Low Temperature Plasma Technologies

Jose L. Lopez, Ph.D.

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

PPPL PRINCETON PLASMA PHYSICS LABORATORY

SULI Introduction to Fusion Energy and Plasma Physics course – June 25, 2020

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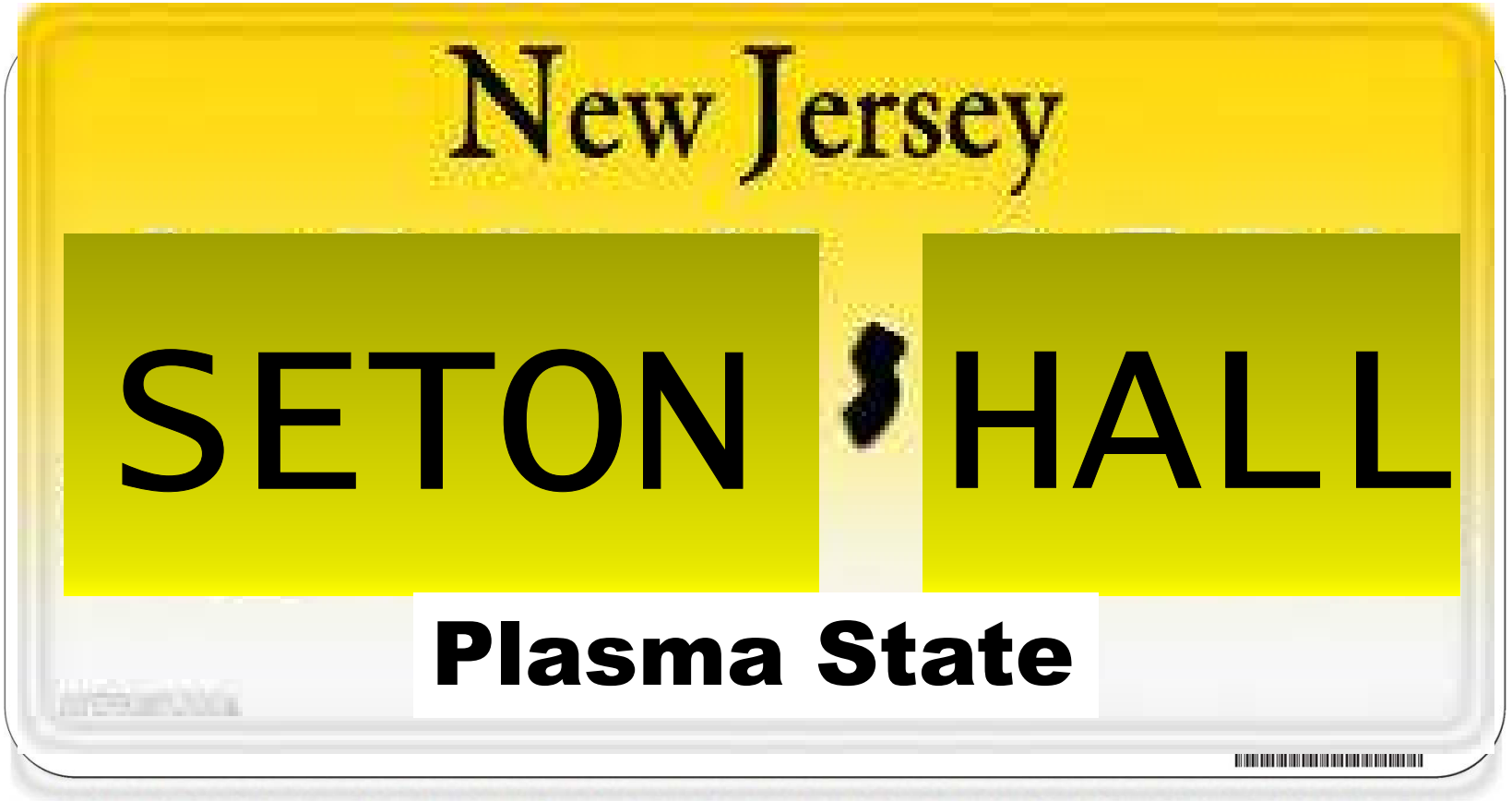
New Jersey – Plasma State



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The Plasma State – New Jersey

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Seton Hall University

Newark, NJ

Nutley, NJ

South Orange, New Jersey

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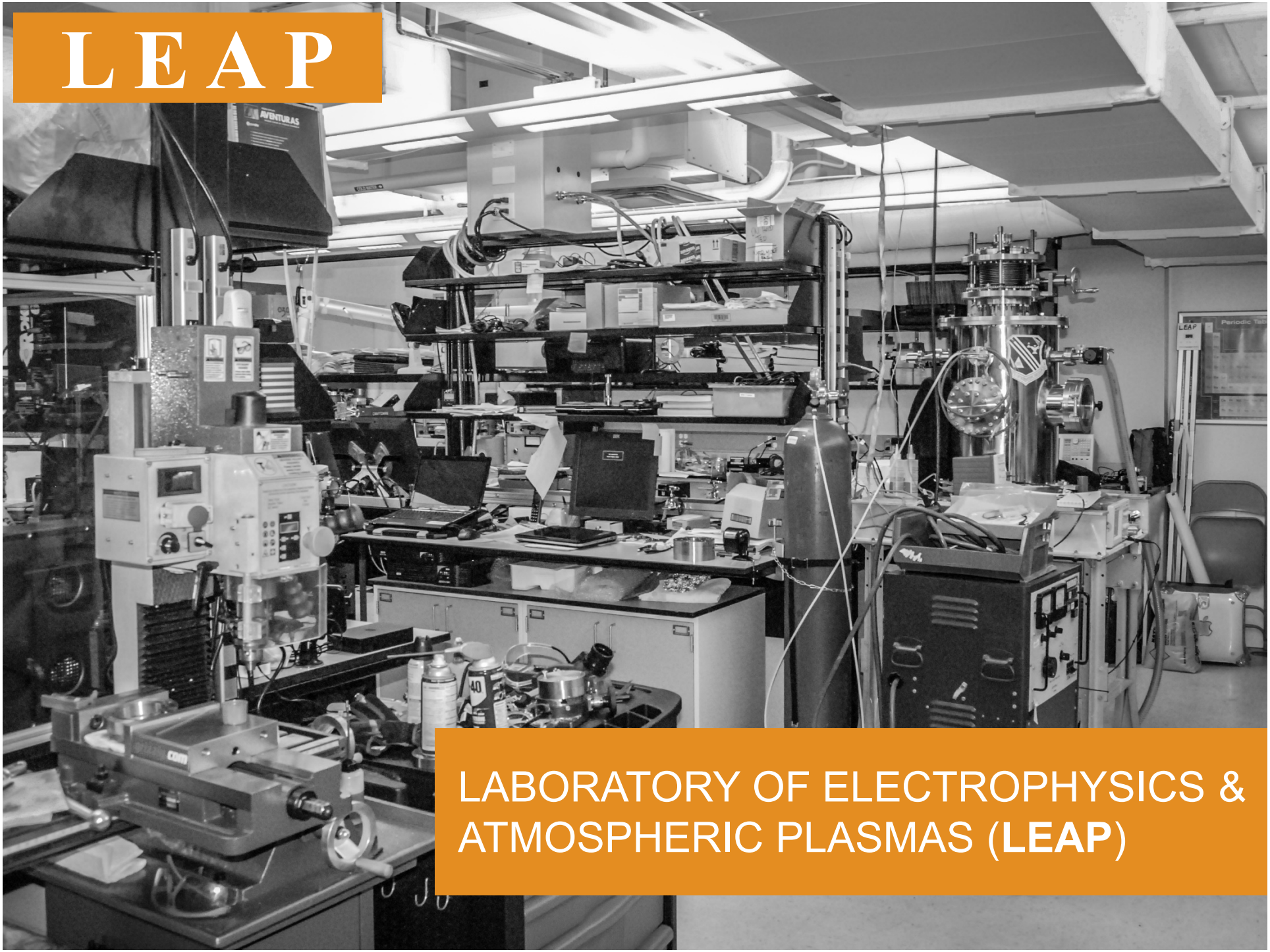
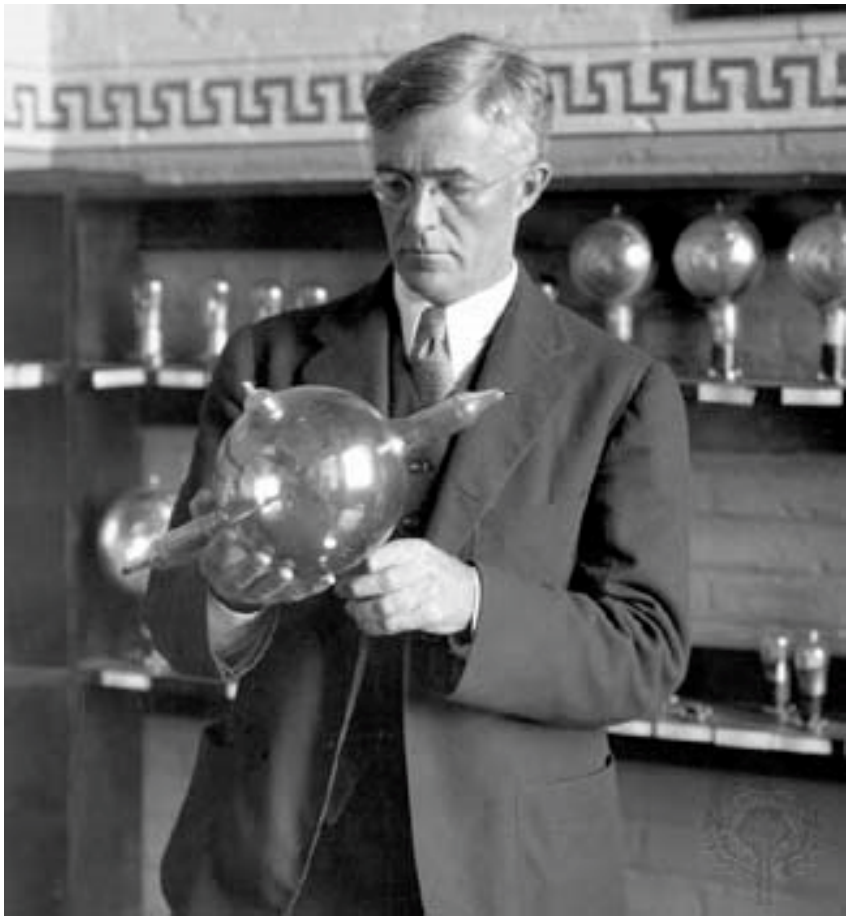
LEAP



LABORATORY OF ELECTROPHYSICS & ATMOSPHERIC PLASMAS (**LEAP**)

New Jersey – The birth place of Plasma Science



Irving Langmuir

Birth of Plasma Science

Birthplace: Hoboken, New Jersey

STEVENS INSTITUTE of TECHNOLOGY
THE INNOVATION UNIVERSITY®

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

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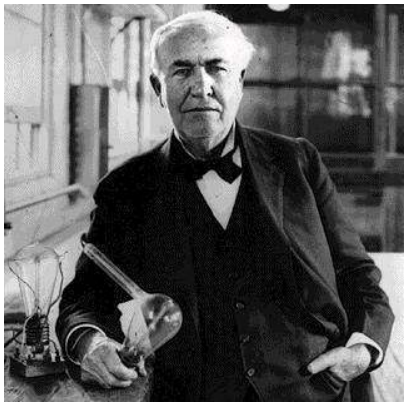
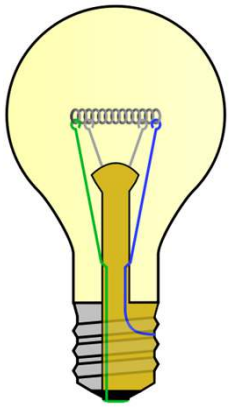
Plasma Lighting Technology



Thomas Edison



Daniel McFarlan Moore

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

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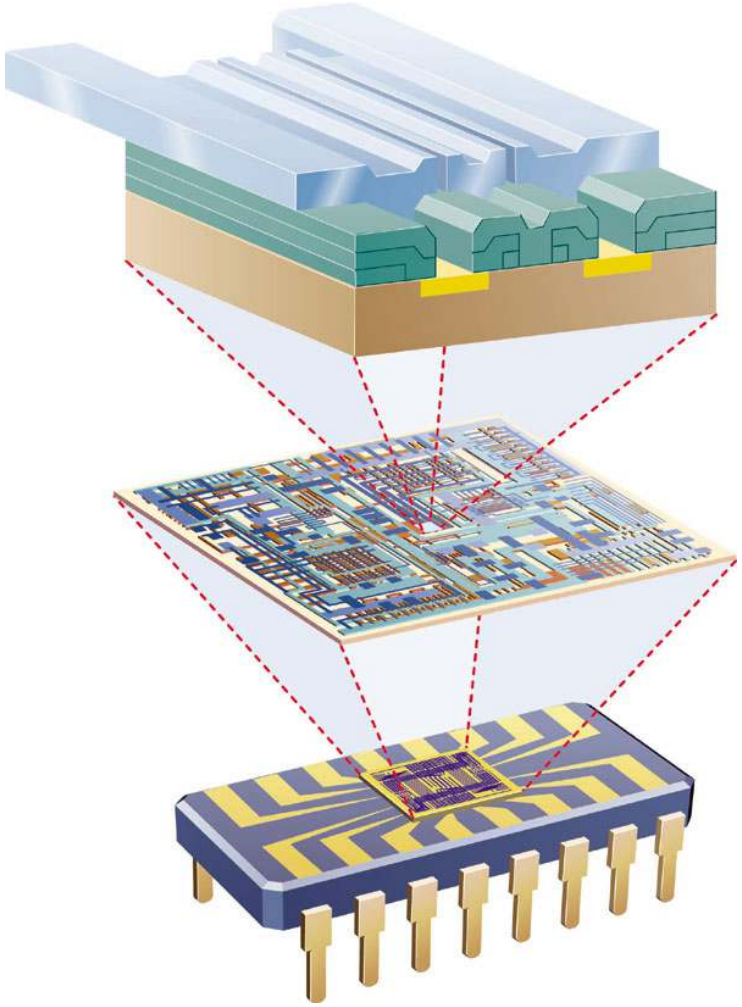
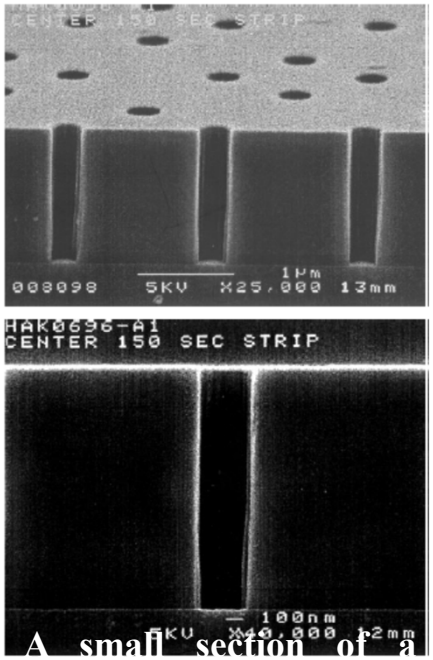
Plasma Enhanced Technology





A small section of a

Bell Laboratories

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

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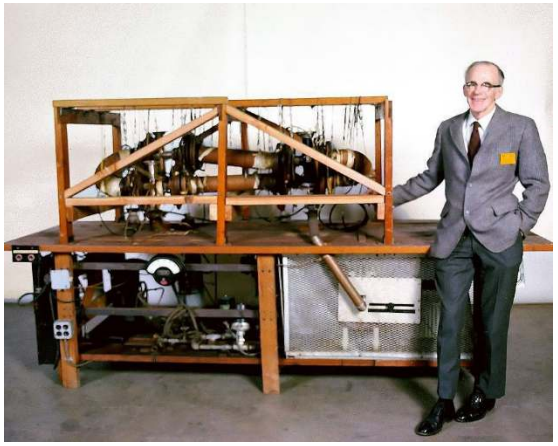
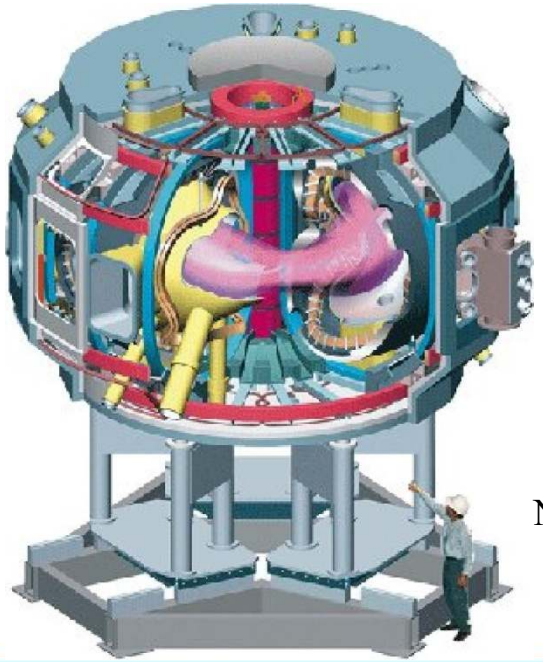
PPPL
PRINCETON PLASMA PHYSICS LABORATORY

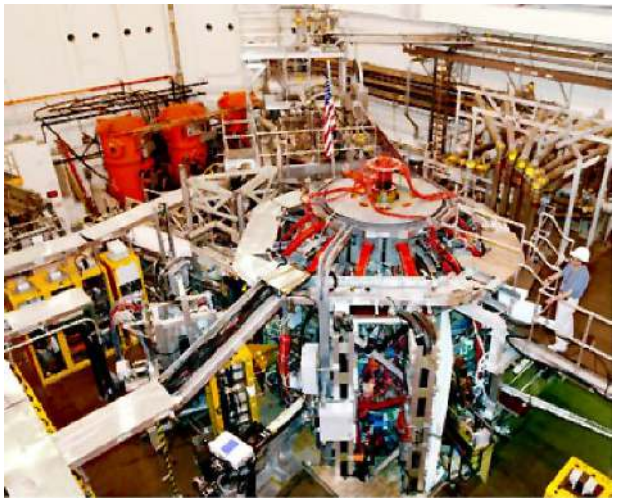
PRINCETON UNIVERSITY

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)

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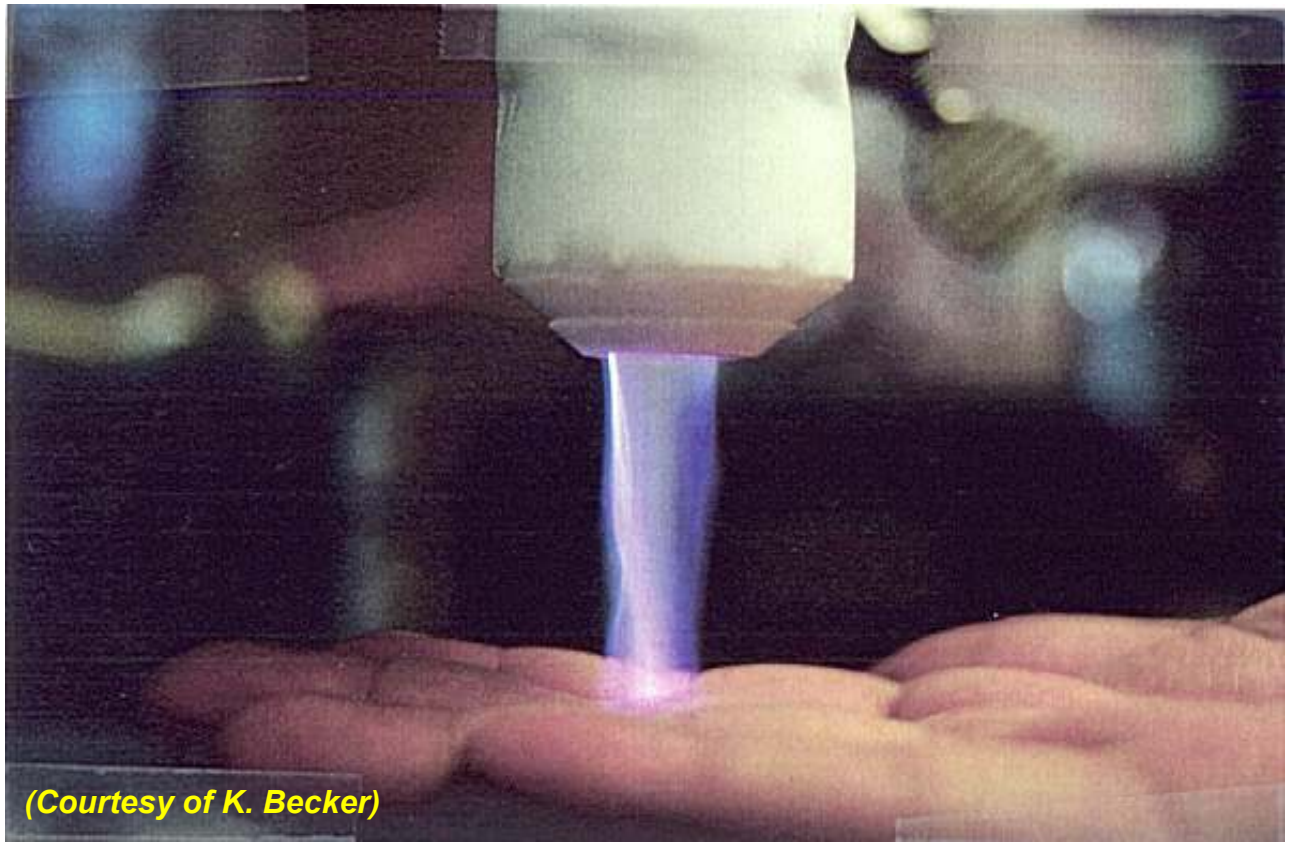
A HOME FOR THE MIND, THE HEART AND THE SPIRIT

DEPARTMENT OF PHYSICS

Atmospheric Cold Plasmas

Erich Kunhardt & Kurt Becker

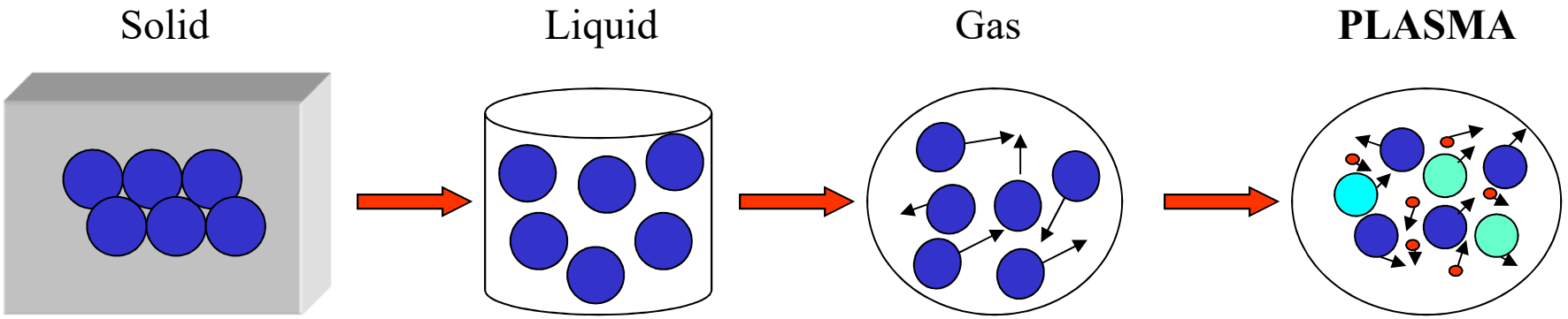
STEVENS Institute of Technology

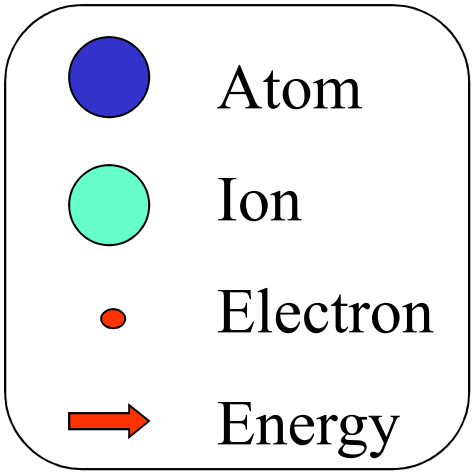


An Atmospheric Pressure Plasma Generated with a Capillary-Plasma-Electrode Discharge

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)*

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

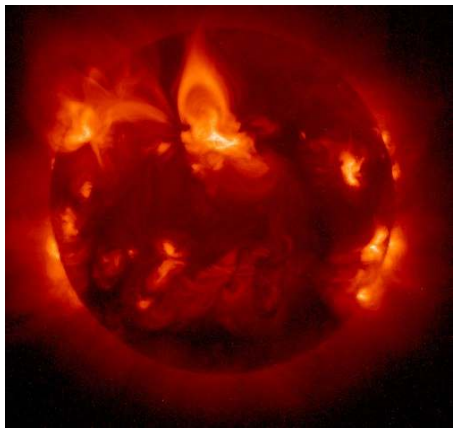
$T_i \approx T_g \approx 300$ K

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

e.g. low-pressure glow discharge

high-pressure cold plasma

Plasmas in Nature

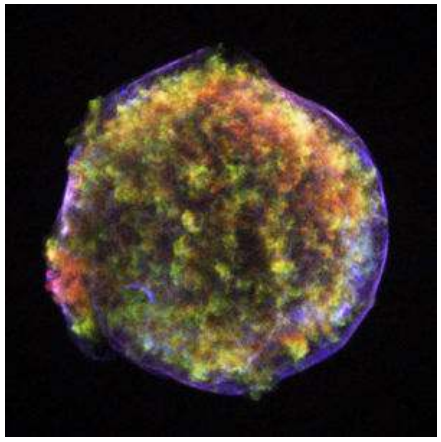


The Sun

Aurora

Lightning

The Comet



Supernova

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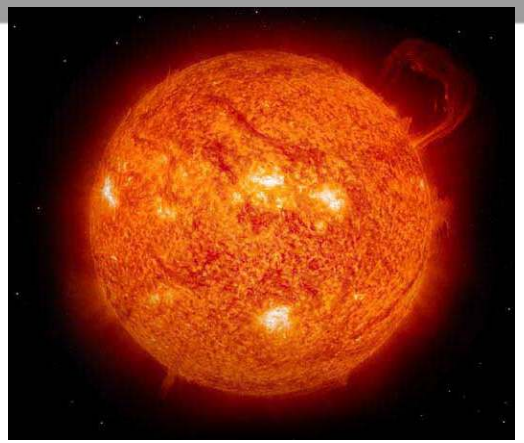
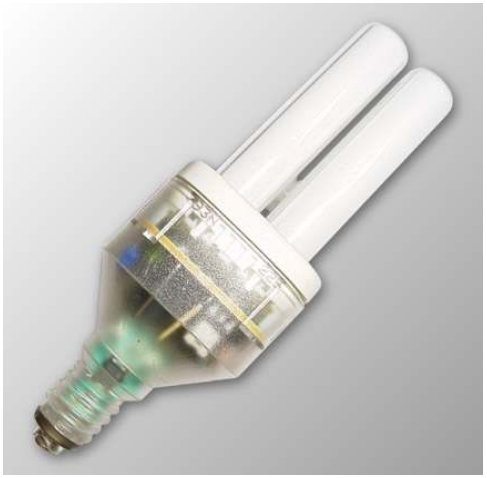
Plasmas are everywhere!!!



Sun

Aurora Borealis (Northern Lights)

Lightning



Fluorescent Lamps

Plasma Display Televisions

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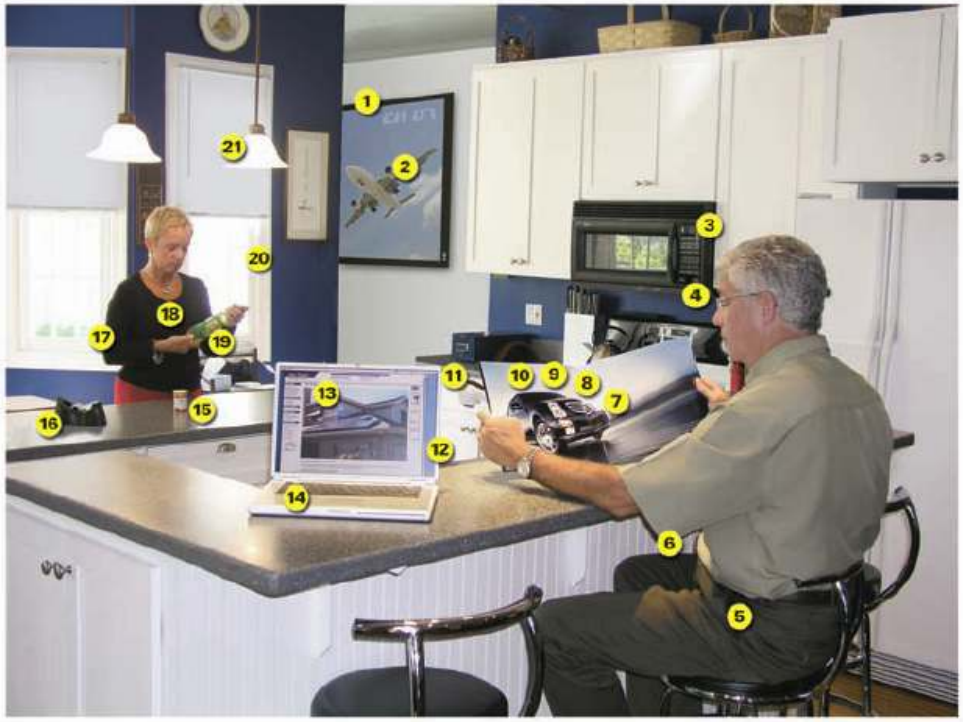
Low-Temperature ("Cold") Plasmas [Non-equilibrium, Non-Thermal]

$T_e >> T_i, T_n$ 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

Low Temperature Plasma (LTP) enabled technology



01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

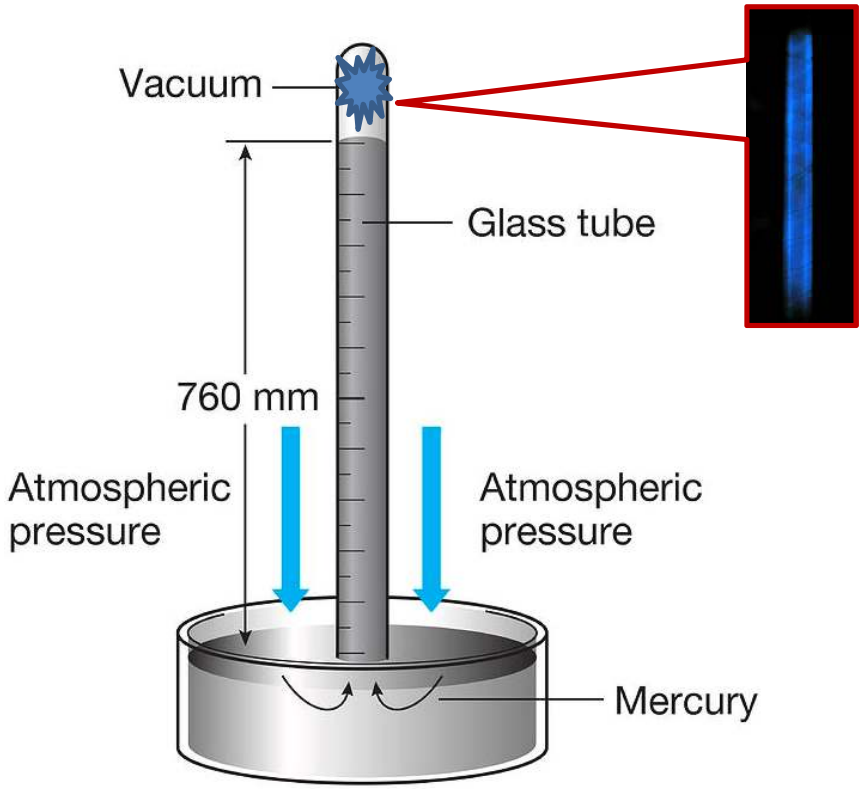
Plasmas in the kitchen. Plasmas and the technologies they enable are pervasive in our everyday life. Each one of us touches or is touched by plasma-enabled technologies every day.

Plasma Science: Advancing Knowledge in the National Interest. Plasma 2010 Committee, Plasma Science Committee, National Research Council. ISBN: 0-309-10944-2, 280 pages, (2007)

The first observation of LTP by Jean Piccard

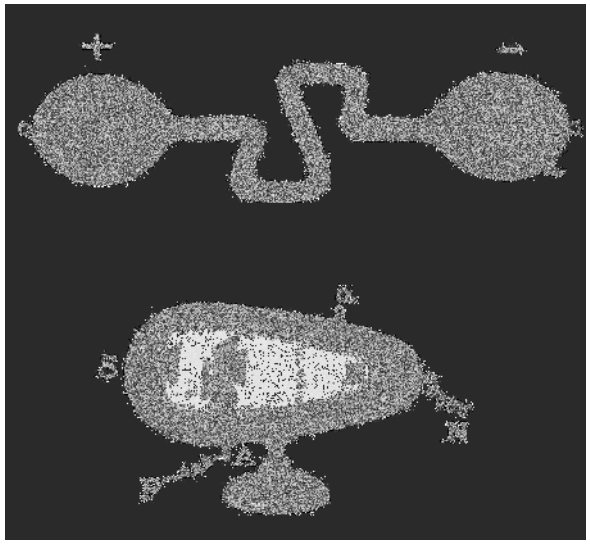
Jean (Félix) Picard (July 21, 1620 –July 12, 1682) was a French astronomer and Catholic priest.
The first person to accurately measure the circumference of the earth. Around 1670!

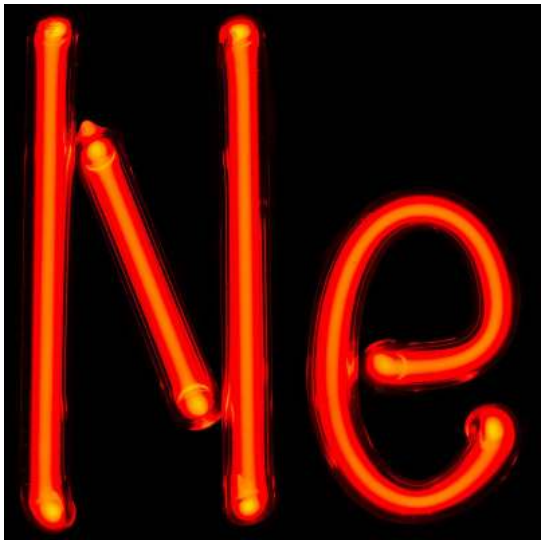
Observed in his barometer tube glowing light that were produced when mercury atoms rubbed against the barometer's glass wall. i.e. first documented observation a *low temperature plasma*.

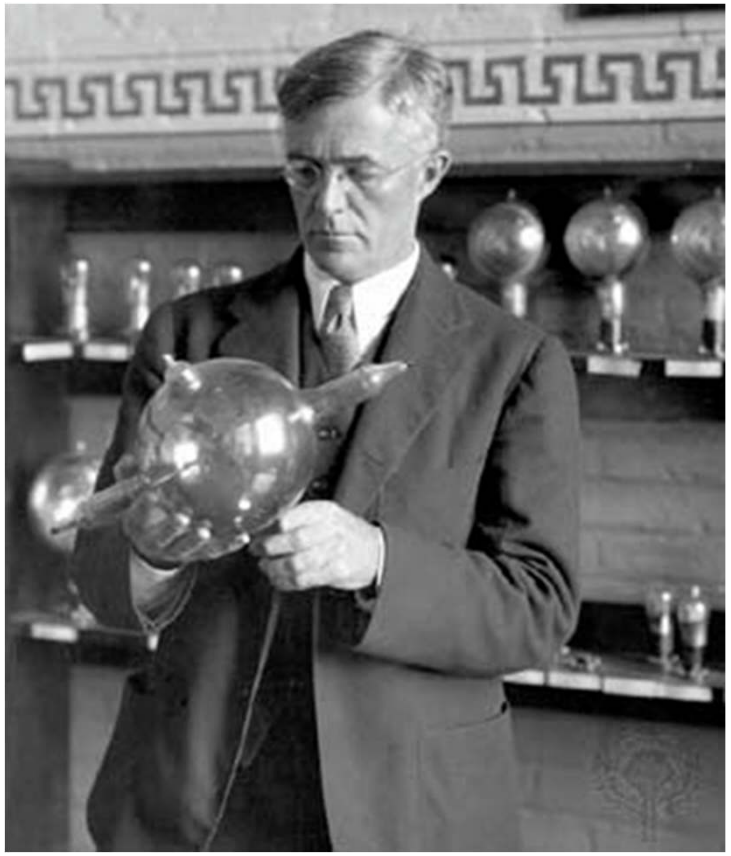


Mercury barometer

Vacuum glows and discharges







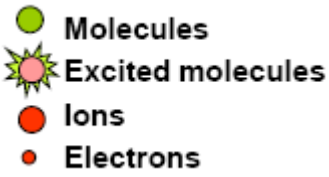
Irving Langmuir

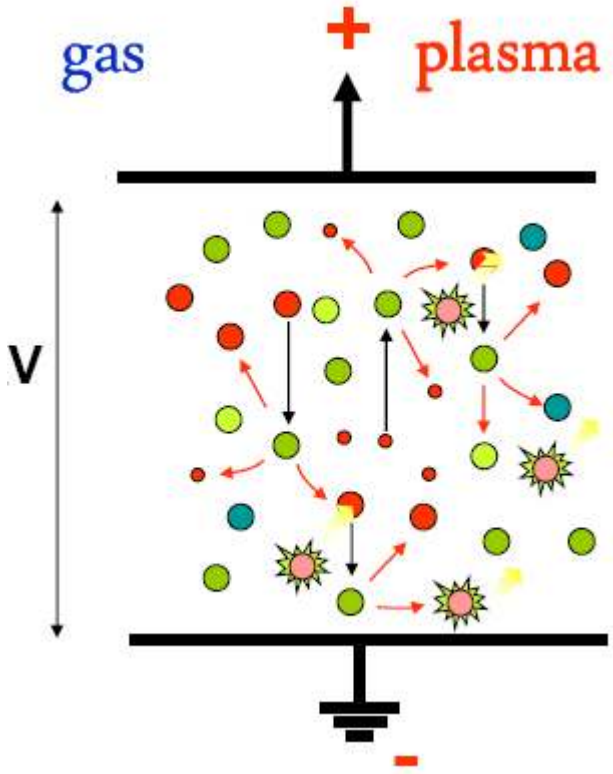
How do we make plasmas?

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

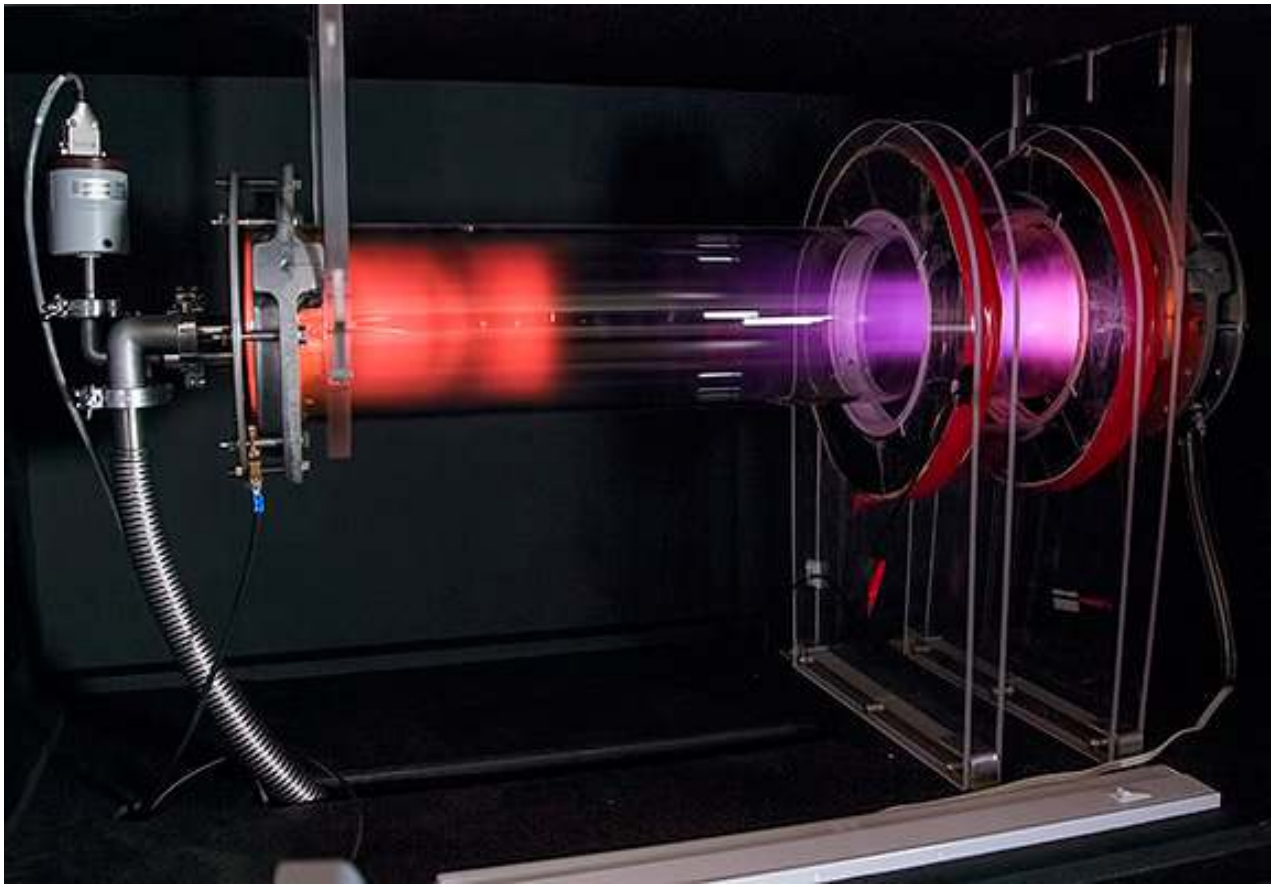
For many plasma applications, an Electric Field is applied to a gaseous environment

Plasma or Gaseous Discharge





PPPL's Remote Glow Discharge Experiment (RGDX)



https://www.pppl.gov/RGDX

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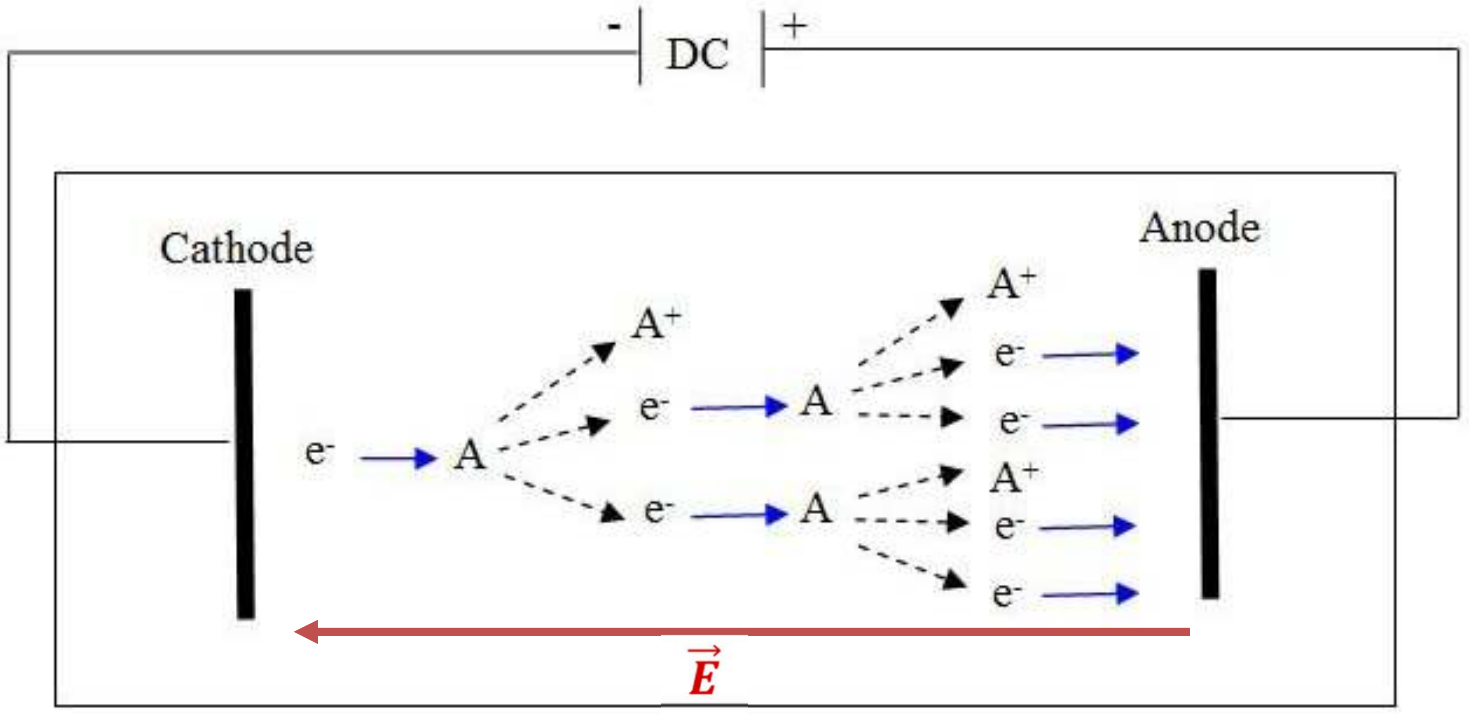
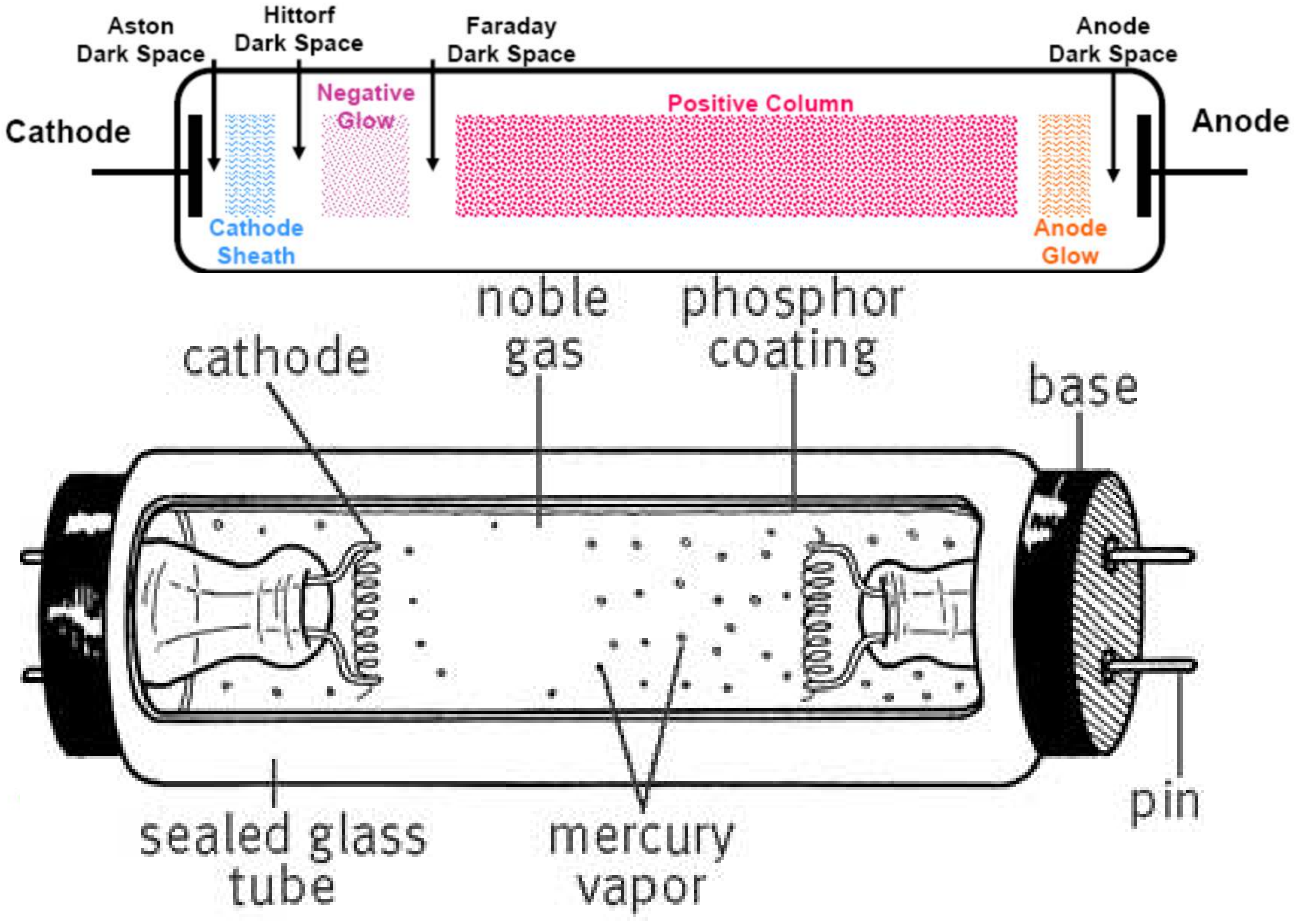
DC Glow Plasma



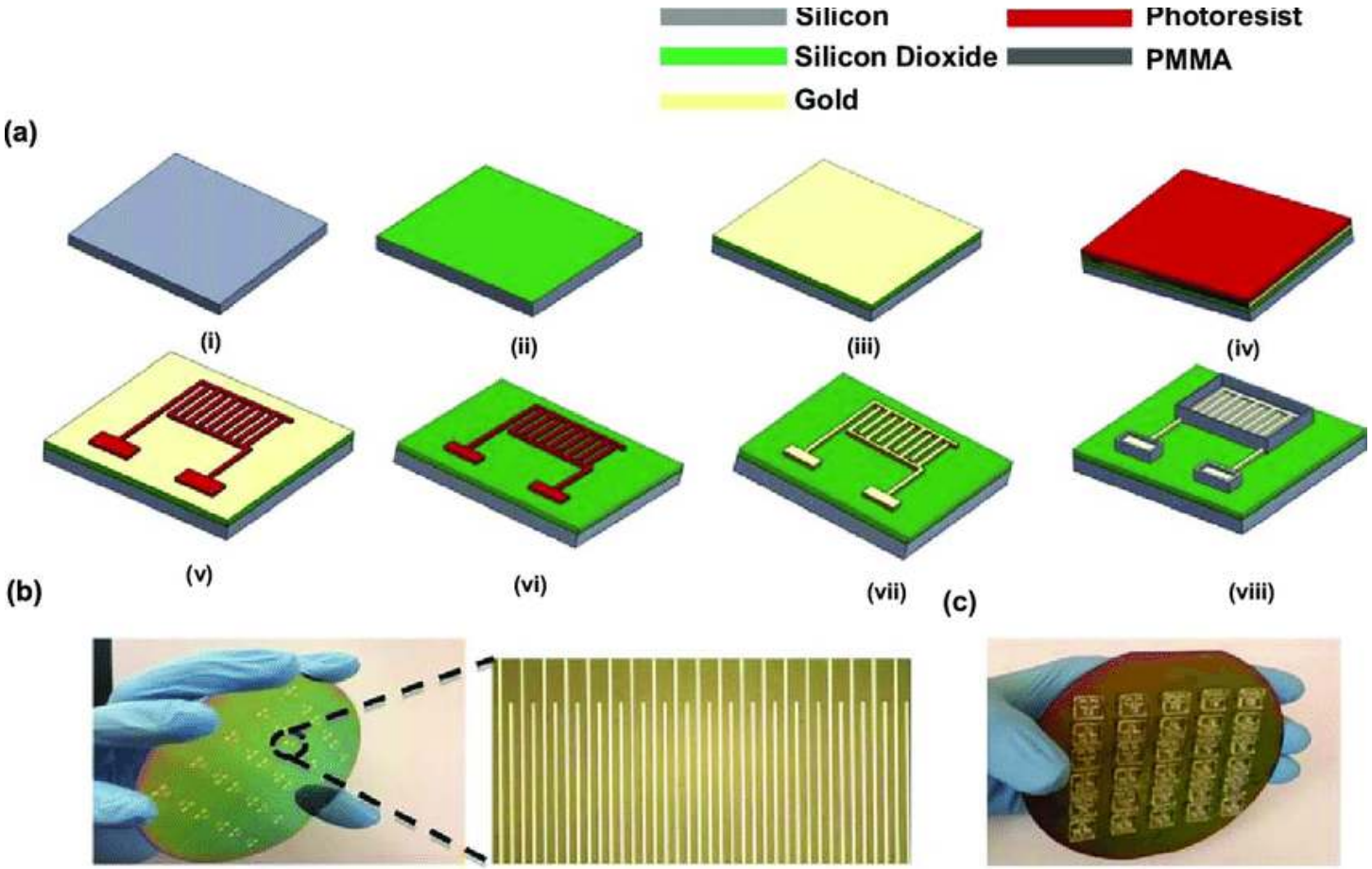
A - neutrals A^+ - ions e^- - electrons

→ Accelerating force - - - - → Reaction path

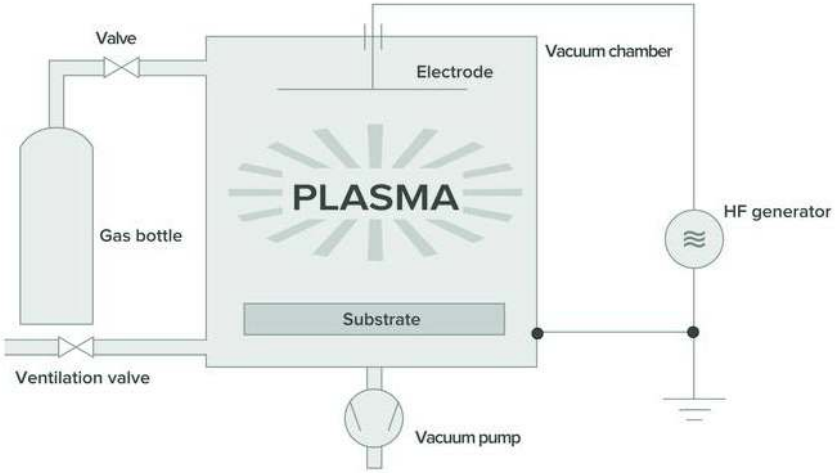
Low-Pressure Glow Discharge Plasmas



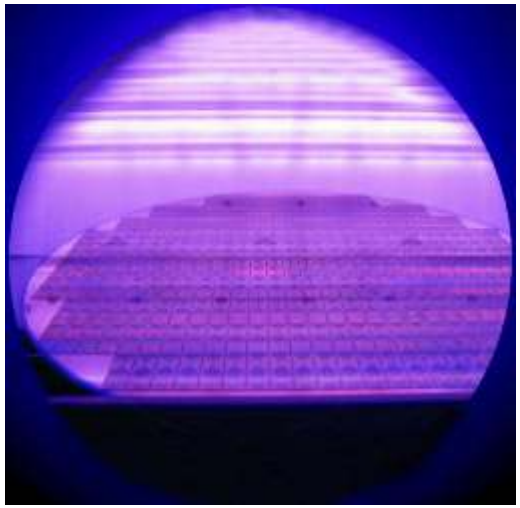
Low- Temperature Plasma enabled Microchip Fabrication

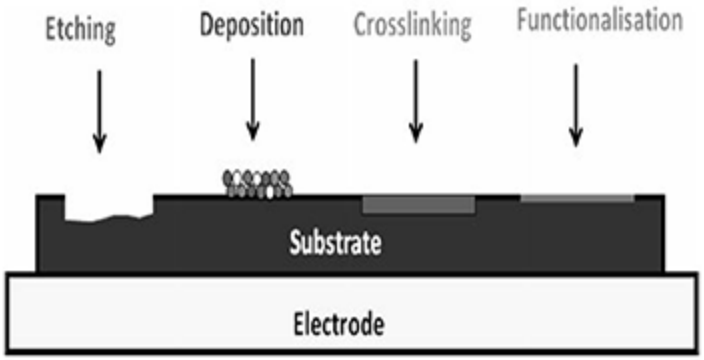


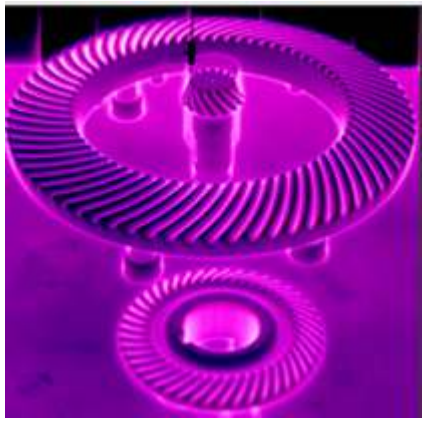
Low-Pressure, Low-Temperature Plasma Processing



Plasma processing of silicon for semiconductor manufacturing.





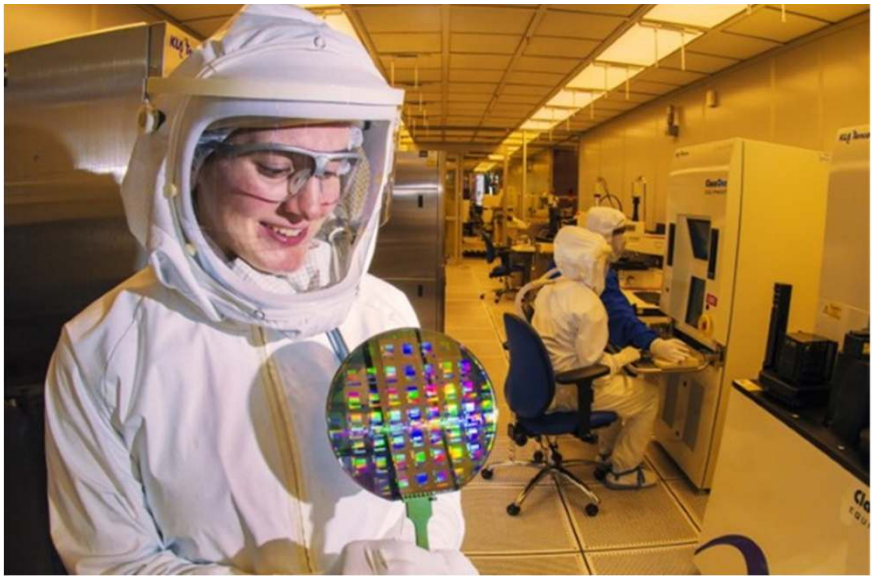


Plasma processing to harden or coat materials.

LTP processing of semiconsductor materials

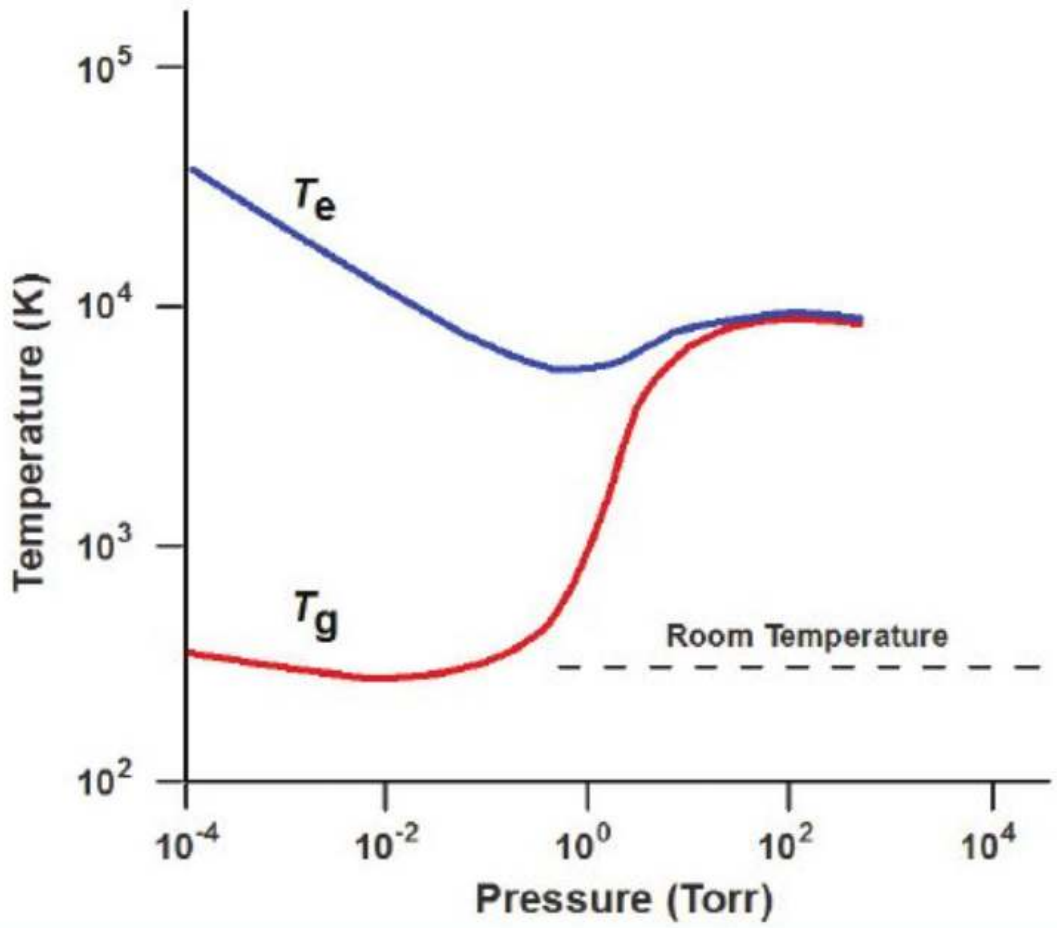
Lawmakers Propose Multibillion Dollar Semiconductor R&D Push

A bipartisan group of lawmakers recently introduced legislation that would channel billions of dollars into manufacturing incentives and new R&D streams to bolster U.S. semiconductor manufacturing in the face of increasing international competition.



Science Policy Bulletin, Number 61: June 24, 2020

Low-Temperature Plasmas



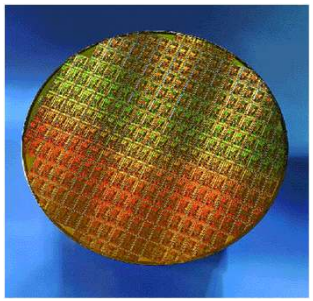
Electron temperatures (T_e) and **gas temperatures (T_g)** versus pressure for a glow discharge.

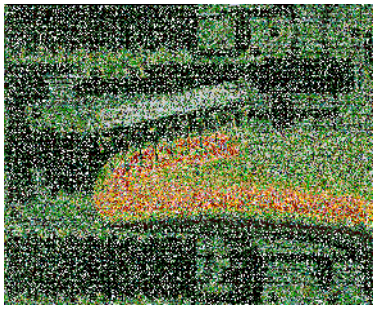
Low temperature plasmas will limit the gas (heavy particles i.e. ions, atoms, molecules, dust, etc.) temperature to room temperature.

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:

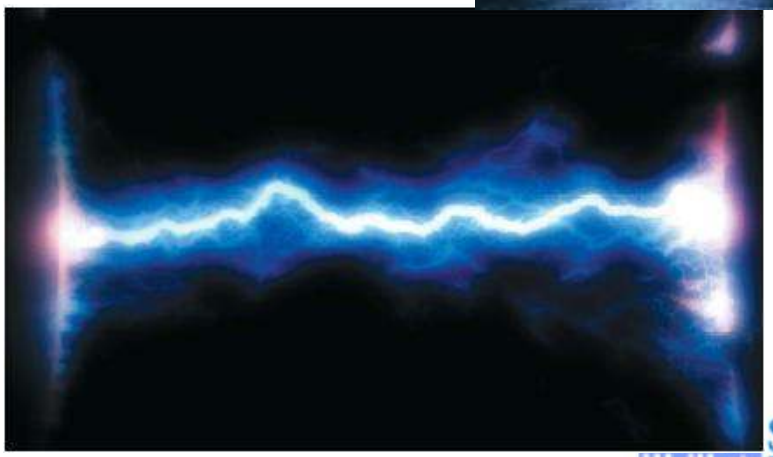
- vacuum chambers
- expensive vacuum pumps
- pressure monitoring and pressure control devices

Generate Plasmas at Atmospheric Pressure!!

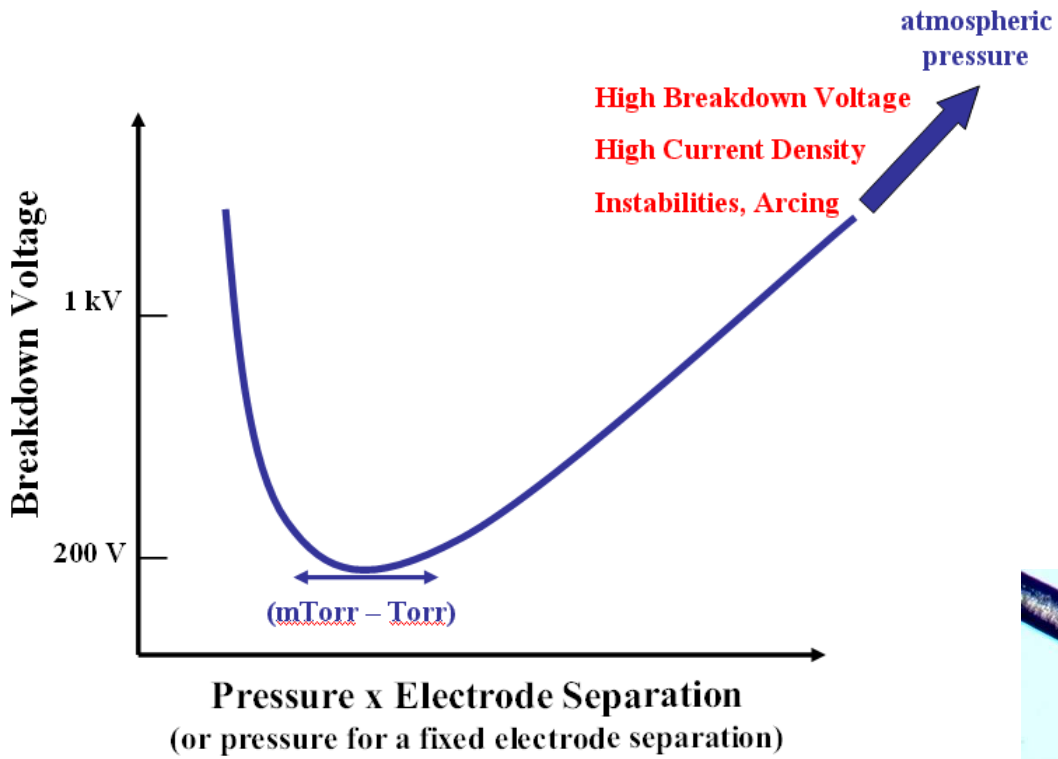
What happens at air pressure?

- 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?

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.

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.

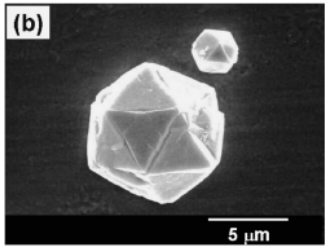
Advantages of Microplasmas

- 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

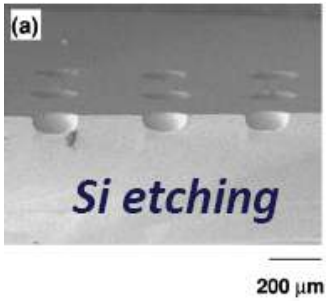


Plasma display

Surface Treatment

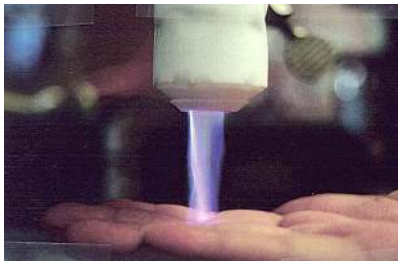
Lighting

Material processing

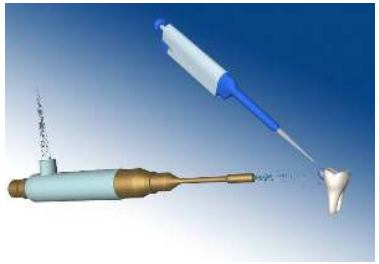


Ozone generation for water cleaning

Bio-application



Dental application



and Many more…

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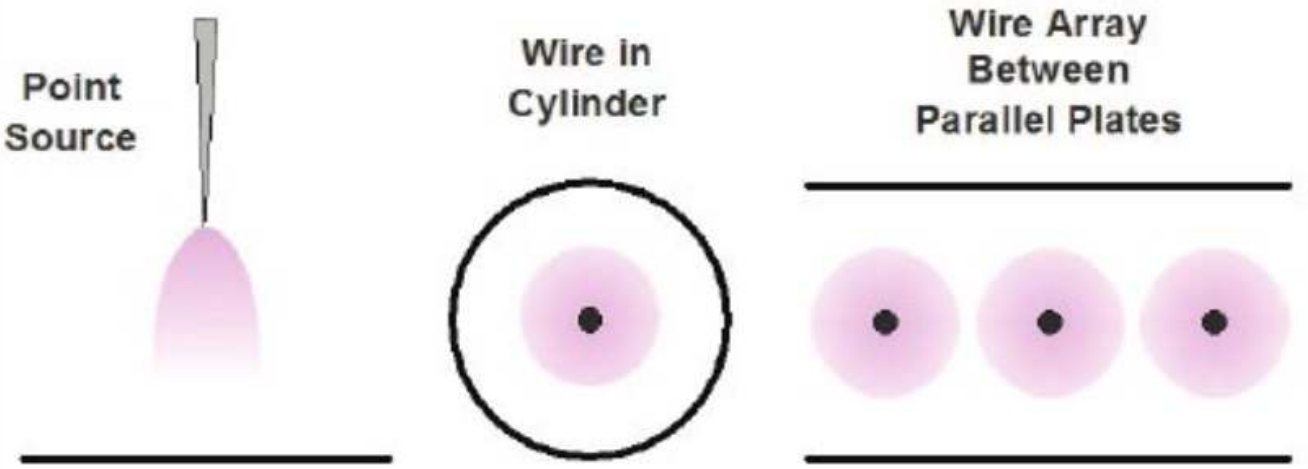
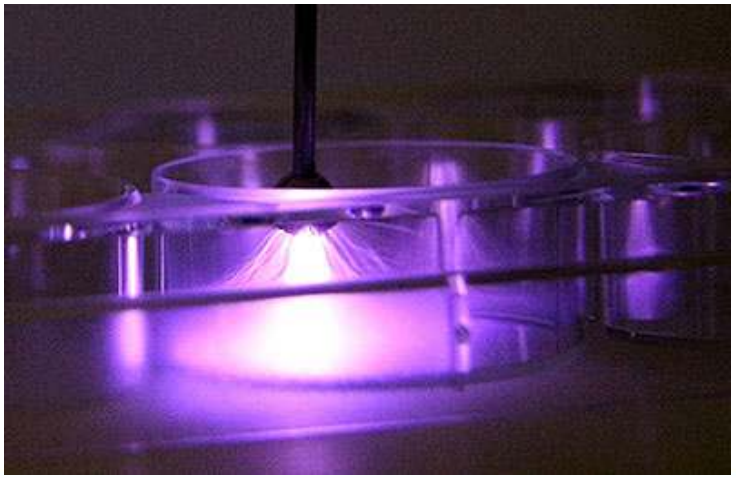
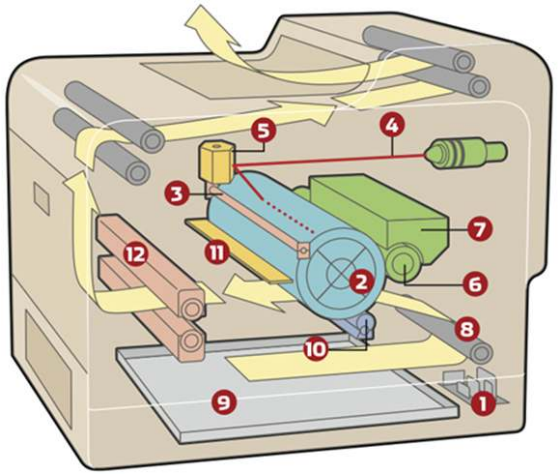
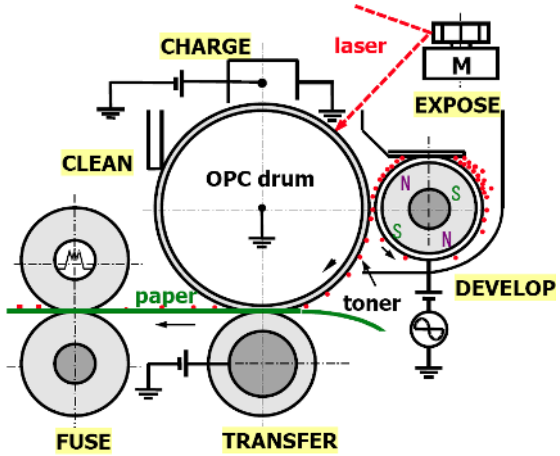
Corona Discharges



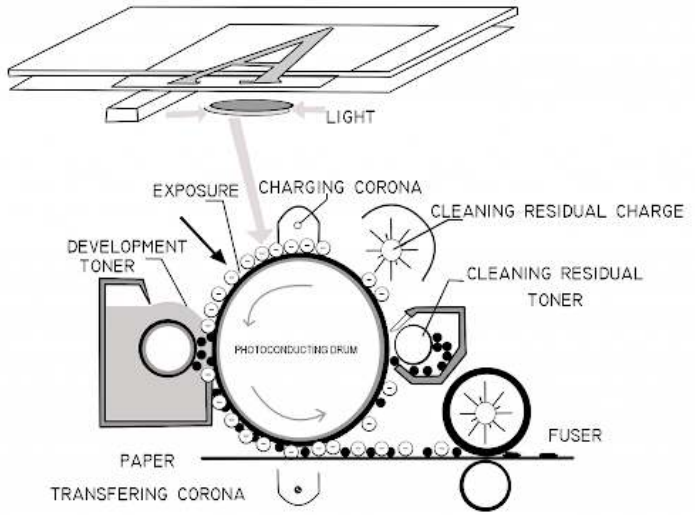


Application of Corona discharges: PRINTERS AND ELECTROPHOTOGRAPHY



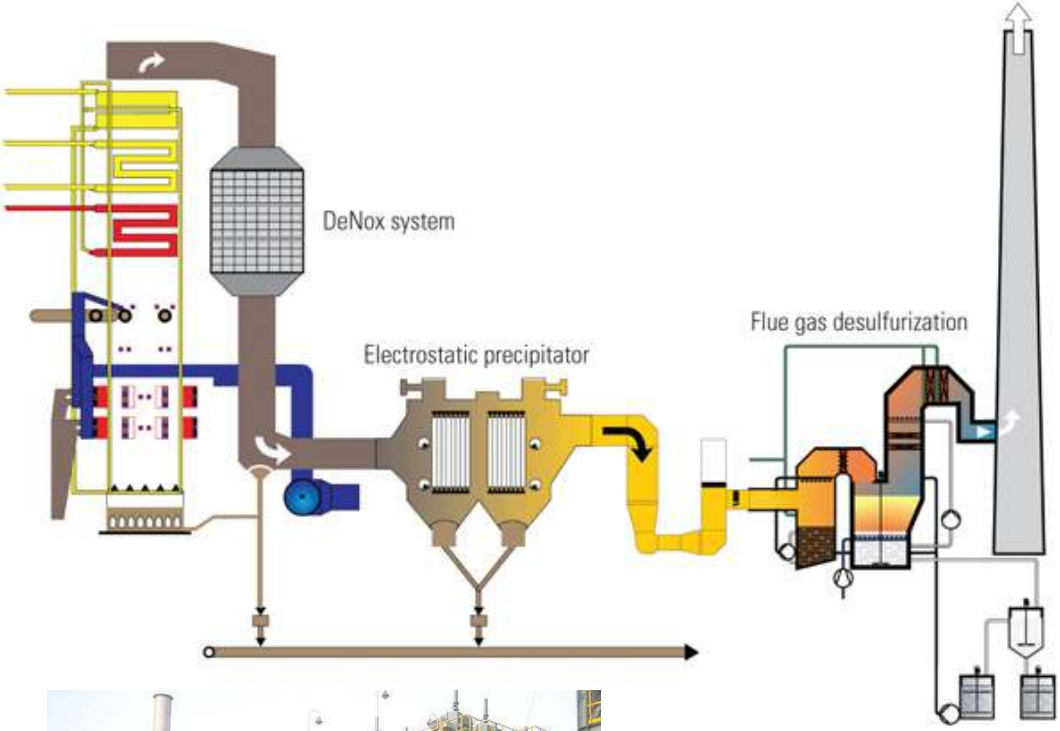


- Electrophotography is used in most electronic printers including laser printers.
- The electrophotography process generally consists of six steps:
  - Charging
  - Exposure
  - Development
  - Transfer
  - Fusing
  - Cleaning

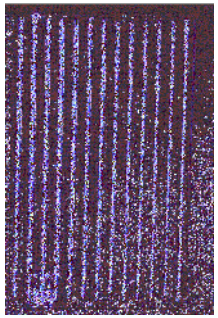


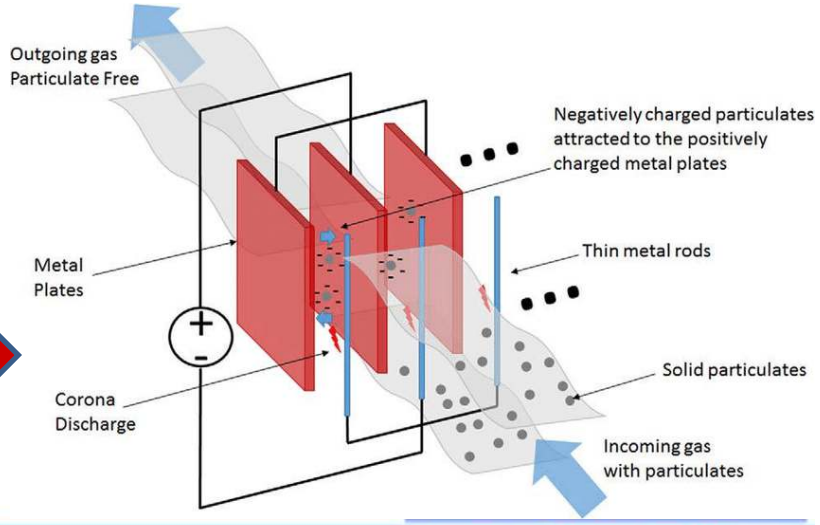
Reference: http://www.theshopperwizard.com/?p=1582

Electrostatic Precipitator

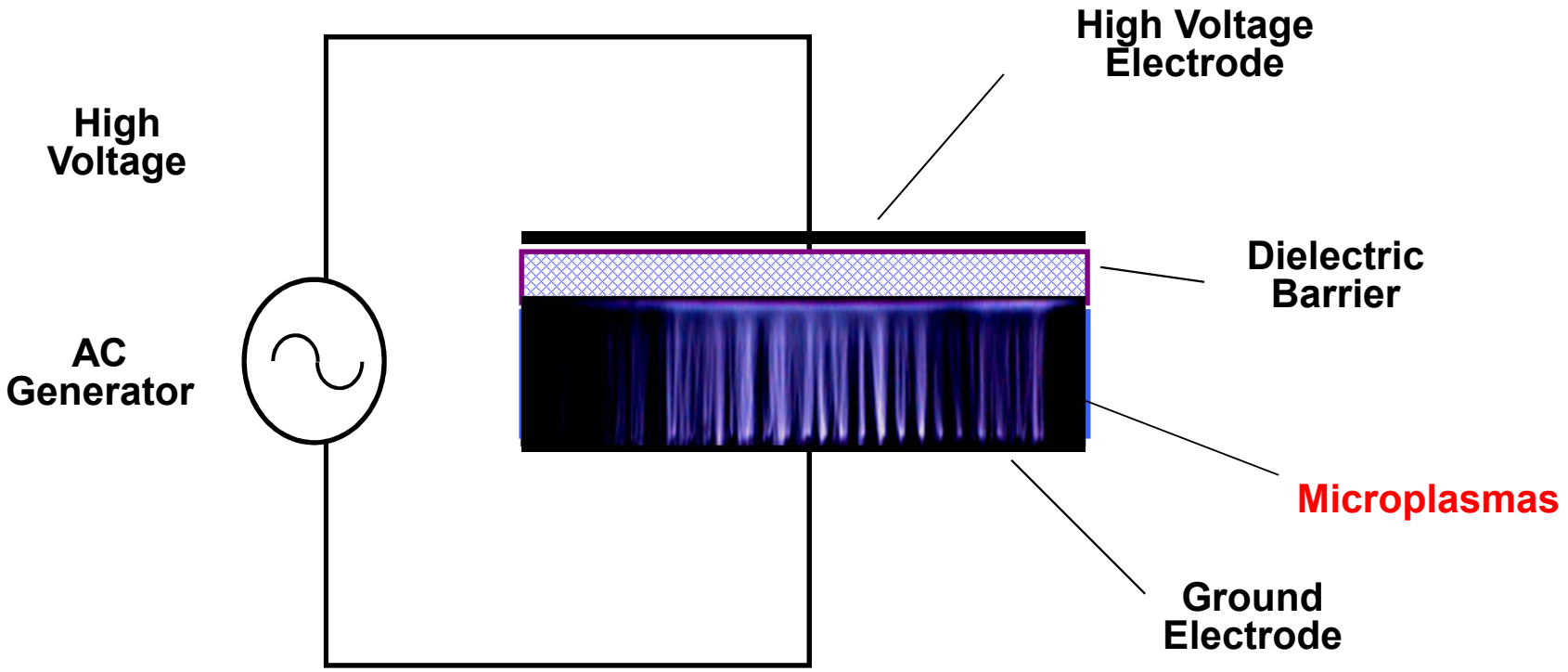


ESP is a physical process in which particles suspended in a gas flow are ionized in a corona discharge, separated from the gas stream under the influence of an electric field and transported to collecting plates, from which they can be removed periodically and mechanically (dry ESP) or continuously by washing (wet ESP).





Dielectric Barrier Discharge (DBD)



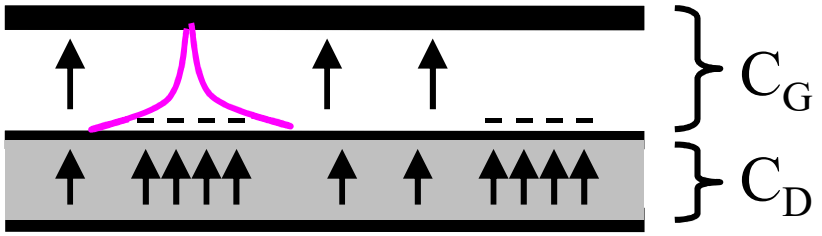
Role of the Dielectric (Insulator)

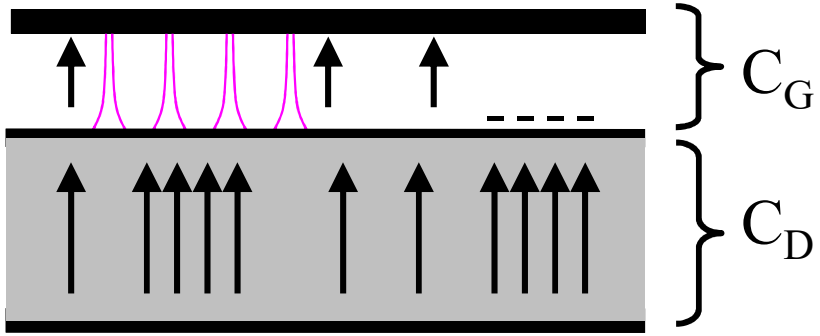
The dielectric is the key for the proper functioning of the discharge.

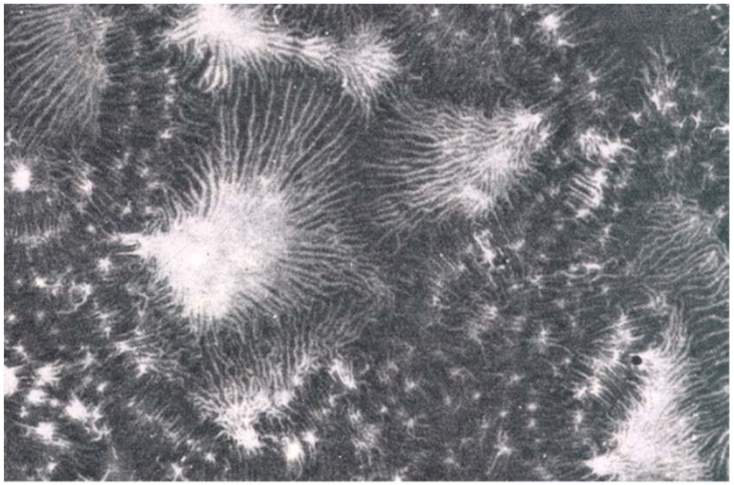
Serves two functions:

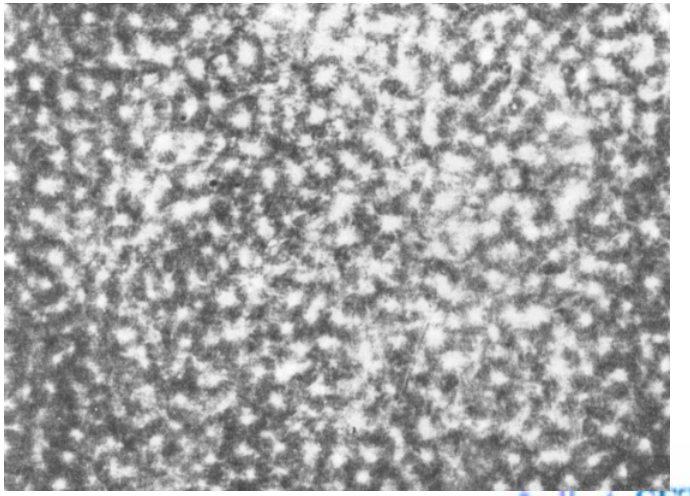
1. Limits the amount of charge transported by a single microplasma
2. Distributes the microplasmas over the entire electrode surface area

Principals of DBD Microplasmas









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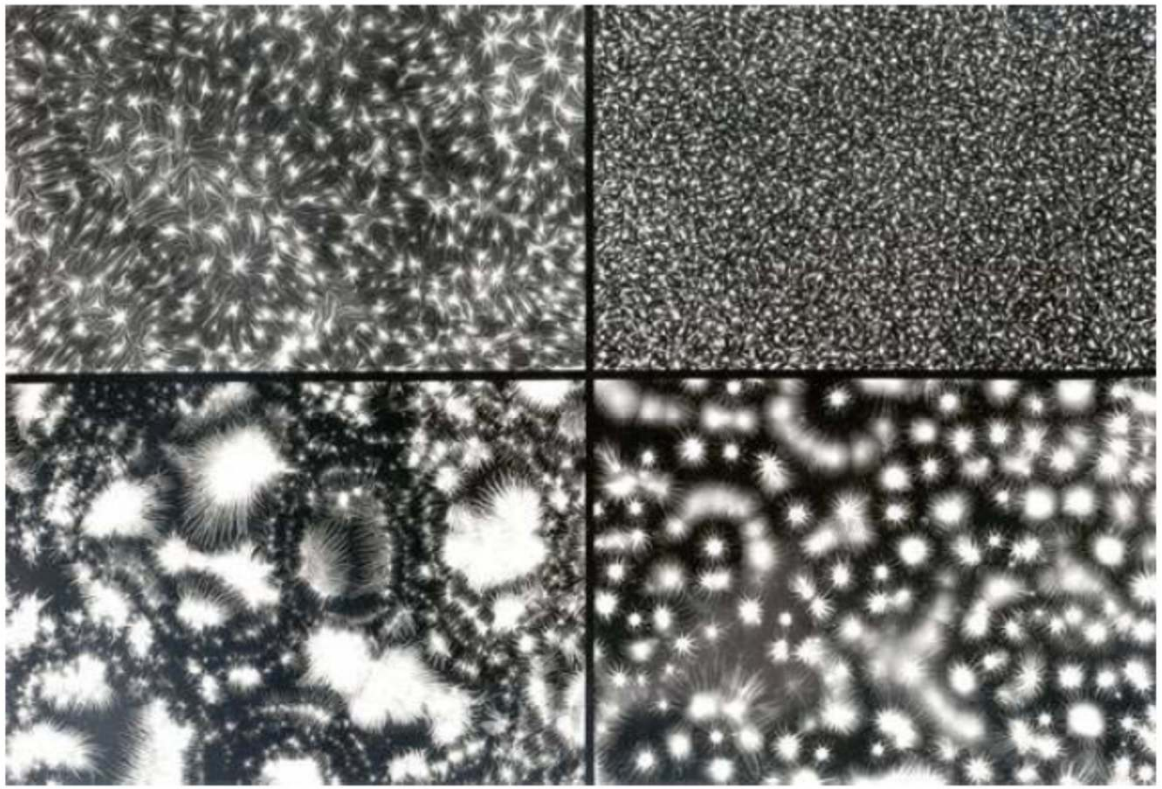
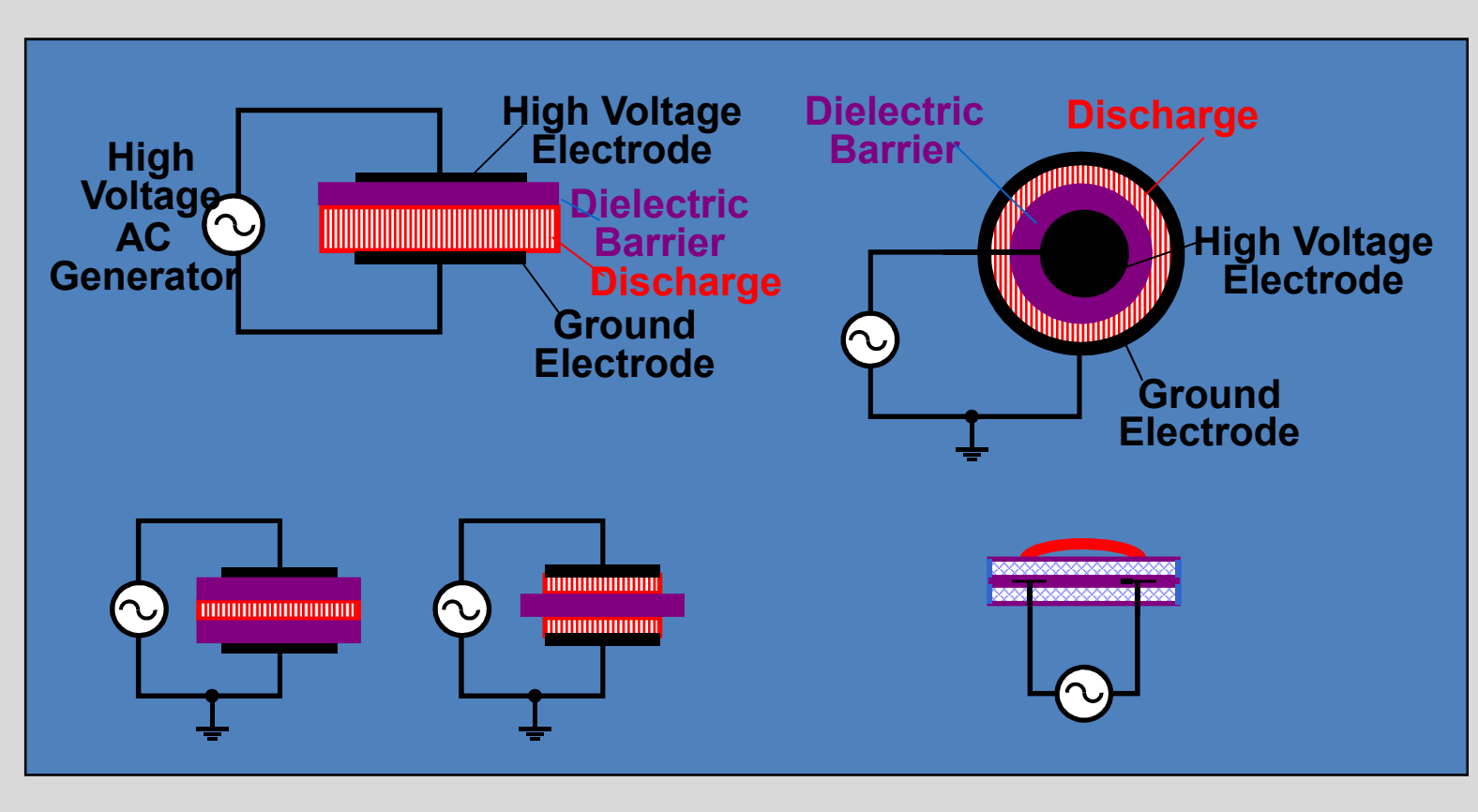
Principals of DBD Microplasmas

Four Different Gap Widths



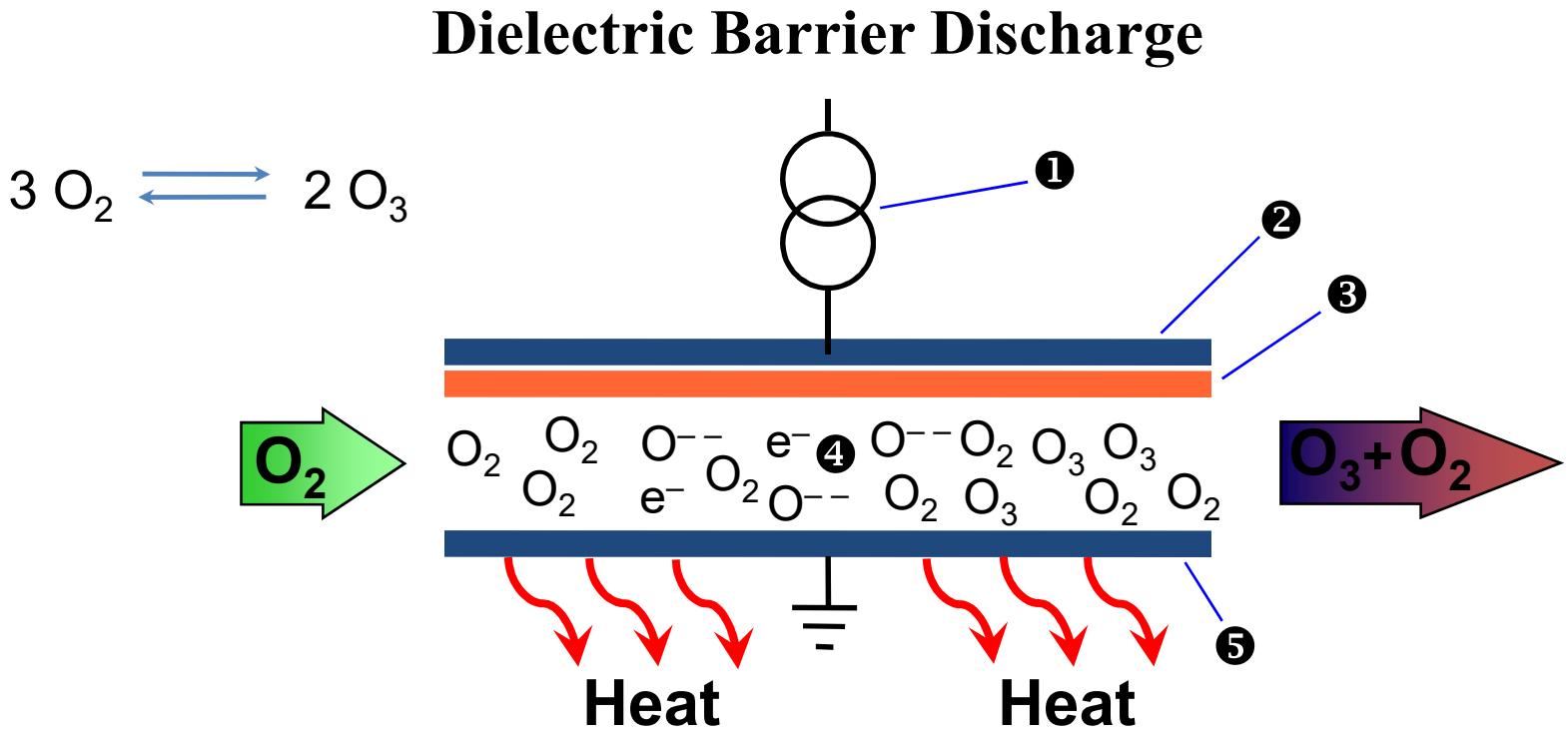
B. Eliasson and U. Kogelschatz. *IEEE Trans Plasma Sci*. 19(2) p309 (1991)

Dielectric Barrier Discharge

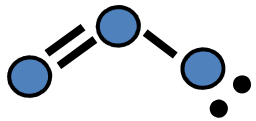


H.E. Wagner, R. Brandenburg, et. al. 'The barrier discharge: basic properties and applications to surface treatment'. *Vacuum*. 71 p417-436 (2003).

Ozone Generator



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

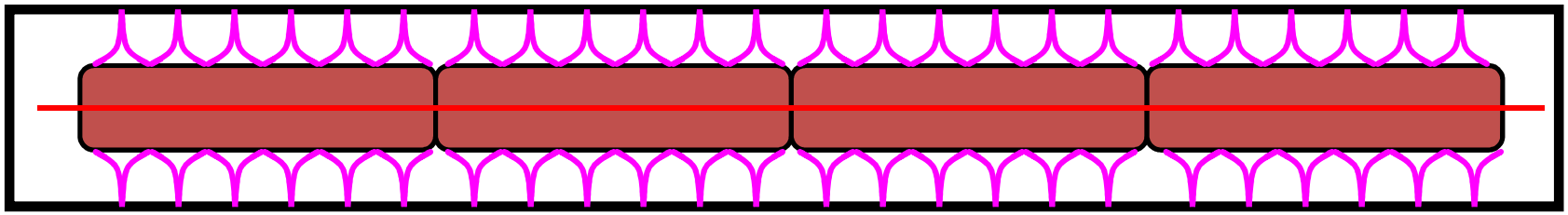
Bubble Diffusion

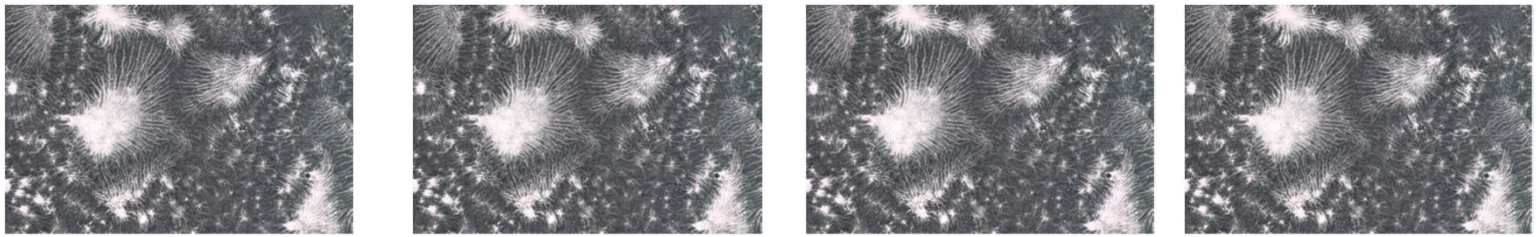
Easy to use

Low energy usage

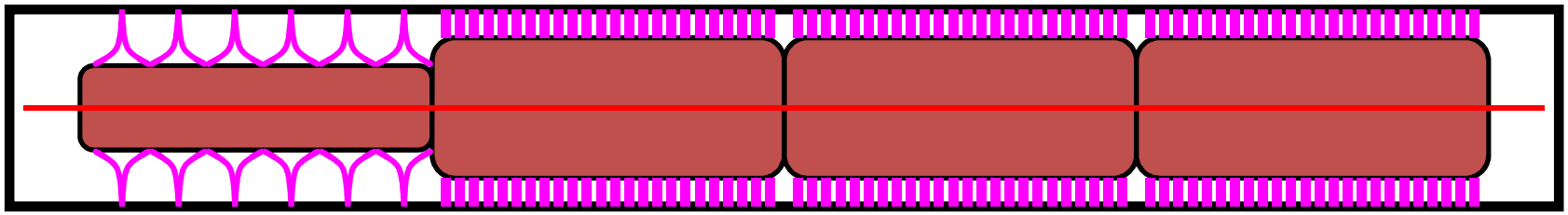
Mass transfer efficiencies to > 90%

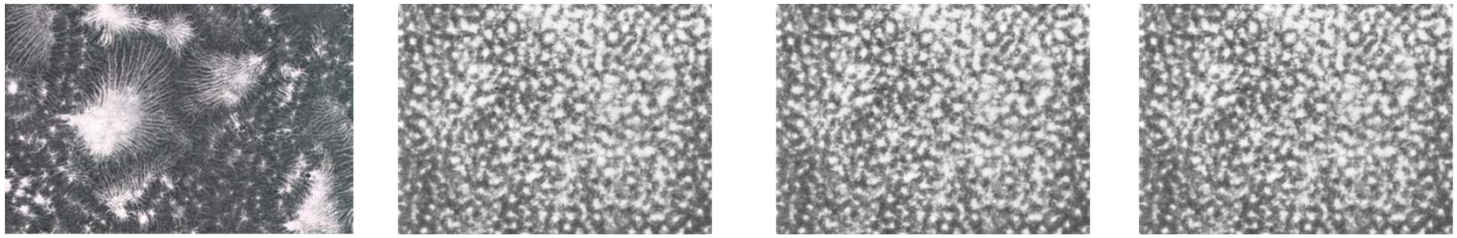
Reference (Traditional) Arrangement



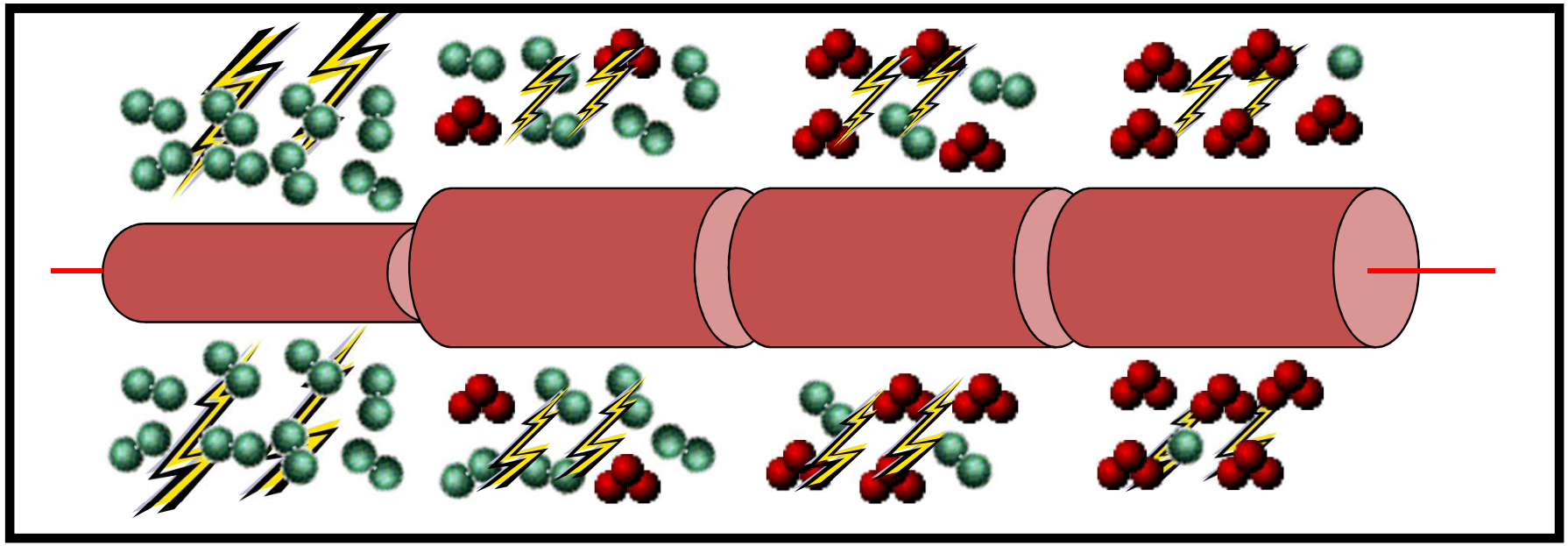


Optimized Arrangement





Intelligent Gap System (IGS)



O_2 → O_3

Molecular Oxygen (O_2) Ozone (O_3)

Environmental and Water Remediation with Plasma Technologies

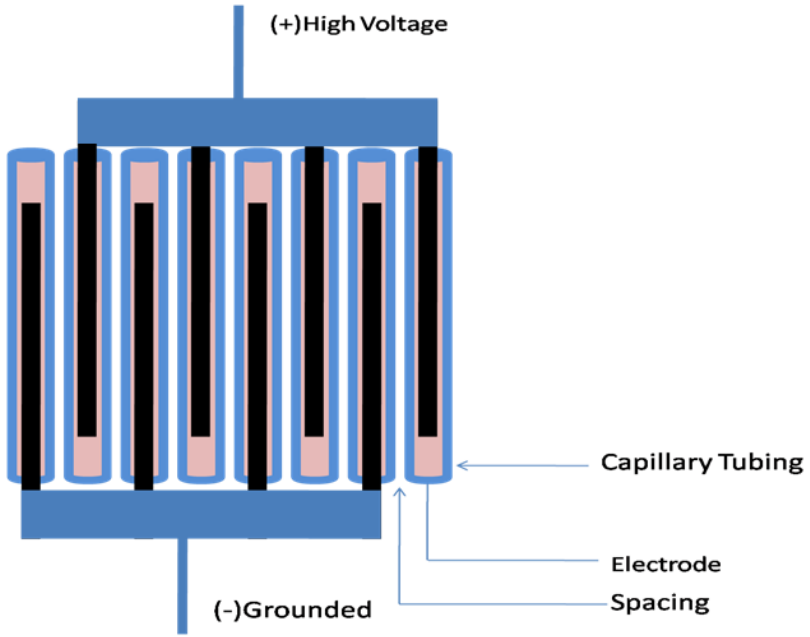
Intelligent Gap System

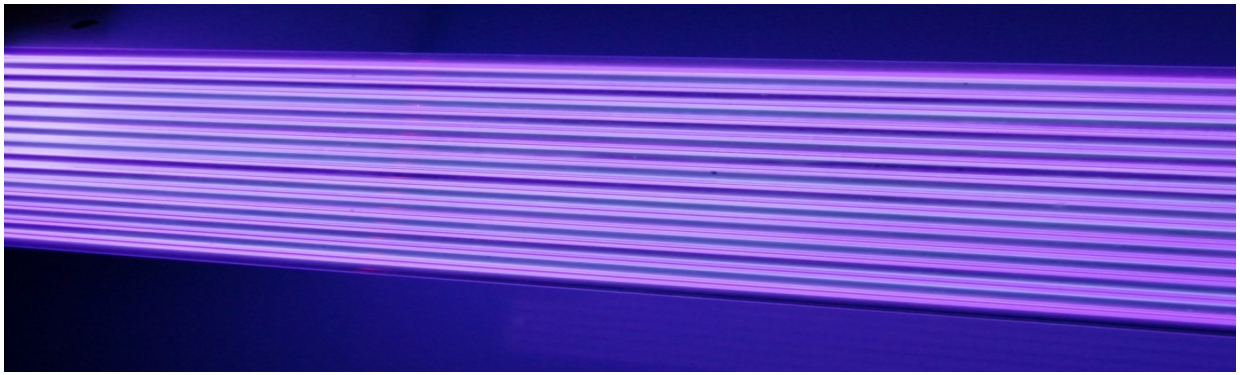
5000 kg/day of ozone

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

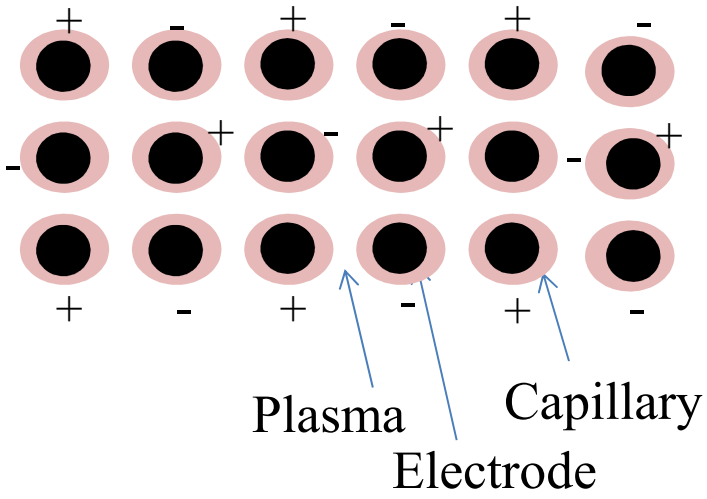
Jose L Lopez. *Progress in Large-Scale Ozone Generation*. **Complex Plasmas: Scientific challenges and Technological Opportunities. Editors – Michael Bonitz, Jose Lopez, Kurt Becker, Hauke Thomsen.** Chp 13, pp. 427-453, Springer Publishing (2014).

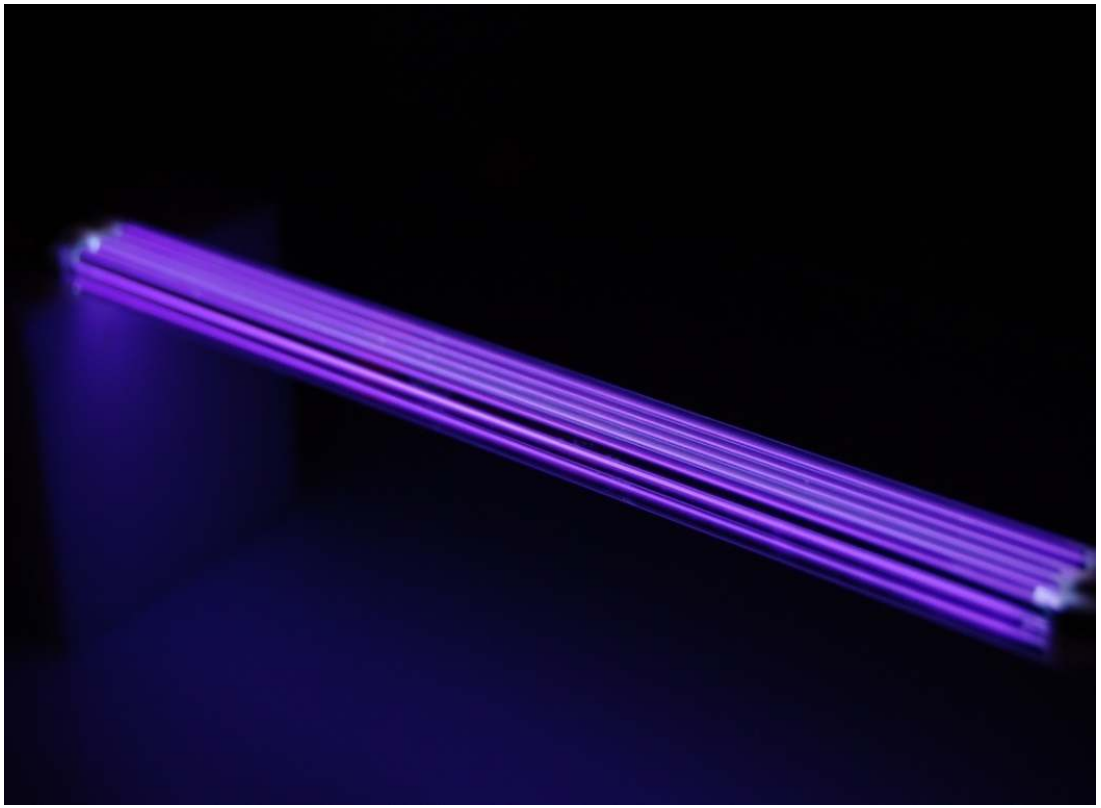
Capillary Dielectric Barrier Discharge



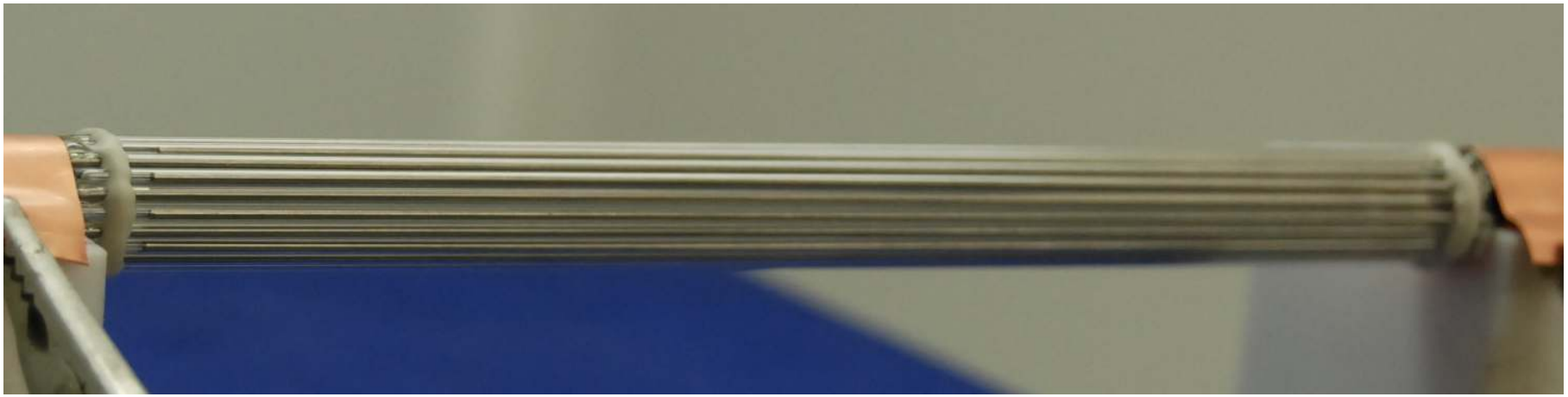


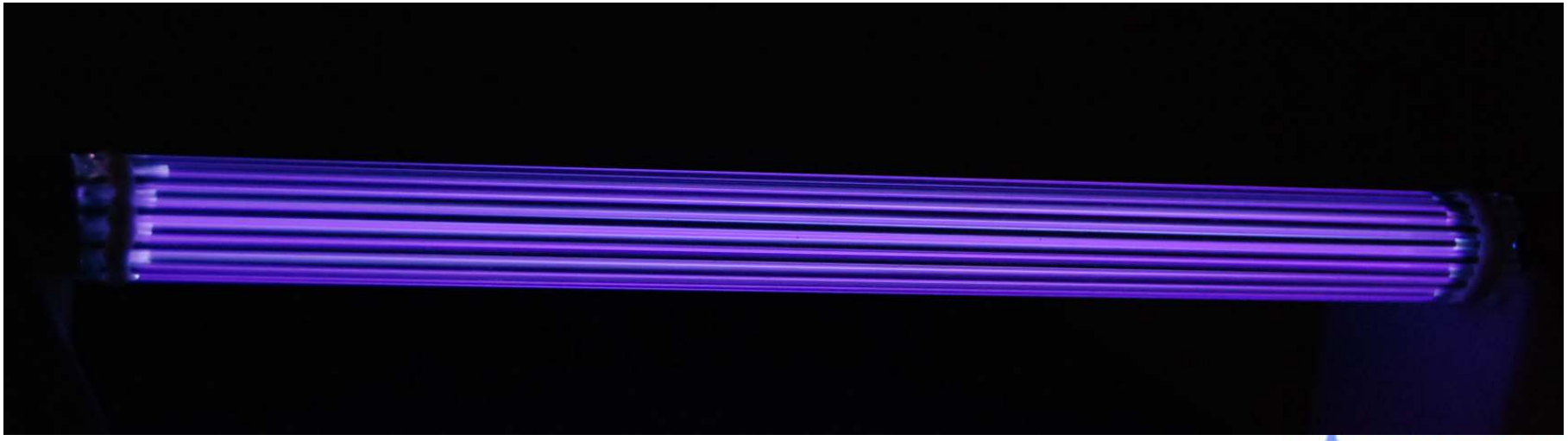
3-D Expansion





Cylindrical Arrangement





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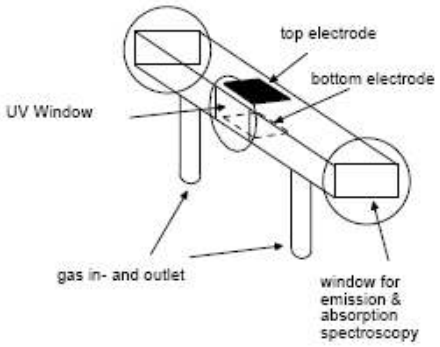
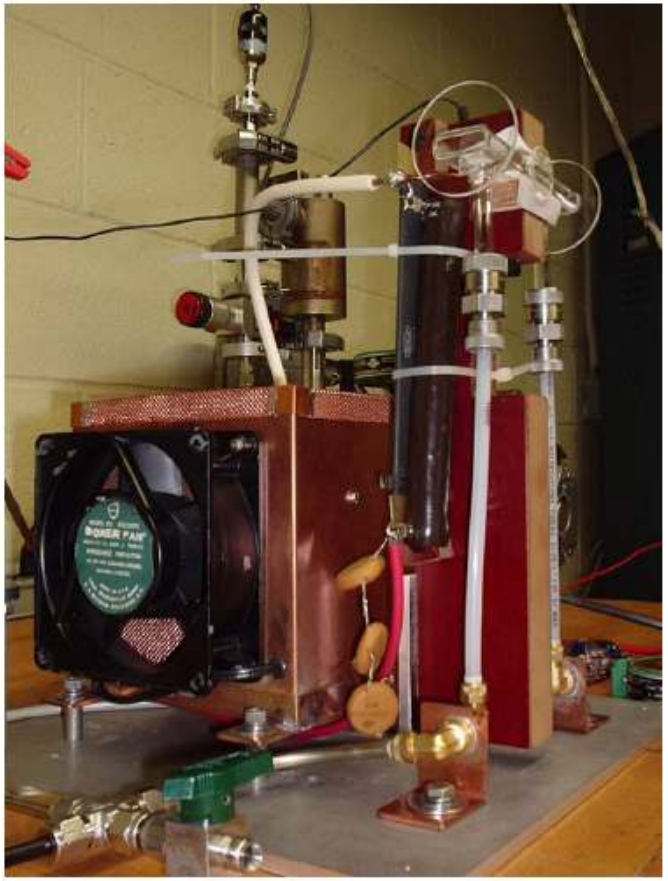
Pulsed DC Homogeneous DBD



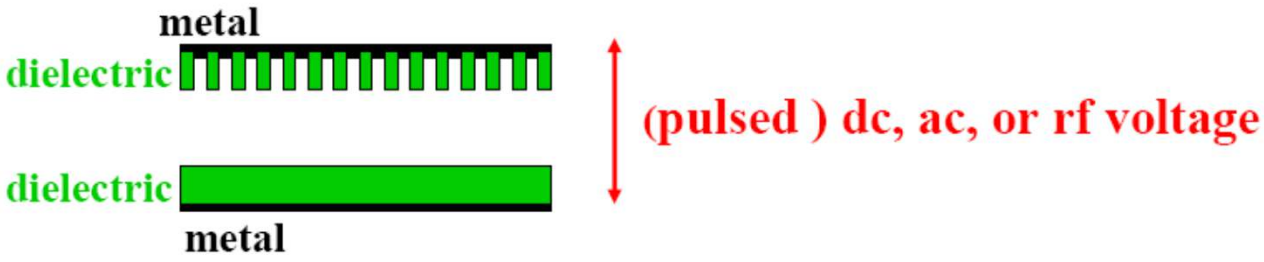
The Dielectric Barrier Discharge (DBD) cell.

A typical plasma in pure nitrogen environment.

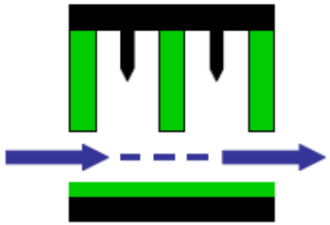


Side view of the DBD cell experiment with the fast high voltage transistor switch connected to the bottom electrode.

Capillary Plasma Electrode (CPE)

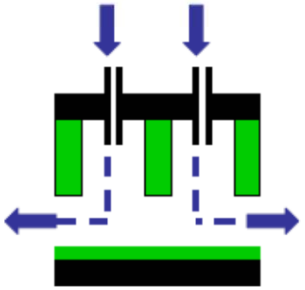


Capillary Plasma Electrode (CPE) Realizations



Solid Pin Electrodes

(Cross Flow)



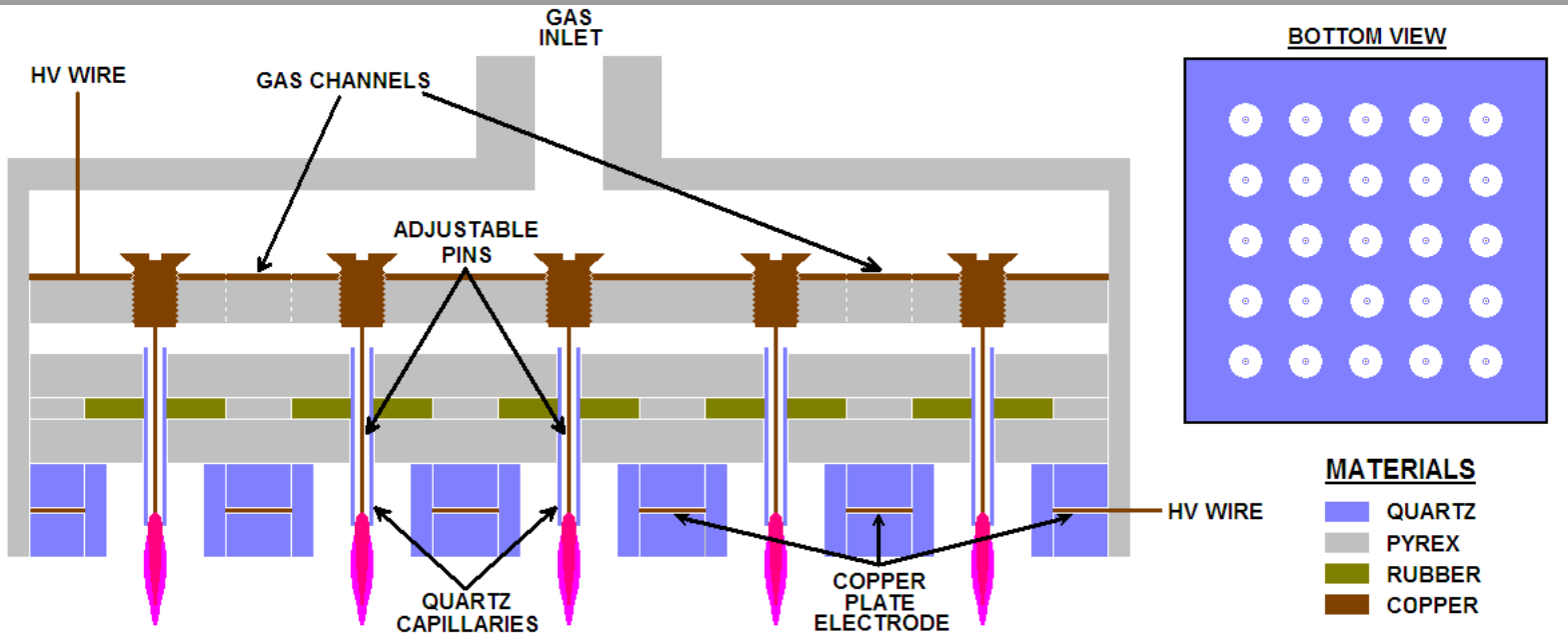
Hollow Pin Electrodes

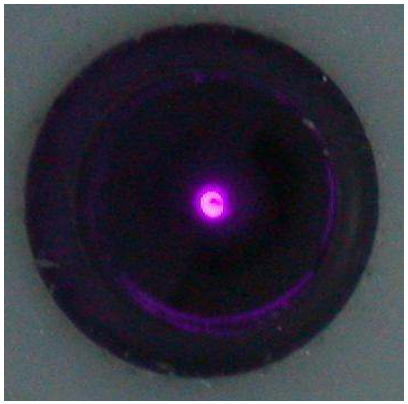
(Flow-Through)

Cylindrical Electrodes

(Longitudinal Flow)

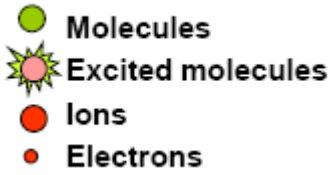
Multi-Capillary Plasma Electrode

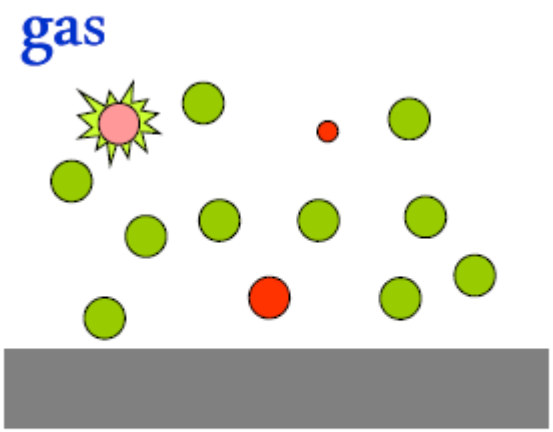




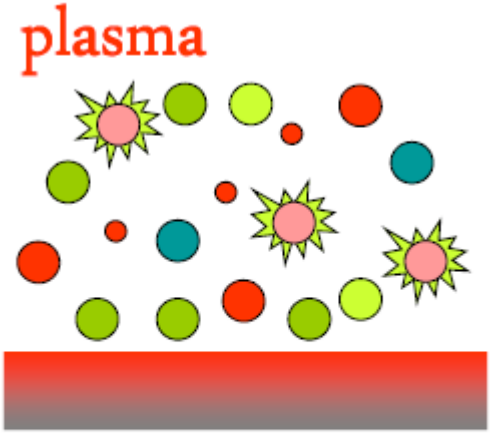
Surface Effects of Microplasmas

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



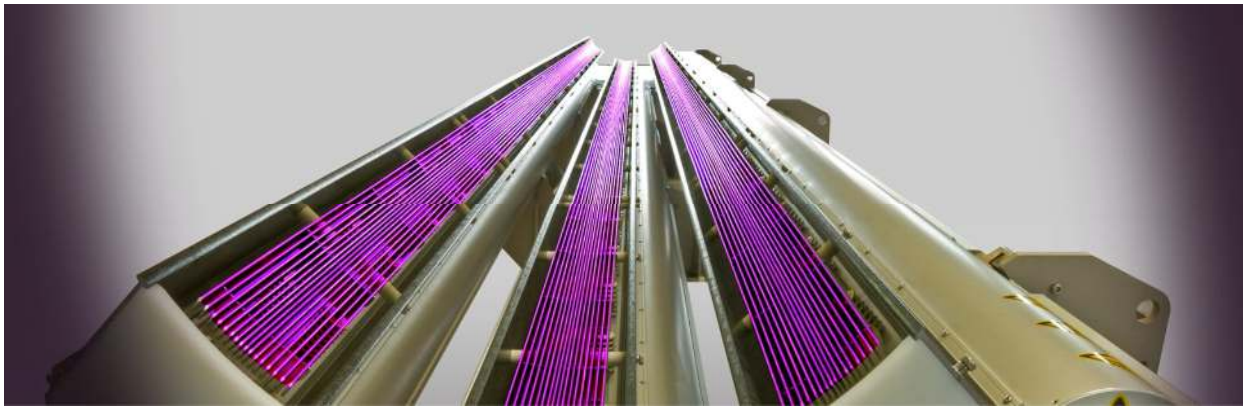


Small changes at the surface



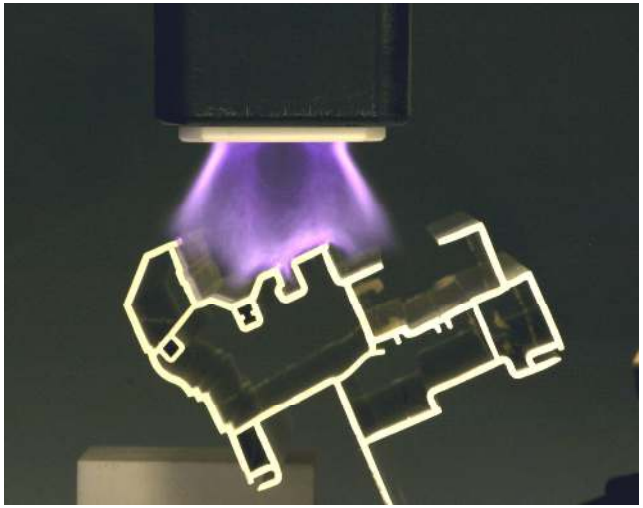
Energy & reactive species can change the surface

Plasma surface treatment for films, glass, paper or plastic sheets, and 3D materials



Reference: www.3dtlc.com

3DT™
THE POWER TO ADHERE



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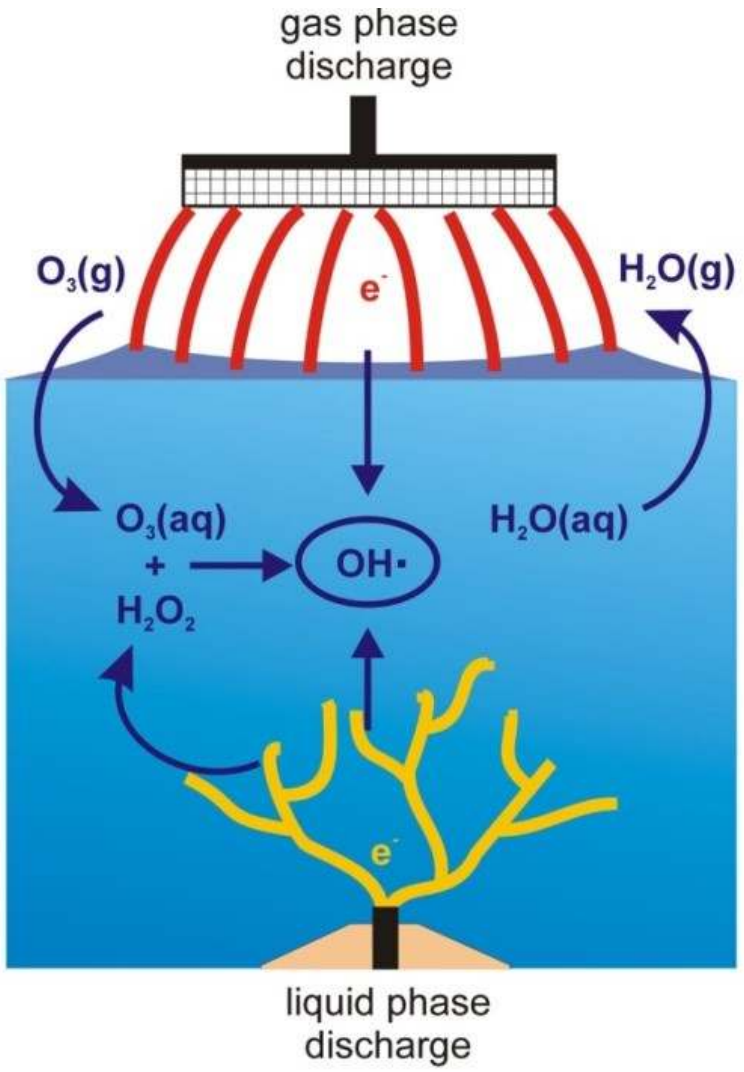
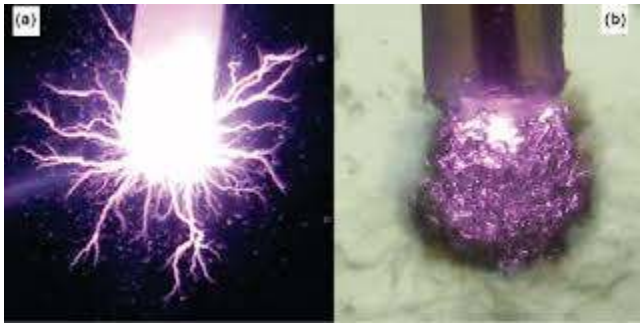
Plasma Discharges in Water





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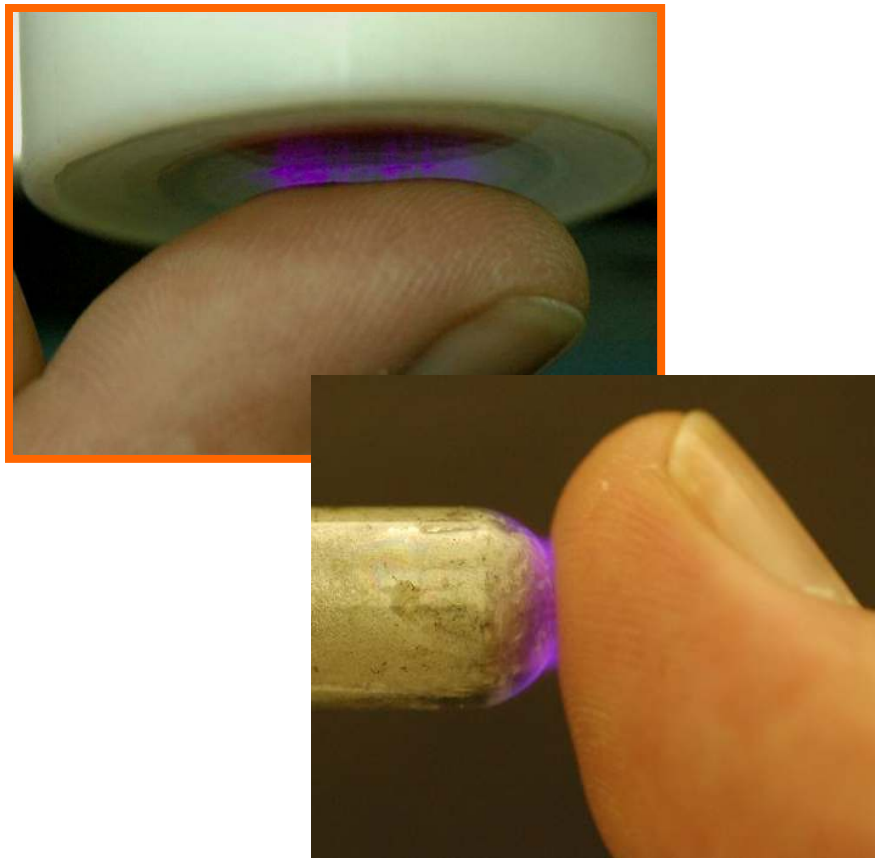
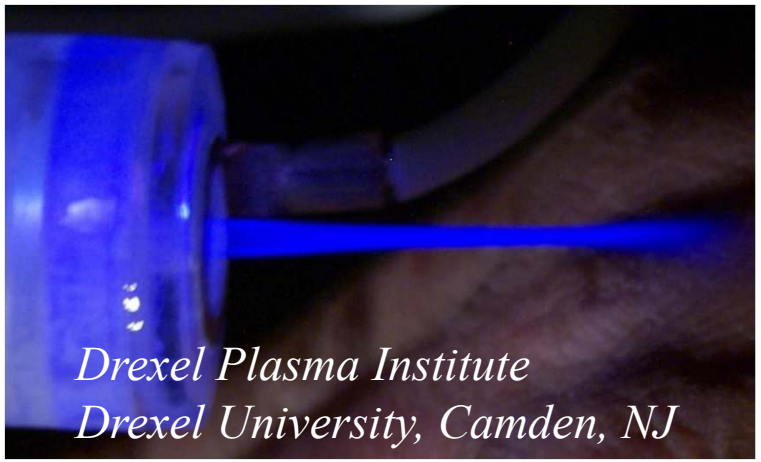
Plasma Application in Medicine

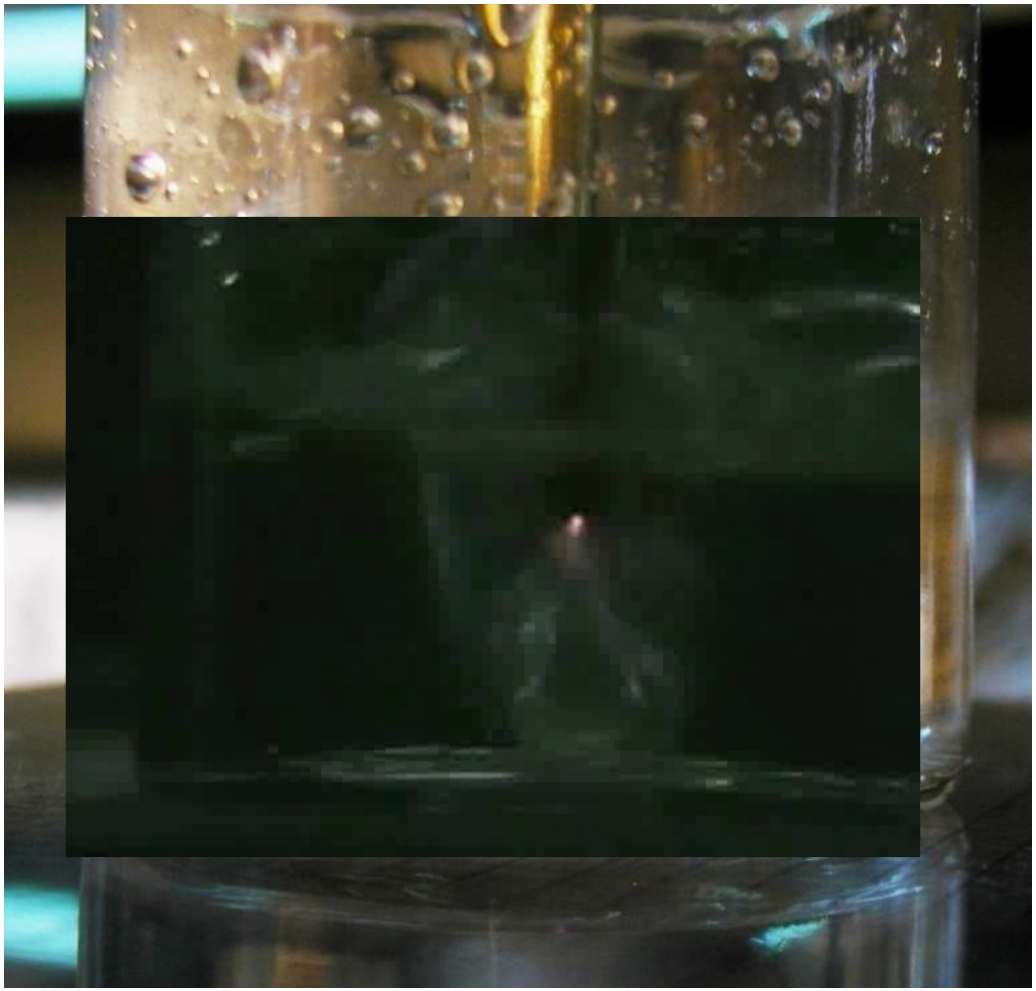
Direct Plasma – Charges on Tissue, Produced In Air or Oxygen

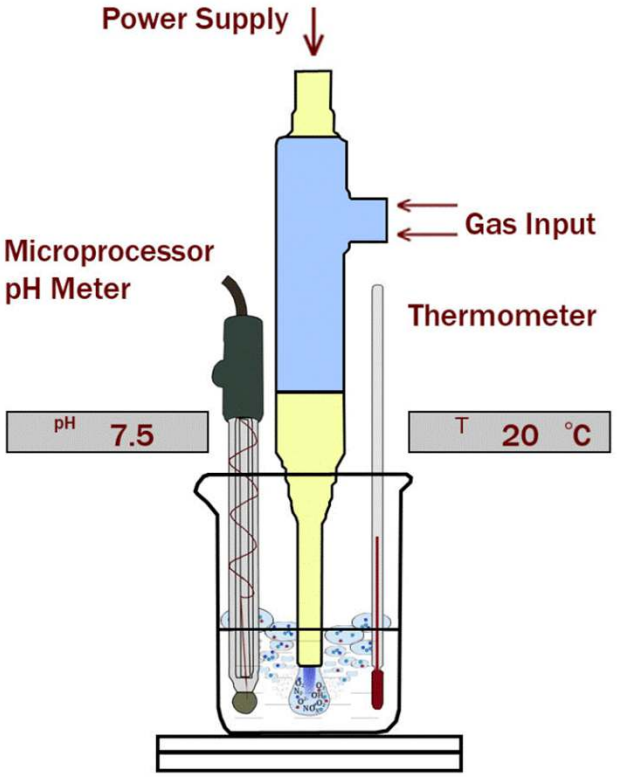


Indirect Plasma – Jet, Often NOT in OXYGEN



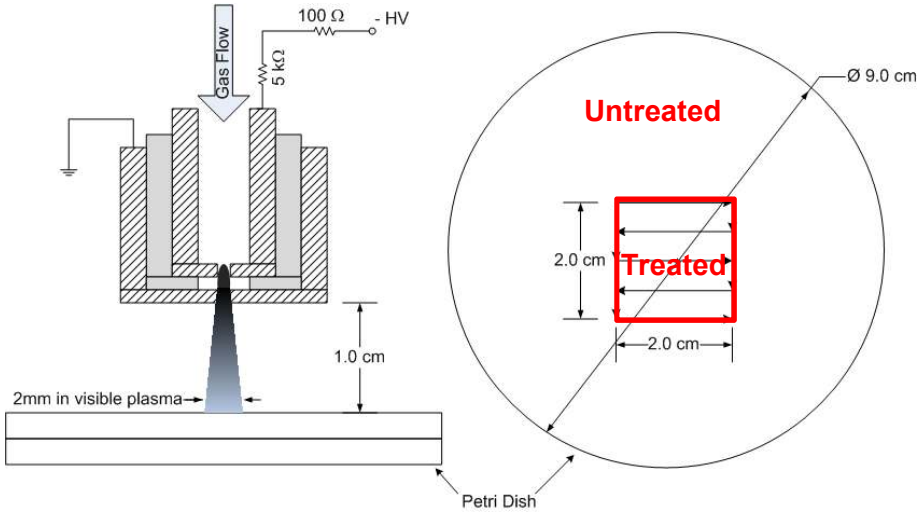
Plasma Micro Jet Inside Water





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

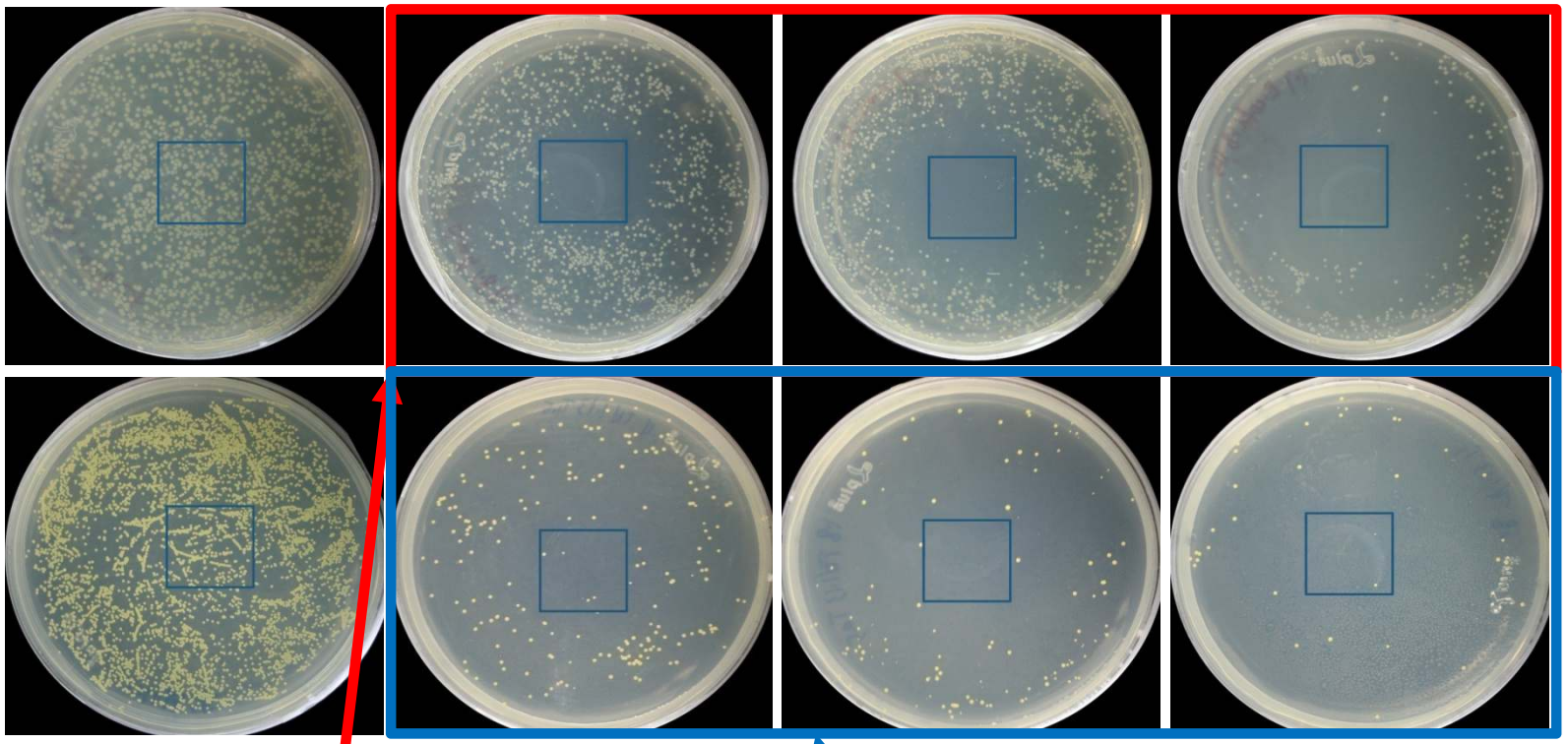
Spore Forming

List of bacteria cultures studied

Experimental Procedure

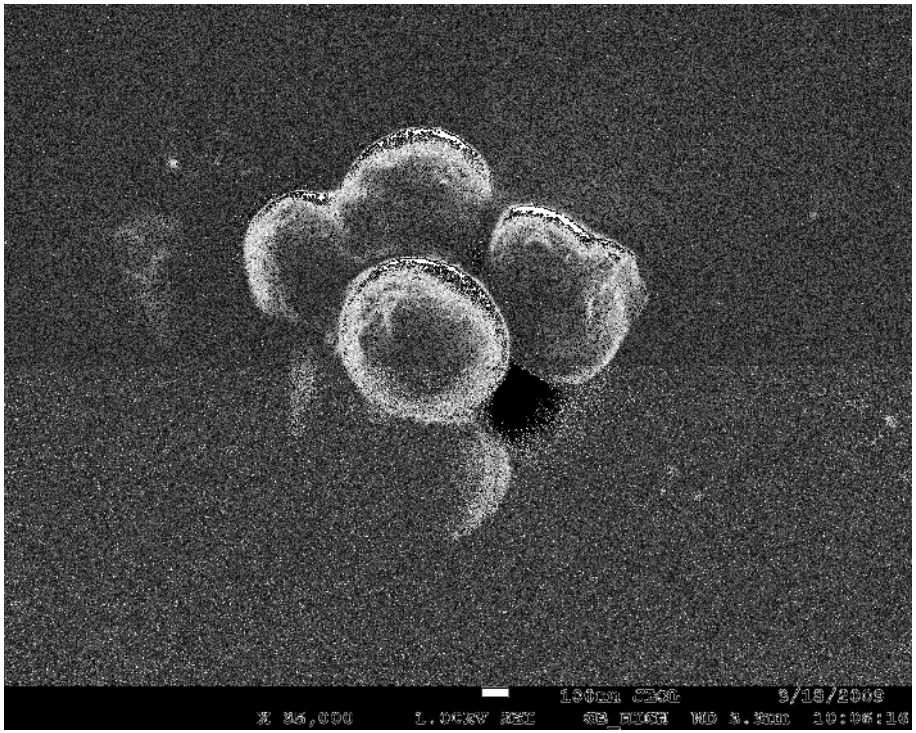
Total path length: 120 mm
Moving speed: 4 mm/s
Time per path: 30 s
Total treatment time: 30s / 60s / 90 s
Area exposure/path: < 1 s (visible plasma),~10 s (radical exposure)

Plasma Dose Effect

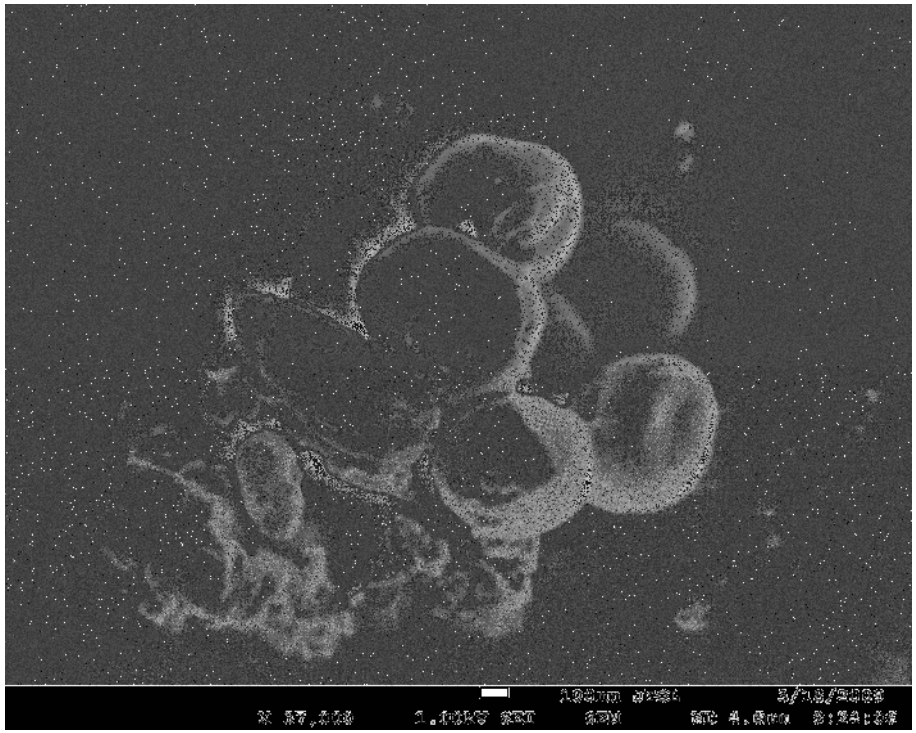


SEM Pictures

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

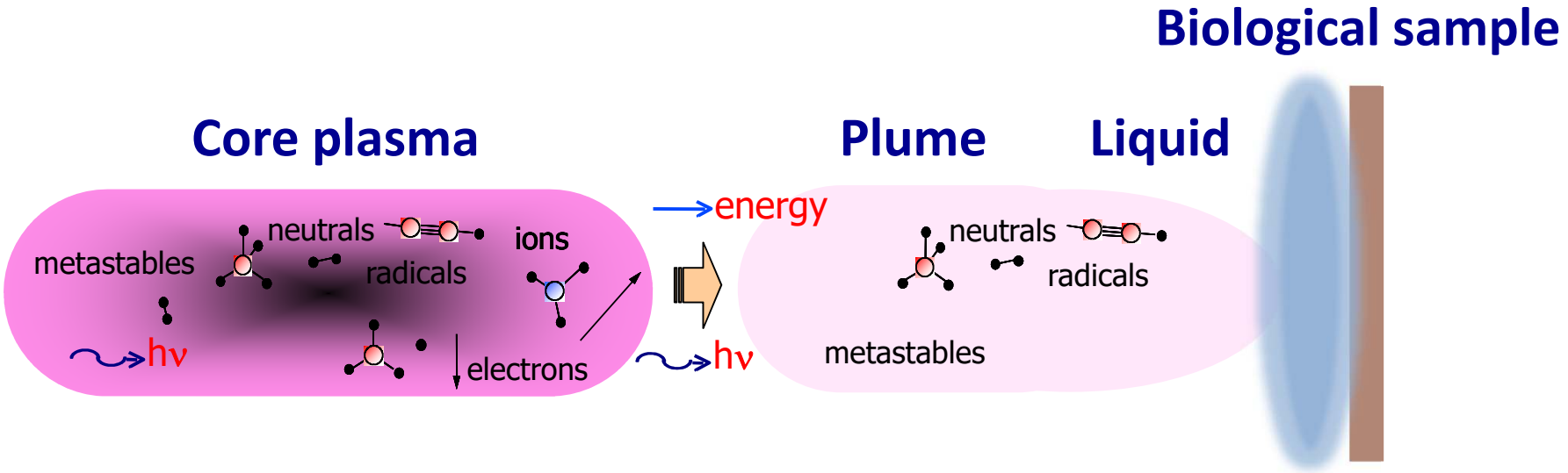
Hemostasis and coagulation in Hairless mice, not immunocompromised (SKH_1)

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

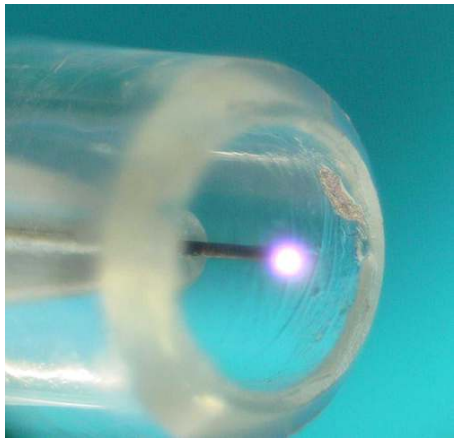
15 seconds of FE-DBD clots the blood and seals the vessel <u>without damaging tissue</u>, preventing additional bleeding.

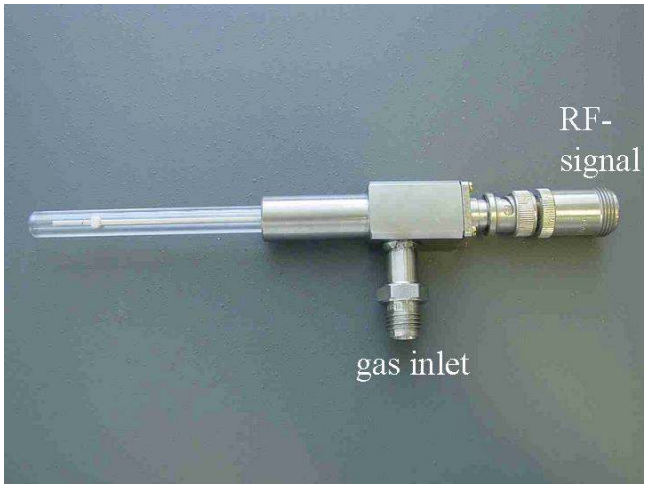
Courtesy: Drexel Plasma Institute

Biological Mechanisms: Plasma Interference into Natural Intracellular Biochemistry



Dental Application



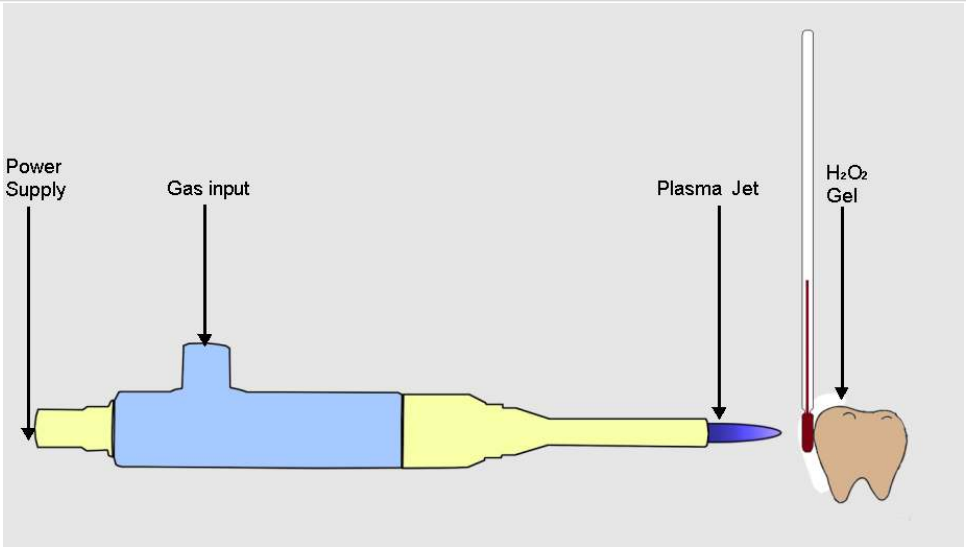


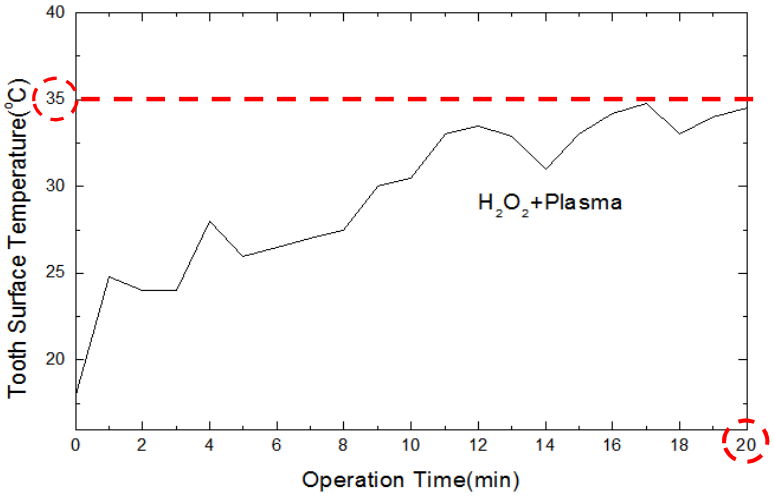
Cleaning of Dental Cavities

Other Applications

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

Teeth Whitening with 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**

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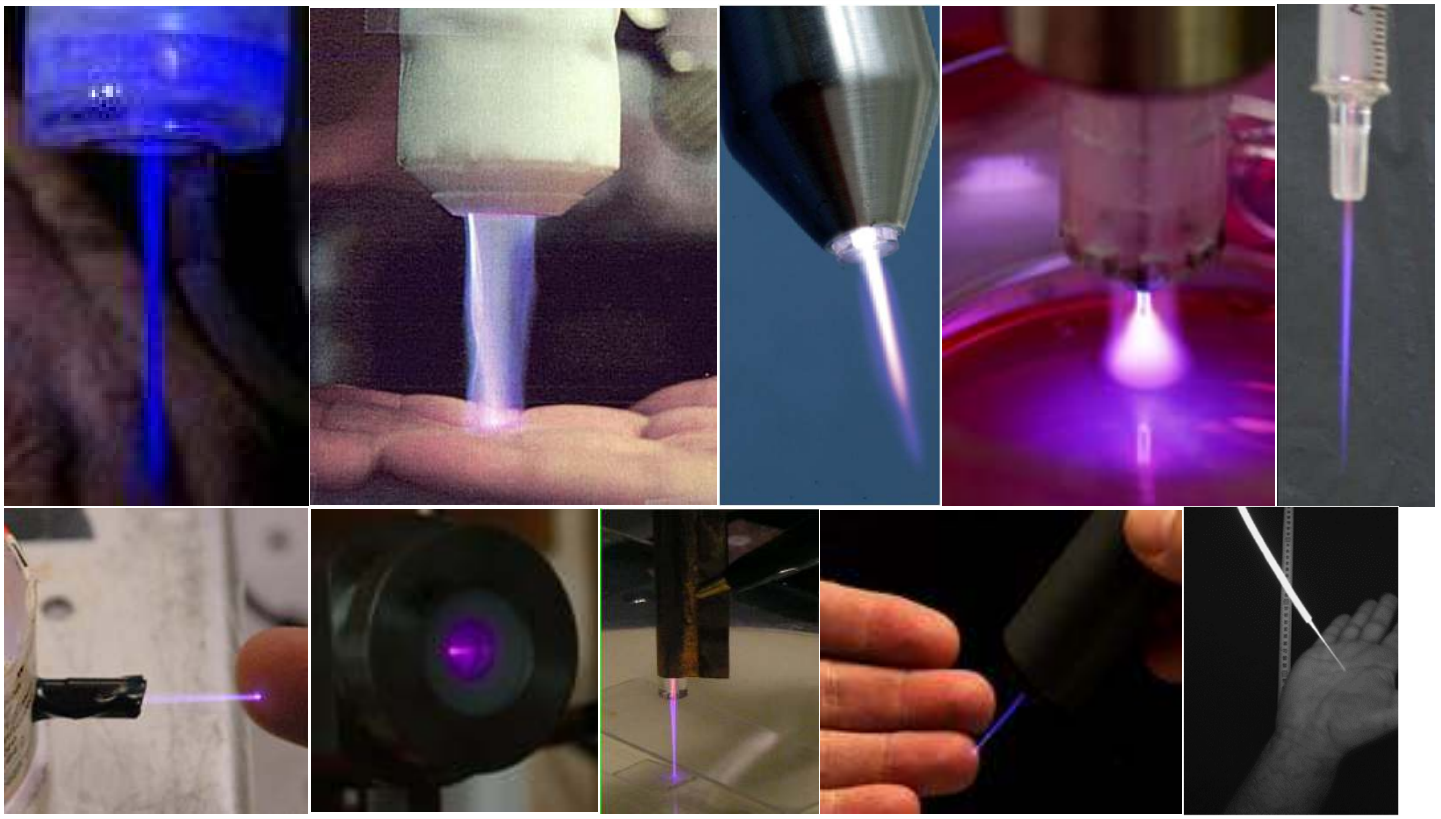
A Brief Collection of Atmospheric Pressure Plasma Jets (APPJ)



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

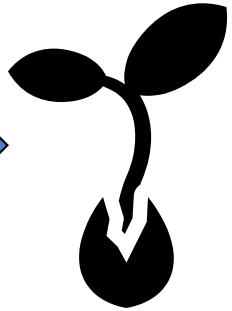
AC, pulsed DC, rf or microwave

New Jersey – Garden State

Our Version of the Atmospheric Pressure Plasma Jet

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

Plasma Processing: Experimental Plan



Plasma Treatment

Measure Plants

Harvest

Distillation

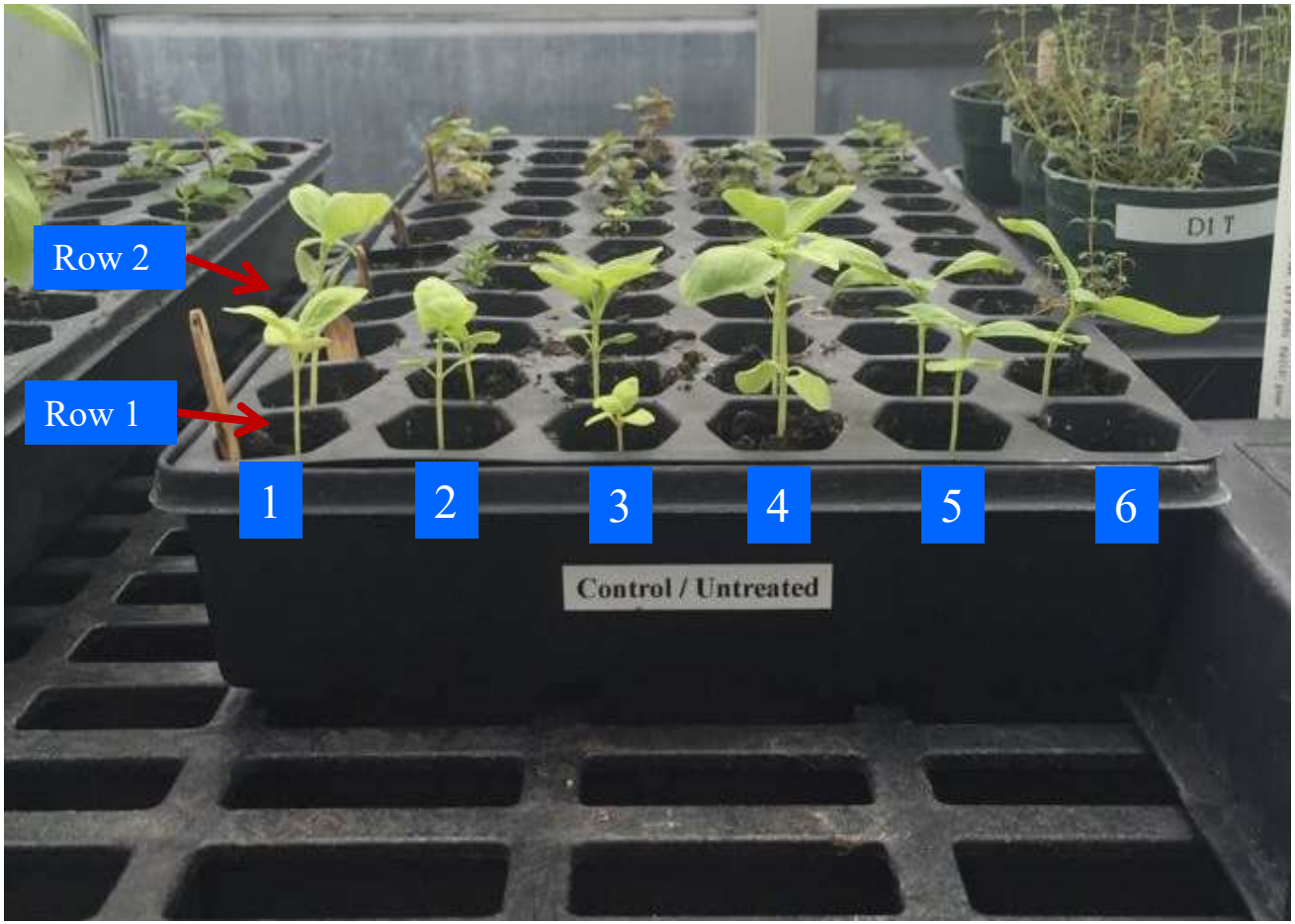
Antioxidant Testing

GC-MS

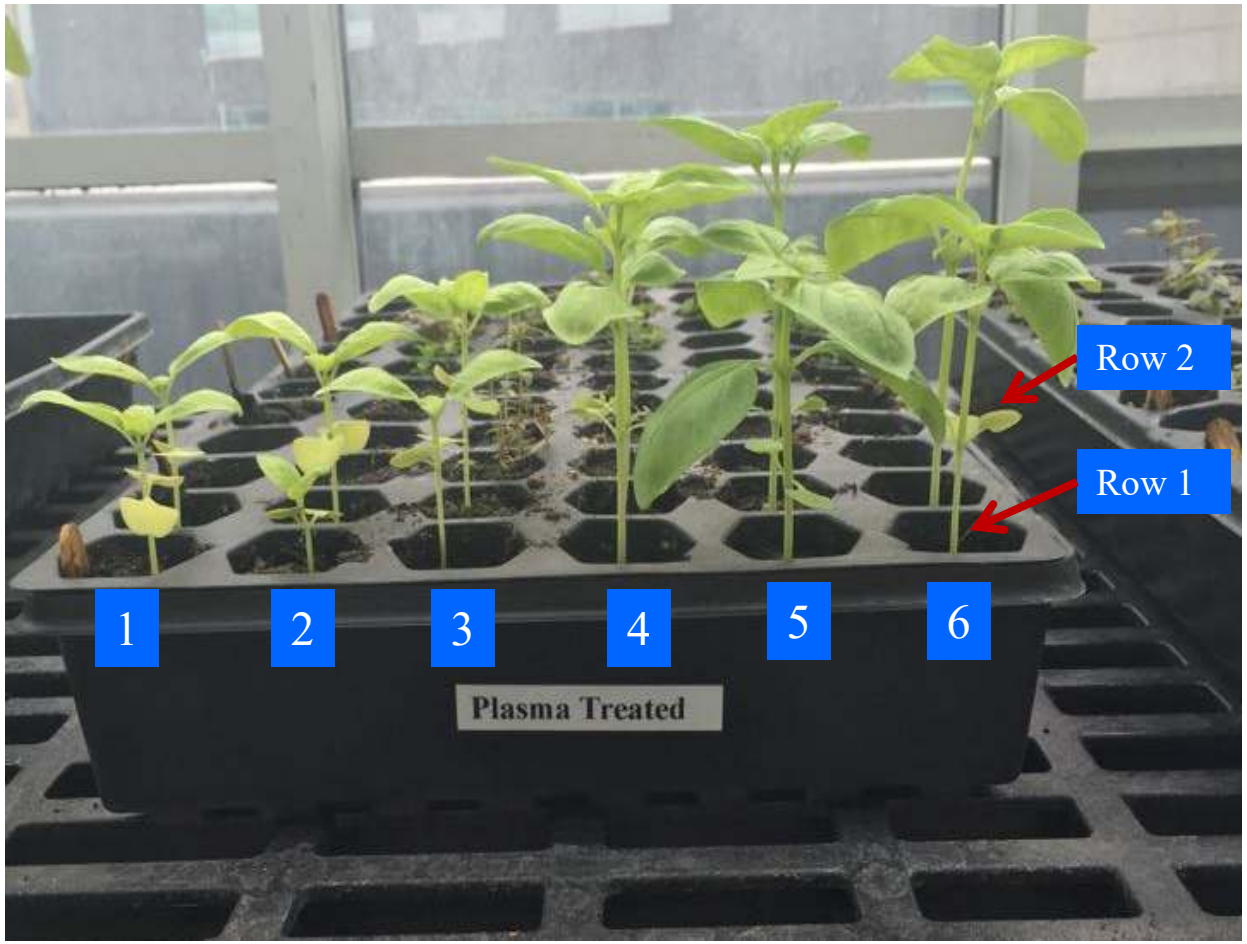
Plasma Seed Treatments

(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).

Untreated (Control) Basil

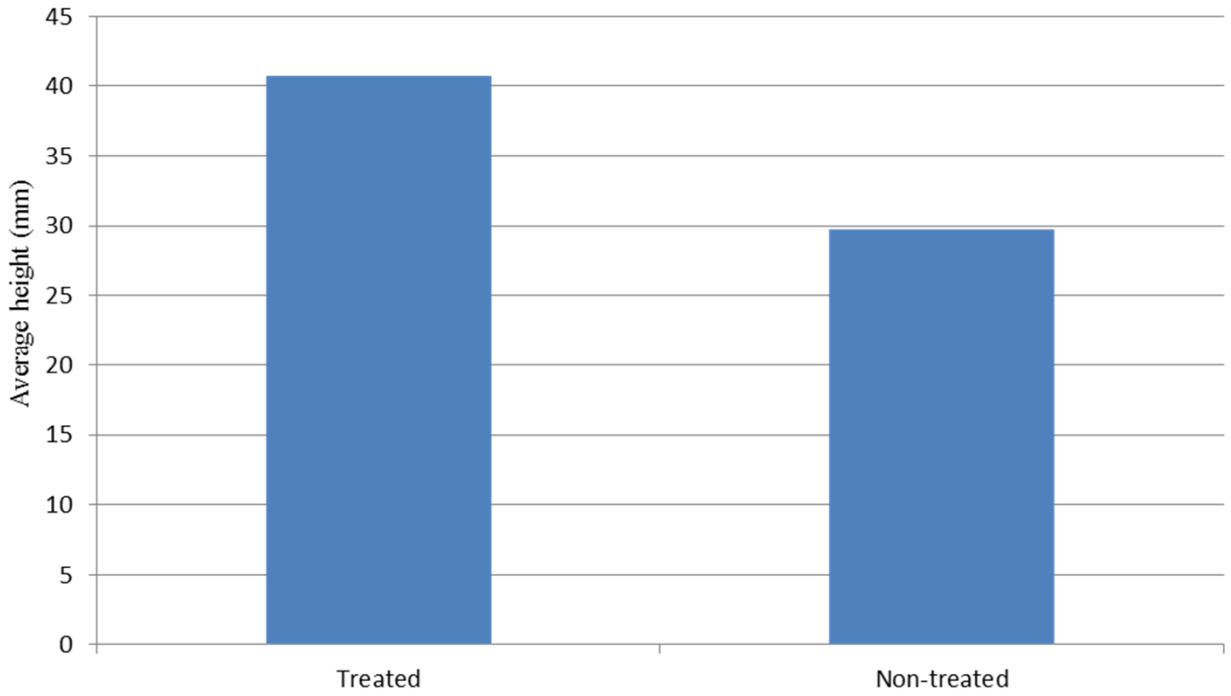


Plasma Treated Basil



Basil: Plasma Treated vs. Untreated

Basil: Plasma Treated vs. Untreated



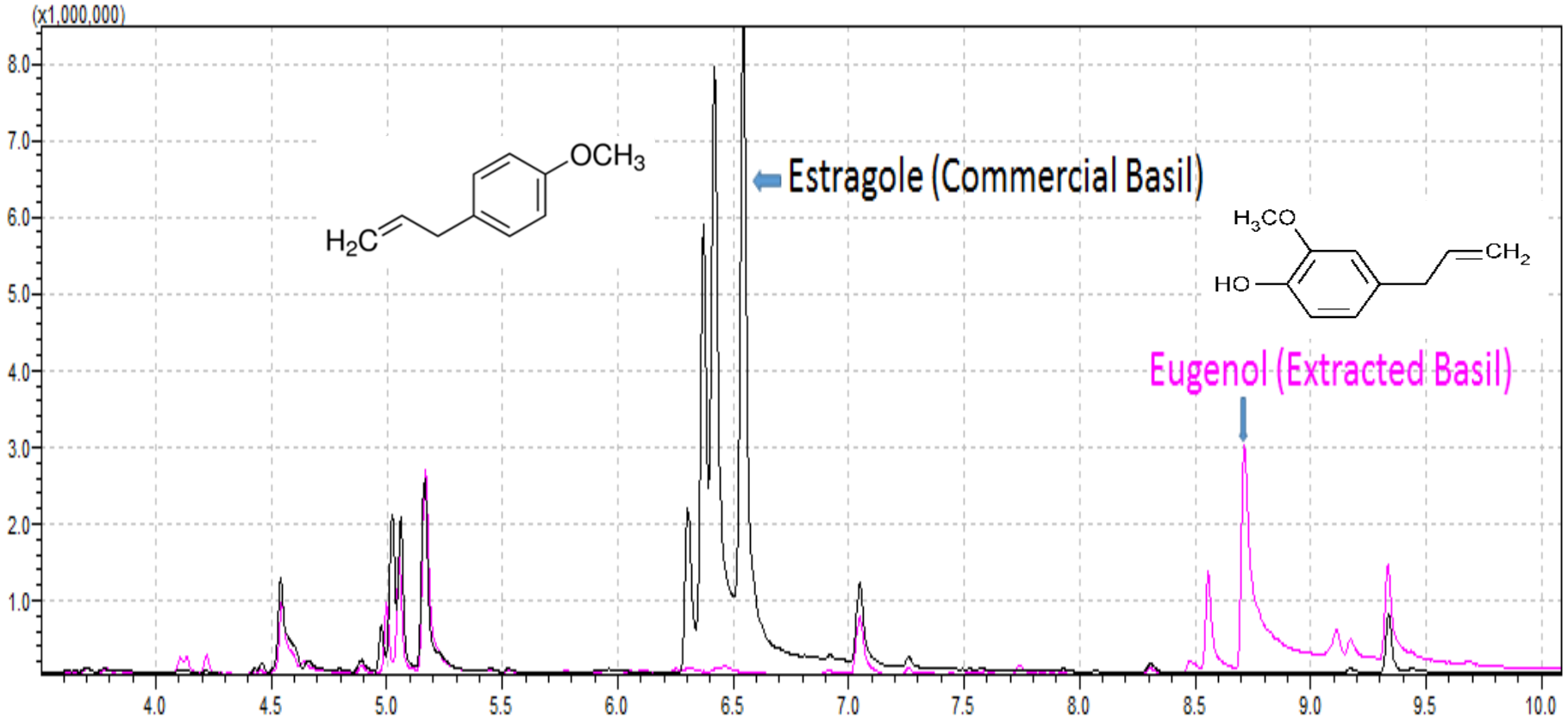
Graph demonstrating average final height of twelve treated and non-treated sweet basil plants after a month of growth from seeds.

Percent Antioxidant Activity – Home-Grown Basil (seed treated)

Antioxidant / Concentration	15 µg/mL	25 µg/mL	50 µg/mL	125 µg/mL	250 µg/mL
Plasma-Treated Basil	48.00%	62.55%	81.55%	90.55%	94.82%
Non-Treated Basil	19.55%	26.91%	46.36%	78.27%	90.64%

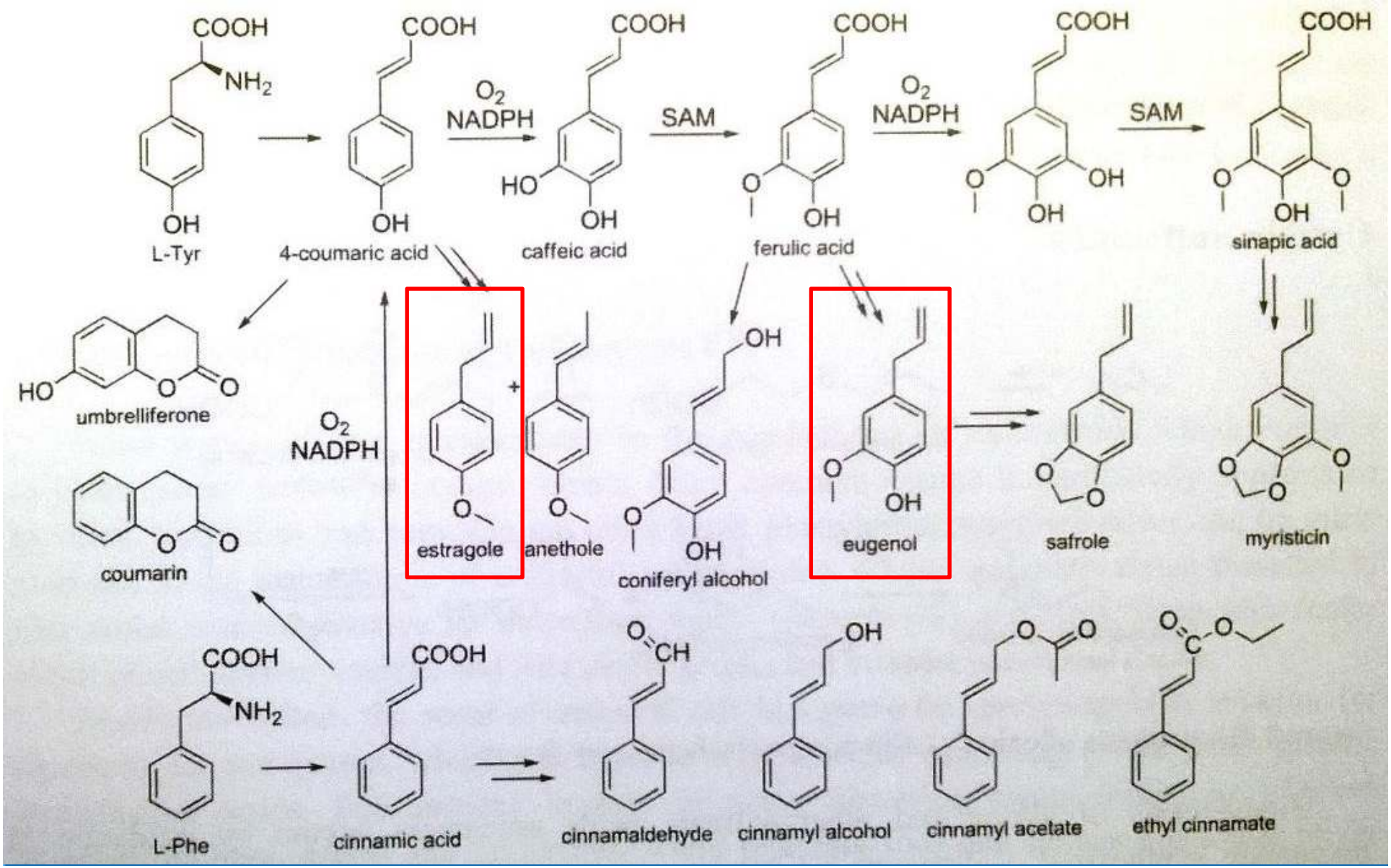
Gas Chromatogram: Overlay of Commercial Oil and Extracted (T + NT)

Shimadzu GC-MS; Column: RTX-5 MS: 15m X 0.25mm X 0.25µm

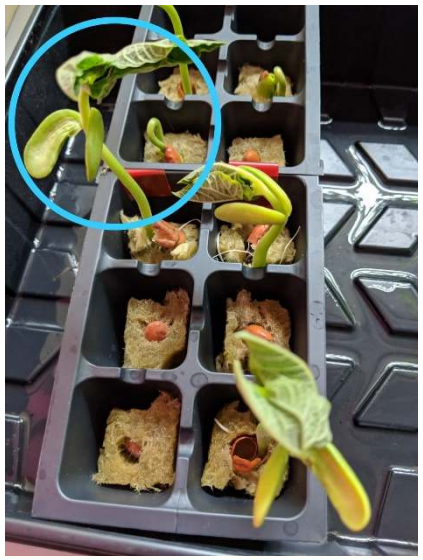


Biosynthesis of Phenylpropanoids and Phenolic Compounds

(Valgimigli, 2012)



Aeroponic & Aquaponic Investigations



Kidney Bean Research

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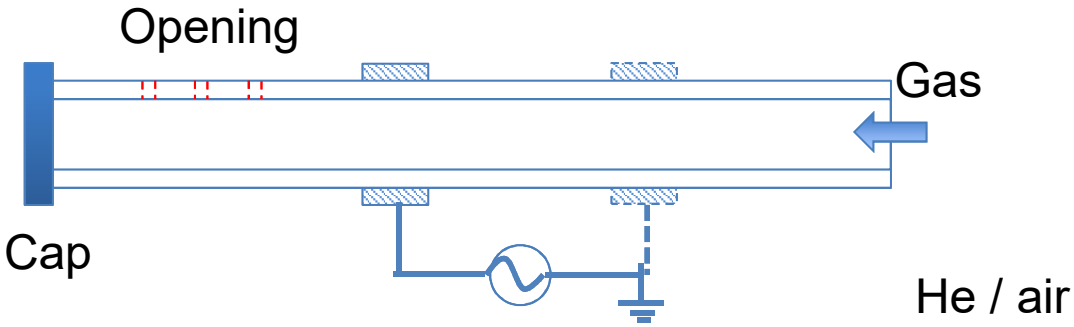
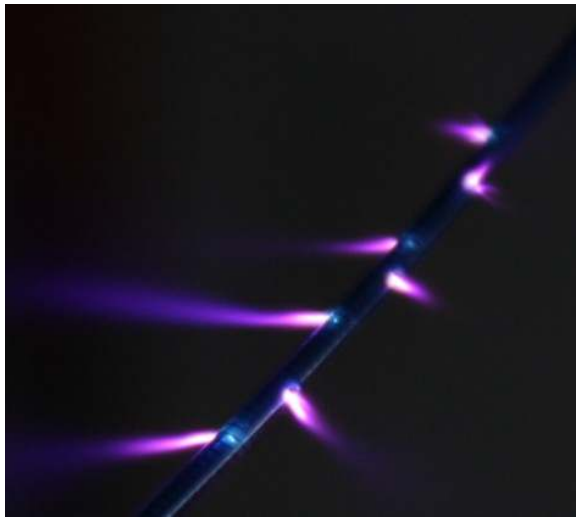
Create plasma jets in multiple directions



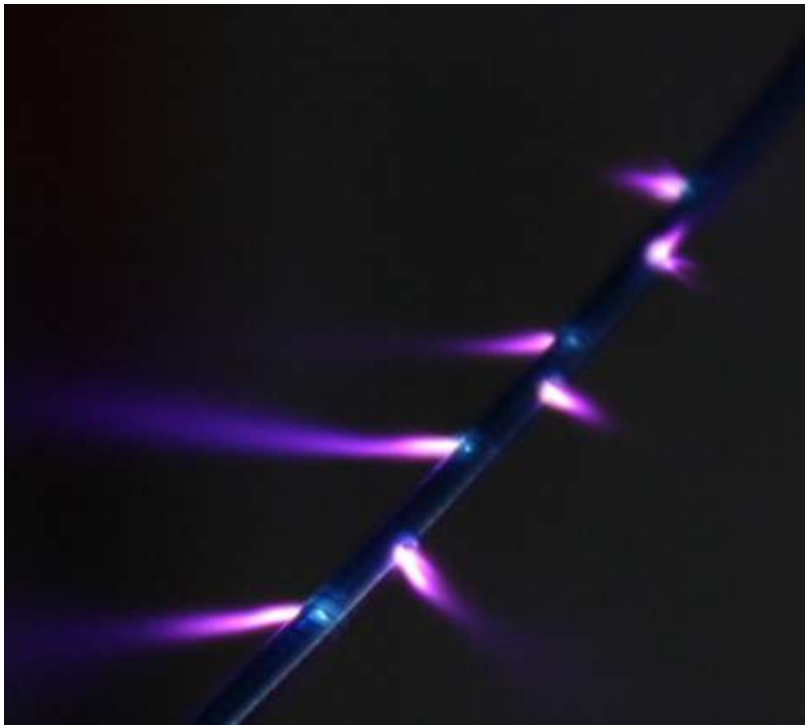
3-D Arrays!



Plasma Jet Array

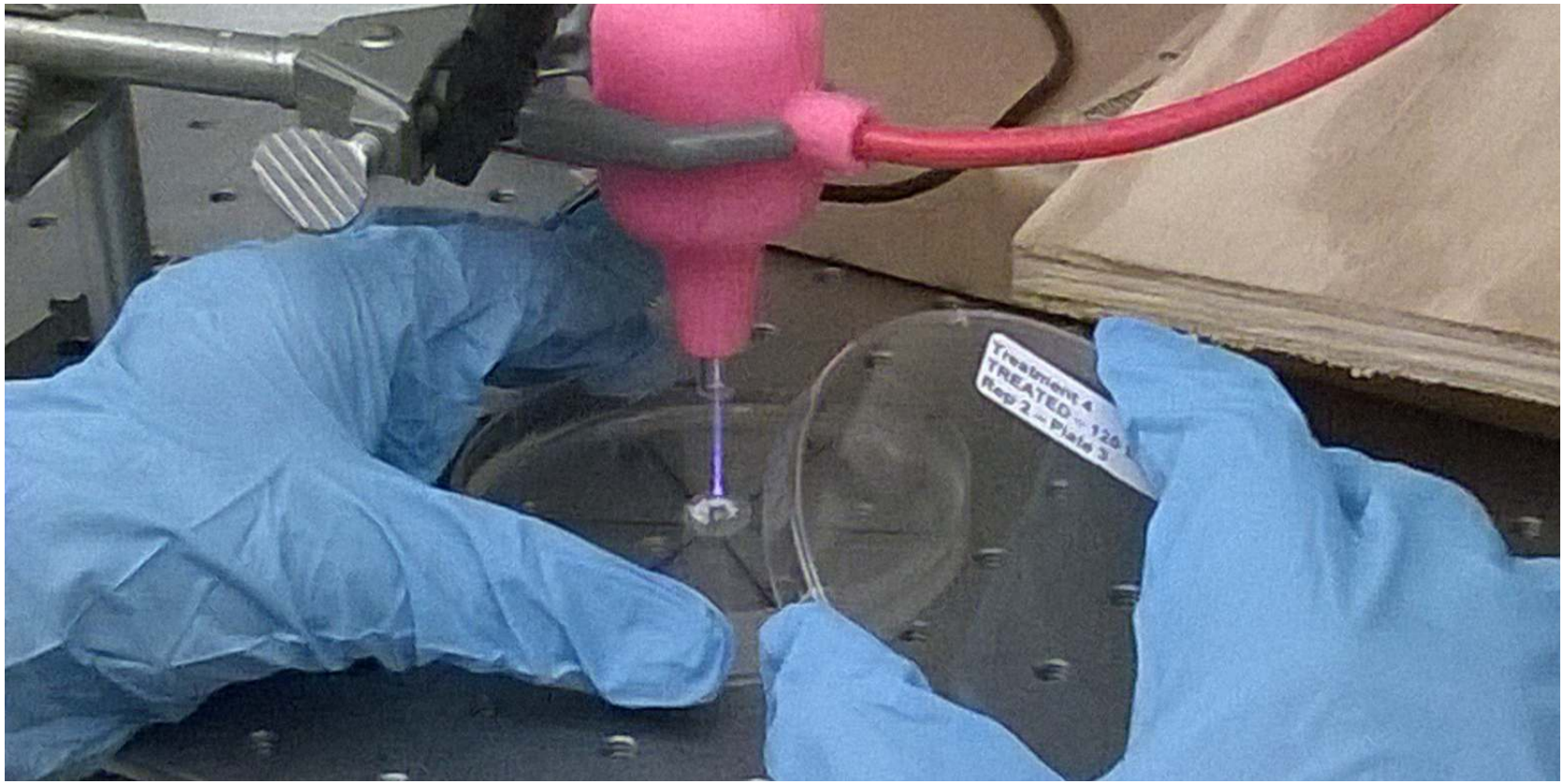
Irrigation: Water & Plasma

Water irrigation in fields and greenhouses



Plasma irrigation for agriculture

Plasma Treatment of Fungi



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

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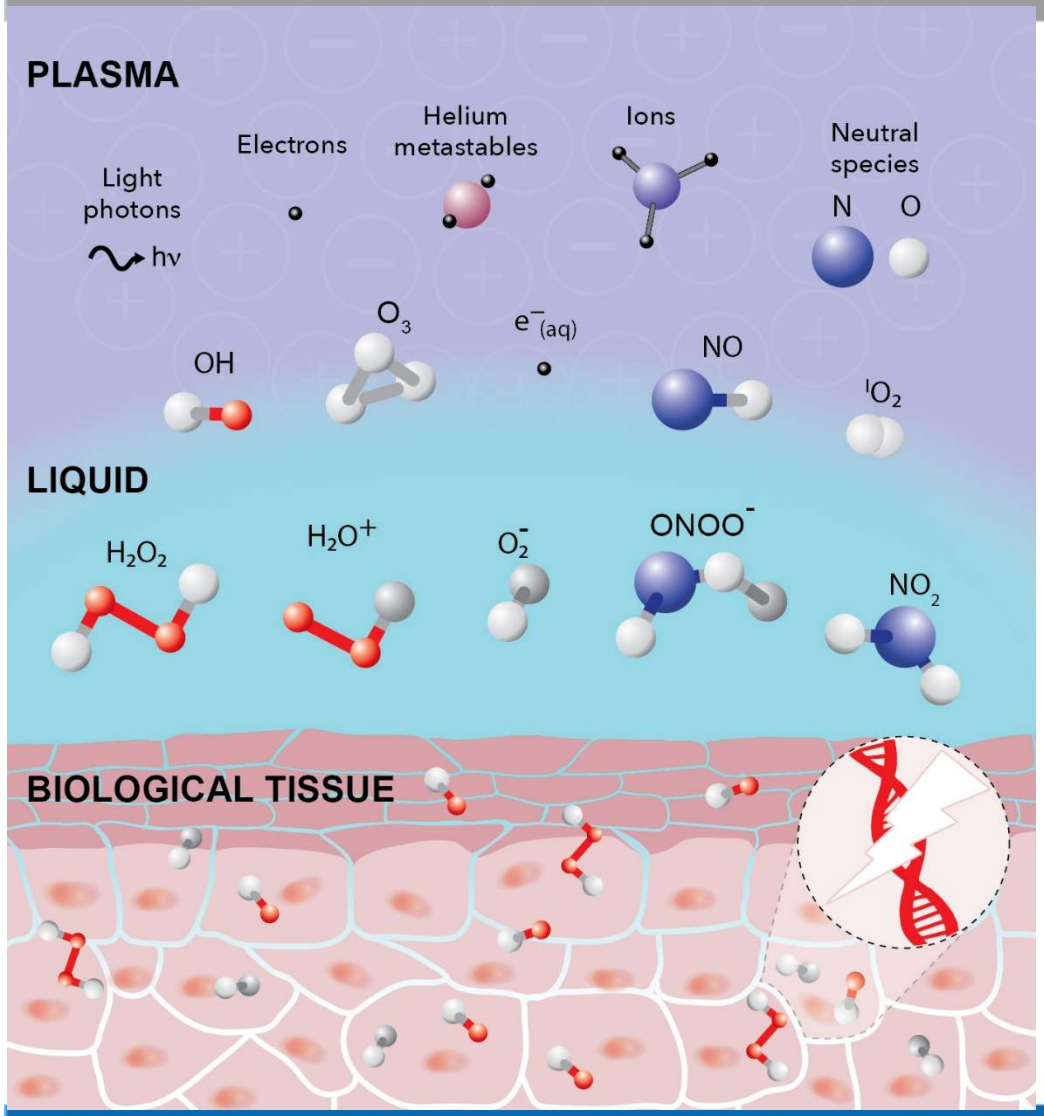
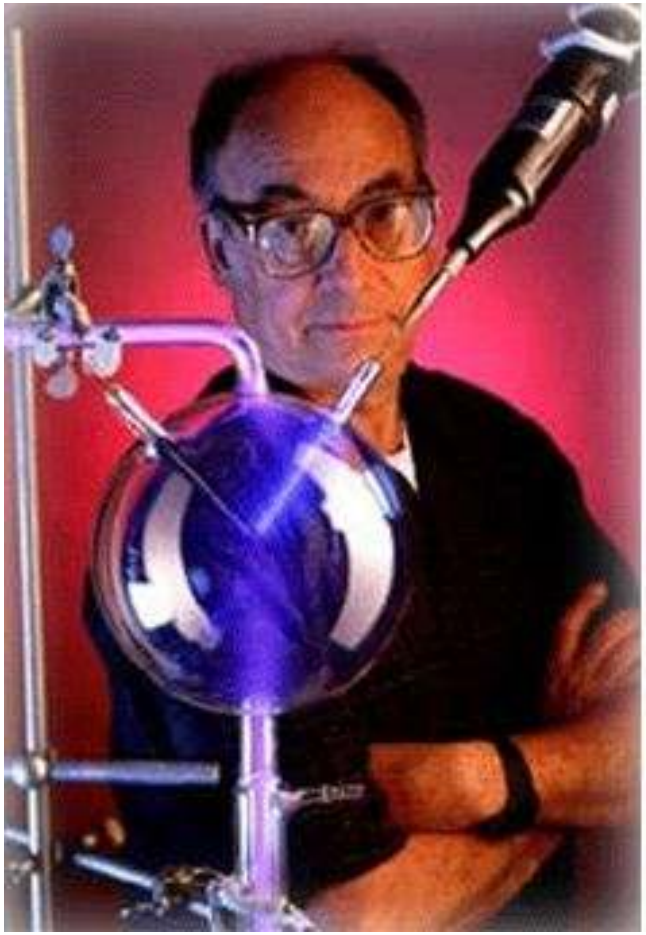
Microplasma interaction with biological materials???

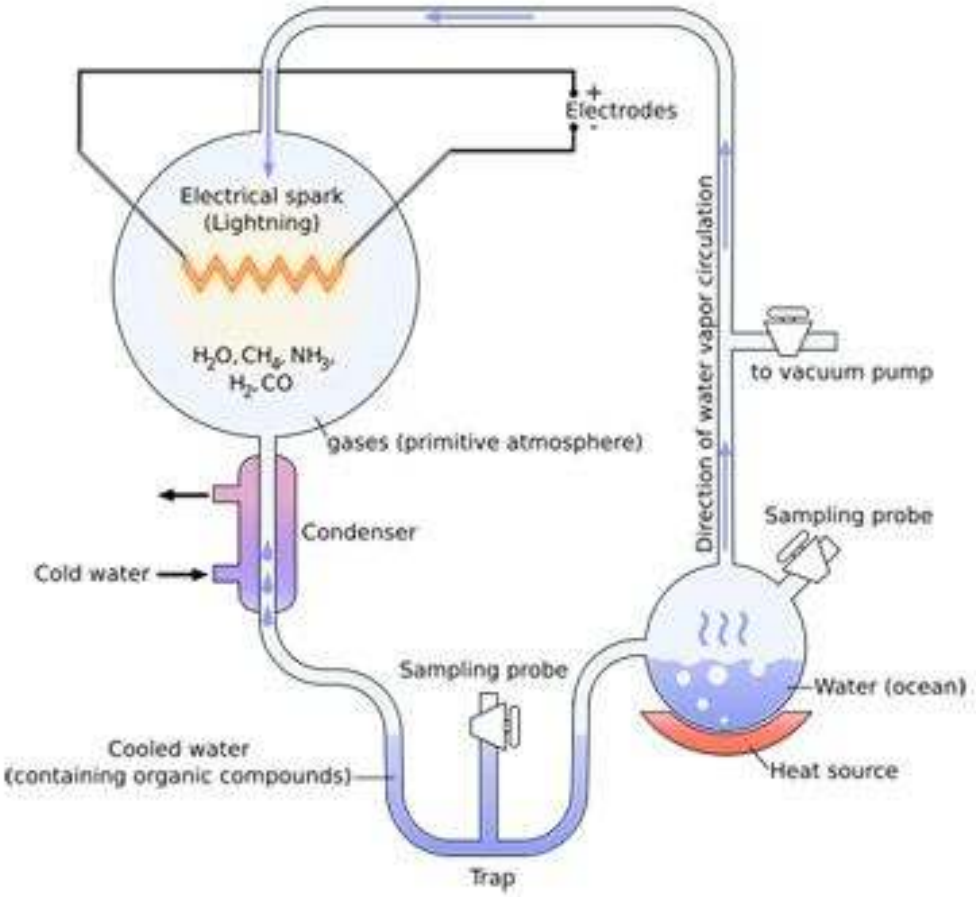


Many unanswered questions as to the role of plasma in the biological interactions with biological materials.

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

Plasma – Spark of Life?





Urey-Miller Experiment – Origin of Life

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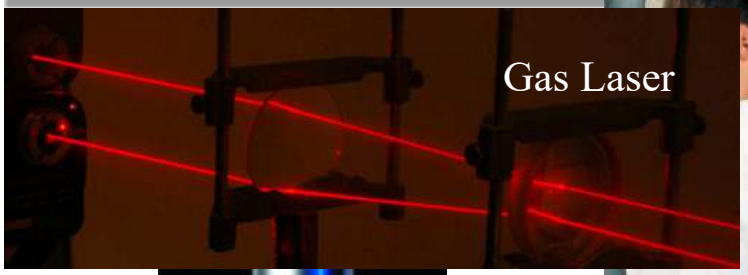
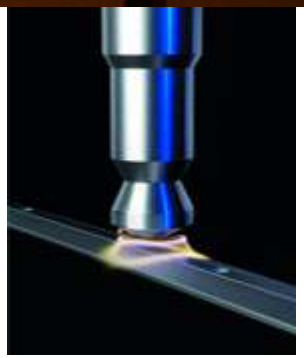
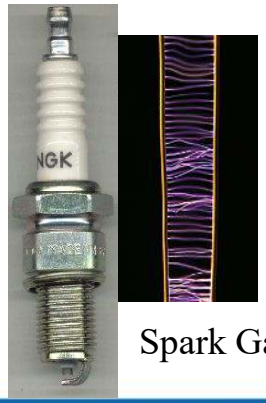
Many, many Innovative Technologies…



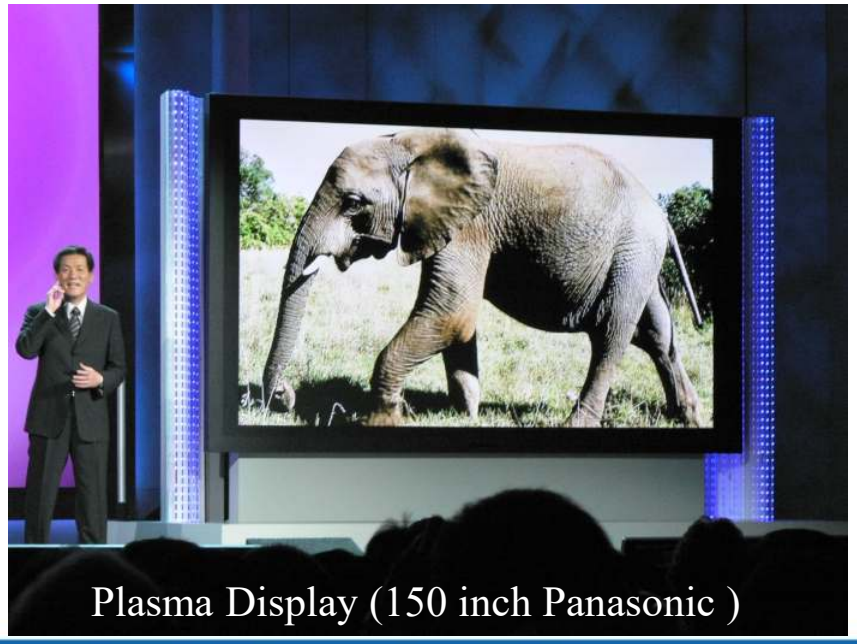
High Intensity
Plasma Arc Lamp



Plasma Surface Treatment



Spark Gap



Plasma Display (150 inch Panasonic)

Fluorescent Lamp

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Star Wars – The Empire Strikes Back

The dangerous plasmas…

The Star Trek: TNG future

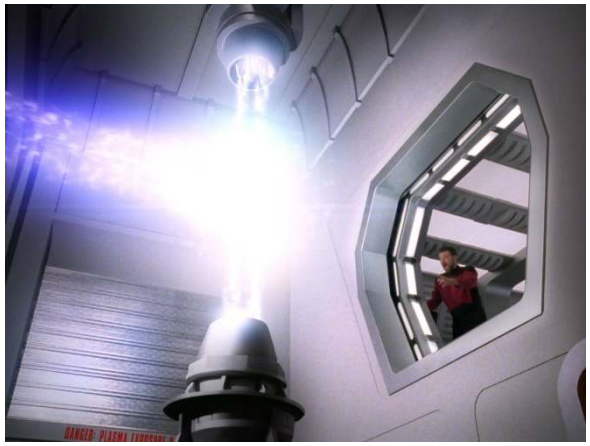
The ST:TNG future is all about plasma technologies…

The Star Trek: TNG future

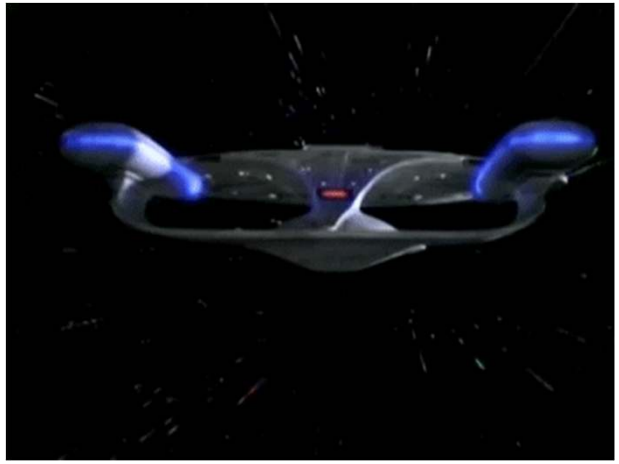
Plasma Torpedoes vs. Plasma shields

The Star Trek: TNG future

Warp Drive core



Plasma injector



Nacelle Warp Drive Engines

Star Trek's Dermal Regenerator

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

Star Trek's Dermal Regenerator

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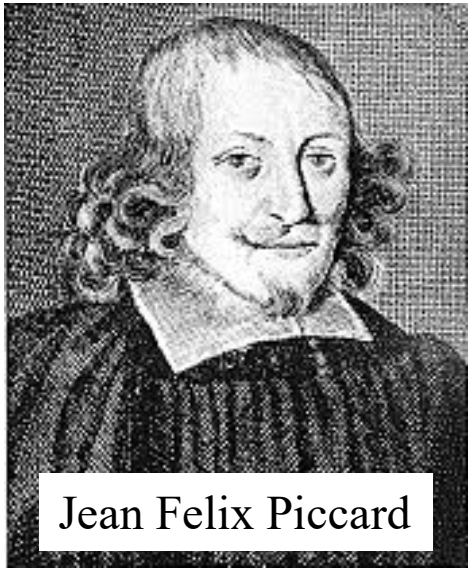
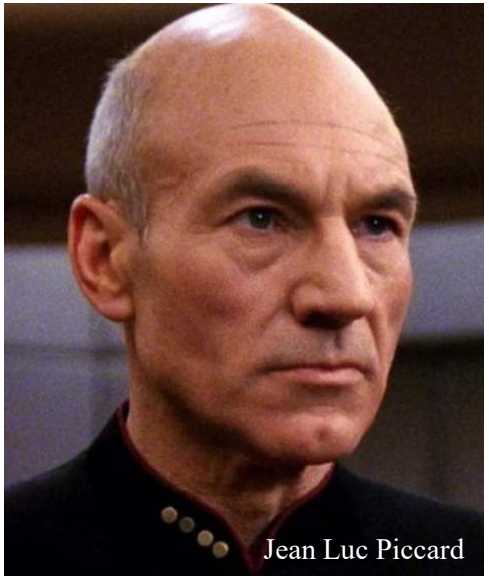
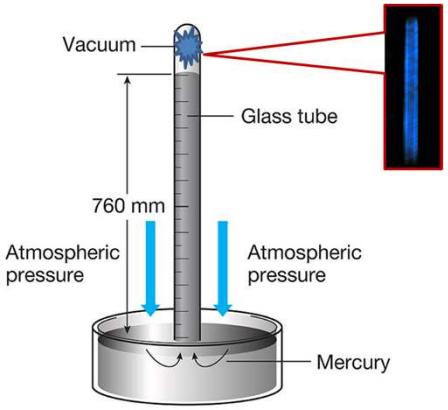
What LTP technologies will the future bring???







Mercury barometer

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

….Yogi Berra

Acknowledgements

Funding Partners:

IEEE Transactions on Plasma Science

IEEE TRANSACTIONS ON
PLASMA SCIENCE

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Senior Editor of Industrial, Commercial, and Medical Applications of Plasmas

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A HOME FOR THE MIND, THE HEART AND THE SPIRIT

DEPARTMENT OF PHYSICS

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

COLLEGE OF ARTS AND SCIENCES

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Questions???

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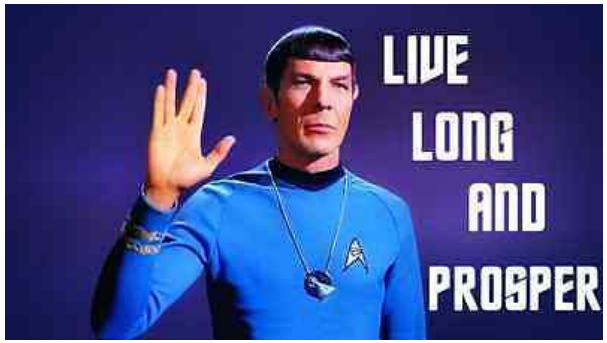
Thank You!



Jose L. Lopez, Ph.D.
Professor of Physics
Seton Hall University
Department of Physics
Laboratory of Electrophysics & Atmospheric Plasmas (LEAP)
Telephone #: (973) 761-9057
Email: jose.lopez1@shu.edu

or
Princeton Plasma Physics Laboratory
Plasma Science & Technology Department
Telephone #: (609) 243-2750
Email: jlopez@pppl.gov