Introduction to plasma theory and demonstration
電漿基礎理論與實作

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2023 summer break

8/28(Mon.) – 9/1(Fri.) 14:00-17:40

Except: 8/29(Tue.) 13:30-17:10

Lecture 2

https://capst.ncku.edu.tw/PGS/index.php/teaching/

https://nckucc.webex.com/nckucc/j.php?MTID=mb9ccf65ba2c981ce1f0f02ea60e1dbf2

開放式教育平台：

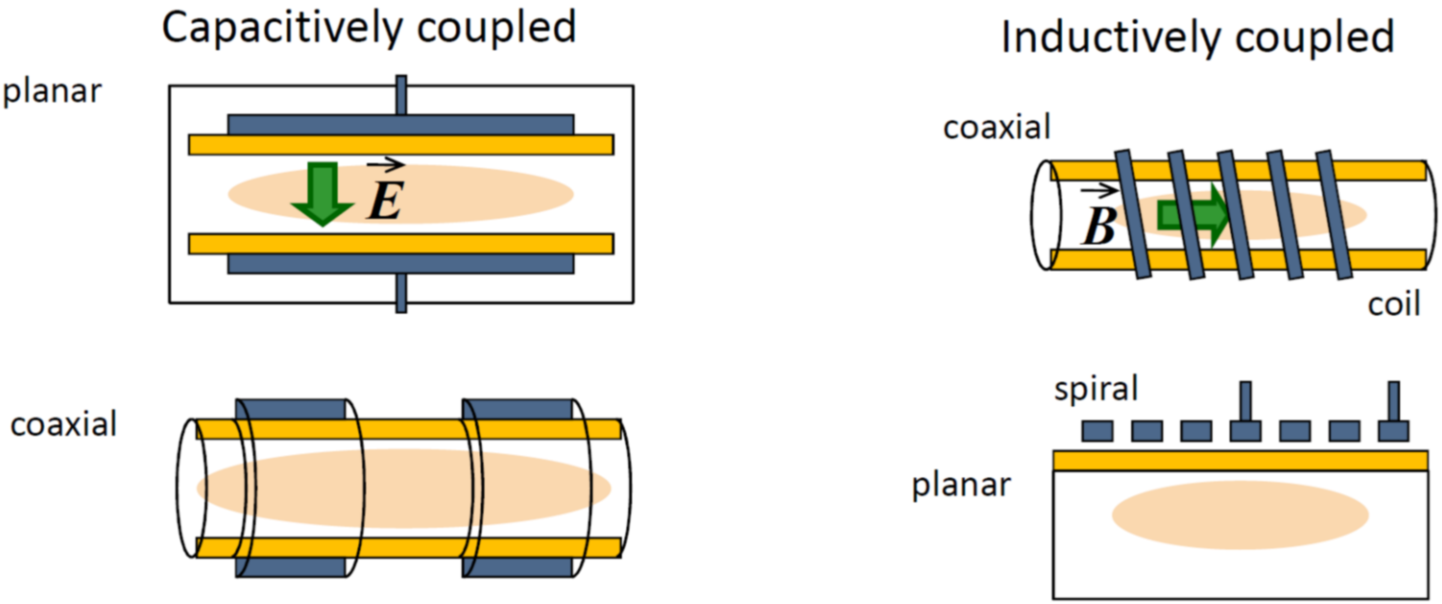
https://i-ocw.ctld.ncku.edu.tw/site/course_content/FTqT2RS1h7j

2023/8/28 updated

Methods of plasma production

- DC electrical discharges
  - Dark electrical discharges in gases
  - DC electrical glow discharges in gases
  - DC electrical arc discharges in gases
- **AC electrical discharges**
  - **RF electrical discharges in gases**
  - **Microwave electrical discharges in gases**
  - **Dielectric-barrier discharges (DBDs)**
- Other mechanism
  - Laser produced plasma
  - Pulsed-power generated plasma

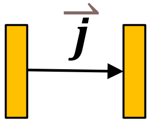
RF can interact with plasma inductively or capacitively



- **DC electrical discharge – a true current in the form of a flow of ions or electrons to the electrodes.**
- **AC electrical discharge – the power supply interacts with the plasma by displacement current.**

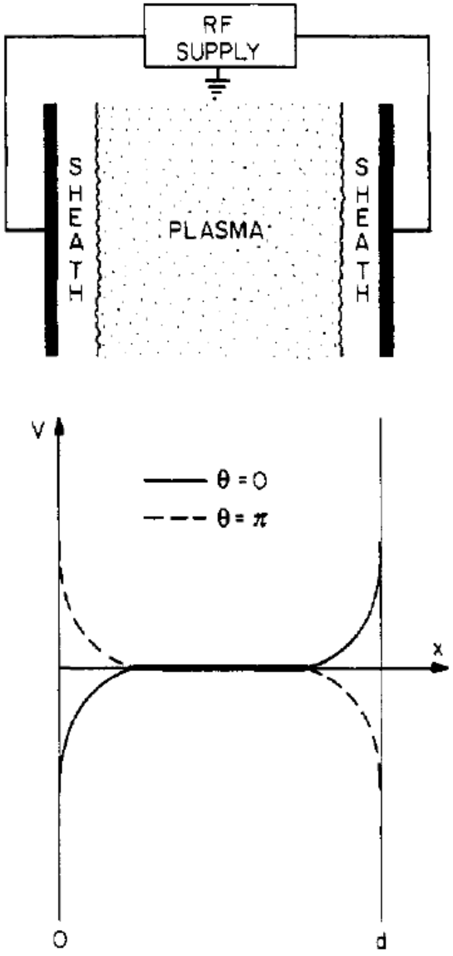
$$\nabla \times \vec{B} = \mu_o \vec{j} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

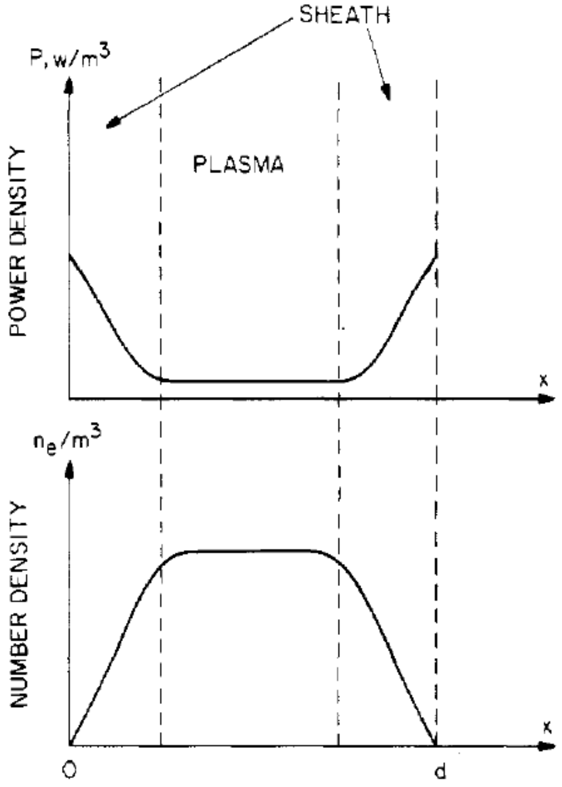
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$



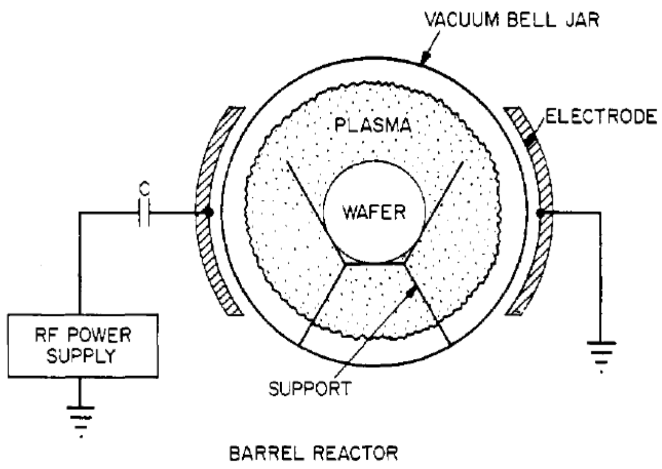
$$\left(\frac{\partial \vec{E}}{\partial t}, \frac{\partial \vec{B}}{\partial t}\right)$$

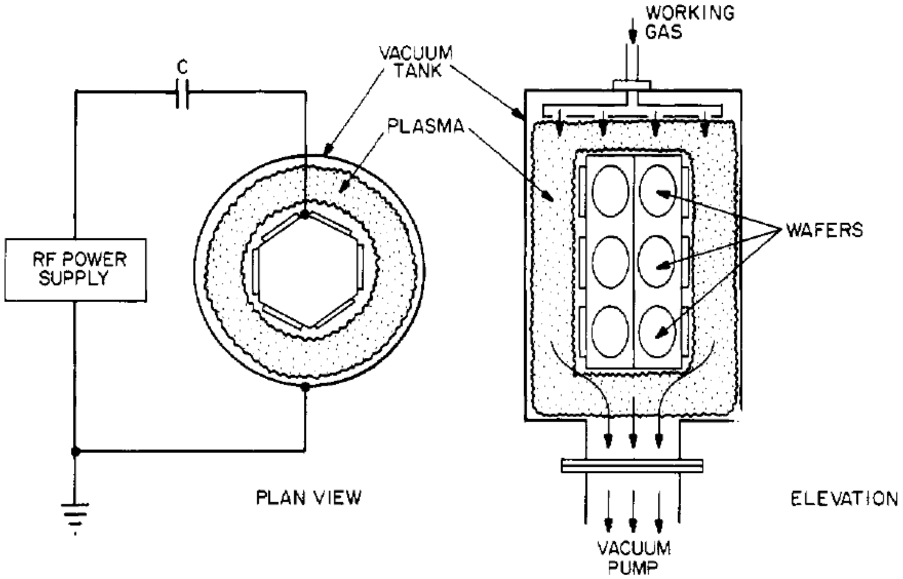
Symmetrical capacitive RF discharge model





Example of capacitively coupled RF plasma source 1



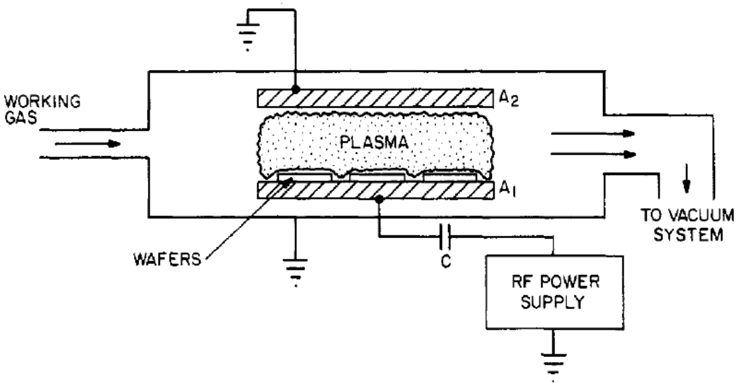


- Barrier reactor – the wafers float electrically and have low ion bombardment energies

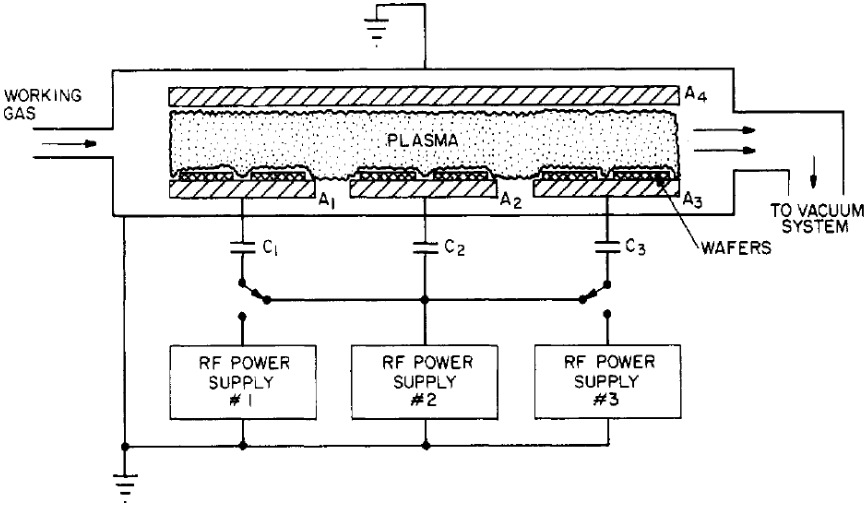
- Hexagonal reactor – the wafers develop a DC bias which leads to a relatively anisotropic, vertical etch.

Example of capacitively coupled RF plasma source 2

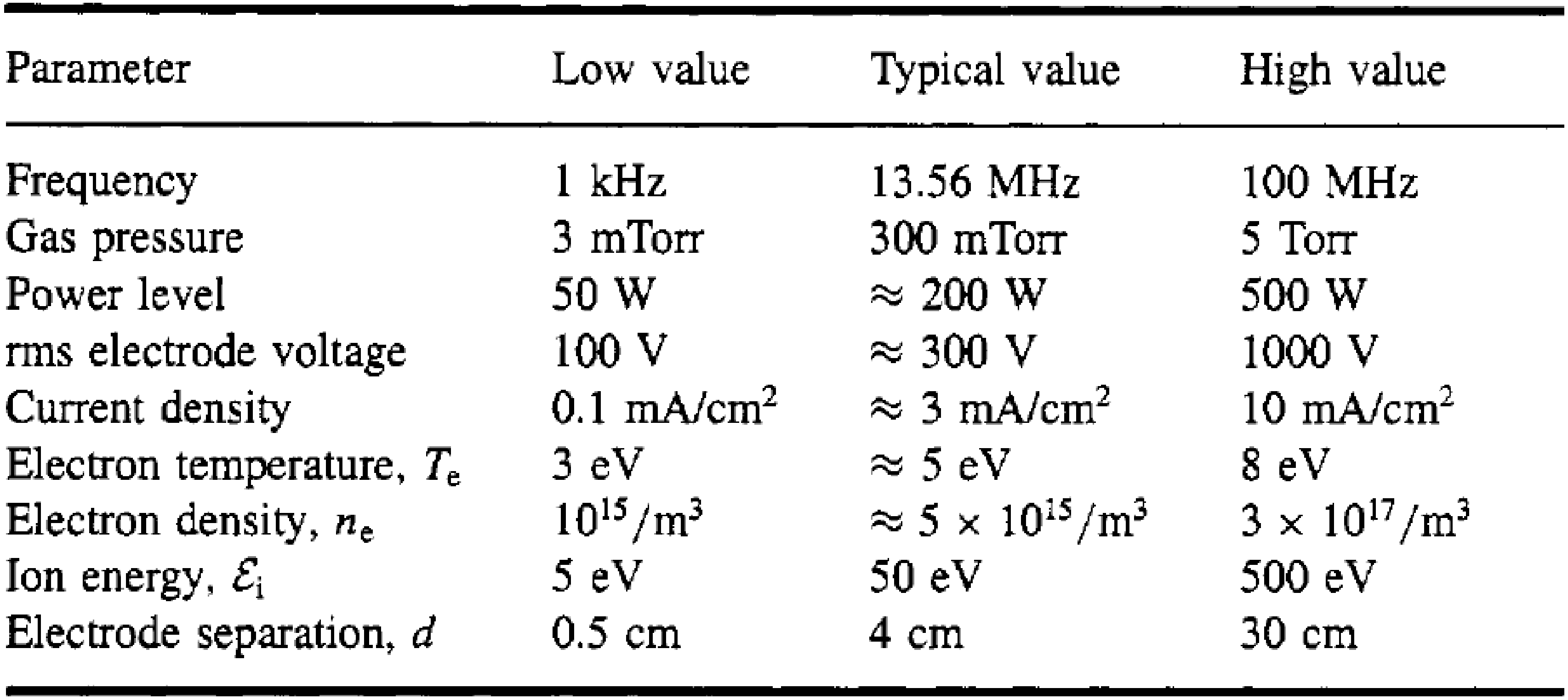
- **Plane parallel reactor**



- **Multiple electrode system**



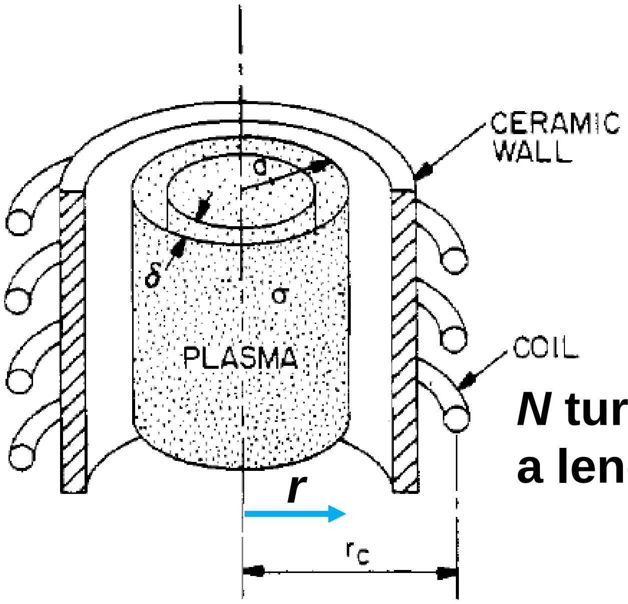
Operating regimes of capacitively coupled plasma reactors used for plasma processing



Parameter	Low value	Typical value	High value
Frequency	1 kHz	13.56 MHz	100 MHz
Gas pressure	3 mTorr	300 mTorr	5 Torr
Power level	50 W	≈ 200 W	500 W
rms electrode voltage	100 V	≈ 300 V	1000 V
Current density	0.1 mA/cm^2	≈ 3 mA/cm^2	10 mA/cm^2
Electron temperature, T_e	3 eV	≈ 5 eV	8 eV
Electron density, n_e	$10^{15}/\mathrm{m}^3$	$\approx 5 \times 10^{15}/\mathrm{m}^3$	$3 \times 10^{17}/\mathrm{m}^3$
Ion energy, $\mathcal{E}_i$	5 eV	50 eV	500 eV
Electrode separation, d	0.5 cm	4 cm	30 cm

Inductively coupled RF discharge

The plasma is generated by the induced electric field from the oscillating magnetic field



N turn within a length of *l*

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\int (\nabla \times \vec{E})\, \mathrm{d}\vec{A} = \int \left(-\frac{\partial \vec{B}}{\partial t}\right) \mathrm{d}\vec{A}$$

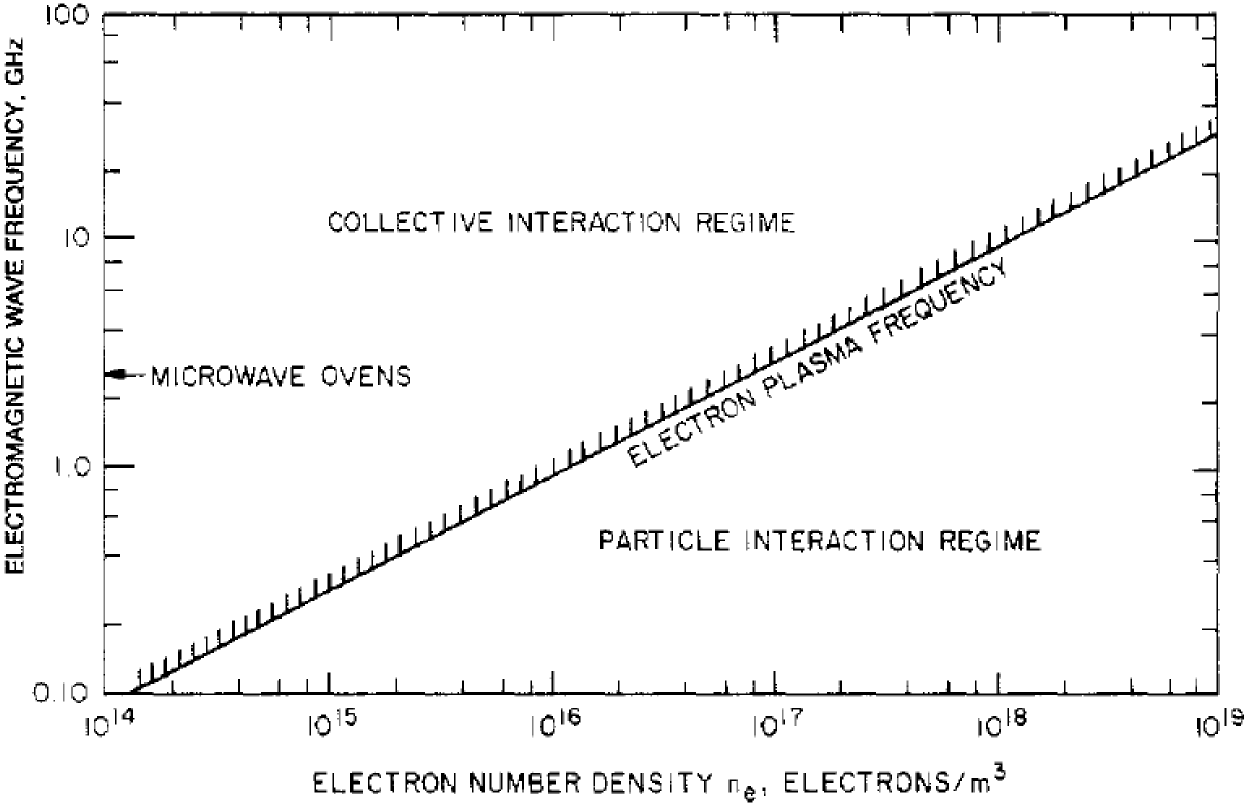
$$2\pi r E = -\pi r^2 \frac{\partial B}{\partial t}$$

$$E = -\frac{r}{2}\frac{\partial B}{\partial t} \qquad B \times l = \mu_o N I$$

$$E = -\frac{r}{2}\mu_o \frac{N}{l}\frac{\partial I}{\partial t}$$

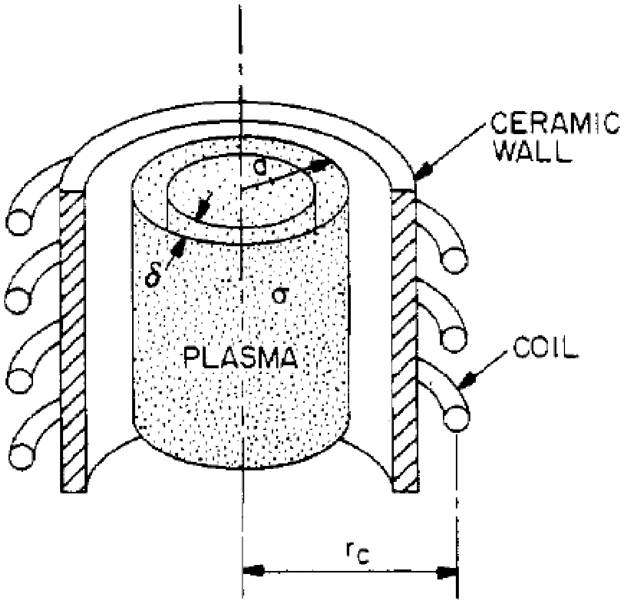
$$|E| = \frac{r}{2}\mu_o \frac{N}{l}\omega I$$

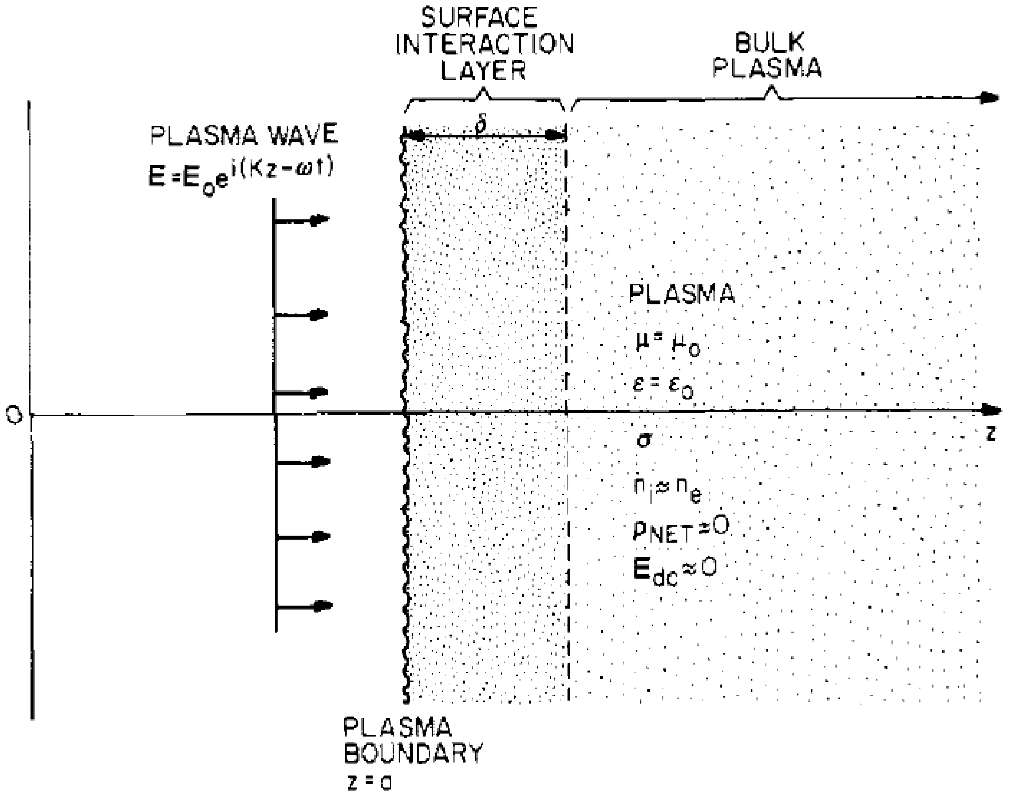
How an electromagnetic wave interacts with a plasma depends on its frequency



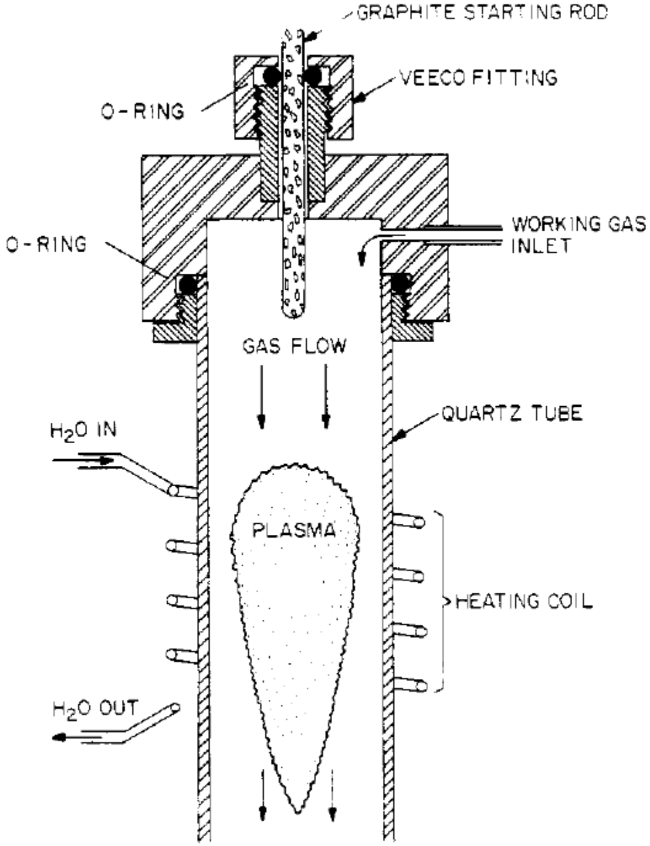
$$\omega_{\mathrm{pe}} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}\,(\mathrm{rad}/s) \qquad n_{\mathrm{cri}} = \frac{\epsilon_0 m_e}{e^2}\,\omega_{\mathrm{pe}}{}^2\,(m^{-3})$$

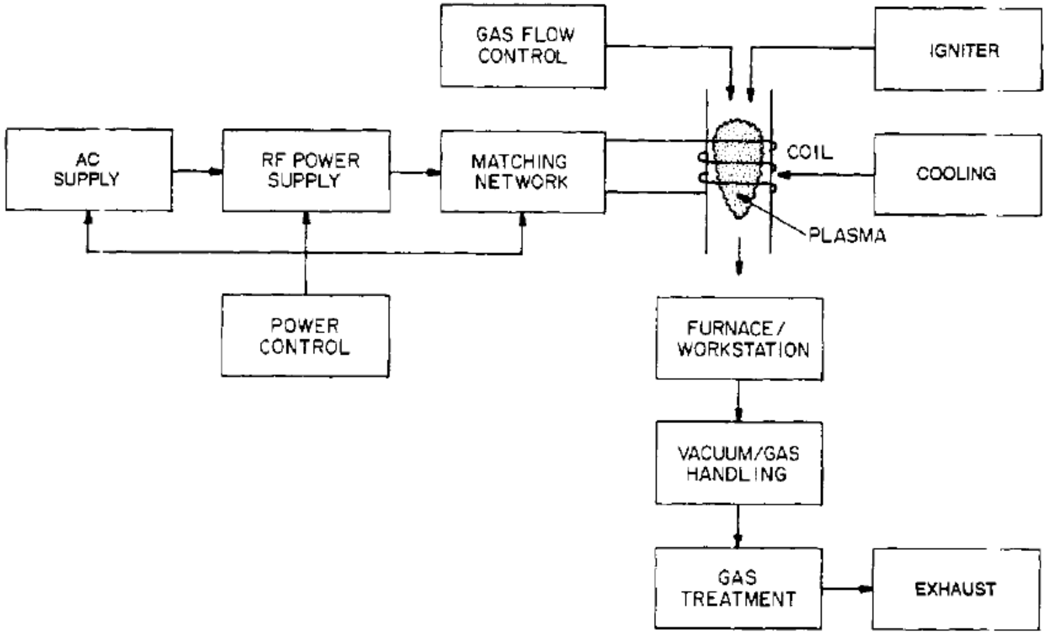
RF energy is strongly absorbed within the skin depth if the frequency is below the electron plasma frequency



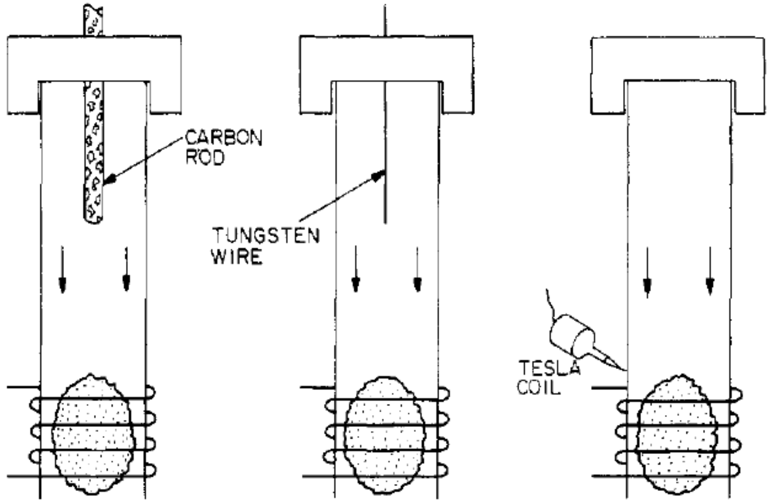


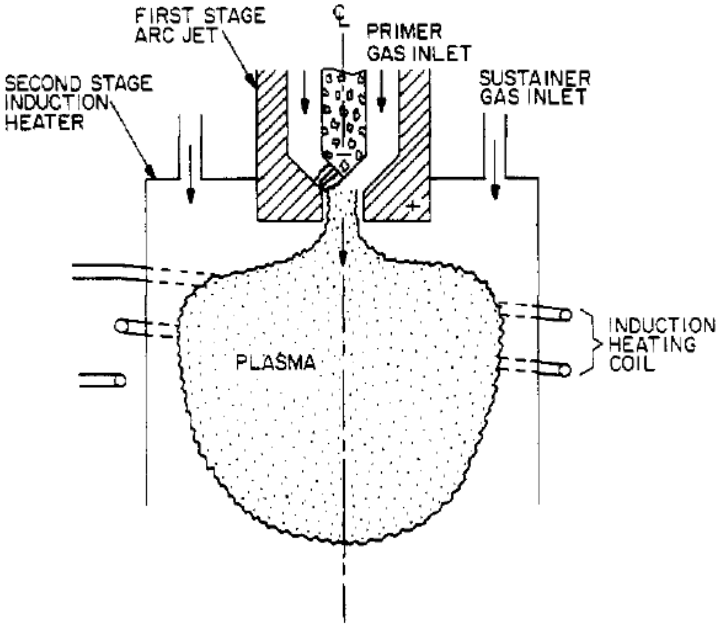
A kilowatt-level inductively coupled plasma torch is shown



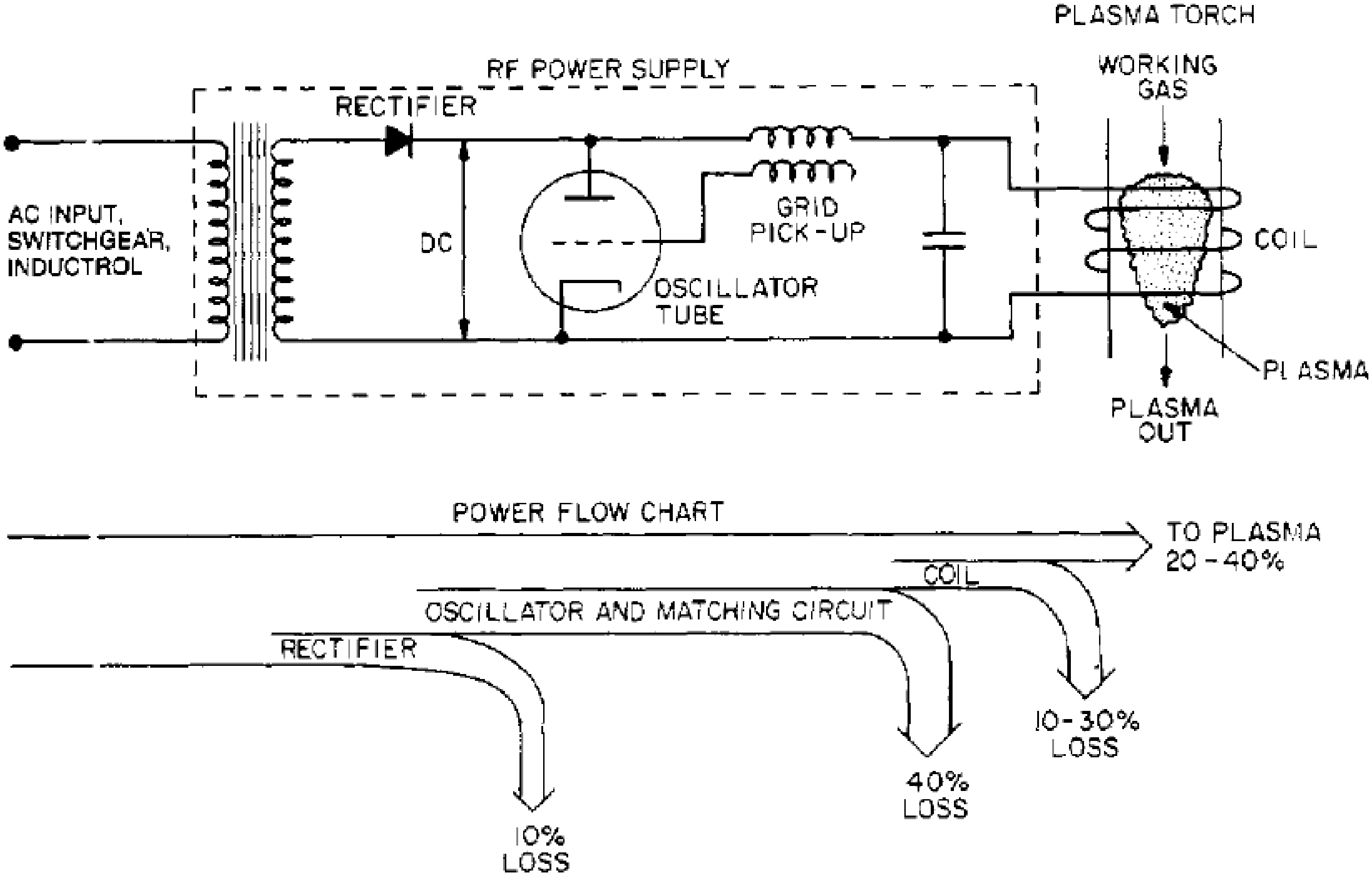


High voltage initiation is usually required for inductive RF plasma torches

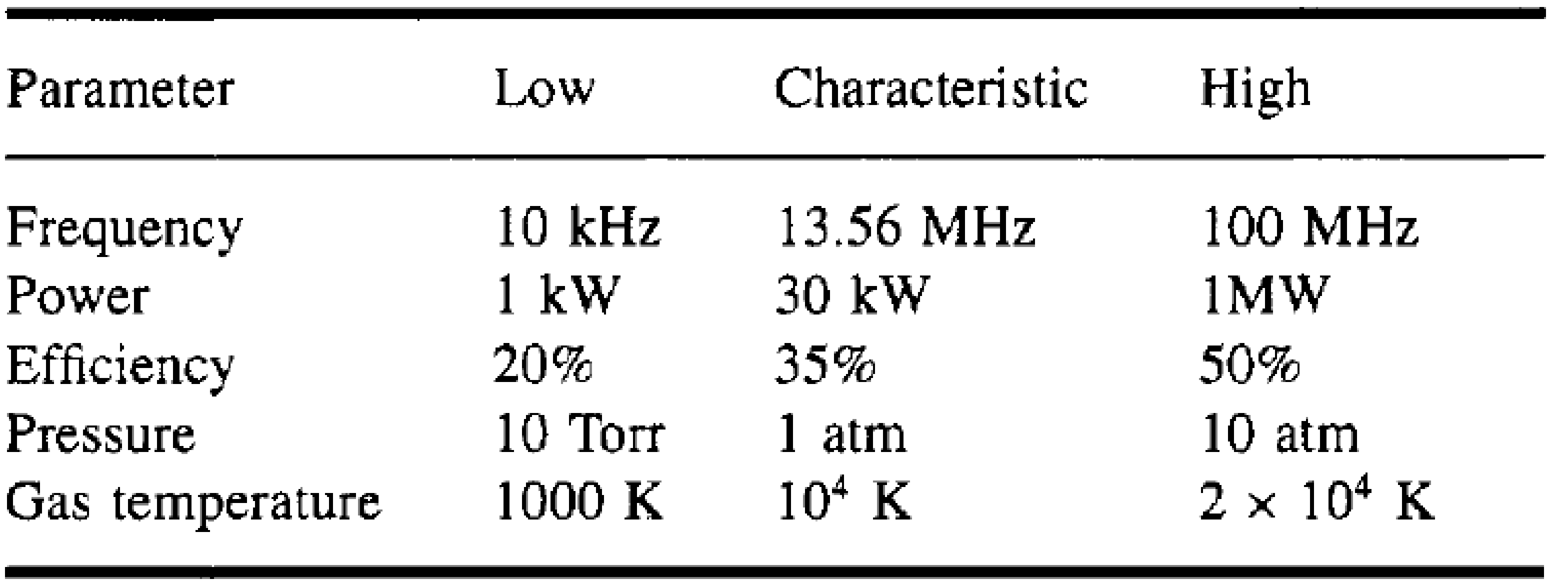




The power supplies are relatively inefficient

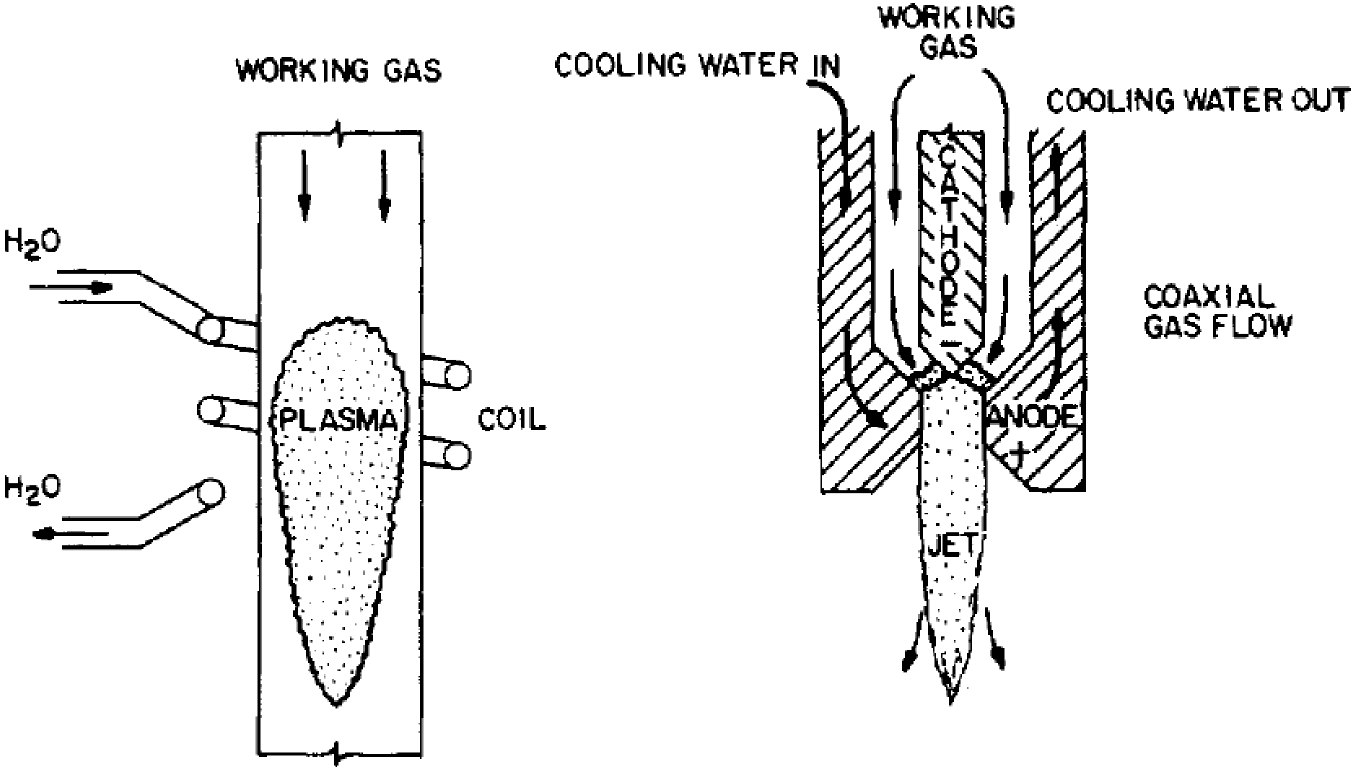


Operating regimes of inductively coupled plasma torches



Parameter	Low	Characteristic	High
Frequency	10 kHz	13.56 MHz	100 MHz
Power	1 kW	30 kW	1MW
Efficiency	20%	35%	50%
Pressure	10 Torr	1 atm	10 atm
Gas temperature	1000 K	10^4 K	2×10^4 K

Inductive RF coupling provides a plasma with less contamination from the electrode

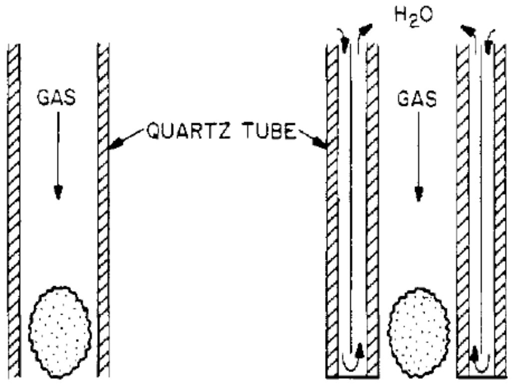


INDUCTIVE PLASMA TORCH

ARC JET

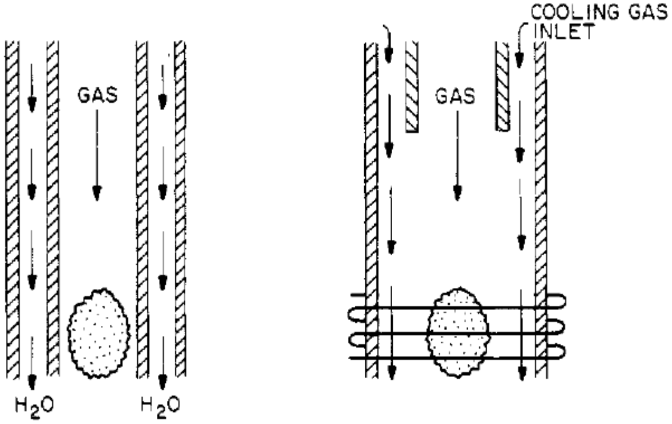
10 – 200 m/sec	JET VELOCITY	500 – 150 m/sec
4 – 40 mm	JET DIAMETER	6 – 10 mm
VARIABLE	JET SHAPE	CYLINDRICAL

Several cooling configurations are shown



a) RADIANT COOLING

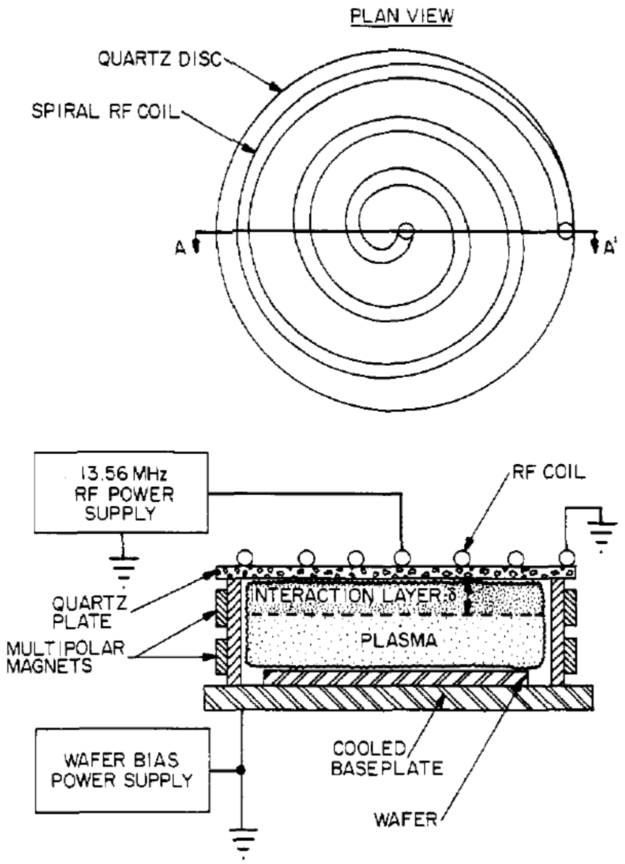
b) COUNTER CURRENT WATER FLOW



c) COAXIAL WATER FLOW

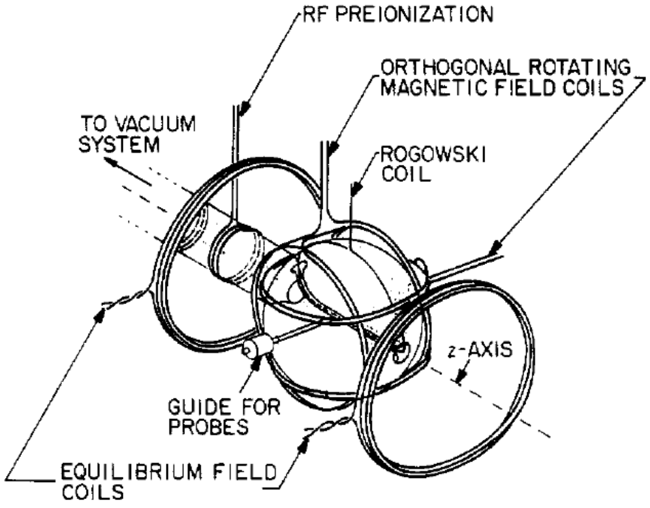
d) COAXIAL GAS FLOW

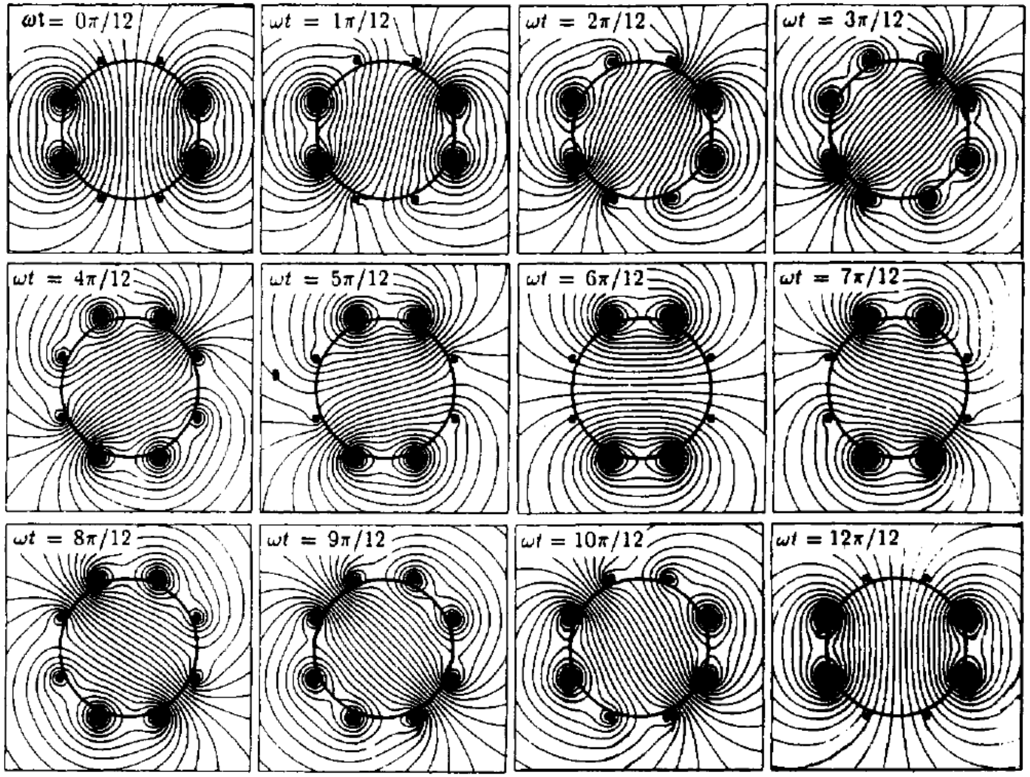
Inductive parallel plate reactor



- **Uniform plasma source**
- **Higher power (2 kW) leading to higher plasma density (up to 10^{18} electrons/m^3)**
- **Lower gas pressure, i. e., longer mean free paths and little scattering of ions and is desired in deposition and etching applications.**

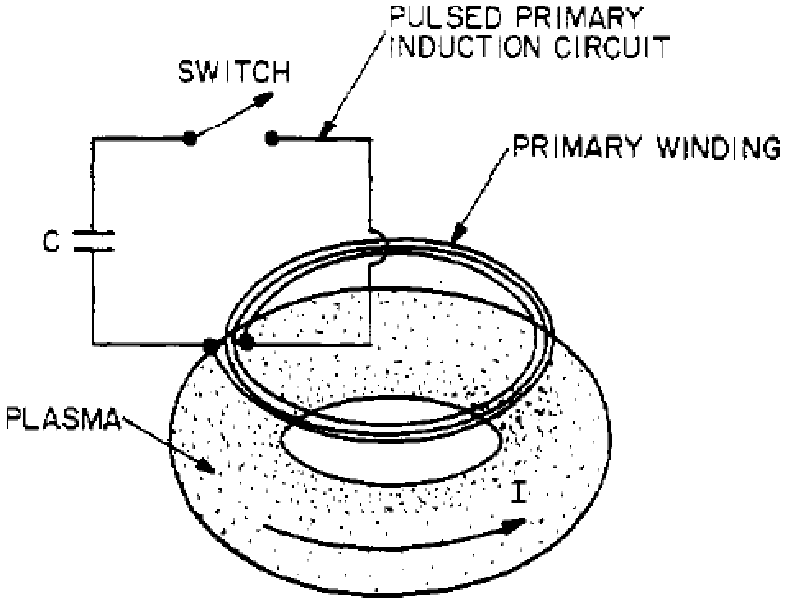
Rotamak

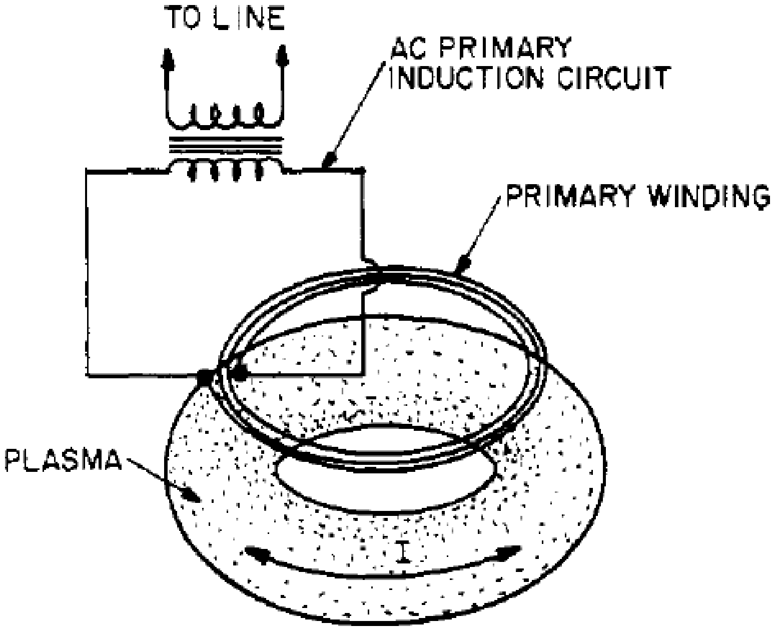




- **The rapidly rotating magnetic field generates large plasma currents, thus heating the plasma to densities and temperatures of interest in many industrial applications**

Inductively heated toroidal plasmas





- **Large currents are induced in the plasma by transformer action from a ramped current in a pulsed primary induction circuit.**

Applications of inductive plasma torches

- **High purity materials production**
  - **Silica and other refractories**
  - **Ultrafine powder**
  - **Spherical fine power**
  - **Refining/purification**
- **High temperature thermal treatment**
  - **Heat treatment**
  - **Plasma sintering**
- **Surface treatment**
  - **Oxidation**
  - **Nitriding**

Applications of inductive plasma torches

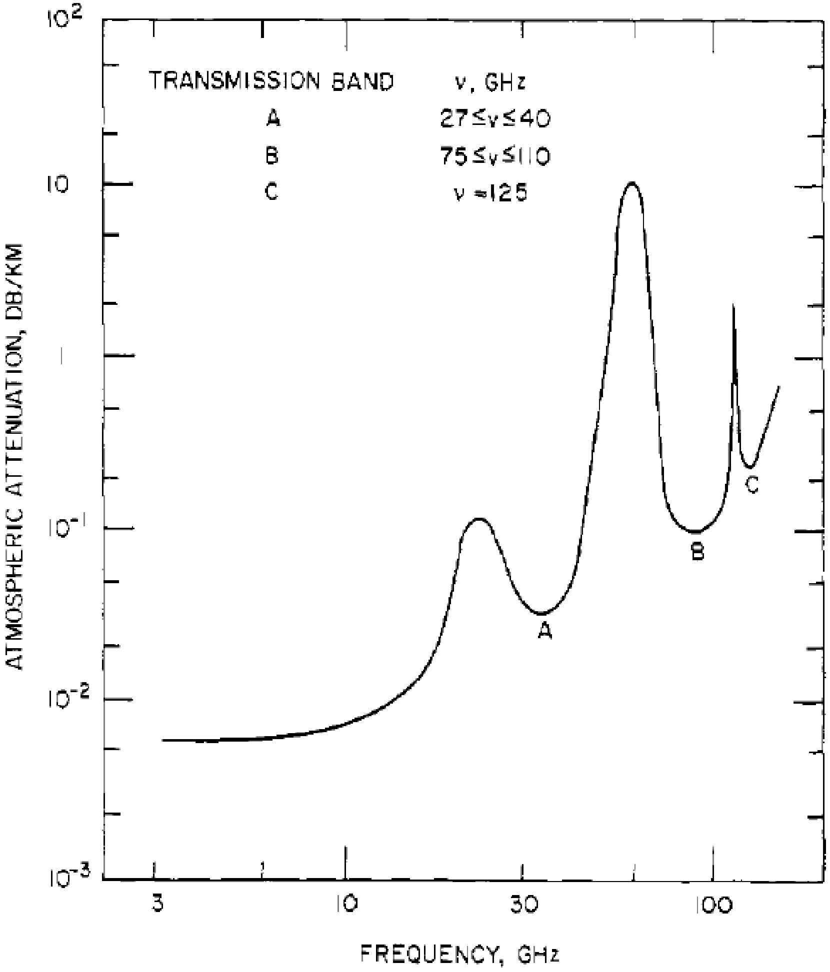
- **Surface coating**
  - **Plasma flame spraying**
  - **Surface coating of powder**
- **Chemical vapor deposition (CVD)**
  - **At atmospheric pressure**
  - **At reduced pressure**
- **Chemical synthesis and processing**

- **Experimental applications**
  - **Laboratory furnace**
  - **High intensity light source**
  - **Spectroscopic analysis**
  - **Isotope separation**
  - **Ion source**
  - **High power density plasma source**

Advantage of using microwave electrical discharges

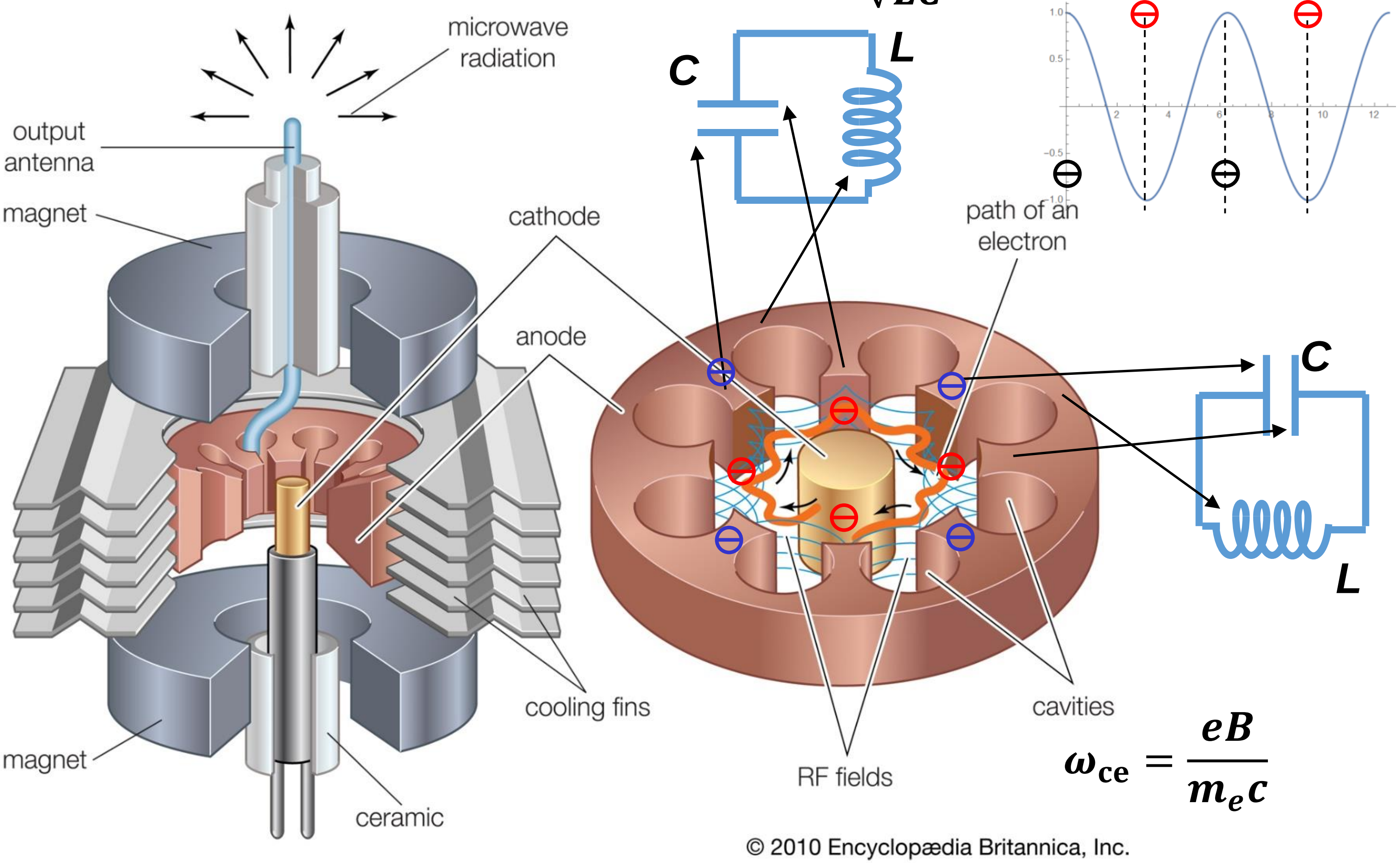
- The wavelength of the microwave is in centimeters range. In contract, the wavelength is 22 m for RF frequency f = 13.6 MHz.
- The electron number density can approach the critical number density. ($7x10^{16}$ m^{-3}) at a frequency of 2.45 GHz.
- The plasma in microwave discharges is quasi-optical to microwave.
- Microwave-generated plasmas have a higher electron kinetic temperature (5 ~ 15 eV) than DC or low frequency RF-generated plasmas (1 or 2 eV).
- Capable of providing a higher fraction of ionization.
- Do not have a high voltage sheath.
- No internal electrodes.

Microwave frequency is determined for those used in communications and radar purposes



Internal of a magnetron

$$\boldsymbol{\omega_{\mathrm{LC}} = \frac{1}{\sqrt{LC}} \equiv 4\omega_{\mathrm{ce}}}$$



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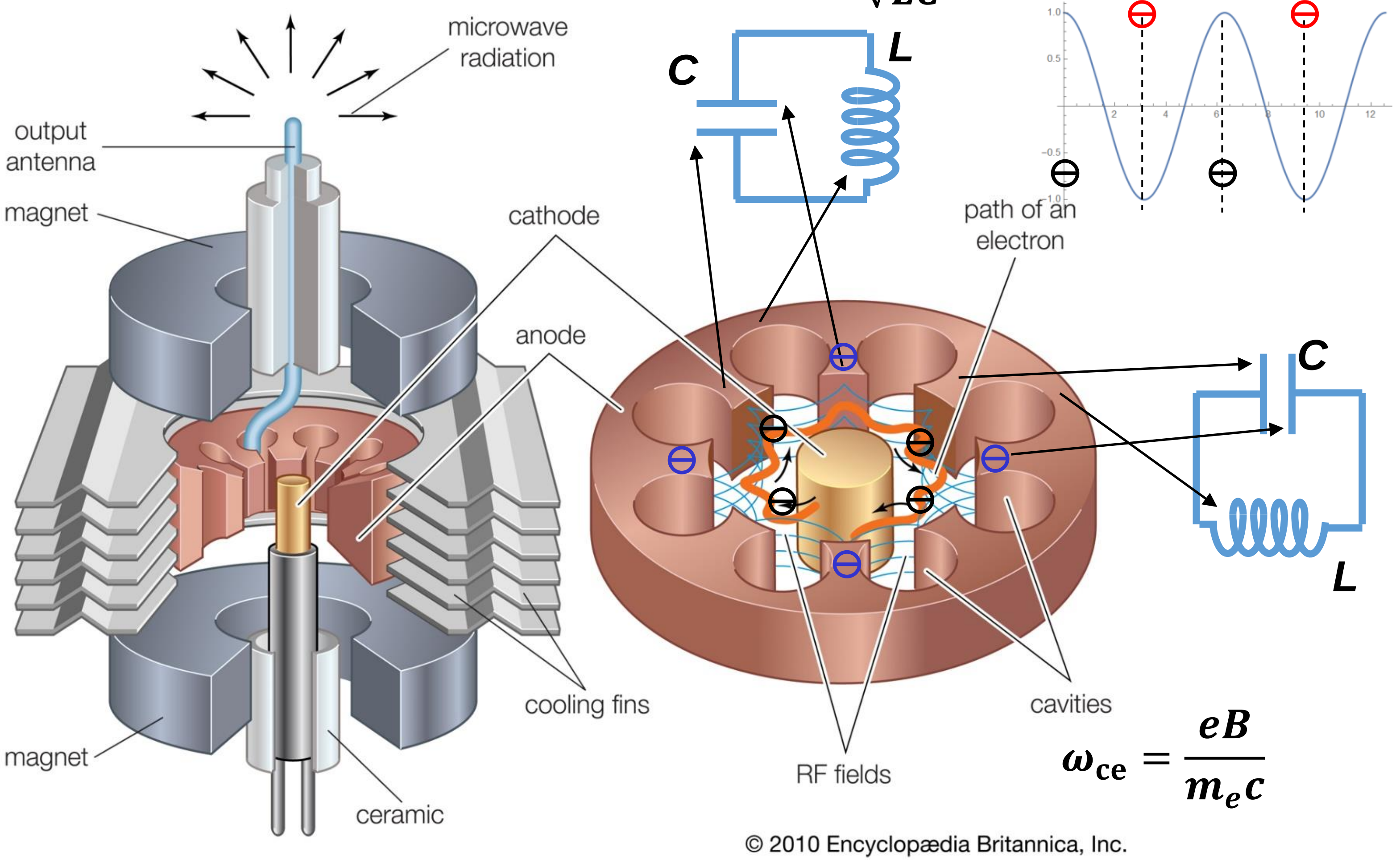
$$\boldsymbol{\omega_{\mathrm{ce}} = \frac{eB}{m_e c}}$$

https://kids.britannica.com/students/article/electron-tube/106024/media?assemblyId=137

Internal of a magnetron

$$\omega_{\mathrm{LC}} = \frac{1}{\sqrt{LC}} \equiv 4\omega_{\mathrm{ce}}$$



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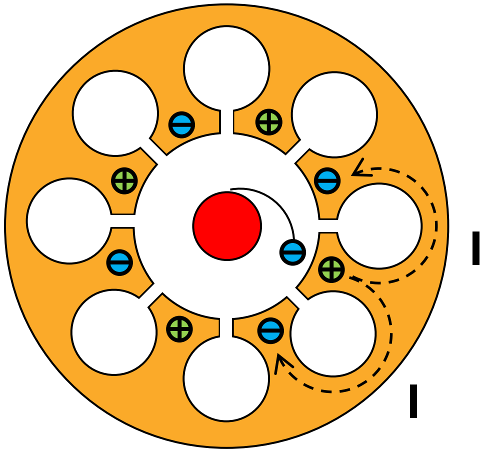
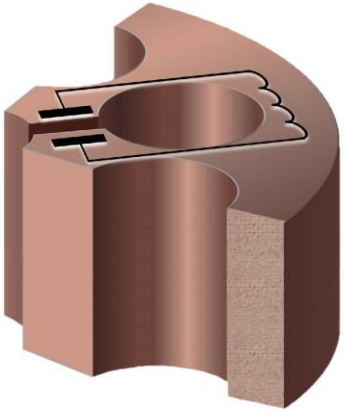
$$\omega_{\mathrm{ce}} = \frac{eB}{m_e c}$$

https://kids.britannica.com/students/article/electron-tube/106024/media?assemblyId=137

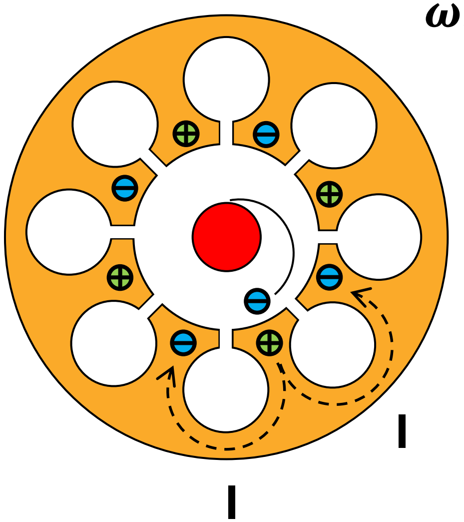
Strong oscillation occurs when the electron cyclotron frequency match the LC oscillation frequency





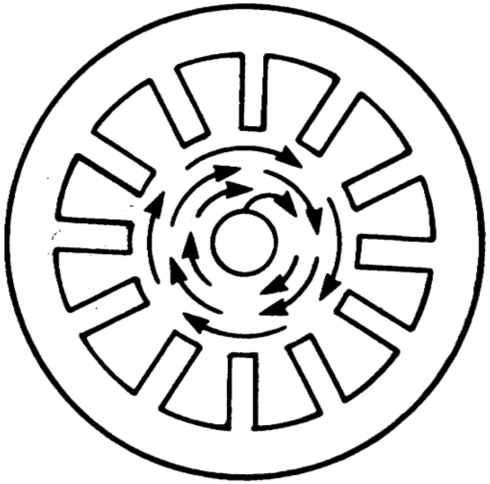
$$\omega_{\mathrm{CE}} = \frac{eB}{mc}$$

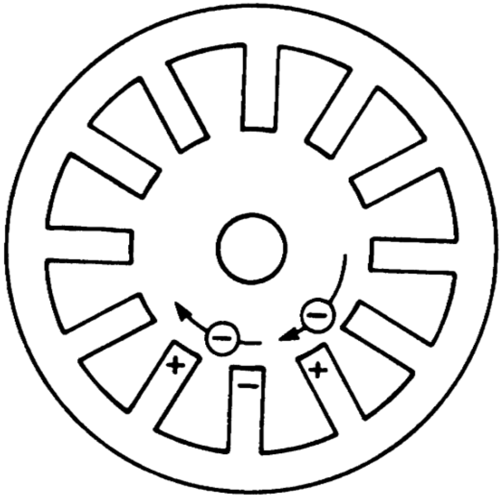
$$\omega = \frac{1}{\sqrt{LC}}$$

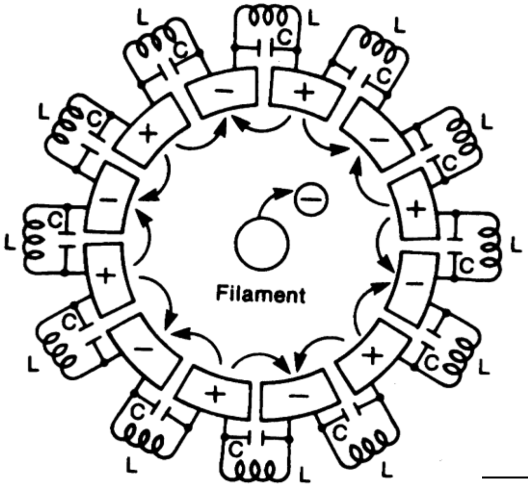


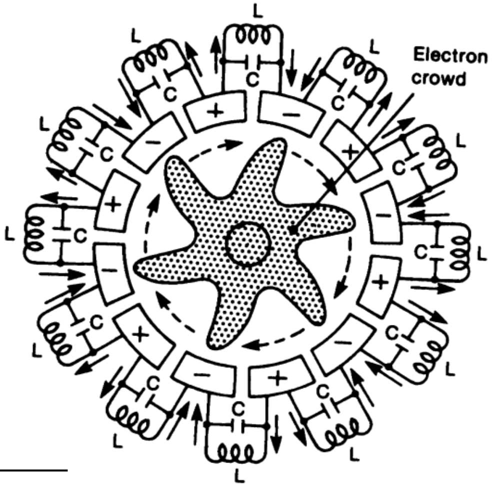
Resonance condition: $\omega_{\mathrm{CE}} = \omega$

Resonance in a magnetron









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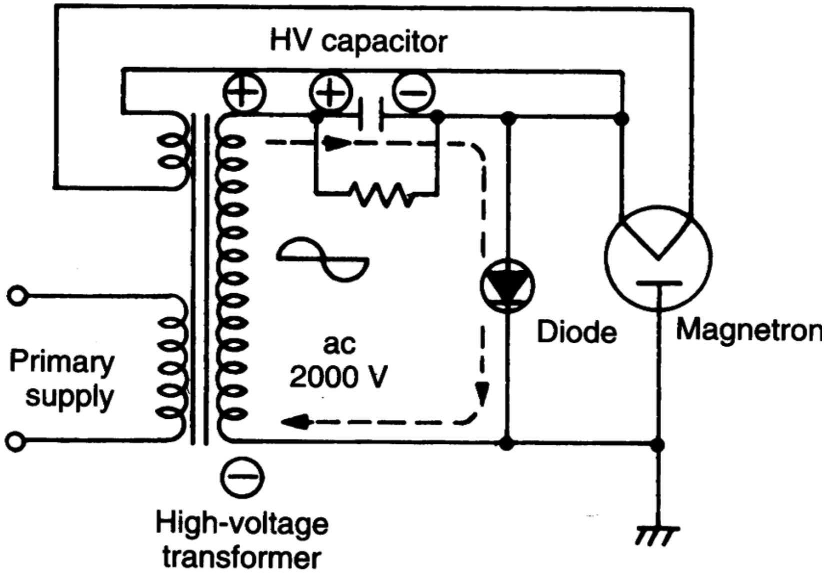
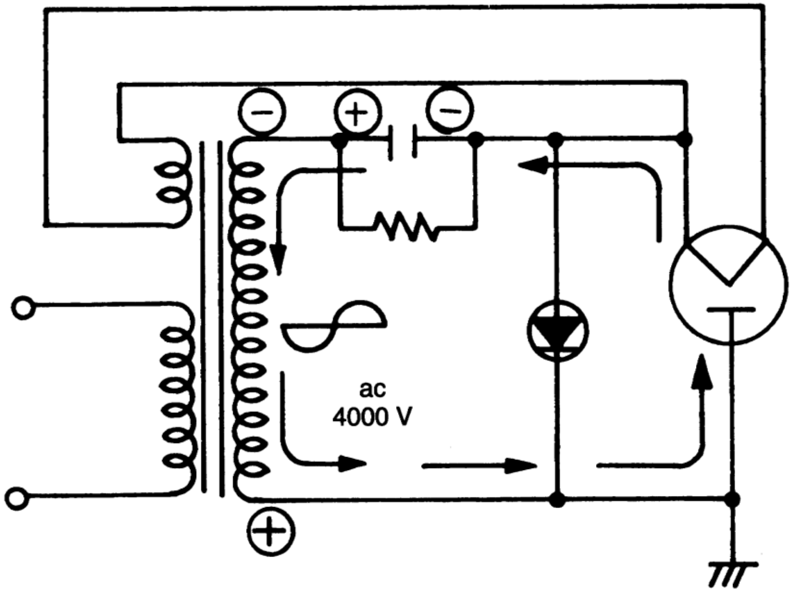
Magnetron schematic diagram





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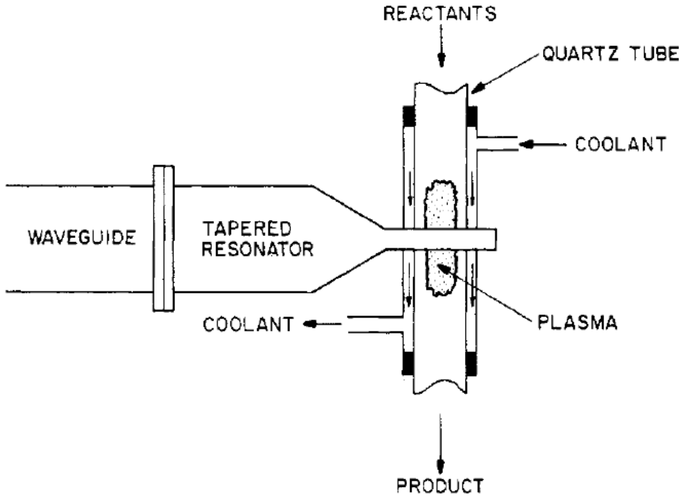
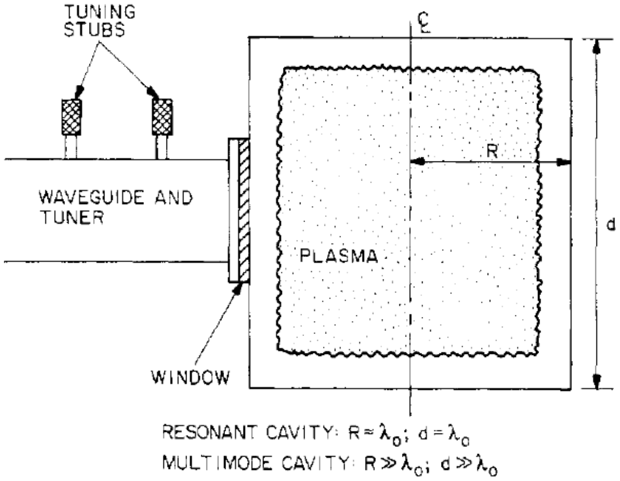
Microwave plasma reactor configurations

- **Waveguide coupled reactor**
- **Resonant or multimode cavity – if the impedance matching is good, more energy can be fed into the cavity.**



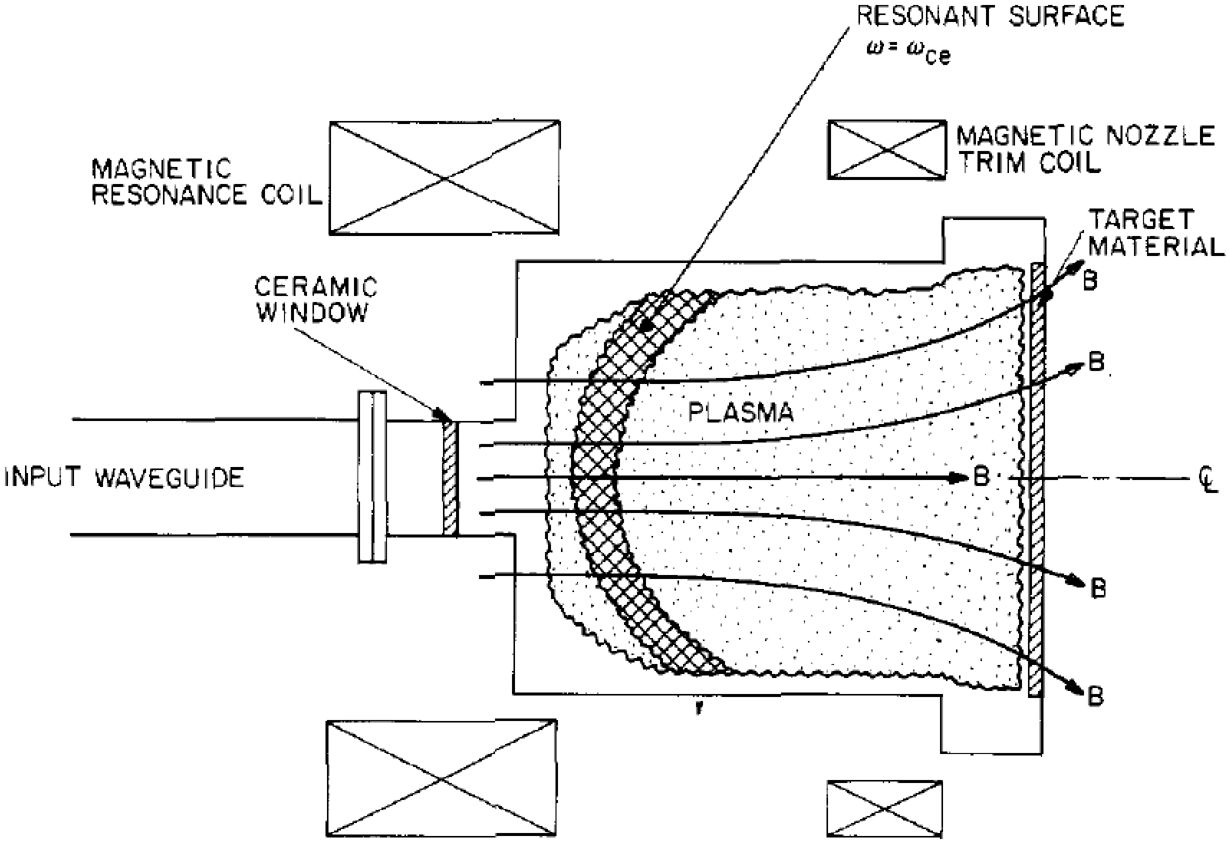


RESONANT CAVITY: $R \approx \lambda_0$; $d = \lambda_0$

MULTIMODE CAVITY: $R \gg \lambda_0$; $d \gg \lambda_0$

Strong absorption occurs when the frequency matches the electron cyclotron frequency

- **Electron cyclotron resonance (ECR) plasma reactor**



Electron cyclotron frequency depends on magnetic field only

$$m_e \frac{d\,\vec{v}}{\mathrm{dt}} = -\frac{e}{c}\,\vec{v} \times \vec{B}$$

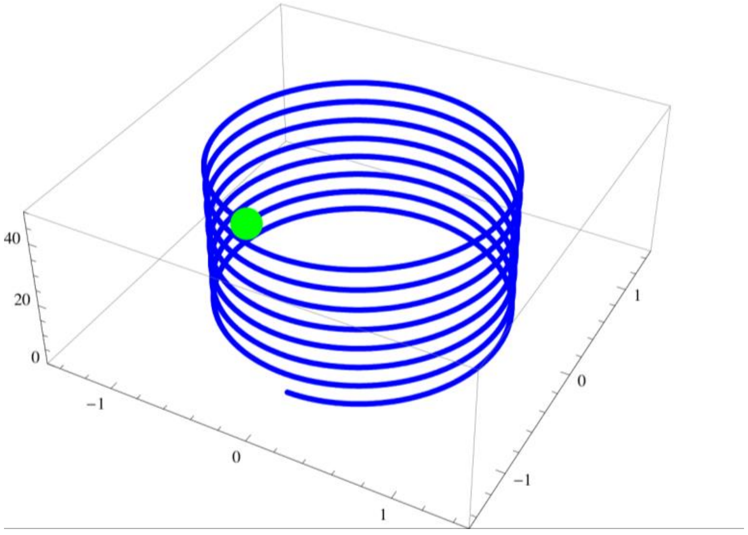
- Assuming $\vec{B} = B\hat{z}$ and the electron oscillates in x-y plane

$$m_e \dot{v}_x = -\frac{e}{c} B v_y \qquad m_e \dot{v}_z = 0$$

$$m_e \dot{v}_y = \frac{e}{c} B v_x$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y = -\left(\frac{eB}{m_e c}\right)^2 v_x$$

$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x = -\left(\frac{eB}{m_e c}\right)^2 v_y$$



- Therefore

$$\omega_{\mathrm{ce}} = \frac{eB}{m_e c}$$

Electrons keep getting accelerated when a electric field rotates in electron’s gyrofrequency

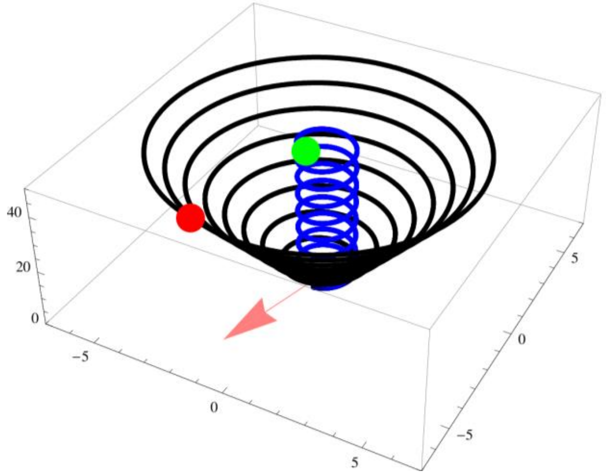
$$m_e \frac{d\vec{v}}{\mathrm{dt}} = -\frac{e}{c}\,\vec{v}\times\vec{B} - e\,\vec{E} \qquad \vec{B} = B_0\hat{z} \qquad \vec{E} = E_0[\hat{x}\cos(\omega\mathrm{t}) + \hat{y}\sin(\omega\mathrm{t})]$$

$$m_e\dot{v}_x = -\frac{e}{c}Bv_y + E_0\cos(\omega\mathrm{t}) \qquad m_e\dot{v}_y = \frac{e}{c}Bv_x + E_0\cos(\omega\mathrm{t}) \qquad m_e\dot{v}_z = 0$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y - \frac{E_0}{m_e}\omega\cos(\omega\mathrm{t}) = -\omega_{\mathrm{ce}}{}^2 v_x - \frac{E_0}{m_e}(\omega_{\mathrm{ce}} + \omega)\cos(\omega\mathrm{t})$$

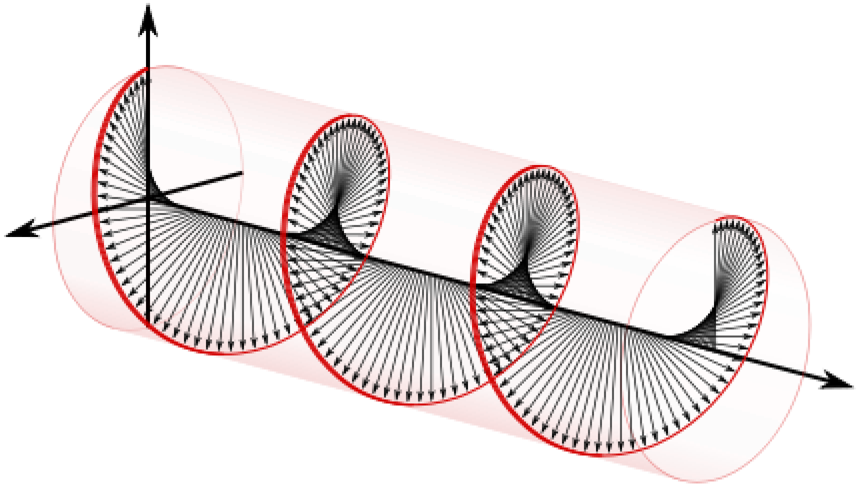
$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x + \frac{E_0}{m_e}\omega\sin(\omega\mathrm{t}) = -\omega_{\mathrm{ce}}{}^2 v_y + \frac{E_0}{m_e}(\omega_{\mathrm{ce}} + \omega)\sin(\omega\mathrm{t})$$

$$\omega_{\mathrm{ce}} = \frac{eB}{m_e c}$$

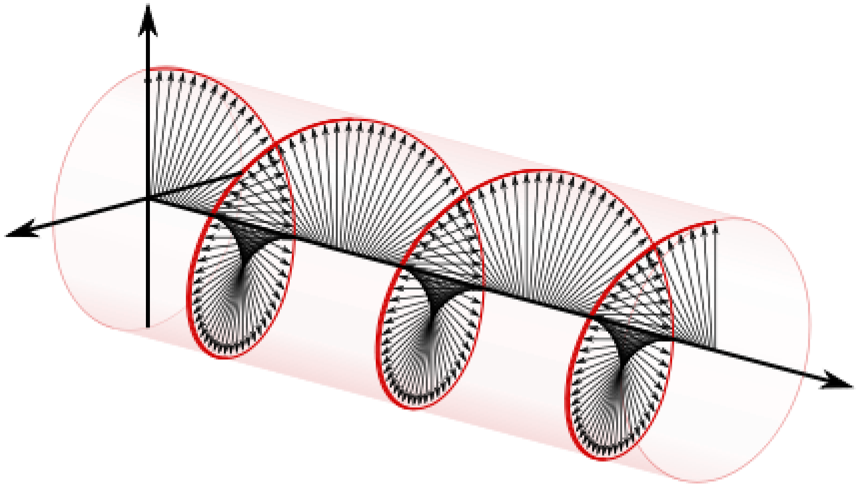


Electric field in a circular polarized electromagnetic wave keeps rotating as the wave propagates

- **Right-handed polarization**



- **Left-handed polarization**



https://en.wikipedia.org/wiki/Circular_polarization

Only right-handed polarization can resonance with electron’s gyromotion

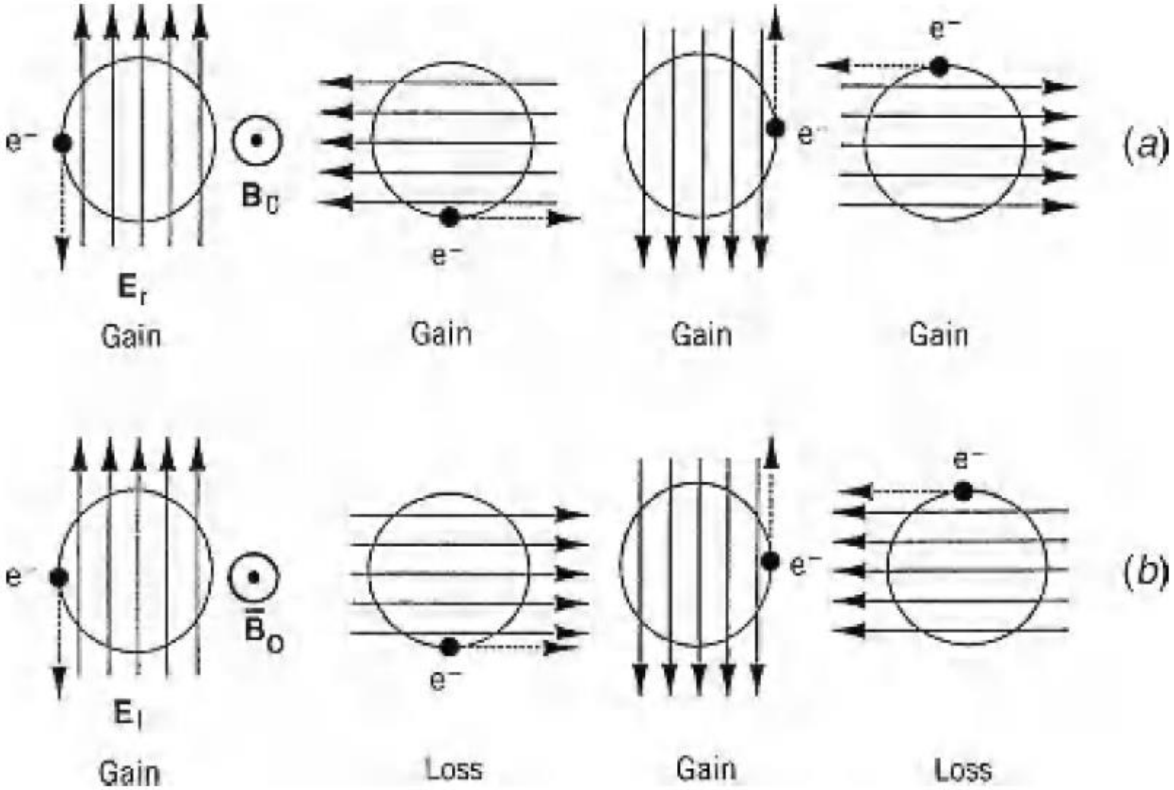
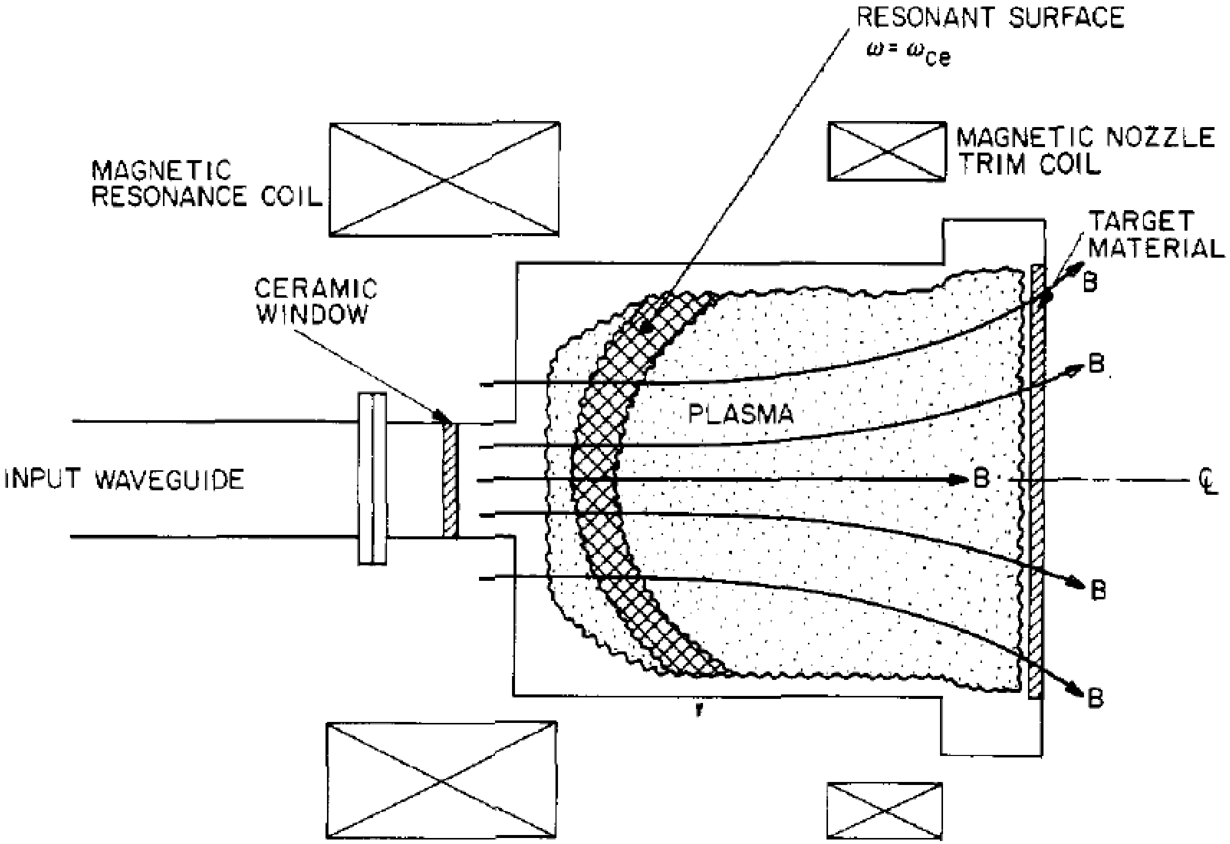


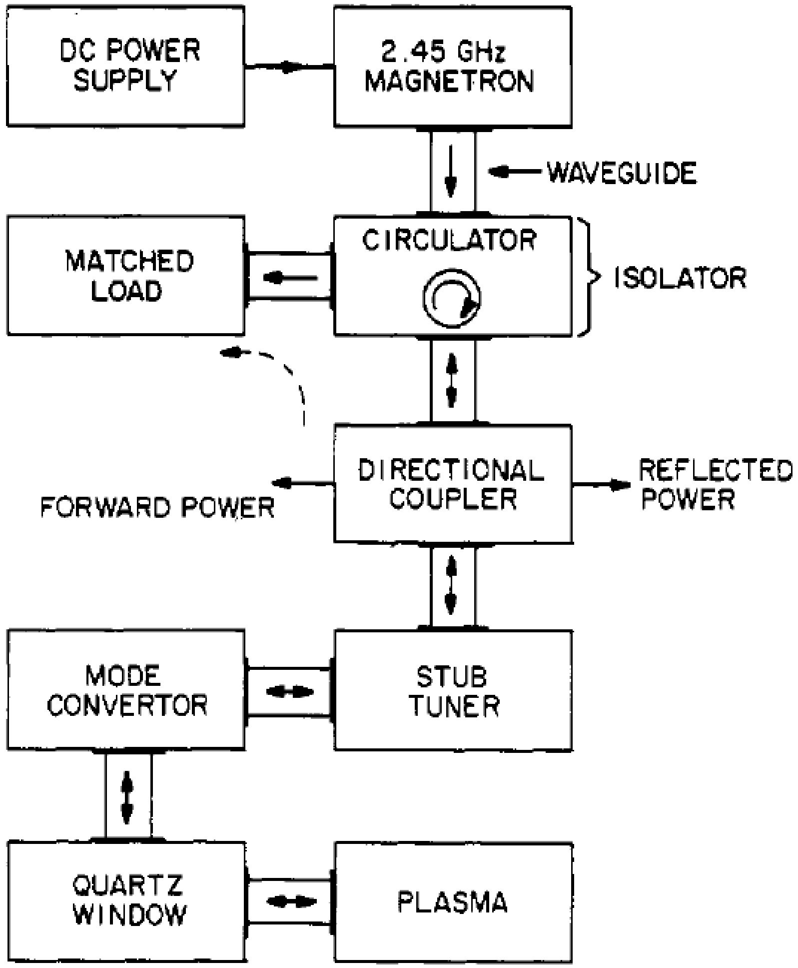
FIGURE 13.5. Basic principle of ECR heating: (*a*) continuous energy gain for right-hand polarization; (*b*) oscillating energy for left-hand polarization (after Lieberman and Gottscho, 1994).

Strong absorption occurs when the frequency matches the electron cyclotron frequency

- **Electron cyclotron resonance (ECR) plasma reactor**



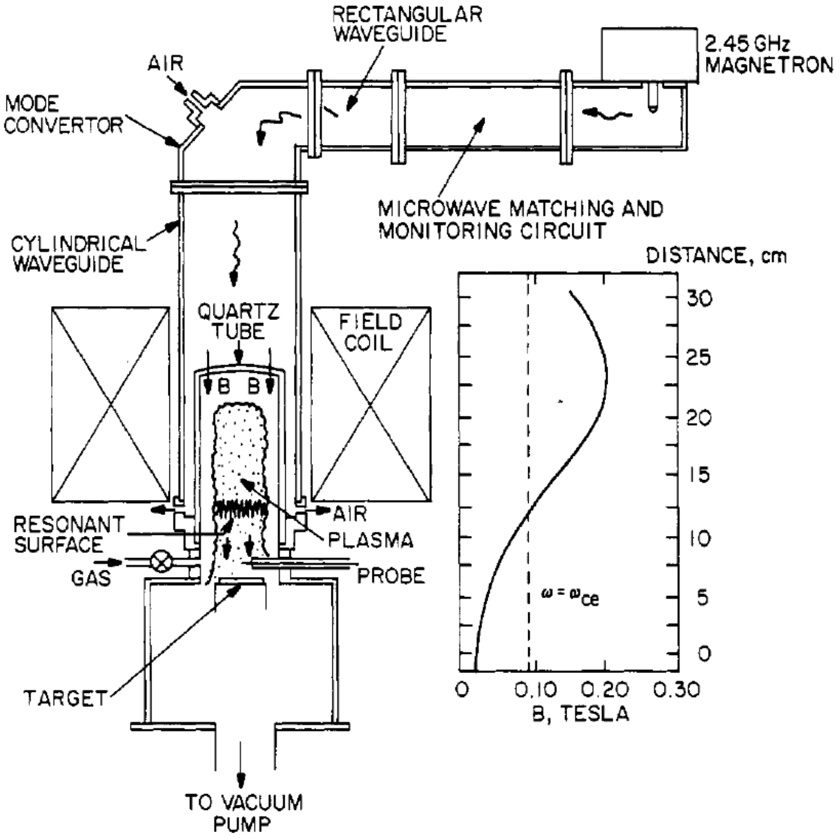
Electron cyclotron resonance (ECR) microwave systems



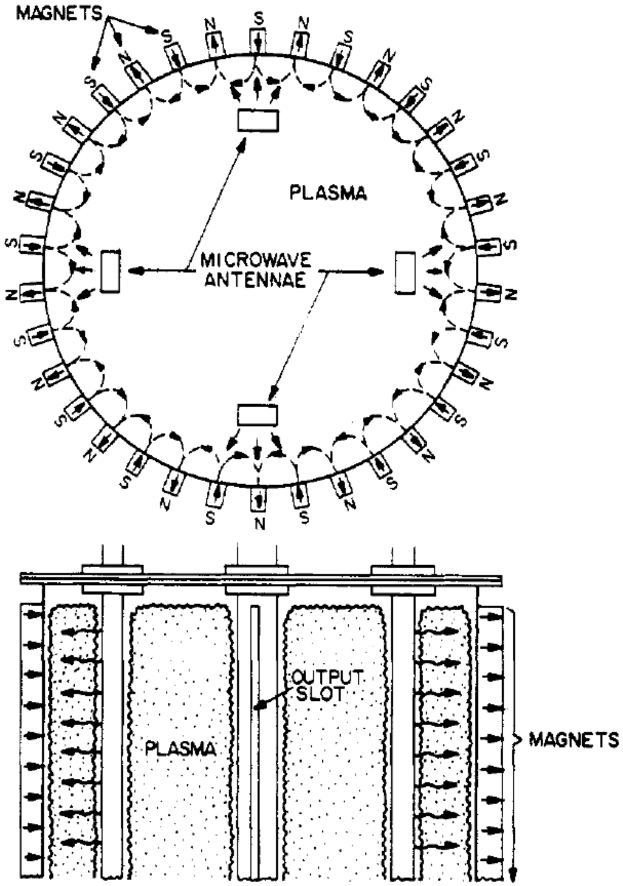
microwave systems

Immersed ECR plasma source

- High particle fluxes on targets for diamond or other thin film deposition
- The ions in the plasma flux can be used for etching.

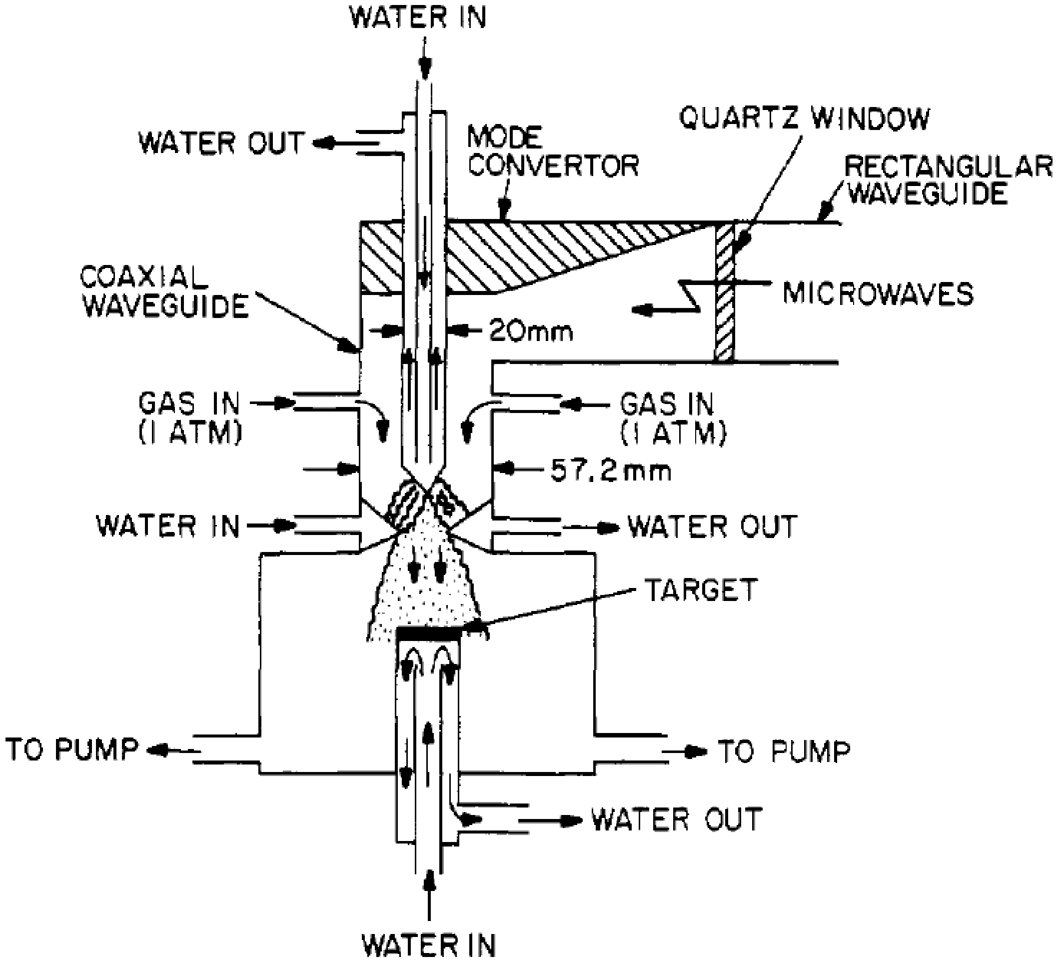


Distributed ECR system



- **Function of the multipolar magnetic field at the tank boundary:**
  - **Provide a resonant surface for ECR absorption**
  - **Improve the confinement of the plasma**

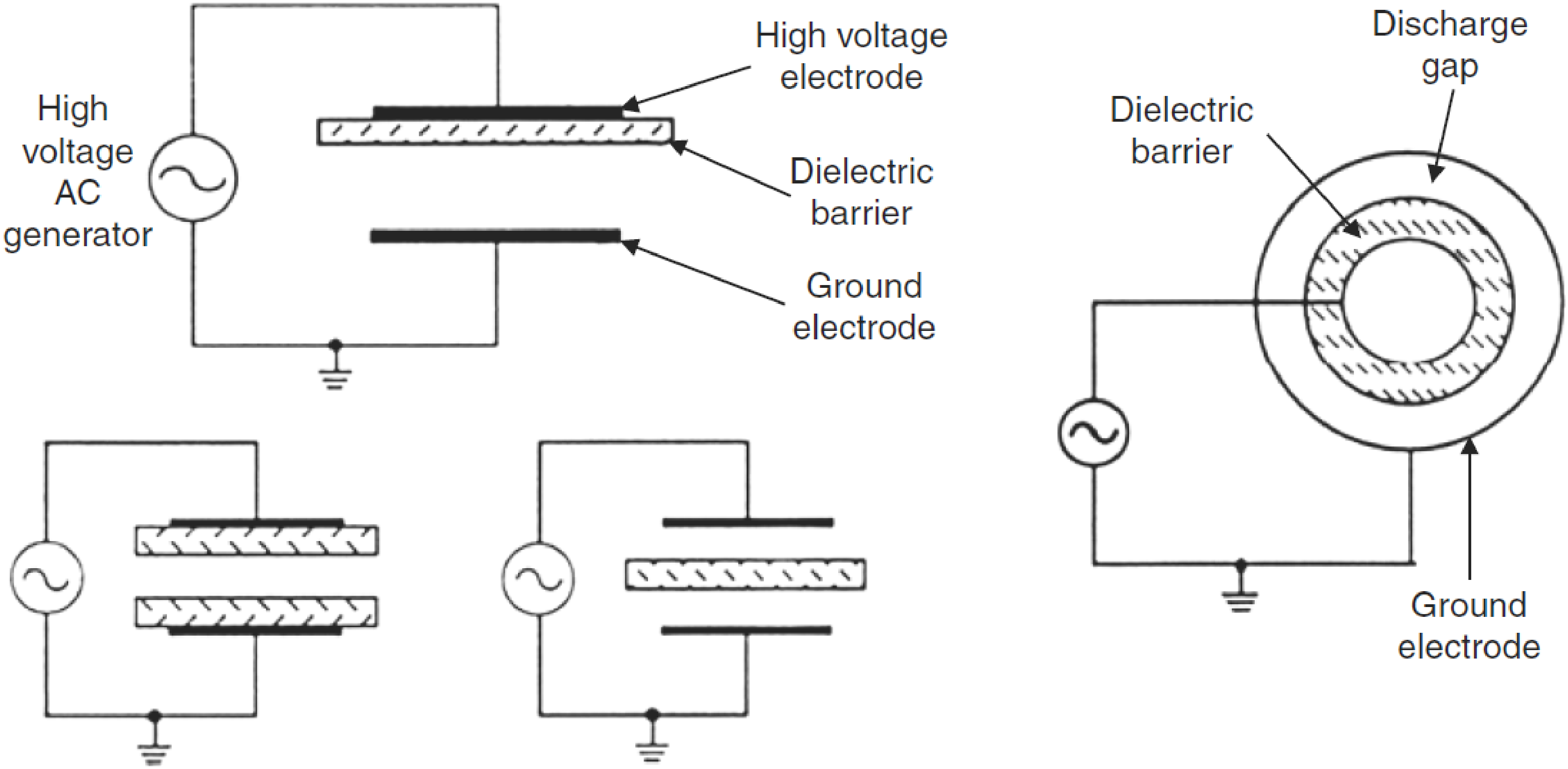
Microwave plasma torch deposit a much faster rate than other types of plasma source for diamond film deposition



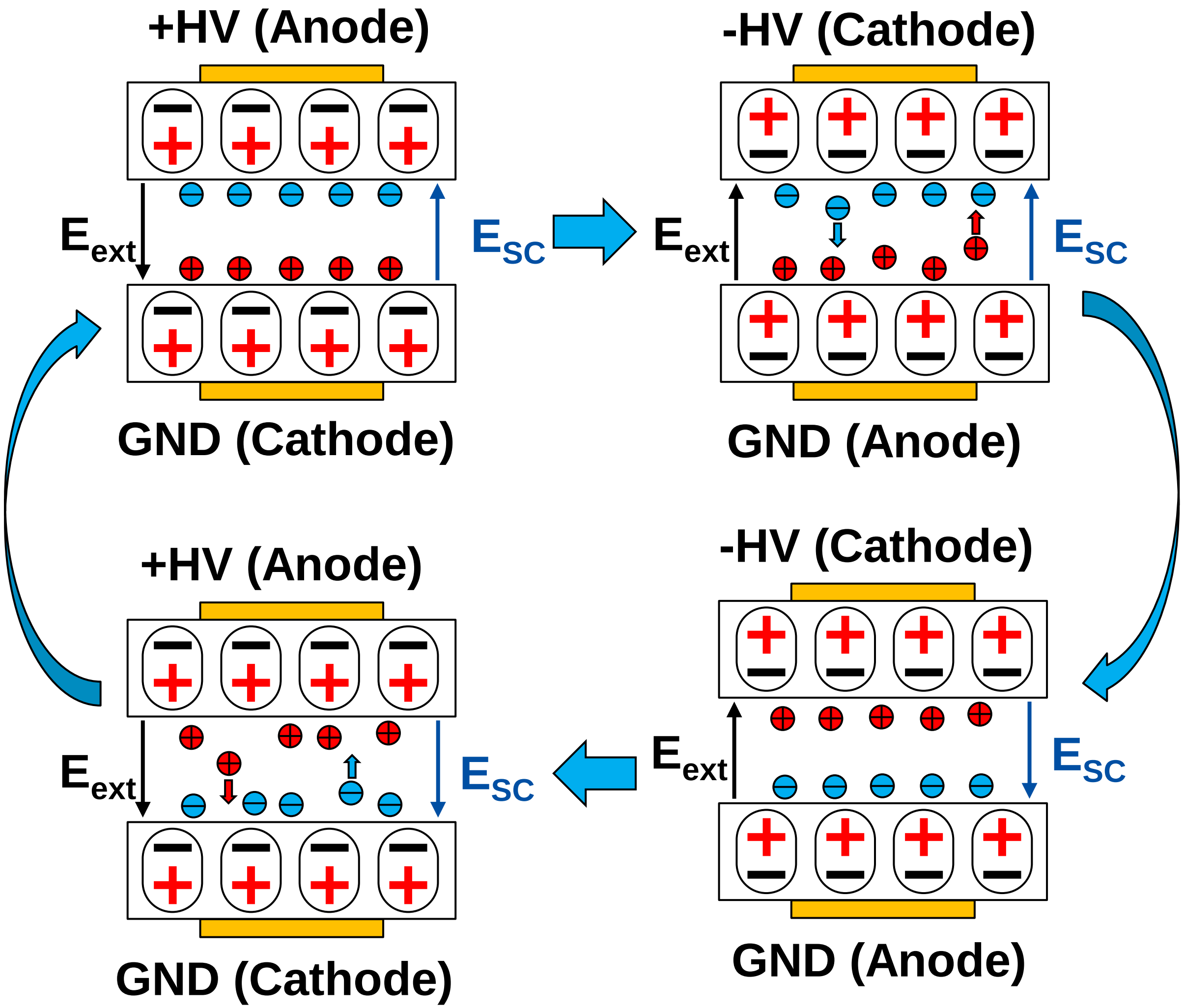
Microwave-generated plasmas have the capability of filling very large volumes with moderately high density

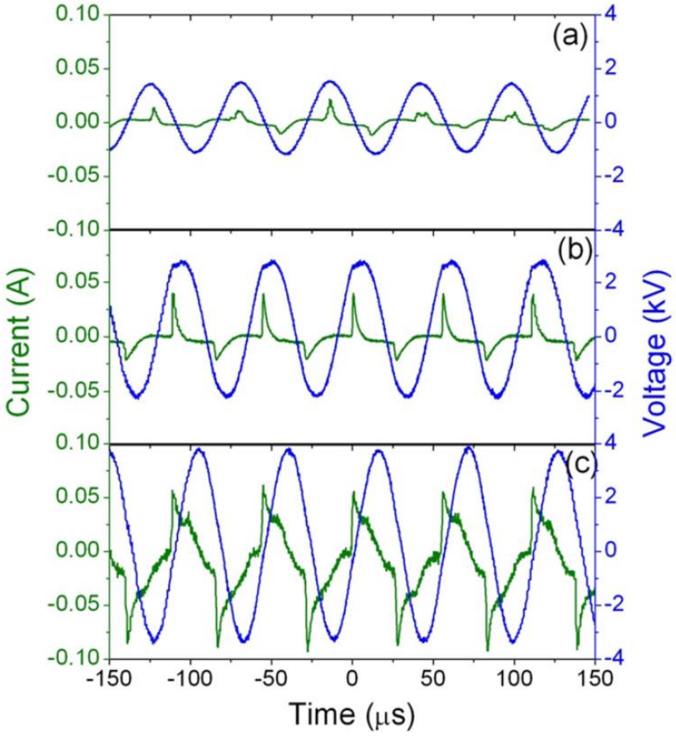
- **Advantages**
  - **Lower neutral gas pressure, i.e., longer ion and neutral mean free paths.**
  - **Higher fraction ionize.**
  - **Higher electron density.**
- **Disadvantages**
  - **Lower ion bombardment energies.**
  - **Less control of the bombarding ion energy.**
  - **Difficult in tuning up and achieving efficient coupling.**
  - **Much more difficult and expensive to make uniform over a large area.**
  - **More expensive.**

Dielectric-barrier discharges (DBDs)



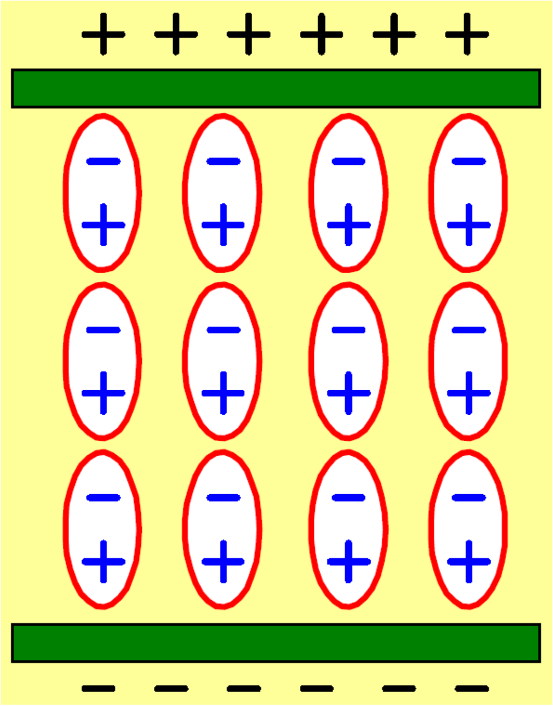
Space charge effect enhance the electric field

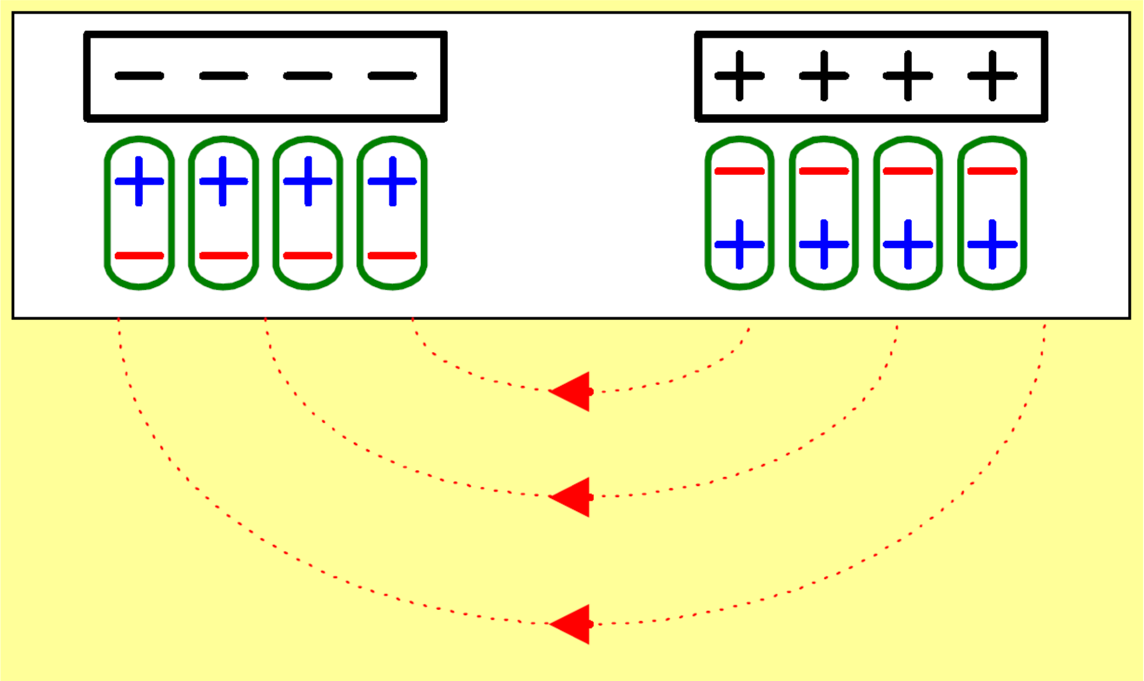




J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

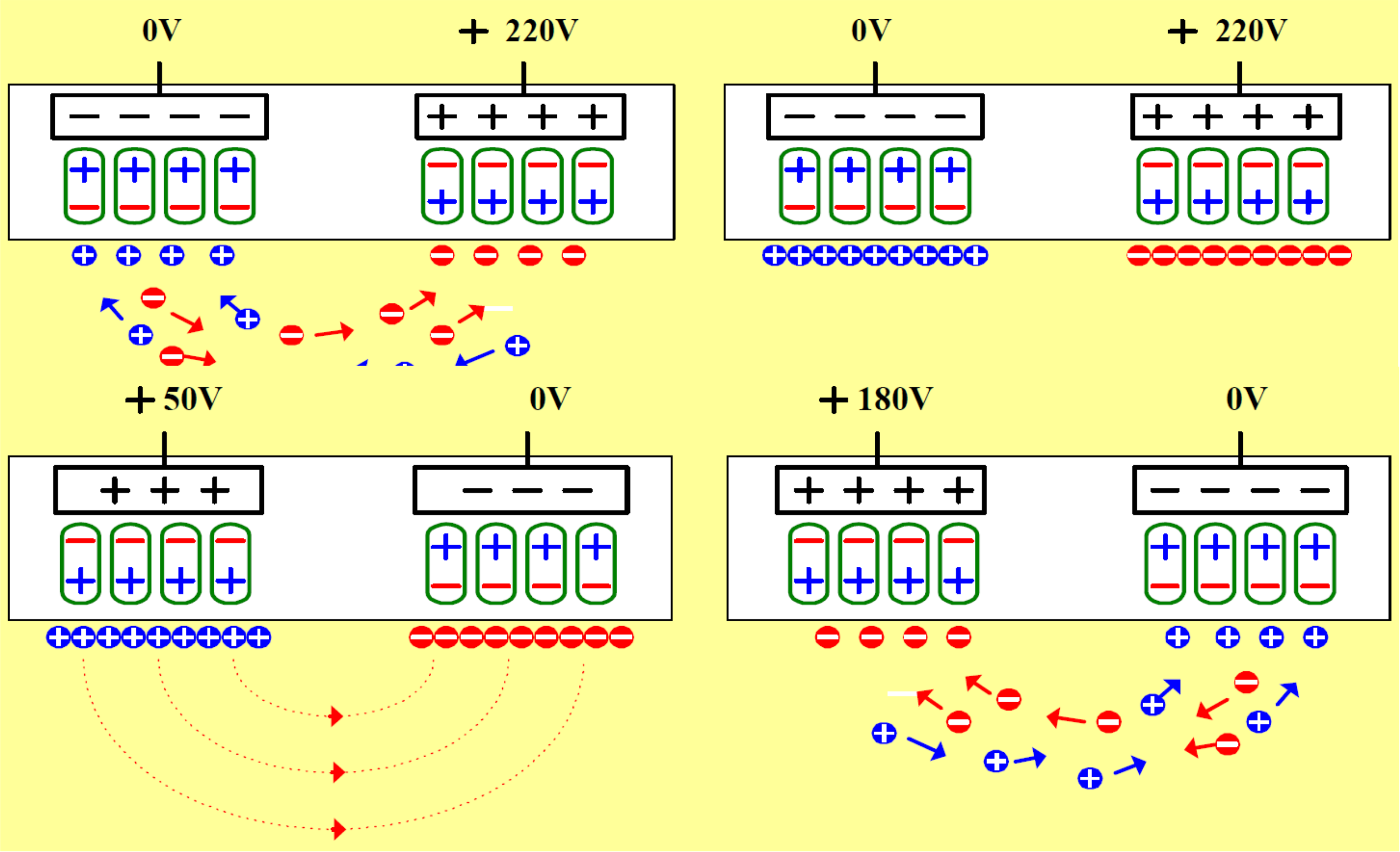
The foundation of AC discharge in plasma display panel





Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

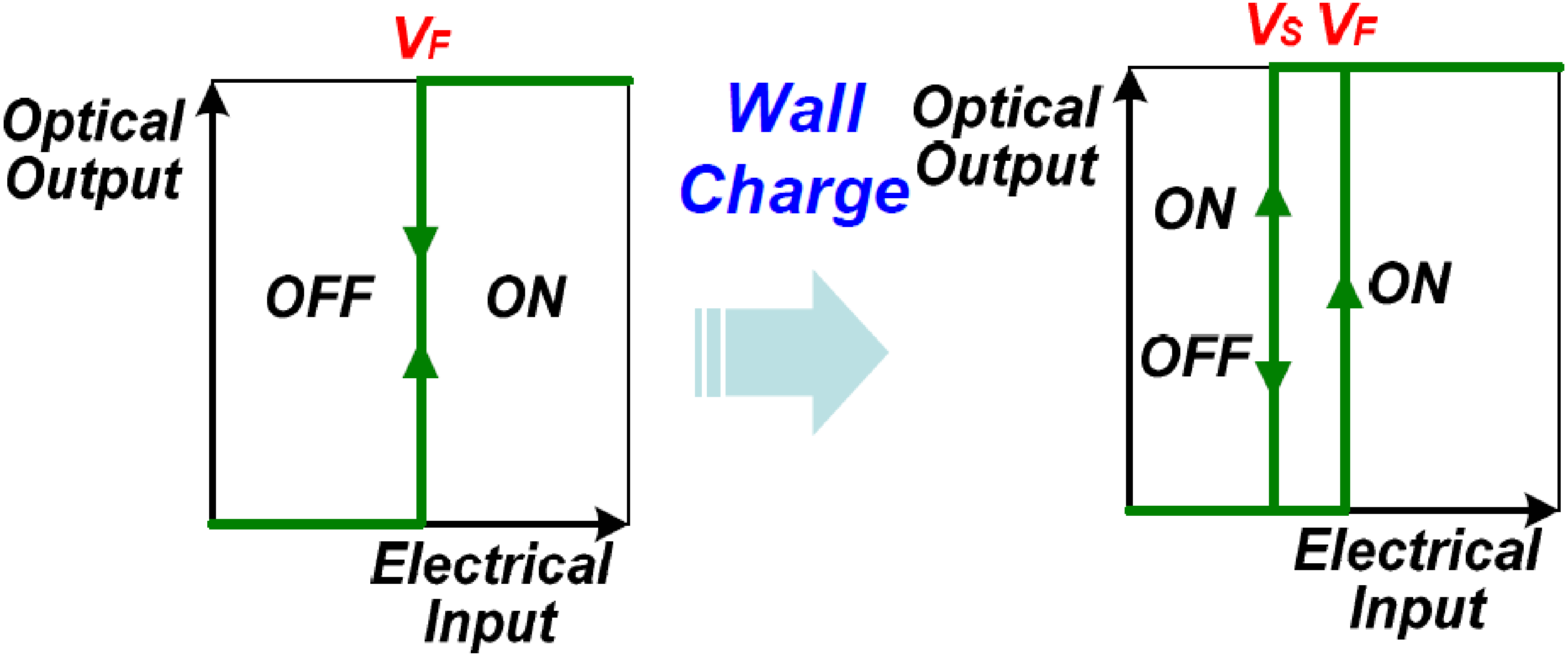
The plasma can be sustained using ac discharged in plasma display panel



- **Wall discharge reduced the required discharge voltage**

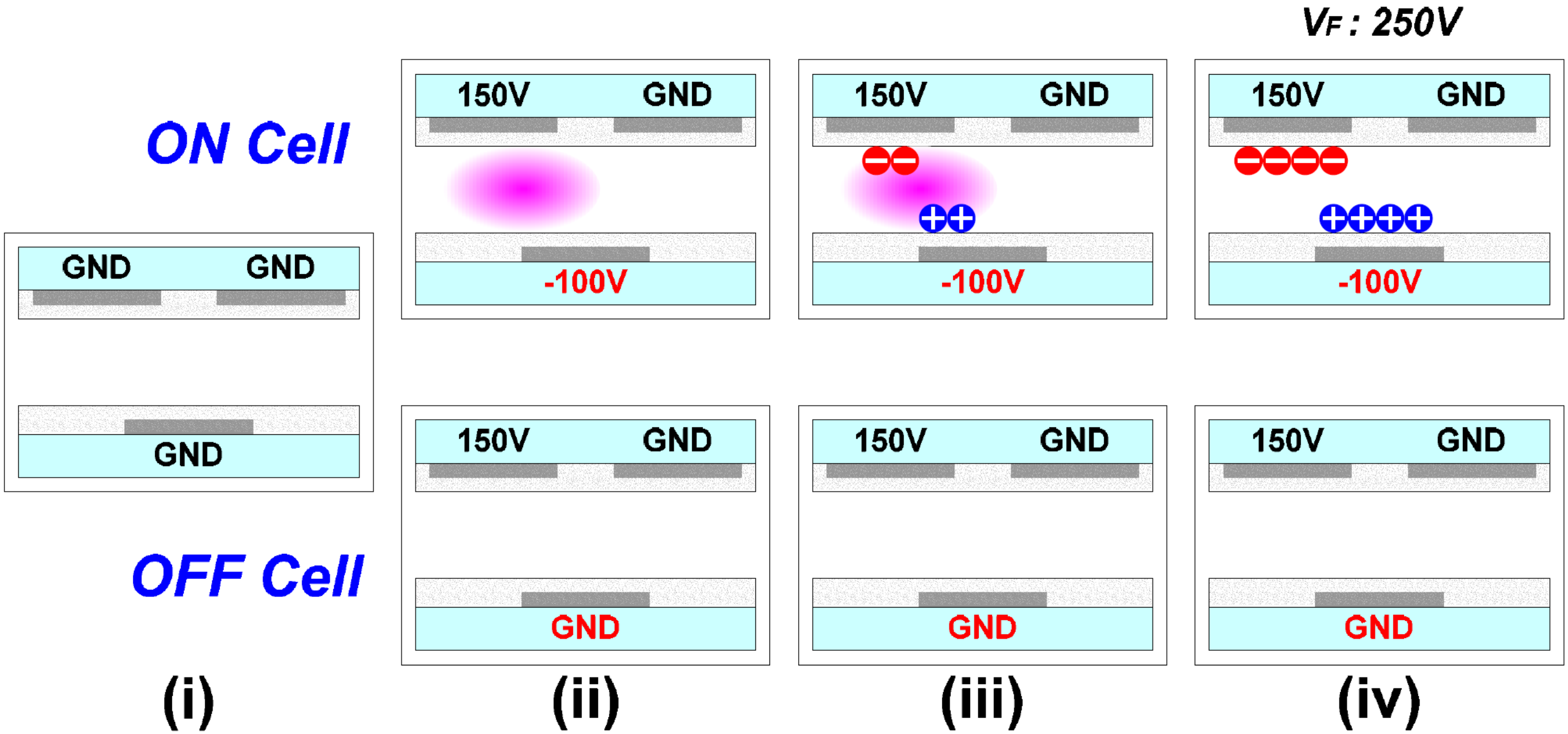
Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

Wall discharge reduced the required discharge voltage



Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

ON/OFF State Selection



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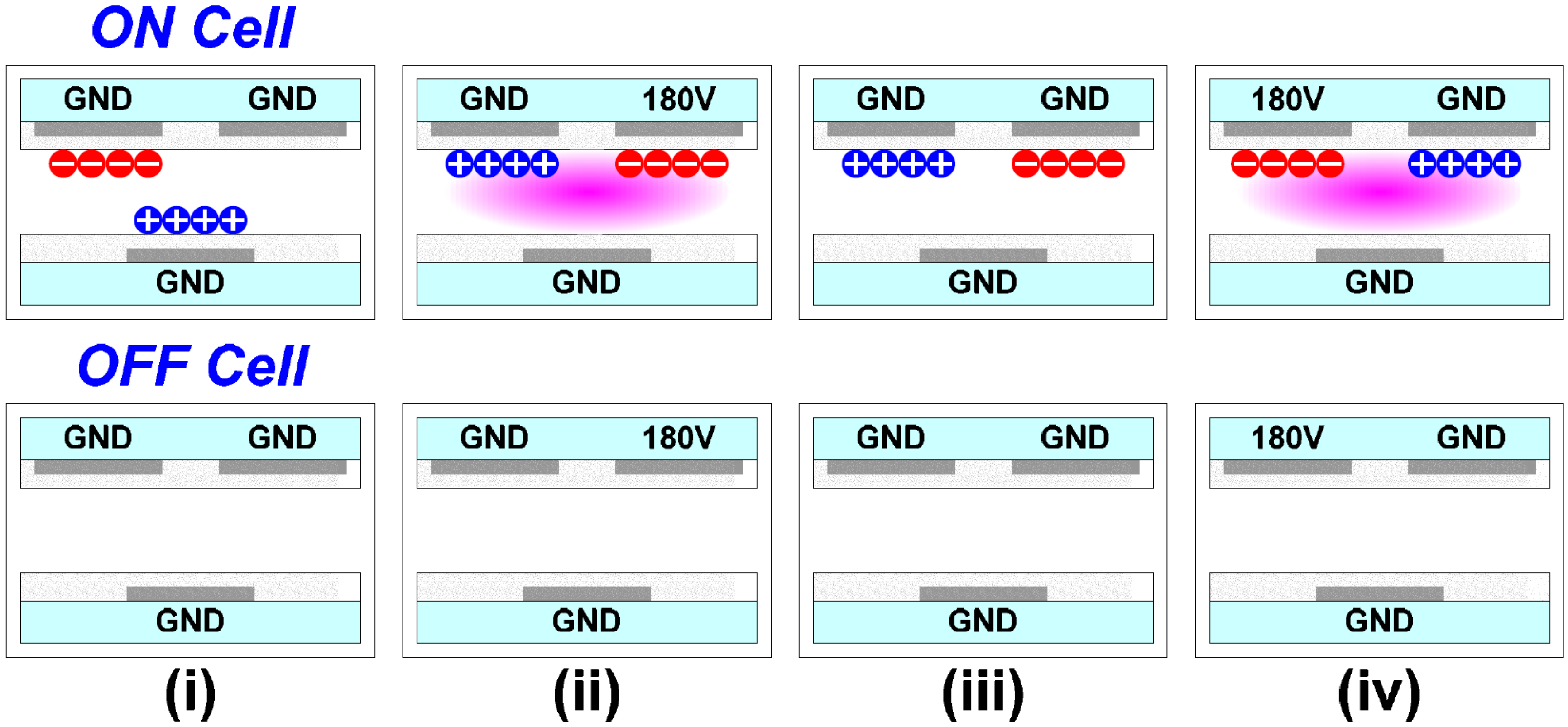
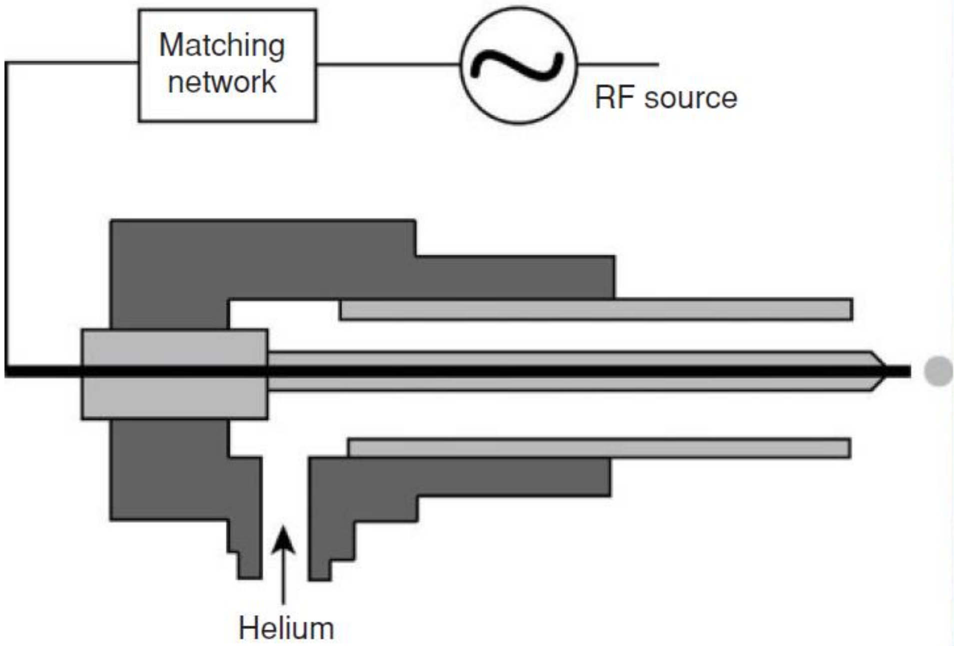
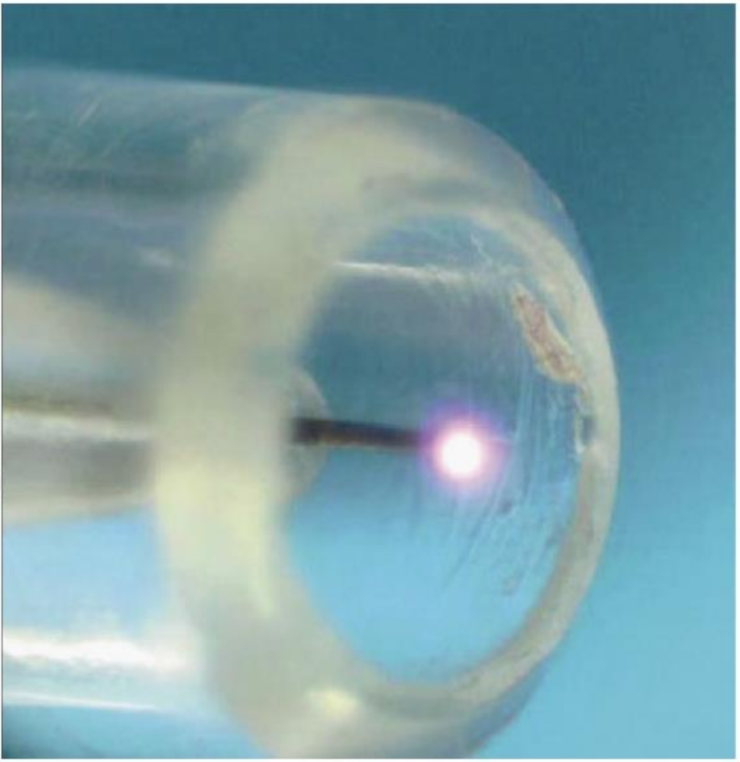
Sustain discharge



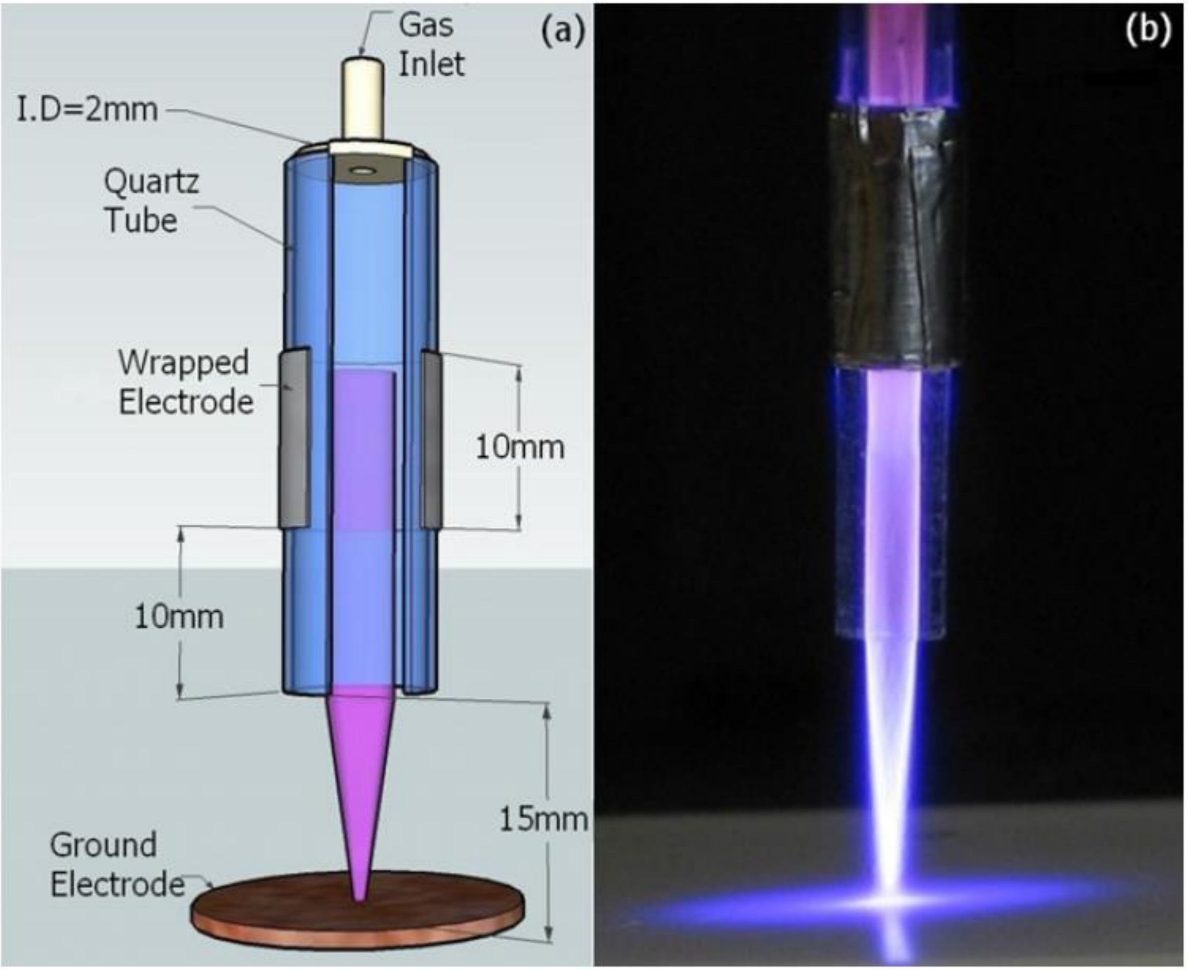
Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

Plasma-needle discharge



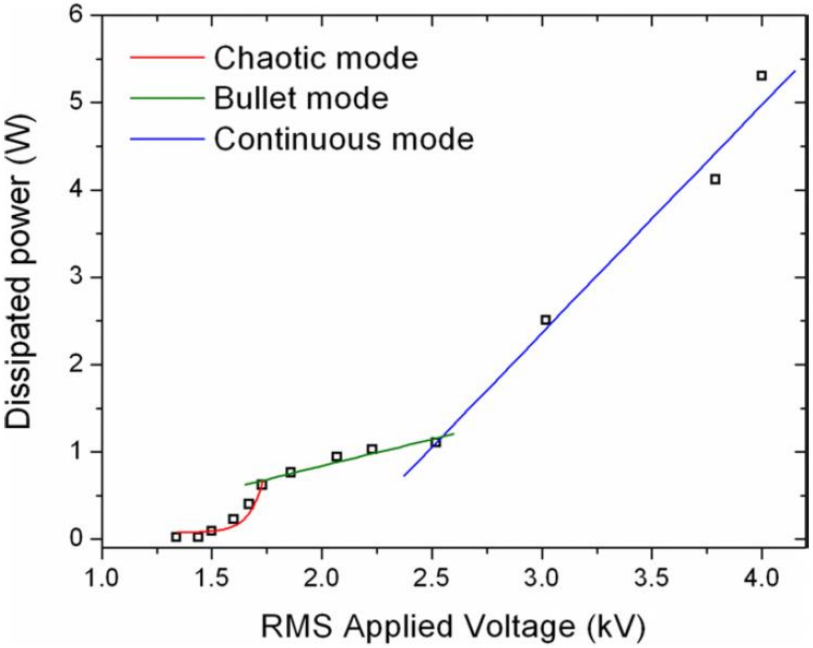


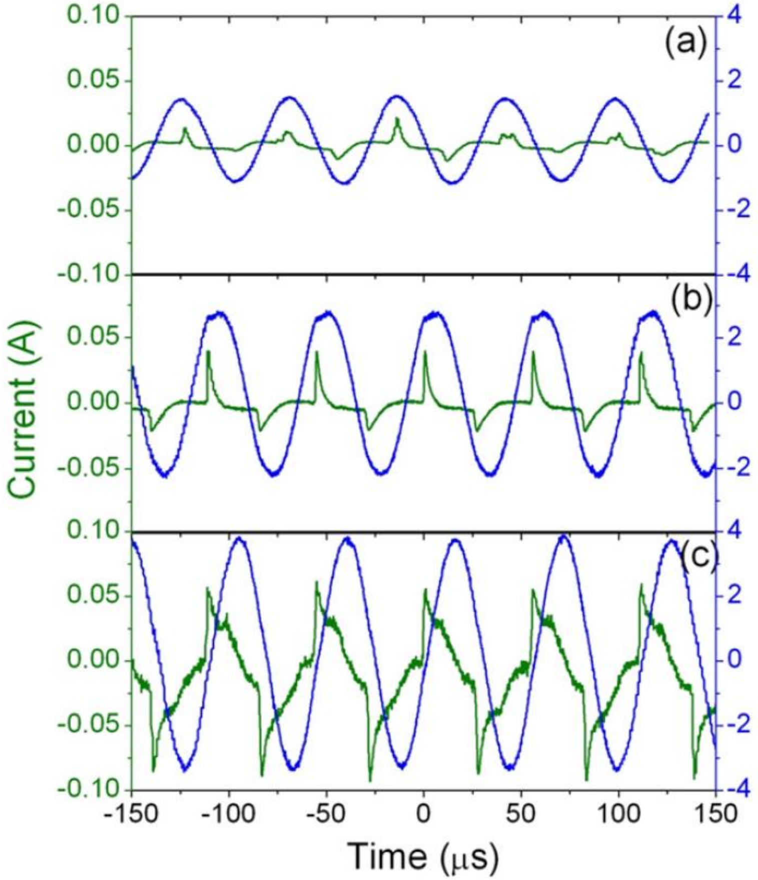
Atmospheric-pressure cold helium microplasma jets



J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

There are three different modes: chaotic, bullet, and continuous mode



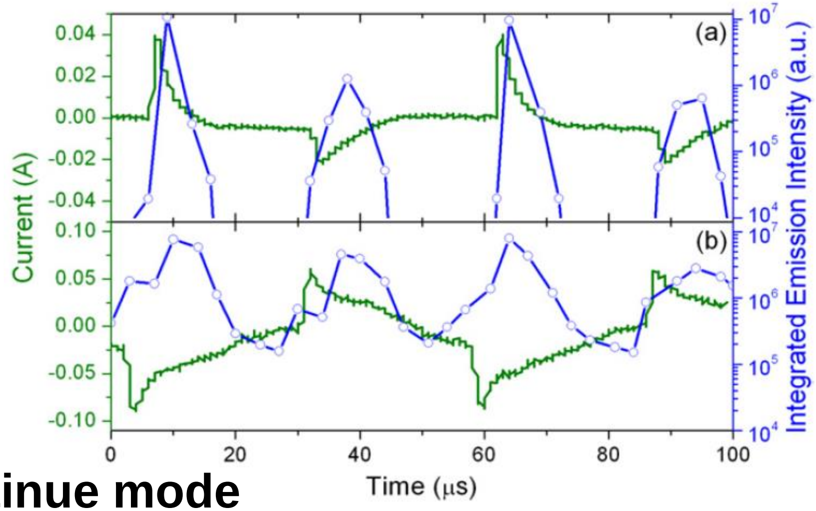


J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

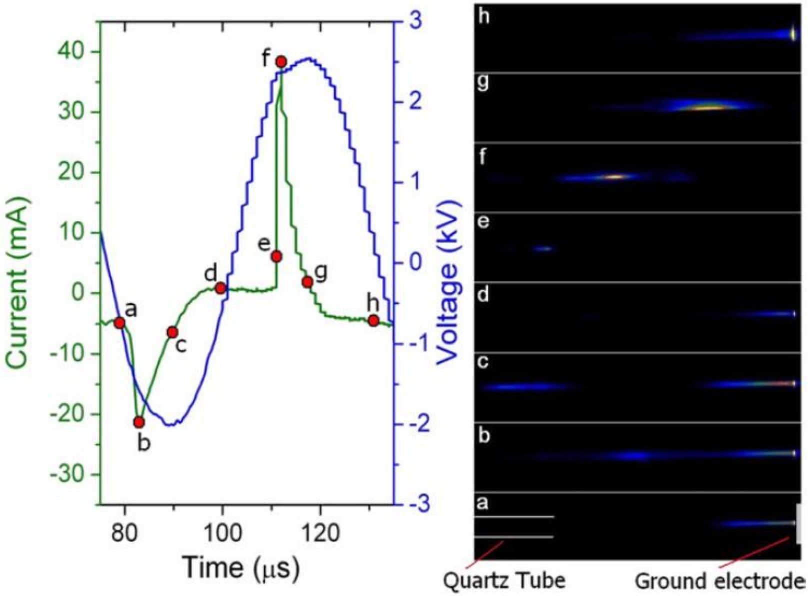
In bullet mode, the plasma jet comes out as a pulse

- **wavelength-integrated optical emission signal (350–800 nm)**
- **Images of bullet mode**

Bullet mode



Continue mode

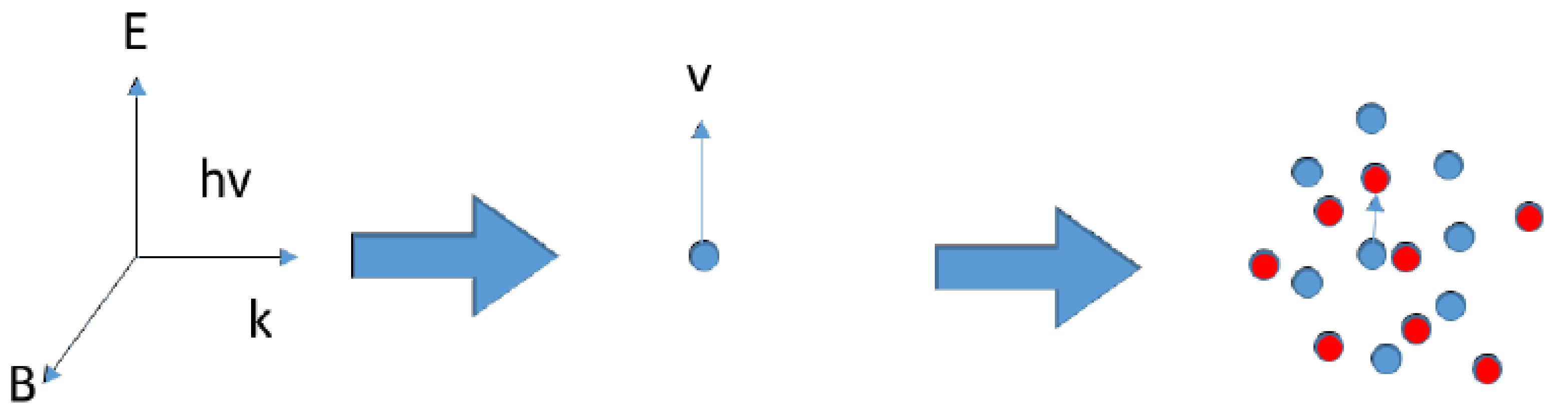


J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

Methods of plasma production

- DC electrical discharges
  - Dark electrical discharges in gases
  - DC electrical glow discharges in gases
  - DC electrical arc discharges in gases
- AC electrical discharges
  - RF electrical discharges in gases
  - Microwave electrical discharges in gases
  - Dielectric-barrier discharges (DBDs)
- **Other mechanism**
  - **Laser produced plasma**
  - **Pulsed-power generated plasma**

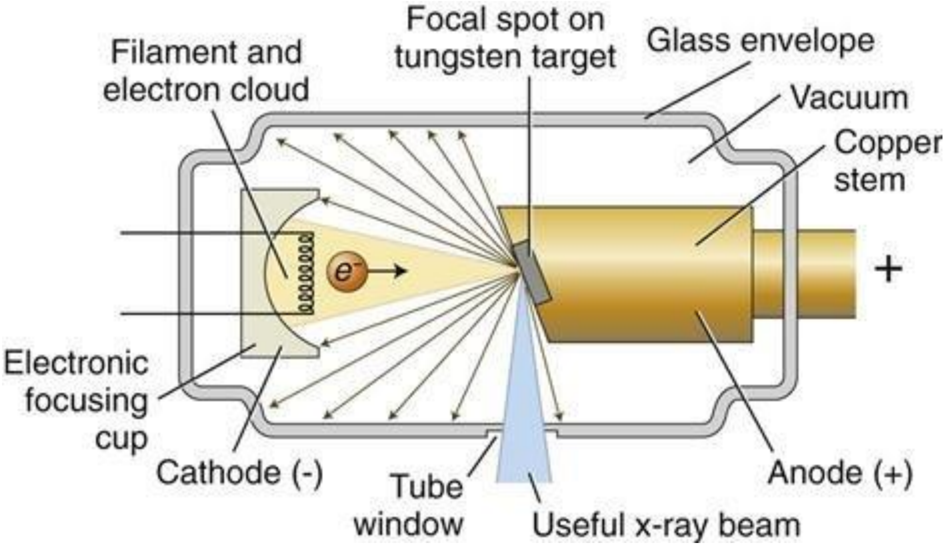
Laser is absorbed in underdense plasma through collisional process called inverse bremsstrahlung

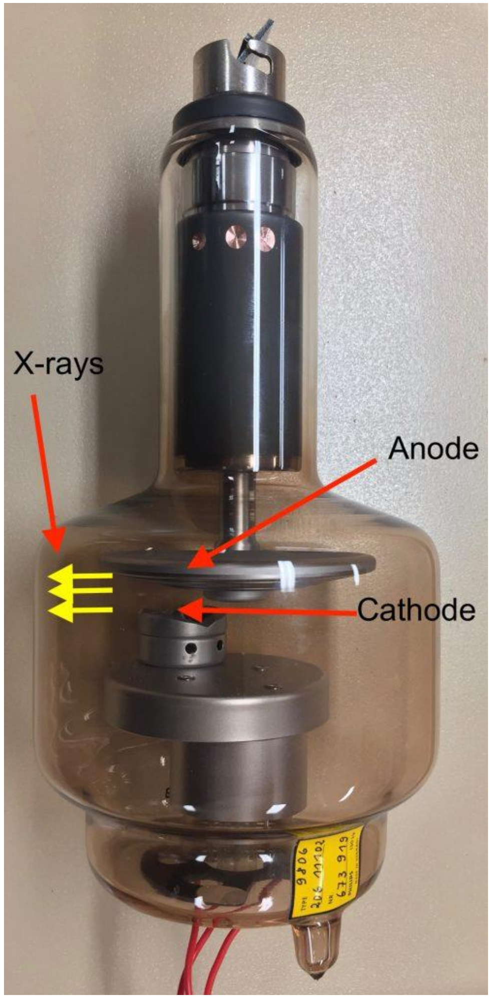


Electrons accelerated by electric fields

Electrons collide with other electrons / ions

X ray is generated via bremsstrahlung emission

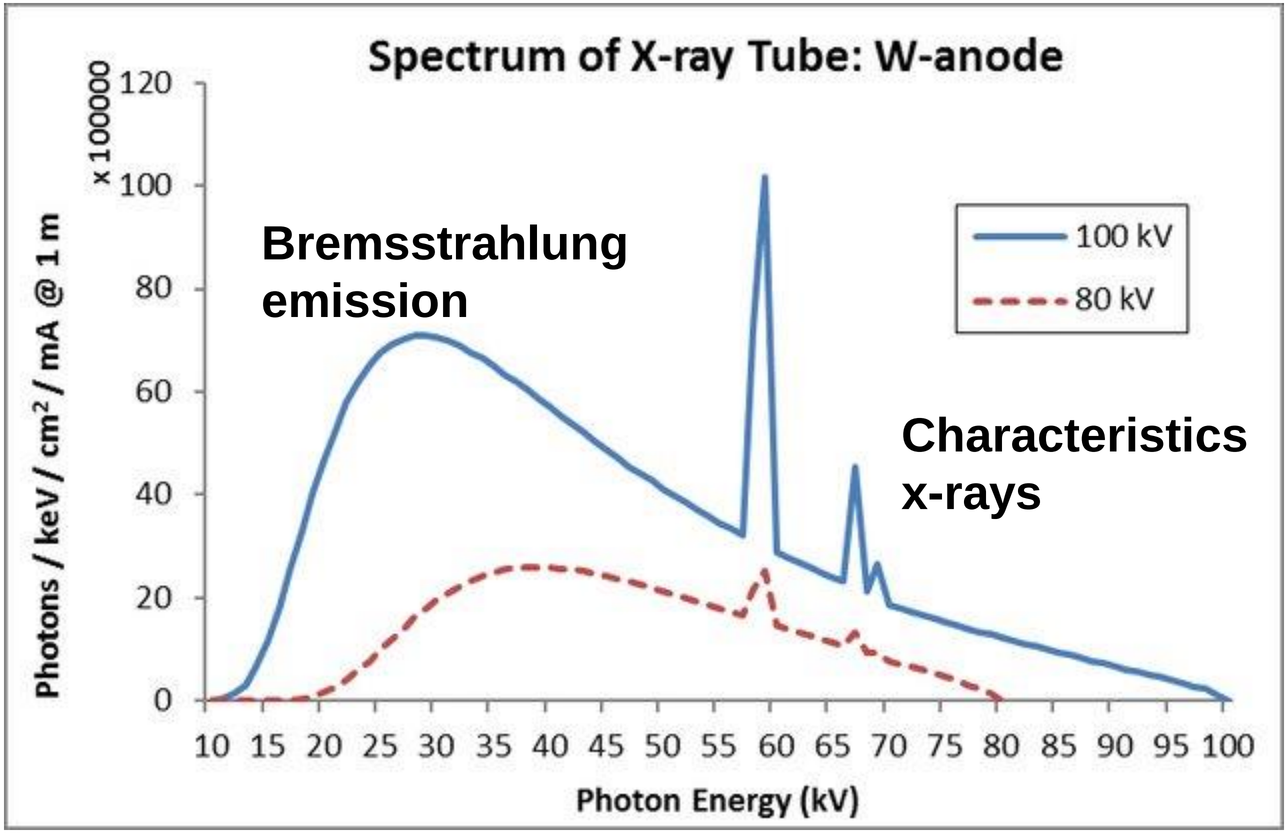




https://www.researchgate.net/publication/327816840_X-ray_imaging_using_100_mm_thick_Gas_Electron_Multipliers_operating_in_Kr-CO2_mixtures/figures?lo=1
https://undergradimaging.pressbooks.com/chapter/radiation-in-medical-imaging/

The x-ray tube generates a broad band x-ray emission

- Spectrum of an X-ray tube with a tungsten anode for 2 different tube voltages calculated with SPEKCALC.

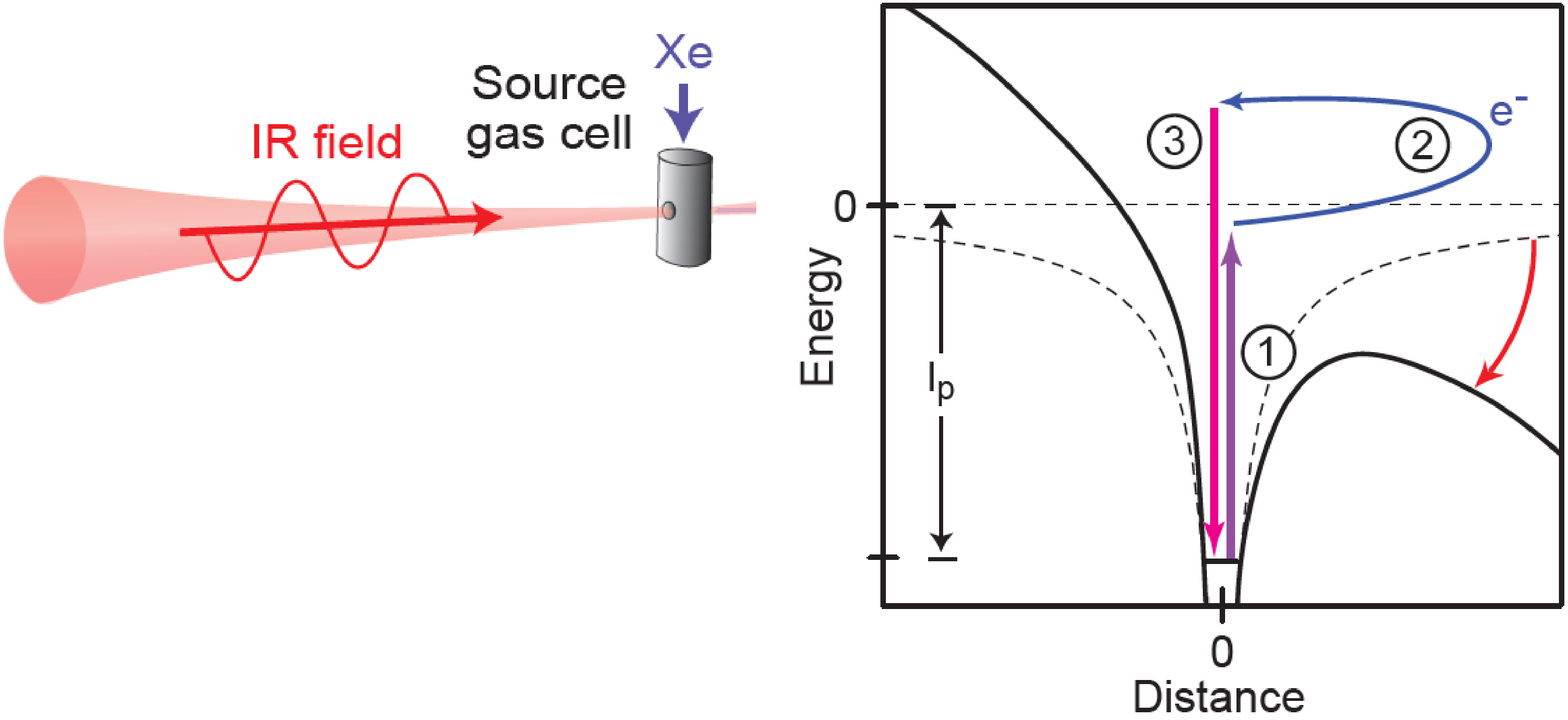


Bremsstrahlung emission

Characteristics x-rays

Electric field of a high-power laser can perturb the potential of a nuclear and thus ionize the atom directly

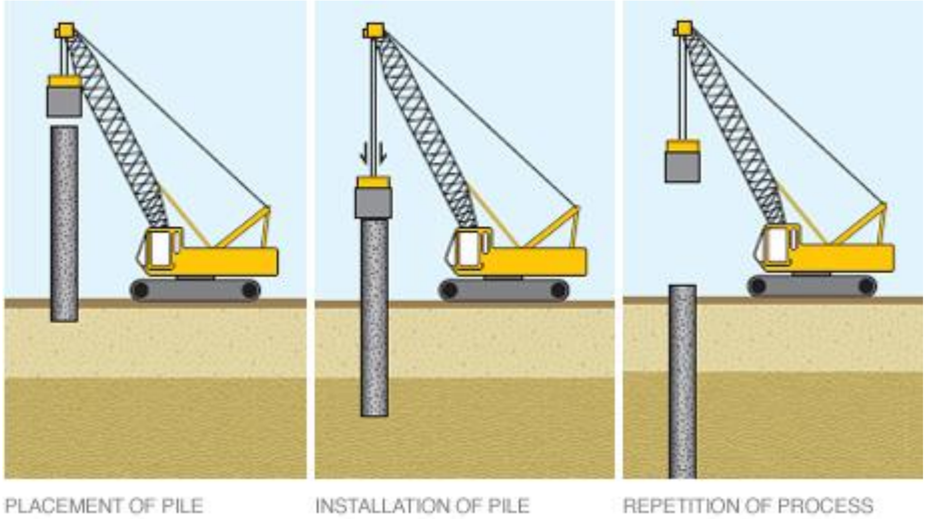
- For I < 10^{18} w/cm^2



M. Krüger, etc., Appl. Sci. 9, 378 (2019)

Driven piles - prefabricated steel, wood or concrete piles are driven into the ground using impact hammers

Driven piles



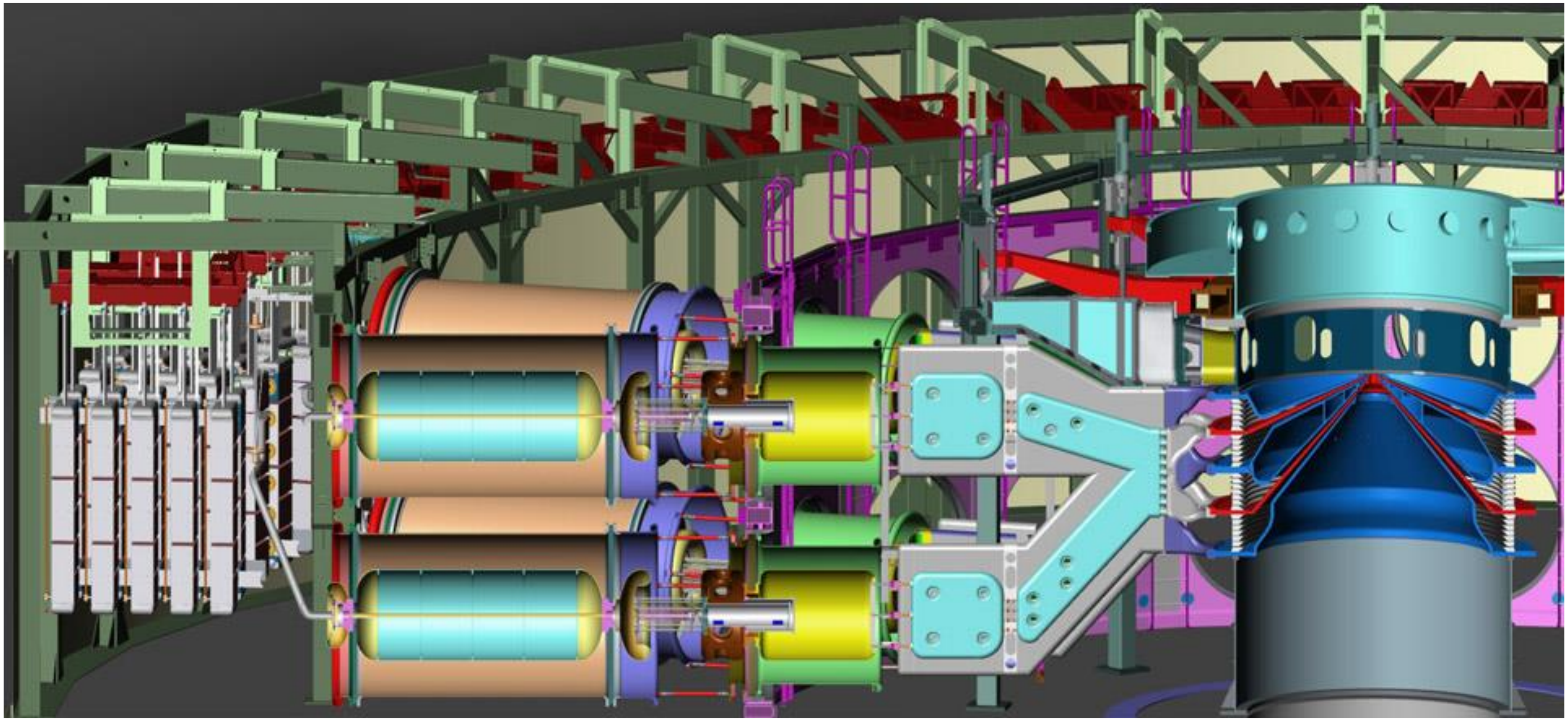
Hammer

http://www.saudifoundations.com/driven.html
http://learnhowtowritesongs.com/tag/thesaurus/

Example of short pulses with a controllable repetition rate

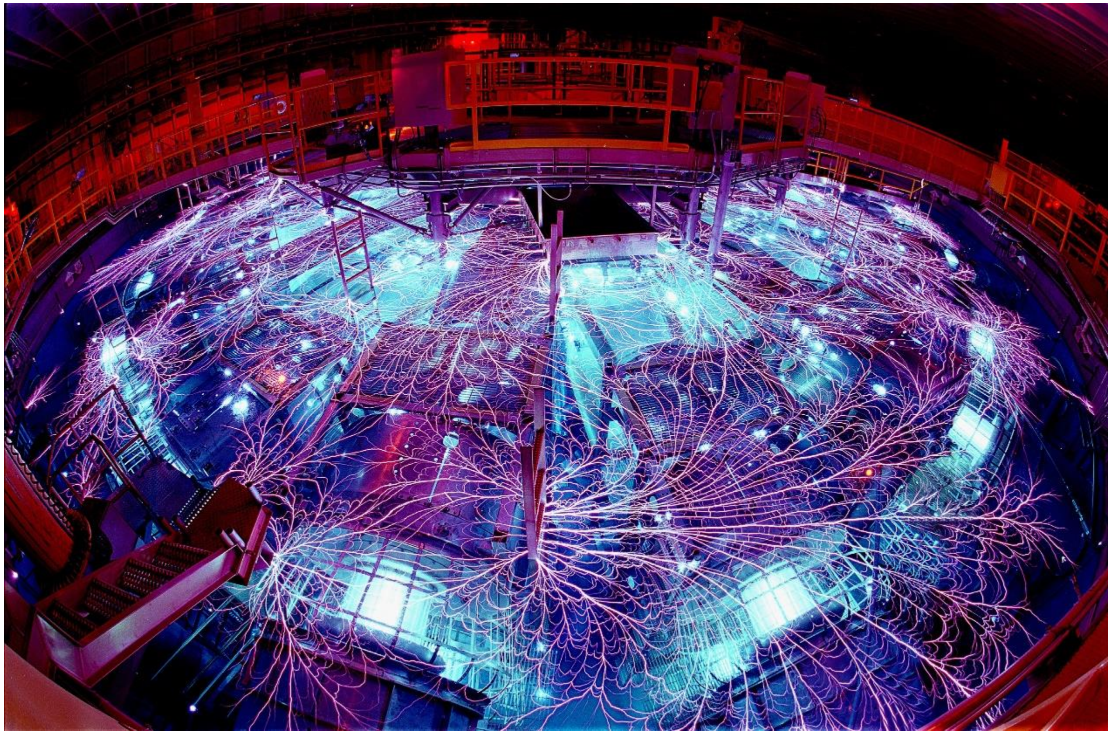
https://www.youtube.com/watch?v=5fe8b4MlPYw

Sandia’s Z machine is the world's most powerful and efficient laboratory radiation source

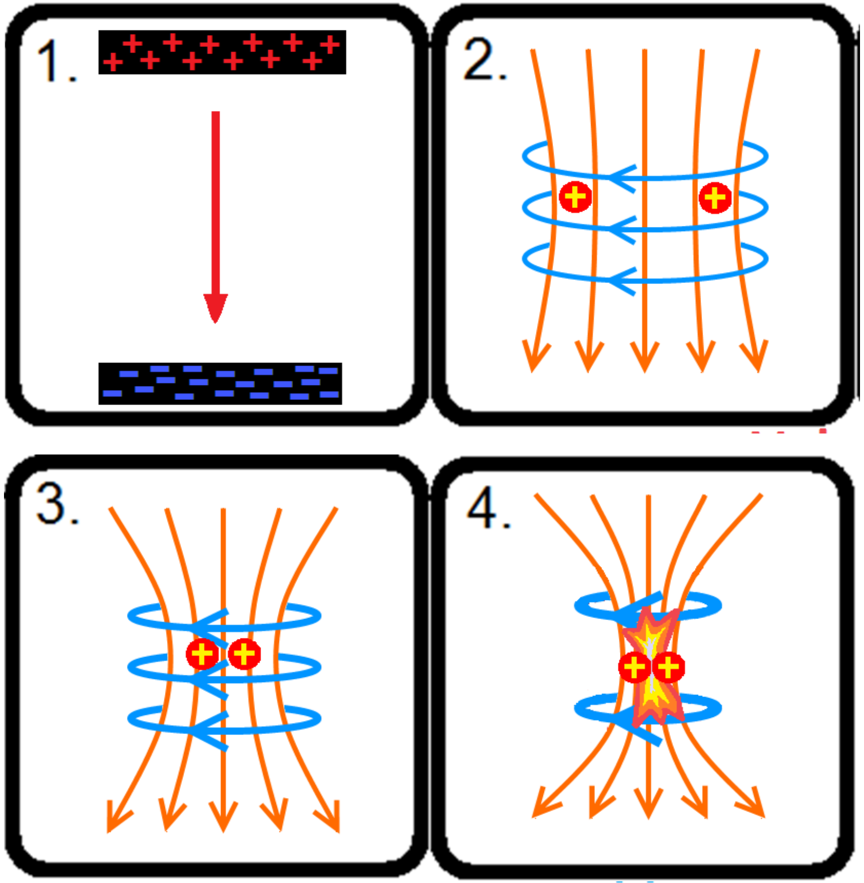


- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine discharge



Plasma can be compressed when parallel propagating current occurs



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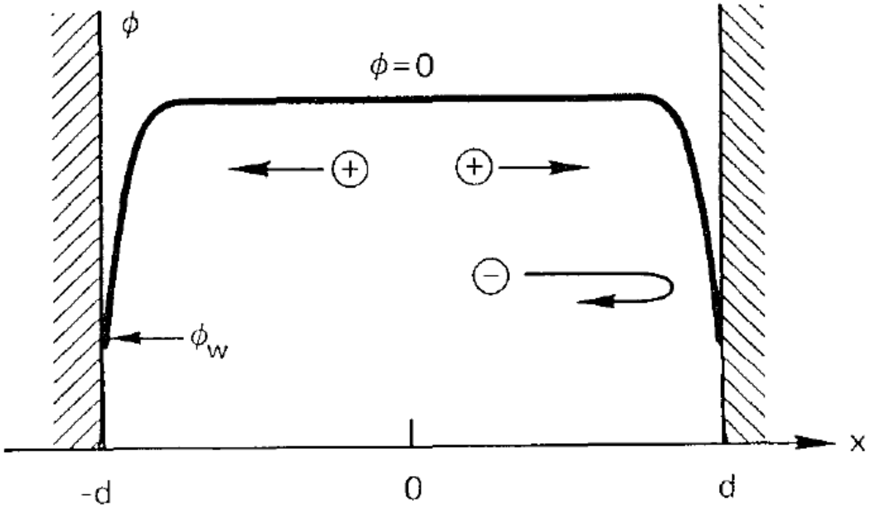
*https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

All plasmas are separated from the walls surrounding them by a sheath



- **When ions and electrons hit the wall, they recombine and are lost.**
- **Since electrons have much higher thermal velocities than ions, they are lost faster and leave the plasma with a net positive charge.**
- **Debye shielding will confine the potential variation to a layer of the order of several Debye lengths in thickness.**
- **A potential barrier is formed to confine electrons electrostatically.**
- **The flux of electrons is just equal to the flux of ions reaching the wall.**

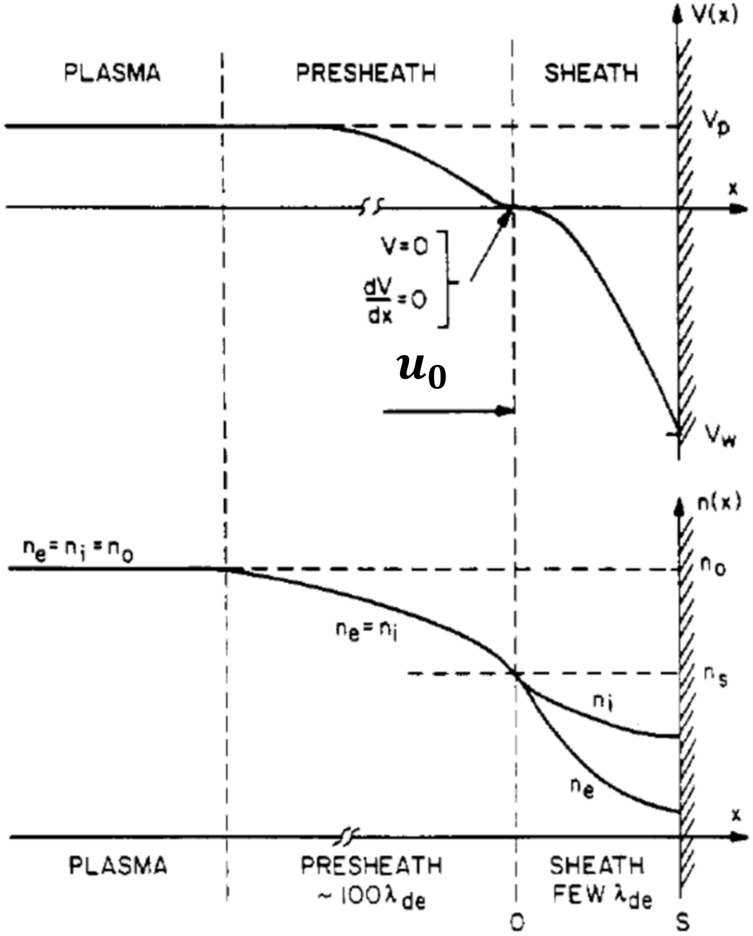
The potential variation in a plasma-wall system can be divided into three parts

- **Electron-free region:**

$$J = \frac{4}{9}\left(\frac{2e}{M}\right)^{1/2} \frac{\epsilon_0 |\phi_w|^{3/2}}{d^2}$$

  - **J is determined by the ion production rate**
  - **Φ_w is determined by the equality of electron and ion fluxes.**
- **Sheath:**
  - **~Debye length, n_e is appreciable.**
  - **A dark layers where no electrons were present to excite atoms to emission.**
  - **Presheath: ions are accelerated to the required velocity u_0 by a potential drop**

$$|\phi| \geq \frac{1}{2}\frac{KT_e}{e} \quad .$$



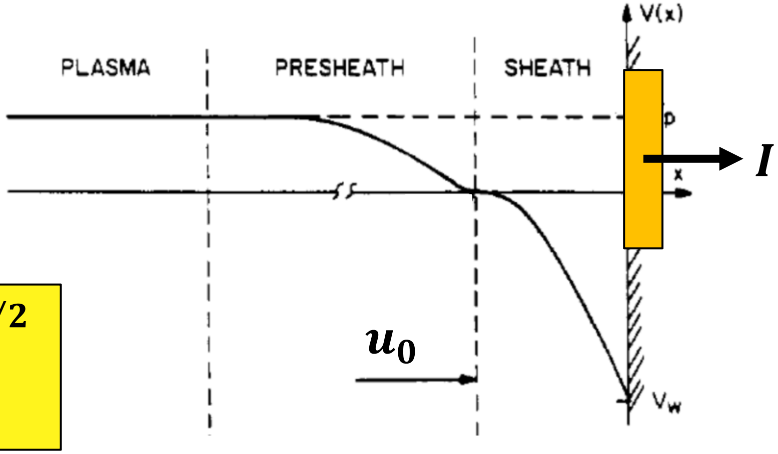
Electrostatic probes (Langmuir probe)

- The electron current can be neglected if the probe is sufficiently negative relative to the plasma to repel most electrons.

$$m{u_0}^2 > KT_e \qquad J = en_0u_0 \qquad I = n_s eA\left(\frac{KT_e}{m}\right)^{1/2}$$

$$|\phi| \simeq \frac{1}{2}\frac{KT_e}{e}$$

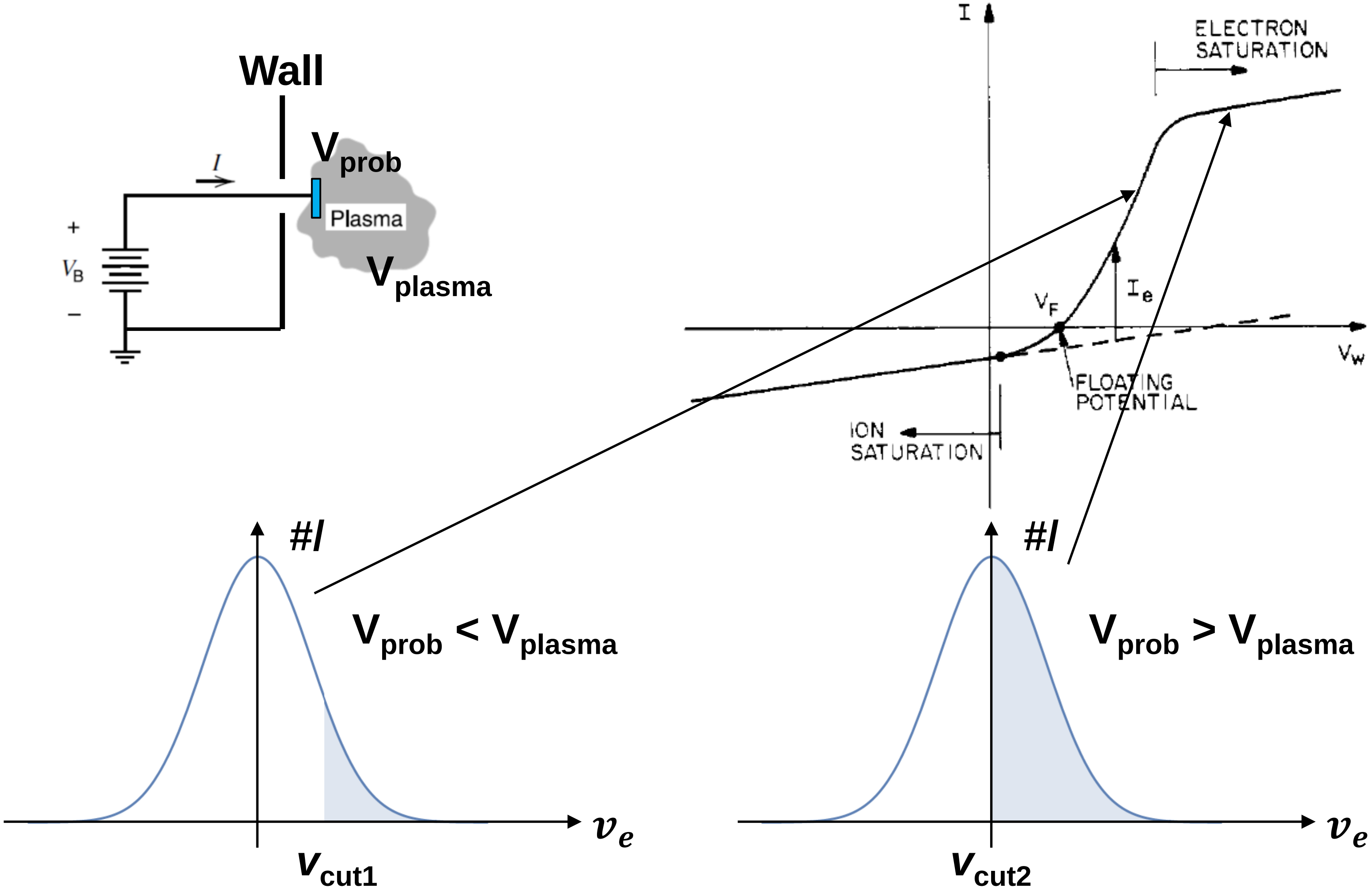
$$n_s = n_0 \exp\left(\frac{e\phi}{KT_e}\right) = n_0 e^{-1/2} = 0.61n_0$$



Bohm current: $I_B \simeq 0.5n_0 eA\left(\frac{KT_e}{m}\right)^{1/2}$

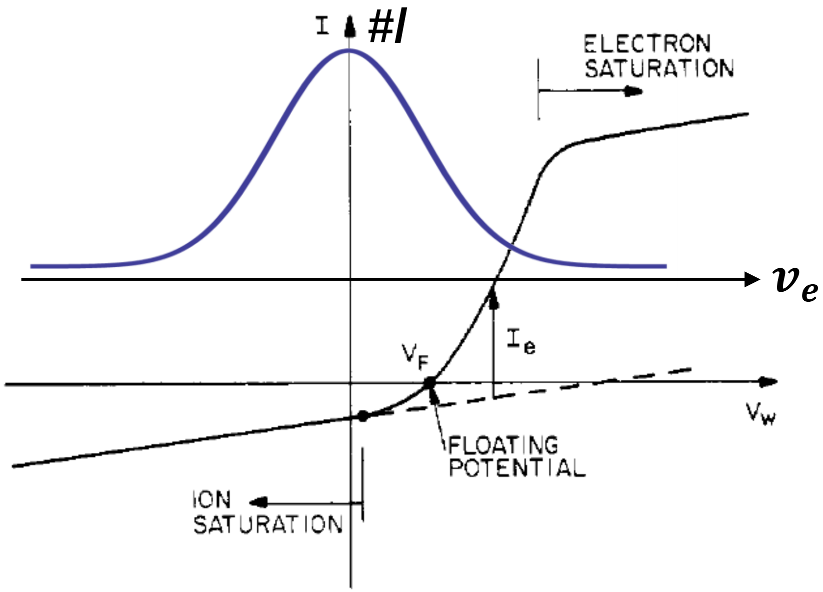
- The plasma density can be obtained once the temperature is known.

Electron temperature can be determined by the slope of the I-V curve between ion and electron saturation



Principles of plasma discharges and materials processing, 2nd edition, by Michael A. Lieberman and Allan J. Lichtenberg

Electron temperature can be determined by the slope of the I-V curve between ion and electron saturation



- **Electron saturation current:**

$$I_{\mathrm{es}} = \frac{1}{4} n_s \exp\left(\frac{\mathrm{eV}_p}{KT_e}\right) \bar{v}_e \mathrm{eA}$$

$$\boxed{n_0 = \frac{4I_{\mathrm{es}}}{\mathrm{eA}}\sqrt{\frac{\pi m_e}{8T_e}}}$$

- **Ion saturation current:**

$$I_{\mathrm{is}} = \mathrm{AJ}_{\mathrm{is}} = \mathrm{eA}\Gamma_{\mathrm{is}}$$

$$\boxed{n_i = \frac{4I_{\mathrm{is}}}{\mathrm{eA}}\sqrt{\frac{\pi m_i}{8KT_i}}}$$

- **Total current:**

$$I = I_{\mathrm{is}} + I_e = I_{\mathrm{is}} + \frac{1}{4} n_s \exp\left(\frac{\mathrm{eV}}{KT_e}\right) \bar{v}_e \mathrm{eA}$$

$$V \equiv \Phi$$

$$\boxed{T_e = \frac{e(I - I_{\mathrm{is}})}{\mathrm{dI/dV}}}$$

Course Outline

1. What is Plasma?
2. Varies kinds of plasma
    a. How plasma is generated
    b. **Plasma in space**
    c. Material Processing
    d. Biomedical application
    e. Pparticle beam source
    f. High energy particle accelerator
    g. Controlled thermonuclear fusion
    h. Neutral beam source
    i. Electrical propulsion

Aurora

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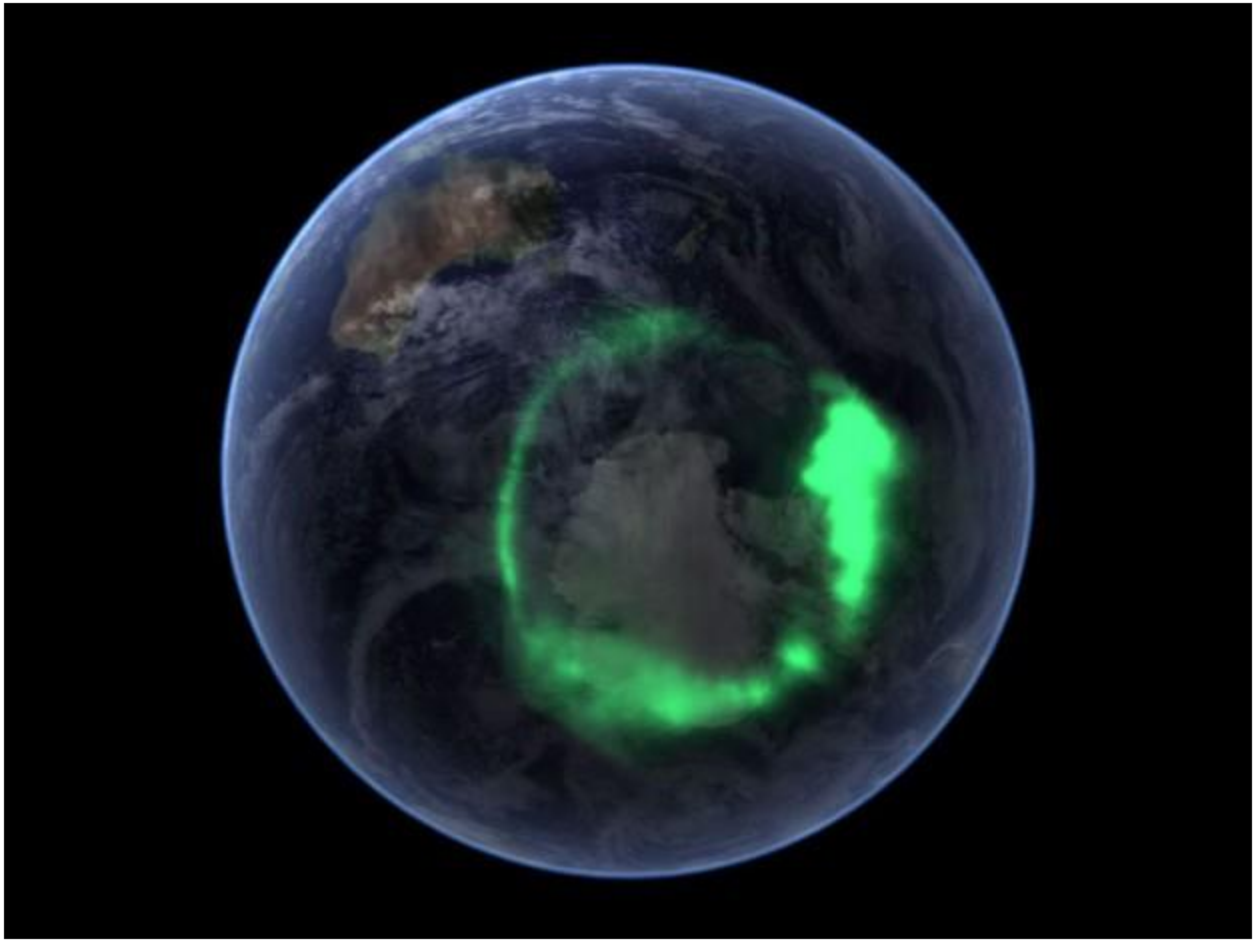
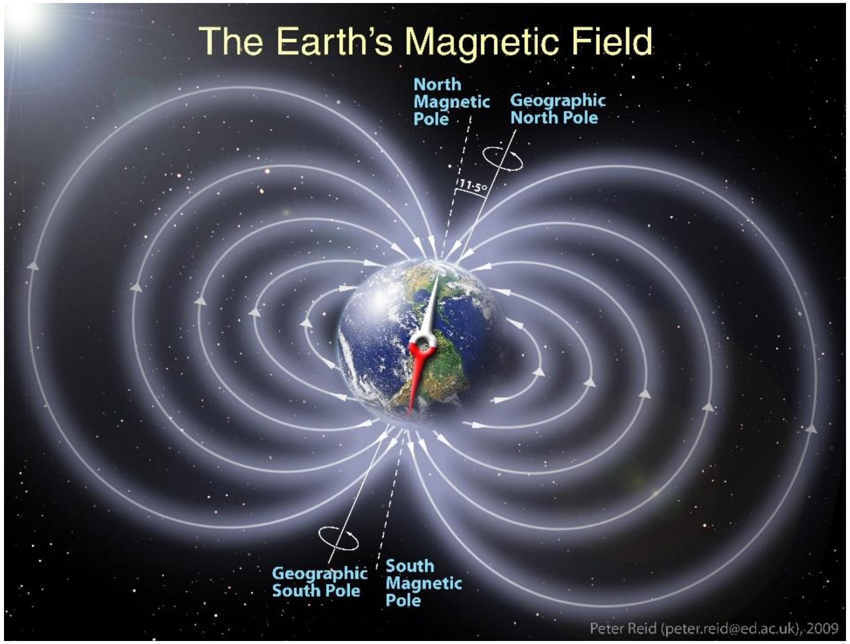
https://en.wiktionary.org/wiki/aurora

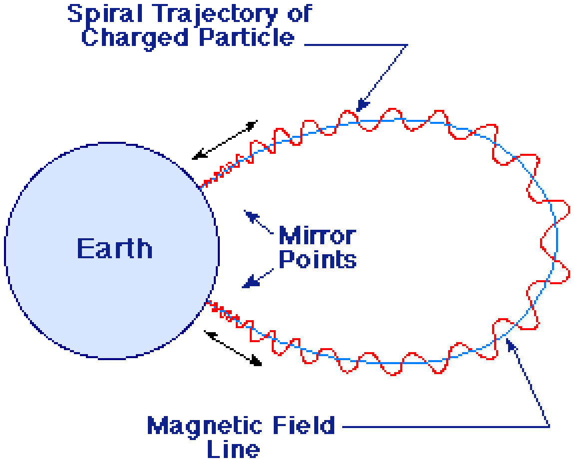
Aurora seen from a satellite



https://flashpack.com/insights/2014/11/20/aurora-australis-forget-the-northern-lights-have-you-heard-about-the-southern-lights/

Earth’s magnetic field





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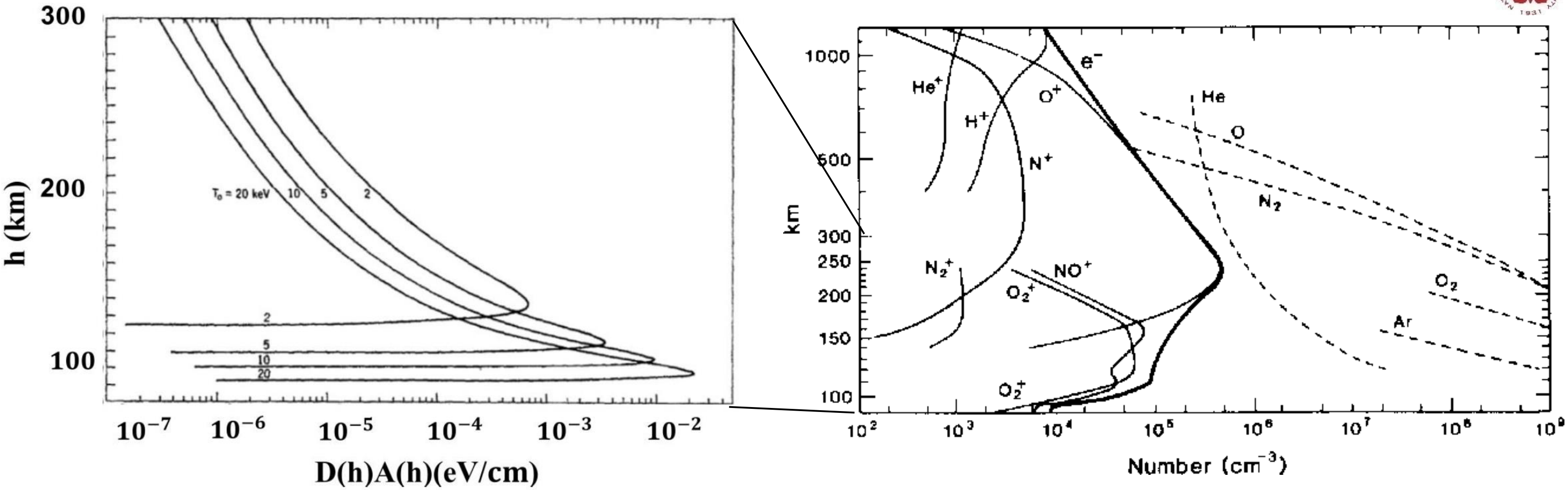
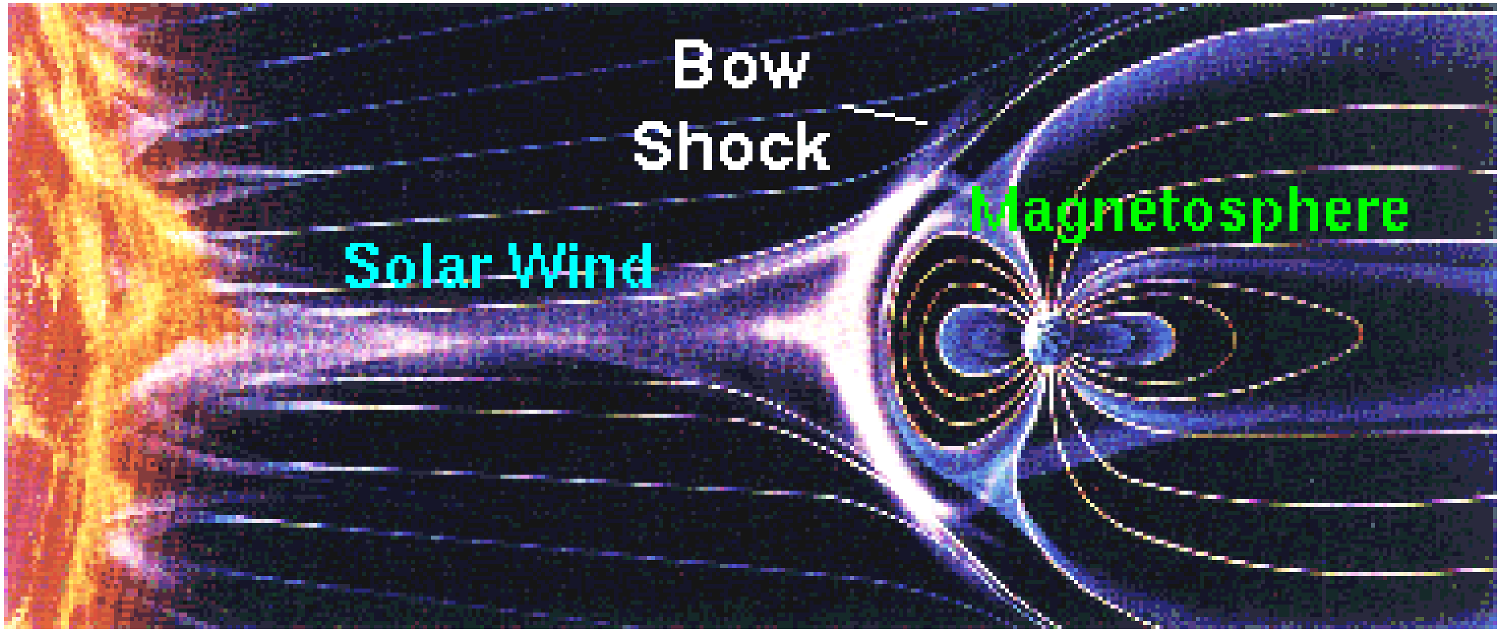
https://www.nasa.gov/mission_pages/sunearth/news/gallery/Earths-magneticfieldlines-dipole.html
http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

Colors of the aurora depends on the penetration depth of energetic electrons



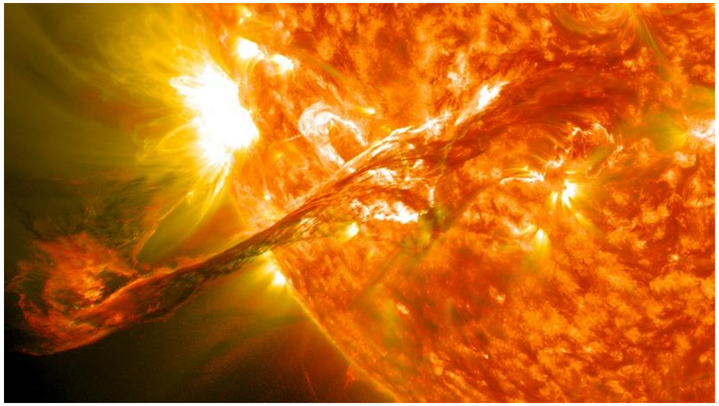
- O_2: green or dark red
- N_2: blue or purple

Earth magnetic fields are strongly influenced by solar wind



http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

A plume of charge particles ejected from the sun was suggested in 19 centries



- 1859, British astronomer Richard C. Carrington and Richard Hodgson made the first observation of what is called a solar fare later. A geomagnetic storm (solar storm) was observed on the following day. Carrington suspected that there may be a connection between them.
- 1910, British astrophysicist Arthur Eddington essentially suggested the existence of the solar wind without naming it.
- 1916, Kristian Birkeland suggested that the ejected material consisted of both ions and electrons.
- 1919, Frederick Lindemann suggested that particles come form the sun include both polarities, protons and electrons.

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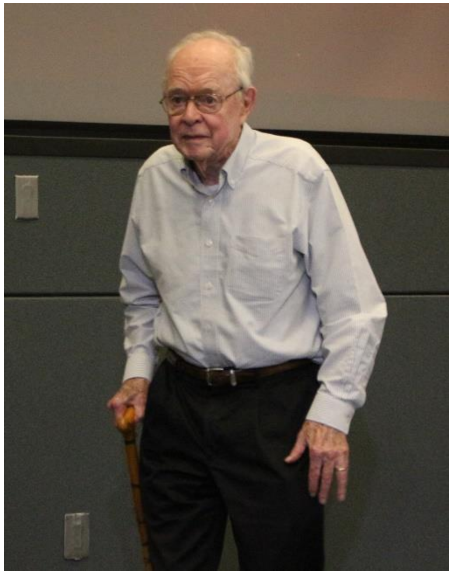
https://en.wikipedia.org/wiki/Solar_flare
https://en.wikipedia.org/wiki/Solar_wind#History

Eugene Parker named the “solar wind”

- 1930s, the temperature of the solar corona is in a million degrees Celsius was determined by scientists.
- Mid-1950s, Sydney Chapman suggested that the “gas” in this temperature must extend way out into space, beyond the orbit of Earth.
- 1950s, Ludwig Biermann suggested that the sun emits a steady stream of particles so that the comet’s tail always points away from the sun.
- 1958, Eugene Parker realized that Chapman’s model and Biermann’s hypothesis are the same phenomenon. He name it “solar wind.” He was the first person showing that the weakening effect of the gravity is similar to the hydrodynamic flow in a de Laval nozzle such that solar wind transits from subsonic to supersonic flow.
- 1959, the Soviet spacecraft Luna 1 directly observed the solar wind.



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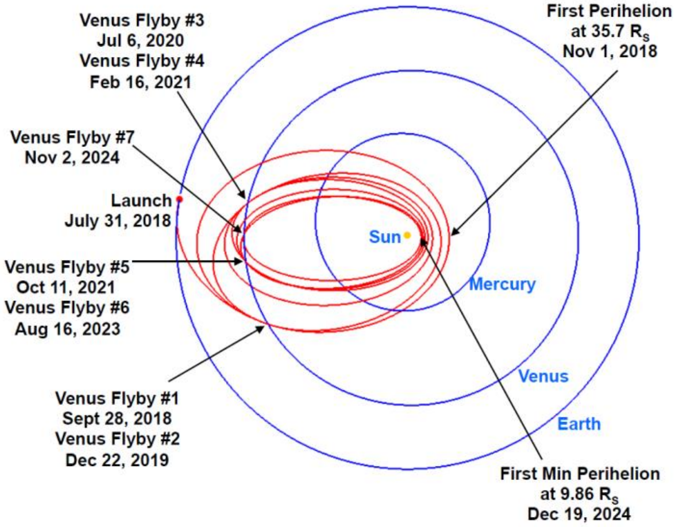
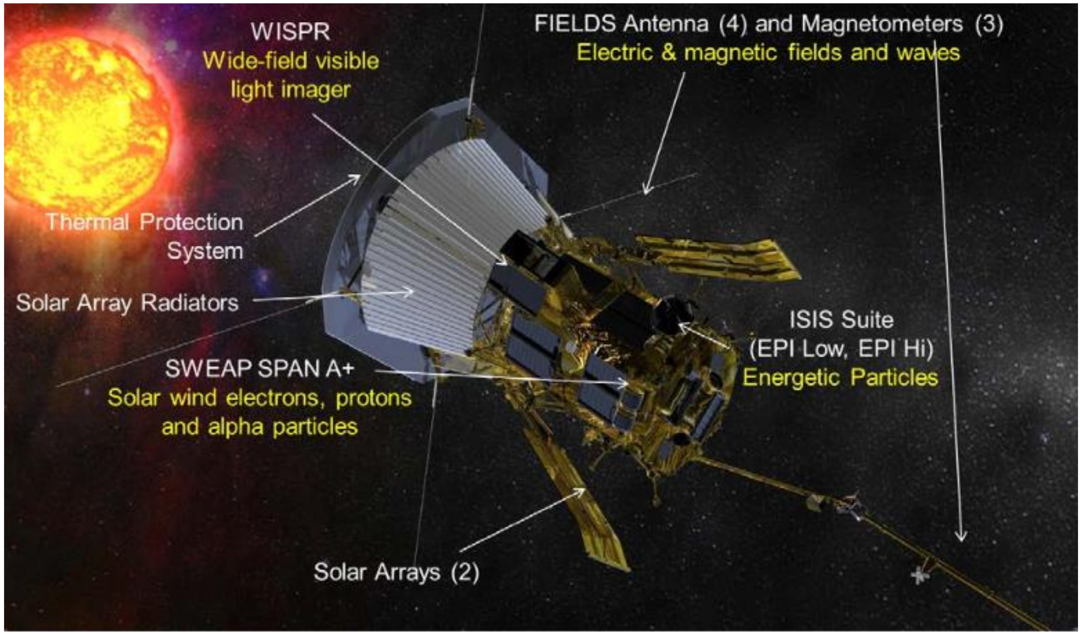
https://en.wikipedia.org/wiki/Solar_wind#History
https://en.wikipedia.org/wiki/Eugene_Parker

Parker Solar Probe launched in 2018 was to observe the outer corona of the sun

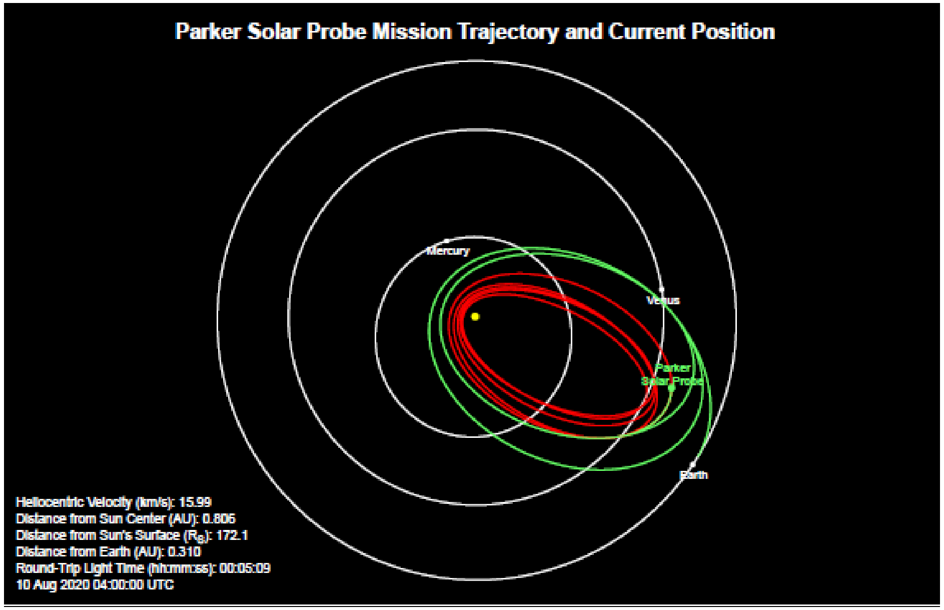
- The goals of the mission are:
    - Trace the flow of energy that heats the corona and accelerates the solar wind.
    - Determine the structure and dynamics of the magnetic fields at the sources of solar wind.
    - Determine what mechanisms accelerate and transport energetic particles.



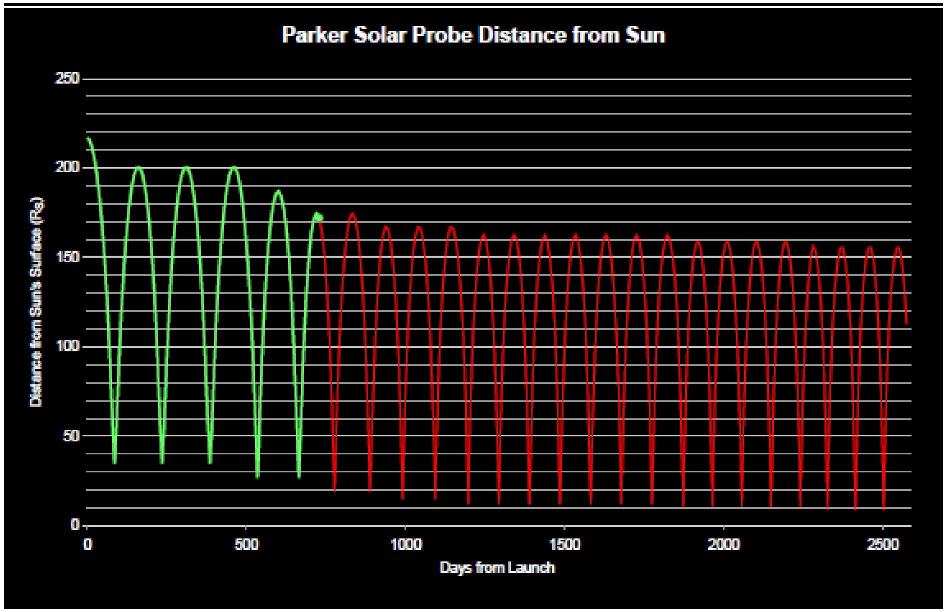


https://en.wikipedia.org/wiki/Parker_Solar_Probe#Mission
D. R. Jones, etc., ASS 17-576

Parker Solar Probe will have 24 perihelion till 2025



Heliocentric Velocity (km/s): 15.99
Distance from Sun Center (AU): 0.806
Distance from Sun's Surface (R_S): 172.1
Distance from Earth (AU): 0.310
Round-Trip Light Time (hh:mm:ss): 00:05:09
10 Aug 2020 04:00:00 UTC

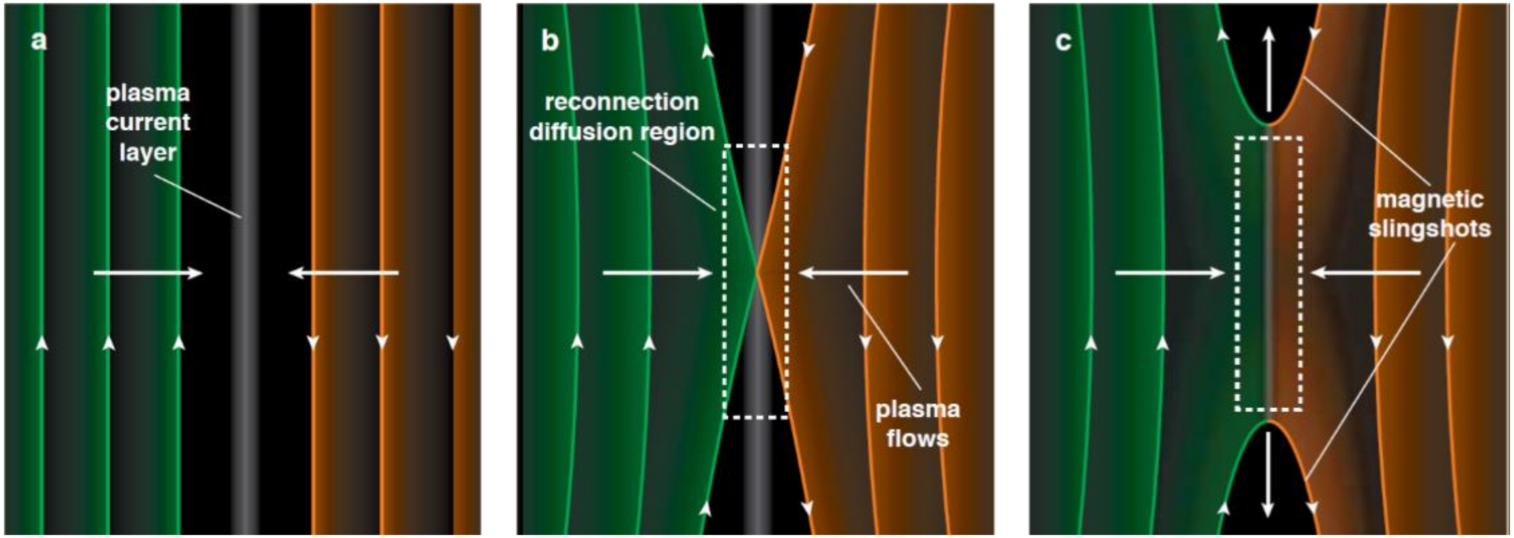


- **More information can be obtained from the following link:**

https://www.nso.edu/wp-content/uploads/2018/04/PSP_DKIST_CSP_v1-1.pdf

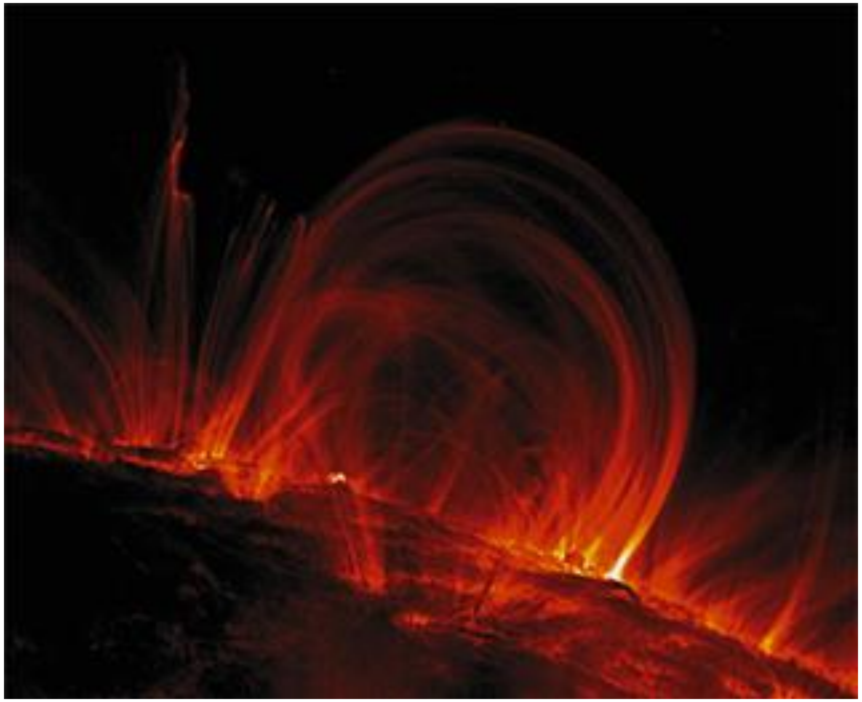
http://parkersolarprobe.jhuapl.edu/The-Mission/index.php

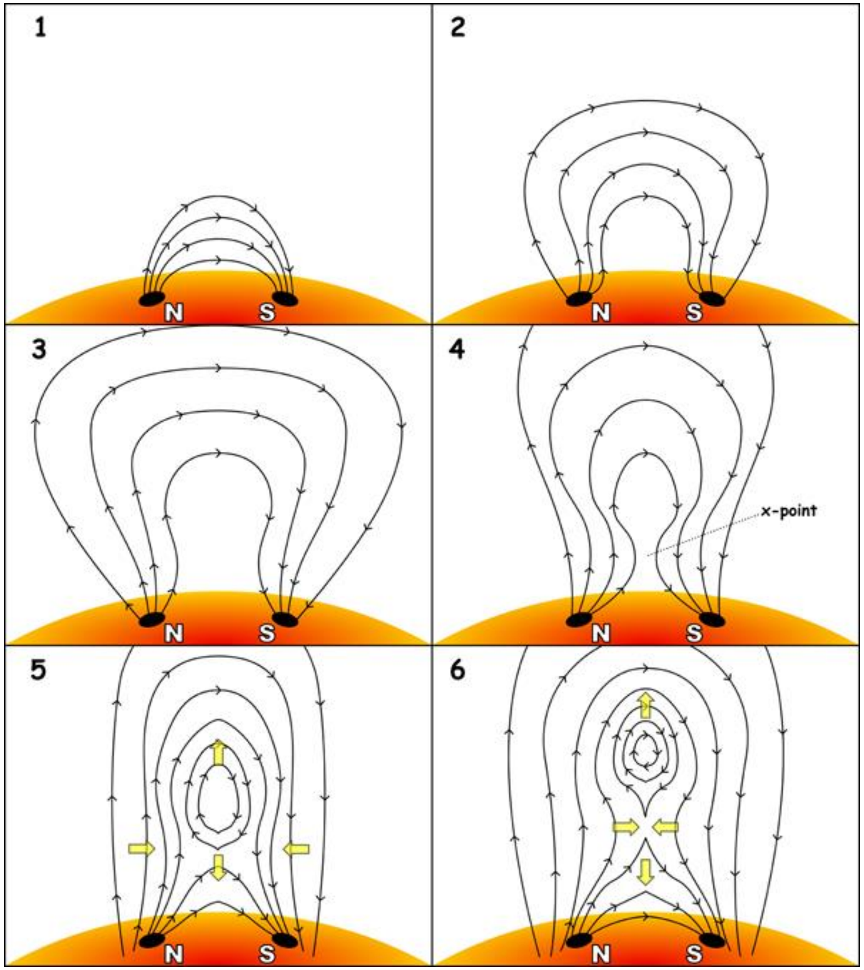
Reconnection



https://www.youtube.com/watch?v=7sS3Lpzh0Zw

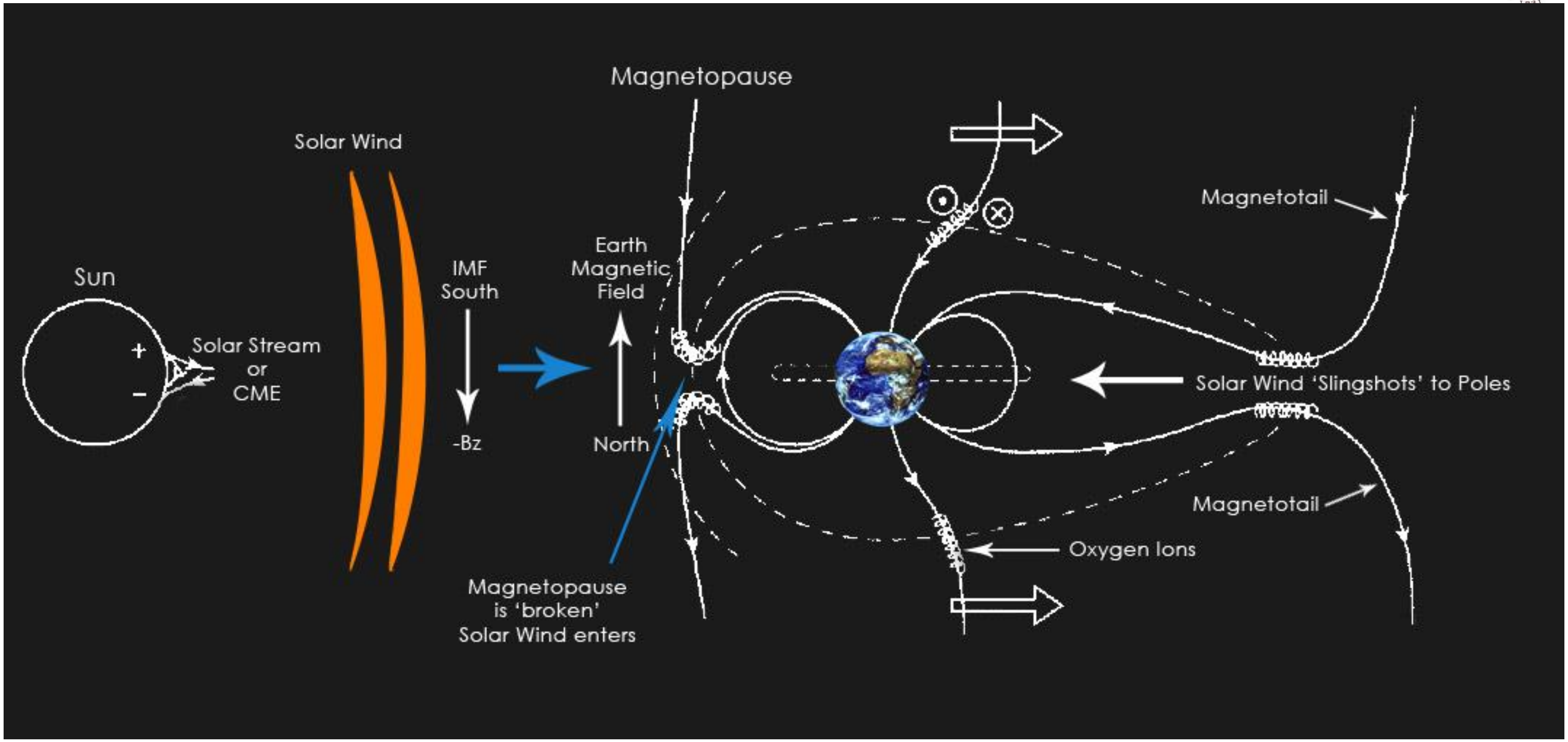
Corona mass ejection (CME)





http://cse.ssl.berkeley.edu/SegwayEd/lessons/exploring_magnetism/in_Solar_Flares/s4.html#sf

Reconnections occur in many locations



- **The Aurora Borealis:**

  https://www.youtube.com/watch?v=lT3J6a9p_o8

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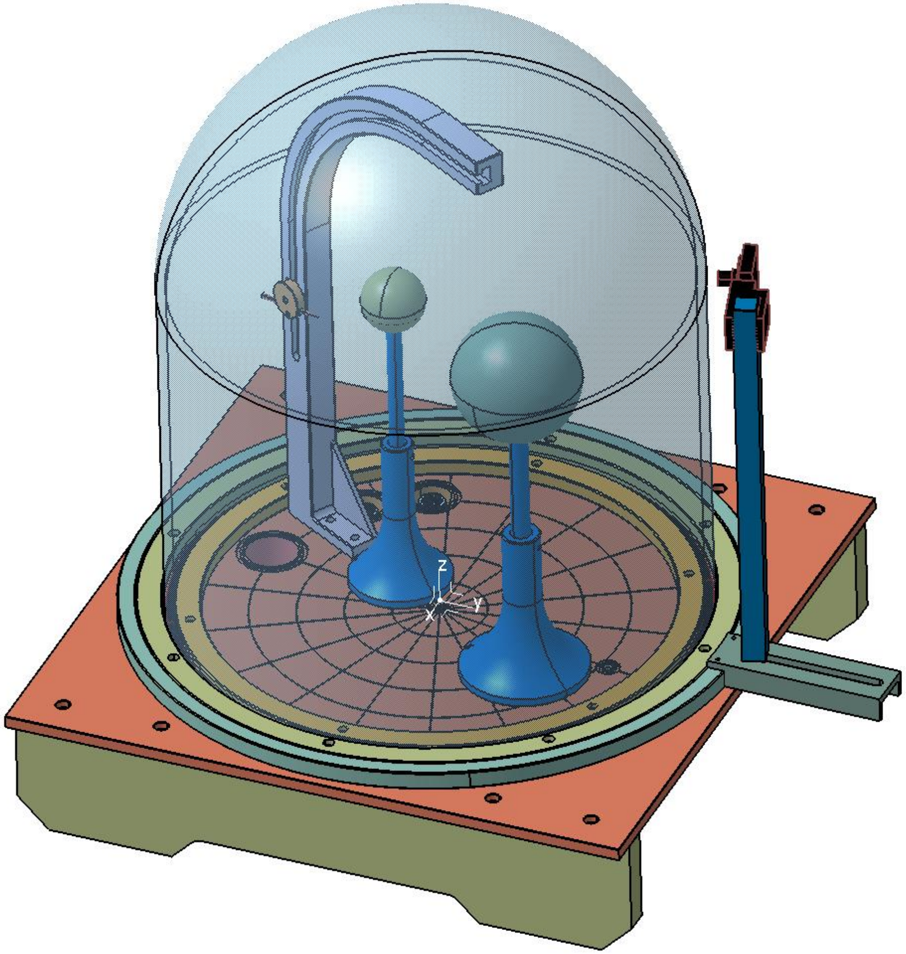
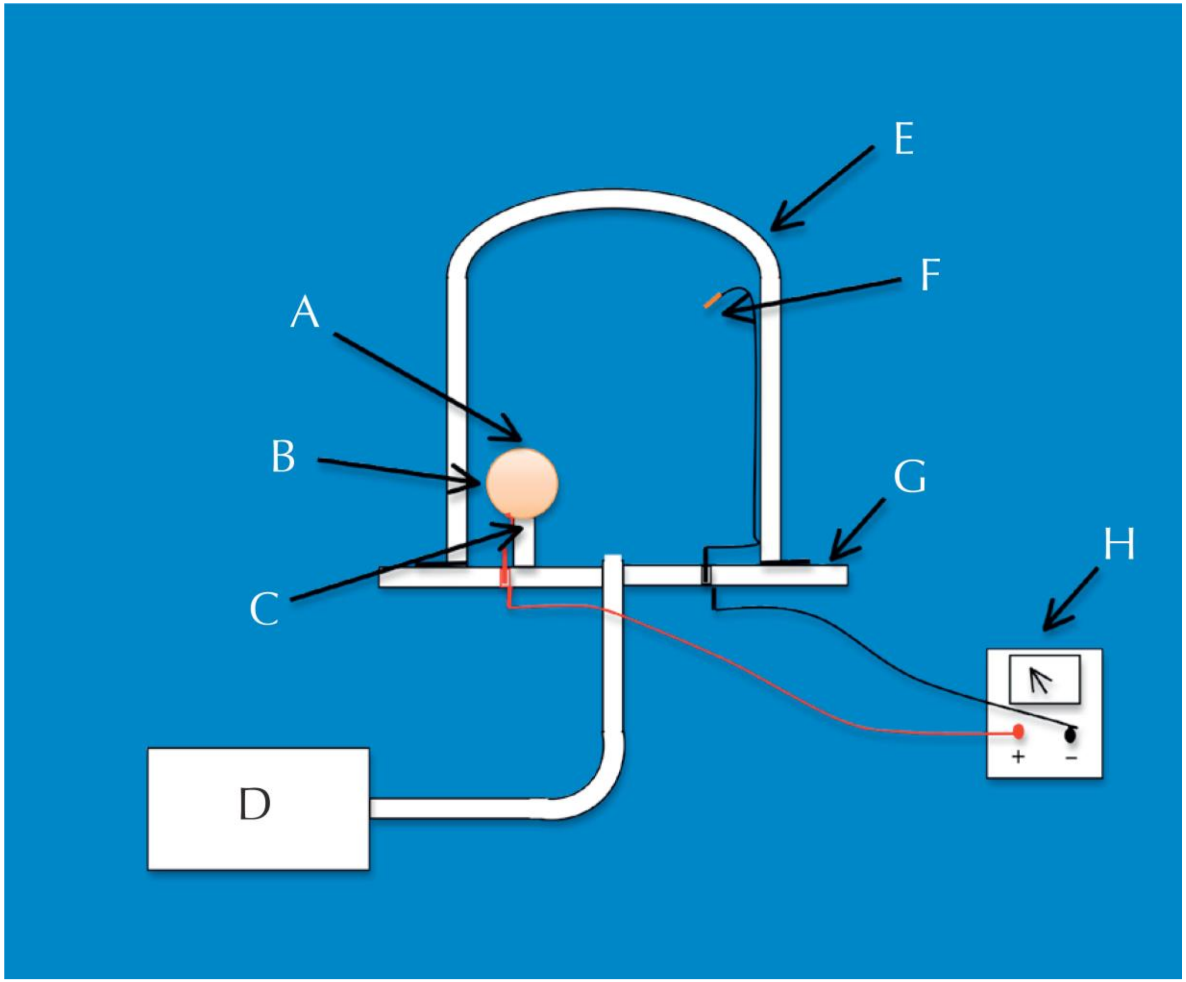
http://www.natalia-robba.com/myblog/travel/the-aurora-borealis-the-northern-lights-everything-you-need-to-know/

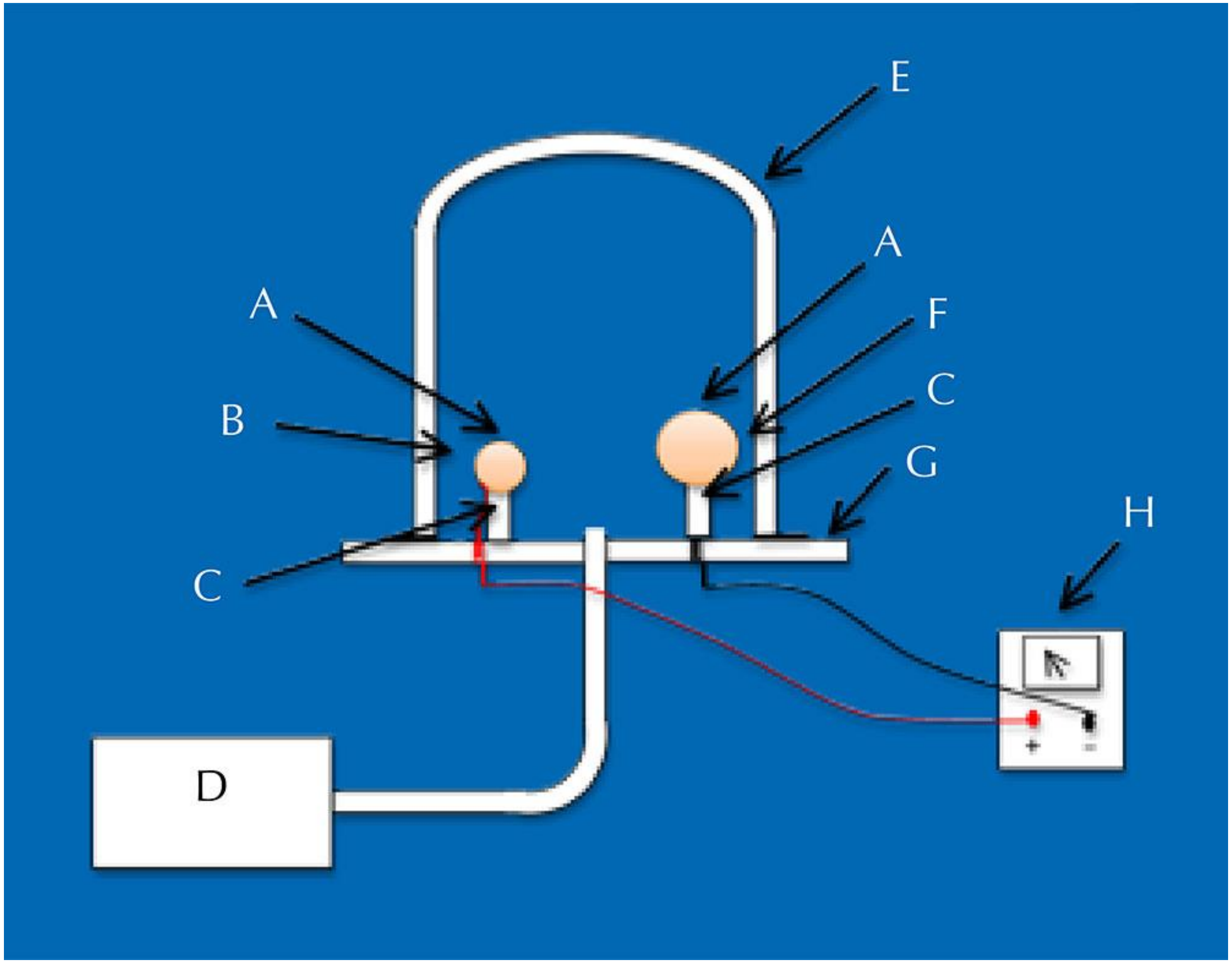
Planeterrella is an aurora simulator



Simple glow discharge is demonstrated

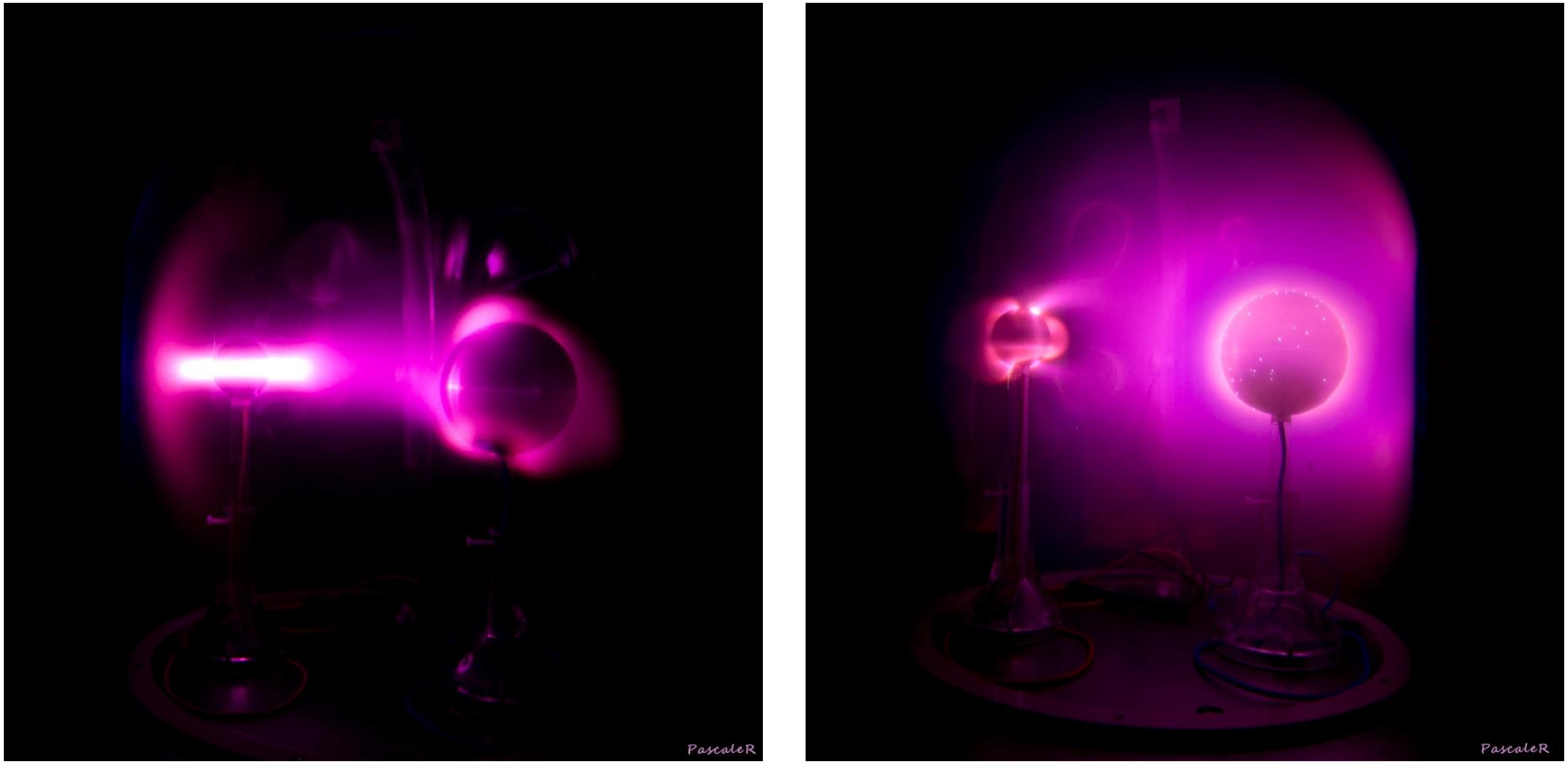


Aurora/ring current are demonstrated

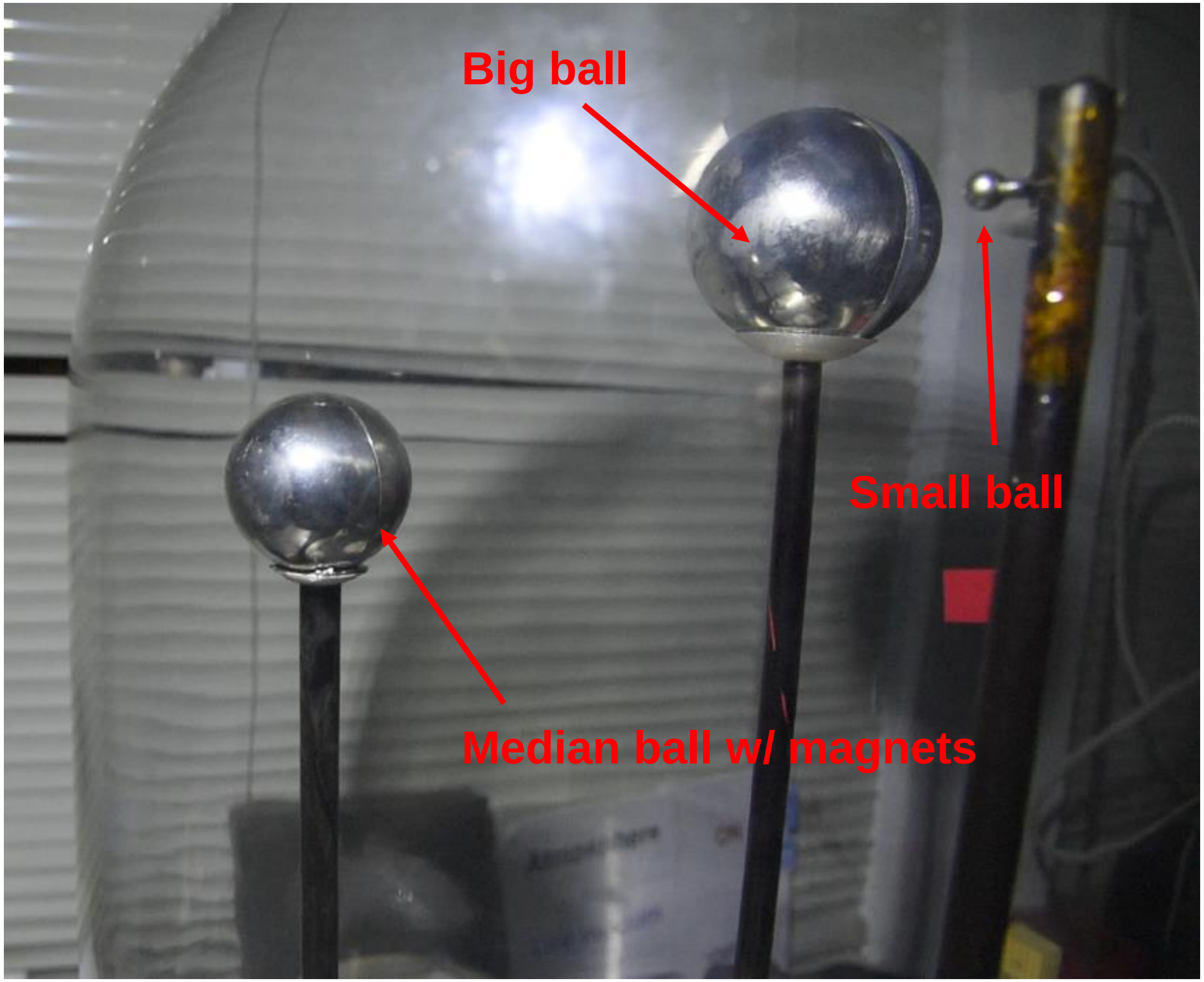


- **B w/ magnet: aurora demonstration**
- **F w/ magnet: ring current**

Aurora and ring current are expected to be seen

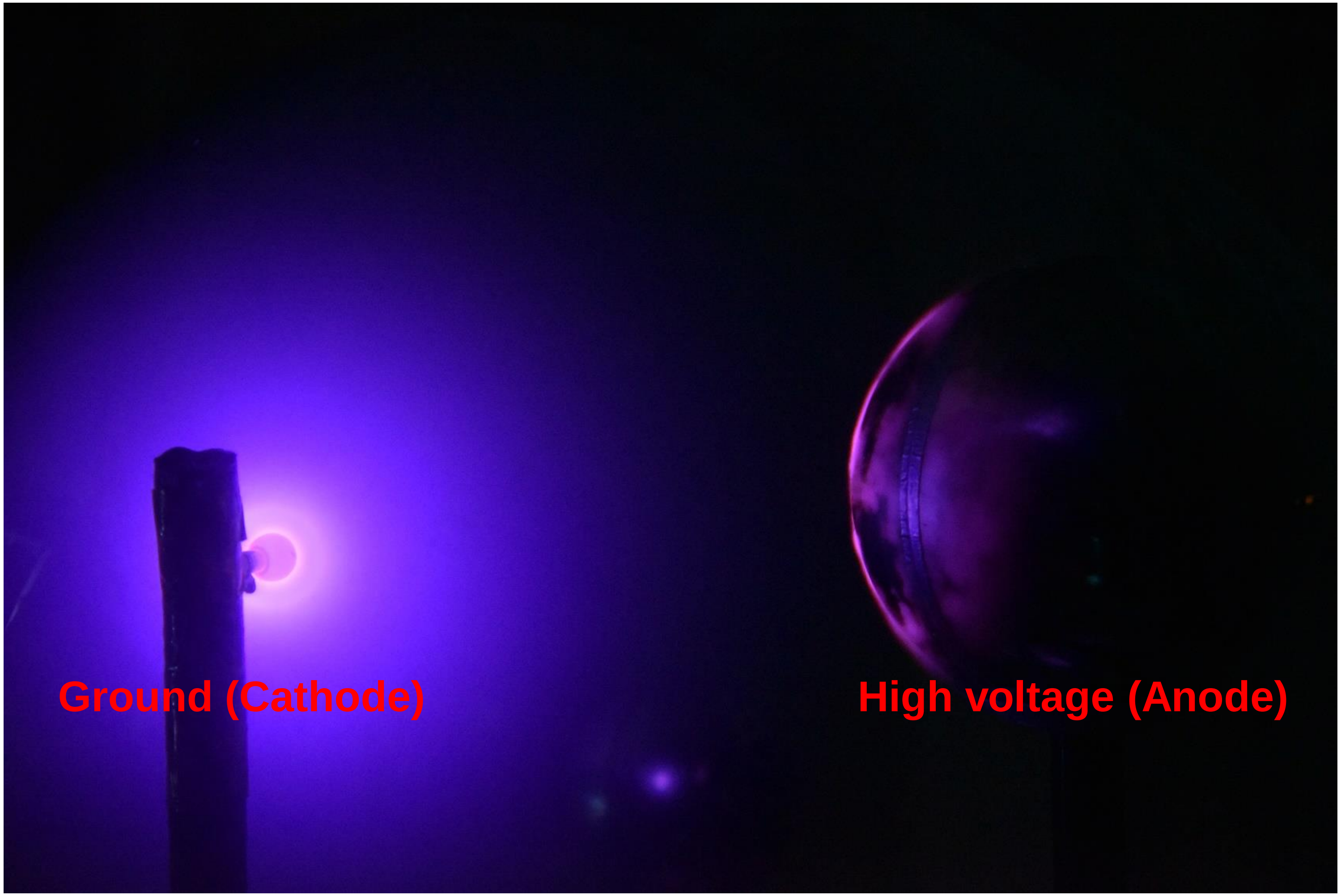


Our Planeterrella

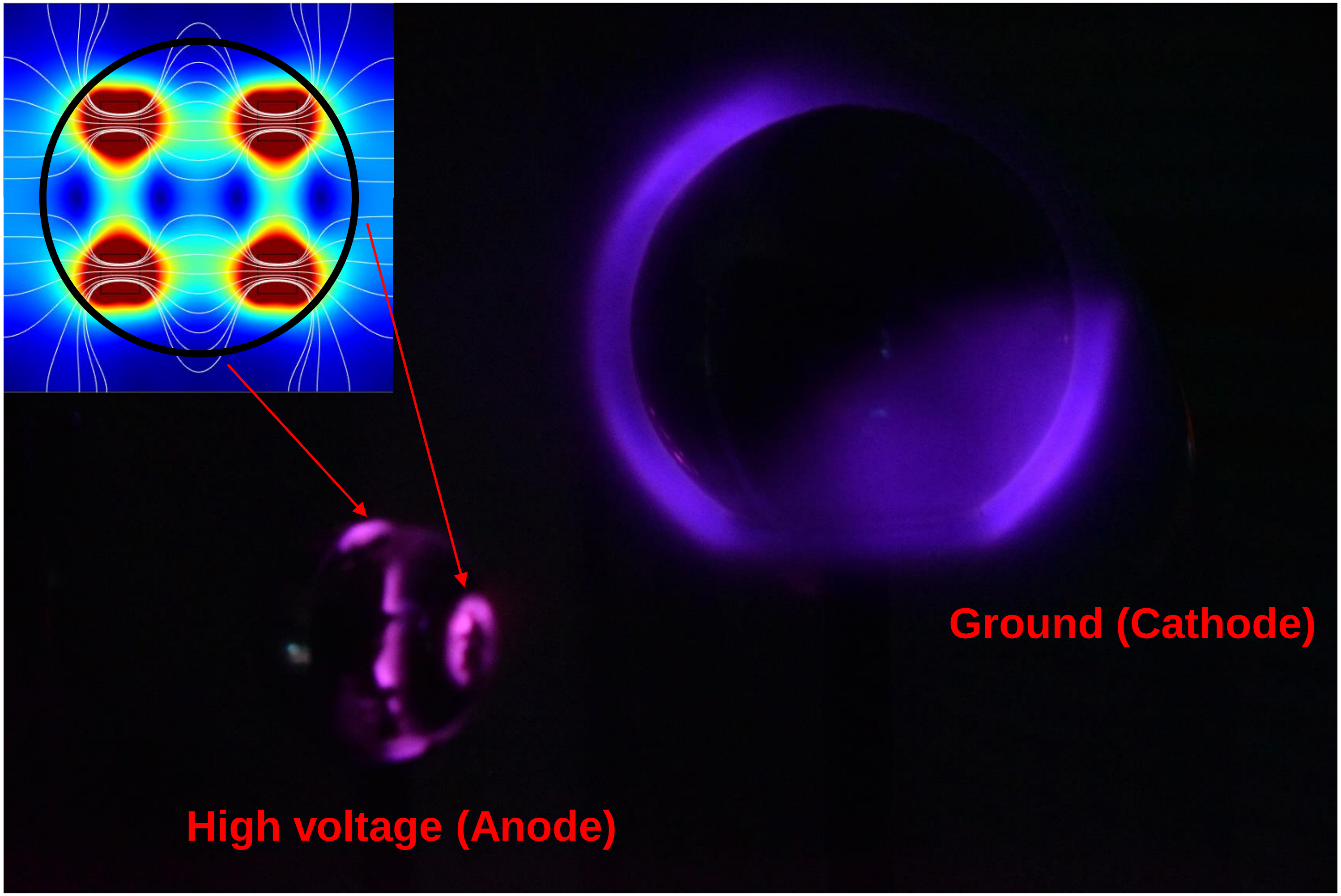


Show video.

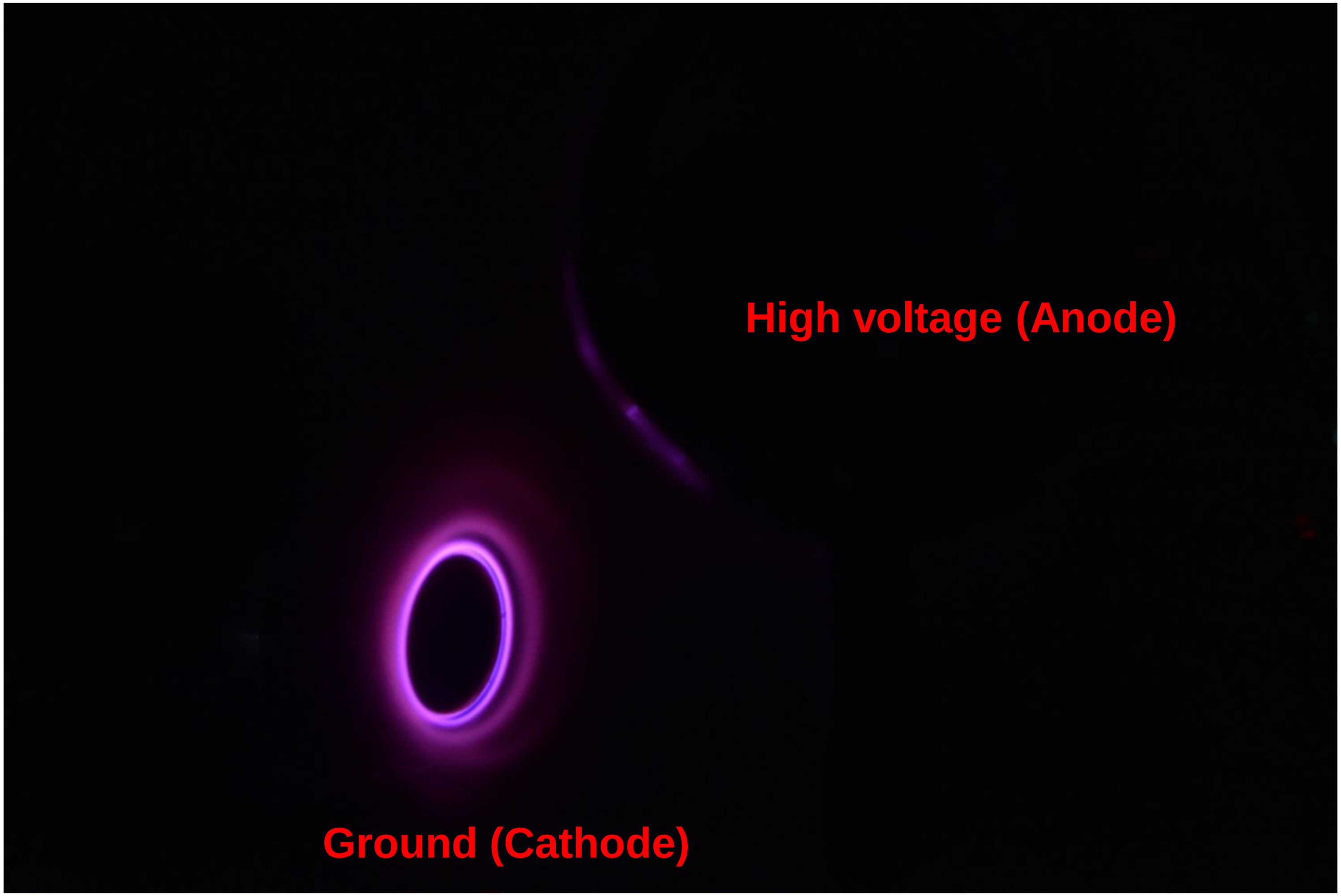
Glow discharge



Aurora demonstration



Ring current demonstration

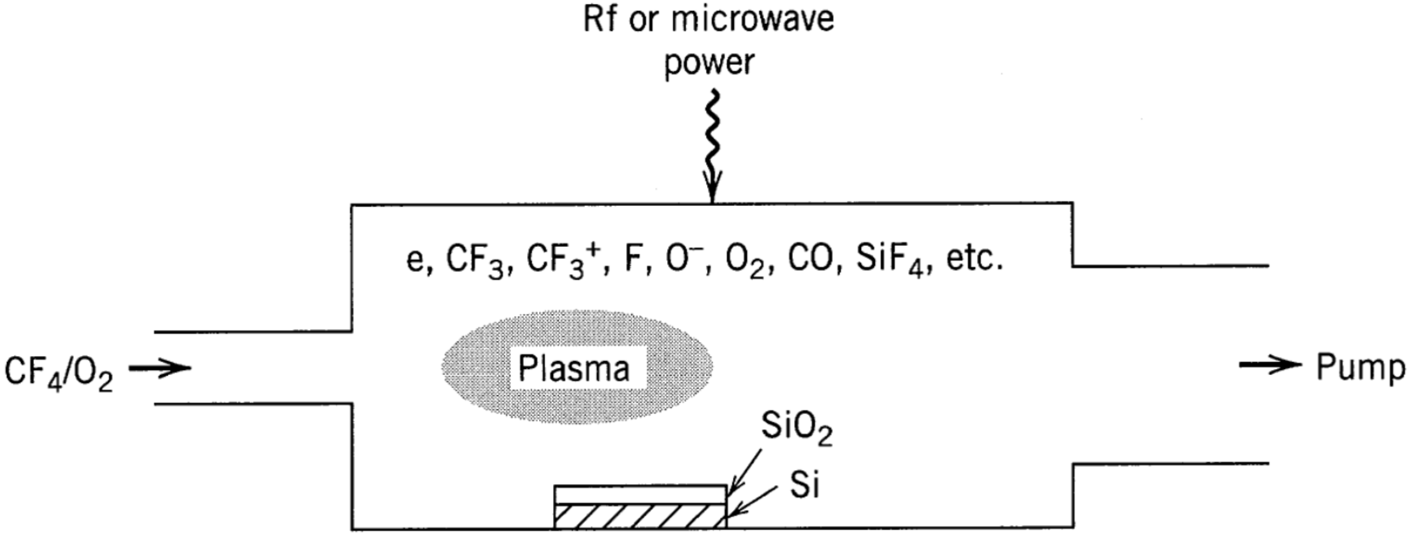


Course Outline

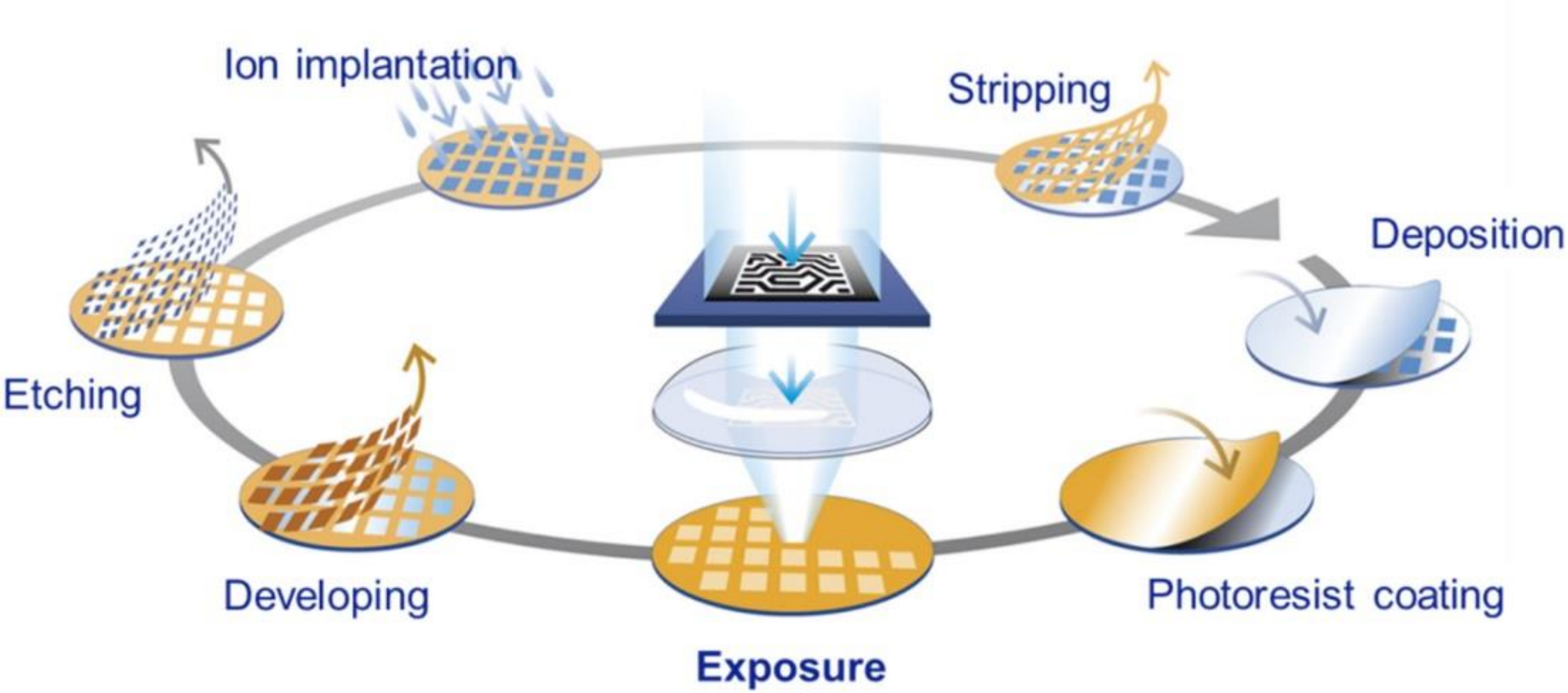
1. What is Plasma?
2. **Varies kinds of plasma**
   a. How plasma is generated
   b. Plasma in space
   c. **Material Processing**
   d. Biomedical application
   e. Pparticle beam source
   f. High energy particle accelerator
   g. Controlled thermonuclear fusion
   h. Neutral beam source
   i. Electrical propulsion

Reference for material processing

- Principles of plasma discharges and materials processing, 2nd edition, by Michael A. Lieberman and Allan J. Lichtenberg
- http://www.eecs.berkeley.edu/~lieber/
- Materials science of thin films, 2nd edition, by Milton Ohring
- Plasma etching, by Dennis M. Manos and Daniel L. Flamm
- Industrial plasma engineering, volume 1, by J. Reece Roth



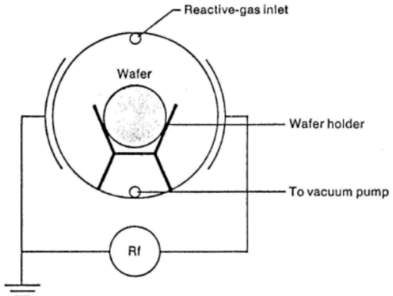
A semiconductor device is fabricated by many repetitive production process



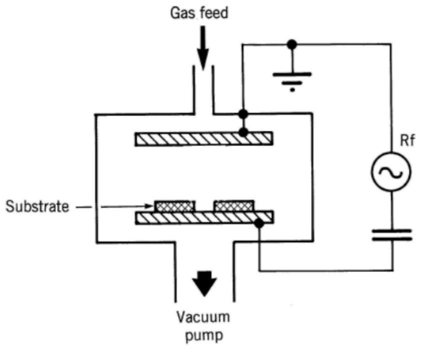
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

Evolution of etching discharges

1st generation
(1 source, multi-wafer, low density)

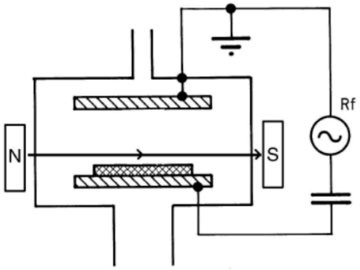


Barrel etcher
(Isotropic etch)

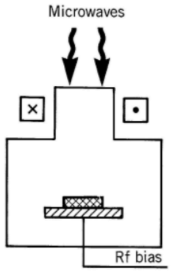


Capacitive
(Anisotropic etch)

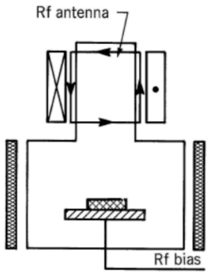
2nd generation
(2 sources, single-wafer, high density)



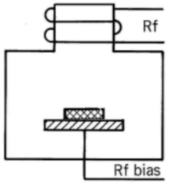
Magnetically enhanced
capacitive discharge



ECR

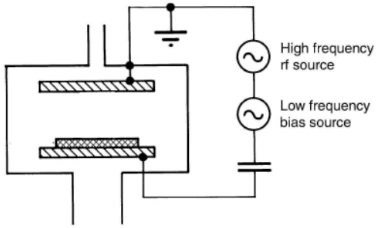


Helicon

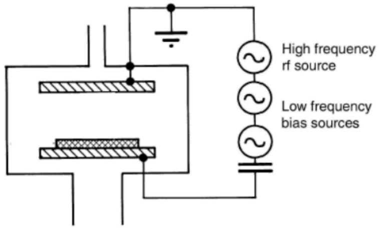


Inductive

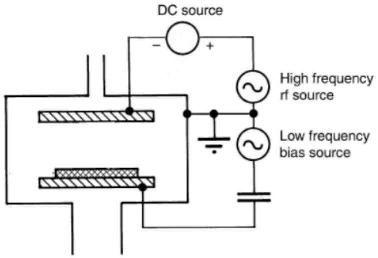
3rd generation
(multi-sources, single-wafer, moderate density)



Dual frequency
capacitive discharge



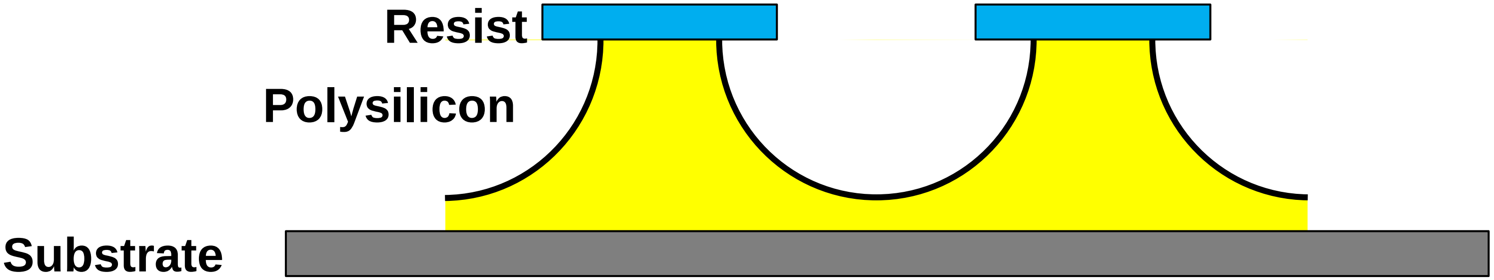
Triple frequency
capacitive discharge



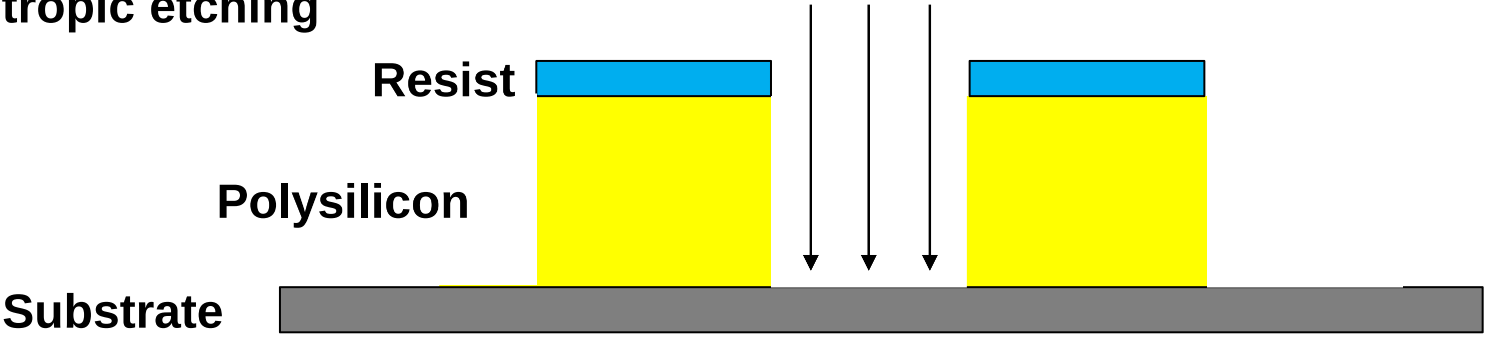
DC/dual frequency
capacitive discharge

There are two types of etching: isotropic vs anistropic

- Isotropic etching

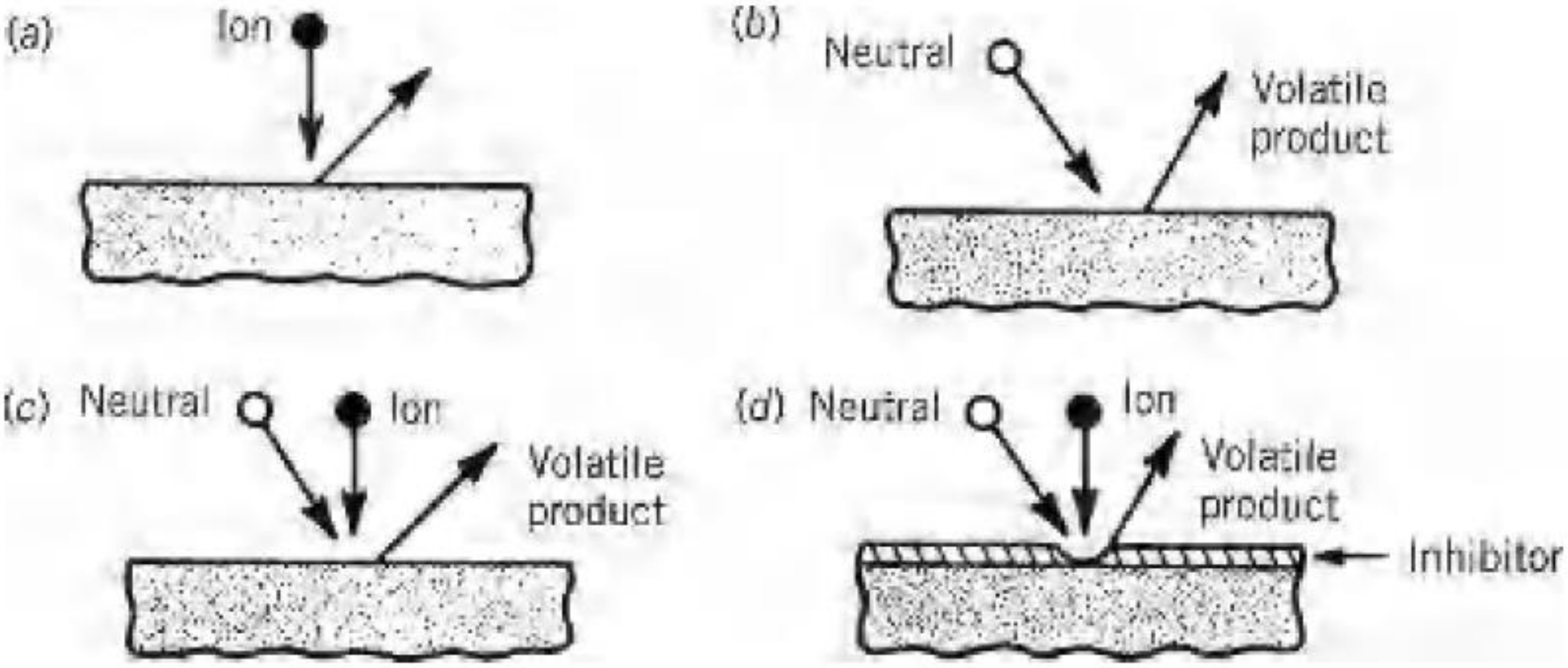


- Anisotropic etching



There are four major plasma etching mechanisms

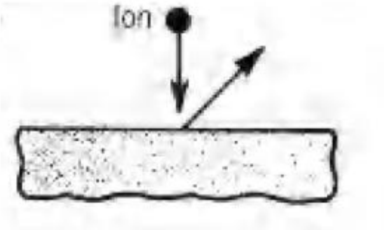
- **Sputtering**
- **Pure chemical etching**



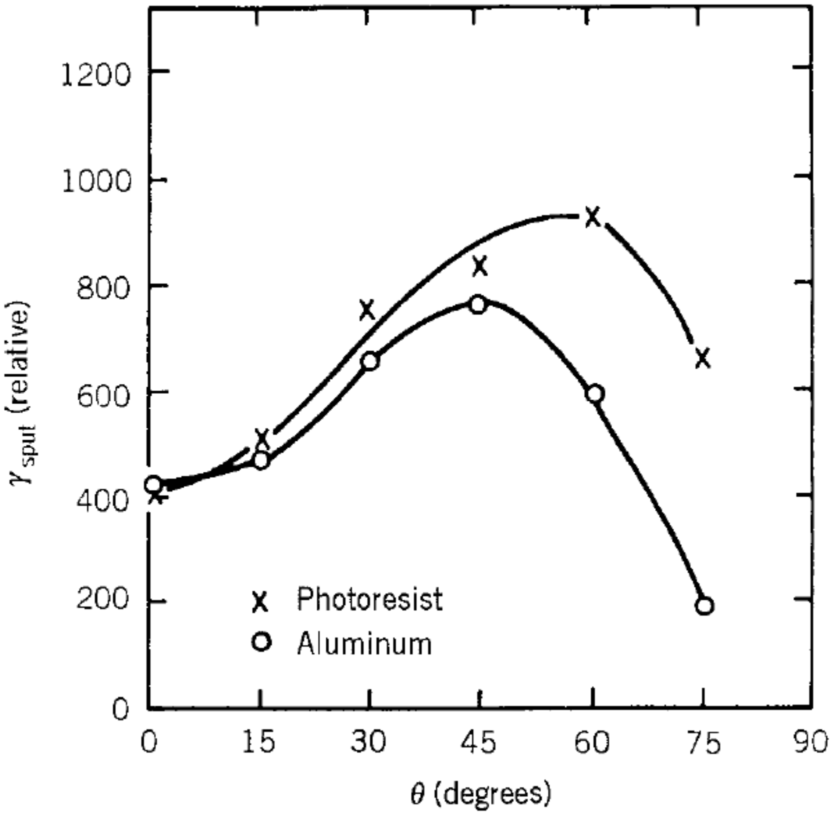
- **Ion energy-driven etching**
- **Ion-enhanced inhibitor etching**

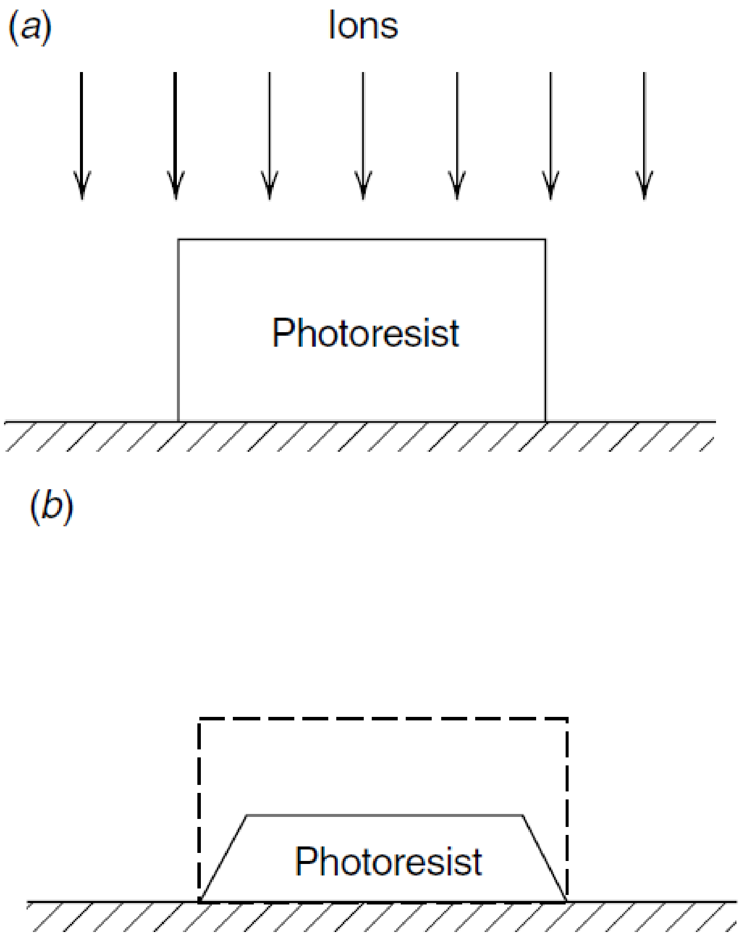
Sputtering is an unselective but anisotropic process

- **Unselective process**
- **Anisotropic process, strongly sensitive to the angle of incidence of the ion**
- **Sputtering rates of different materials are roughly the same**
- **Sputtering rates are generally low because the yield is typically of order one atom per incident ion**
- **Sputtering is the only one of the four etch processes that can remove involatile products from a surface**
- **The process is generally under low pressure since the mean free path of the sputtered atoms must be large enough to prevent redeposition on the substrate or target**



Topographical patterns might not be faithfully transferred during sputter etching





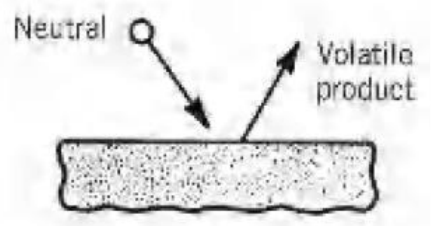
Pure chemical etching

Atoms or molecules chemically react with the surface to form gas-phase products

- Highly chemically selective, e.g.,

$$\mathrm{Si(s)} + 4\mathrm{F} \longrightarrow \mathrm{SiF_4(g)}$$

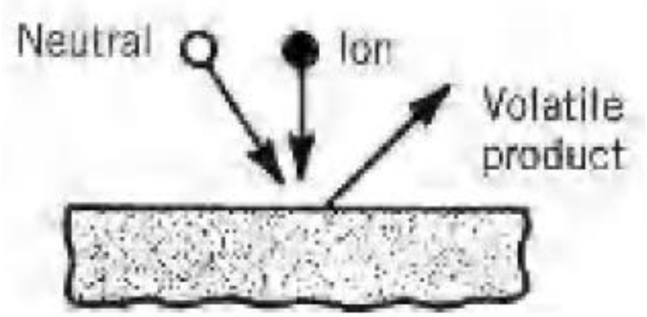
$$\text{photoresist} + \mathrm{O(g)} \longrightarrow \mathrm{CO_2(g)} + \mathrm{H_2O(g)}$$

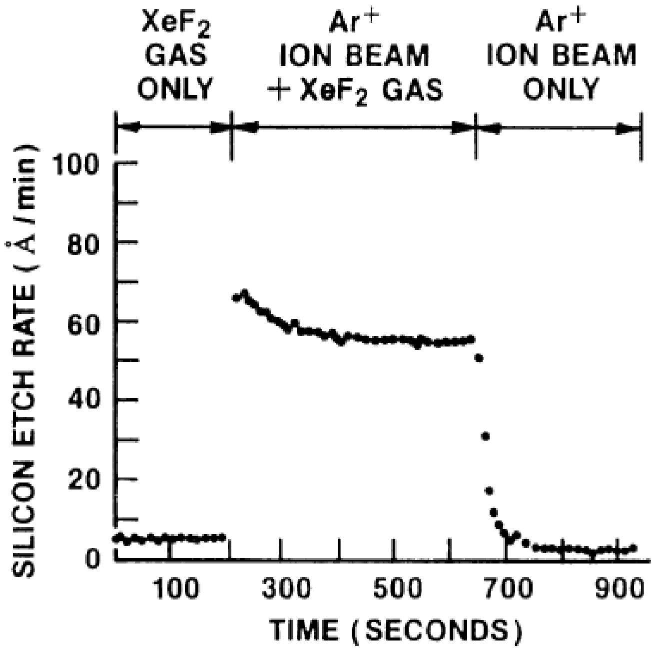


- Almost invariably isotropic
- Etch products must be volatile
- The etch rate can be quite large
- Etch rate are generally not limited by the rate of arrival of etchant atoms, but by one of a complex set of reactions at the surface leading to formation of etch products

Ion-enhanced energy-driven etching

The discharge supplies both etchants and energetic ions to the surface





- **Low chemical etch rate of silicon substrate in XeF2 etchant gas**
- **Tenfold increase in etch rate with XeF2 + 500 V argon ions, simulating ion-enhanced plasma etching**
- **Very low "etch rate" due to the physical sputtering of silicon by ion bombardment alone**

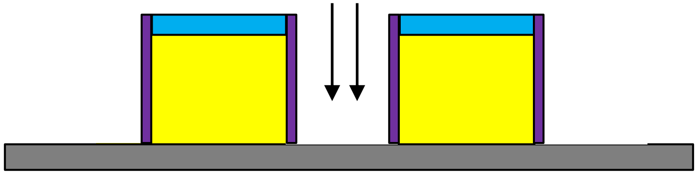
Ion-enhanced energy-driven etching has the characteristic of both sputtering and pure chemical etching

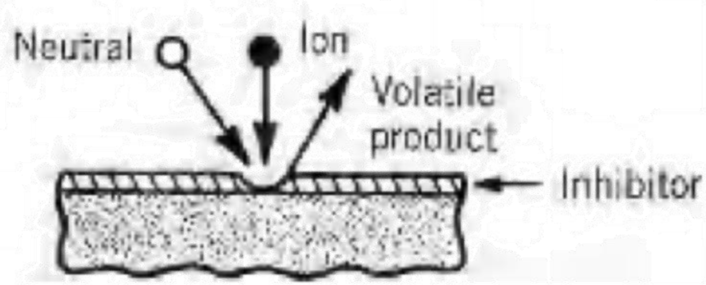
- Chemical in nature but with a reaction rate determined by the energetic ion bombardment
- Product must be volatile
- Highly anisotropic

Ion-enhanced inhibitor etching

An inhibitor species is used

- Inhibitor precursor molecules that absorb or deposit on the substrate form a protective layer or polymer film
- Etchant is chosen to produce a high chemical tech rate of the substrate in the absence of either ion bombardment or the inhibitor
- Ion bombardment flux prevents the inhibitor layer from forming or clears it as it forms
- Where the ion flux does not fall, the inhibitor protects the surface from the etchant
- May not be as selective as pure chemical etching
- A volatile etch product must be formed
- Contamination of the substrate and final removal of the protective inhibitor film are other issues





Comparison of different processes

	Sputtering etching	Pure chemical etching	Ion energy-driven etching	Ion-enhanced Inhibitor etching
Selectivity	X	O	O	O
Anisotropic	O	X	O	O
Volatile product	X	O	O	O

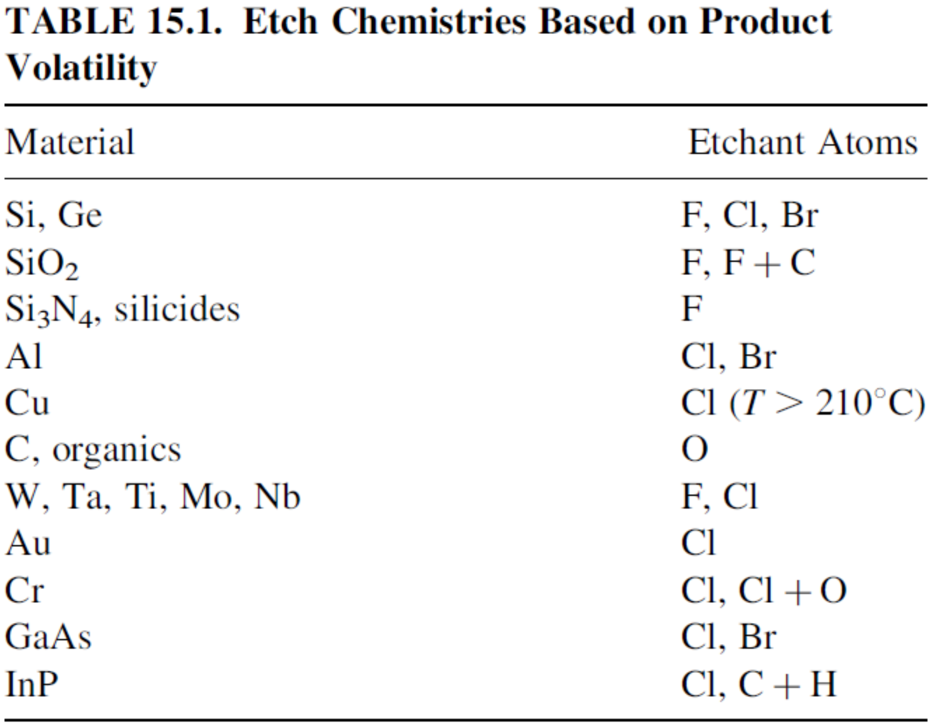
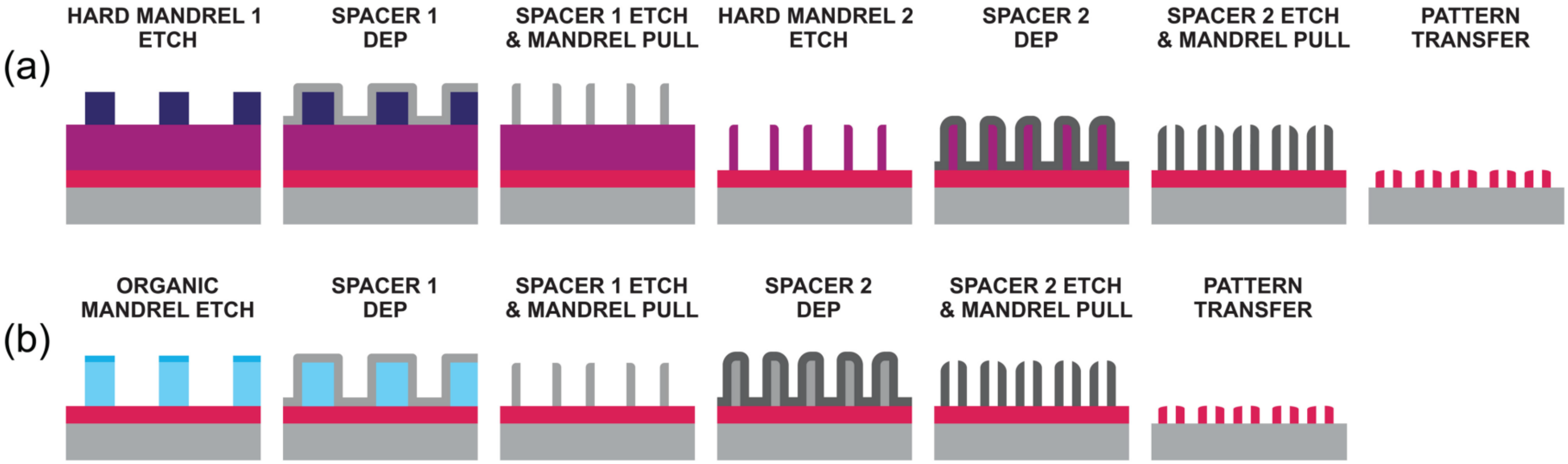


TABLE 15.1. Etch Chemistries Based on Product Volatility

Material	Etchant Atoms
Si, Ge	F, Cl, Br
SiO_2	F, F + C
Si_3N_4, silicides	F
Al	Cl, Br
Cu	Cl ($T > 210°C$)
C, organics	O
W, Ta, Ti, Mo, Nb	F, Cl
Au	Cl
Cr	Cl, Cl + O
GaAs	Cl, Br
InP	Cl, C + H

Fine periodic pattern can be made by using self-aligned quadruple patterning

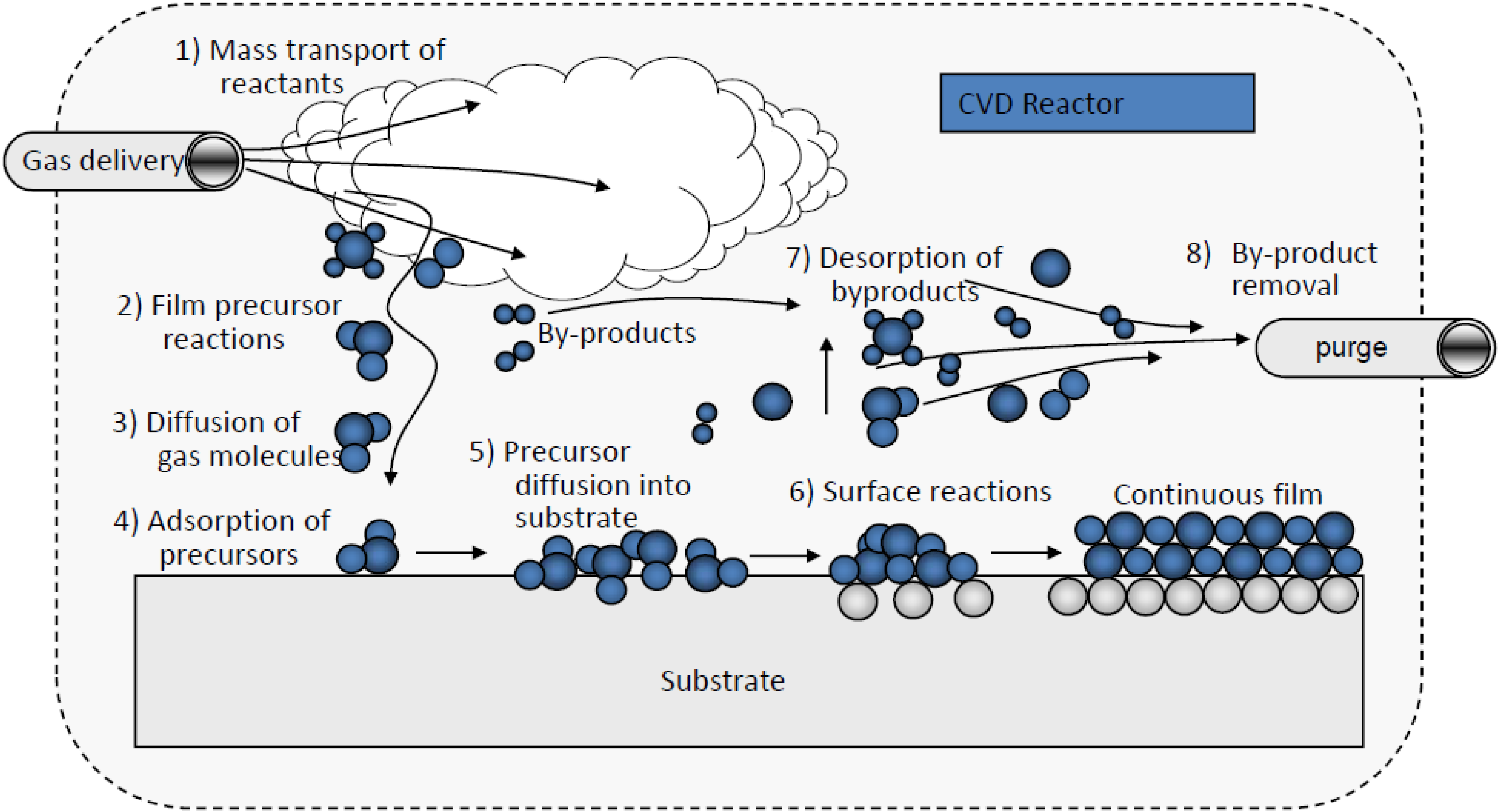


H. C. M. Knoops *et al.*, J. Vac. Sci. Technol. **A 37**, 030902 (2019)

Deposition and implementation

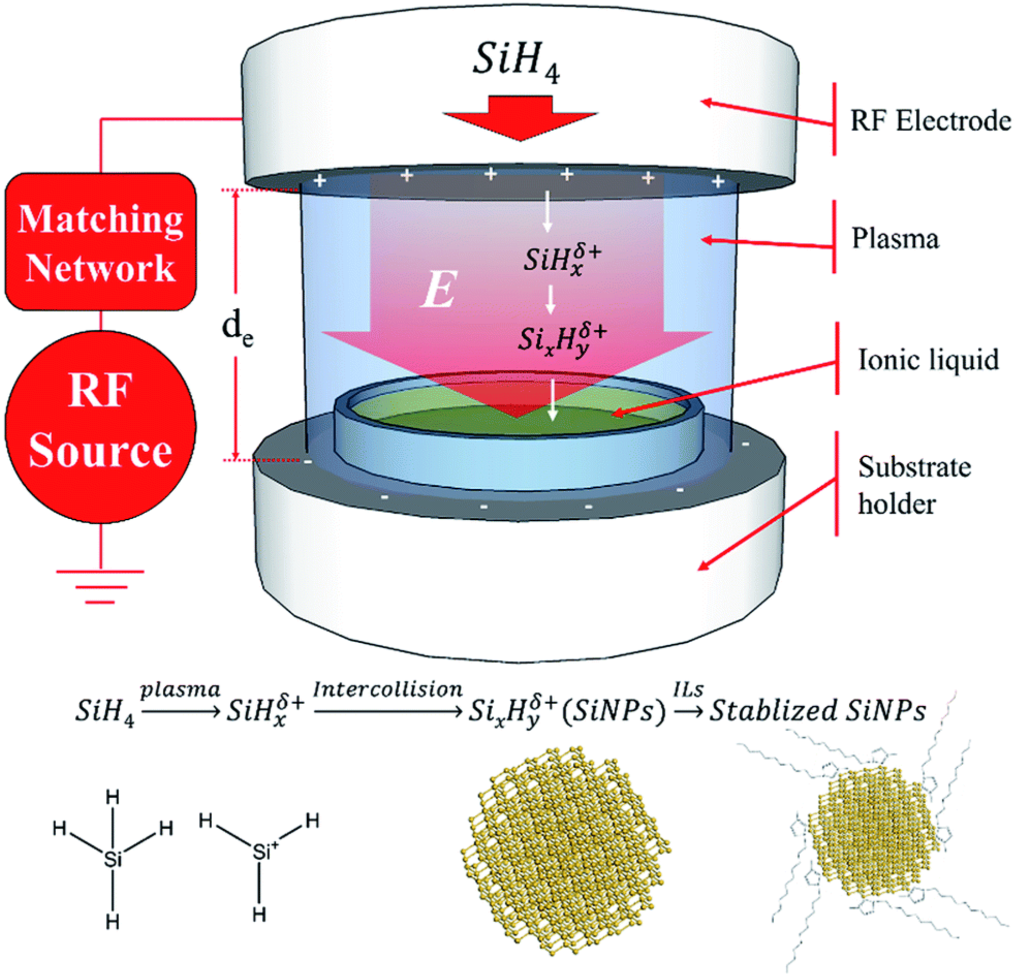
- **Plasma-assisted deposition, implantation, and surface modification are important material processes for producing films on surfaces and modifying their properties**
- **Example processes:**
  - **Plasma-enhanced chemical vapor deposition (PECVD)**
  - **Sputter deposition / physical vapor deposition (PVD)**
  - **Plasma-immersion ion implantation (PIII)**

Chemical Vapor Deposition (CVD)



http://www.ece.uah.edu/courses/material/EE410-Wms/

Plasma-enhanced chemical vapor deposition (PECVD)



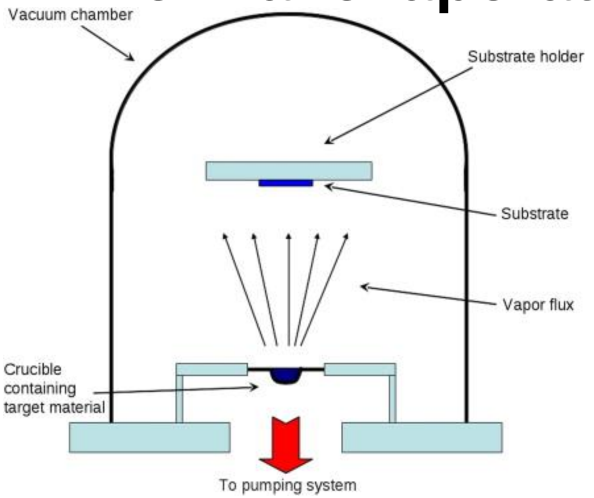
Films can be deposited in low temperatures using plasma deposition

- Device structures are sensitive to temperature, high-temperature deposition processes cannot be used in many cases
- High-temperature films can be deposited at low temperatures
- Unique films not found in nature can be deposited, e.g., diamond

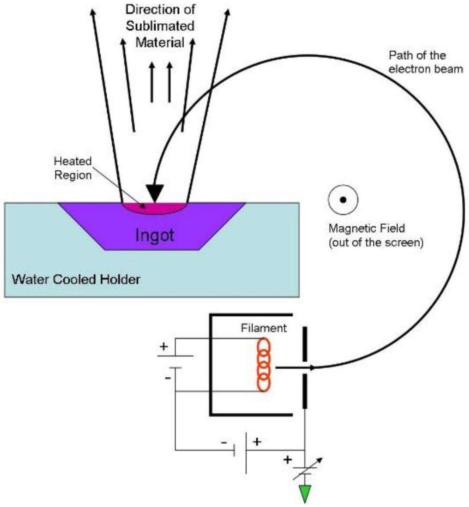
PVD

Physical vapor deposition can be achieved by heating the deposited material

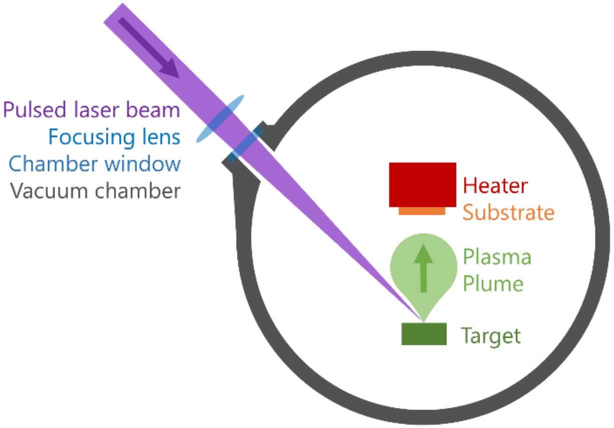
- **Thermal evaporator**



- **Electron-beam evaporator**



- **Pulsed-laser deposition**



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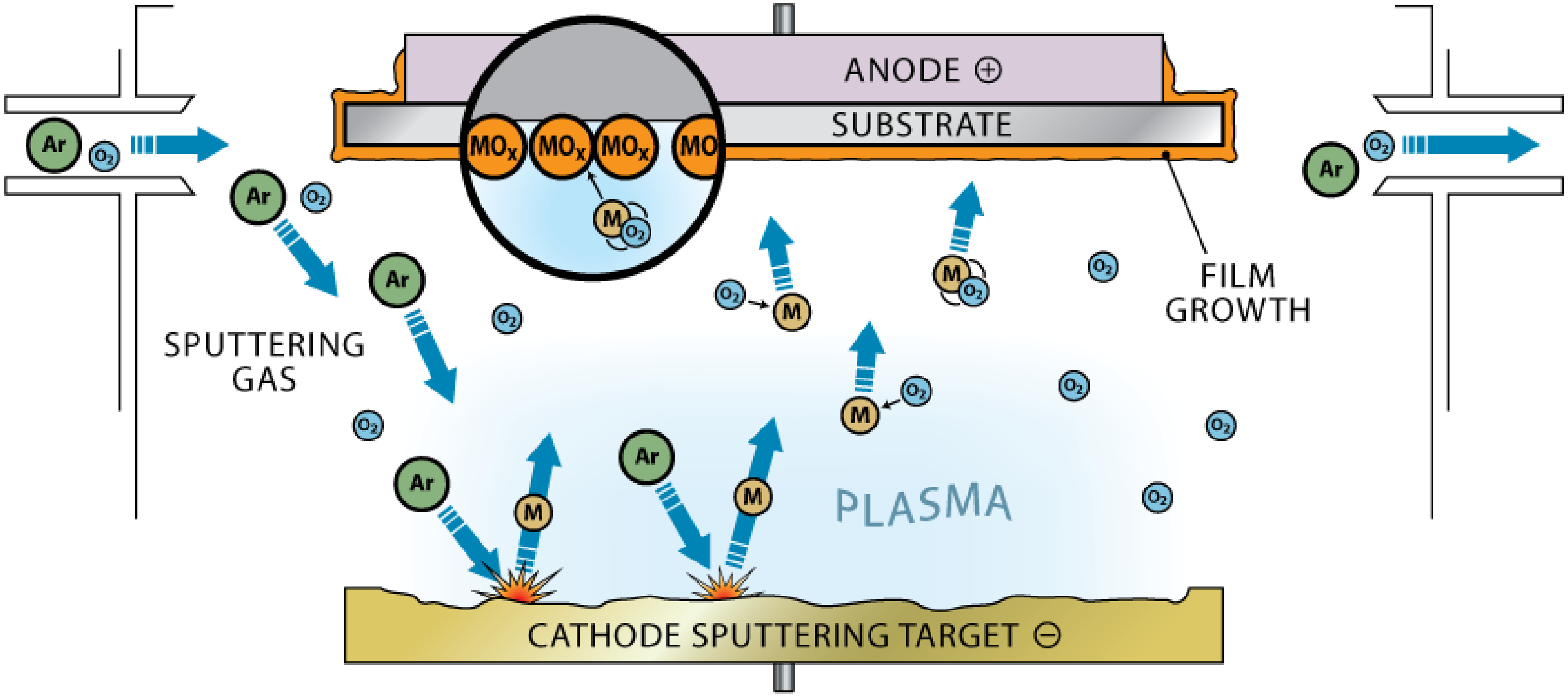
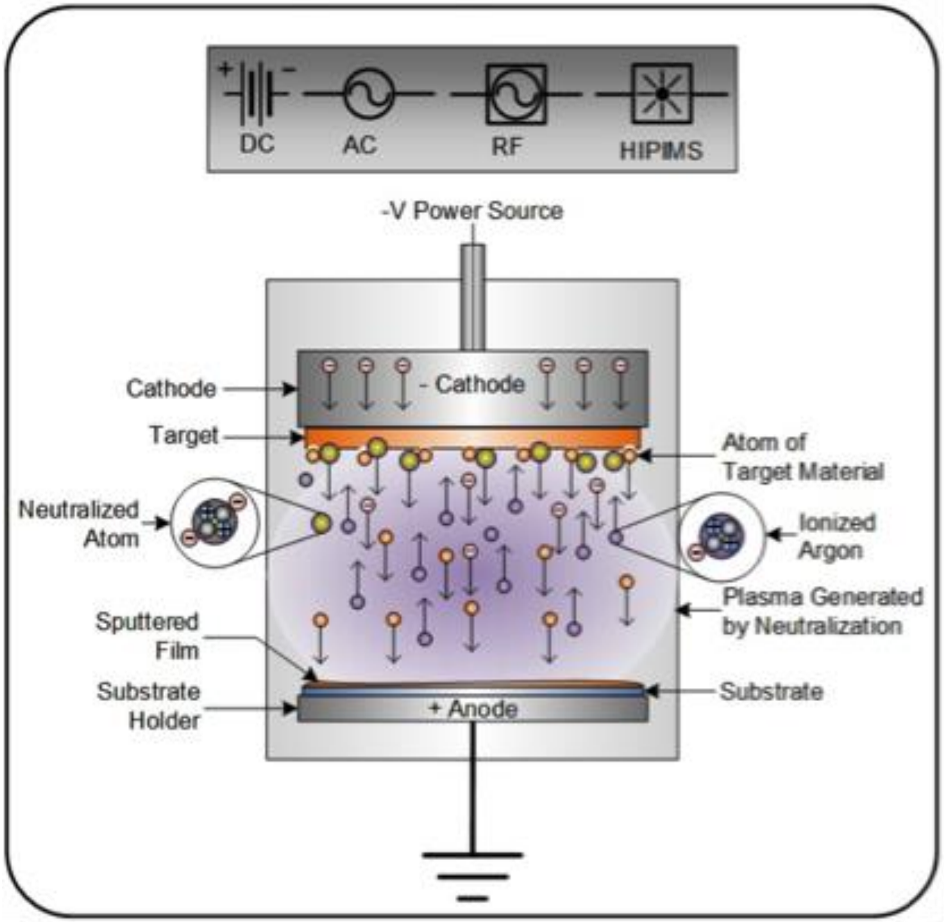
https://en.wikipedia.org/wiki/Pulsed_laser_deposition
Engineered biomimicry by A. Lakhtakia and R. J. Martin-Palma
https://en.wikipedia.org/wiki/Electron-beam_physical_vapor_deposition

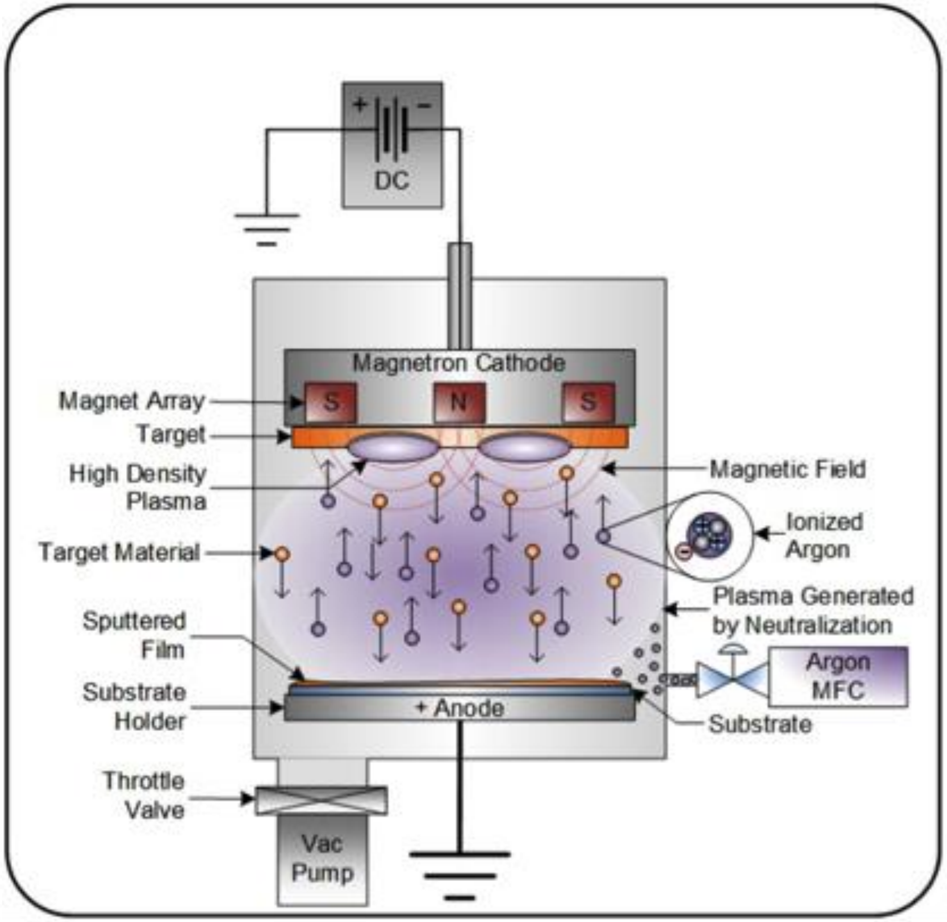
Sputtering deposition



http://lnf-wiki.eecs.umich.edu/wiki/Sputter_deposition

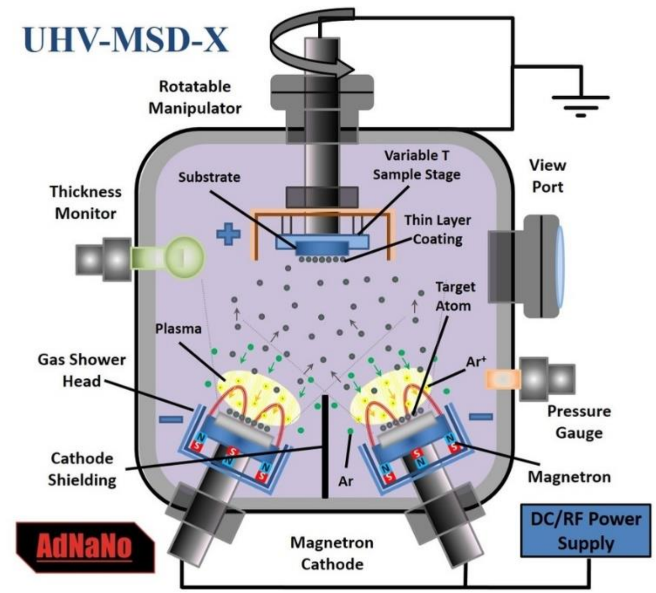
Magnetron sputtering provides higher deposition rates than conventional sputtering





http://www.semicore.com/what-is-sputtering

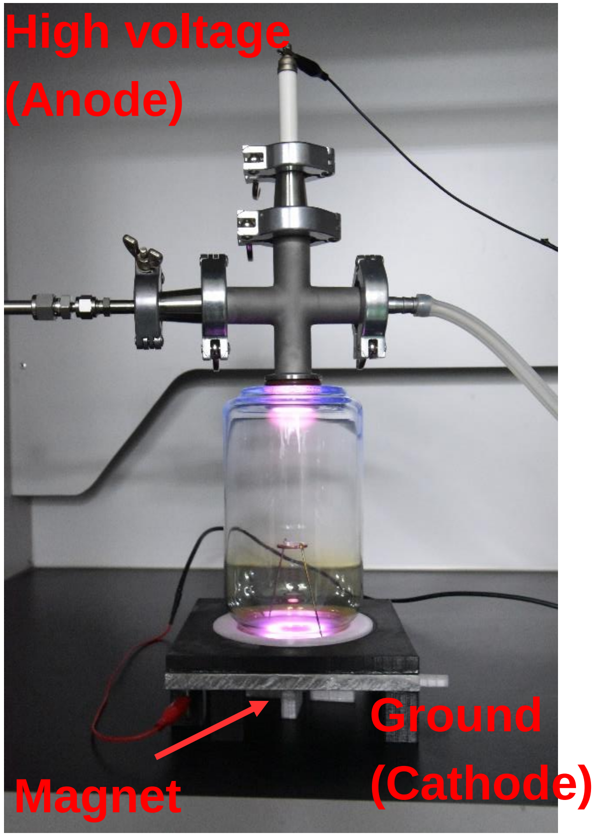
Examples of magnetron sputtering deposition



https://angstromengineering.com/tech/magnetron-sputtering/pulsed-dc/
https://dynavac.com/wp-content/uploads/2017/09/Confocal-Sputtering-2.jpg
https://www.adnano-tek.com/magnetron-sputtering-deposition-msd.html

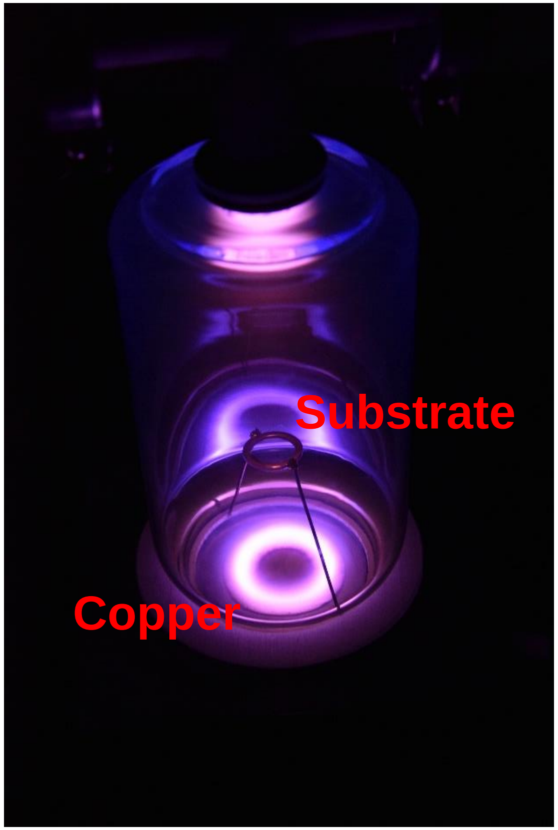
Demonstration experiments – magnetron sputtering

- System



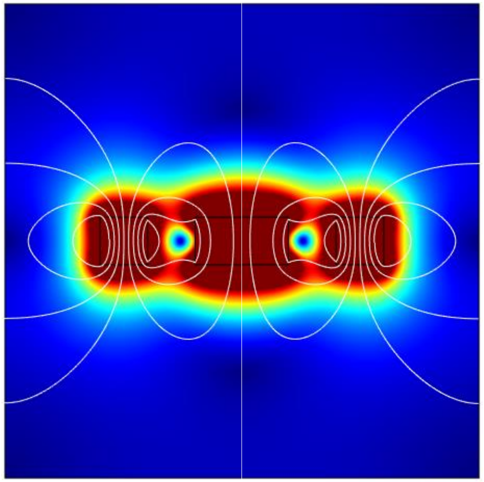
- Without magnet

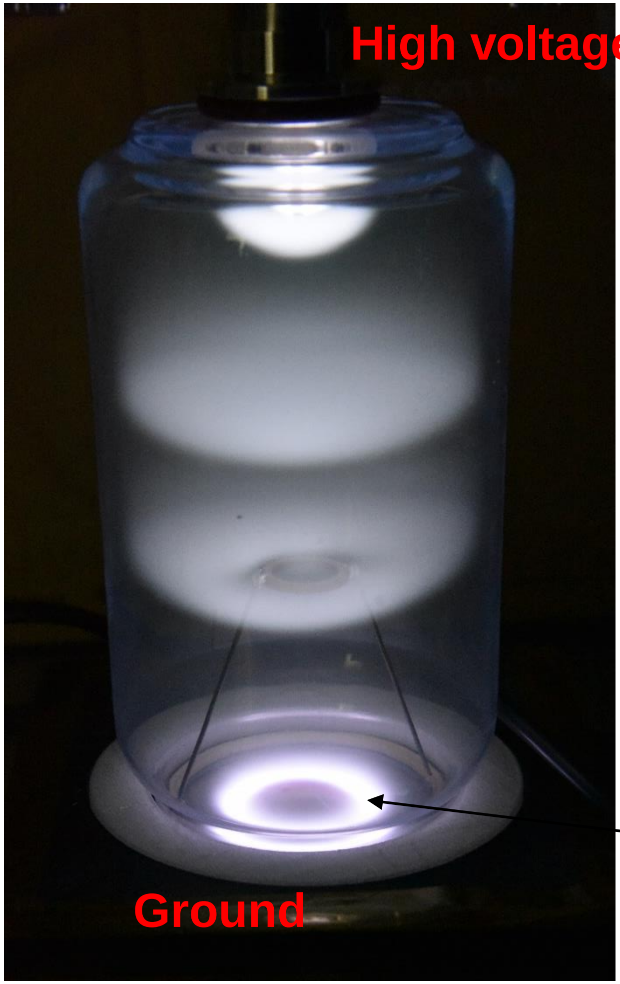
- With magnet



Show video.

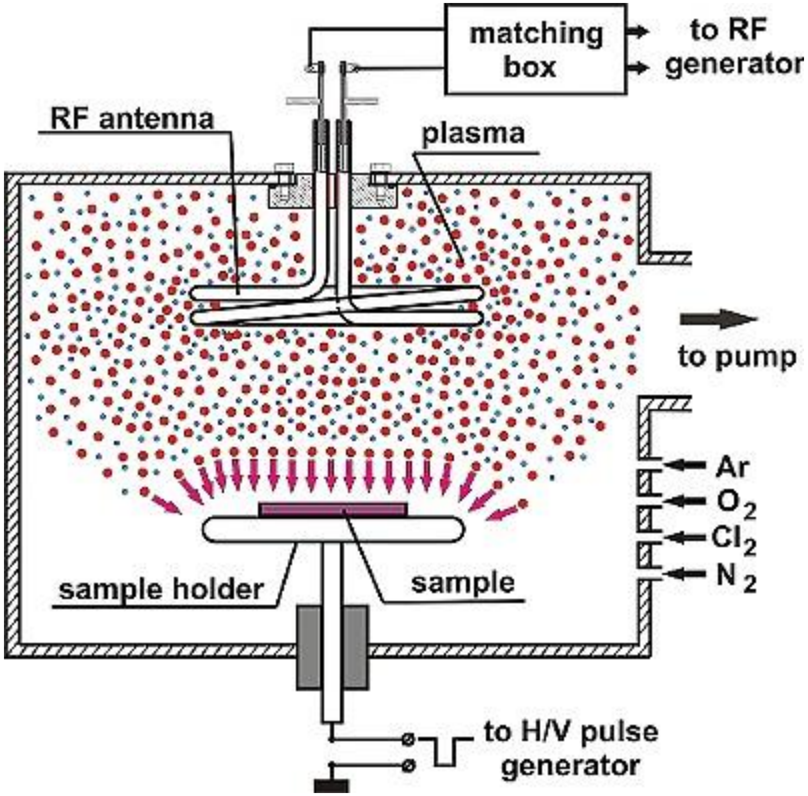
A bright ring occurs when the magnet is inserted into the system

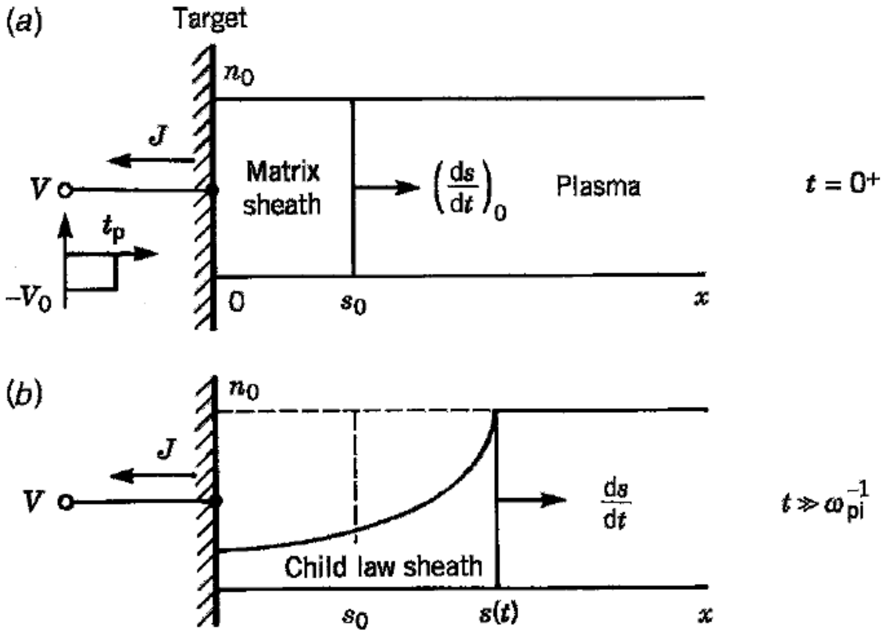




Confined electrons

Plasma-immersion ion implantation (PIII)



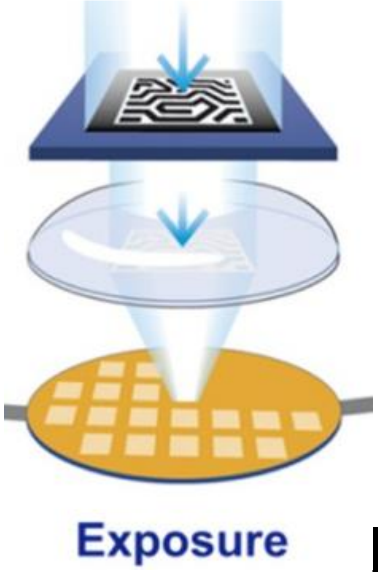


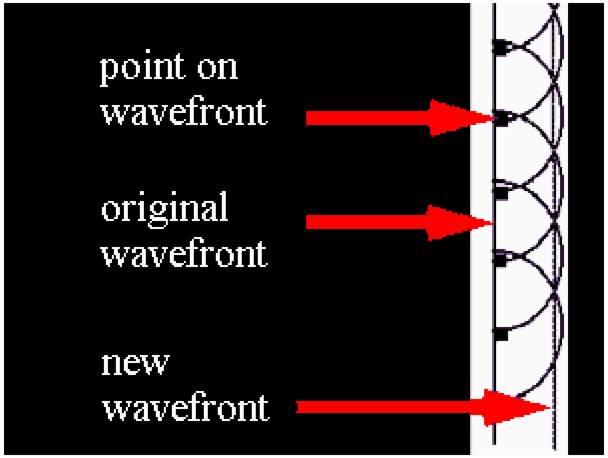
- **Silicon doping – ions such as B, P, As are implanted**
- **Surface hardening of metals – N, C are implanted**

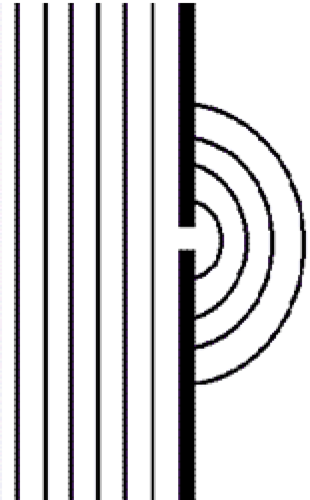
https://www.hzdr.de/db/Cms?pOid=10890&pNid=306

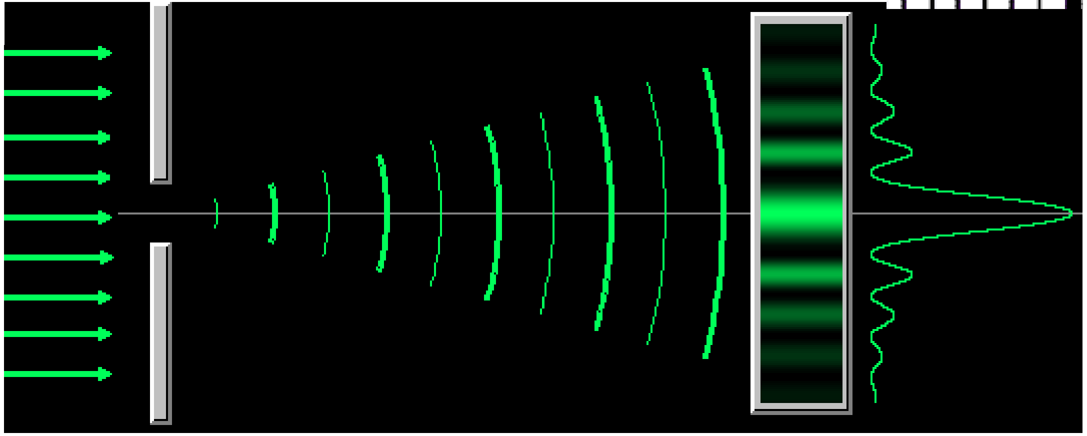
Exposure

Diffraction becomes significant when the linewidth of the pattern on the mask becomes smaller and smaller





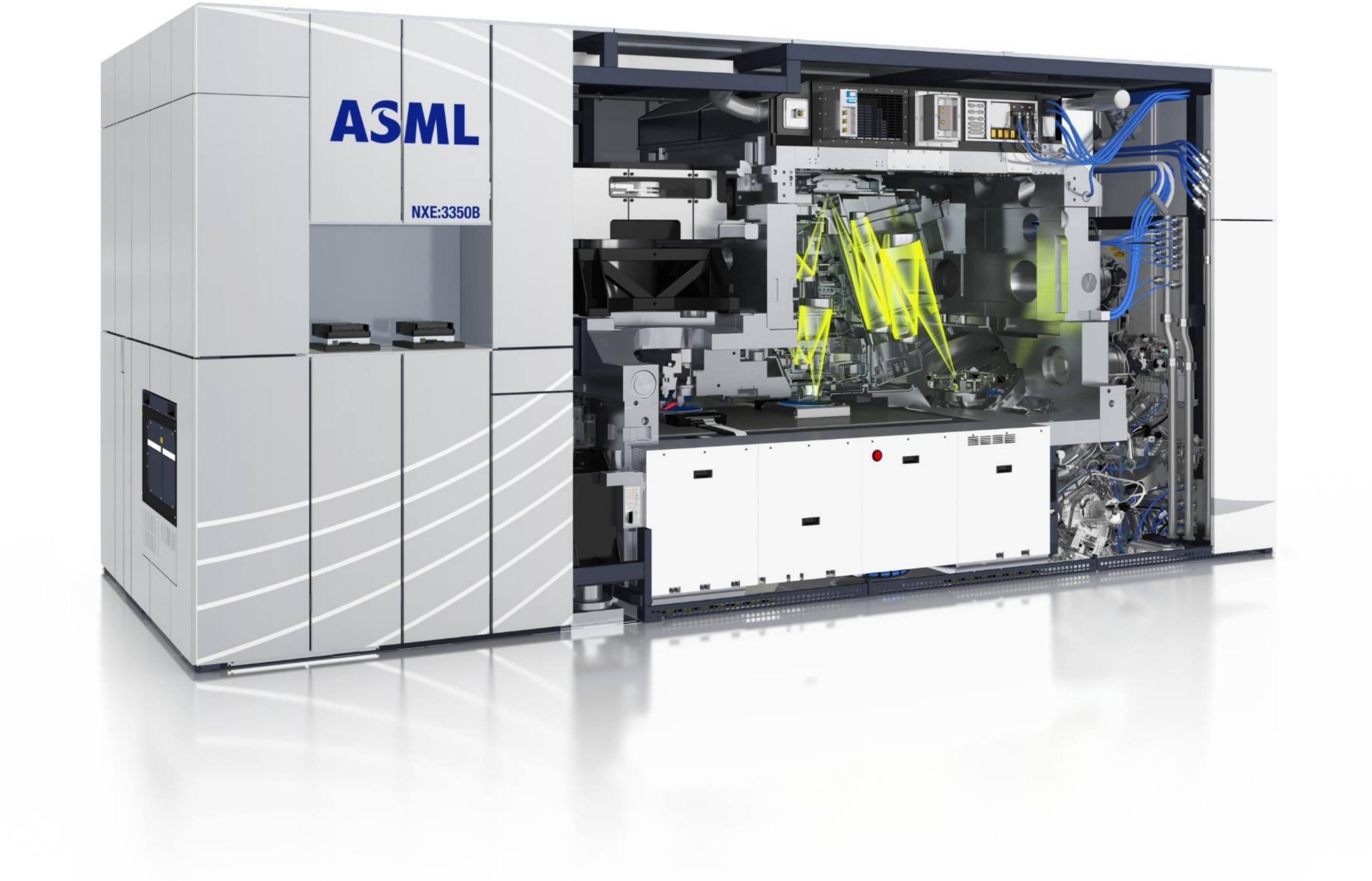




- **Shorter wavelength (in EUV region) is more favorable for finer pattern.**

Surf. Topogr.: Metrol. Prop. **4** (2016) 023001
http://labman.phys.utk.edu/phys222core/modules/m9/diffraction.htm

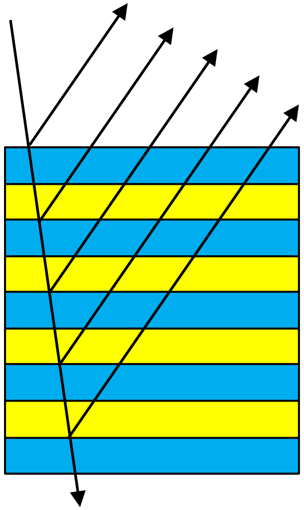
EUV lithography becomes important for semiconductor industry



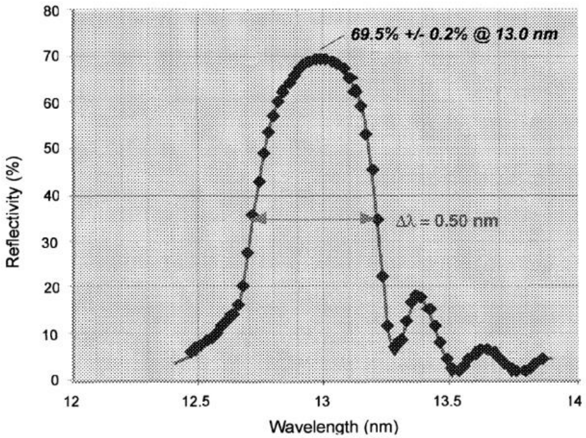
http://finance.technews.tw/2019/01/25/euv-asml-2018/

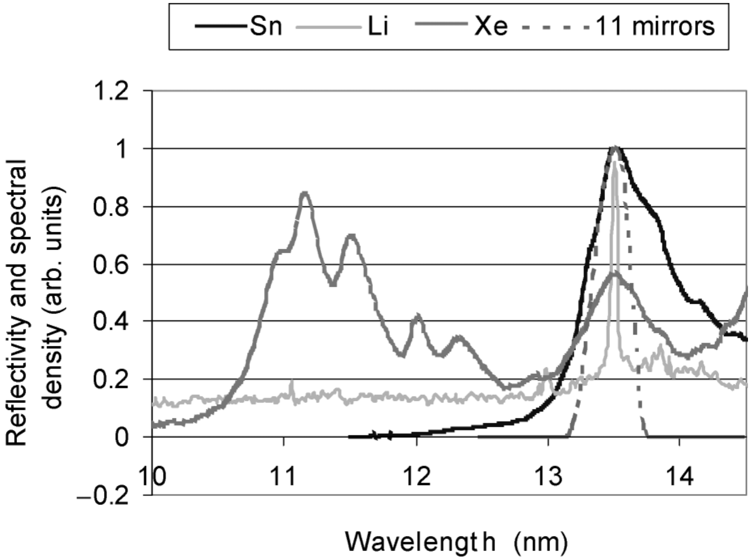
EUV light is generated from laser-produced plasma (LPP)

- **Multilayer mirror**



- **Mo/Si mirror**





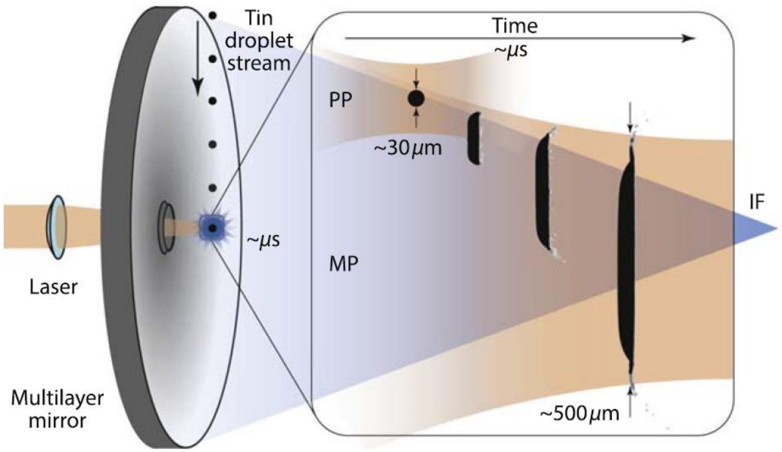
- **$\lambda = 13.5\ \mathrm{nm} \pm 1\%$ is required.**
- **At T=35-40 eV (~450,000 K), in-band emission occurs.**
- **Xenon:**
  - **$4p^64d^8 \rightarrow 4p^64d^75p$ from single ion stage Xe^{10+}**
  - **UTA @ 11 nm**

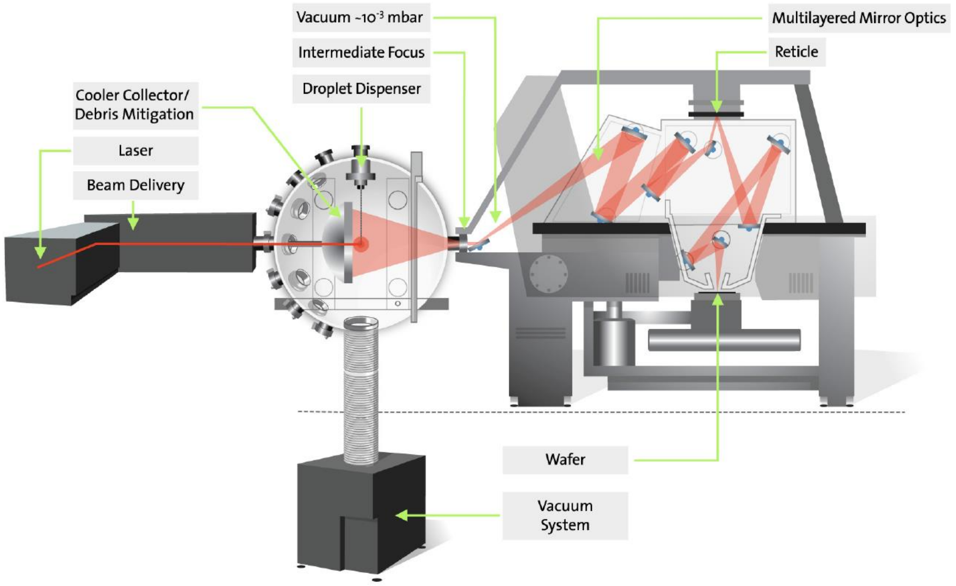
- **Tin:**
  - **$4p^64d^N \rightarrow 4p^54d^{N+1} + 4p^64d^{N-1}4f$ $(1 \le N \le 6)$ in ions ranging from Sn^{8+} to Sn^{12+}**
  - **UTA @ 13.5 nm**

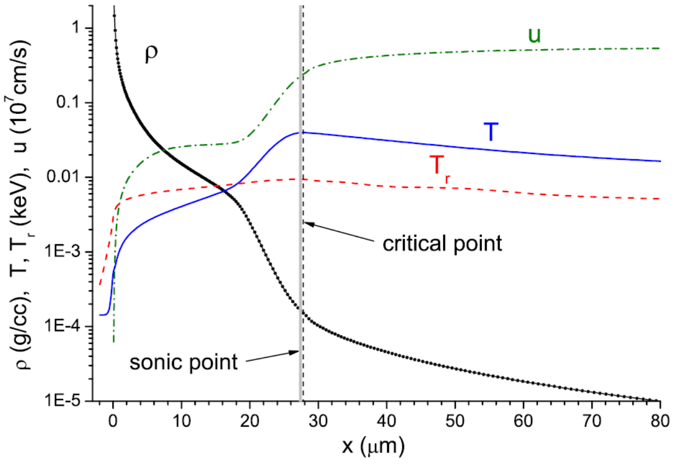
- UTA: unresolved transition array

E. Louis, etc., Proc. SPIE 4146, 60 (2000)
V. Bakshi, EUV sources for lithography

Laser produced plasma is used to heat Tin droplet for radiating EUV light at 13.5 nm







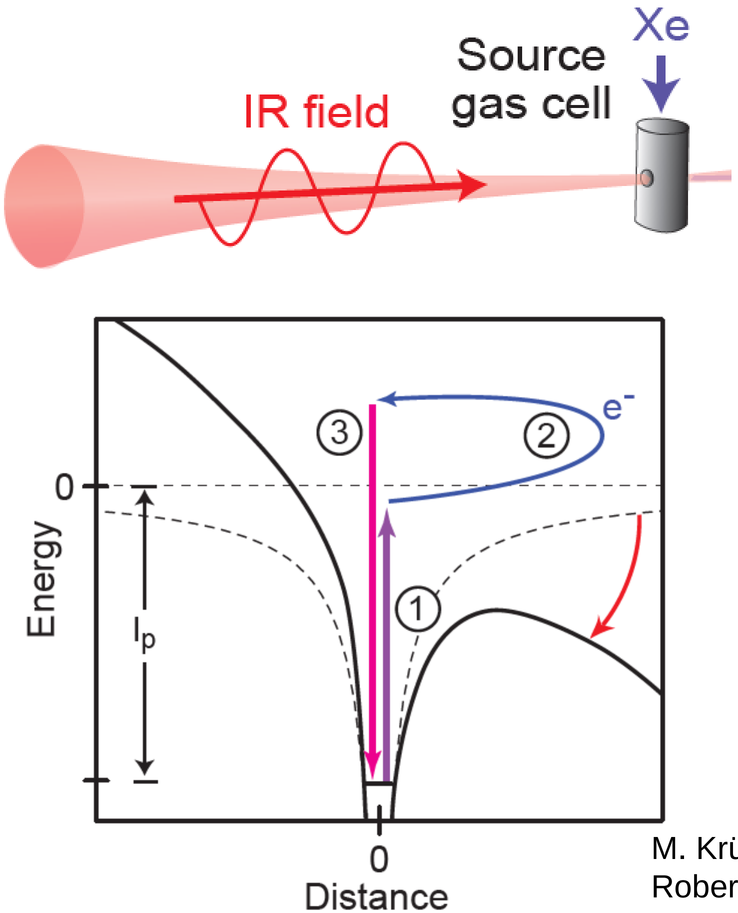
- **ASML introduction**

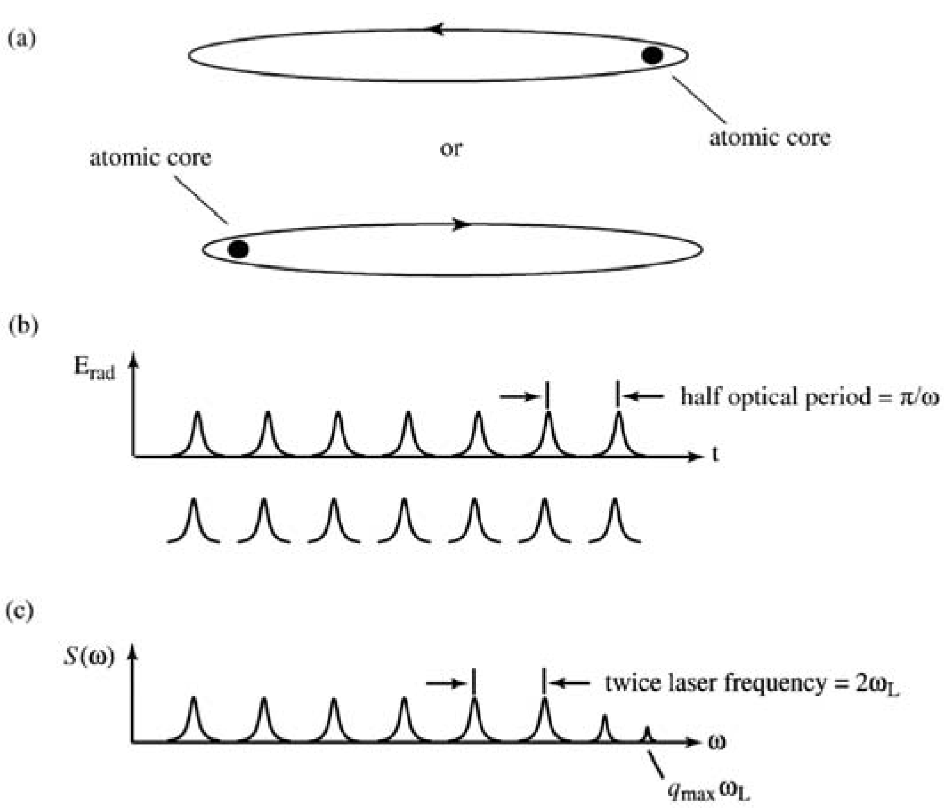
  https://www.youtube.com/watch?v=NHSR6AHNiDs

O. O. Versolato, Plasma Sources Sci. Technol. 28, 083001 (2019)
M. M. Basko, etc., Phys. Plasmas 22, 053111 (2015)
R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)

High-harmonic electromagnetic (EM) waves can be generated with a high-power short pulse laser

- An atom can be ionized directly by the electric field of a high-power laser with I ~ 10^{18} w/cm^2.
- High-harmonic EM wavs are generated when electrons oscillate around the nuclear.

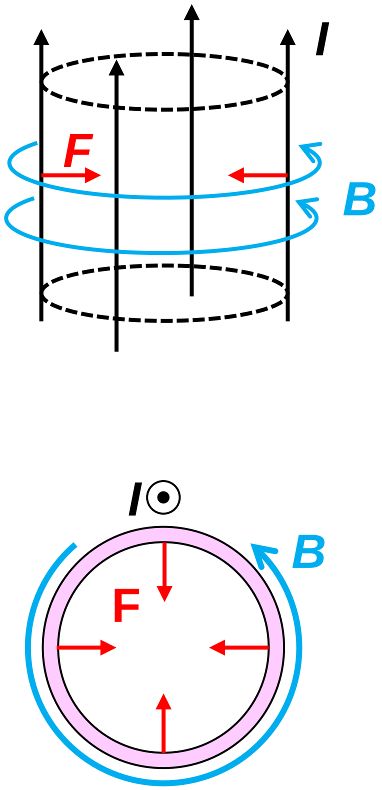




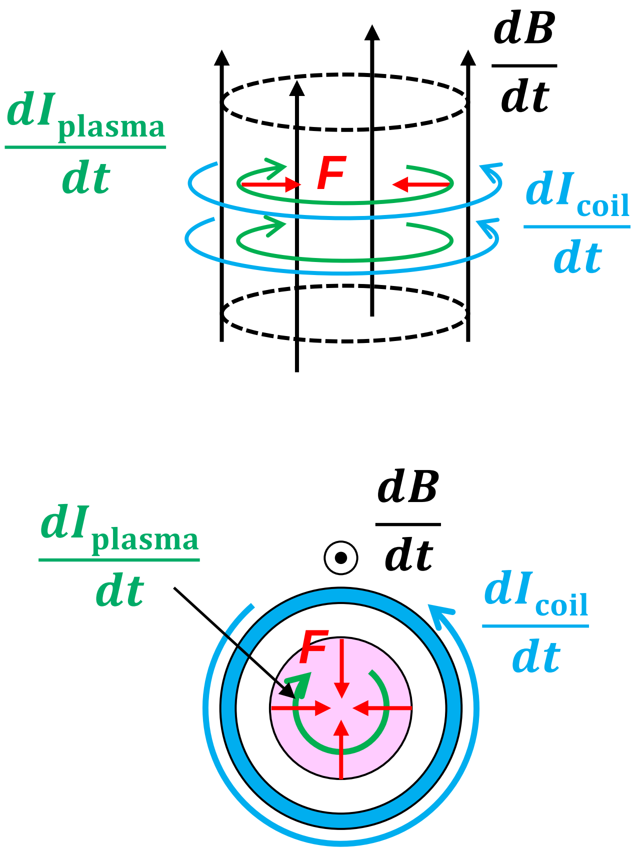
M. Krüger, etc., Appl. Sci. 9, 378 (2019)
Robert Boyd. Nonlinear optics. Academic Press, Amsterdam Boston, 2008.

Plasma can be heated via pinch compression

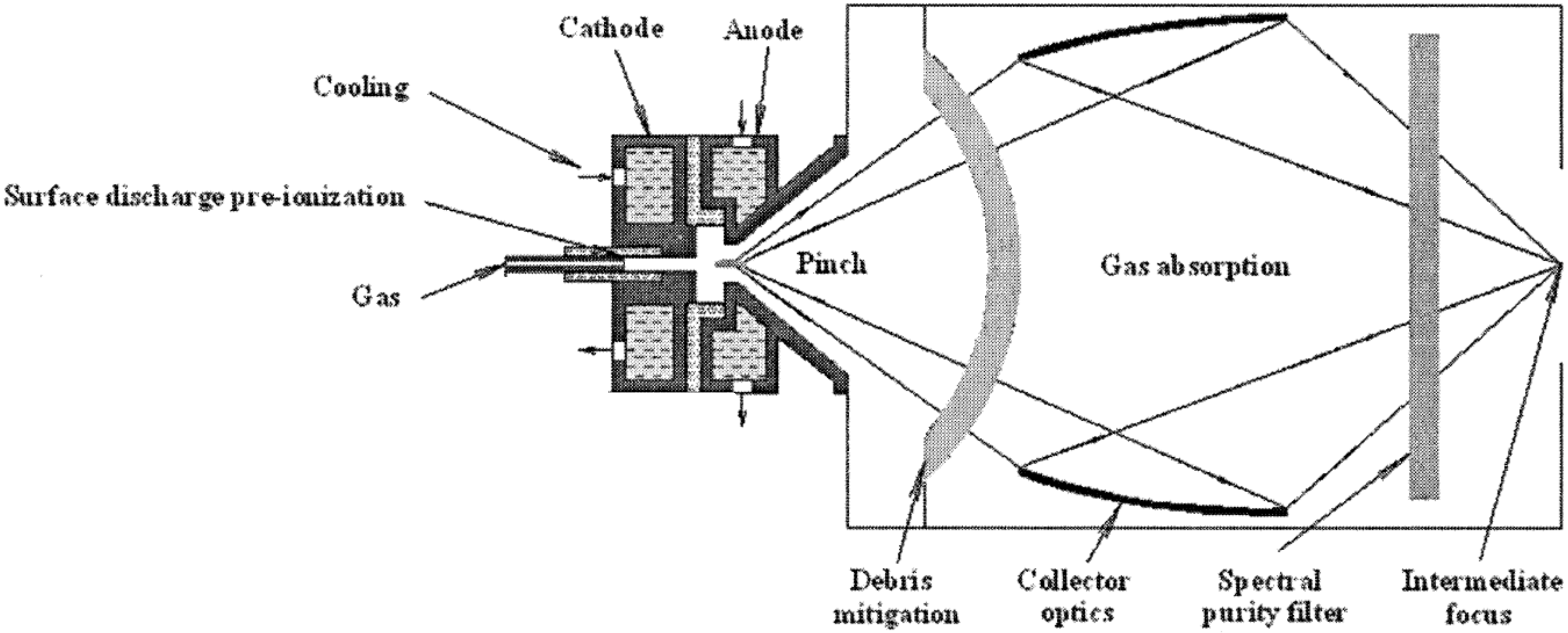
- **Z pinches**



- **Theta pinches**

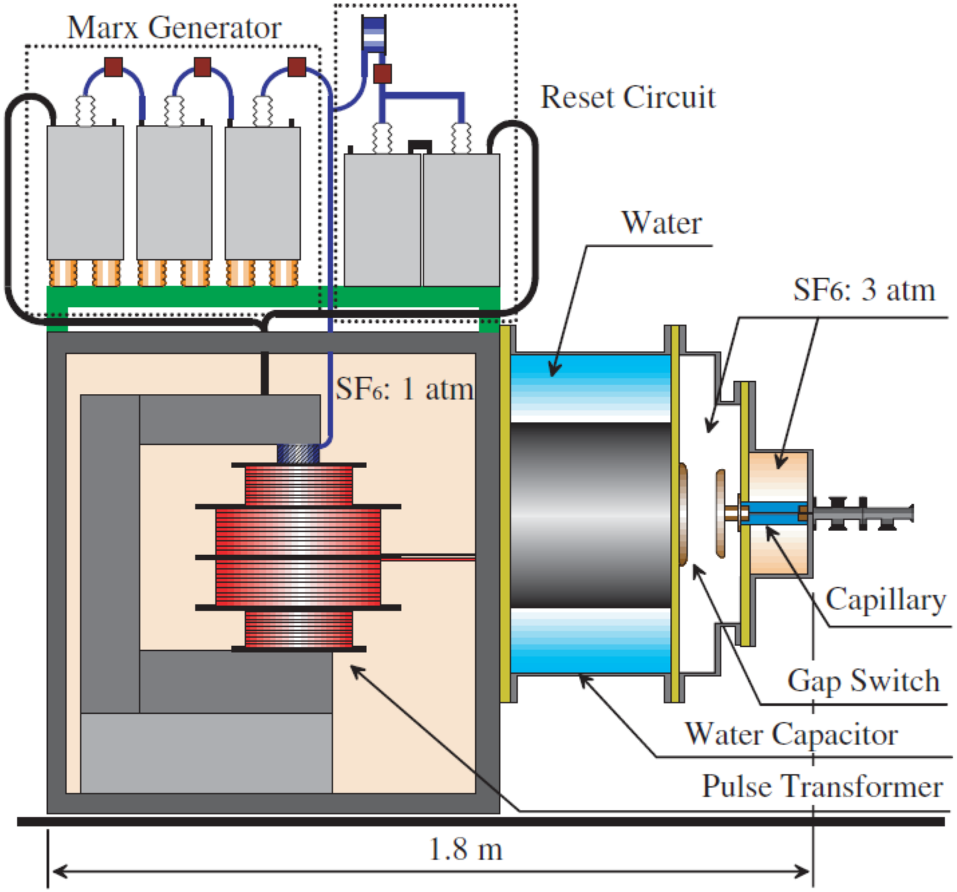


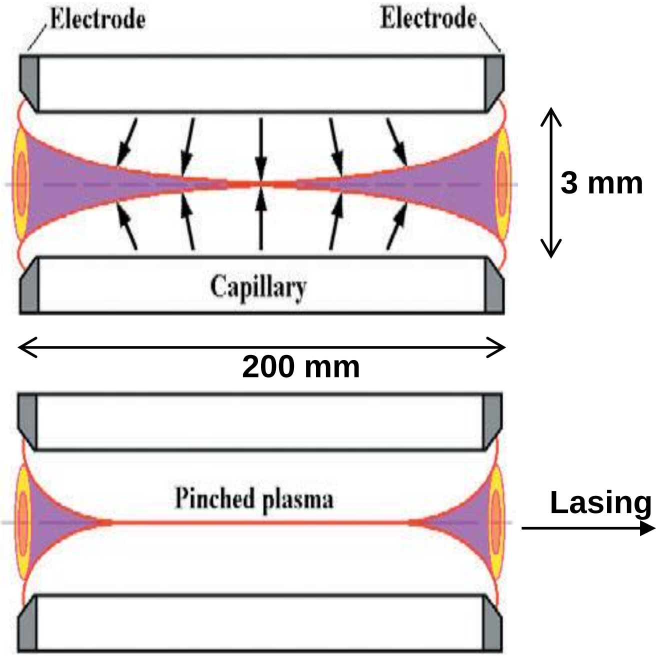
Discharge produced plasma can generate EUV light for EUV lithography



V. Borisov, etc., Proc. SPIE 6611, Laser Optics 2006: High-Power Gas Lasers, 66110B (12 April 2007)

Soft x-ray laser can be generated using a capillary z-pinch discharge





- If 200～500 mTorr Ar is used as the filled gas, 46.9 nm (26.5 eV) Ne-like Ar laser can be built.

Y. Hayashi, etc., Plasma Sources Sci. Technol. 13, 675 (2004)

Our method is to generate EUV light using gas-puff theta pinches

- **Initial plasma is generated via arc discharge.**
- **Plasma is then heated by theta pinches.**
- **Adiabatic compression:**

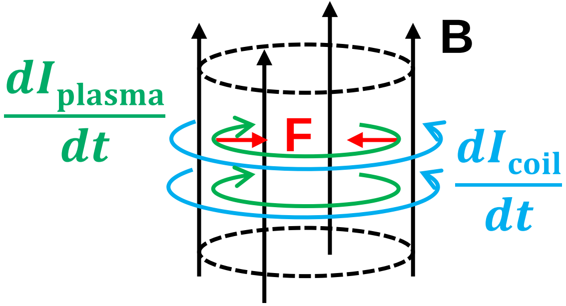
$$TV^{\gamma-1} = \text{const} \quad T_\mathrm{f} = T_\mathrm{o}\left(\frac{r_\mathrm{o}}{r_\mathrm{f}}\right)^{4/3}$$

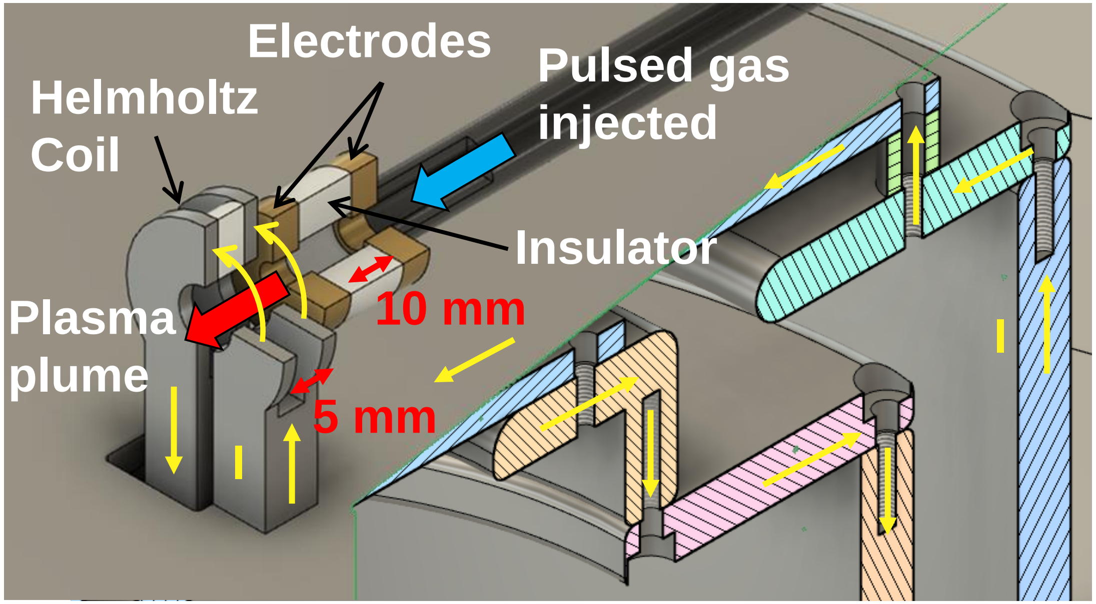
$$T_\mathrm{o} = 1 \sim 10\ \mathrm{eV} \quad T_\mathrm{f} = 40\ \mathrm{eV}$$

Comp. ratio: $\frac{r_\mathrm{o}}{r_\mathrm{f}} = 16 \sim 3$

- **Advantages:**
  - **Energy is directed used for generating and heating plasma.**
  - **Electrodes are away from hot plasma.**
  - **Less current is used to generate plasma.**

- **Theta pinches:**



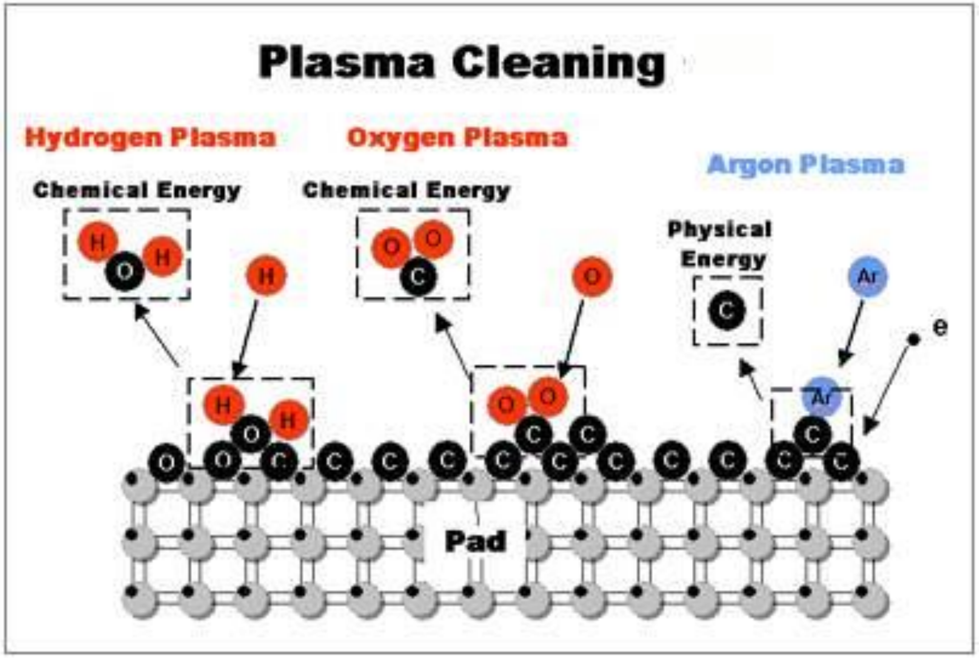


- **Gas-puff theta pinches potentially generate EUV light with high conversion efficiency and with long system life time.**

Plasma cleaning

Plasma can be used for cleaning surface

- Cleaning mechanisms:
  - Chemical reactions by free radicals
  - Physical sputtering by high energy ions



楦鼎奈米科技股份有限公司
https://www.ecplaza.net/products/plasma-cleaning_111807

Free radicals are generated and used in chemical reactions

$$e^- + H_2 \rightarrow 2H \bullet \qquad e^- + O_2 \rightarrow 2O \bullet \qquad \mathrm{O} \bullet + O_2 \rightarrow O_3$$

- **Highly reactive free radicals generated in plasma may react with the hydrocarbon contaminants of surface oxide.**
- **Both H• and O• can react with grease or oil on surface to form volatile hydrocarbons.**

$$\mathrm{H} \bullet_{(g)} + C_n H_{2n+2(s)} \rightarrow \mathrm{CH}_{4(s)}$$

$$\mathrm{O} \bullet_{(g)} + C_n H_{2n+2(s)} \rightarrow \mathrm{CO}_{(s)} + \mathrm{CH}_x O_{y(g)} + H_2 O_{(g)}$$

- **O• is more reactive than H•. But O• may also react with surface metal to form oxide, deteriorating the material properties. Nevertheless, H• can make metal oxide back to metal.**

$$\mathrm{O} \bullet + \mathrm{Me} \rightarrow \mathrm{MeO}$$

$$\mathrm{H} \bullet + \mathrm{MeO} \rightarrow \mathrm{Me} + H_2 O$$

The effect of chemical reactions is increased as the pressure increases

- **Advantages:**
  - **Stable gas products are formed.**
  - **No redeposition problem.**
  - **High etching selectivity.**

- **Disadvantages:**
  - **Higher concentration of H_2 or O_2 is required to ensure an appropriate etching rate.**
  - **H_2 safety or O_2 strong oxidation ability needs to be monitored.**

High energy ions are used in physical sputtering cleaning

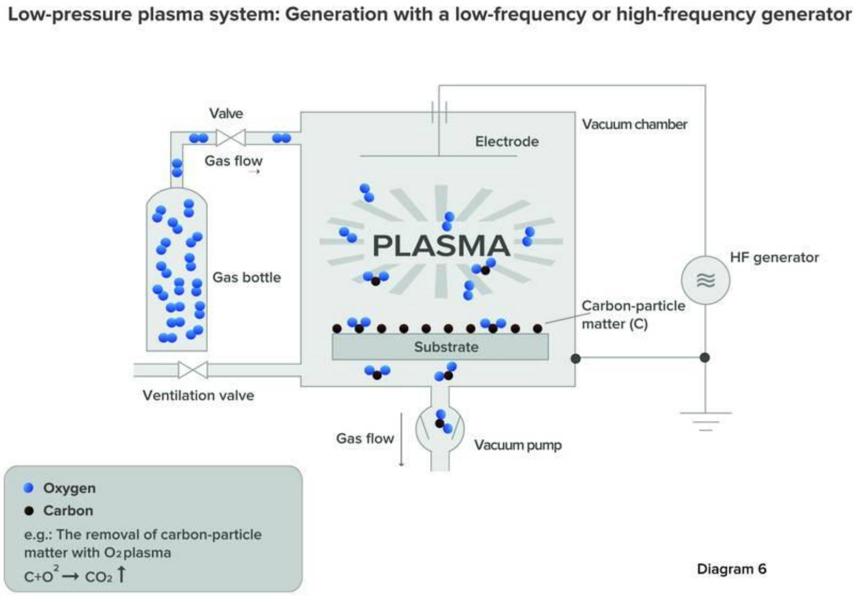
- Ions generated in plasma can be accelerated toward the substrate to physically bombard away the atoms of contaminants.
- The physical sputtering rate increases as the following quantities increase:
  - Plasma density;
  - Accelerating voltage;
  - Mass of bombardment atoms.
- The physical sputtering is also enhanced by lowering the pressure.
- High cathode bias is used.
- Ar^+ has strong sputtering effect.

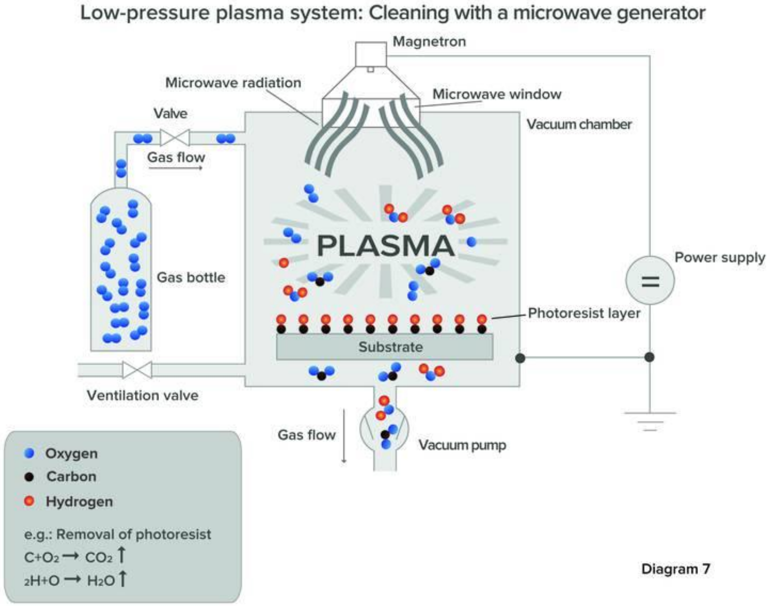
The physical sputtering rate increases with higher cathode bias and Ar concentration and lower pressure

- **Advantages:**
  - **Highly efficient cleaning effect can be achieved.**
  - **Gas consumption rate can be very low.**

- **Disadvantages:**
  - **Etching problems – non-selective etching by physical sputtering.**
  - **Redeposition problems: the products sputtered out may be highly unstable and tend to deposit again downstream.**

Plasma cleaning examples





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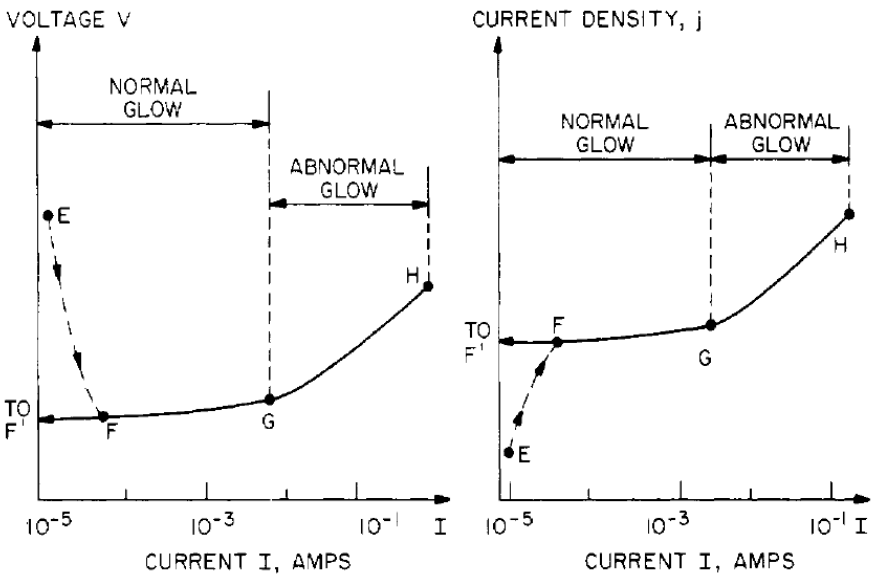
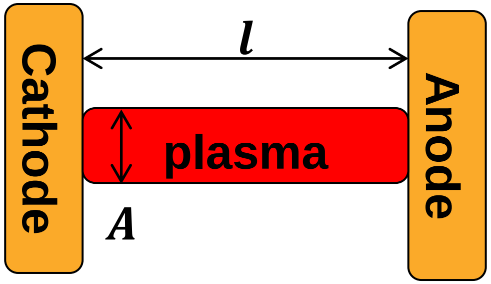
https://www.plasma.com/en/plasmatechnik/low-pressure-plasma/cleaning/

Abnormal glow discharge occurs when the cross section of the plasma covers the entire surface of the cathode

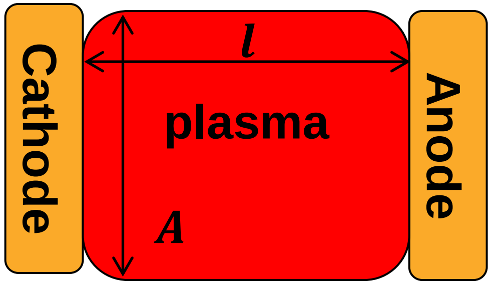


$$R = \eta \frac{l}{A}$$

- **Normal glow discharge:**

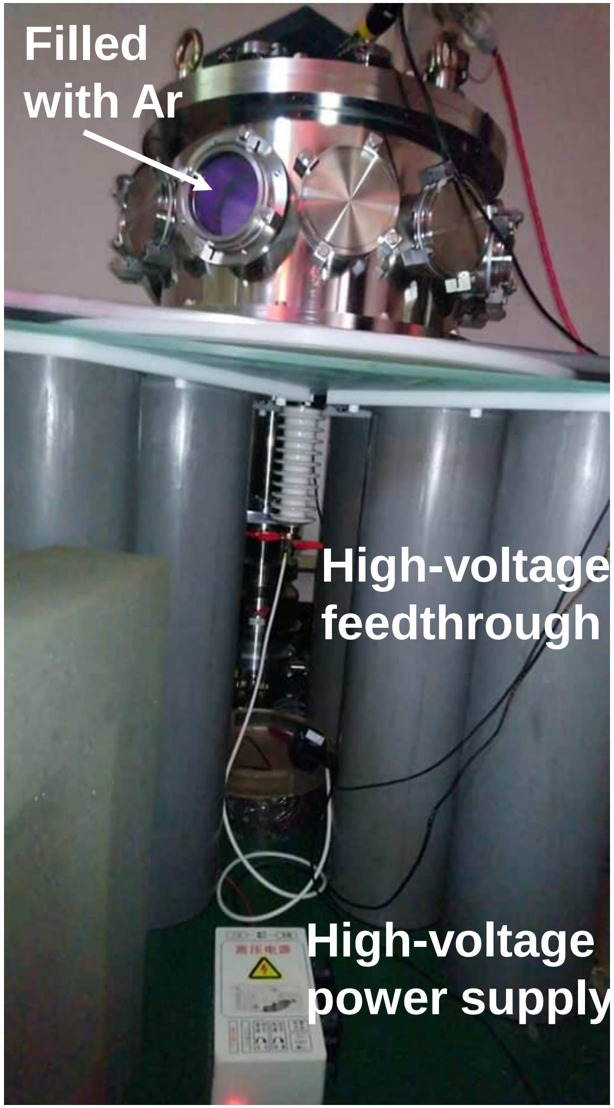


- **Abnormal glow discharge:**



- **Surface cleaning using plasma needs to work in the abnormal glow discharge region.**

Plasma cleaning needs to work in the regime of abnormal glow discharge



Filled with Ar

High-voltage feedthrough

High-voltage power supply

- Top view

- Side view

Course Outline

1. What is Plasma?
2. **Varies kinds of plasma**
   a. How plasma is generated
   b. Plasma in space
   c. Material Processing
   d. **Biomedical application**
   e. Pparticle beam source
   f. High energy particle accelerator
   g. Controlled thermonuclear fusion
   h. Neutral beam source
   i. Electrical propulsion

Plasma medicine

- **Reference:**
  - **“Applied Plasma Medicine”, by G. Fridman, et al., Plasma Process. Polym., 5, 503, 2008**
  - **“Plasma Medicine”, by A. Fridman and G. Fridman**

Outline

- Example of several plasma discharges for plasma medicine
- Living tissue sterilization
- Blood coagulation
- Nitrogen oxide (NO) treatment
- Non-thermal plasma treatment of melanoma skin cancer
- Skin regeneration
- Facemask regeneration

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Plasma is characterized by the electron and ion temperatures

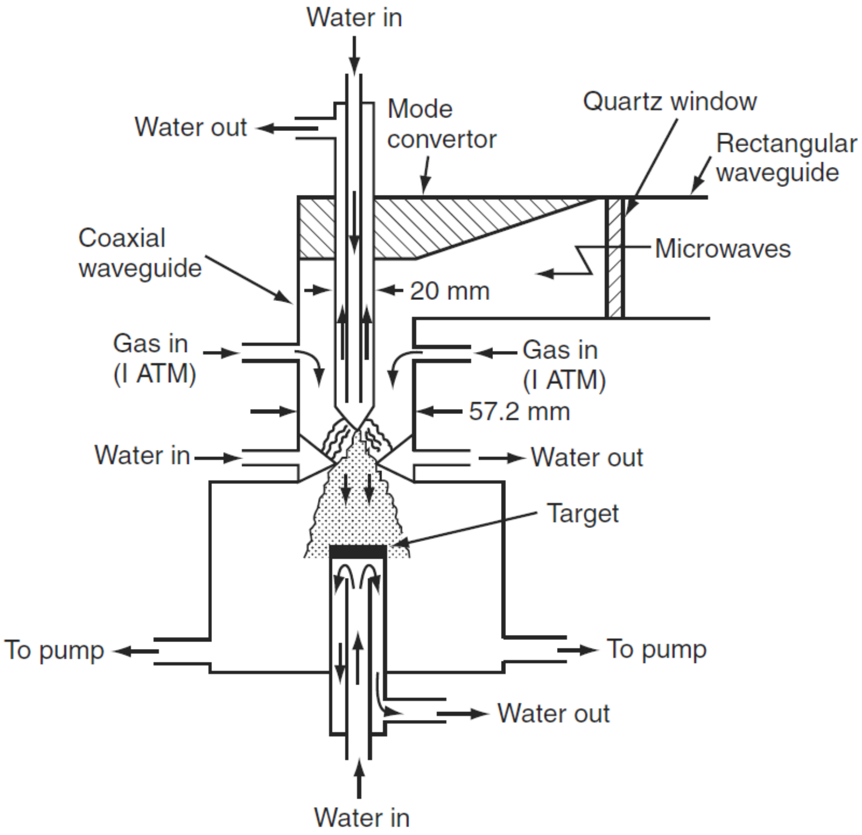
- **Non-thermal plasma**
  - **$T_i << T_e$**
  - **Also called non-equilibrium plasma**
- **Thermal plasma**
  - **$T_i \approx T_e$**
- **Earlier applications of plasma in medicine – thermal effects of plasma**

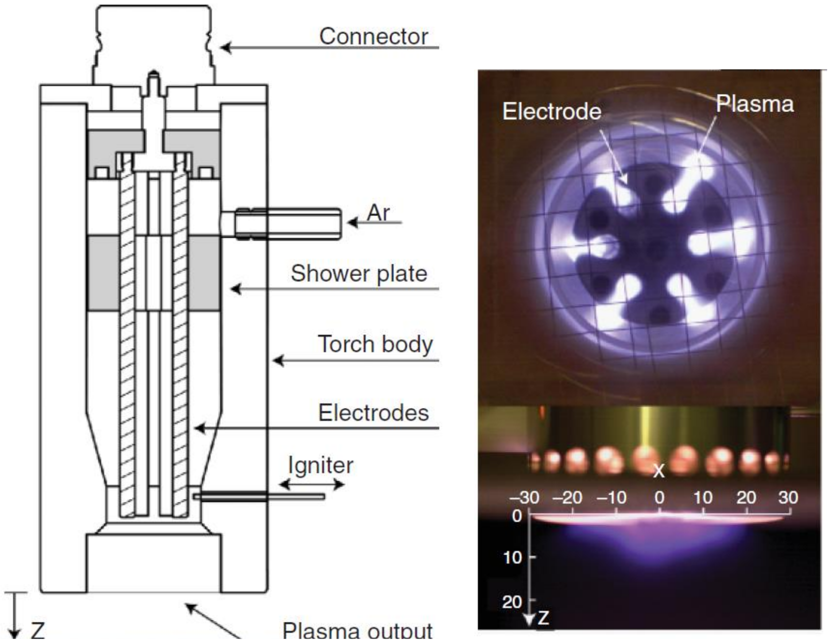
Plasma can provide good surface treatment with low temperature

Treatment	Surface treatment level	Depth	Temperature	Cost
Chemical	**Large**	**Deep**	**Room temperature ~200 ℃**	**Medium**
Heat	**Only oxidizing**	**Deep**	**High temperature**	**Cheap**
Radiation	**Small**	**Whole sample**	**High temperature**	**Expensive**
Plasma	**Large**	**Surface**	**Room temperature ~100 ℃**	**Cheap ~ Medium**

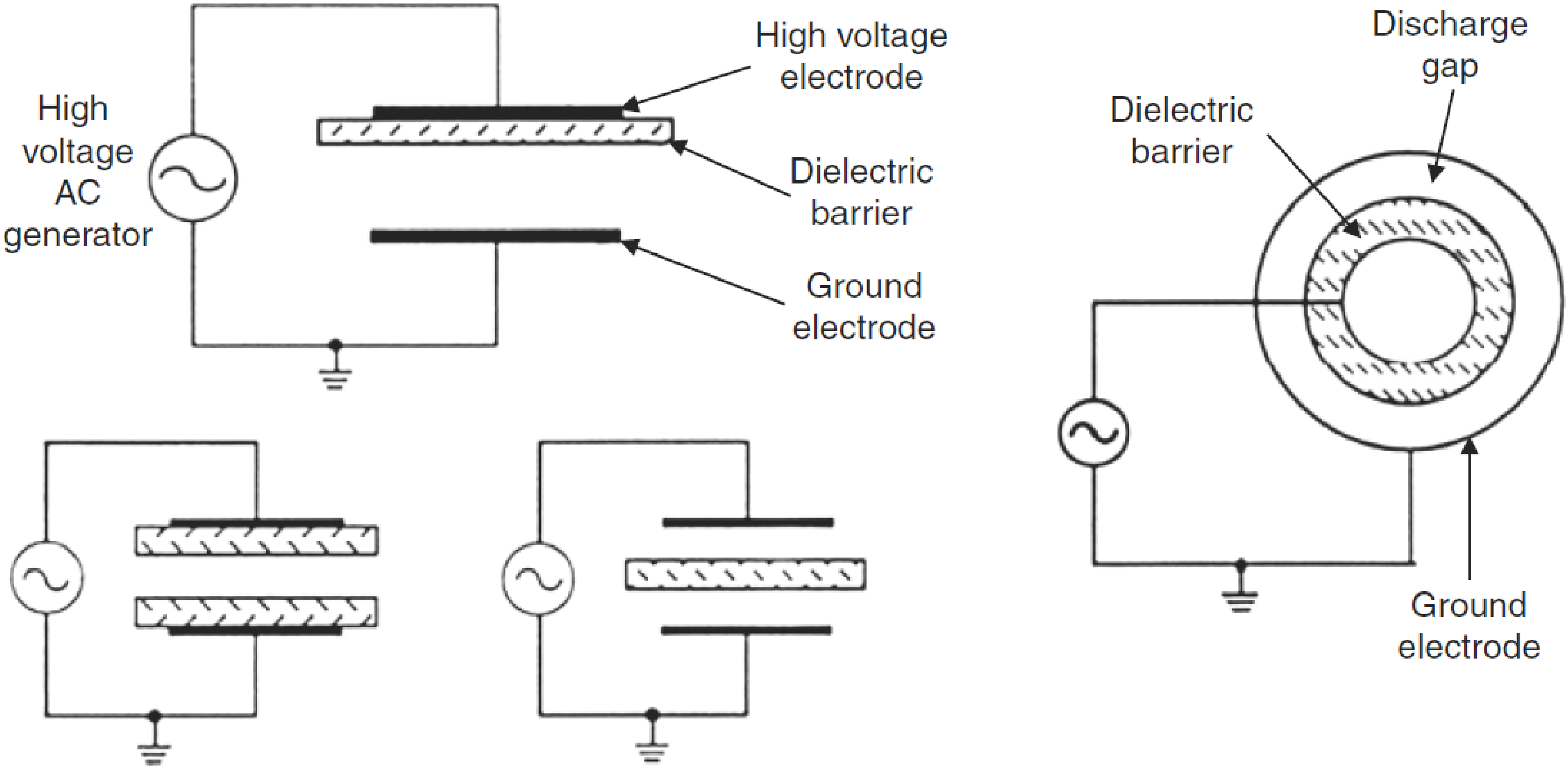
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

Microwave plasma torch

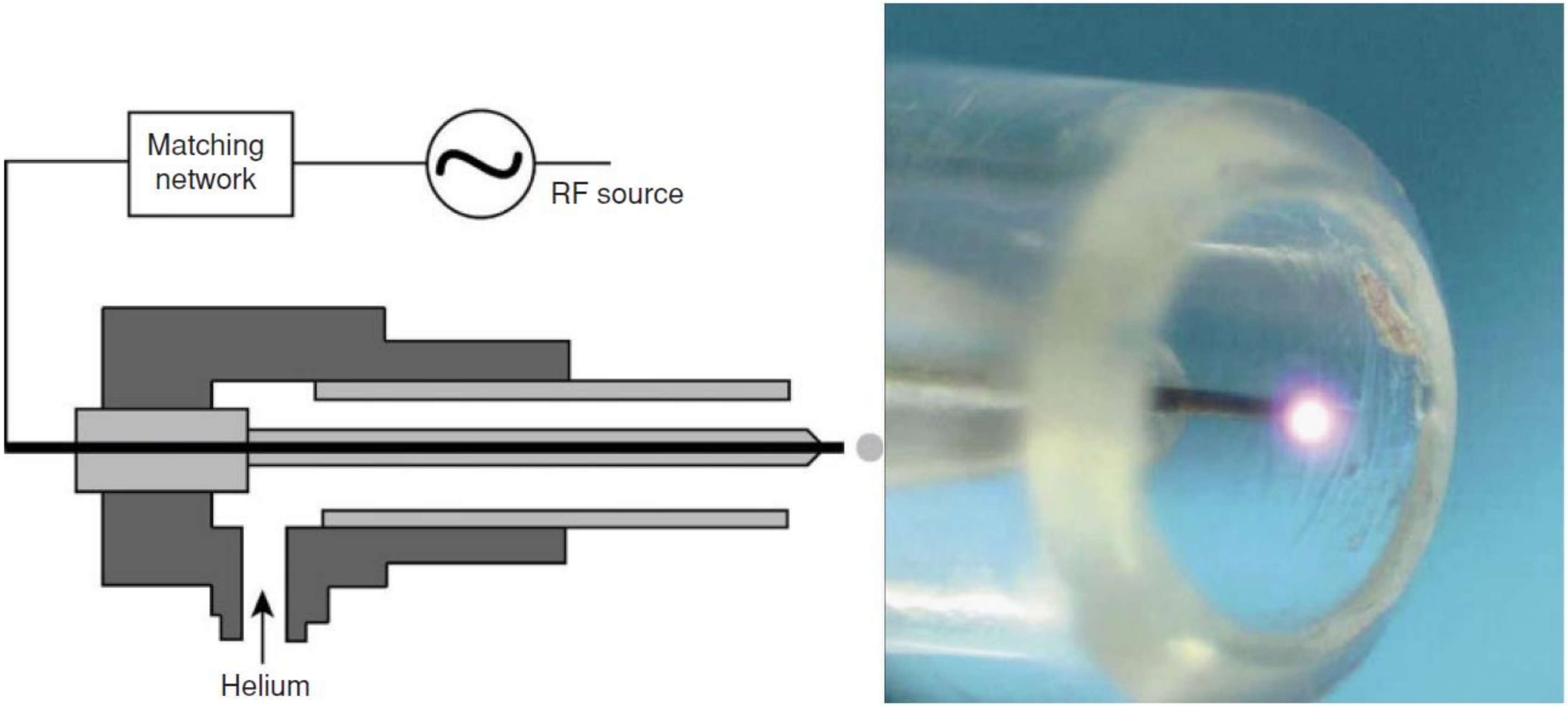




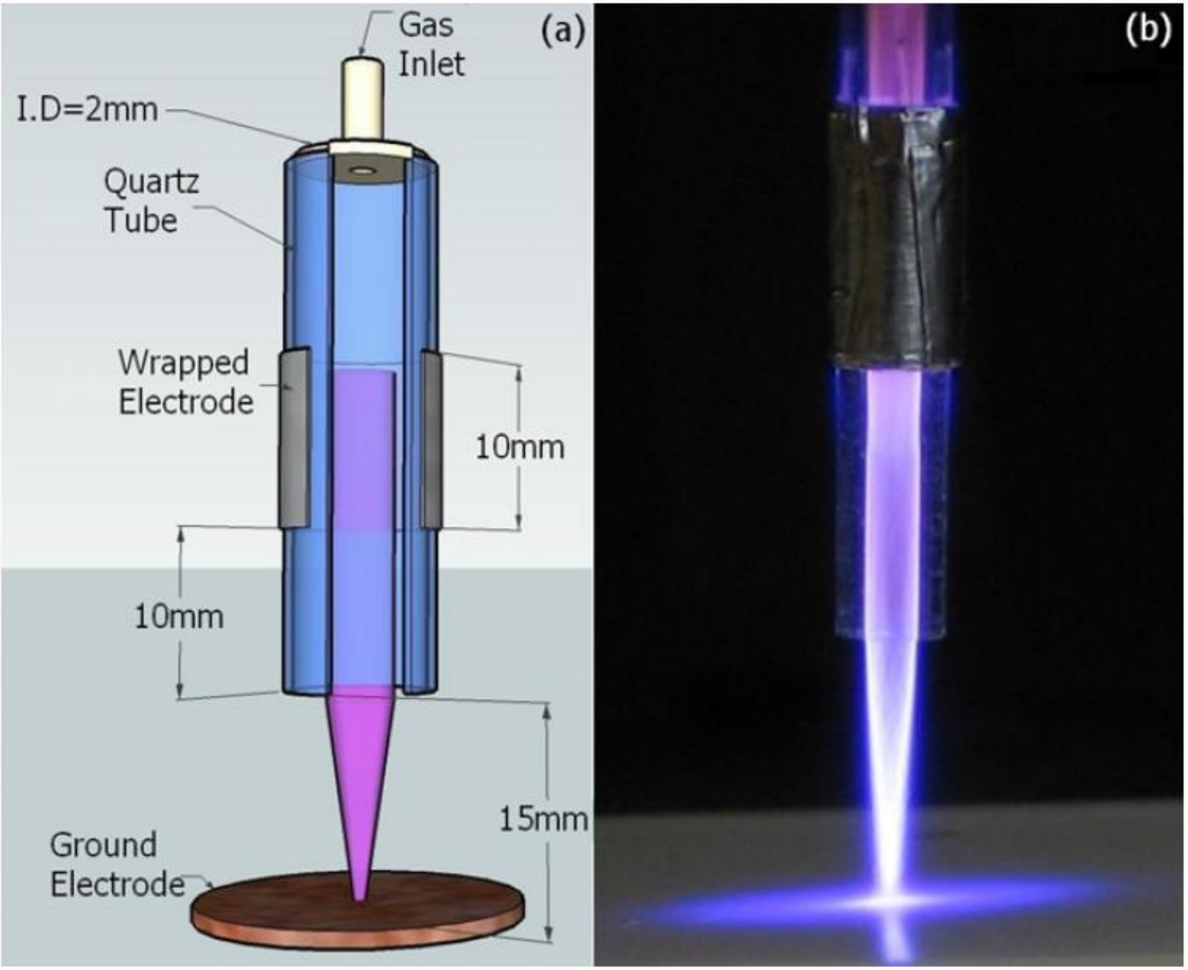
Dielectric-barrier discharges (DBDs)



Plasma-needle discharge

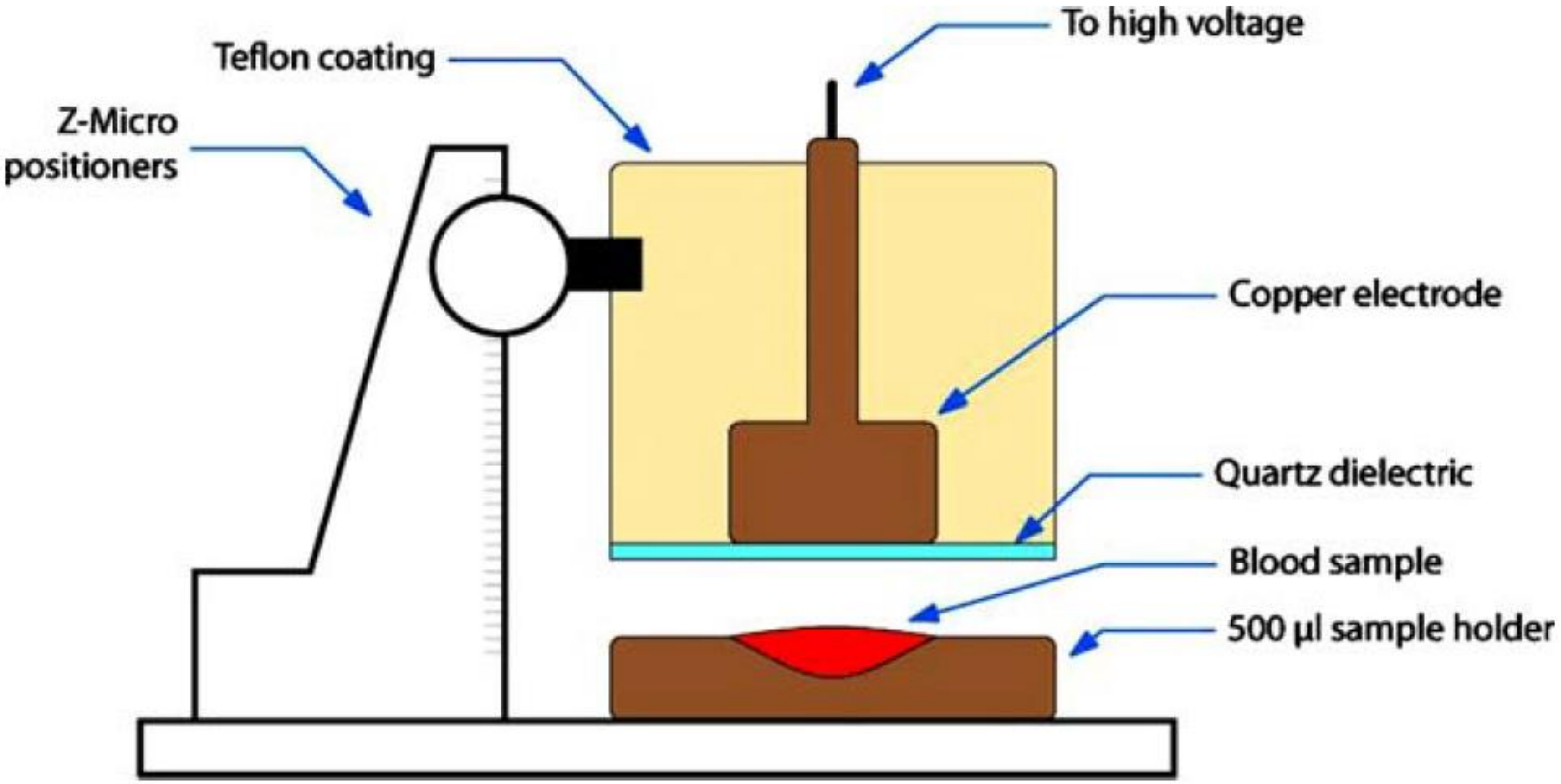


Atmospheric-pressure cold helium microplasma jets



J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

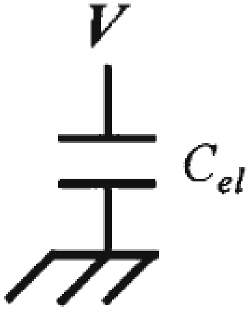
Floating-electrode dielectric barrier discharge (FE-DBD)

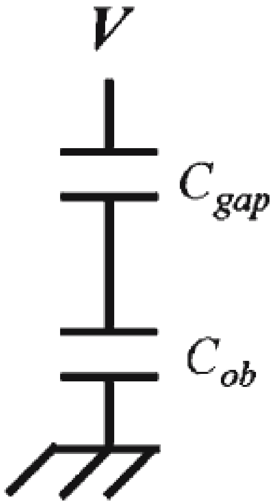


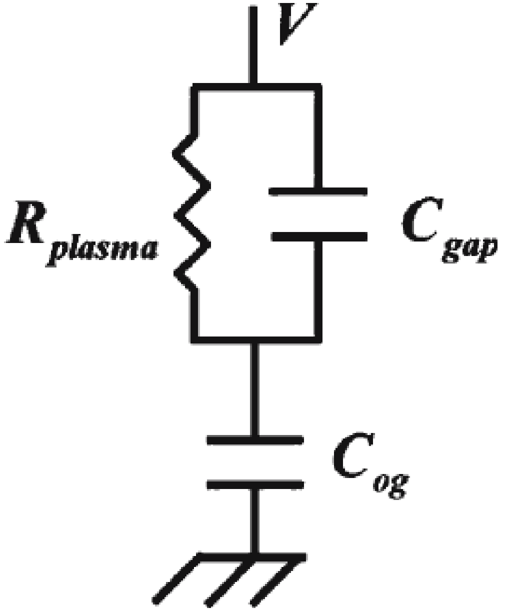
G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

Simplified electrical schematic of FE-DBD

- **electrode itself**
- **electrode near the treated object**
- **e-plasma discharge**





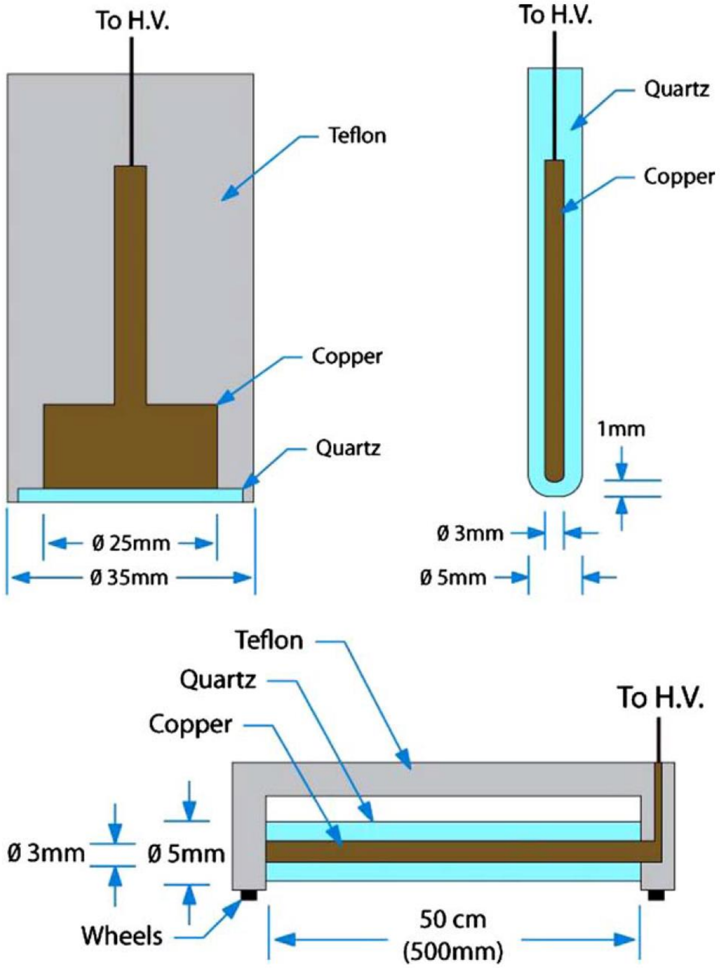


$$C_{\text{ob}} >> C_{\text{gap}} \Rightarrow V_{\text{ob}} << V_{\text{gap}}$$

G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

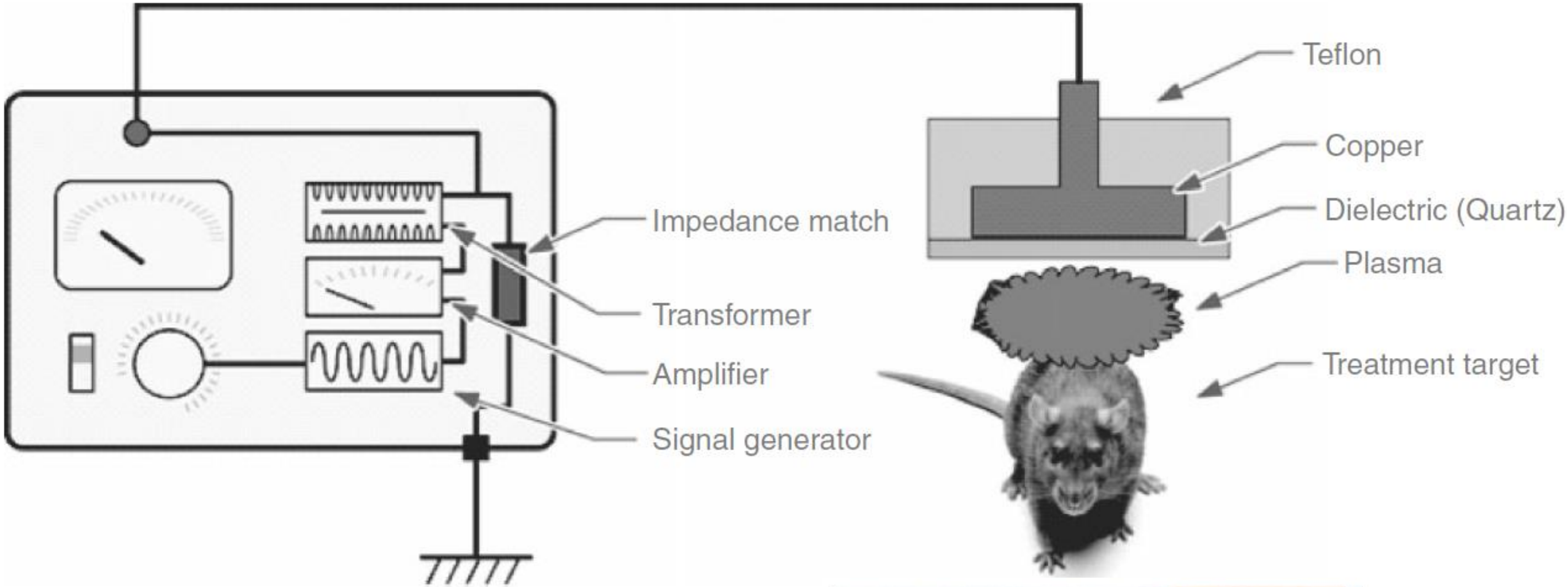
Depending on the needs, the size and the shape of FE-DBD treatment electrodes can vary

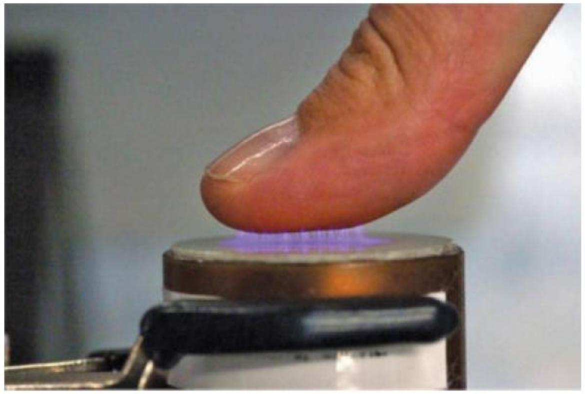
- **Round**
- **Wand**
- **Roller**



G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

FE-DBD is a direct plasma medicine





G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)
Plasma medicine, by Alexander Fridman and Gary Friedman

Outline

- Example of several plasma discharges for plasma medicine
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Bacteria concentration reduces after being treated with FE-DBD

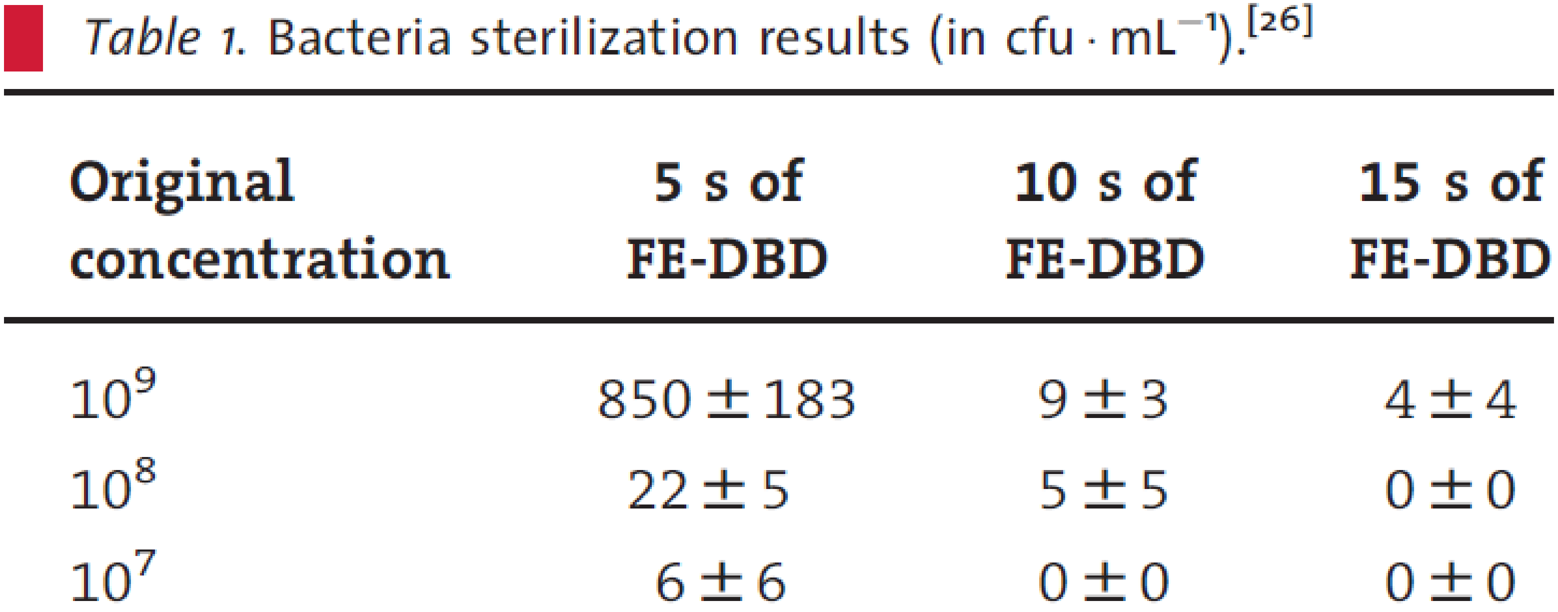


Table 1. Bacteria sterilization results (in cfu · mL^{-1}).[26]

Original concentration	5 s of FE-DBD	10 s of FE-DBD	15 s of FE-DBD
10^9	850 ± 183	9 ± 3	4 ± 4
10^8	22 ± 5	5 ± 5	0 ± 0
10^7	6 ± 6	0 ± 0	0 ± 0

- **Maximum acceptable dose – the highest dose that doesn’t cause a damage on skin**

G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)

The power of FE-DBD is low enough such that the tissue is not damaged by the plasma

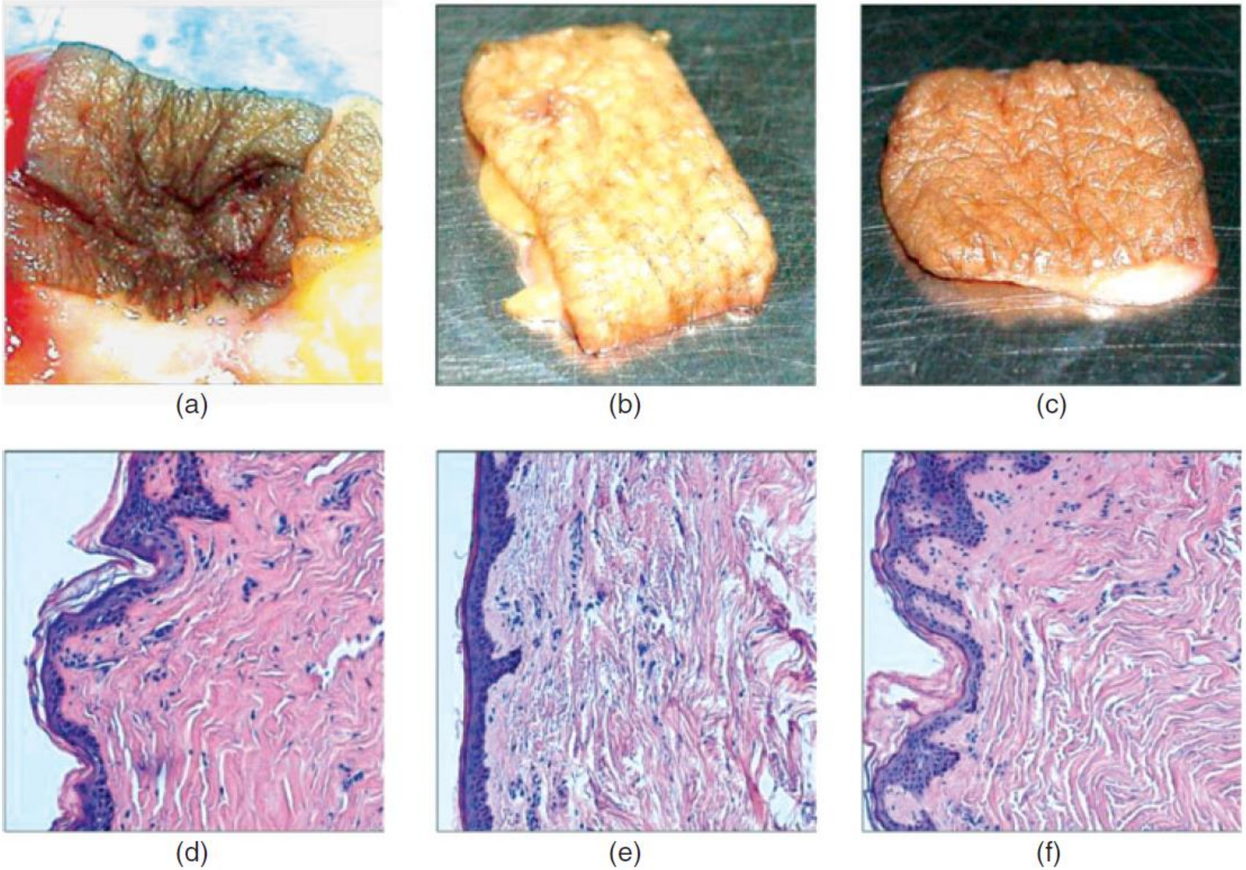
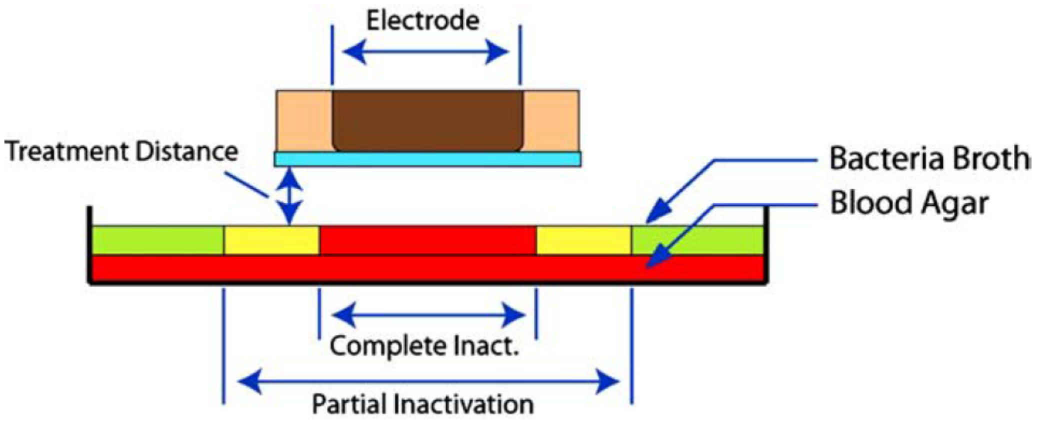


Figure 6.23 *Photos (top) and tissue histology (bottom) of cadaver skin samples after FE-DBD treatment: (a, d) control; (b, e) after 15 s of treatment; and (c, f) after 5 min of treatment – no visible damage is detected.*

G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)
Plasma medicine, by Alexander Fridman and Gary Friedman

Bacteria is inactivated by the plasma



- ~1.3×10^7 cfu/cm^2 (10^9 cfu/ml) of skin flora

  (CFU: colony-forming unit)
- Treated by FE-DBD plasma for 10 s

G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

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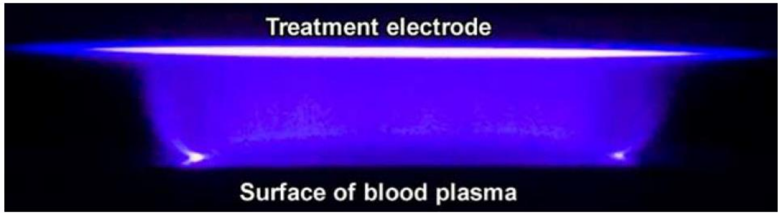
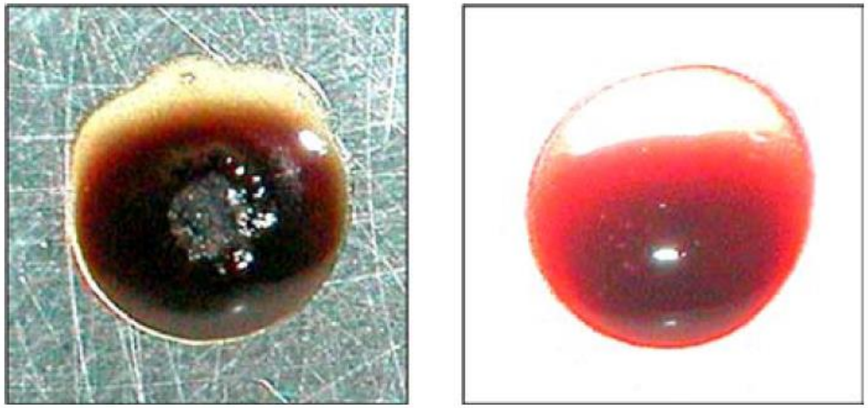
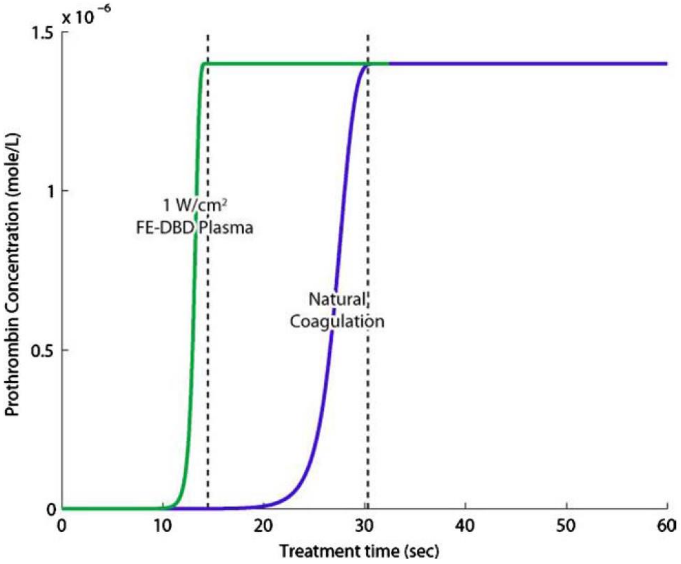
Plasma can stimulate blood coagulation

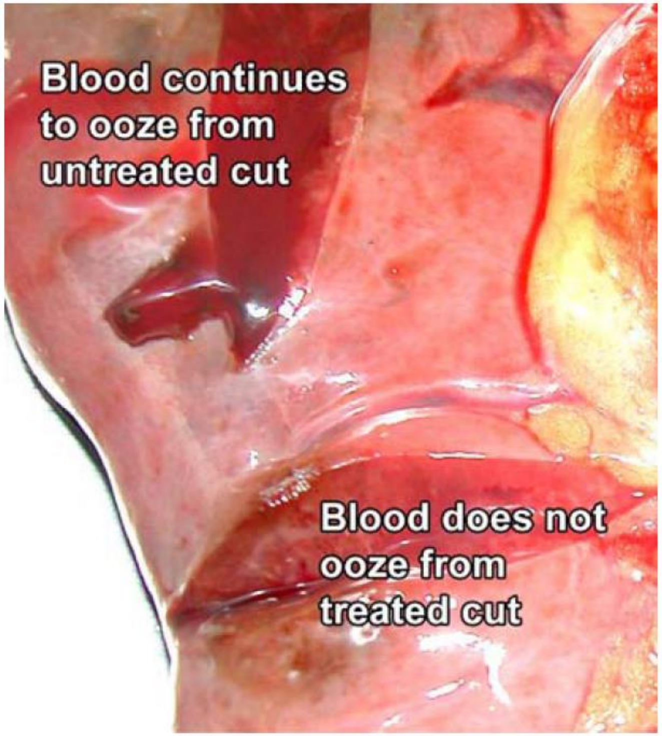


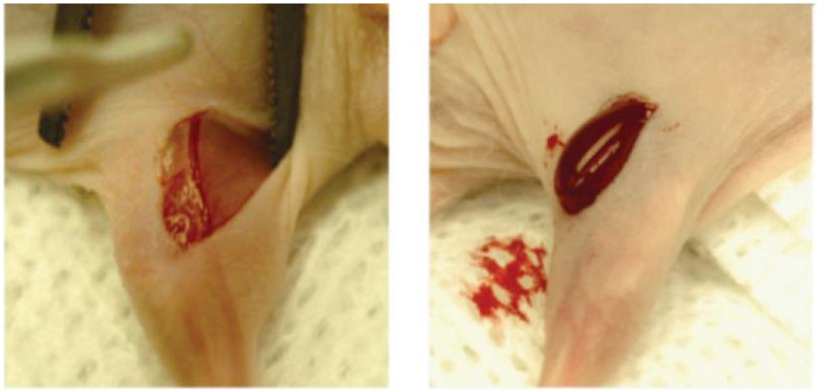




G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

Example of blood coagulation using plasma





Saphenous vein
is a major blood vessel for a mouse

(a)

If left untreated following a cut
animal will bleed out (control)

(b)

15 seconds at 0.8 Watt/cm^2 stops the
bleeding completely right after treatment

(c)

G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)
G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)
Plasma medicine, by Alexander Fridman and Gary Friedman

Outline

- Example of several plasma discharges for plasma medicine
- Living tissue sterilization
- Blood coagulation
- Nitrogen oxide (NO) treatment
- Non-thermal plasma treatment of melanoma skin cancer
- Skin regeneration
- Facemask regeneration

Nitrogen oxide (NO) serves a multitude of essential biological functions

- **Blood coagulation**
- **Immune system**
- **Early apoptosis (細胞凋亡)**
- **Neural communication and memory**
- **Relaxation of flat bronchial (支氣管) and gastrointestinal muscles (胃腸肌肉)**
- **Hormonal (激素) and sex functions**
- **Anti-microbial (抗微生物) and anti-tumor (抗腫瘤) defense**
- **Play an important role in tumor growth, immunodeficiency (免疫缺陷), cardiovascular (心血管), liver (肝), gastrointestinal tract (胃腸道) disease**

NO treatment of wound pathologies

Before treatment

21st day of NO-therapy (10 seances)

After 2 months of NO-therapy

- **Decrease in the trophic ulcer area:**
  - **Traditional treatment methods: 0.7% per day**
  - **NO treatment methods: 1.7% per day**

G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)
Plasma medicine, by Alexander Fridman and Gary Friedman

NO treatment of wound pathologies

Before treatment

After 4.5 months of NO-therapy
(3 courses; 12 seances per course)

G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)
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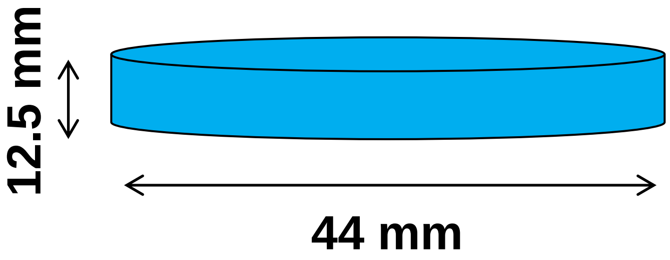
Non-thermal plasma treatment of melanoma skin cancer (黑色素瘤皮膚癌)

- **Melanoma cancer cell line (ATCC A2-58) was used**
- **~1.5x10^6 per dish**



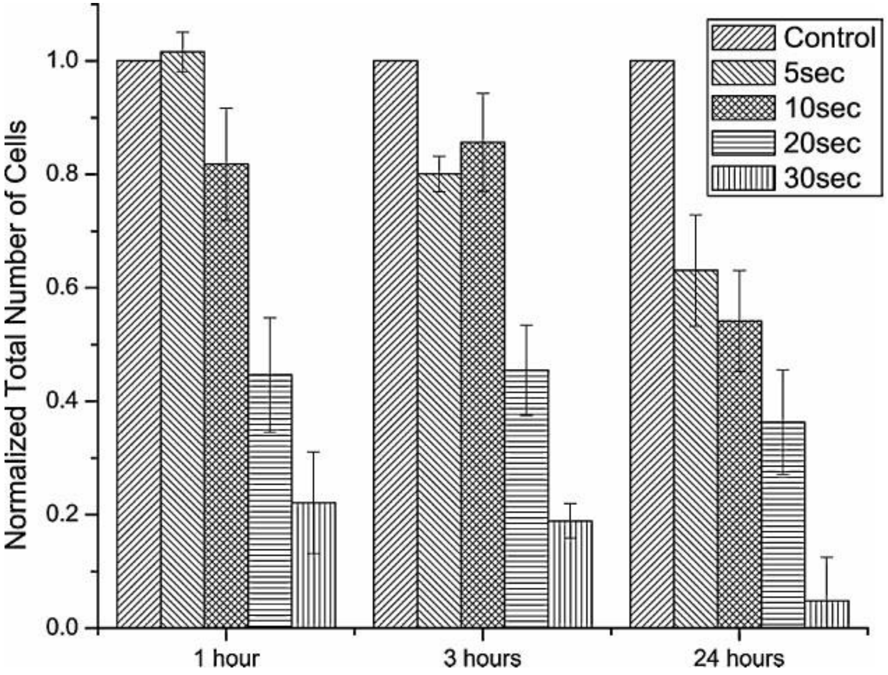
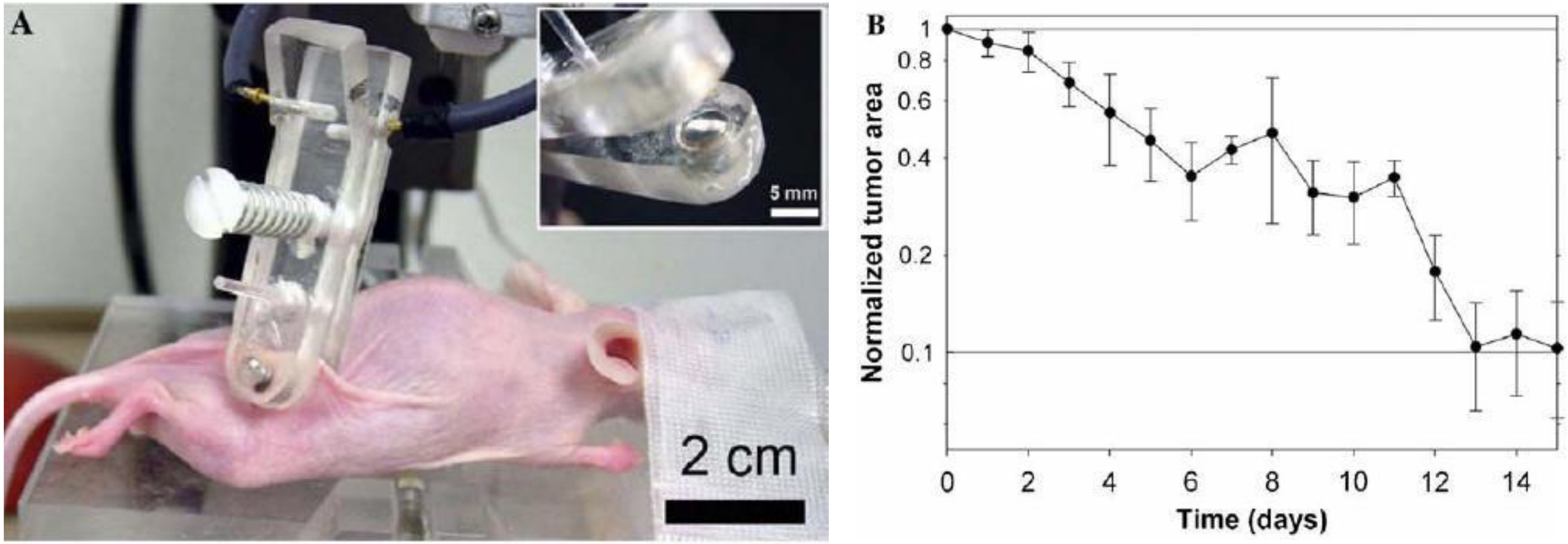


Figure 22. Results of FE-DBD treatment of melanoma cancer cells: Control, 5, 10, 20, and 30 s, counted 1, 3, and 24 h post-treatment.[27]

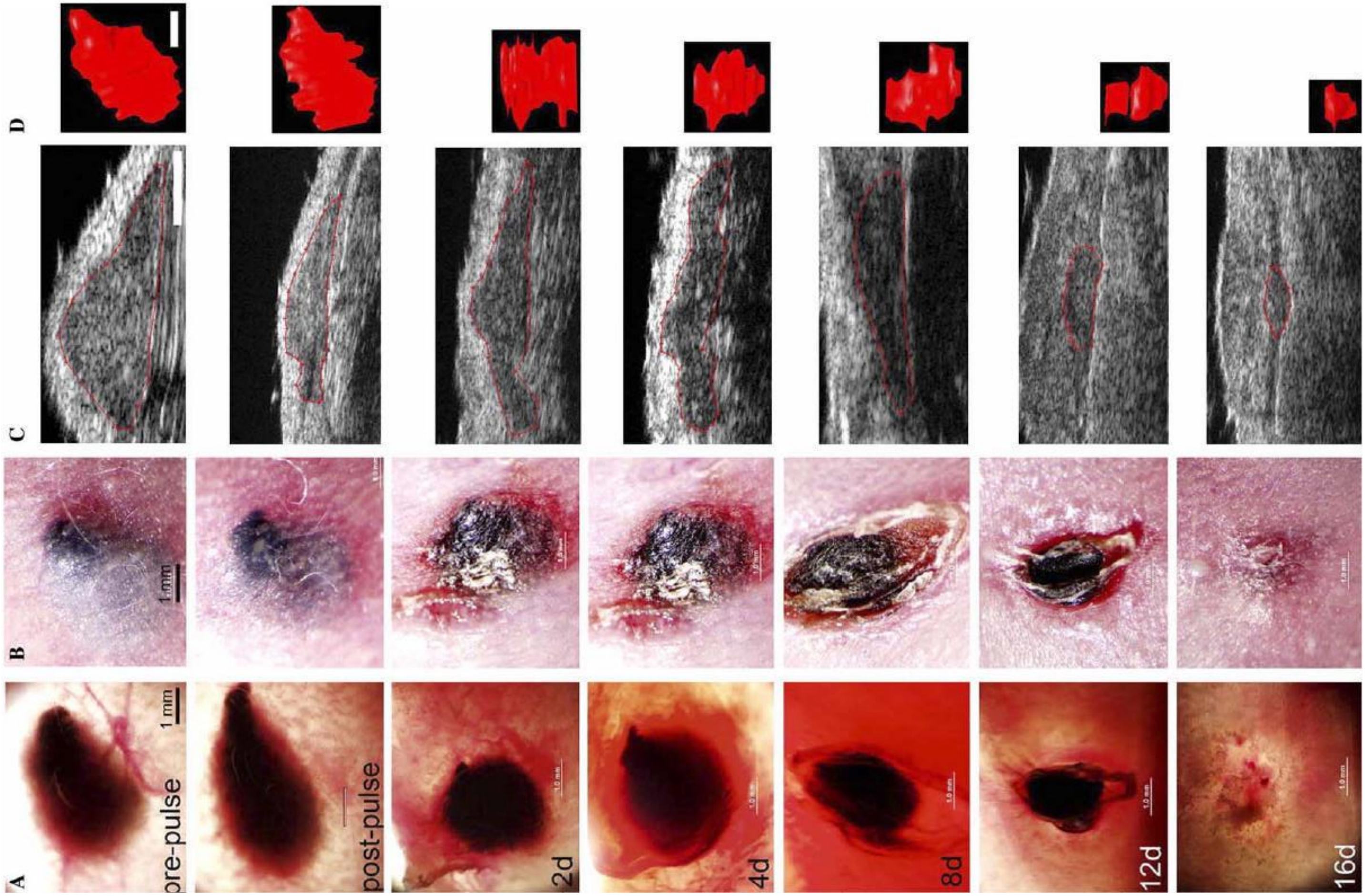
G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)

SKH-1 hairless mouse is treated with parallel plate electrode under isoflurane inhalation anesthesia



Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

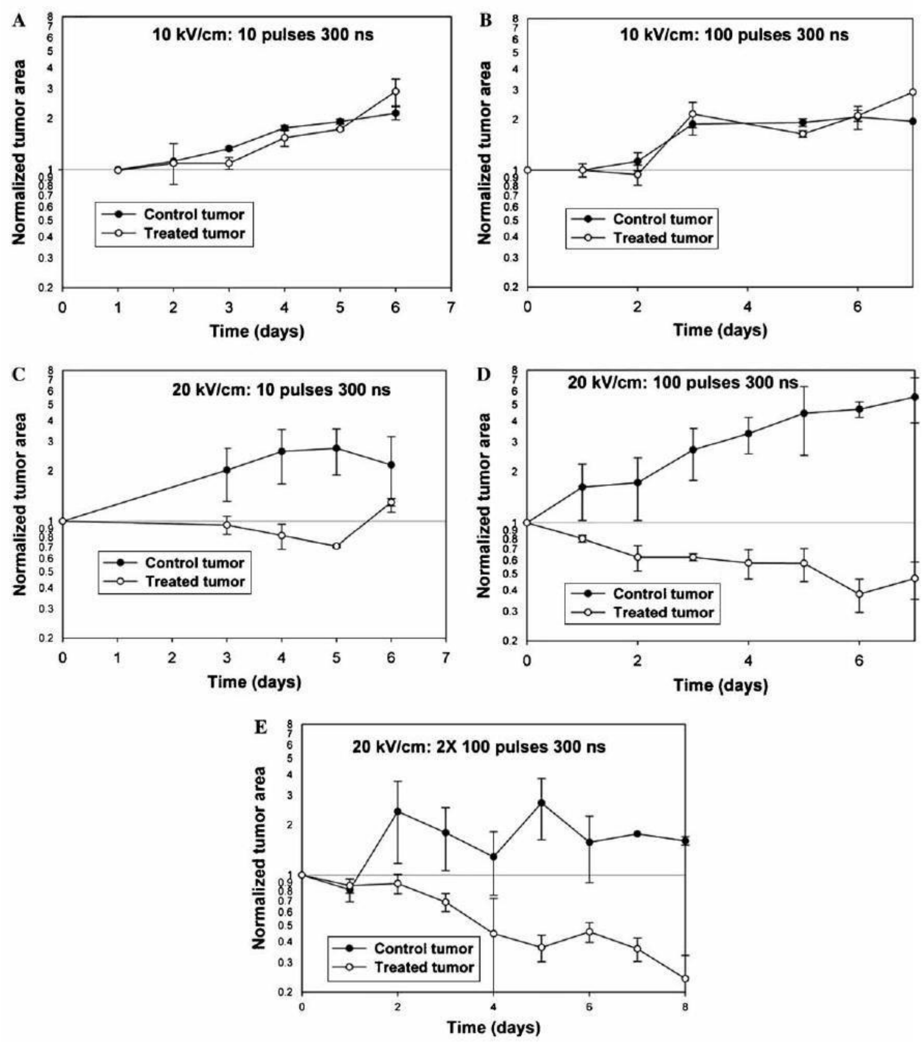
Melanoma shrinks after the treatment



- **Day 0-3: 3 applications of 100 pulses (300 ns, 40 kv/cm, 0.5 Hz), 30 min apart**
- **Day 4: single application using 5 mm diameter parallel plate electrode**

Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

Electric field of 20 kV/cm is needed to treat Melanoma



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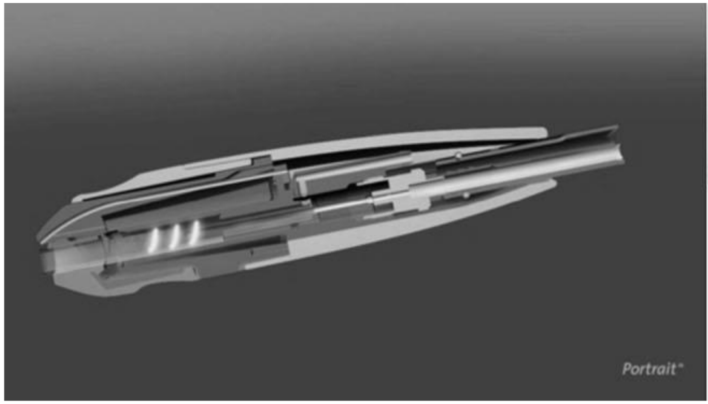
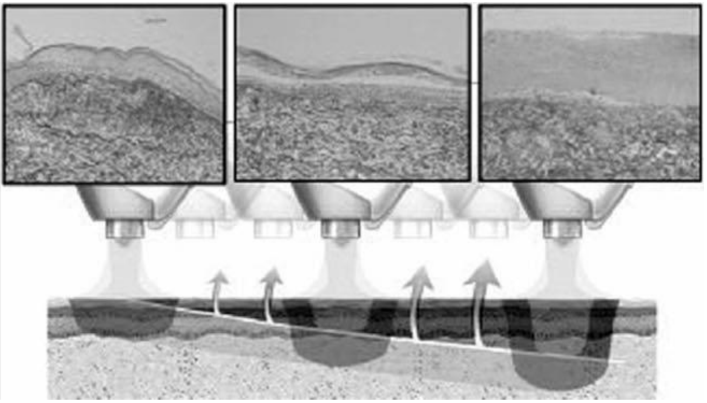
Plasma skin regeneration (PSR) is a novel skin treatment device





- PSR provides 1-2 J or 3-4 J per pulse for lower or higher power, respectively
- The skin is damaged slightly by the nitrogen plasma jet
- Skin regeneration is stimulated
- Local anesthetic (麻藥) is required and a systemic anesthetic, administered orally is recommended
- Ablative-like effect, similar to that of laser skin resurfacing can also be achieved, but with higher doses

Zones of the face and associated treatment energy settings

M. A. Bogle, *et al.*, Arch. Dermatol.,**143**, 168 (2007)

This particular patient-rated improvement in overall skin rejuvenation was 85%

- **Patients reported minimal discomfort following the procedure and reported over 60% improvement in their skin condition**

M. A. Bogle, *et al.*, Arch. Dermatol.,**143**, 168 (2007)

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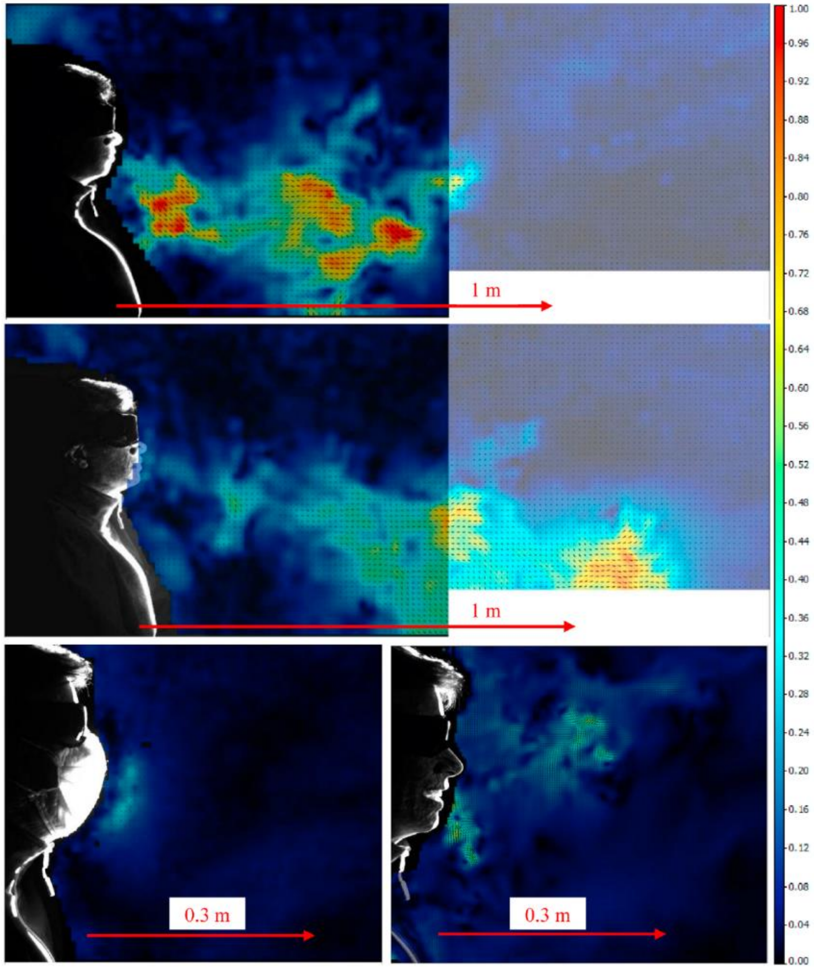
A face mask do restrict the air flow from the mouth and the nose



Coughing over one breath w/o mask.

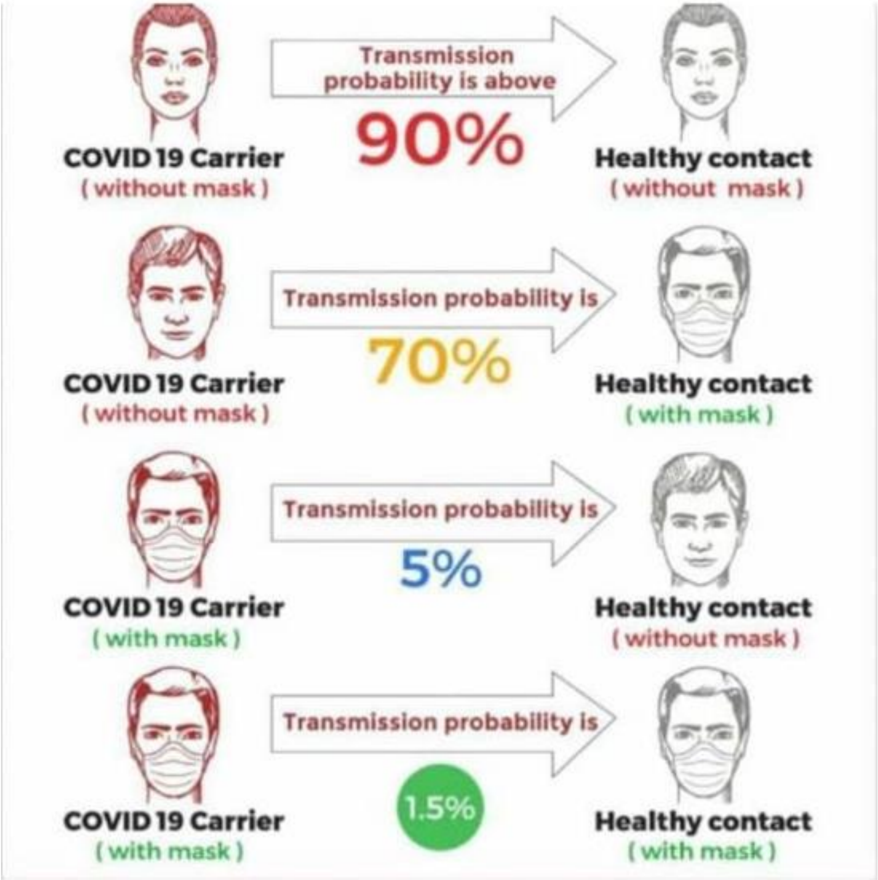
Coughing over a longer periods of time w/o mask.

Coughing over one breath w/ mask.

Talking w/o mask.

C. J. Kähler , *et al.*, J. Aerosol Science, **148**, 105617 (2020)

Wearing face mask can reduce the Covid-19 transmission probability significantly



http://www.riderta.com/coronavirus

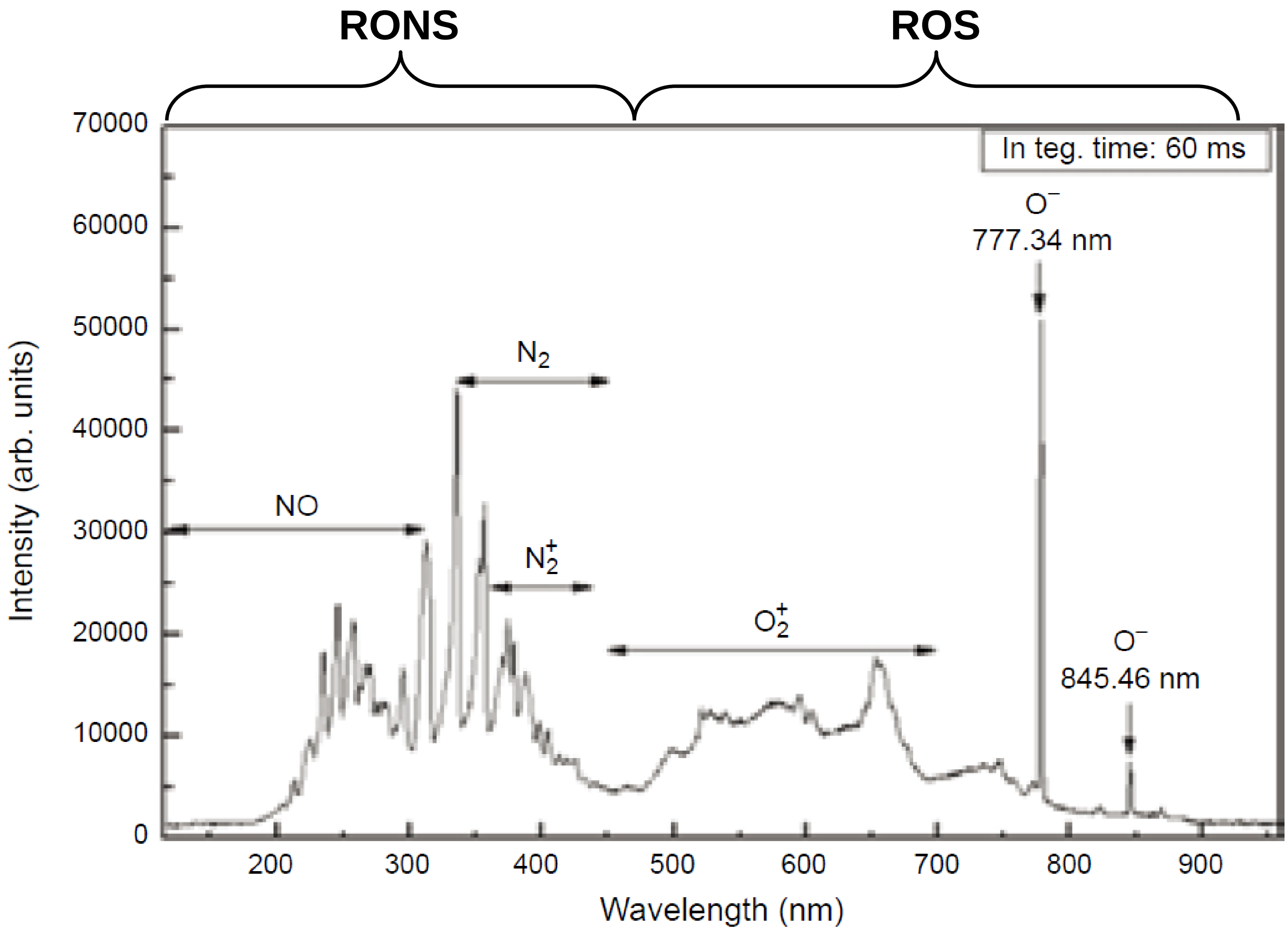
Plasma can provide good surface treatment with low temperature

Treatment	Surface treatment level	Depth	Temperature	Cost
Chemical	Large	Deep	Room temperature ~200 ℃	Medium
Heat	Only oxidizing	Deep	High temperature	Cheap
Radiation	Small	Whole sample	High temperature	Expensive
Plasma	Large	Surface	Room temperature ~100 ℃	Cheap ~ Medium

- **Atmospheric plasma can generate radicals, ozone, reactive oxygen/nitrogen/NH (ROS，RONS), UV light, electrons, charged particles.**

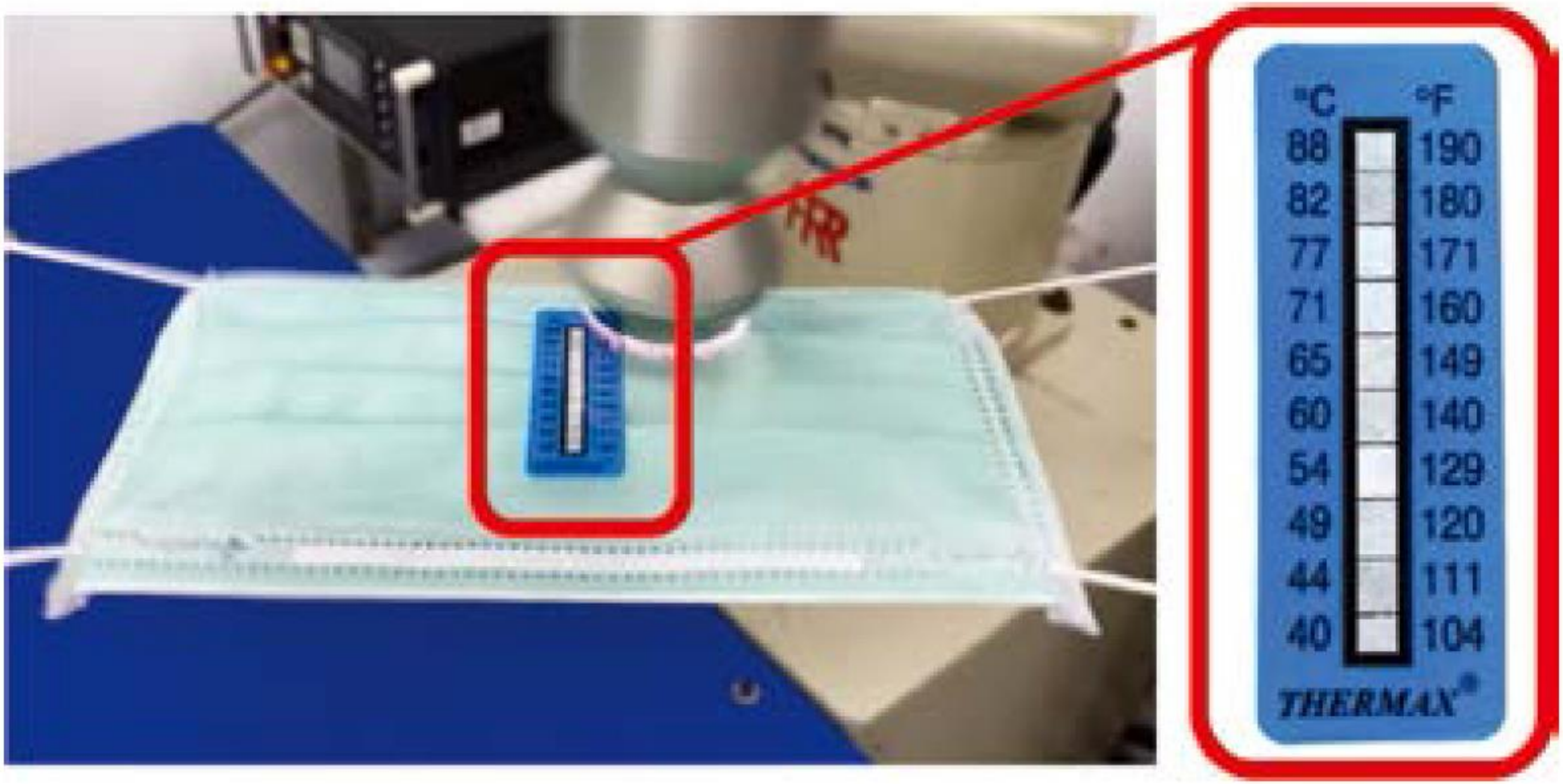
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

Plasma can generate ROS and RONS



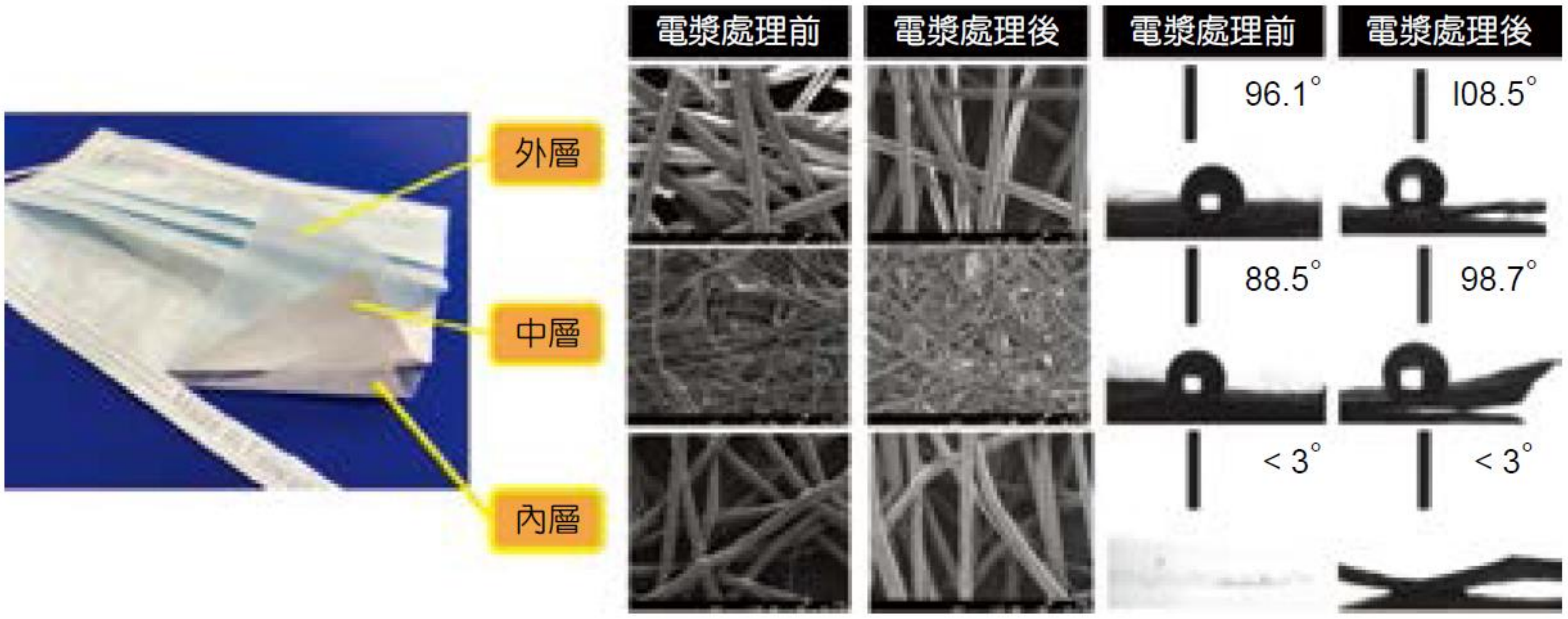
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

The temperature of the mask under plasma treamtment is below 40 ℃



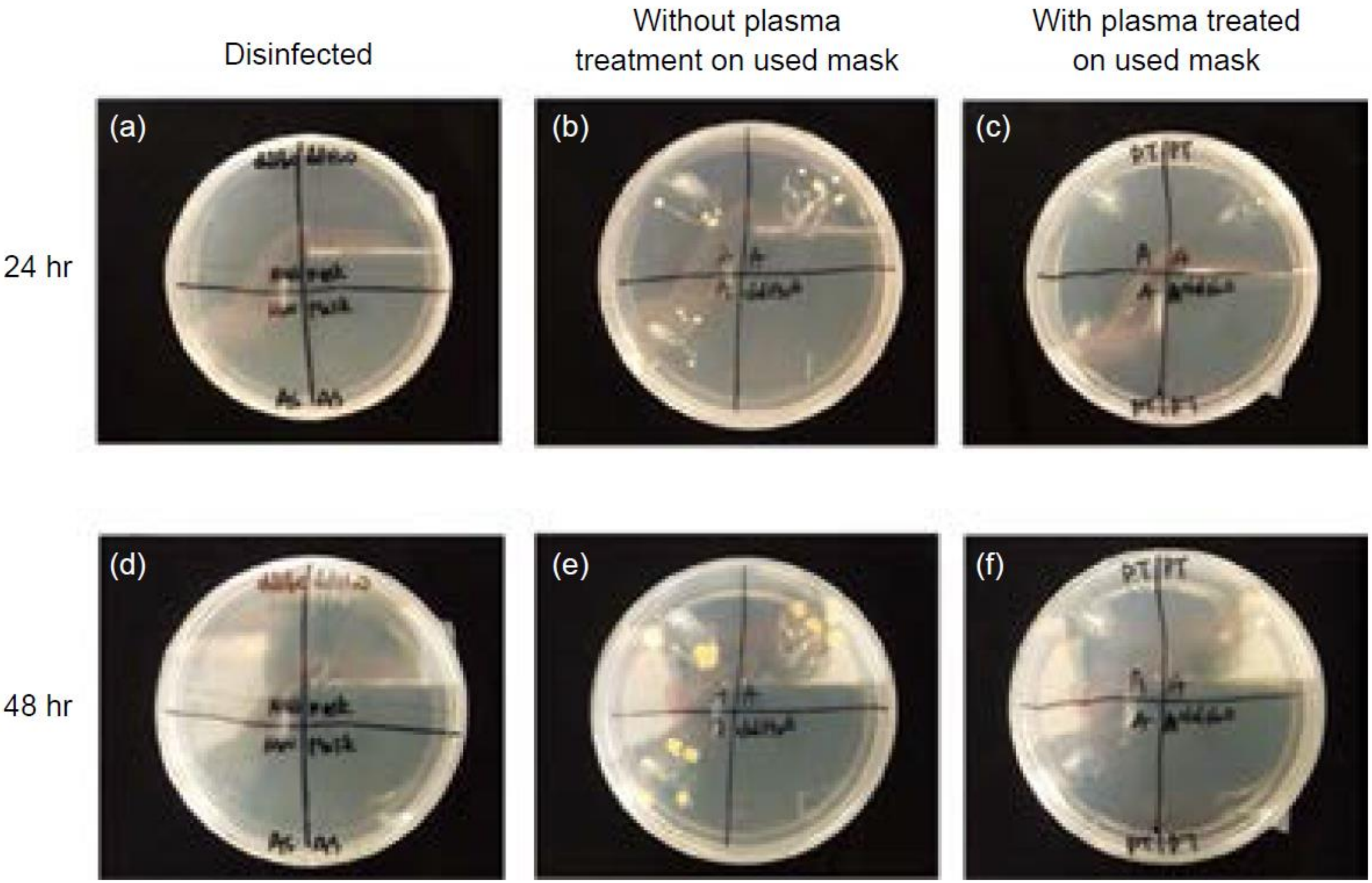
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

The surface quality of the face mask was not influenced by the plasma treament



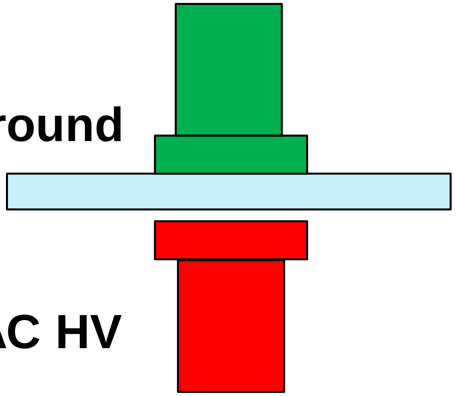
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

The growth of the bacteria on the face mask was suppressed



Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

DBD plasma demonstration



Ground

25 kHz AC HV