Atmospheric Non-thermal Plasma Jet and its Applications

Dr. Eng./ Kamal M. A. Ahmed

Assistant Professor

Egyptian Atomic Energy Authority

Outline

1 Introduction
Plasma, sources & configurations

2 Plasma Jet
Design, components & diagnostics

3 Measurements
Electrical & temperature& wettability

4 Plasma Applications

Outline

Introduction

A Plasma in our life

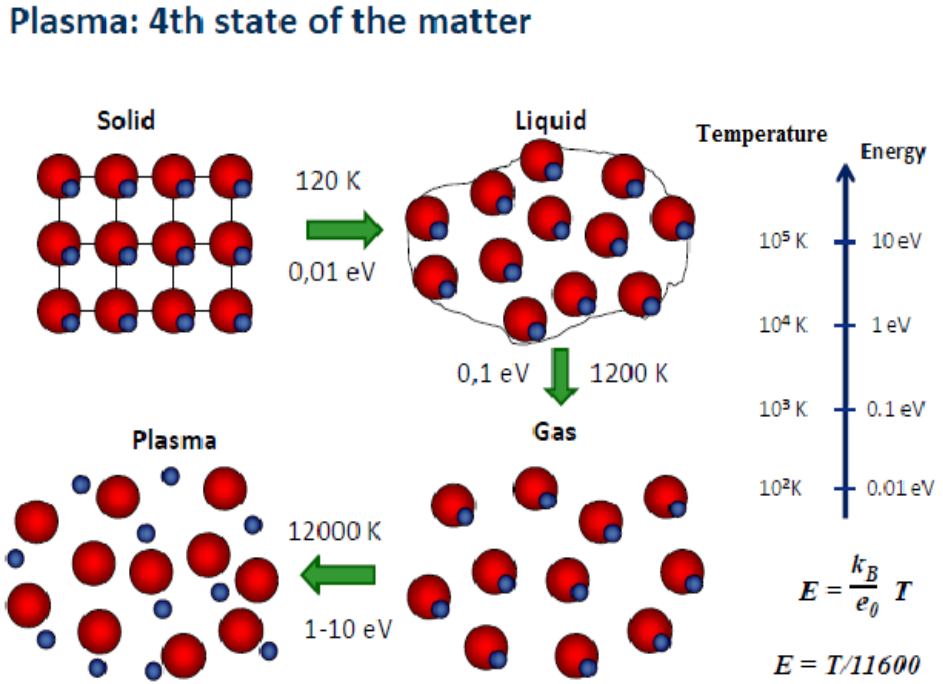
B Plasma classifications

C Electrical safety & Plasma sources

D Plasma configurations

Plasma definition

- plasmas are mostly generated by ***electrical discharges***



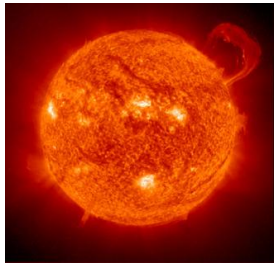
Plasma in our life

Plasmas occur naturally comprise the majority of the universe (95 or 99).

Natural Plasma

- Well-known **examples** :
  - the **Sun**
  - **stars**
  - the **ionosphere**
  - **Lightning**

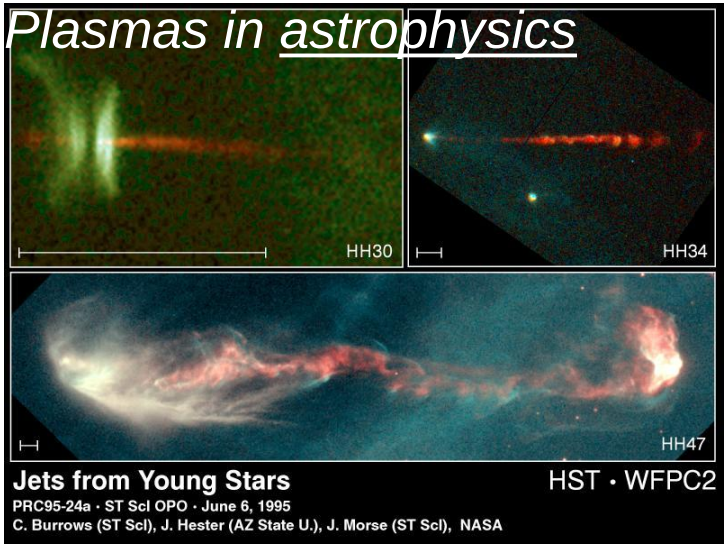
Lightning



Plasmas in Solar physics

Aurora (U. of Alaska)

الشفق القطبي



Plasma in our life

but also can be manmade.

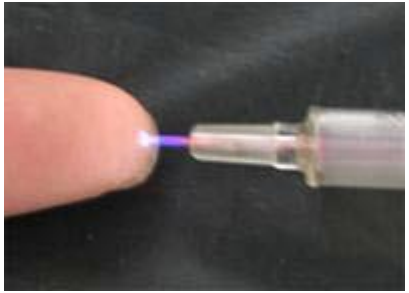
Artificial Plasma

- **Lighting**

Plasma display

Melting

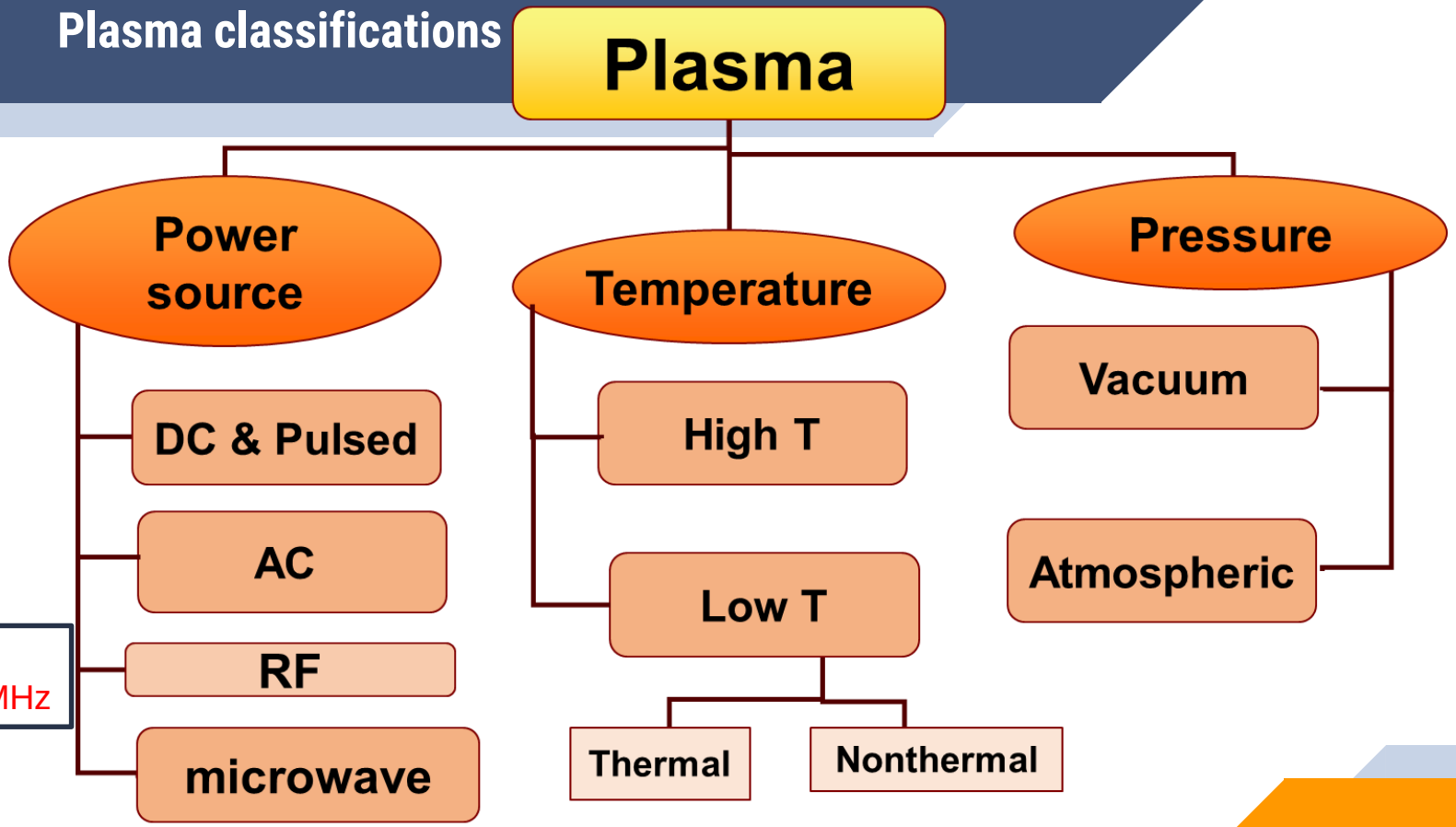
- **Spray Coatings**



Biomedical

Cutting

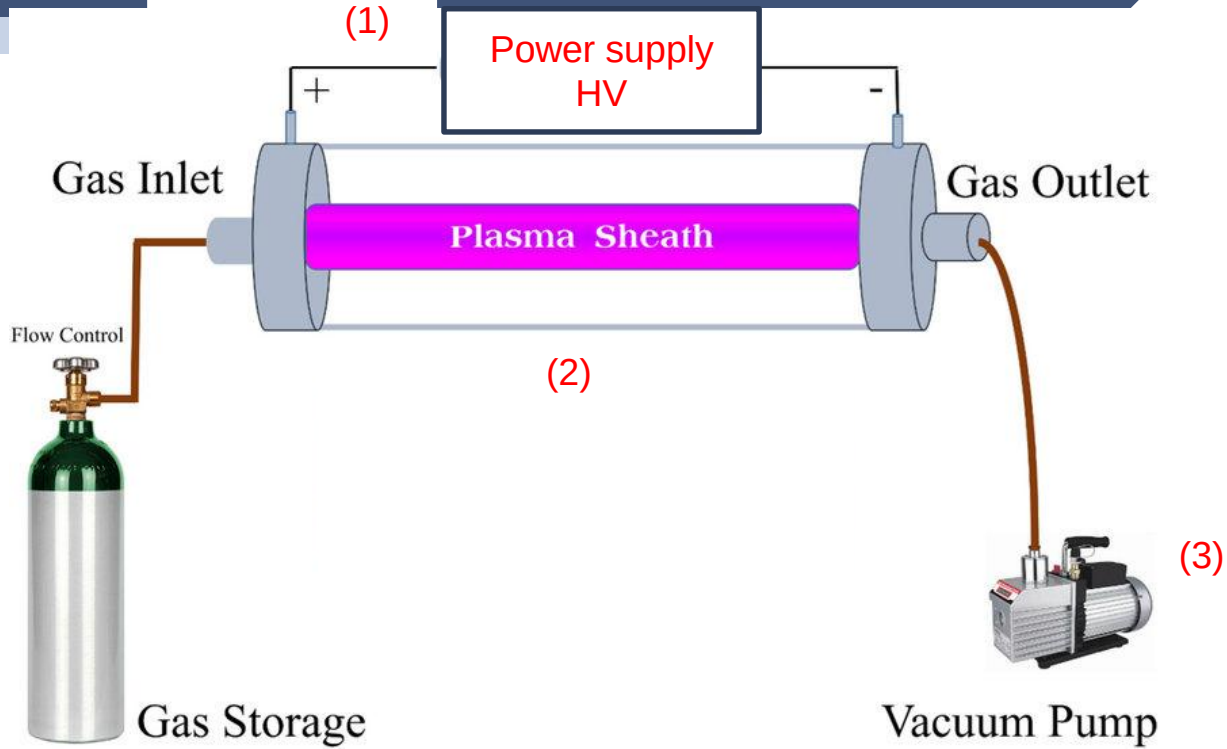
Plasma classifications



kHz
13.56 MHz

2.54 GHz

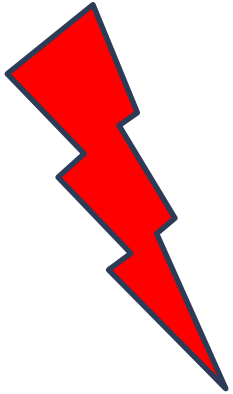
How to produce plasma



What voltage and current are dangerous for humans?

Electrical safety

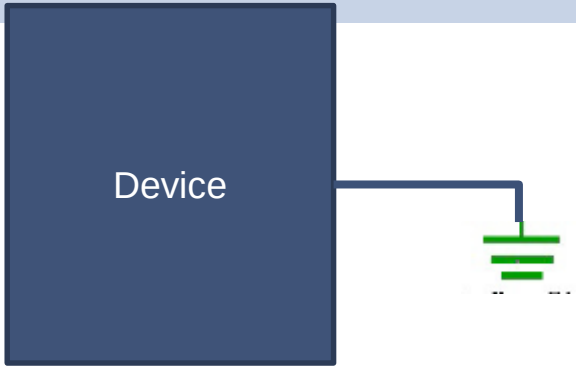
Electricity in touch

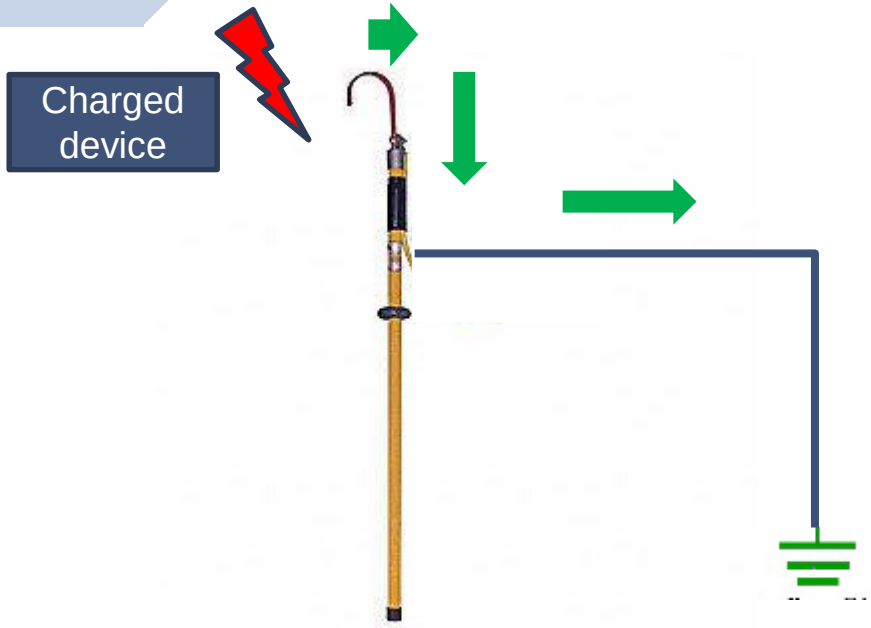


Current < 30 mA
Voltage < 50 V AC, 50 Hz

- ✓ **Earthing**

Earthing

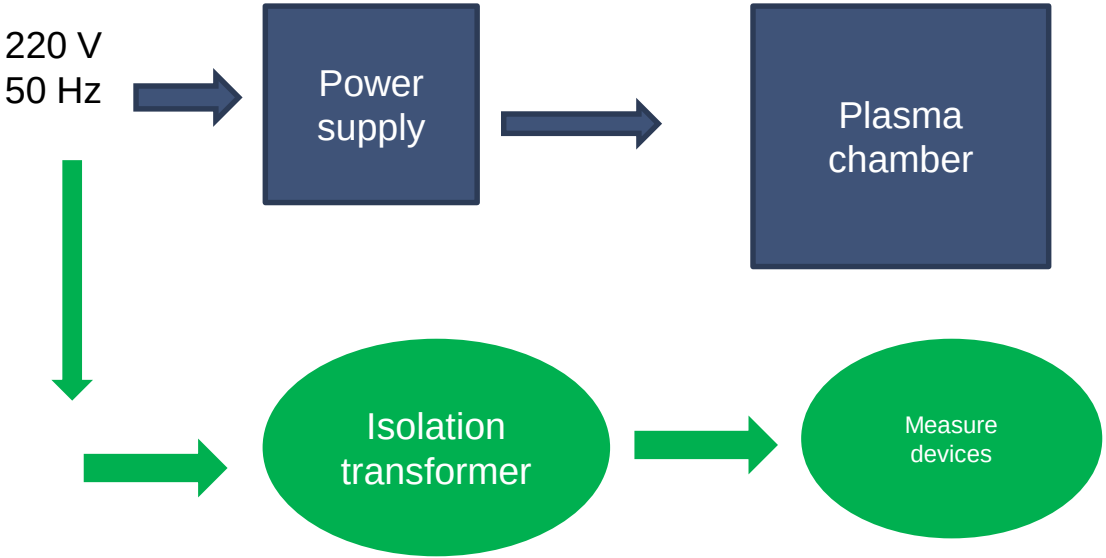




Earthing rod

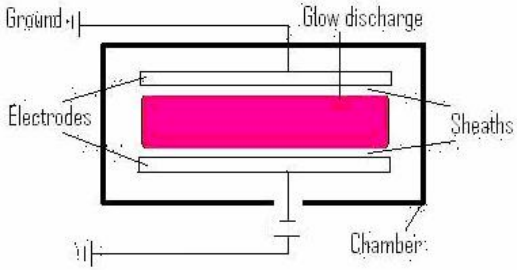
For the measurements devices

Should be isolated from the plasma source and the power supply

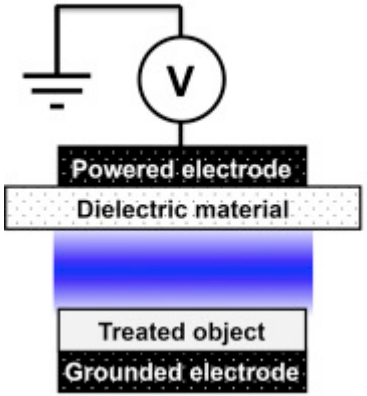


✓ The coaxial cables should be 50 ohm

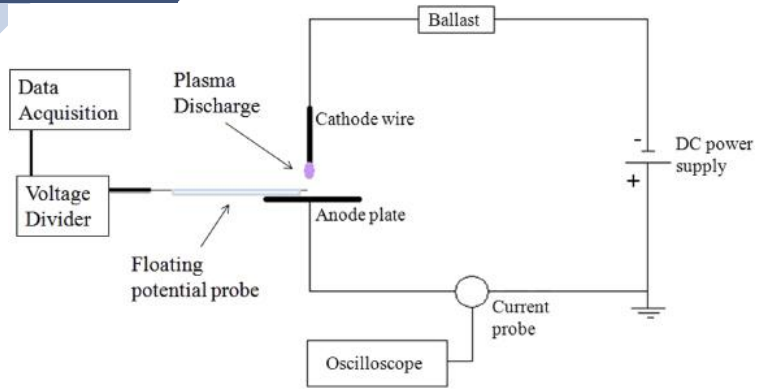
Plasma Configurations



✓ **Glow discharge**

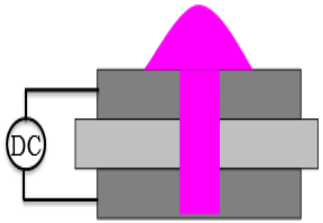


✓ **DBD**

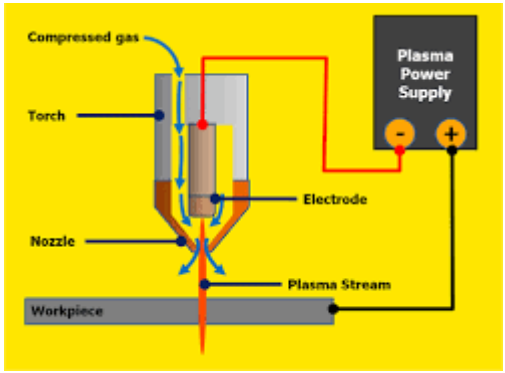


✓ **Corona discharge**

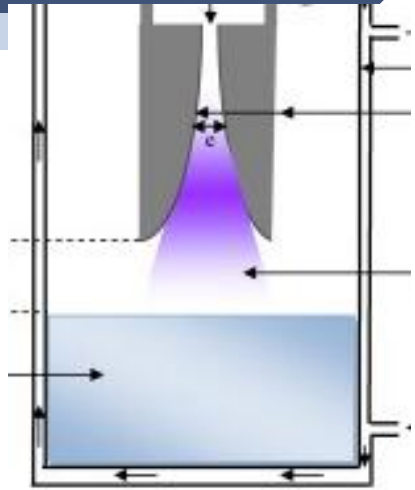
Plasma Configurations



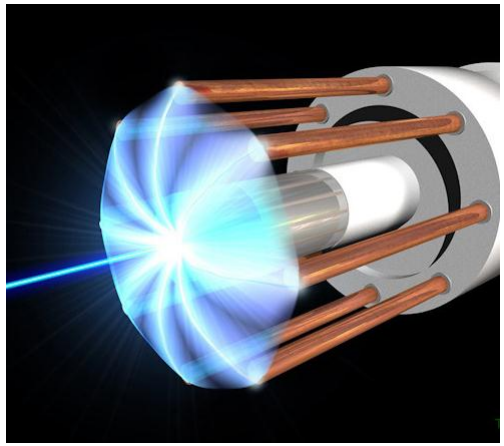
✓ MHCD



✓ Plasma torch



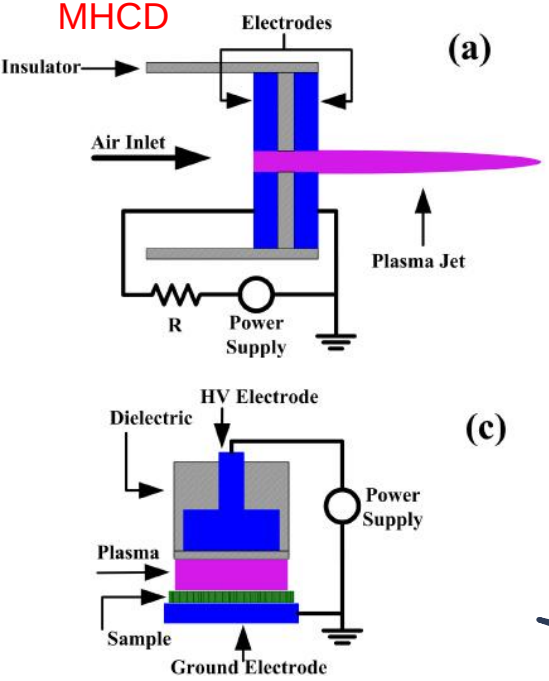
✓ Gliding arc discharge



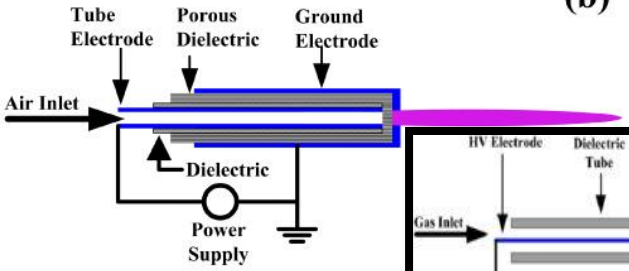
✓ Plasma focus

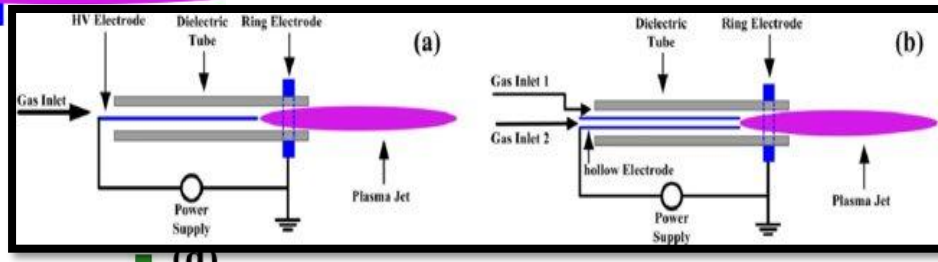
Plasma Jet Configurations

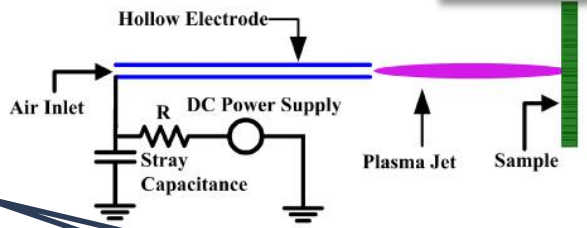
MHCD



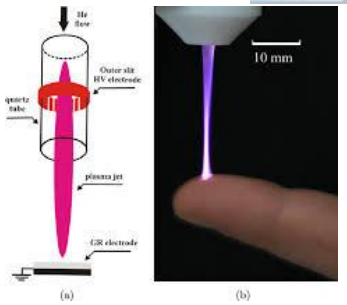
Coaxial discharge







Pin-to-ring discharge



Floating electrode

Outline

1 Introduction

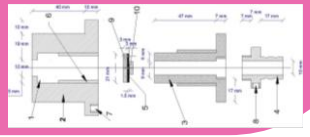
2 **Plasma Jet**

3 Measurements

4 Plasma Applications

Plasma Jet

1 Design Goals



2 Device Components

3 Diagnostics

Design goals

1. Advantages of Atmospheric plasma
2. NON-thermal (Cold) Plasma Ch/cs
3. Gas selection
4. Power source's choice; Neon Power supply
5. Factors affect the plasma operation
6. Electrode & insulators

Advantages of Atmospheric plasma

- No Vacuum equipment's Required
- Lower Purchase and Maintenance Costs
- Can be operated in open air with large treatment areas.
- Minimum cooling is required
- Different configurations and geometries are available

NON-thermal (Cold) Plasma ch/cs

- ✓ **The majority of the electrical energy deposited in the Non-thermal (cold) plasma heats the electrons instead of heating the background gas.**

$$T_{gas} \ll T_e$$

- ➢ **Because the ions and the neutrals remain relatively cold, cold plasmas is used for the treatment of heat sensitive materials including polymers and biological tissues.**

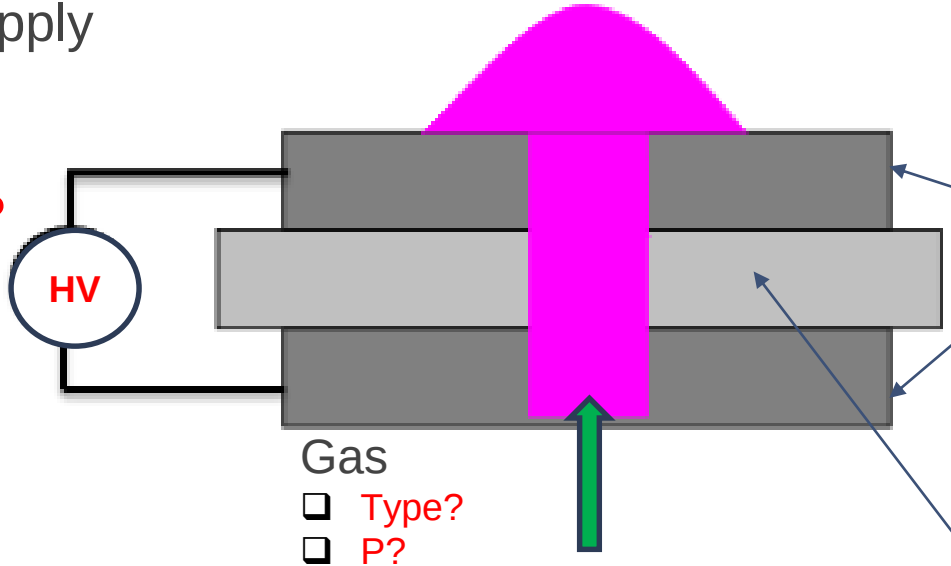
- ➢ **Its characteristics include a strong thermodynamic non- equilibrium nature, low gas temperature, presence of reactive chemical species and high selectivity offer a tremendous potential to utilize these cold plasma sources in a wide range of applications.**

Factors affecting the plasma operation

(Supply frequency, working voltage, gas type, flow rate, working pressure, electrode spacing and electrode material)

Power supply

- V?
- I?
- f(Hz)?



Electrodes

- Material
- Dimensions : spacing & hole
- Configuration

Gas

- Type?
- P?
- Flow rate

Insulator

Gas selection

- Gas can be Air, H_2, He, O_2, N_2, Ar, CH_4,..etc.

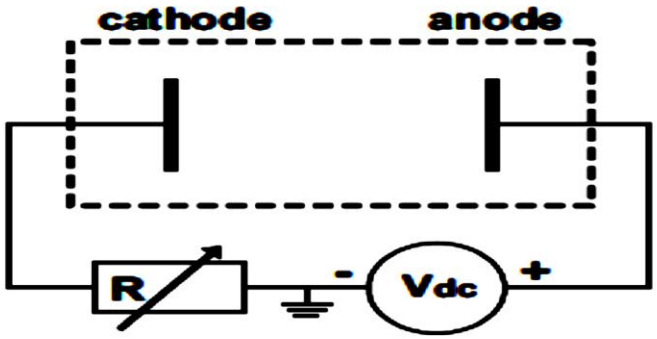
Using Air is an advantageous

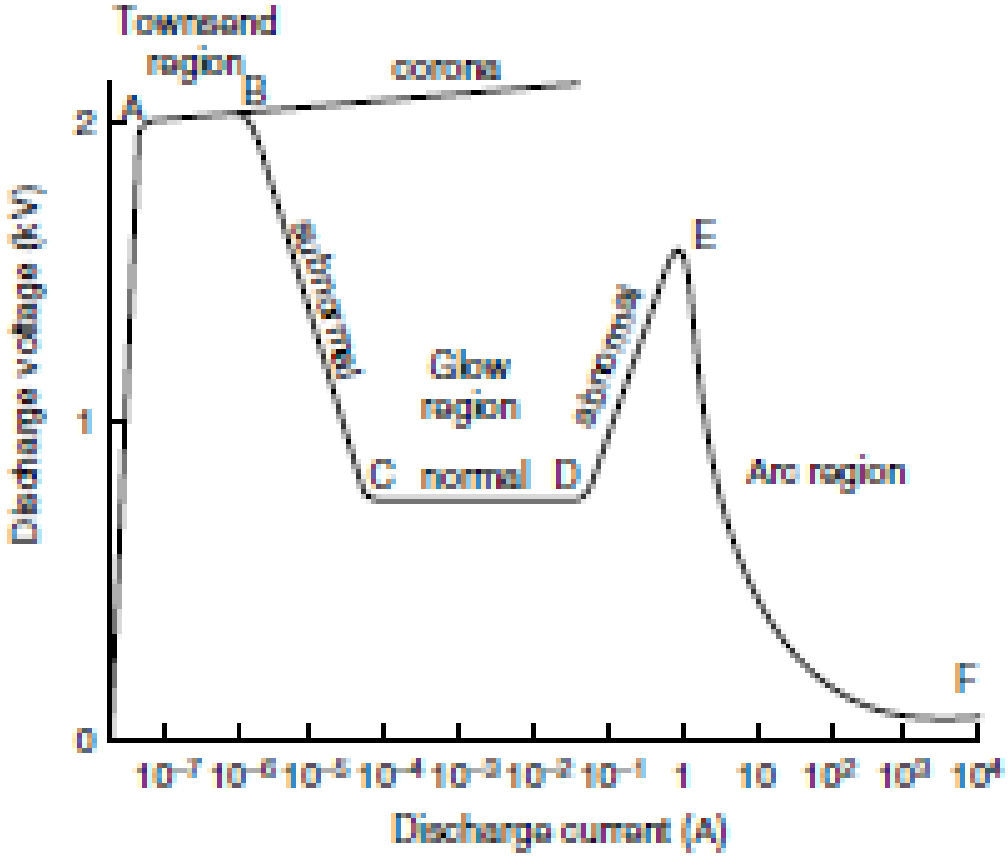
- Low cost
- Portability
- Ozone generation

Endless Air
50% cost reduction

- Higher flow rates helps in Cooling of the system

I-V Ch/s



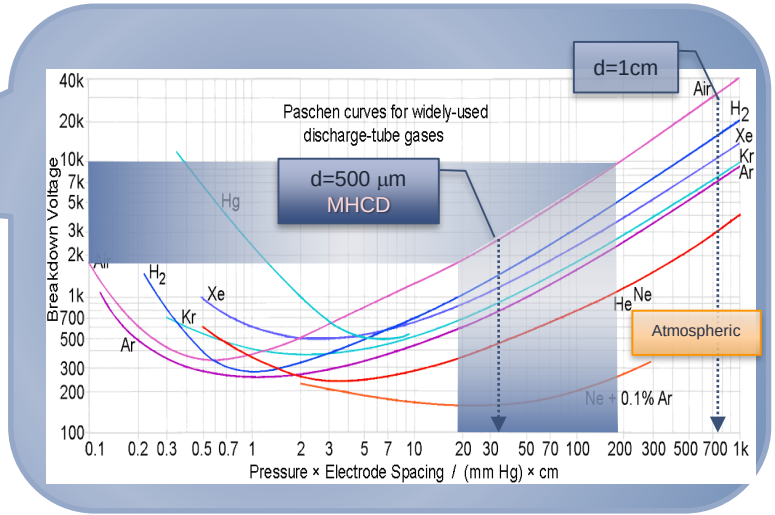


$$V = Vdc - RI$$

Power source's choice

$$V_b = \frac{B(p.d)}{\ln[A(p.d)] - \ln[\ln(1 + 1/\gamma_{se})]}$$

The breakdown voltage must exceed



- depends on the pressure, **p** and electrode spacing, **d**.
- **Vb** will exceed hundred **kV** for atmospheric pressure
- Solution is : **MHCD** (d in micrometer range)

- To reduce breakdown voltage, the power supply frequency is increased.
- So RF is favored over DC
- Low frequency RF is favored due to :
  - Higher Ion Density.
  - Increased Efficiency.
  - Better Uniformity.

What about higher cost of RF Supply

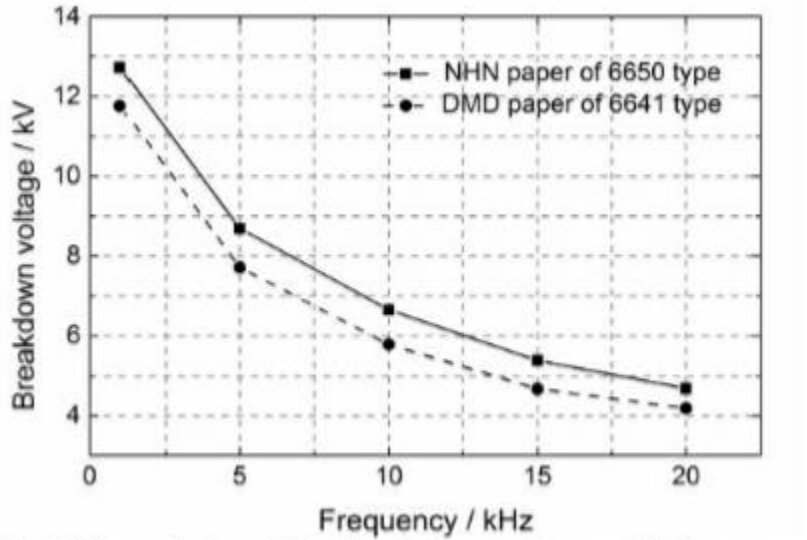


Fig. 5 The variation of the breakdown voltage with frequency

Neon Power supply

- ✓ **A neon power supply is chosen as a low-cost power supply. (Available in Local Markets)**

Low Cost

Output
10 kV, 30 mA and 20 kHz

Electrode selection

Electrode’s material can be

- Stainless steel,
- Aluminum,
- Graphite deposition,
- Copper
- Tungsten
- ….etc

Insulator selection

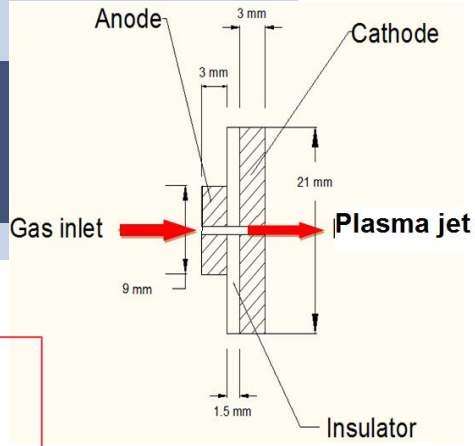
- Sustain HV
- Stand for high T (melting point)

Material	Melting point(°C)
Alumina	2072
Porcelain	1400
Glass	1500
Mica	1250
Teflon	**335**
Mylar	**254**
Silicon rubber	200
PVC	160
Acrylic	160

ANPJ

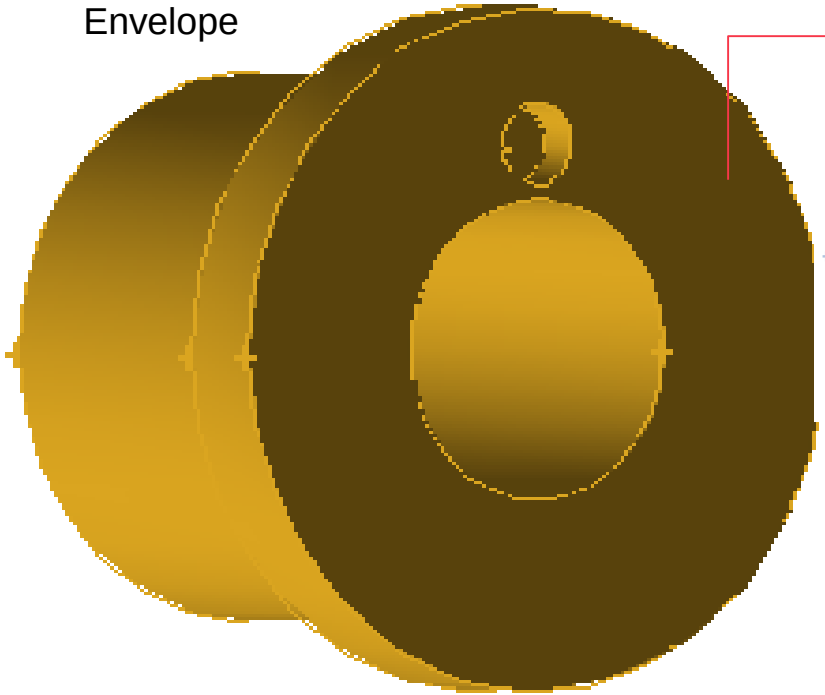
Atmospheric Nonthermal Plasma Jet

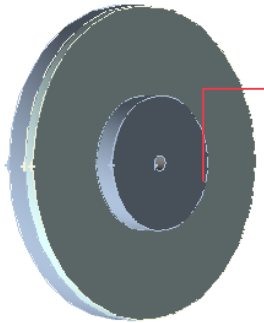
Plasma jet



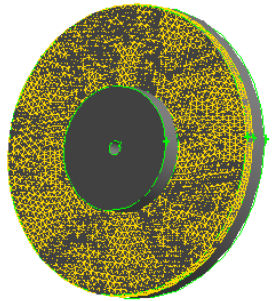
Envelope

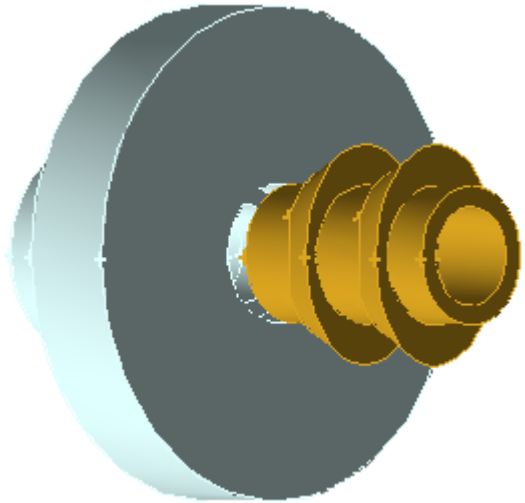
Power supply





Electrodes





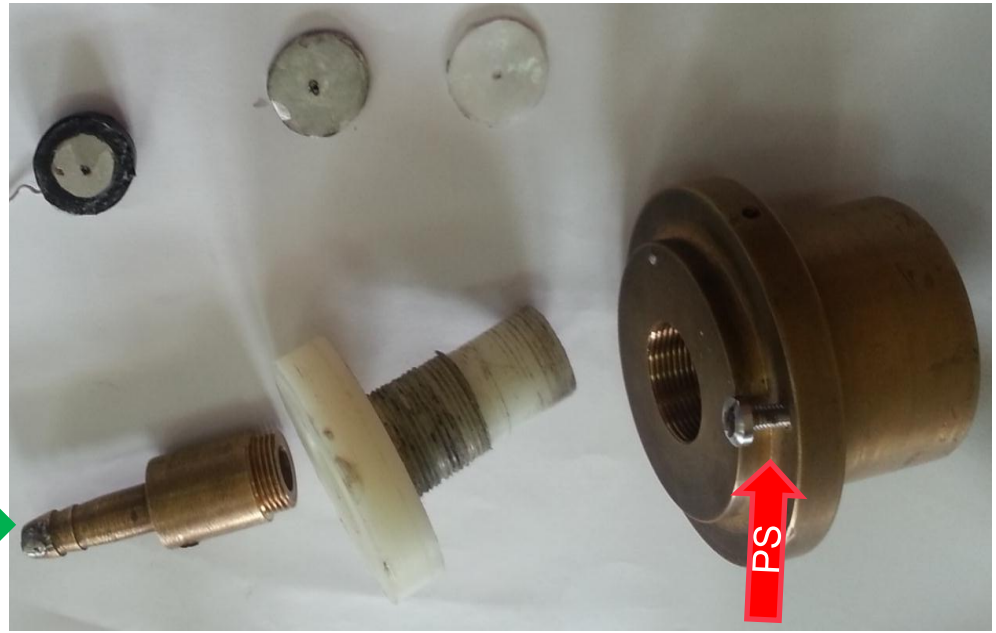
Gas inlet

Plasma jet in our lab.

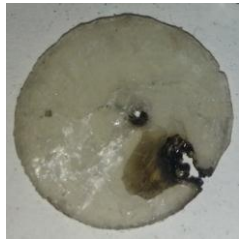
Electrodes

Envelope

PS



Gas inlet

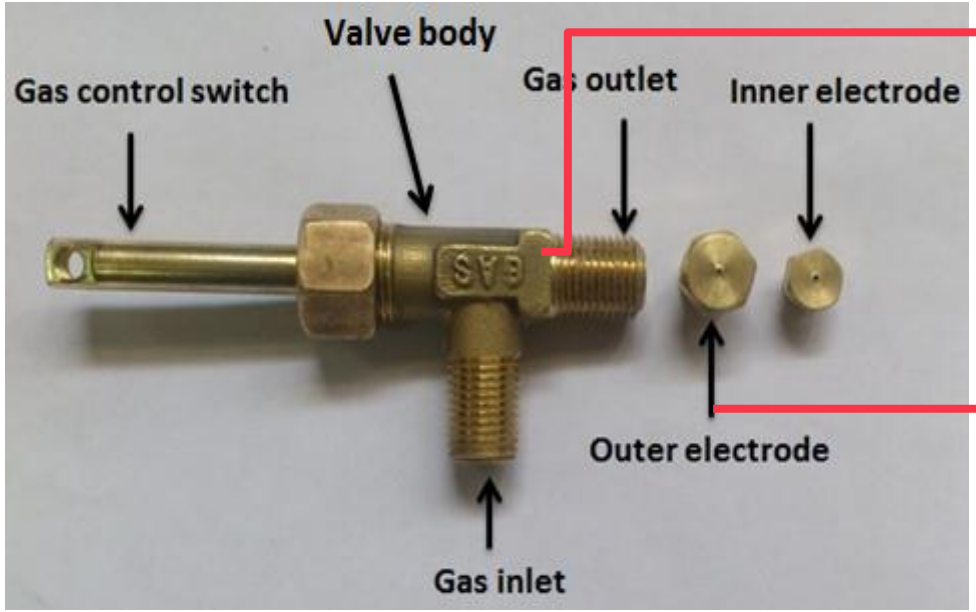


Mylar

Teflon

ANPJ-II

ANPJ-II

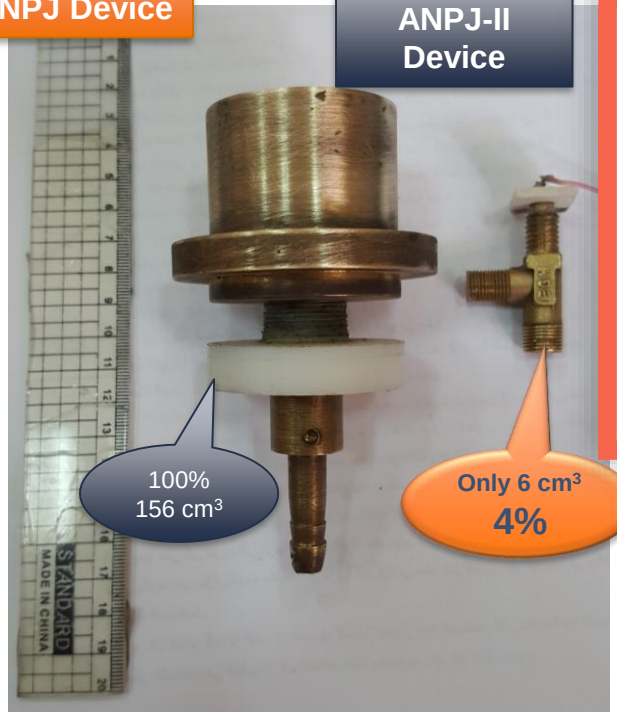


Power supply

Comparison

Previous
ANPJ Device

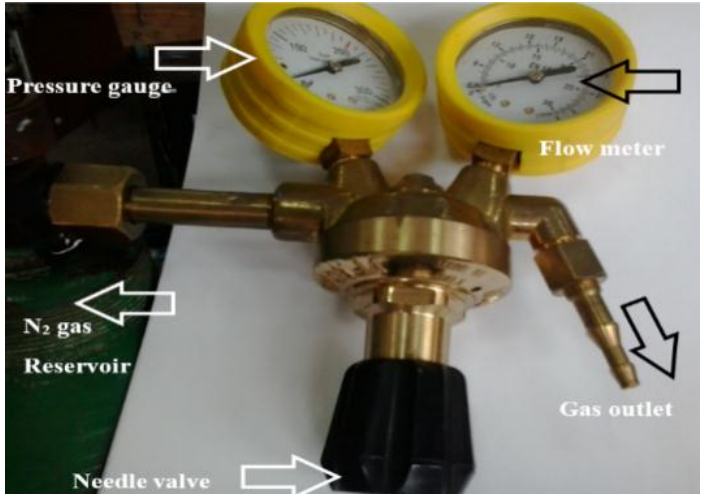
New
ANPJ-II Device



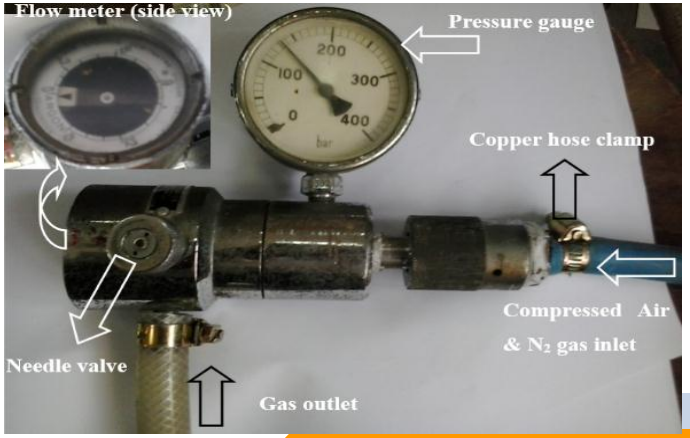
	Previous design	Developed design	Reduction (%)
Material of electrodes	Aluminum	Brass	–
Cathode diameter (mm)	21	8	61.9
Cathode nozzle diameter (mm)	0.8	0.5	37.5
Anode diameter (mm)	9	7.5	16.7
Anode nozzle diameter (mm)	0.8	0.4	50
Insulator	Teflon	Ceramic	–
Total volume (cm^3)	156	6	96
The widest area (cm^2)	3.85	0.37	90
Electrode system cost ($)	17	1	94

Flow system

N_2

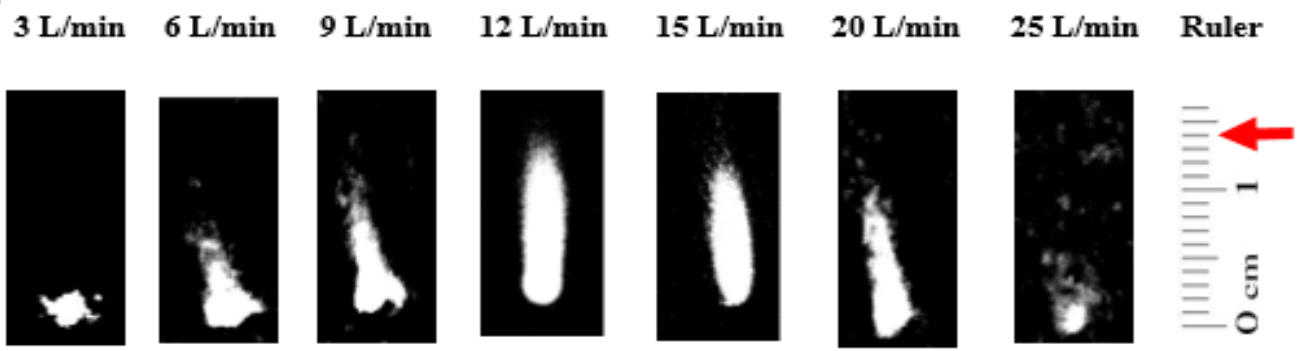


Air



- The flow rate in the range from 3 to 25 L/min.

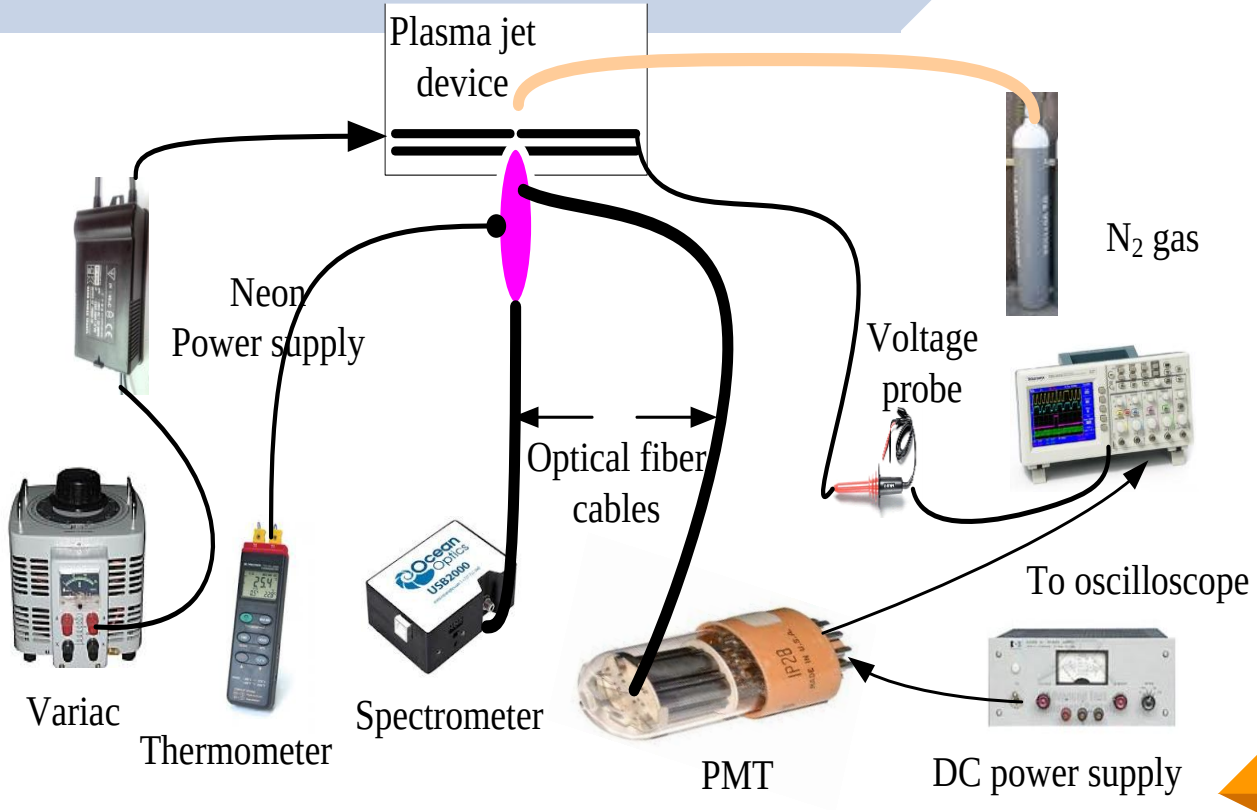
Plasma jet length



Plume length	Previous design	Developed design	Increasing ratio
Air	7 mm	8.2 mm	17.1%
Nitrogen	14 mm	20 mm	42.9%

Diagnostics tools

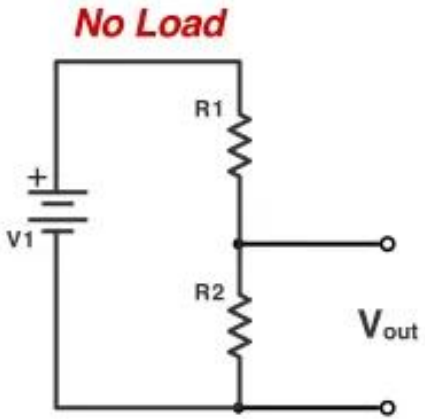
Diagnostic devices



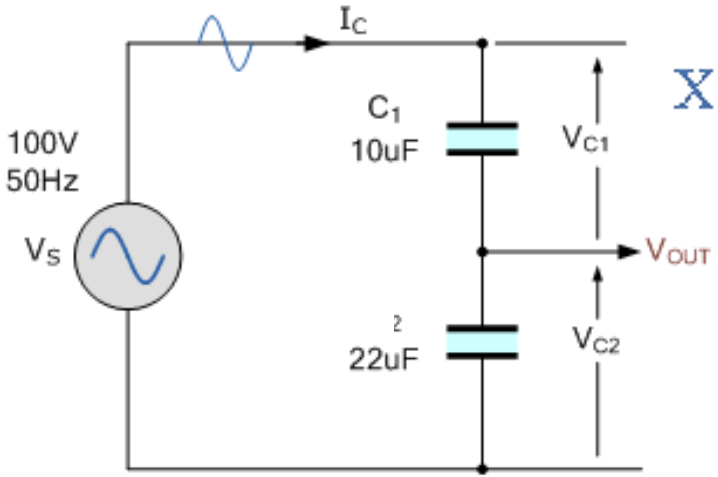
Diagnostics devices

- ✓ Voltage divider
- ✓ Rogowski coil
- ✓ Photomultiplier Tube
- ✓ Optical Emission Spectroscopy
- ✓ Gas and components’ temperature

Voltage divider



$$V_{out} = V_1 \frac{IR_2}{I(R_1 + R_2)} = \frac{V_1 R_2}{(R_1 + R_2)}$$



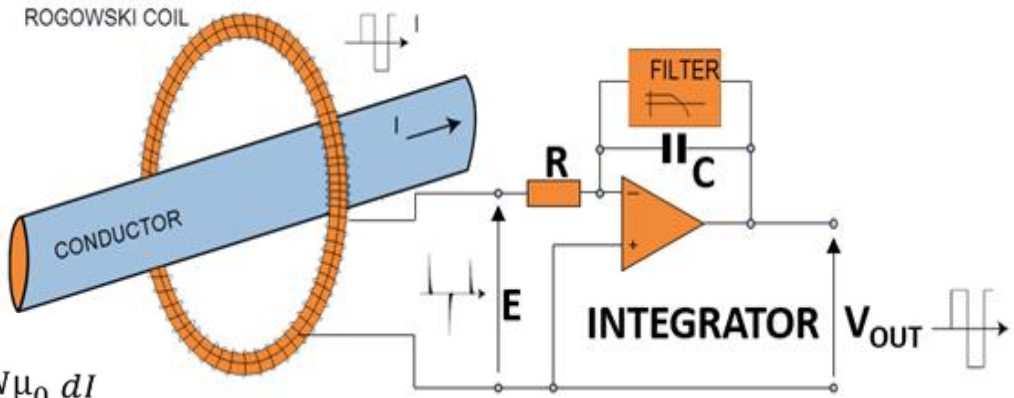
$$X_{C1} = \frac{1}{2\pi f C_1}$$

$$X_{C2} = \frac{1}{2\pi f C_2}$$

$$V_{C2} = V_S \left(\frac{X_{C2}}{X_{CT}} \right)$$

Scale the voltage to be suitable for the measurement device

Rogowski coil



The voltage produced by a Rogowski coil is $V = \frac{-AN\mu_0}{l}\frac{dI}{dt}$

where $A = \pi r^2$ is the area of one of the small loops,

N = is the number of turns,

$l = 2A\pi r$ is the length of the winding (the circumference of the ring),

$\frac{dI}{dt}$ is the rate of change of the current threading the loop ,

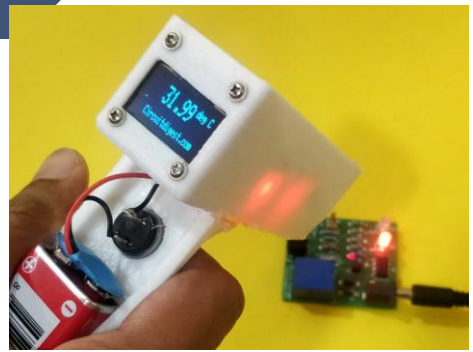
R is the major radius of the toroid, and r is its minor radius.

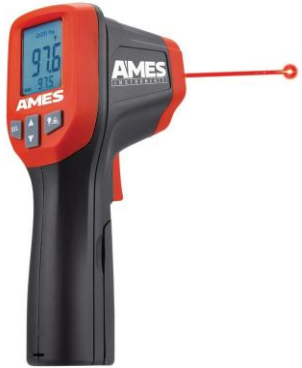
$\mu_0 = 4\pi\ x\ 10^{-7}$ (Magnetic constant) ,

Temperature measurements

Thermometer

- ✓ thermocouple or IR





- ☑ used to measure the gas temperature
- ☑ Thermocouples act as a transducer converting thermal energies into electrical
- ☑ Thermocouples are flexible, inexpensive, and provide fairly accurate temperature measurements.

Outline

1 Introduction

2 Plasma Jet

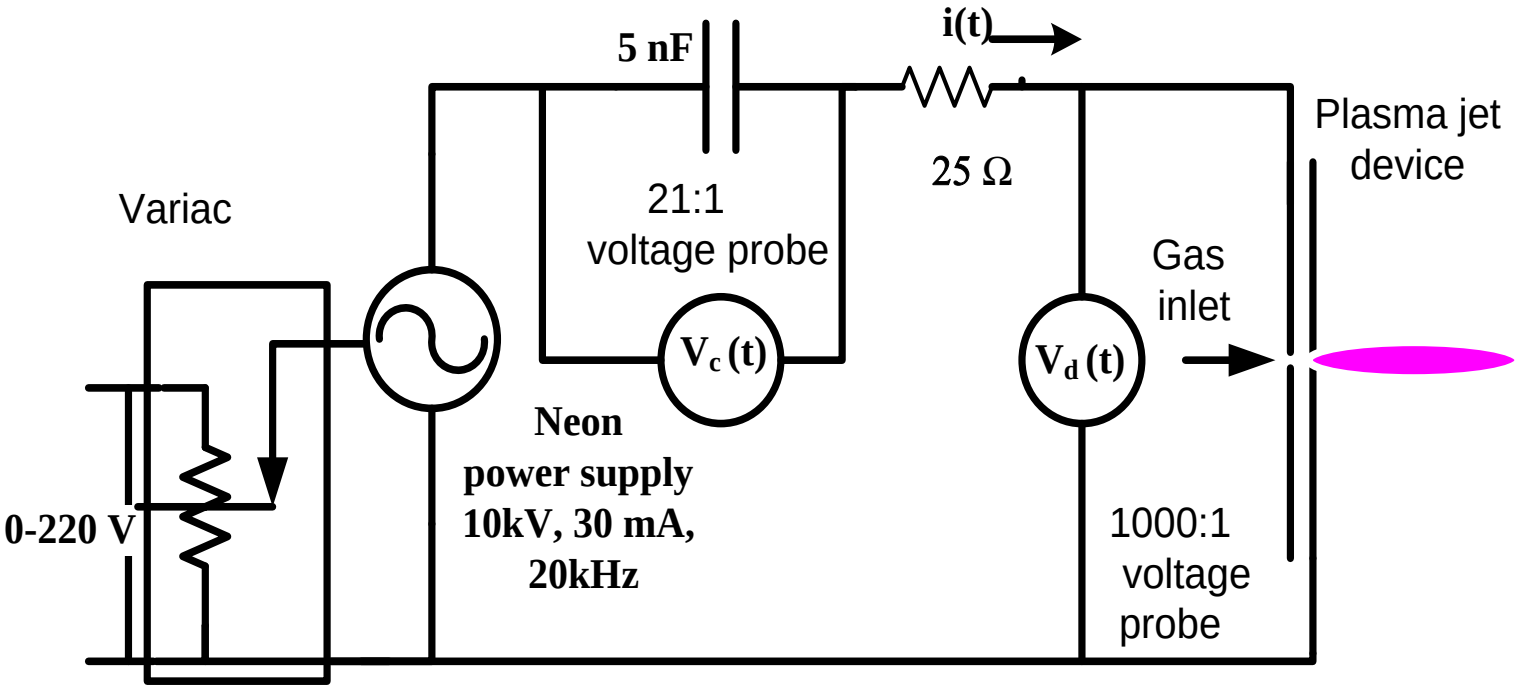
3 Measurements

4 Plasma Applications

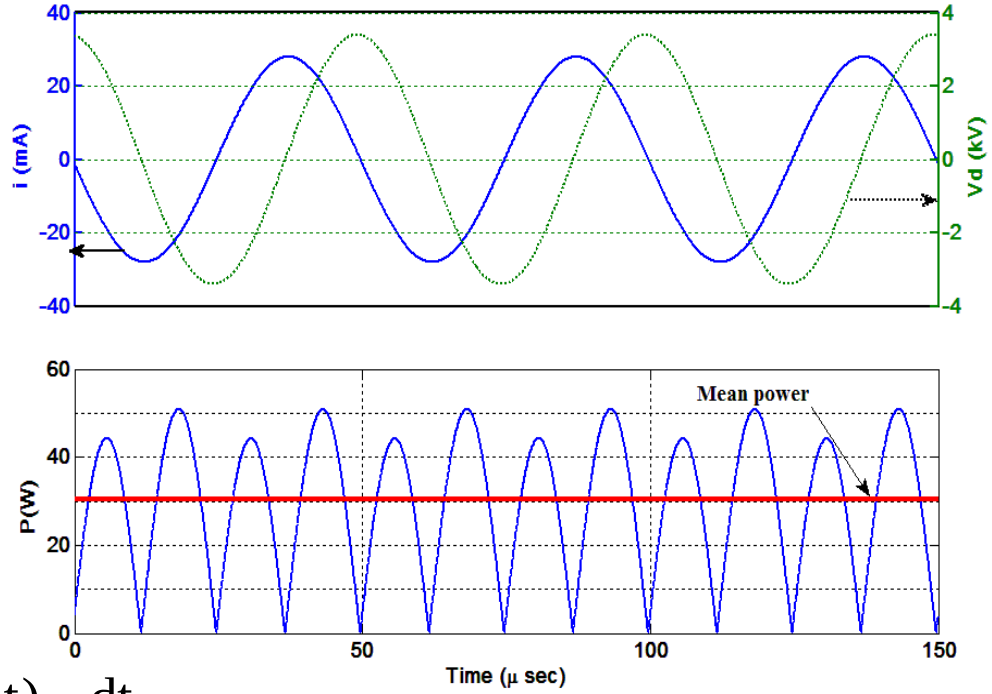
Electrical measurements

Current, voltage and power measurements

Electric circuit



Electrical Ch/s

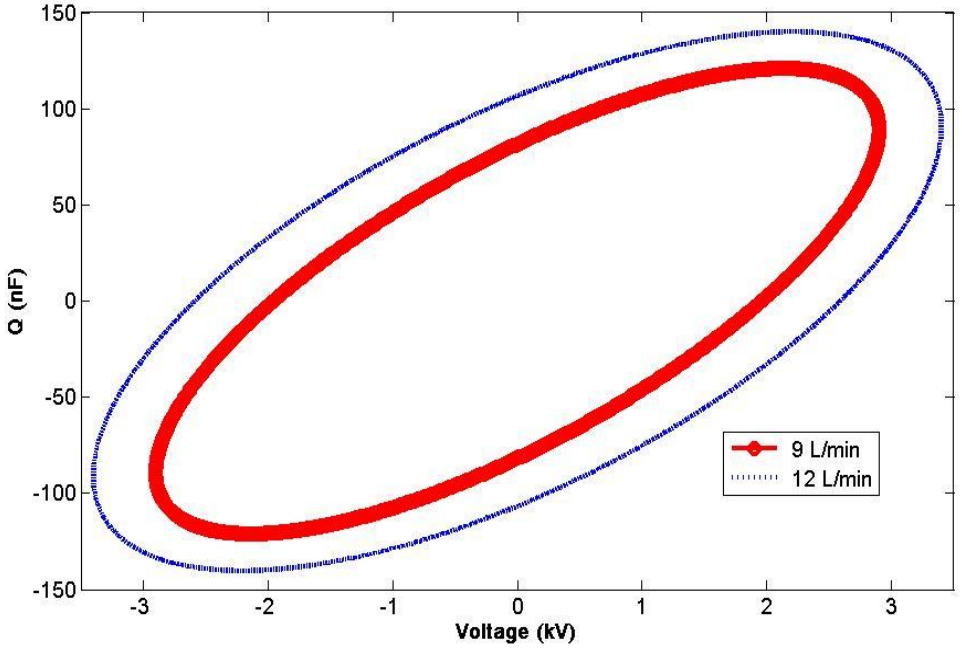


$$P = \frac{1}{T} \int i(t) \quad V_d(t) \quad dt$$

Electric Ch/cs Lissajous figure Method

$$u_C(t) = 1/C \int_{t_1}^{t_2} i(t)dt = Q(t)/C.$$

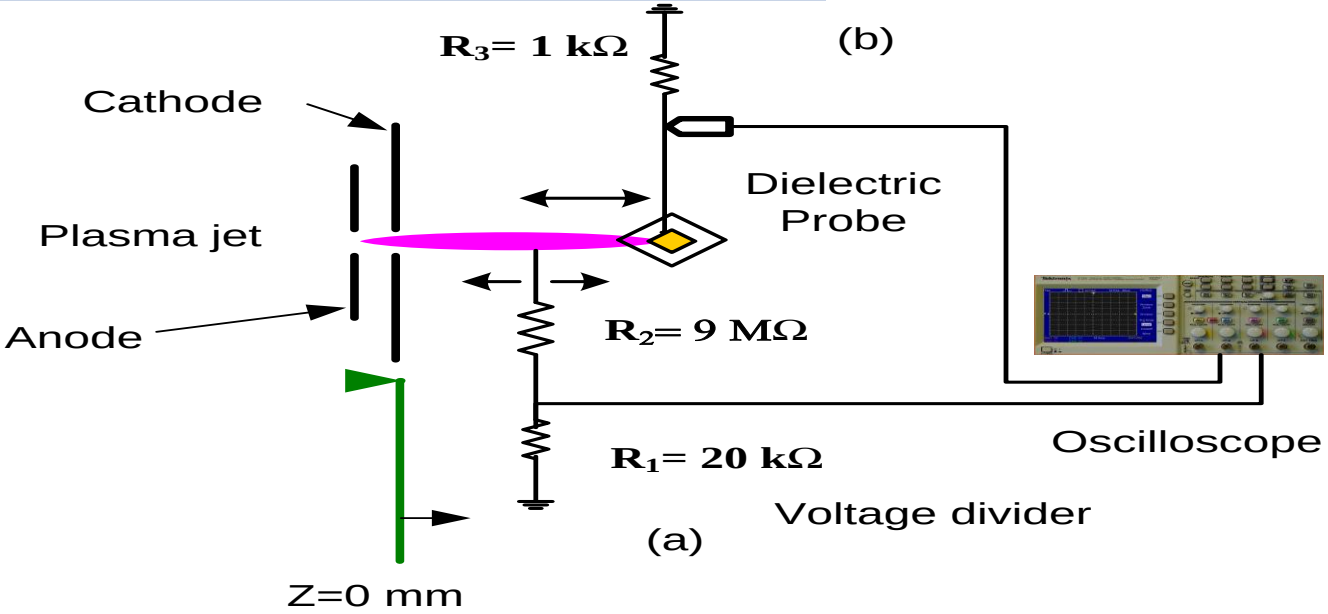
Charge



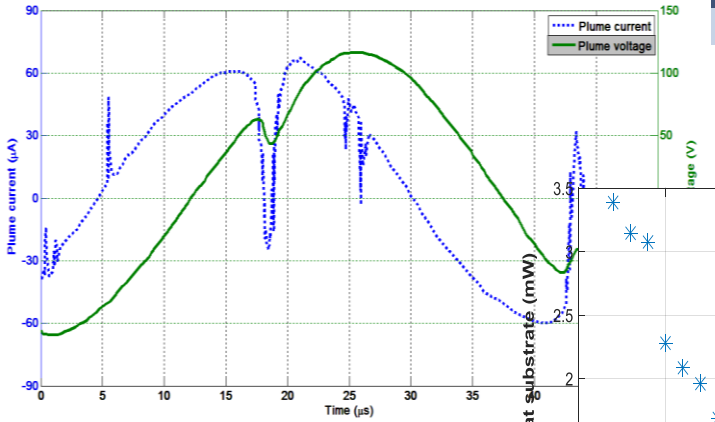
$$P = \frac{1}{T} \int V_d(t) \quad dQ$$

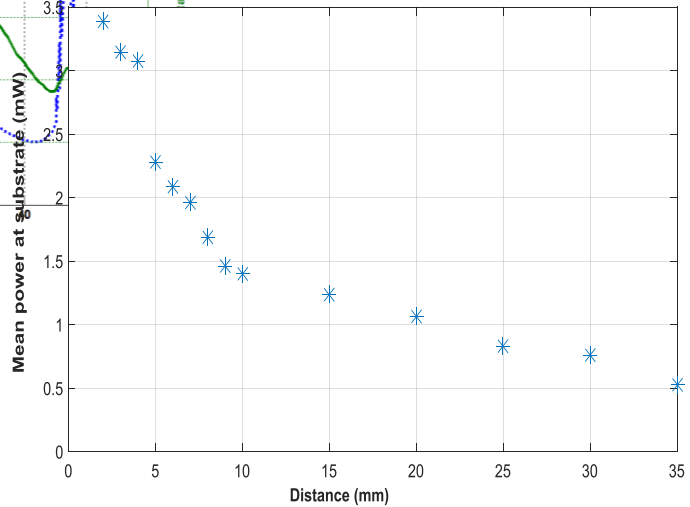
Discharge voltage

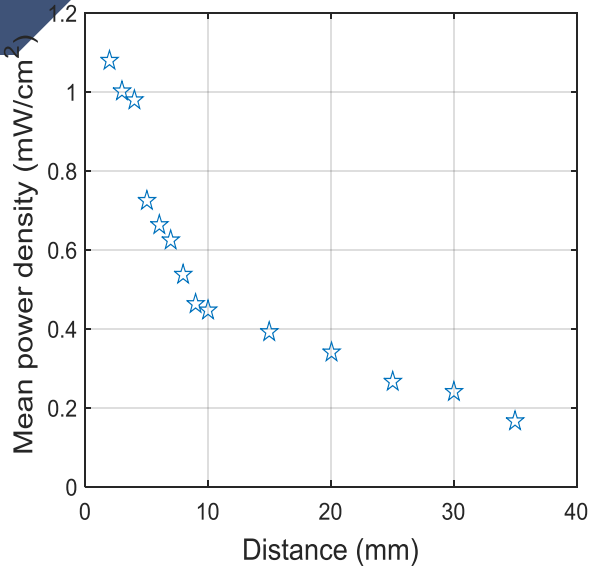
Plume electrical measurements



Plume electrical measurements







A safely plasma dose is generated from the plasma jet device even when the exposure time is relatively long (220h).

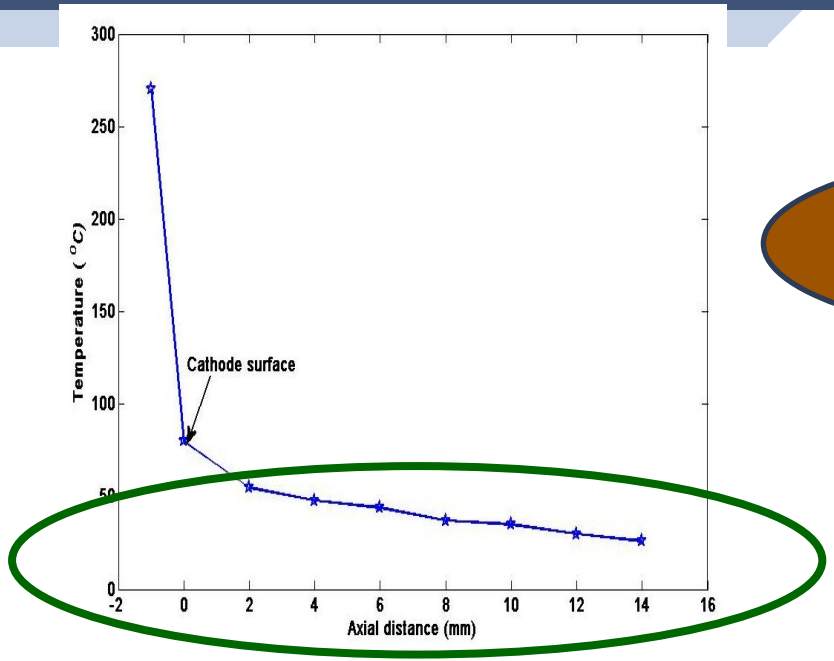
Plasma power density equals 0.17 mW/cm^2 << 135 J/cm^2

Temperature measurements

Gas and electron temperature measurements

Gas temperature

Gas T



<50 °C

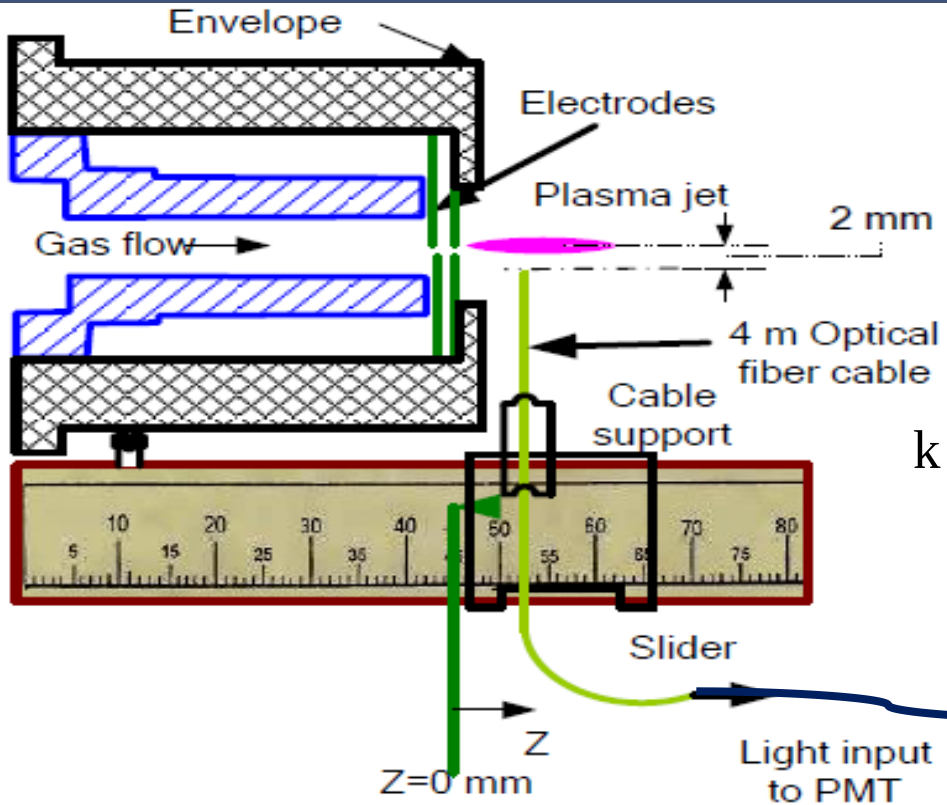
✓ Cold plasma

For heat- sensitive treatments

Polymer & biomedical

Axial distance

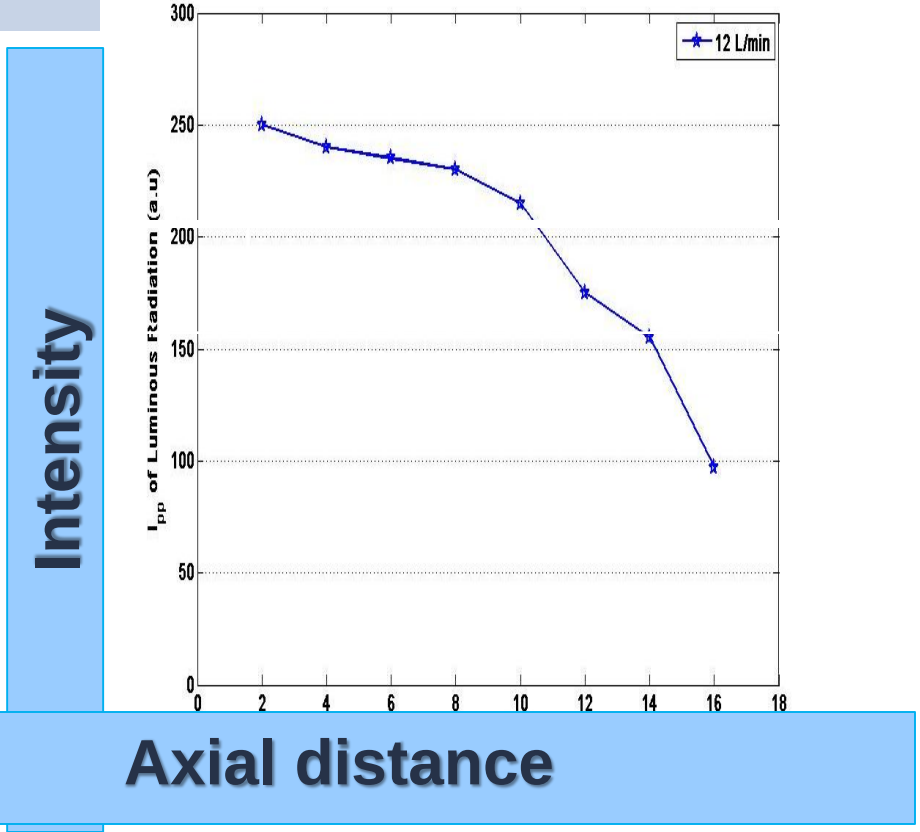
Spectroscopy- photomultiplier



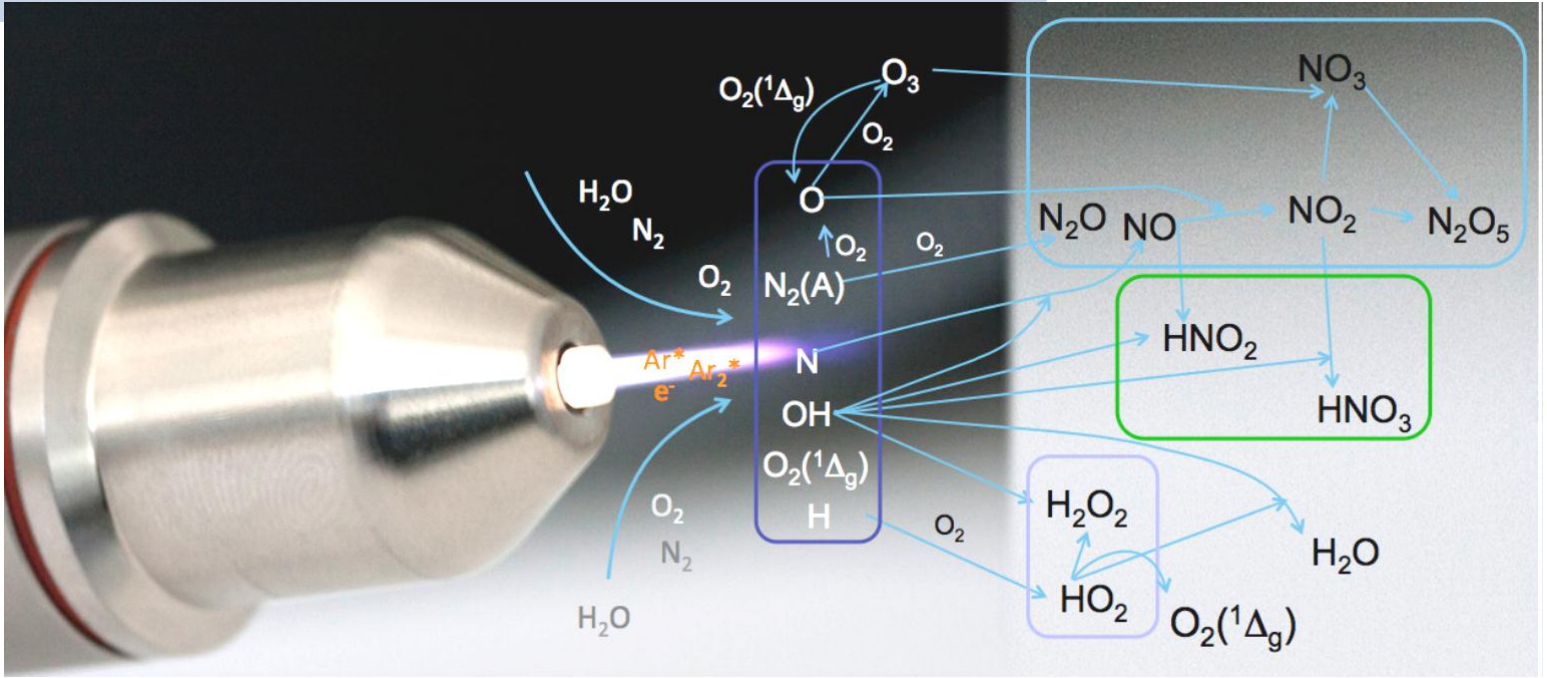
$$k\ T_{exc} = \frac{(E_1 - E_2)}{\ln\left(\frac{g_2 A_2\ \lambda_1 I_1}{g_1 A_1 \lambda_2 I_2}\right)} \quad \text{in} \quad eV$$

Plume intensity

N_2



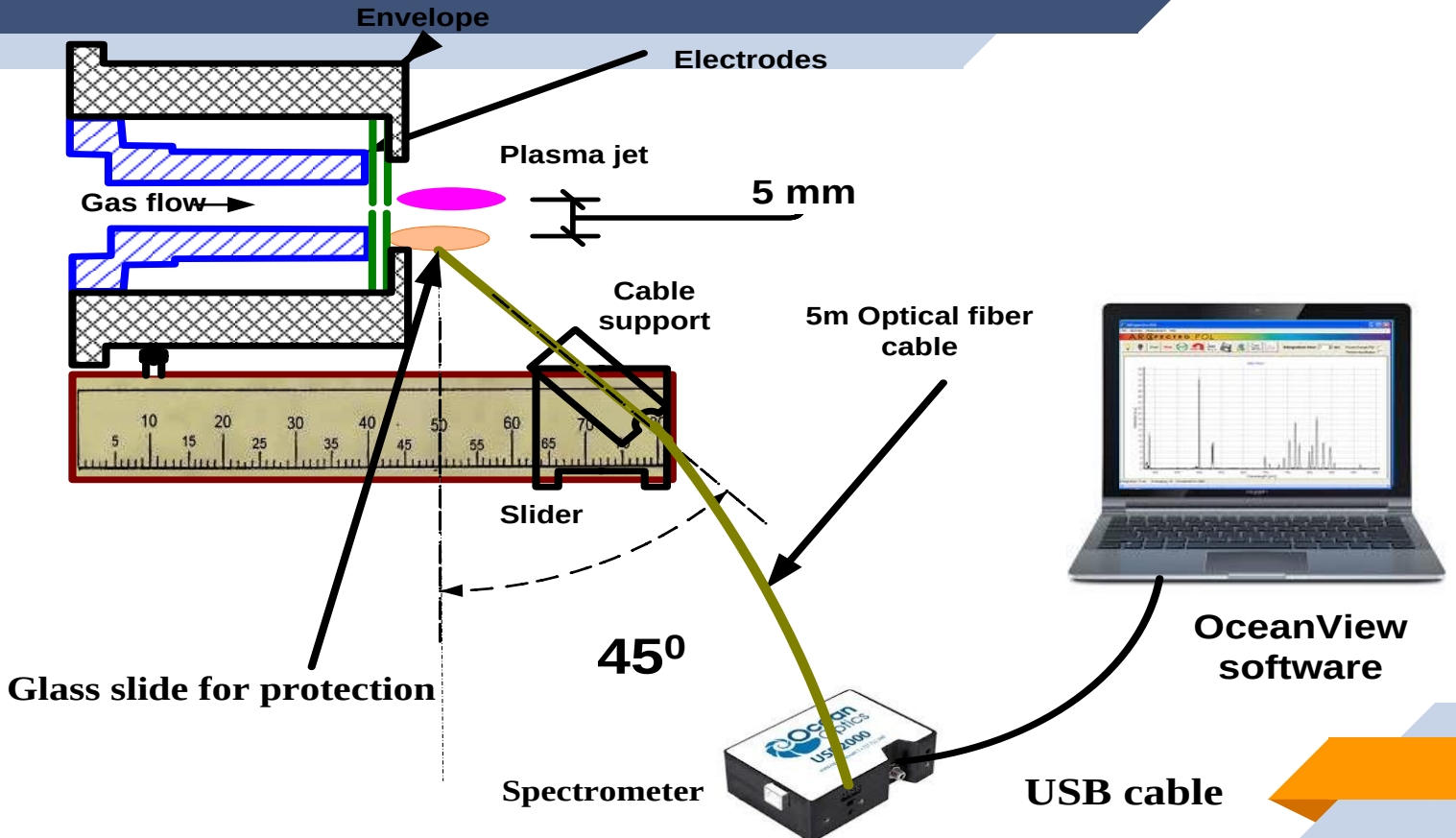
Species emission from plasma jet



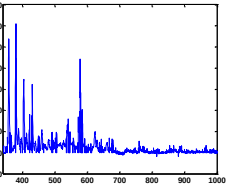
- ✓ **Ozone**
- ✓ **NO**
- ✓ **OH**

Stephan Reuter, J. Phys. D: Appl. Phys. 51 (2018) 233001

Spectroscopy- Spectrometer



Excitation Electron Temperature (Algorithm for spectrometer)



Output Data from Spectrometer

Data Acquistion

System Equalization

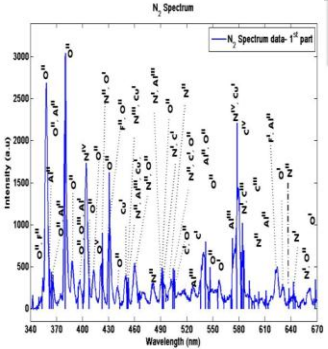
Background Subtraction

Temperature Estimation

Peak Detection

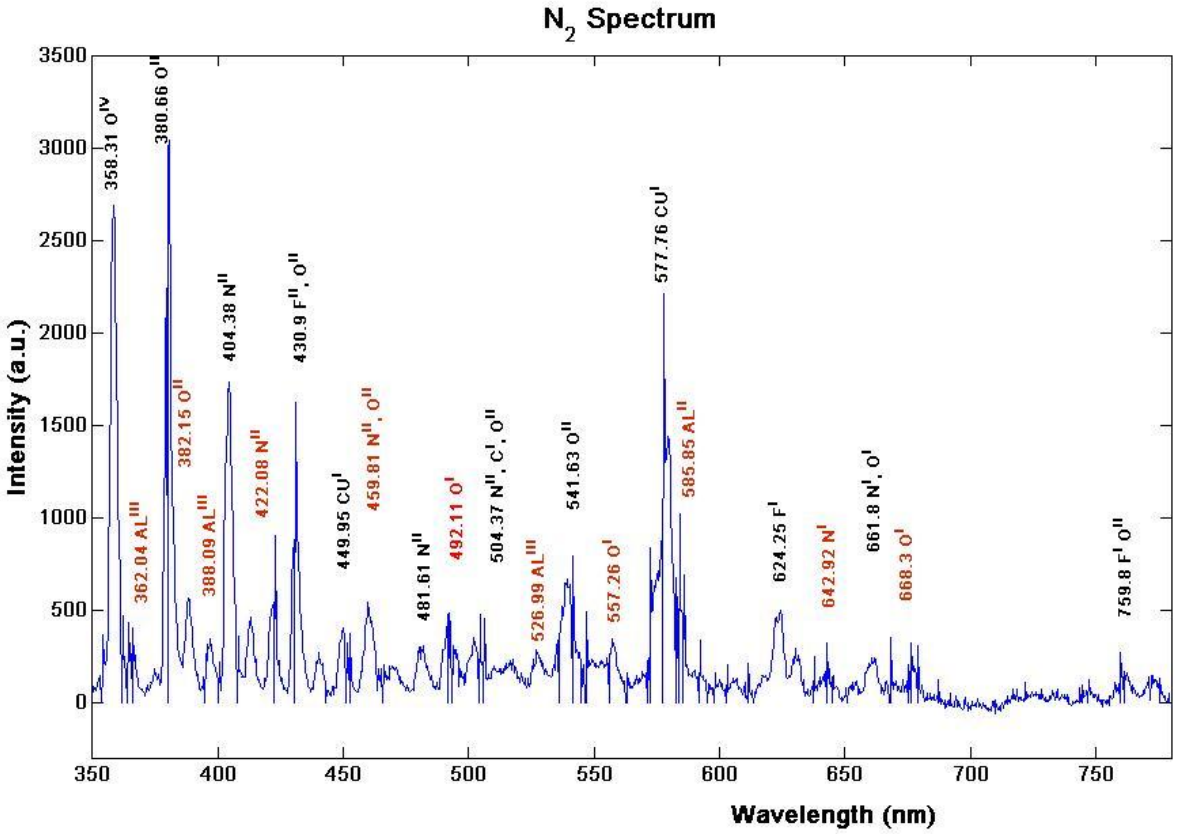
Peak Modeling

Peak Identification



$$kT_{exc} \ \alpha - \frac{E_k}{\ln\left(\frac{I\ \lambda}{A_{ki} g_k}\right)}$$

Spectrum



https://www.nist.gov/

Electron vs gas temperature

11680

T_e

~ 1 eV

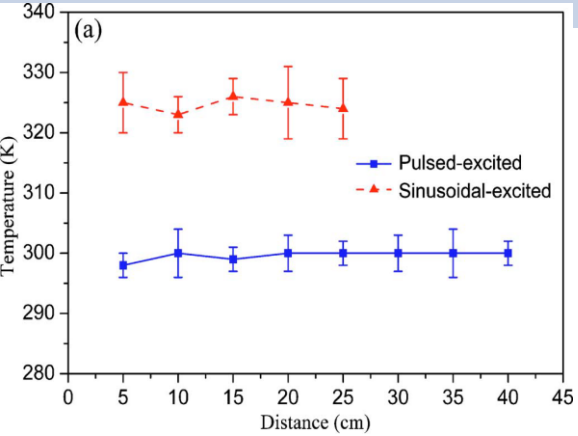
<400 K

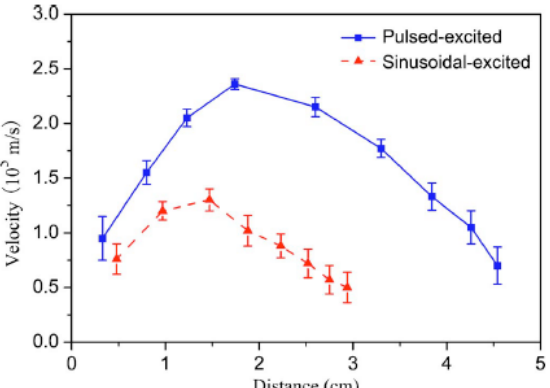
T_{gas}

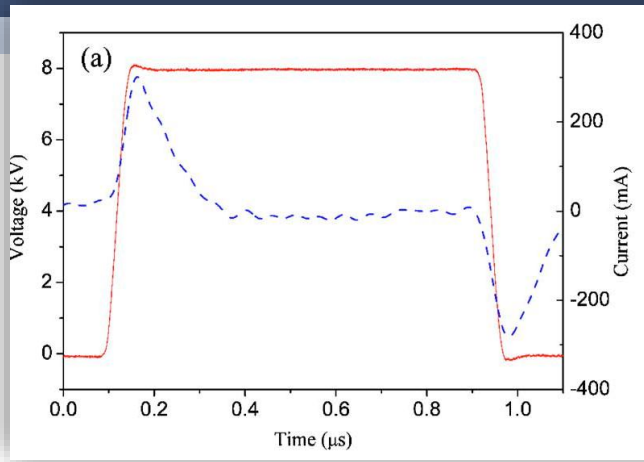
$T_{gas} << T_e$

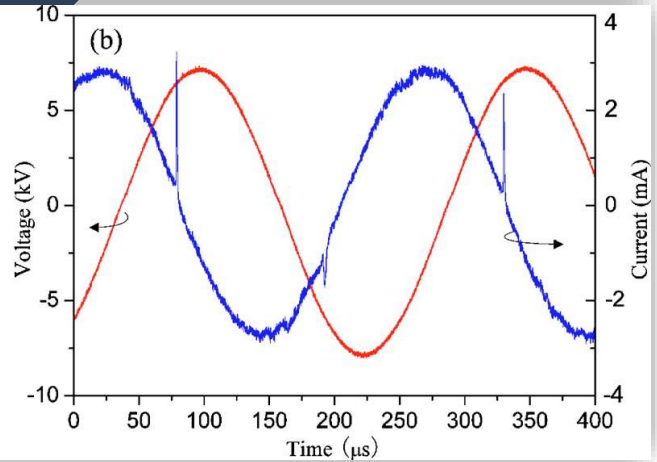
✓ **Cold plasma**

Sine vs pulsed wave comparison









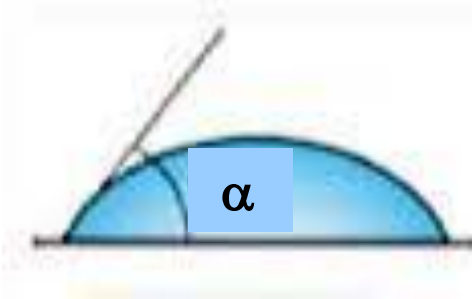
Advantages of pulsed

- ✓ Less temperature
- ✓ Higher velocity
- ✓ Less energy consumption

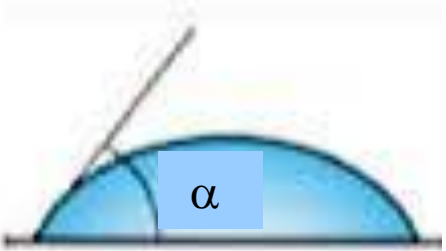
Xiong et al., PHYSICS OF PLASMAS 17, 043506 (2010)

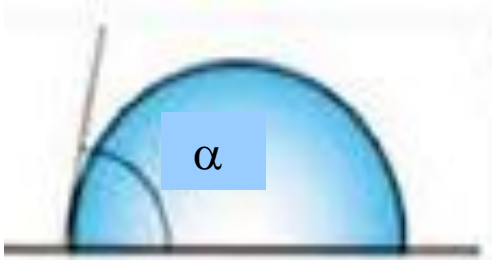
Wettability

Contact angle measurements

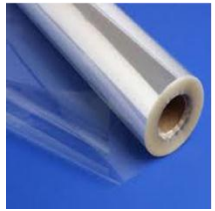


Contact angle & wettability





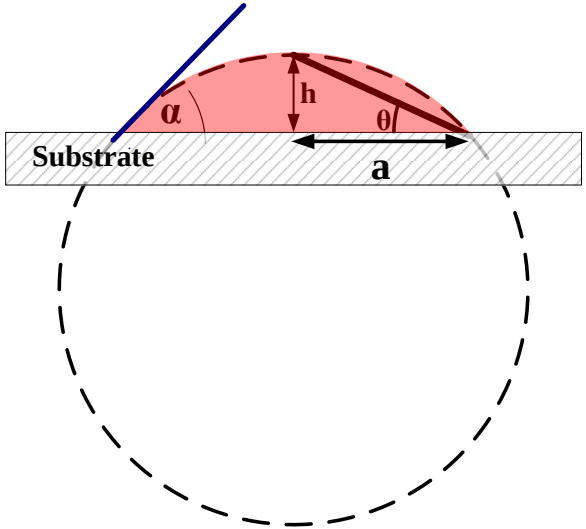
Smaller	Contact angle	Larger
Better	Wettability	Worse
Better	adhesiveness	Worse



Contact angle Measurements spherical cap approach

$$\theta = \tan^{-1}\left(\frac{h}{a}\right) ;$$

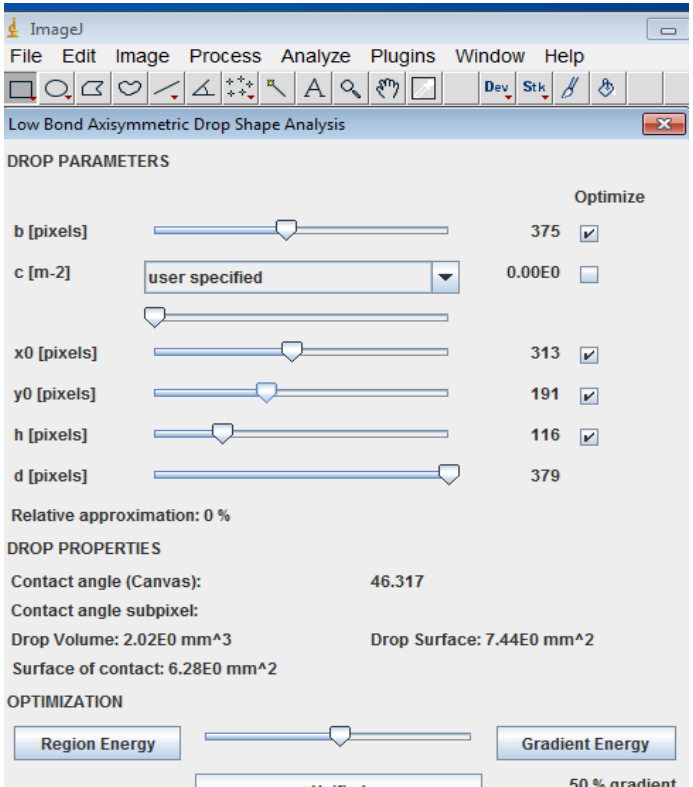
$$\alpha = 2\ \theta$$



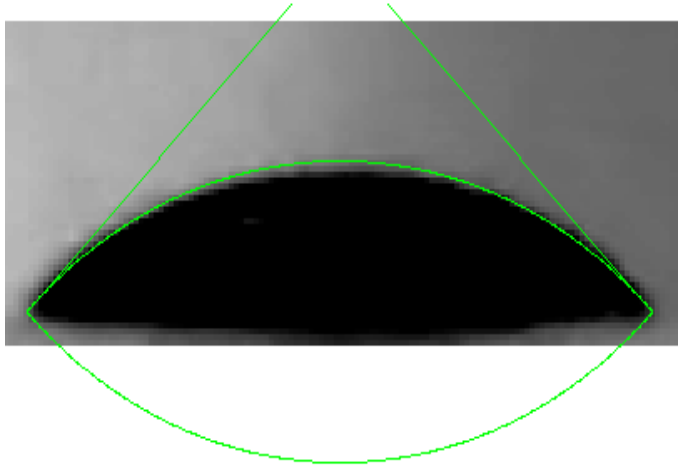
$$V = \frac{\pi}{6} h\ (h^2 + 3a^2)$$

- V is known , a is computed, h is calculated
- Contact angle is measured

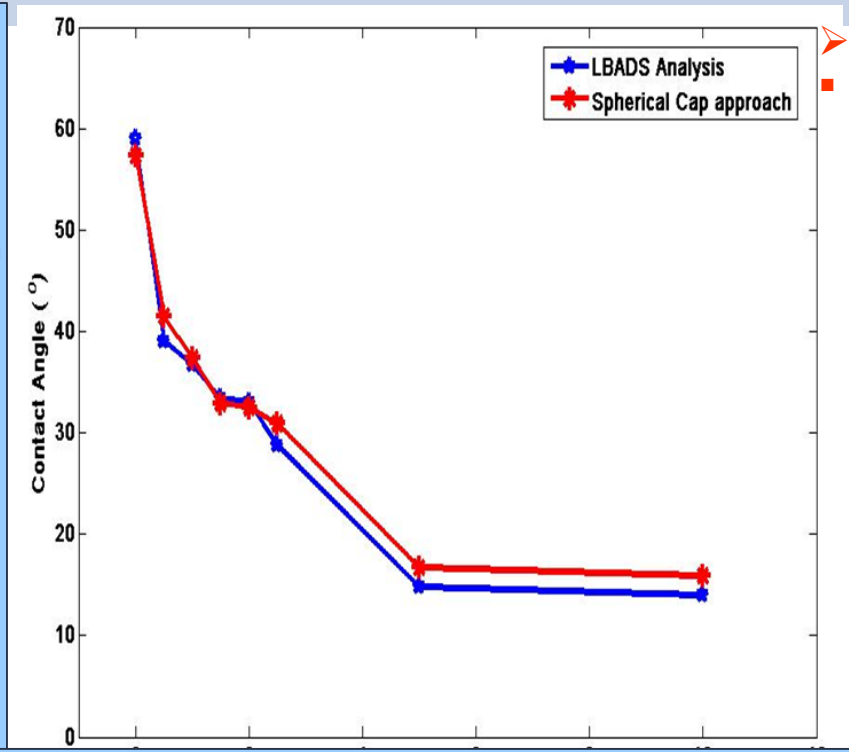
Contact angle Measurements
LBADS approach



ImageJ



Contact angle



Contact angle

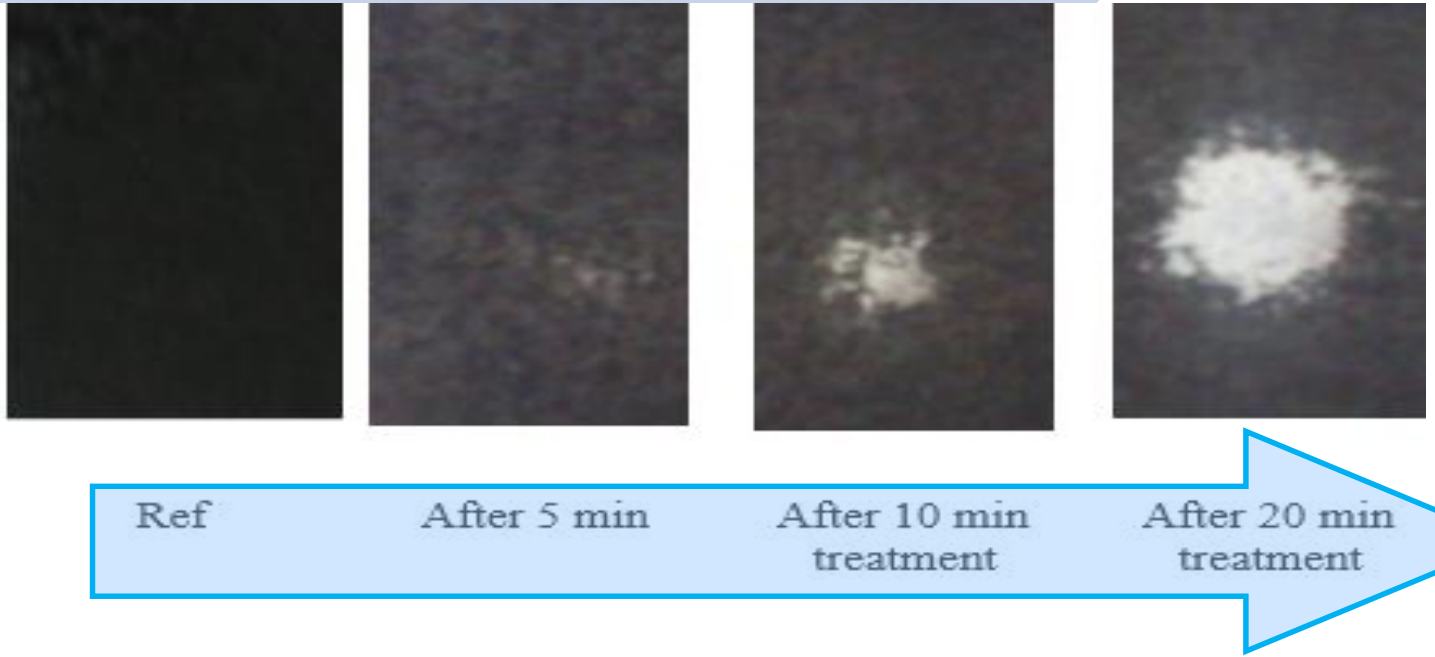
Treatment time

- **Wettability improvement of Mylar substrate**
  - **by measuring contact angle (spherical cap, LBADS)**

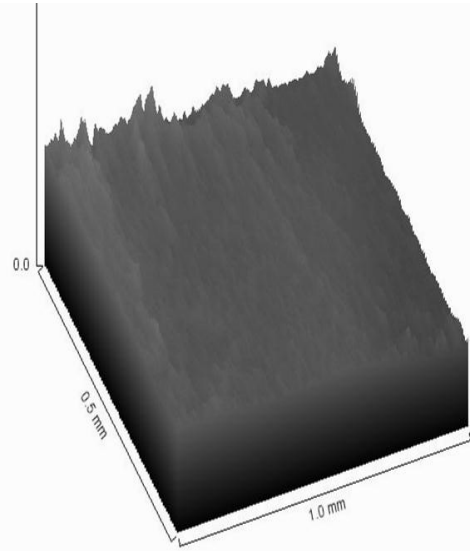
N_2

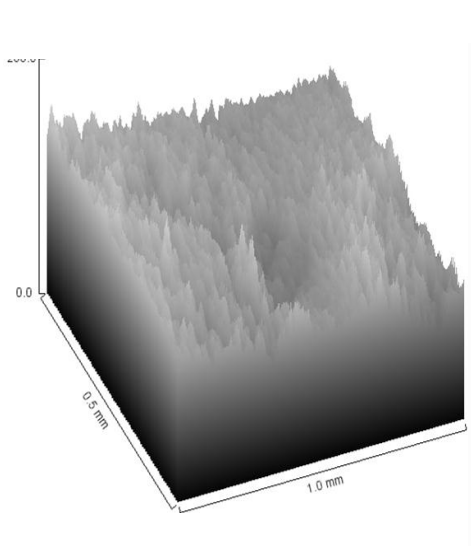
59 14

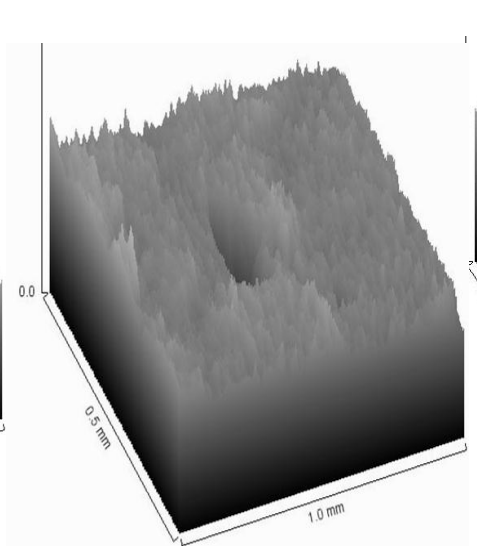
Ink removal

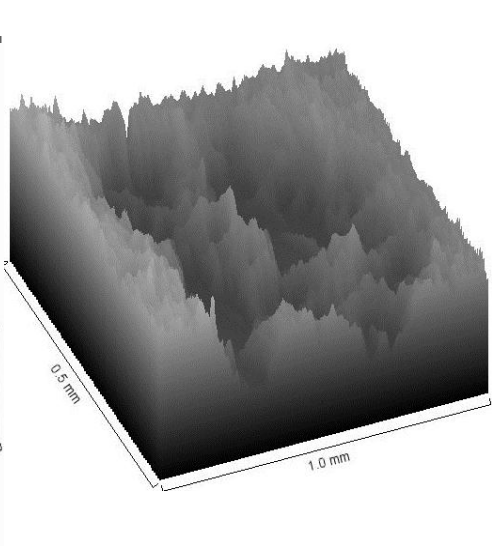

Ref
After 5 min
After 10 min treatment
After 20 min treatment

Ink removal

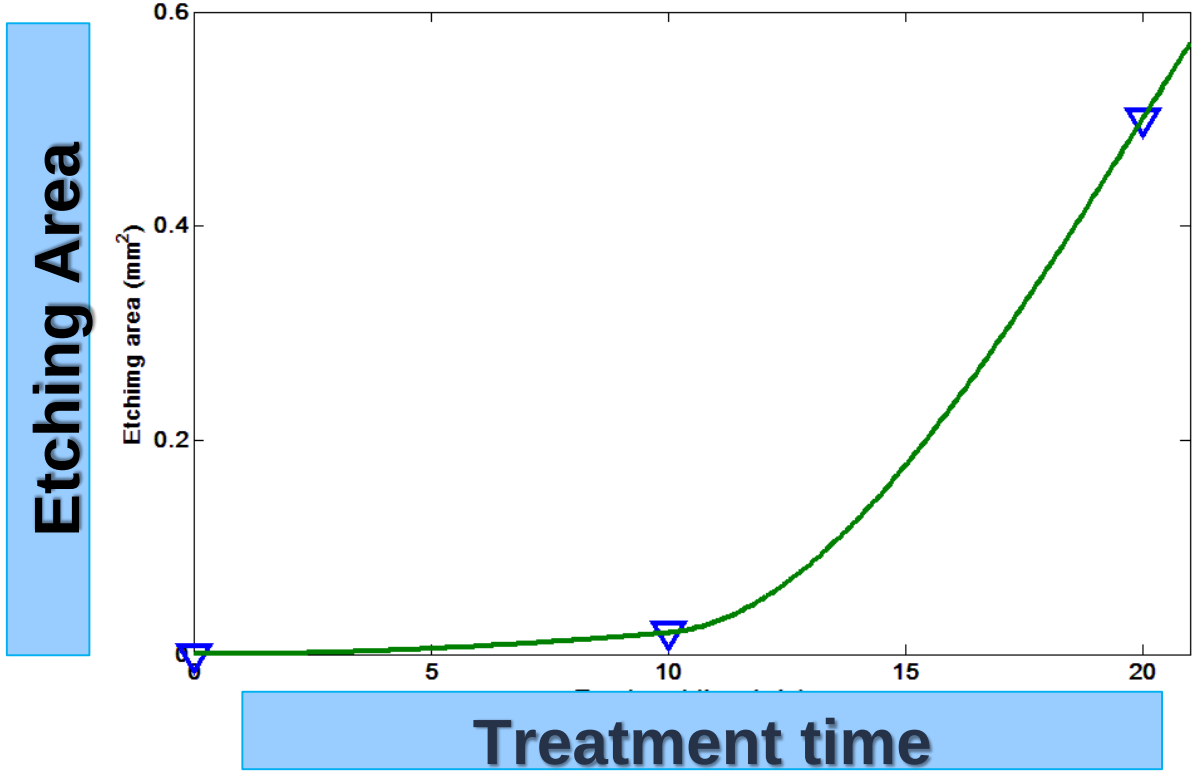


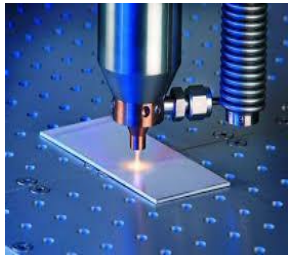


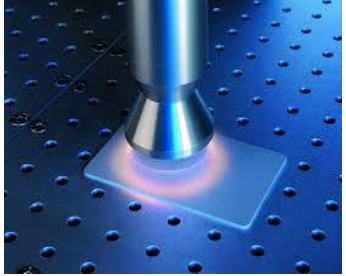




Etching area



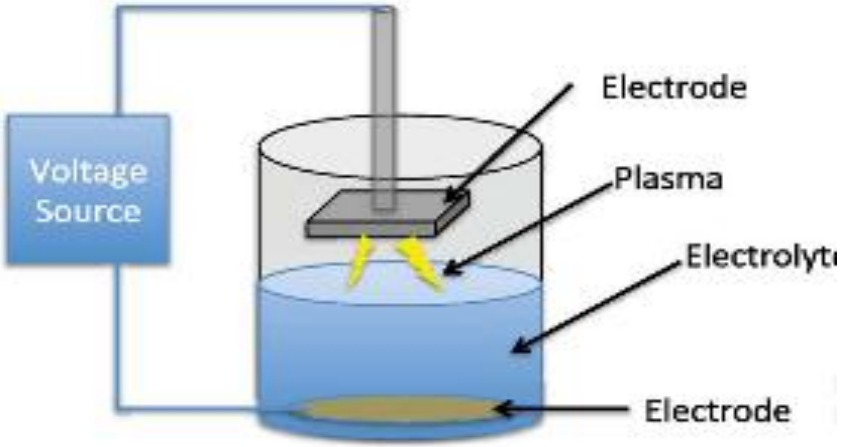


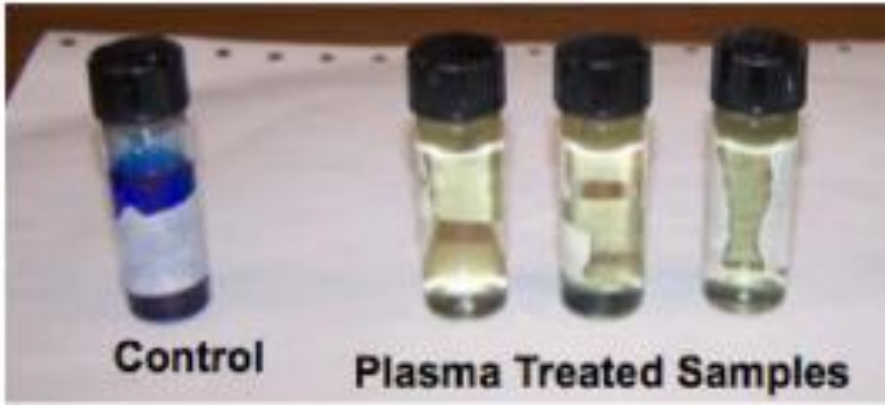


Plasma applications

- Water treatment
- Plasma chemical removal of corrosion
- Surface/Polymer treatment
- Bacterial inactivation/ Wound healing
- **In dentistry**
- Antimicrobial treatment of foods
- In Agriculture

Water treatment





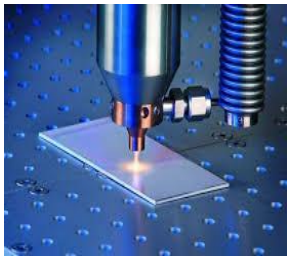
https://ieeexplore.ieee.org/document/6184321/figures#figures

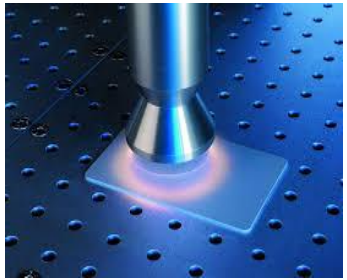
Plasma chemical removal of corrosion

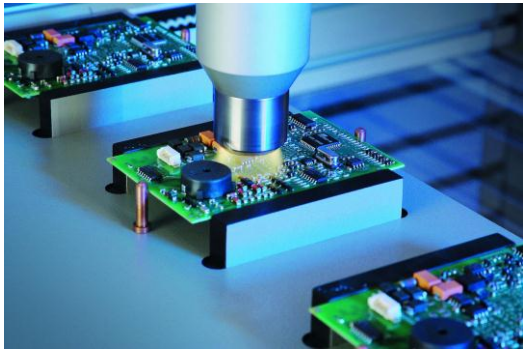
Before treatment

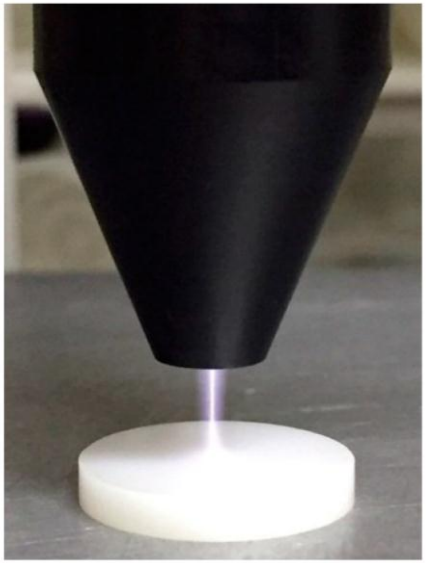
After treatment

Surface treatment



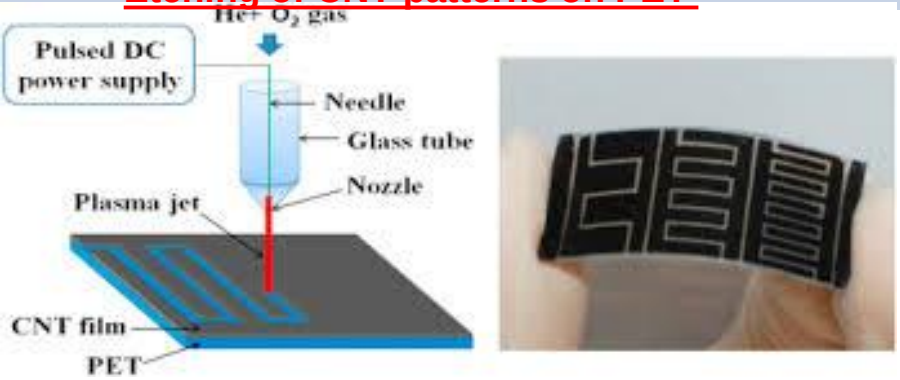




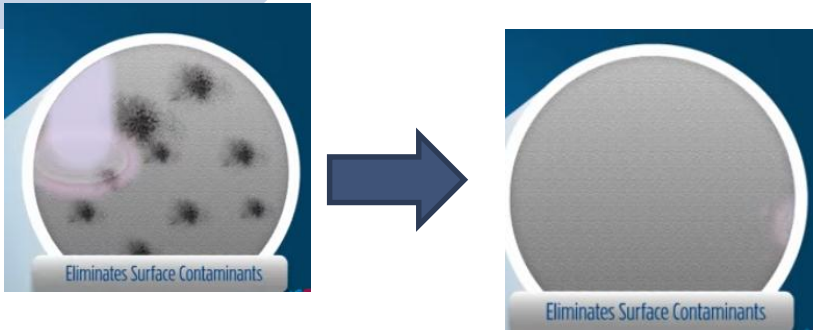


Polymer treatment

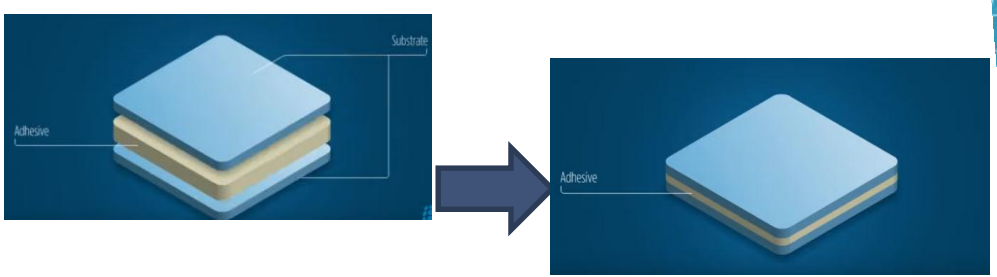
Etching of CNT patterns on PET

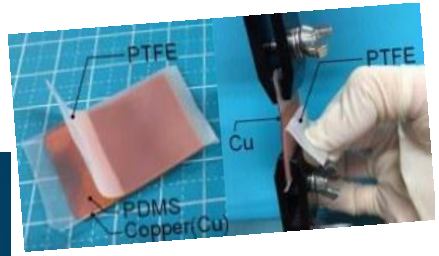


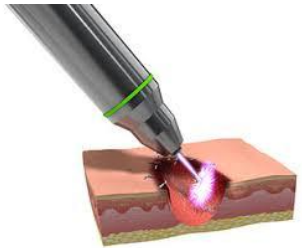
Cleaning



Increasing the adhesive process

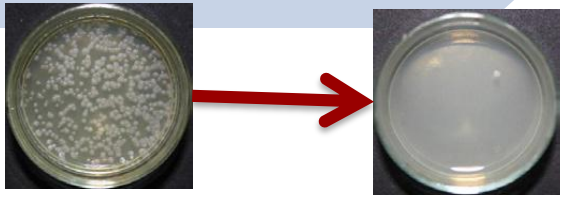


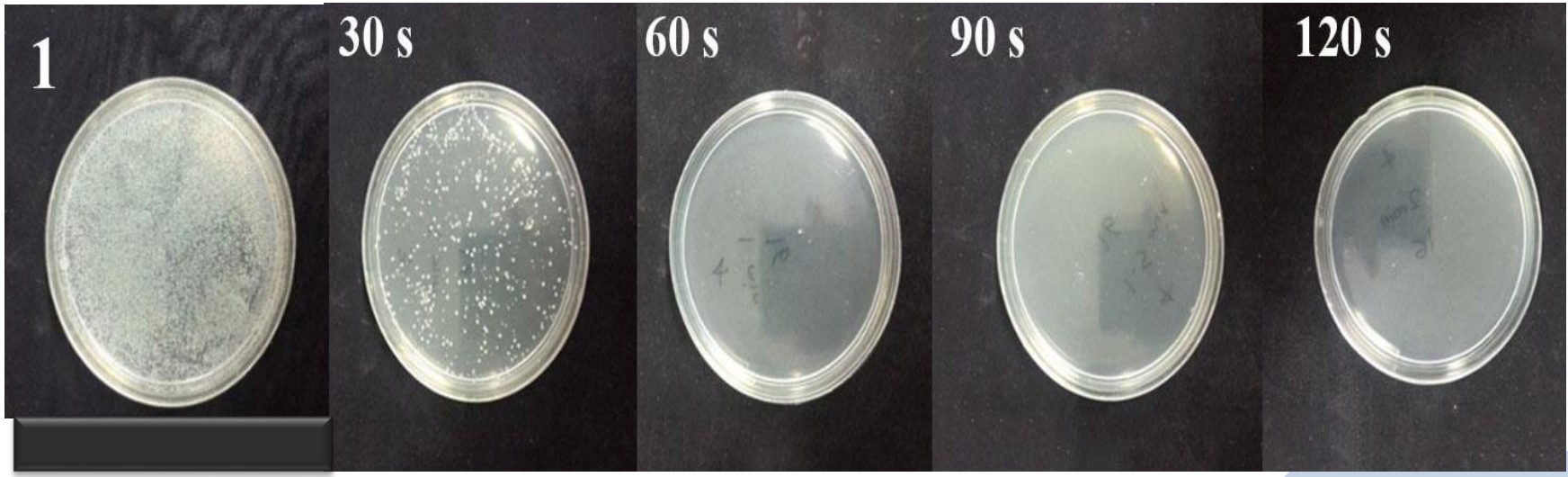




https://www.sciencedirect.com/science/article/abs/pii/S0008622316307977

Bacterial inactivation



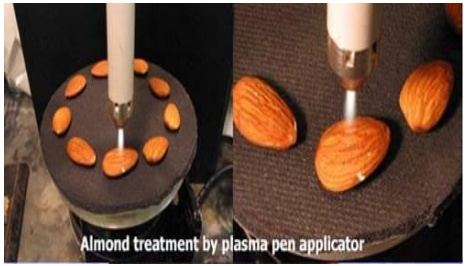


Wound healing

In dentistry

https://physicsworld.com/a/plasmas-are-cool-for-dental-disinfectio

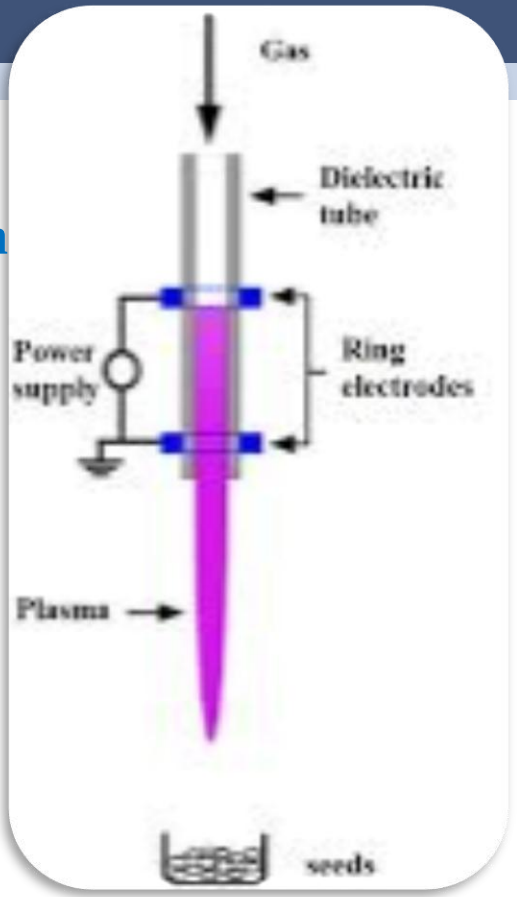
Antimicrobial treatment of foods



Control

In Agriculture

- Increase rooting speed
- Reduce water consumption
- Enhance seed germination
- Stimulate plant growth
- Prevent pests



Useful Software/Article resources

Article resources

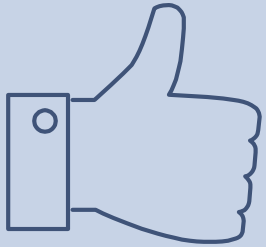
- http://gen.lib.rus.ec/
- EKB بنك المعرفة المصري
- Researchgate
- Sci-hub.tw
- Facebook groups
  - https://www.facebook.com/groups/ResearchPaperThesisArticlesandBooks/
  - https://www.facebook.com/groups/paperreqest/
  - https://www.facebook.com/groups/ScientificPapers/
  - https://www.facebook.com/groups/literaturefree/

Useful Software

- ✓ MATLAB
- ✓ ORIGIN
- ✓ ENGAUGE DIGITIZER
- ✓ IMAGEJ

For Latex beginner's
https://www.overleaf.com

THANKS!



Any questions?

You can find me at

Kamal_hagag@yahoo.com

https://www.facebook.com/kamal.abdelaziz

01094146069