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

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Institute of Space and Plasma Sciences, National Cheng Kung University

2023 summer break

8/28(Mon.) – 9/1(Fri.) 14:00-17:40

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

Lecture 1

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

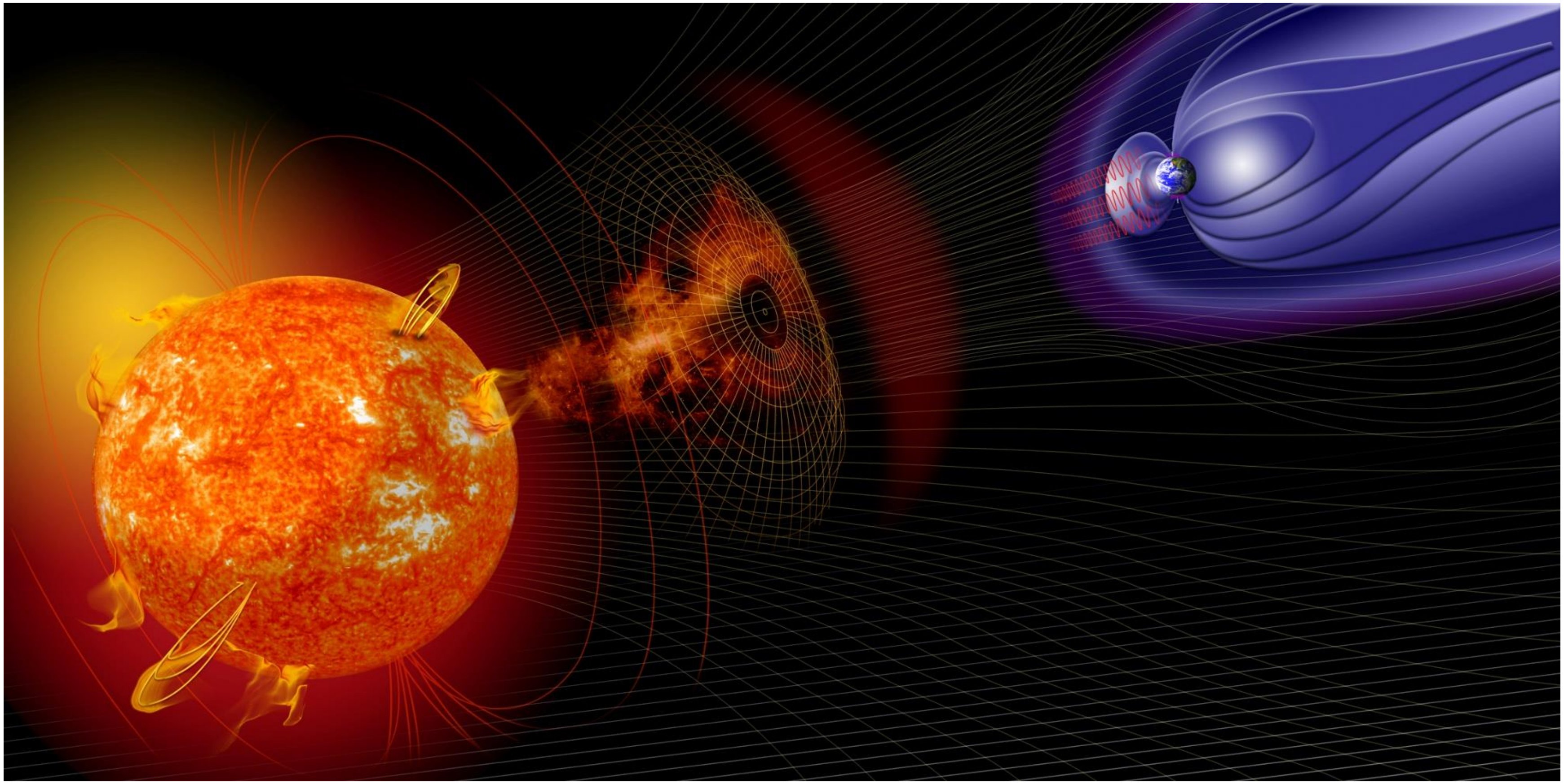
https://nckucc.webex.com/nckucc/j.php?MTID=mb9ccf65ba2c981ce1f0f02ea60e1dbf2

開放式教育平台：

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

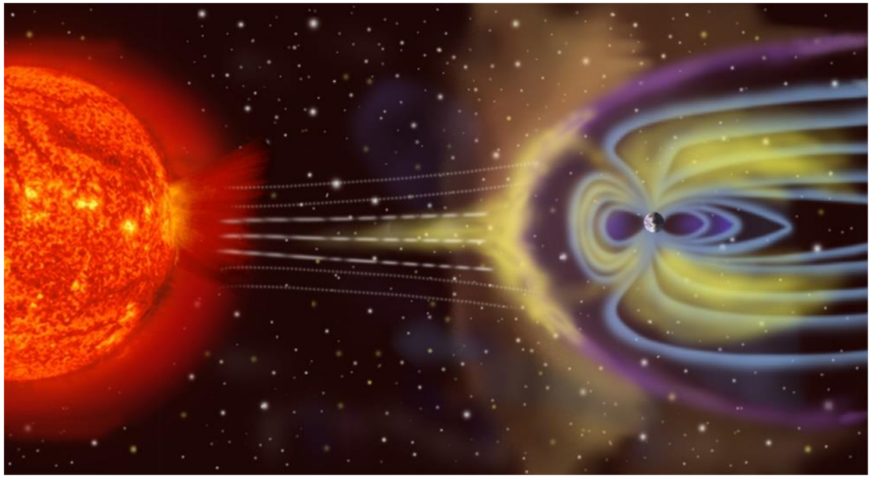
2023/8/27 updated

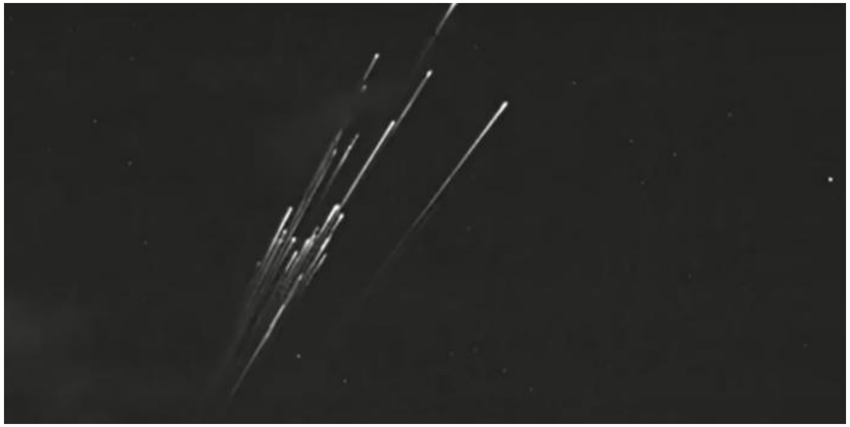
Most of the material in space is plasma



https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html

Forty SpaceX’s Starlink satellites were destroyed by a geomagnetic storm on 2022/2/4



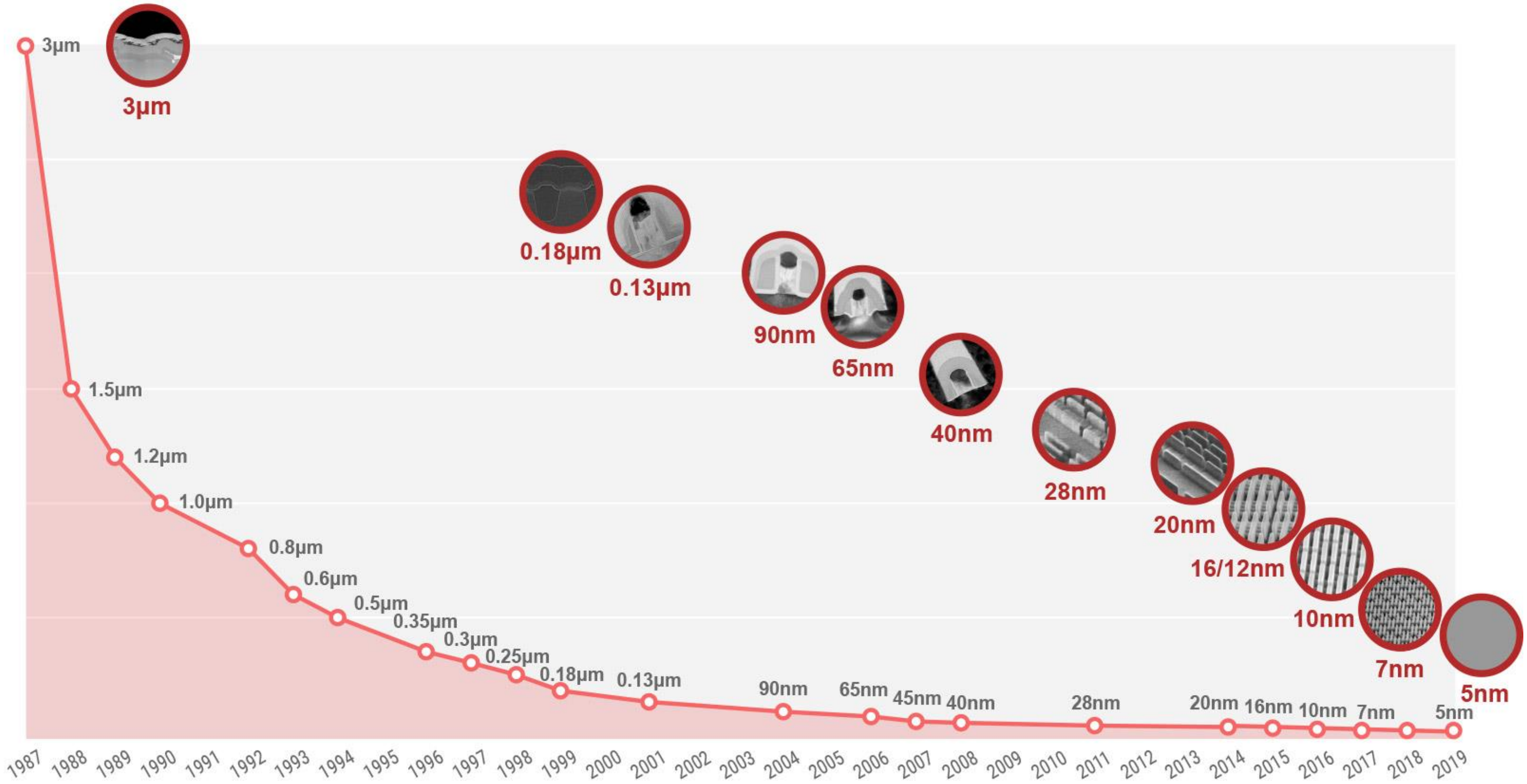


- **Geomagnetic storms occur when intense solar wind near Earth spawns shifting currents and plasmas in Earth's magnetosphere. This interaction can warm Earth's upper atmosphere and increase atmospheric density high enough above the planet to affect satellites in low orbits like SpaceX's new Starlink craft.**

https://en.wikipedia.org/wiki/Geomagnetic_storm
https://wonderfulengineering.com/watch-the-40-starlink-satellites-destroyed-by-a-geomagnetic-storm-burn-up-in-the-sky/

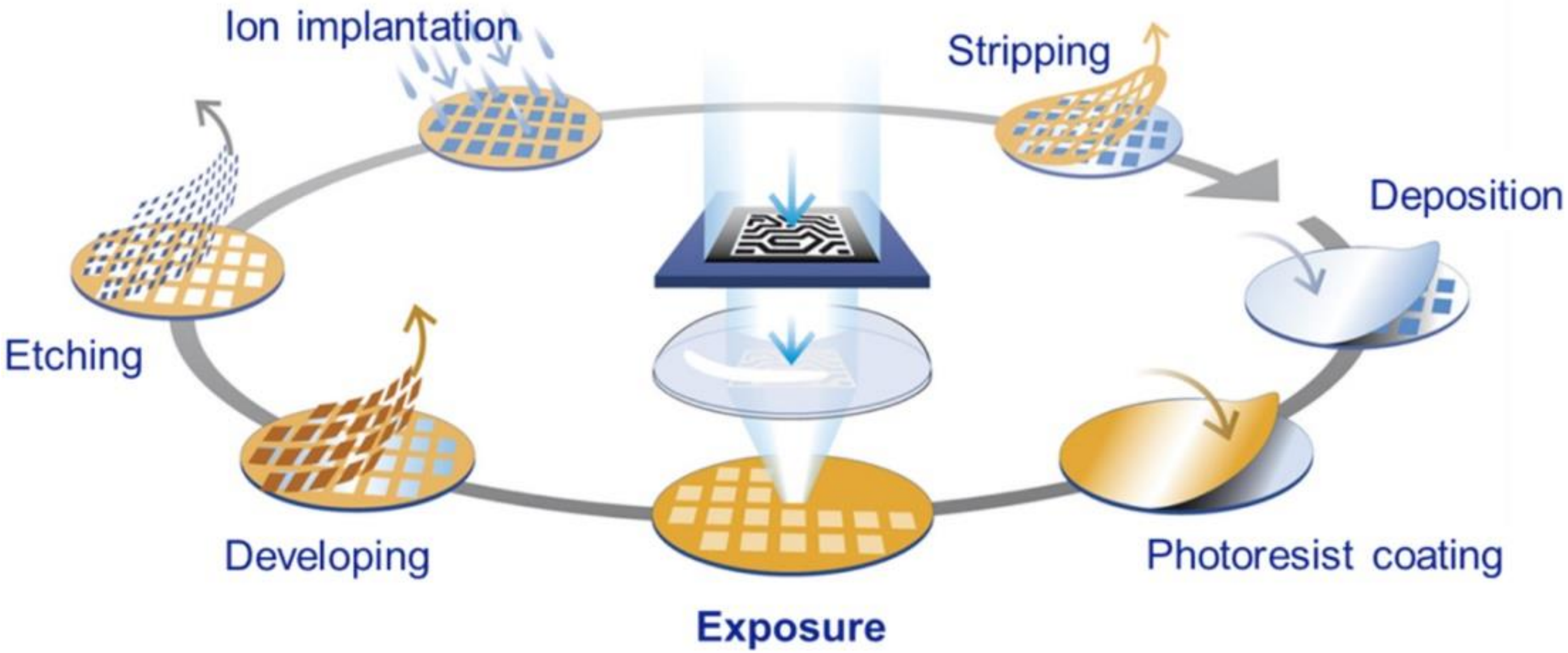
Plasma plays an important role on semiconductor manufacturing

- **The process technology of Taiwan Semiconductor Manufacturing Company Limited (TSMC):**



https://www.tsmc.com/chinese/dedicatedFoundry/technology/logic.htm

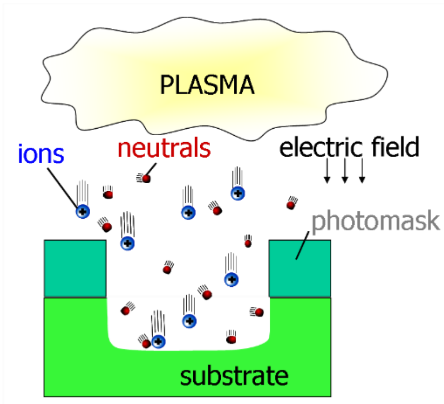
Plasma is commonly used in semiconductor manufacture



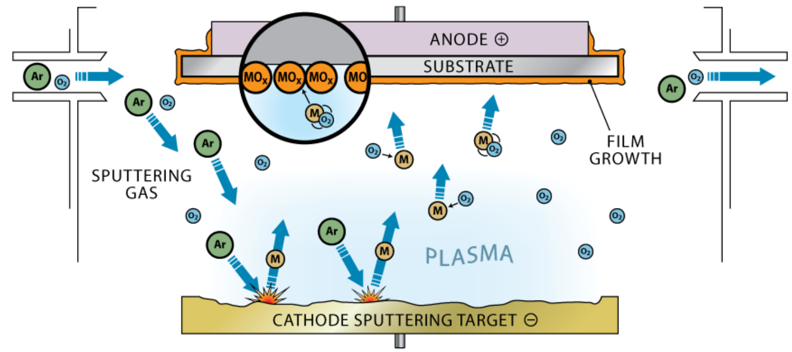
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

Plasma is widely used in semiconductor fabrication

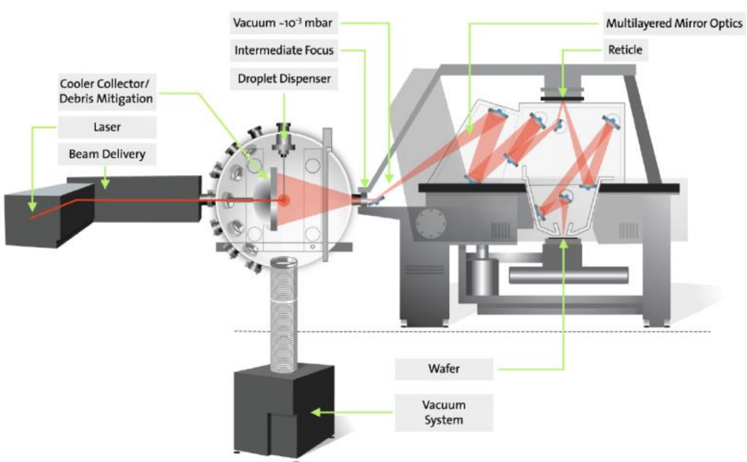
- **Etching**



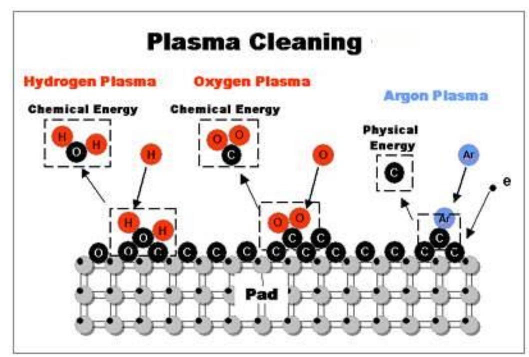
- **Deposition**



- **EUV light source**



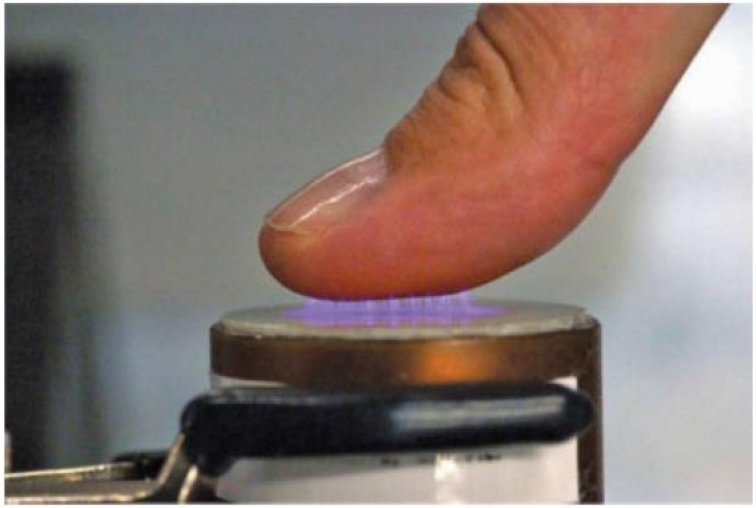
- **Plasma cleaning**

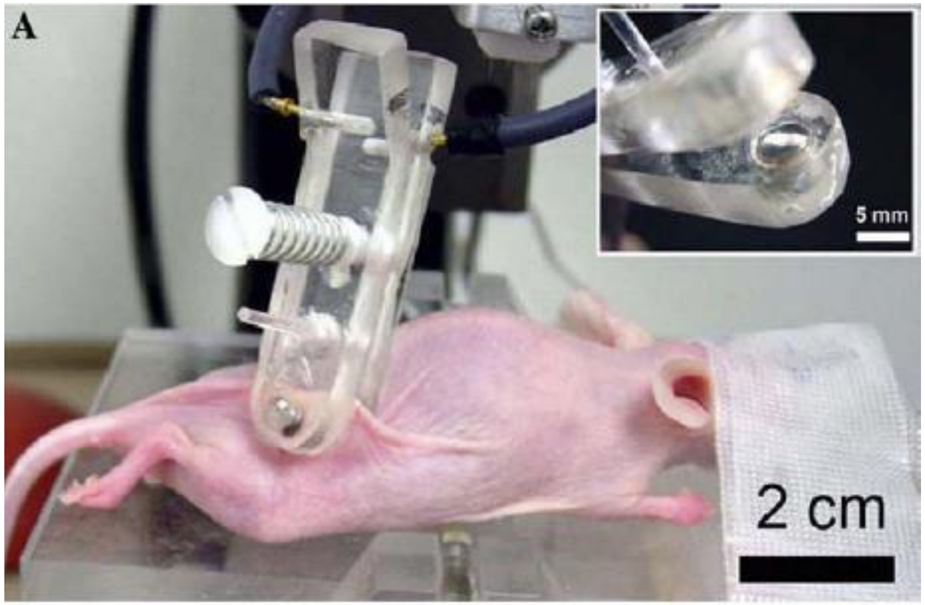


https://www.scorec.rpi.edu/research_plasmaetchmodeling.php
http://lnf-wiki.eecs.umich.edu/wiki/Sputter_deposition

R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)
馗鼎奈米科技股份有限公司
https://www.ecplaza.net/products/plasma-cleaning_111807

Atmospheric plasma can b used in biomedical applications

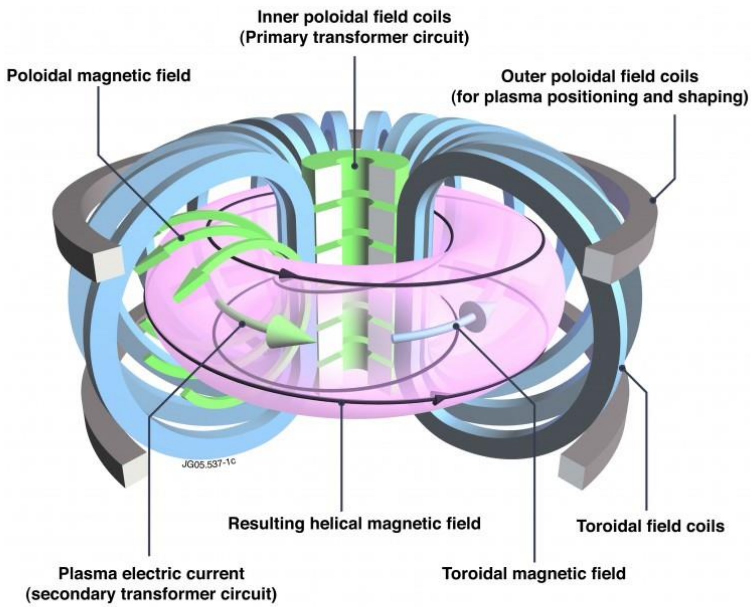


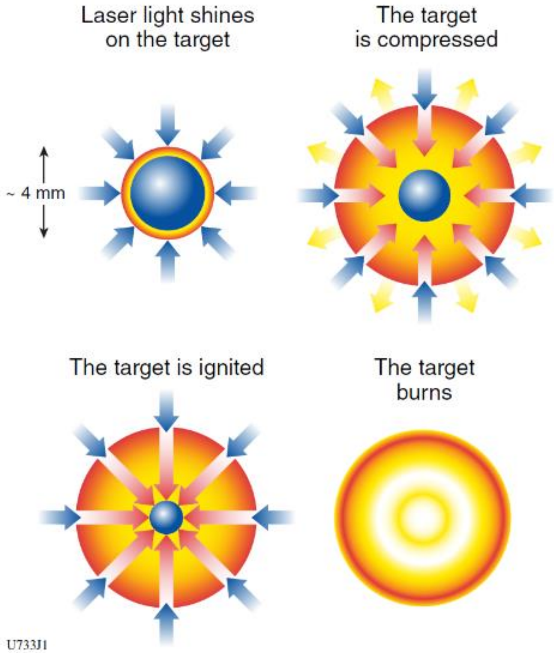


Plasma medicine, by Alexander Fridman and Gary Friedman
Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

Nuclear fusion as an unlimited green energy source is getting closed-1

- **Magnetic confinement fusion**
- **Inertial confinement fusion**

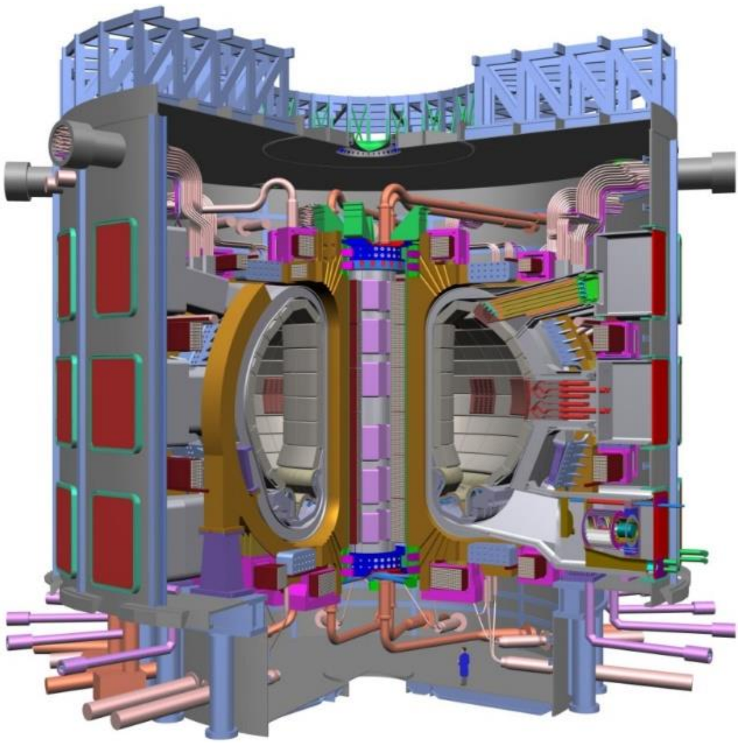




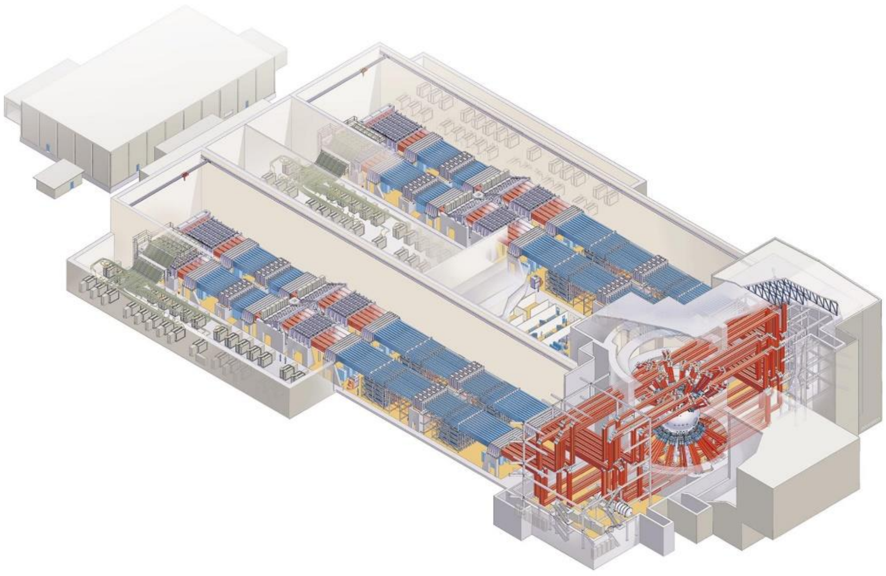
https://www.euro-fusion.org/2011/09/tokamak-principle-2/
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

Nuclear fusion as an unlimited green energy source is getting closed-2

- **Magnetic confinement fusion**



- **Inertial confinement fusion**



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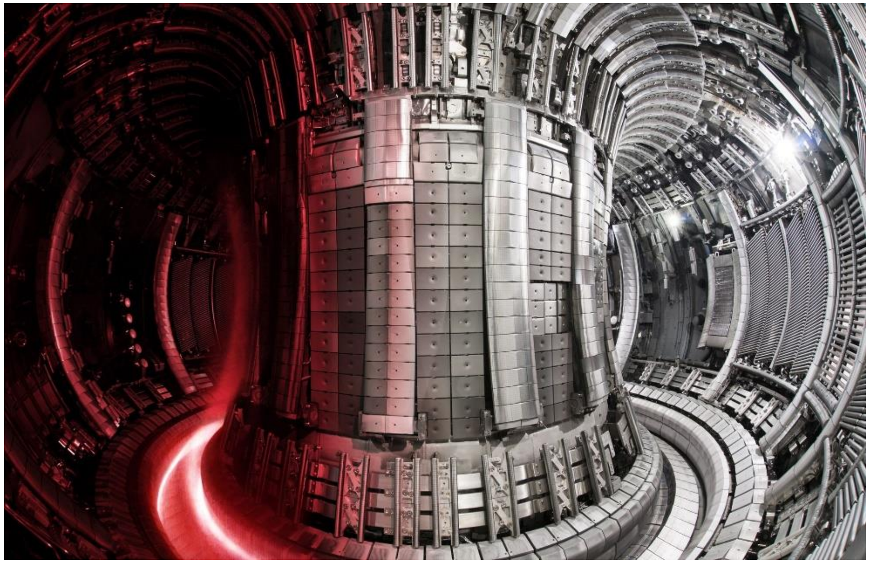
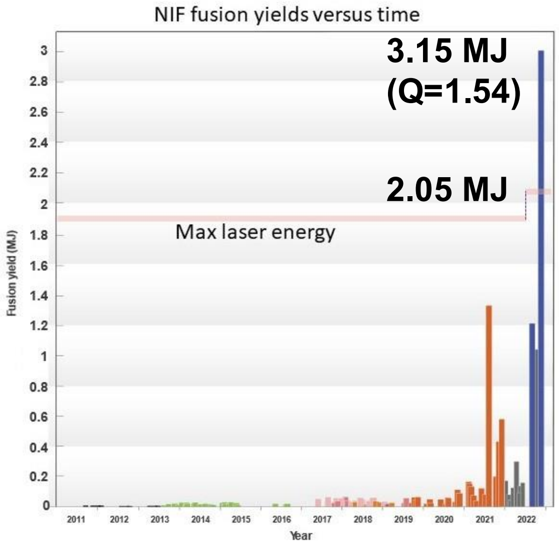
https://www.iter.org
https://zh.wikipedia.org/wiki/國家點火設施

“Ignition” (target yield larger than one) was achieved for the first time in NIF on 2022/12/5

- **Magnetic confinement fusion (MCF)**
- **Inertial confinement fusion (ICF)**





- **Record-breaking 59 megajoules of sustained fusion energy in Joint European Torus (JET) facility in Oxford demonstrates powerplant potential and strengthens case for ITER.**
- **National Ignition Facility (NIF) achieved a target yield of 1.54 and repeated the experiment on 2023/7/30.**

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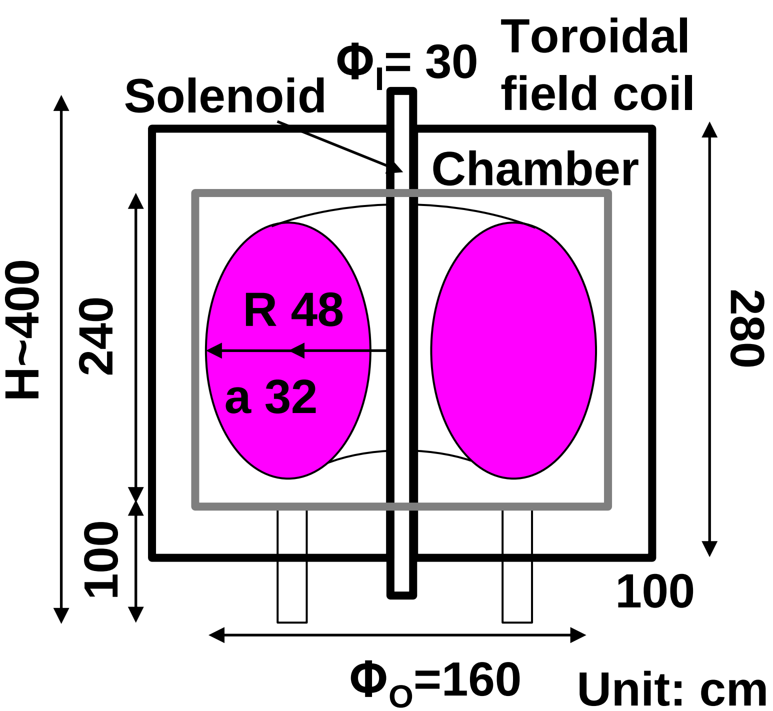
https://ccfe.ukaea.uk/resources/#gallery
https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/

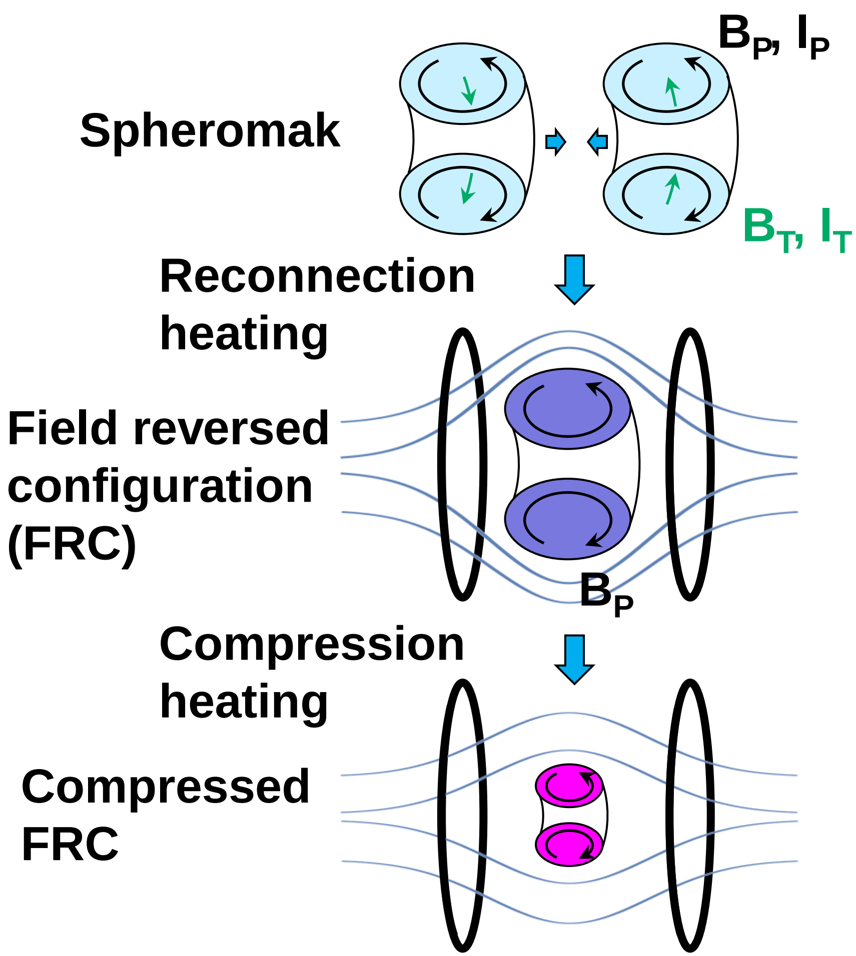
Fusion projects in Inst. Space and Plasma Sciences , National Cheng Kung University

- 國科會計畫 - 磁約束高溫電漿研究

Formosa Integrated Research Spherical Tokamak (FIRST)

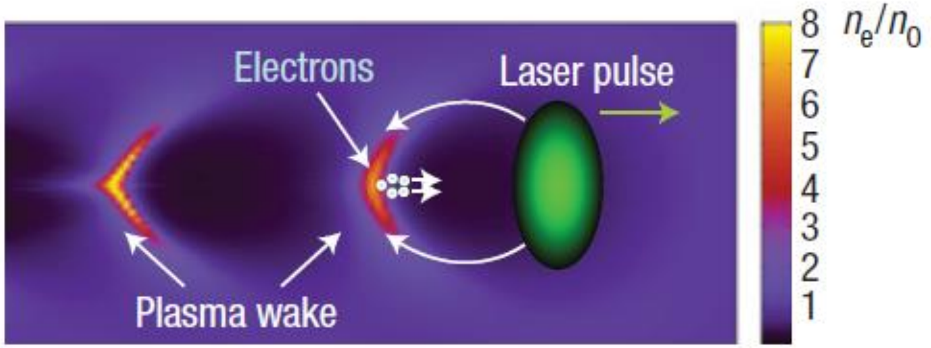


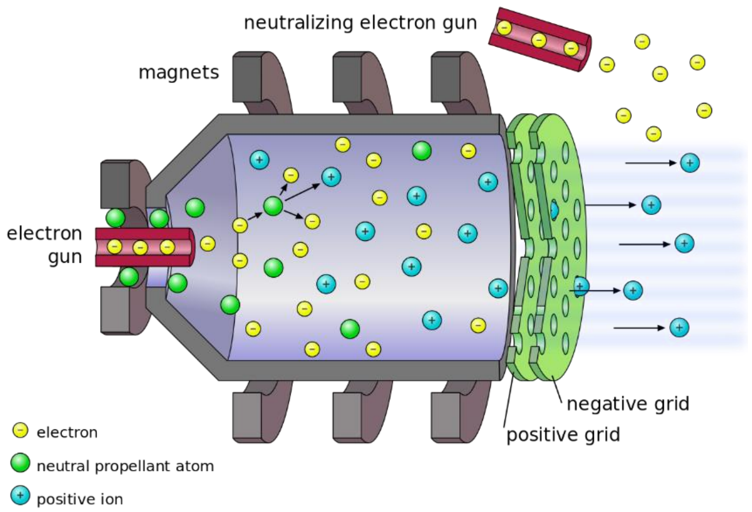
- Magneto-inertial fusion (MIF)

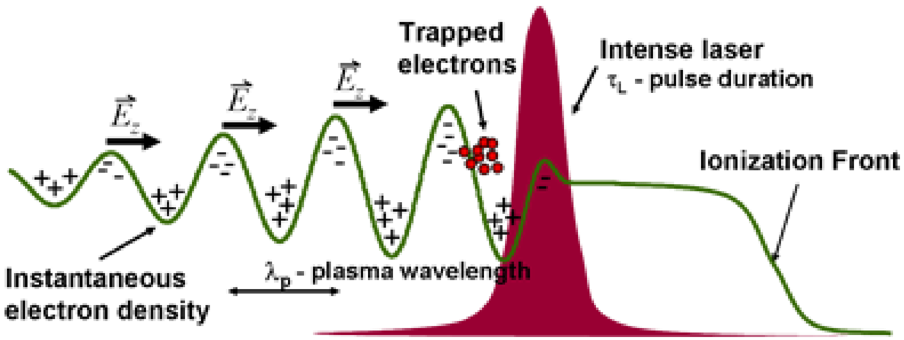


- **We welcome anyone interested in fusion research to join our team!**

Plasma can be used as particle accelerators and thrusters

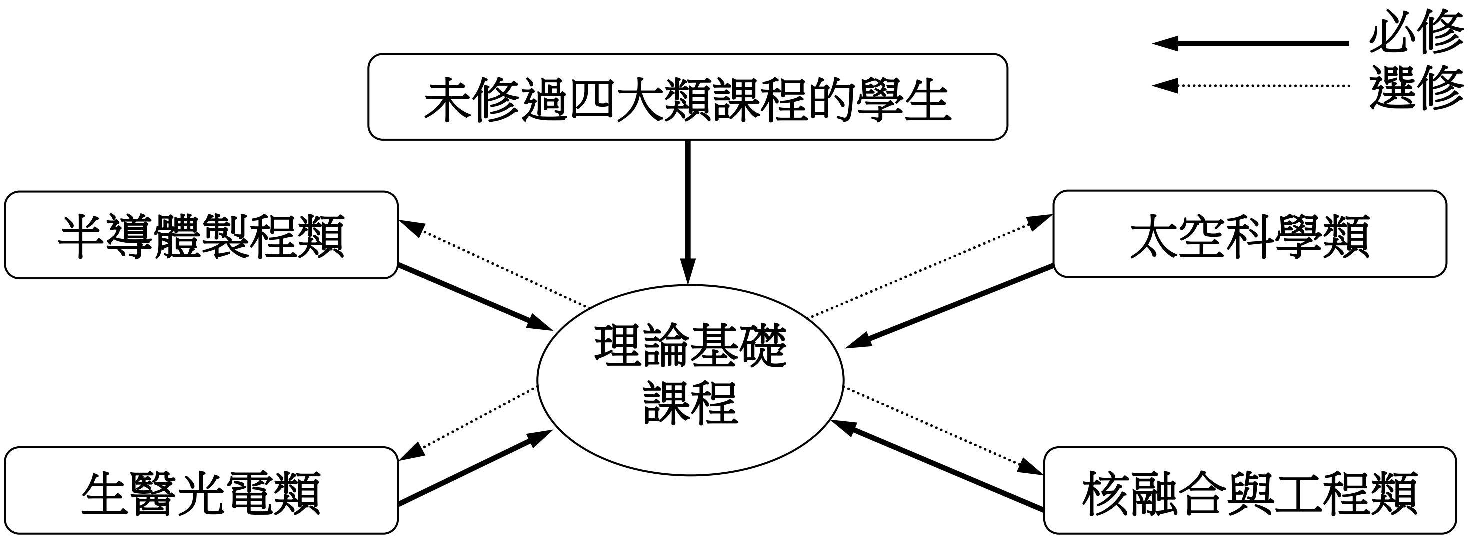






V. Malka, *et al.*, Nature Physics **4**, 447 (2008)
http://cuos.engin.umich.edu/researchgroups/hfs/research/laser-wakefield-acceleration/
https://zh.wikipedia.org/wiki/File:Electrostatic_ion_thruster-en.svg

深入的電漿知識請選修 電漿學分學程



- 將培養具備電漿科技研究與產業應用等多元專業且更具競爭力之跨領域人才.

課程列表

- 先修課程

開課系所	課程名稱	說明
全校	工程數學	符合其中一門或相對應之數學課程
物理系	物理數學	
數學系	應用數學方法	
全校	電磁學	或相對應之課程

- 理論基礎課程

開課系所	課程名稱	說明
電漿所	電漿物理	必修
電漿所	電漿現象之應用*	
模組化課程	電漿基礎理論與實作*	
電漿所	太空物理	(任選三學分)
電漿所	電動力學與電漿物理之數值模擬	
應數所/光電系/物理系	數值分析	
應數所	氣體動力學方程的數學理論	
物理所	電動力學	
化學系	電分析化學	
化學系	應用電化學	

課程列表(續)

- 太空科學類

開課系所	課程名稱
電漿所	高等太空物理
電漿所	閃電物理
電漿所	高等磁層物理(一)(二)
電漿所	電磁層磁層耦合與電離層物理
電漿所	太空物理專題
電漿所	數據處理與資料分析
地科所	太空物理
地科所	太空天氣
地科所	高層大氣與電離層特論
地科所	電離層模式數值模擬(一)(二)
地科所	全球導航衛星系統大氣遙測特論
測量系	空間資訊整合與應用

- 核融合與工程類

開課系所	課程名稱
電漿所	托克馬克物理
電漿所	核融合電漿科學
電漿所	高等電漿物理
電漿所	電漿波與加熱
電漿所	電漿量測
電漿所	脈衝功率系統
電機所	高電壓工程特論
電機所	電力測試與保護
電機所	能量轉換
微電所	高電壓工程特論

課程列表(續)

- 生醫光電類

開課系所	課程名稱
地科所	X光結晶學
化學所	蛋白質與蛋白質體學
化學所	核磁共振光譜學
光電所	奈米光學
光電所	電漿子光學原理與應用
光電所	生醫光譜學原理
光電所	生醫組織光學
光電所	光電數值模擬
光電系	生醫光電導論
口醫所	蛋白質結構與影像分析
醫工所	生物電化學

- 半導體製程類

開課系所	課程名稱
電漿所	半導體電漿製程原理
電機所	奈米世代半導體製程概論
機械系	半導體製程
微電所	半導體元件物理
微電所	半導體製程
工科所	半導體製程技術
工科所	奈米製程技術與實作
化工系	半導體材料與製程
材料系	微奈米元件製程與設計
材料系	奈米材料分析與實作

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. Particle beam source
   f. High energy particle accelerator
   g. Controlled thermonuclear fusion
   h. Neutral beam source
   i. Electrical propulsion

Course Outline

4. Demonstration

a. Magnetron sputtering

b. Dielectric barrier discharge (DBD)

c. Magnetic mirror

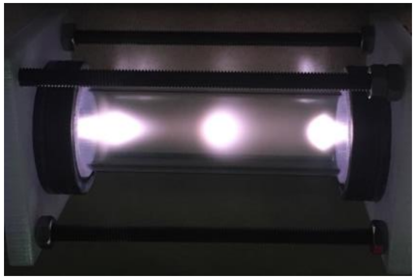
d. Tesla coil

e. Planeterrella

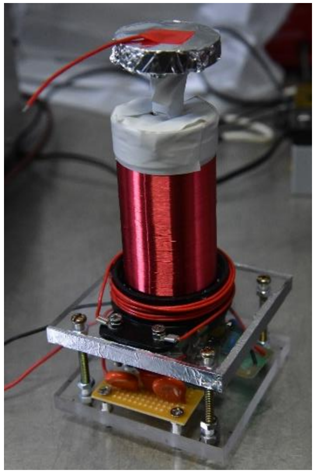
Planeterrella

Magnetron sputtering

DBD plasma



Magnetic mirror



Tesla Coil

Grading

• **Presentations**	**40 %**	**Everyone needs to present a topic for up to 5 mins taught in the previous day. The topic will be randomly assigned at the beginning of the course.**
• **Final report**	**60 %**	**Write a report talking about a plasma application or plasma application/phenomenon.**

Reference for the section "What is Plasma?"

- Introduction to plasma theory, by Dwight R. Nicholson
- Introduction to plasma physics and controlled fusion, by Francis F. Chen
- Principles of plasma physics for engineers and scientists, by Umran S. Inan and Marek Golkowski
- The physics of plasma, by T. J. M. Boyd and J. J. Sanderson
- Principles of plasma physics, by Krall and Trivelpiece
- NRL Plasma Formulary, Naval Research Laboratory, 2013 by J. D. Huba

Course Outline

1. **What is Plasma?**
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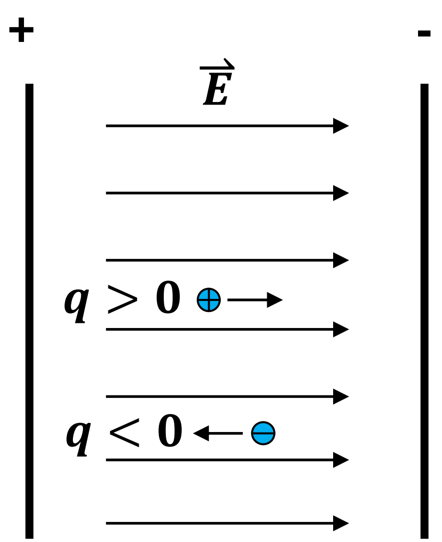
   i. **Electrical propulsion**

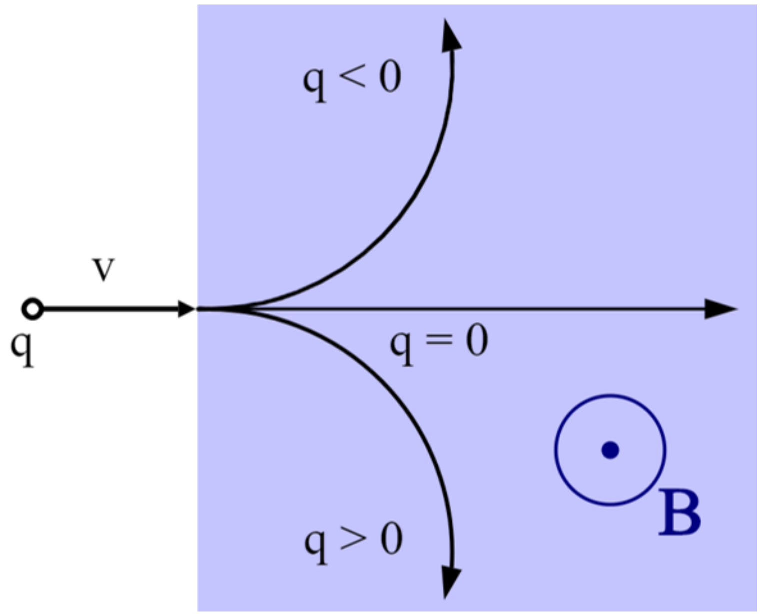
Charged particles are accelerated due to Lorentz force under electromagnetic fields

- **Lorentz force:** $$\vec{F} = q\,\vec{E} + q\,\vec{v} \times \vec{B}$$

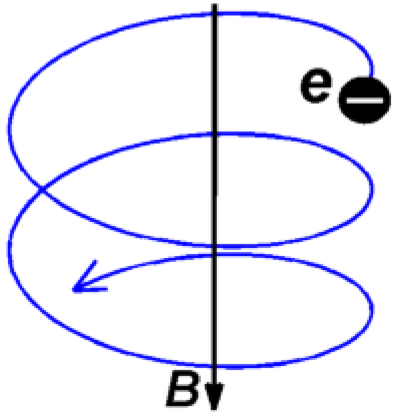
- **Force under electric fields**

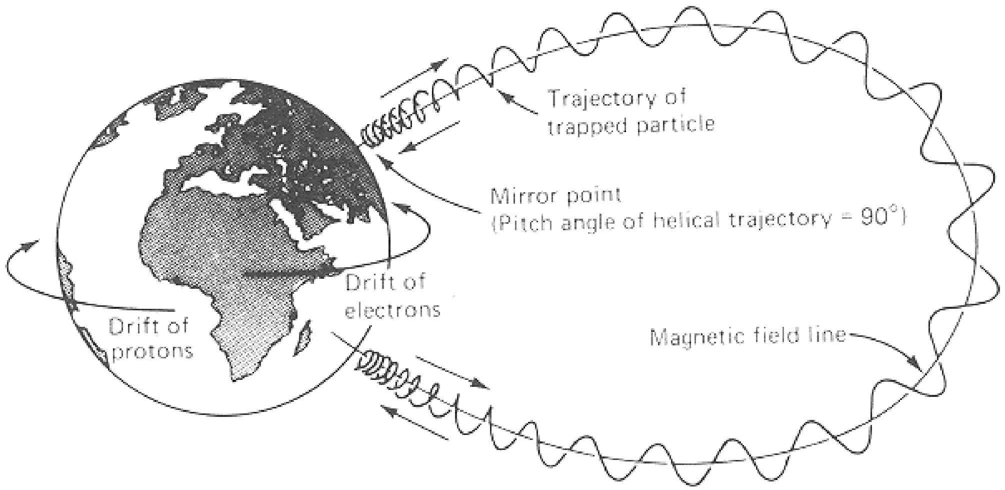


- **Force under magnetic fields**



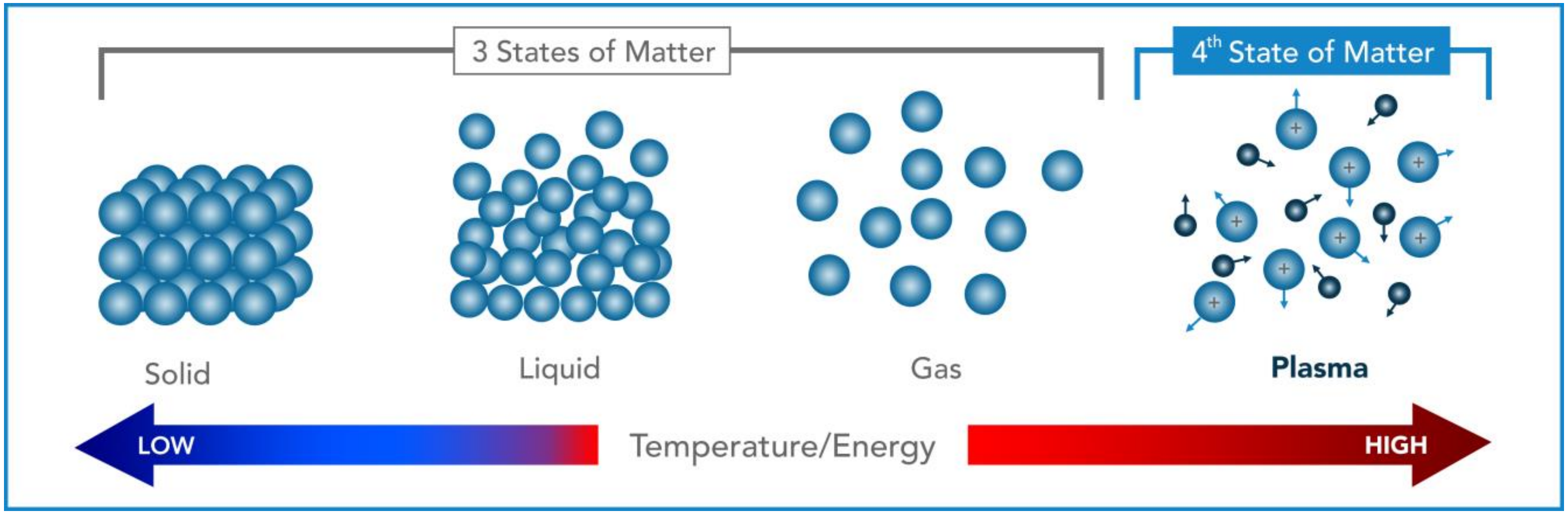
Charged particles gyro around magnetic field lines





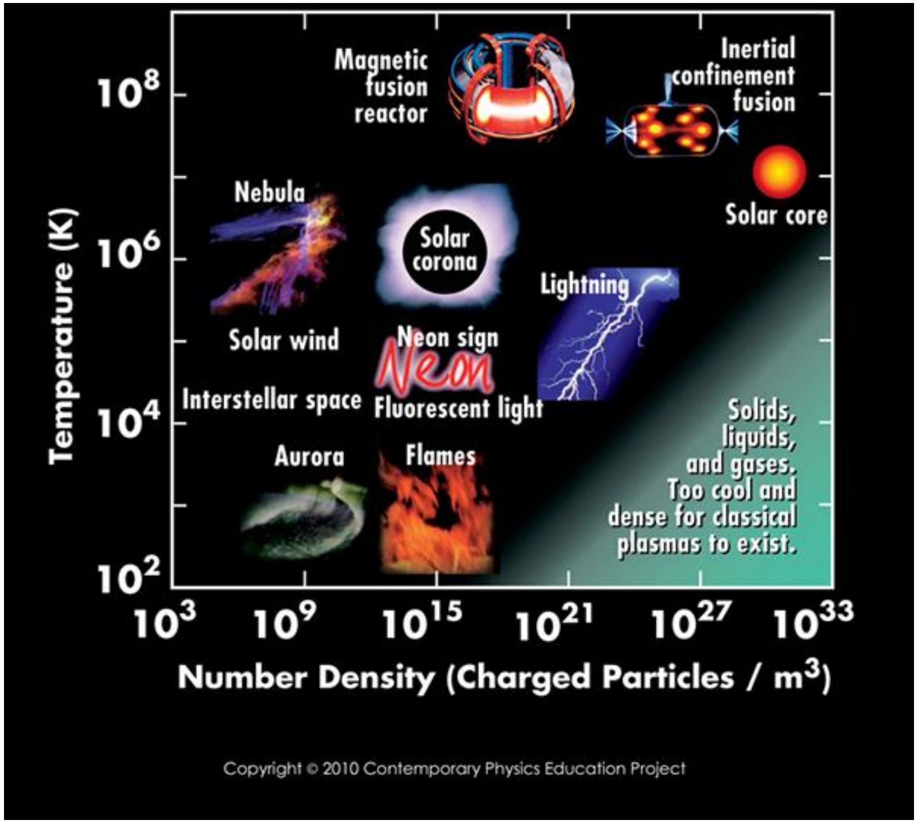
http://www.ipp.cas.cz/vedecka_struktura_ufp/tokamak/tokamak_compass/diagnostics/mikrovlnne-diagnostiky/ece-ebw-radiometr.html
http://www-ssg.sr.unh.edu/tof/Smart/Students/lees/periods.html

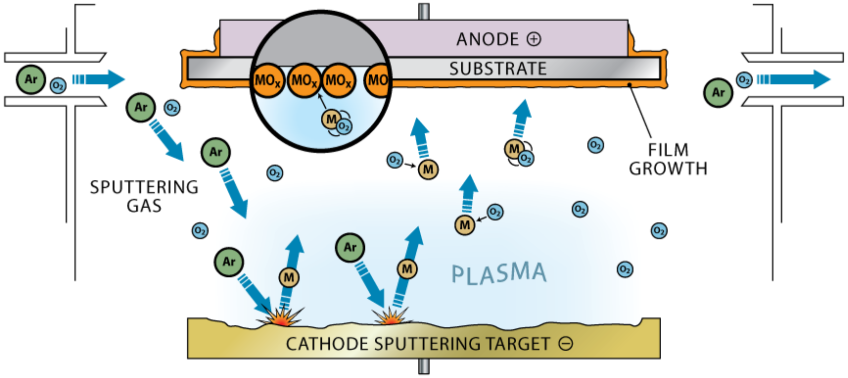
Plasma is the 4th state of matter



http://tetronics.com/our-technology/what-is-plasma/

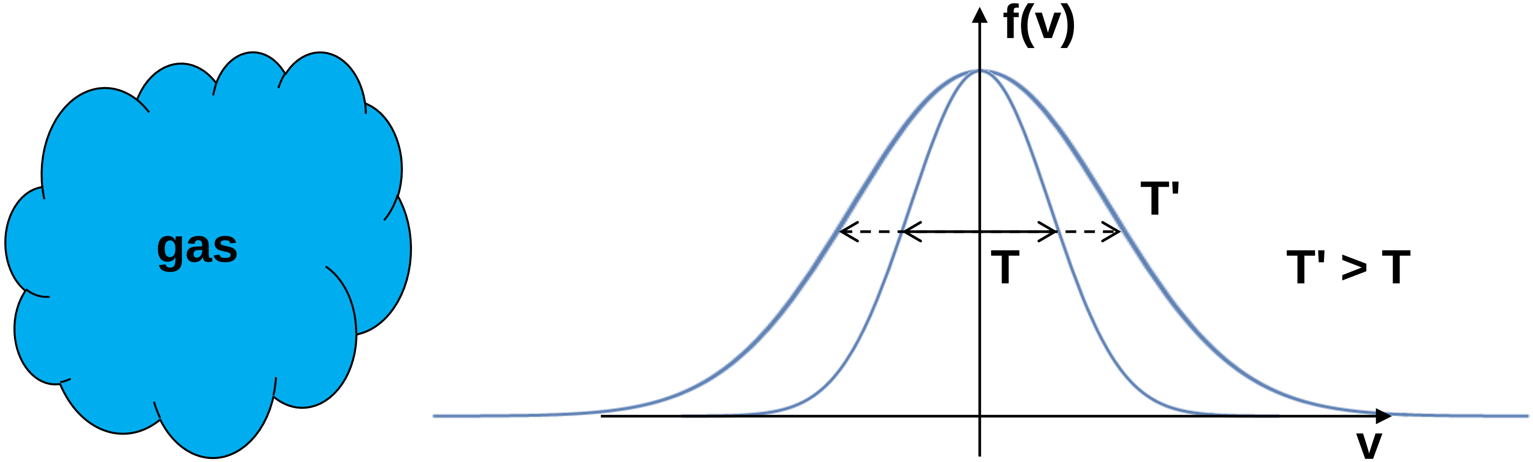
Plasma is everywhere

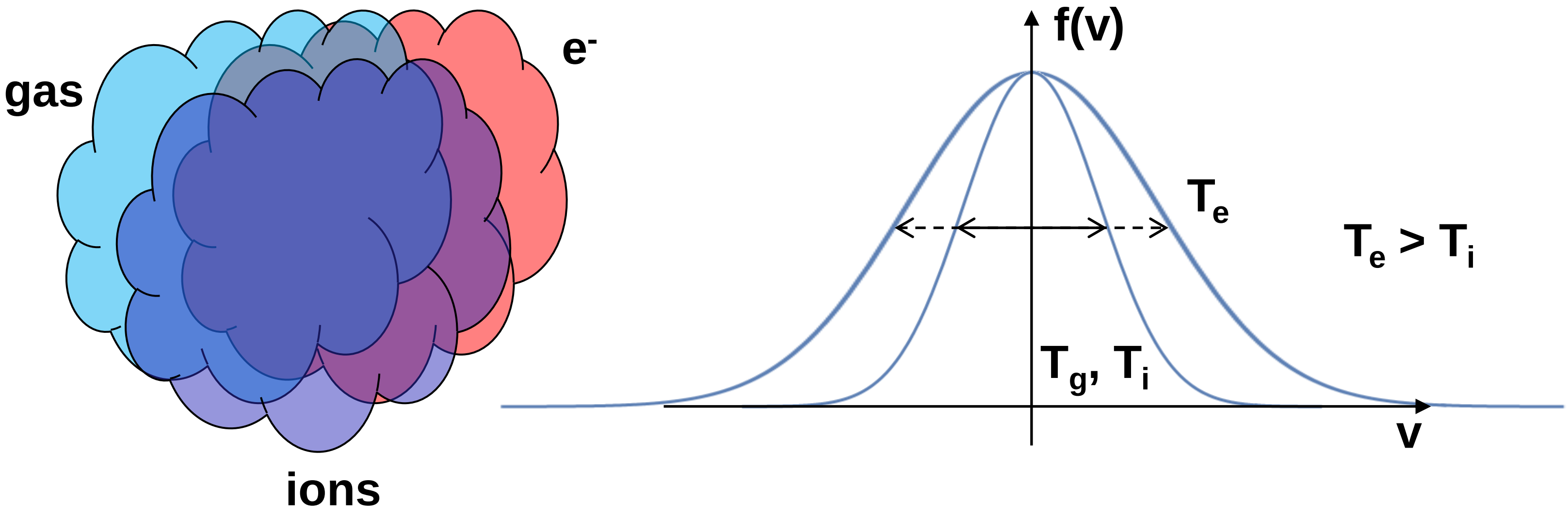




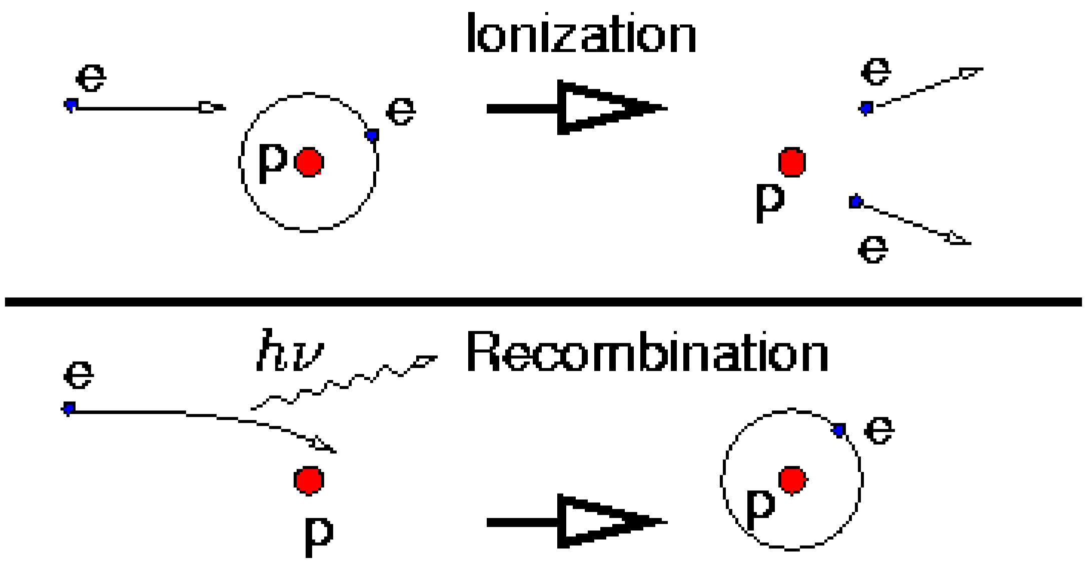
https://lasers.llnl.gov/science/understanding-the-universe/plasma-physics
http://lnf-wiki.eecs.umich.edu/wiki/Sputter_deposition
https://simple.wikipedia.org/wiki/Fluorescent_lamp

In plasma, there are ions, electrons, and neutral gas



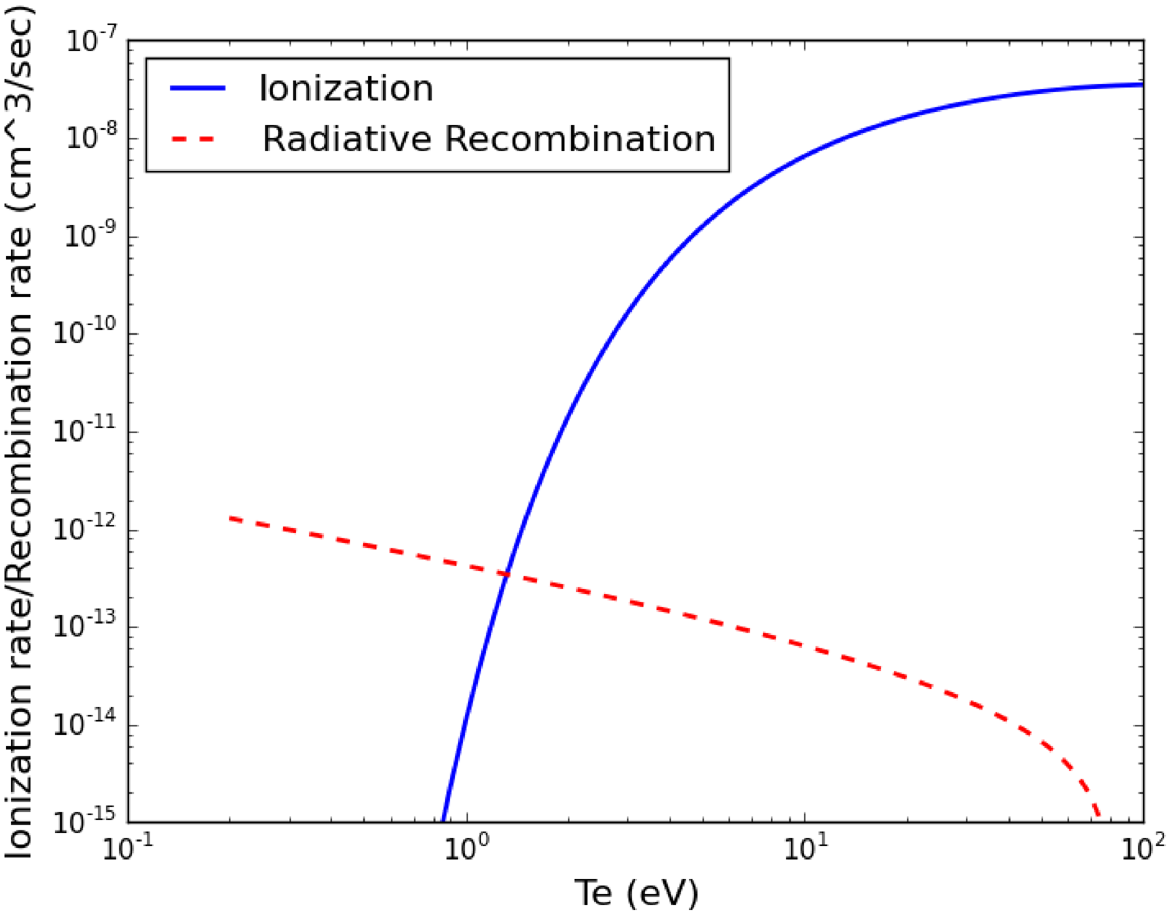


A plasma is a gas in which an important fraction of the atoms is ionized so that the electrons and ions are separated freely



http://ocw.mit.edu/courses/nuclear-engineering/22-611j-introduction-to-plasma-physics-i-fall-2003/lecture-notes/

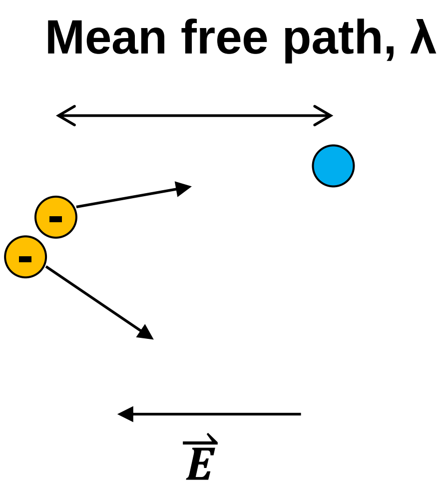
A plasma can be created when the ionization rate is higher than the recombination rate



J. D. Huba \NRL Plasma Formulary", Naval Research Laboratory, 2013

Mean free path is important in ionization process

- **For an electron to acquire enough energy between collisions, its <u>mean free path</u> in the material must be sufficiently long.**



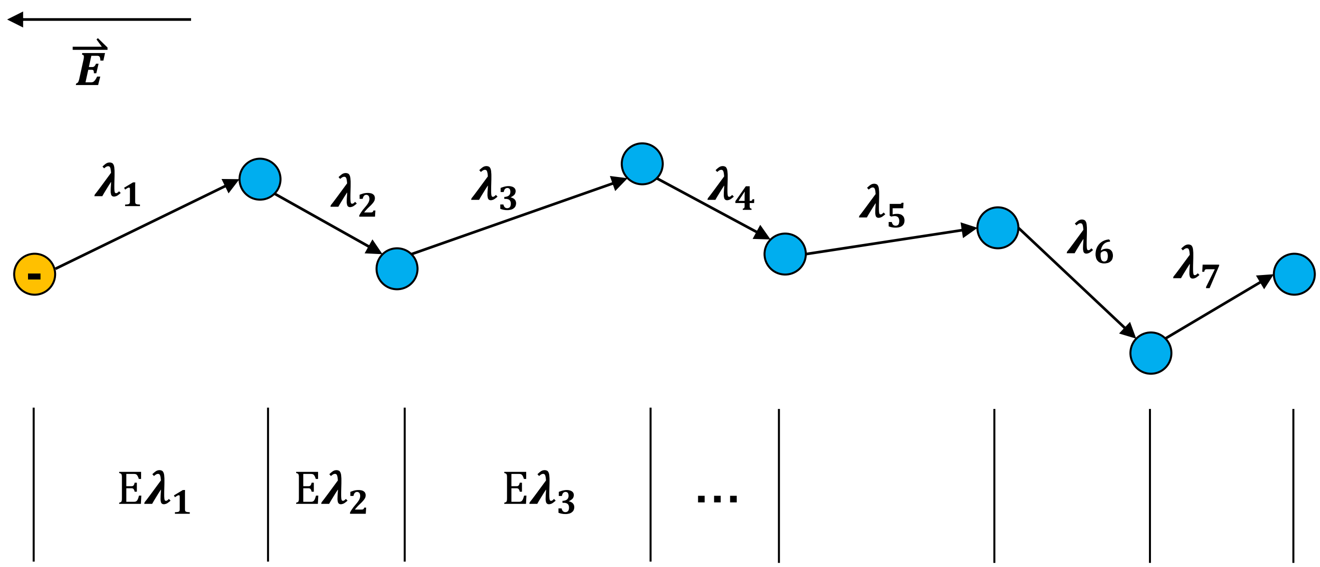
$$E_{\mathrm{k}} = e \times E \times \lambda = \mathrm{eV}$$

Electron impact ionization is the most important process in a breakdown of gases

- **Electron impact ionization: A + e$^-$ $\rightarrow$ A$^+$ + e$^-$ + e$^-$**
  - **The most important process in the breakdown of gases but is not sufficient alone to result in the breakdown.**

$$eE\lambda_{e,i} \geq eV_\mathrm{i}$$

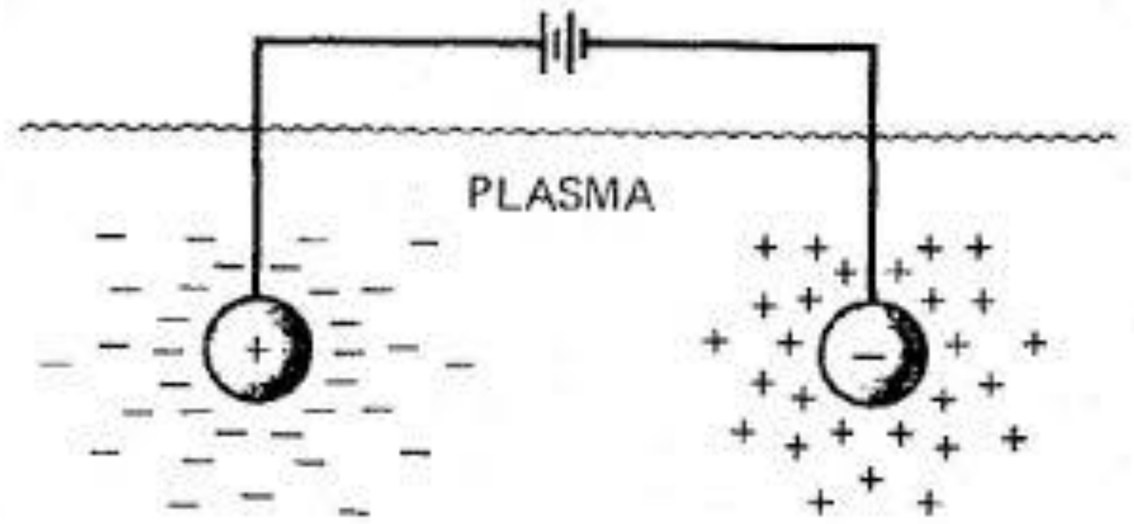
V_i: ionization potential



There are several Important plasma parameters that need to be considered

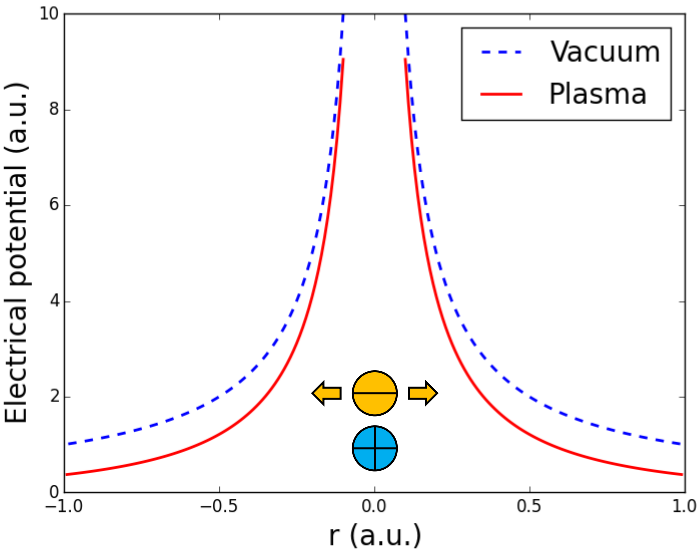
- **Debye length** $$\lambda_D \equiv \left(\frac{KT_e}{4\pi ne^2}\right)^{1/2}$$
- **Plasma parameter** $$\Lambda \equiv n\frac{4\pi}{3}{\lambda_D}^3$$
- **Plasma frequency** $$\omega_{\mathrm{pe}} \equiv \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$$
- **Collision time** $$\tau_e \equiv \frac{3\sqrt{m_e}(KT_e)^{3/2}}{4\sqrt{2\pi}n\ln\Lambda}$$
- **Hall parameter** $\chi \equiv \omega_{\mathrm{ce}}\tau_e$ **, where** $\omega_{\mathrm{ce}} \equiv \dfrac{eB}{m_e c}$ **is the electron gyrofrequency**
- **Plasma beta** $\beta \equiv \dfrac{P}{P_B}$ **, where** $P_B \equiv \dfrac{B^2}{8\pi}$ **is the magnetic pressure**

A test ion in the plasma gathers a shielding cloud that tends to cancel its own charge



Francis F. Chen, \Introduction to plasma physics and controlled fusion"

Debye shielding is a phenomenon such that the potential due to a test charge in a plasma falls off much faster than in vacuum



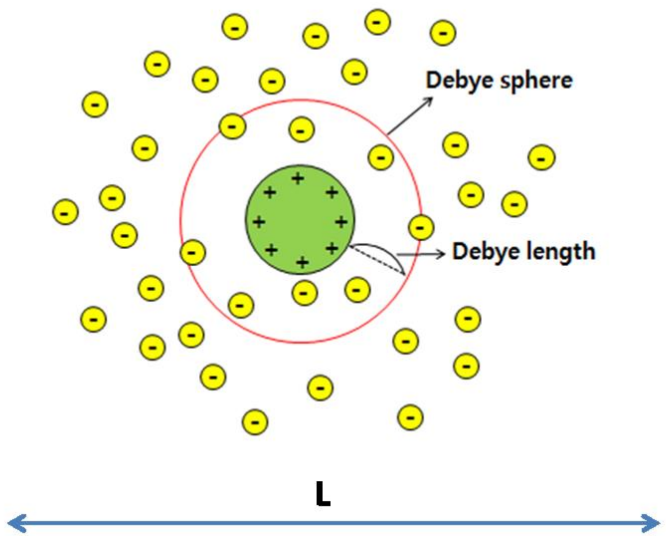
- **Vacuum potential:**

$$\phi = \frac{\phi_0}{r}$$

- **Potential in a plasma**

$$\phi = \frac{\phi_0}{r} \exp\left(-\frac{r}{\lambda_D}\right) \quad \lambda_D \approx \left(\frac{KT_e}{4\pi n e^2}\right)^{1/2}$$

Plasma parameter Λ is the number of particles in a sphere with radius of λ_D



- **Plasma parameter:**

$$\Lambda \equiv n \frac{4\pi}{3} {\lambda_D}^3$$

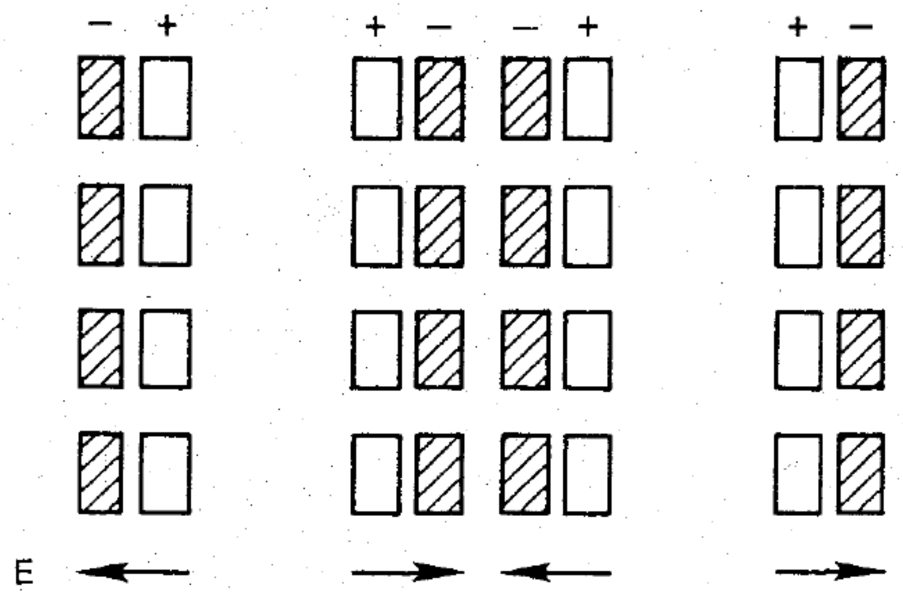
- **Criterion for an ionized gas to be plasma:**

$$\lambda_D \ll L$$

- **Requirement of "collective behavior":**

$$\Lambda \gg 1$$

Electron plasma frequency is the characteristic frequency such that electrons oscillate around their equilibrium positions



Mechanism of plasma oscillations.

- **Plasma frequency:**

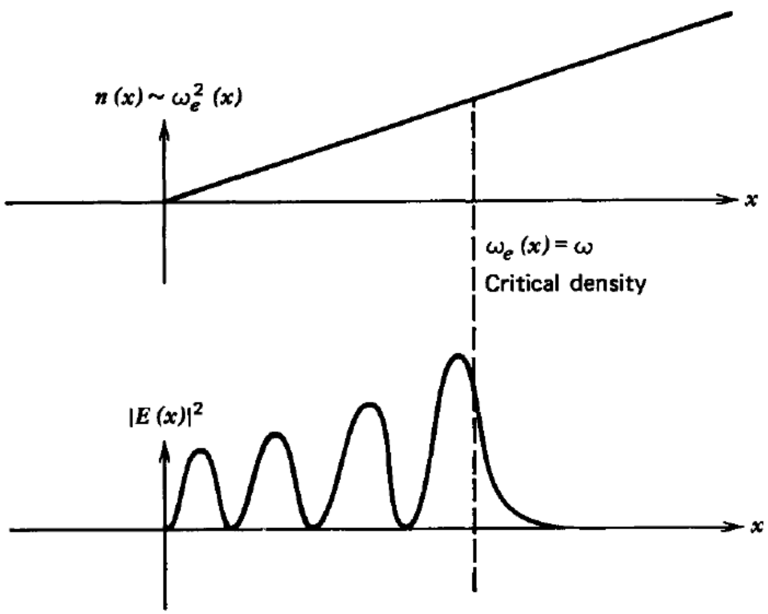
$$\omega_{\mathrm{pe}} \equiv \omega = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$$

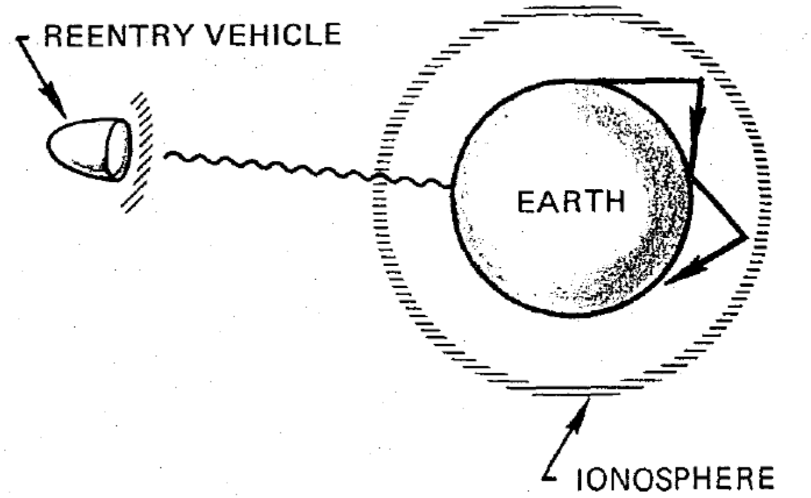
- **Wave number k becomes imaginary when** $\omega < \omega_e$.

$$E = E_0 e^{i(\mathrm{kx}-\omega\mathrm{t})} = E_0 e^{-k_I t} e^{i(k_R x-\omega\mathrm{t})}$$

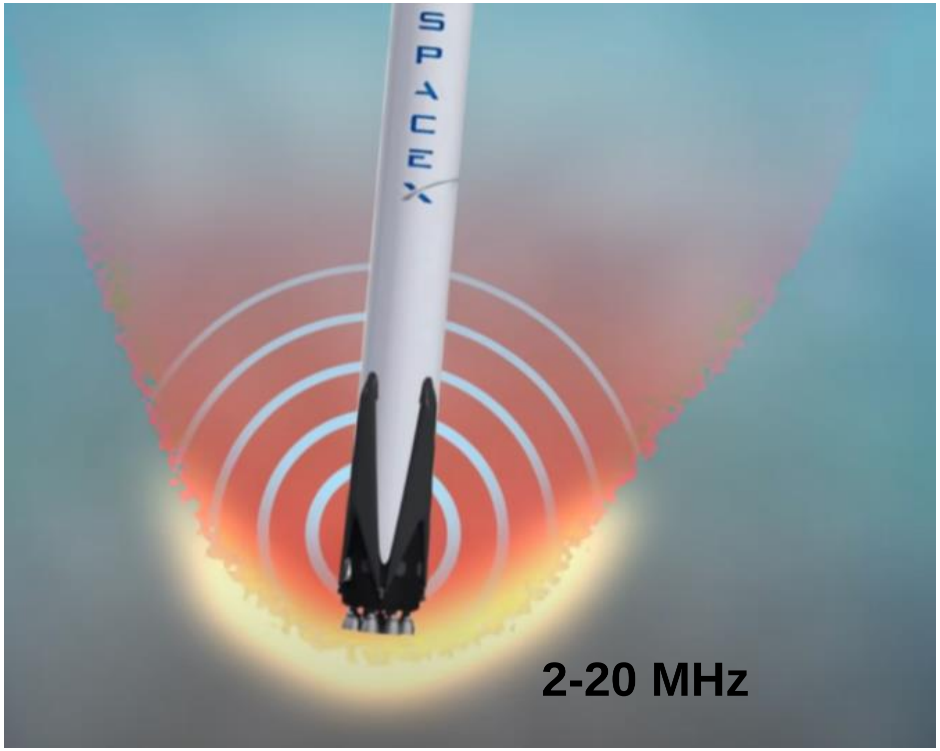
The cutoff of the electromagnetic wave is important in laser fusion and in the interaction of radio waves with the ionosphere

$$\omega_{\mathrm{pe}} \equiv \omega = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$$





SpaceX moves their S-band transmitter to the top of their rocket to avoid communication blackout



https://www.youtube.com/watch?v=Bf4rPsS_fwA

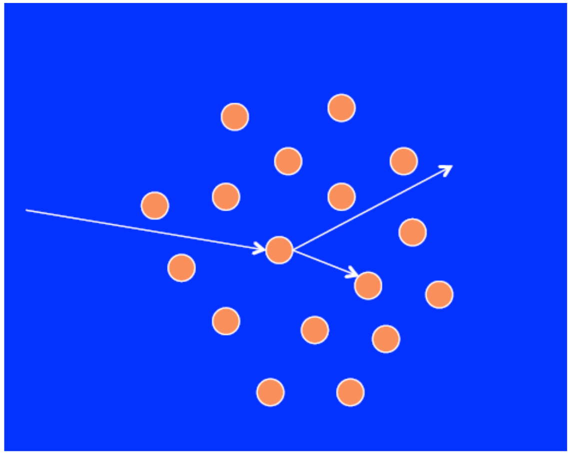
Comparison between the mean free path and the system size L determines the regime of the plasma

- With more careful derivation, the collisional time is obtained:

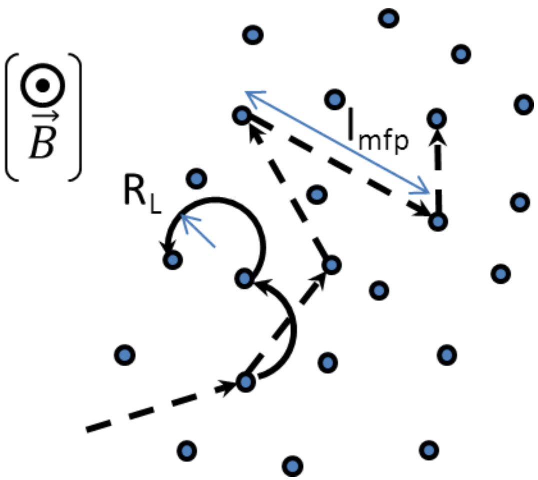
$$\tau_e = {\nu_c}^{-1} = \frac{4\sqrt{2\pi} n \ln \Lambda}{3\sqrt{m_e}(KT_e)^{3/2}}$$

- Mean free path: $l_{\mathrm{mfp}} = v_e \tau_e$

$$\begin{cases} l_{\mathrm{mfp}} < L & \text{Fluid Theory} \\ l_{\mathrm{mfp}} > L & \text{Kinetic Theory} \end{cases}$$



Thermal conduction perpendicular to the magnetic field can be suppressed when the plasma is magnetized



- Plasma is magnetized when

$$\frac{R_L}{l_{\mathrm{mfp}}} = \frac{v_e}{\omega_{\mathrm{ce}}}\frac{1}{v_e\tau_e} < 1$$

i.e., the hall parameter

$$\chi \equiv \omega_{\mathrm{ce}}\tau_e > 1$$

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

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

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

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

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

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

- Therefore

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

Plasma β is the ratio between hydro pressure and magnetic pressure

- **Momentum equation in Magnetohydrodynamics (MHD) approach:**

$$\rho \frac{d\vec{v}}{\mathrm{dt}} + \rho(\vec{v}\cdot\vec{\nabla})\,\vec{v} = -\vec{\nabla}p + \frac{1}{c}\,\vec{j}\times\vec{B}$$

$$\vec{\nabla}\times\vec{B} = \frac{4\pi}{c}\,\vec{j}$$

$$\vec{j}\times\vec{B} = \frac{c}{4\pi}(\vec{\nabla}\times\vec{B})\times\vec{B} = \frac{c}{4\pi}\left[(\vec{B}\cdot\vec{\nabla})\times\vec{B} - \frac{1}{2}\,\vec{\nabla}B^2\right]$$

$$\rho \frac{d\vec{v}}{\mathrm{dt}} + \rho(\vec{v}\cdot\vec{\nabla})\,\vec{v} = -\vec{\nabla}\left(p + \frac{B^2}{8\pi}\right) + \frac{1}{4\pi}(\vec{B}\cdot\vec{\nabla})\times\vec{B}$$

- **Magnetic pressure:** $\frac{B^2}{8\pi}$

$$\beta \equiv \frac{p}{B^2/8\pi}$$

- **Magnetic tension:** $\frac{1}{4\pi}(\vec{B}\cdot\vec{\nabla})\times\vec{B}$

- **Pressure can be treated as energy density, i.e., energy per volume.**

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. Particle beam source
   f. High energy particle accelerator
   g. Controlled thermonuclear fusion
   h. Neutral beam source
   i. Electrical propulsion

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

Methods of plasma production

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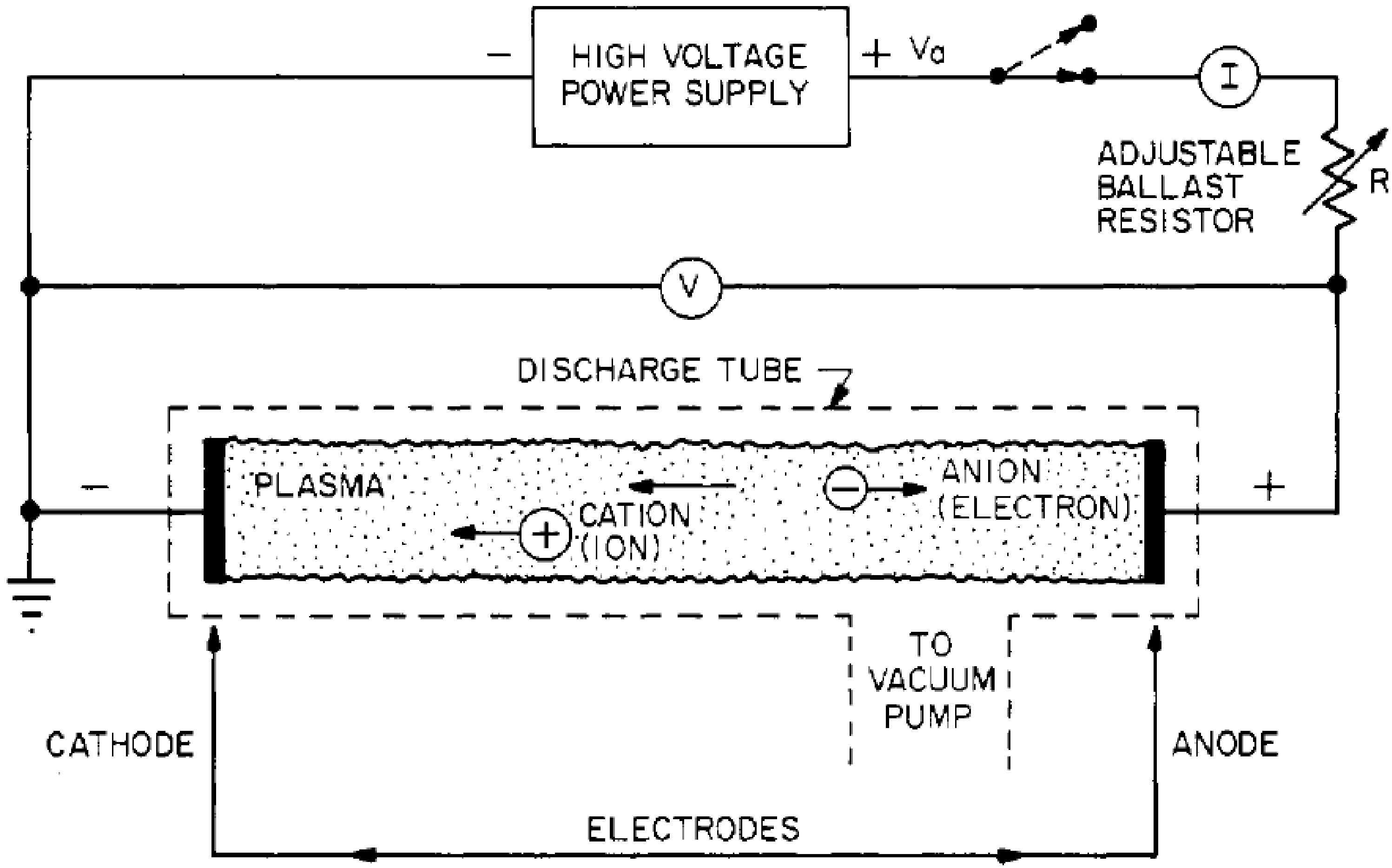
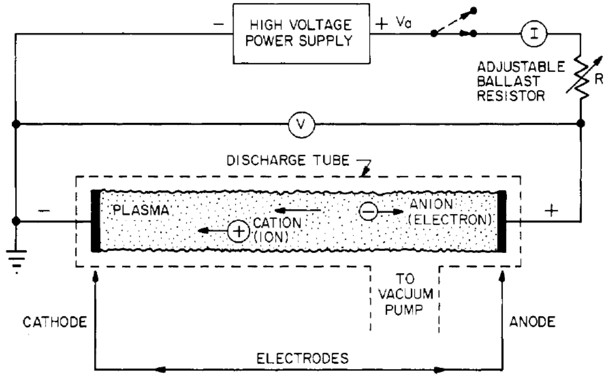
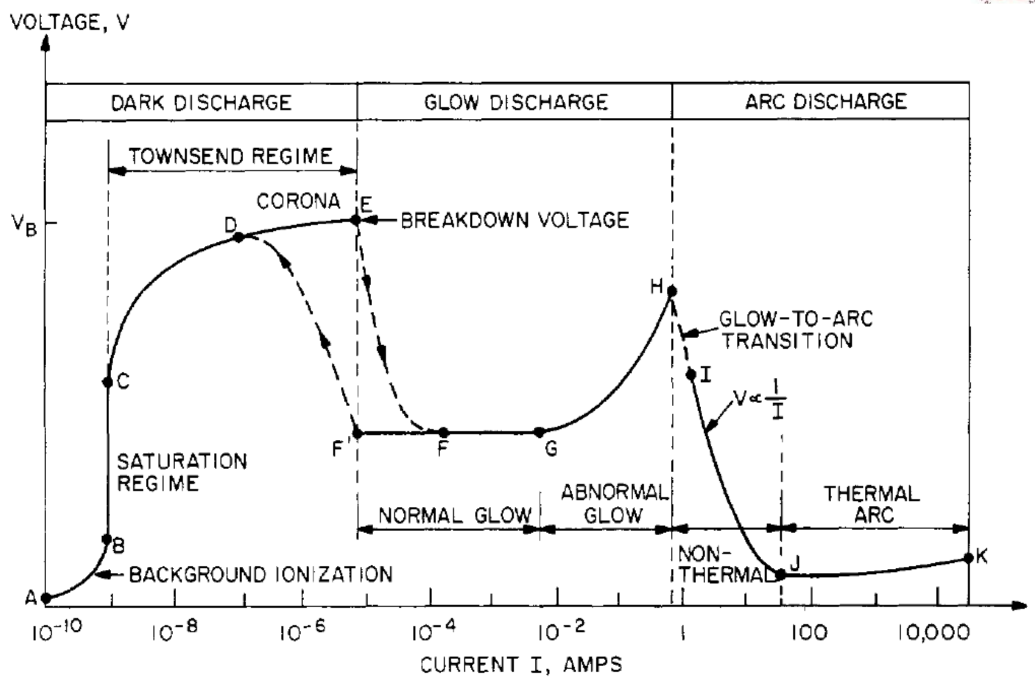
Electrical discharge physics was studied using the classical low pressure electrical discharge tube



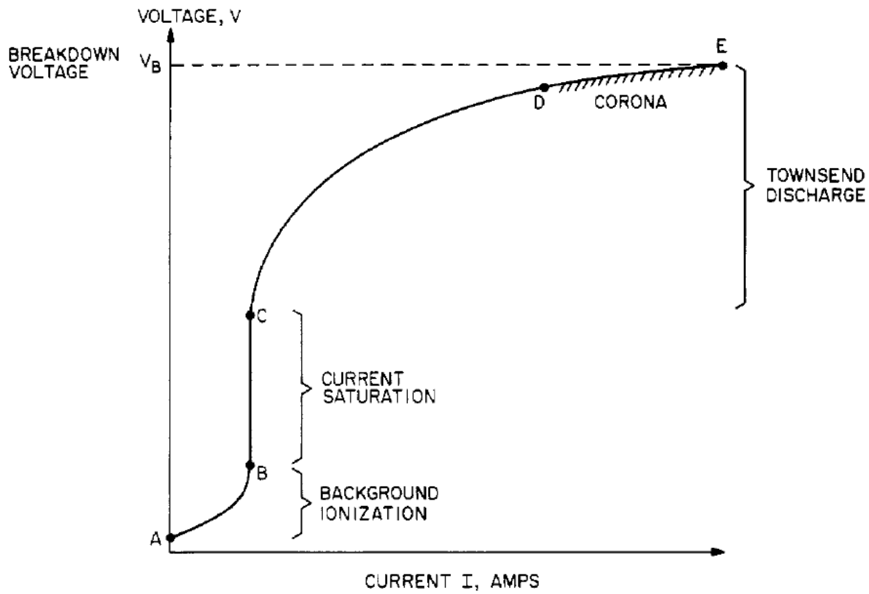
The V-I curve is nonlinear in a DC electrical discharge tube

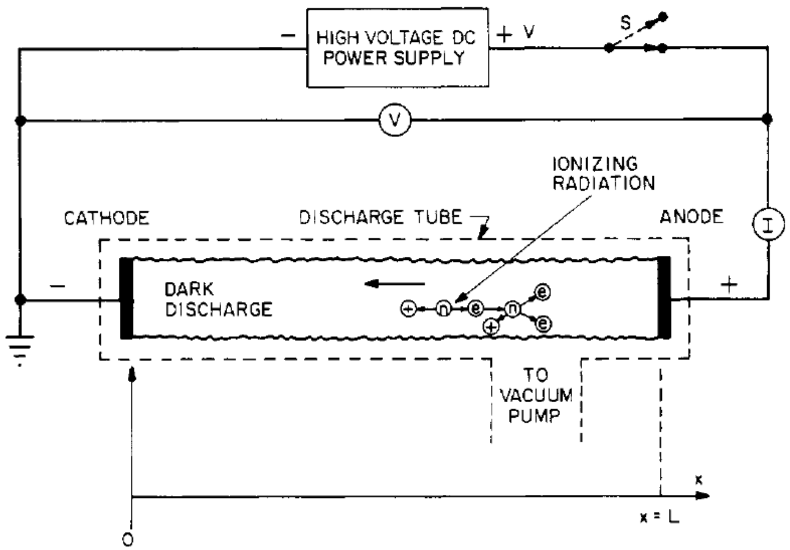




- **Depends on the voltage, the adjustable ballast resistor, the voltage-current characteristic behaves differently in different regime.**
  - **Dark discharge**
  - **Glow discharge**
  - **Arc discharge**

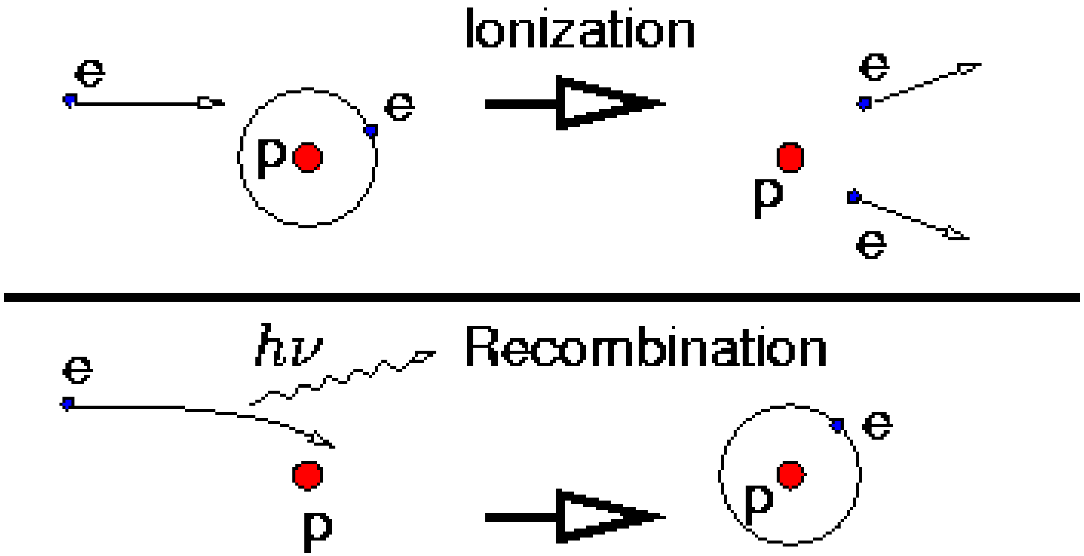
In background ionization, ions and electrons are created by ionization from background radiation





- **Sources of background radiation:**
  - **Cosmic rays**
  - **Radioactive minerals in the surroundings**
  - **Static charges**
  - **Other sources**
- **In a dark discharge, the excitation light is so little and is not visible**

A plasma is a gas in which an important fraction of the atoms is ionized so that the electrons and ions are separated freely

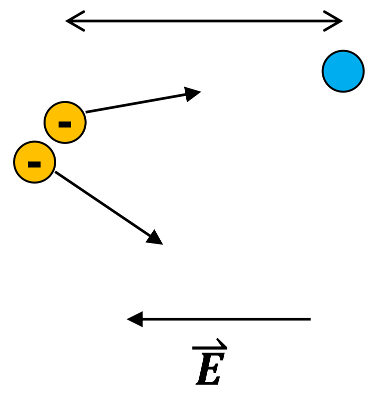


http://ocw.mit.edu/courses/nuclear-engineering/22-611j-introduction-to-plasma-physics-i-fall-2003/lecture-notes/

Mean free path is important in ionization process

- **For an electron to acquire enough energy between collisions, its <u>mean free path</u> in the material must be sufficiently long.**

Mean free path, λ



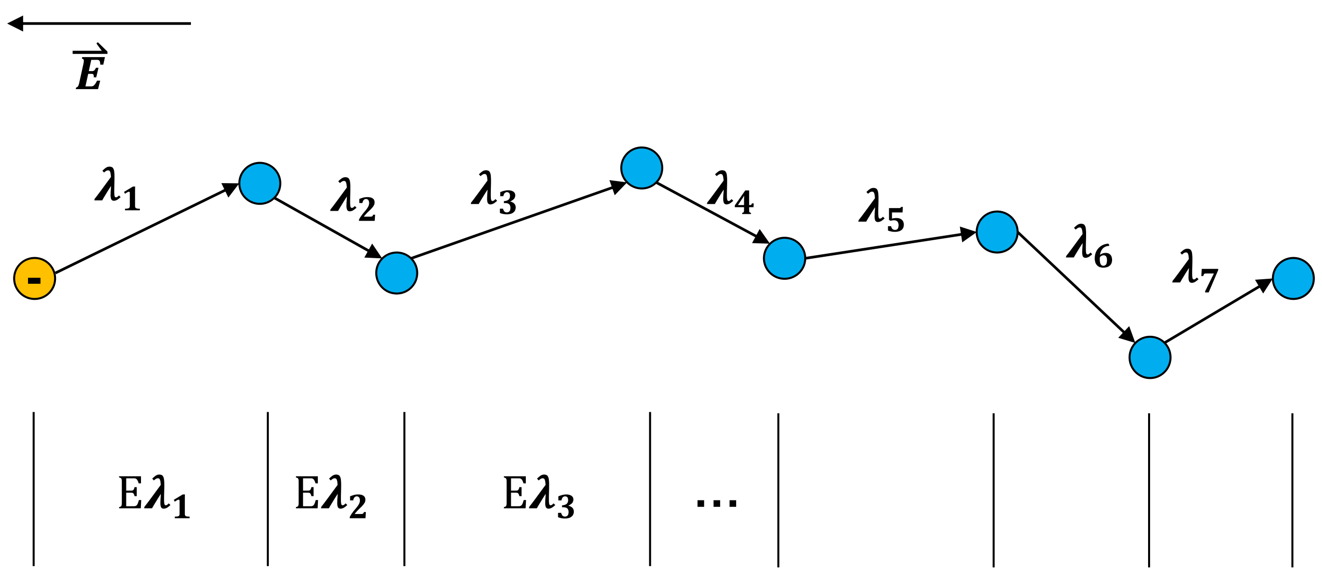
$$E_{\mathrm{k}} = e \times E \times \lambda = \mathrm{eV}$$

Electron impact ionization is the most important process in a breakdown of gases

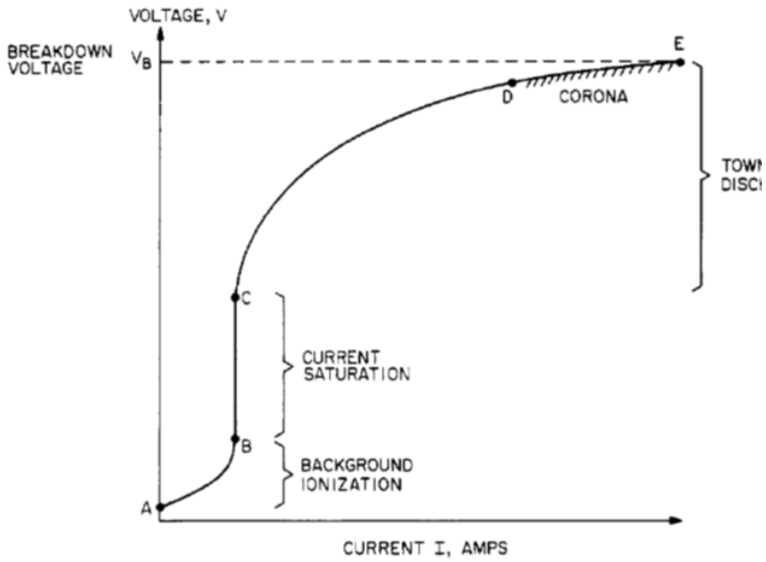
- **Electron impact ionization: A + e$^-$ $\rightarrow$ A$^+$ + e$^-$ + e$^-$**
  - **The most important process in the breakdown of gases but is not sufficient alone to result in the breakdown.**

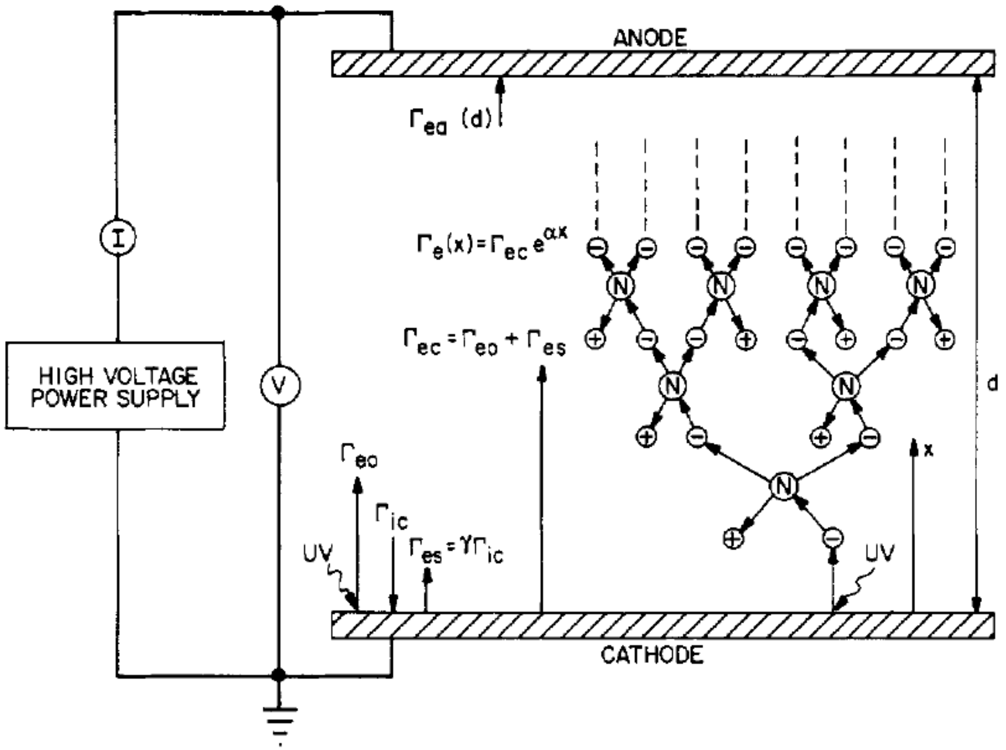
$$eE\lambda_{e,i} \geq eV_{\mathrm{i}}$$

V_{i}: ionization potential



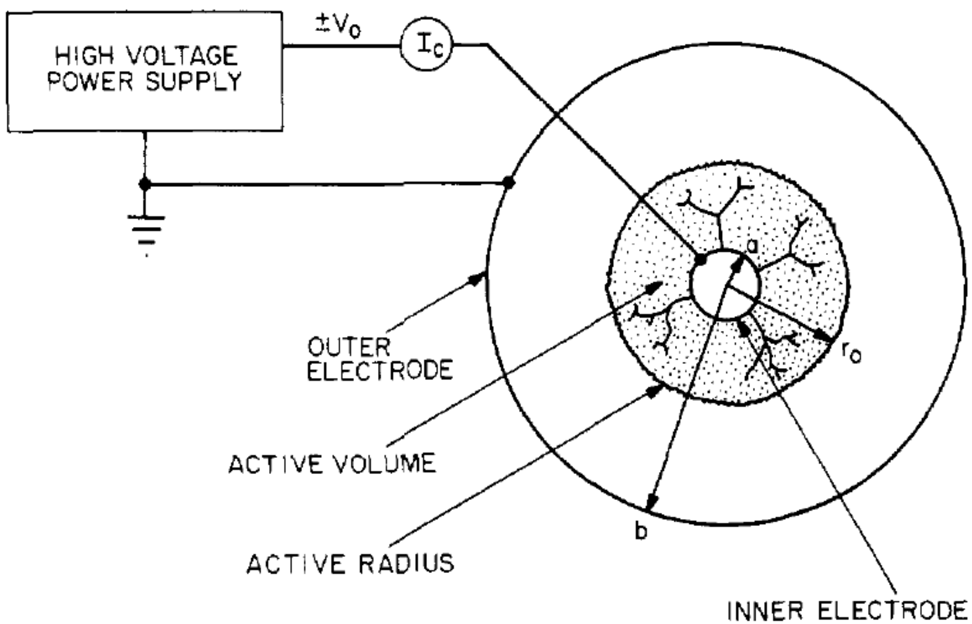
The region where the current exponentially increases is called the Townsend discharge





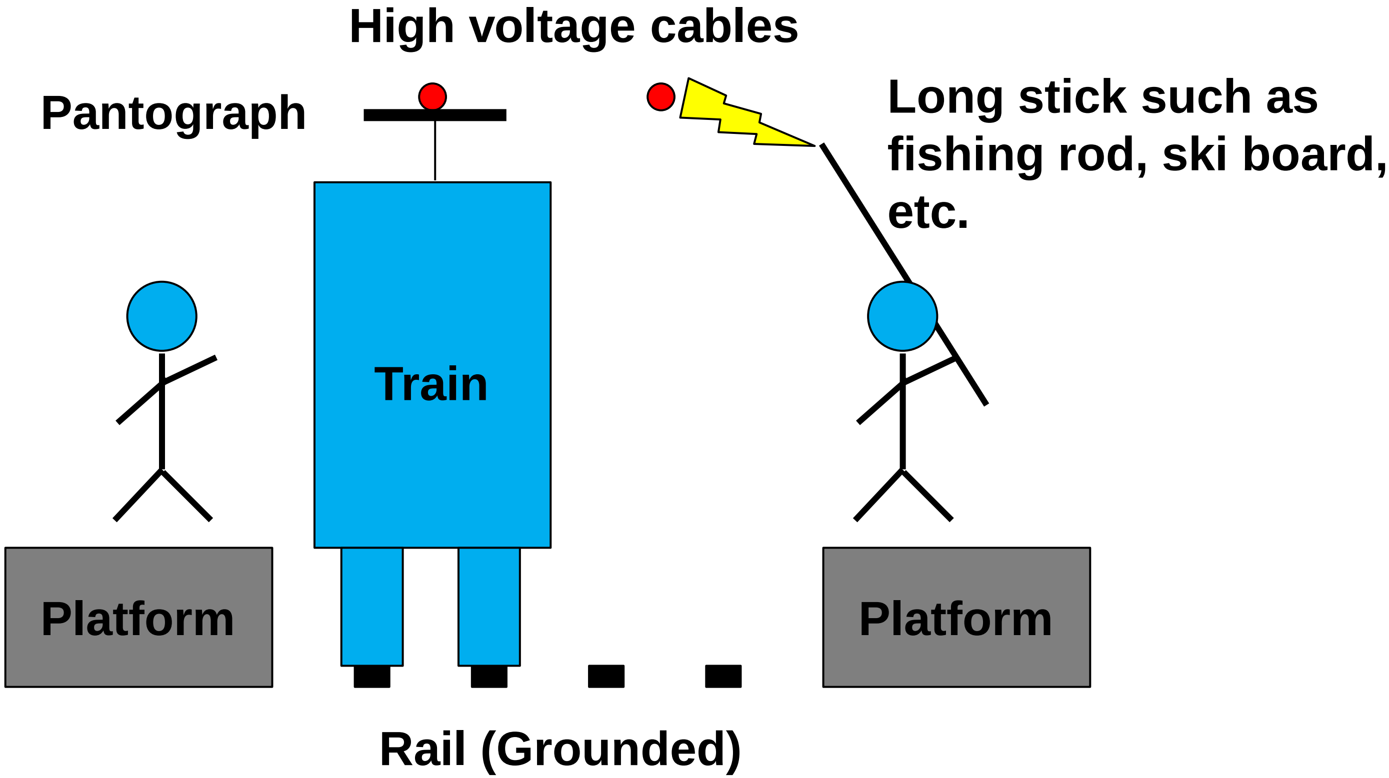
- **The phenomenon of the number of electrons increase exponentially is called the avalanche breakdown.**

Phenomenology of corona generated by a fine wire



- **The point of corona initiation is that point at which the voltage on the inner conductor of radius a is high enough that corona is just detectable.**
- **The electric field will drop off to the breakdown value at a radius r_0 called the active radius.**

Don't bring a long stick to a train station



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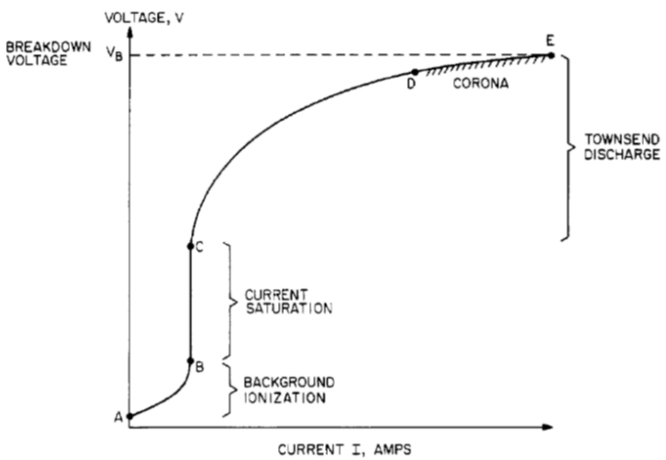
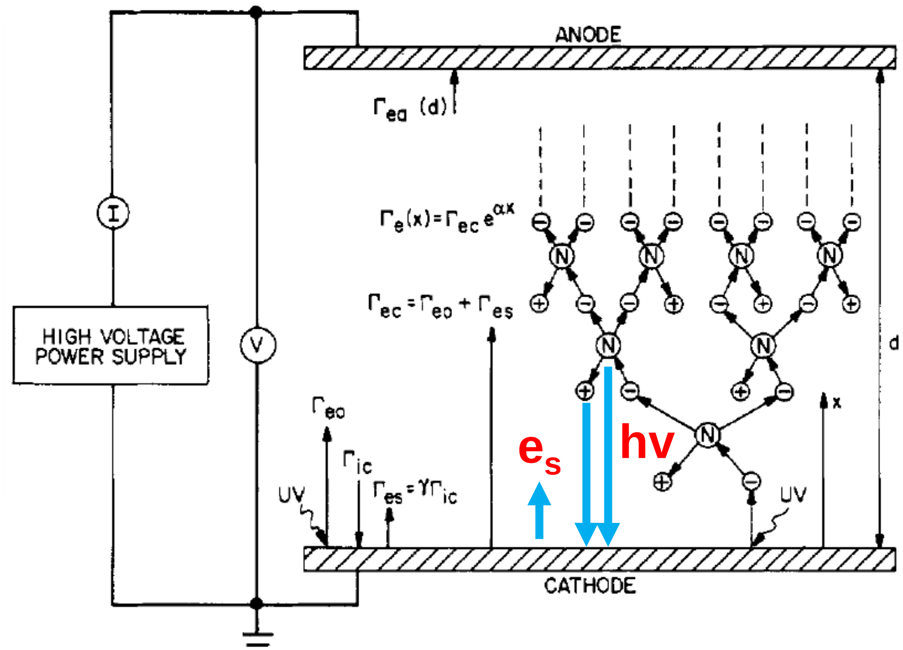
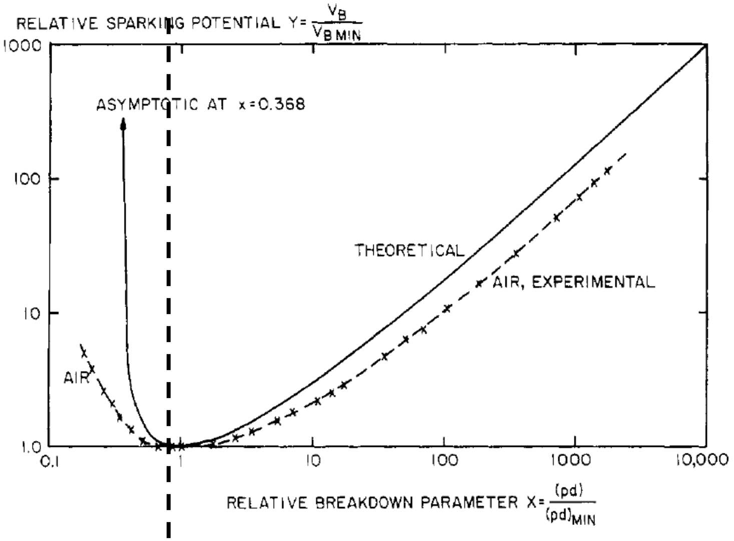




- **Primary electrons: electrons from the cathode due to photoemission, background radiation, static chages, or other processes.**
- **Secondary electrons: electrons emitted from the cathode per incident ion or photon created from ionization in gas.**

- **Electrical breakdown occurs when applied voltage is greater than the breakdown voltage**

Collision frequency and electron energy gained from electric field are both important to electrical breakdown

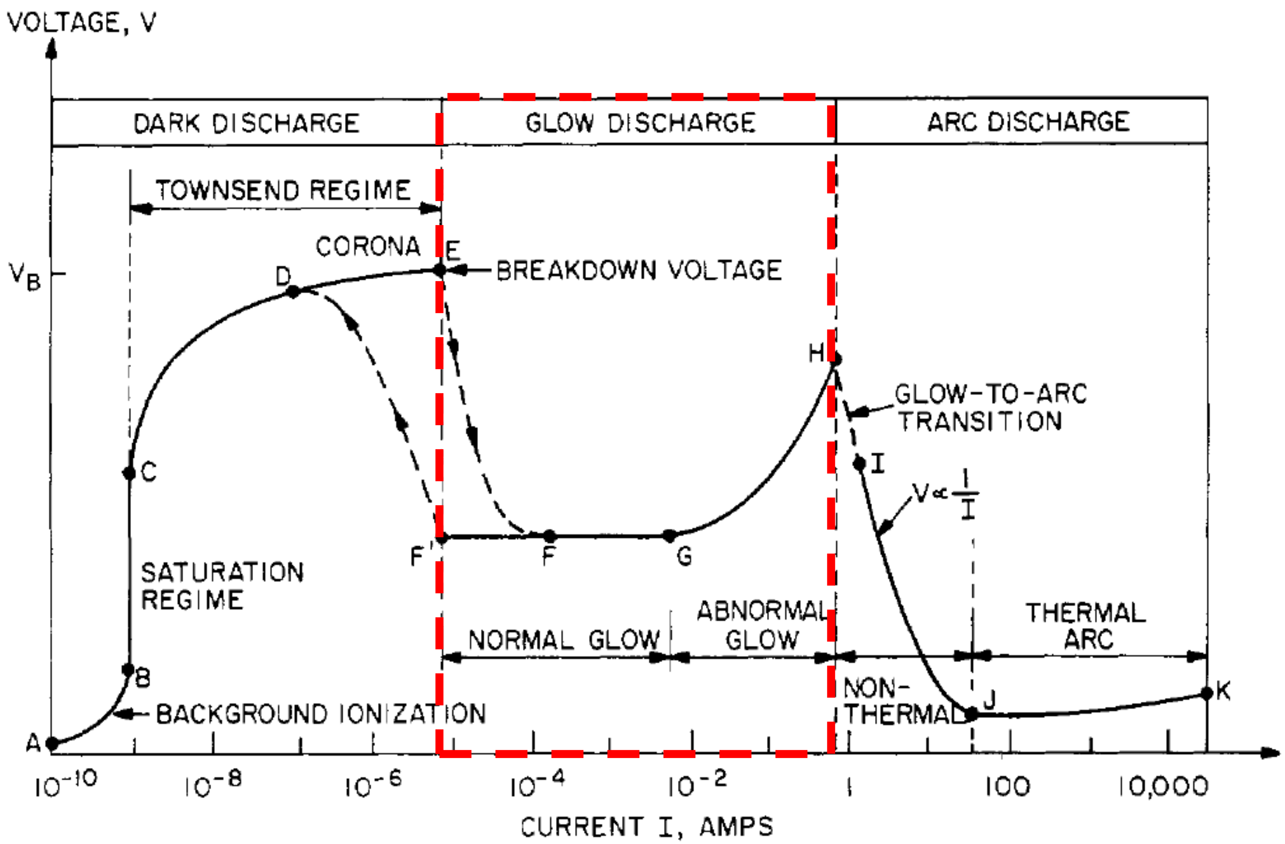


- **Collision is not frequent enough even the electrons gain large energy between each collision.**
- **Electrons do not gain enough energy between each collision even collisions happen frequently.**

- **The minimum of the Paschen curve corresponds to the Stoletow point, the pressure at which the volumetric ionization rate is a maximum.**

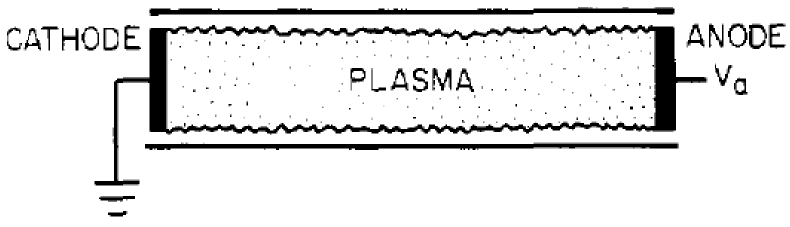
DC electrical glow discharges in gases

- The internal resistance of the power supply is relatively low, then the gas will break down at the voltage V_B, and the discharge tube will move from the dark discharge regime into the low pressure normal glow discharge regime.

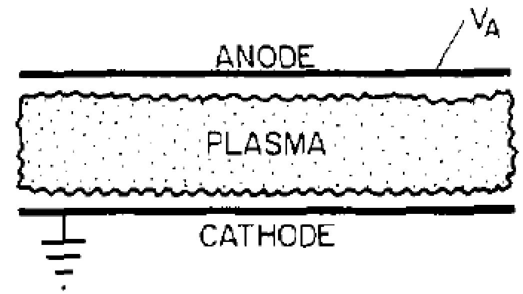


The plasma is luminous in the glow discharge regime

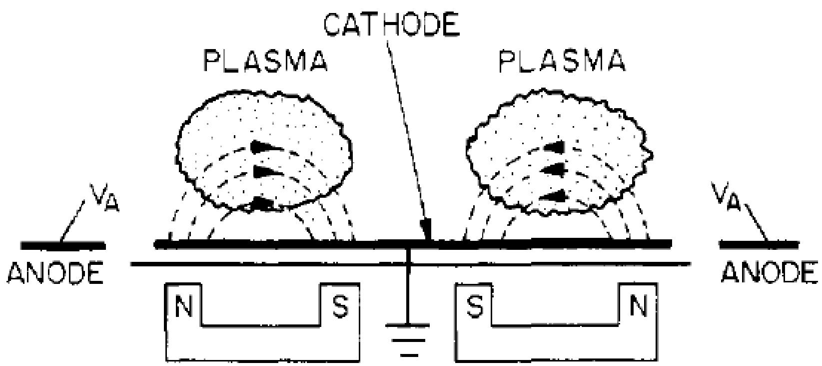
- **The luminosity arises because the electron energy and number density are high enough to generate visible light by excitation collisions.**



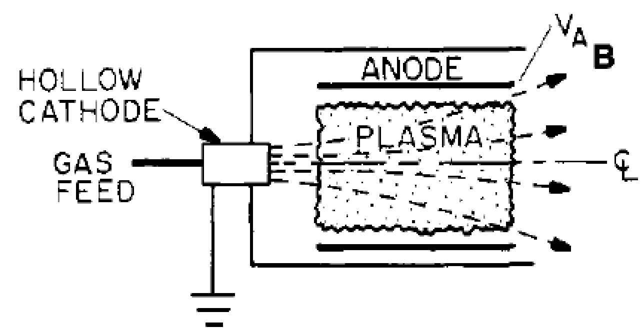
CLASSICAL DC ELECTRICAL DISCHARGE TUBE



PARALLEL PLATE PLASMA REACTOR

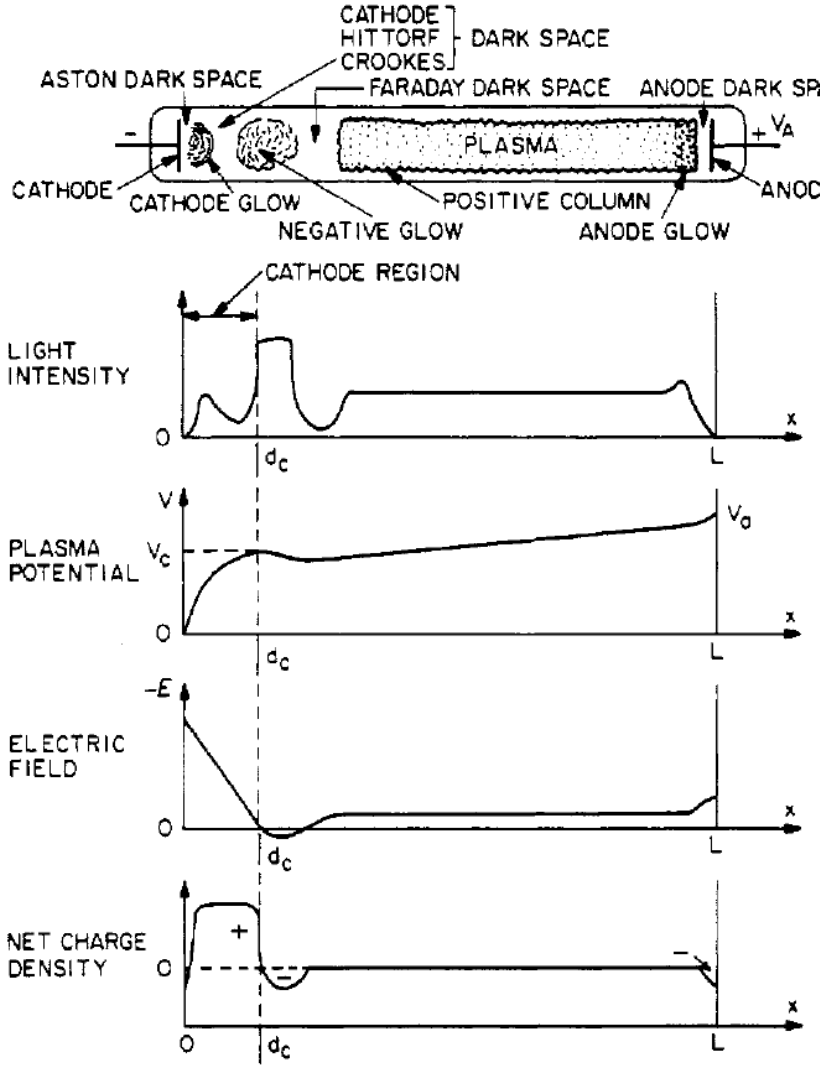


COPLANAR MAGNETRON REACTOR



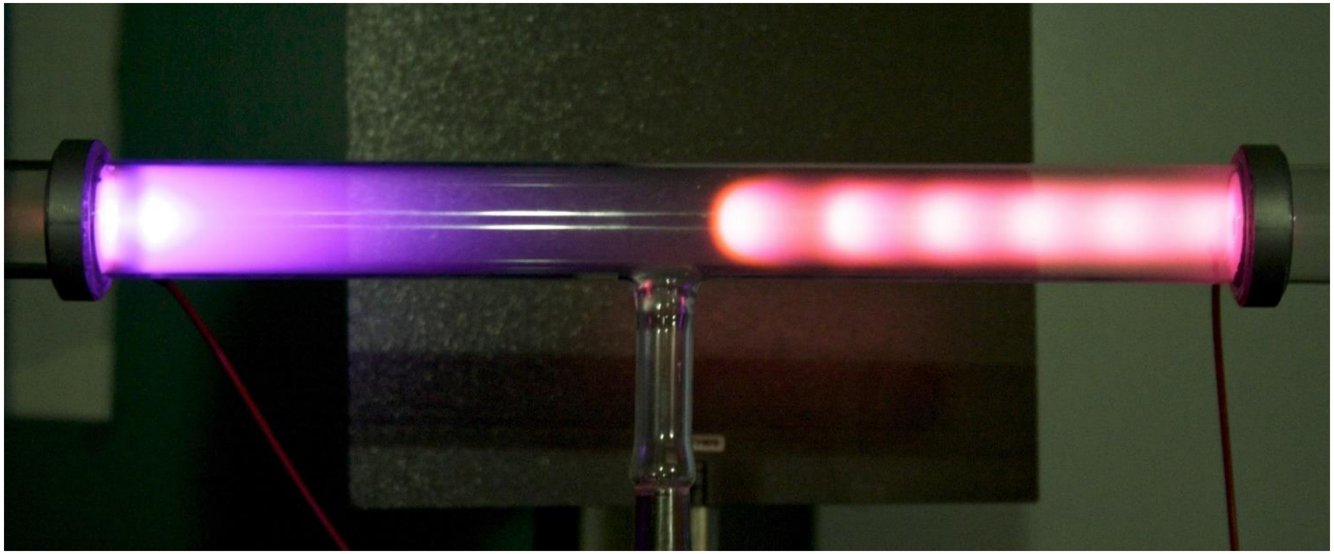
COAXIAL ELECTRON BOMBARDMENT DISCHARGE CHAMBER

Low pressure normal glow discharge



Striated discharges

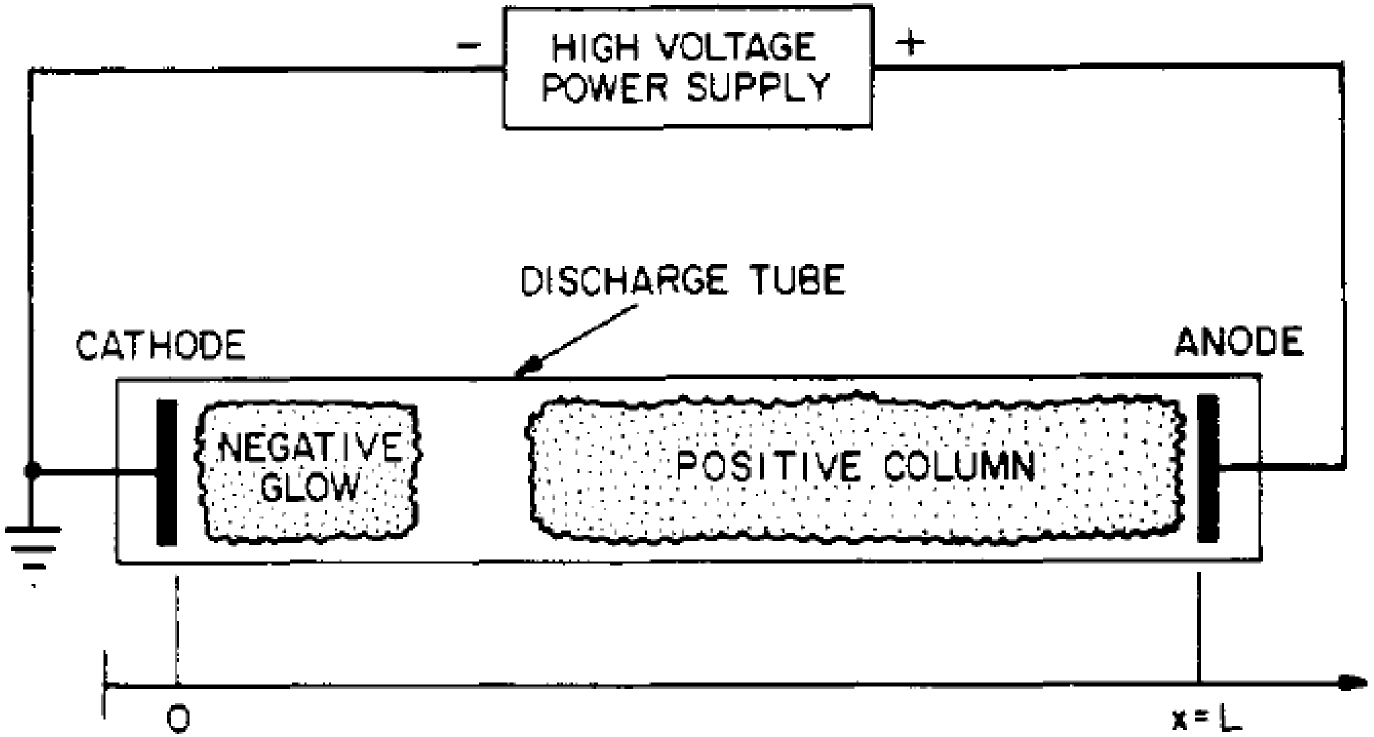
- **Moving or standing striations are, respectively, traveling waves or stationary perturbations in the electron number density which occur in partially ionized gases, including the positive columns of DC normal glow discharge tubes.**
- **https://youtu.be/Be4RljMTOWE**



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

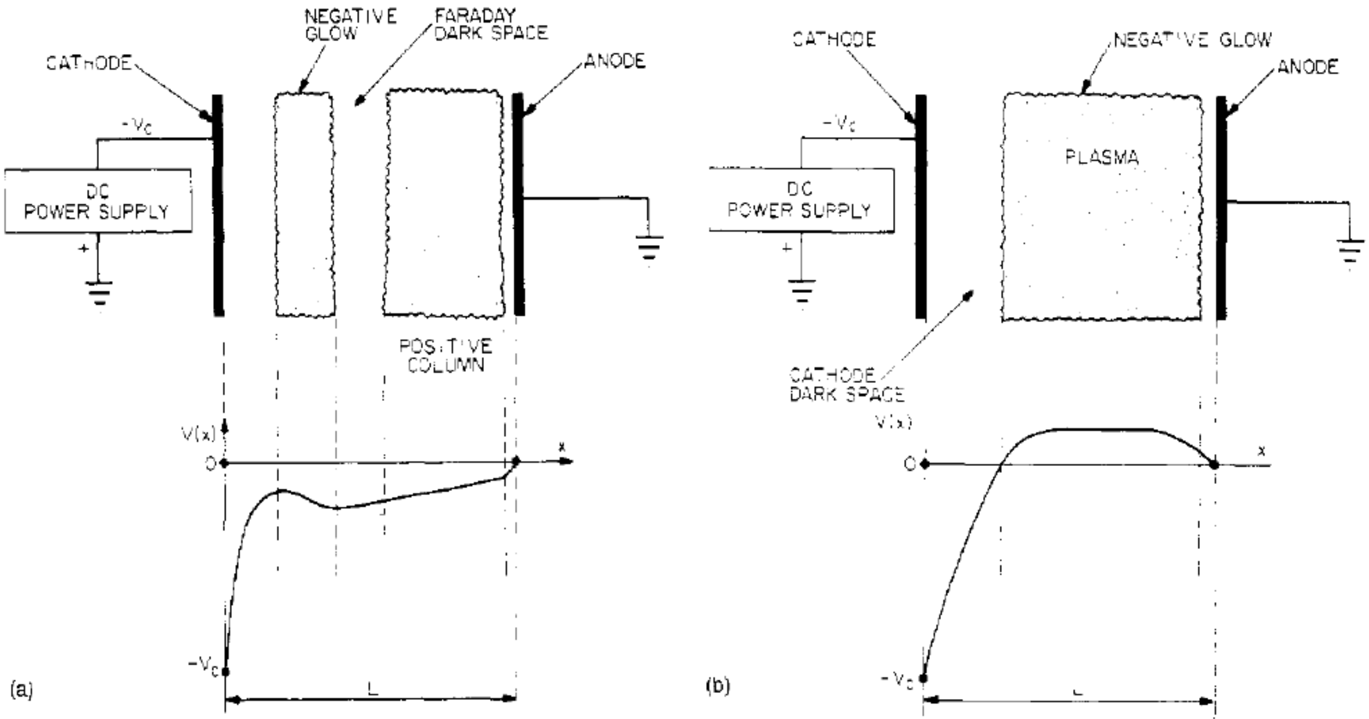
Cylindrical glow discharge sources

- **This configuration is used in lighting devices, such as fluorescent lights and neon advertising signs.**



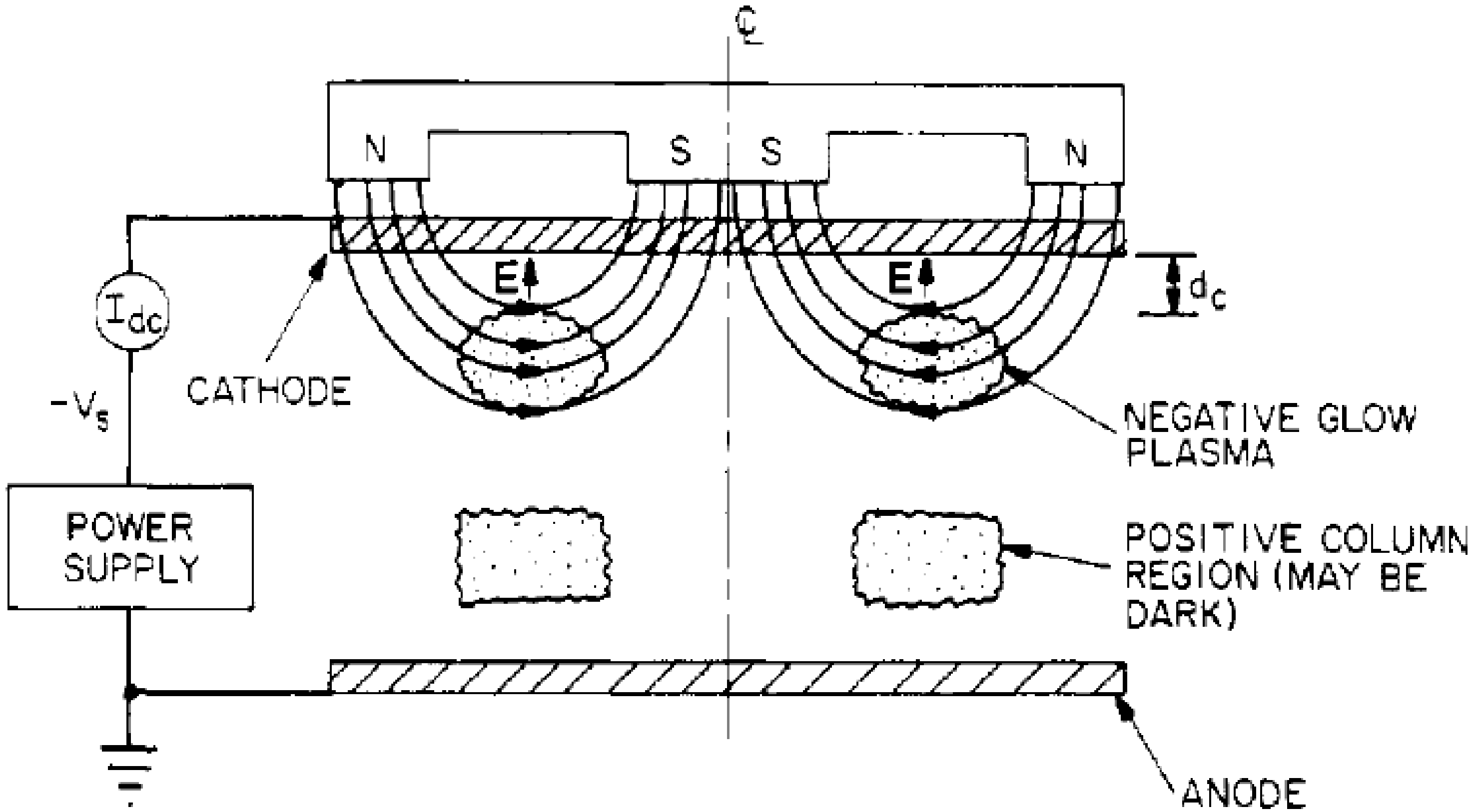
Parallel plate sources are widely used for plasma processing and plasma chemistry applications

- **Unobstructed operation**
- **Obstructed operation**



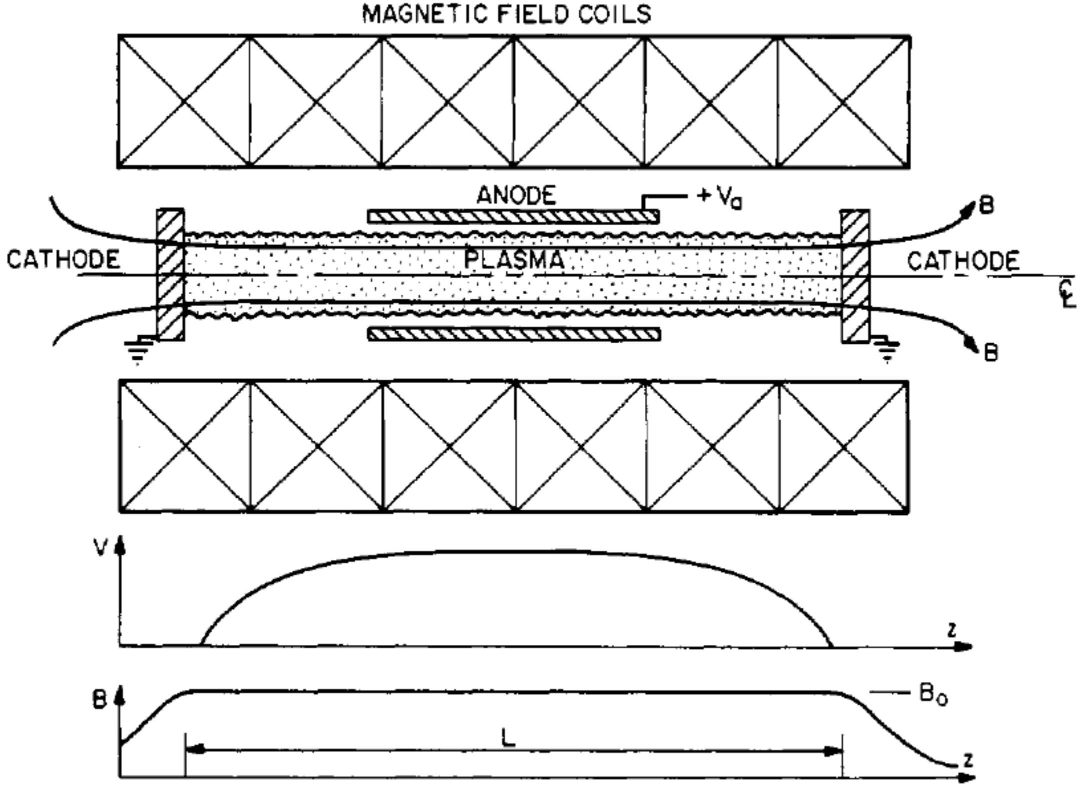
- **The obstructed configuration is used for plasma processing, where high ion energies bombarding the cathode, over large areas and at vertical incidence, are desired.**

Magnetron plasma source are used primarily for plasma-assisted sputtering and deposition



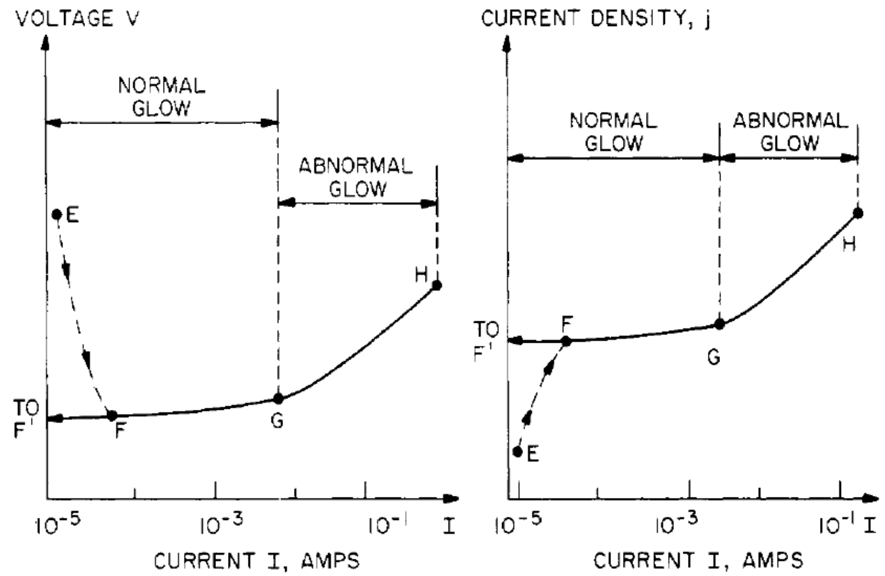
- **When several hundred voltages are applied between the parallel plates, a glow discharge will form, with a negative glow plasma trapped in the magnetic mirrors above the magnet pole pieces.**

Penning discharge plasma sources produce a dense plasma at pressures far below than most other glow discharges



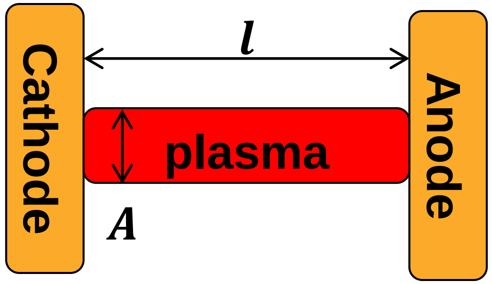
- **Strong axial magnetic fields: to prevent electrons from intercepting the anode.**
- **Axial electric fields: electrons are reflected by opposing cathodes.**
- **Multiple reflection of the electrons along axis.**

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

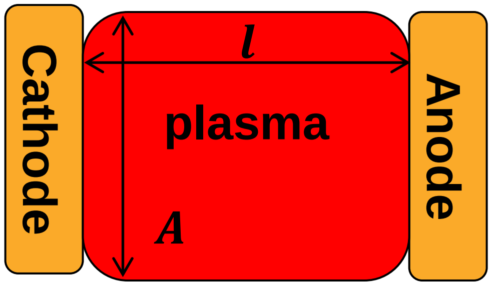


$$R = \eta \frac{l}{A}$$

- **Normal glow discharge:**

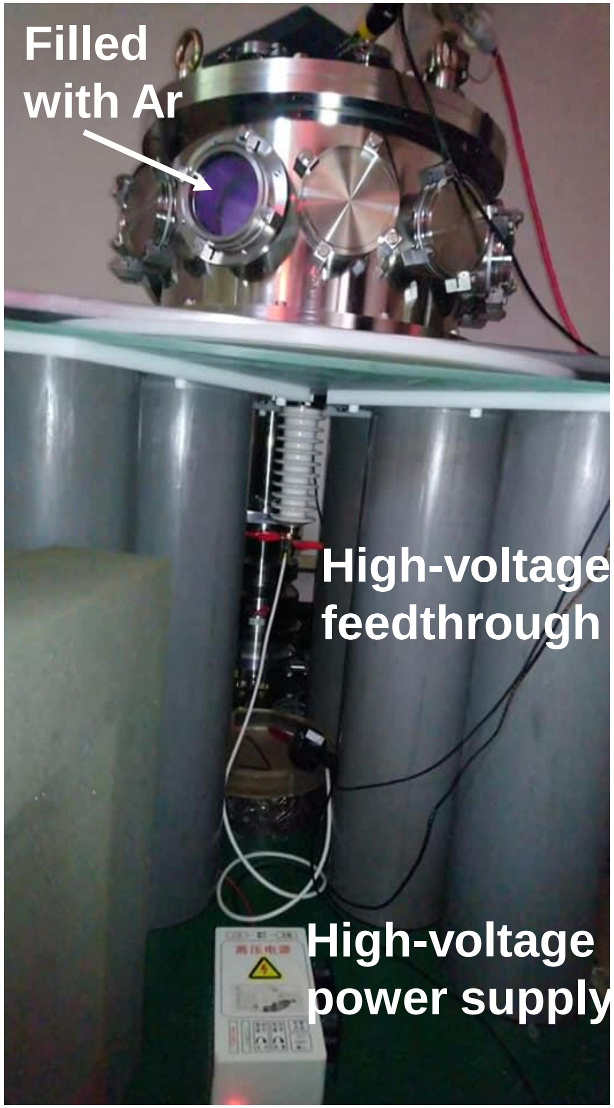


- **Abnormal glow discharge:**

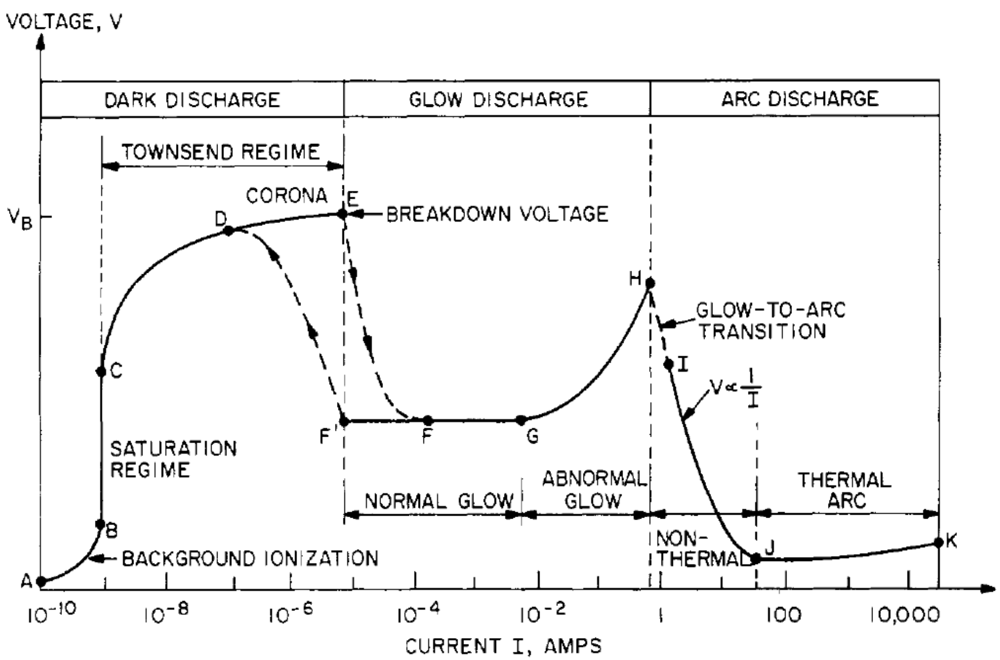


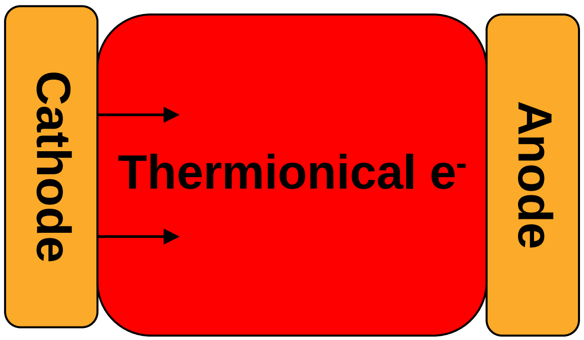
- **Surface cleaning using plasma needs to work in the abnormal glow discharge region.**

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



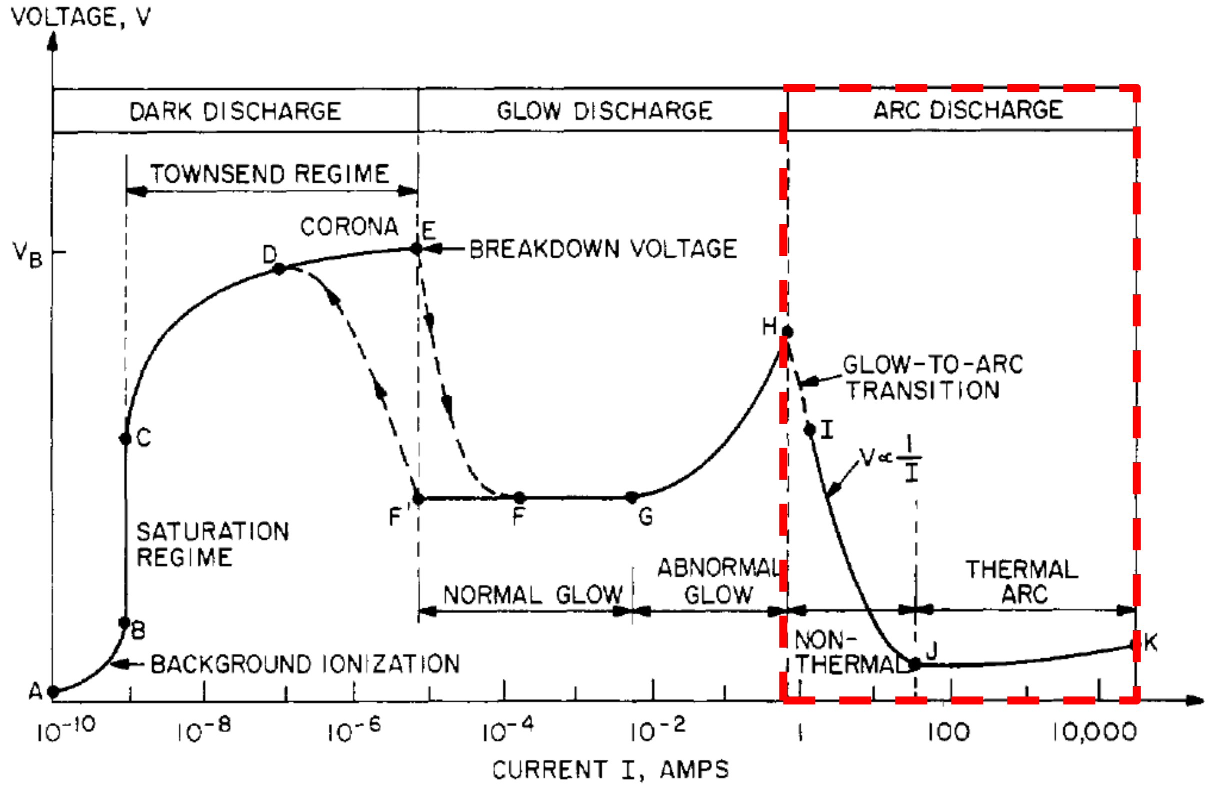
Discharge may enter glow-to-arc transition region if the cathode gets hot enough to emit electrons thermionically





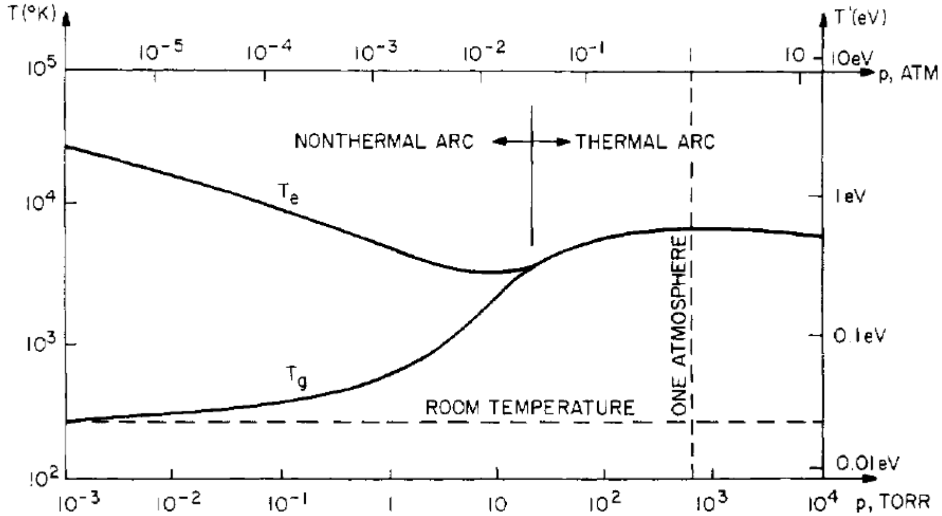
- If the cathode gets hot enough to emit electrons thermionically and the internal impedance of the power supply is sufficiently low, the discharge will make a transition into the arc regime.

DC electrical arc discharges in gases



- **An arc is highly luminous and is characterized by high currents (> 1 A) and current densities (A=cm² t kA/cm²).**
- **Cathode voltage fall is small (£10 V) in the region of high spatial gradients within a few mm of the cathode.**

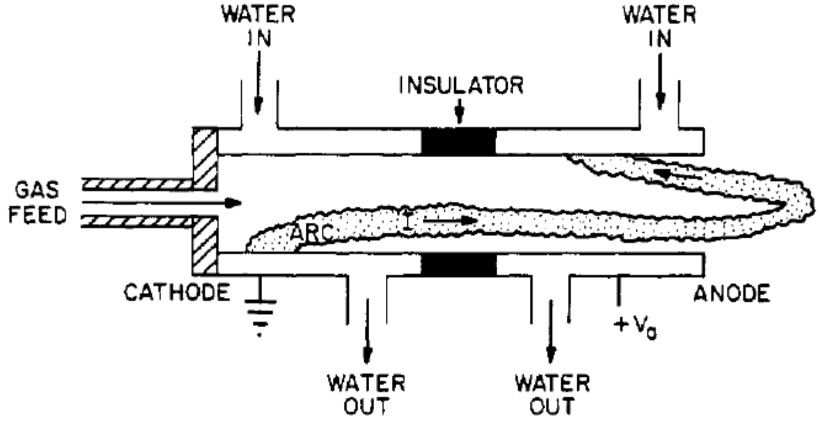
An arc can be non-thermal or thermionic



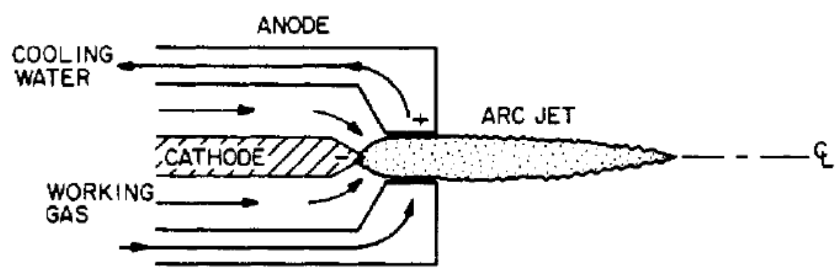
Plasma parameter	Non-thermal arc	Thermal arc
Equilibrium state	Kinetic	LTE
Electron density, n_e (electrons/m^3)	$10^{20} < n_e < 10^{21}$	$10^{22} < n_e < 10^{25}$
Gas pressure, p (Pa)	$0.1 < p < 10^5$	$10^4 < p < 10^7$
Electron temperature, T_e', (eV)	$0.2 < T_e' < 2.0$	$1.0 < T_e' < 10$
Gas temperature, T_g' (eV)	$0.025 < T_g' < 0.5$	$T_g' = T_e'$
Arc current, I (A)	$1 < I < 50$	$50 < I < 10^4$
E/p (V/m-Torr)	High	Low
IE (kW/cm)	$IE < 1.0$	$IE > 1.0$
Typical cathode emission	Thermonic	Field
Luminous intensity	Bright	Dazzling
Transparency	Transparent	Opaque
Ionization fraction	Indeterminate	Saha equation
Radiation output	Indeterminate	LTE

Non-transferred arc

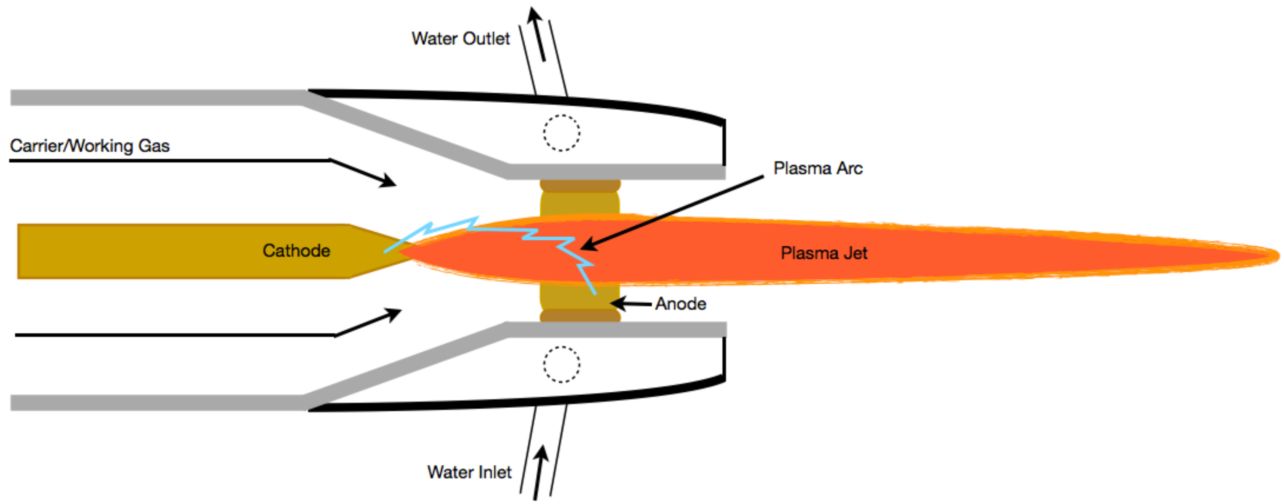
- **Gas fed along the axis blows the arc out toward the material which is to be heated.**

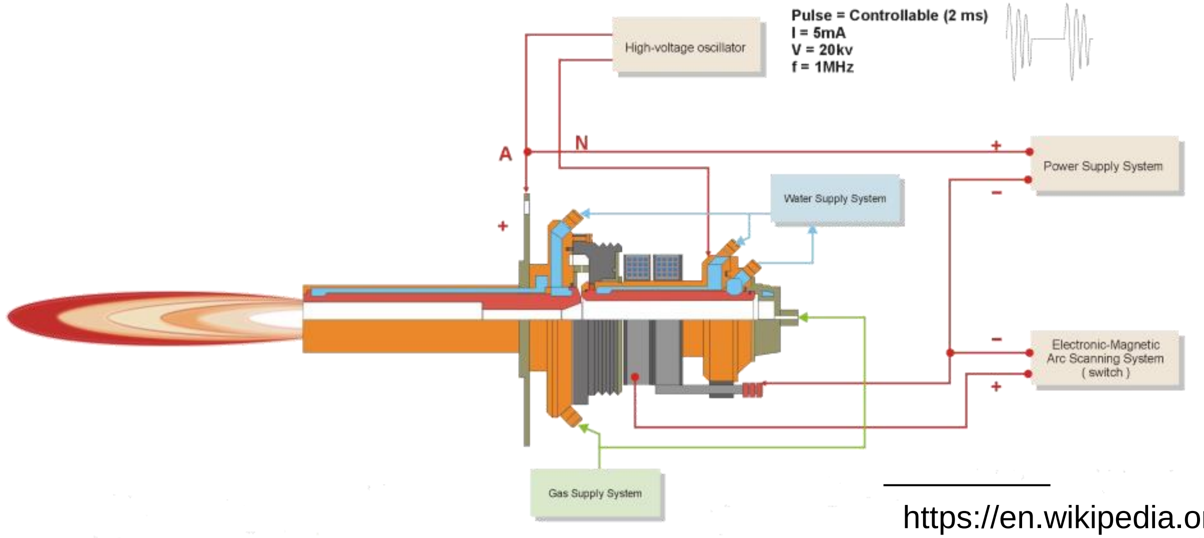


- **A working gas is fed in coaxially and forms a very hot arc jet, at supersonic velocities.**



Plasma torches are used in waste disposal

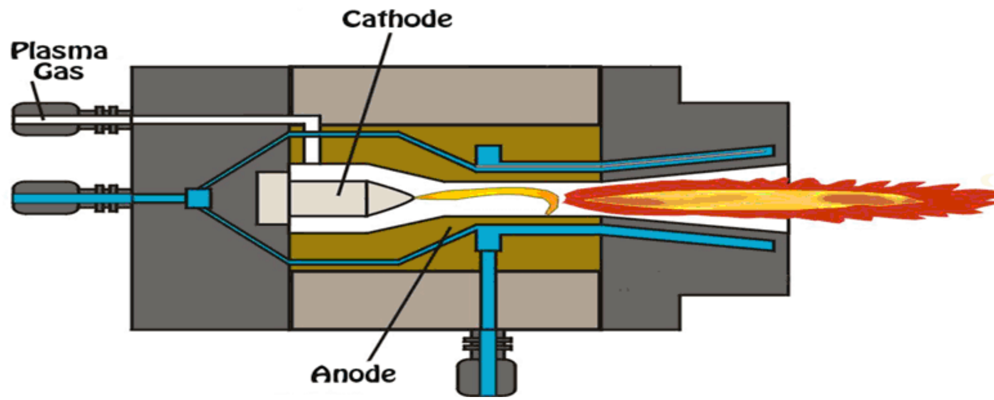




https://en.wikipedia.org/wiki/Plasma_torch
http://www.httcanada.com/torches.html

Application – Plasma torch
(電漿熔融爐 by奧特拉斯/豐映科技)

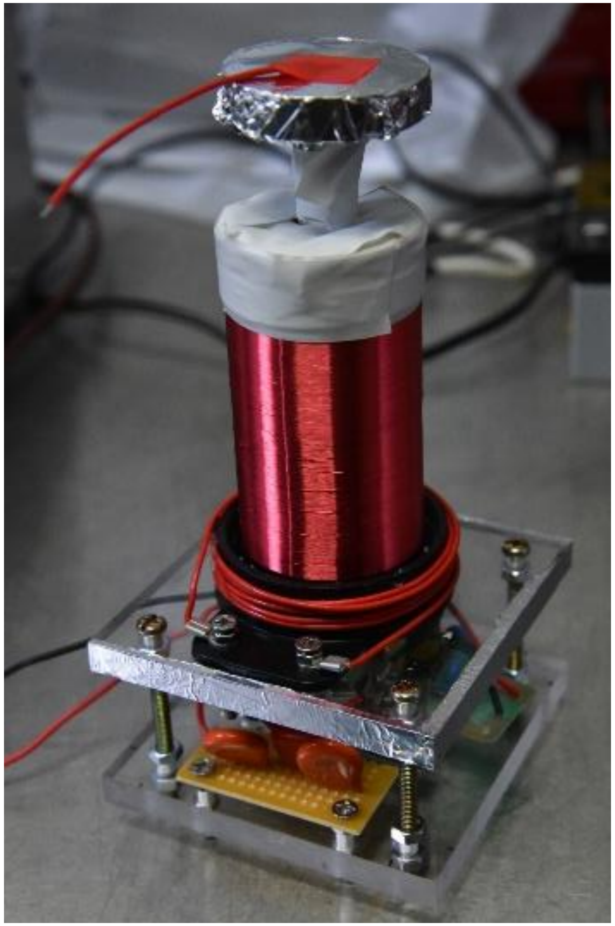
- **Non-Transferred arc**
- **Transferred arc**



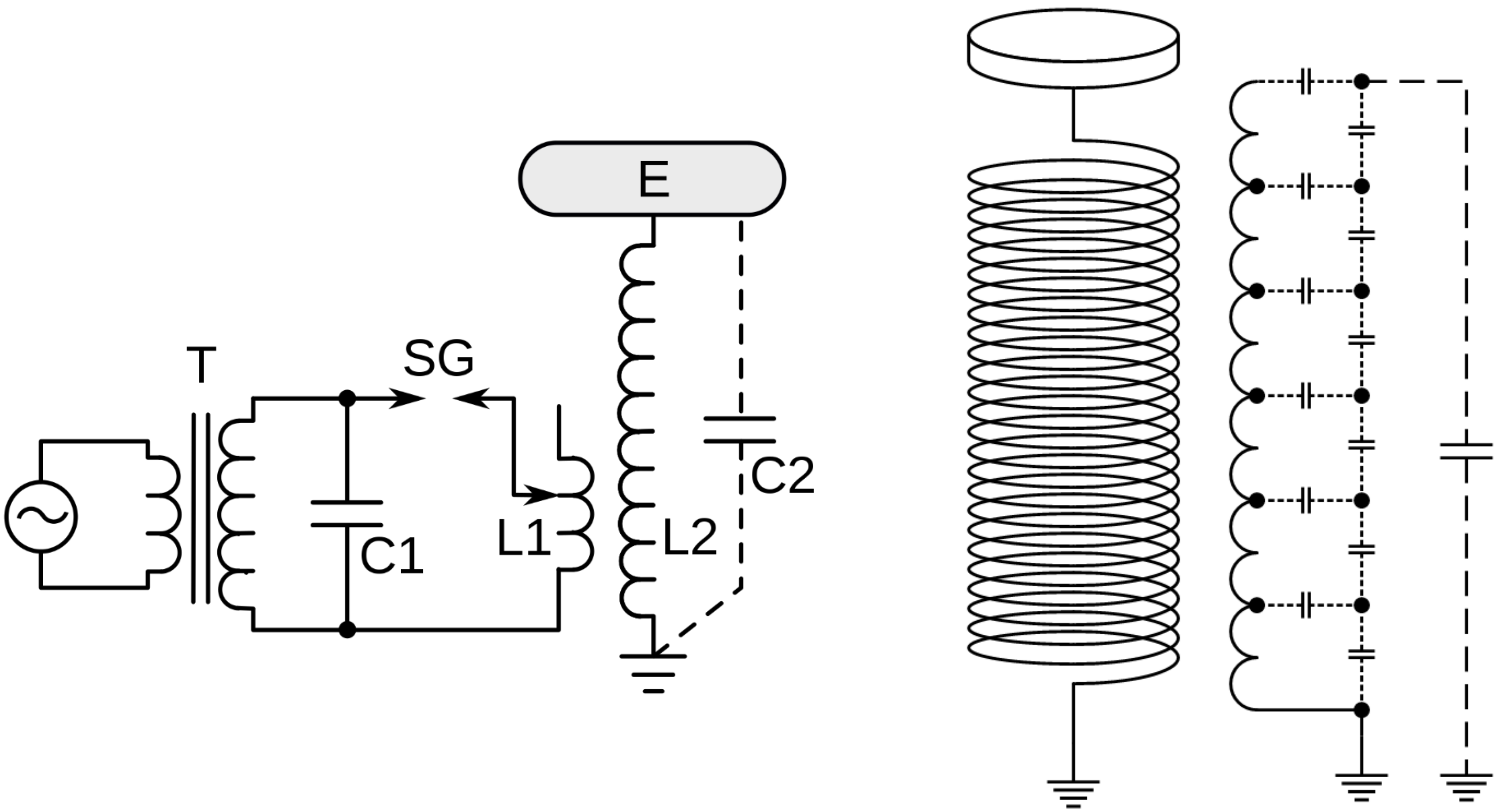
型式 / 特性	非傳輸型	傳輸型
電極結構	兩個電極皆在火炬本體上	一個電極在火炬本體上，另一電極在被處理物上(或爐底電極)
操作/安裝空間	較小	較大(尤其垂直高度)
氣流量	較大 (100%)	較小 (20%)
中心溫度(℃)	4,000～10,000	15,000～20,000
能量密度(MJ/kg)	5～40	20～200
功率控制參數	電流、氣流量	電流、氣流量、電弧長度
電能轉換熱能效率(%)	80～90	≧90
熔融機制	1.火焰直接加熱 2.電能使用效率較低(45%)	1.火焰直接加熱 2.熔漿電阻加熱 3.電能使用效率較高(60%)

https://www.atlas-innotek.com/projects/e6oFj63K47PYPqPe2
http://www.resi.com.tw/PlasmaTorch.htm

Tesla coil can generate high voltage

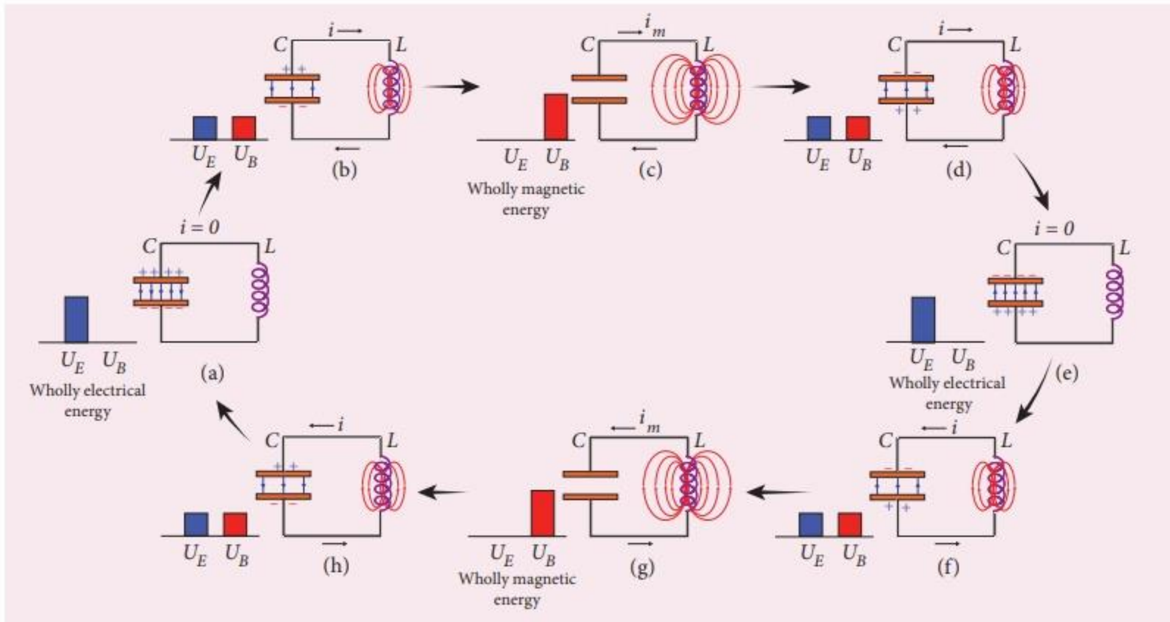


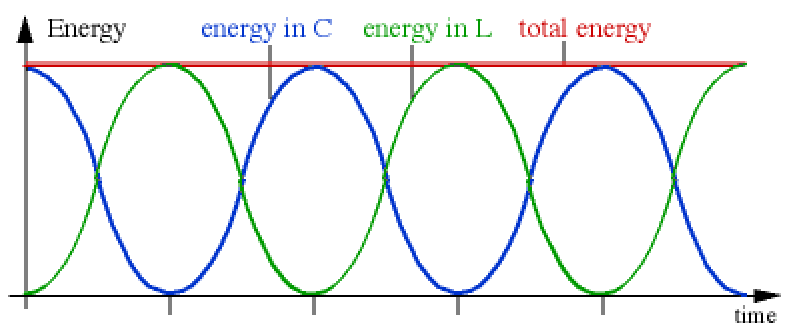
The high voltage is generated by two resonant LC circuits



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

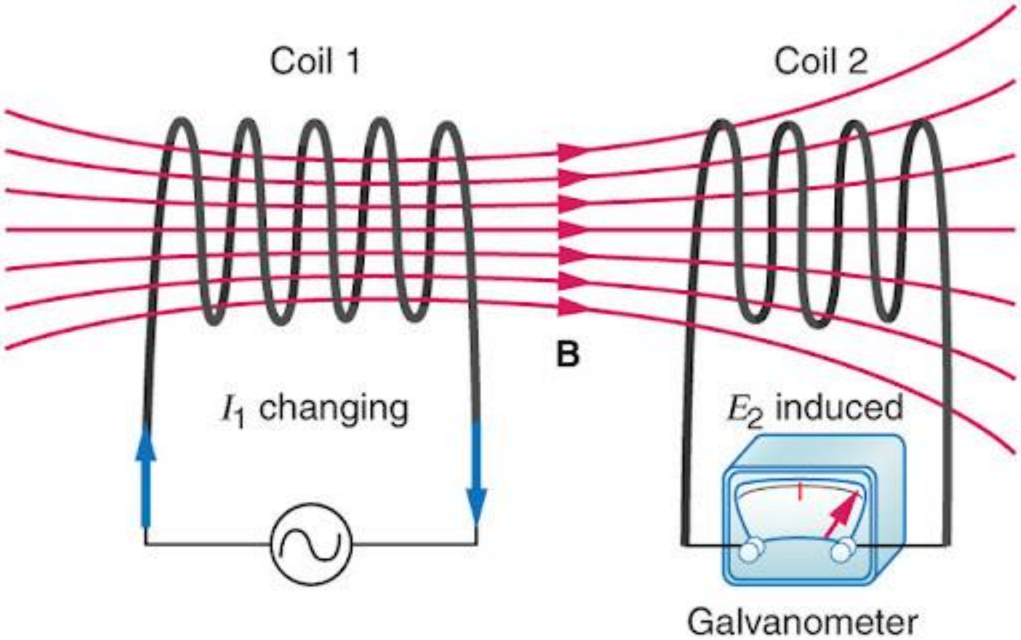
Energy is oscillating between the capacitor and the inductor

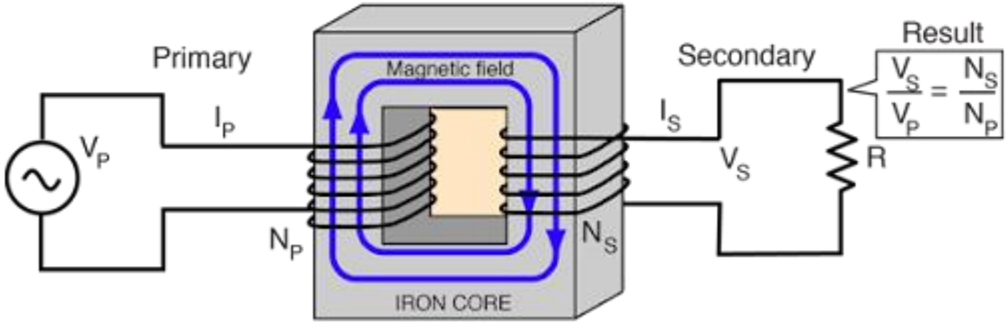




https://www.brainkart.com/article/Energy-conversion-during-LC-oscillations_38532/
http://ffden-2.phys.uaf.edu/webproj/211_fall_2016/Mark_Underwood/mark_underwood/Primary.html

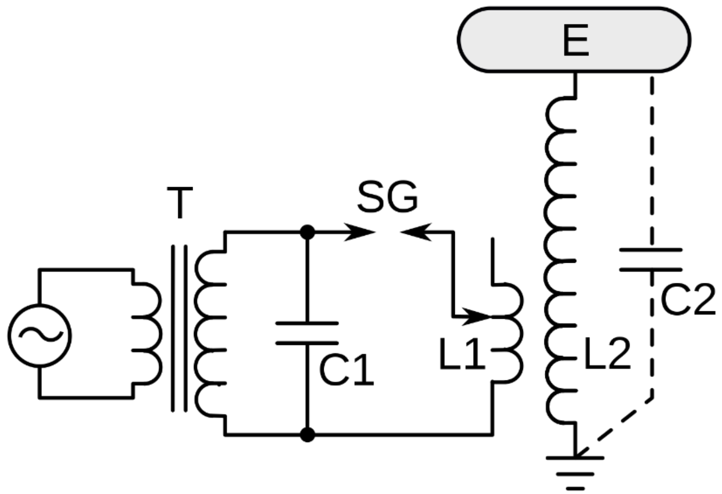
Voltage of two separated coils can be transferred by mutual inductance between two coils

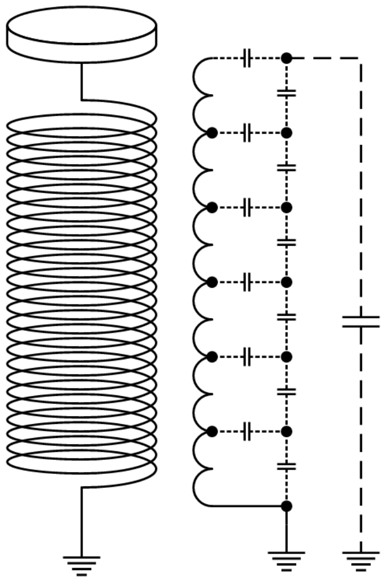


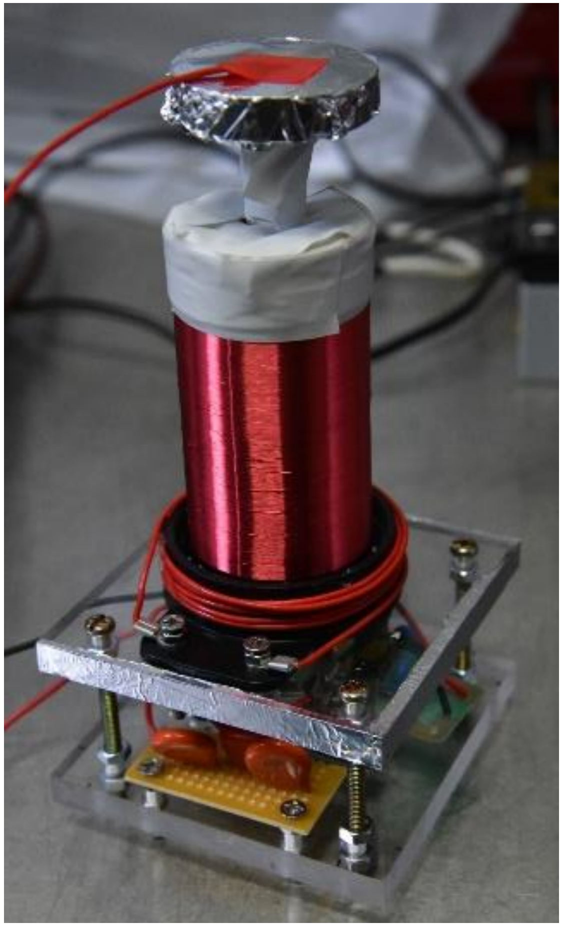


http://www.physics.louisville.edu/cldavis/phys299/notes/mag_mutualind.html
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/indmut.html

The high voltage is generated by two resonant LC circuits

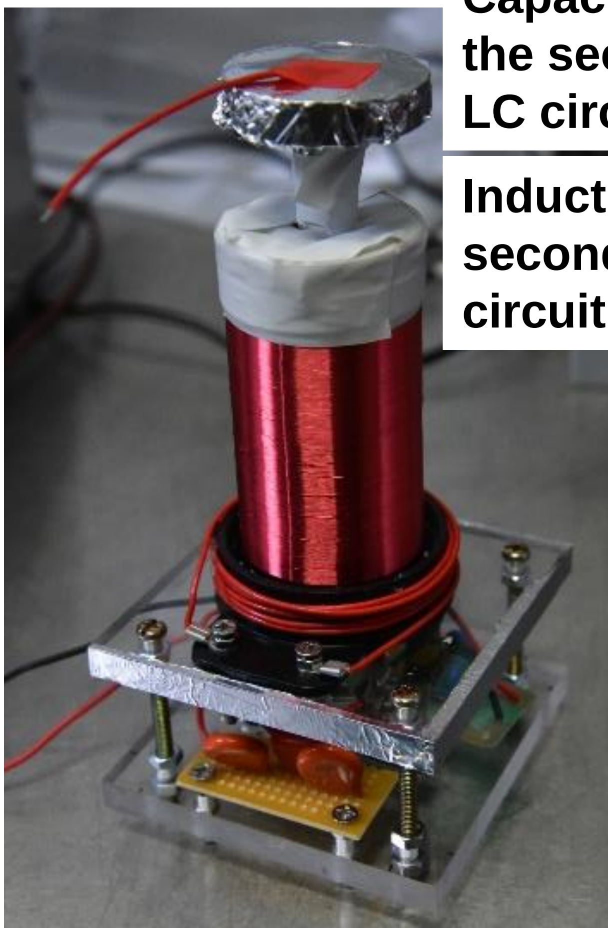






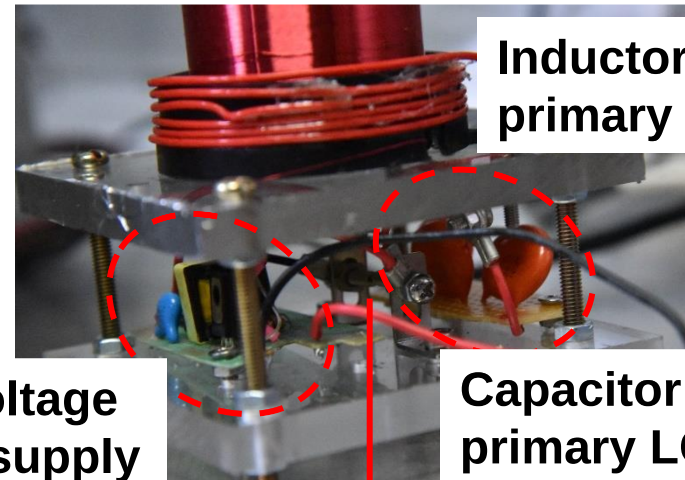
https://en.wikipedia.org/wiki/Tesla_coil

Components of the tesla coil



Capacitor of the secondary LC circuit

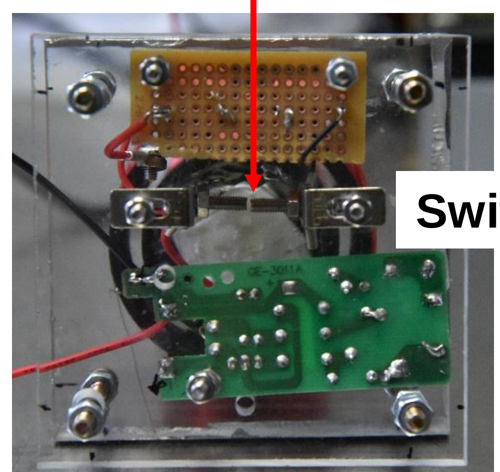
Inductor of the secondary LC circuit



Inductor of the primary LC circuit

High voltage power supply

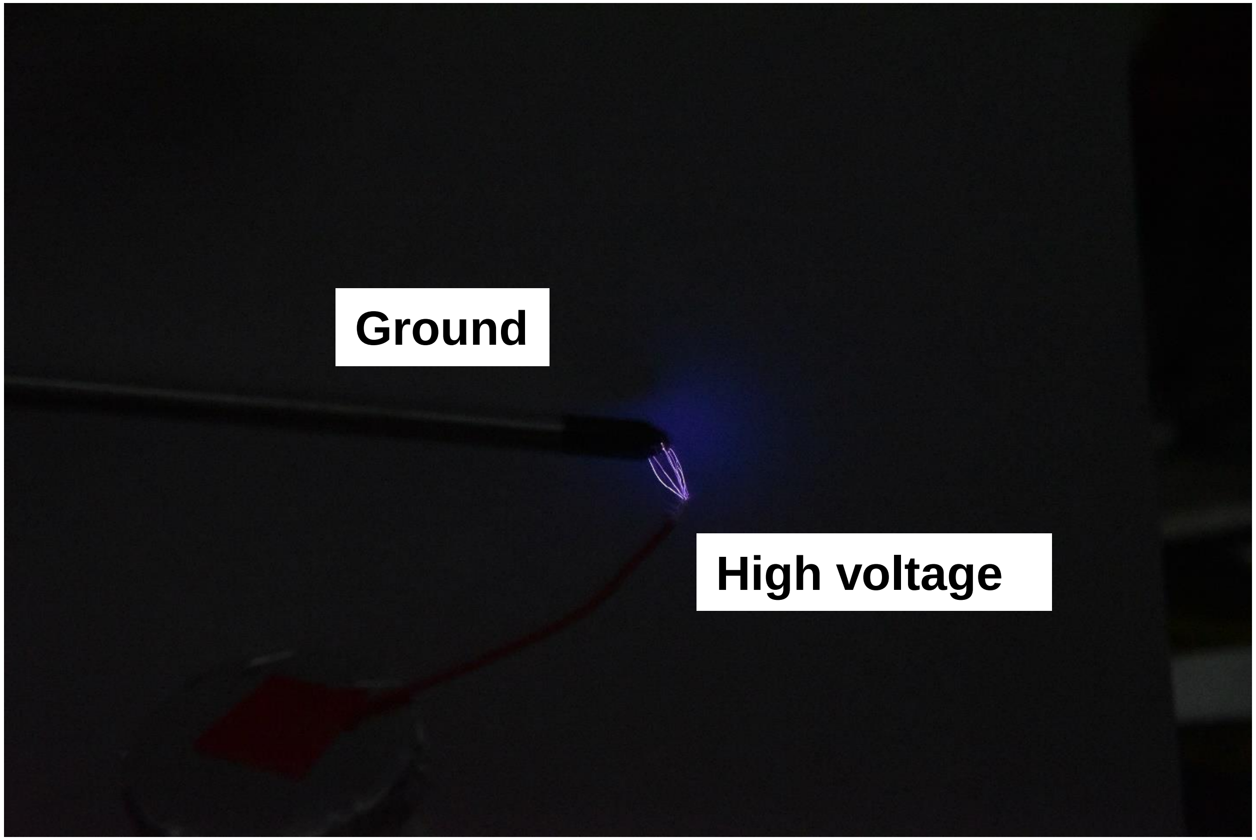
Capacitor of the primary LC circuit



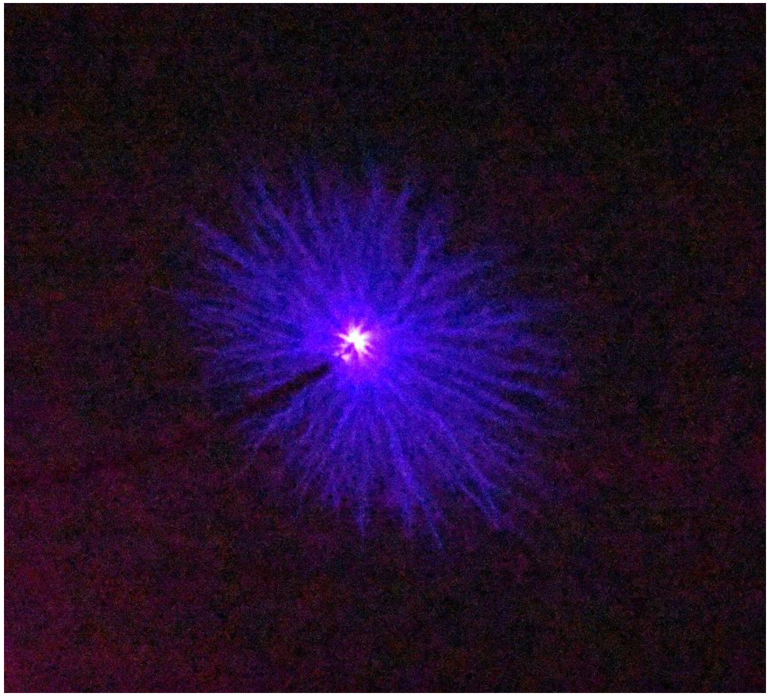
Switch

Show video.

Arc discharge occur between the high voltage and a grounded electrode



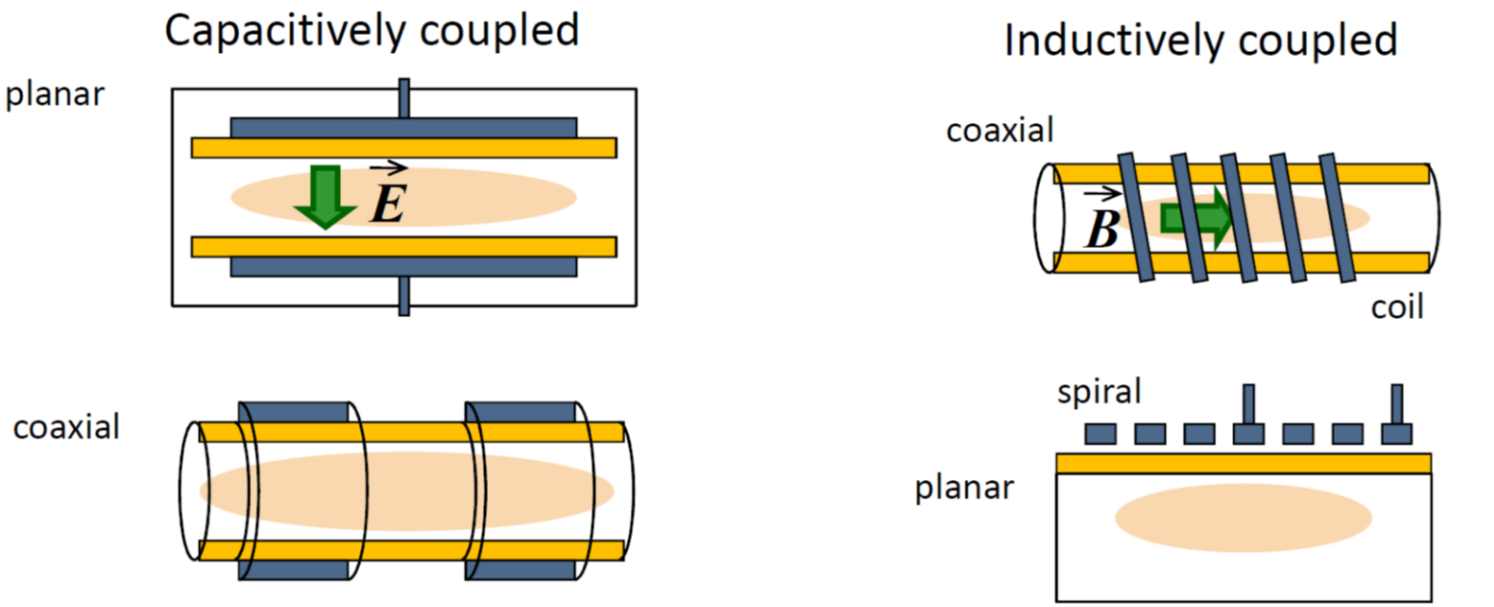
Corona discharge occurs when the electric field drops below a certain value



Methods of plasma production

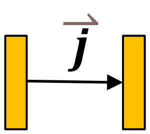
- DC electrical discharges
  - Dark electrical discharges in gases
  - DC electrical glow discharges in gases
  - DC electrical arc discharges in gases
- **AC electrical discharges**
  - **RF electrical discharges in gases**
  - **Microwave electrical discharges in gases**
  - **Dielectric-barrier discharges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

RF can interact with plasma inductively or capacitively



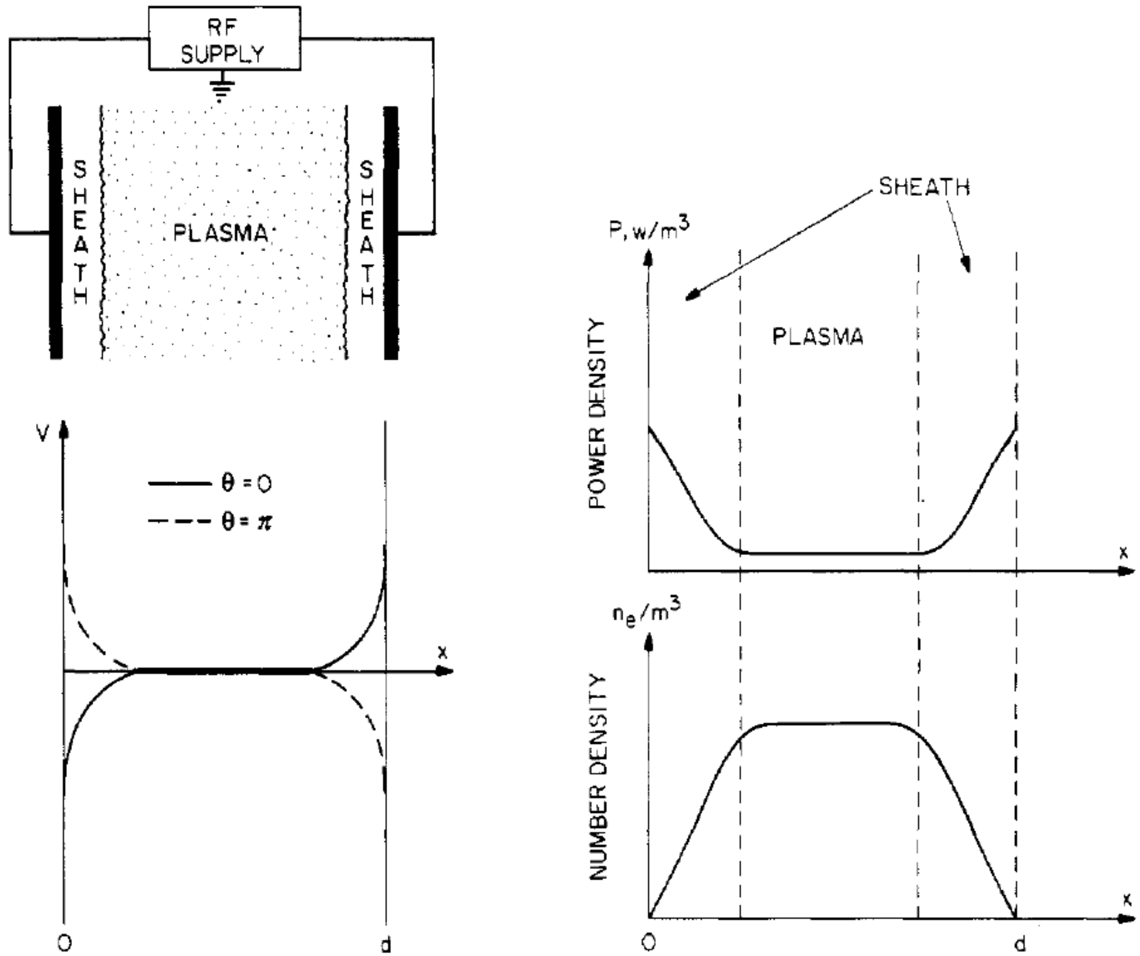
- **DC electrical discharge – a true current in the form of a flow of ions or electrons to the electrodes.**
- **AC electrical discharge – the power supply interacts with the plasma by displacement current.**

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

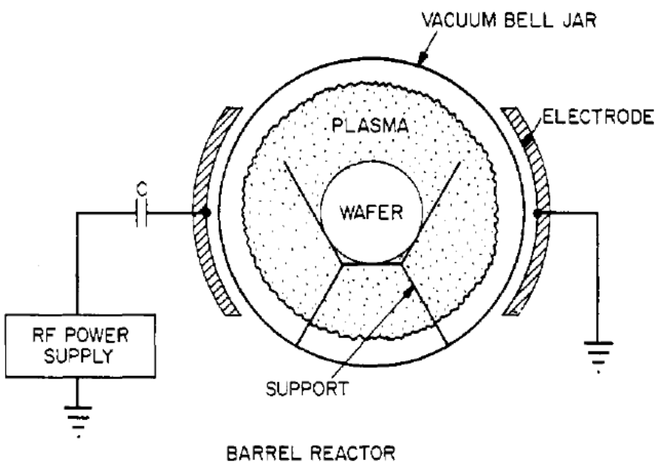


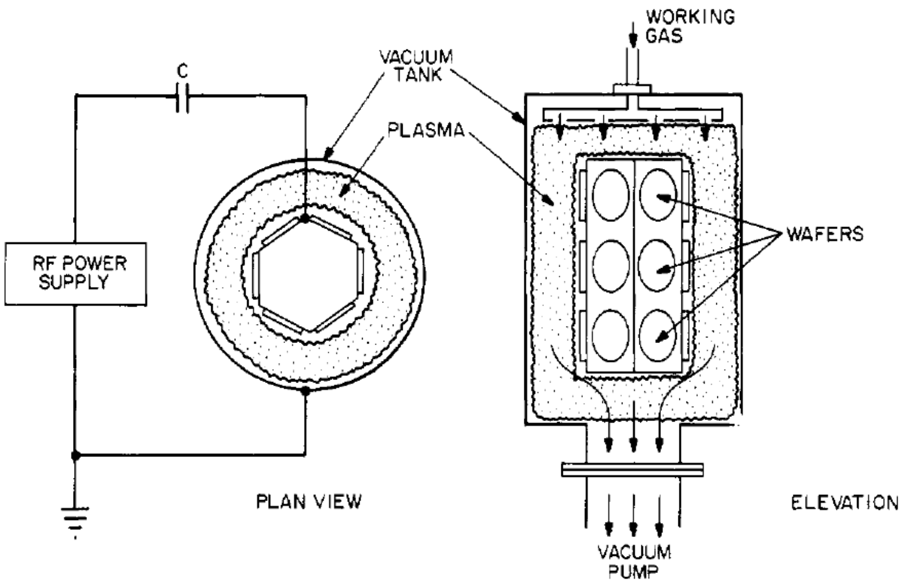
$$\left(\frac{\partial \vec{E}}{\partial t}, \frac{\partial \vec{B}}{\partial t}\right)$$

Symmetrical capacitive RF discharge model



Example of capacitively coupled RF plasma source 1

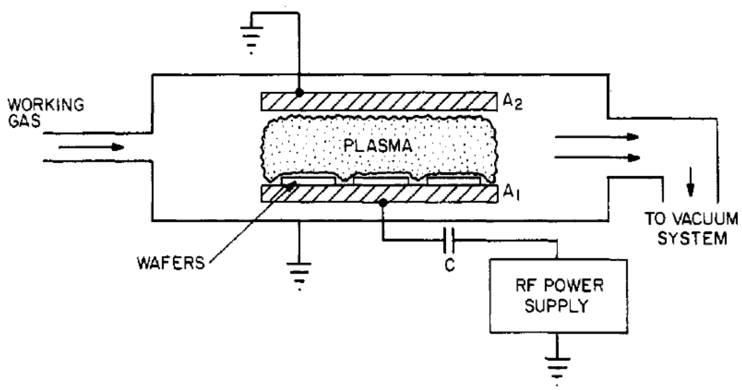




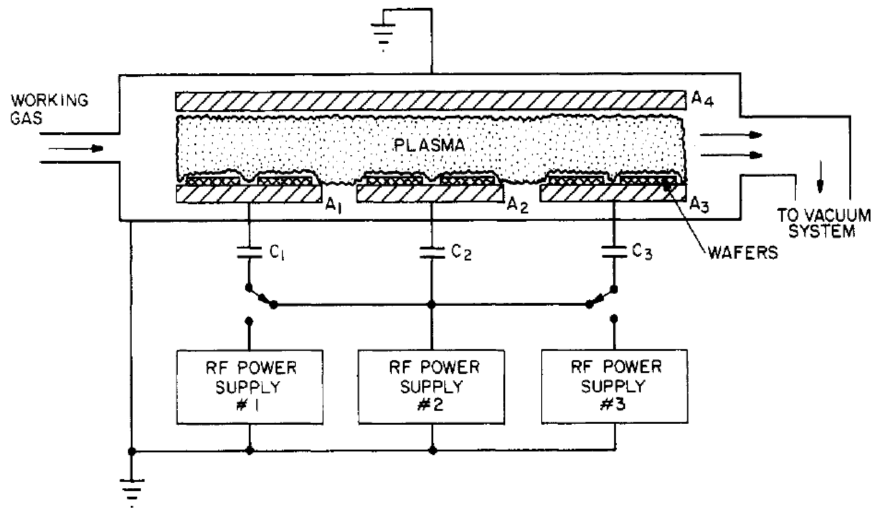
- **Barrier reactor – the wafers float electrically and have low ion bombardment energies**
- **Hexagonal reactor – the wafers develop a DC bias which leads to a relatively anisotropic, vertical etch.**

Example of capacitively coupled RF plasma source 2

- **Plane parallel reactor**



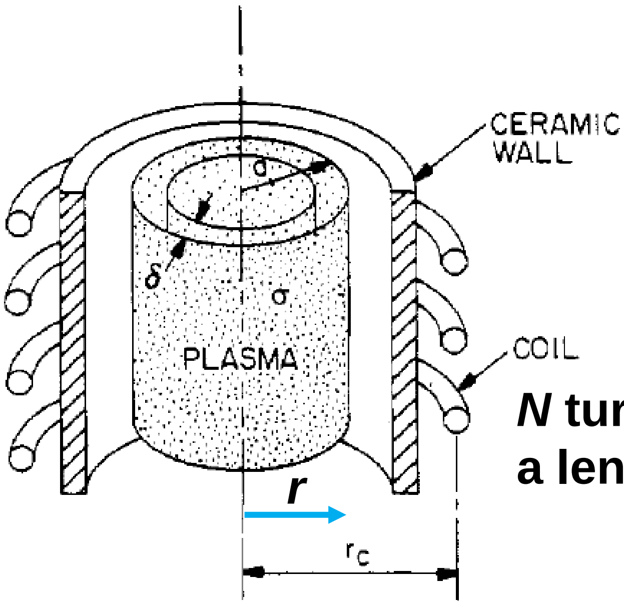
- **Multiple electrode system**



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	$\approx$ 200 W	500 W
rms electrode voltage	100 V	$\approx$ 300 V	1000 V
Current density	0.1 mA/cm^2	$\approx$ 3 mA/cm^2	10 mA/cm^2
Electron temperature, T_e	3 eV	$\approx$ 5 eV	8 eV
Electron density, n_e	$10^{15}/\text{m}^3$	$\approx 5 \times 10^{15}/\text{m}^3$	$3 \times 10^{17}/\text{m}^3$
Ion energy, $\mathcal{E}_i$	5 eV	50 eV	500 eV
Electrode separation, d	0.5 cm	4 cm	30 cm

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



N turn within a length of *l*

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

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

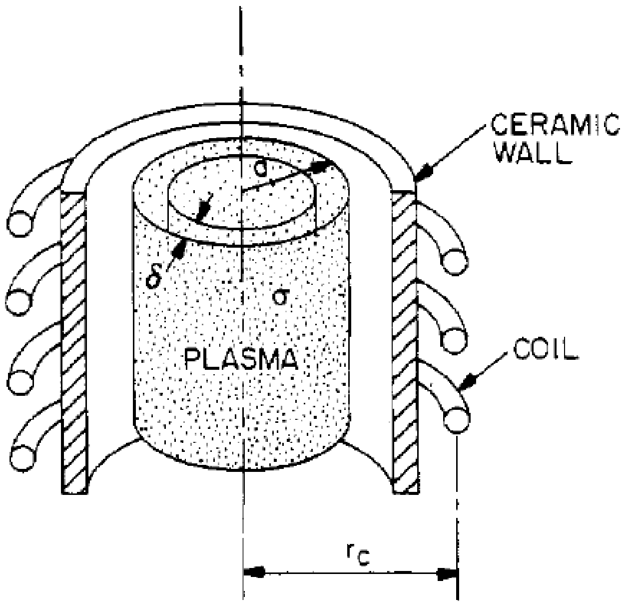
$$2\pi r E = -\pi r^2 \frac{\partial B}{\partial t}$$

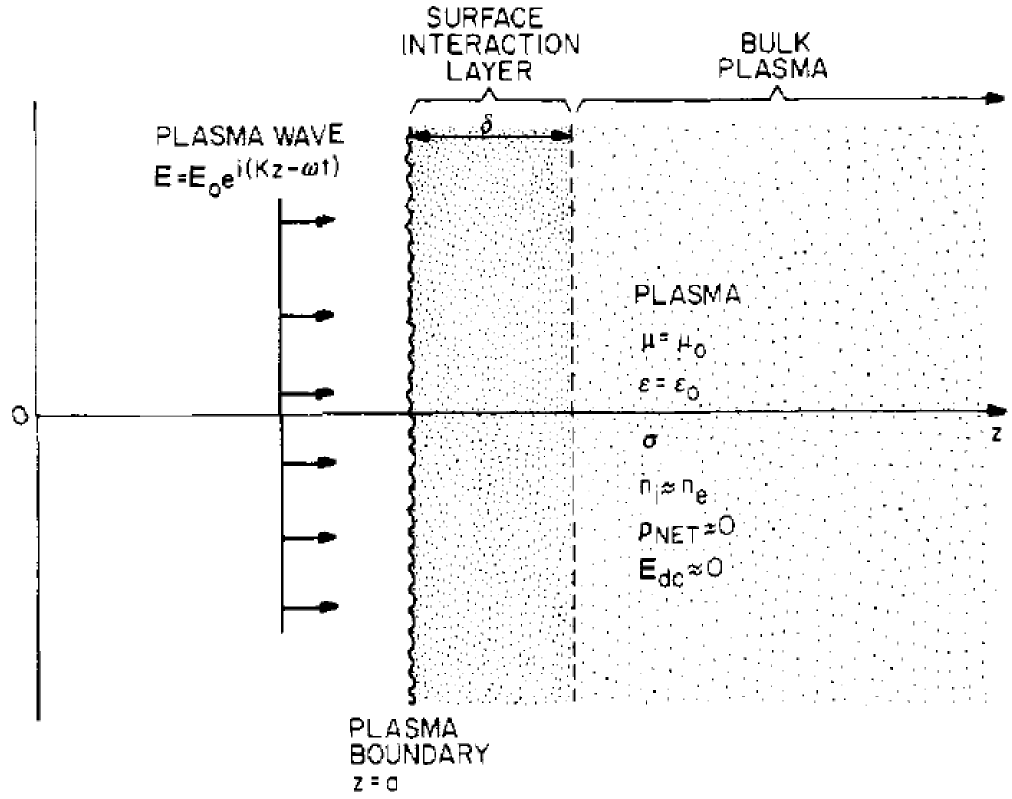
$$E = -\frac{r}{2}\frac{\partial B}{\partial t} \qquad B \times l = \mu_o N I$$

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

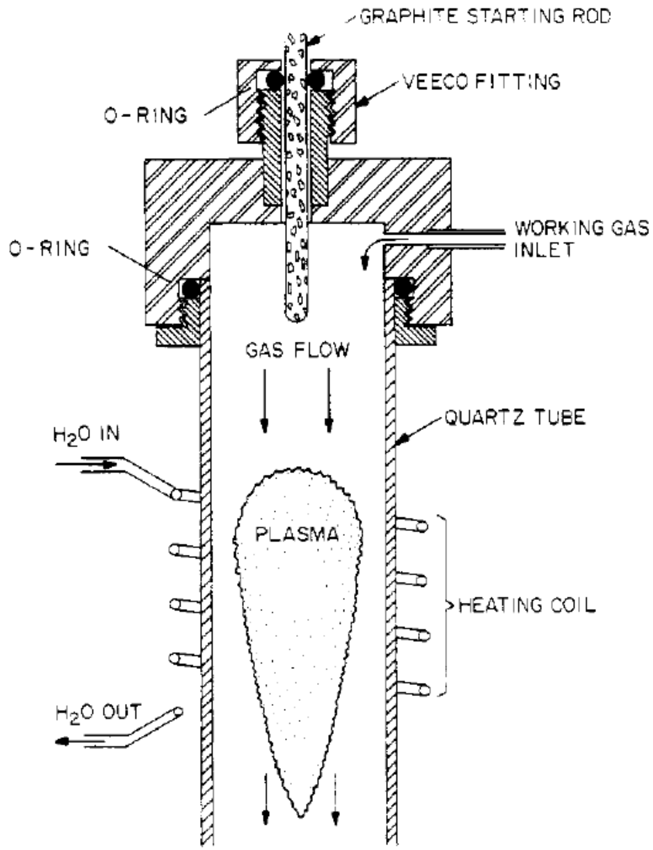
$$|E| = \frac{r}{2}\mu_o \frac{N}{l}\omega I$$

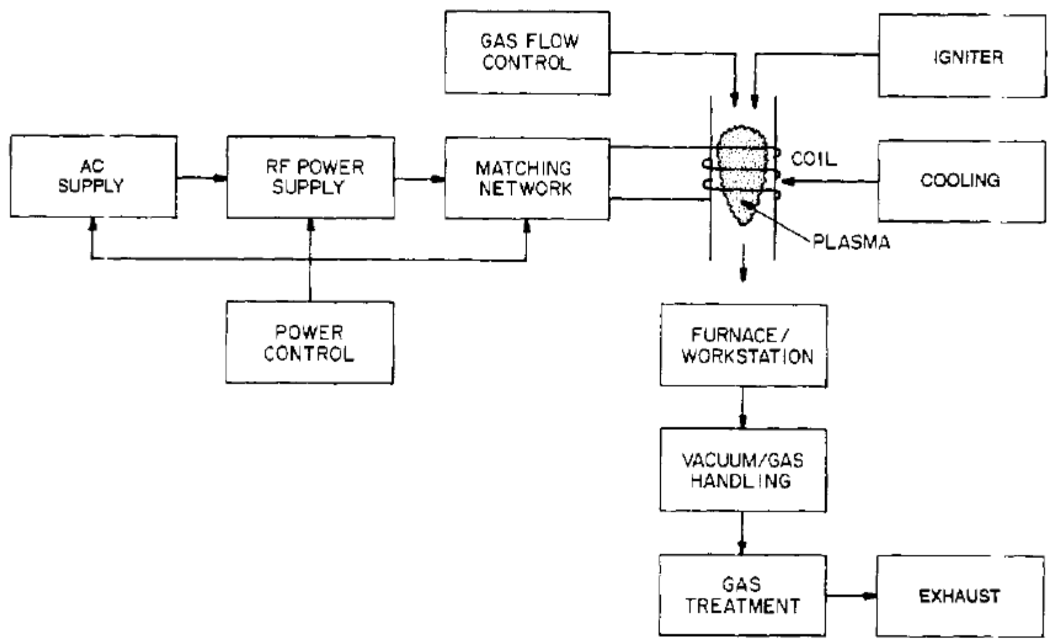
RF energy is strongly absorbed within the skin depth if the frequency is below the electron plasma frequency



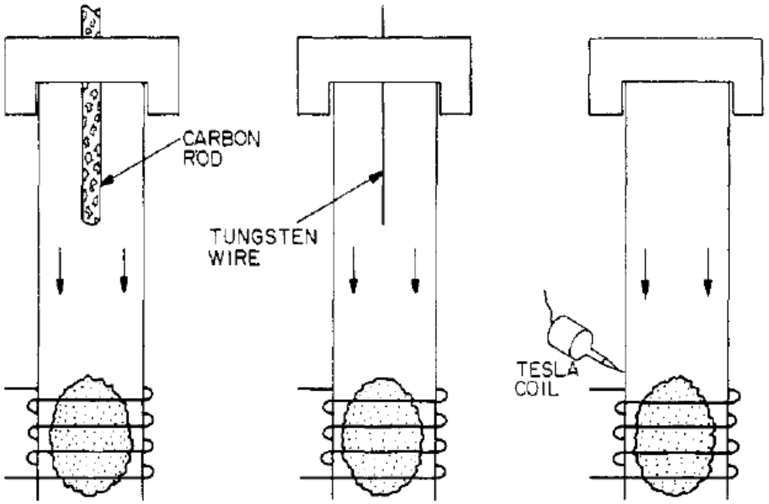


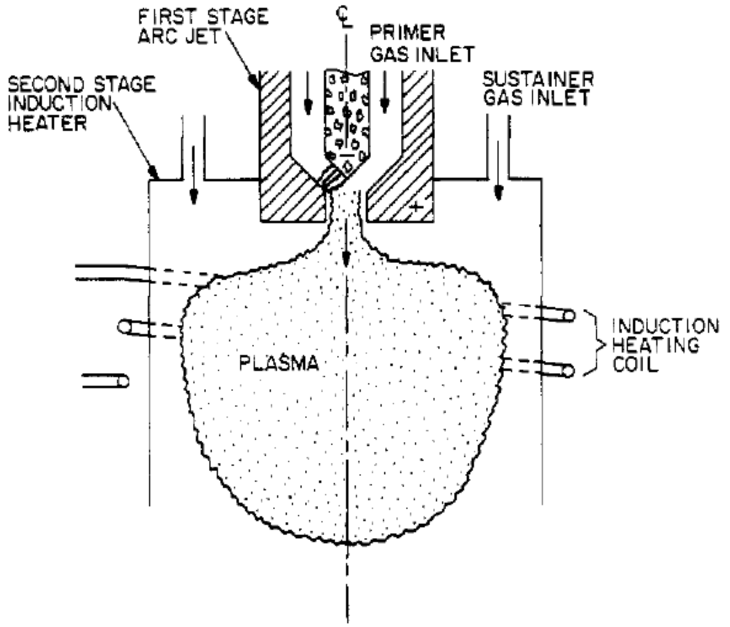
A kilowatt-level inductively coupled plasma torch is shown



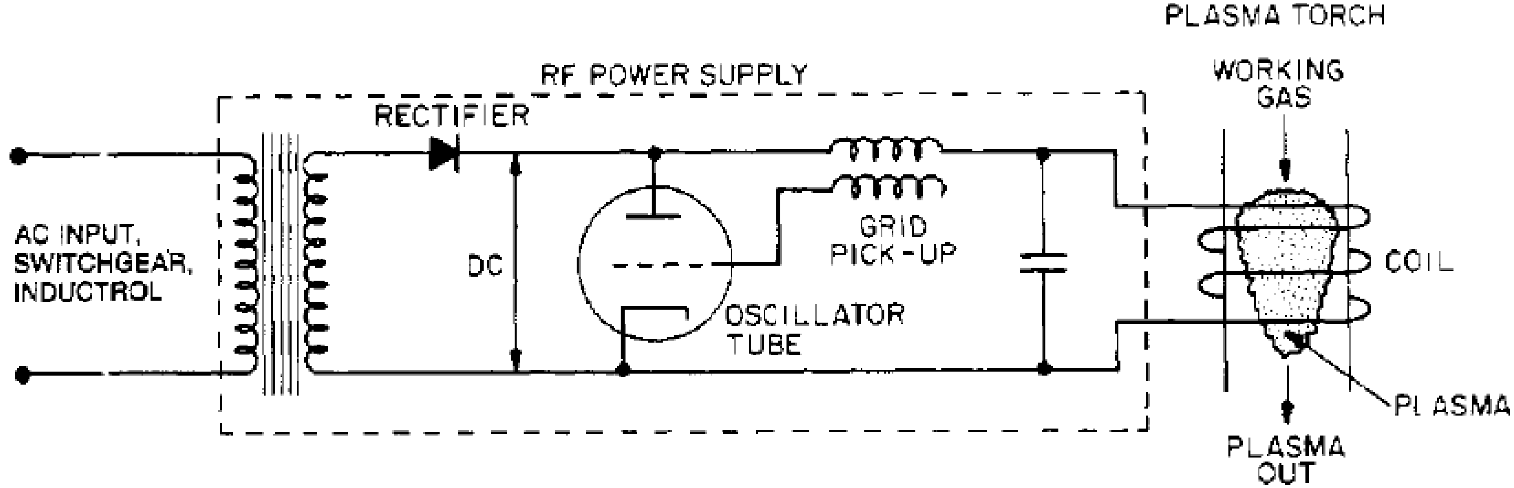


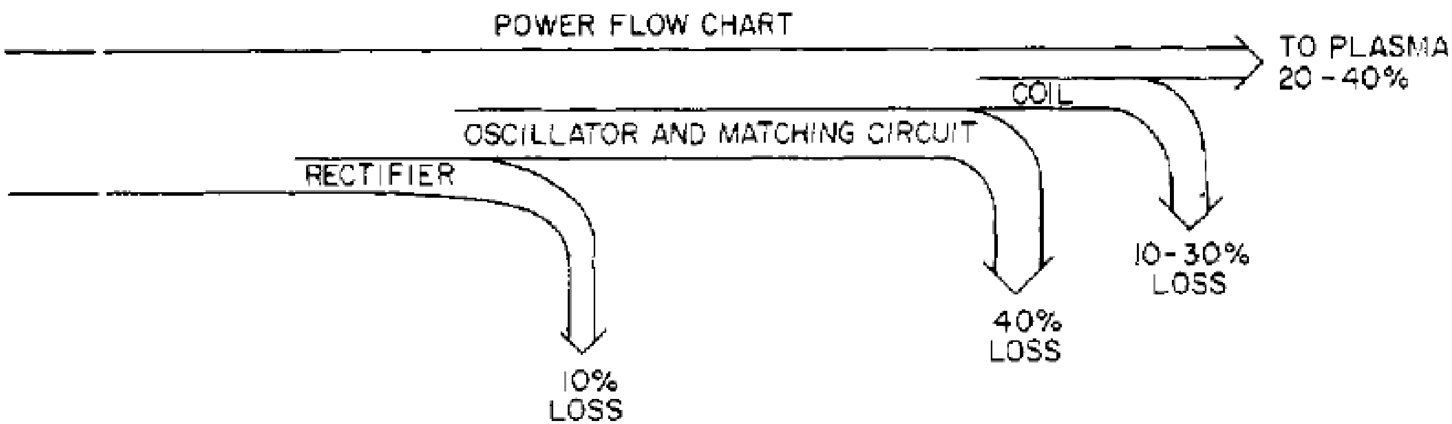
High voltage initiation is usually required for inductive RF plasma torches





The power supplies are relatively inefficient

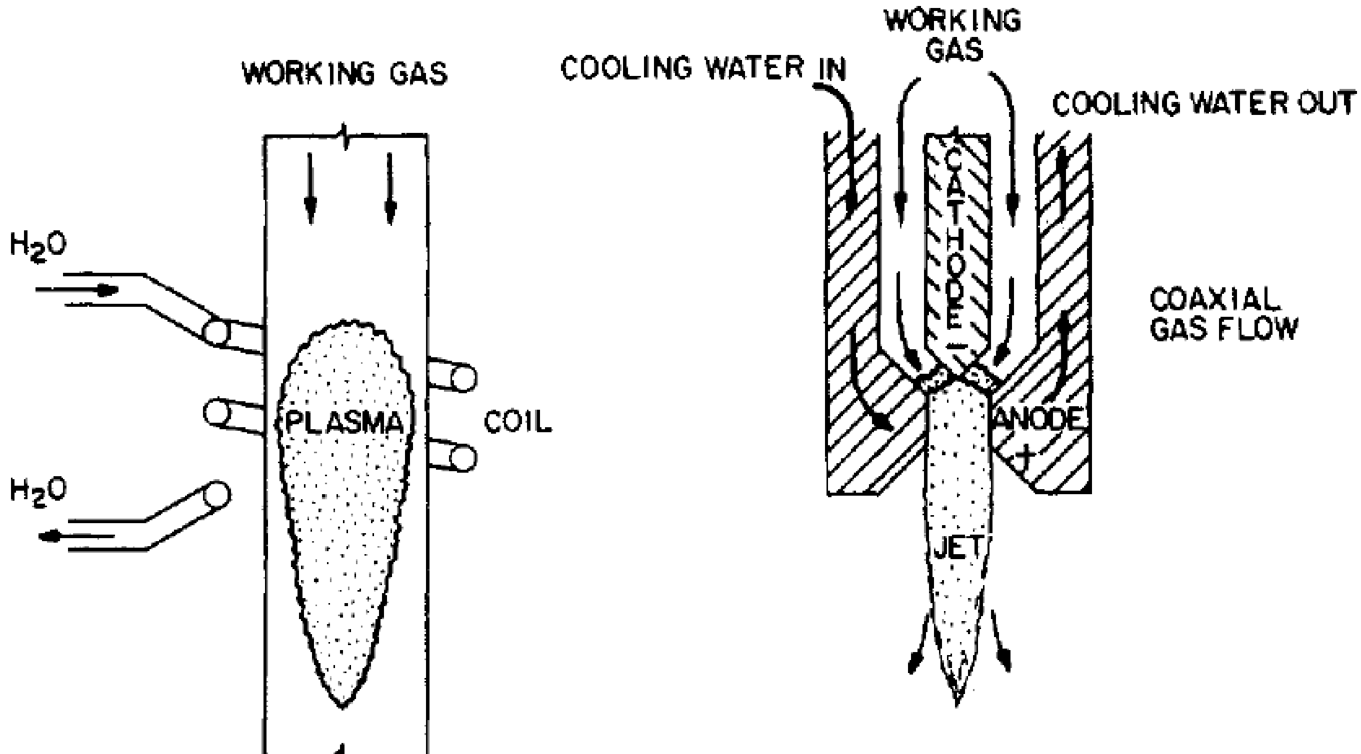




Operating regimes of inductively coupled plasma torches

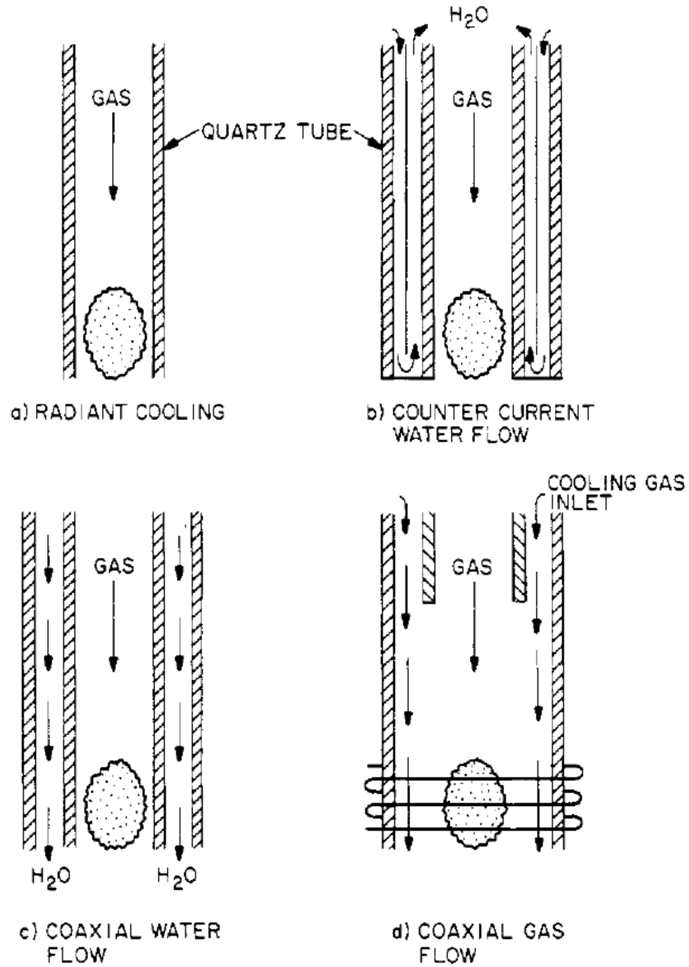
Parameter	Low	Characteristic	High
Frequency	10 kHz	13.56 MHz	100 MHz
Power	1 kW	30 kW	1MW
Efficiency	20%	35%	50%
Pressure	10 Torr	1 atm	10 atm
Gas temperature	1000 K	10^4 K	2×10^4 K

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

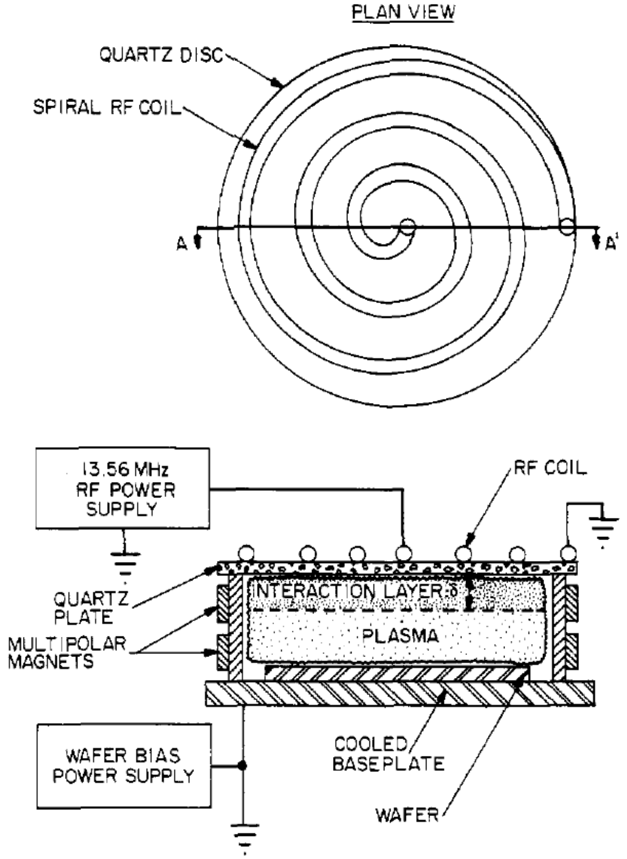


INDUCTIVE PLASMA TORCH		ARC JET
10 – 200 m/sec	JET VELOCITY	500–150 m/sec
4–40 mm	JET DIAMETER	6–10 mm
VARIABLE	JET SHAPE	CYLINDRICAL

Several cooling configurations are shown

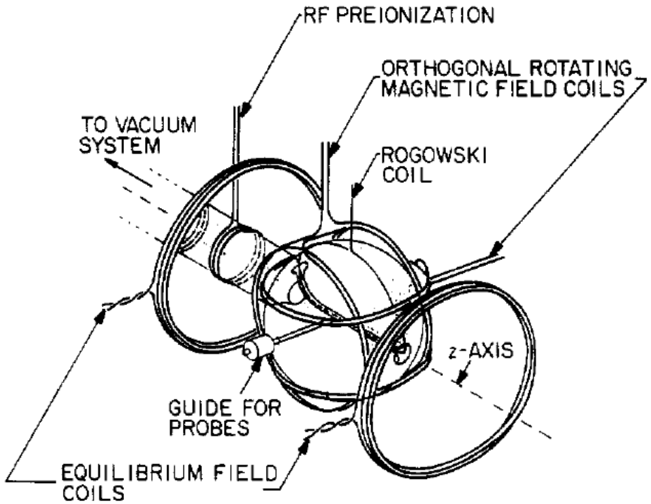


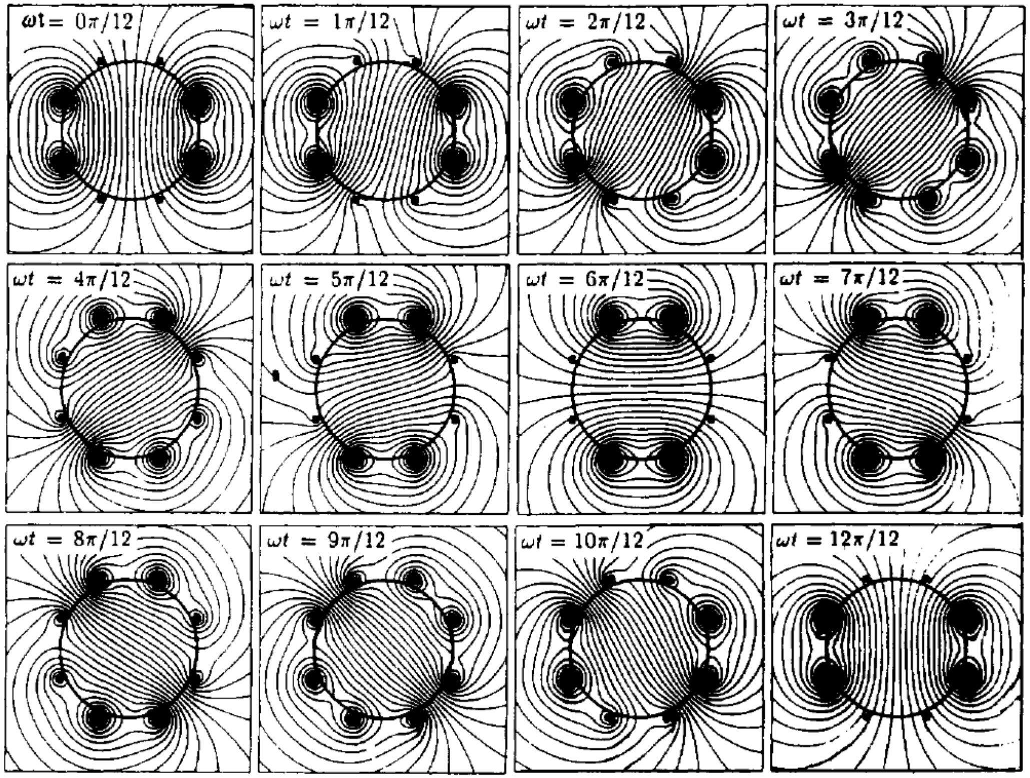
Inductive parallel plate reactor



- **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.**

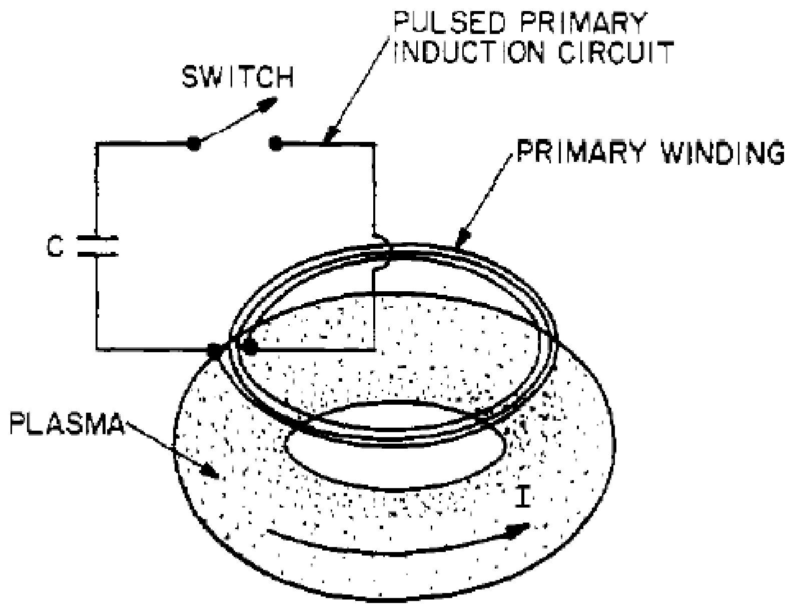
Rotamak

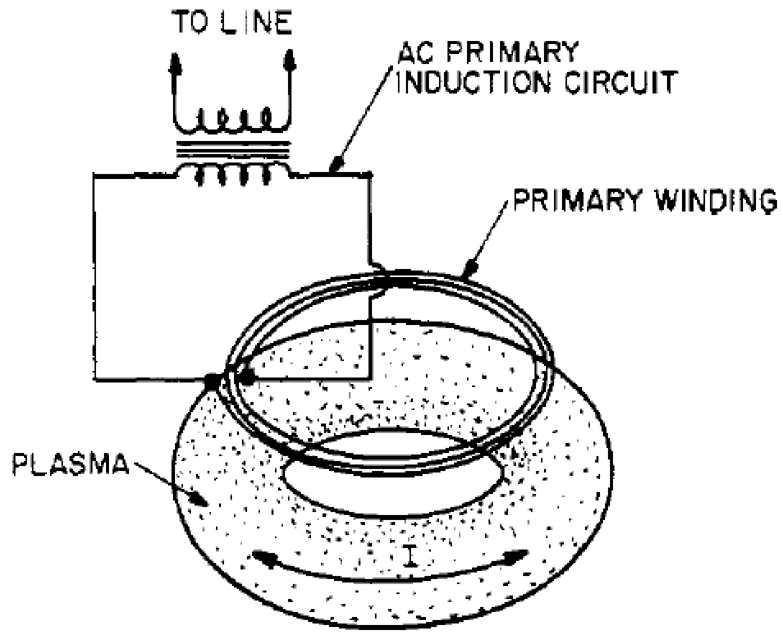




- **The rapidly rotating magnetic field generates large plasma currents, thus heating the plasma to densities and temperatures of interest in many industrial applications**

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**

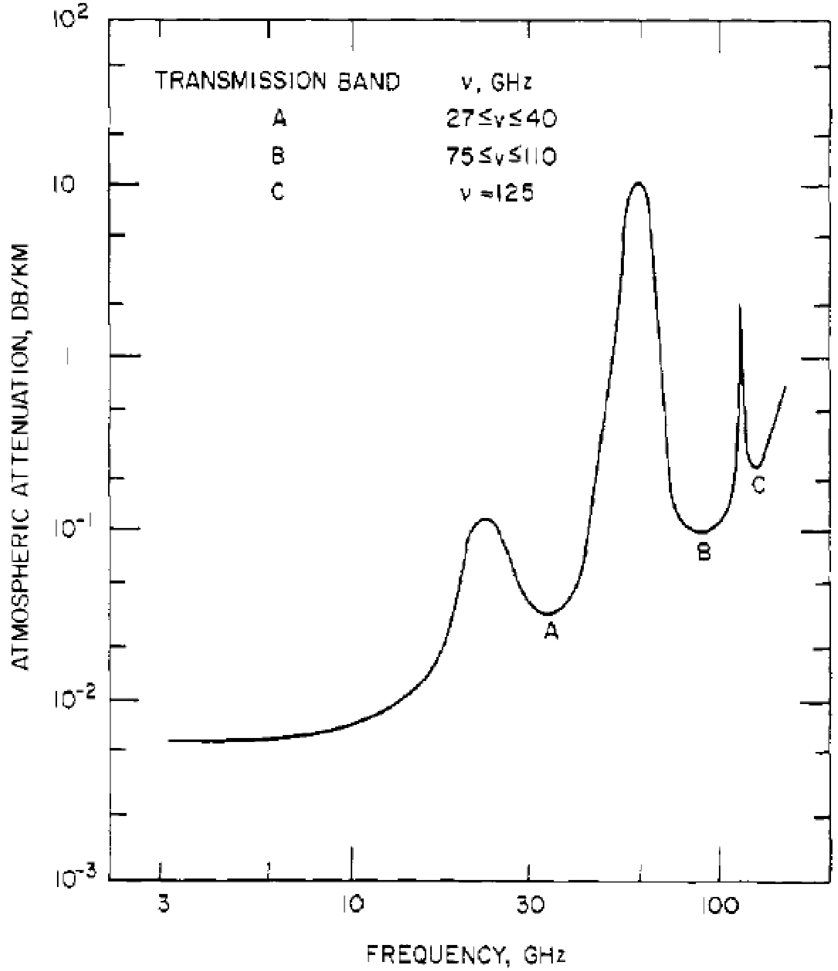
Applications of inductive plasma torches

- 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

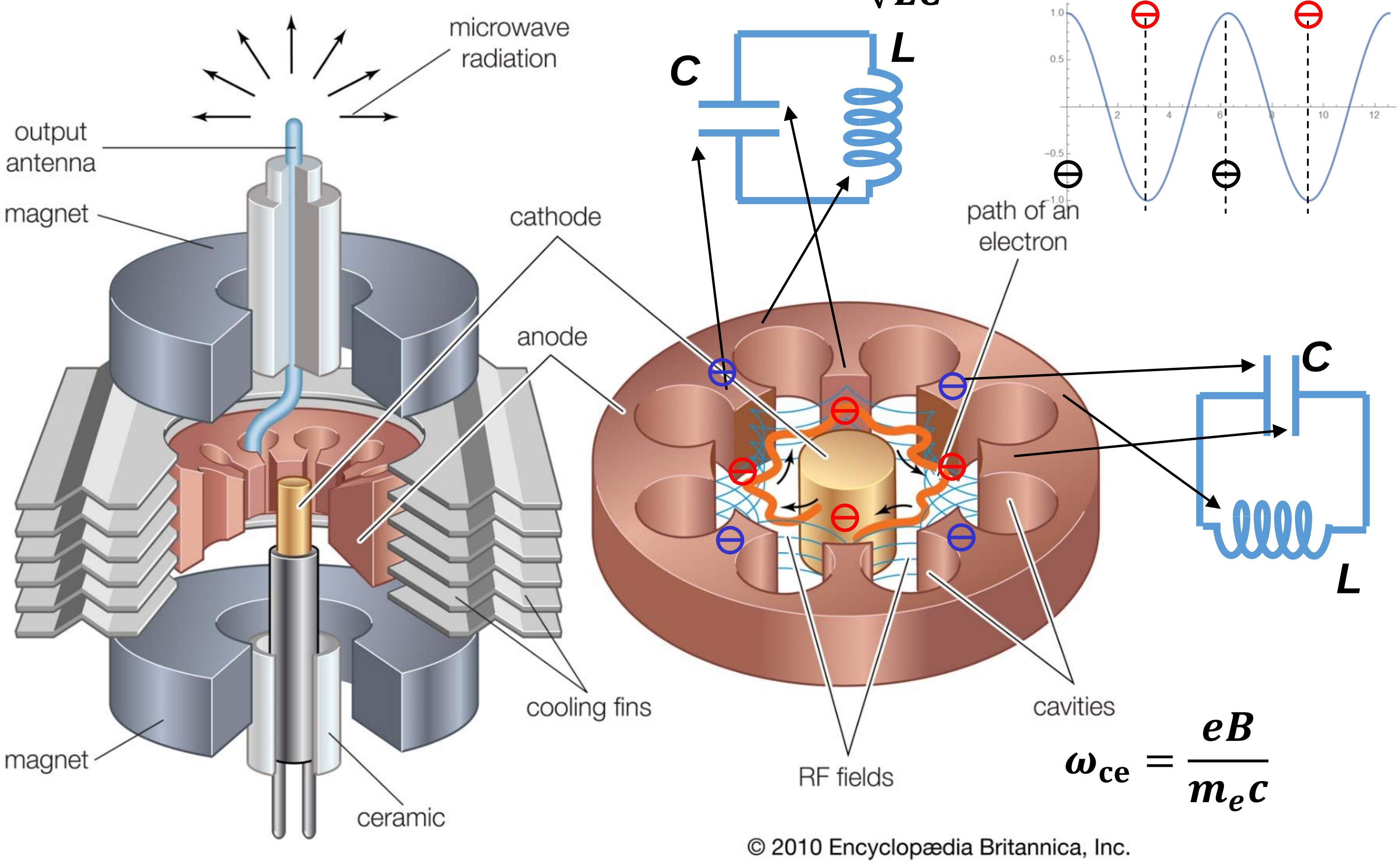
- The wavelength of the microwave is in centimeters range. In contract, the wavelength is 22 m for RF frequency f = 13.6 MHz.
- The electron number density can approach the critical number density. (7×10^{16} m^{-3}) at a frequency of 2.45 GHz.
- The plasma in microwave discharges is quasi-optical to 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

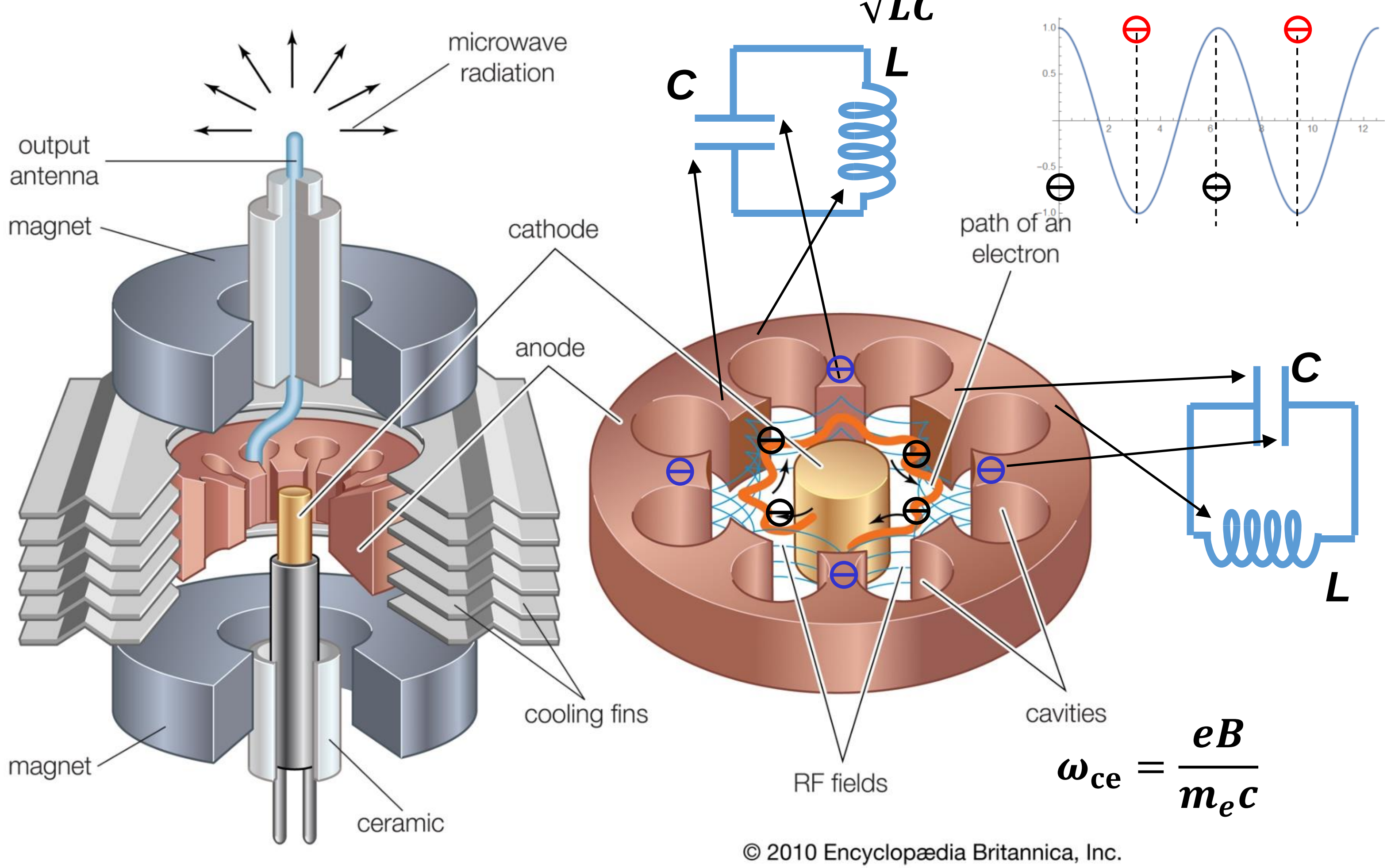
$$\omega_{\mathrm{LC}} = \frac{1}{\sqrt{LC}} \equiv 4\omega_{\mathrm{ce}}$$



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

Internal of a magnetron

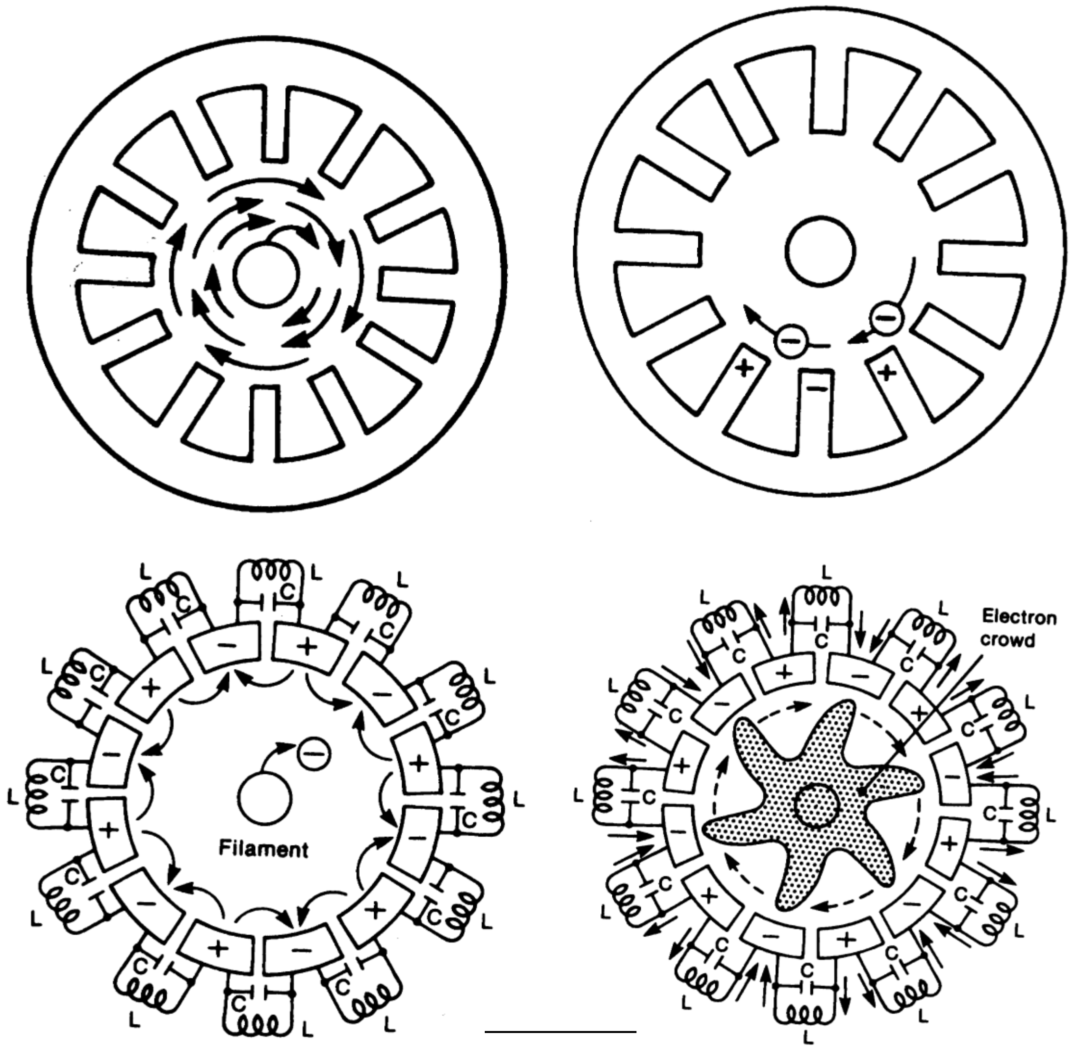
$$\omega_{\mathrm{LC}} = \frac{1}{\sqrt{LC}} \equiv 4\omega_{\mathrm{ce}}$$



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

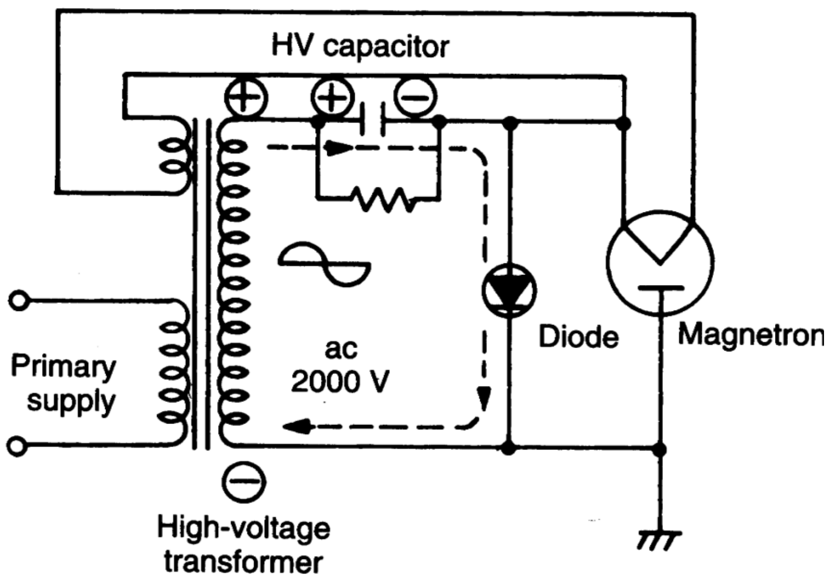
https://kids.britannica.com/students/article/electron-tube/106024/media?assemblyId=137

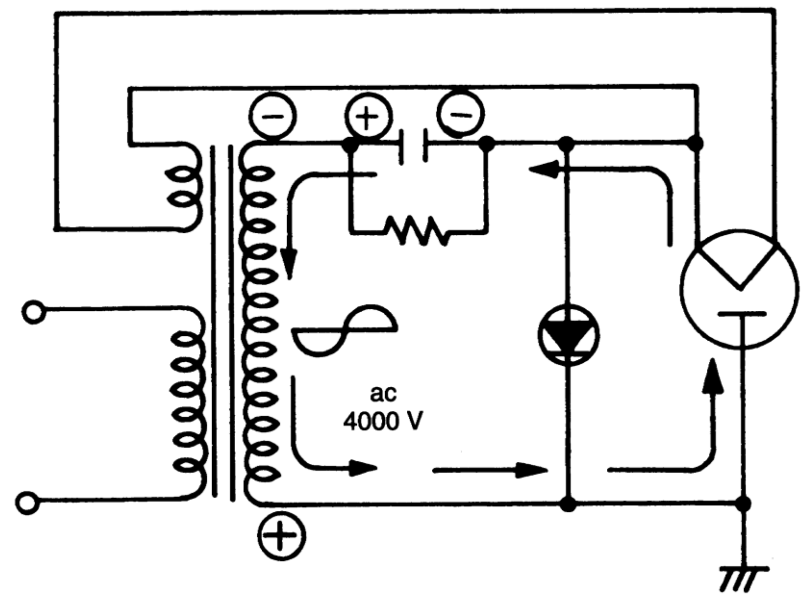
Resonance in a magnetron



http://cdn.preterhuman.net/texts/government_information/intelligence_and_espionage/homebrew.military.and.espionage.electronics/servv89pn0aj.sn.sourcedns.com/_gbpprorg/mil/herf1/index.html

Magnetron schematic diagram

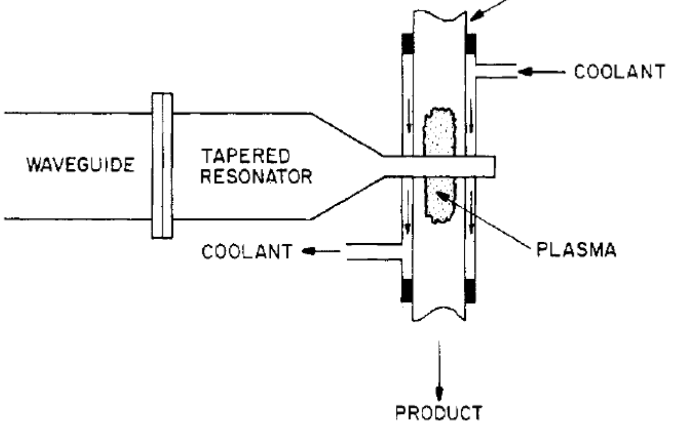




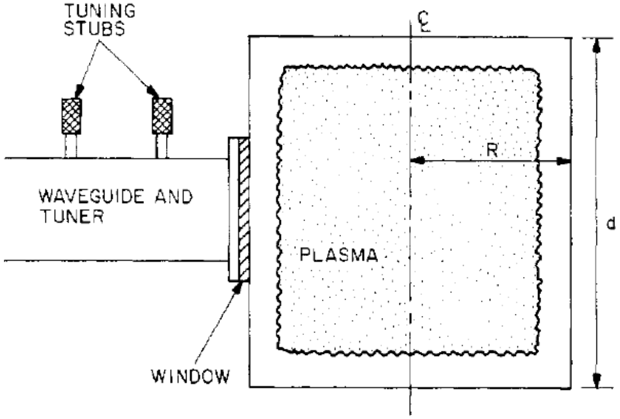
http://cdn.preterhuman.net/texts/government_information/intelligence_and_espionage/homebrew.military.and.espionage.electronics/servv89pn0aj.sn.sourcedns.com/_gbpprorg/mil/herf1/index.html

Microwave plasma reactor configurations

- **Waveguide coupled reactor**

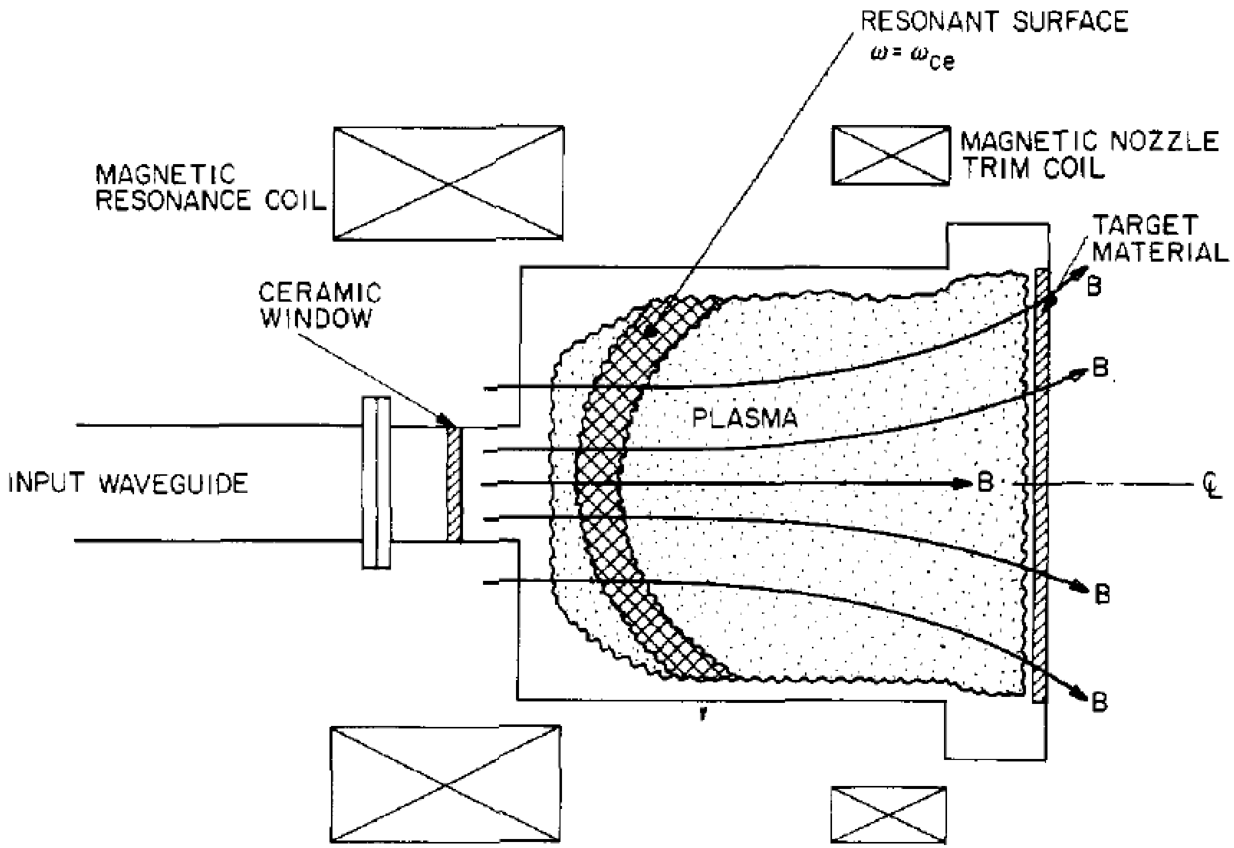


- **Resonant or multimode cavity – if the impedance matching is good, more energy can be fed into the cavity.**



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

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

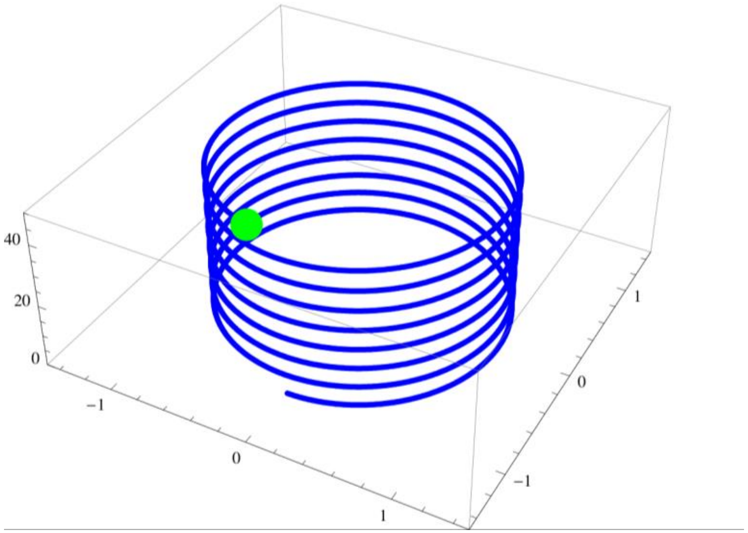
- Assuming $\vec{B} = B\hat{z}$ and the electron oscillates in x-y plane

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

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

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

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



- Therefore

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

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

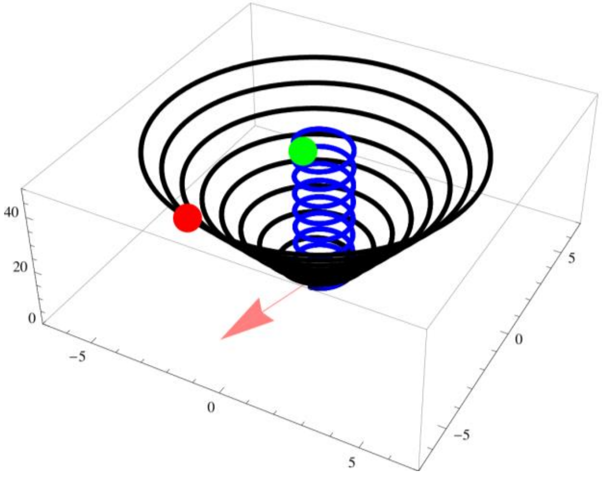
$$m_e \frac{d\vec{v}}{dt} = -\frac{e}{c}\vec{v}\times\vec{B} - e\vec{E} \qquad \vec{B} = B_0\hat{z} \qquad \vec{E} = E_0[\hat{x}\cos(\omega t) + \hat{y}\sin(\omega t)]$$

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

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

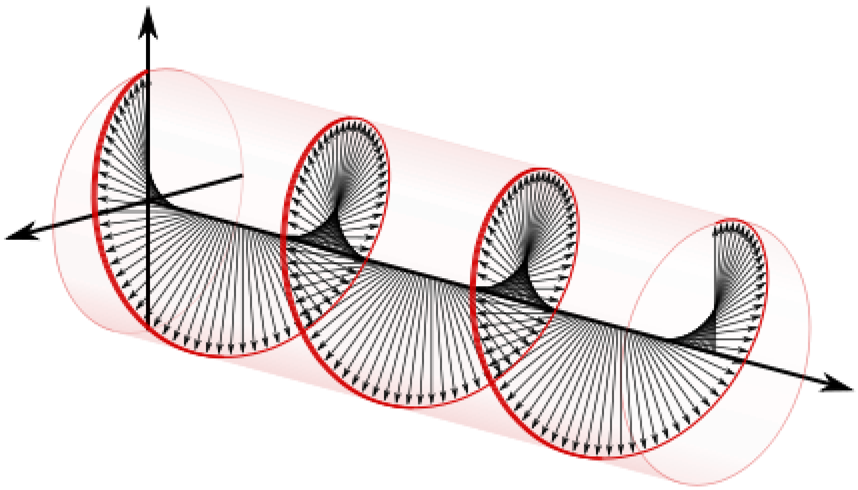
$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x + \frac{E_0}{m_e}\omega\sin(\omega t) = -\omega_{ce}{}^2 v_y + \frac{E_0}{m_e}(\omega_{ce}+\omega)\sin(\omega t)$$

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

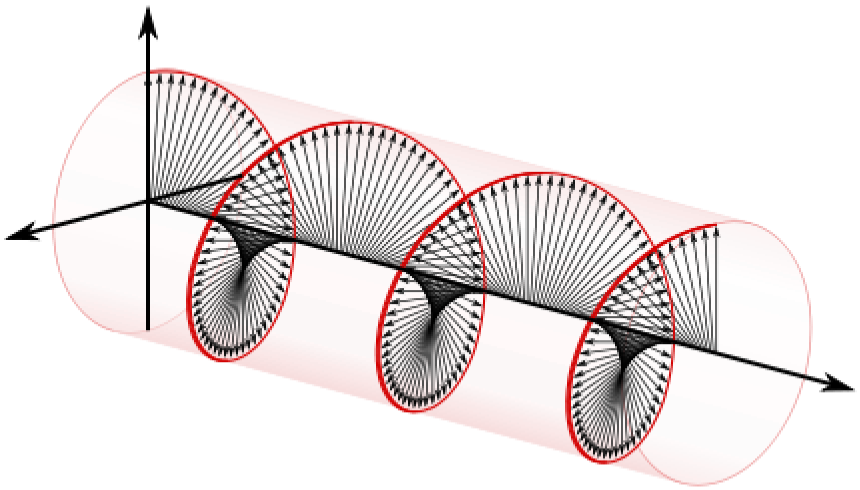


Electric field in a circular polarized electromagnetic wave keeps rotating as the wave propagates

- **Right-handed polarization**



- **Left-handed polarization**



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

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

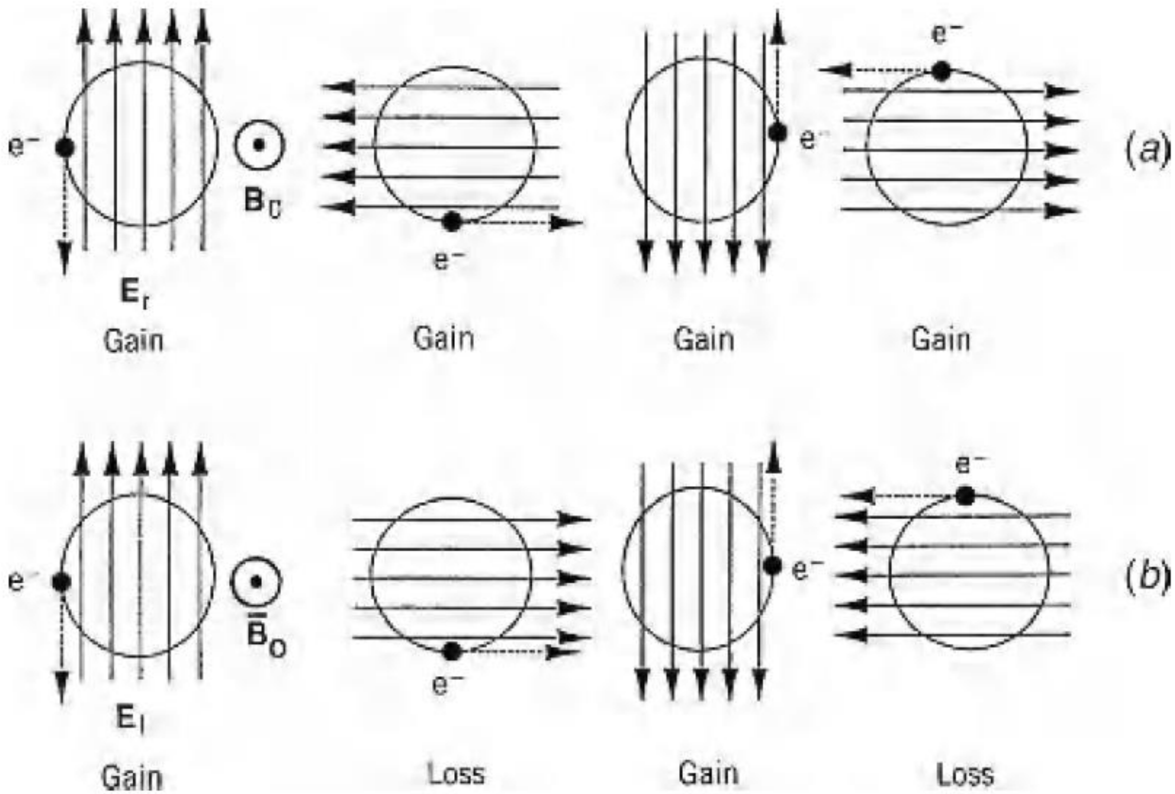
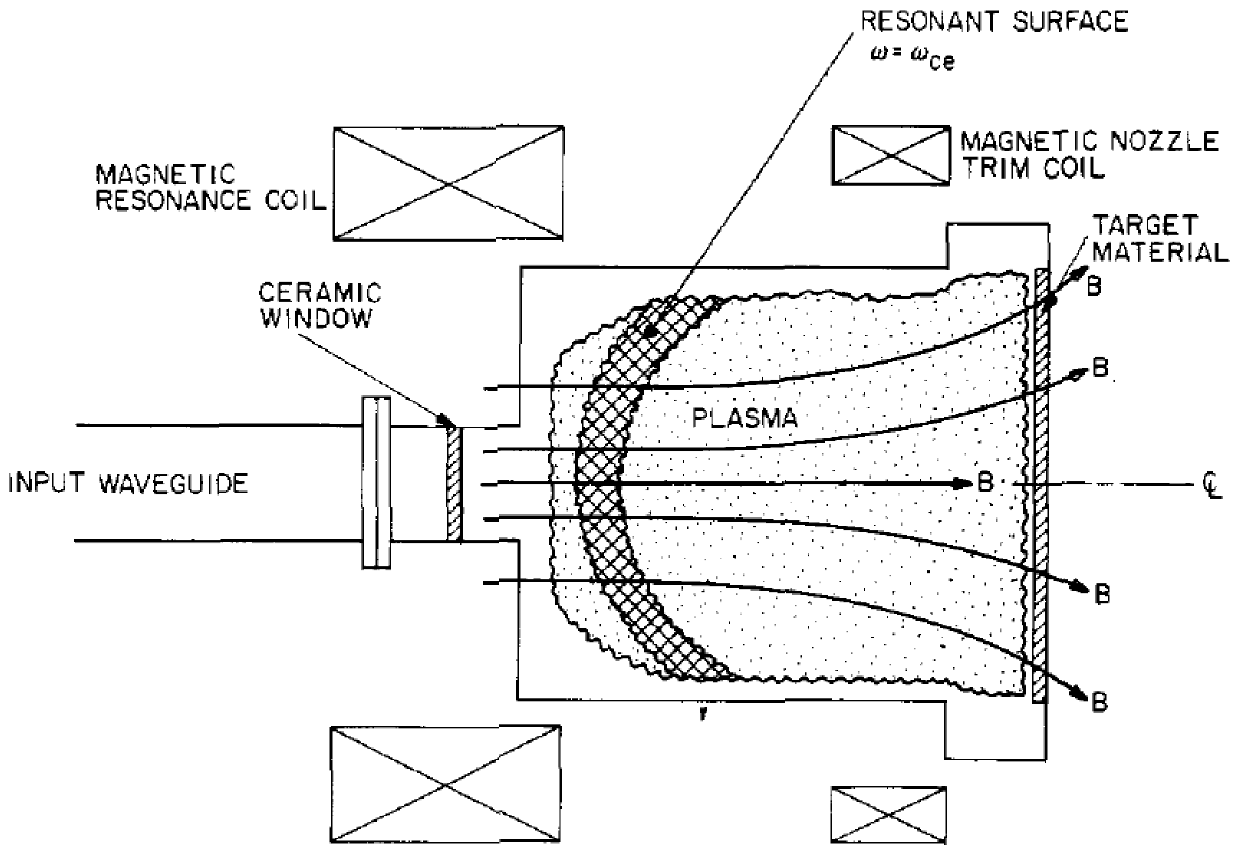


FIGURE 13.5. Basic principle of ECR heating: (*a*) continuous energy gain for right-hand polarization; (*b*) oscillating energy for left-hand polarization (after Lieberman and Gottscho, 1994).

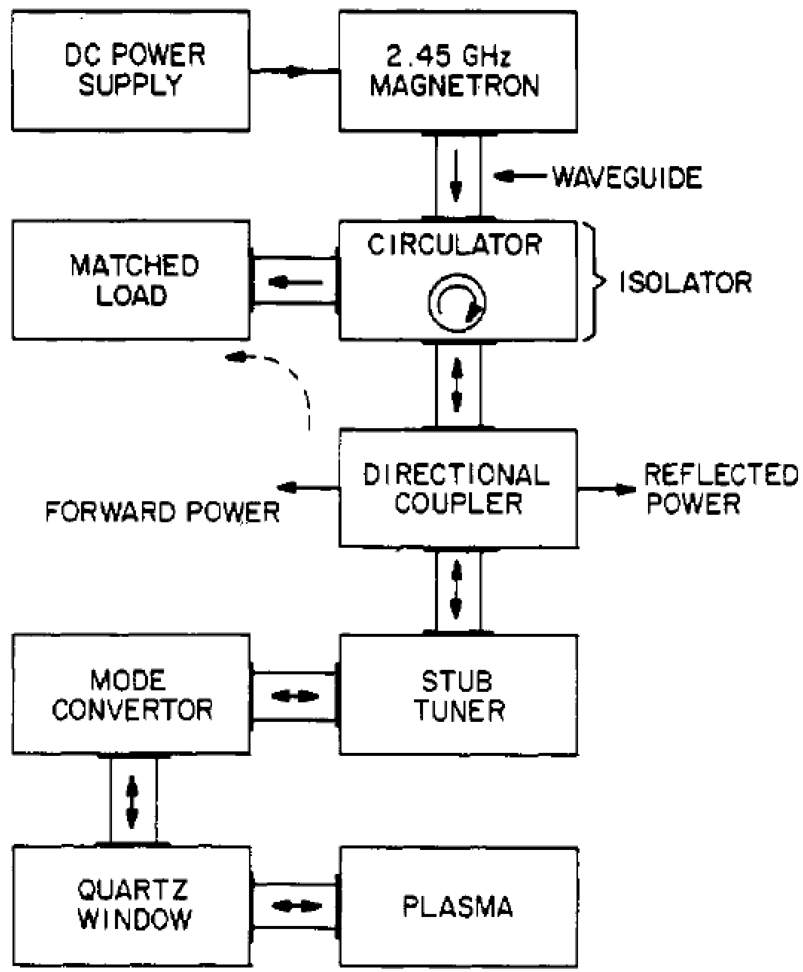
Strong absorption occurs when the frequency matches the electron cyclotron frequency

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



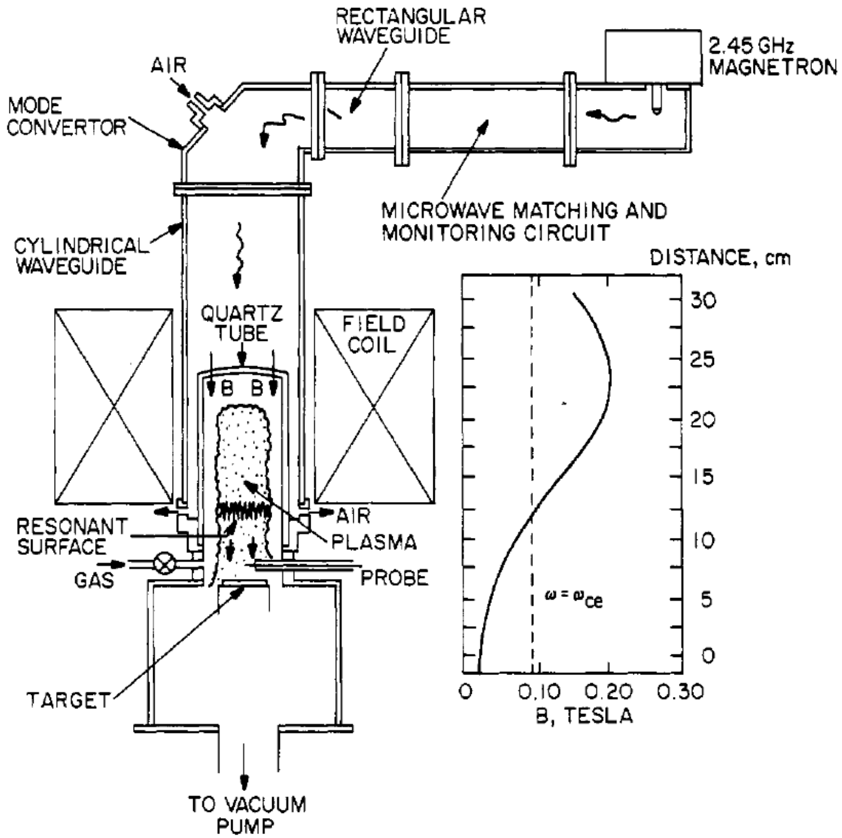
Electron cyclotron resonance (ECR) microwave systems

microwave systems

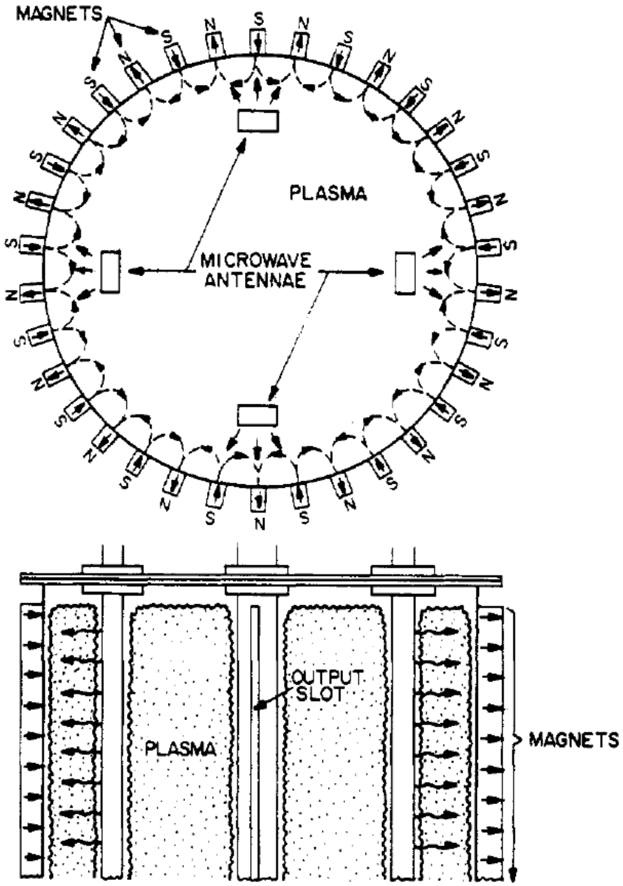


Immersed ECR plasma source

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

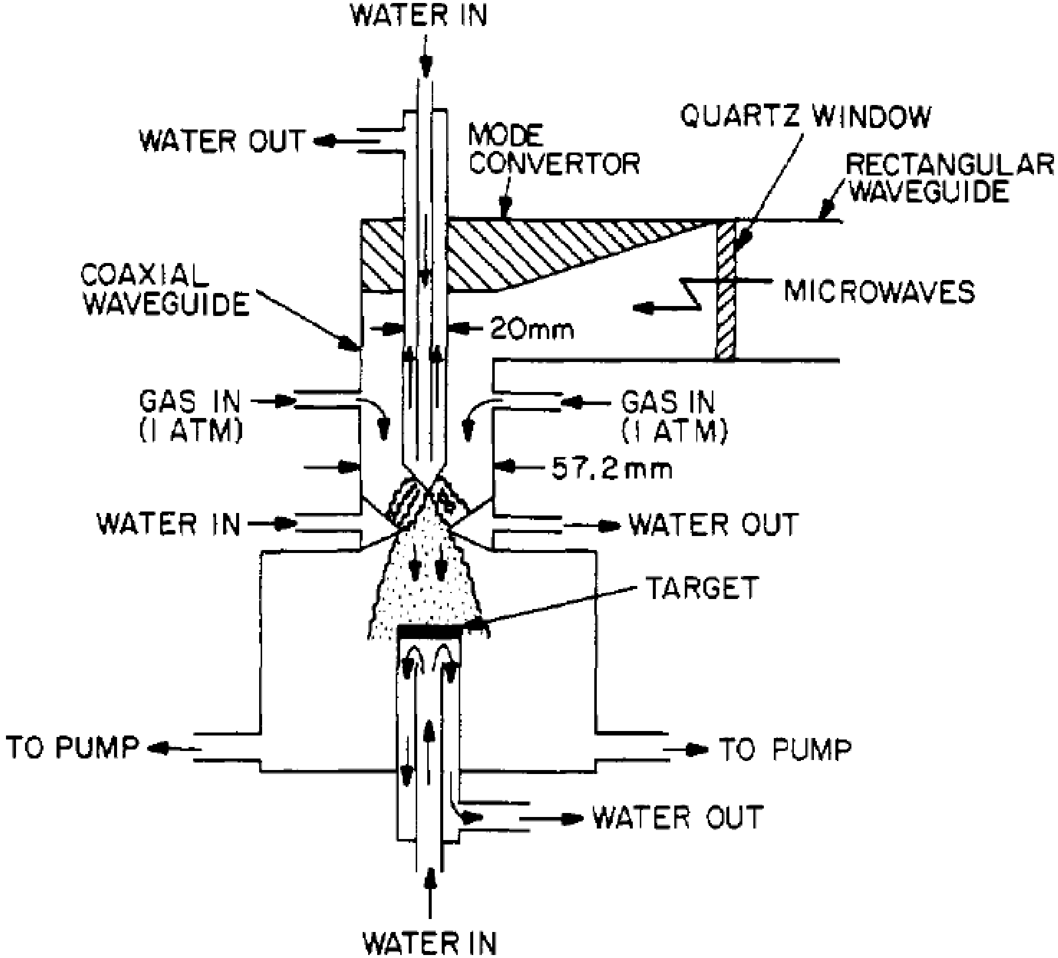


Distributed ECR system



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

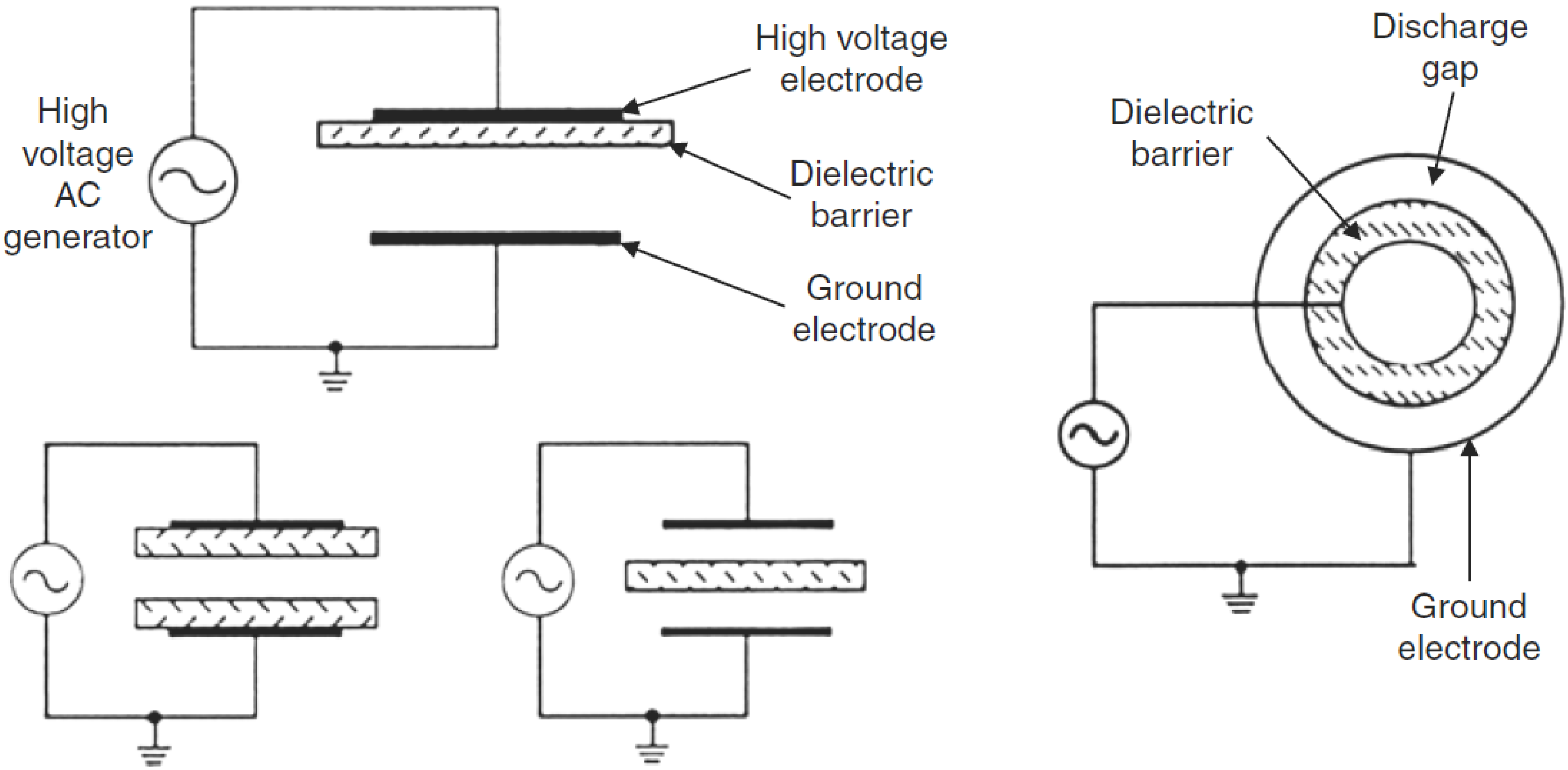
Microwave plasma torch deposit a much faster rate than other types of plasma source for diamond film deposition



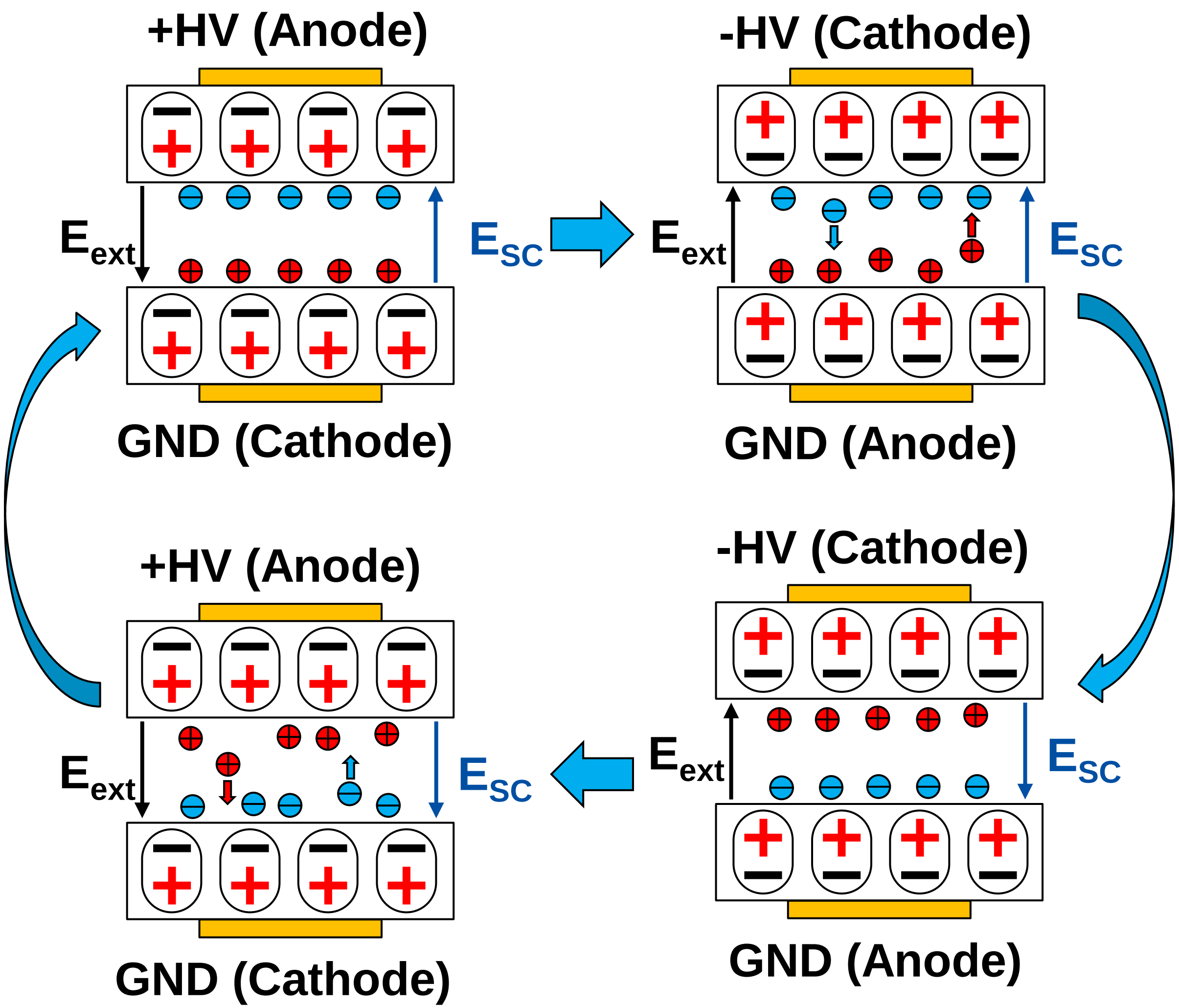
Microwave-generated plasmas have the capability of filling very large volumes with moderately high density

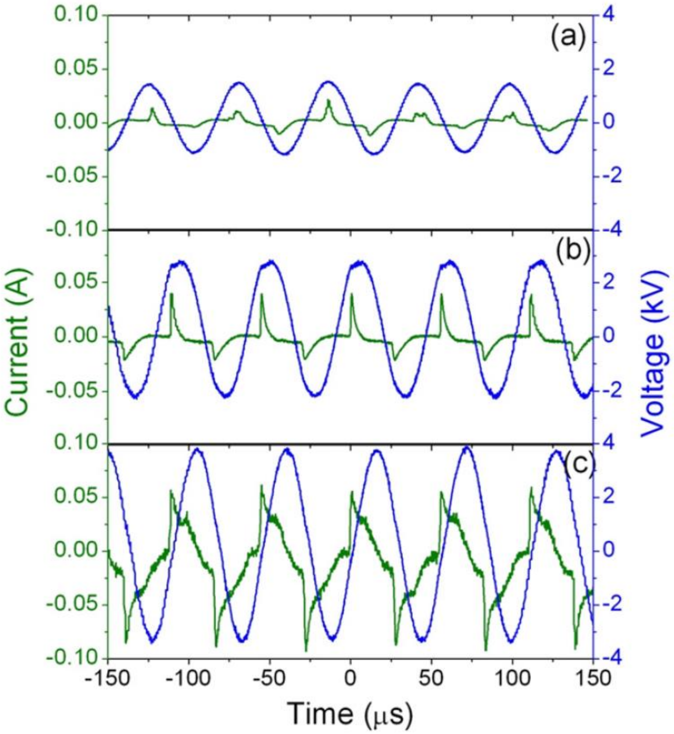
- **Advantages**
  - **Lower neutral gas pressure, i.e., longer ion and neutral mean free paths.**
  - **Higher fraction ionize.**
  - **Higher electron density.**
- **Disadvantages**
  - **Lower ion bombardment energies.**
  - **Less control of the bombarding ion energy.**
  - **Difficult in tuning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

Dielectric-barrier discharges (DBDs)



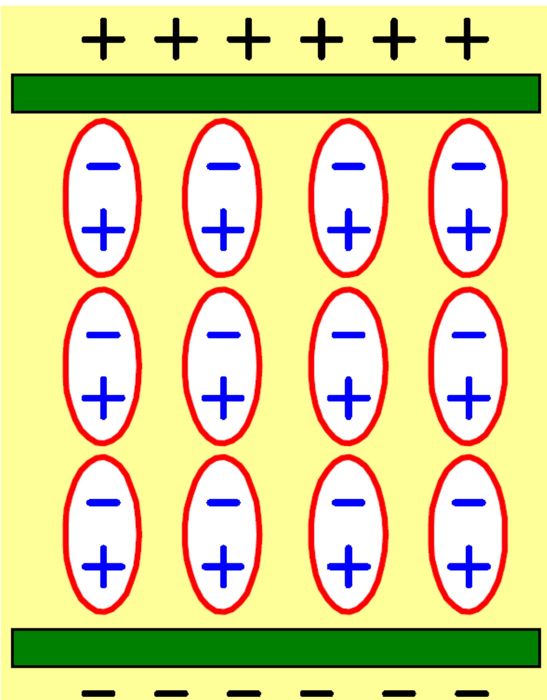
Space charge effect enhance the electric field

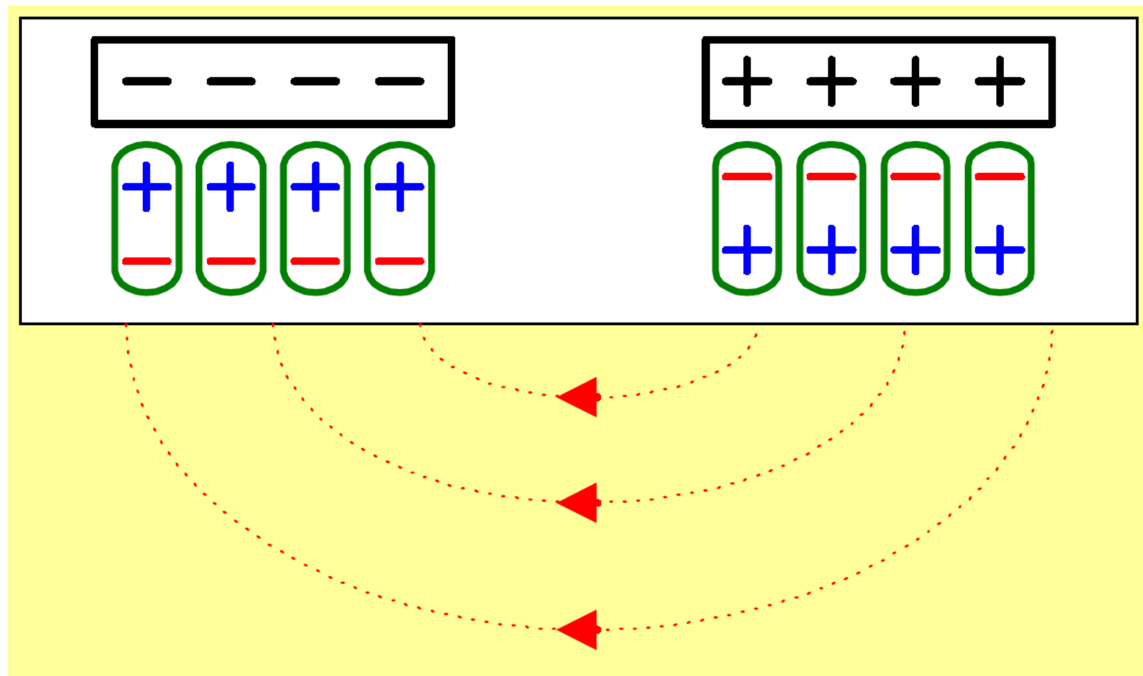




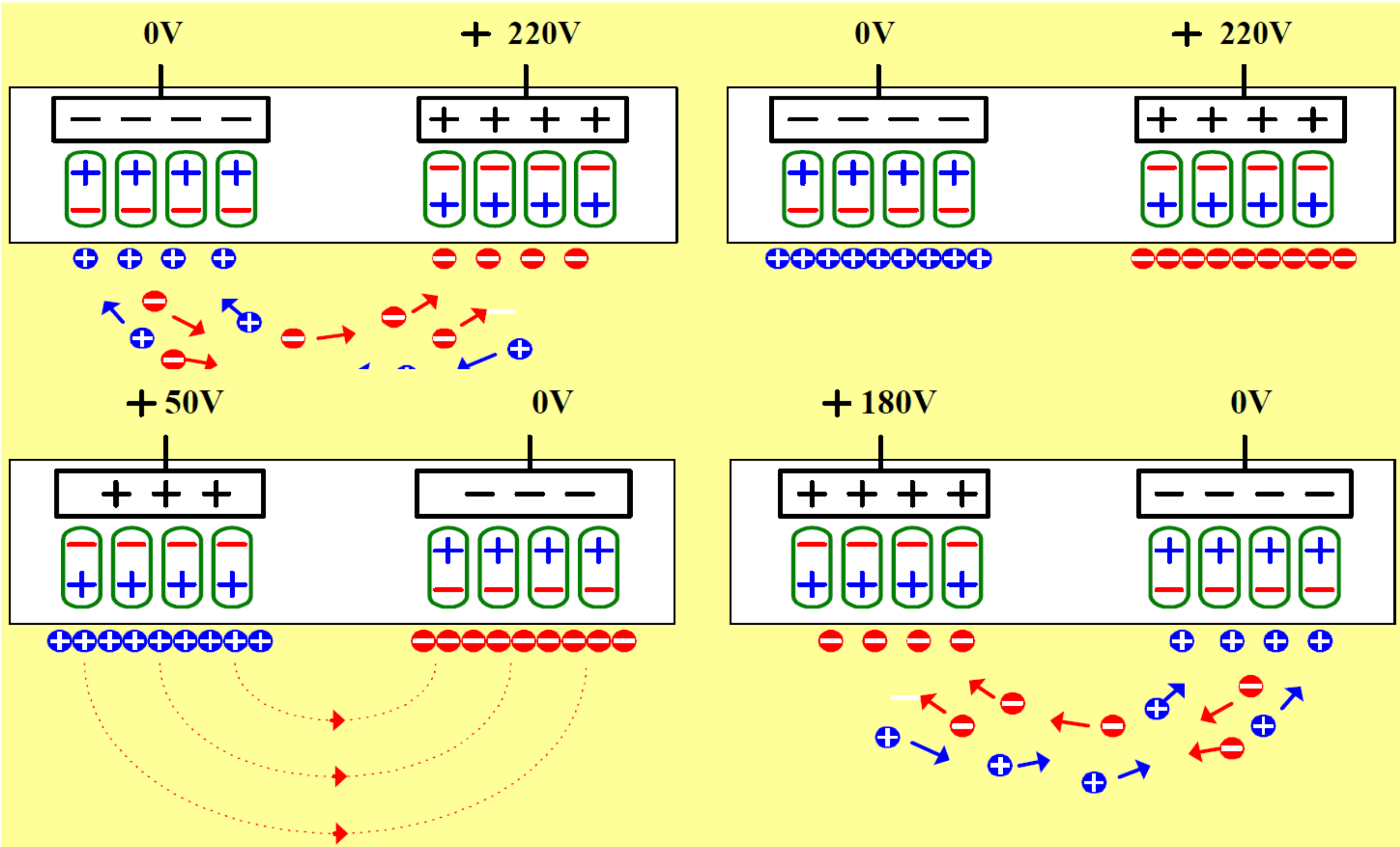
J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

The foundation of AC discharge in plasma display panel





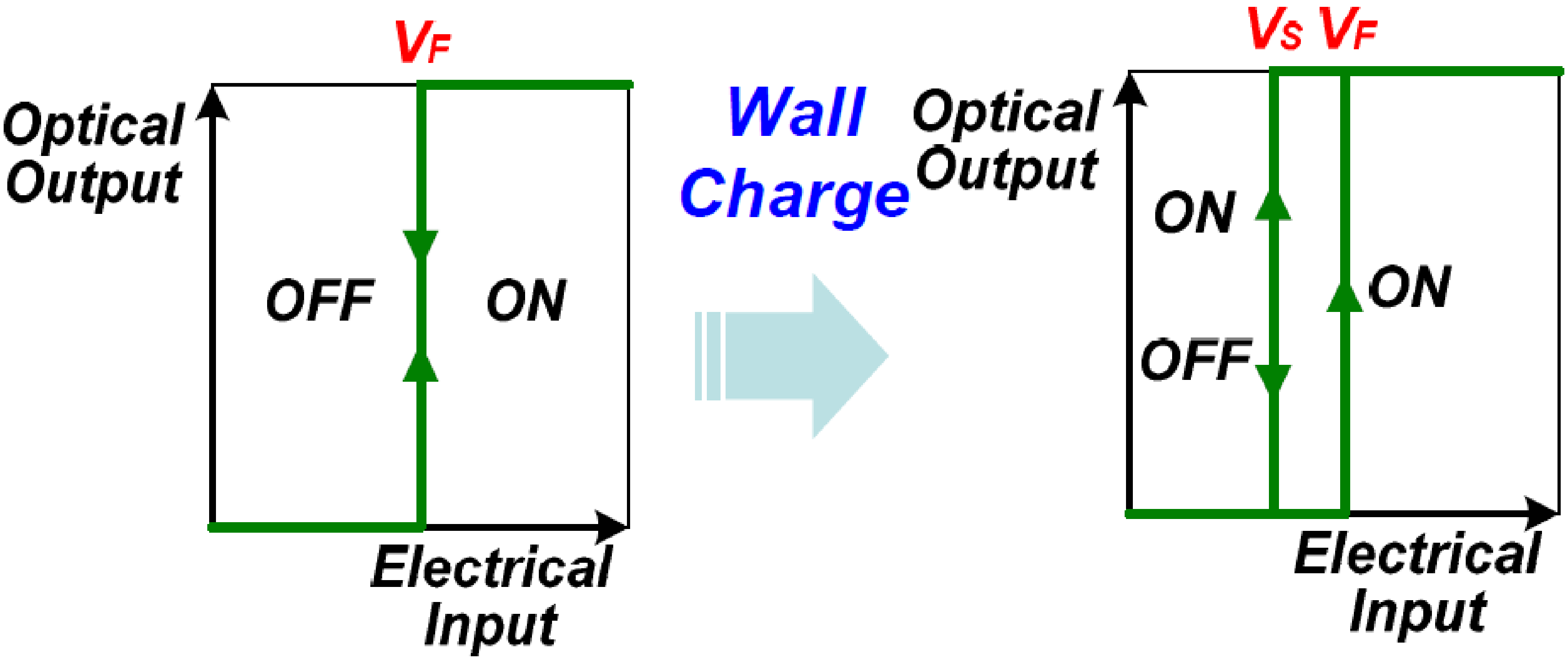
The plasma can be sustained using ac discharged in plasma display panel



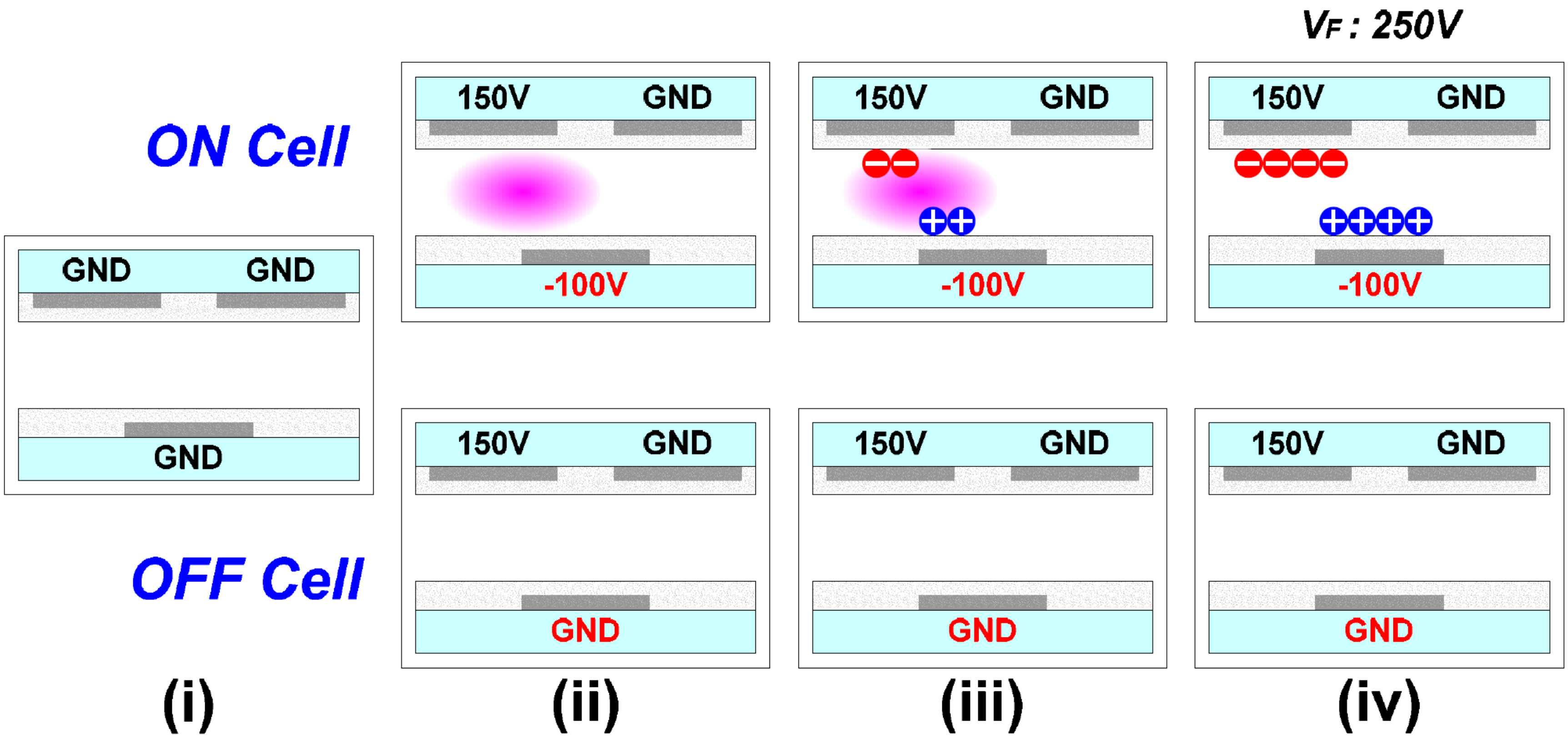
- **Wall discharge reduced the required discharge voltage**

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

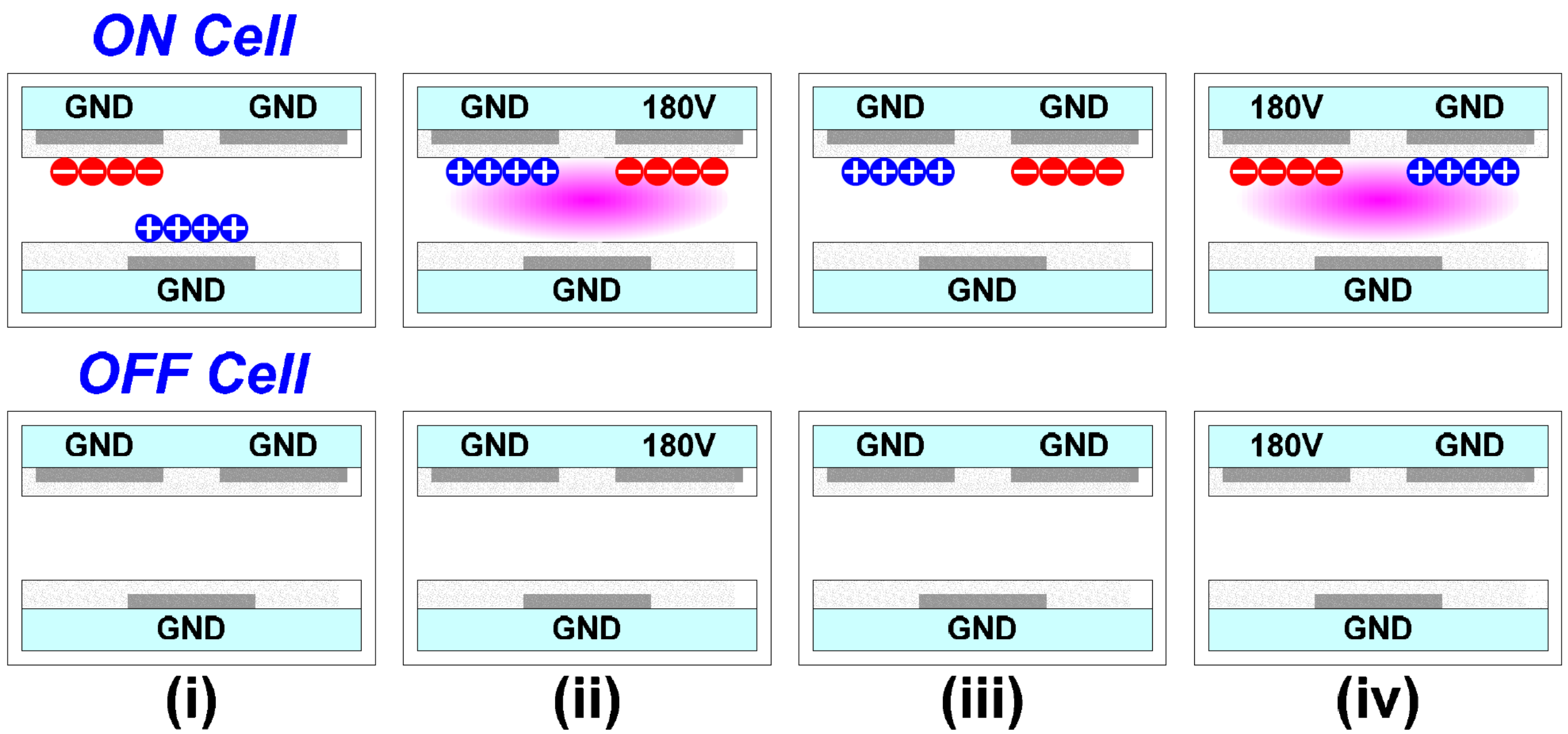
Wall discharge reduced the required discharge voltage



ON/OFF State Selection

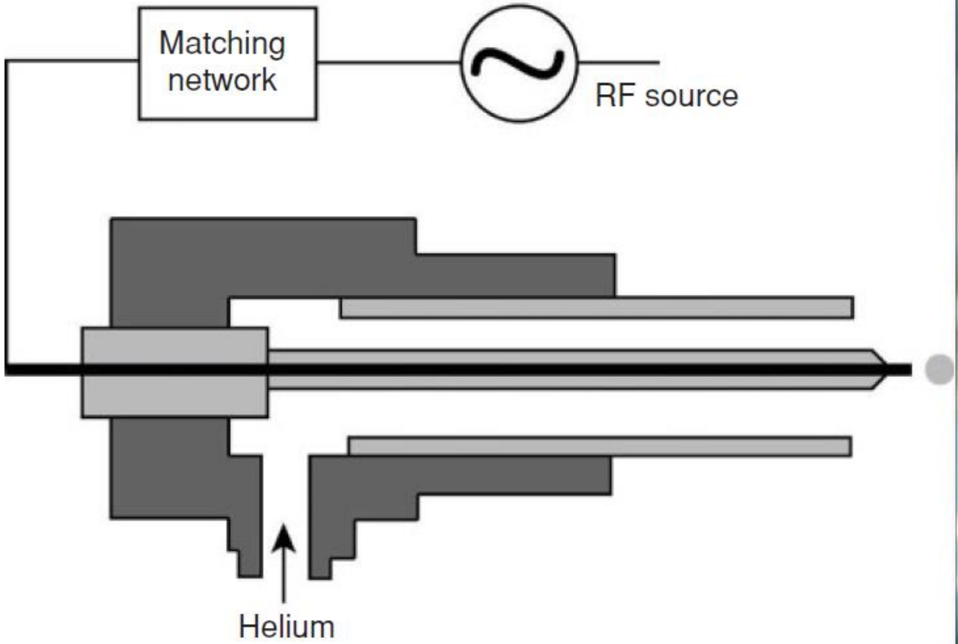


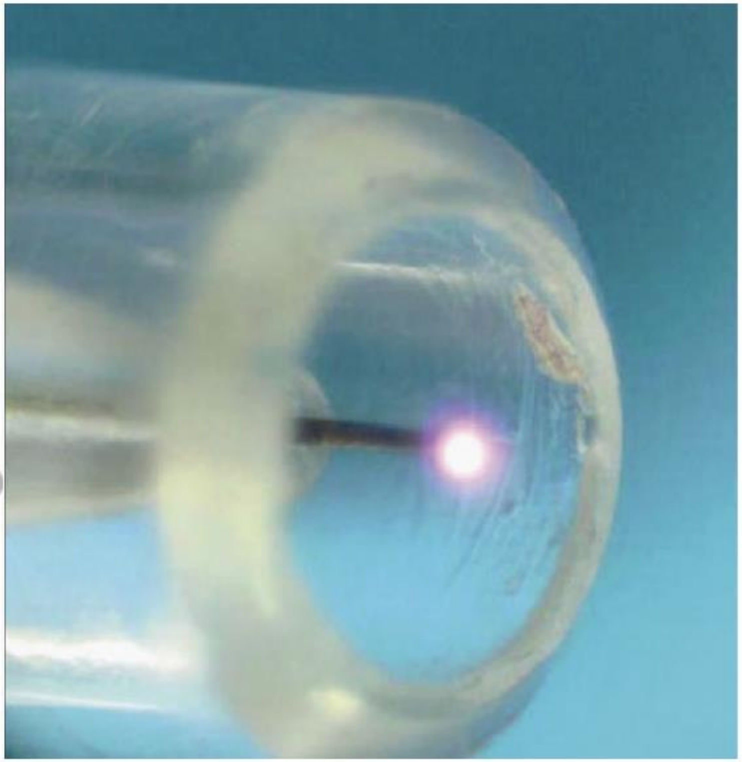
Sustain discharge



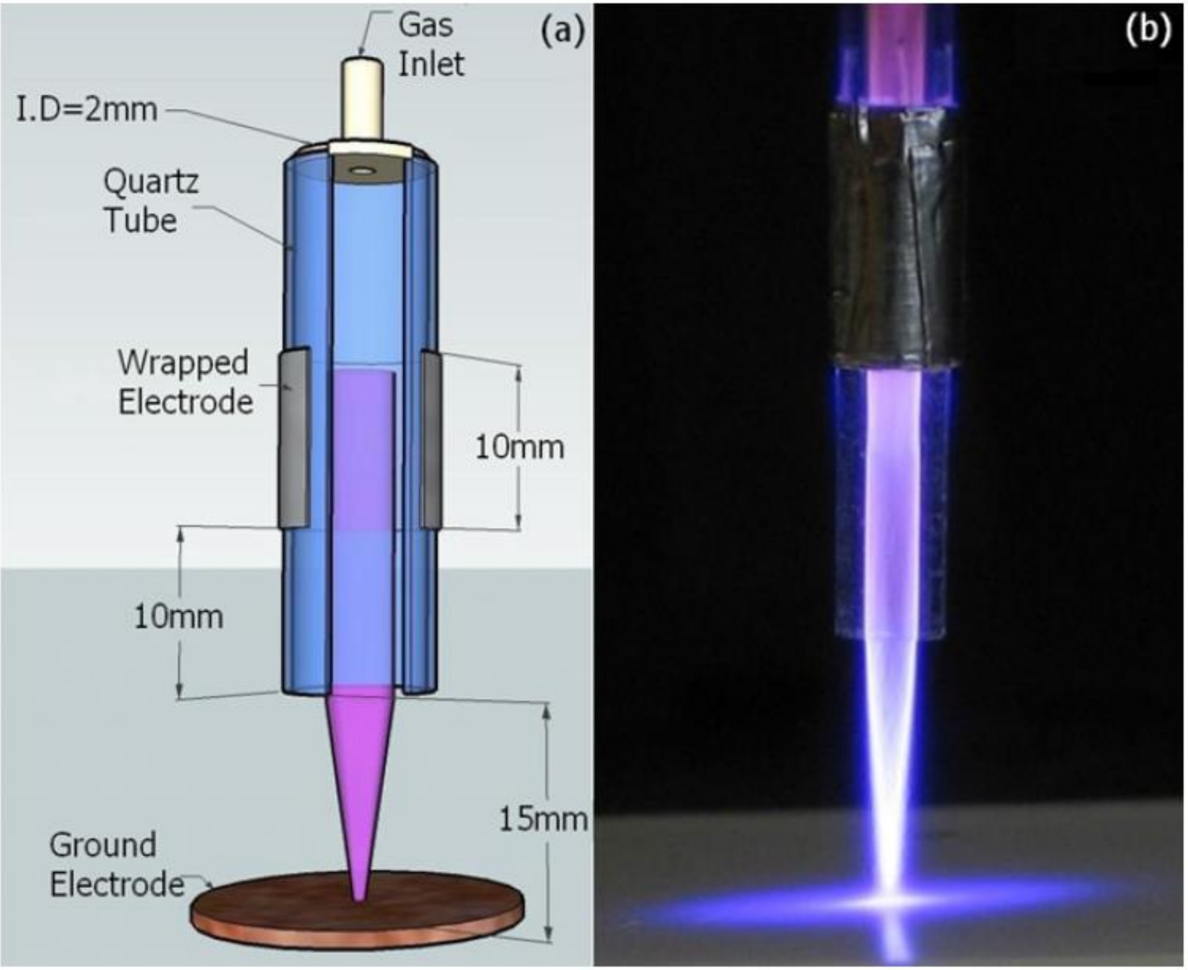
Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

Plasma-needle discharge



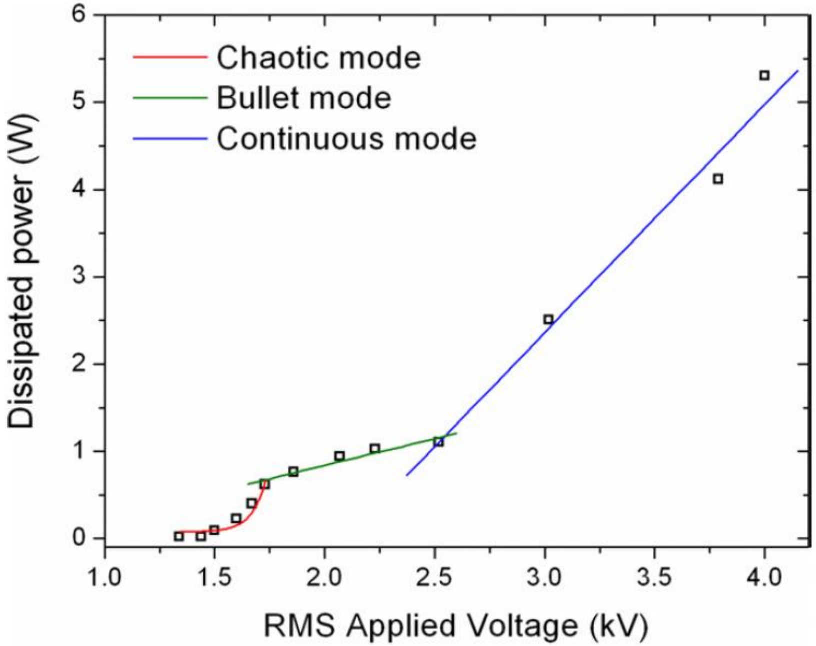


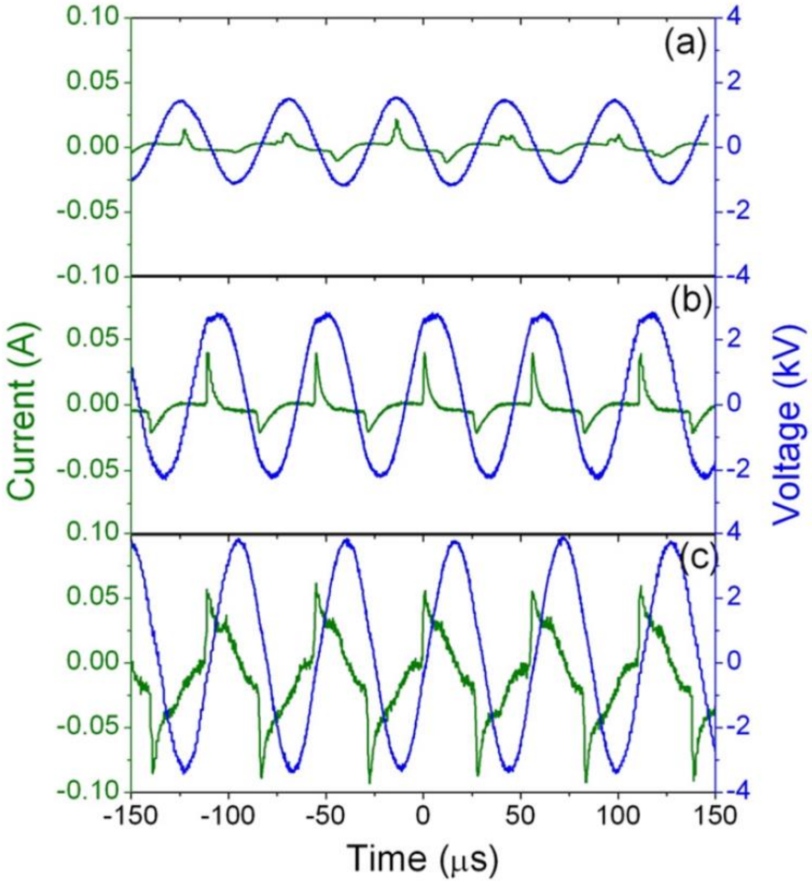
Atmospheric-pressure cold helium microplasma jets



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

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



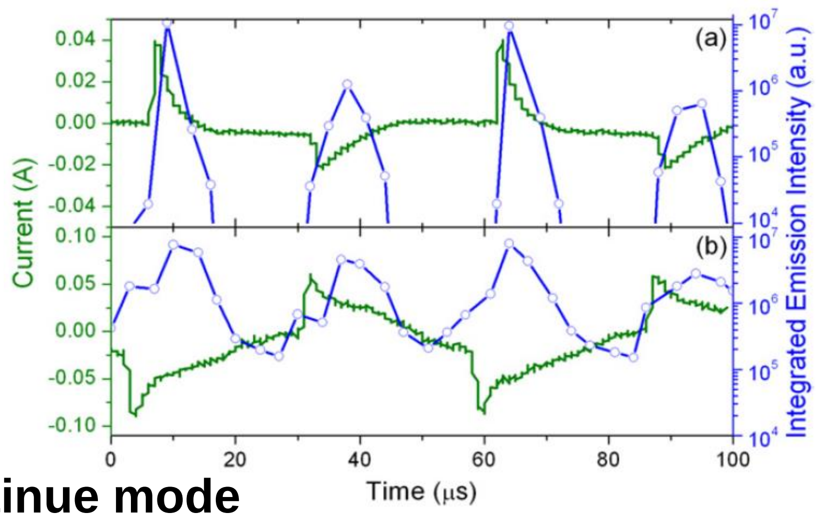


J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

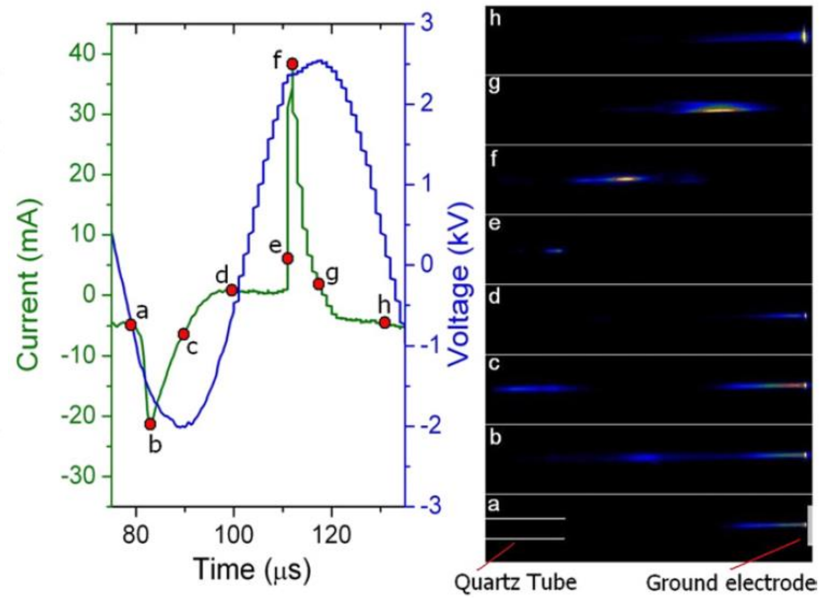
In bullet mode, the plasma jet comes out as a pulse

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

Bullet mode



Continue mode

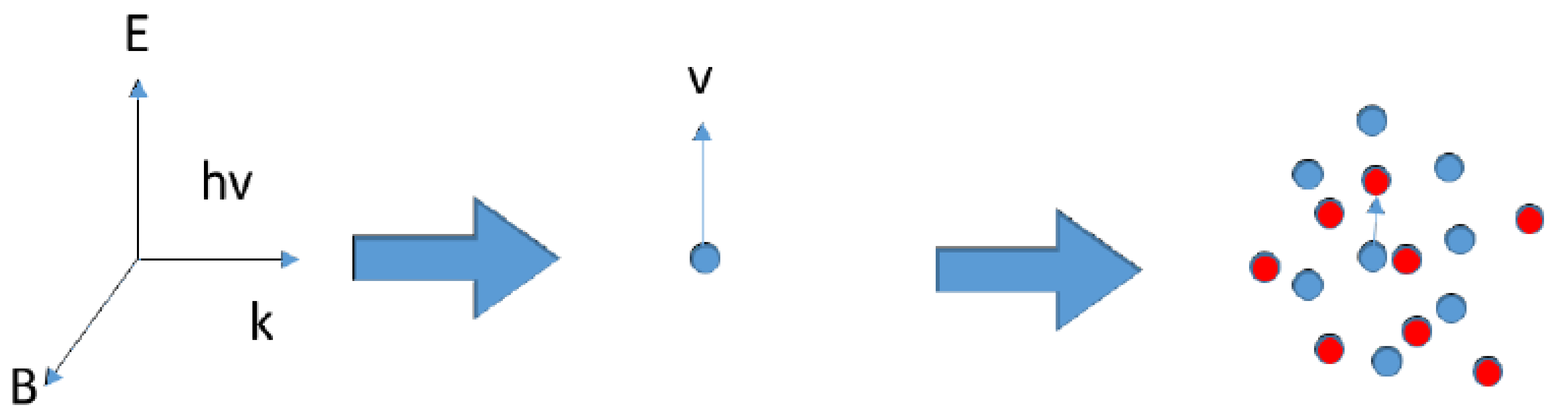


J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

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

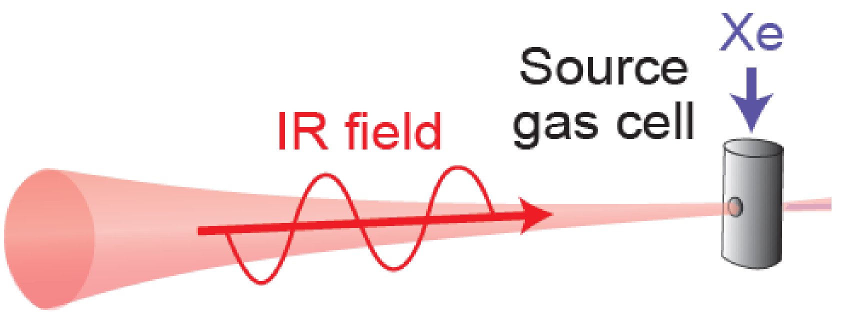


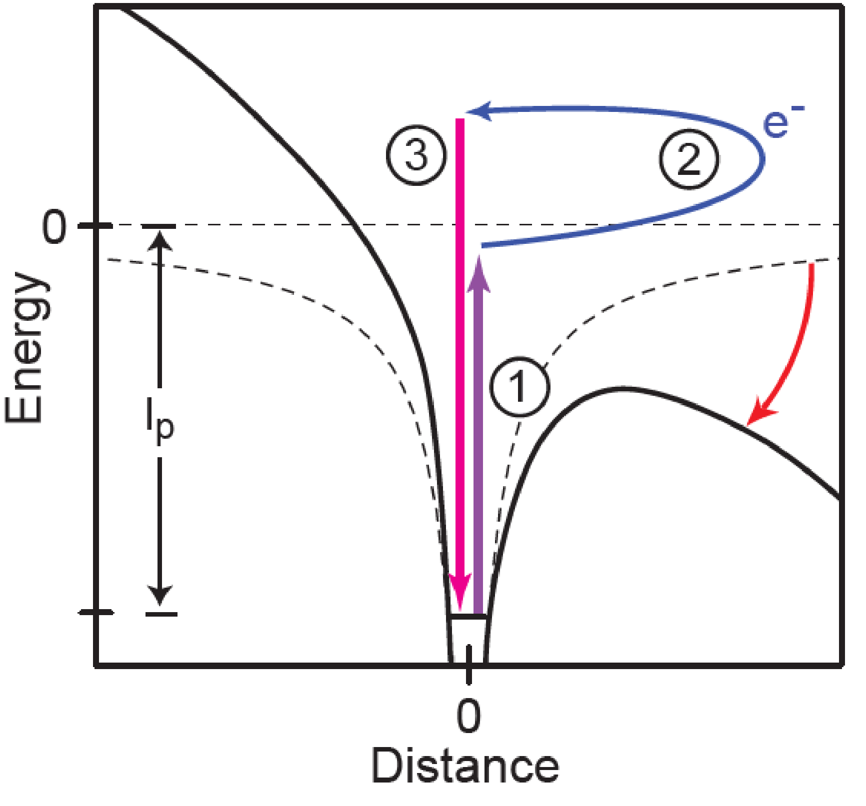
Electrons accelerated by electric fields

Electrons collide with other electrons / ions

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**



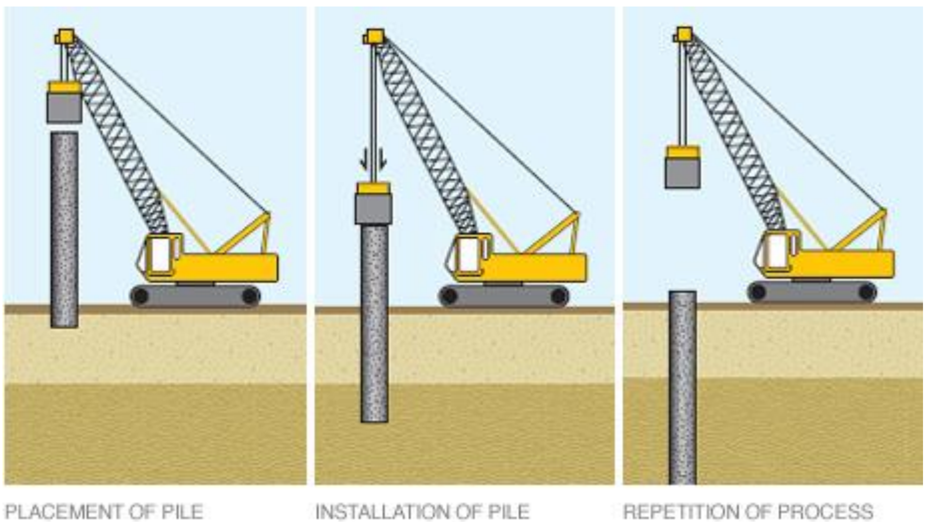


M. Krüger, etc., Appl. Sci. 9, 378 (2019)

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

Driven piles

Hammer

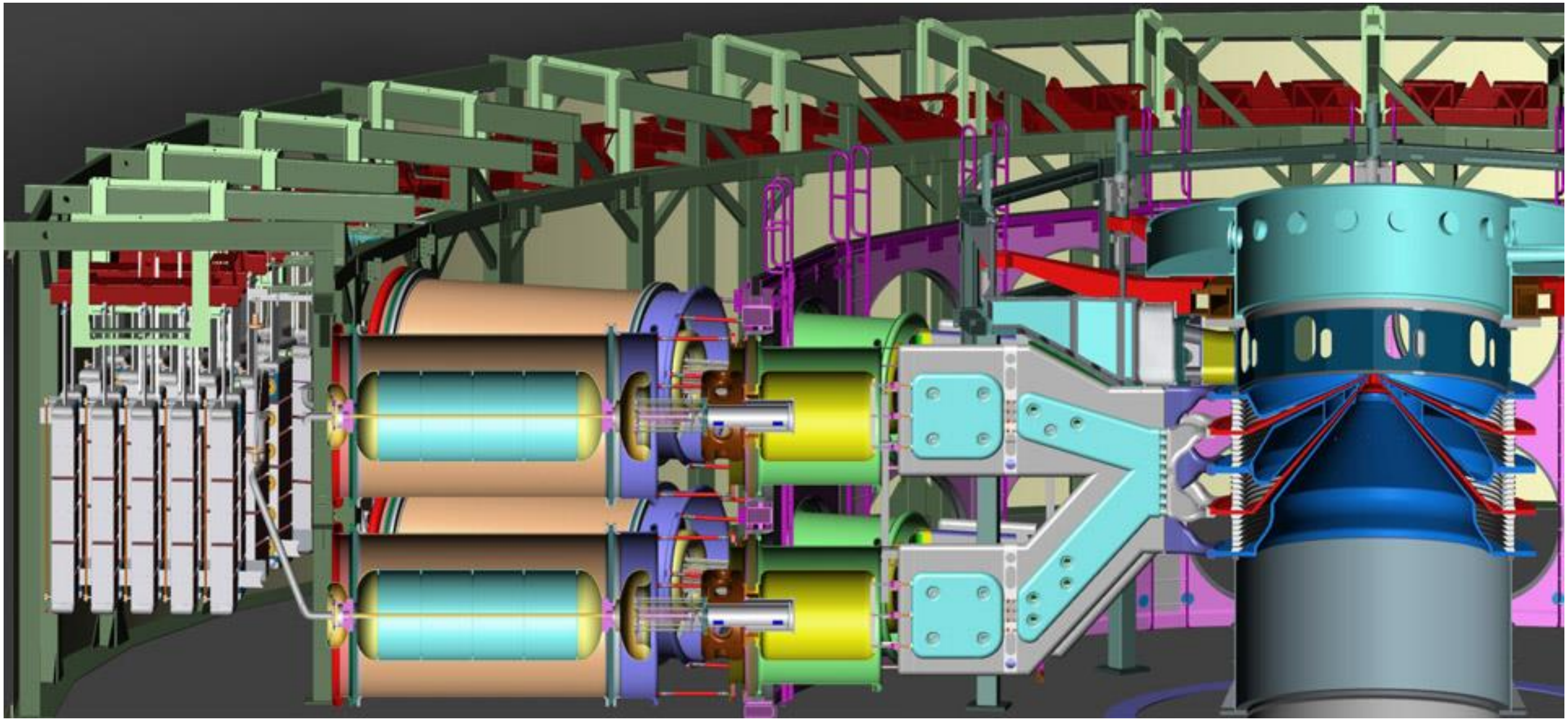


http://www.saudifoundations.com/driven.html
http://learnhowtowritesongs.com/tag/thesaurus/

Example of short pulses with a controllable repetition rate

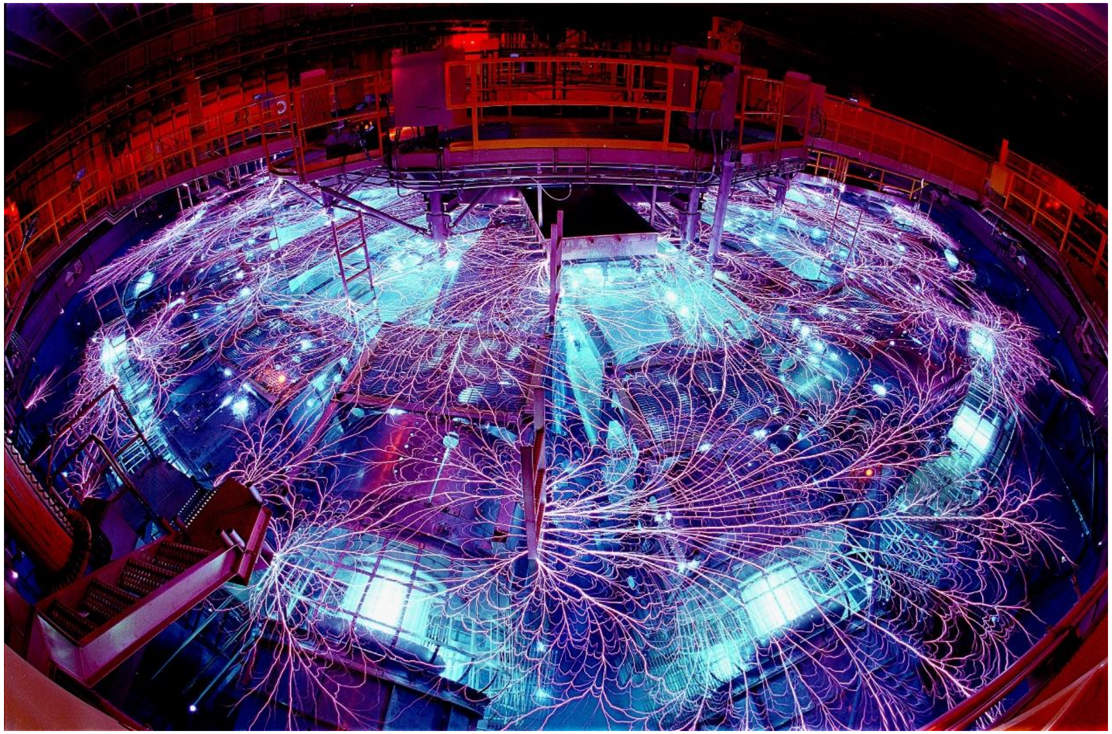
https://www.youtube.com/watch?v=5fe8b4MlPYw

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

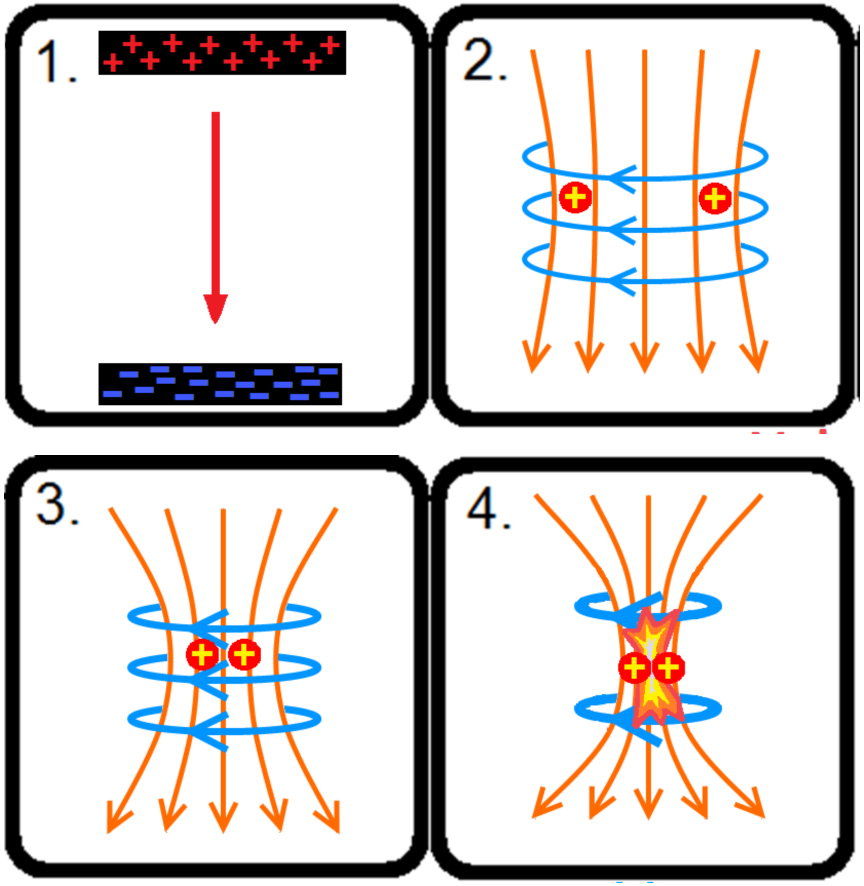


- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine discharge

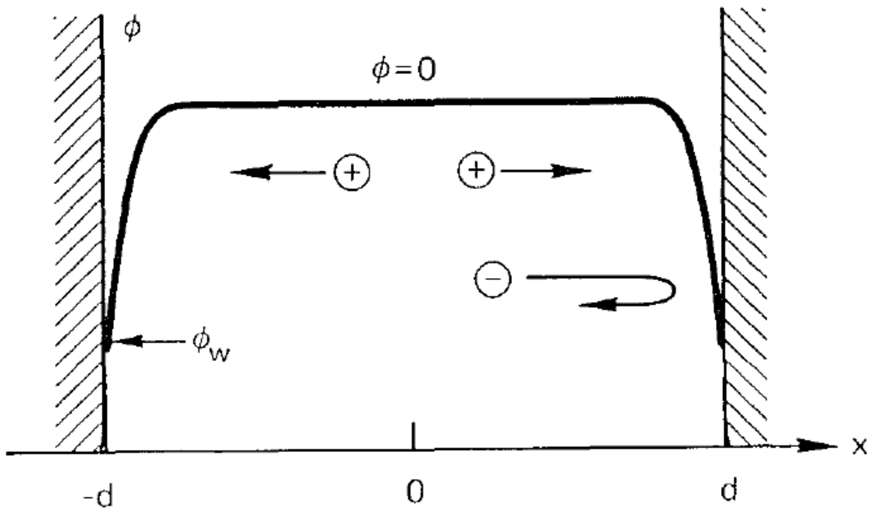


Plasma can be compressed when parallel propagating current occurs



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

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



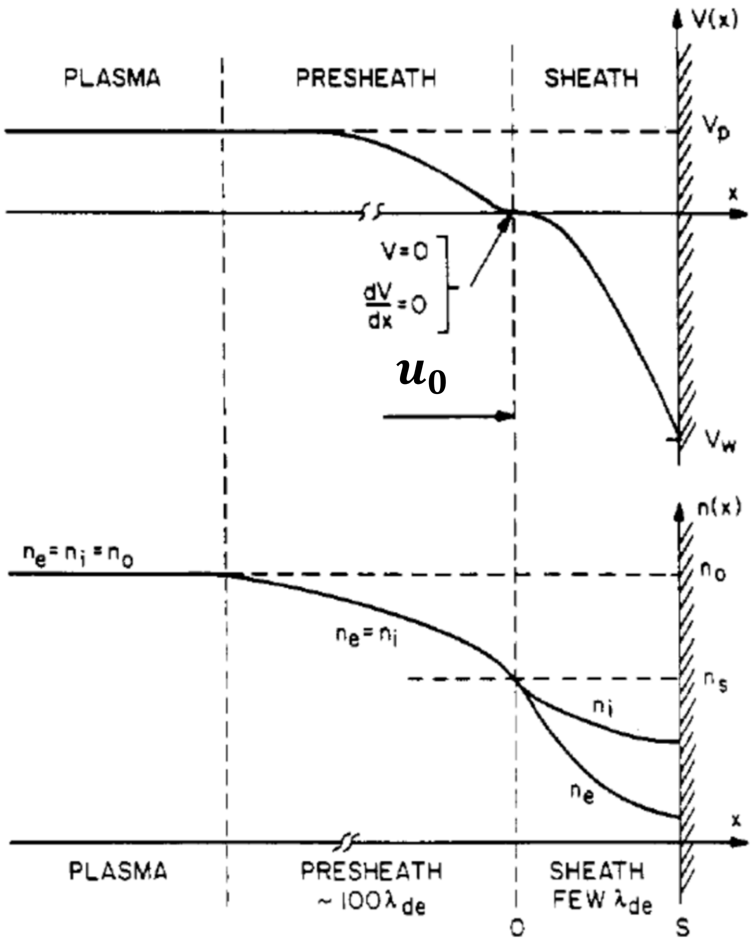
- When ions and electrons hit the wall, they recombine and are lost.
- Since electrons have much higher thermal velocities than ions, they are lost faster and leave the plasma with a net positive charge.
- Debye shielding will confine the potential variation to a layer of the order of several Debye lengths 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** $|\phi| \geq \frac{1}{2}\frac{KT_e}{e}$.



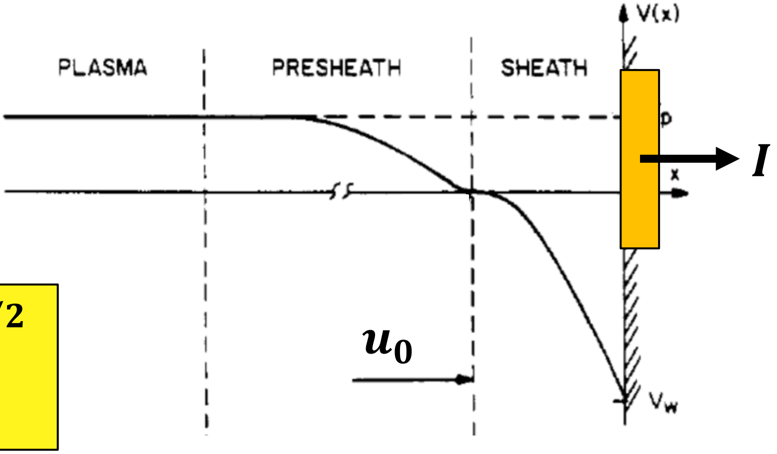
Electrostatic probes (Langmuir probe)

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

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

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

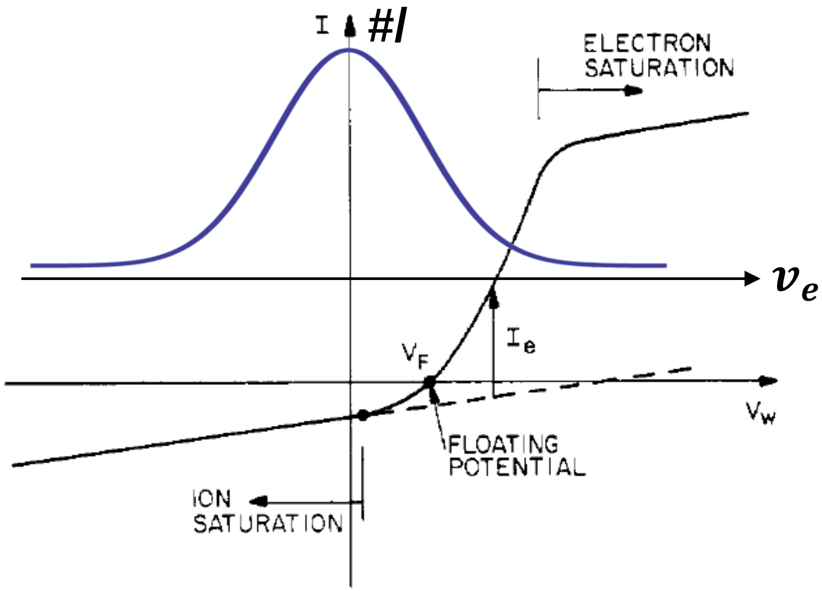
$$n_s = n_0\exp\left(\frac{e\phi}{KT_e}\right) = n_0e^{-1/2} = 0.61n_0$$



$$\boxed{\textbf{Bohm current: } I_B \simeq 0.5n_0eA\left(\frac{KT_e}{m}\right)^{1/2}}$$

- 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



- **Electron saturation current:**

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

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

- **Ion saturation current:**

$$I_{is} = AJ_{is} = eA\Gamma_{is}$$

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

- **Total current:**

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

$$V \equiv \Phi$$

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

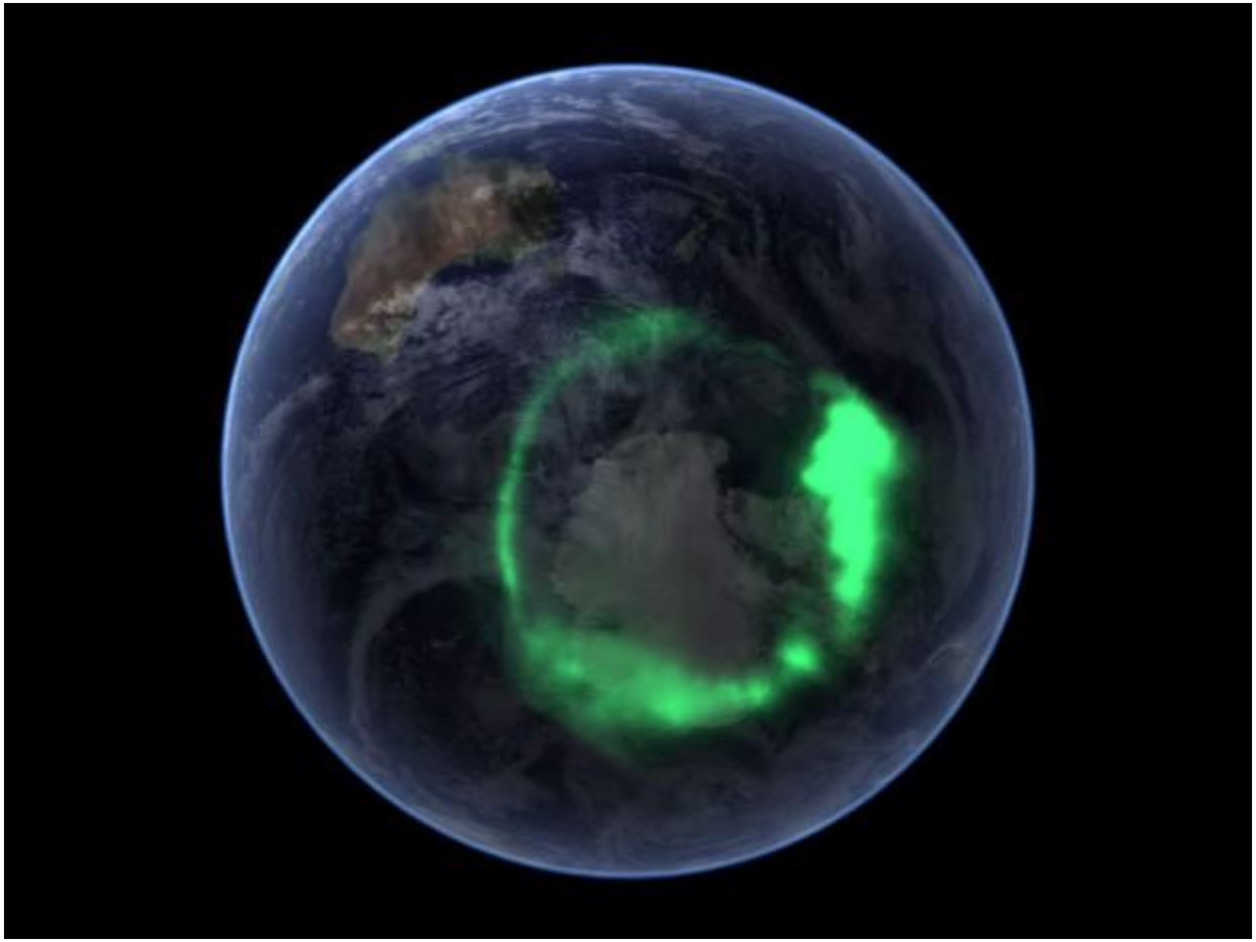
Course Outline

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

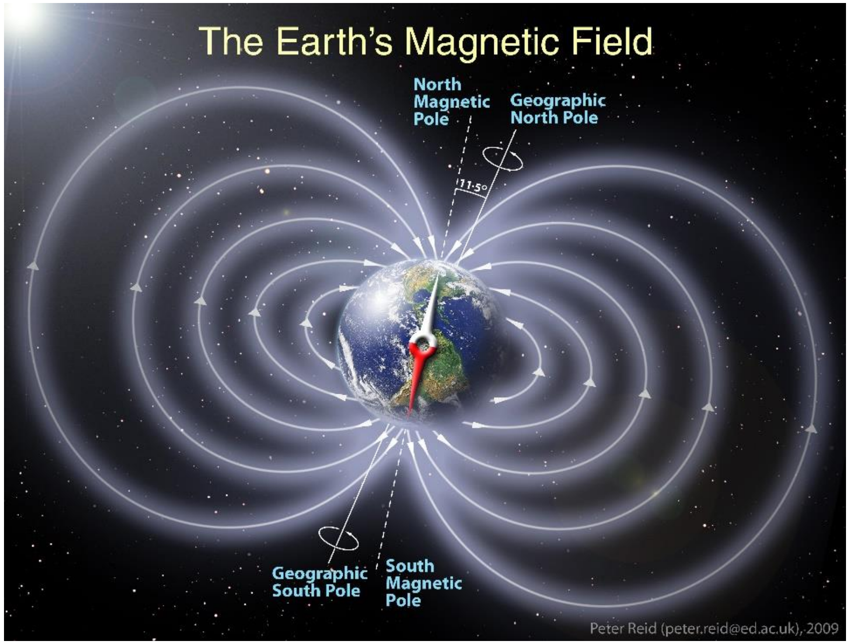
https://en.wiktionary.org/wiki/aurora

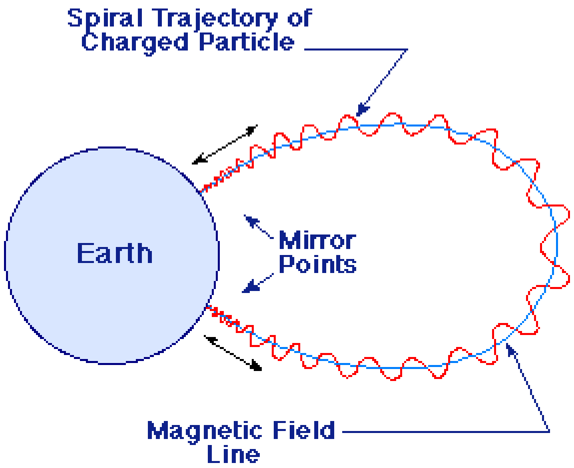
Aurora seen from a satellite



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

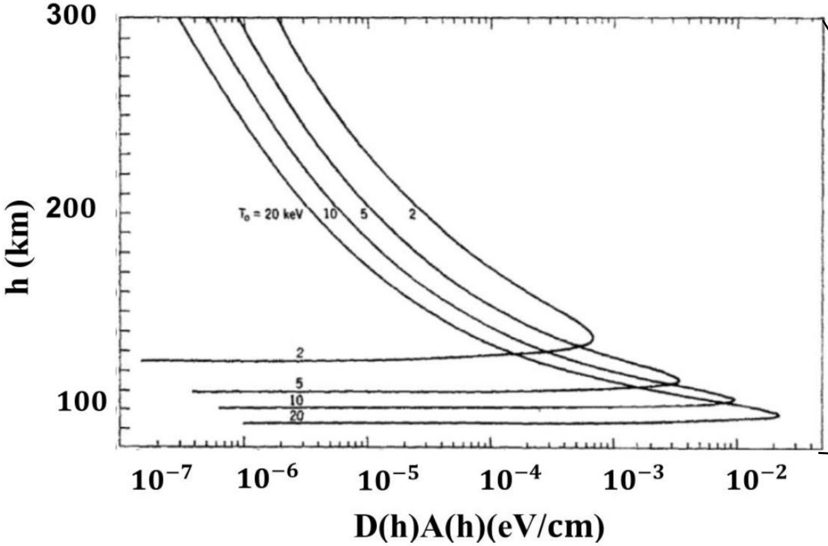
Earth's magnetic field

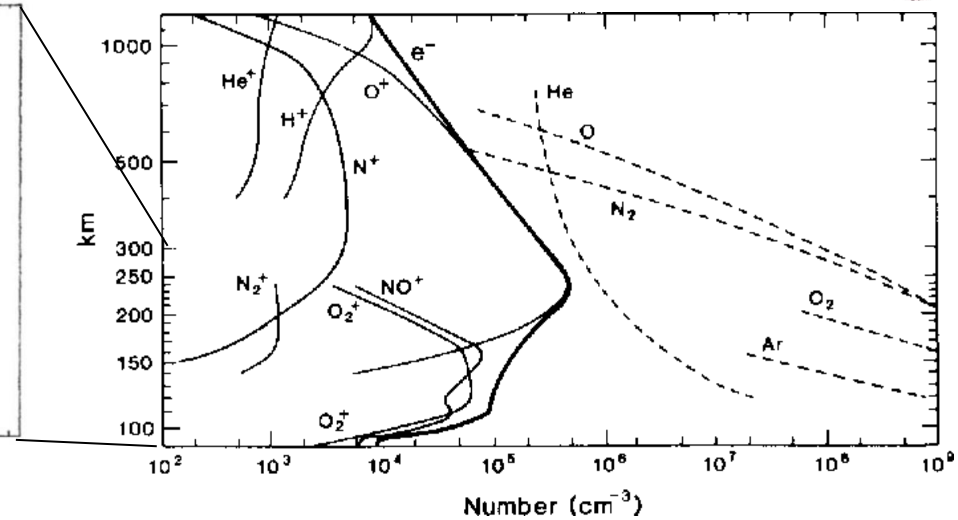




https://www.nasa.gov/mission_pages/sunearth/news/gallery/Earths-magneticfieldlines-dipole.html
http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

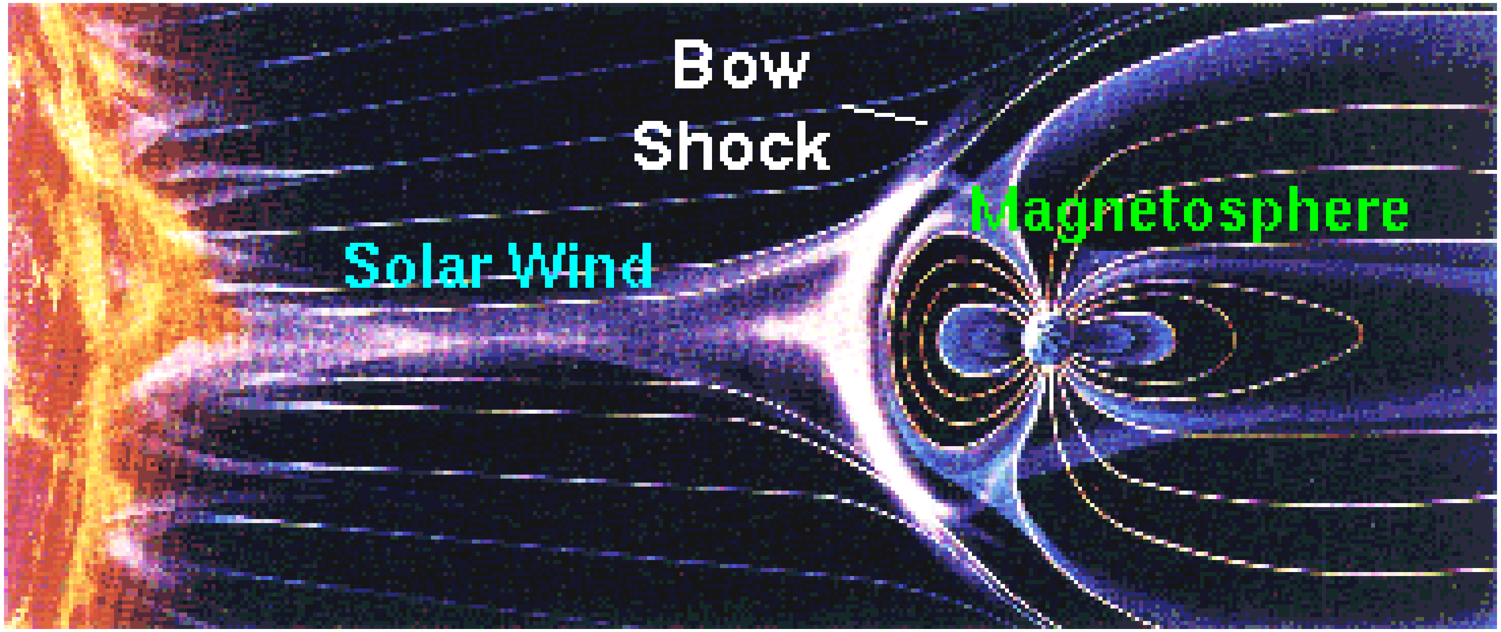
Colors of the aurora depends on the penetration depth of energetic electrons





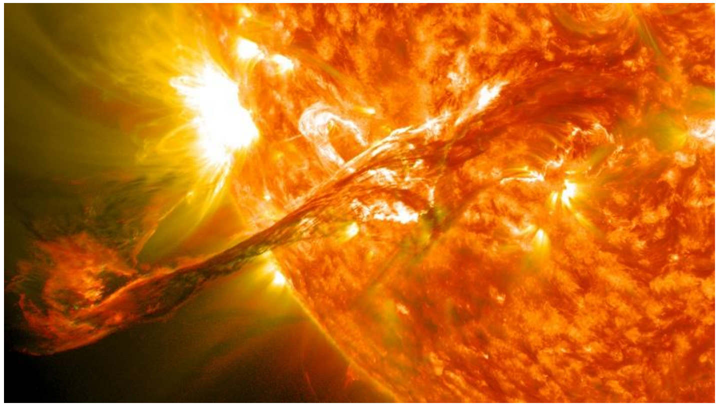
- O_2: green or dark red
- N_2: blue or purple

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

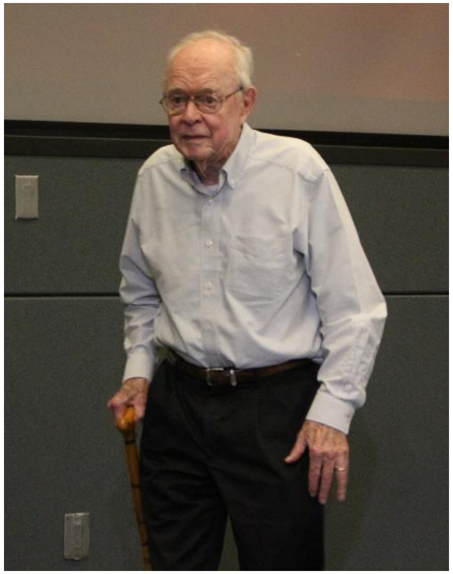


- **1859, British astronomer Richard C. Carrington and Richard Hodgson made the first observation of what is called a solar fare later. A geomagnetic storm (solar storm) was observed on the following day. Carrington suspected that there may be a connection between them.**
- **1910, British astrophysicist 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.**

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

Eugene Parker named the “solar wind”

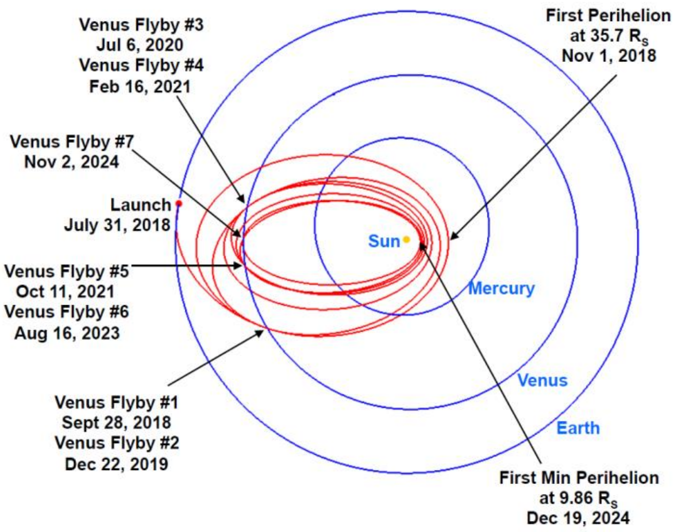
- **1930s, the temperature of the solar corona is in a million degrees Celsius was determined by scientists.**
- **Mid-1950s, Sydney Chapman suggested that the “gas” in this temperature must extend way out into space, beyond the orbit of Earth.**
- **1950s, Ludwig Biermann suggested that the sun emits 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.**

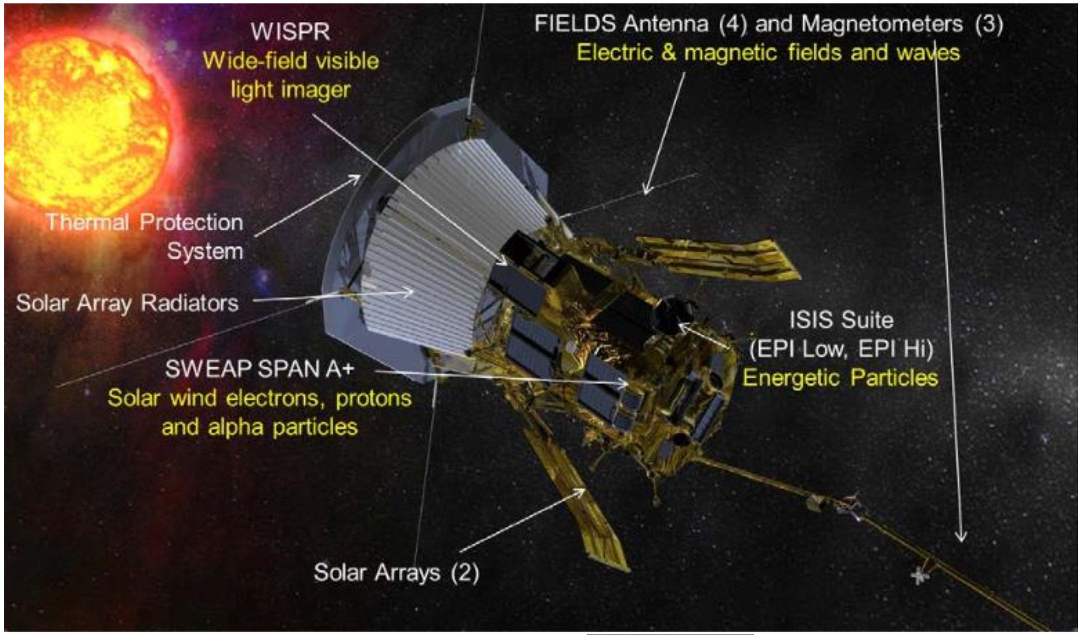


https://en.wikipedia.org/wiki/Solar_wind#History
https://en.wikipedia.org/wiki/Eugene_Parker

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

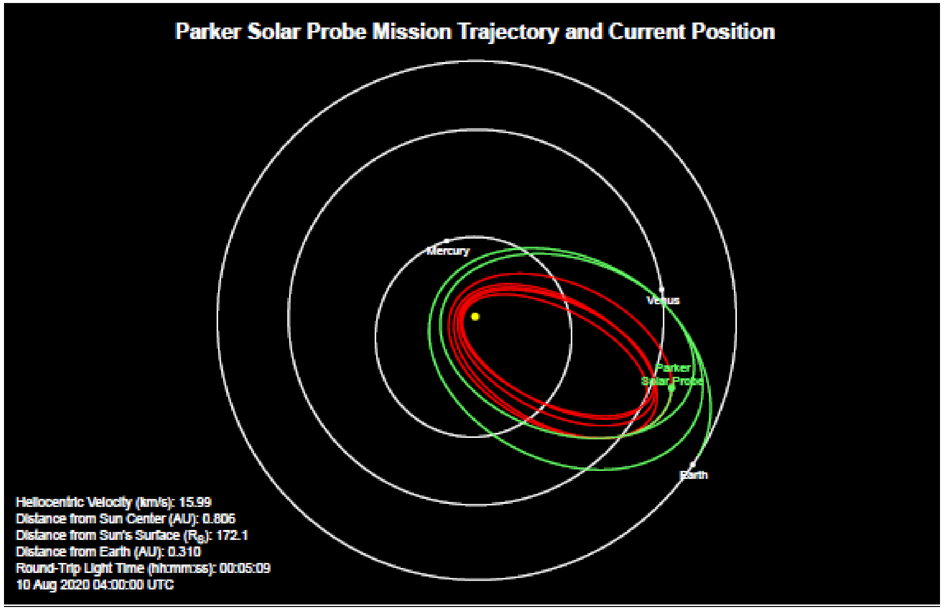
- **The goals of the mission are:**
  - **Trace the flow of energy that heats the corona and accelerates the solar wind.**
  - **Determine the structure and dynamics of the magnetic fields at the sources of solar wind.**
  - **Determine what mechanisms accelerate and transport energetic particles.**

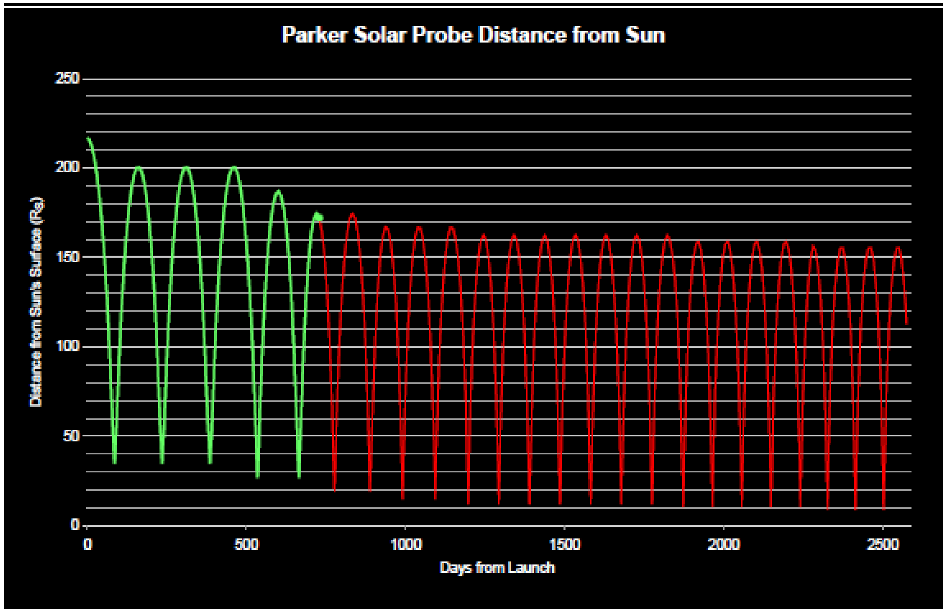




https://en.wikipedia.org/wiki/Parker_Solar_Probe#Mission
D. R. Jones, etc., ASS 17-576

Parker Solar Probe will have 24 perihelion till 2025



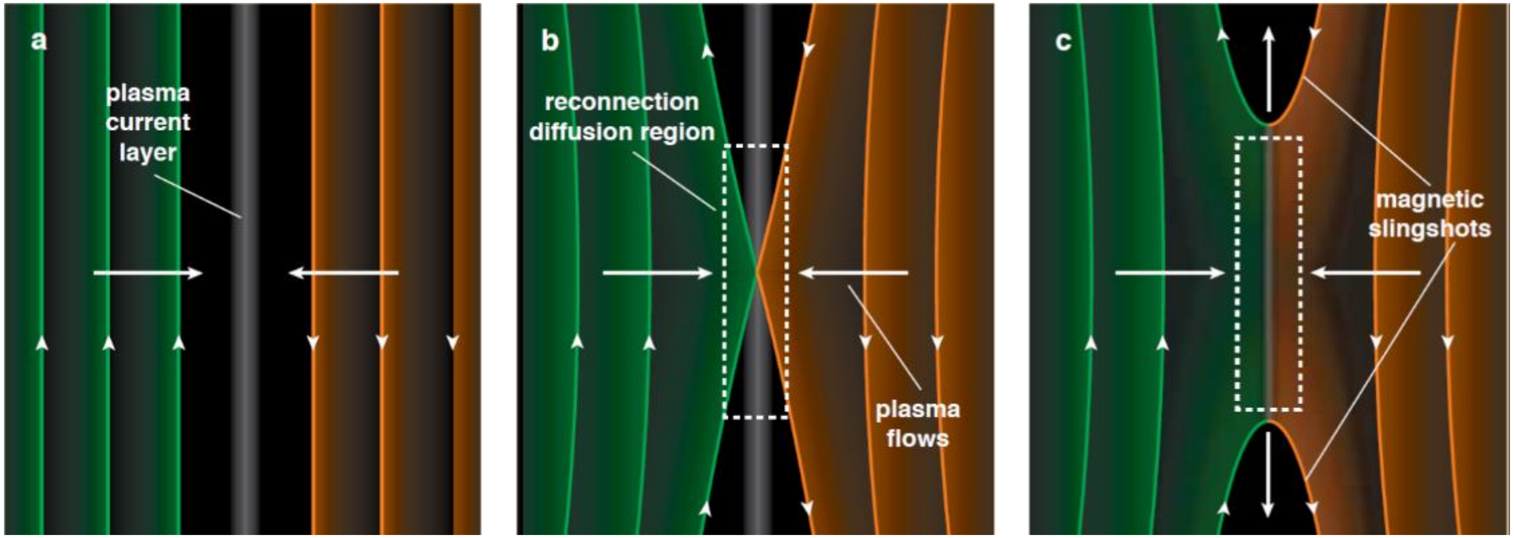


- **More information can be obtained from the following link:**

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

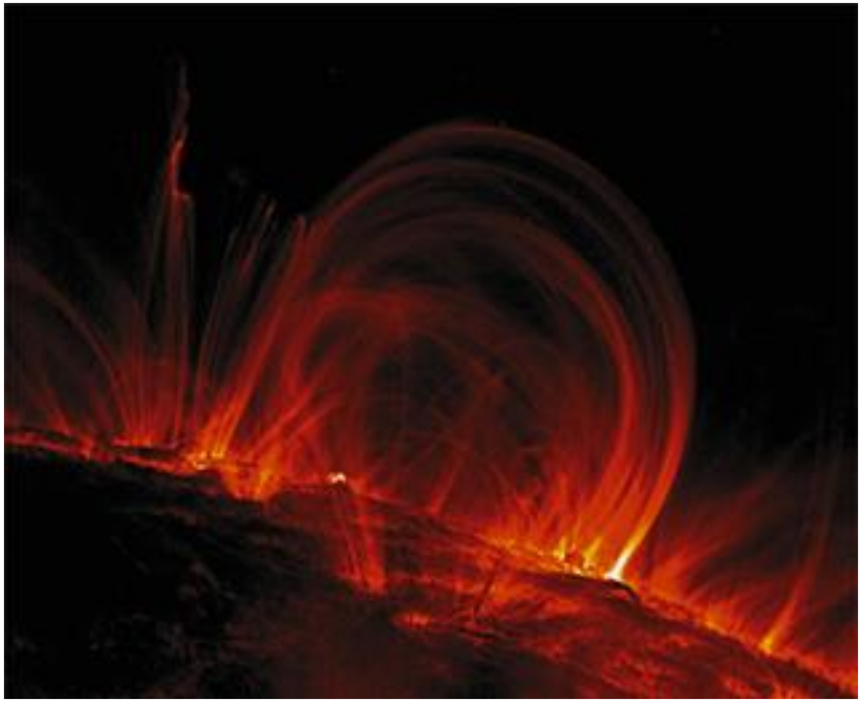
http://parkersolarprobe.jhuapl.edu/The-Mission/index.php

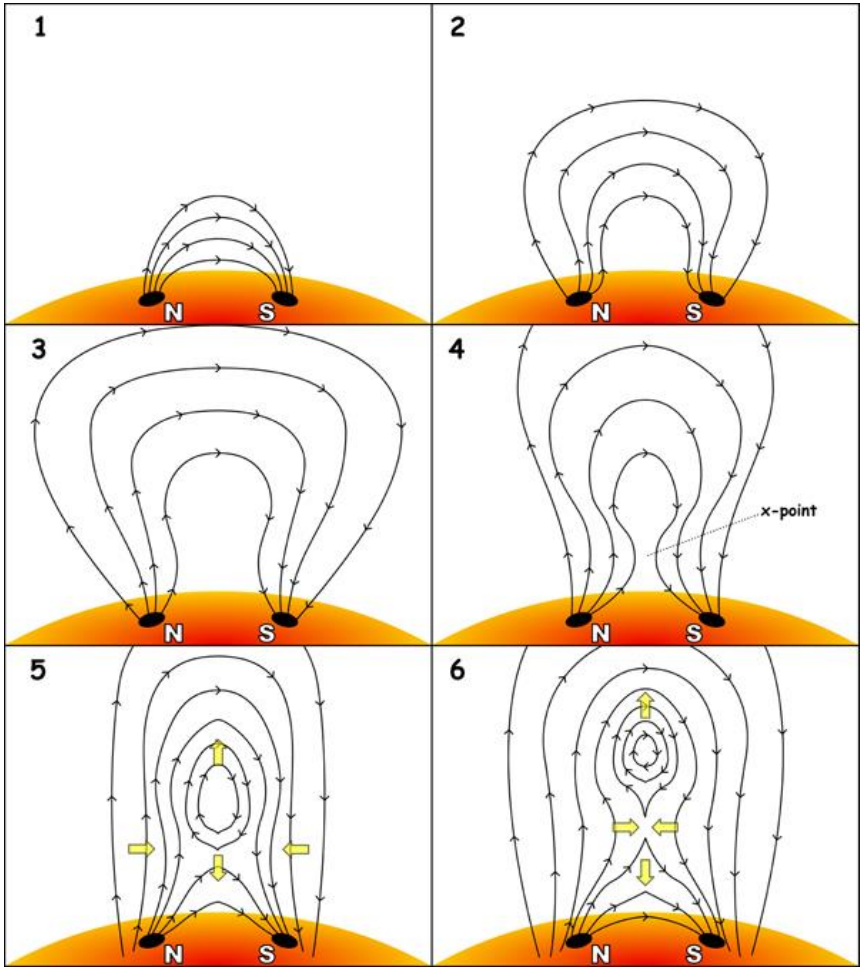
Reconnection



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

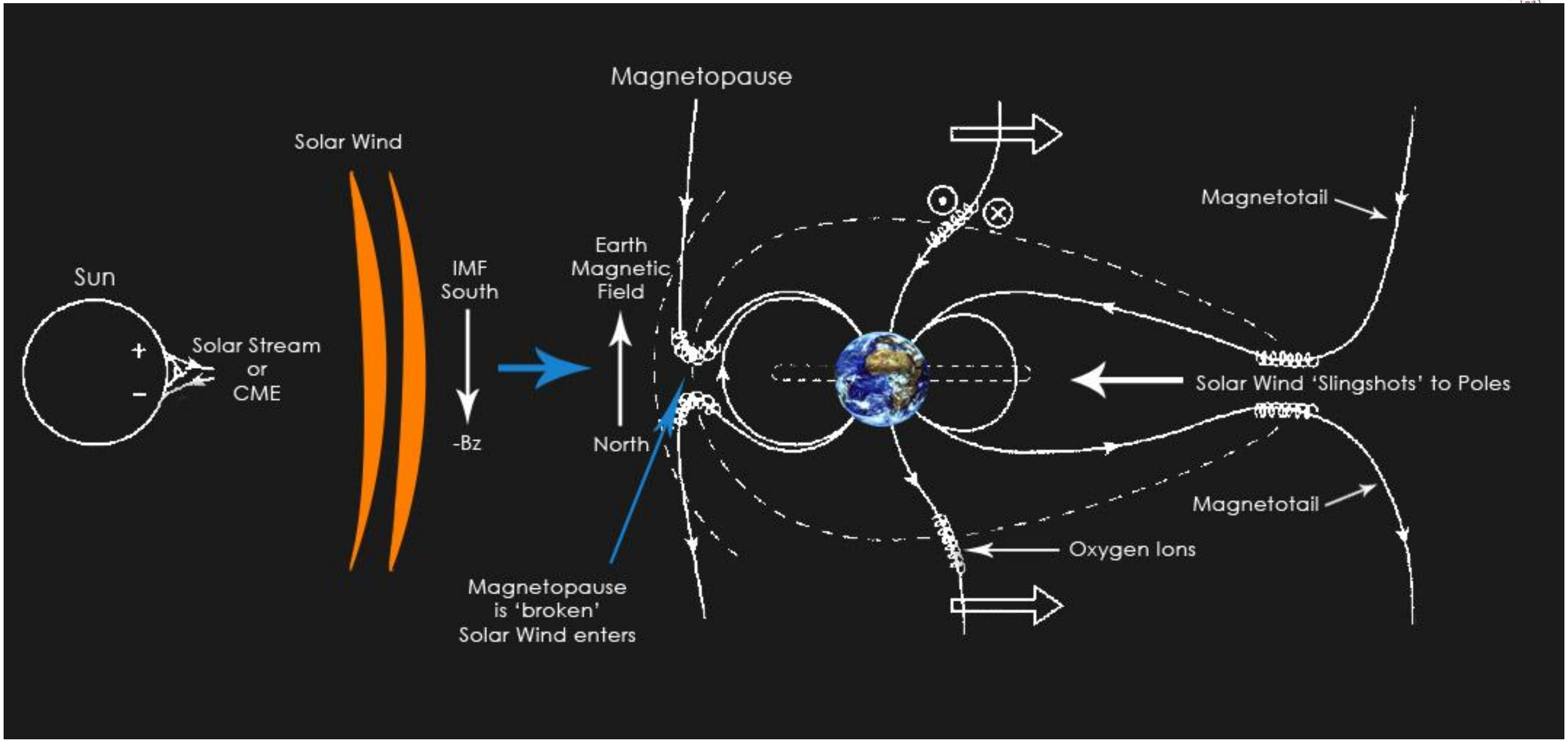
Corona mass ejection (CME)





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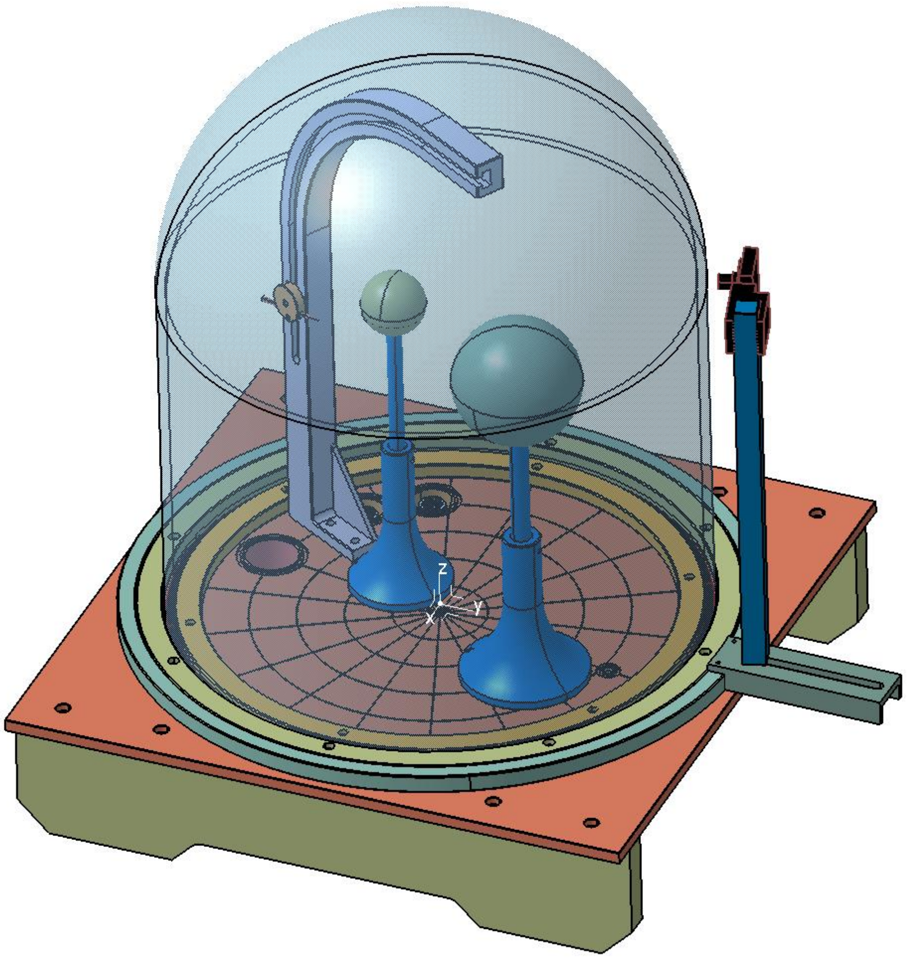
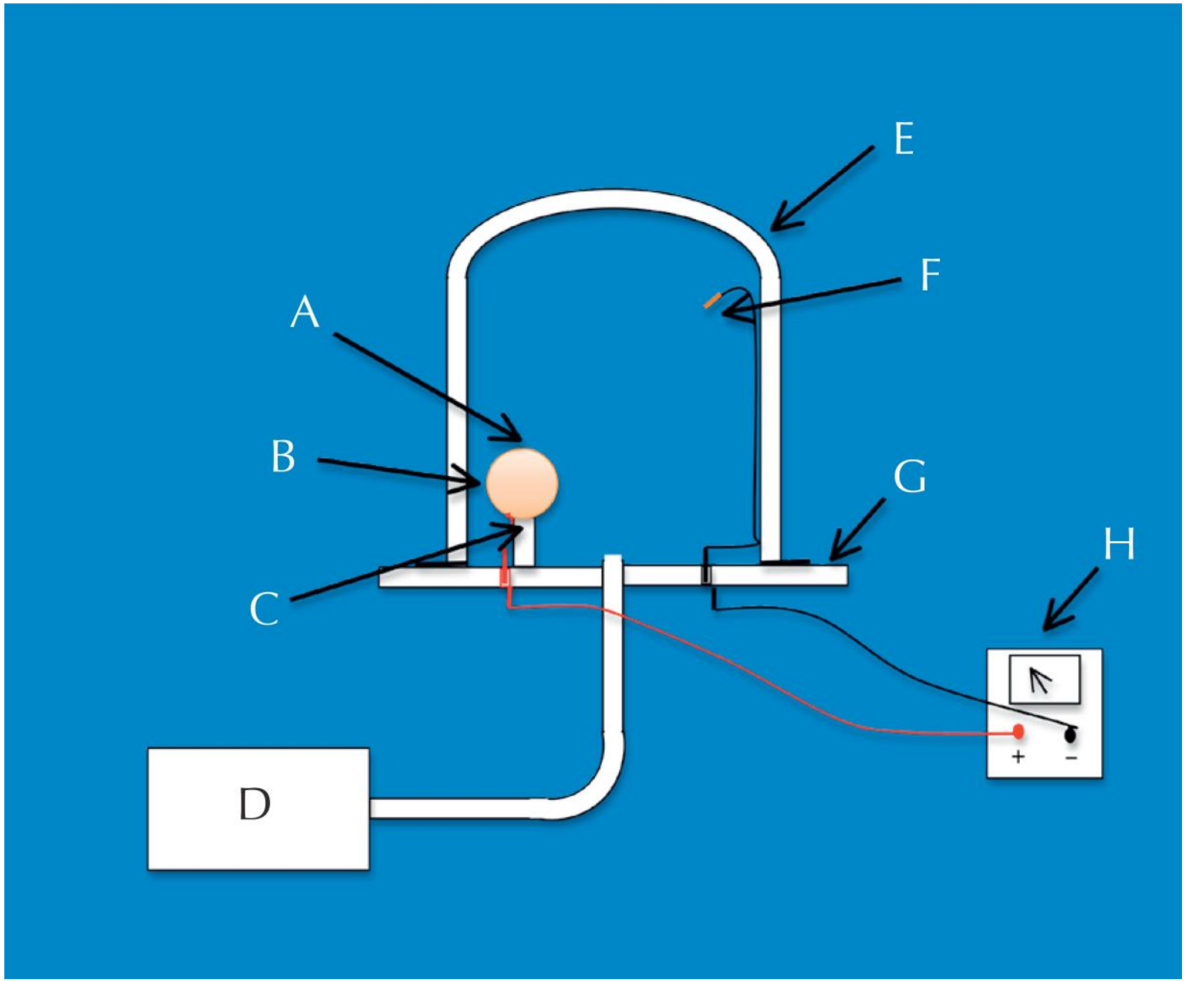
http://www.natalia-robba.com/myblog/travel/the-aurora-borealis-the-northern-lights-everything-you-need-to-know/

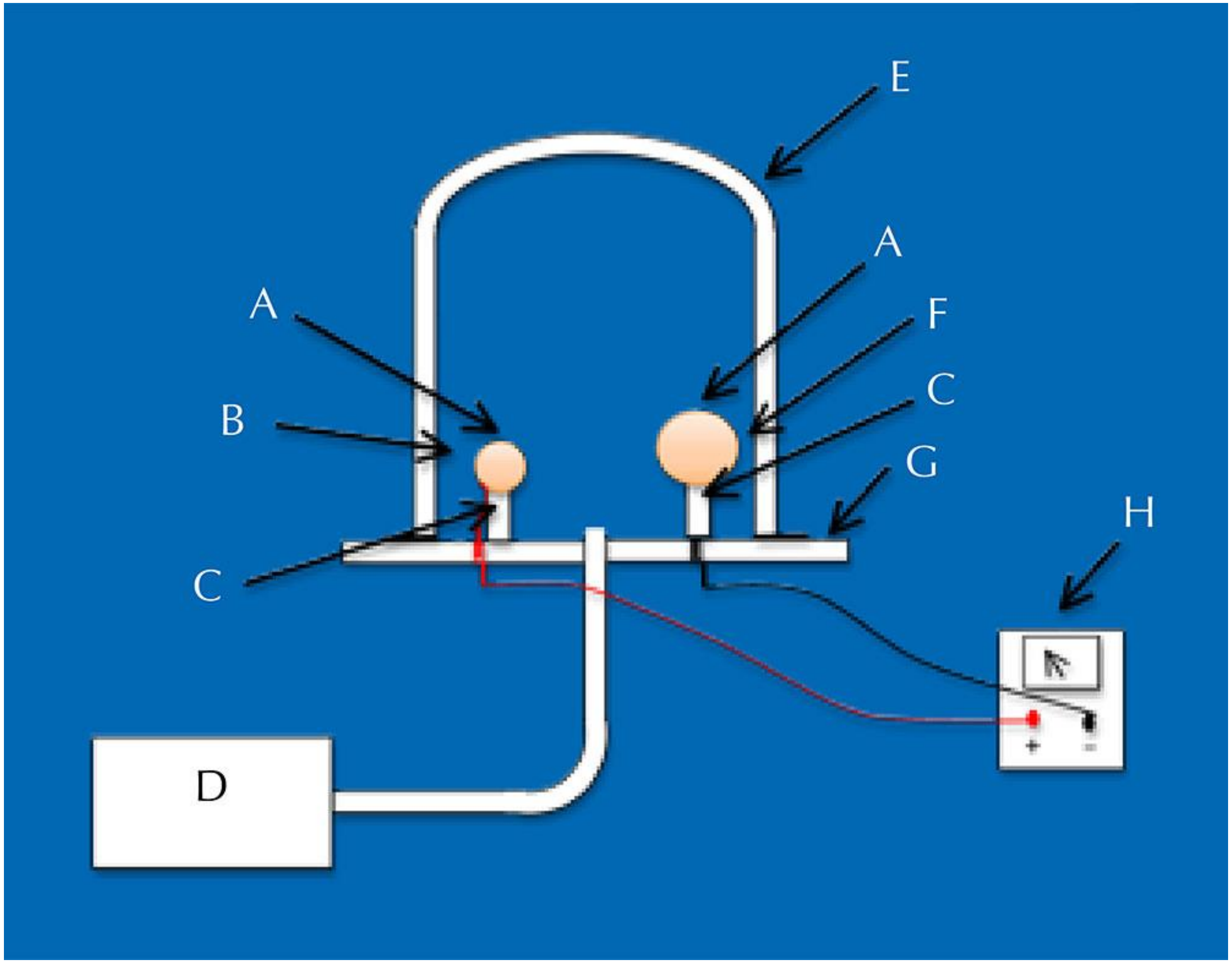
Planeterrella is an aurora simulator



Simple glow discharge is demonstrated

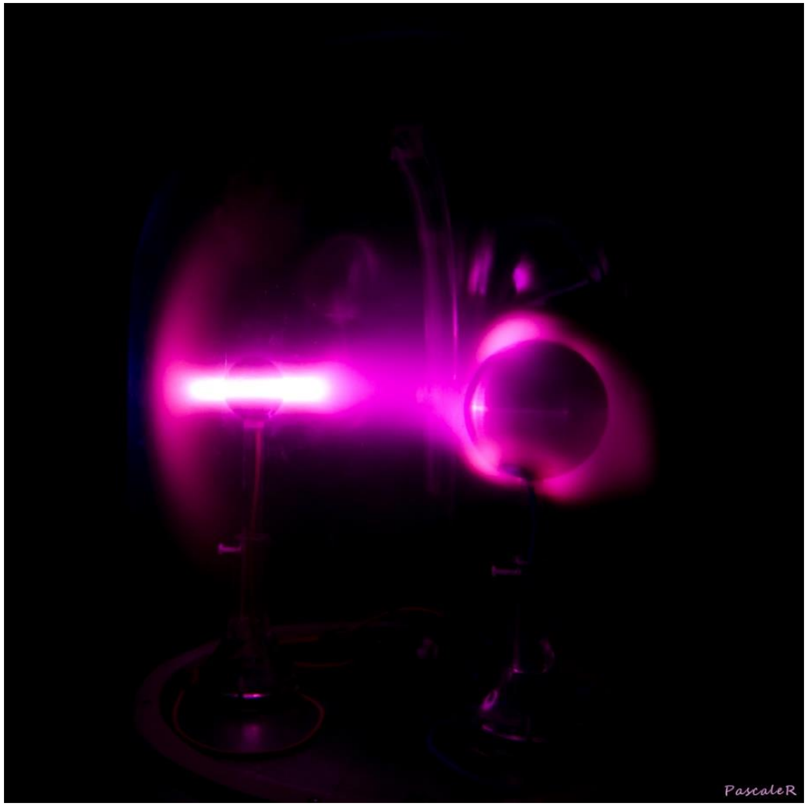


Aurora/ring current are demonstrated

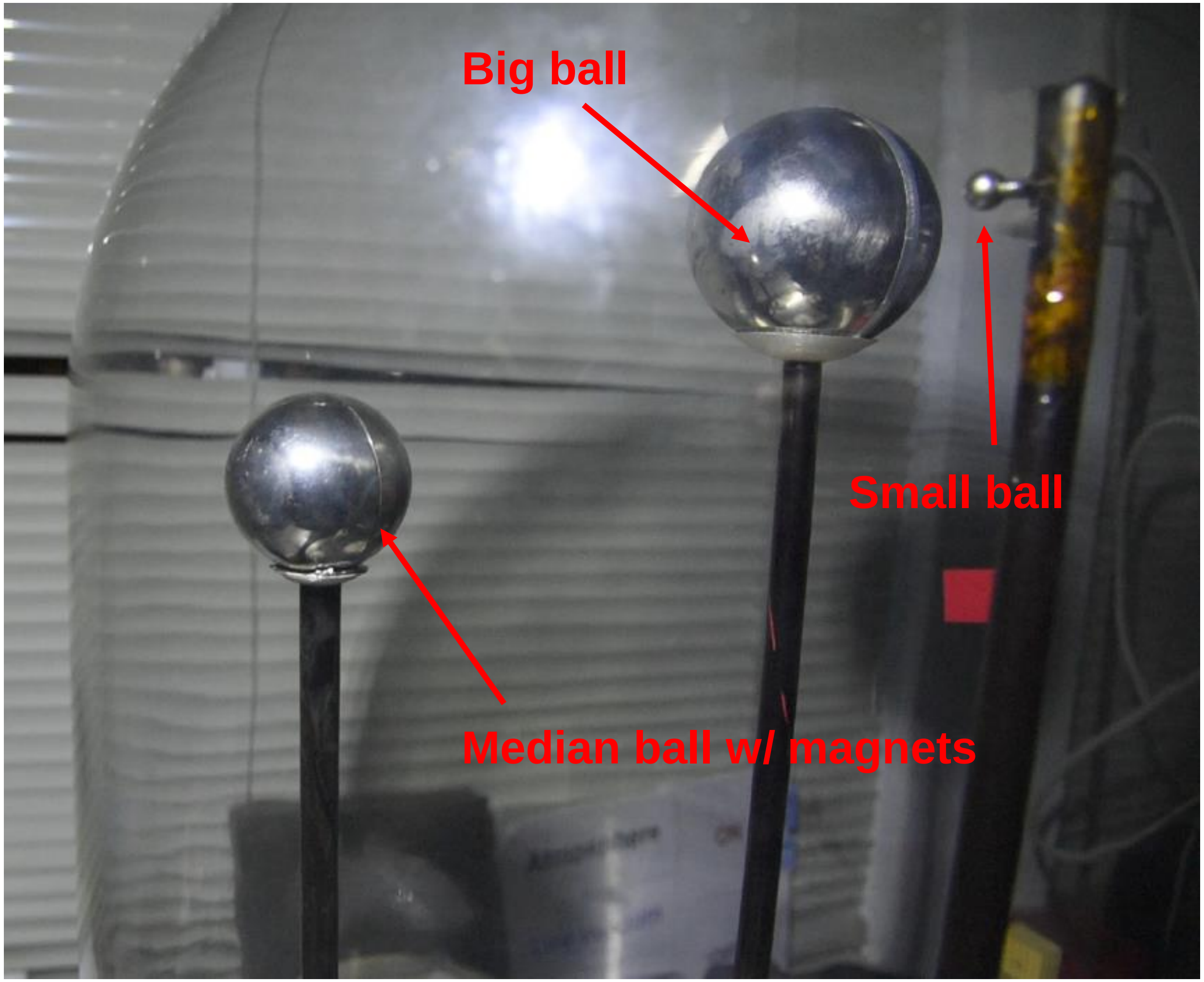


- **B w/ magnet: aurora demonstration**
- **F w/ magnet: ring current**

Aurora and ring current are expected to be seen

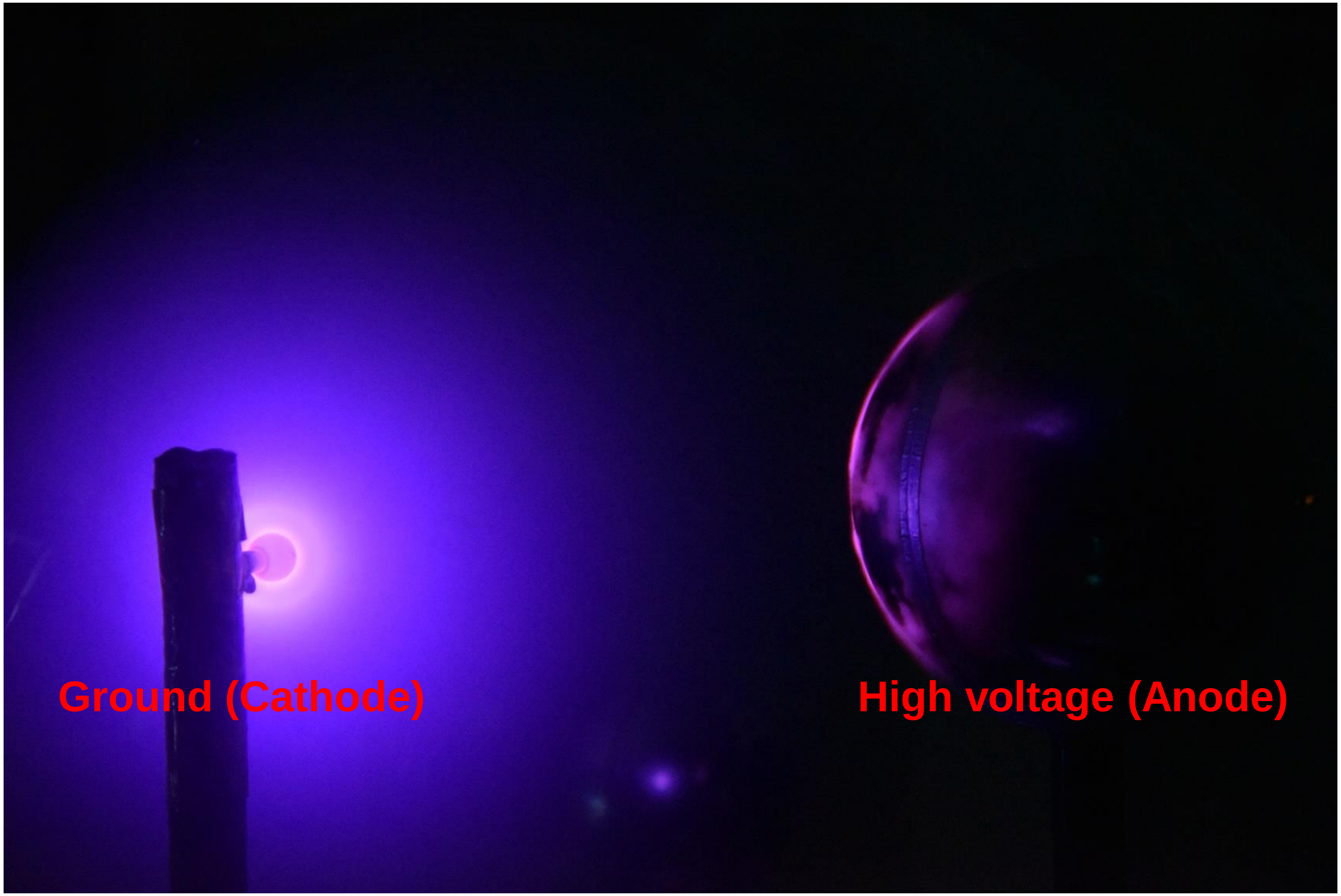


Our Planeterrella

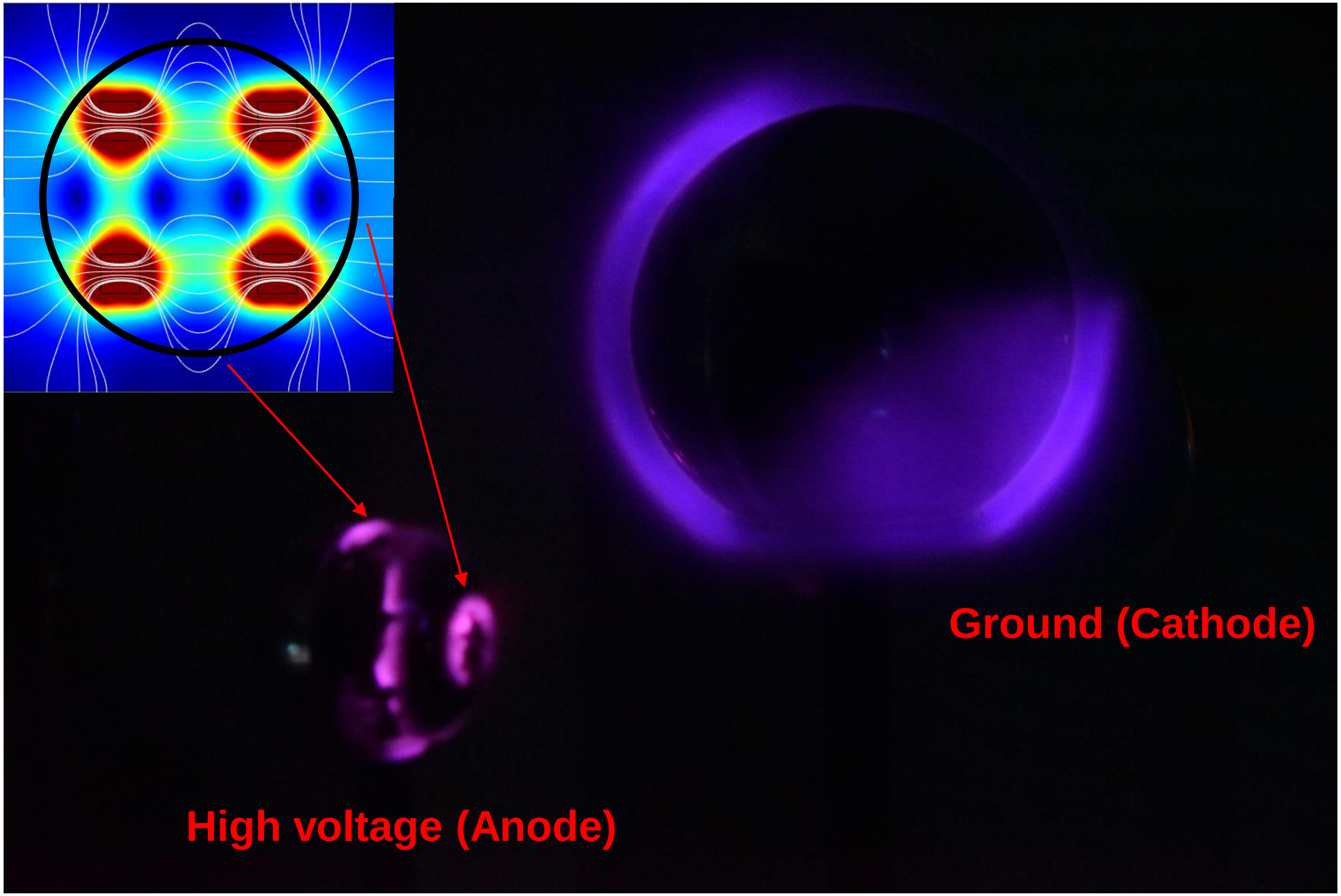


Show video.

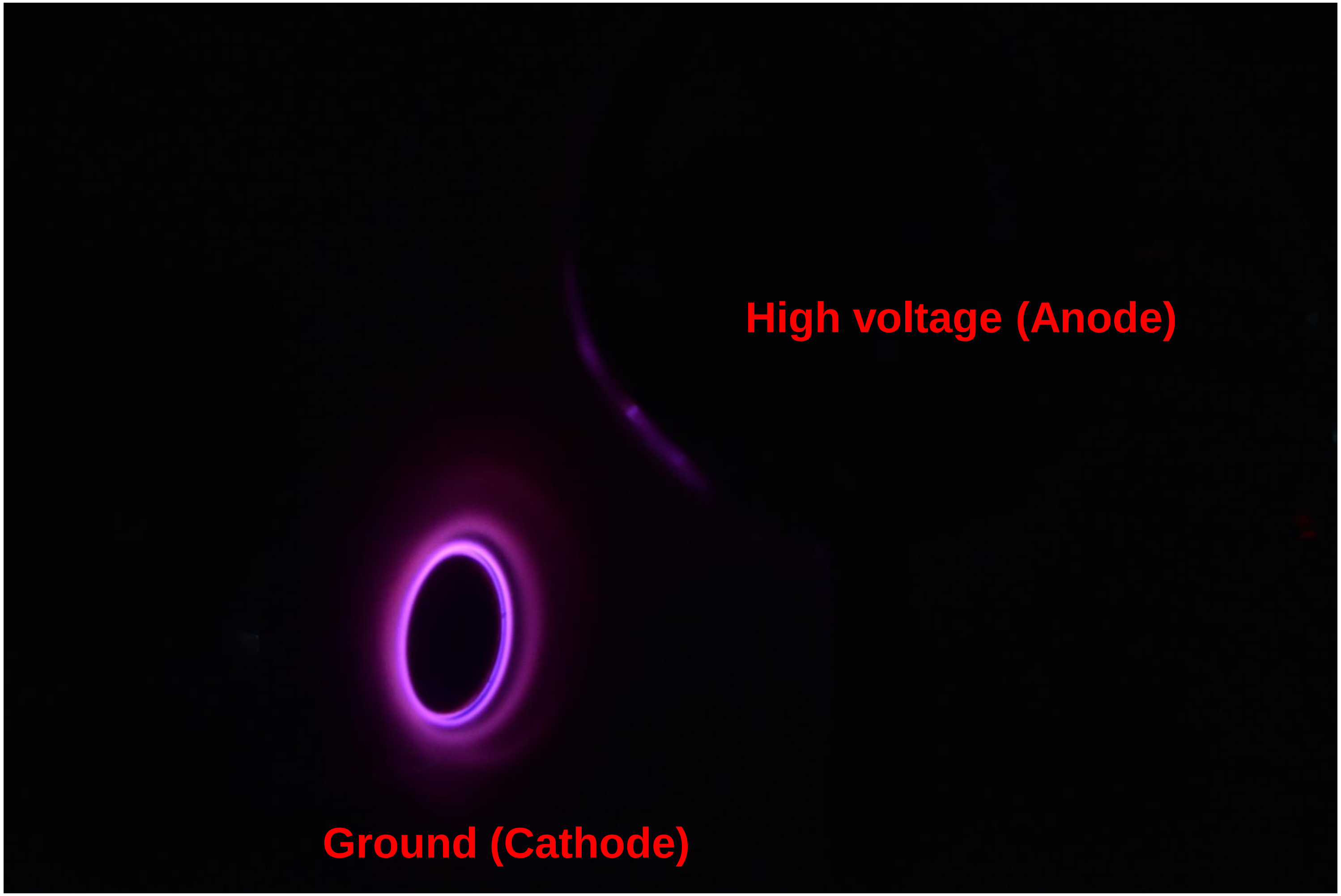
Glow discharge



Aurora demonstration



Ring current demonstration

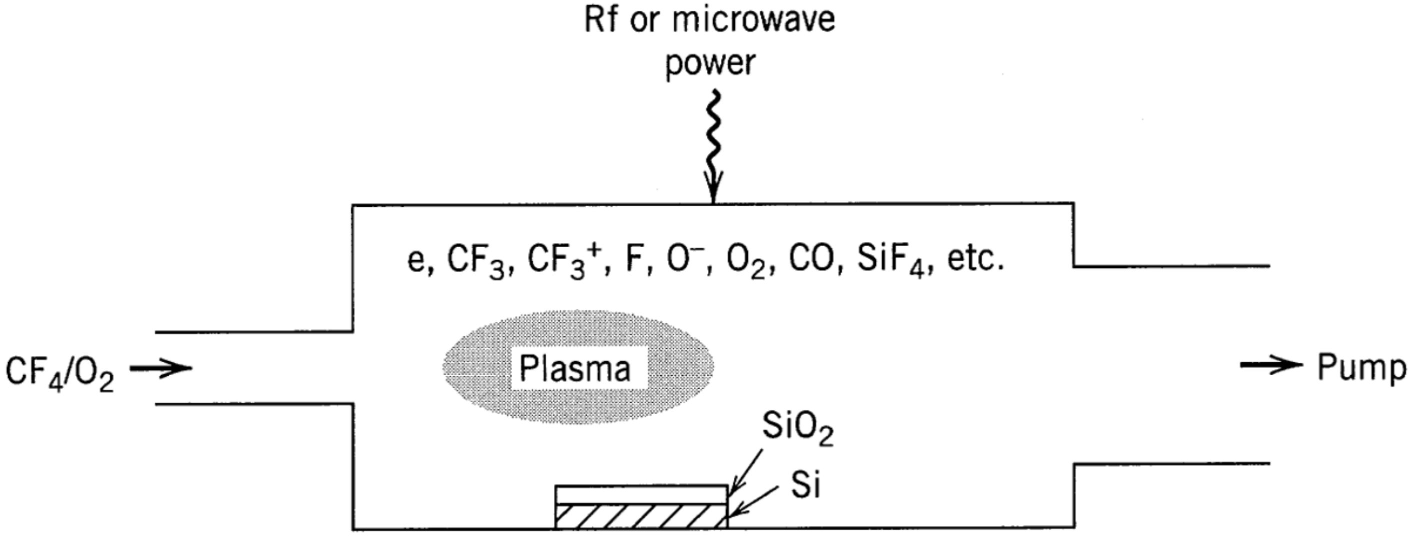


Course Outline

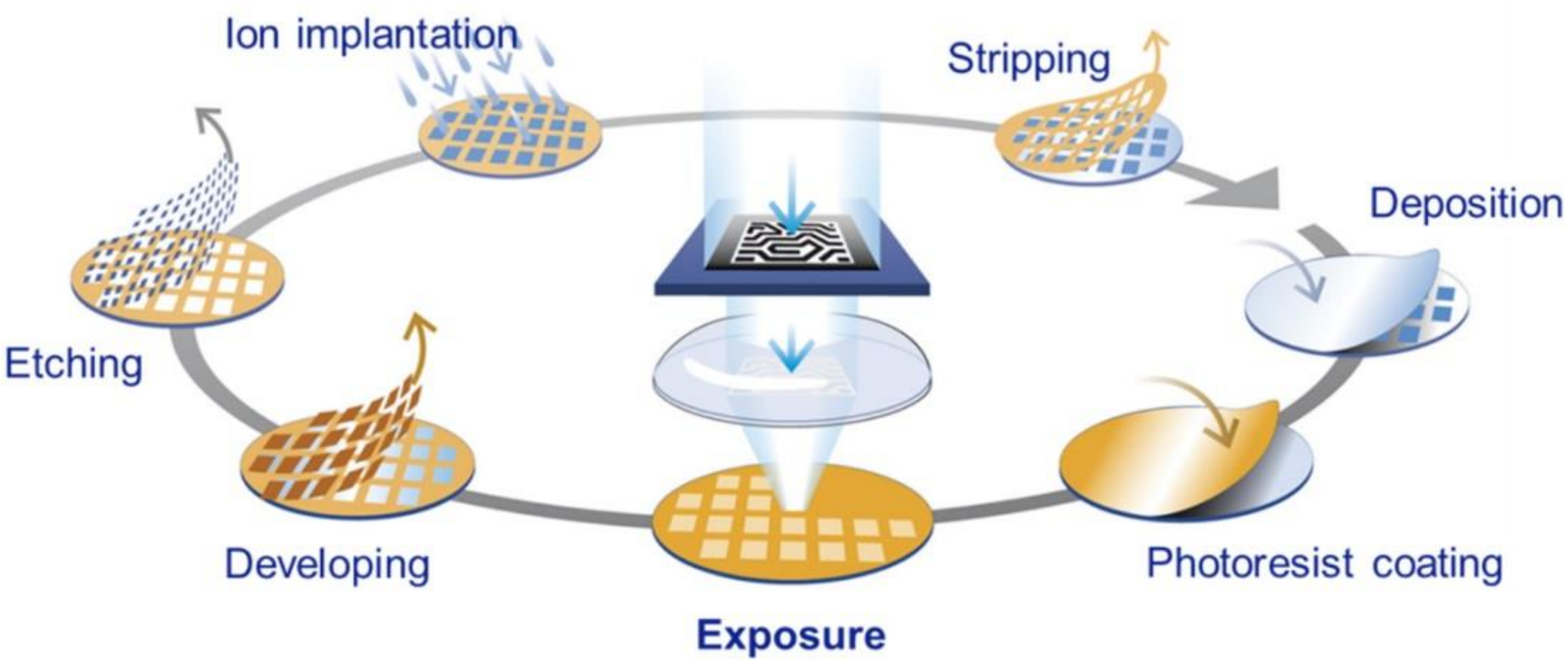
1. What is Plasma?
2. Varies kinds of plasma
   a. Plasma in space
   b. How plasma is generated
   c. Material Processing
   d. Biomedical application
   e. Pparticle beam source
   f. High energy particle accelerator
   g. Controlled thermonuclear fusion
   h. Neutral beam source
   i. Electrical propulsion

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



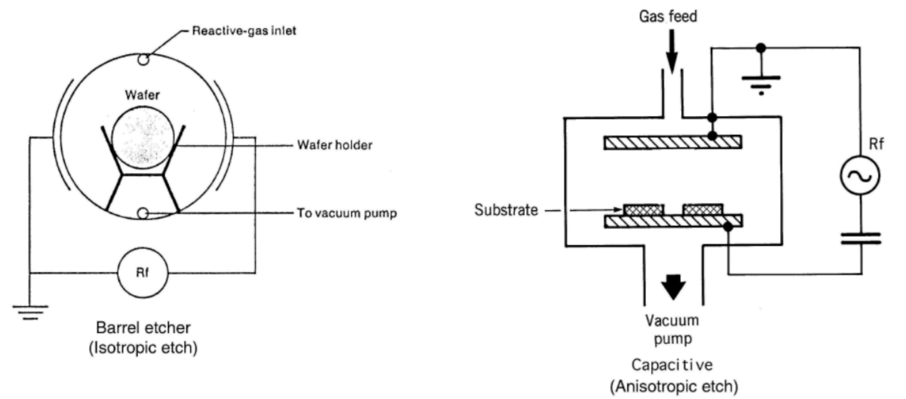
A semiconductor device is fabricated by many repetitive production process



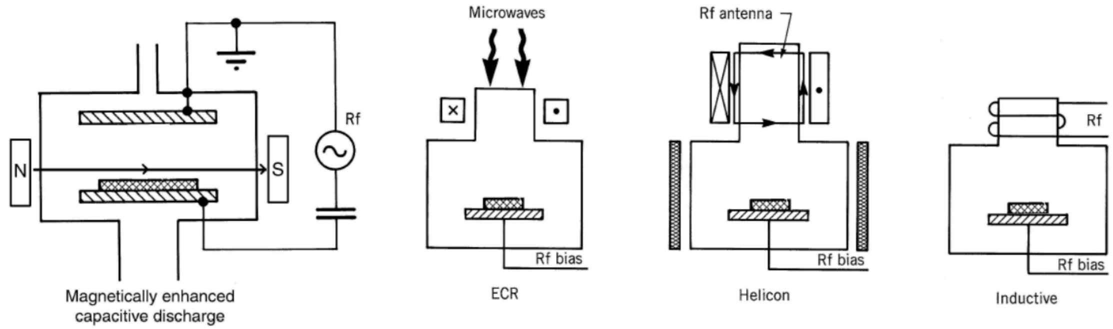
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

Evolution of etching discharges

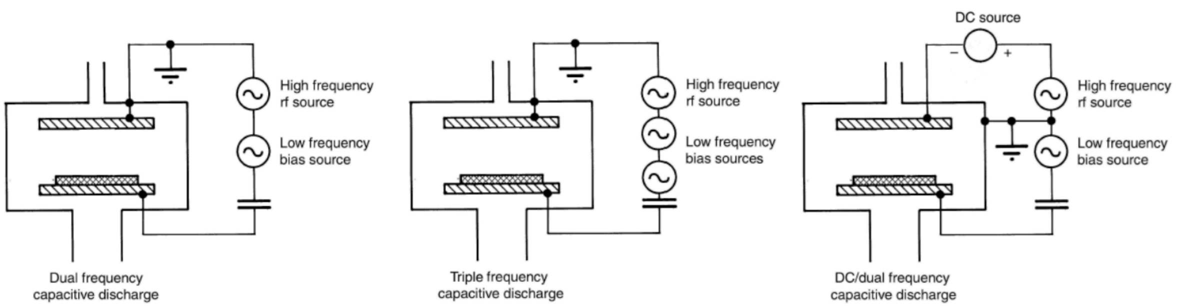
1st generation
(1 source, multi-wafer, low density)



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

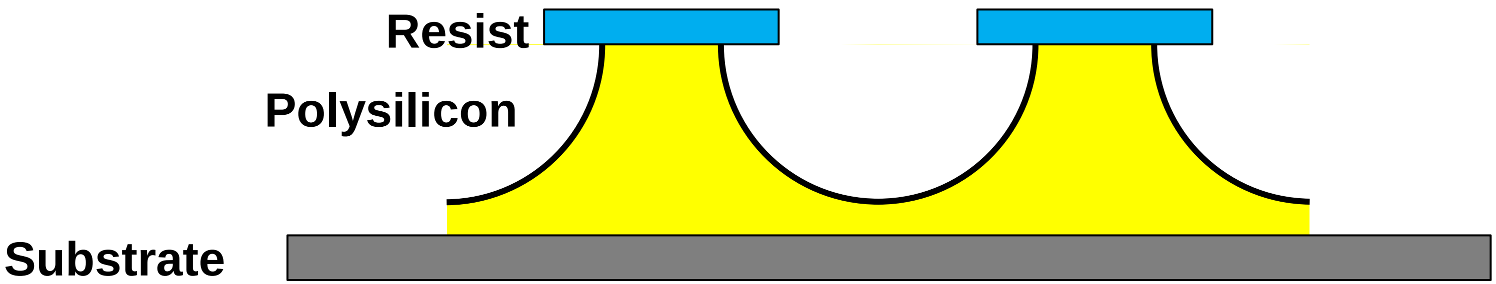


3rd generation
(multi-sources, single-wafer, moderate density)

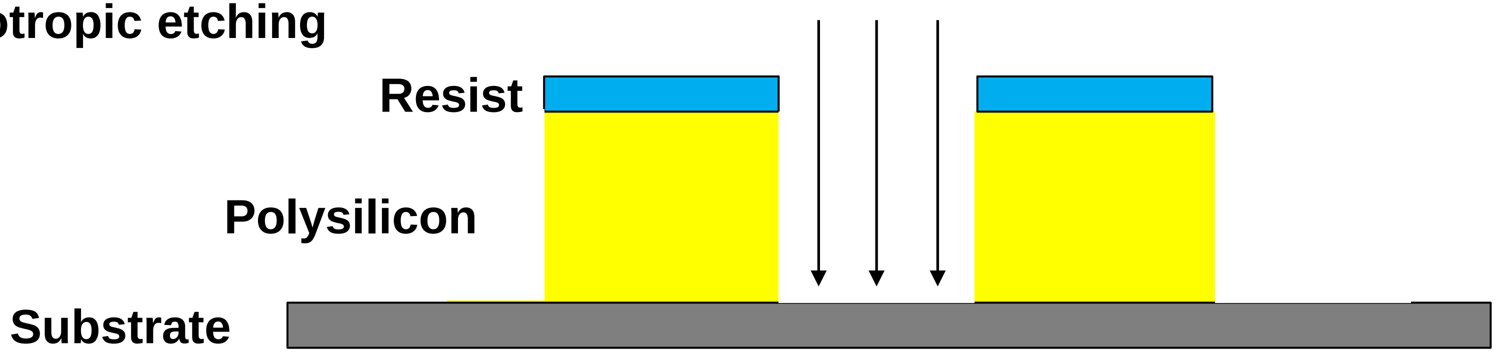


There are two types of etching: isotropic vs anistropic

- **Isotropic etching**

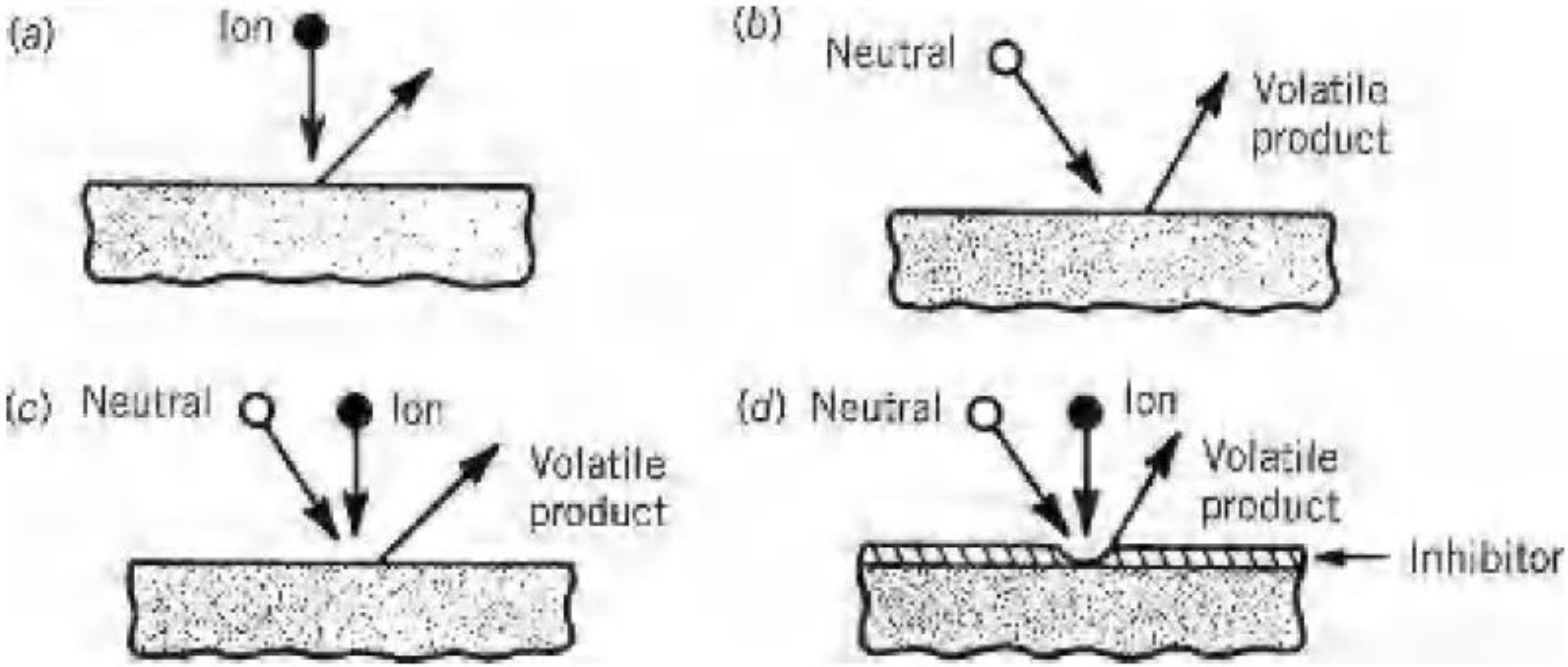


- **Anisotropic etching**



There are four major plasma etching mechanisms

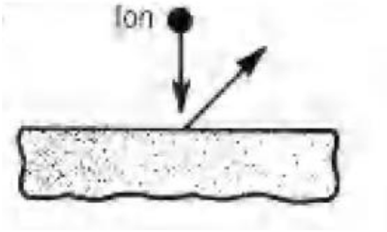
- **Sputtering**
- **Pure chemical etching**



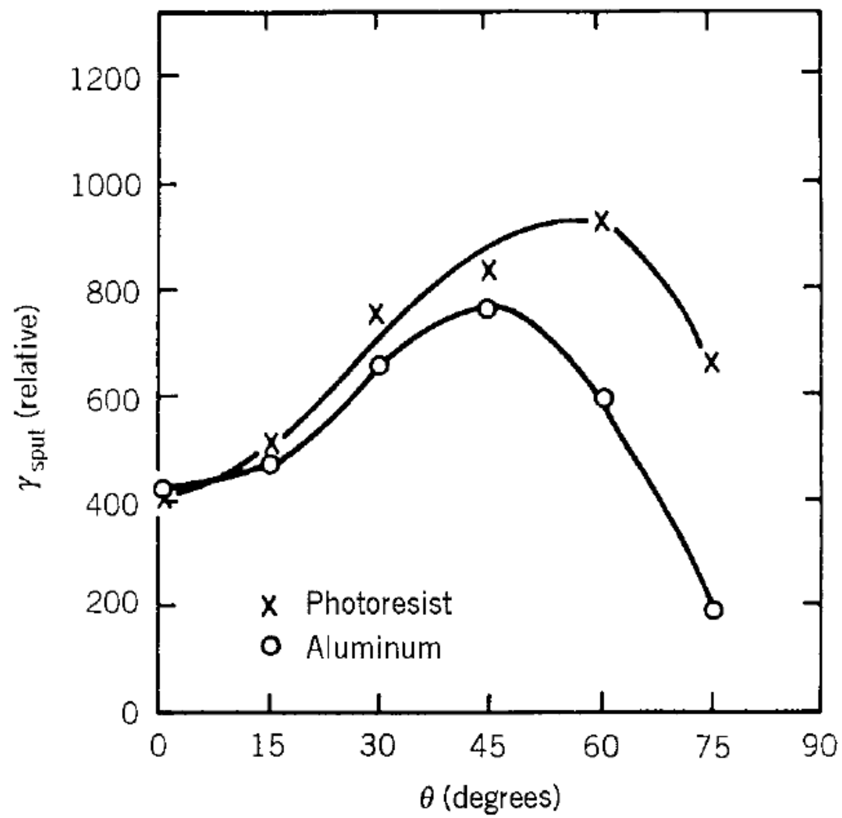
- **Ion energy-driven etching**
- **Ion-enhanced inhibitor etchin**

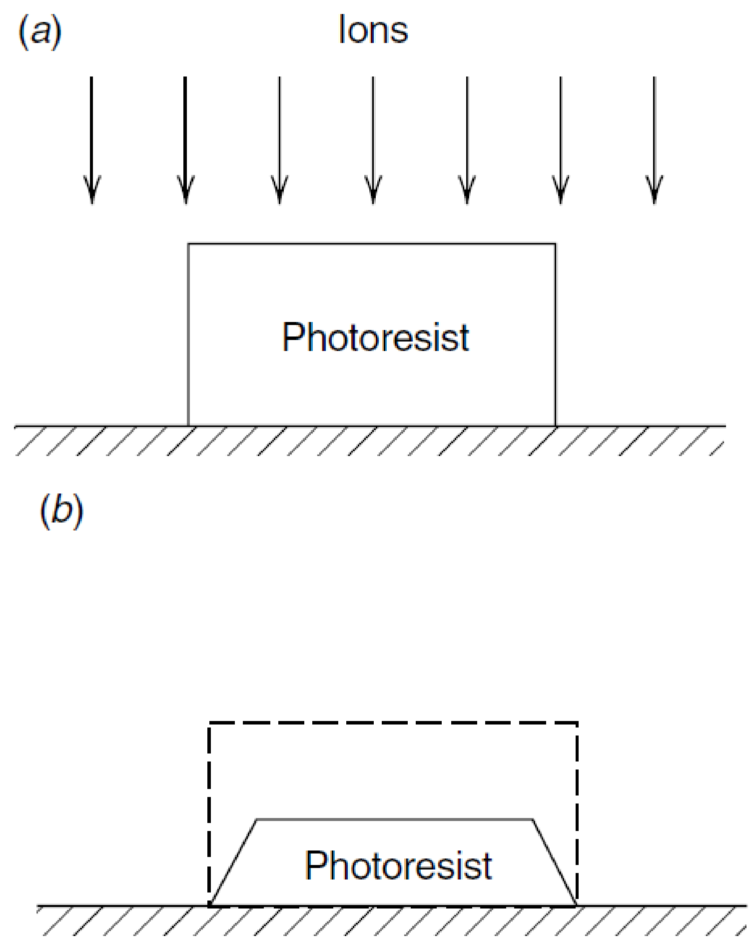
Sputtering is an unselective but anisotropic process

- 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

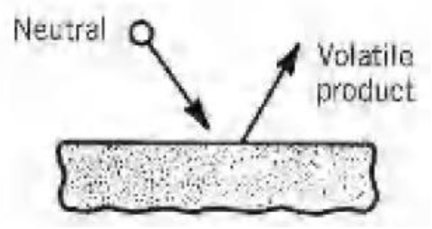




Pure chemical etching

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

- Highly chemically selective, e.g.,



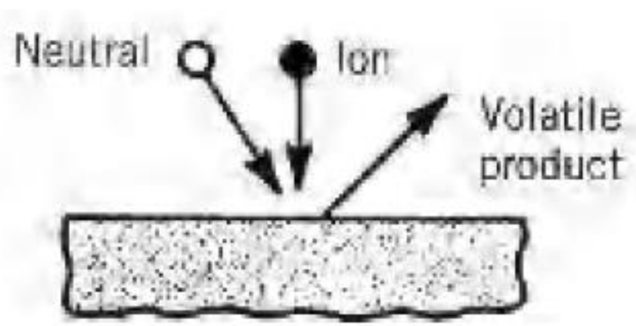
$$Si(s) + 4F \longrightarrow SiF_4(g)$$

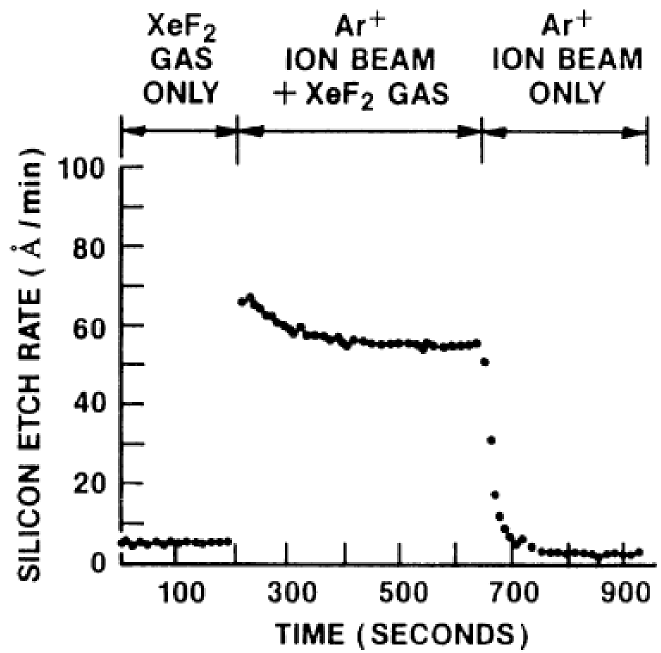
$$\text{photoresist} + O(g) \longrightarrow CO_2(g) + H_2O(g)$$

- 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**

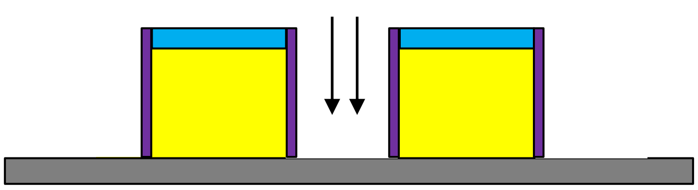
Ion-enhanced energy-driven etching has the characteristic of both sputtering and pure chemical etching

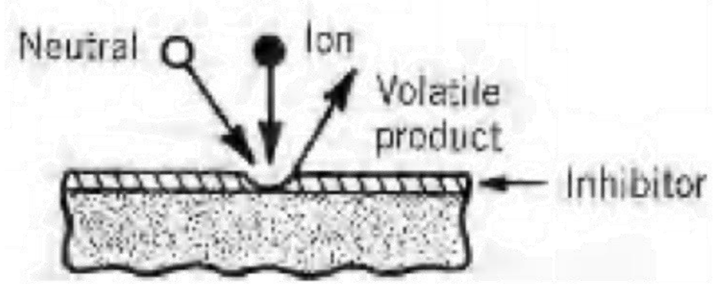
- **Chemical in nature but with a reaction rate determined by the energetic ion bombardment**
- **Product must be volatile**
- **Highly anisotropic**

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

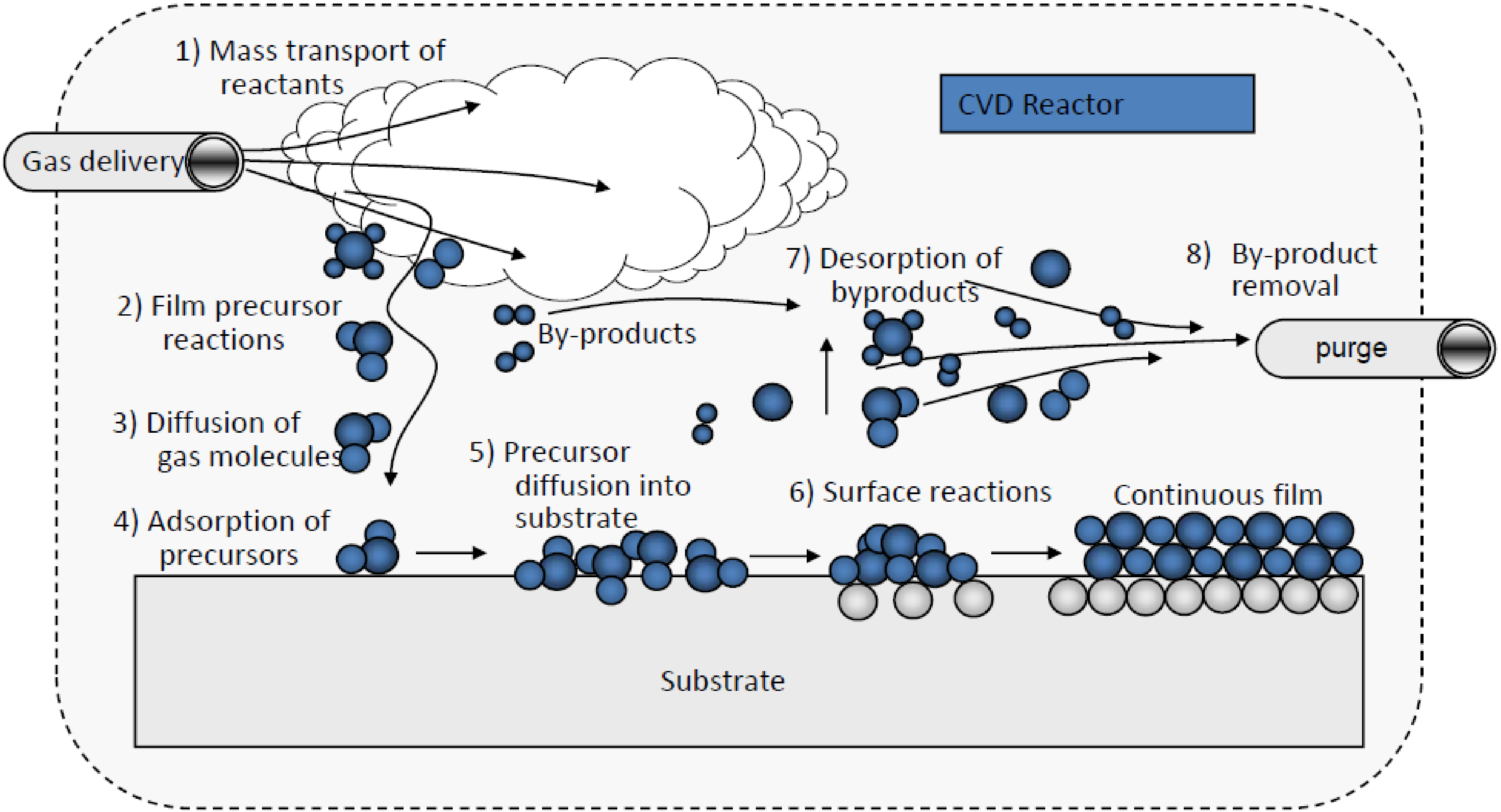
TABLE 15.1. Etch Chemistries Based on Product Volatility

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

Deposition and implementation

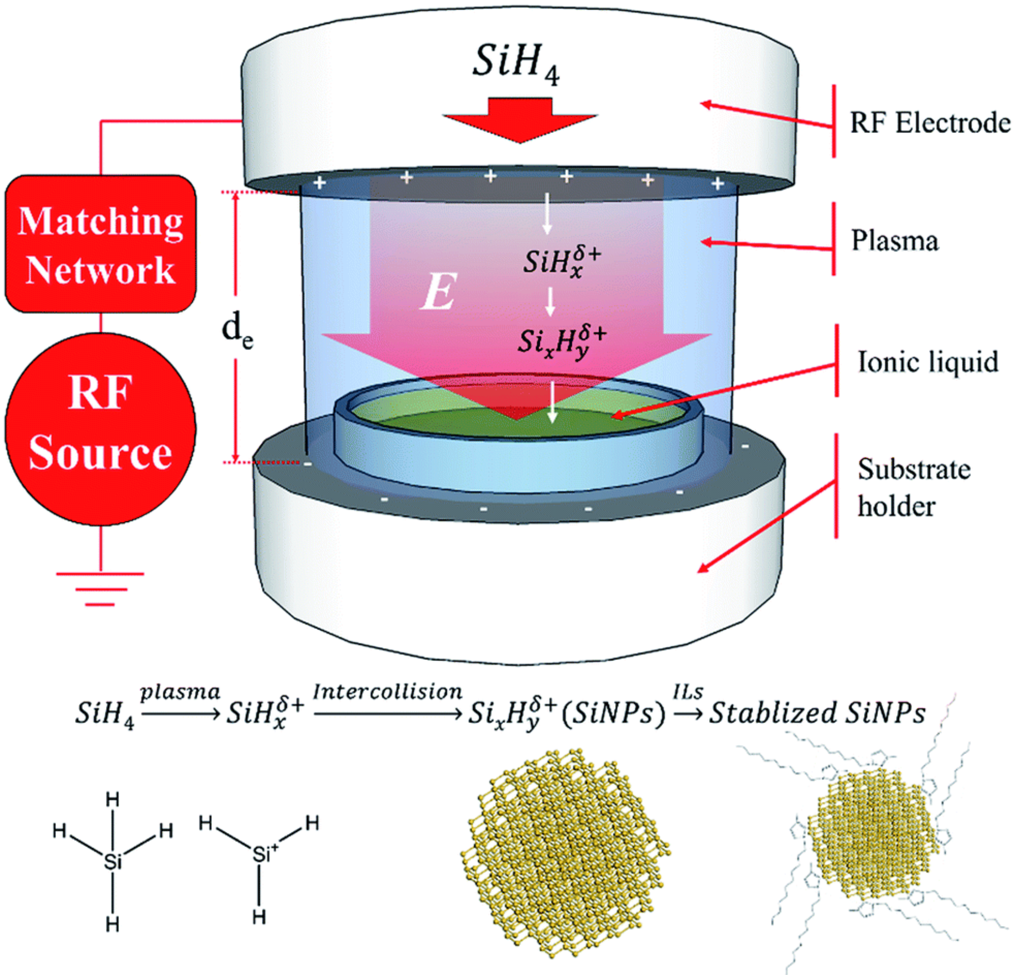
- Plasma-assisted deposition, implantation, and surface modification are important material processes for producing films on surfaces and modifying their properties
- Example processes:
  - Plasma-enhanced chemical vapor deposition (PECVD)
  - Sputter deposition / physical vapor deposition (PVD)
  -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

Chemical Vapor Deposition (CVD)



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

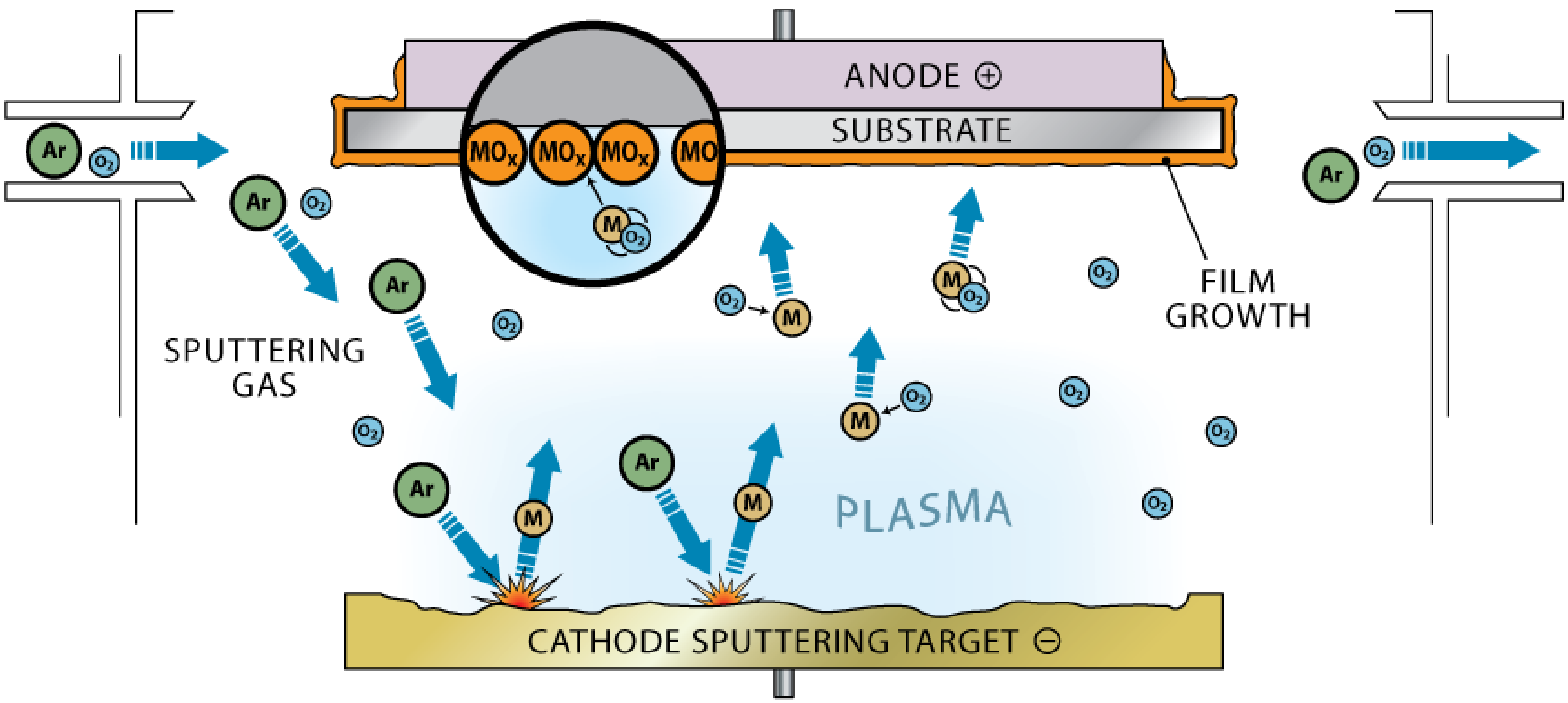
Plasma-enhanced chemical vapor deposition (PECVD)



Films can be deposited in low temperatures using plasma deposition

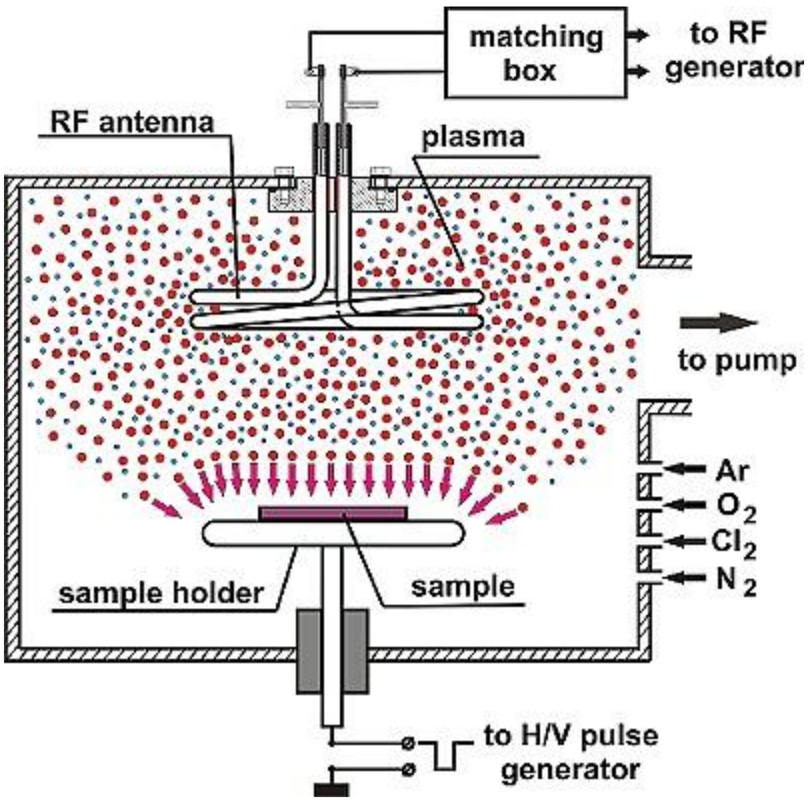
- **Device structures are sensitive to temperature, high-temperature deposition processes cannot be used in many cases**
- **High-temperature films can be deposited at low temperatures**
- **Unique films not found in nature can be deposited, e.g., diamond**

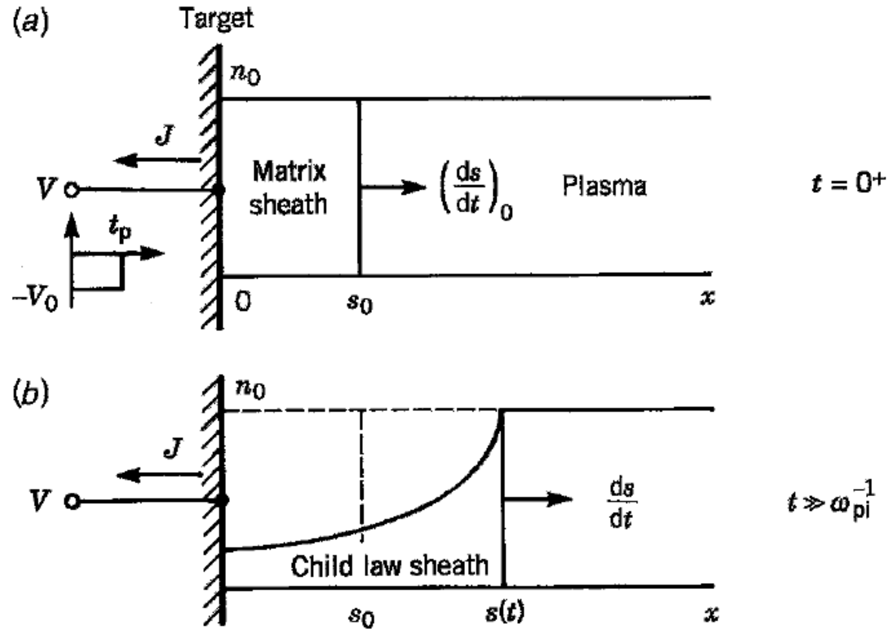
Sputtering deposition



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

Plasma-immersion ion implantation (PIII)



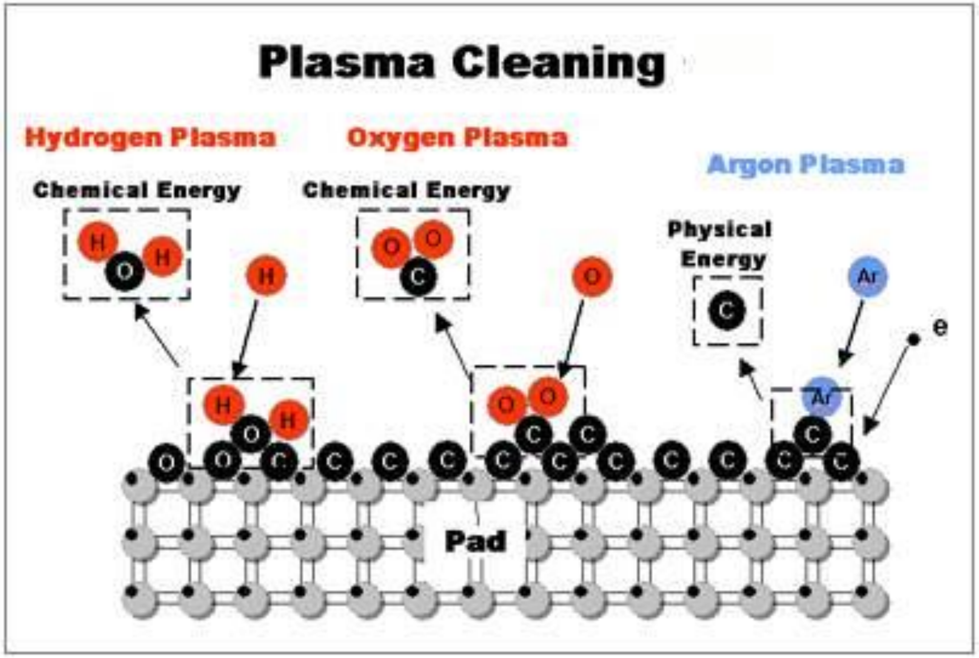


- Silicon doping – ions such as B, P, As are implanted
- Surface hardening of metals – N, C are implanted

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

Plasma can be used for cleaning surface

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



迪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 contaminatns of surface oxide.**
- **Both H• and O• can react with grease or oil on surface to form volatile hydrocarbons.**

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

$$\mathrm{O}\bullet_{(g)} + C_nH_{2n+2(s)} \rightarrow \mathrm{CO}_{(s)} + \mathrm{CH}_xO_{y(g)} + H_2O_{(g)}$$

- 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.

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

$$\mathrm{H}\bullet + \mathrm{MeO} \rightarrow \mathrm{Me} + H_2O$$

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

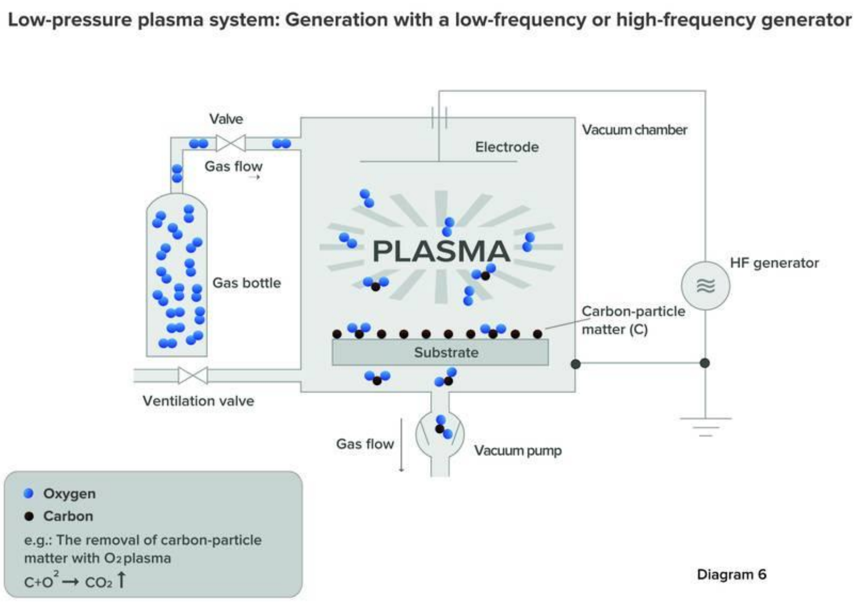
- Ions generated in plasma can be accelerated toward the substrate to physically bombard away the atoms of contaminants.
- The physical sputtering rate increases as the following quantities increase:
  - Plasma density;
  - Accelerating voltage;
  - Mass of bombardment atoms.
- The physical sputtering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

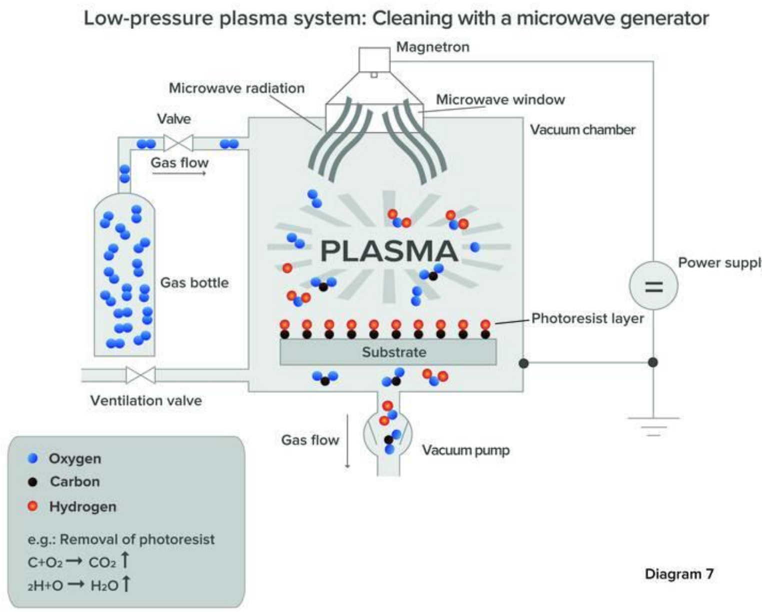
The physical sputtering rate increases with higher cathode bias and Ar concentration and lower pressure

- **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.**

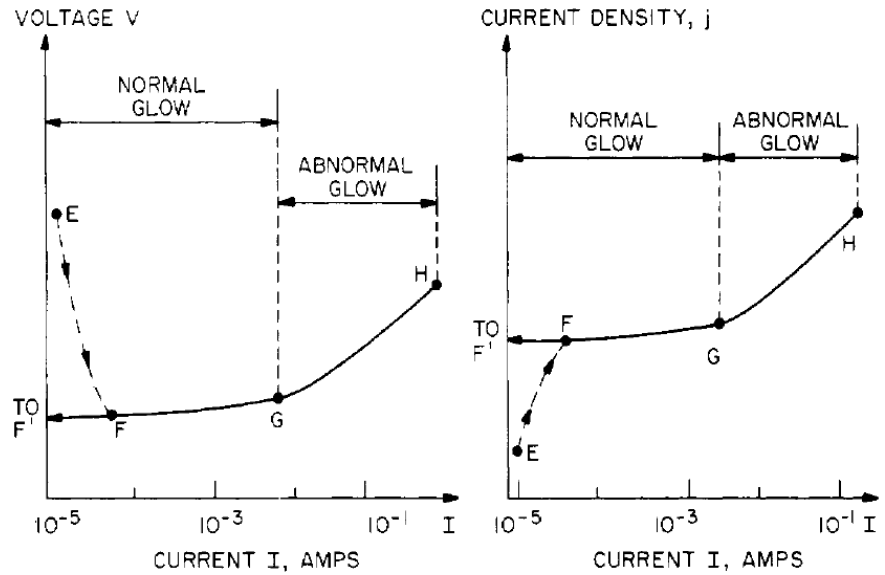
Plasma cleaning examples





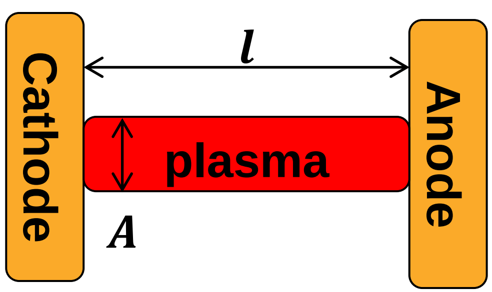
https://www.plasma.com/en/plasmatechnik/low-pressure-plasma/cleaning/

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

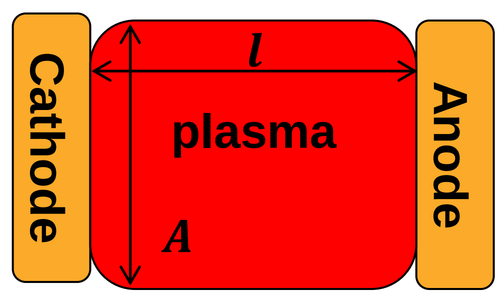


$$R = \eta \frac{l}{A}$$

- **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