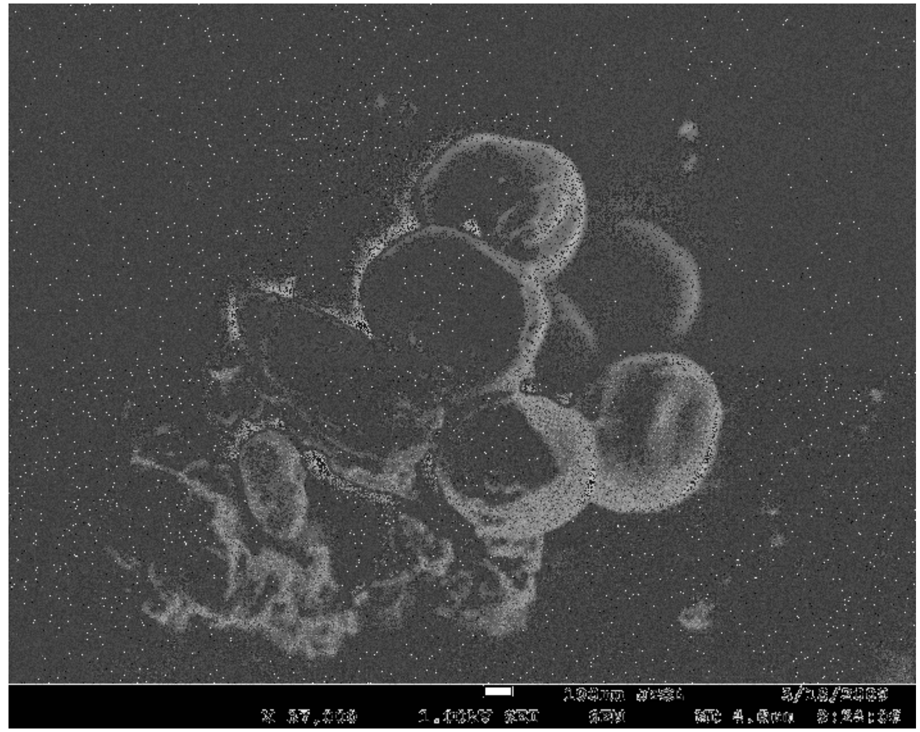


SEM Pictures

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

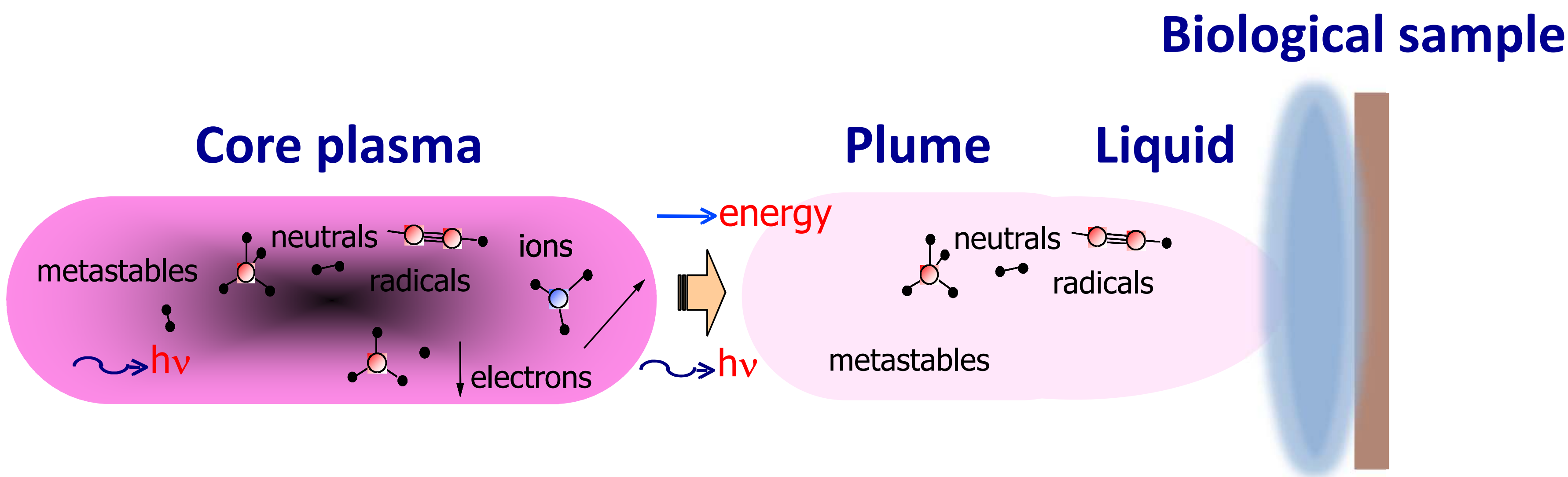
Hemostasis and coagulation in Hairless mice, not immunocompromised (SKH_1)

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

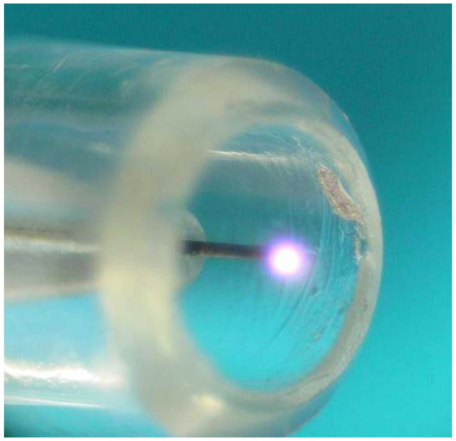
15 seconds of FE-DBD clots the blood and seals the vessel <u>without damaging tissue</u>, preventing additional bleeding.

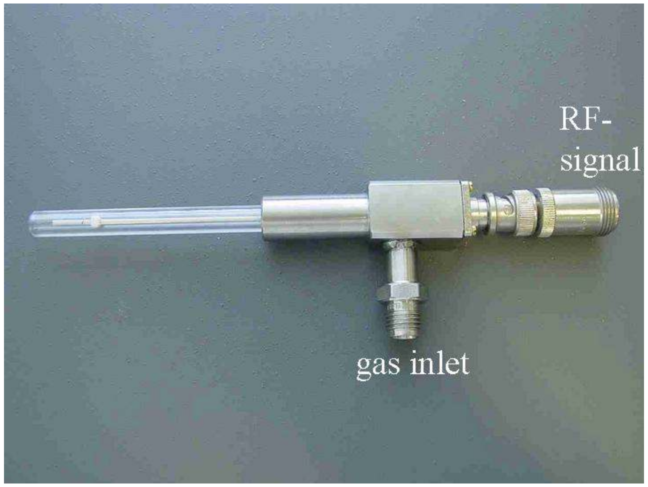
Courtesy: Drexel Plasma Institute

Biological Mechanisms: Plasma Interference into Natural Intracellular Biochemistry



Dental Application



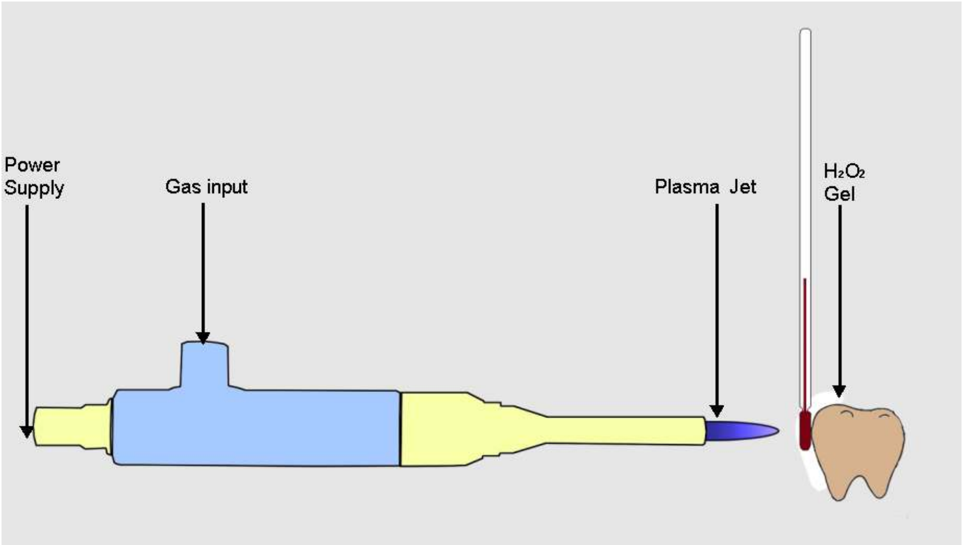


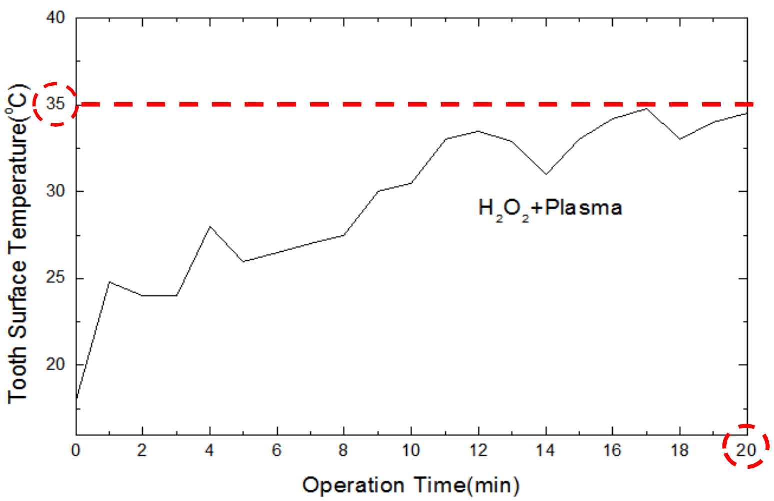
Cleaning of Dental Cavities

Other Applications

- **Bio Decontamination**
- **Sterilization of Medical Instruments and Wounds**

Teeth Whitening with low temperature 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.

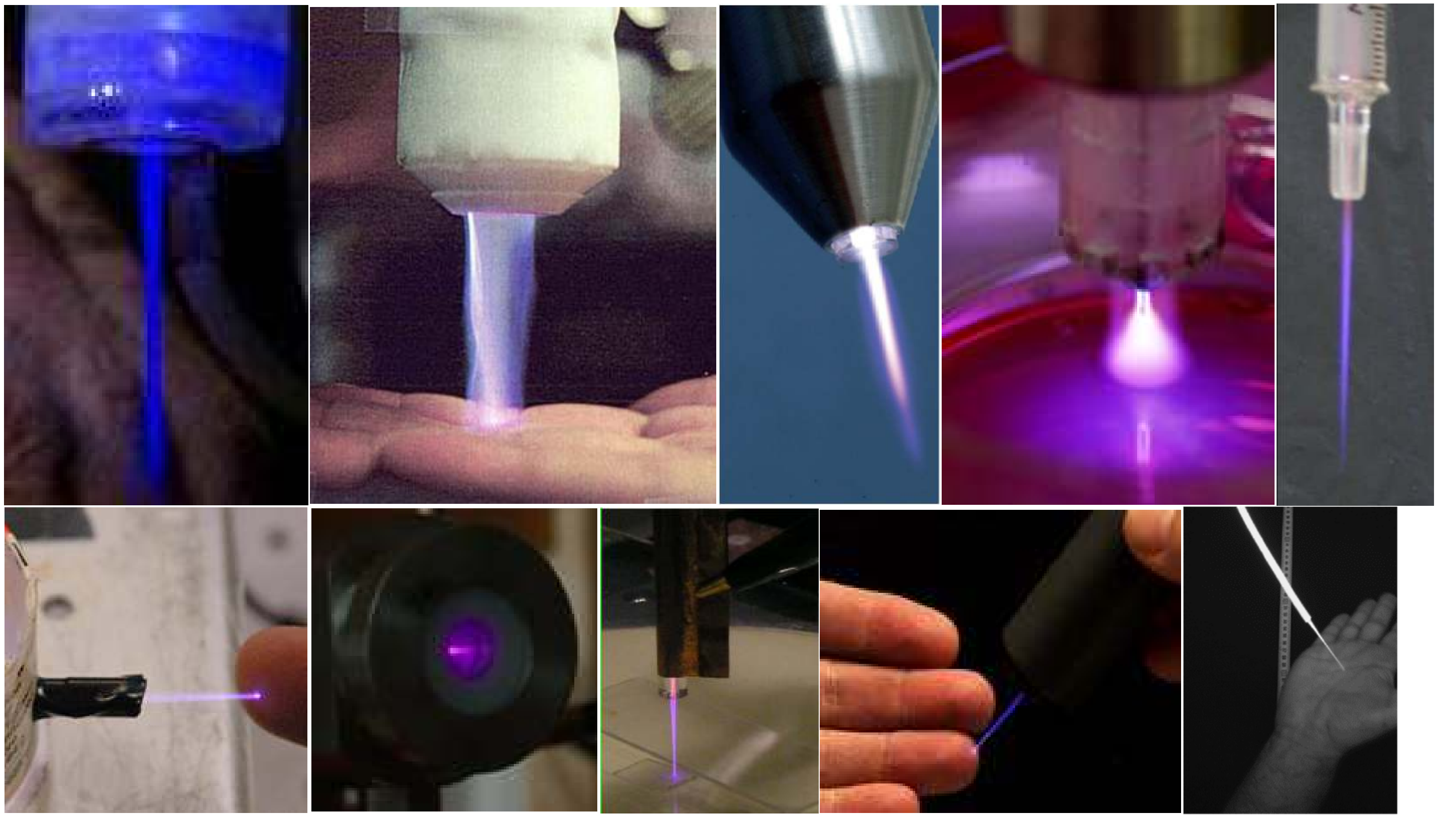
"No thermal-damages"

Teeth Whitening with low temperature plasma

H_2O_2 **before** 20min H_2O_2 **after**

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

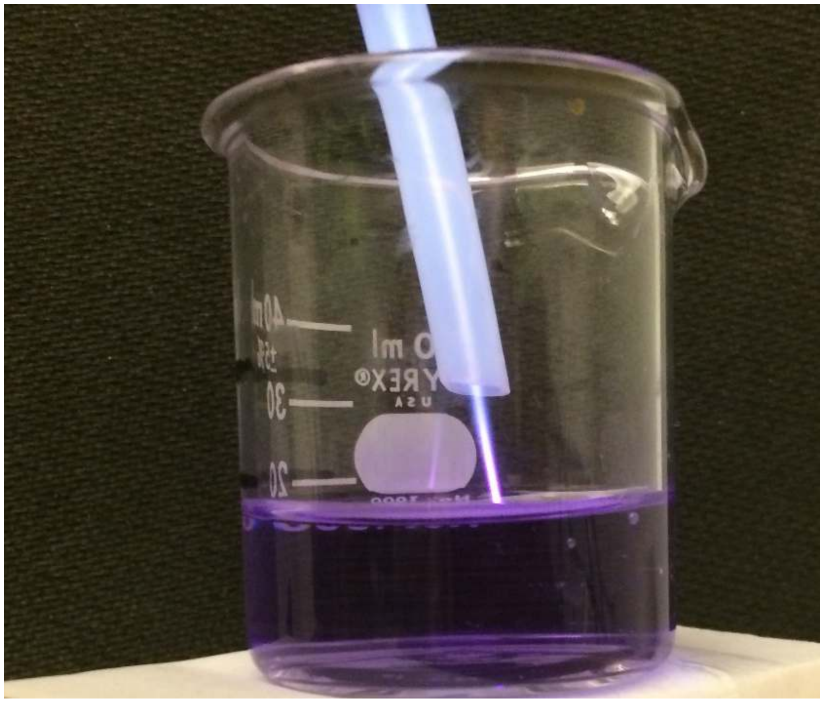
A Brief Collection of Atmospheric Pressure Plasma Jets (APPJ)



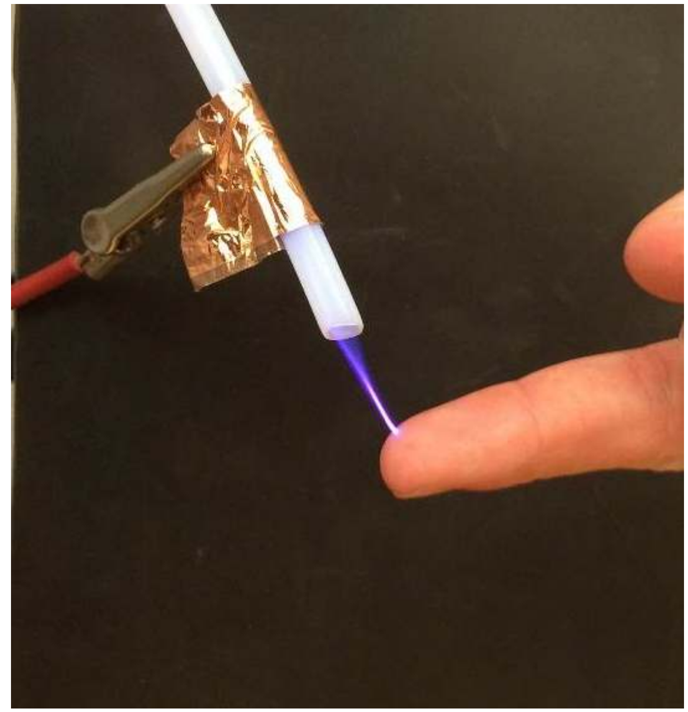
Gases used: Helium, Argon… or mixed with reactive gases (O_2, CH_4…)

AC, pulsed DC, rf or microwave

Our Version of the Atmospheric Pressure Plasma Jet



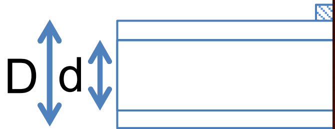
Interaction with aqueous environments



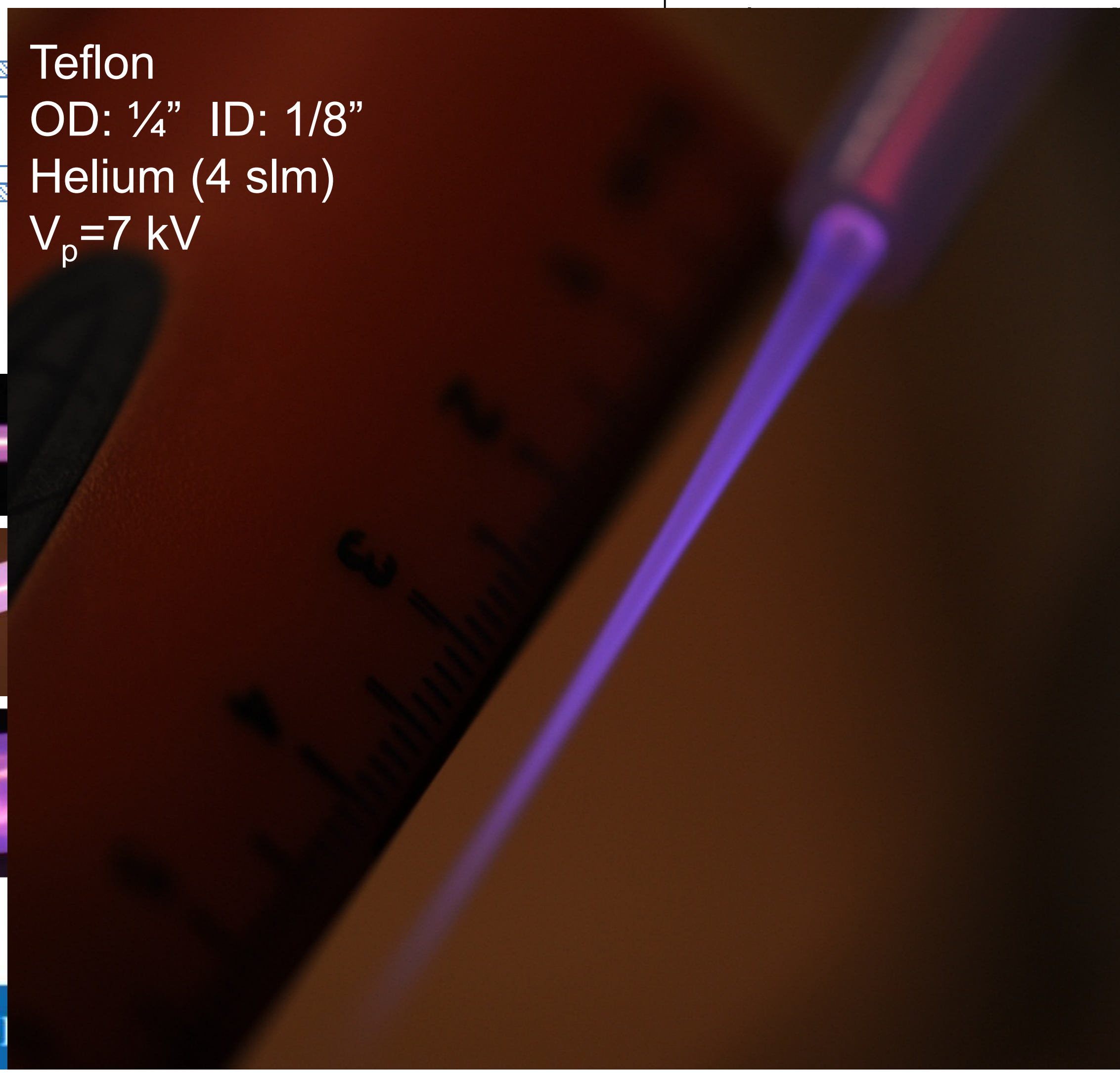
Interaction with organic surfaces

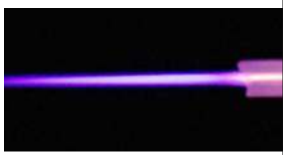
Our Version of Atmospheric Pressure Plasma Jet

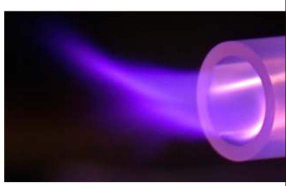
We couldn’t resist to try it out…



- Tubing material: Glass, Teflon, Peek
  , D: 0.0625-0.5”)
  Tape (1” wide)
  96%),
  6%)
  -15 kV

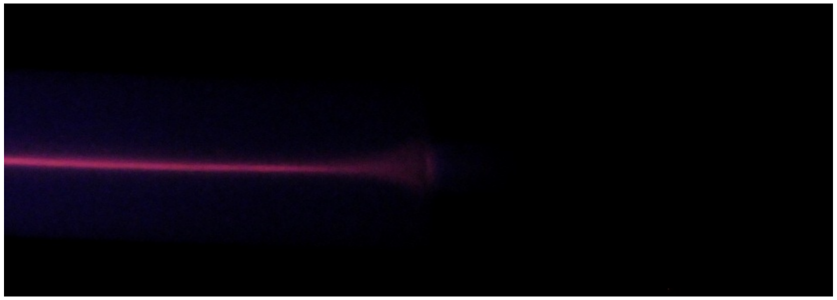


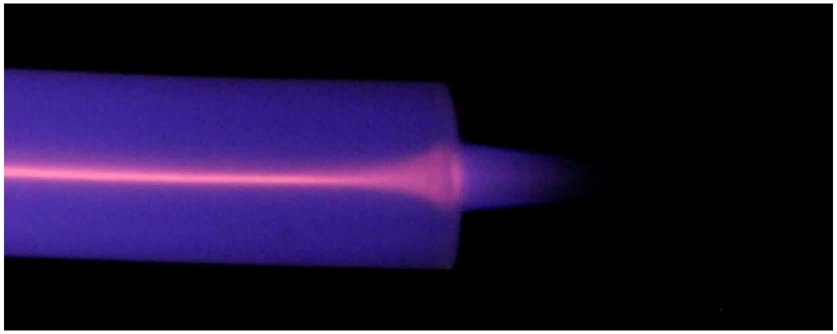


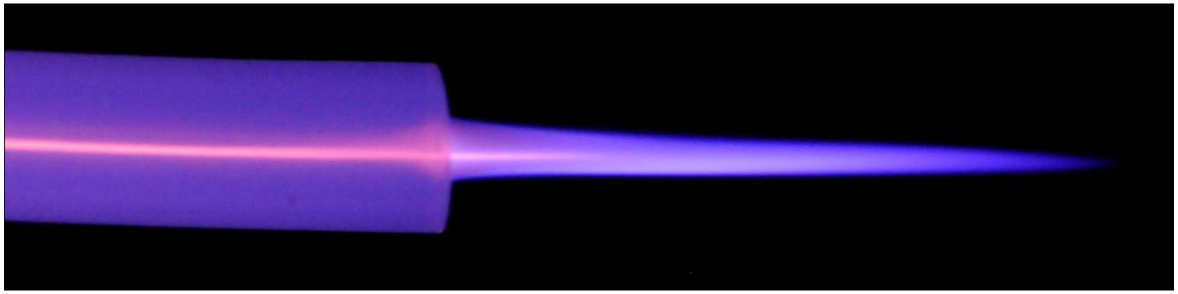


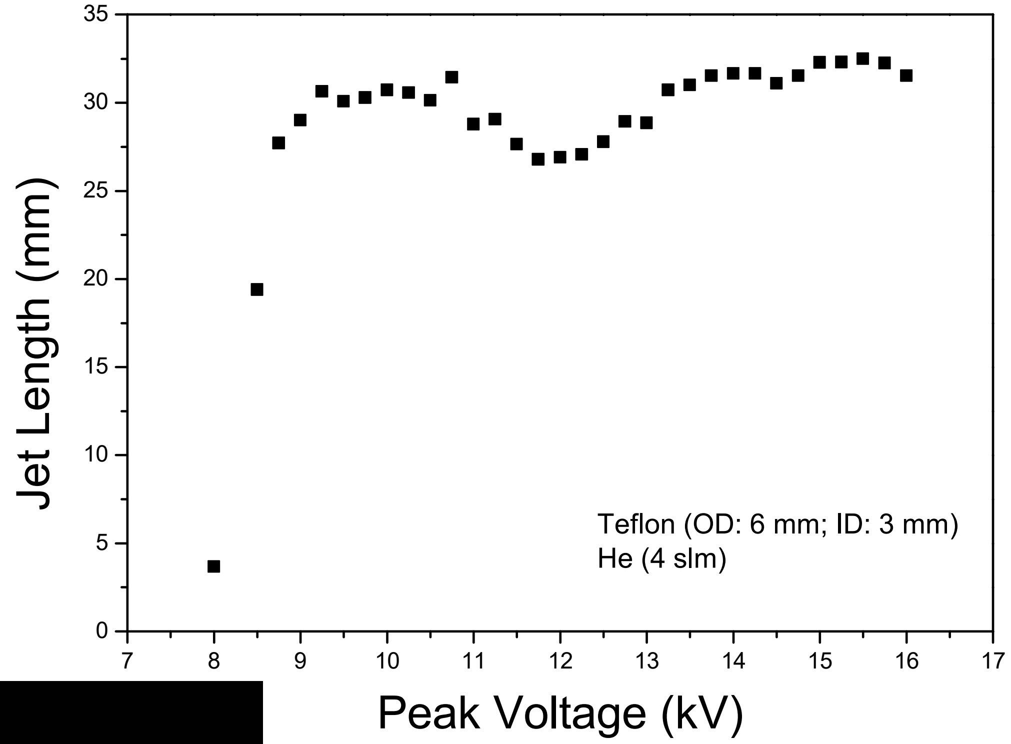
nd downstream

Jet Length vs. applied voltage

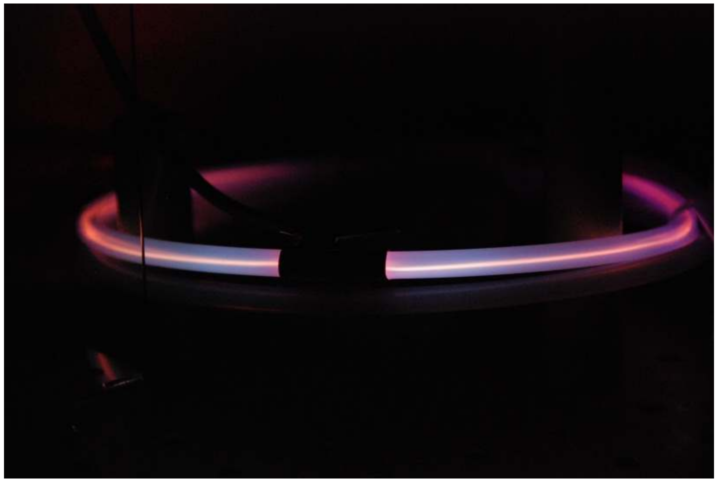


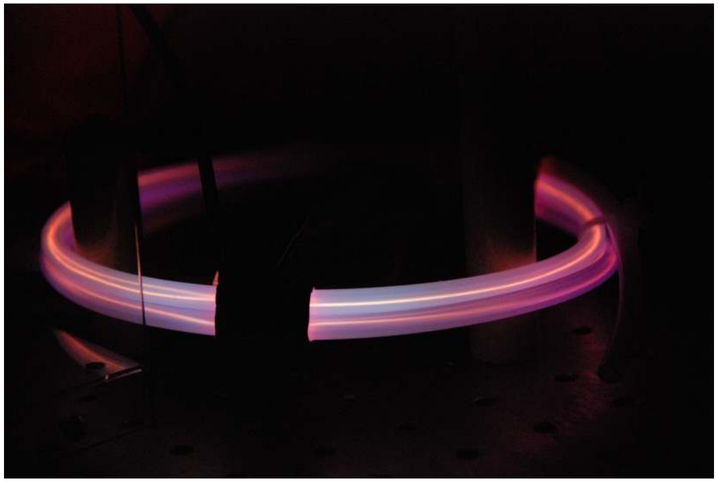


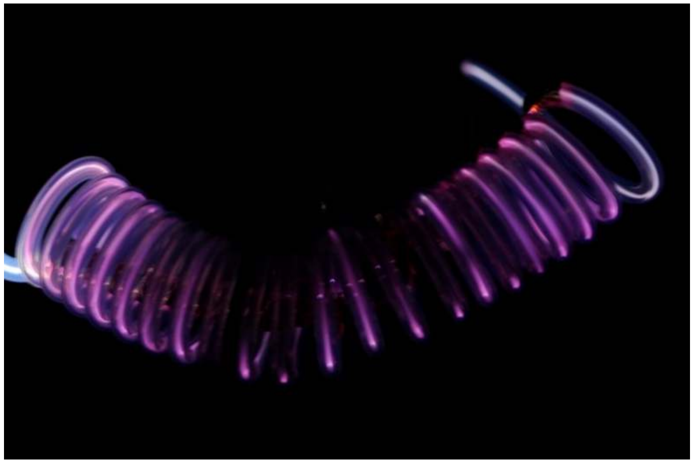




Plasma in a Curved Teflon Tubing

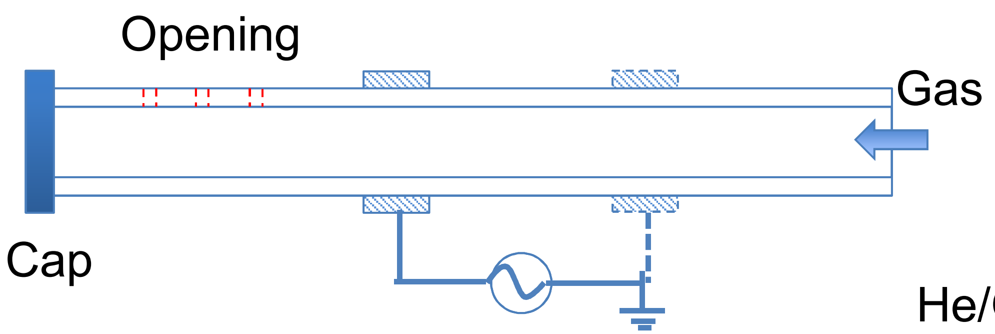






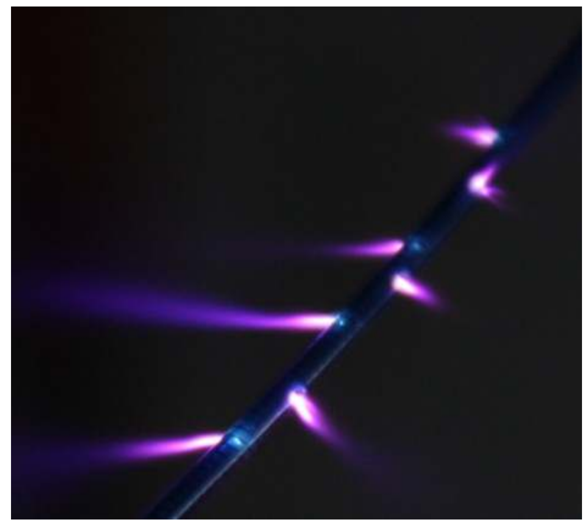
Distance the streamer can travel inside the insulating tubing depends on applied voltage, location of the powered electrode, type of working gas.

Move plasma jets in multiple directions



He/O_2 (2%)

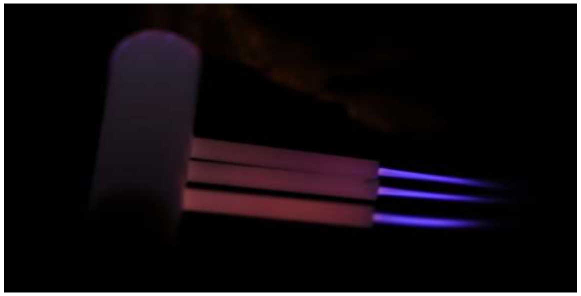
3-D Arrays!

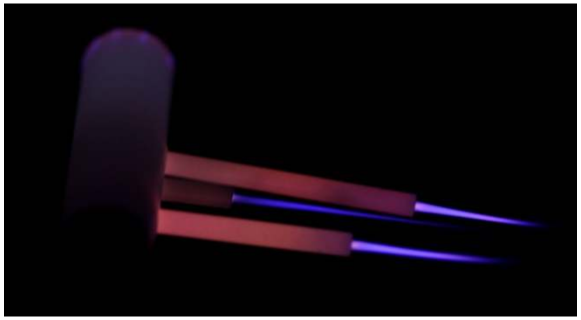


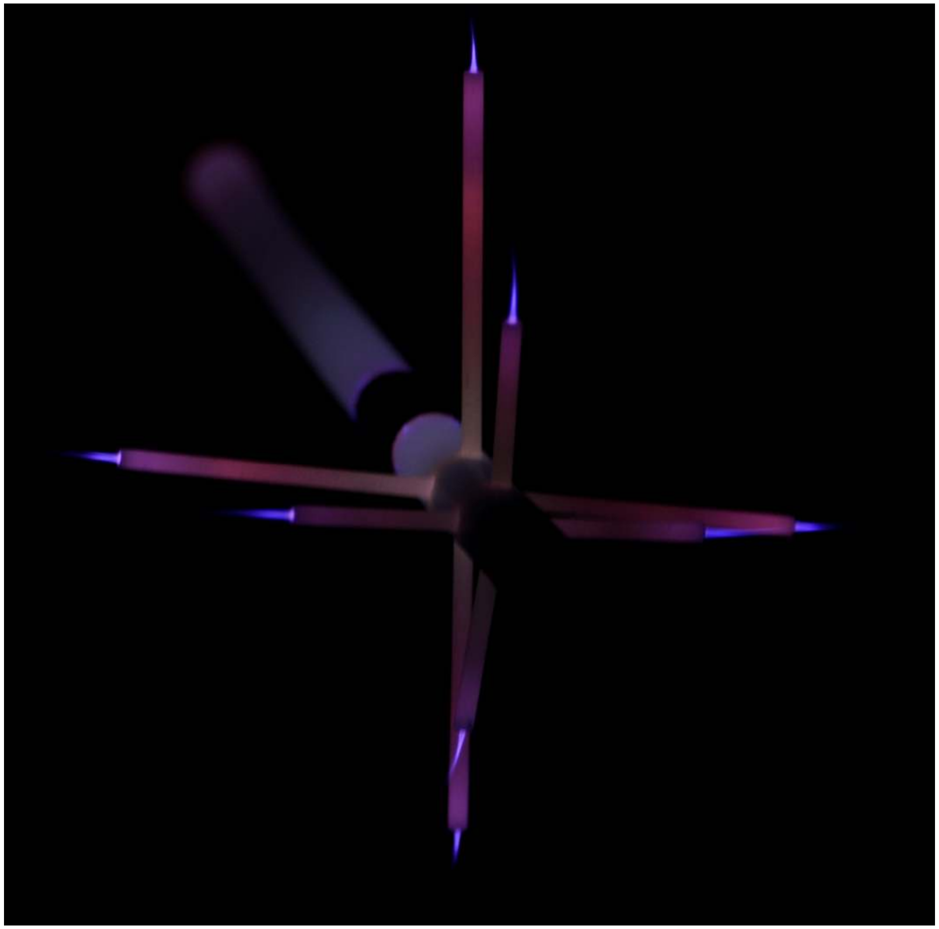
Plasma Jet Array

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

Further Extension of these Plasma Jets



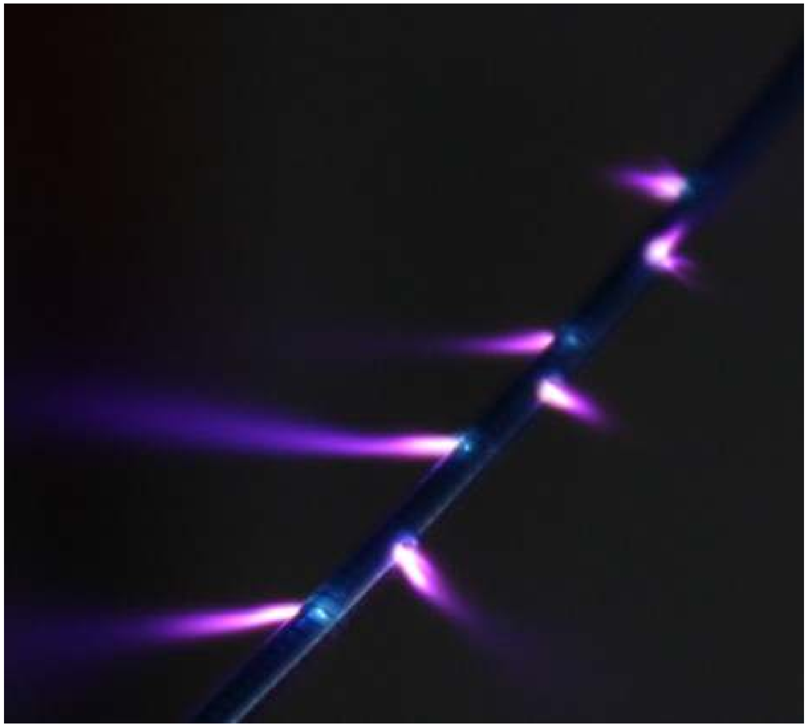




New Jersey – Garden State

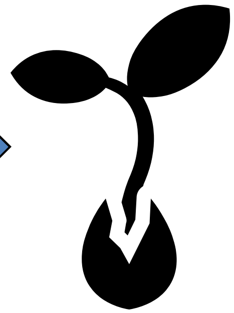
Irrigation: Water & Plasma

Water irrigation in fields and greenhouses



Plasma irrigation for agriculture

Plasma Processing: Experimental Plan



Plasma Treatment

Measure Plants

Harvest

Distillation

Antioxidant Testing

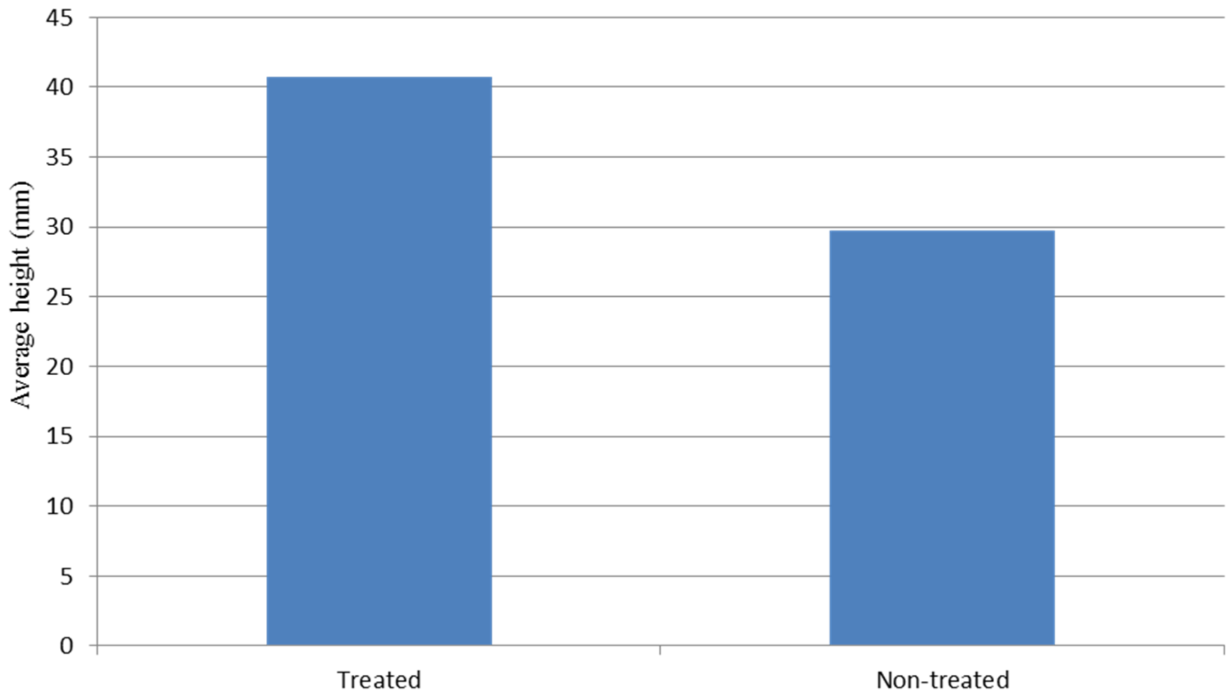
GC-MS

Plasma Seed Treatments

(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).

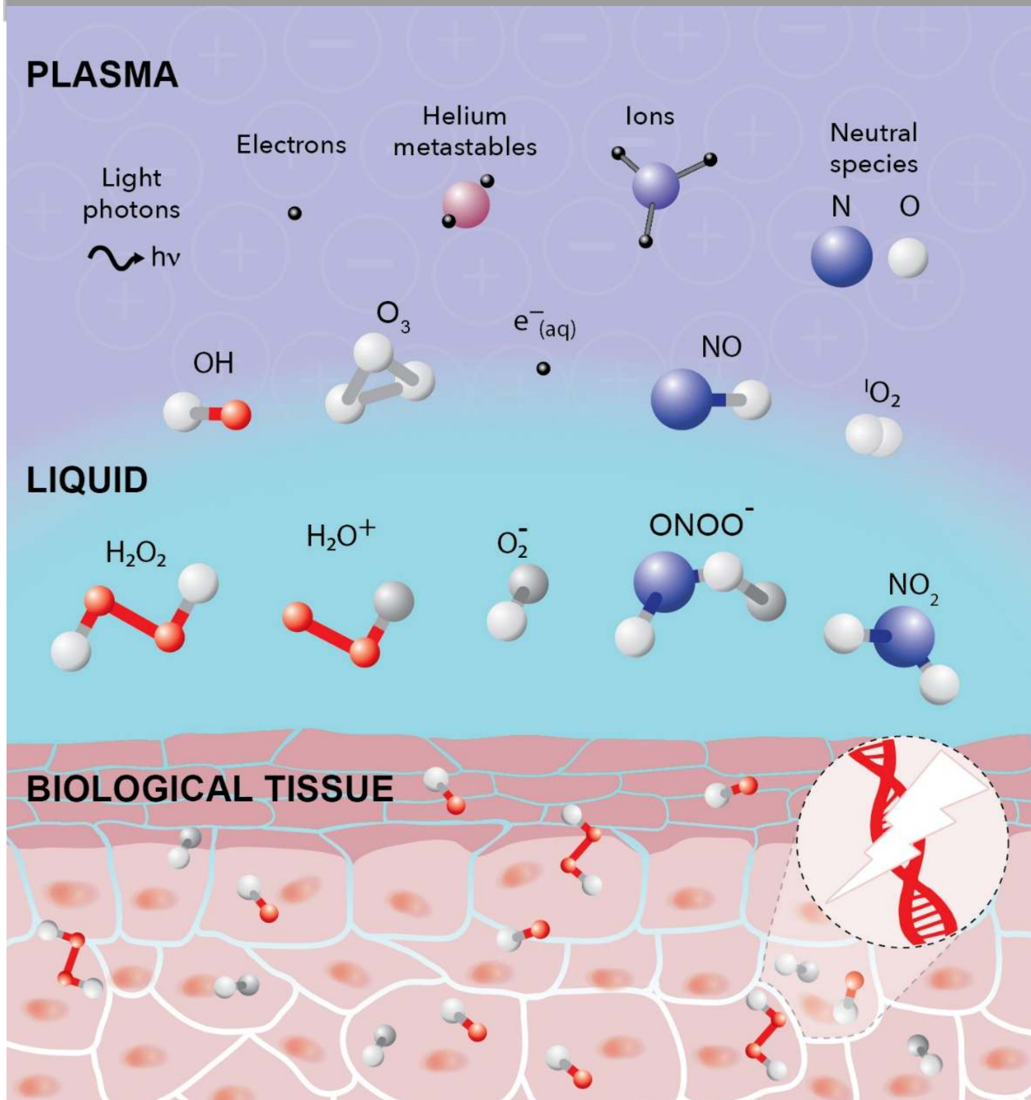
Basil: Plasma Treated vs. Untreated

Basil: Plasma Treated vs. Untreated



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

Low Temperature Plasma interaction with biological materials???



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

- What are the low temperature plasmas doing to the live biological materials?
- Can low temparture sources be tailored to better control interactions with biological materials?

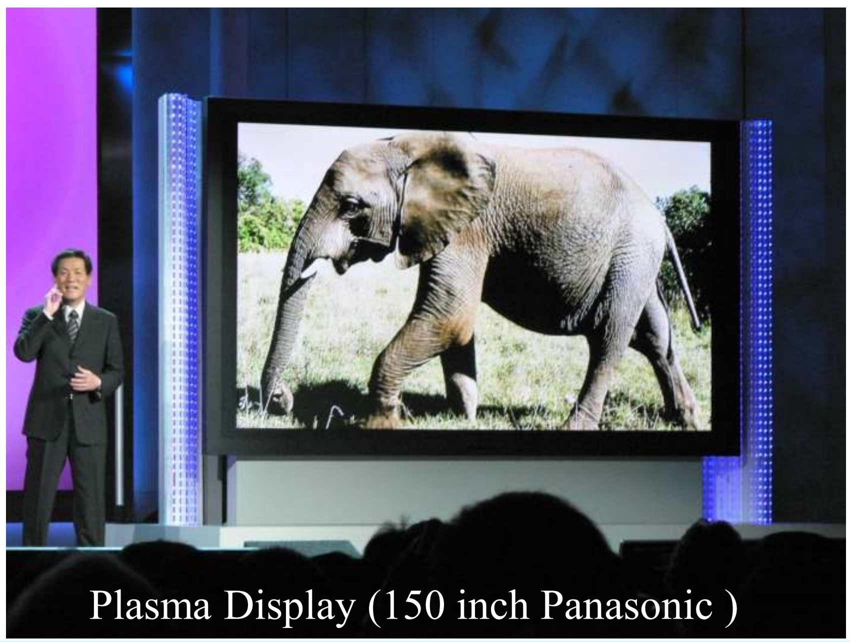
Many, many Innovative Technologies…


Gas Laser

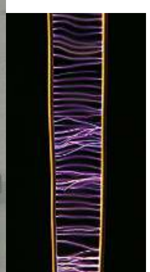

Ozone generator


High Intensity
Plasma Arc Lamp


Plasma Surface Treatment


Plasma Display (150 inch Panasonic)


Fluorescent Lamp

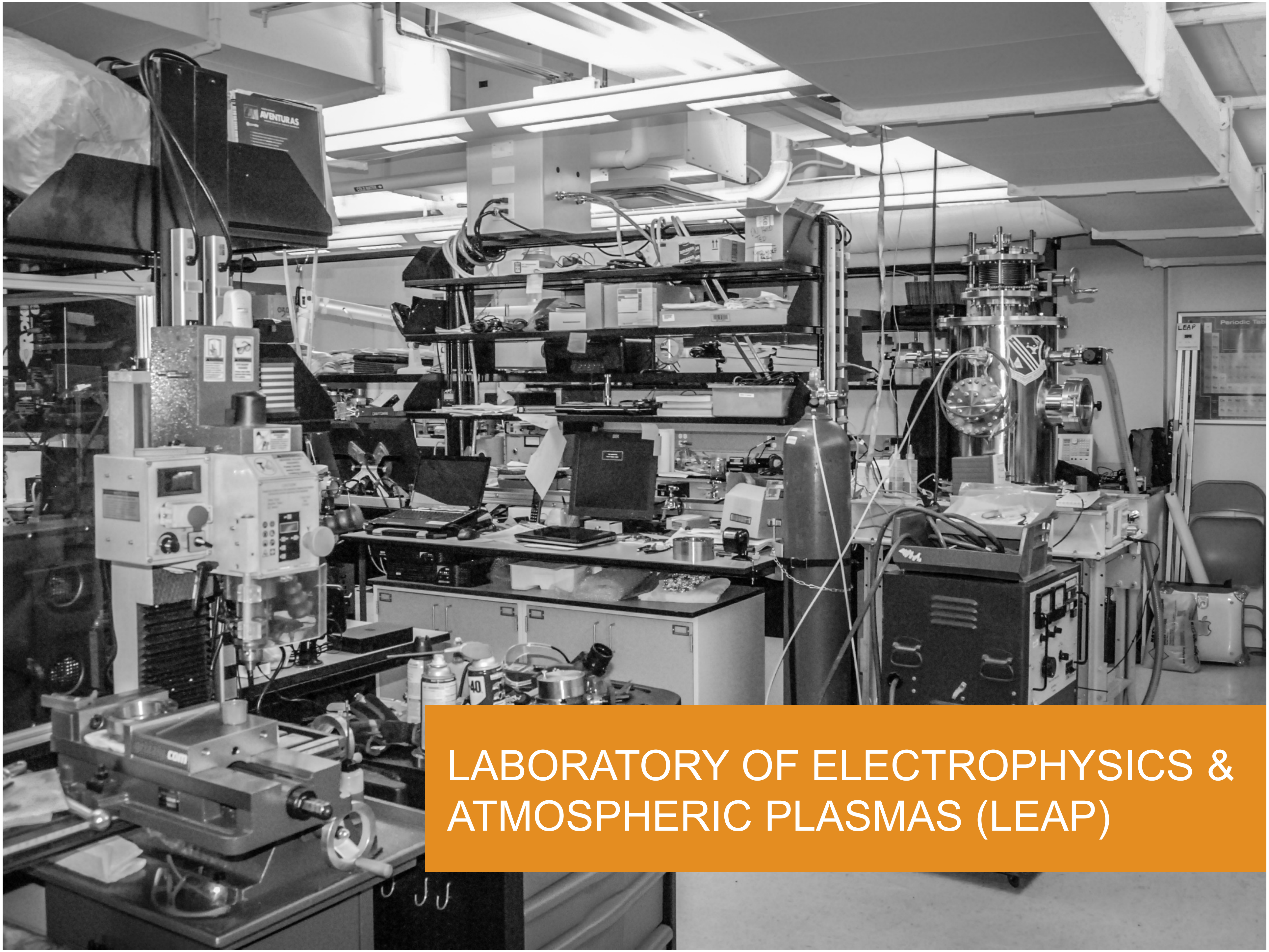


Spark Gap

Acknowledgements

Funding Partners:

IEEE TRANSACTIONS ON
PLASMA SCIENCE

Jose L. Lopez – Seton Hall University
Senior Editor of Industrial, Commercial, and Medical Applications of Plasmas



LABORATORY OF ELECTROPHYSICS & ATMOSPHERIC PLASMAS (LEAP)

Masters of Science (M.S.) in Physics

Two M.S. in Physics 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

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DEPARTMENT OF PHYSICS

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

….Yogi Berra

Questions???

SETON HALL UNIVERSITY

Thank You!

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