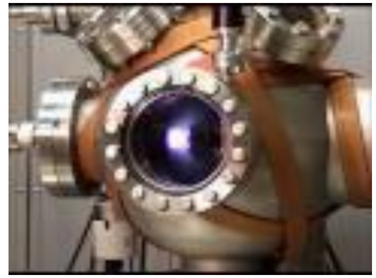
RF Capacitive Discharges

EE 403/503

Introduction to Plasma Processing

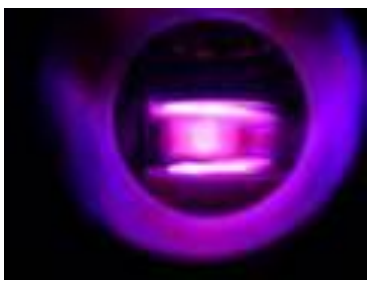
November 9, 2011

Indium Tin oxide sputtering 0:21



Sputtering Process Blue Wave Semiconductors 0:48

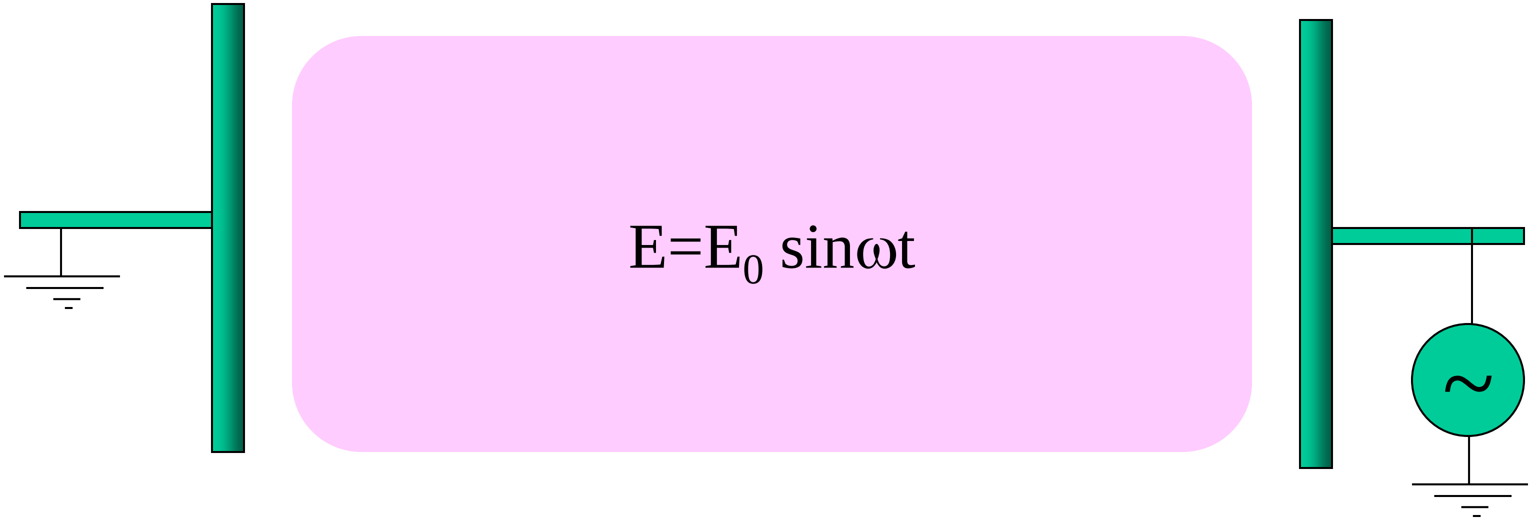
PVD Process 0:44



Evolution Plasma RF 3:11

Zolastar Coating Process 1:54

COATING OF OPTICAL LENS 0:21



$$m\dot{V} = -eE - mV\nu_c$$

<u>Collision frequency for the momentum transfer:</u>
Loss of electron momentum per second due to the scattering by inelastic collision with atoms or molecules

$$m\dot{V} = -eE_0 \sin 2\pi\nu t - mV\nu_c$$

$$m\dot{V} = -eE_0 \sin 2\pi\nu t - mV\nu_c$$

Solution:

Displacement Amplitude

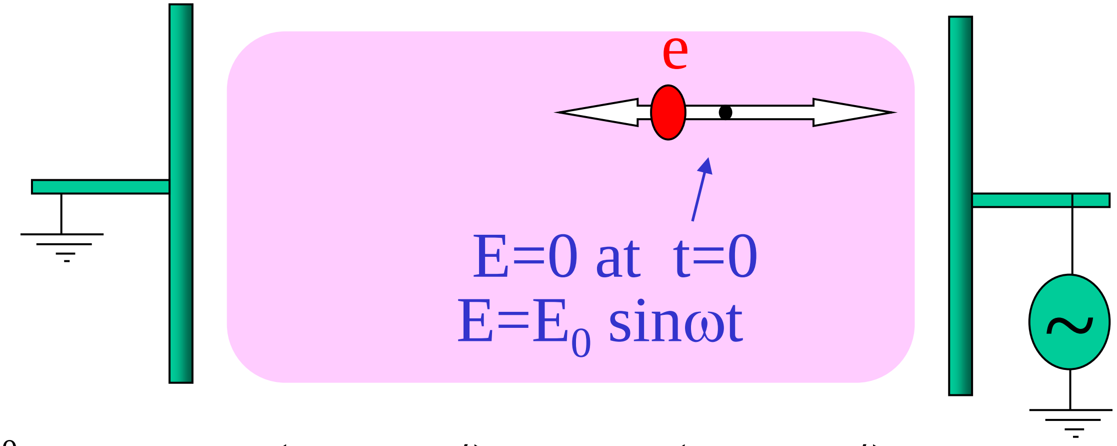
$$x = \frac{eE_0}{2\pi m\nu\sqrt{4\pi^2\nu^2 + \nu_c^2}} \sin(2\pi\nu t + \phi) = x_0 \sin(2\pi\nu t + \phi)$$

$$V = \frac{eE_0}{m\sqrt{4\pi^2\nu^2 + \nu_c^2}} \cos(2\pi\nu t + \phi)$$

$$\phi = \arctan\frac{\nu_c}{2\pi\nu}$$

← **Phase Shift**

v is superimposed with random motion



$$x = \frac{eE_0}{2\pi m\nu\sqrt{4\pi^2\nu^2+\nu_c^2}}\sin(2\pi\nu t+\phi) = x_0\sin(2\pi\nu t+\phi)$$

$$v = \frac{eE_0}{m\sqrt{4\pi^2\nu^2+\nu_c^2}}\cos(2\pi\nu t+\phi) = v_0\cos(2\pi\nu t+\phi)$$

$$\phi = \arctan\frac{\nu_c}{2\pi\nu}$$

$\nu_c \rightarrow 0$

$$\begin{cases} x_0 = \dfrac{eE_0}{4\pi^2 m\nu^2} \\ v_0 = \dfrac{eE_0}{2\pi m\nu} \\ \phi = 0 \end{cases}$$

$\nu_c >> \nu$

$$\begin{cases} x_0 = \dfrac{eE_0}{2\pi m\nu_c\nu} = \dfrac{\mu_e E_0}{2\pi\nu} \Rightarrow \boxed{x = x_0\cos 2\pi\nu t} \\ v_0 = \dfrac{eE_0}{m\nu} = -\mu_e E_0 \Rightarrow \boxed{v = -\mu_e E(t) = v_d} \\ \phi = \dfrac{\pi}{2} \end{cases}$$

ν=13.56 MHz p<10^{-2} Torr P>0.1 Torr

Power Coupling to the Plasma

$$x = \frac{eE_0}{2\pi m \nu \sqrt{4\pi^2 \nu^2 + \nu_c^2}} \sin(2\pi\nu t + \phi)$$

$$\phi = \arctan \frac{\nu_c}{2\pi\nu}$$

$$p = \frac{dW}{dt} = \frac{F_e dx}{dt} = eE_0 \sin(\omega t) \frac{dx}{dt}$$

For only one electron

$$\overline{P} = n_e \times \int_0^T p\,dt = \frac{e^2 n_e E_0^2}{2m} \frac{\nu_c}{(\omega^2 + \nu_c^2)}$$

Power absorbed

$$\overline{U} = \frac{1}{T}\int_0^T U\,dt = \frac{1}{T}\int_0^T \frac{1}{2}\varepsilon_0 E_0^2 \sin(\omega t)\,dt = \frac{1}{4}\varepsilon_0 E_0^2$$

Electrostatic Energy

$$\overline{P} = \overline{U} \frac{2\omega_p^2 \nu_c}{(\omega^2 + \nu_c^2)} = \overline{U}\nu^*$$

Energy Transfer Frequency

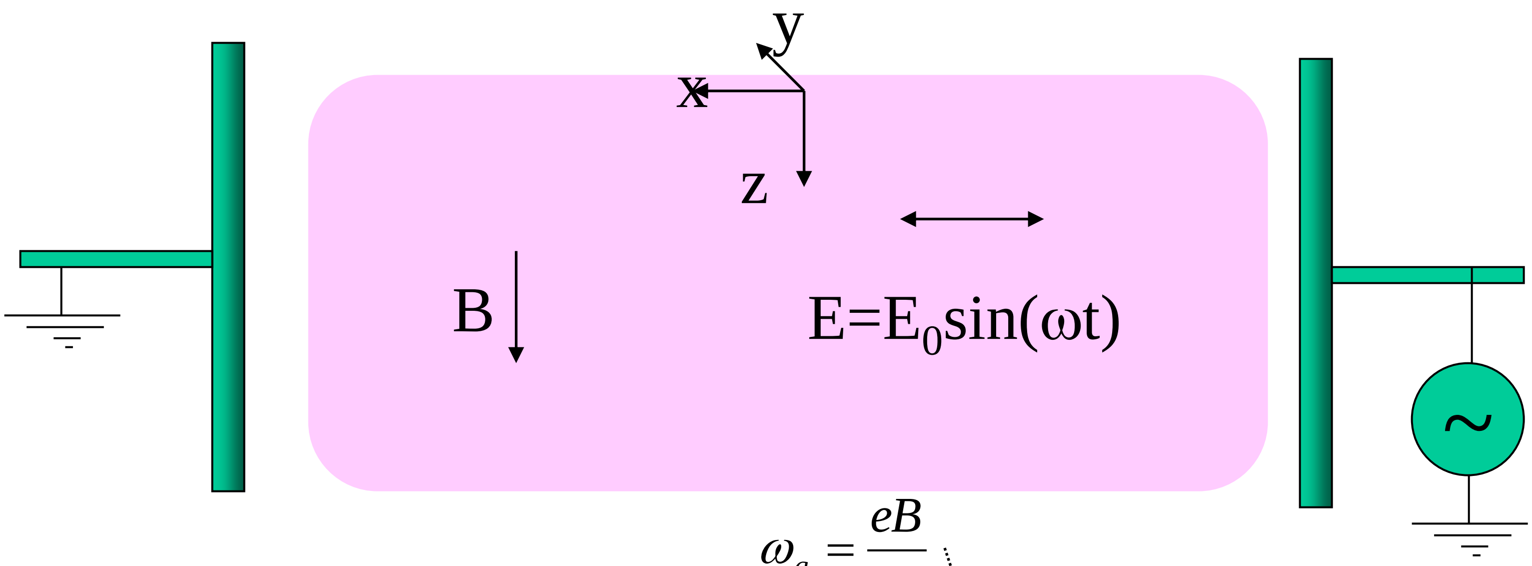
Optimum Power coupling to Plasma

$$\overline{P} = \overline{U}\,\frac{2\omega_p^2 \nu_c}{(\omega^2 + \nu_c^2)} = \overline{U}\,\nu^*$$

1- $\omega \rightarrow 0$ Best Coupling

$$\frac{d\nu^*}{d\nu_c} = \frac{2\omega_p^2}{(\omega^2 + \nu_c^2)}(\omega^2 - \nu_c^2) = 0 \Rightarrow \omega = \nu_c$$

Energy Coupling with Magnetized Plasmas



$$\omega_g = \frac{eB}{m}$$

$$m\dot{v} = -eE - e(v \times B) - mv\nu_c$$

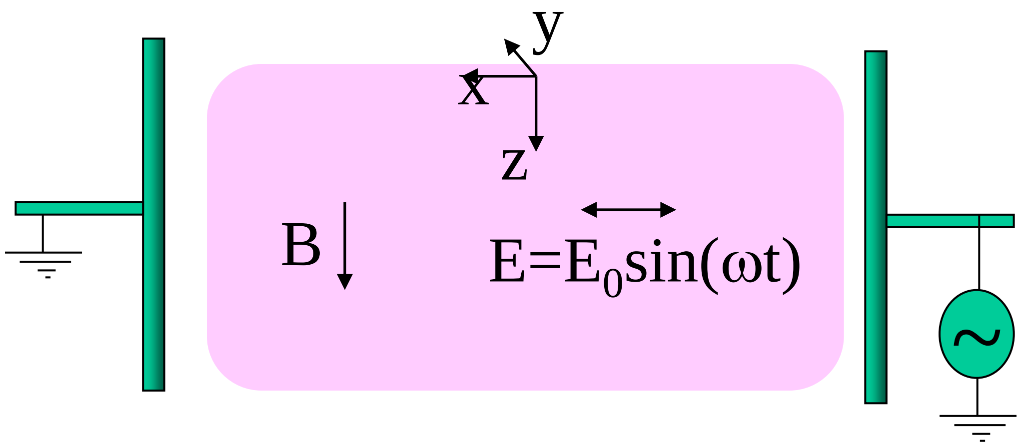
$$\begin{cases} \dfrac{d^2x}{dt^2} + \nu_c \dfrac{dx}{dt} + \omega_g \dfrac{dy}{dt} = -\dfrac{eE_0}{m}\sin\omega t \\ \dfrac{d^2y}{dt^2} + \nu_c \dfrac{dy}{dt} - \omega_g \dfrac{dx}{dt} = 0 \\ \dfrac{d^2z}{dt^2} + \nu_c \dfrac{dz}{dt} = 0 \end{cases}$$

Solution:

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

$$\frac{d^2y}{dt^2} + \nu_c \frac{dy}{dt} - \omega_g \frac{dx}{dt} = 0$$

$$\frac{d^2z}{dt^2} + \nu_c \frac{dz}{dt} = 0$$



$$\begin{cases} x = C_1 \sin\omega t + C_2 \cos\omega t \\ y = C_3 \sin\omega t + C_4 \cos\omega t \\ z = z_0 - \dfrac{v_{z_0}}{\nu_c}\exp(-\nu_c t) \xrightarrow[t \to \infty]{} z_0 \end{cases}$$

For C_1, C_2, C_3, and C_4 see equations 12.34-12.37.

Power Coupling to the Plasma (with B)

$$\overline{P} = \underbrace{\frac{1}{4}\varepsilon_0 E_0^2}_{\overline{U}} \times \underbrace{\frac{e^2 n_e}{\varepsilon_0 m}}_{\omega_p^2} \times \nu_c \left[\frac{1}{(\omega+\omega_g)^2+\nu_c^2} + \frac{1}{(\omega-\omega_g)^2+\nu_c^2} \right]$$

ν^* Energy transfer frequency

Low pressure

$$\nu_c << \omega_g \qquad \nu^* \approx 2\omega_p^2 \nu_c \left[\frac{(\omega^2+\omega_g^2)}{(\omega^2-\omega_g^2)^2} \right]$$

$$\nu_c >> \omega_g \qquad \nu^* \approx 2\omega_p^2 \nu_c \left[\frac{1}{(\omega^2+\nu_c^2)} \right]$$

High pressure

$$\nu_{Plasma} = 8.98\sqrt{n_e}$$

$$\omega_{gyro} = 2.8\times 10^{10} B$$

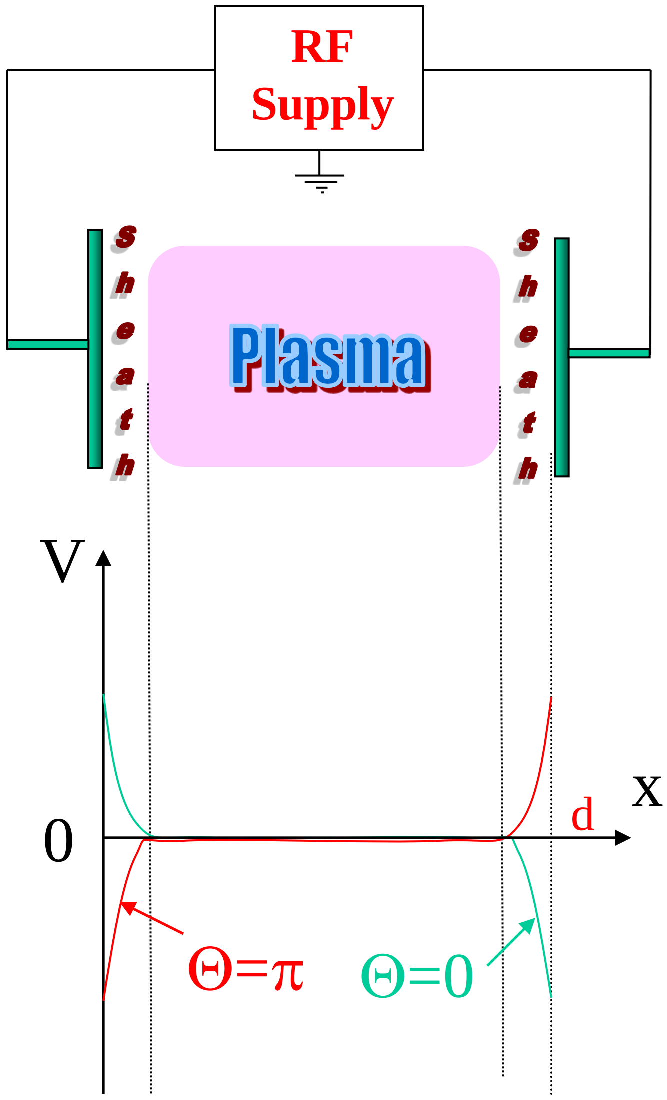
Optimum Power coupling to Plasma (with B)

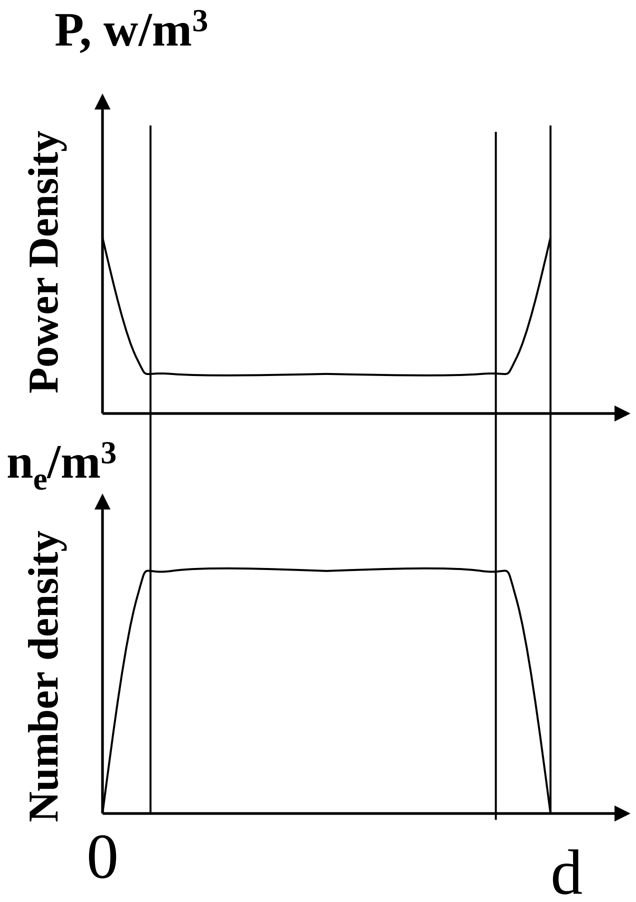
$$\nu^* = \omega_p \times \nu_c \left[\frac{1}{(\omega + \omega_g)^2 + \nu_c} + \frac{1}{(\omega - \omega_g)^2 + \nu_c} \right]$$

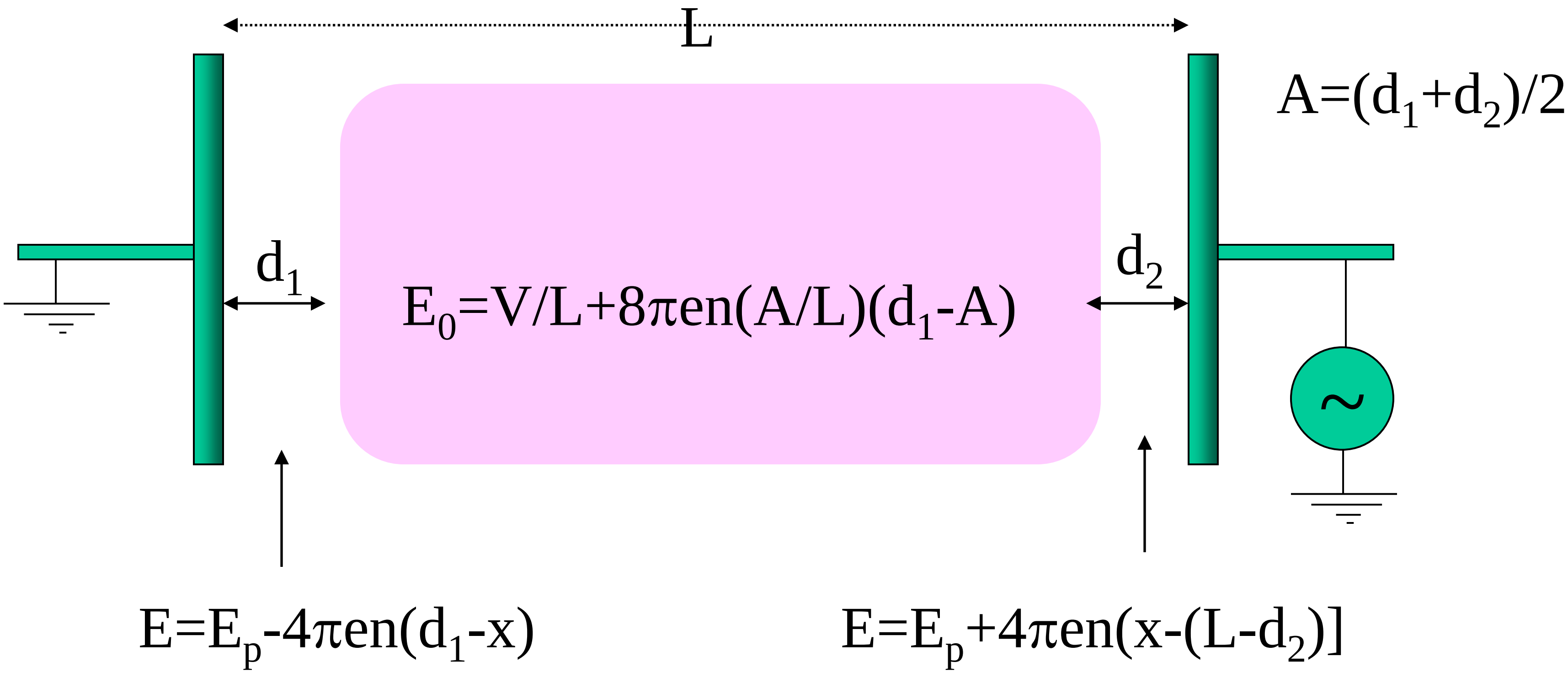
$$\frac{d\nu^*}{d\omega_g} = 0 \Rightarrow \omega_{g,opt} \approx \omega \left(1 - \frac{\nu_c^4}{\omega^2} \right)^{1/2} \approx \omega \qquad \omega \geq \frac{\nu_c}{\sqrt{3}}$$

$$\frac{d\nu^*}{d\omega} = 0 \Rightarrow \omega_{opt} \approx \omega_g \left(1 - \frac{\nu_c^4}{\omega_g^4} \right)^{1/2} \approx \omega_g \qquad \begin{cases} \omega \geq \frac{\nu_c}{\sqrt{3}} \\ \nu << \nu_g \end{cases}$$

$$\frac{d\nu^*}{d\nu_c} = 0 \Rightarrow \nu_{c,opt} = \sqrt{(\omega^2 - \omega_g^2)}$$


RF
Supply
sheath
Plasma
sheath
V
0
X
d
Θ=π
Θ=0

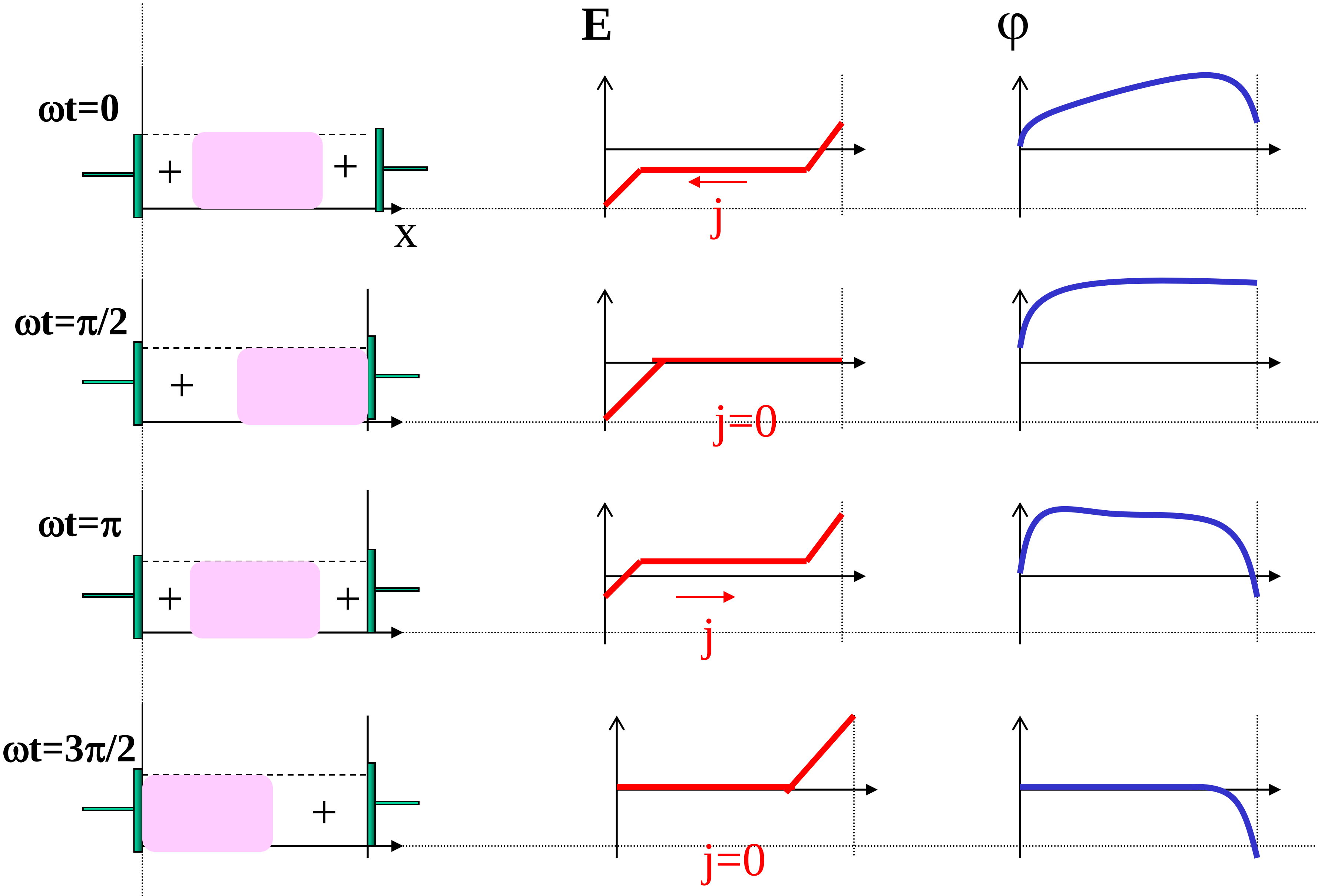

P, w/m3
Power Density
ne/m3
Number density
0
d



$$m\dot{v} = -eE_0 \sin 2\pi\nu t - mv\nu_c$$

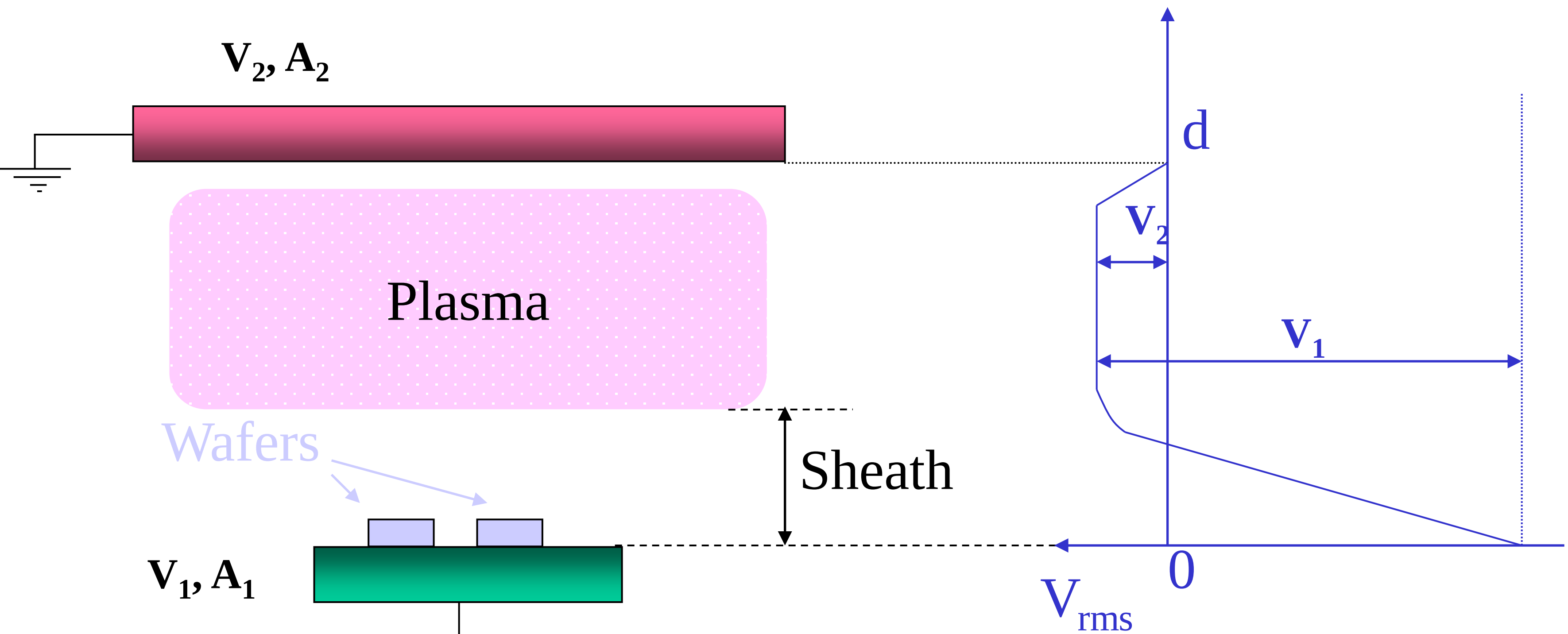
Solution for E_p

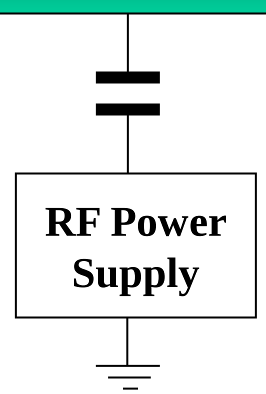
$$E_p = \frac{V_0 e^{i\omega t}}{L} \frac{\omega^2 - i\omega\nu_c}{\omega^2 - \omega_p^2 2A/L - i\omega\nu_c}$$



E
φ
ωt=0
+
+
x
j
ωt=π/2
+
j=0
ωt=π
+
+
j
ωt=3π/2
+
j=0

Reactive Ion Etching





$$I_1 = I_2$$

$$A_1 e n_{i1} v_{i1} = A_2 e n_{i2} v_{i2}$$

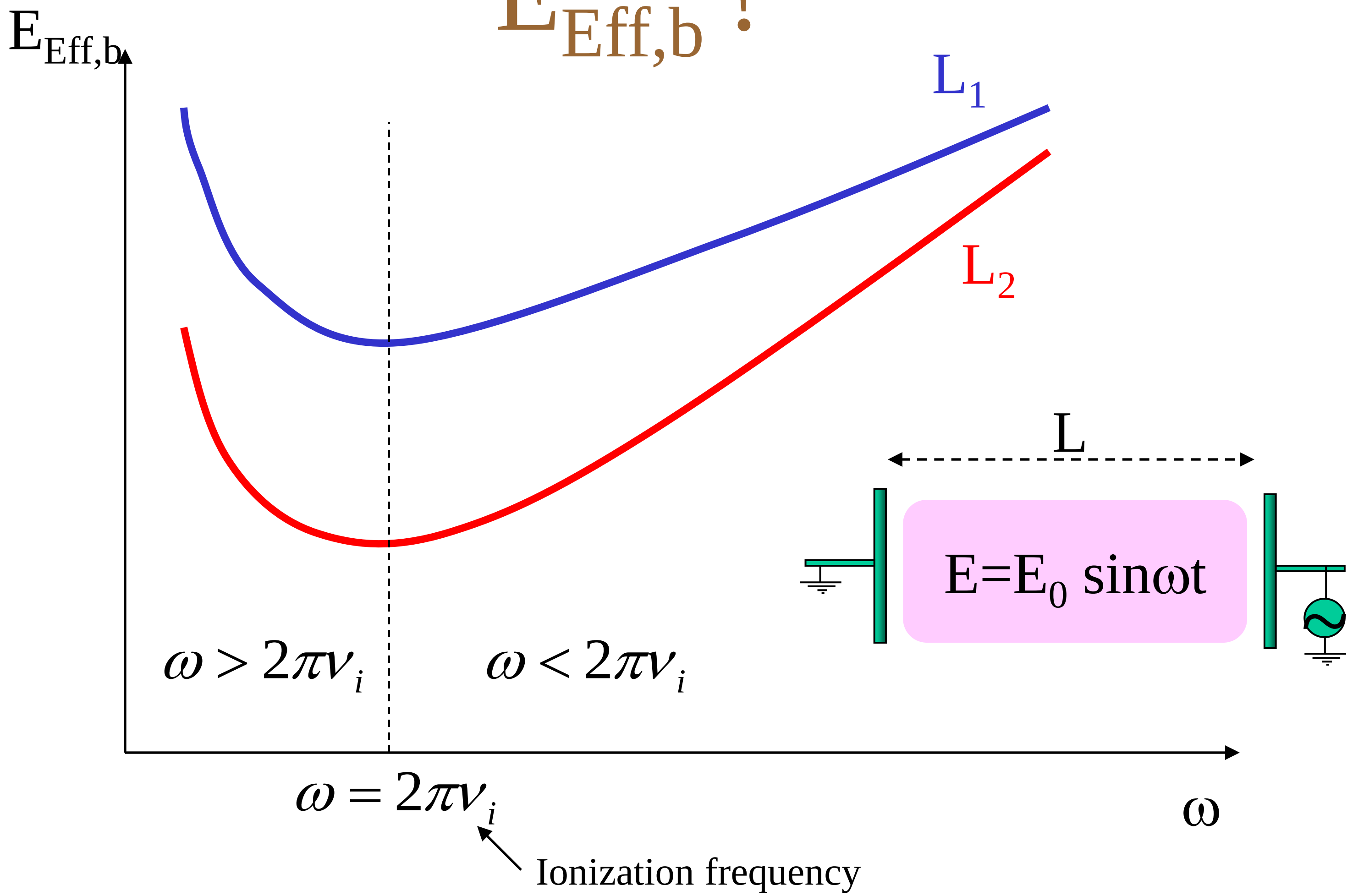
$$A_1 e n_{i1} \sqrt{\frac{2eV_1}{m_i}} = A_2 e n_{i2} \sqrt{\frac{2eV_2}{m_i}}$$

$$eV = \frac{1}{2} m v^2 \Rightarrow v = \sqrt{\frac{2eV}{m}}$$

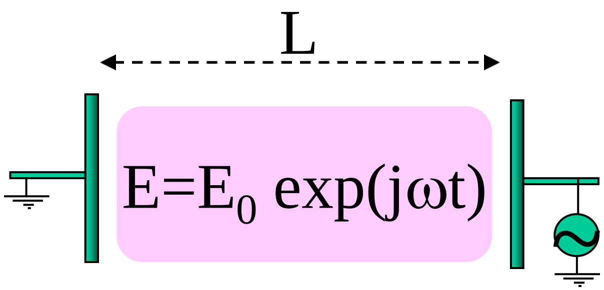
$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^2 \Rightarrow \frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^q \Leftrightarrow 1.0 \le q \le 2.5$$

Breakdown in RF Capacitive Discharges

$E_{Eff,b}$?



E_{eff} ?



$$P = jE = n_e e v E = n_e e \mu E^2$$

$$m\dot{V} = -eE - mV\nu_c$$

$$V = \frac{-e}{m_e(\nu_c + j\omega)} E_0 e^{-j\omega t} + Ce^{-\nu_c t}$$

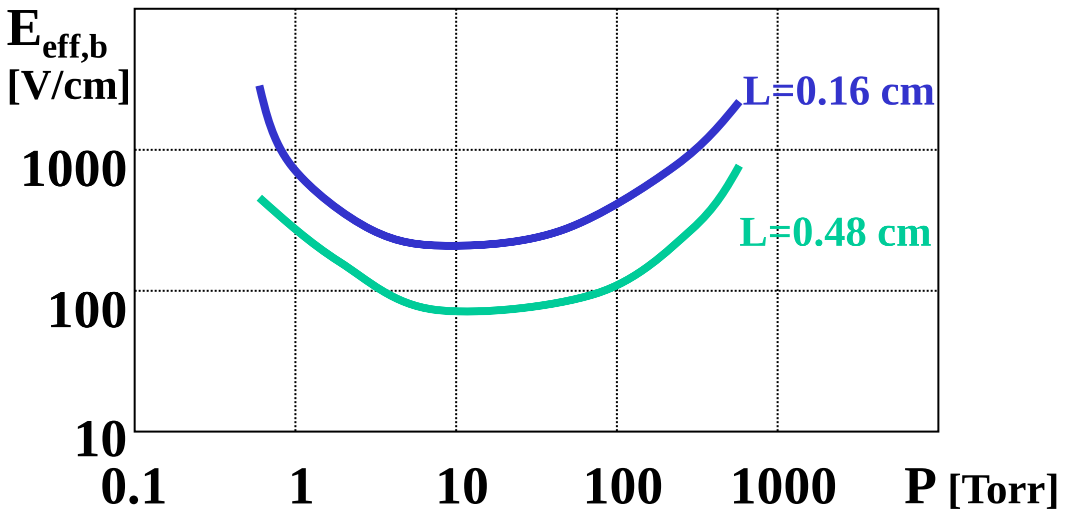
$$Ce^{-\nu_c t} \xrightarrow[t \to \inf]{} 0$$

$$\mu_e = \frac{e\nu_c}{m_e(\nu_c^2 + \omega^2)} - j\frac{e\omega}{m_e(\nu_c^2 + \omega^2)}$$

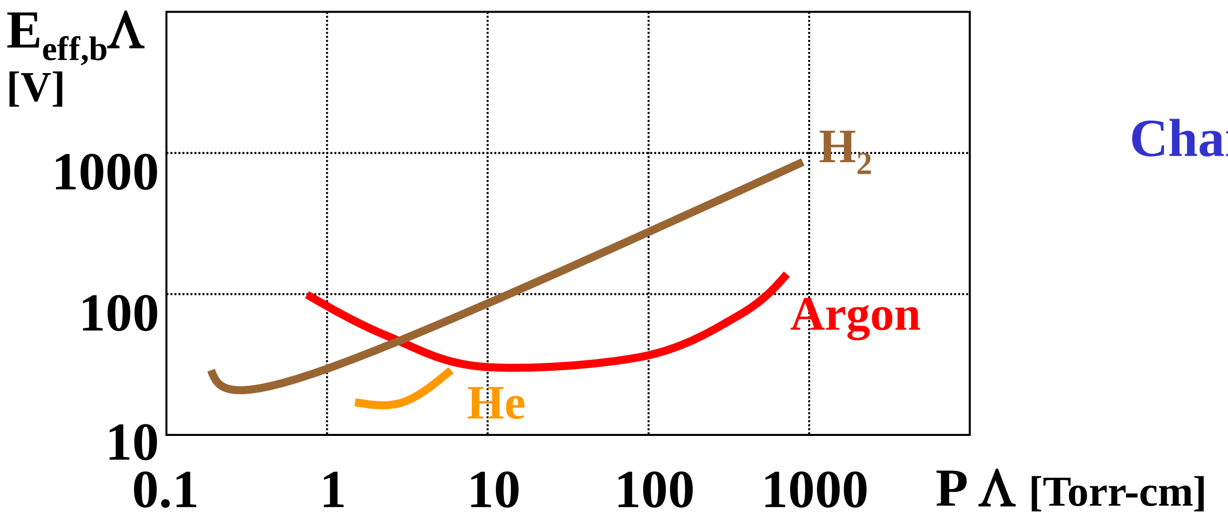
$$\Re e(\mu_e)$$

$$E_{eff}^2 = \frac{\nu_c^2}{\nu_c^2 + \omega^2} E^2$$

Argon



$$E_{eff}^2 = \frac{\nu_c^2}{\nu_c^2 + \omega^2} E^2$$

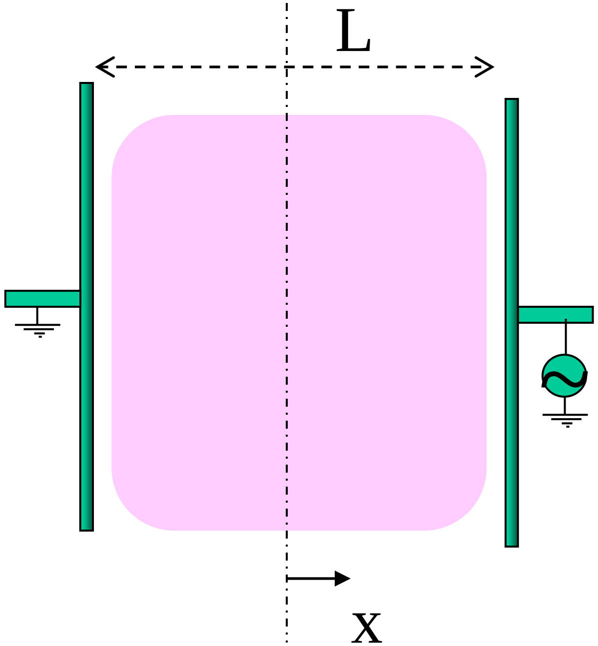


Λ ???

Characteristic Length

Condition for Breakdown:

Power input > losses



Loss Mechanism:

1- Diffusion → $\vec{S}_e = -D_e \nabla n_e$ **Fick's Law**

2- Volume Recombination

3- Electron Attachment

} **Negligible here**

Steady State

$$\frac{\partial n_e}{\partial t} = \nu_i n_e + n_a - \nabla \cdot \vec{S}_e$$

ionization

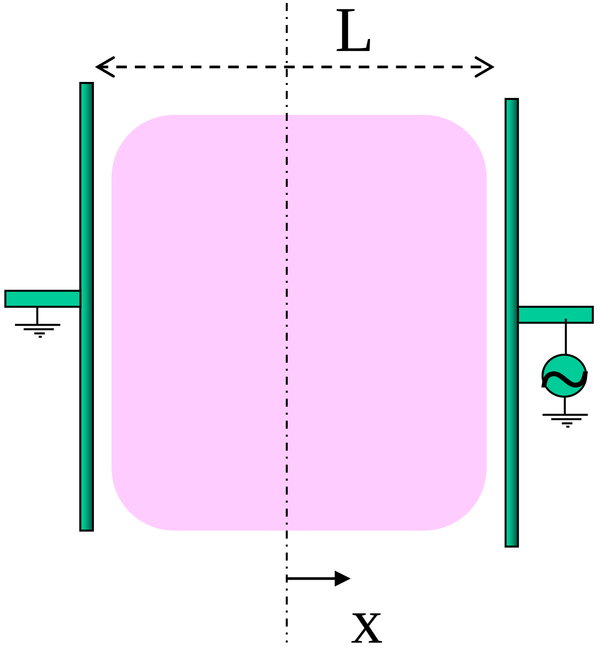
Charge Generation per second (External cause)

n_e=0 at $x = \pm \frac{L}{2}$

Solution

$$n_e = \frac{n_a}{\nu_i}\left\{\frac{\cos\sqrt{\frac{\nu_i}{D_e}}\,x}{\cos\sqrt{\frac{\nu_i}{D_e}}\,\frac{L}{2}} - 1\right\}$$

$$n_e = \frac{n_a}{\nu_i}\left\{\frac{\cos\sqrt{\frac{\nu_i}{D_e}}x}{\cos\sqrt{\frac{\nu_i}{D_e}}\frac{L}{2}} - 1\right\}$$



Condition for breakdown:

$$n_e \rightarrow \infty$$

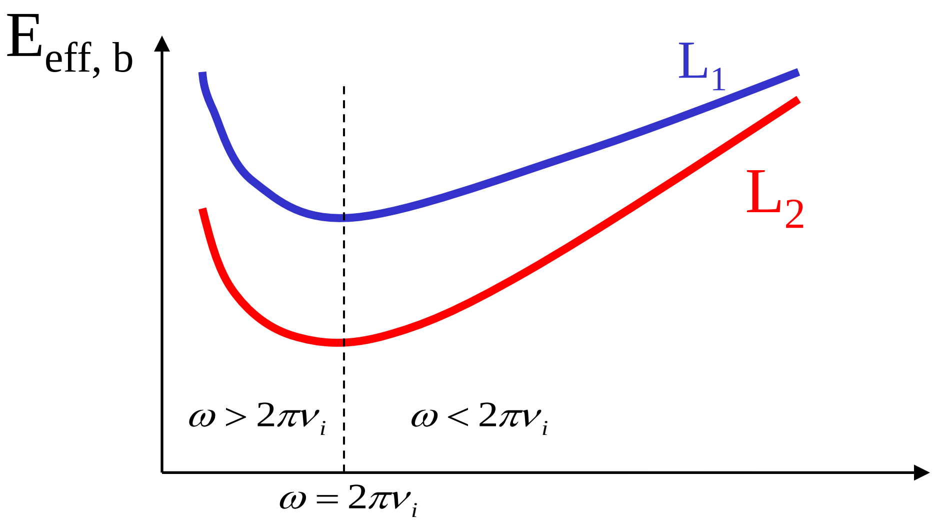
$$\cos\sqrt{\frac{\nu_i}{D_e}}\frac{L}{2} \rightarrow 0 \Rightarrow \sqrt{\frac{\nu_i}{D_e}}\frac{L}{2} = (2n+1)\frac{\pi}{2}$$

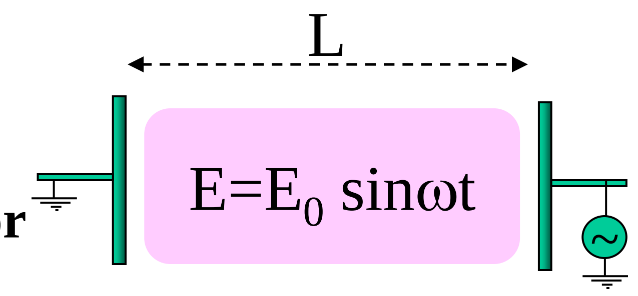
Summary

1- RF to plasma coupling is very poor at low pressure.

2- At higher pressures, the electron must acquire energy such that $e\lambda_e E_{Eff, b} > \chi_I$ for ionization but λ_e decreases with increasing pressure.

3- The minimum field requirement occurs at $2\pi\nu_i = \omega$. This point is the most favorable coupling point.





4- The volume to surface ratio increases with increasing L and a more favorable balance for charge carriers and a smaller field is permissible.

5- $E_{Eff, b} < E_{DC, b}$ since the lifetime of the electron in a RF field is much greater than in a dc discharge. More collisions are possible and the field strength required for breakdown is decreased.