Application of Plasma Phenomena

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Lecture 3

2024 spring semester

Tuesday 9:10-12:00

Materials:

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

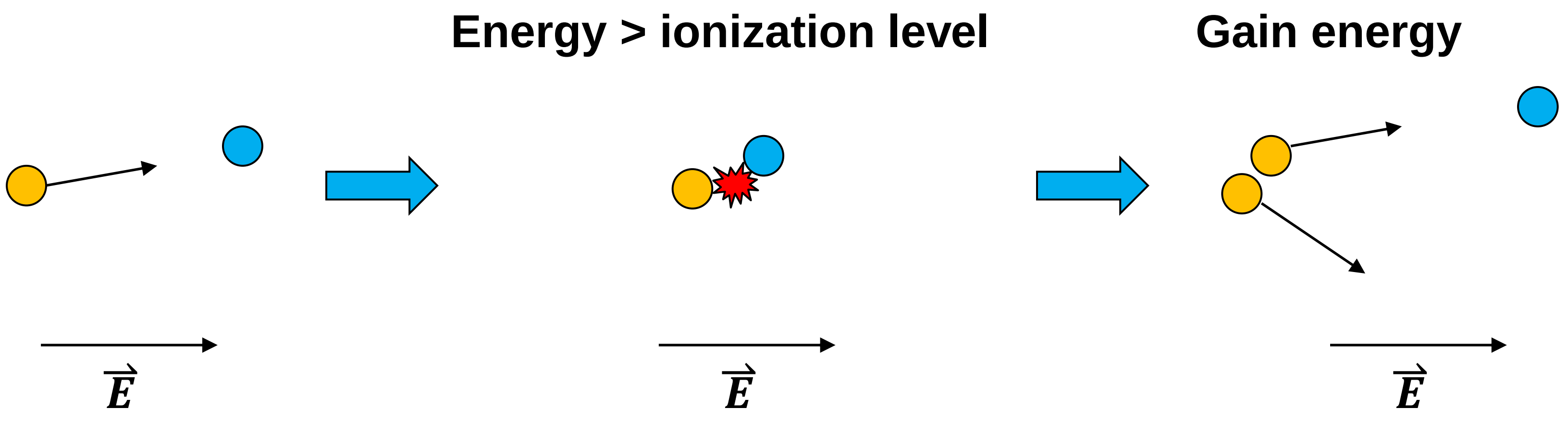
Online courses:

https://nckucc.webex.com/nckucc/j.php?MTID=m4082f23c59af0571015416f6e58dd803

2024/3/12 updated

Collisions play an important role in ionization process

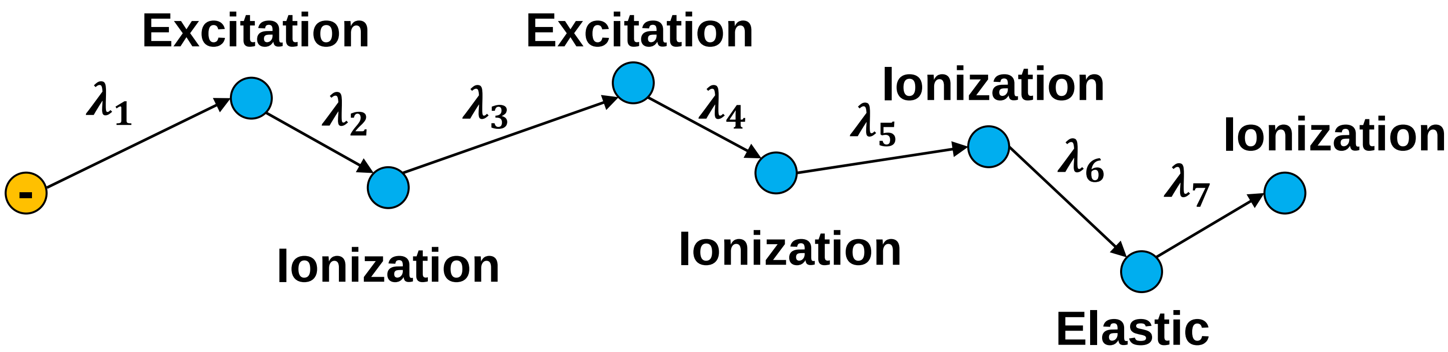
- At the microscopic level, breakdown requires the presence of sufficiently energy charge particles that have acquired enough energy from the applied electric field between two energy-dissipating collisions to ionize the material and to create more charge particles.



More complex collisions

- **Total collisional cross section:**

$$\sigma(v) = \sigma_{\mathrm{el}} + \sigma_{\mathrm{ex}} + \sigma_{\mathrm{ion}} + \cdots = \Sigma_i \sigma_i$$

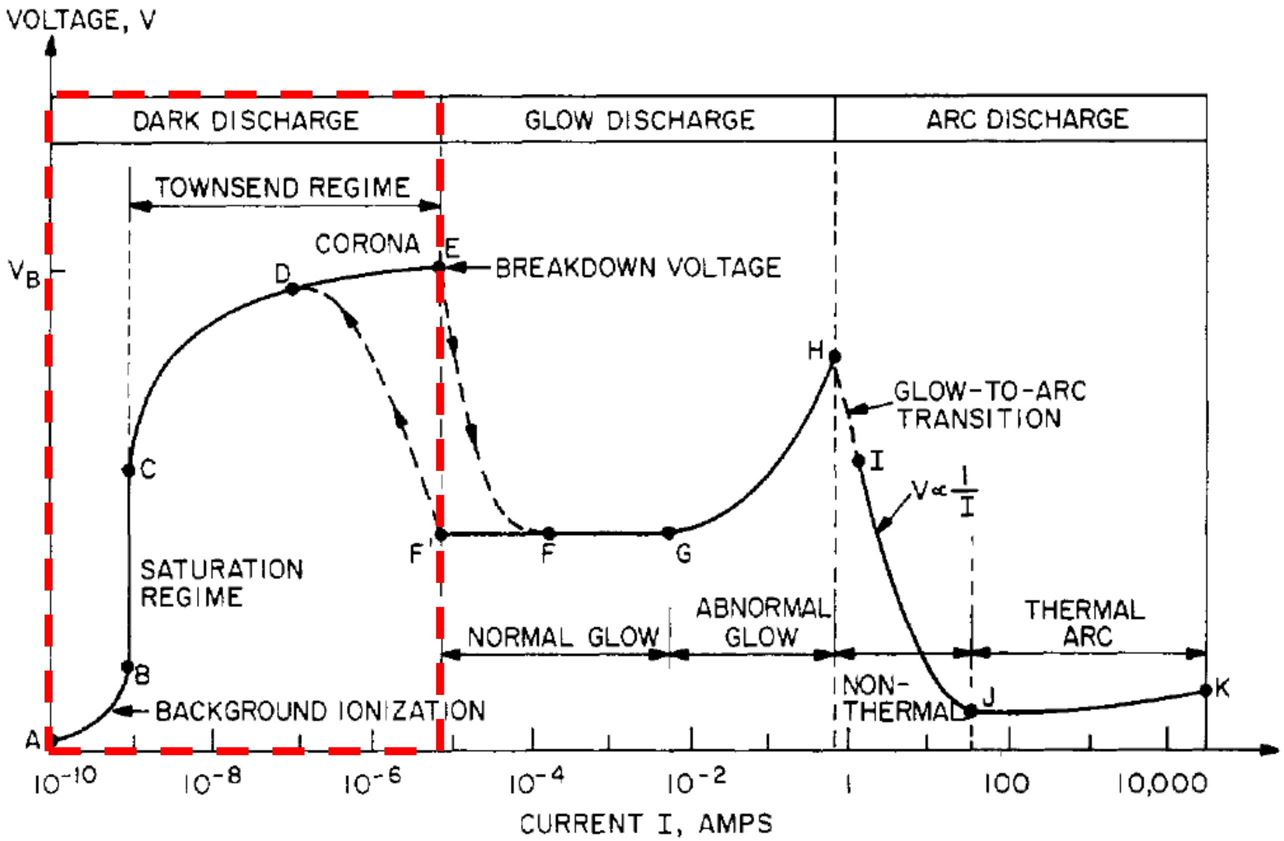


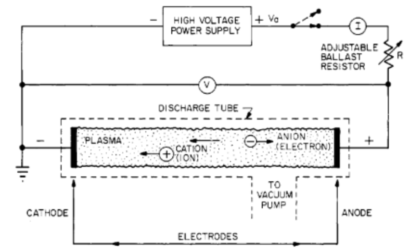
- **Inert gas can be ionized easier since there are less exciting state compared to gas molecules.**
- **Molecules, e.g., SF_6, dry air (with O_2), that capture electron easier provides a higher breakdown voltage.**

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

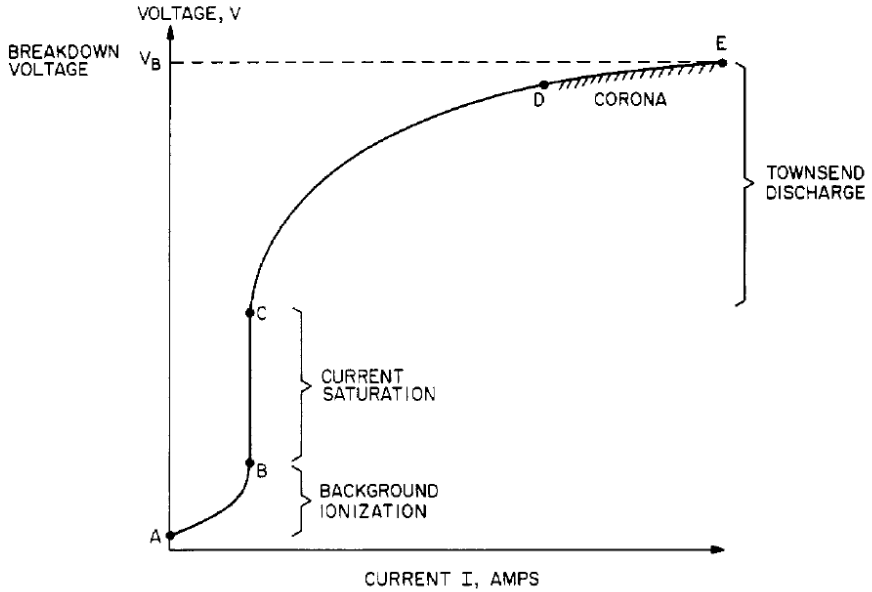
In a dark discharge, the excitation light is so little and is not visible

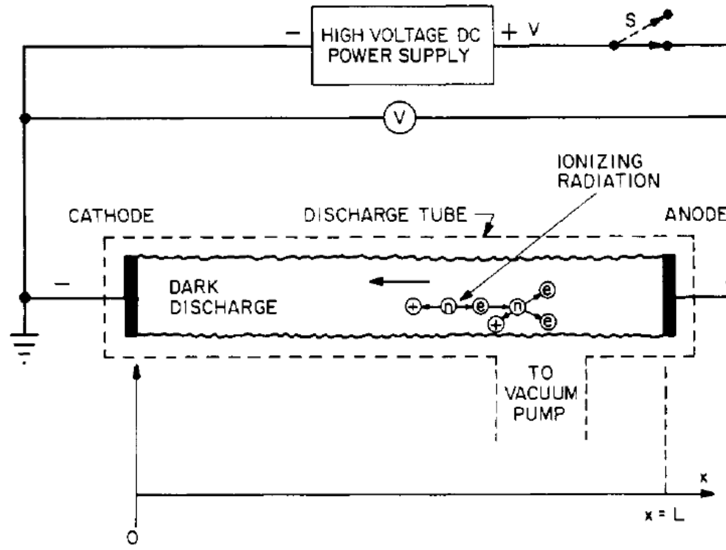




- In dark discharge, with the exception of the more energetic corona discharges, the number density of excited species is so small so that it does not emit enough light to be seen by a human observer.

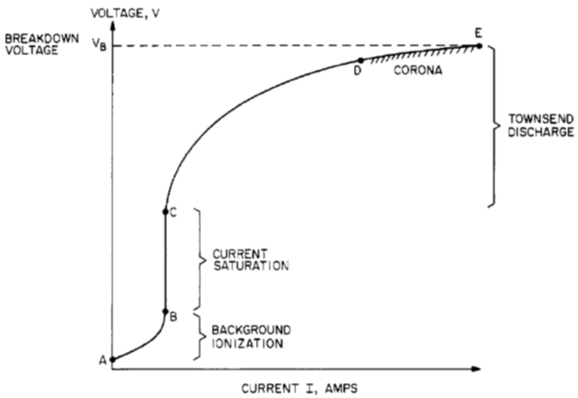
In background ionization, ions and electrons are created by ionization from background radiation

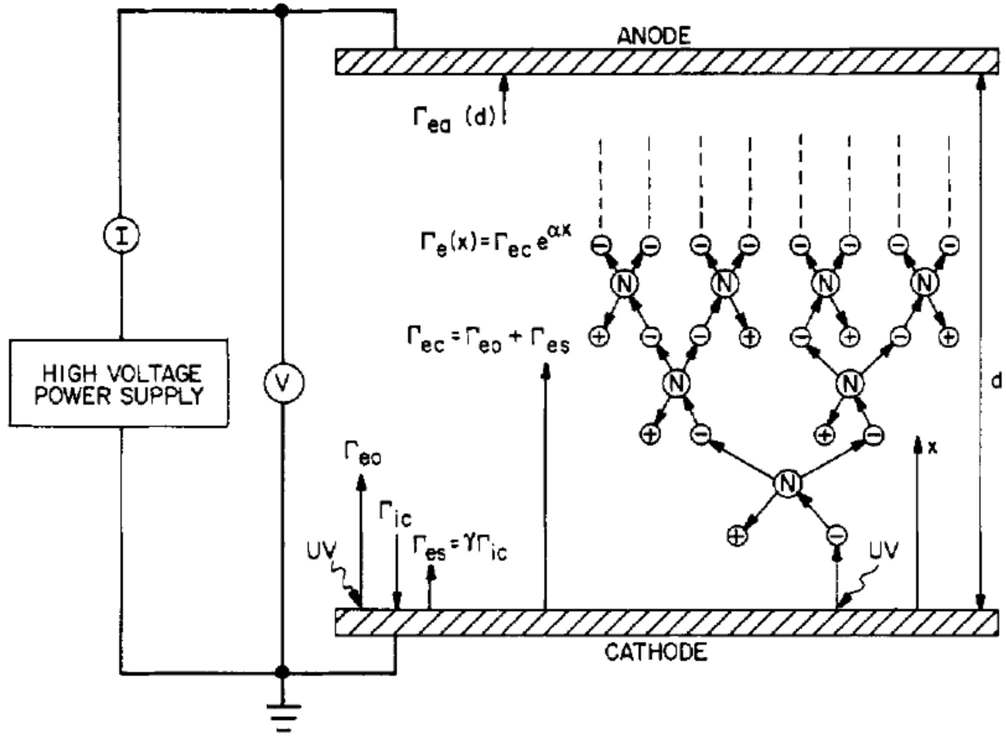




- **Sources of background radiation:**
  - **Cosmic rays**
  - **Radioactive minerals in the surroundings**
  - **Electrostatic charge**
  - **UV light illumination**
  - **Other sources**

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





- **Electrons from photo- or secondary electron emission from the cathode:**

$$\Gamma_{ec} = \Gamma_{e0} + \Gamma_{es}\left(\text{electrons}/m^2 - s\right)$$

- **Volume ionization source from the ionization of the background gas by energetic electrons accelerated in the electric field:**

$$S_e = R_e = n_e n_0 \langle\sigma v\rangle_{ne}$$

Derivation of Townsend's first ionization coefficient

$$\frac{1}{\lambda_i} = \frac{\nu_{\mathrm{ei}}}{\bar{v}_e} = \frac{n_0\langle\sigma v\rangle_{\mathrm{ne}}}{\bar{v}_e} = \frac{p}{T}\frac{\langle\sigma v\rangle_{\mathrm{ne}}}{\bar{v}_e} \equiv Ap \qquad A \equiv \frac{1}{T}\frac{\langle\sigma v\rangle_{\mathrm{ne}}}{\bar{v}_e}$$

- Number of primary electrons with energy higher than the ionization potential:

$$dn_e = -n_e\frac{\mathrm{d}x_i}{\lambda_i} \quad \Rightarrow \quad \frac{n_e(x_i)}{n_{\mathrm{e0}}} = \exp\left(-\frac{x_i}{\lambda_i}\right)$$

$$\alpha \equiv \frac{\#/\text{ ionization collisions}}{\text{per electron}} \times (\#/\text{electron with E} > \text{ionization potential})$$

$$= \frac{1}{\lambda_i}\frac{n_e(x_i)}{n_{\mathrm{e0}}} = \frac{1}{\lambda_i}\exp\left(-\frac{x_i}{\lambda_i}\right)$$

$$\alpha = Ap\,\exp(-Apx_i)$$

$$\frac{\alpha}{p} = A\exp\left(-\frac{AV^*}{E/p}\right) \equiv A\exp\left(-\frac{C}{E/p}\right) \equiv f\left(\frac{E}{p}\right) \qquad x_i \approx \frac{V^*}{E} \text{ where } V^* > V_i$$

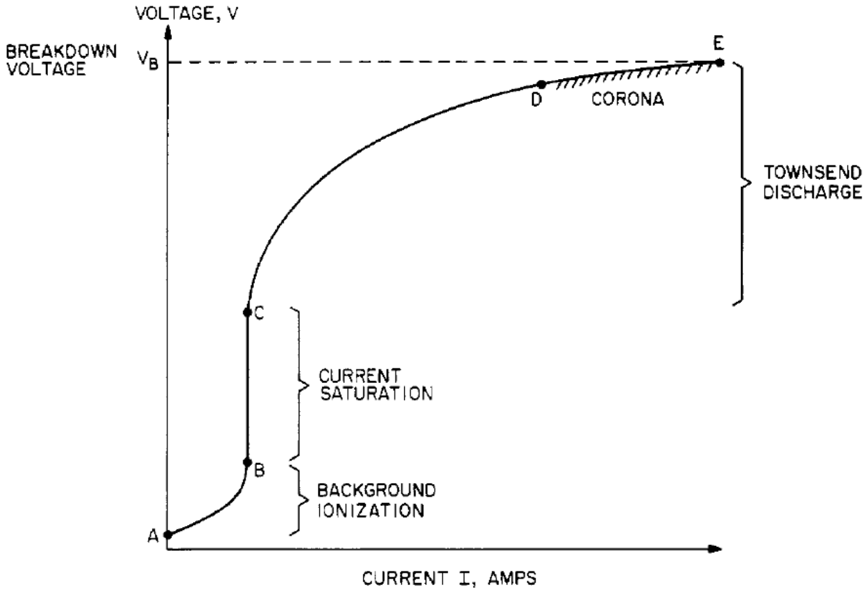
- The parameters A and C must be experimentally determined.

Phenomenological constants A and C of Townsend's first ionization coefficient for selected gases

Gas	*A* ion pairs/m-Torr	*C* V/m-Torr
A	1200	20 000
Air	1220	36 500
CO_2	2000*	46 600
H_2	1060	35 000
HCl	2500*	38 000
He	182	5 000
Hg	2000	37 000
H_20	1290*	28 900
Kr	1450	22 000
N_2	1060	34 200
Ne	400	10 000
Xe	2220	31 000

* These values may be high by as much as a factor of two.

Corona discharge (unipolar discharge) is a very low current, continuous phenomenon



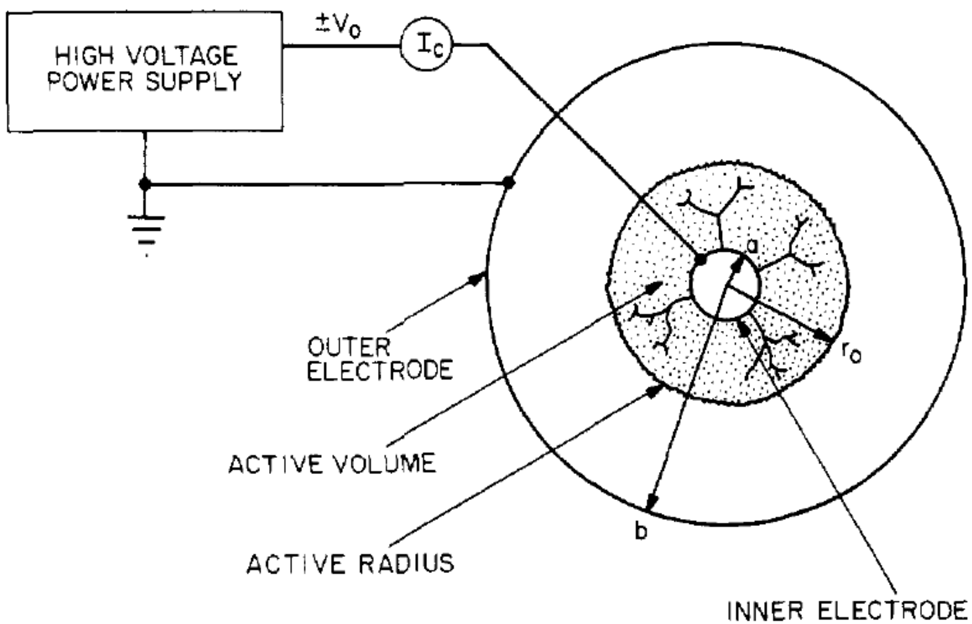
- **Break down condition for dry air:**

$$E_B = 3000 + \frac{1.35}{d}\,\mathrm{kV}/m$$

$$V_B = 3000d + 1.35\ \mathrm{kV}$$

- **Corona can initiate on sharp points at potentials as low as 5 kV.**
- **It can initiate from sharp points, fine wires, sharp edges, asperities, scratches or anything which creates a localized electric field greater than the breakdown electric field of the medium surrounding it.**
- **It can be a “glow discharge”, i.e., visible to eyes. For low currents, the entire corona is dark.**

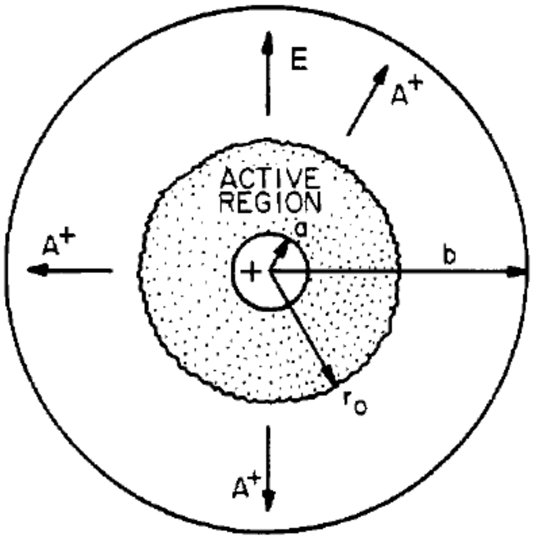
Phenomenology of corona generated by a fine wire



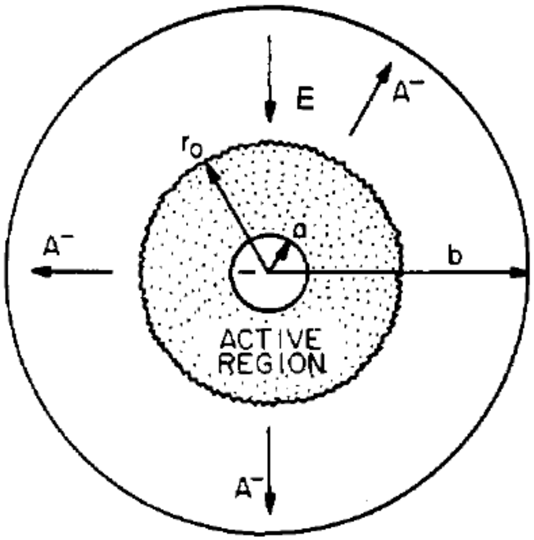
- **The point of corona initiation is that point at which the voltage on the inner conductor of radius a is high enough that corona is just detectable.**
- **The electric field will drop off to the breakdown value at a radius r_0 called the active radius.**

Corona can occur for both positive and negative polarity

- **Positive polarity**

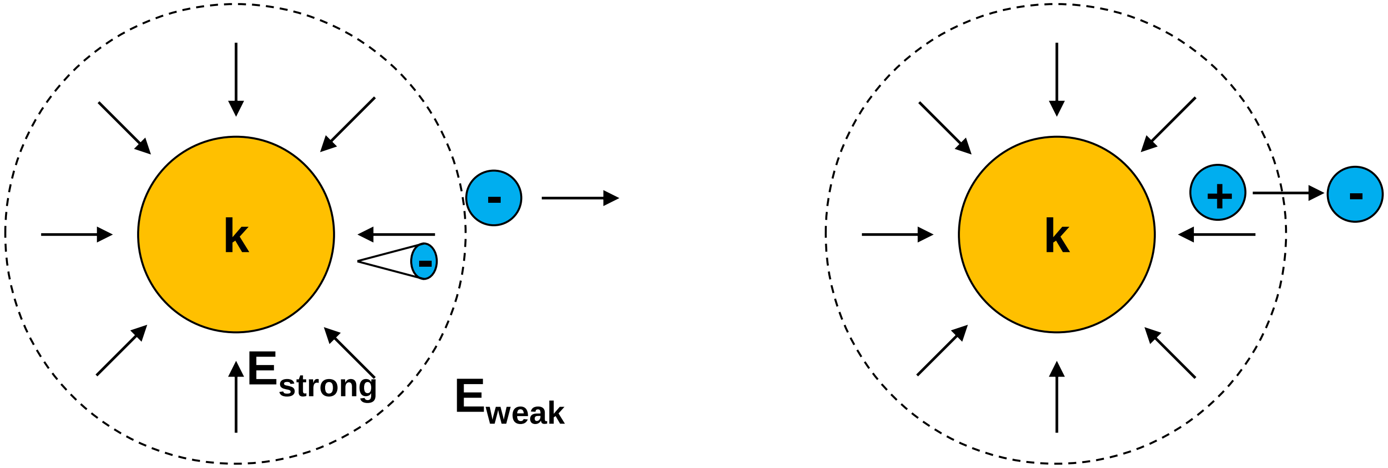


- **Negative polarity**



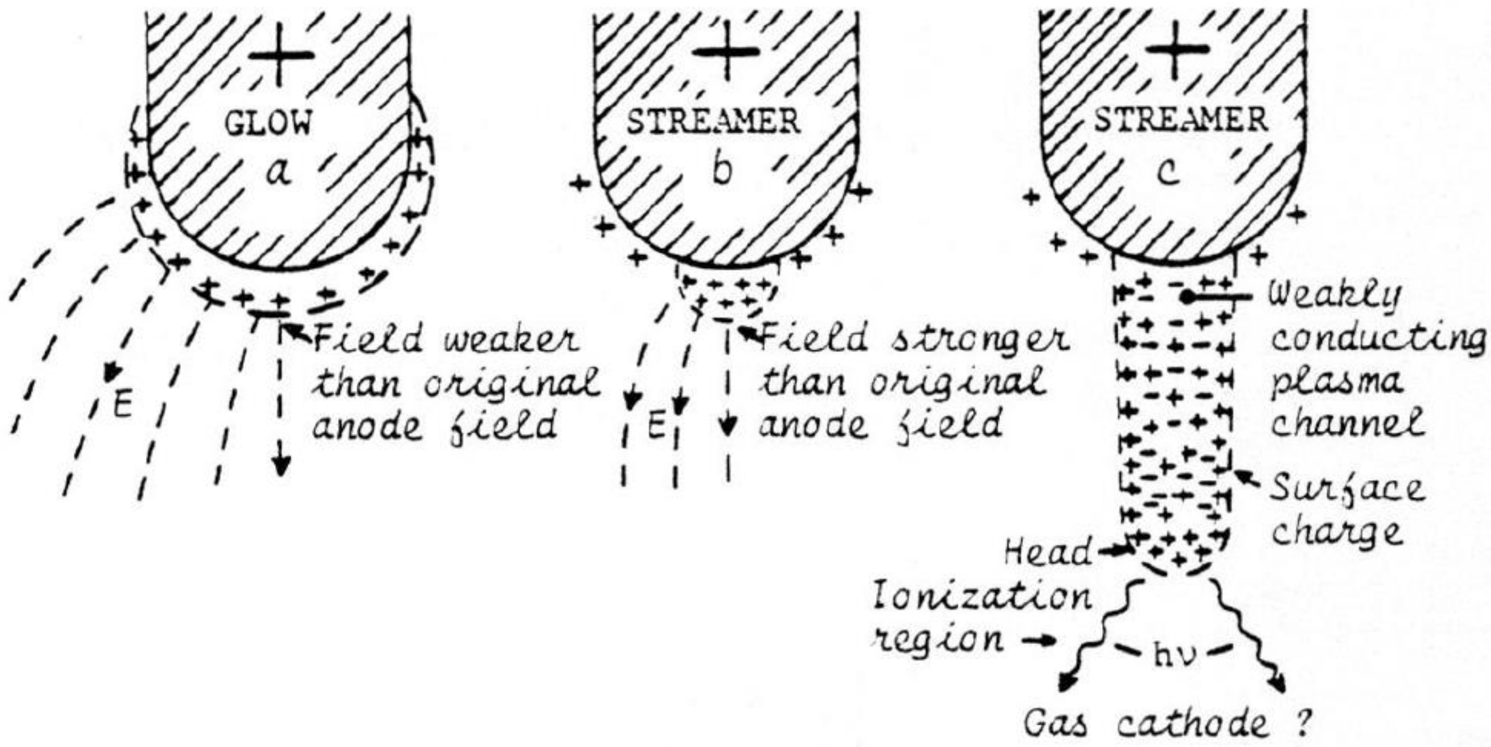
- **The initiation voltages or coronal current are slightly different between positive and negative polarity.**
- **A continuous (positive polarity, DC) or intermittent (negative polarity, usually) current, usually in the order of uA ~ mA per decimeter of length will flow to the power supply.**

Negative point corona, also known as Trichel pulses



- **Avalanche toward anode occurs in the strong electric field region.**
- **No further ionization occurs in the weak field region.**
- **Electrons are slow down by positively charged ions (ion+) behind.**
- **Electrons attach to gas molecules forming negatively charged ions (ion-).**
- **The presence of the negative ions reduces the electric field at the point electrode and the discharge extinguishes.**
- **When positively/negatively charged ions drifted away, the original high-field conditions are re-established**

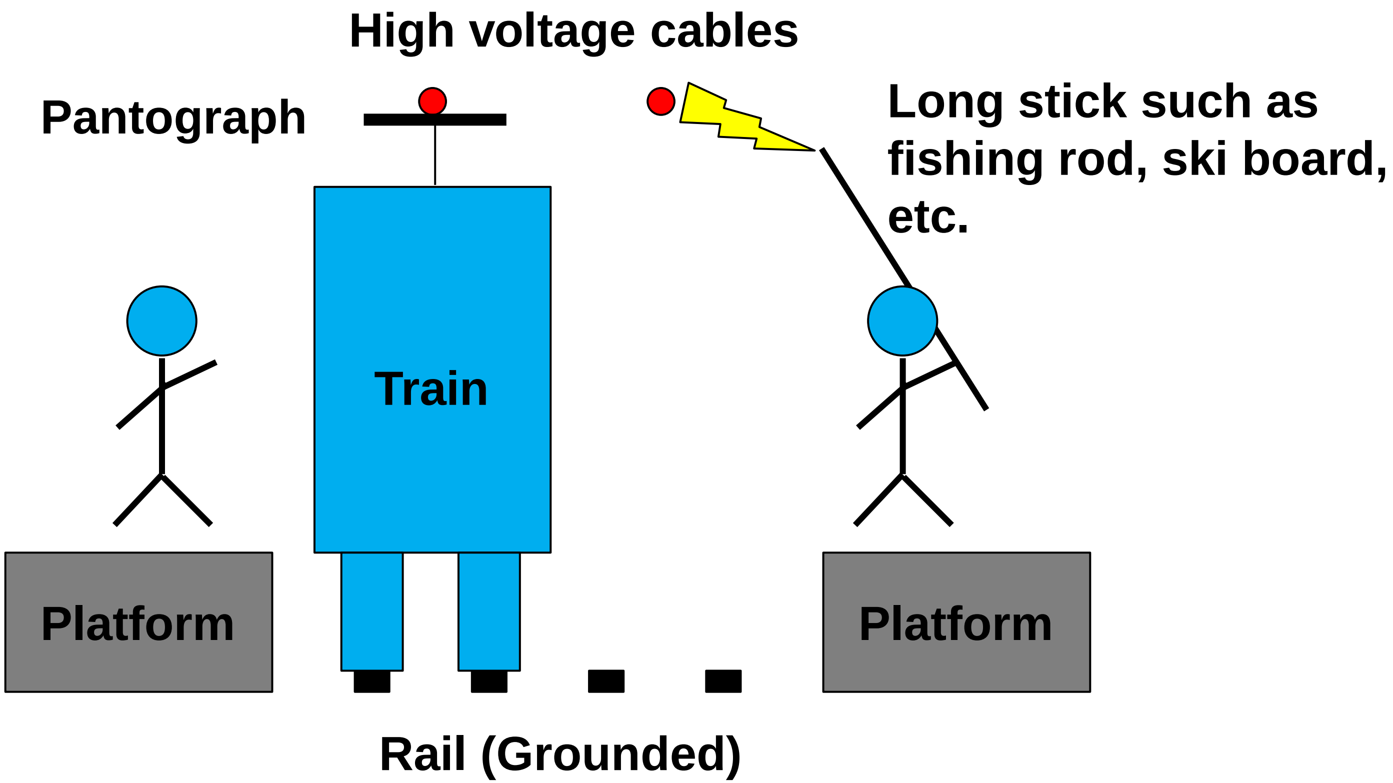
Positive point corona



- **Electron avalanche initiated near the high-field region propagating toward anode.**
- **Streamer is developed.**
- **Lateral avalanches feed into the streamer core.**

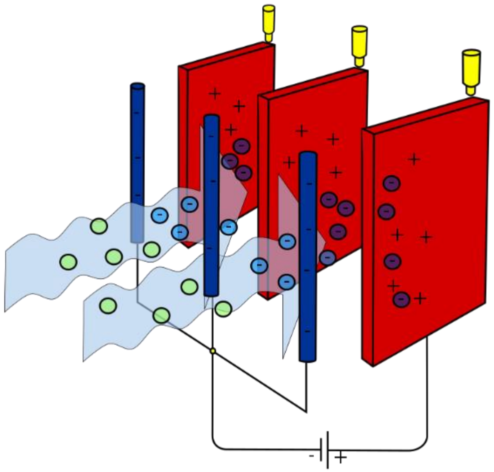
M. Goldman and R. S. Sigmond, IEEE Trans. Elec. Insulation, **EI-17**, 90 (1982)

Don’t bring a long stick to a train station



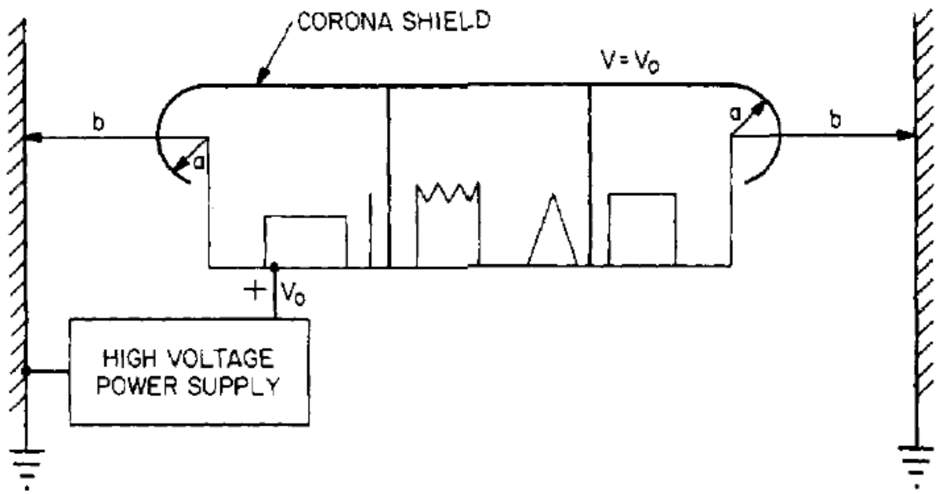
A corona discharge causes some problems even no breakdown occurs

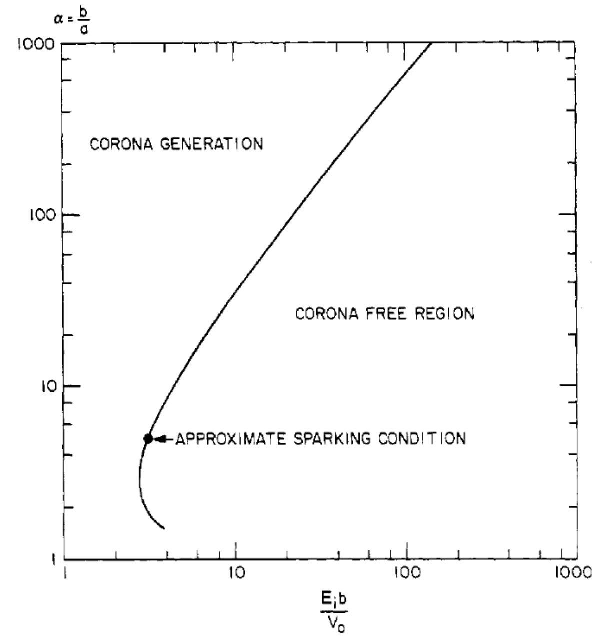
- **Ozone (O_3) is generated.**
- **Rubber is destroyed by O_3.**
- **NO_3^+ is generated with moisture.**
- **Disadvantage:**
  - **Power losses.**
  - **Radio frequency (RF) interference.**
  - **Reduce the service life of solid and liquid insulation via initiating partial discharge.**
  - **Chemical decomposition.**
- **Advantage:**
  - **Pseudospark discharge – fast switch.**
  - **Electrostatic precipitator (dust remover) using corona discharge.**
  - **Hair dryer**



https://zh.wikipedia.org/wiki/%E9%9D%99%E7%94%B5%E9%99%A4%E5%B0%98

A corona shield is used to suppress corona





- **Cylindrical approximation:**

$$E_s = \frac{V_0}{a\ln(b/a)} = \frac{bV_0}{\text{a b}\ln(b/a)} \qquad \chi \equiv \frac{b}{a} \qquad \Rightarrow \qquad \frac{E_i b}{V_0} = \frac{\chi}{\ln\chi}$$

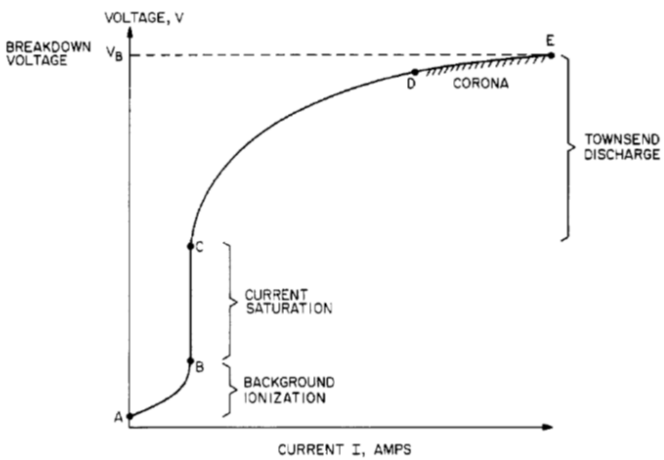
$$E_s \equiv E_i \;\; (E@\text{ surface for corona initiation})$$

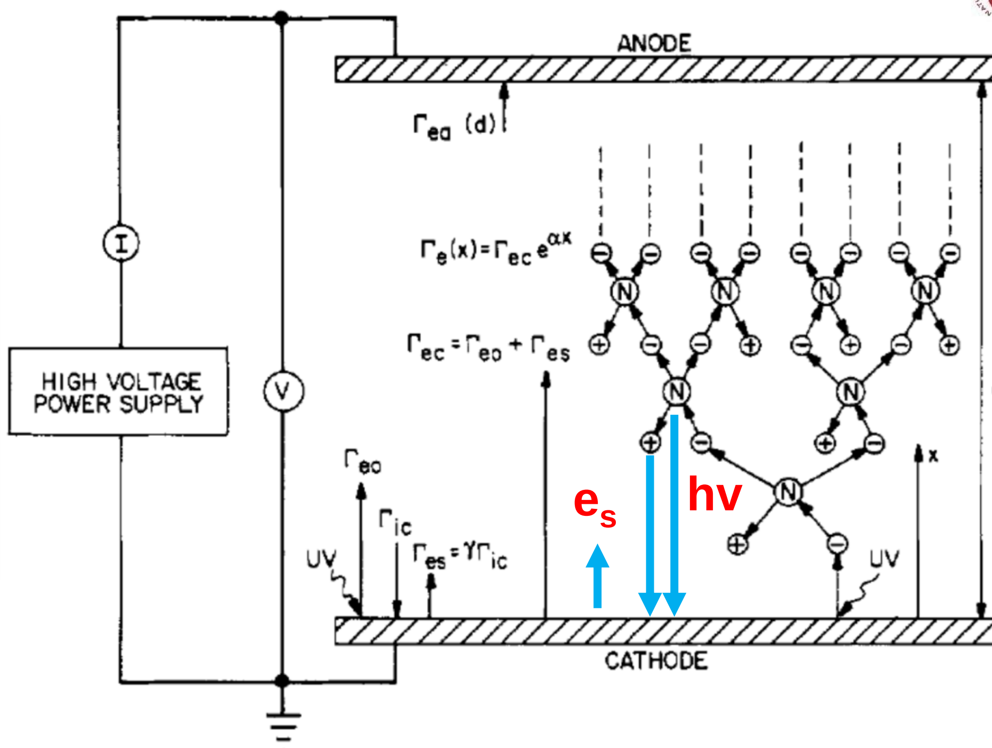
- **For b=0.5 m, V_0=50 kV, E_i~E_B~3 MV/m**

$$\frac{E_B b}{V_0} = \frac{3\times10^6\times0.5}{5\times10^4} = 30 = \frac{\chi}{\ln\chi}$$

$$\chi \approx 150, i.e., a = 0.33\text{mm}$$

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





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

Derivation of electrical breakdown

- **Secondary electron emission coefficient:**

$$\gamma \equiv \frac{\#/\text{ of electrons emitted}}{\#/\text{ of incident ions or photons}}$$

$$\Gamma_{es} = \gamma \Gamma_{ic}$$

$$\Gamma_{ec} = \Gamma_{e0} + \Gamma_{es}$$

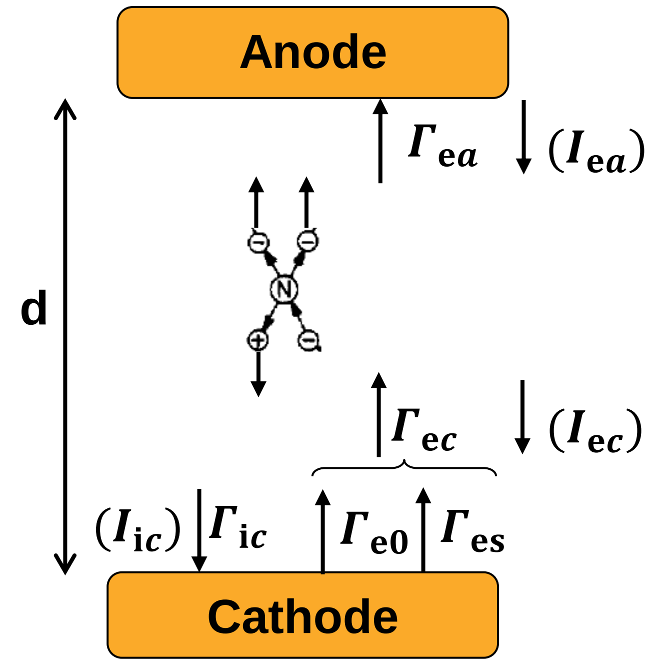
$$I_{ea} = I_{ec} + I_{ic} \quad \Rightarrow \quad \Gamma_{ea} = \Gamma_{ec} + \Gamma_{ic}$$

$$\Gamma_{ea} - \Gamma_{ec} = \Gamma_{ic} = \frac{\Gamma_{es}}{\gamma} \qquad (\Gamma_{ea} = \Gamma_{ec} e^{\alpha d})$$

$$\Gamma_{es} = \gamma(\Gamma_{ea} - \Gamma_{ec}) = \gamma \Gamma_{ec}\left(e^{\alpha d} - 1\right)$$

$$\Gamma_{ec} = \Gamma_{es} + \Gamma_{e0} = \gamma \Gamma_{ec}\left(e^{\alpha d} - 1\right) + \Gamma_{e0}$$

$$\Gamma_{ec} = \frac{\Gamma_{e0}}{1 - \gamma(e^{\alpha d} - 1)}$$



$$\Gamma_{ea} = \Gamma_{e0} \frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \left(\text{electrons}/m^2 - s\right)$$

$$J = J_0 \frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \left(A/m^2\right)$$

The Townsend condition for ignition (avalanche grows)

$$J = J_0 \frac{e^{\alpha d}}{1-\gamma(e^{\alpha d}-1)} (A/m^2)$$

- The Townsend condition for ignition or called avalanche grows occurs when

$$1-\gamma\left(e^{\alpha d}-1\right)=0$$

$$\gamma e^{\alpha d} = \gamma + 1 \quad \text{or} \quad \ln\left(1+\frac{1}{\gamma}\right) = \alpha d$$

$$\mathrm{Apd}\exp\left(-\frac{\mathrm{Cpd}}{V_B}\right) = \ln\left(1+\frac{1}{\gamma}\right)$$

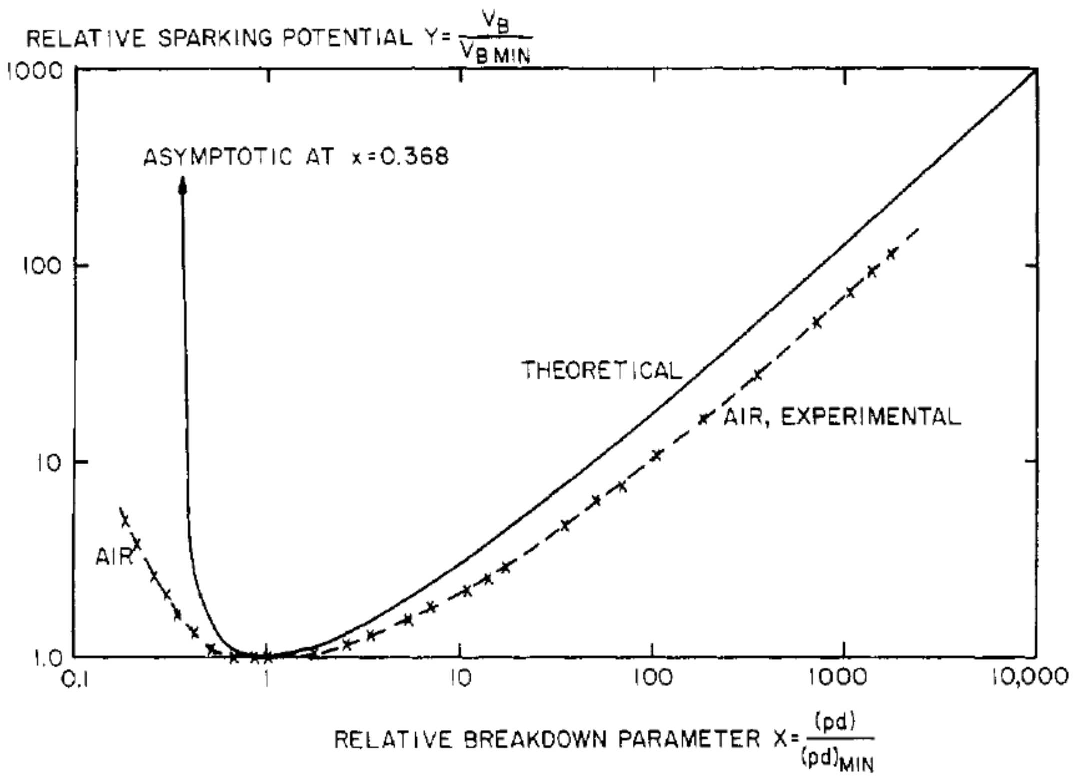
$$\frac{\alpha}{p} = A\exp\left(-\frac{C}{E/p}\right) \quad E_B = \frac{V_B}{d}$$

$$V_B = \frac{\mathrm{Cpd}}{\ln\left[\frac{\mathrm{Apd}}{\ln\left(1+\frac{1}{\gamma}\right)}\right]} = f(\mathrm{pd})$$

$$(pd)_{\min} = \frac{e}{A}\ln\left(1+\frac{1}{\gamma}\right) = \frac{2.718}{A}\ln\left(1+\frac{1}{\gamma}\right)$$

$$V_{B,\min} = 2.718\frac{C}{A}\ln\left(1+\frac{1}{\gamma}\right)$$

Universal Paschen's curve

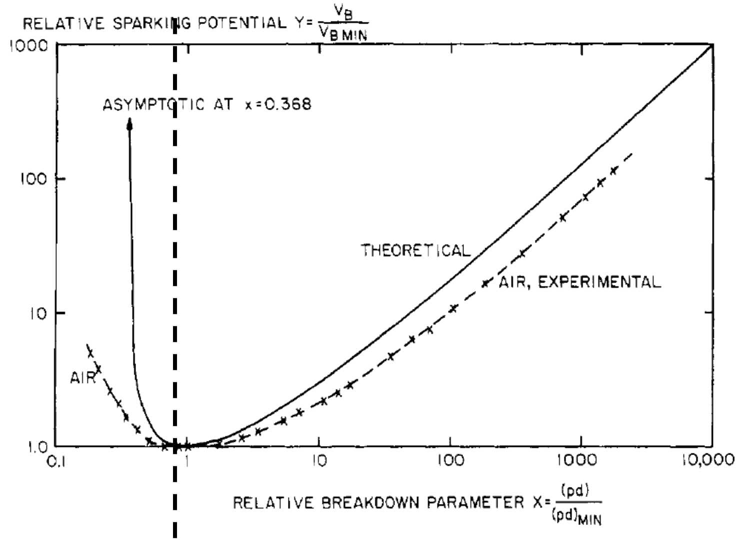


$$V_B = \frac{\mathrm{Cpd}}{\ln\left[\frac{\mathrm{Apd}}{\ln\left(1+\frac{1}{\gamma}\right)}\right]} = f(\mathrm{pd})$$

$$Y \equiv \frac{V_B}{V_{B,\min}} \qquad X \equiv \frac{\mathrm{pd}}{(\mathrm{pd})_{\min}}$$

$$Y = \frac{V_B}{V_{B,\min}} = \frac{X}{1+\ln X}$$

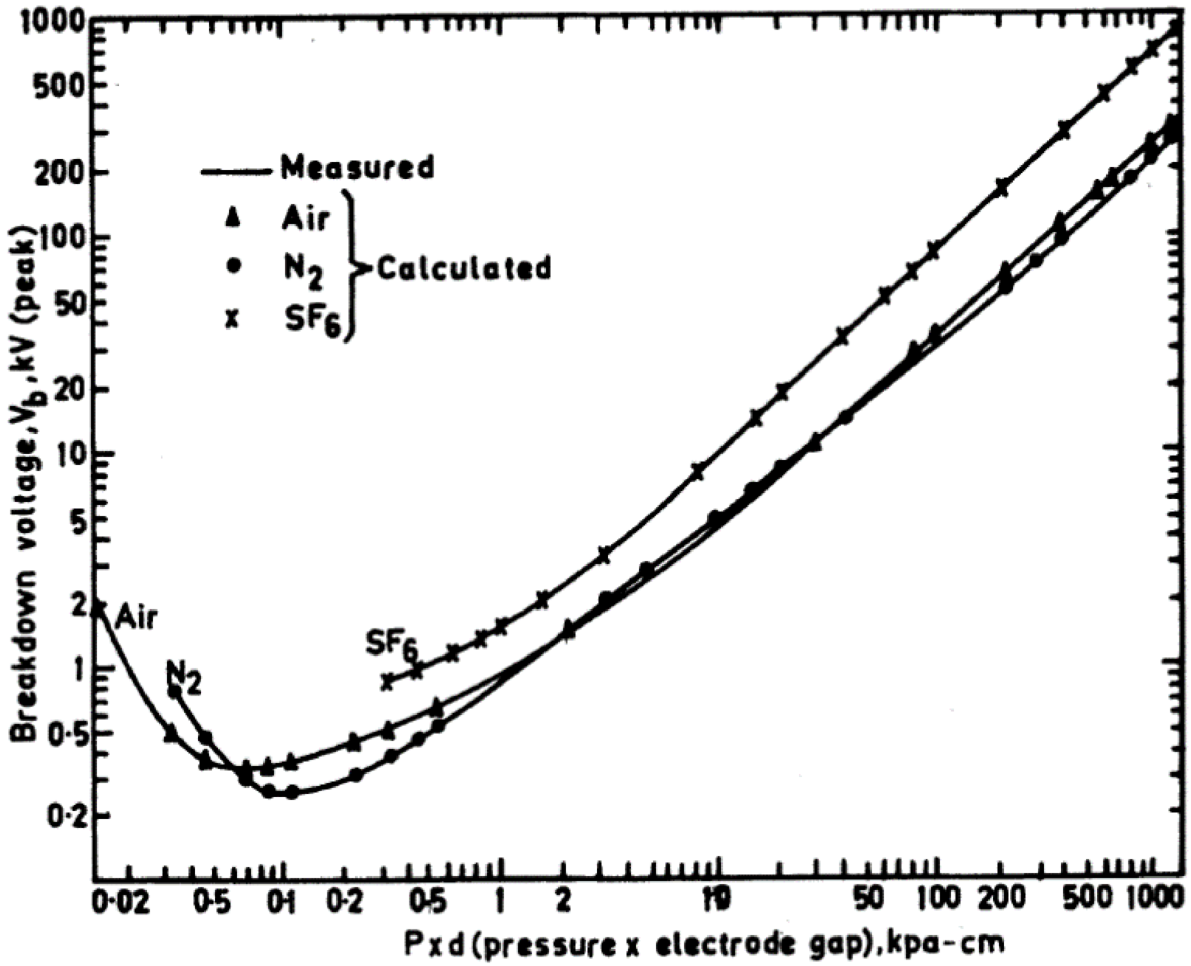
Collision frequency and electron energy gained from electric field are both important to electrical breakdown



- **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.**

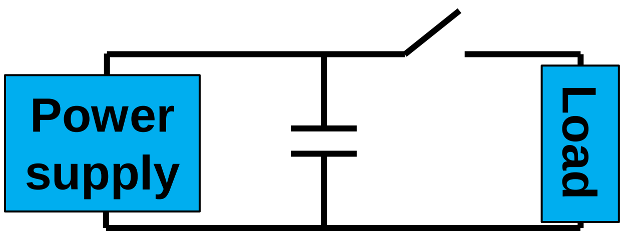
- **The minimum of the Paschen's curve corresponds to the Stoletow point, the pressure at which the volumetric ionization rate is a maximum.**

Experimental Paschen's curve

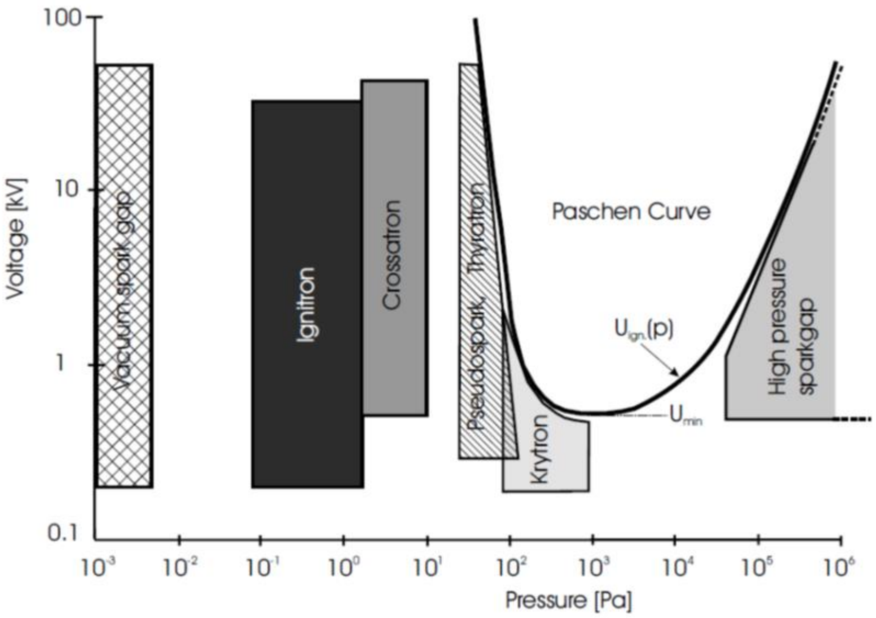


Paschen's curve is used to design different high voltage high current switches in pulsed-power system

- **Pulsed-power system**

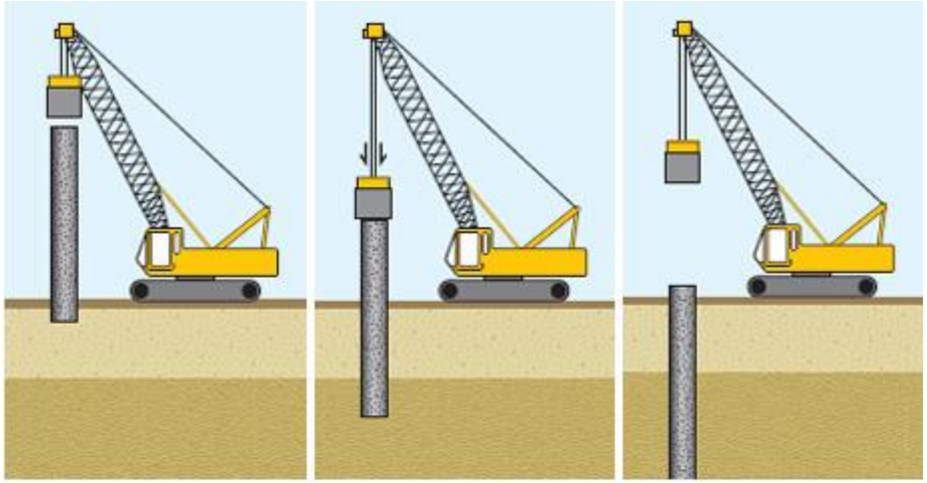


Low power **High power**



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

- **Driven piles**
- **Hammer**



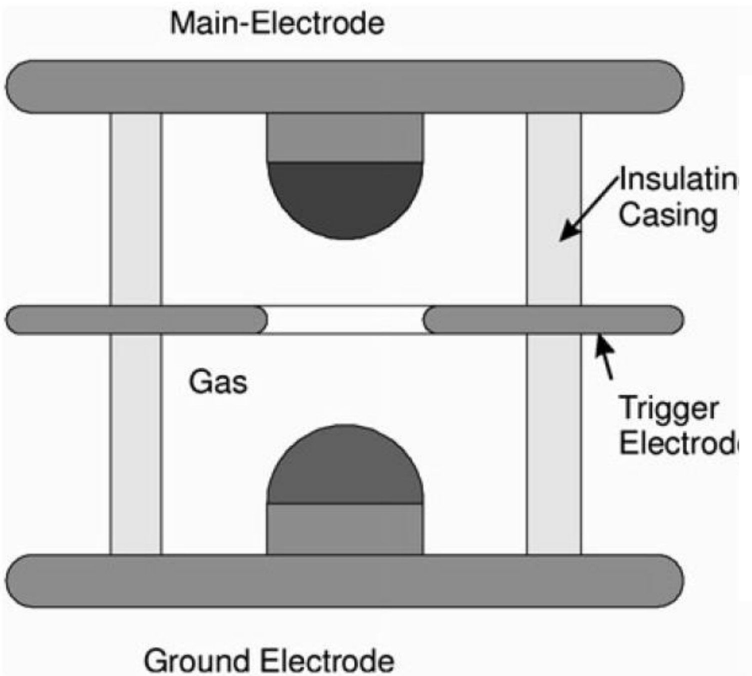
PLACEMENT OF PILE INSTALLATION OF PILE REPETITION OF PROCESS

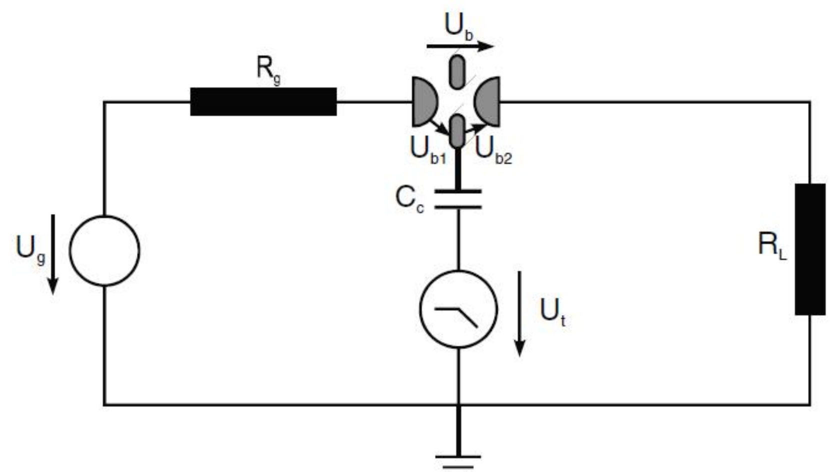
http://www.saudifoundations.com/driven.html
http://learnhowtowritesongs.com/tag/thesaurus/

Example of short pulses with a controllable repetition rate

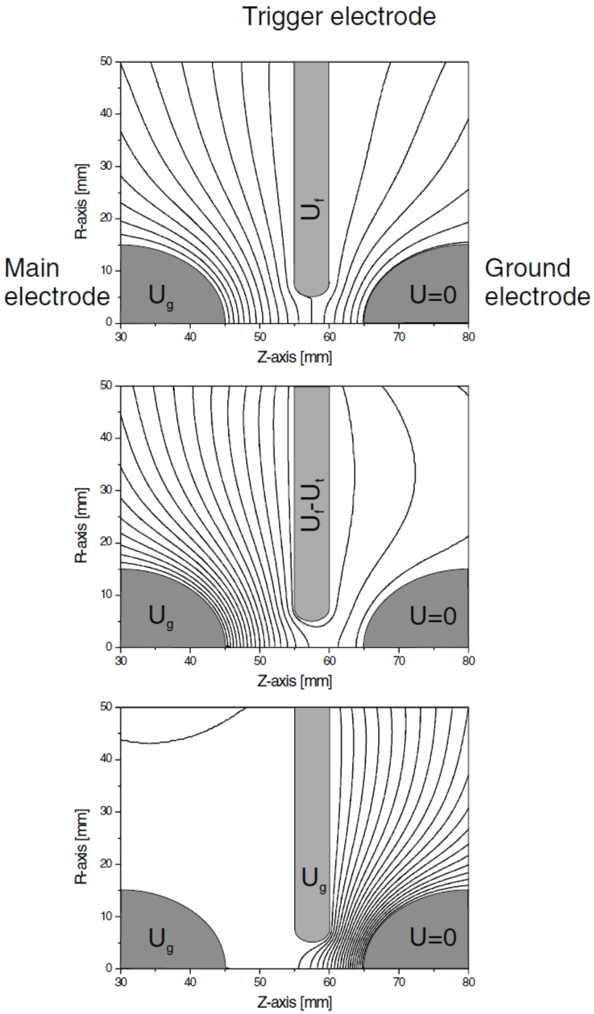
https://www.youtube.com/watch?v=5fe8b4MlPYw

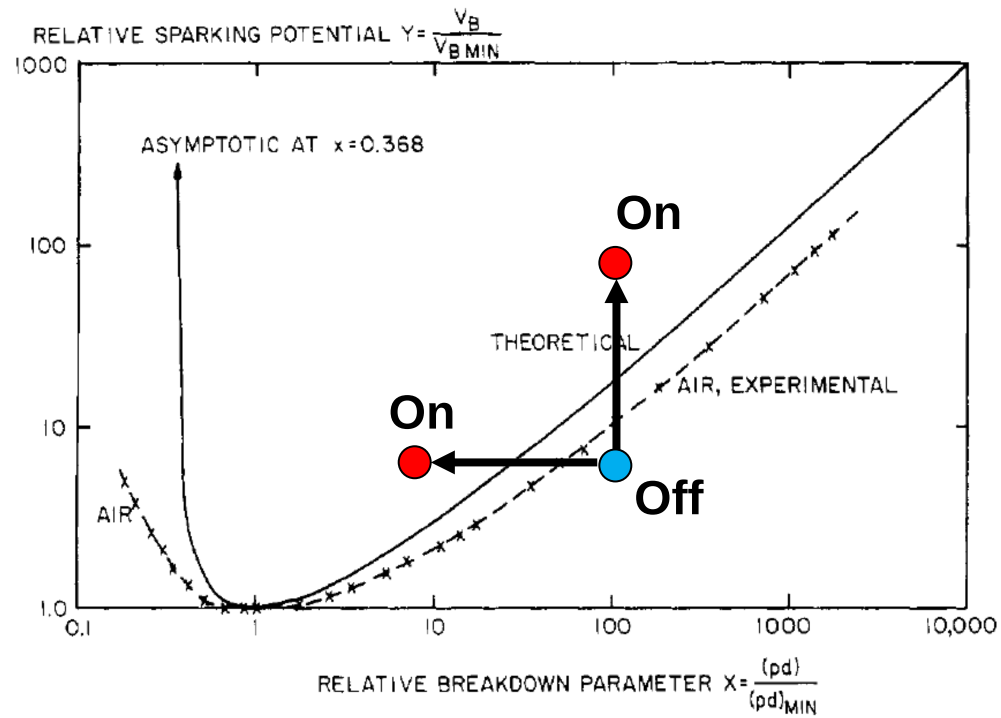
Spark-gap switch





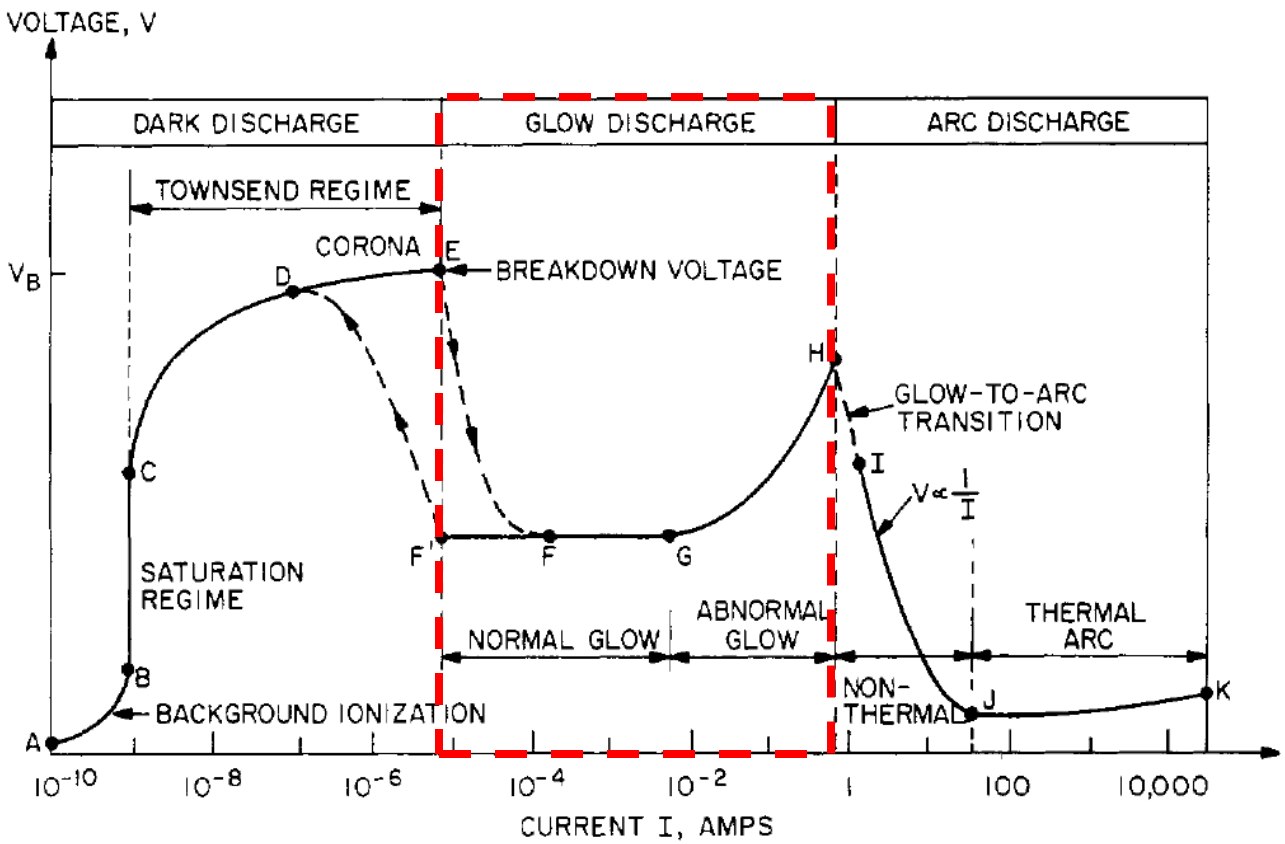
A spark gap switch is closed when electron breakdown occurs





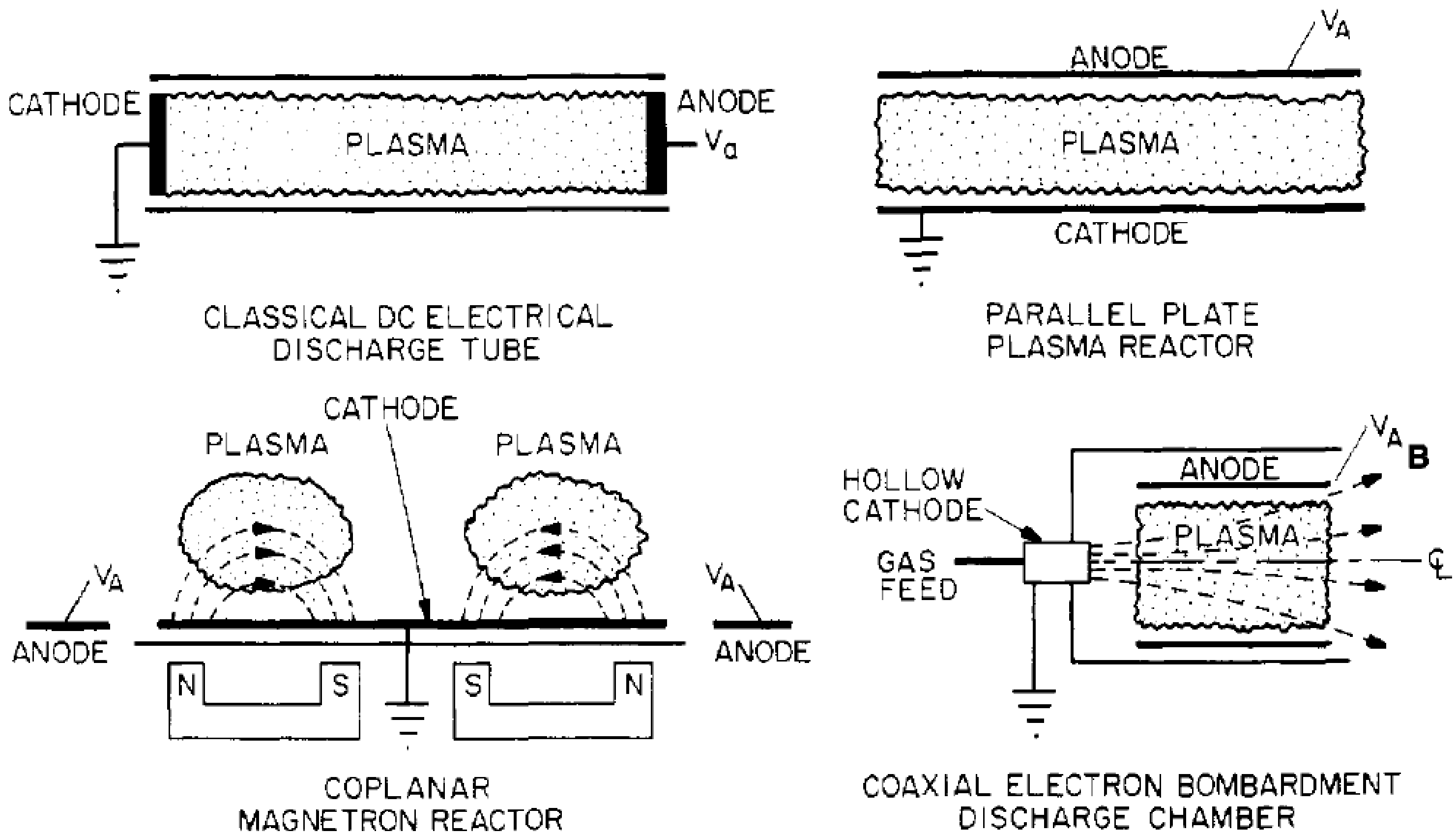
DC electrical glow discharges in gases

- 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.



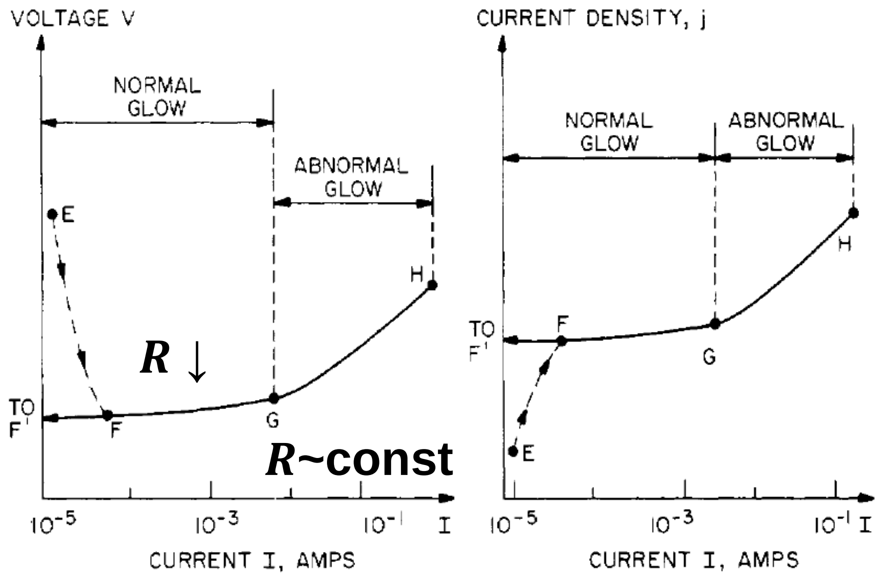
The plasma is luminous in the glow discharge regime

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



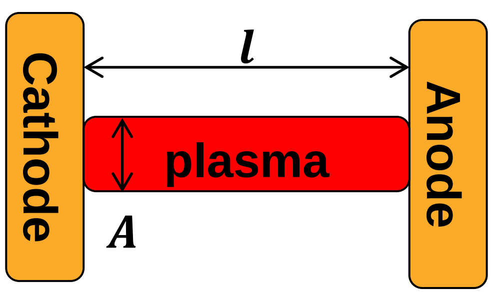
Abnormal glow discharge occurs when the cross section of the plasma covers the entire surface of the cathode

$$R = \frac{V}{I}$$

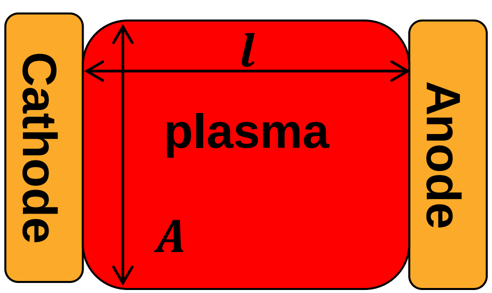


$$R = \eta \frac{l}{A}$$

- **Normal glow discharge:**

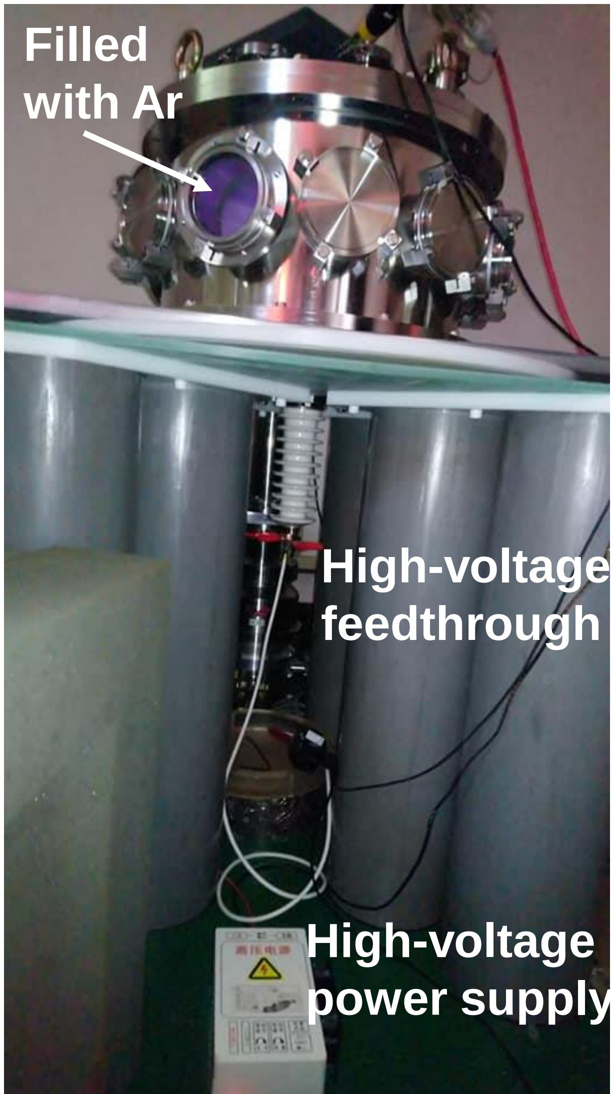


- **Abnormal glow discharge:**

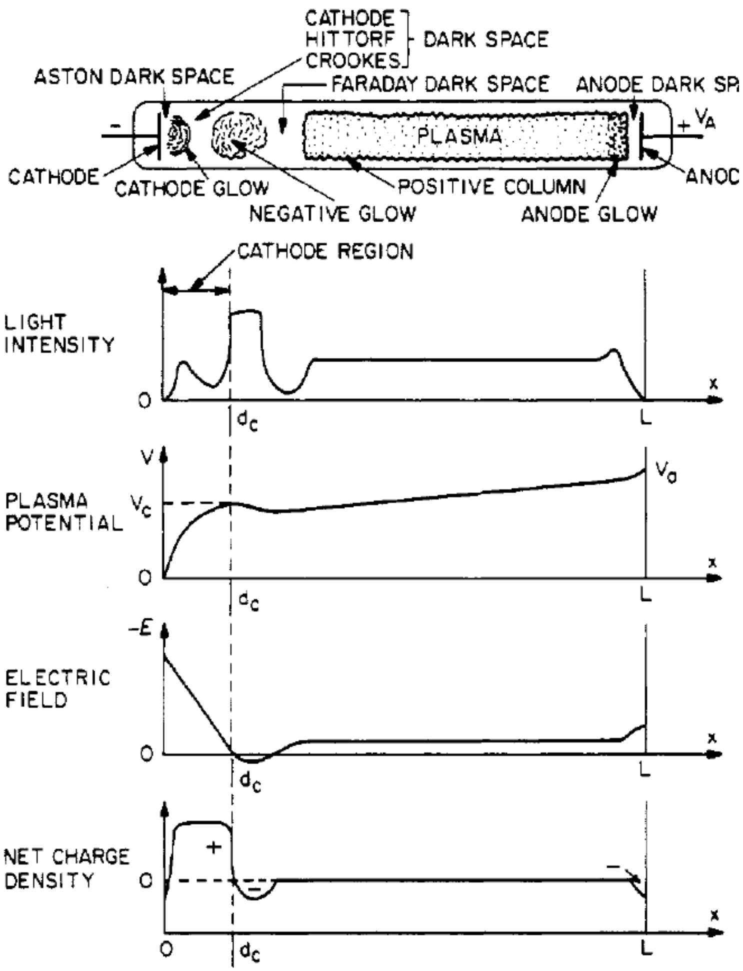


- **Surface cleaning using plasma needs to work in the abnormal glow discharge region.**

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

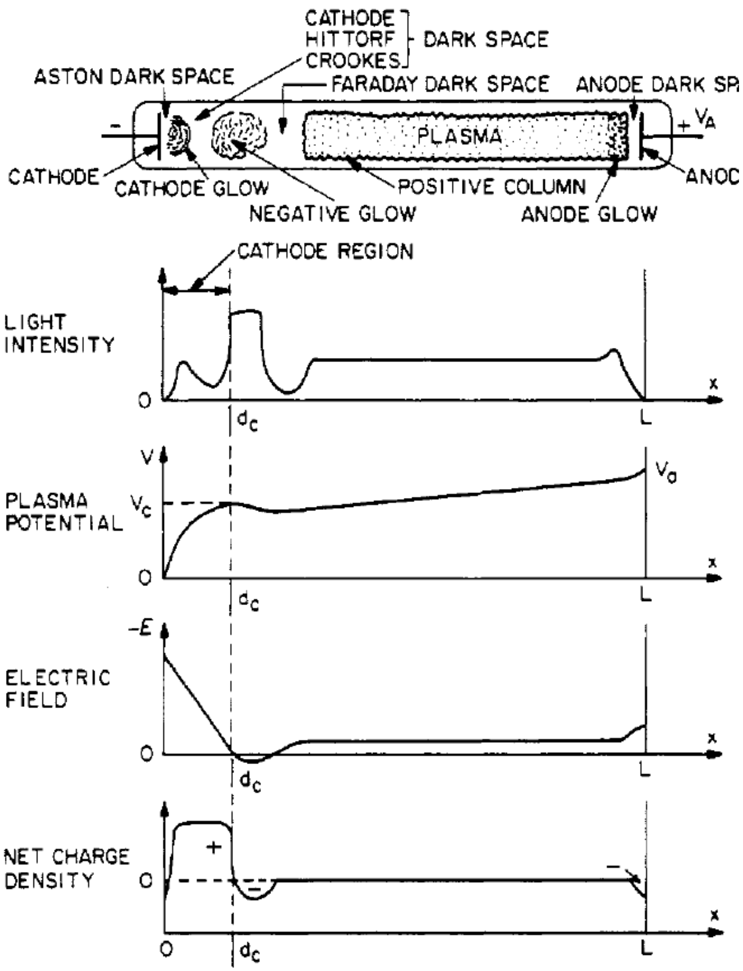


Low pressure normal glow discharge



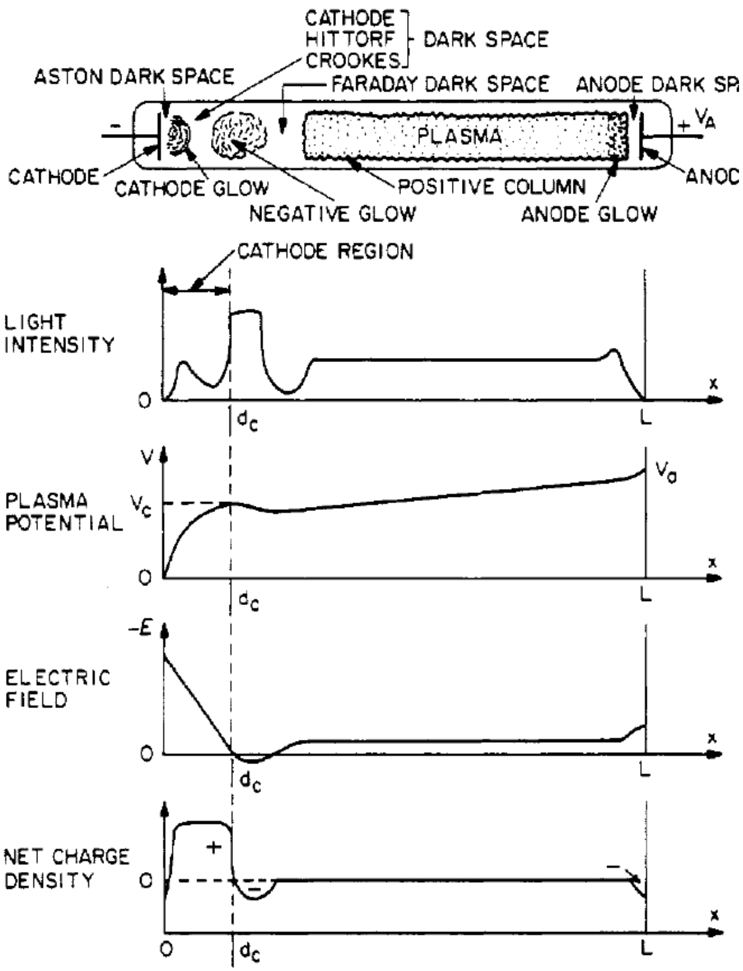
- **<u>Cathode</u>: made of an electrically conducting metal with 2nd e^- emission γ, of which has a significant effect on the operation of the discharge tube.**
- **<u>Aston dark space</u>: a thin region with a strong electric field and a negative space charge. The electrons are of too low a density and/or energy to excite the gas, so it appears dark.**
- **<u>Cathode glow</u>: has a relatively high ion number density. The length depends on the type of gas and the gas pressure.**
- **<u>Cathode (Crookes, Hittorf) dark space</u>: has a moderate electric field, a positive space charge, and a relatively high ion density.**

Low pressure normal glow discharge



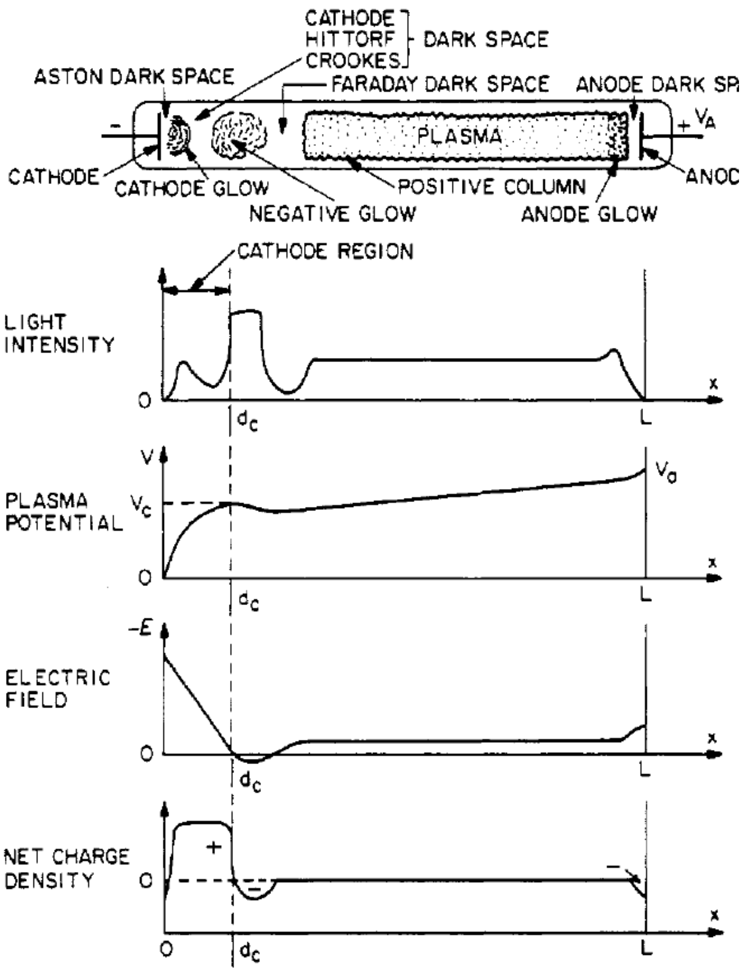
- <u>**Cathode region**</u>**: most of the voltage drop (cathode fall) across the discharge tube appears between the cathode and the boundary between the cathode dark space and the negative glow. Electrons are accelerated to energies high enough to produce ionization and avalanching in this region. The axial length will adjust itself such that $d_c p \sim (dp)_{min}$ where (dp) is the Paschen minimum.**

Low pressure normal glow discharge



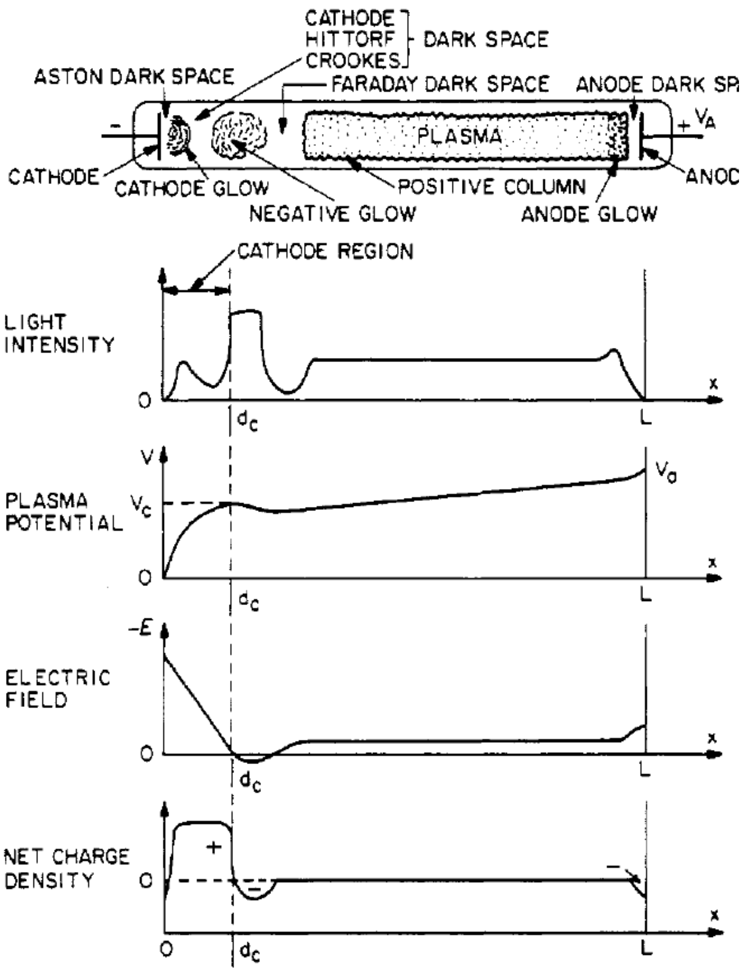
- **<u>Negative glow</u>: the brightest light intensity in the entire discharge. It has a relatively low electric field and is usually long compared to the cathode glow. Electrons carry almost the entire current in the negative glow region. Electrons which have been accelerated in the cathode region produce ionization and intense excitation in the negative glow, hence the bright light output observed.**

Low pressure normal glow discharge



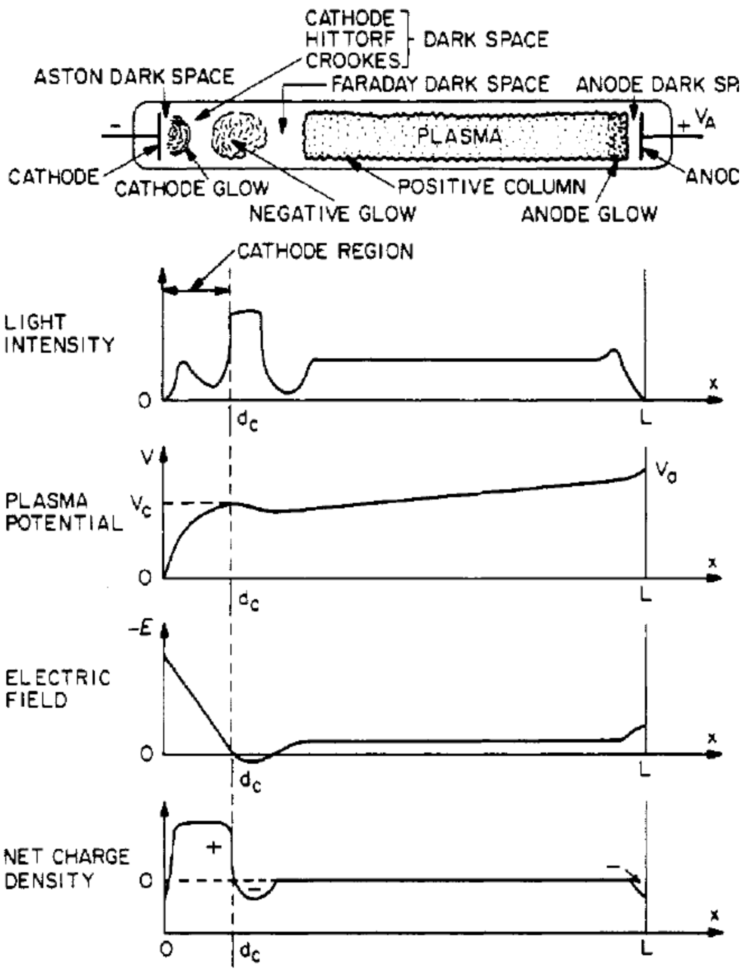
- **<u>Faraday dark space</u>: the electron energy in it is low as a result of ionization and excitation interactions in the negative glow. The electron number density decreases by recombination and radial diffusion, the net space charge is very low, and the axial electric field is relatively small.**

Low pressure normal glow discharge



- **<u>Positive column</u>: quasi-neutral, the electric field is small and is just large enough to maintain the required degree of ionization at its cathode end. Since the length of cathode region remains constant, the positive column lengthens as the length of the discharge tube is increased.**

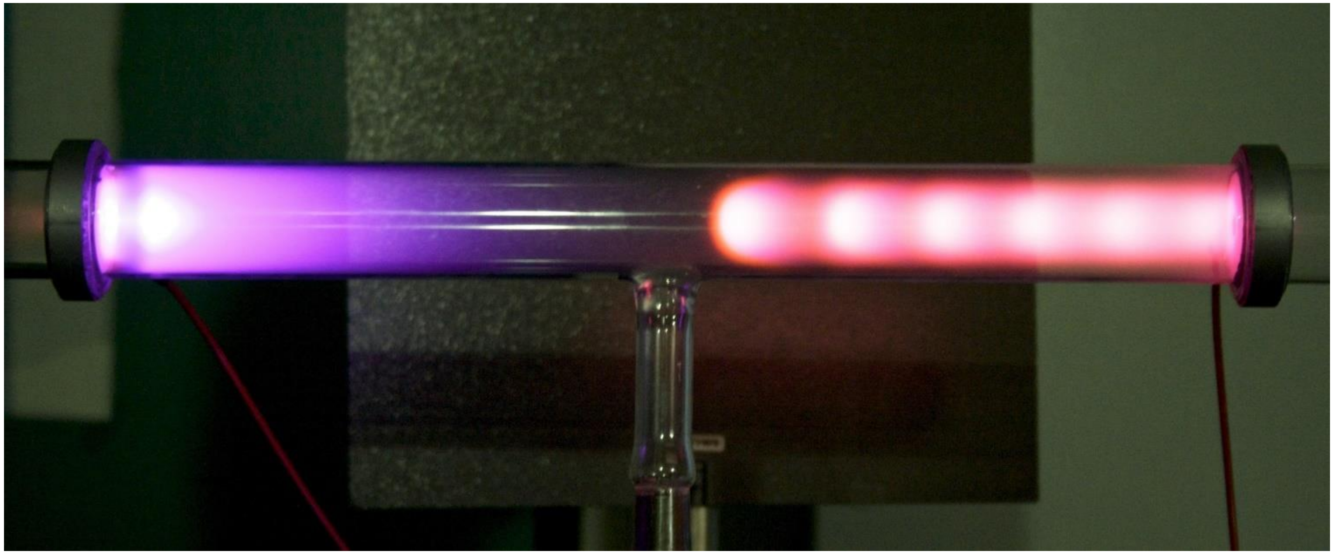
Low pressure normal glow discharge



- **<u>Anode glow</u>: the boundary of the anode sheath, slightly more intense than the positive column.**
- **<u>Anode dark space</u>: has a negative space charge due to electrons traveling from the positive column to the anode and a higher electric field than the positive column. The anode pulls electrons out of the positive column and acts like a Langmuir probe in electron saturation in this respect.**

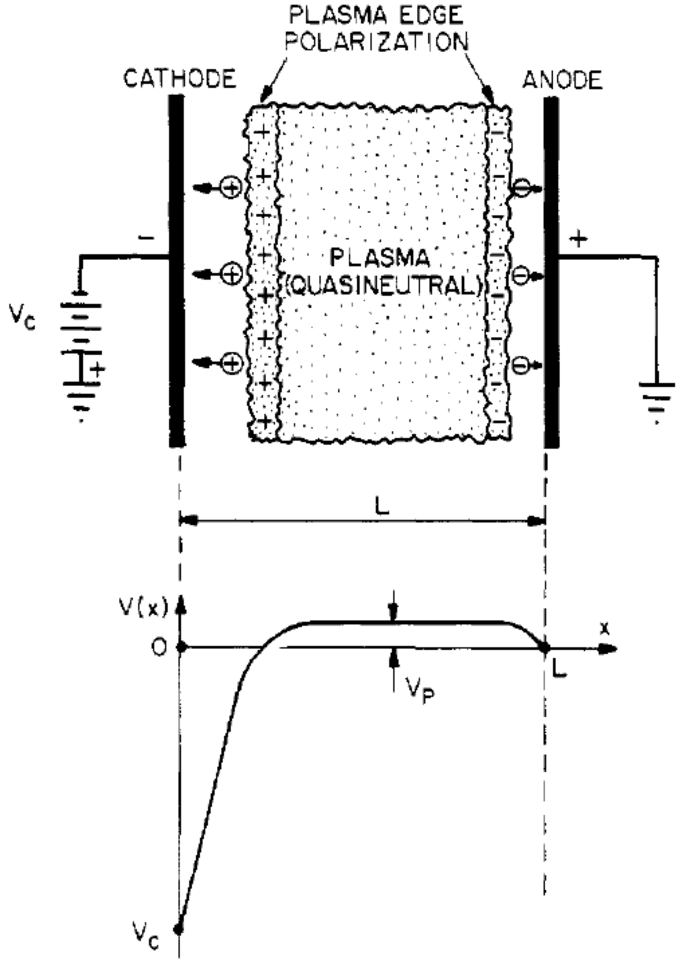
Striated discharges

- **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

Obstructed discharges



$$L < d_c$$

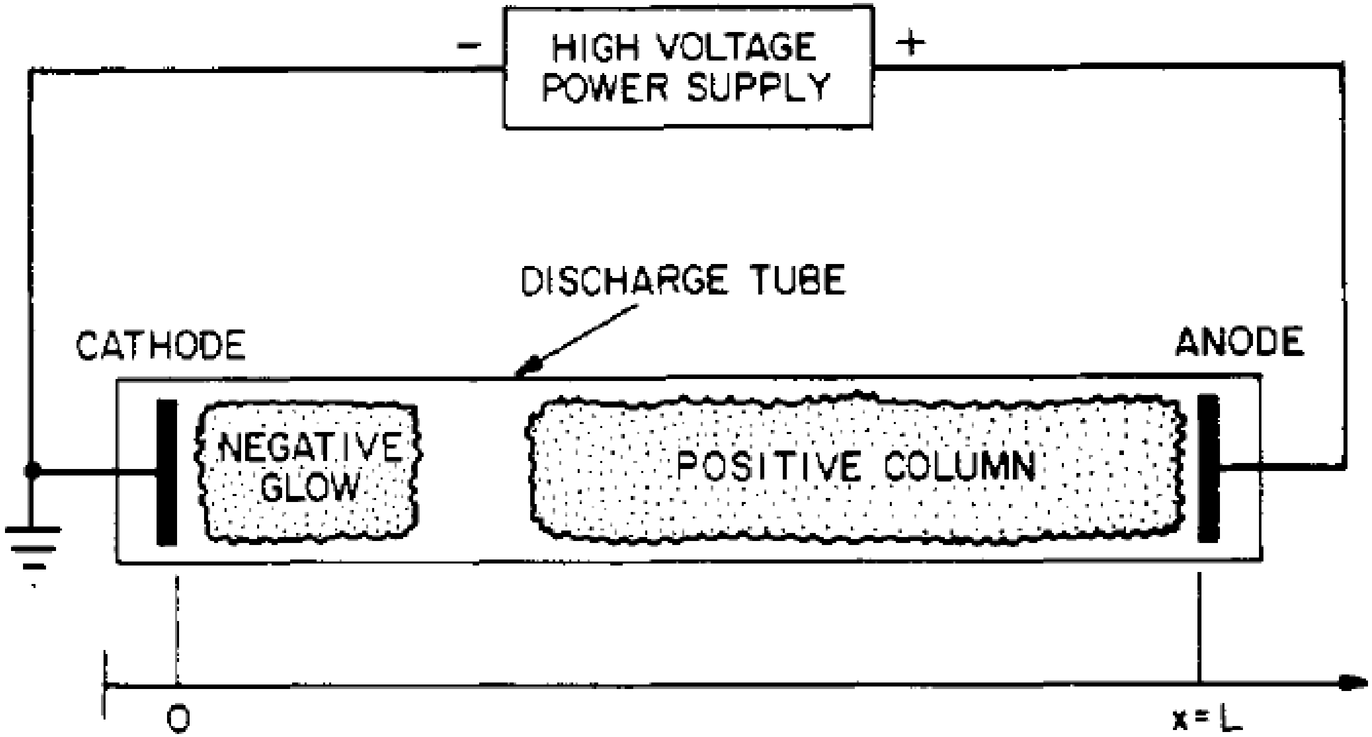
at the Paschen minimum, i.e., $(pd_c)_{min}$

$$V_c > V_{Paschen}$$

- **The obstructed glow discharge finds many uses in industry, where the high electron number densities generated by such discharge are desired. It will operate with a higher anode voltage. Such high voltage drops are sometimes desirable to accelerate ions into a wafer for deposition or etching purposes.**

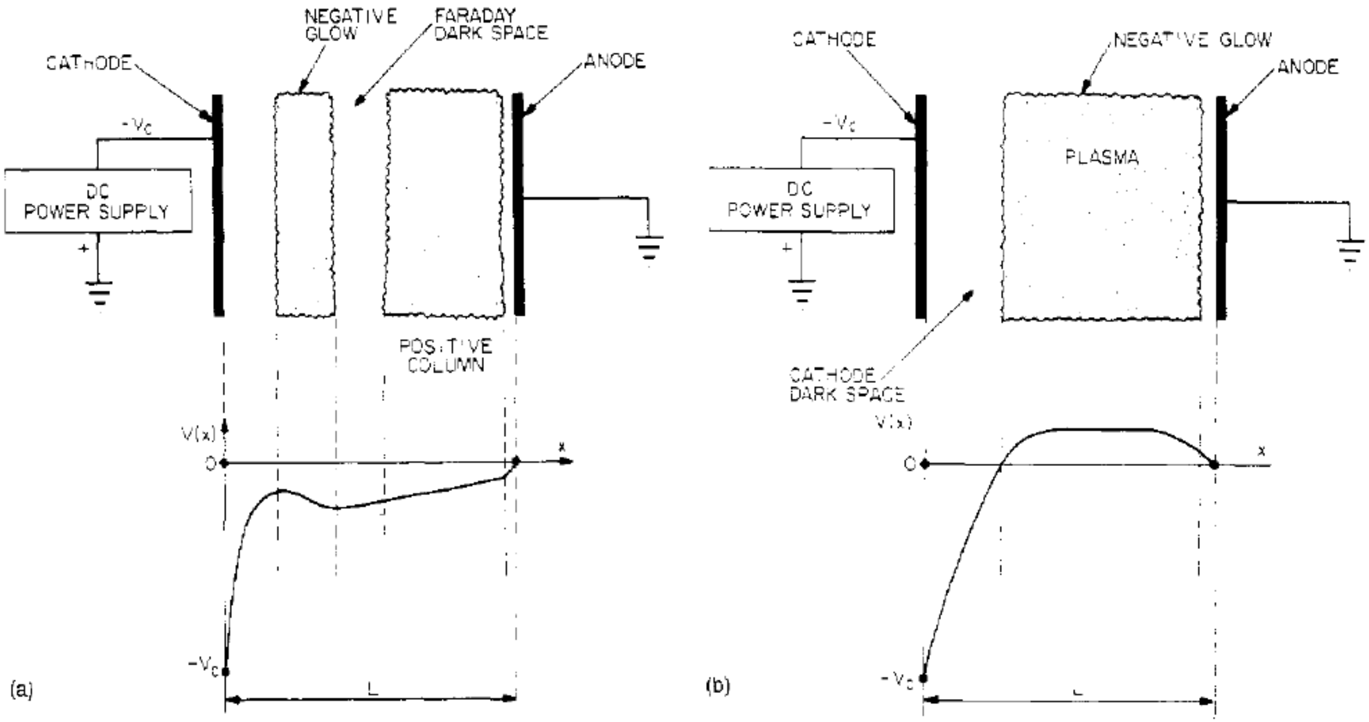
Cylindrical glow discharge sources

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



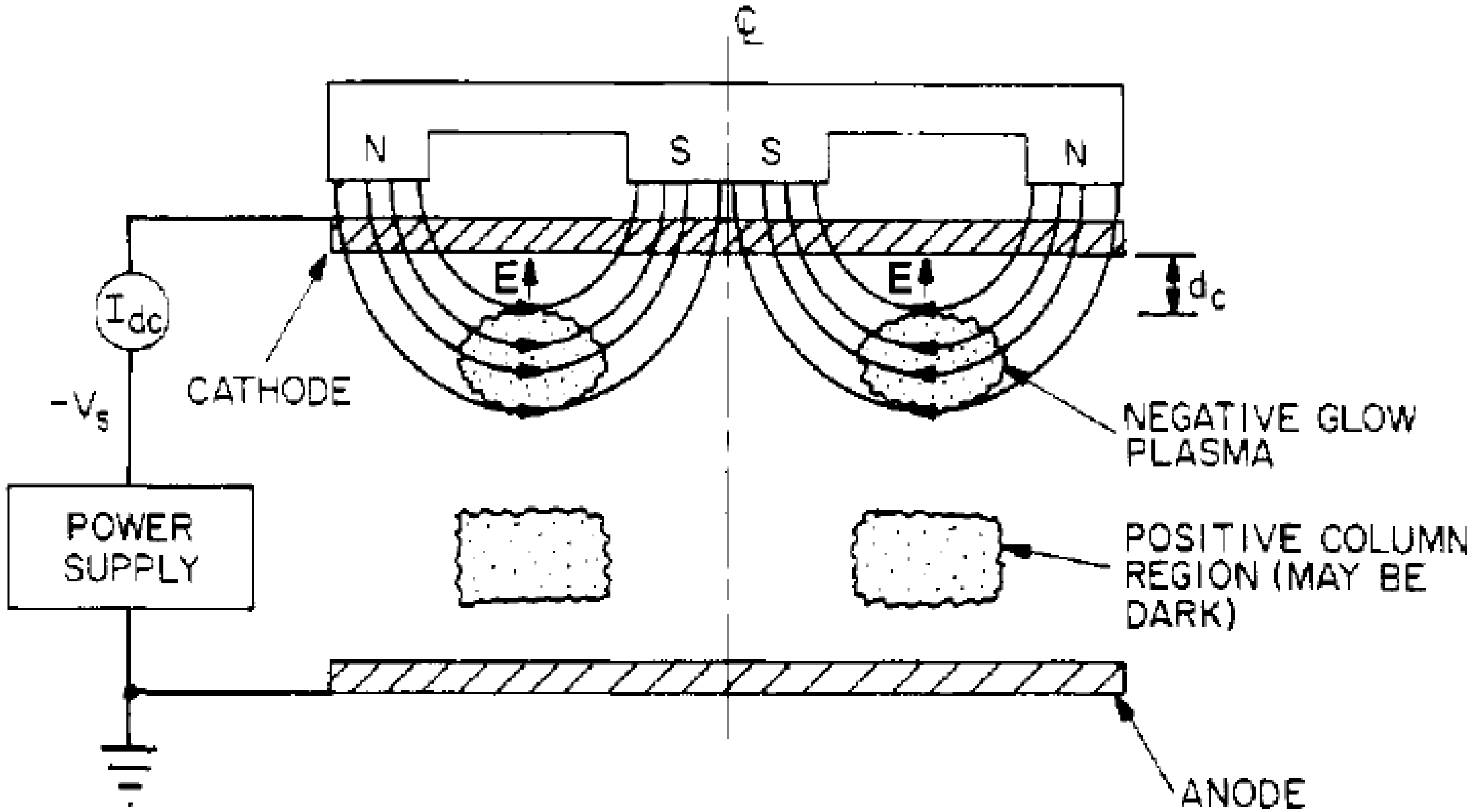
Parallel plate sources are widely used for plasma processing and plasma chemistry applications

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



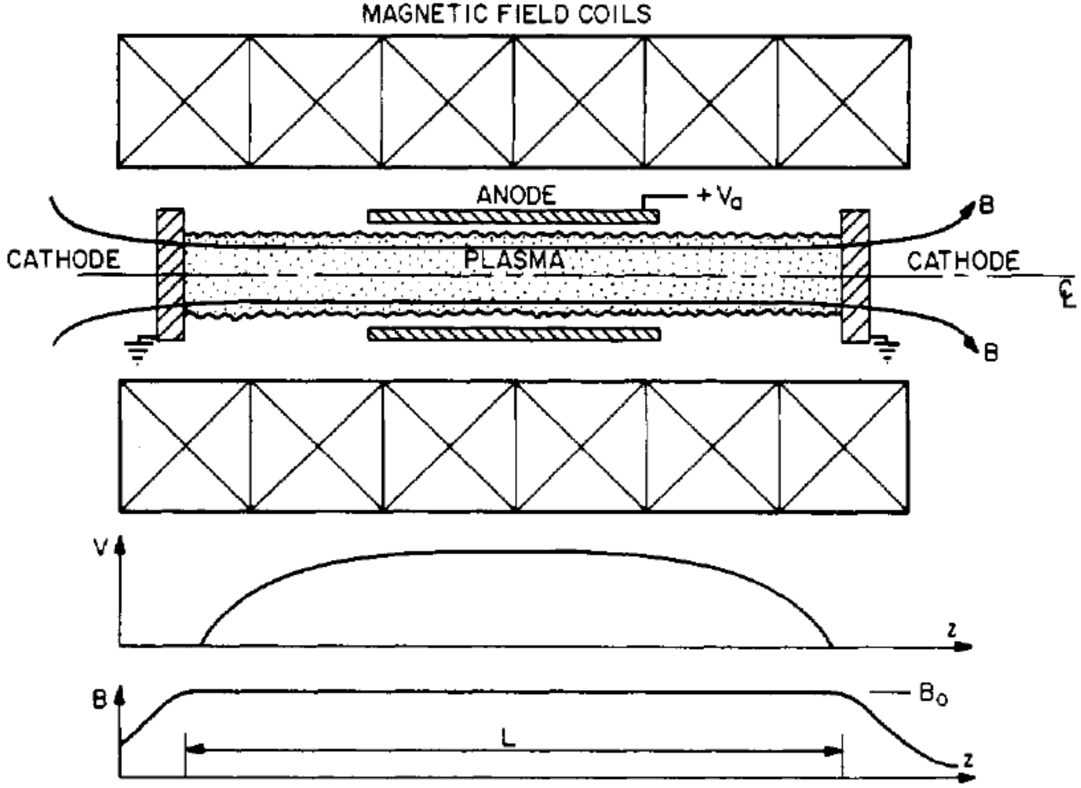
- **The obstructed configuration is used for plasma processing, where high ion energies bombarding the cathode, over large areas and at vertical incidence, are desired.**

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



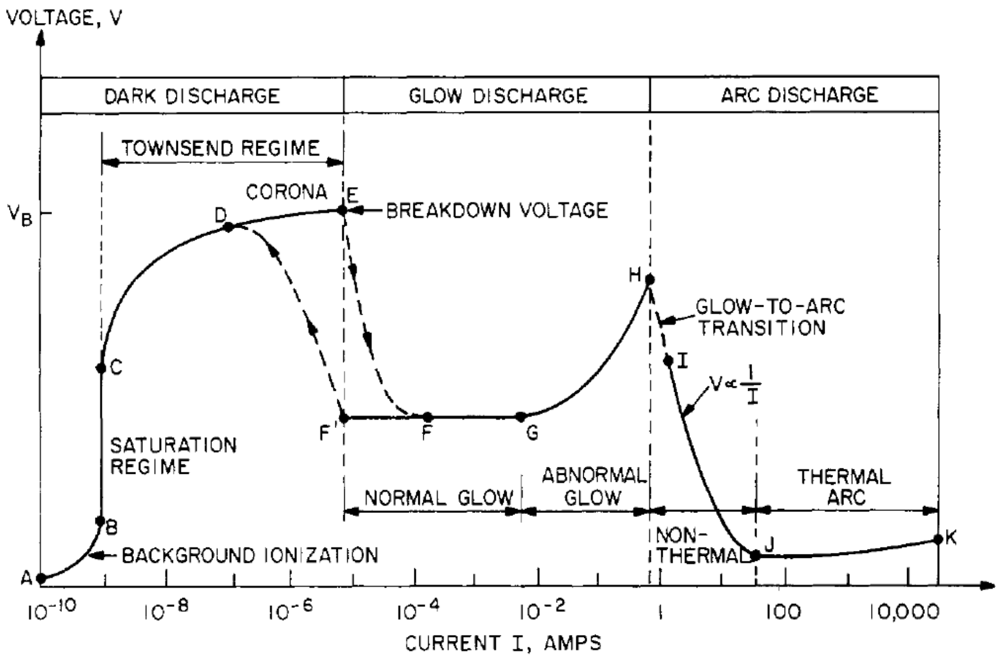
- **When several hundred voltages are applied between the parallel plates, a glow discharge will form, with a negative glow plasma trapped in the magnetic mirrors above the magnet pole pieces.**

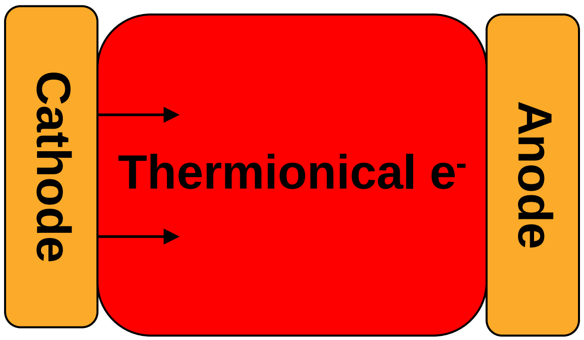
Penning discharge plasma sources produce a dense plasma at pressures far below than most other glow discharges



- **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.**

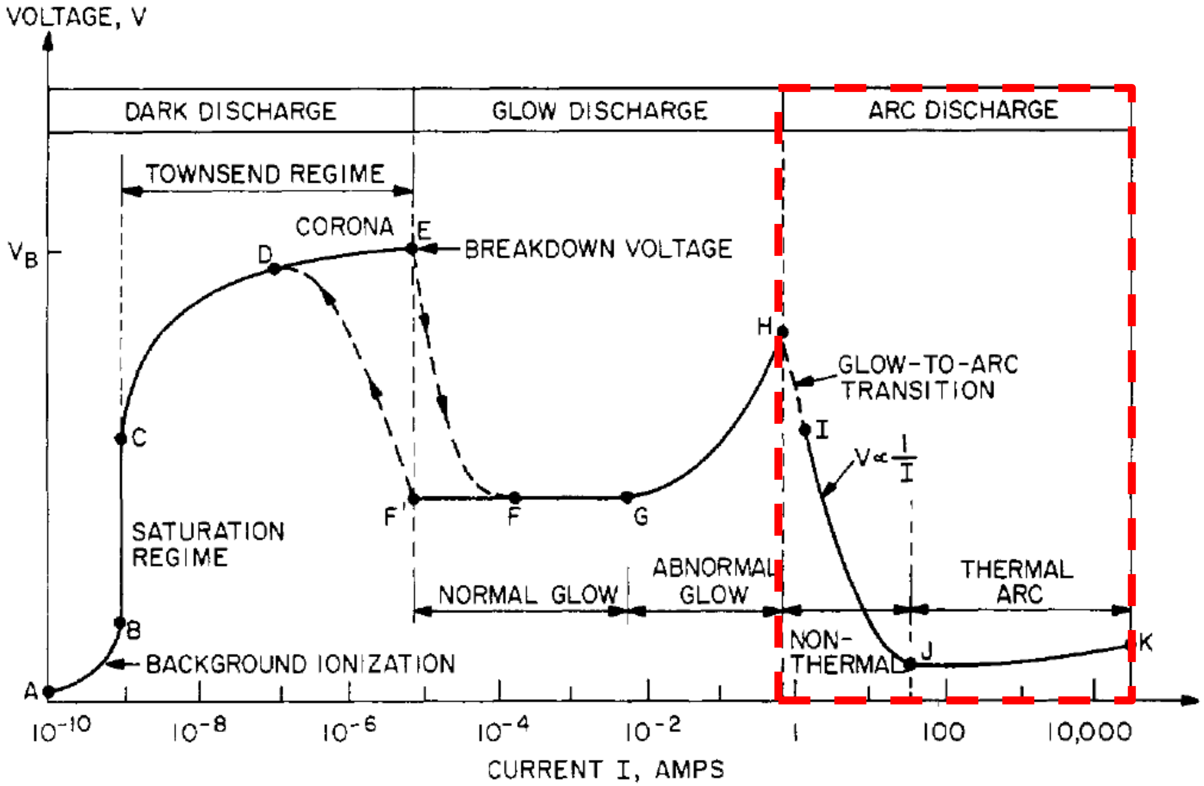
Discharge may enter glow-to-arc transition region if the cathode gets hot enough to emit electrons thermionically





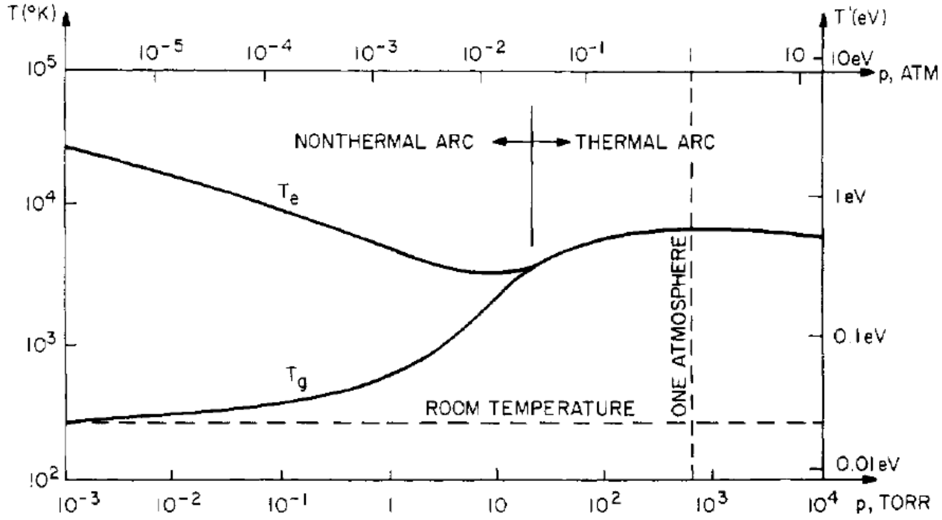
- If the cathode gets hot enough to emit electrons thermionically and the internal impedance of the power supply is sufficiently low, the discharge will make a transition into the arc regime.

DC electrical arc discharges in gases



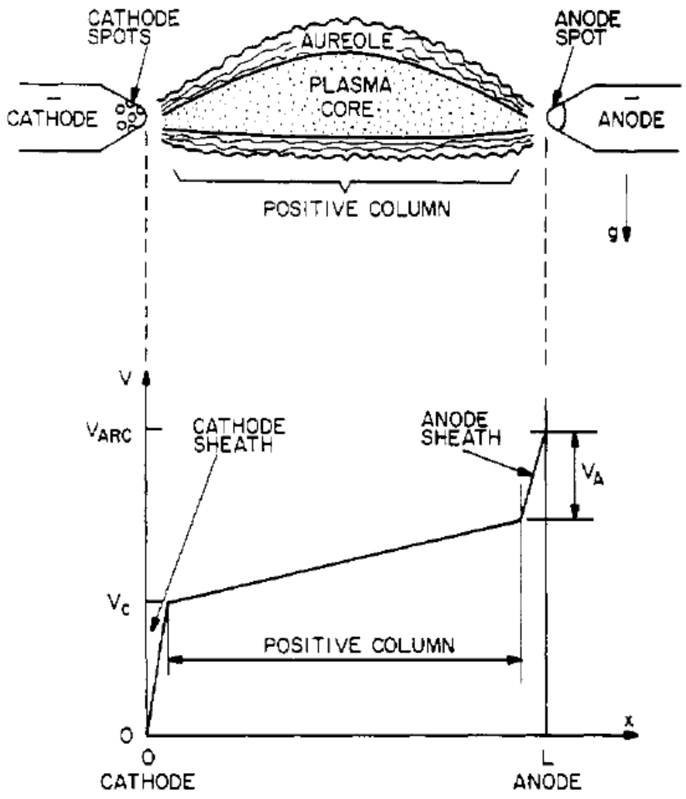
- **An arc is highly luminous and is characterized by high currents (> 1 A) and current densities (A=cm² t kA/cm²).**
- **Cathode voltage fall is small (£10 V) in the region of high spatial gradients within a few mm of the cathode.**

An arc can be non-thermal or thermionic



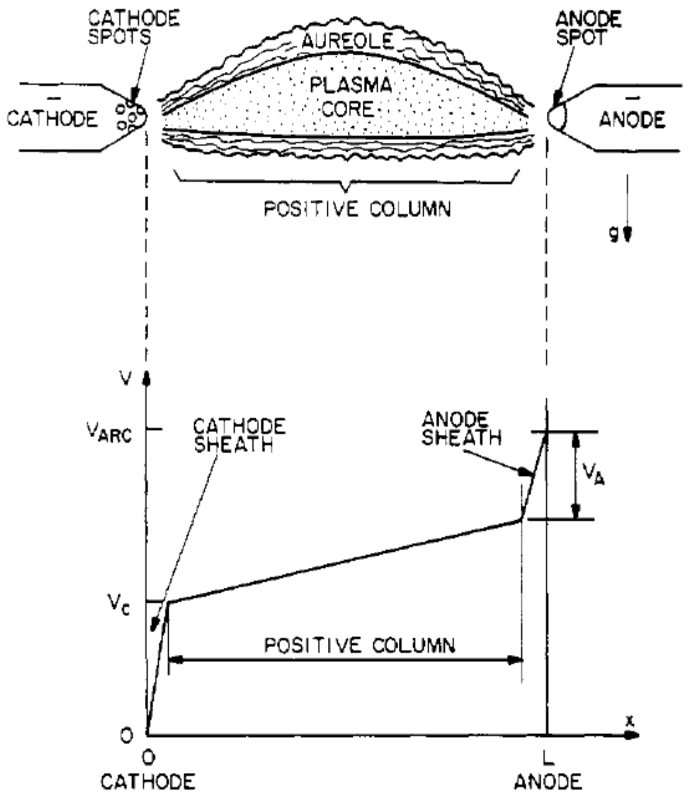
Plasma parameter	Non-thermal arc	Thermal arc
Equilibrium state	Kinetic	LTE
Electron density, n_e (electrons/m^3)	$10^{20} < n_e < 10^{21}$	$10^{22} < n_e < 10^{25}$
Gas pressure, p (Pa)	$0.1 < p < 10^5$	$10^4 < p < 10^7$
Electron temperature, T_e', (eV)	$0.2 < T_e' < 2.0$	$1.0 < T_e' < 10$
Gas temperature, 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

Classical arc were mostly used as lighting devices and operated as non-thermal arcs



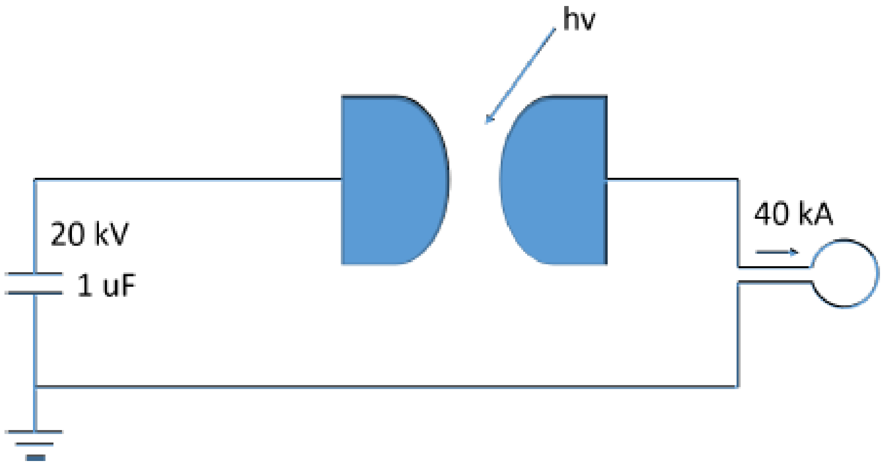
- **<u>Cathode</u> - emits electrons thermionically**
- **<u>Cathode spots</u> - several hot spots causing material losses through vaporization and move over the cathode surface with a velocity ~ m/s.**
- **<u>Cathode sheath</u> - voltage drop (cathode fall) ~ 10 V in < 1 mm.**
- **<u>Positive column</u> - little drop in voltage.**
- **<u>Plasma core</u> - hot region in thermodynamic equilibrium and radiates like a black body.**
- **<u>Aureole</u> - flaming gases where plasma chemistry takes place.**

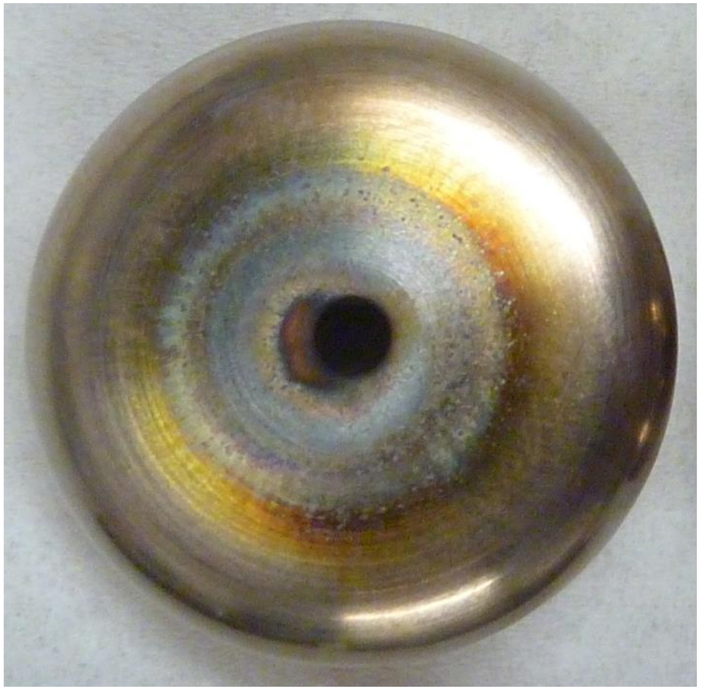
Classical arc were mostly used as lighting devices and operated as non-thermal arcs



- **Anode sheath** - voltage drop (anode fall) ~ cathode fall and is comparable to or less than the ionization potential of the gas.
- **Anode spot** - a single 'hot spot' where the current density is high.
- **Anode** - usually made of a high melting point, refractory metal and is similar or slightly hotter than cathode.

Example

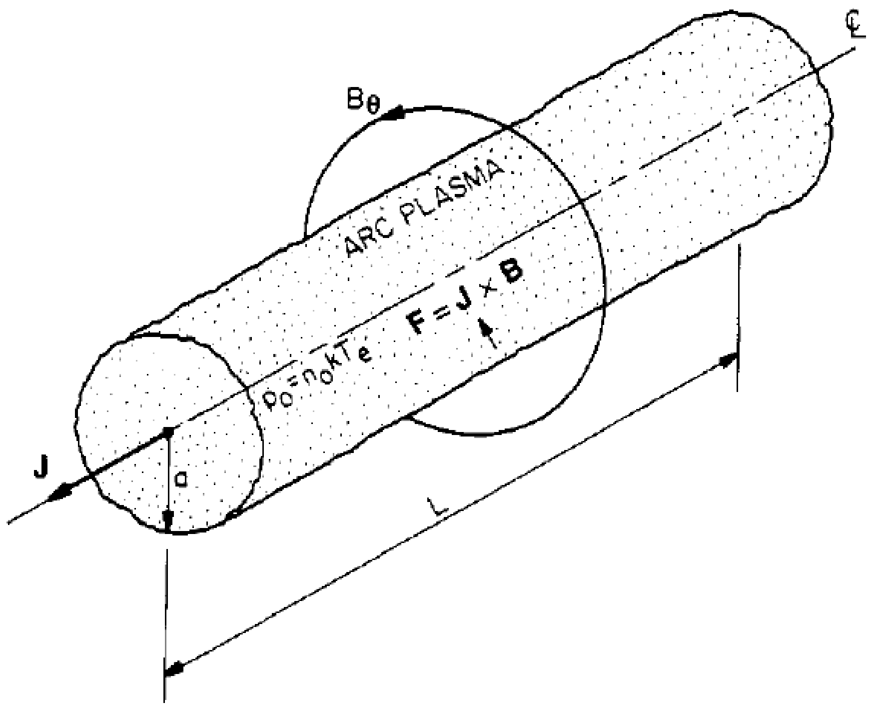




Note 1 - the cathode fall in arc is usually too small for secondary election emission so that the emission relies on thermionic and field emission

- Non-thermal, low intensity arcs - relies on thermionic emission
  - Non-self sustained thermionic emission - cathode must be heated externally.
  - Self sustained thermionic emission - cathode surface is raised to and maintained by the heat flux from the arc
- Thermal, high intensity arcs: relies on field emission
  - high current and current densities
  - cathode temperature is determined by the heat transfer to the cathode and the cathode cooling mechanism and is usually too cool to emit thermionically.

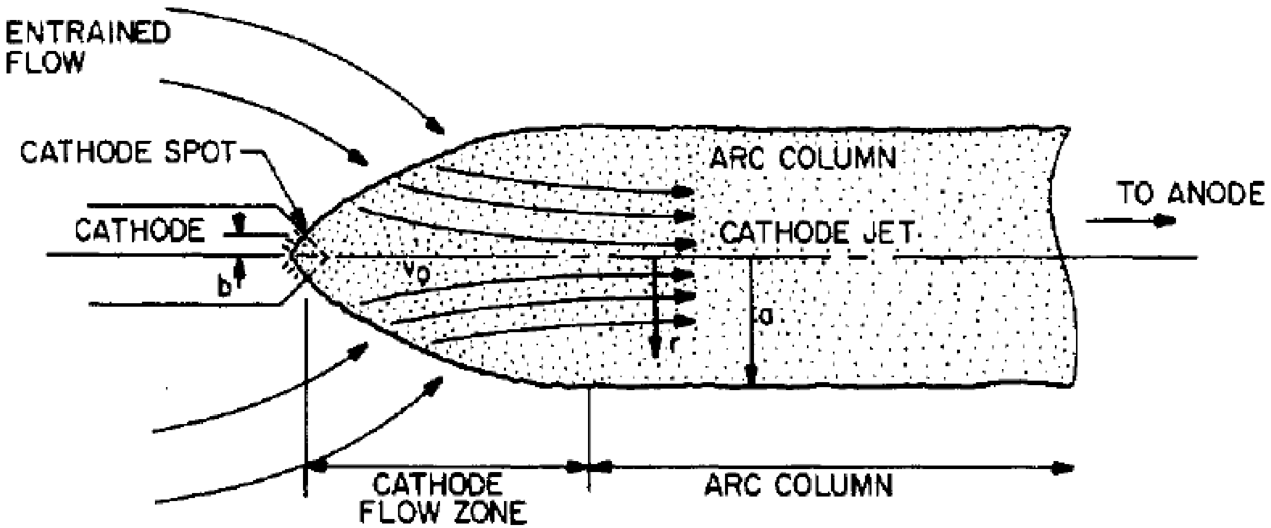
The arc tends to be pinched to smaller diameter



$$B_\theta = \frac{1}{2}\mu_0 J_z r \qquad r \le a$$

$$\vec{F} = \vec{J} \times \vec{B} = F_r \hat{r} = -\frac{1}{2}\mu_0 J_z{}^2 r\hat{r} \left(N/m^3\right)$$

Cathode jet is driven by the axial pressure gradient

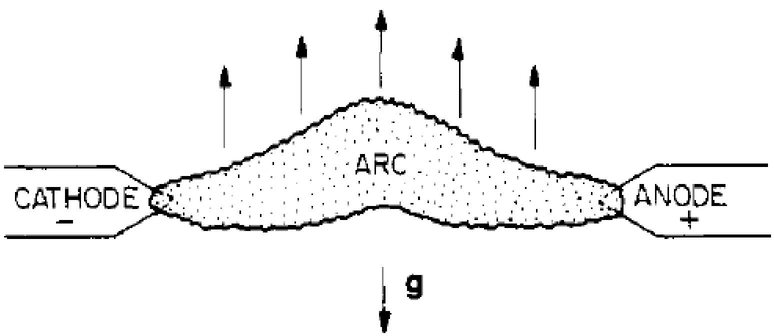


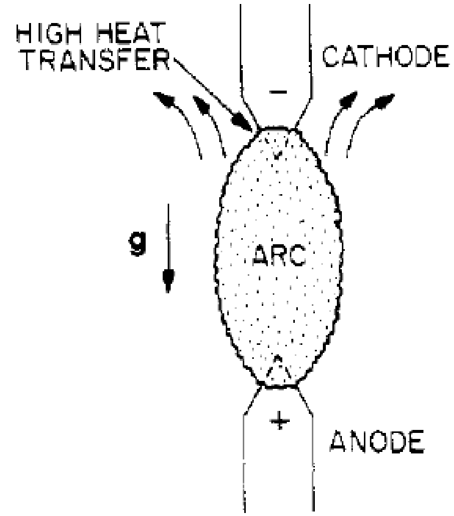
$$\nabla p = \vec{j} \times \vec{B} \qquad B_\theta = \frac{1}{2}\mu_0 J_z r \qquad r \le r_{\max}$$

$$p(r) = \int_r^{r_{\max}} J_z B_\theta \, \mathrm{d}r = \frac{1}{4}\mu_0 {J_z}^2\left({r_{\max}}^2 - r^2\right) \quad p_0 = \frac{\mu_o I^2}{4\pi^2 {r_{\max}}^2} \quad \text{where} \quad I = \pi {r_{\max}}^2 J_z$$

$\because b < a \;, \therefore p_b > p_a$

Example - Linear Arcs (free-burning arc)

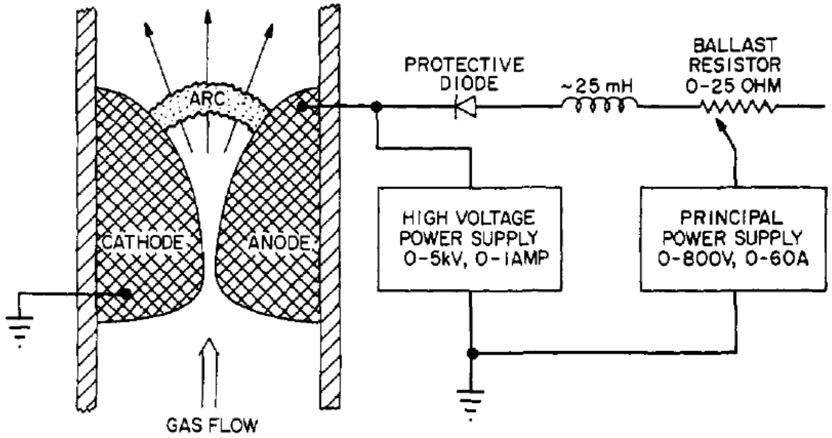




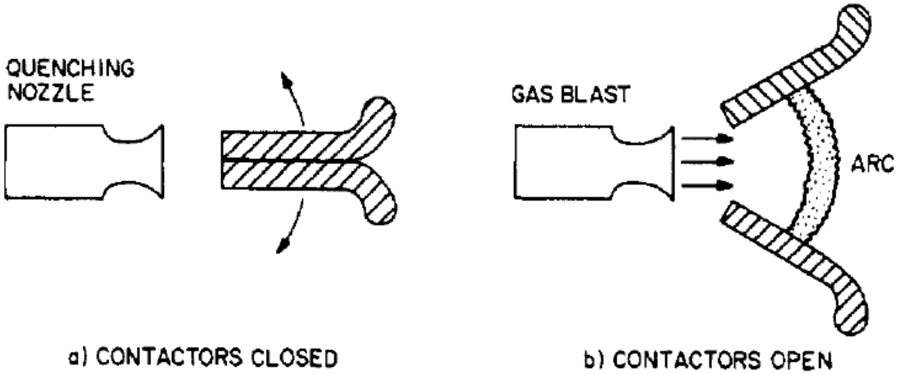
- The buoyancy of the hot gases causes a horizontal linear arc to bow upward, resulting in an arched appearance that gave the ‘arc’ its name.
- The cathode is usually operated at the top, in order to better balance the heat loads on the two electrodes.

Expanding Arcs

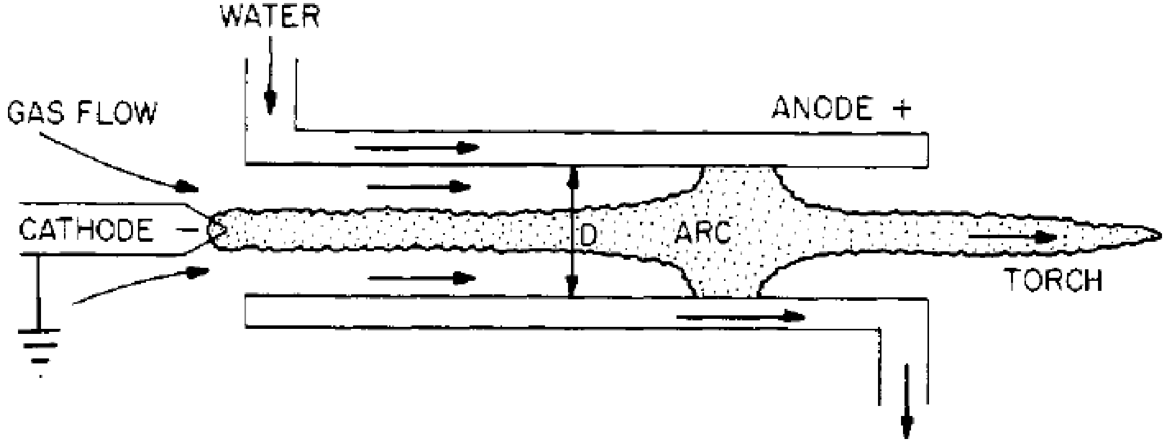
- **The gliding arc is used for toxic waste disposal and destructive plasma chemistry.**



- **Heavy duty switchgear:**



Wall-stabilized arc



- **Radial power balance:**

$$\sigma E^2 = -\nabla \cdot (\kappa \nabla T) = -\frac{1}{r}\frac{d}{\mathrm{dr}}\left(r\kappa \frac{dT}{dr}\right)$$

- **Assume that the axial electric field E is constant *σ* and *κ* are not function of temperature:**

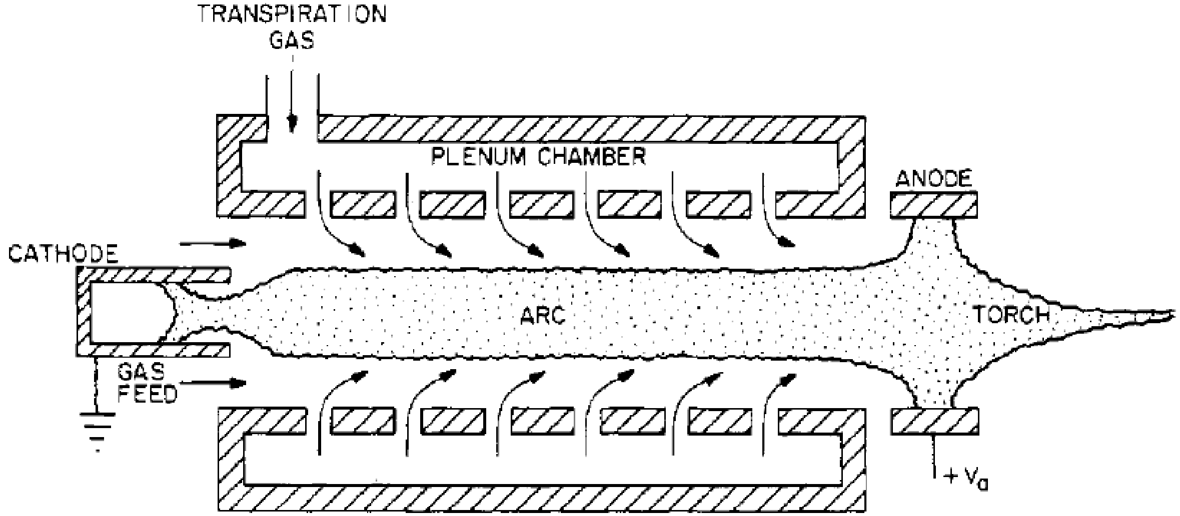
$$T_0 = T_{\mathrm{w}} + \frac{\sigma E^2 a^2}{4\kappa}$$

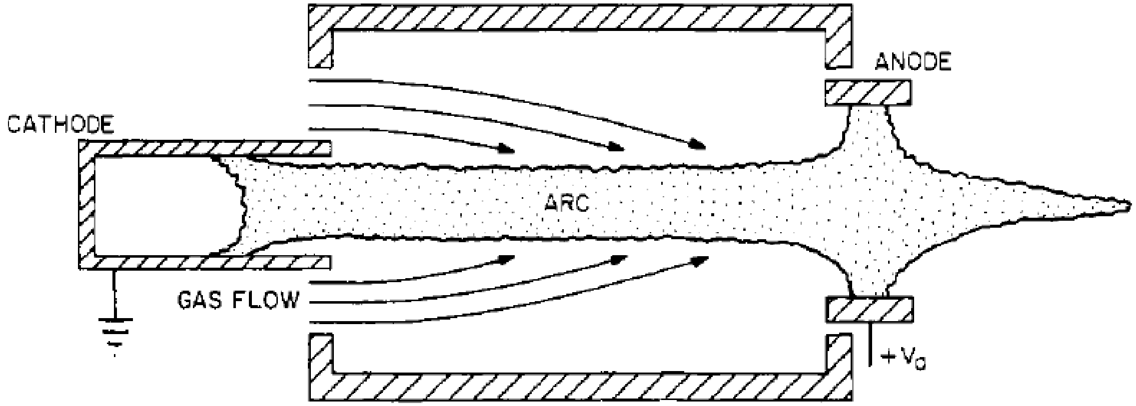
- **Wall-stabilized effect:**

$$T \downarrow \Rightarrow \ \kappa \downarrow \Rightarrow \ T_0 \uparrow \Rightarrow \ \sigma \uparrow \Rightarrow$$ **the arc will be pulled back on axis**

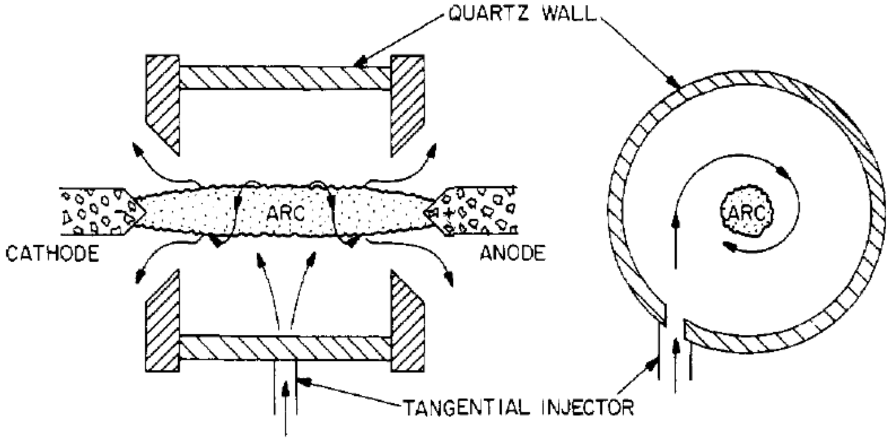
$$\tau_e = \frac{3\sqrt{m_e}(\mathrm{kT}_e)^{3/2}}{4\sqrt{2\pi}\mathrm{n}\lambda \mathrm{e}^4 z} \qquad \kappa = 3.2\frac{\mathrm{nkT}_e \tau_e}{m_e} \propto T_e{}^{5/2} \qquad \sigma = \frac{\mathrm{ne}^2 \tau_e}{m_e} \propto T_e{}^{3/2}$$

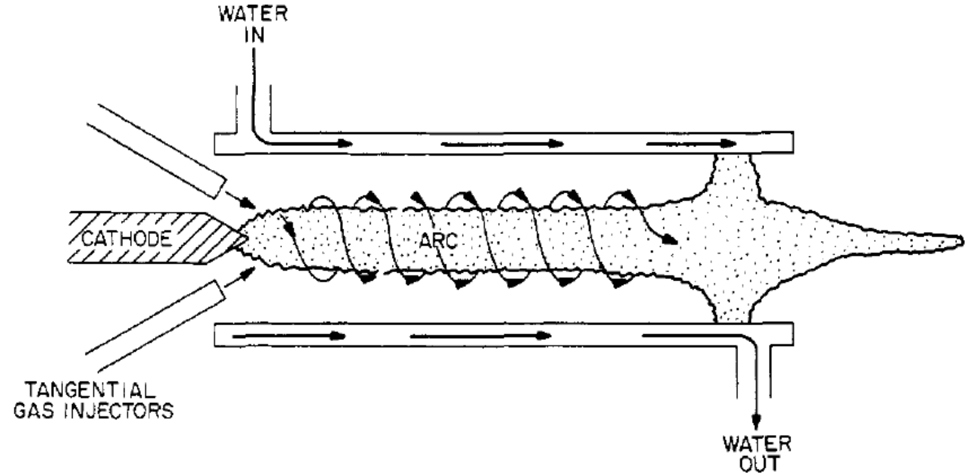
Arc can be stabilized by air flow





Arc can be stabilized by the vortex flow

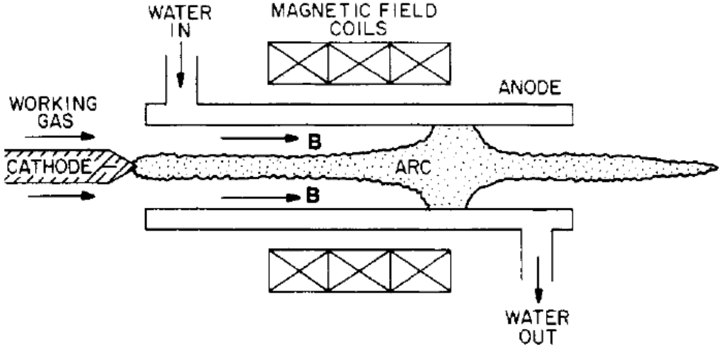




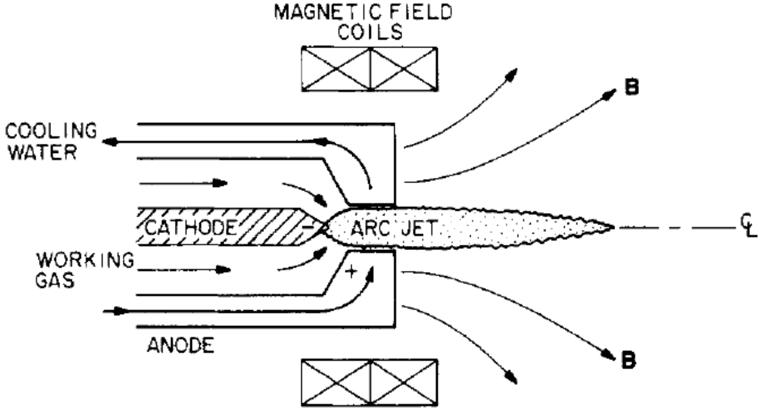
- **The vortex flow is very effective in reducing the heat flux to the wall.**

Magnetically stabilized arc

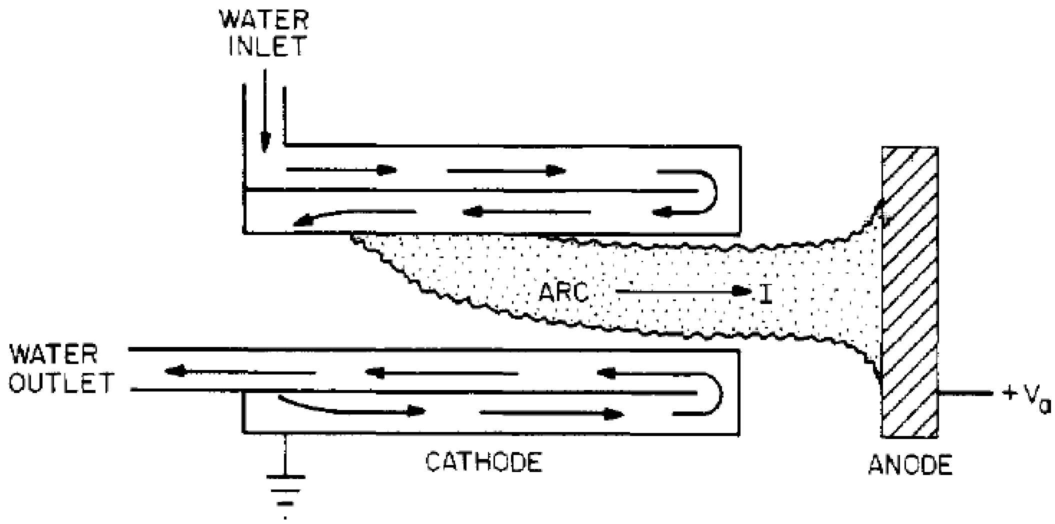
- An axial magnetic field provides $\vec{J} \times \vec{B}$ forces which rotate the arc spoke to avoid high local heat loads on the anode.



- An axial magnetic mirror coaxial with the anode so that the magnetic field maximum is near the plane of the arc rotation.



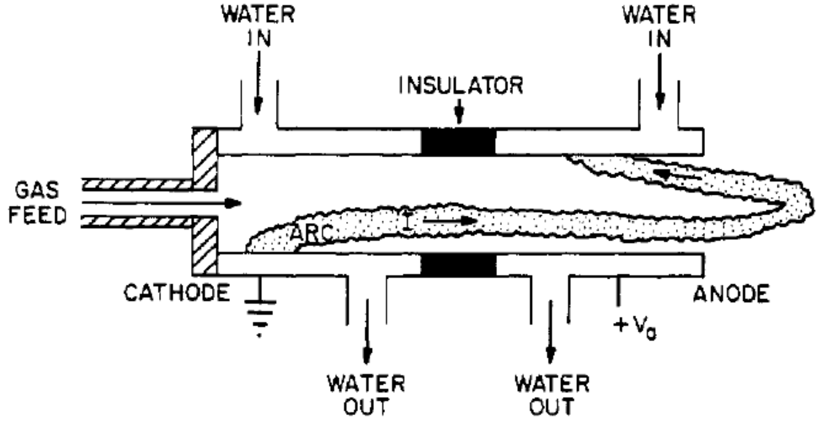
Transferred arc is good for metal melting and refining industry



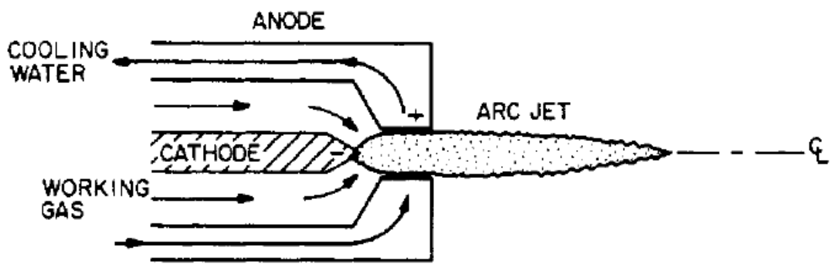
- **Capable of operating at the multi-megawatt level for duration (100s ~1000s hours) that are not possible for thermionically emitting cathodes or uncooled, incandescent cathodes operating in air.**
- **The arc root moves over the cathode surface, further reducing the cathode heat load and increasing the lifetime of the hardware.**
- **The object to be heated is used as the anode since the anode receives the heat deposition from the cathode jet.**

Non-transferred arc

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



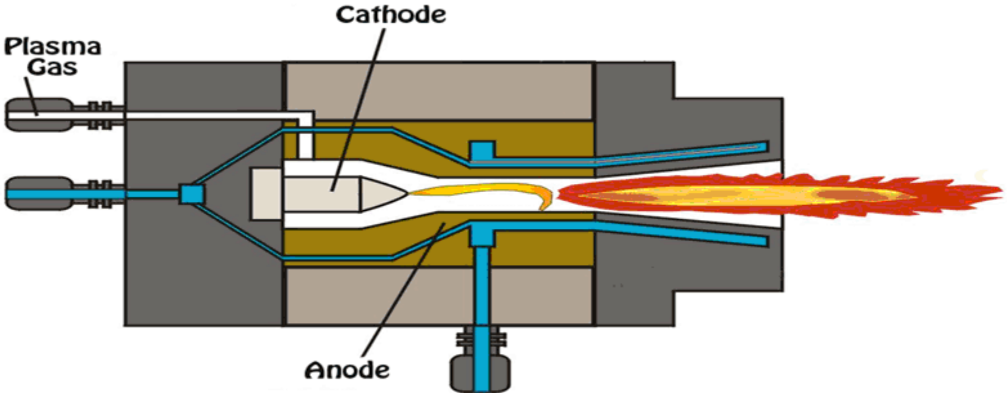
- **A working gas is fed in coaxially and forms a very hot arc jet, at supersonic velocities.**



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

- **Non-Transferred arc**

- **Transferred arc**



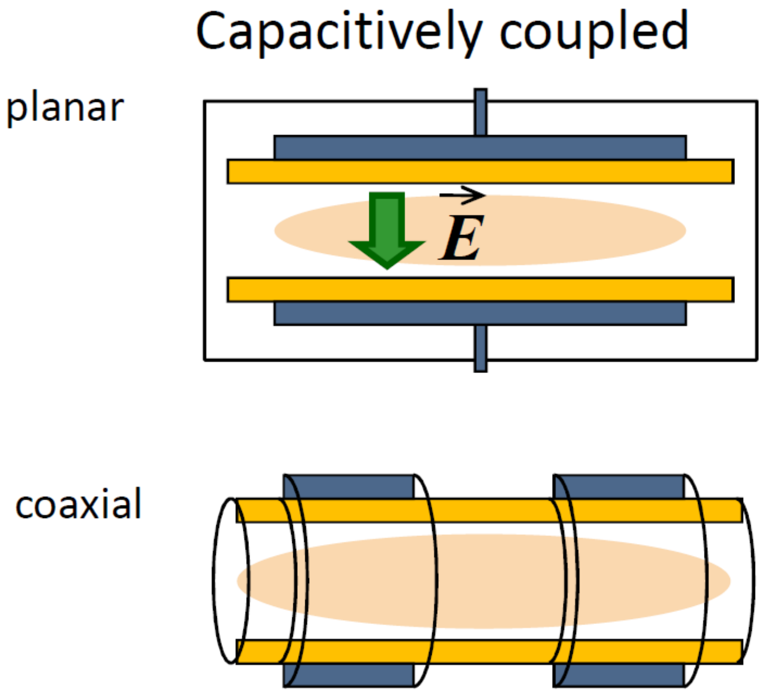
特性 \ 型式	非傳輸型	傳輸型
電極結構	兩個電極皆在火炬本體上	一個電極在火炬本體上，另一電極在被處理物上(或爐底電極)
操作/安裝空間	較小	較大(尤其垂直高度)
氣流量	較大 (100%)	較小 (20%)
中心溫度(℃)	4,000～10,000	15,000～20,000
能量密度(MJ/kg)	5～40	20～200
功率控制參數	電流、氣流量	電流、氣流量、電弧長度
電能轉換熱能效率(%)	80～90	≧90
熔融機制	1.火焰直接加熱 2.電能使用效率較低(45%)	1.火焰直接加熱 2.熔漿電阻加熱 3.電能使用效率較高(60%)

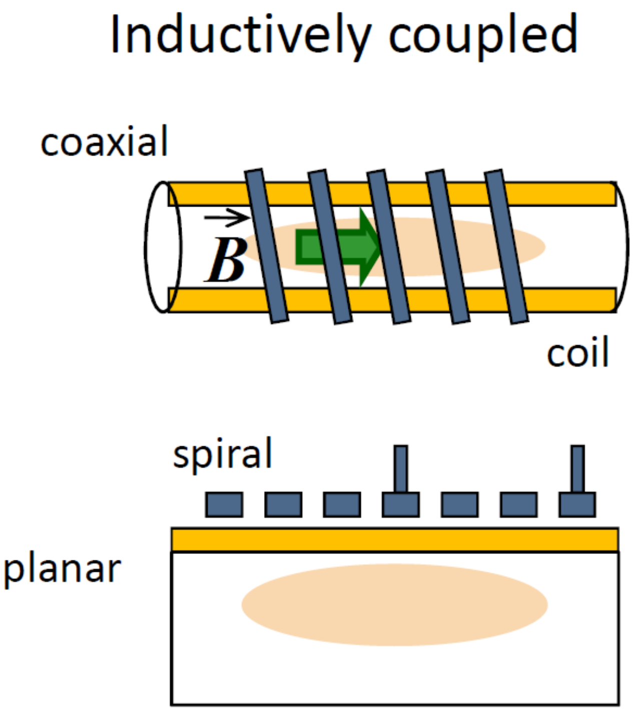
https://www.atlas-innotek.com/projects/e6oFj63K47PYPqPe2
http://www.resi.com.tw/PlasmaTorch.htm

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

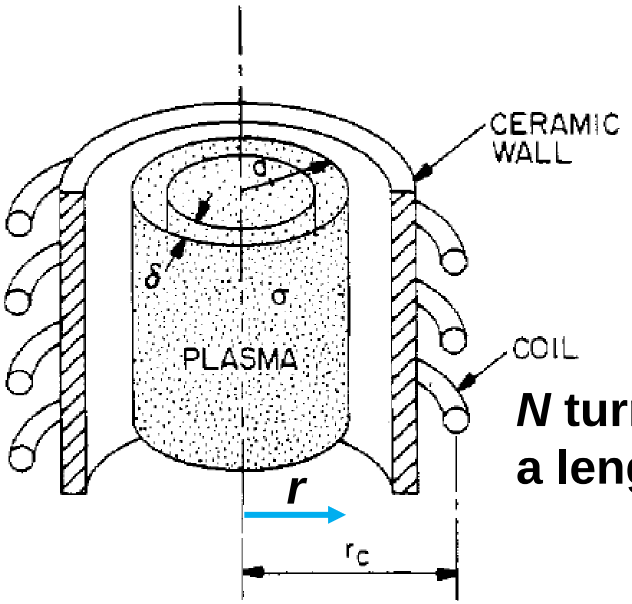




AC electrical discharges deliver energy to the plasma without contact between electrodes and the plasma

- **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.**
  - **Inductive radio frequency (RF) electrical discharges**
  - **Capacitive RF electrical discharges**
  - **Microwave electrical discharges**
  - **Dielectric-barrier discharges (DBDs)**
- **Other mechanism**
  - **Laser produced plasma**
  - **Pulsed-power generated plasma**

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



N **turn within a length of *l***

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

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

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

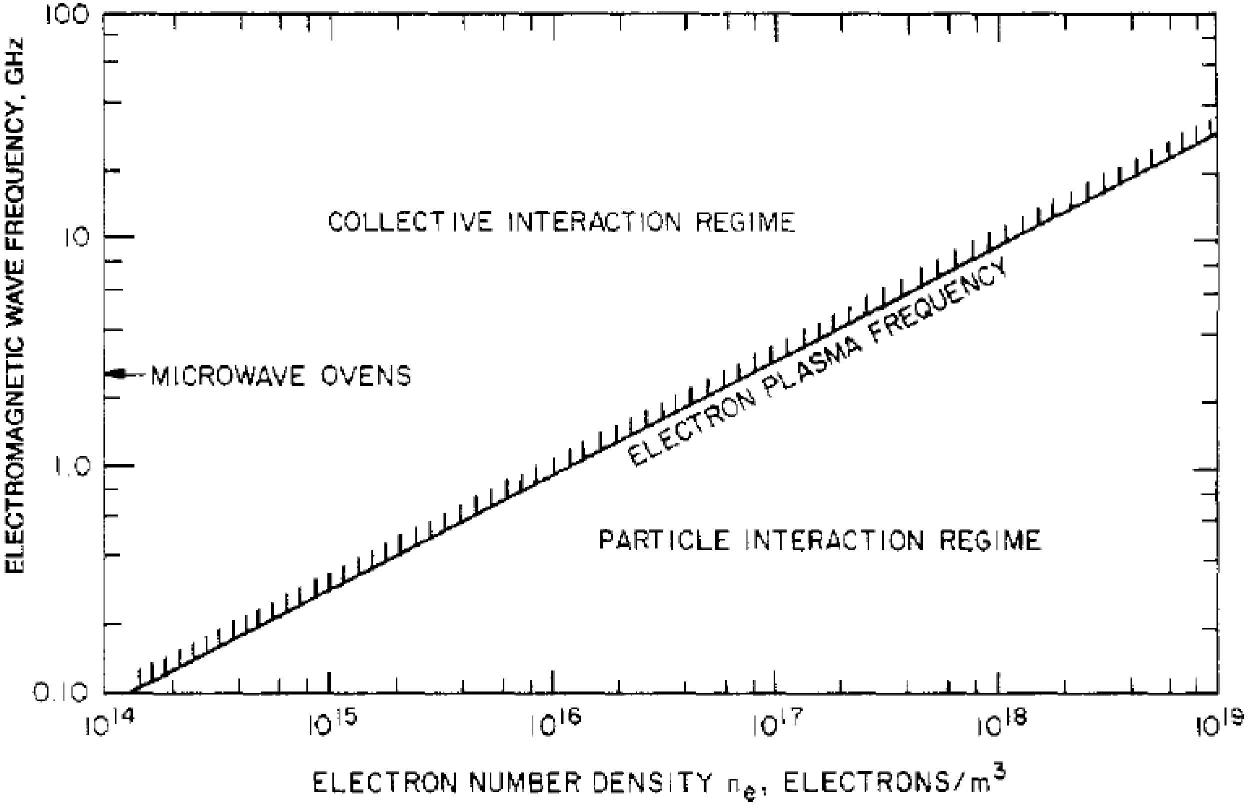
$$E = -\frac{r}{2}\frac{\partial B}{\partial t}$$

$$B \times l = \mu_o N I$$

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

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

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



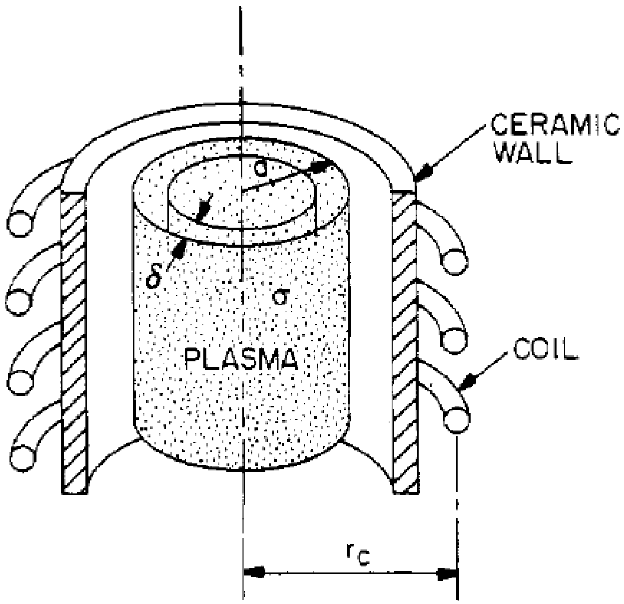
$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \, (\mathrm{rad}/s)$$

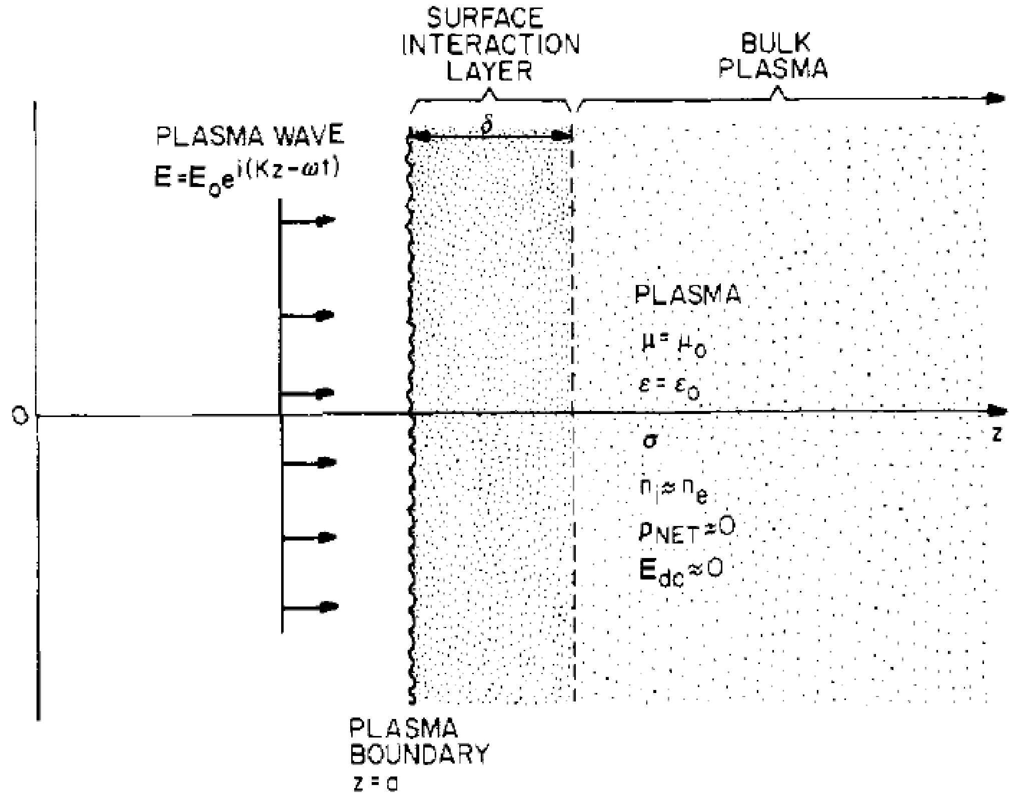
$$n_{cri} = \frac{\epsilon_0 m_e}{e^2} \omega_{pe}^2 (m^{-3})$$

$$n_{760\ \mathrm{Torr}\ /\ 300\mathrm{K}} = 2.45 \times 10^{25}\ \mathrm{m}^{-3}$$

$$n_{0.1\ \mathrm{Torr},\ 1\ \%\ \mathrm{ionization}} = 3.2 \times 10^{19}\ \mathrm{m}^{-3}$$

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





Skin depth is calculated using Maxwell's equations

$$\nabla \cdot \vec{E} \approx 0(\text{quasi} - \text{neutral}) \qquad \nabla \cdot \vec{B} = 0$$

$$\vec{J} = \sigma \vec{E}\ (\text{Ohm}'s\text{law})$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

$$\nabla \times \left(\nabla \times \vec{E}\right) = -\frac{\partial}{\partial t}\left(\nabla \times \vec{B}\right) = \nabla\left(\nabla \cdot \vec{E}\right) - \nabla^2 \vec{E} \sim -\nabla^2 \vec{E}$$

$$\frac{\partial^2 \vec{E}}{\partial z^2} - \mu_0 \sigma \frac{\partial \vec{E}}{\partial t} - \mu_0 \epsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \qquad \vec{E} = \vec{E}_0 \exp[-i(\text{kz} - \omega\text{t})] \qquad k \equiv \alpha + \frac{i}{\delta}$$

$$\left(-k^2 + \text{i}\omega\mu_0\sigma + \mu_0\epsilon_0\omega^2\right)\vec{E} = 0$$

$$\alpha = \sqrt{\frac{\sigma\mu_0\omega}{2}}\left[\frac{\omega\epsilon_0}{\sigma} + \sqrt{1 + \left(\frac{\omega\epsilon_0}{\sigma}\right)^2}\right]^{1/2}$$

$$\frac{1}{\delta} = \sqrt{\frac{\sigma\mu_0\omega}{2}}\left[\sqrt{1 + \left(\frac{\omega\epsilon_0}{\sigma}\right)^2} - \frac{\omega\epsilon_0}{\sigma}\right]^{1/2}$$

Skin depth is calculated using Maxwell's equations

$$\alpha = \sqrt{\frac{\sigma\mu_0\omega}{2}}\left[\frac{\omega\epsilon_0}{\sigma} + \sqrt{1 + \left(\frac{\omega\epsilon_0}{\sigma}\right)^2}\right]^{1/2} \qquad \frac{1}{\delta} = \sqrt{\frac{\sigma\mu_0\omega}{2}}\left[\sqrt{1 + \left(\frac{\omega\epsilon_0}{\sigma}\right)^2} - \frac{\omega\epsilon_0}{\sigma}\right]^{1/2}$$

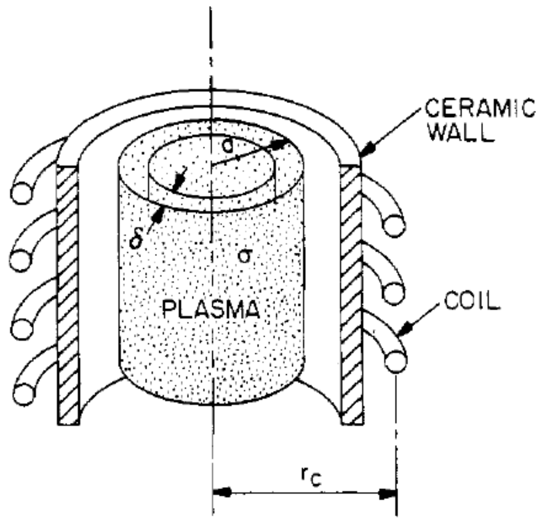
- **In most industrial plasma,** $\frac{\omega\epsilon_0}{\sigma} \ll 1$ **. Note that** $\sigma = \frac{e^2 n_e}{m_e \nu_c} = \frac{\epsilon_0 {\omega_{pe}}^2}{\nu_c}$ **so** $\nu_c \omega << {\omega_{pe}}^2$ **is required.**

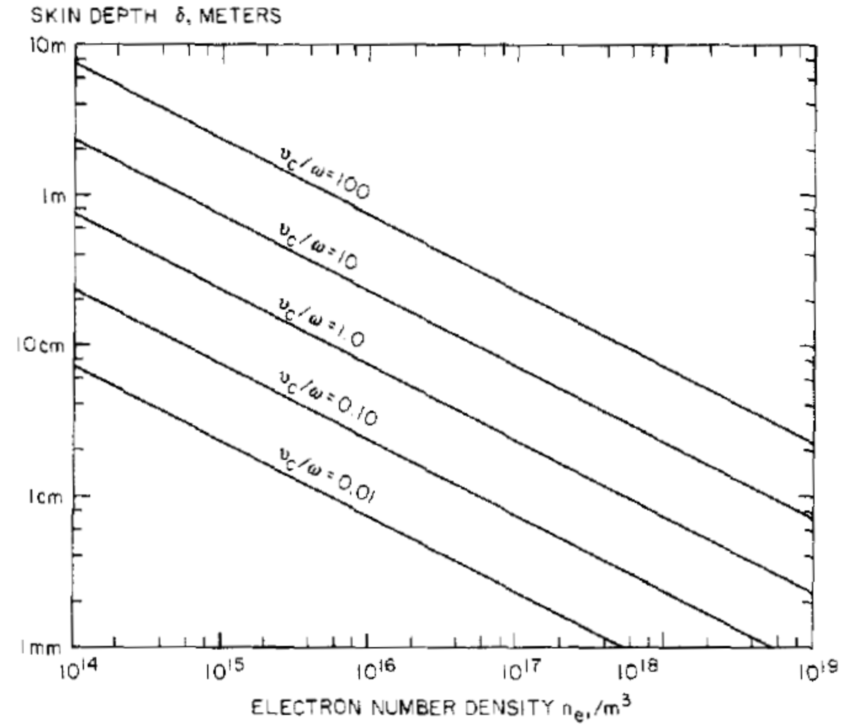
$$\alpha \approx \sqrt{\frac{\sigma\mu_0\omega}{2}}\,(m^{-1})$$

skin depth: $$\delta \approx \sqrt{\frac{2}{\sigma\mu_0\omega}} = \frac{c}{2\pi\nu_{pe}}\sqrt{\frac{\nu_c}{\pi\nu}}\,(m)$$

- **The skin depth δ ~ the distance that an electromagnetic wave propagates into a medium during one period of the electron plasma frequency.**

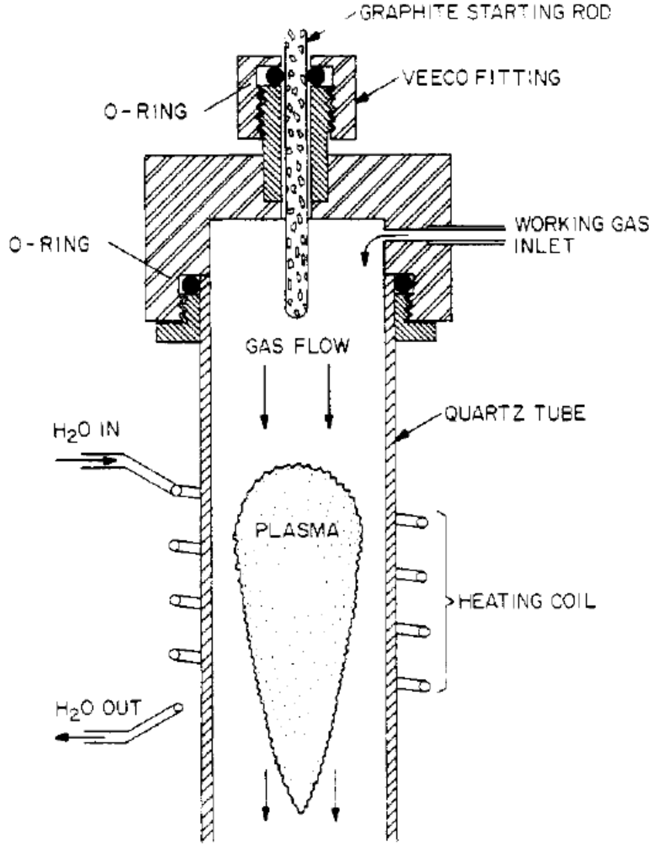
Skin depth needs to be carefully considered in the design of inductive industrial plasma reactors

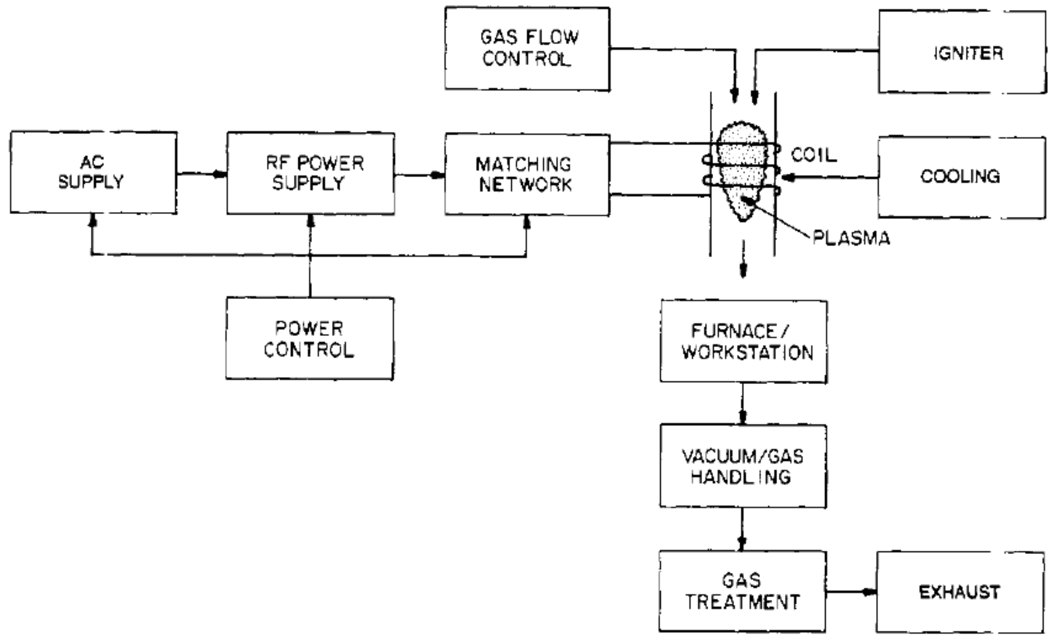




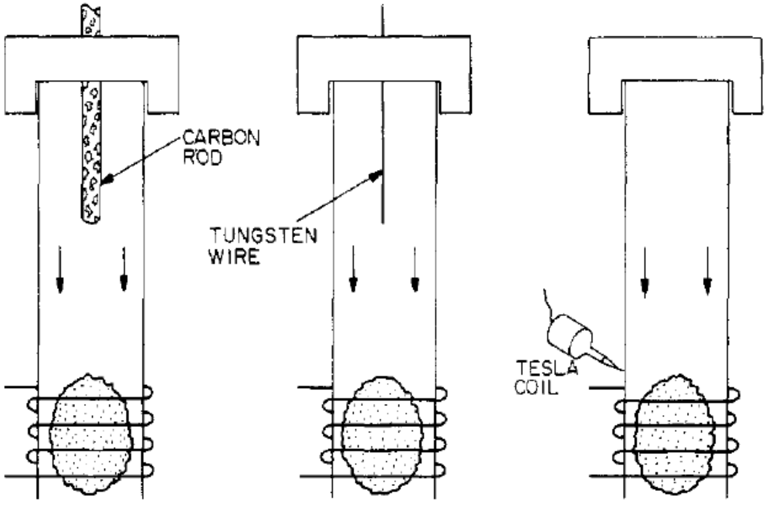
- **Boulos et al showed that the energy coupling parameter is maximum when 1.5δ ≤ a ≤ 3δ. However, it doesn't mean the plasma will be uniformly heated.**

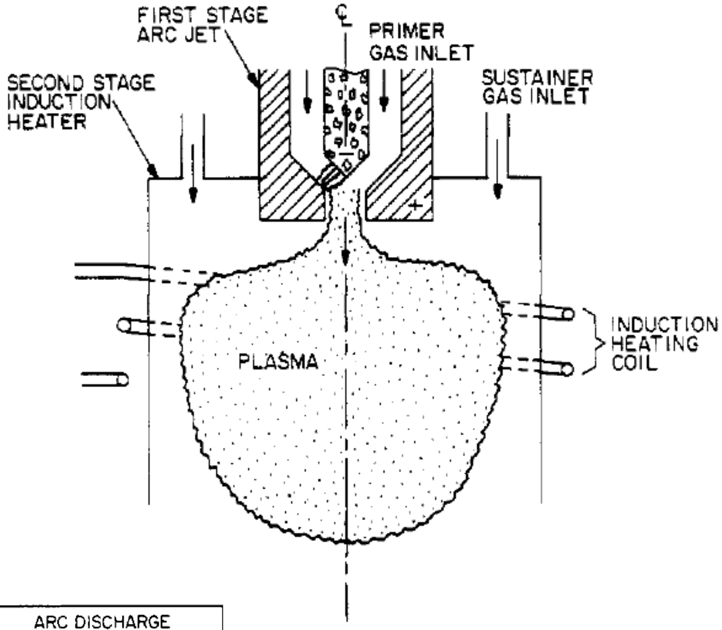
A kilowatt-level inductively coupled plasma torch is shown

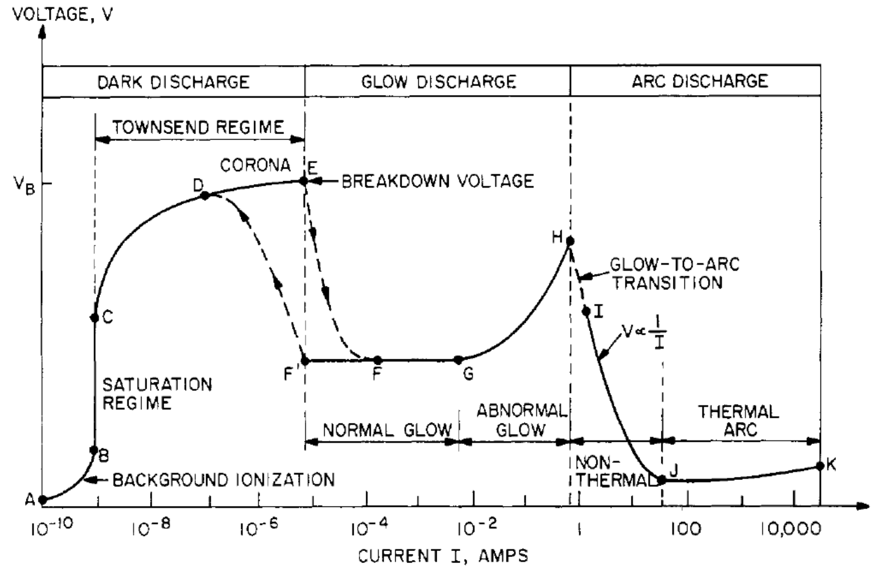




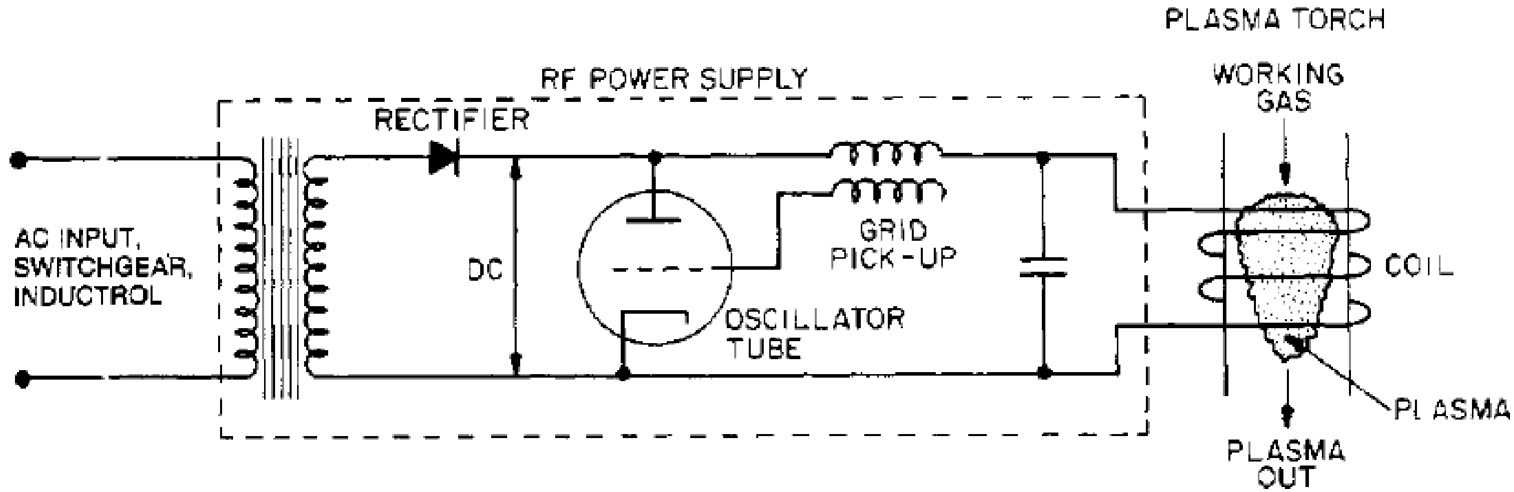
High voltage initiation is usually required for inductive RF plasma torches

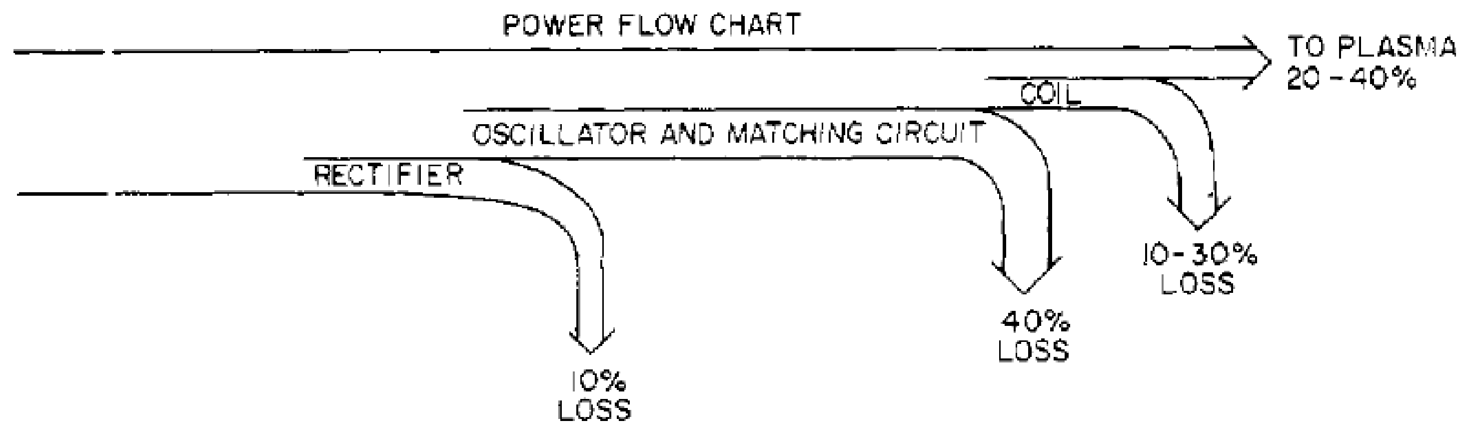






The power supplies are relatively inefficient

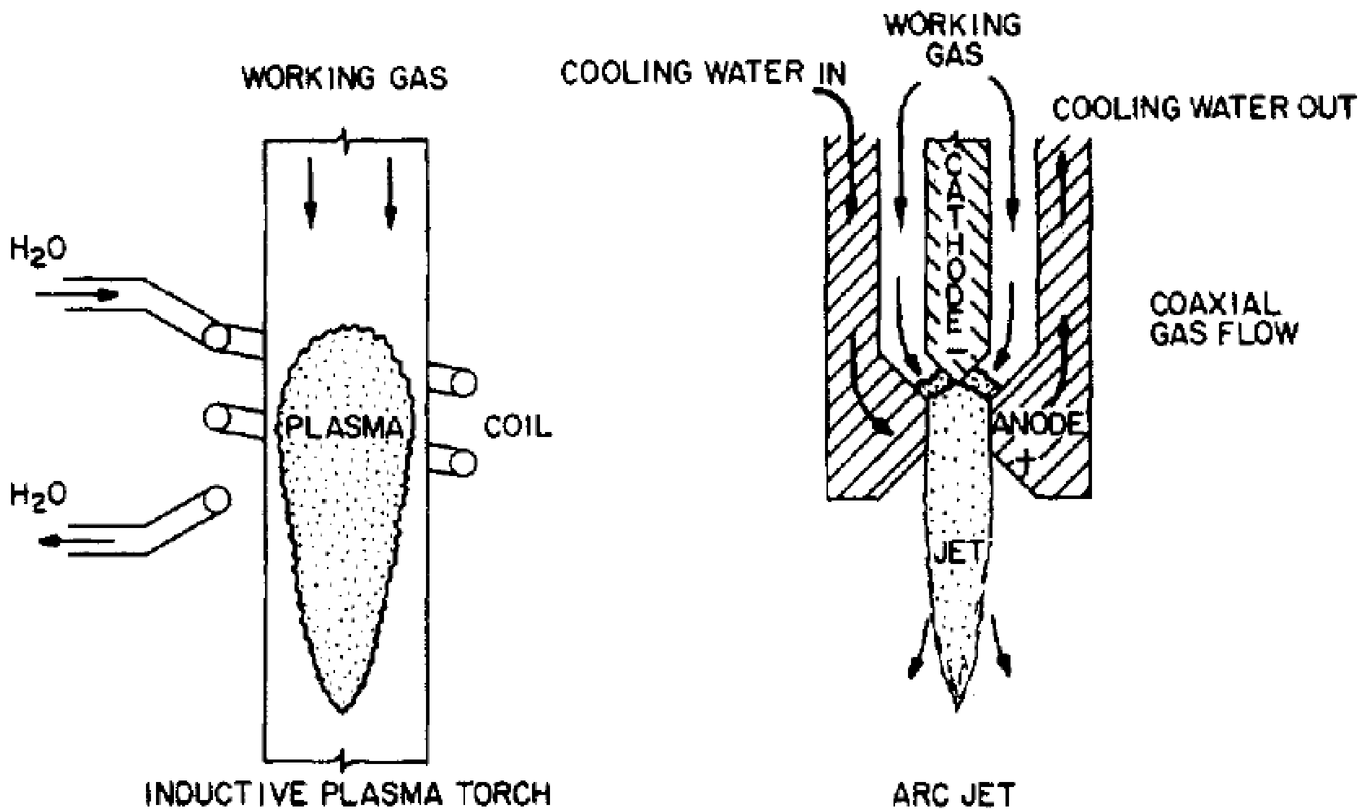




Operating regimes of inductively coupled plasma torches

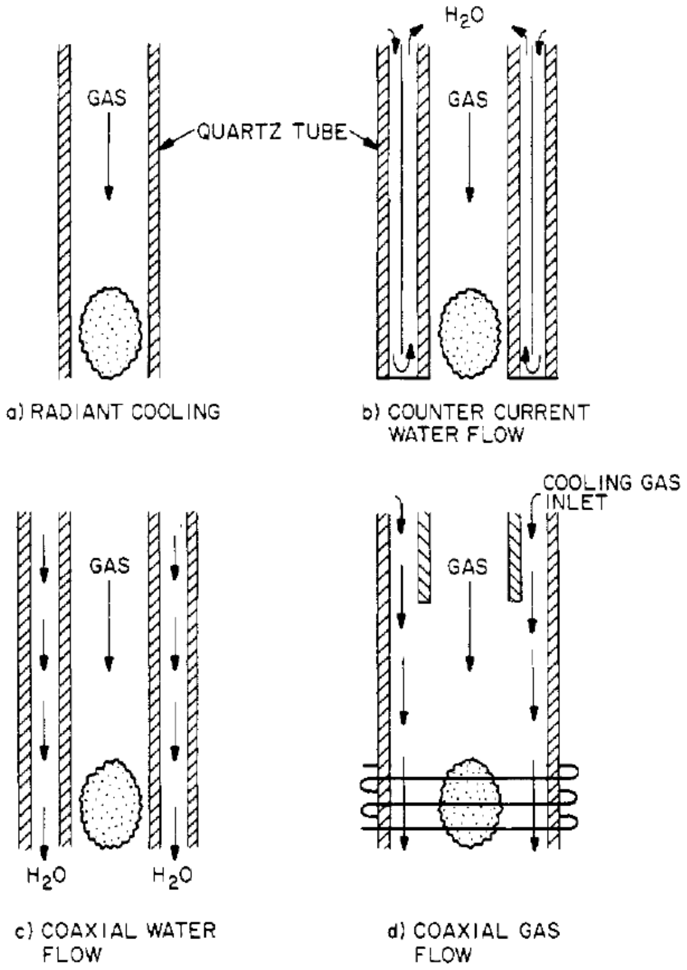
Parameter	Low	Characteristic	High
Frequency	10 kHz	13.56 MHz	100 MHz
Power	1 kW	30 kW	1MW
Efficiency	20%	35%	50%
Pressure	10 Torr	1 atm	10 atm
Gas temperature	1000 K	10^4 K	2×10^4 K

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

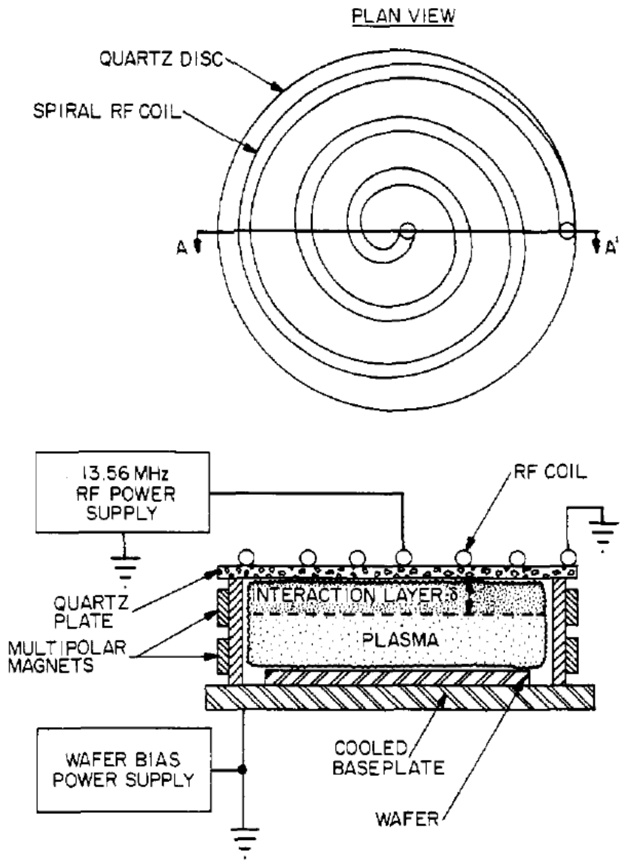


10 - 200 m/sec	JET VELOCITY	500-150 m/sec
4-40 mm	JET DIAMETER	6-10 mm
VARIABLE	JET SHAPE	CYLINDRICAL

Several cooling configurations are shown

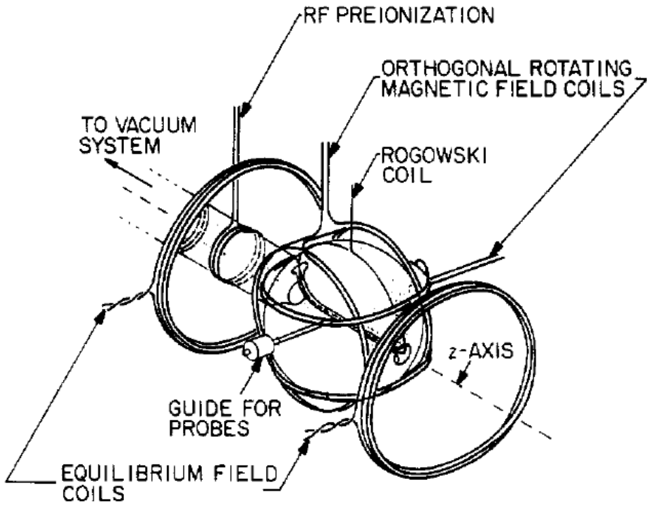


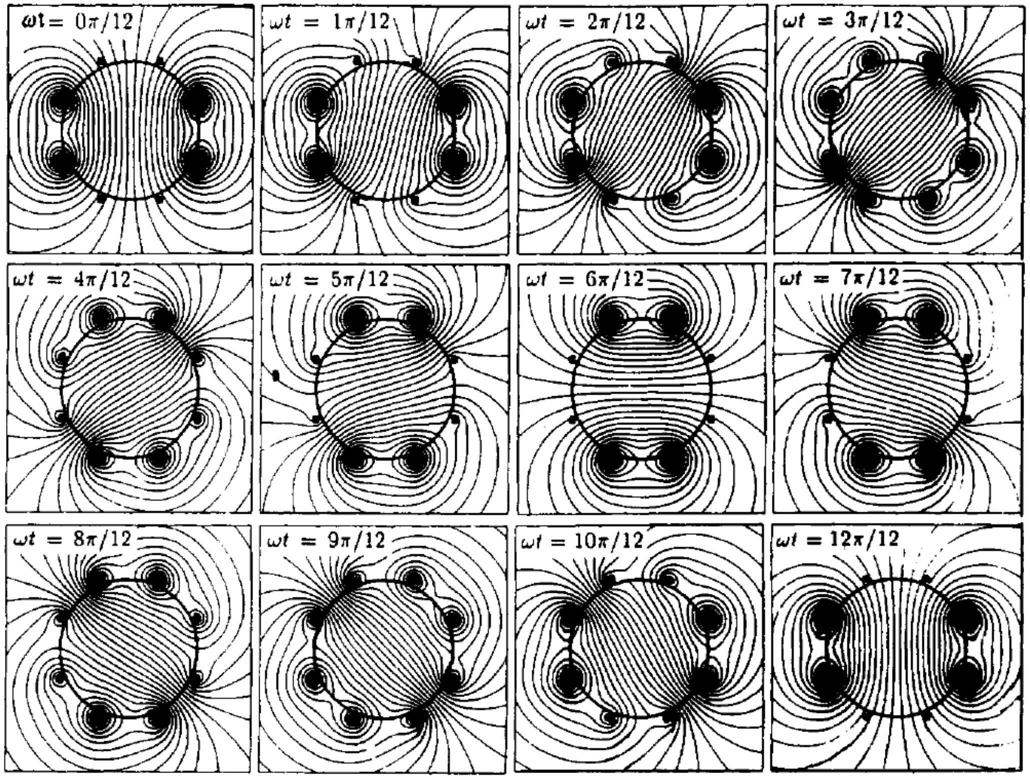
Inductive parallel plate reactor



- **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.**

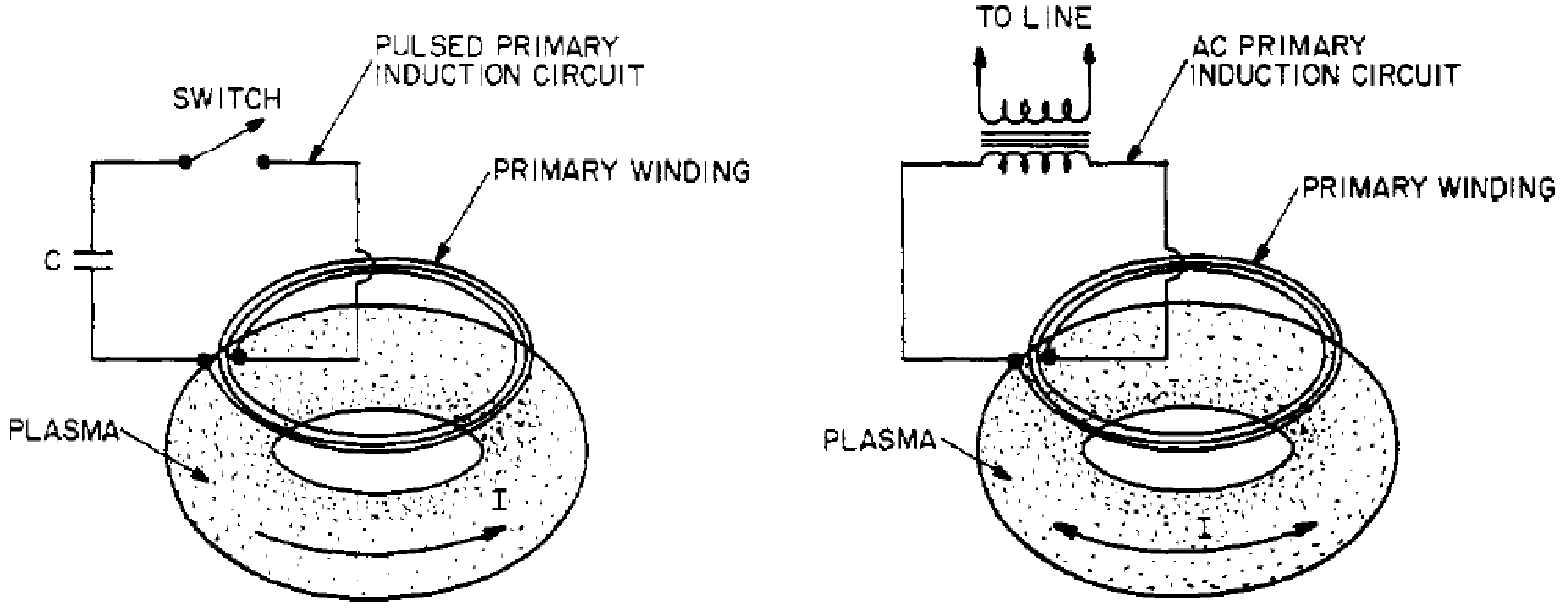
Rotamak





- **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

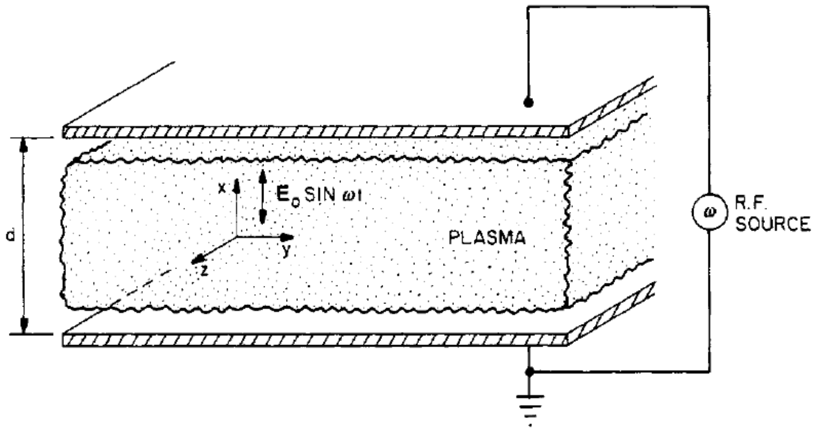
Applications of inductive plasma torches

- 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

AC electrical discharges deliver energy to the plasma without contact between electrodes and the plasma

- 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.
  - Inductive radio frequency (RF) electrical discharges
  - **Capacitive RF electrical discharges**
  - Microwave electrical discharges
  - Dielectric-barrier discharges (DBDs)
- Other mechanism
  - Laser produced plasma
  - Pulsed-power generated plasma

Capacitive RF coupling plasma without magnetic fields



$$\vec{F} = m\,\vec{a} = -\nu_c m\,\vec{v} - e\,\vec{E}$$

$$m\frac{\mathrm{d}v_y}{\mathrm{dt}} + m\nu_c v_y = 0$$

$$v_y(t) = v_{y0}\exp(-\nu_c t)$$

$$m\frac{d^2x}{\mathrm{dt}^2} + m\nu_c\frac{dx}{\mathrm{dt}} = eE_0\sin(\omega\mathrm{t})$$

$$x = C_1\sin(\omega\mathrm{t}) + C_2\cos(\omega\mathrm{t})$$

$$C_1 = -\frac{eE_0}{m}\frac{1}{\omega^2 + \nu_c{}^2}$$

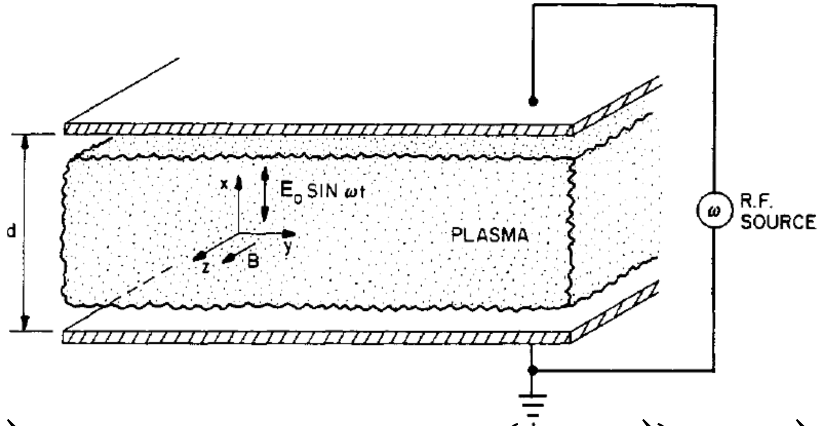
$$C_2 = -\frac{\nu_c eE_0}{\omega\mathrm{m}}\frac{1}{\omega^2 + \nu_c{}^2}$$

$$v_x(t) = -\frac{eE_0\omega}{m(\omega^2+\nu_c{}^2)}\left[\cos(\omega\mathrm{t}) - \frac{\nu_c}{\omega}\sin(\omega\mathrm{t})\right]$$

$$P = \frac{dW}{dt} = \mathrm{eE_0}\sin(\omega\mathrm{t})v_x$$

$$\bar{P}_{\mathrm{tot}} = n_e\bar{P} = \frac{1}{4}\epsilon_0 E_0{}^2\frac{2n_e e^2}{m\epsilon_0}\frac{\nu_c}{\omega^2 + \nu_c{}^2}$$

Capacitive RF coupling plasma with magnetic fields



$$\frac{d^2x}{\mathrm{dt}^2}+\nu_c\frac{dx}{\mathrm{dt}}+\omega_c\frac{\mathrm{dy}}{\mathrm{dt}}=-\frac{eE_0}{m}\sin(\omega t)$$

$$\frac{d^2y}{\mathrm{dt}^2}+\nu_c\frac{dx}{\mathrm{dt}}-\omega_c\frac{\mathrm{dy}}{\mathrm{dt}}=0 \qquad \omega_c=\frac{eB}{m}$$

$$\vec{F}=m\,\vec{a}=-\nu_c m\,\vec{v}-e\left(\vec{v}\times\vec{B}\right)-e\,\vec{E}$$

$$x=C_1\sin(\omega t)+C_2\cos(\omega t)$$

$$y=C_e\sin(\omega t)+C_4\cos(\omega t)$$

$$m\frac{d^2x}{\mathrm{dt}^2}+m\nu_c\frac{dx}{\mathrm{dt}}+\mathrm{eB}\frac{\mathrm{dy}}{\mathrm{dt}}=-eE_0\sin(\omega t)$$

$$m\frac{\mathrm{dv}_y}{\mathrm{dt}}+m\nu_c v_y-\mathrm{eB}\frac{\mathrm{dx}}{\mathrm{dt}}=0$$

$$C_1=-\frac{eE_0}{2m}\left[\frac{\omega+\omega_c}{(\omega+\omega_c)^2+{\nu_c}^2}+\frac{\omega-\omega_c}{(\omega-\omega_c)^2+{\nu_c}^2}\right]$$

$$m\frac{\mathrm{dv}_z}{\mathrm{dt}}+m\nu_c v_z=0$$

$$C_2=-\frac{\nu_c eE_0}{2\omega \mathrm{m}}\left[\frac{1}{(\omega+\omega_c)^2+{\nu_c}^2}+\frac{1}{(\omega-\omega_c)^2+{\nu_c}^2}\right]$$

$$v_z(t)=v_{z0}\exp(-\nu_c t)$$

$$C_3=\frac{\omega_c(C_1\nu_c+C_2\omega)}{\omega^2+{\nu_c}^2} \qquad C_4=-\frac{\omega_c(C_1\omega-C_2\nu_c)}{\omega^2+{\nu_c}^2}$$

The coupling efficient for capacitive RF with magnetic fields is less than DC electrical discharge

$$P = \frac{dW}{dt} = \mathrm{eE_0 sin(\omega t)} v_x$$

$$\bar{P}_{\mathrm{tot}} = n_e \bar{P} = \frac{1}{4}\epsilon_0 {E_0}^2 \frac{n_e e^2}{m\epsilon_0} \nu_c \left[\frac{1}{(\omega+\omega_c)^2 + {\nu_c}^2} + \frac{1}{(\omega-\omega_c)^2 + {\nu_c}^2}\right]$$

$$= \frac{1}{4}\epsilon_0 {E_0}^2 \times {\omega_{\mathrm{pe}}}^2 \nu_c \left[\frac{1}{(\omega+\omega_c)^2 + {\nu_c}^2} + \frac{1}{(\omega-\omega_c)^2 + {\nu_c}^2}\right]$$

- DC, unmagnetized discharge ($\omega=\omega_c=0$): $\nu_{*0} = \frac{2{\omega_{\mathrm{pe}}}^2}{\nu_c}$
- Low collisionality ($\omega_c >> \nu_c$):

$$\nu_* \approx \nu_{*0} {\nu_c}^2 \left[\frac{\omega^2 + {\omega_c}^2}{(\omega^2 - {\omega_c}^2)^2}\right] \rightarrow \nu_{*0} \frac{{\nu_c}^2}{{\omega_c}^2} \ll \nu_{*0} \quad (\omega, \nu_c \ll \omega_c)$$

- High collisionality ($\omega_c << \nu_c$):

$$\nu_* \approx \nu_{*0} \frac{{\nu_c}^2}{\omega^2 + {\nu_c}^2} \approx \nu_{*0} (\omega, \omega_c << \nu_c)$$

- Resonant ($\omega=\omega_c$):

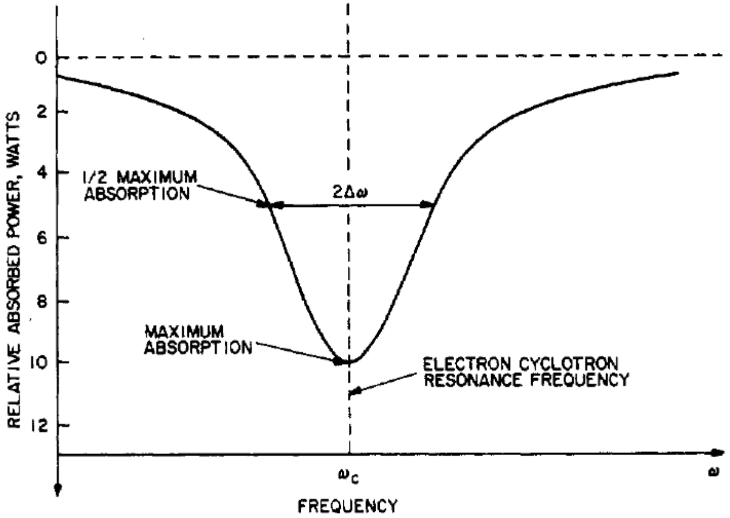
$$\nu_* = \nu_{*0} \frac{2{\omega_c}^2 + {\nu_c}^2}{4{\omega_c}^2 + {\nu_c}^2} \rightarrow \frac{1}{2} \nu_{*0} (\omega = \omega_c >> \nu_c)$$

Collision frequency can be measured using capacitive RF electrical discharges

$$\bar{P}(\omega_c) = \frac{1}{4}\epsilon_0 {E_0}^2 \times \nu_{*0}\frac{2+(\nu_c/\omega_c)^2}{4+(\nu_c/\omega_c)^2} = \frac{1}{4}\epsilon_0 {E_0}^2 \times \nu_{*0}\frac{2+\epsilon^2}{4+\epsilon^2}$$

$$\bar{P}(\omega_c \pm \Delta\omega) = \frac{1}{4}\epsilon_0 {E_0}^2 \times \frac{\nu_{*0}}{2}\left(\frac{\nu_c}{\omega_c}\right)^2\left[\frac{1}{(2\pm\Delta\omega/\omega_c)^2+(\nu_c/\omega_c)^2}+\frac{1}{(\Delta\omega/\omega_c)^2+(\nu_c/\omega_c)^2}\right]$$

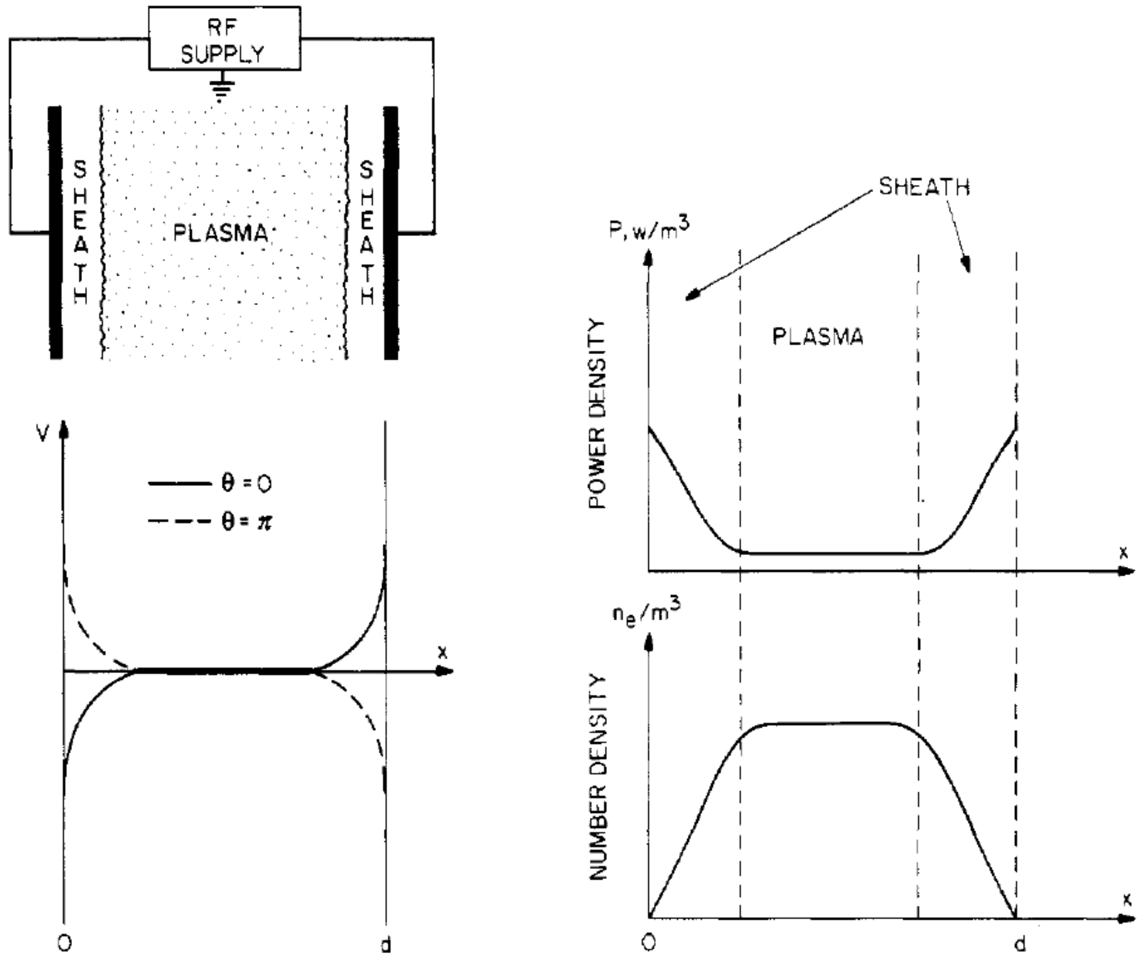
$$= \frac{1}{4}\epsilon_0 {E_0}^2 \times \frac{\nu_{*0}}{2}\epsilon^2\left[\frac{1}{(2\pm\delta)^2+\epsilon^2}+\frac{1}{\delta^2+\epsilon^2}\right] \quad \text{where } \delta \equiv \frac{\Delta\omega}{\omega_c}, \epsilon \equiv \frac{\nu_c}{\omega_c}$$



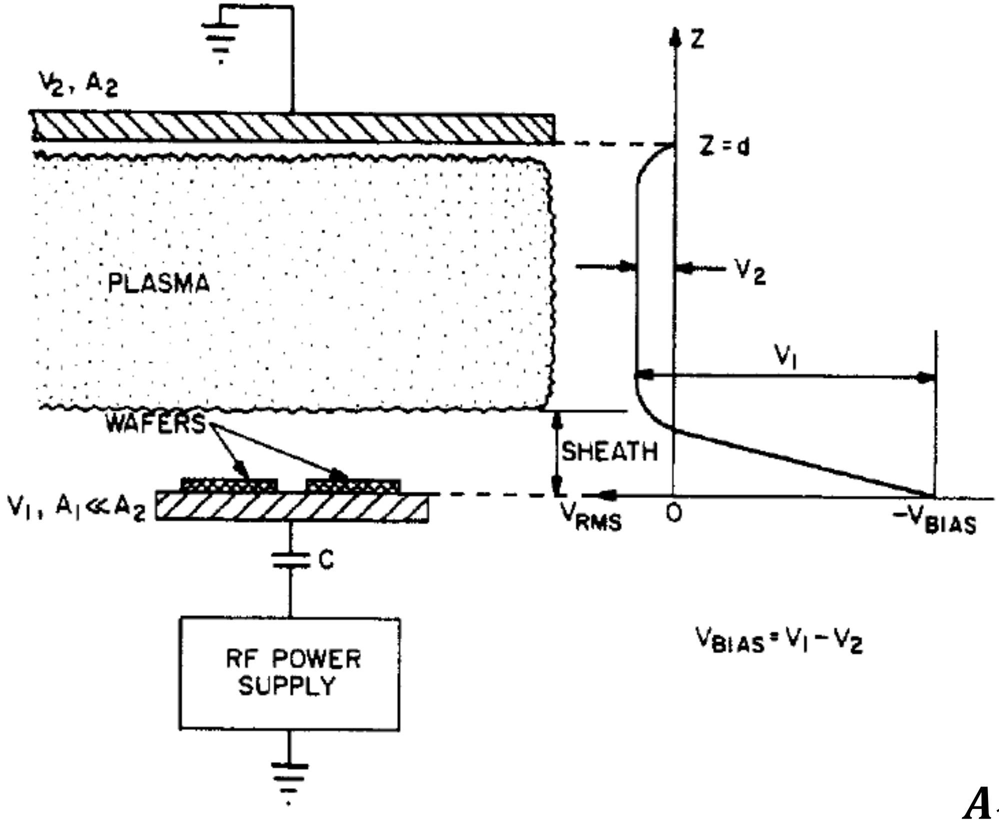
For $\delta \approx \epsilon << 1$,

$$\bar{P}(\omega_c \pm \nu_c) = \frac{1}{2}\bar{P}(\omega_c)$$

Symmetrical capacitive RF discharge model



Empirical scaling of electrode voltage drop



$$I_1 = A_1 J_1 = A_1 e n_{i1} \bar{v}_{i1}$$

$$I_2 = A_2 J_2 = A_2 e n_{i2} \bar{v}_{i2}$$

$$\bar{v}_{i1} = \sqrt{\left(\frac{2eV_1}{m_i}\right)}$$

$$\bar{v}_{i2} = \sqrt{\left(\frac{2eV_2}{m_i}\right)}$$

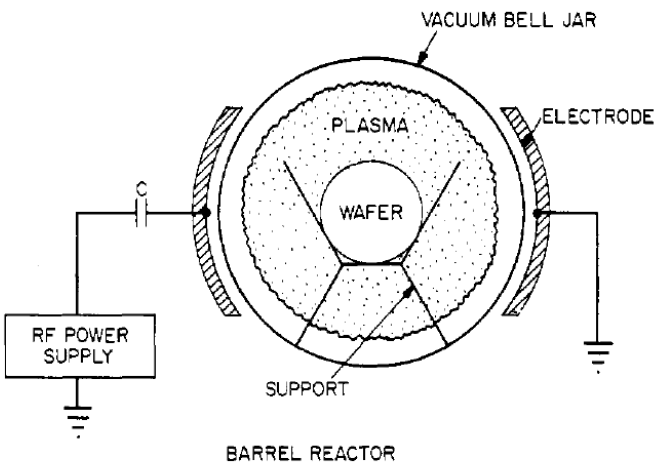
Assuming: $I_1 = I_2$ $n_{i1} = n_{i2}$

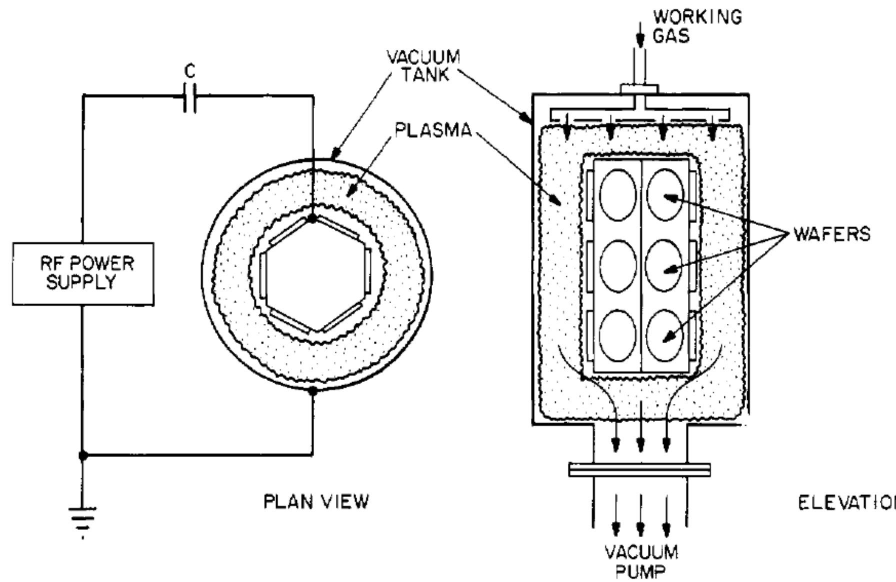
$$A_1 e n_{i1} \sqrt{\left(\frac{2eV_1}{m_i}\right)} = A_2 e n_{i2} \sqrt{\left(\frac{2eV_2}{m_i}\right)}$$

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^2$$

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^q \text{ where } 1.0 \le q \le 2.5$$

Example of capacitively coupled RF plasma source 1

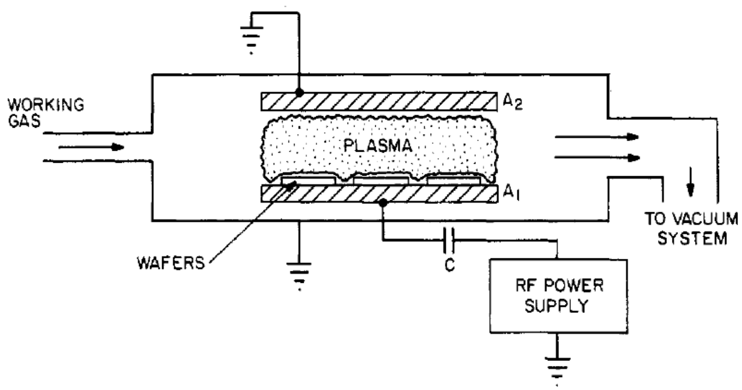




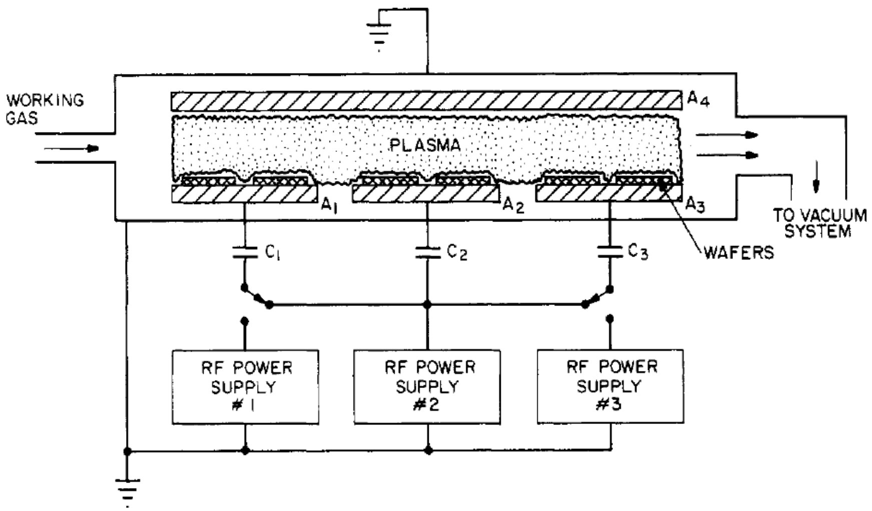
- **Barrier reactor – the wafers float electrically and have low ion bombardment energies**
- **Hexagonal reactor – the wafers develop a DC bias which leads to a relatively anisotropic, vertical etch.**

Example of capacitively coupled RF plasma source 2

- **Plane parallel reactor**



- **Multiple electrode system**



Operating regimes of capacitively coupled plasma reactors used for plasma processing

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

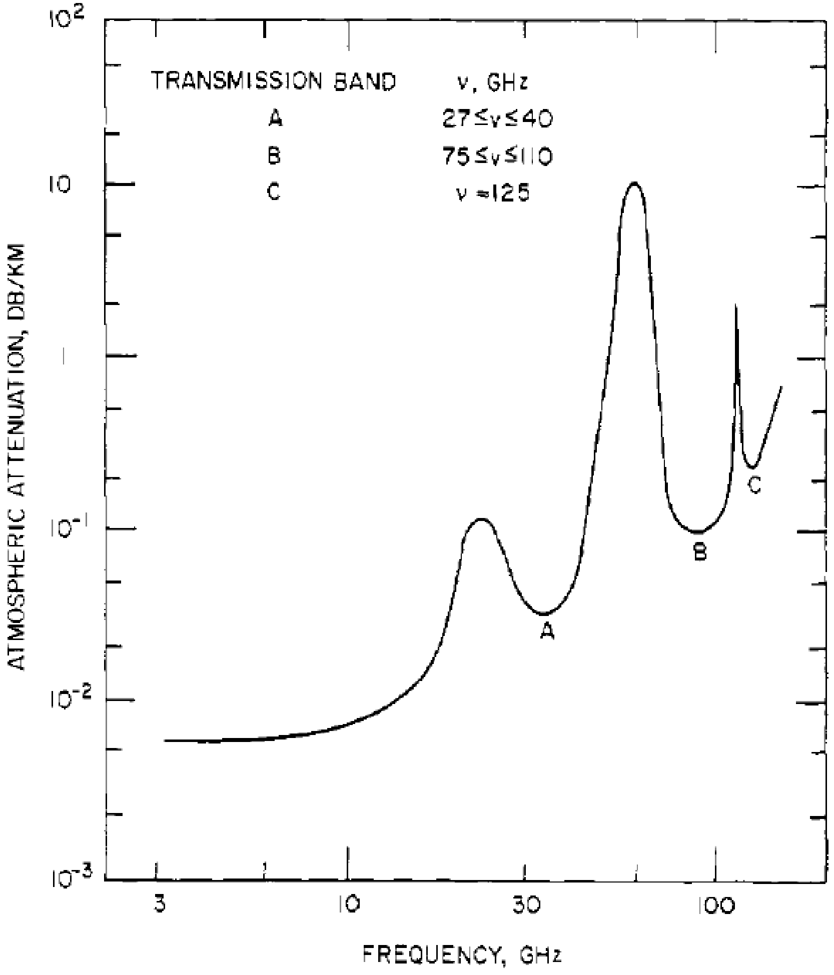
AC electrical discharges deliver energy to the plasma without contact between electrodes and the plasma

- 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.
  - Inductive radio frequency (RF) electrical discharges
  - Capacitive RF electrical discharges
  - **Microwave electrical discharges**
  - Dielectric-barrier discharges (DBDs)
- Other mechanism
  - Laser produced plasma
  - Pulsed-power generated plasma

Advantage of using microwave electrical discharges

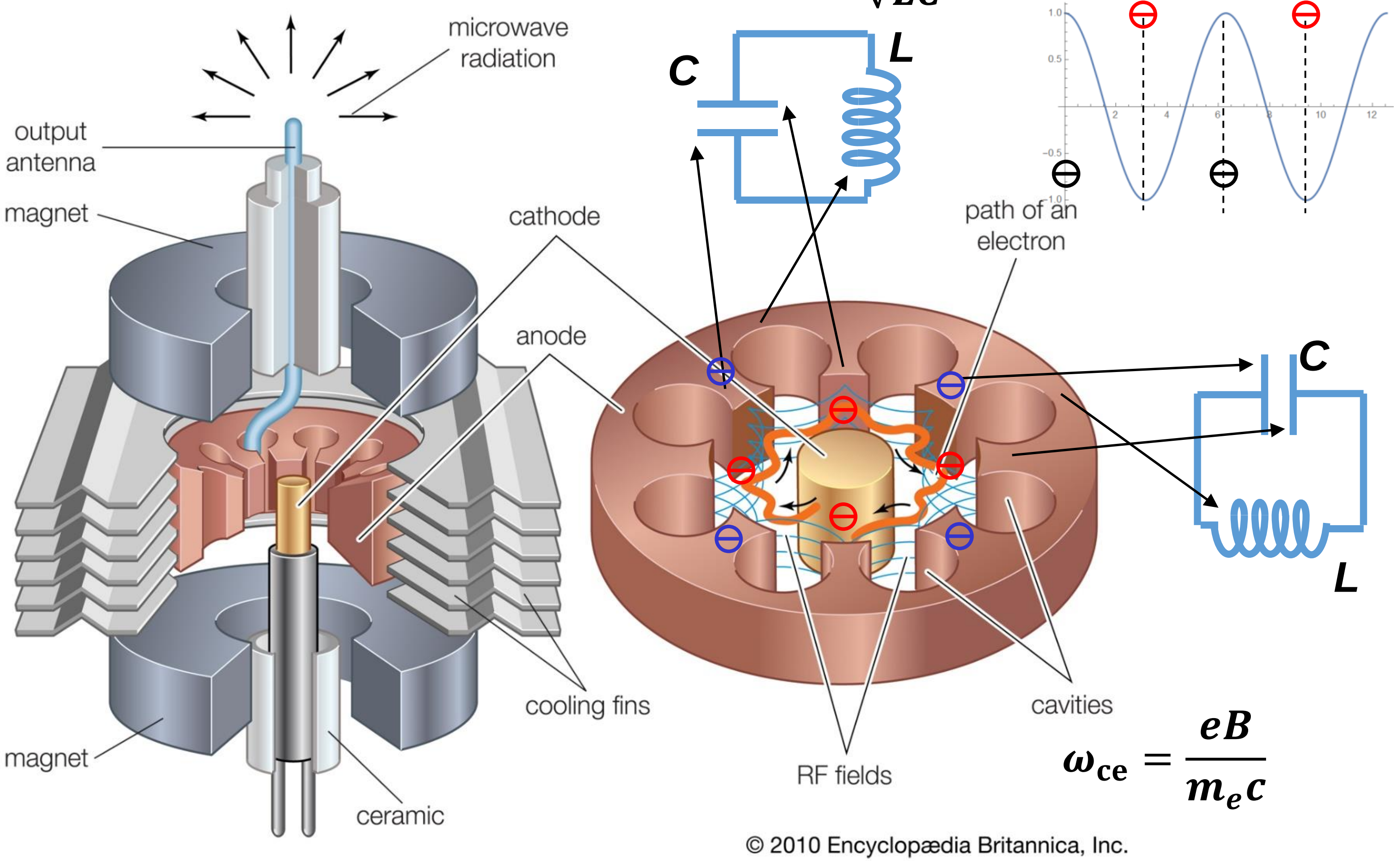
- **The wavelength of the microwave is in centimeters range. In contract, the wavelength is 22 m for RF frequency f = 13.6 MHz.**
- **The electron number density can approach the critical number density. ($7x10^{16}$ m^{-3}) at a frequency of 2.45 GHz.**
- **The plasma in microwave discharges is quasi-optical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

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



Internal of a magnetron

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

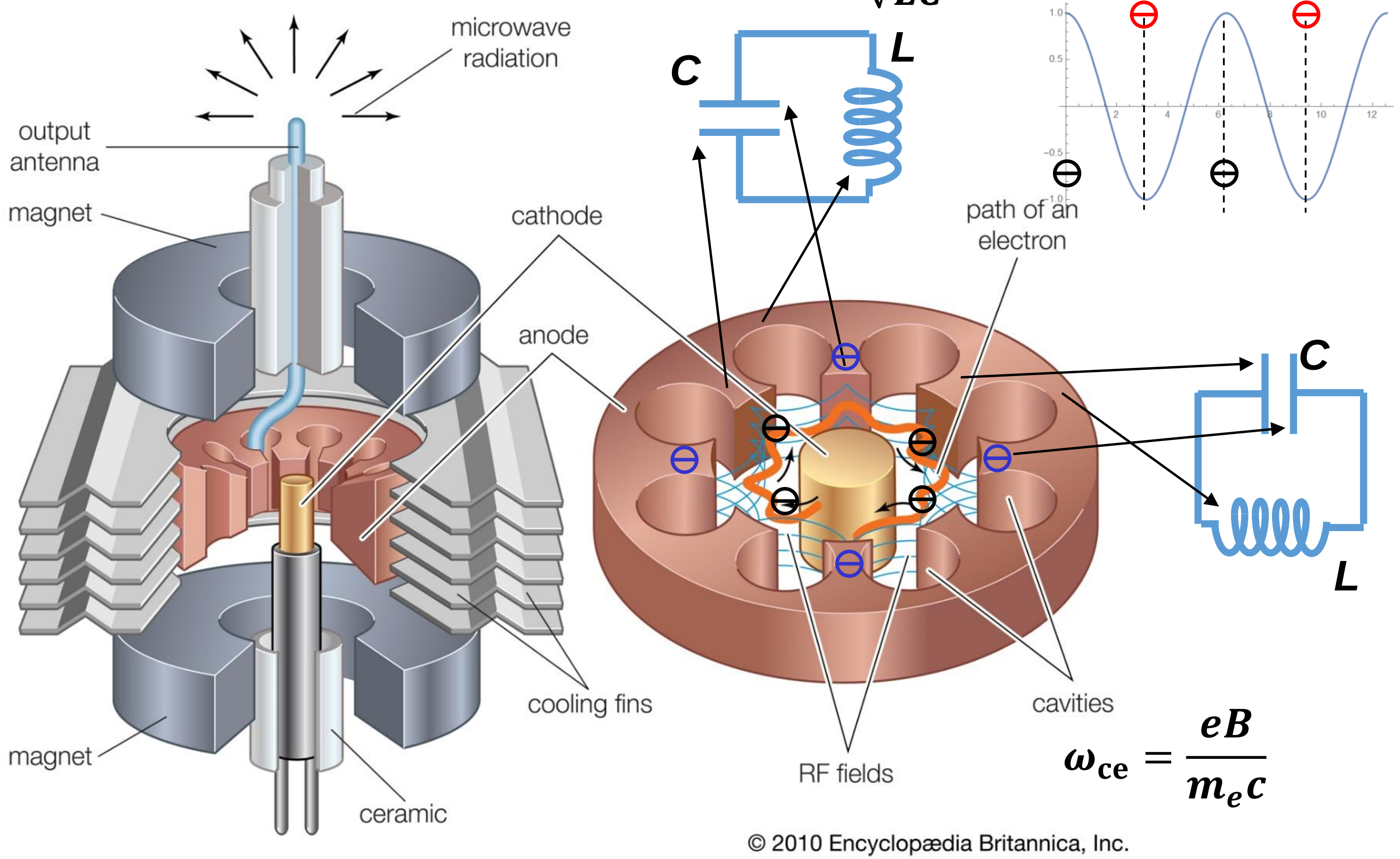


$$\omega_{ce} = \frac{eB}{m_e c}$$

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

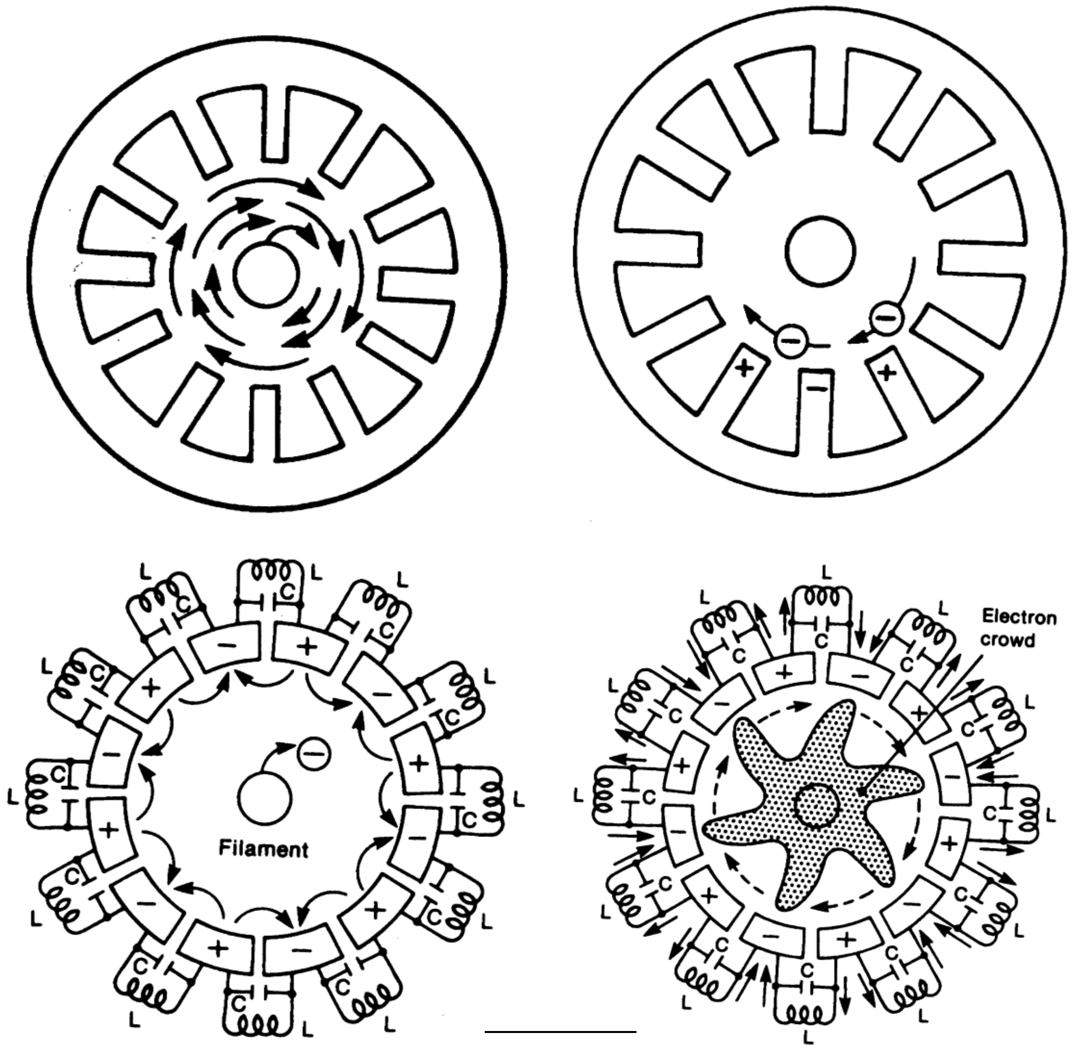
Internal of a magnetron

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



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

Resonance in a magnetron



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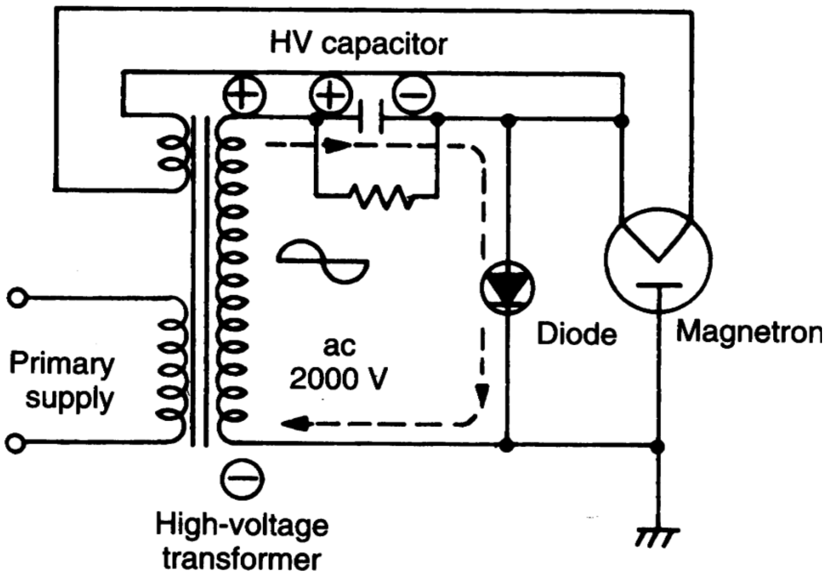
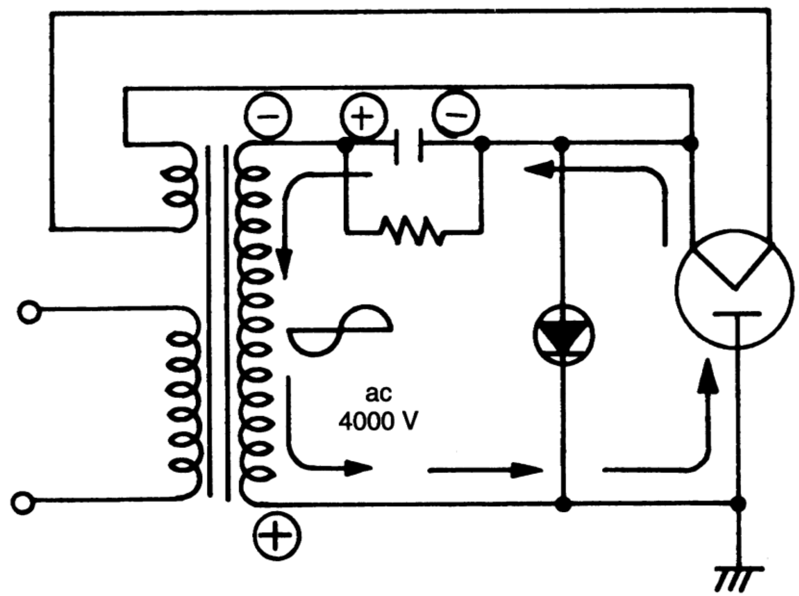
Magnetron schematic diagram

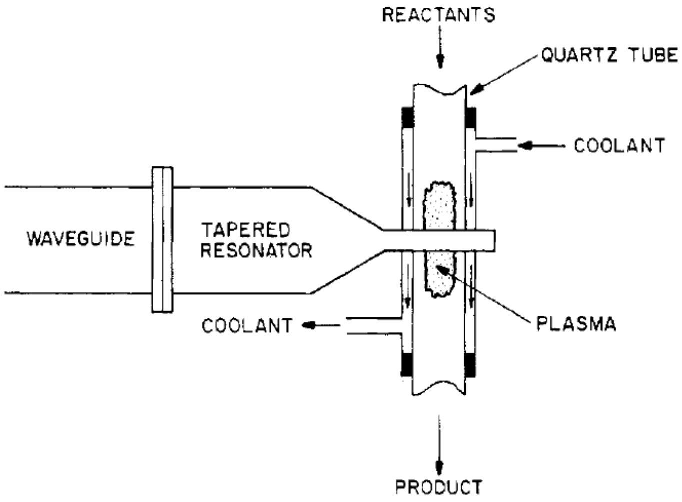




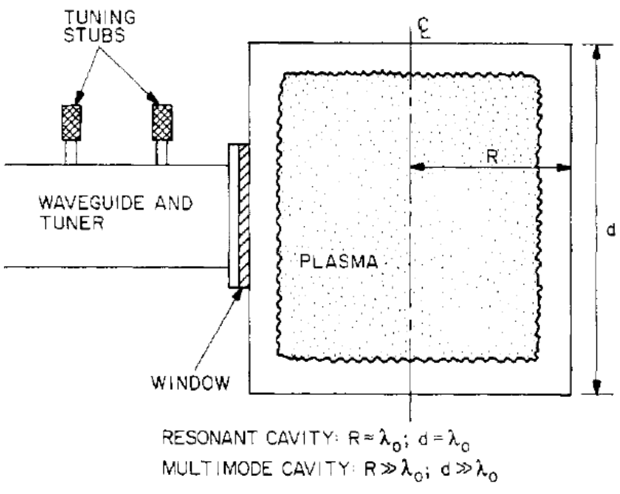
http://cdn.preterhuman.net/texts/government_information/intelligence_and_espionage/homebrew.military.and.espionage.electronics/servv89pn0aj.sn.sourcedns.com/_gbpprorg/mil/herf1/index.html

Microwave plasma reactor configurations

- **Waveguide coupled reactor**

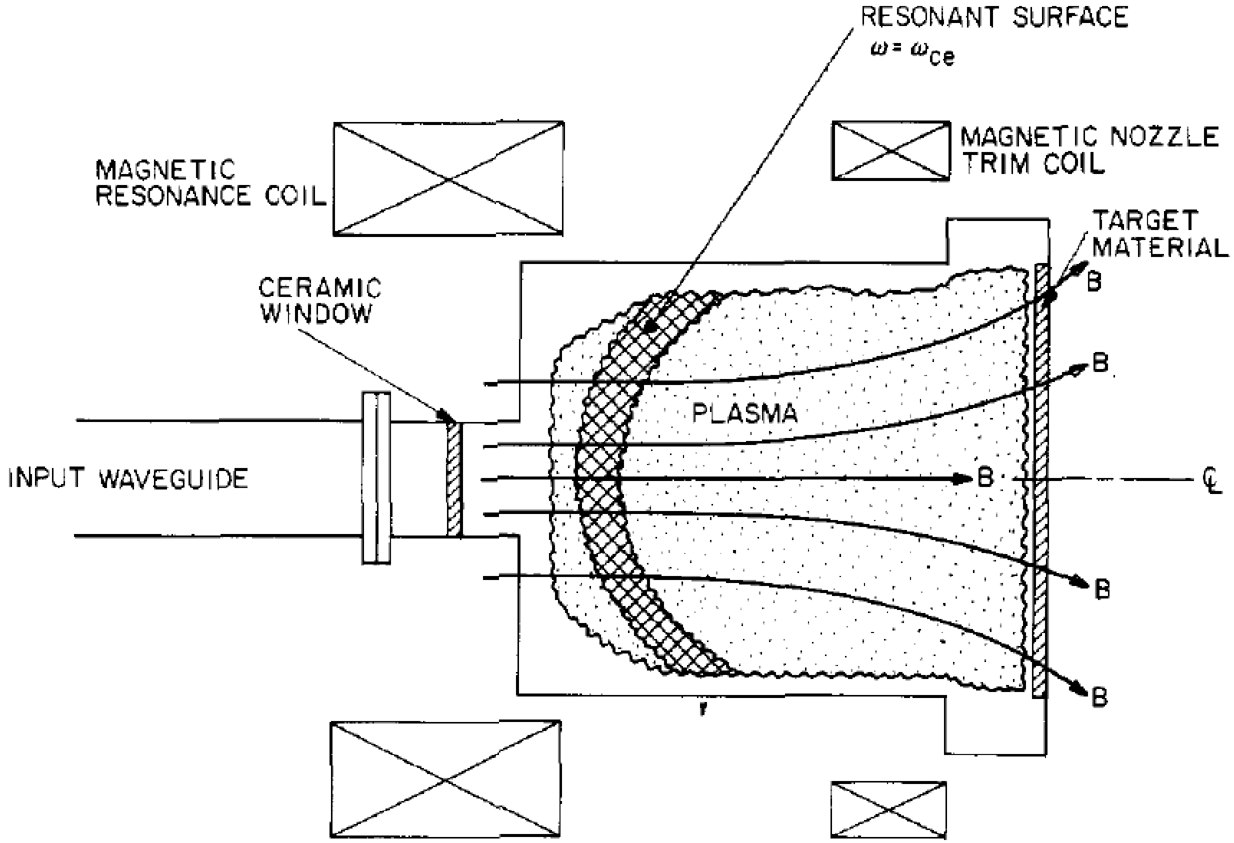


- **Resonant or multimode cavity – if the impedance matching is good, more energy can be fed into the cavity.**



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

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

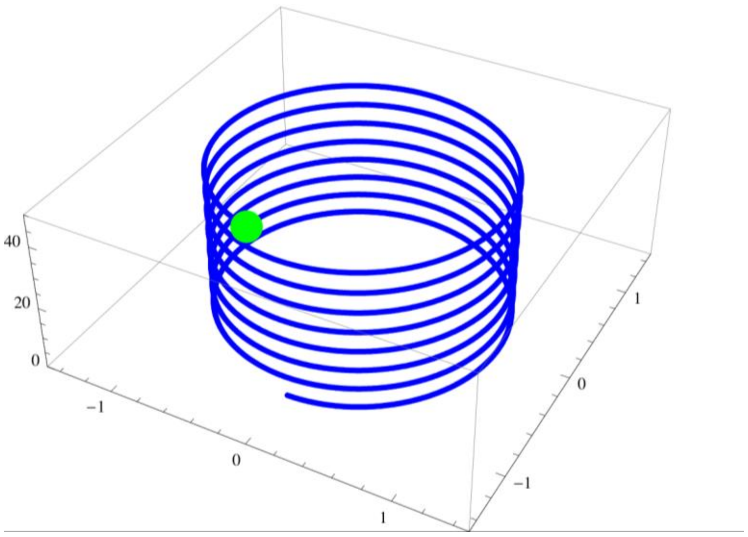
- **Assuming** $\vec{B} = B\hat{z}$ **and the electron oscillates in x-y plane**

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

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

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

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



- **Therefore**

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

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

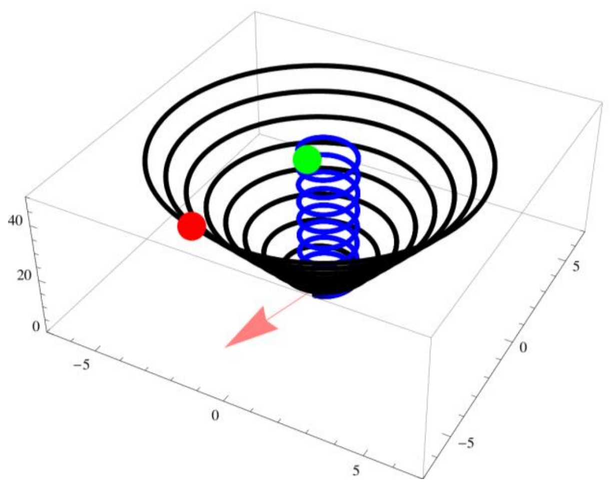
$$m_e \frac{d\vec{v}}{\mathrm{dt}} = -\frac{e}{c}\,\vec{v}\times\vec{B} - e\,\vec{E} \qquad \vec{B} = B_0\hat{z} \qquad \vec{E} = E_0[\hat{x}\cos(\omega t) + \hat{y}\sin(\omega t)]$$

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

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

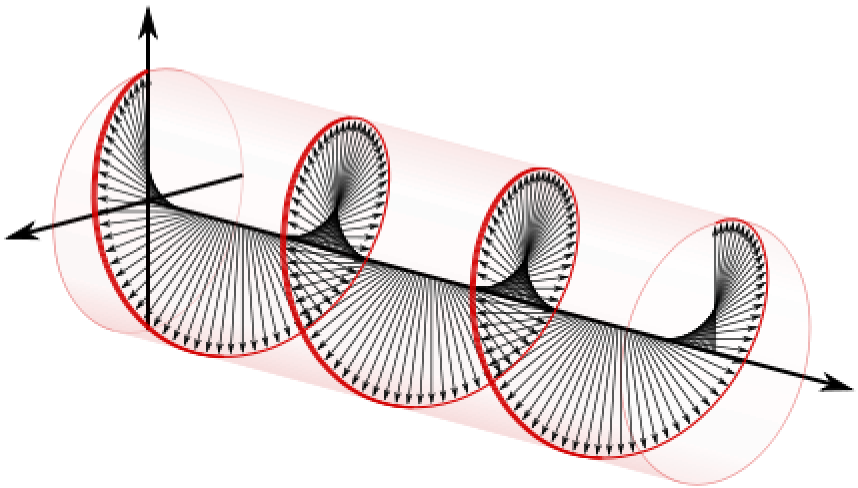
$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x + \frac{E_0}{m_e}\omega\sin(\omega t) = -\omega_{ce}{}^2 v_y + \frac{E_0}{m_e}(\omega_{ce} + \omega)\sin(\omega t)$$

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

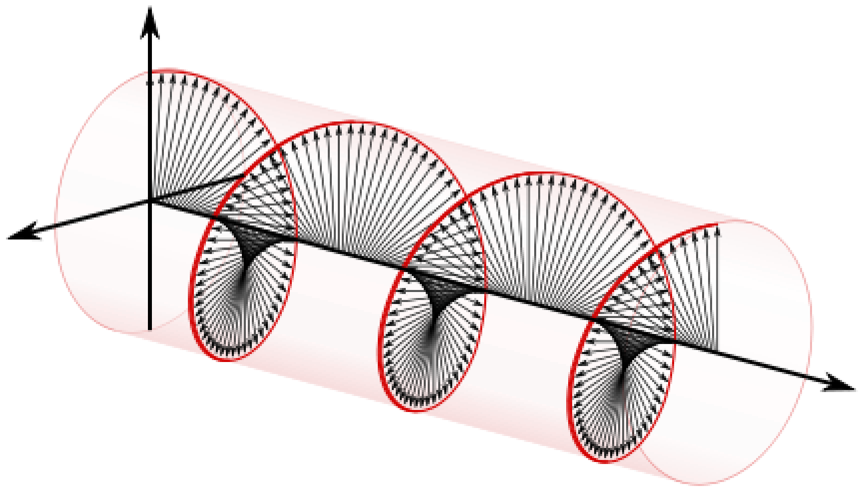


Electric field in a circular polarized electromagnetic wave keeps rotating as the wave propagates

- **Right-handed polarization**



- **Left-handed polarization**



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

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

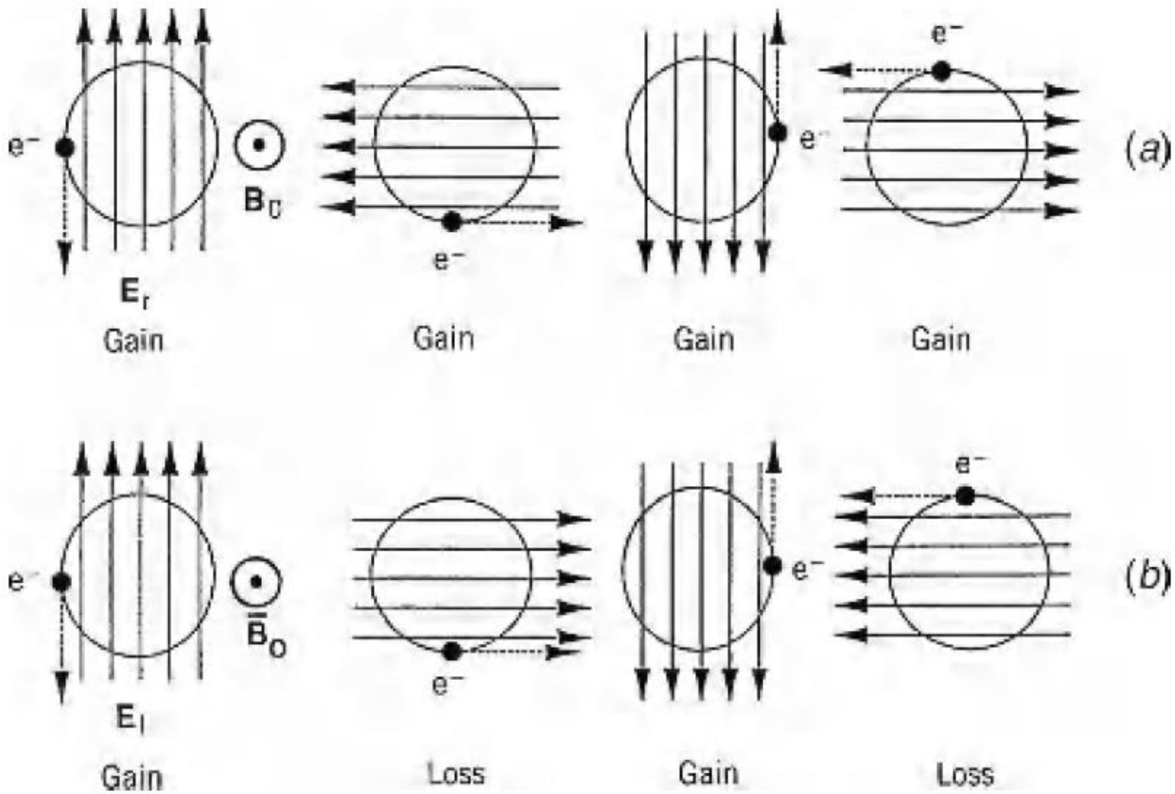
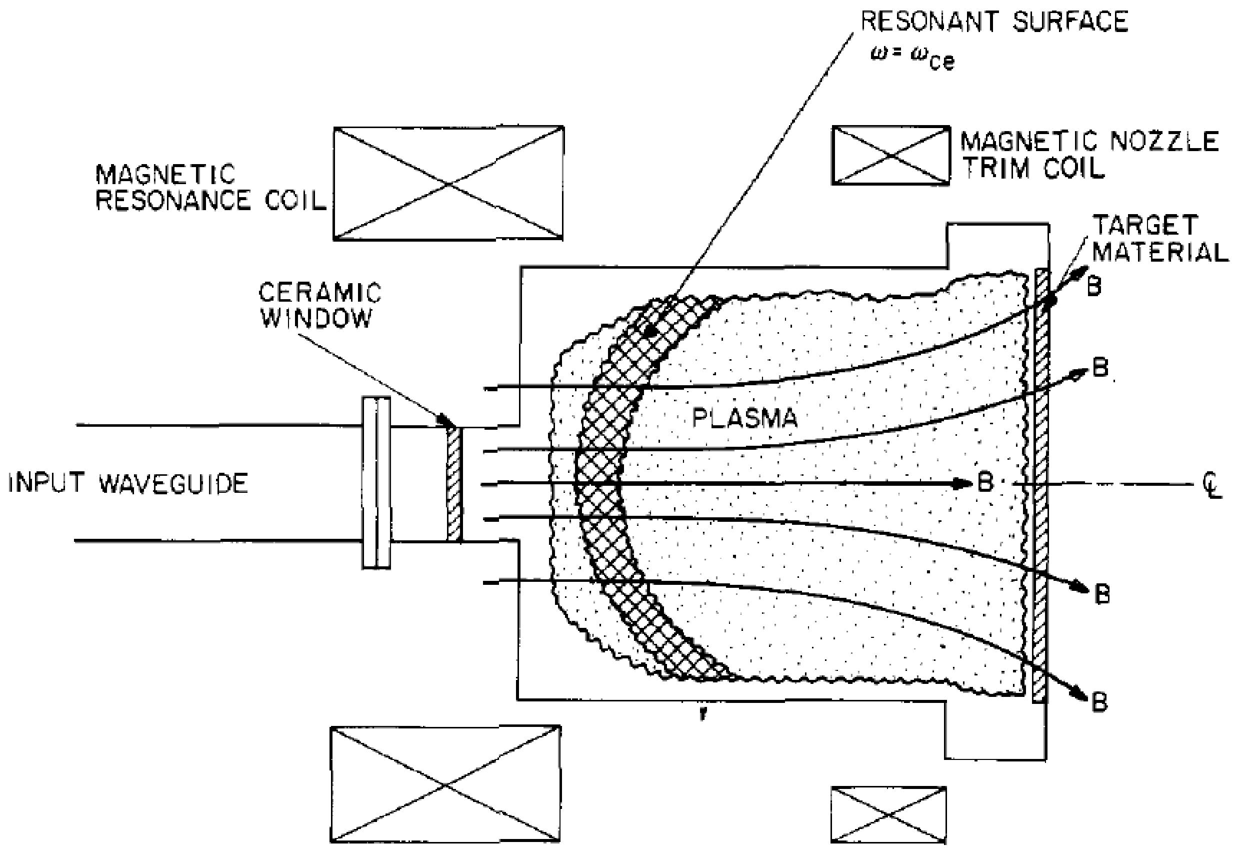


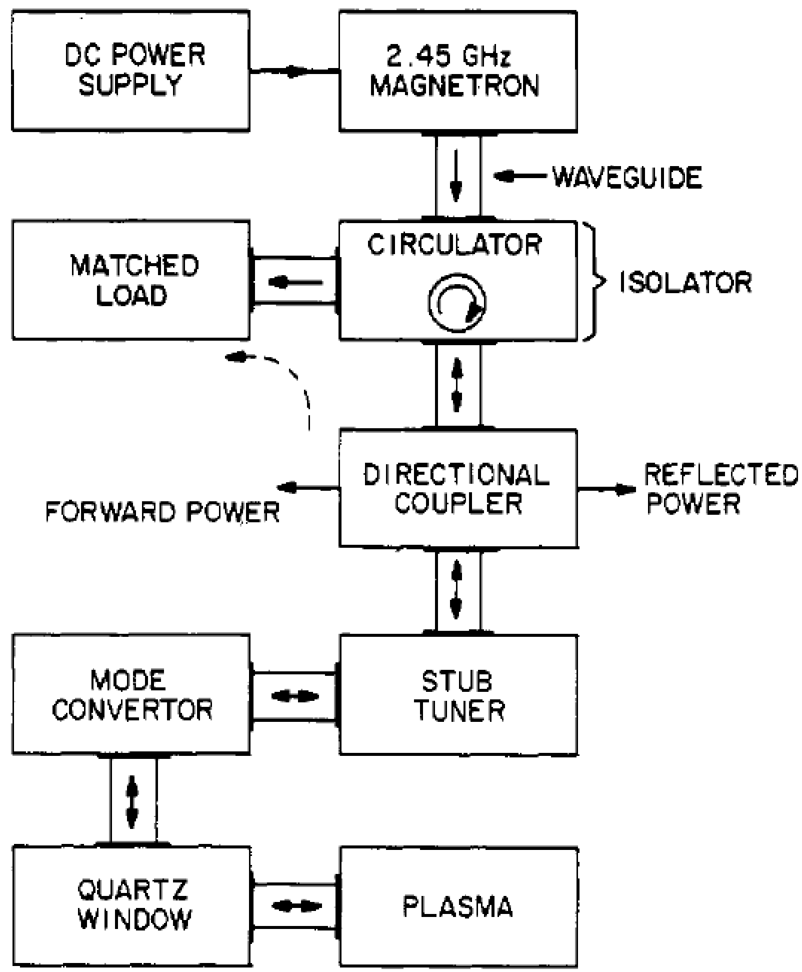
FIGURE 13.5. Basic principle of ECR heating: (*a*) continuous energy gain for right-hand polarization; (*b*) oscillating energy for left-hand polarization (after Lieberman and Gottscho, 1994).

Strong absorption occurs when the frequency matches the electron cyclotron frequency

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



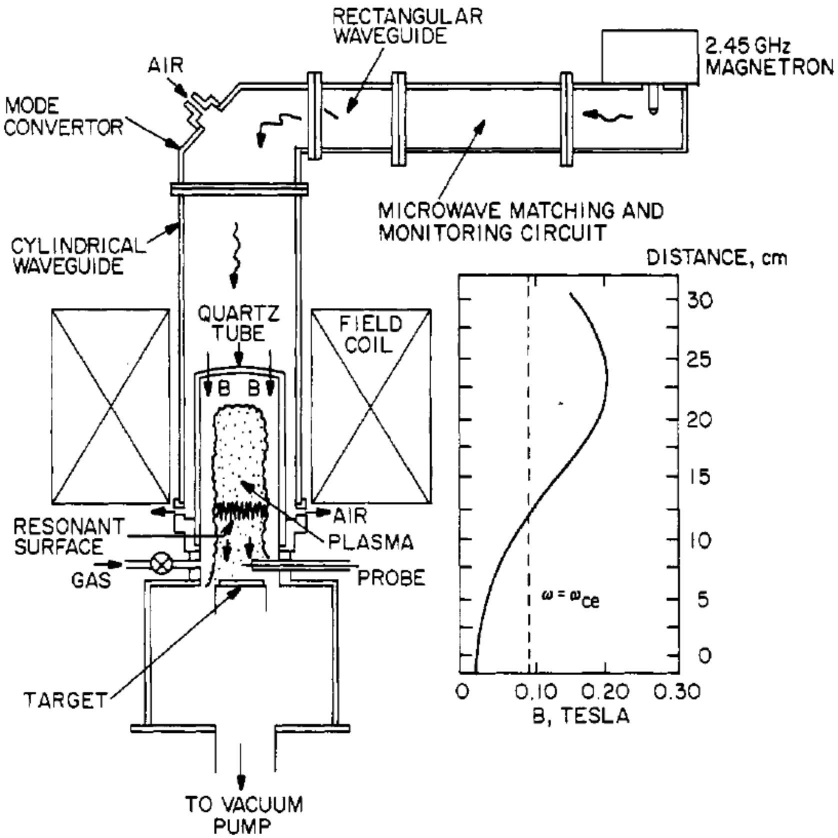
Electron cyclotron resonance (ECR) microwave systems



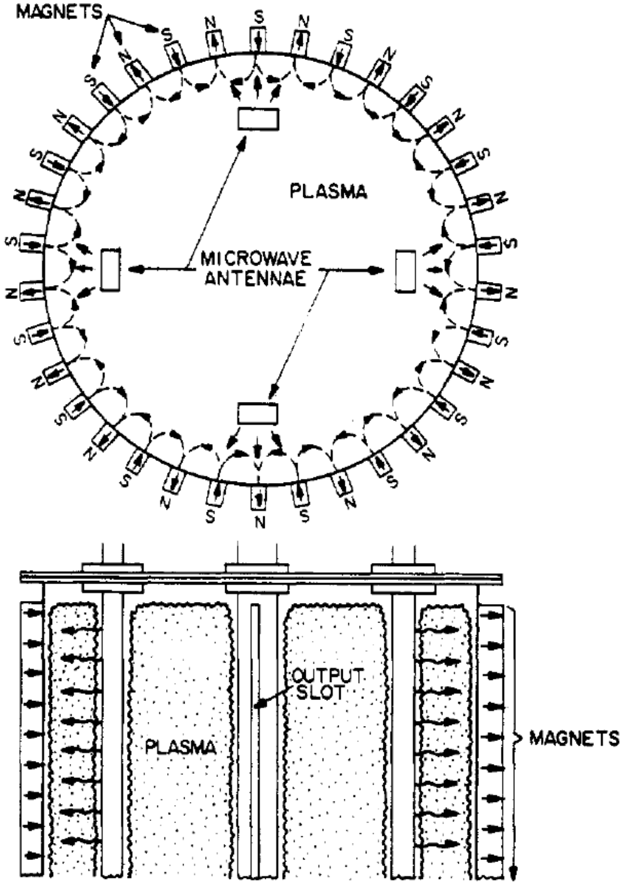
microwave systems

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.**

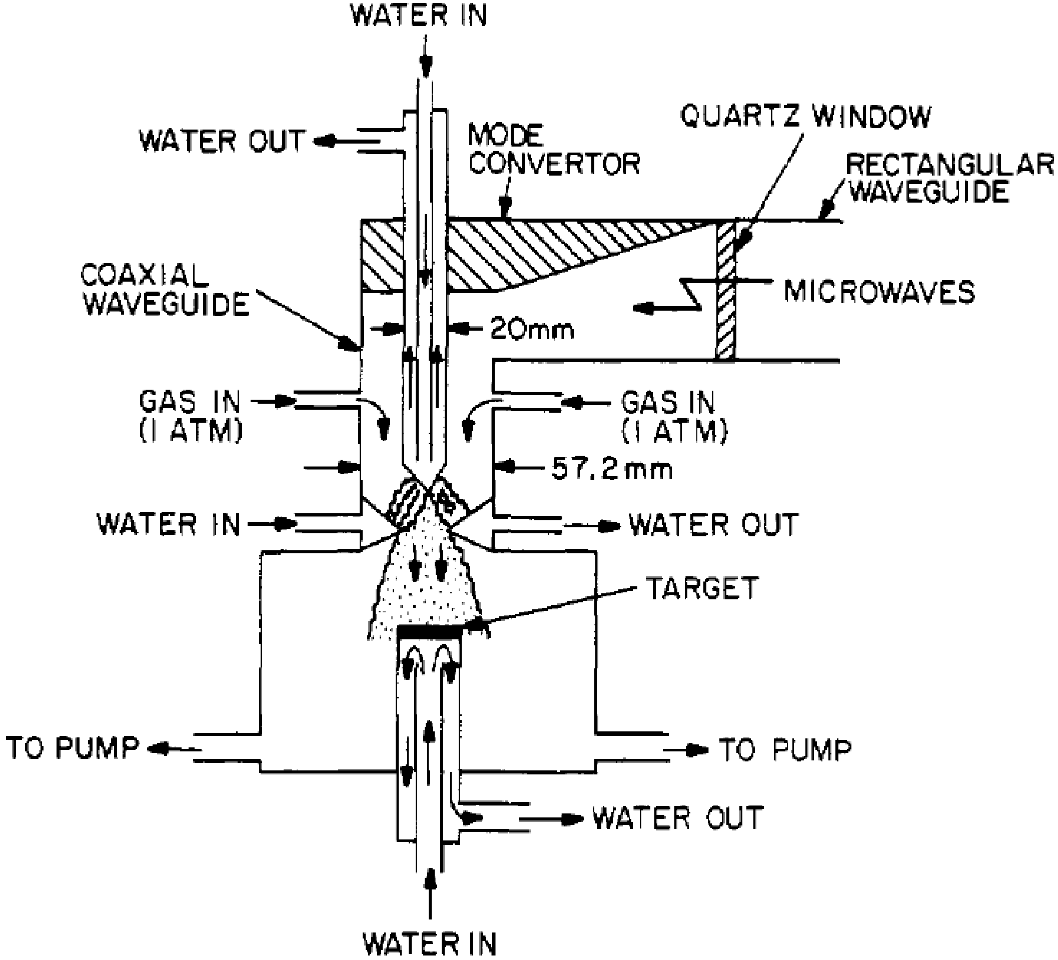


Distributed ECR system



- **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



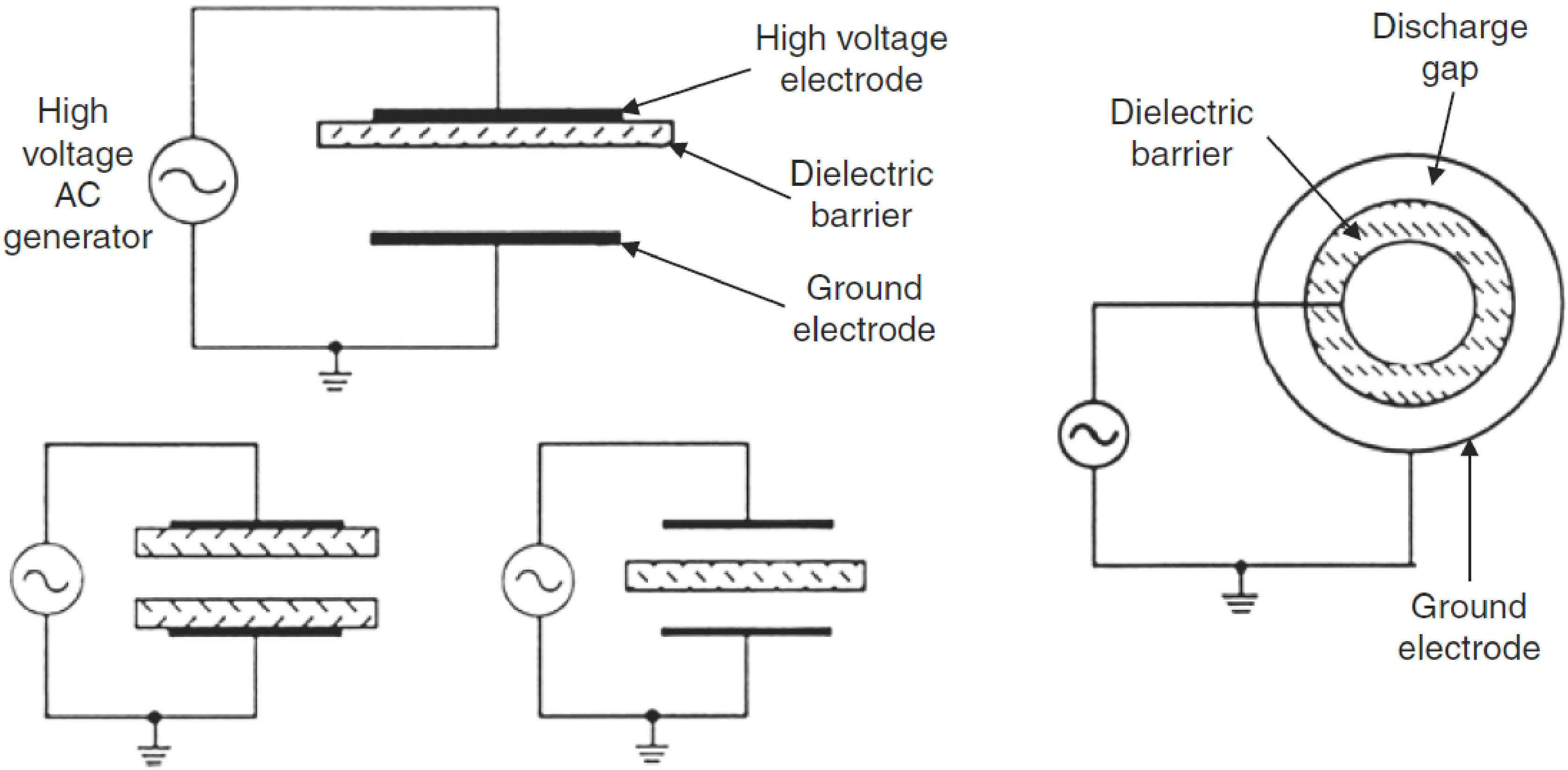
Microwave-generated plasmas have the capability of filling very large volumes with moderately high density

- **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.**

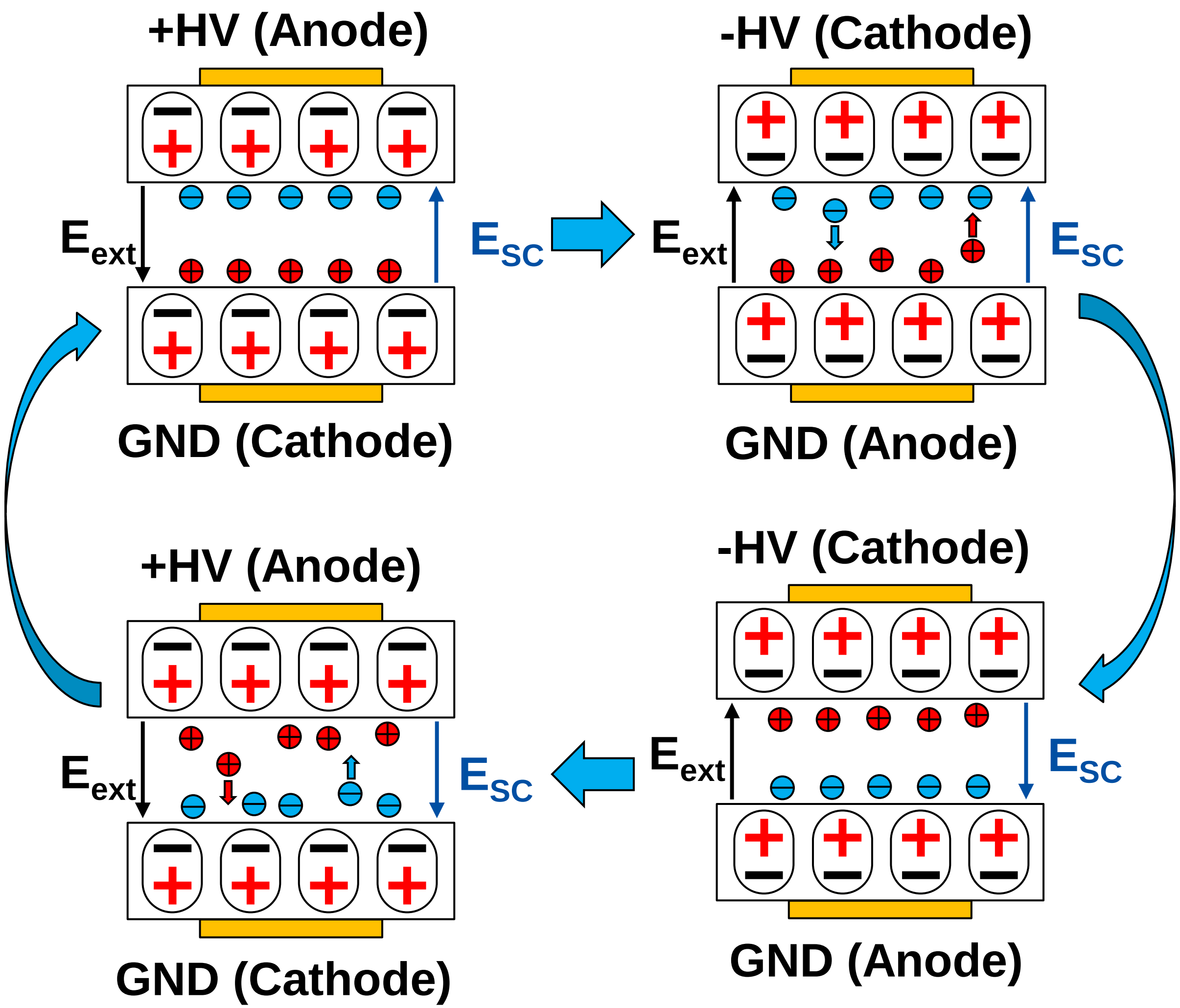
AC electrical discharges deliver energy to the plasma without contact between electrodes and the plasma

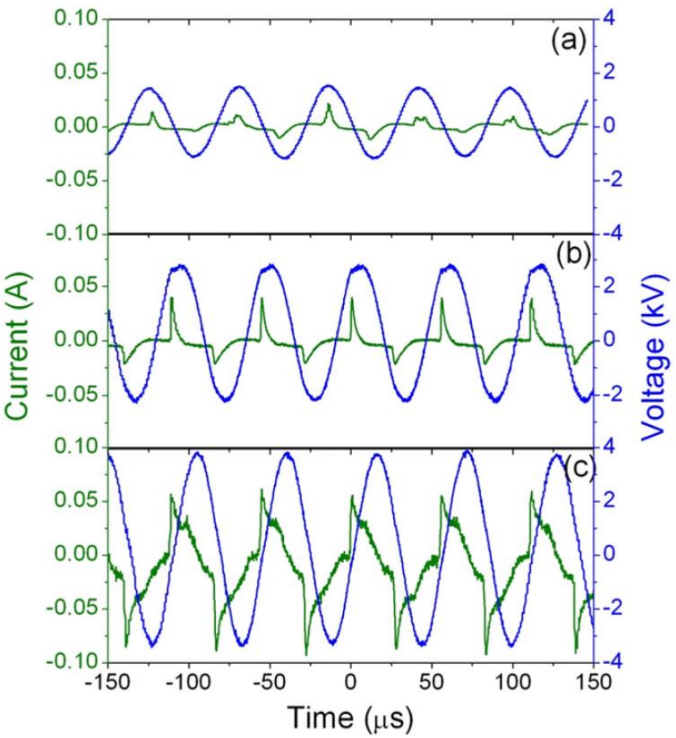
- DC electrical discharge – a true current in the form of a flow of ions or electrons to the electrodes.
- AC electrical discharge – the power supply interacts with the plasma by displacement current.
  - Inductive radio frequency (RF) electrical discharges
  - Capacitive RF electrical discharges
  - Microwave electrical discharges
  - **Dielectric-barrier discharges (DBDs)**
- Other mechanism
  - Laser produced plasma
  - Pulsed-power generated plasma

Dielectric-barrier discharges (DBDs)



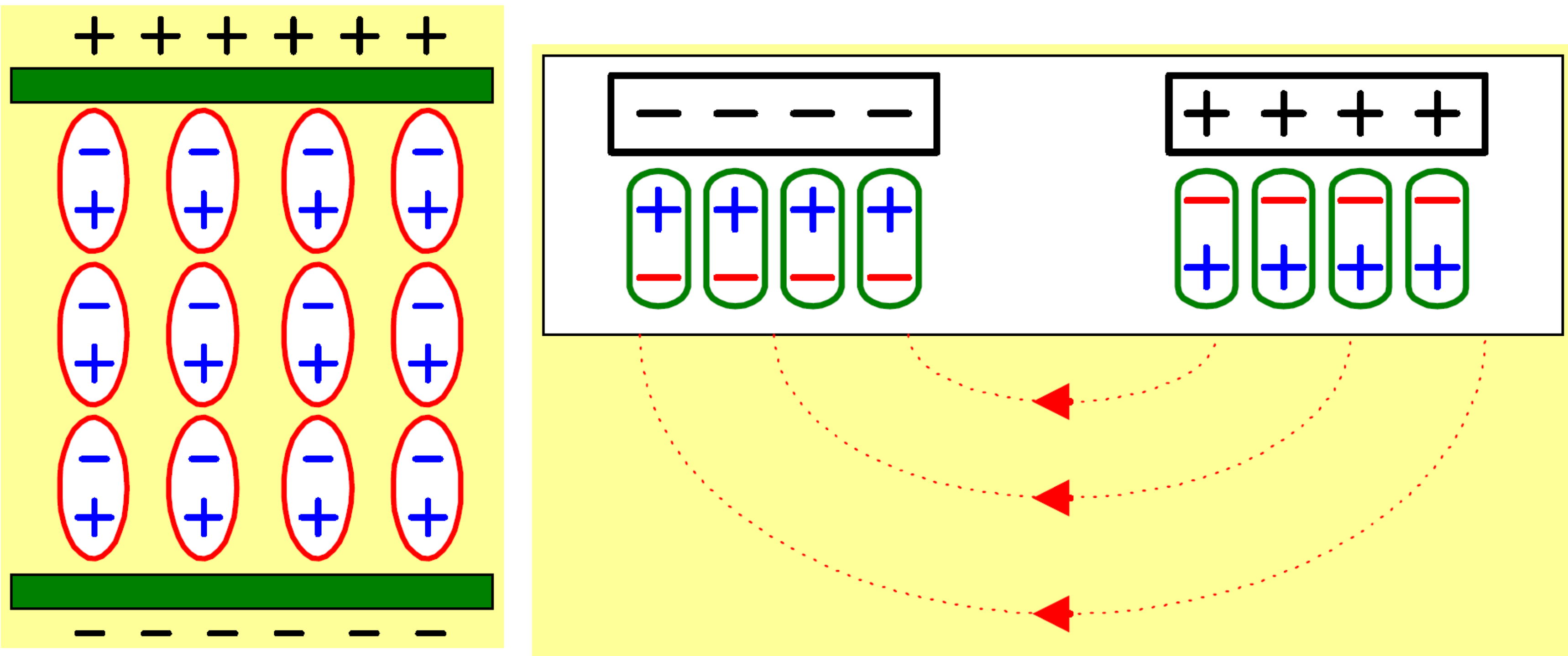
Space charge effect enhance the electric field



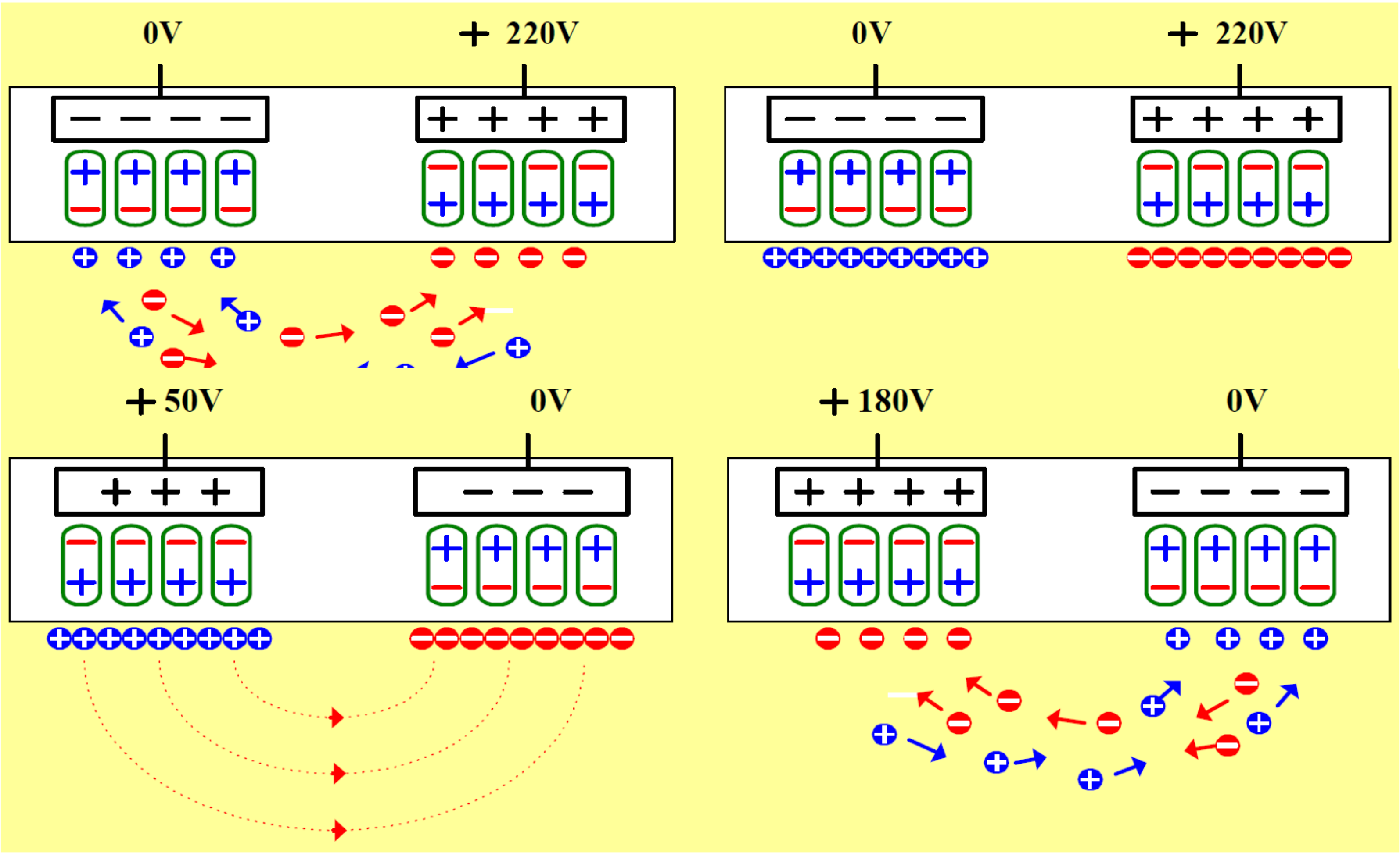


J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

The foundation of AC discharge in plasma display panel

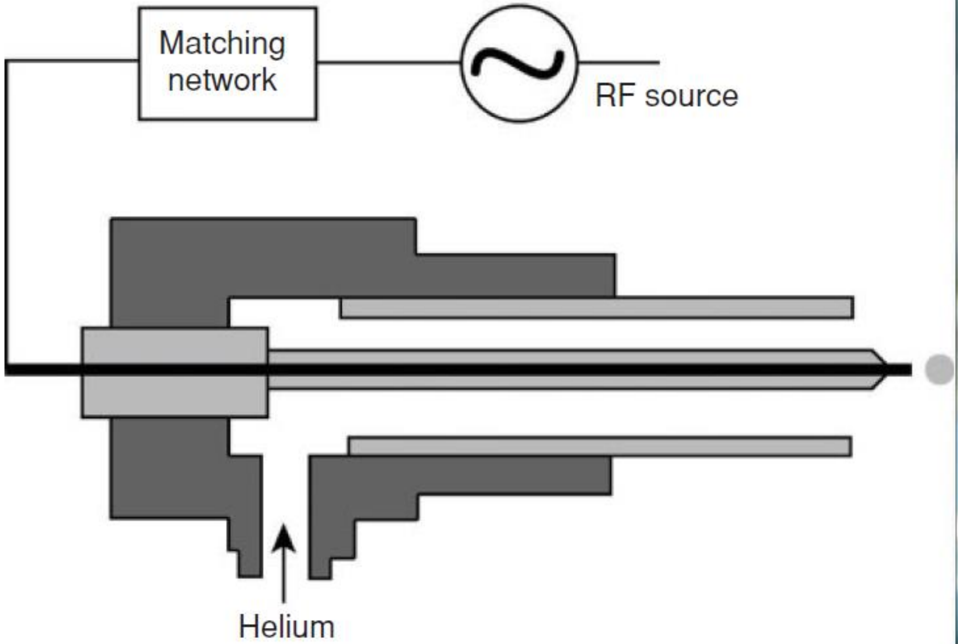


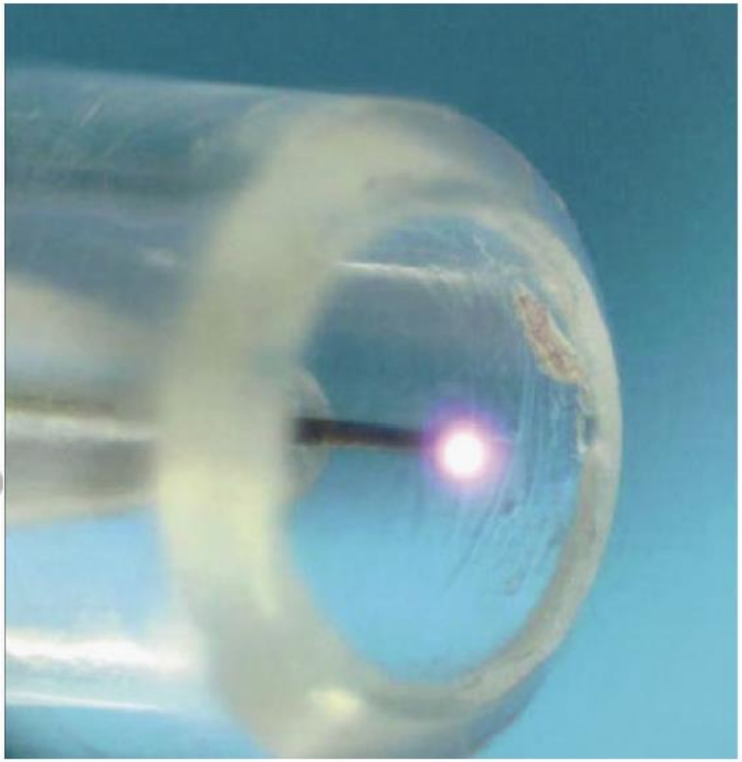
The plasma can be sustained using ac discharged in plasma display panel



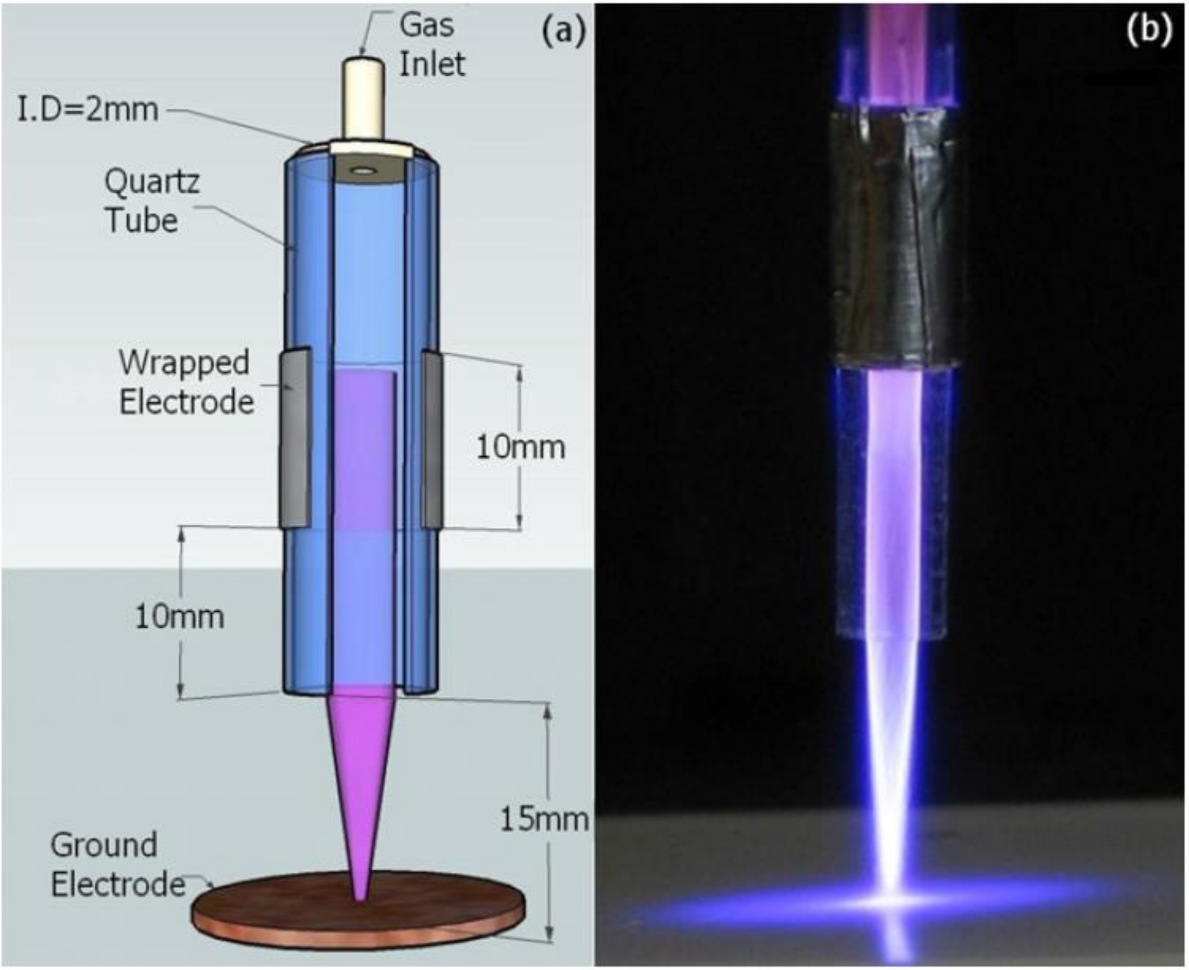
- **Wall discharge reduced the required discharge voltage**

Plasma-needle discharge



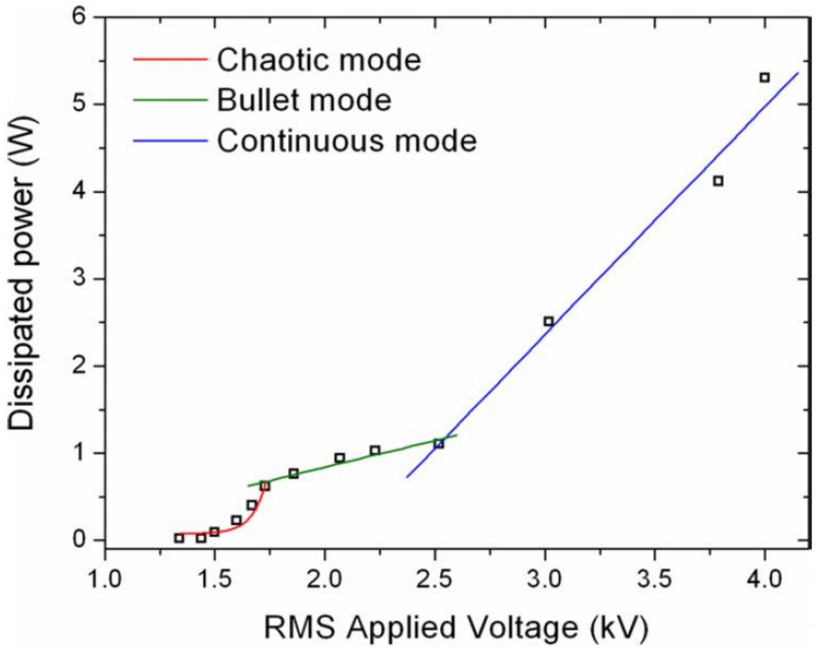


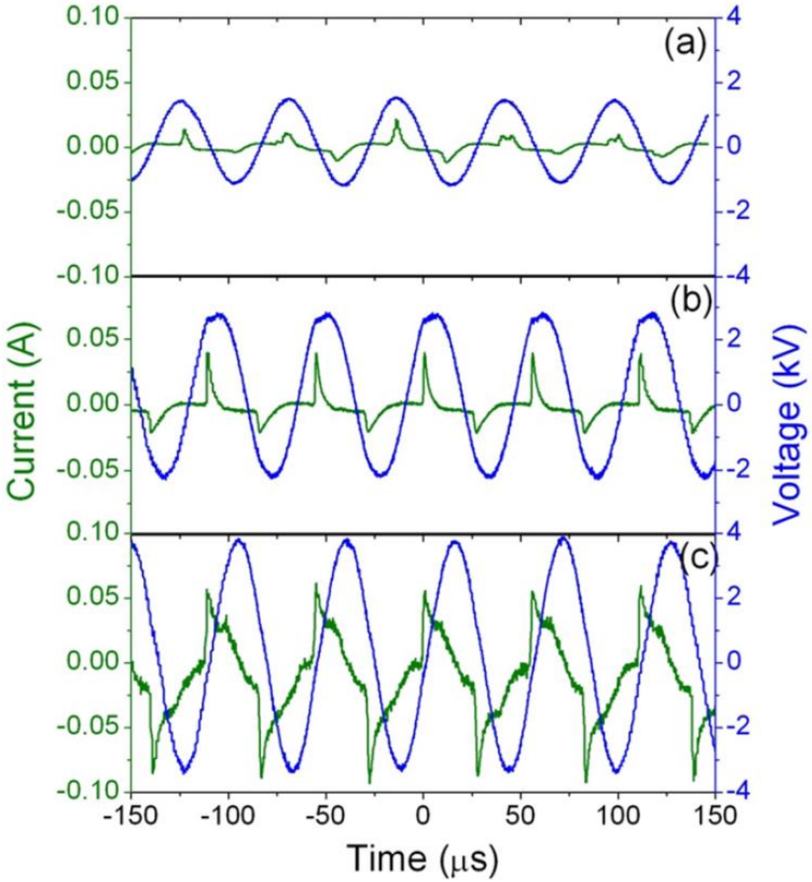
Atmospheric-pressure cold helium microplasma jets



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

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



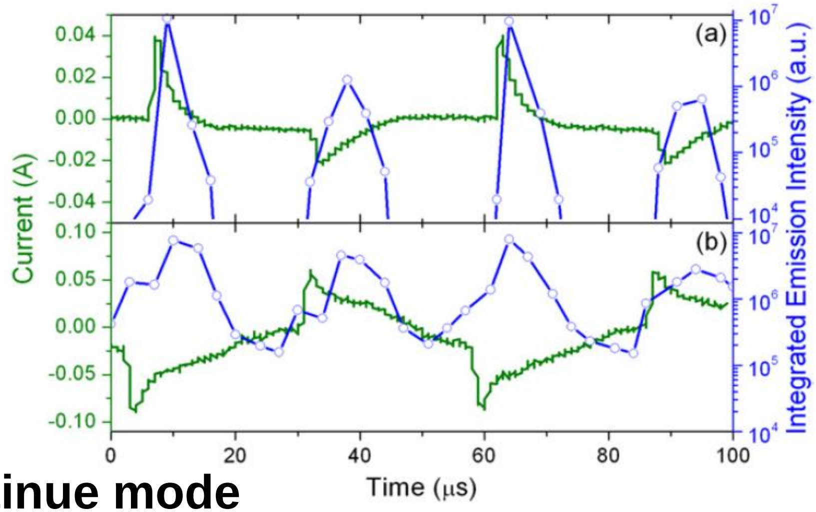


J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

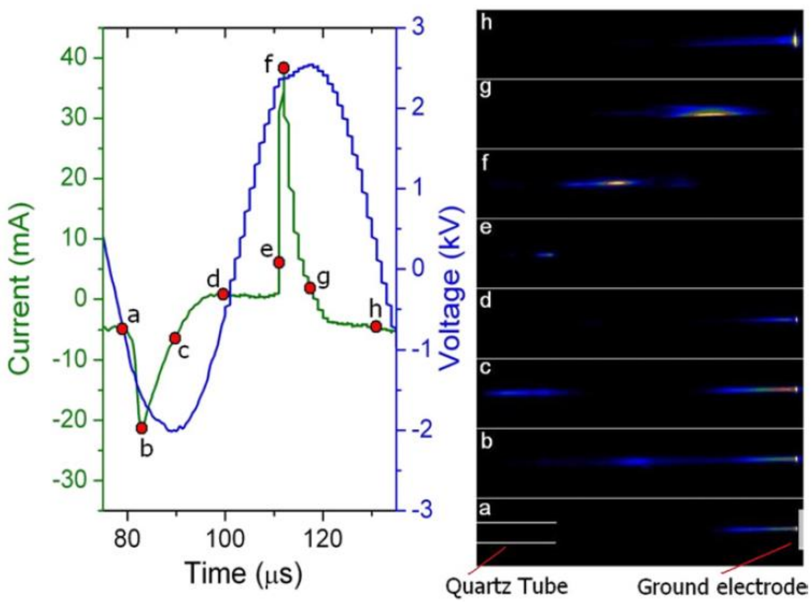
In bullet mode, the plasma jet comes out as a pulse

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

Bullet mode



Continue mode



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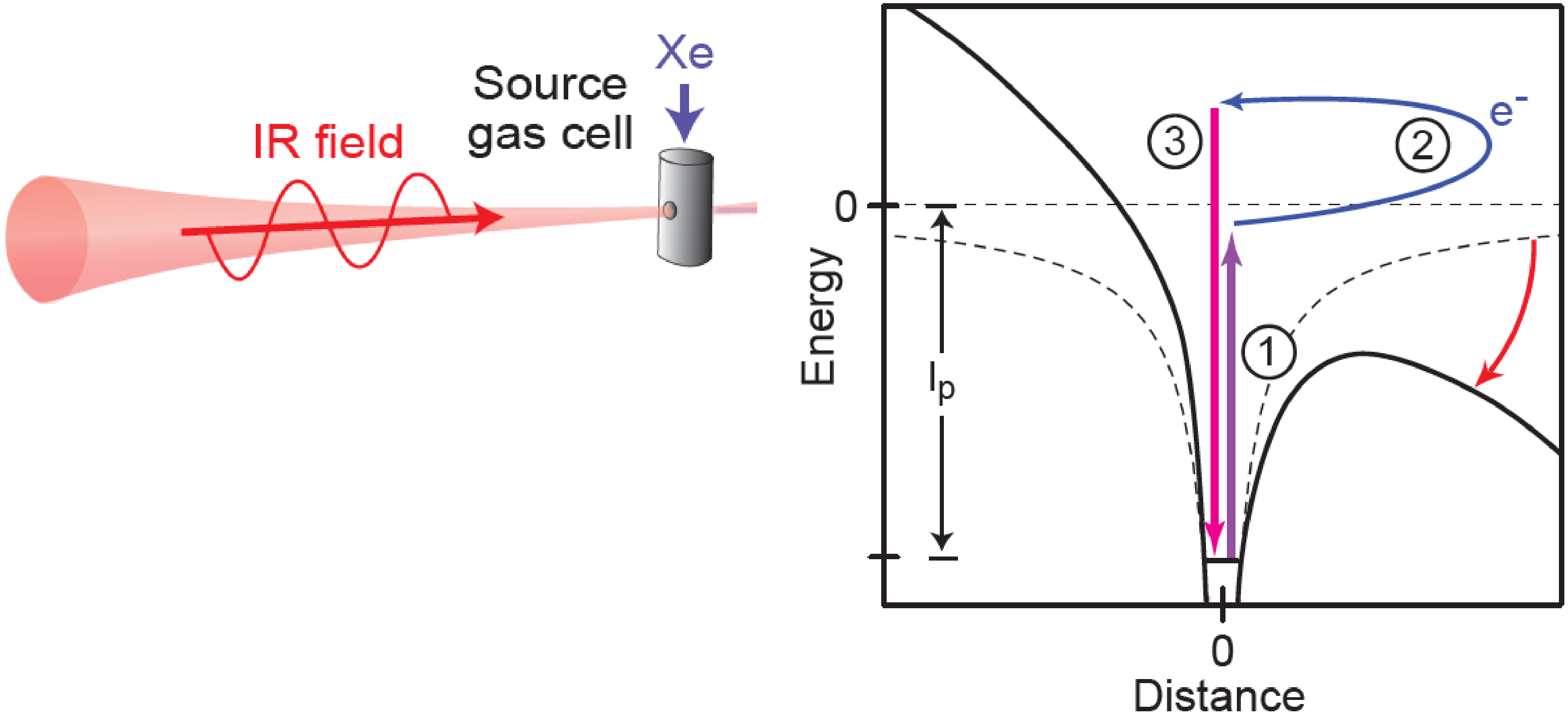
  - Microwave electrical discharges
  - Dielectric-barrier discharges (DBDs)
- Other mechanism
  - **Laser produced plasma**
  - Pulsed-power generated plasma

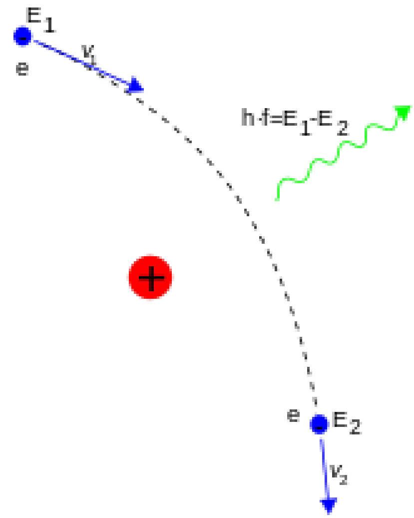
Electric field of a high-power laser can perturb the potential of a nuclear and thus ionize the atom directly



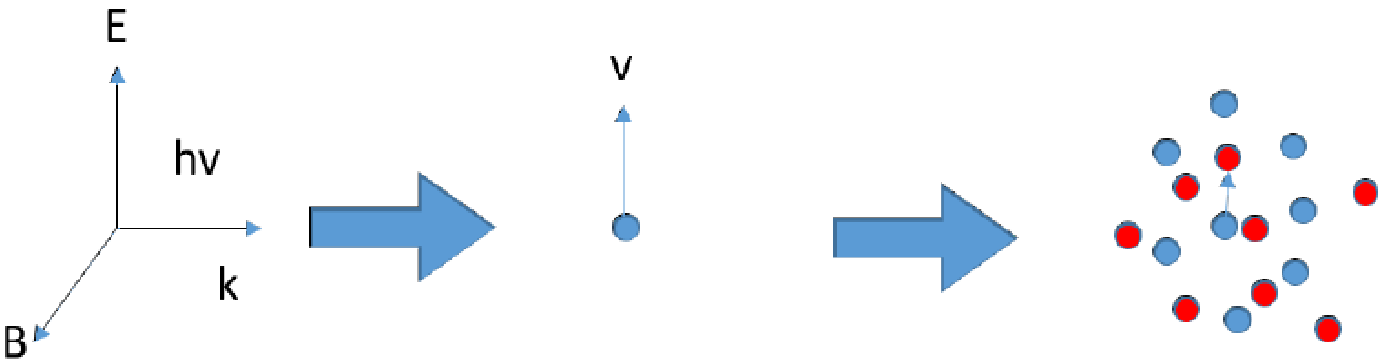
M. Krüger, etc., Appl. Sci. 9, 378 (2019)

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

- **Bremsstrahlung**



- **Inverse bremsstrahlung**



Electrons accelerated by electric fields

Electrons collide with other electrons / ions

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  - Inductive radio frequency (RF) electrical discharges
  - Capacitive RF electrical discharges
  - Microwave electrical discharges
  - Dielectric-barrier discharges (DBDs)
- Other mechanism
  - Laser produced plasma
  - **Pulsed-power generated plasma – it will be introduced later.**