# Plasma Sources & Wave Propagation


Presented by

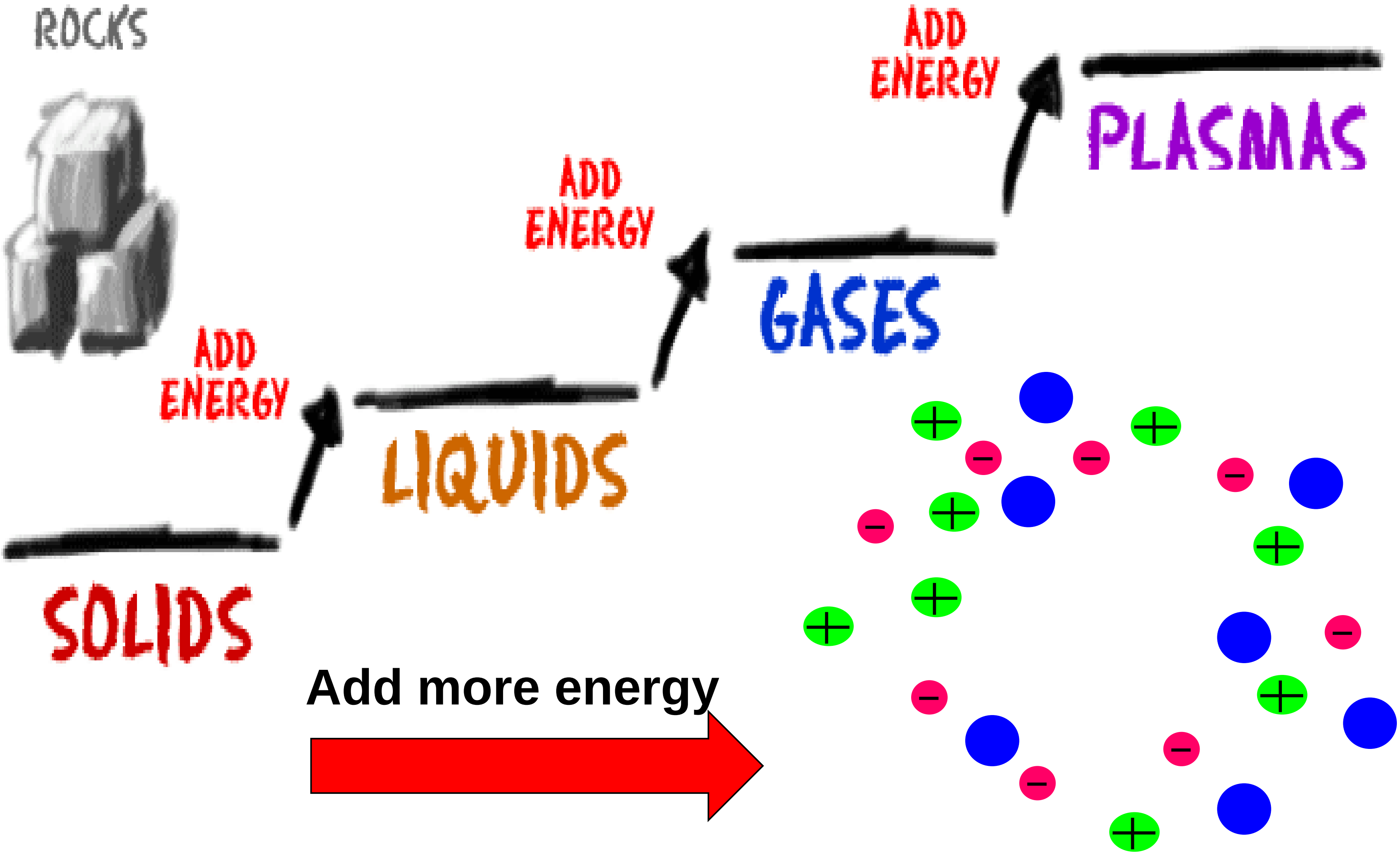
Dr. Mahmoud Saad Afify

Department of Physics, Faculty of Science, University of Benha

# Outlines

- **Introduction**
- **Cold and thermal plasma**
- **DC glow discharge, RF, Microwave, and pulsed plasma**
- **Observations of waves in plasma**

# The fourth state of matter "Plasma"

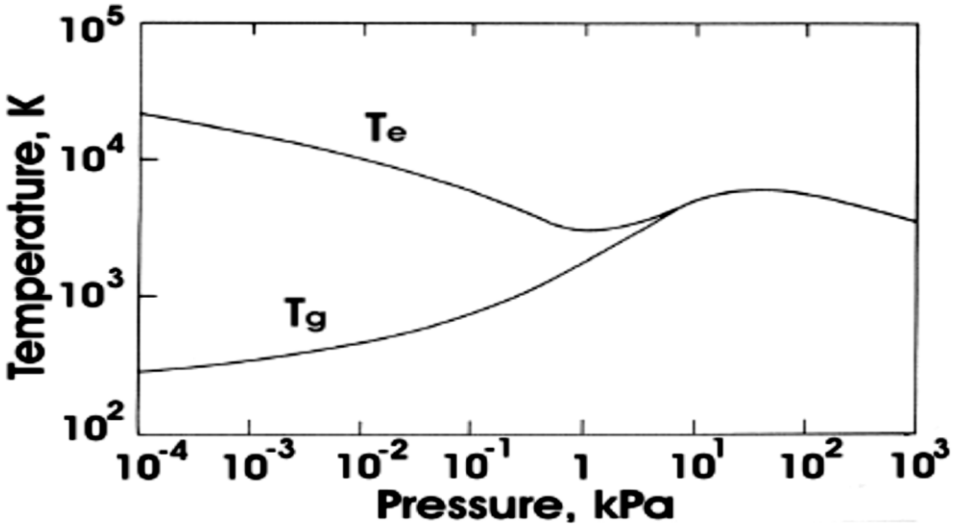



Plasma
Wind turbine: protective wear coating
Plasma
Architectual glass: thermal insulation, self-cleaning, mirror coating
Plasma
Aircraft turbine: pro- tective wear resistant coating
Plasma
Car: xenon headlights, wear protection, friction reduction
Plasma
Implants: biocompatibility, antimicrobial features
Plasma
Functional clothing: thermal insulation, breathability, flexible sensors, water-repellant
Plasma
Food packaging: barrier layers, antimicrobial features
Plasma
Notebook: LED backlight, reflective coating on CD
Plasma
Tools: polishing, hardening, decoating, hard layer coating
Plasma
PET bottle: barrier layer for product preservation
Plasma
Smartphone: adhesion, battery, semiconductor technology, display
Plasma
Mug: printability of polymers
Plasma
Lenses: anti-reflection coating, lotus effect, scratch protection
Plasma
Camera lens: optical coatings

# Plasma sources

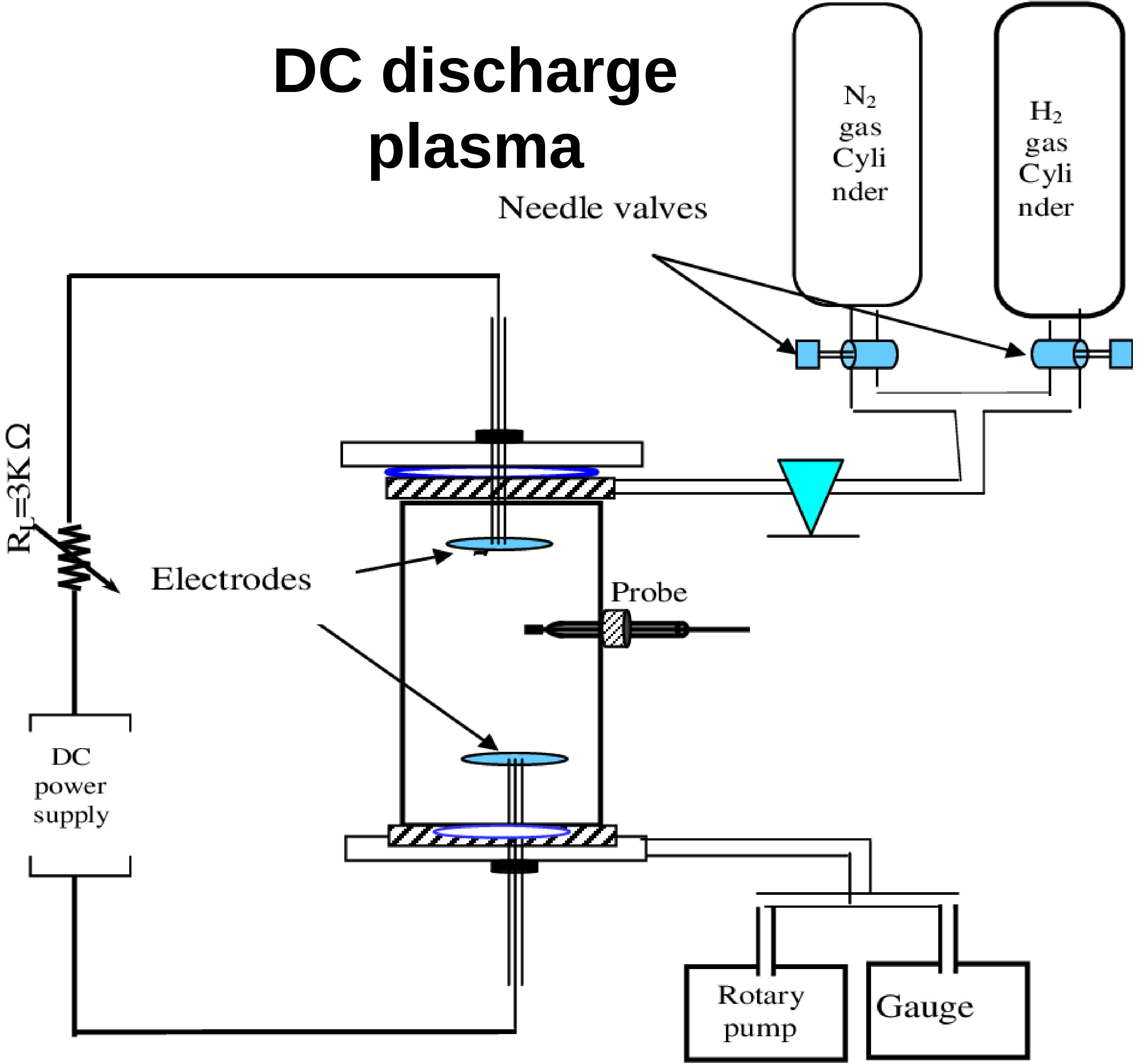
**Cold plasmas** are those with **low pressure** and $T_e >> T_h$. It is obtained in DC discharge, RF discharge, and short pulse discharges.

**Thermal plasmas**, are those with **high pressure** and $T_e \sim T_h$. It is produced in plasma arc.

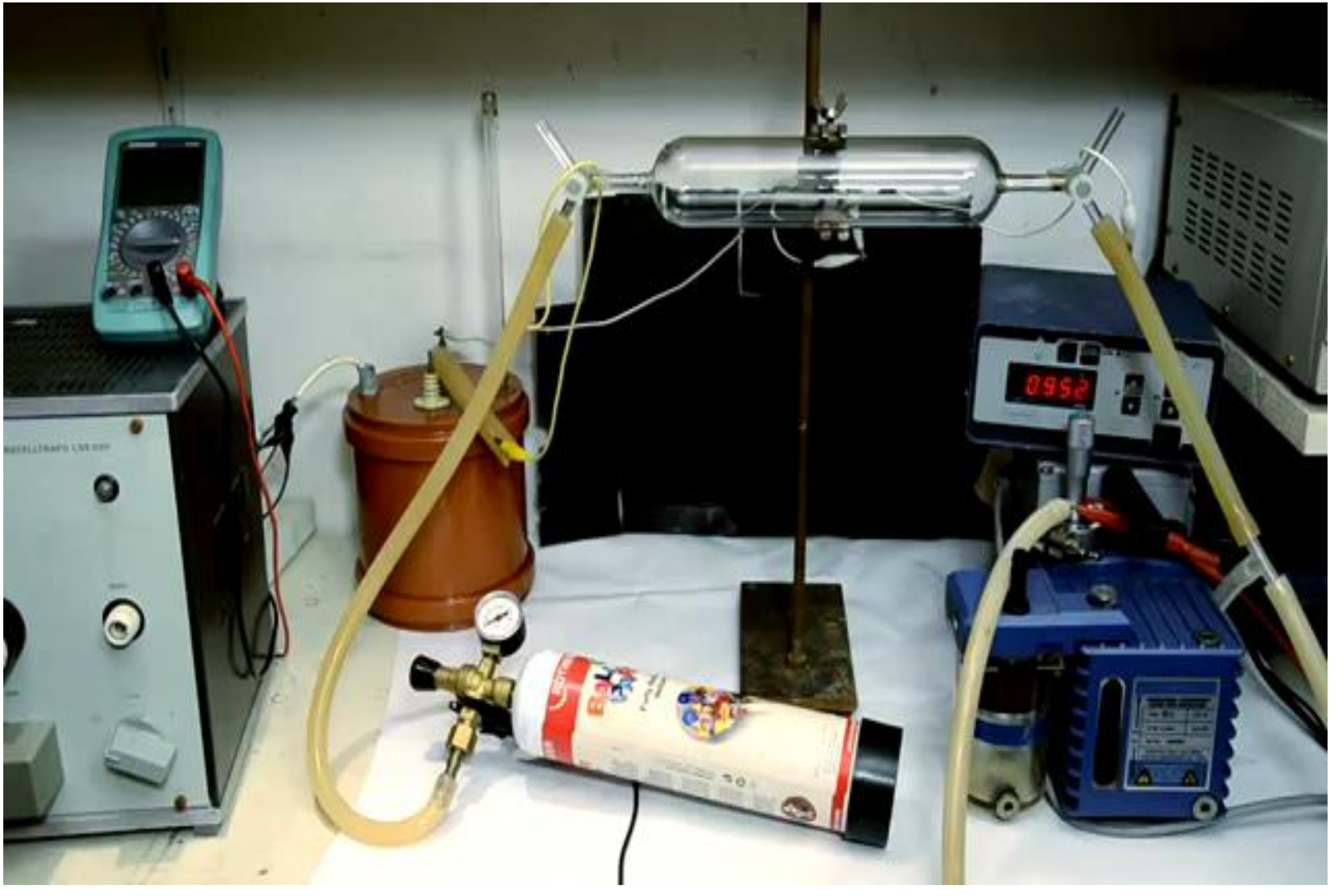


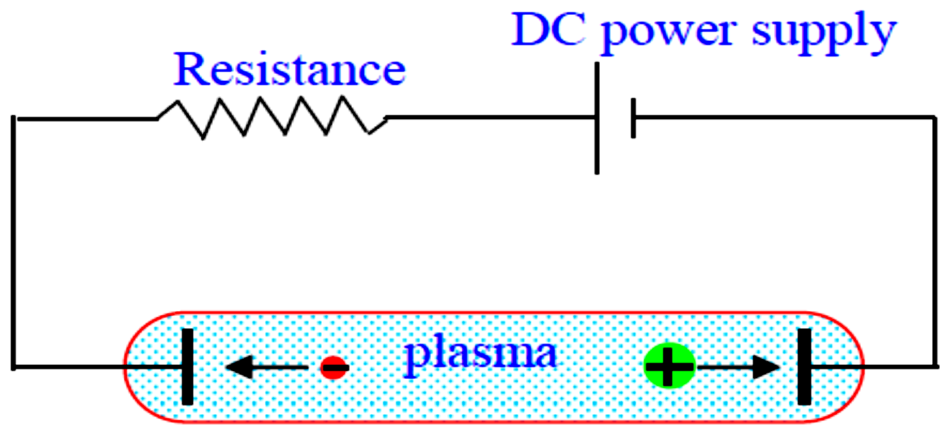

$(T_e >> T_h)$

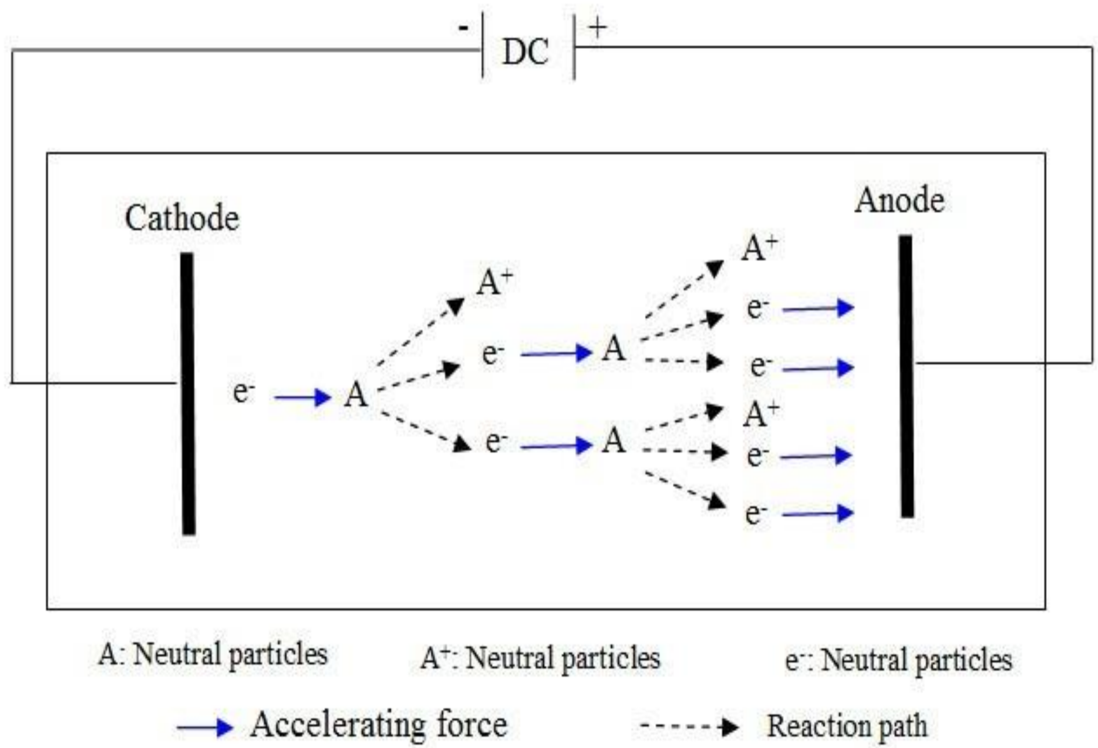
# DC discharge plasma

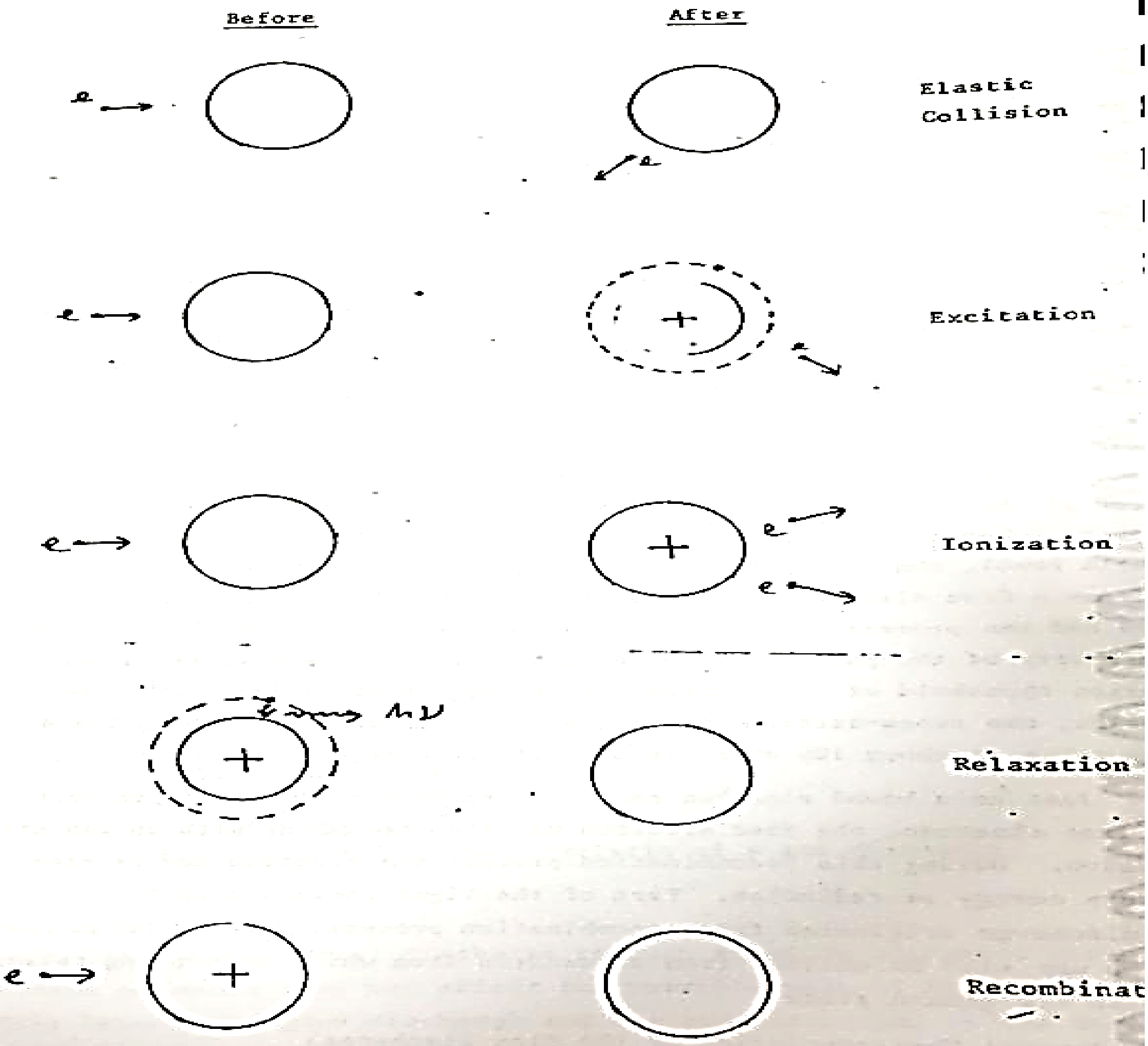


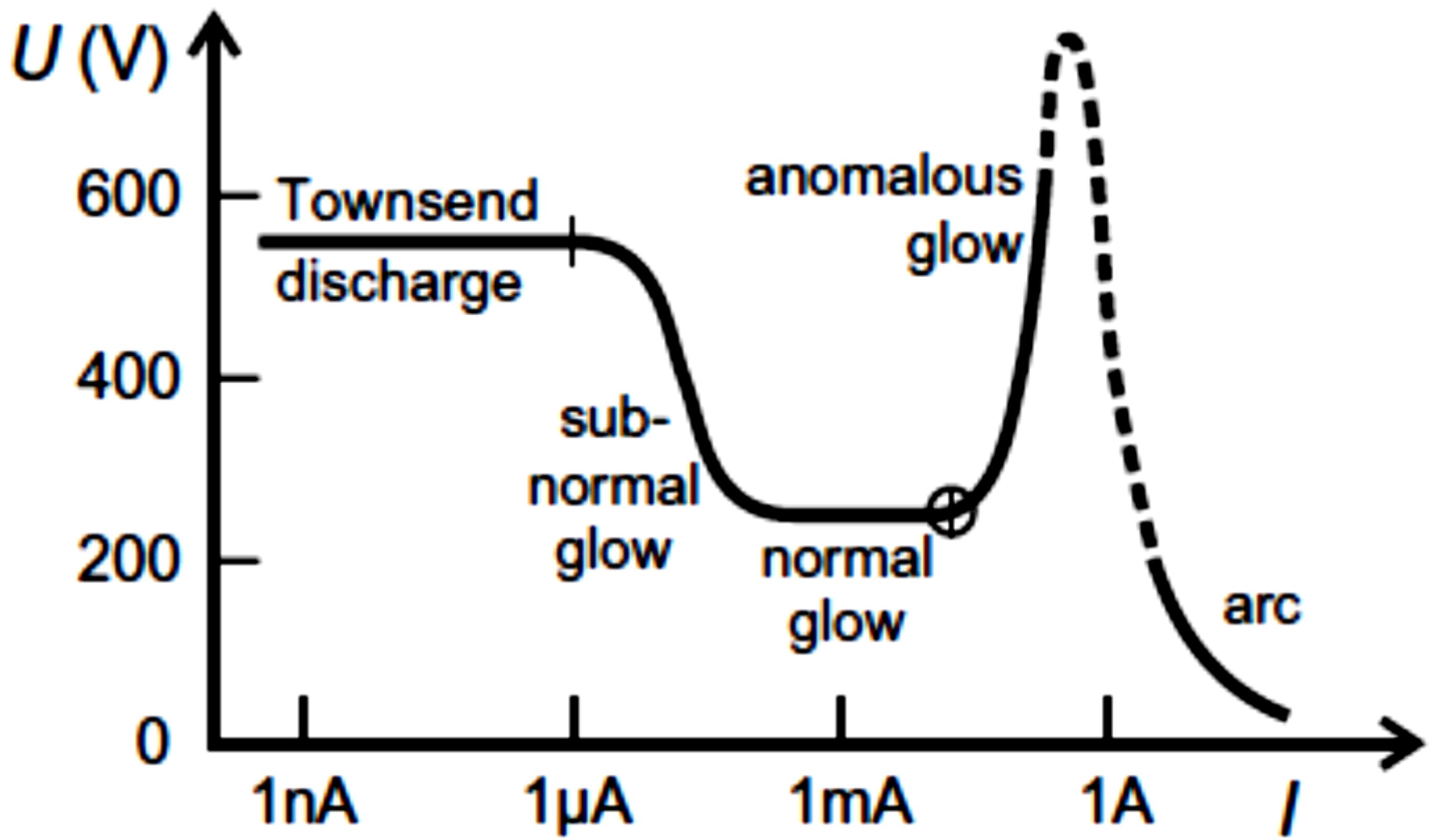
# DC discharge experiment

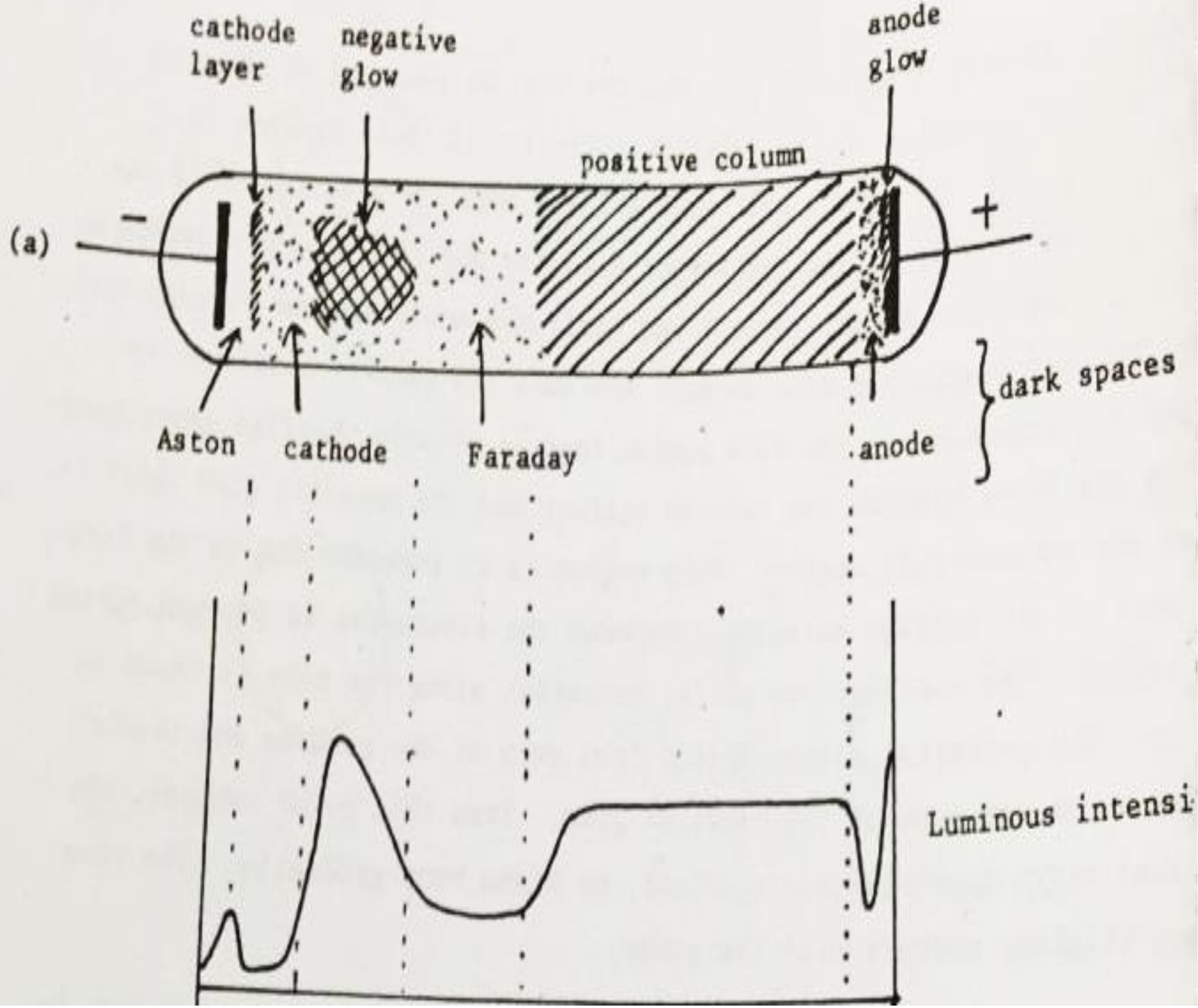


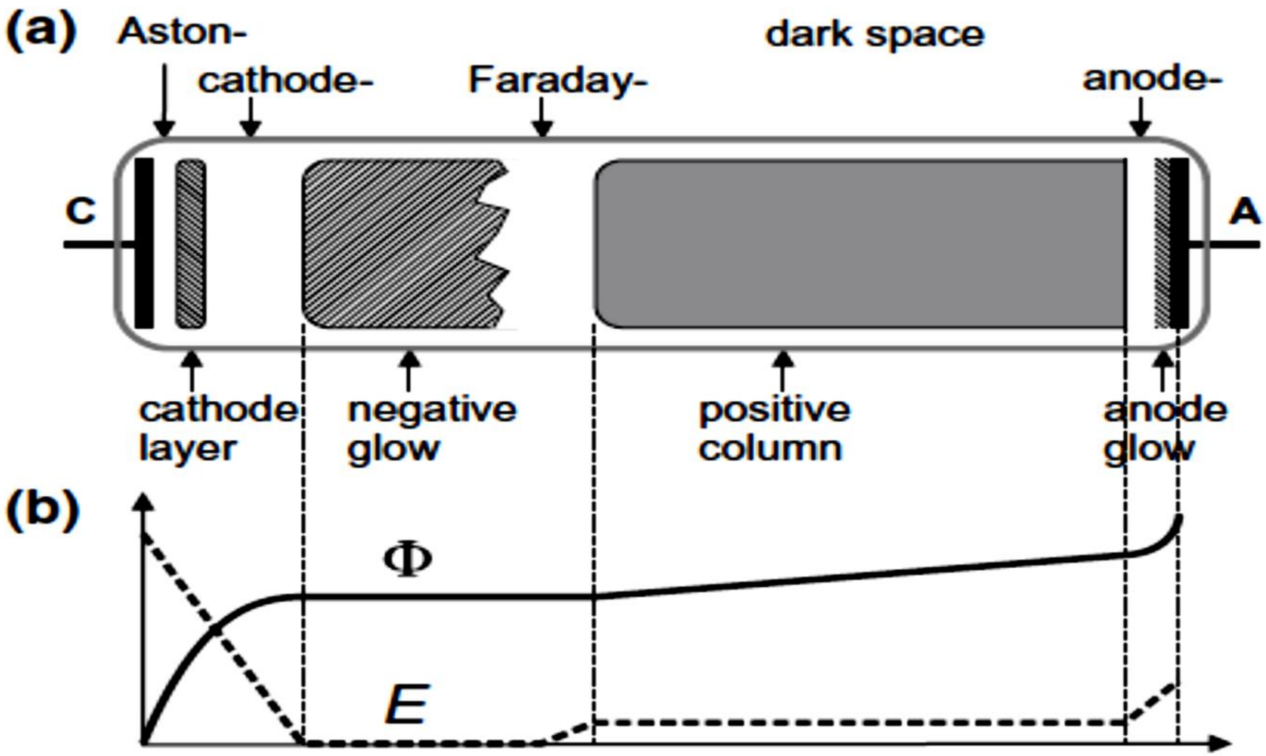

DC power supply
Resistance
plasma


-
DC
+
Cathode
Anode
e-
A
A+
A: Neutral particles
A+: Neutral particles
e-: Neutral particles
Accelerating force
Reaction path


Before
After
Elastic Collision
Excitation
Ionization
hν
Relaxation
Recombinat

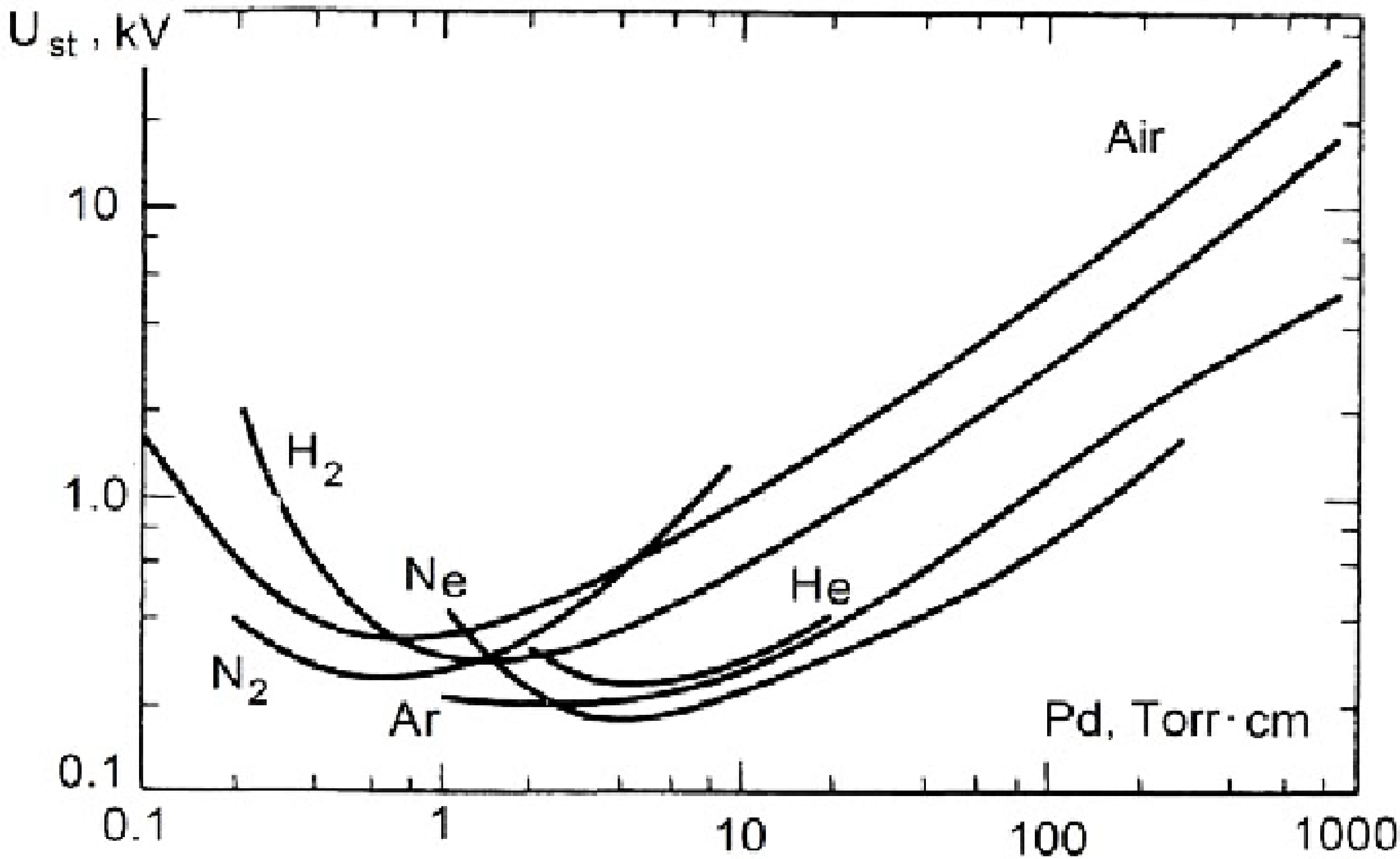

U (V)
600
400
200
0
Townsend
discharge
sub-
normal
glow
normal
glow
anomalous
glow
arc
1nA
1µA
1mA
1A
I


cathode
layer
negative
glow
anode
glow
positive column
(a)
−
+
Aston
cathode
Faraday
anode
dark spaces
Luminous intensi



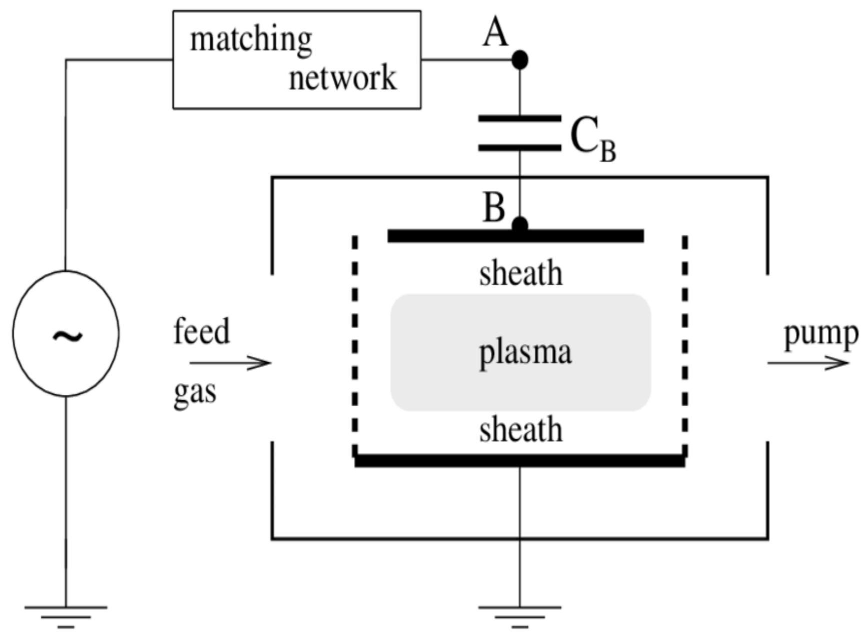

**The** **negative glow** **is mostly field-free,** ***E*** **≈ 0. In the** **positive column**, **the axial electric field is** **constant**.

# Mean Free Path



# Radio Frequency Discharge

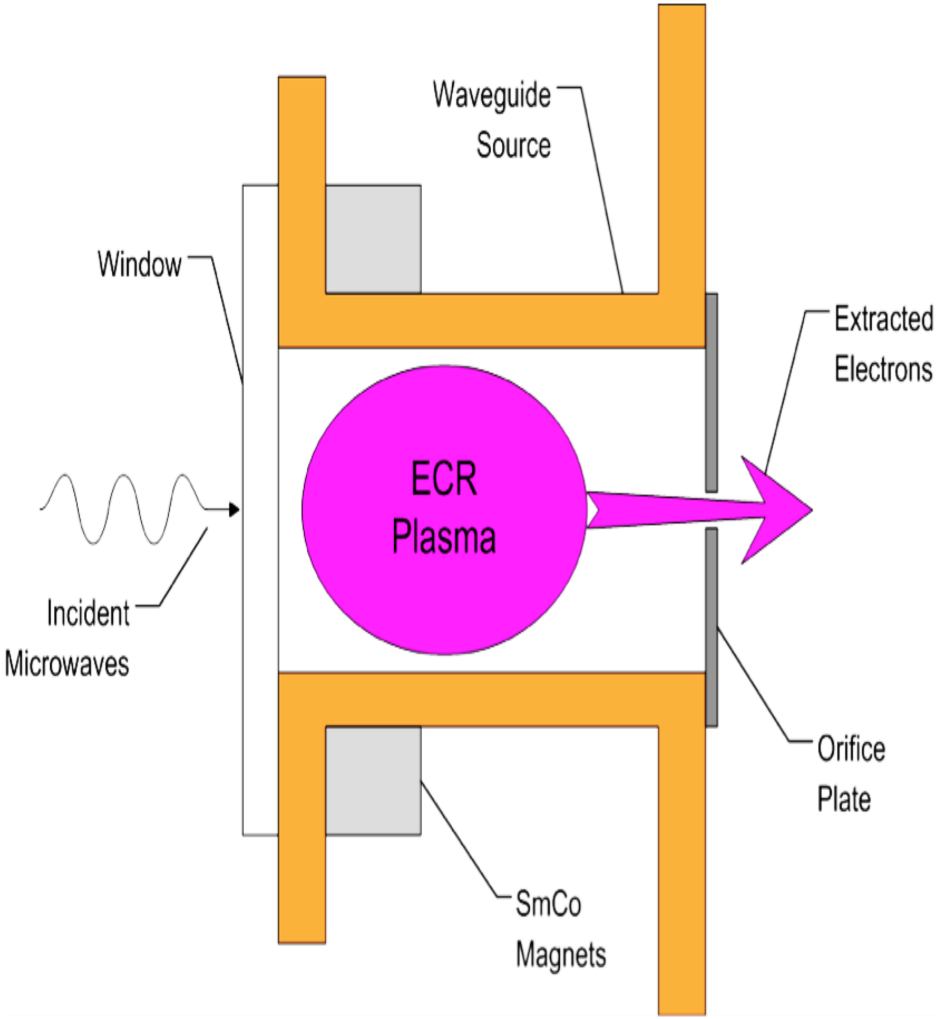
1. In RF plasmas, Conductive and nonconductive electrodes can be used.
2. RF plasmas can be sustained with internal as well as external electrodes.
3. RF plasmas are characterized by higher ionization efficiencies.
4. RF plasmas can be sustained at lower gas pressures.
5. In RF plasmas the energy of the ions bombarding the sample is controlled.



# Microwave Plasmas

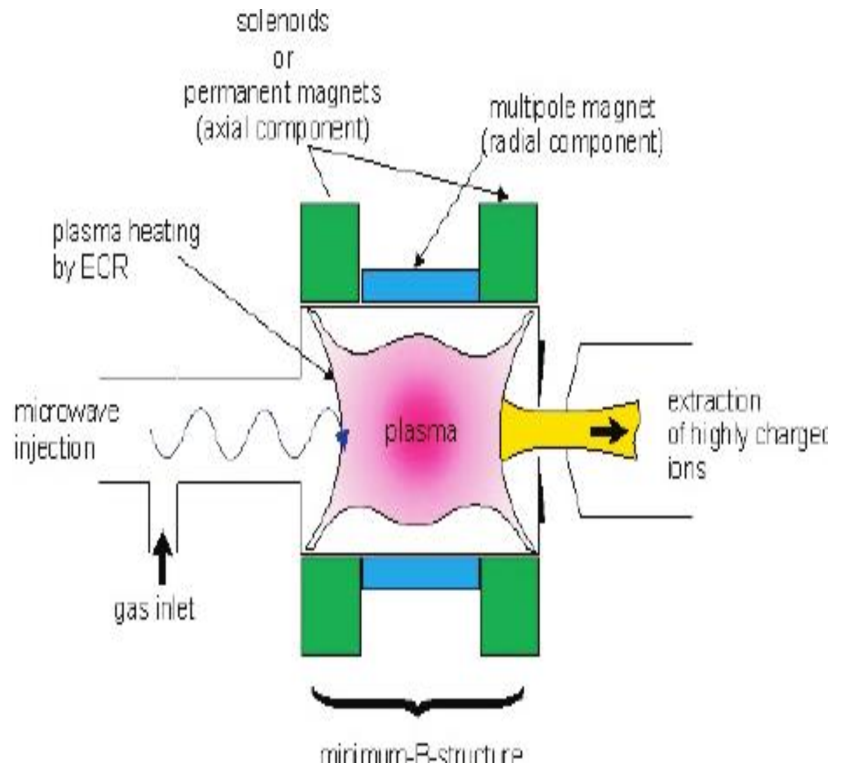
1. The excitation of the plasma by microwaves is similar to the excitation with RF, while differences result from the ranges of frequencies.

2. Also, it is difficult to sustain Microwave discharges at low pressures (< 1 torr)

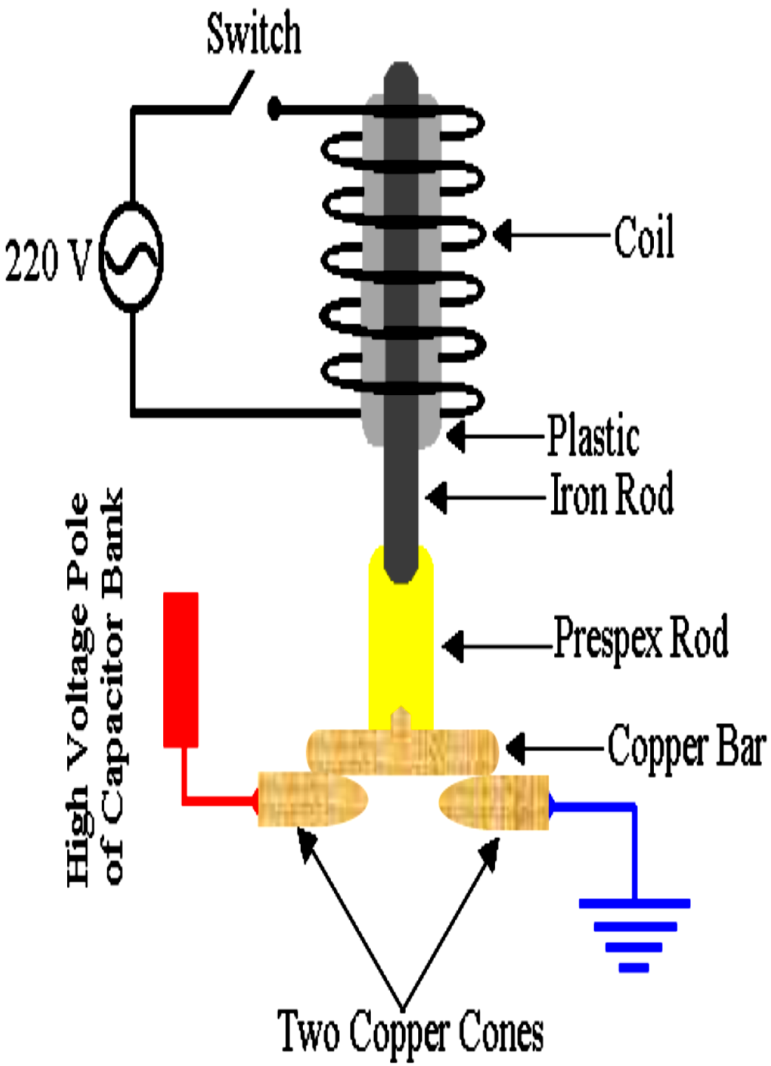


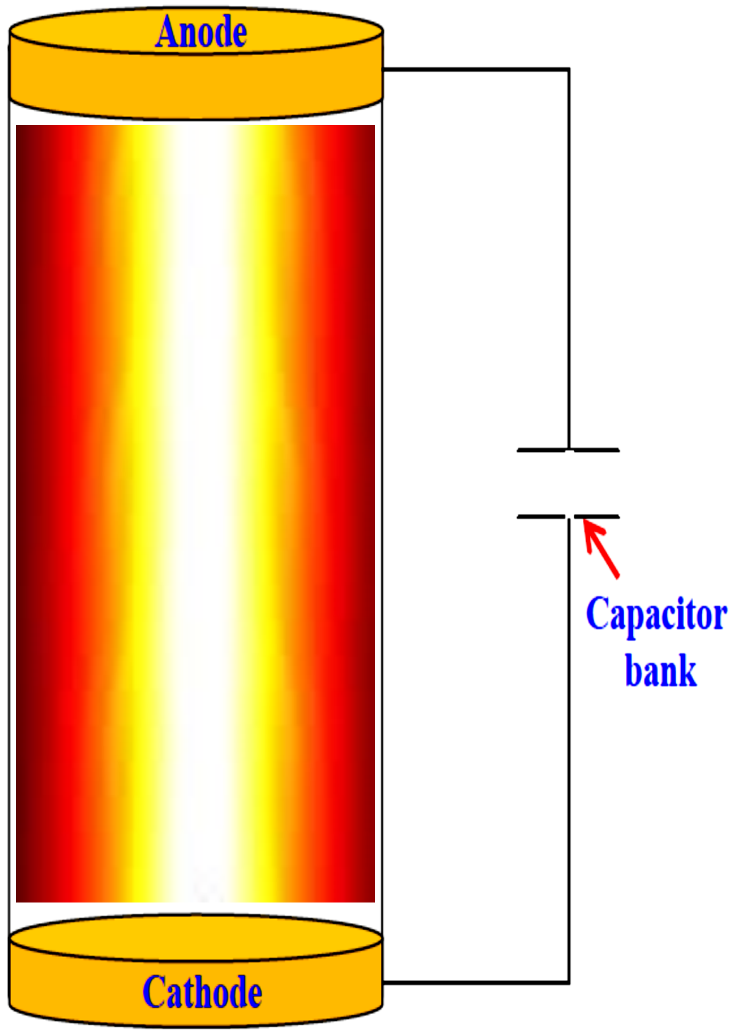
# Electron Cyclotron Resonance Plasmas

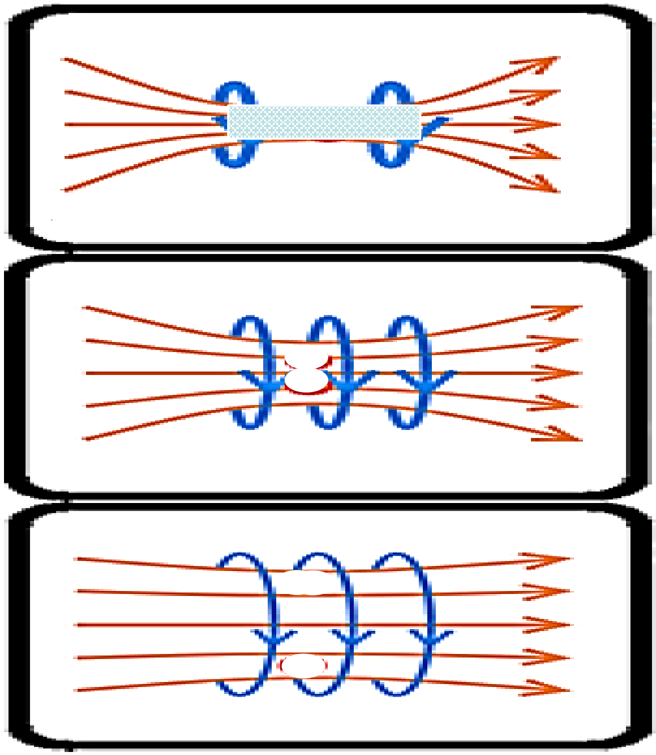
1. It can sustain at low pressures.
2. High ionization efficiency.
3. Wide range of achievable ion energies.
4. Electrodeless coupling of the electric power to the plasma.

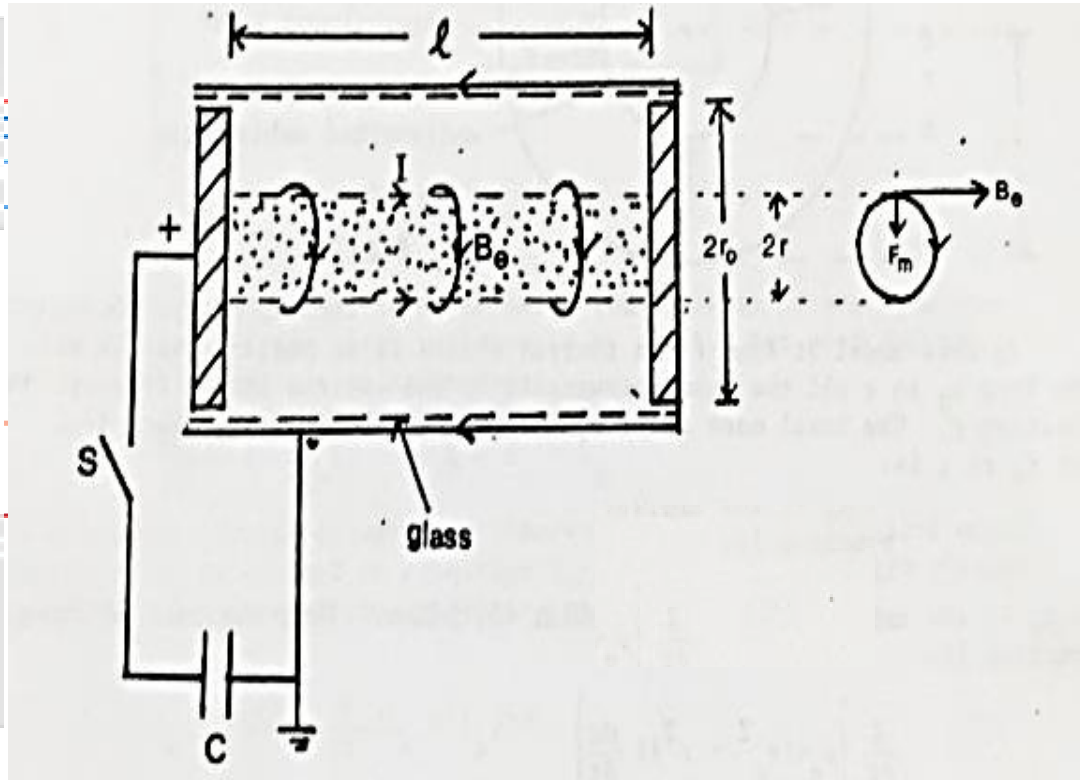


# Linear Z-pinch device

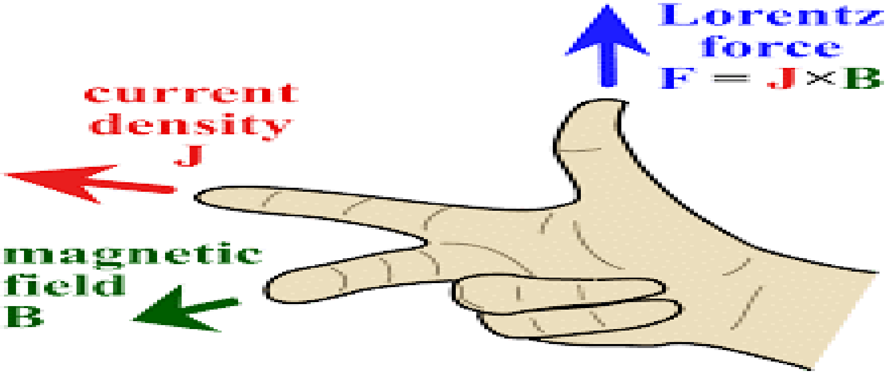


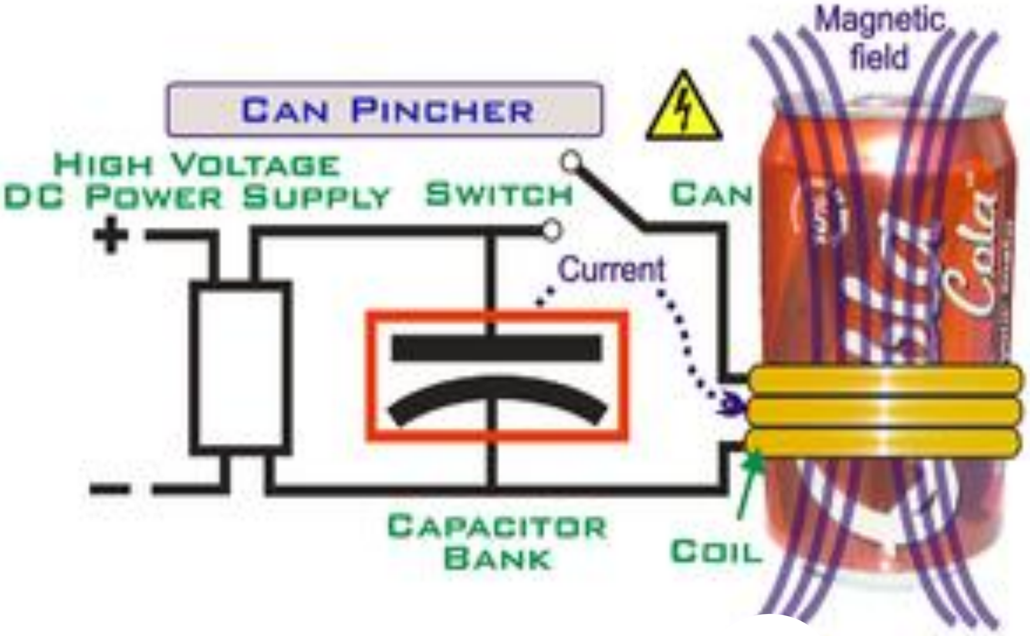


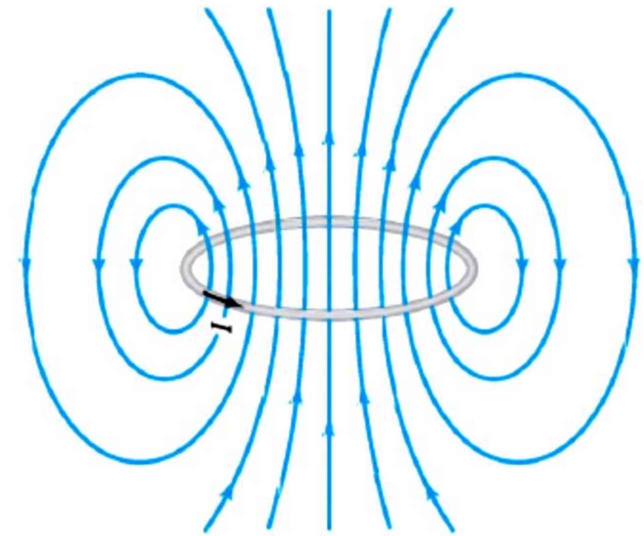


ℓ
I
+
$B_e$
$2r_0$
2r
$F_m$
$B_e$
S
glass
C

Lorentz
force
F = J×B
current
density
J
magnetic
field
B


Magnetic
field
CAN PINCHER
HIGH VOLTAGE
DC POWER SUPPLY
SWITCH
CAN
+
Current
-
CAPACITOR
BANK
COIL


I

# Visualization of pinch effect

Subject: Date:



the magnetic force can be represented by the following term:

$$F = J \times B_\theta \rightarrow (1)$$

where the azimuthal magnetic field $B_\theta$ can be determined using ampere's law

$$B_\theta = \frac{\mu I}{2\pi r} \rightarrow (2)$$

since $\nabla \times B_\theta = \mu J \rightarrow (3)$ {from stoke's theorm}

substituting from (3) in (1)

$$\therefore F = \frac{1}{\mu}[\nabla \times B_\theta \times B_\theta] = \frac{1}{\mu}\left\{(B_\theta \cdot \nabla)B_\theta - \frac{1}{2}\nabla B_\theta^2\right\}$$

$$\because \nabla \cdot B = 0 \Rightarrow (B_\theta \cdot \nabla) B_\theta / \mu = \nabla \frac{B_\theta^2}{\mu}$$

Subject: (2) Date

$$\therefore F = \frac{1}{\mu}\left\{\nabla B_\theta^2 - \frac{1}{2}\nabla B_\theta^2\right\}$$

$$\therefore F = \frac{1}{2\mu}\nabla B_\theta^2 \rightarrow (4)$$

the last equation has the same dimension as $\nabla P$ (the mechanical tensile stress).

thus $\boxed{\frac{B_\theta^2}{2\mu}}$ represents the concept of magnetic pressure.

$\# \quad \mu = \frac{N}{A^2} \quad ; \quad B = \frac{N\,sec}{C\,m} \Rightarrow B^2 = \frac{N^2 sec^2}{C^2 m^2}$

$\because I = \frac{C}{sec} \Rightarrow B^2 = \frac{N^2}{A^2 m^2}$

$\therefore \frac{B^2}{\mu} = \frac{N^2}{A^2 m^2} \cdot \frac{A^2}{N} = \frac{N}{m^2}$

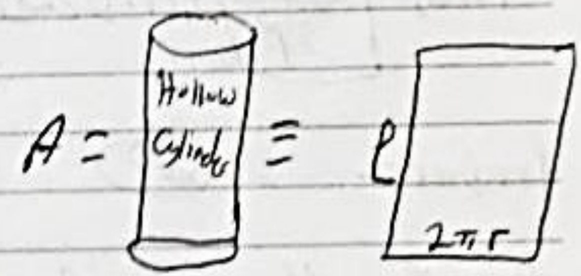
$\therefore \nabla P = \nabla \frac{N}{m^2} = \frac{1}{2\mu}\nabla B^2 = \frac{1}{2}\nabla \frac{N}{m^2}$

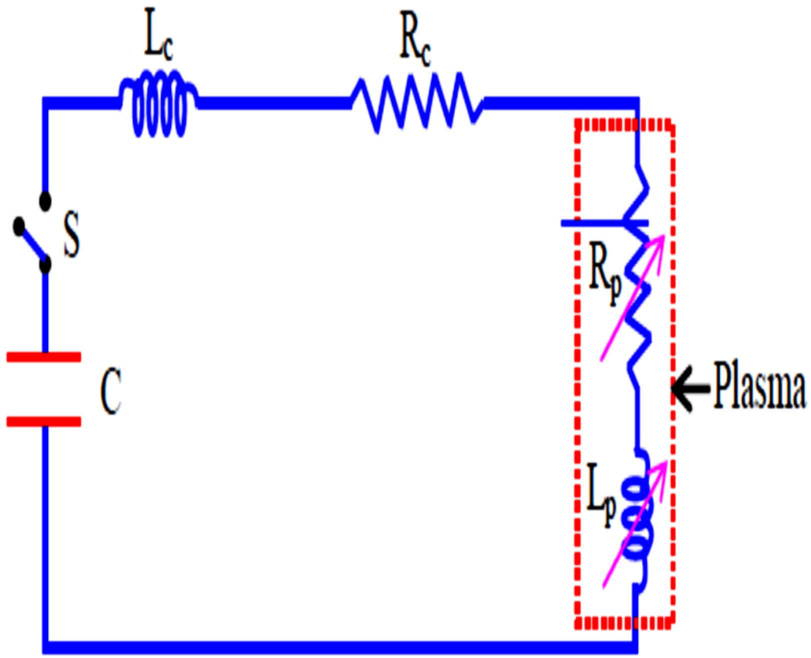
Considering the magnetic pressure $\frac{B_0^2}{2\mu}$ is uniform across the current sheath. Thus the total force acting radially inwards is:-

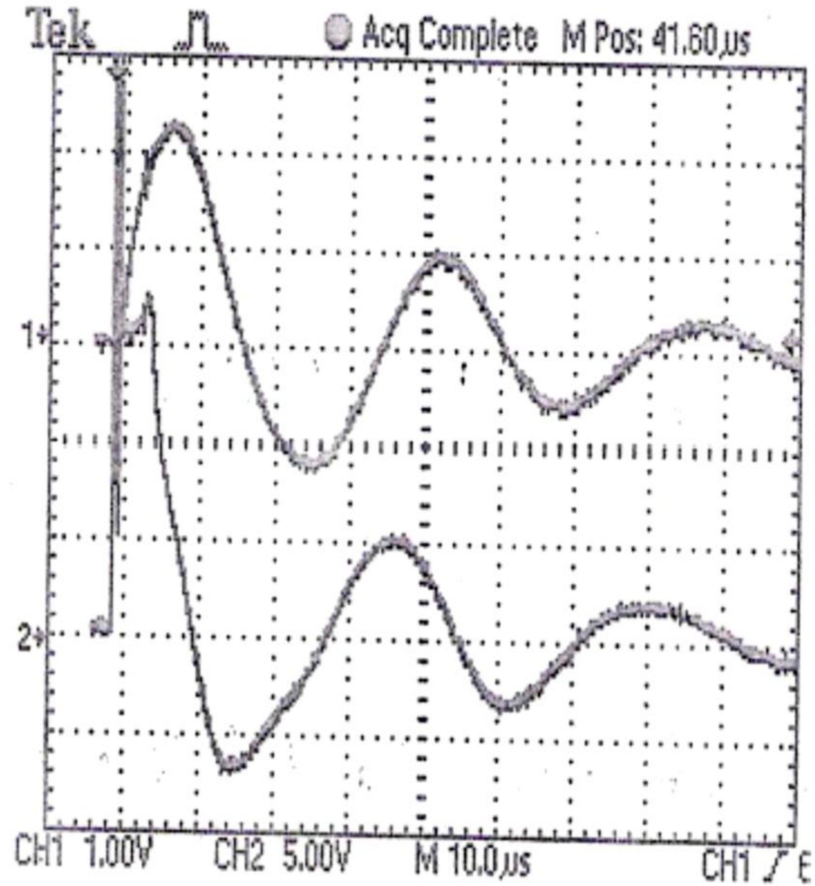
$$F = \frac{B_0^2}{2\mu}(2\pi r l) = \frac{\mu I^2 l}{4\pi r} \rightarrow (5)$$

where $B_0 = \frac{\mu I}{2\pi r}$ , $P_m = \frac{F}{A} \Rightarrow F = P_m A$

$$F = \frac{B_0^2}{2\mu}(2\pi r l)$$

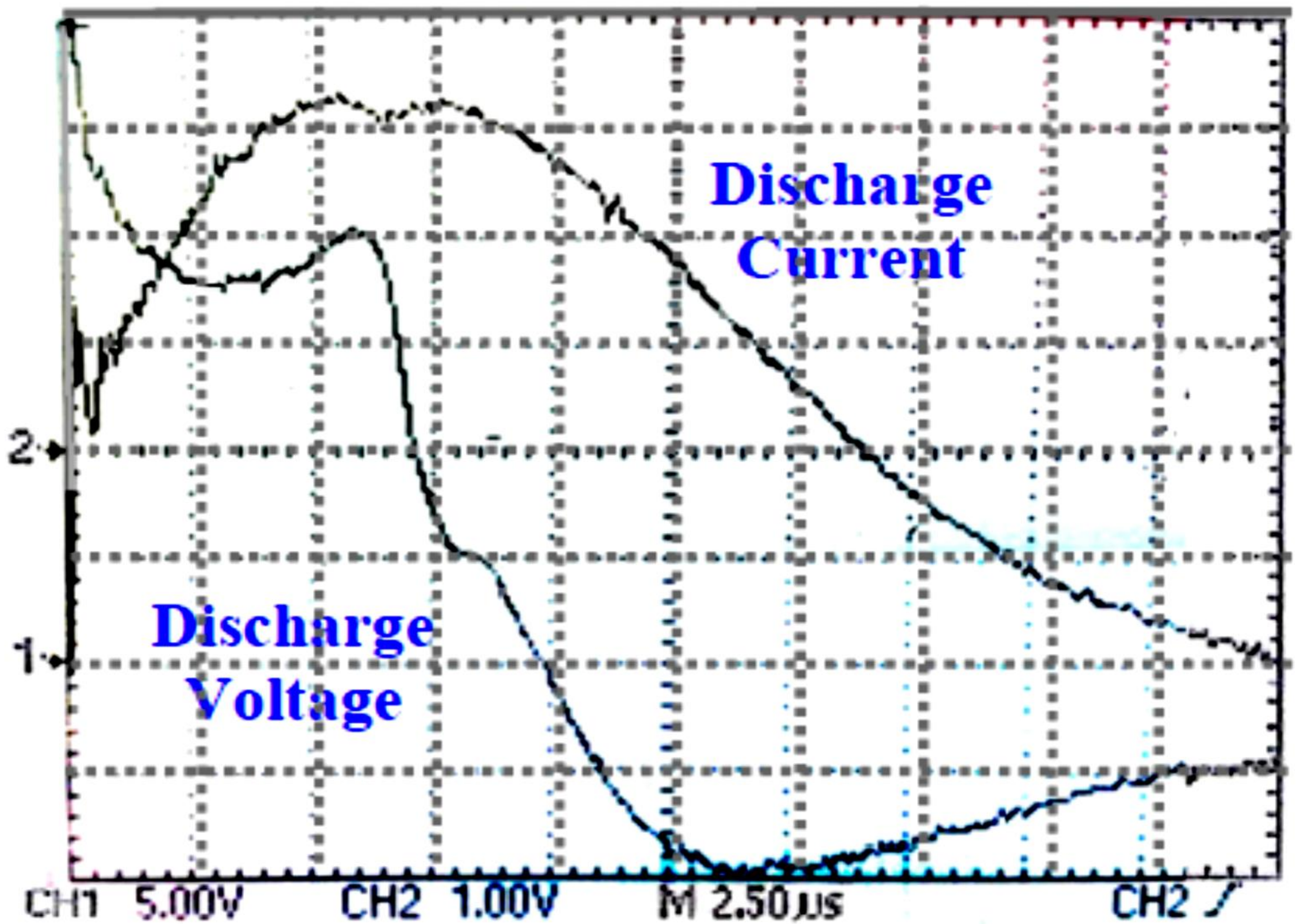



$L_c$
$R_c$
S
C
$R_p$
$L_p$
Plasma


Tek
Acq Complete M Pos: 41.60 μs
1
2
CH1 1.00V CH2 5.00V M 10.0 μs CH1

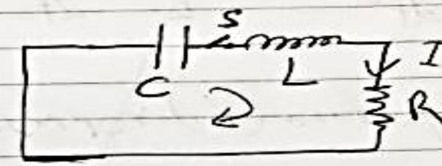
In any electric circuit, there can be three basic components: resistance, capacitance, and inductance, in addition to a source of emf. (There can also be more complex components, such as diodes or transistors.)

Because some resistance is always present, electrical oscillators generally need a periodic input of power to compensate for the energy converted to thermal energy in the resistance.


Discharge
Current
Discharge
Voltage
2
1
CH1 5.00V
CH2 1.00V
M 2.50µs
CH2

# L – C – R Circuit

Kirchoff's law can be used to write the circuit equations




$$-L\frac{dI}{dt} - IR + \frac{Q}{C} = 0$$

$\therefore I = -\frac{dQ}{dt}$ as the charge decreases on the capacitor $\therefore Q = -\int I\,dt$

$$-L\frac{dI}{dt} - IR - \frac{\int I\,dt}{C} = 0$$

Differentiate the last equation.

$$L\frac{d^2I}{dt} + R\frac{dI}{dt} + \frac{I}{c} = 0$$

Subject: (5) Date:

$$\frac{d^2 I}{dt^2} + \frac{R}{L}\frac{dI}{dt} + \frac{I}{LC} = 0 \rightarrow (6)$$

- Equation (6) represents a second-order differential equation in variable $\underline{I}$ and this equation is Called " Damped harmonic oscillator "

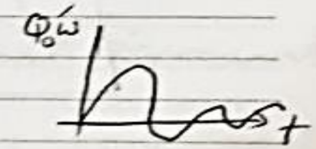
- Equation (6) has a solution of the form:

$$I = Q_0 \omega' \, e^{\frac{-Rt}{2L}} \sin \omega' t \rightarrow (7)$$

where $\omega' = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$

Thus, the system will be underdamped when

$$\frac{1}{LC} > \frac{R^2}{4L^2}$$




$\because Q_0 = CV_0 \quad , \omega' \simeq \frac{1}{\sqrt{LC}} \Rightarrow Q_0\omega' = V_0\sqrt{\frac{C}{L}}$

Subject: (6) Date:

Therefore, Equation (7) can be rewritten as

$$I = V_0 \left(C/L\right)^{1/2} e^{-\frac{Rt}{2L}} \sin \acute{\omega} t \longrightarrow (8)$$

$$\therefore I = I_0 \, e^{-\frac{Rt}{2L}} \sin \acute{\omega} t \longrightarrow (9)$$

where $\boxed{I_0 = V_0 \left(C/L\right)^{1/2}}$ is the peak discharge current.

The corresponding time to the peak discharge current can be determined as,

$$\because \acute{\omega} = 2\pi f = \frac{2\pi}{t}$$

$$\therefore \boxed{t = \frac{2\pi}{\acute{\omega}} = 2\pi \left(LC\right)^{1/2}}$$

Finally, This is a damped sinusoidal discharge with frequency $\acute{\omega}$ and damping

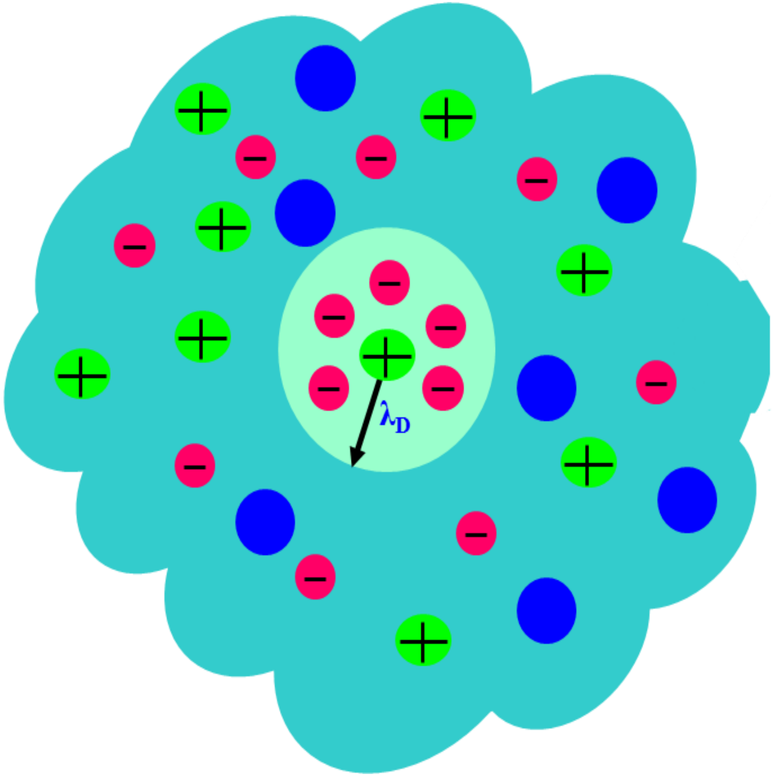
The energy stored in the electric field of the capacitor at any time $t$ is

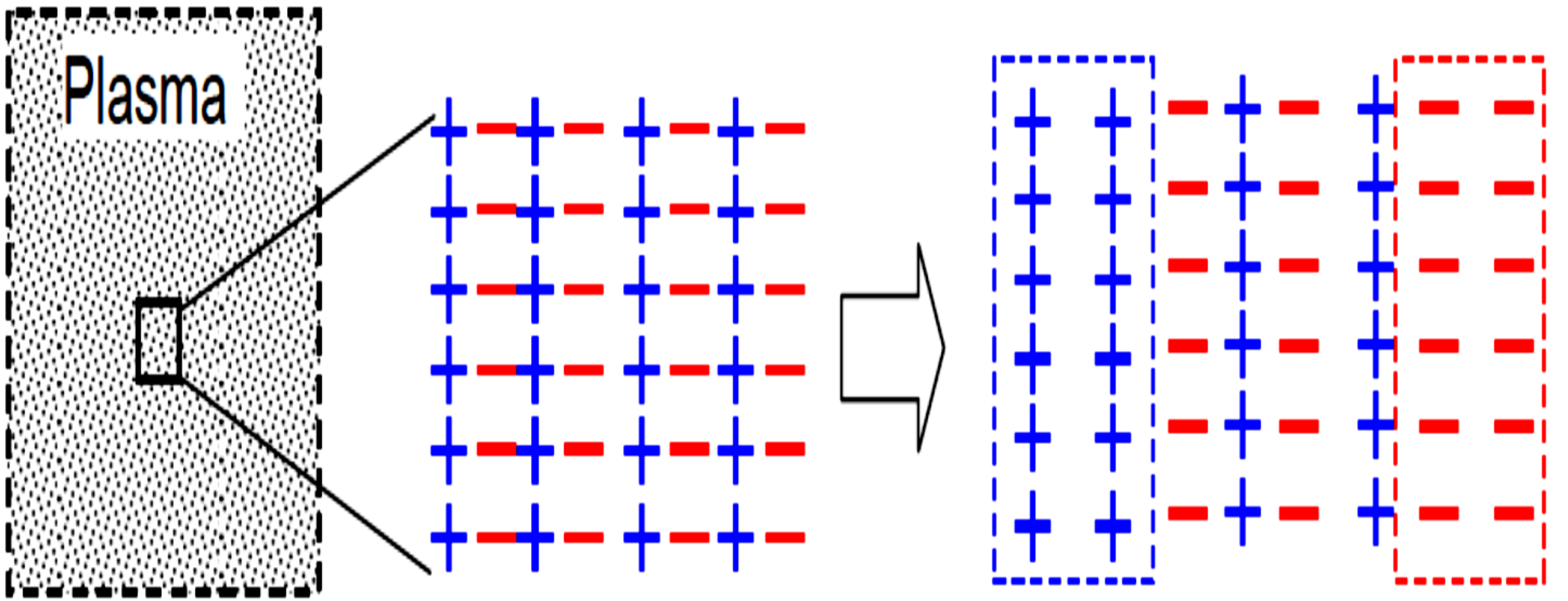
$$\frac{1}{2}\frac{Q^2}{C}$$

the energy is stored in the magnetic field of the inductor. At any time t,

$$\frac{1}{2}LI^2$$

# Collective behavior

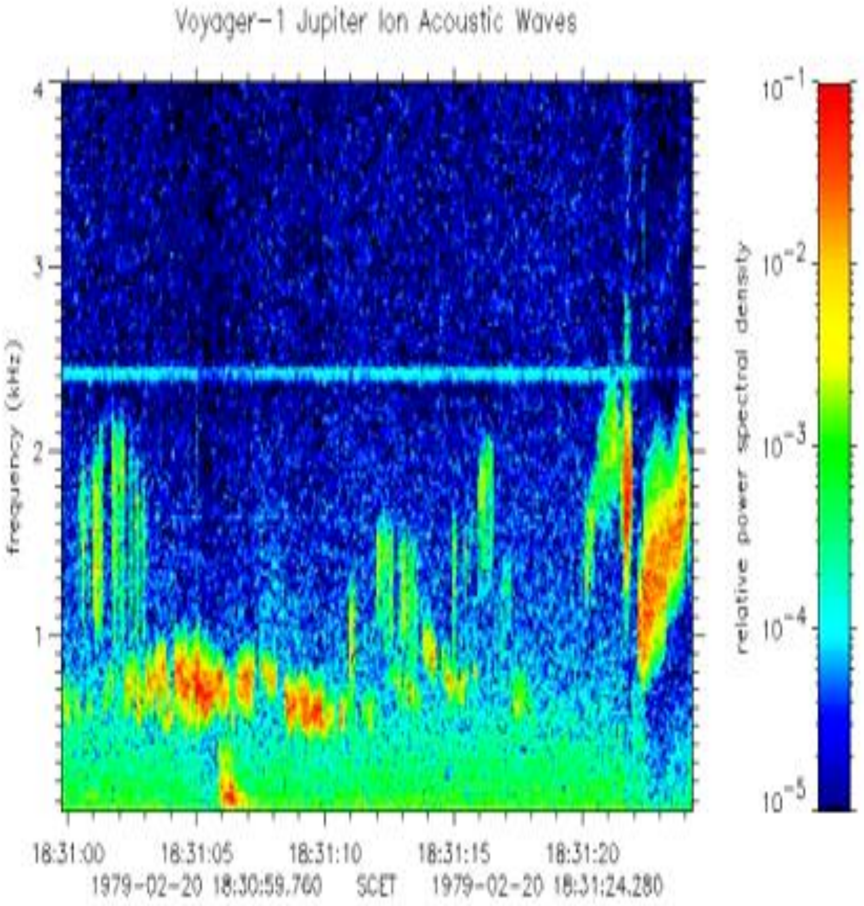


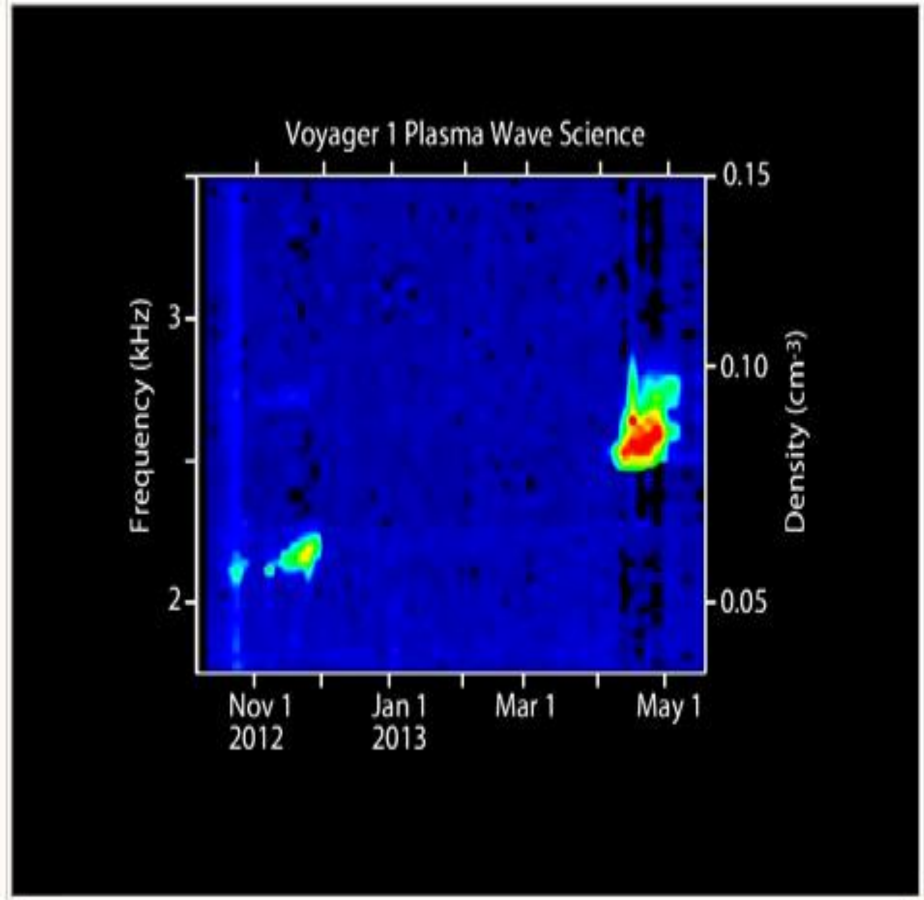

Plasma

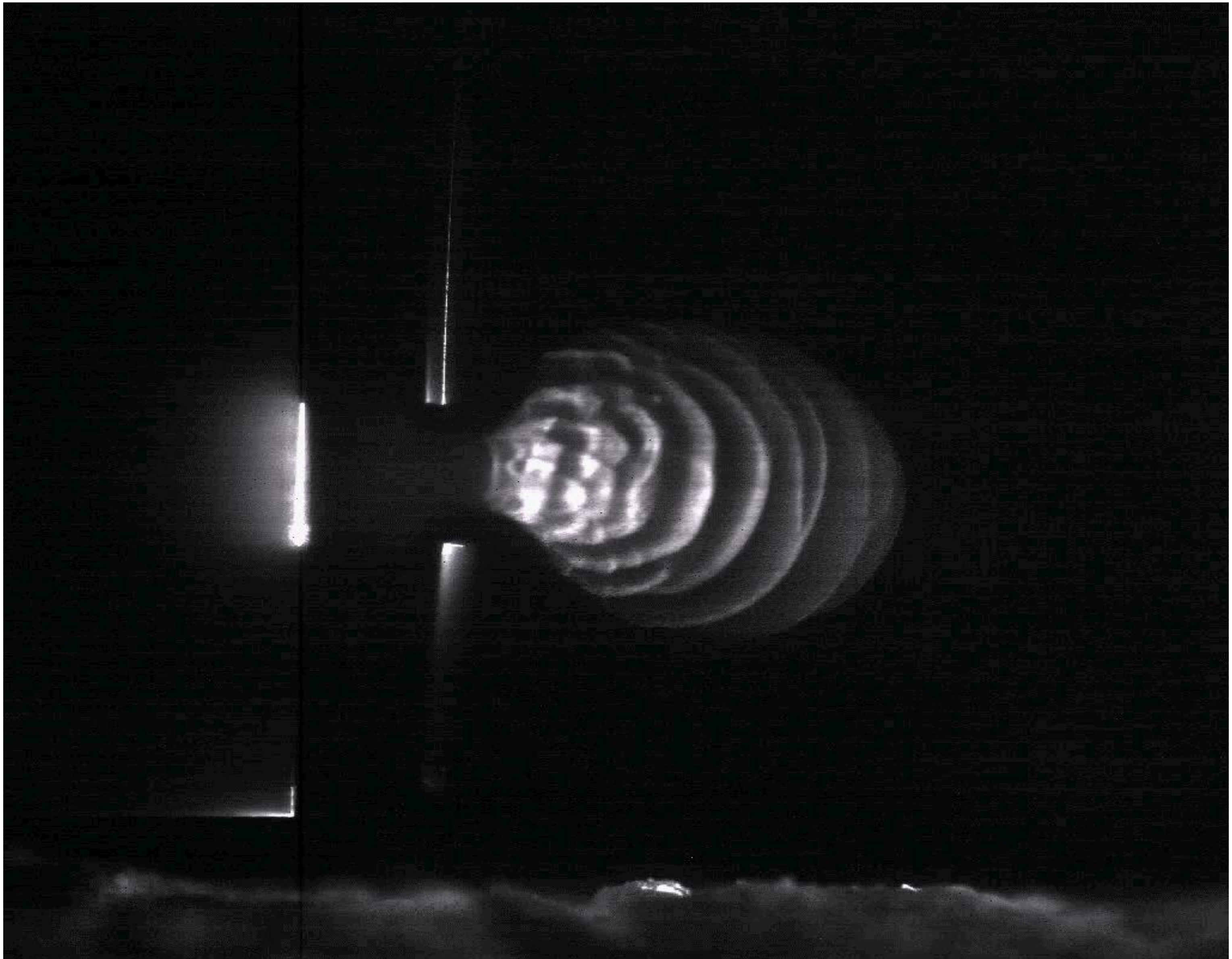
# Reason for Fourier series

**Plasma oscillation could be propagated and so we have a wave.**


Hertz's Experiment


Voyager-1 Jupiter Ion Acoustic Waves
frequency (kHz)
4
3
2
1
18:31:00
18:31:05
18:31:10
18:31:15
18:31:20
1979-02-20 18:30:59.760 SCET 1979-02-20 18:31:24.280
relative power spectral density
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$


Voyager 1 Plasma Wave Science
Frequency (kHz)
3
2
Density (cm$^{-3}$)
0.15
0.10
0.05
Nov 1
2012
Jan 1
2013
Mar 1
May 1



**Recall that any wave has three basic properties:**

**1) Amplitude – the height of the wave**

**2) Frequency – a number of waves passing through in a given second**

**3) Phase – where the phase is at any given moment.**

**# According to Fourier, any periodic function can be represented by an infinite series of sinusoidal functions with frequency ω and wavelength λ.**

**# The Exponential Fourier Series is**

$$n = \overline{n}\, e^{i(kx - \omega t)}$$

**where we consider the periodic function to be the plasma density as an example. Also, we consider 1D only.**

**By convention, the exponential notation means that the real part of the expression is to be taken as the measurable quantity.**

$$e^{j\omega t} = \cos \omega t + j \sin \omega t$$

$\therefore Re(n) = \bar{n} \cos(Kx - \omega t)$

where $\bar{n} \rightarrow$ is the amplitude

$Kx - \omega t \equiv \phi$ represents the phase

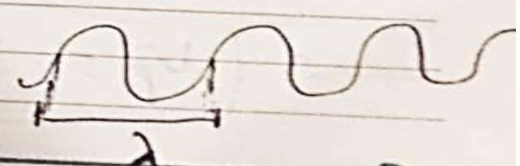
$K \rightarrow$ is the wave number $(K = \frac{2\pi}{\lambda})$

$\omega = 2\pi f \rightarrow$ is the angular frequency.

# the phase velocity of a wave is the rate at which the wave propagates in some medium.

# $v_p = \lambda / T \equiv \frac{\omega}{K} \rightarrow (1)$

to show how we get the formula of Eq-(1), Consider after time $\underline{\underline{t}}$, the source has produced $\boxed{\omega t / 2\pi = f t}$ oscillations.



thus, the initial wave front has propagated away from the source through space to the distance $x$ to fit the same number of oscillations :

$$x = \left(\frac{\omega t}{2\pi}\right)\lambda$$

$$\frac{2\pi x}{\lambda} = \omega t$$

$$\boxed{Kx = \omega t}$$

thus the propagation velocity $v_p$ is

$$\boxed{v_p = \frac{x}{t} = \omega / K}$$

∵ the refractive index $n = \frac{c}{v_p}$

$$\therefore \boxed{v_p = \frac{c}{n}}$$

and since (n) for the plasma is less than 1 (i.e., $n_{plasma} < 1$).

# So the phase velocity for plasma waves is larger than the light velocity ----.??
this violate the theory of relativity.

# However, this does not violate the theory of relativity, because an infinitely long wave train of constant amplitude cannot carry information.

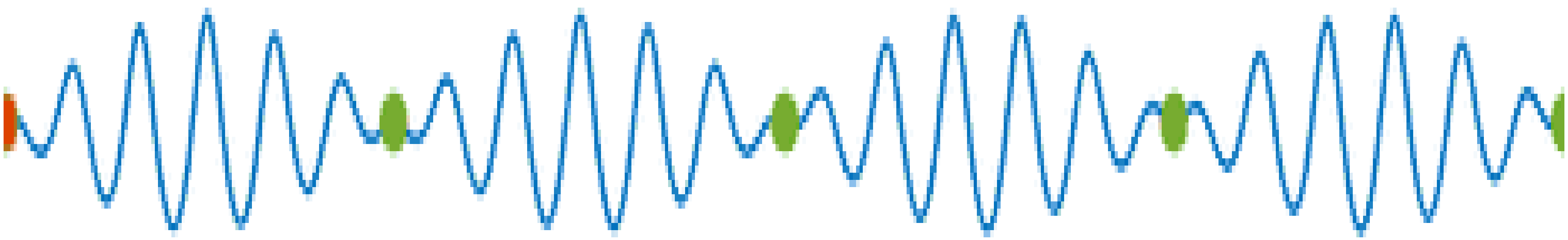
# the carrier of a radio wave, for instance, carries no information until it is modulated.

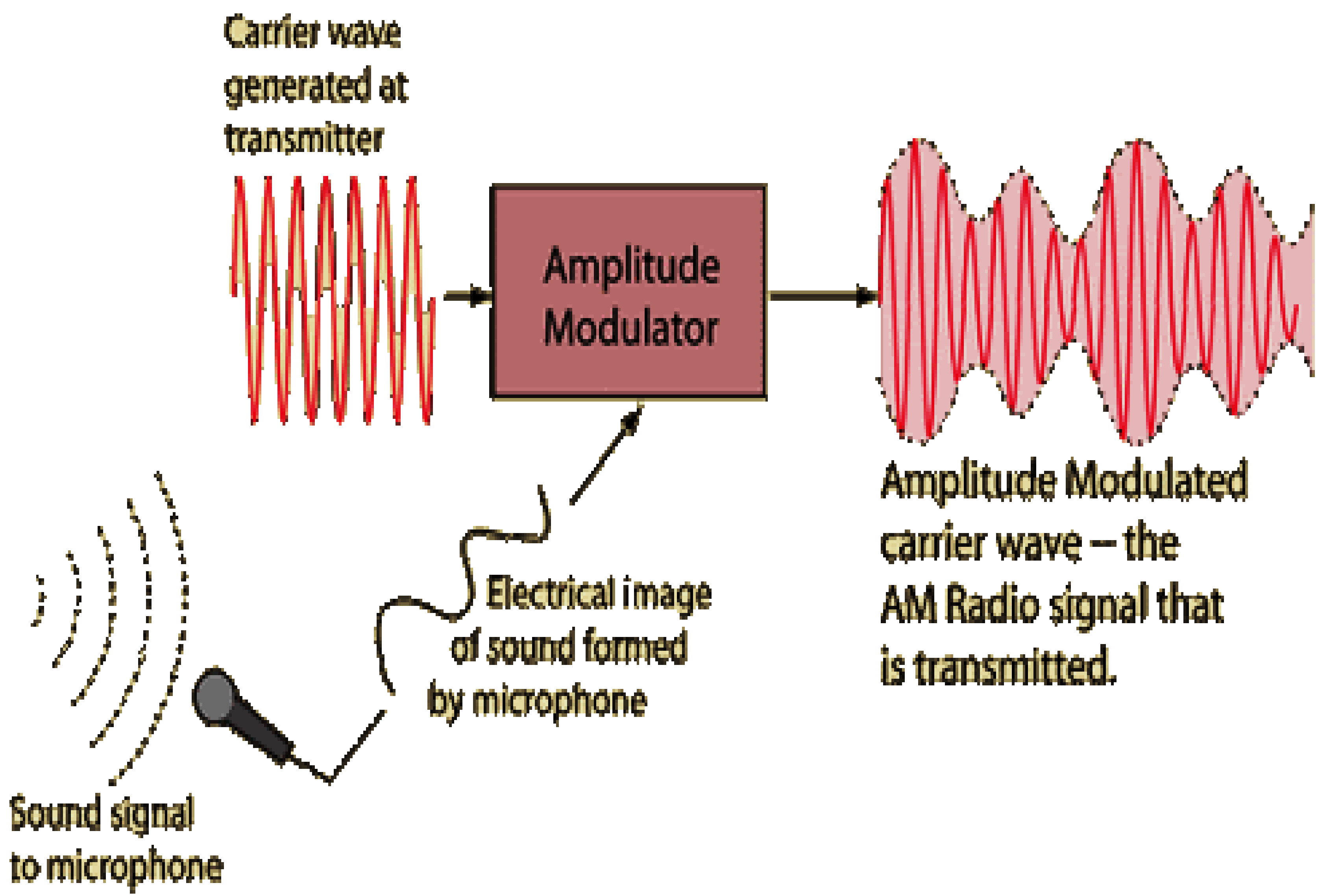
# the modulation information does not travel at the phase velocity but at the group velocity which is always less than $\underline{c}$.

Subject: 4 Date:

$$v_g = \frac{d\omega}{dK}$$ ; $v_g < v_p$

we can apply this concept to electron plasma waves.




Carrier wave generated at transmitter
Amplitude Modulator
Amplitude Modulated carrier wave – the AM Radio signal that is transmitted.
Electrical image of sound formed by microphone
Sound signal to microphone

# The concept of Modulation


Wait for me!