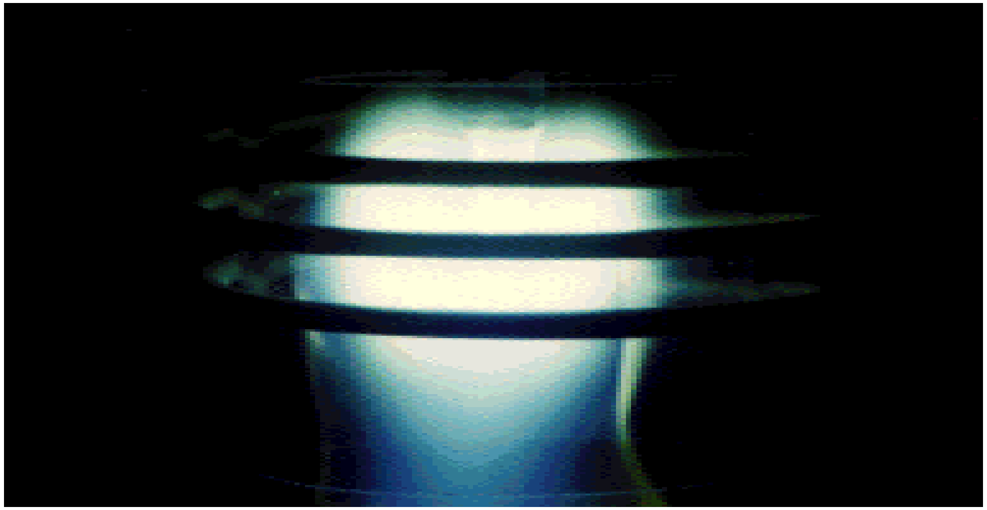
RF Inductive Discharges



EE 403/503

Introduction to Plasma Processing

November 2, 2011

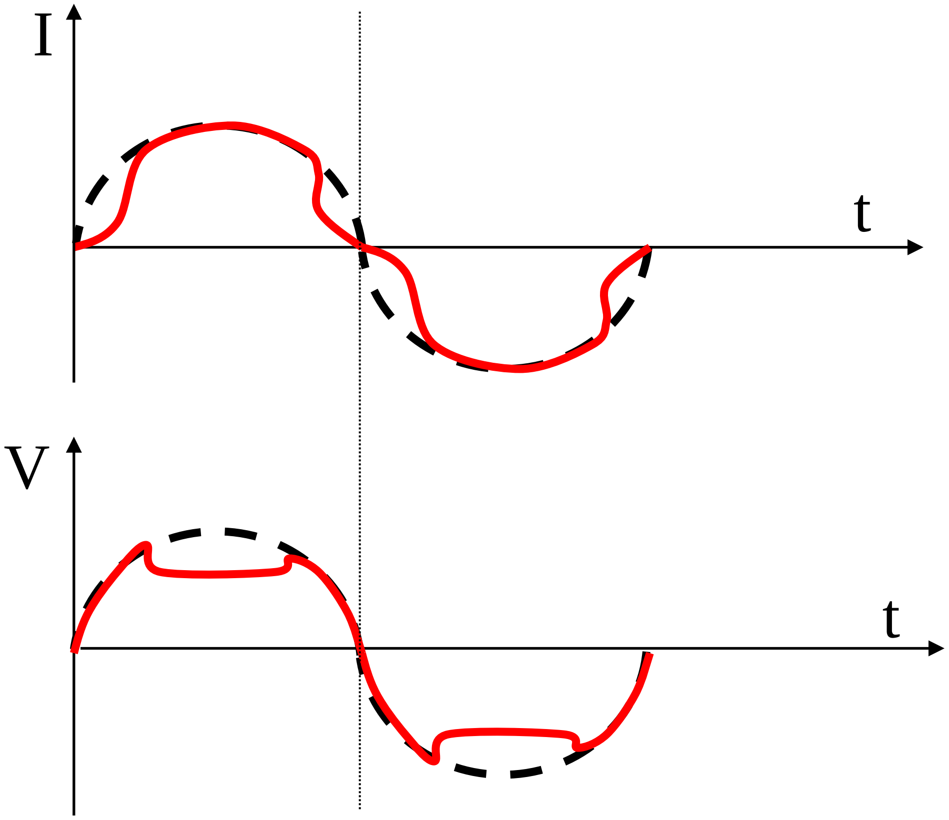
Outline

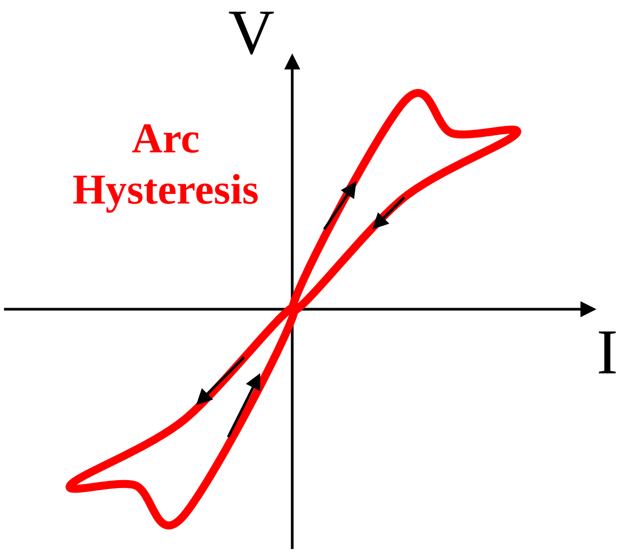
1- RF Inductive Discharge

2- RF Capacitive Discharge

3- MW Discharge (quasi-optical)

AC Arc

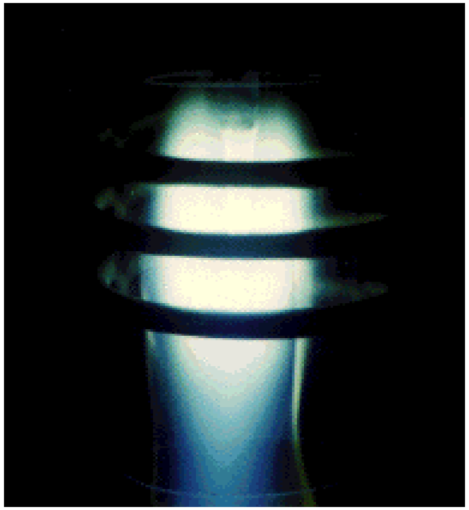




The arc extinguishes at V=0 but the remaining ions reignite the arc at relatively low breakdown voltage.
Very high frequency eliminate the arc hysteresis.

RF Discharges

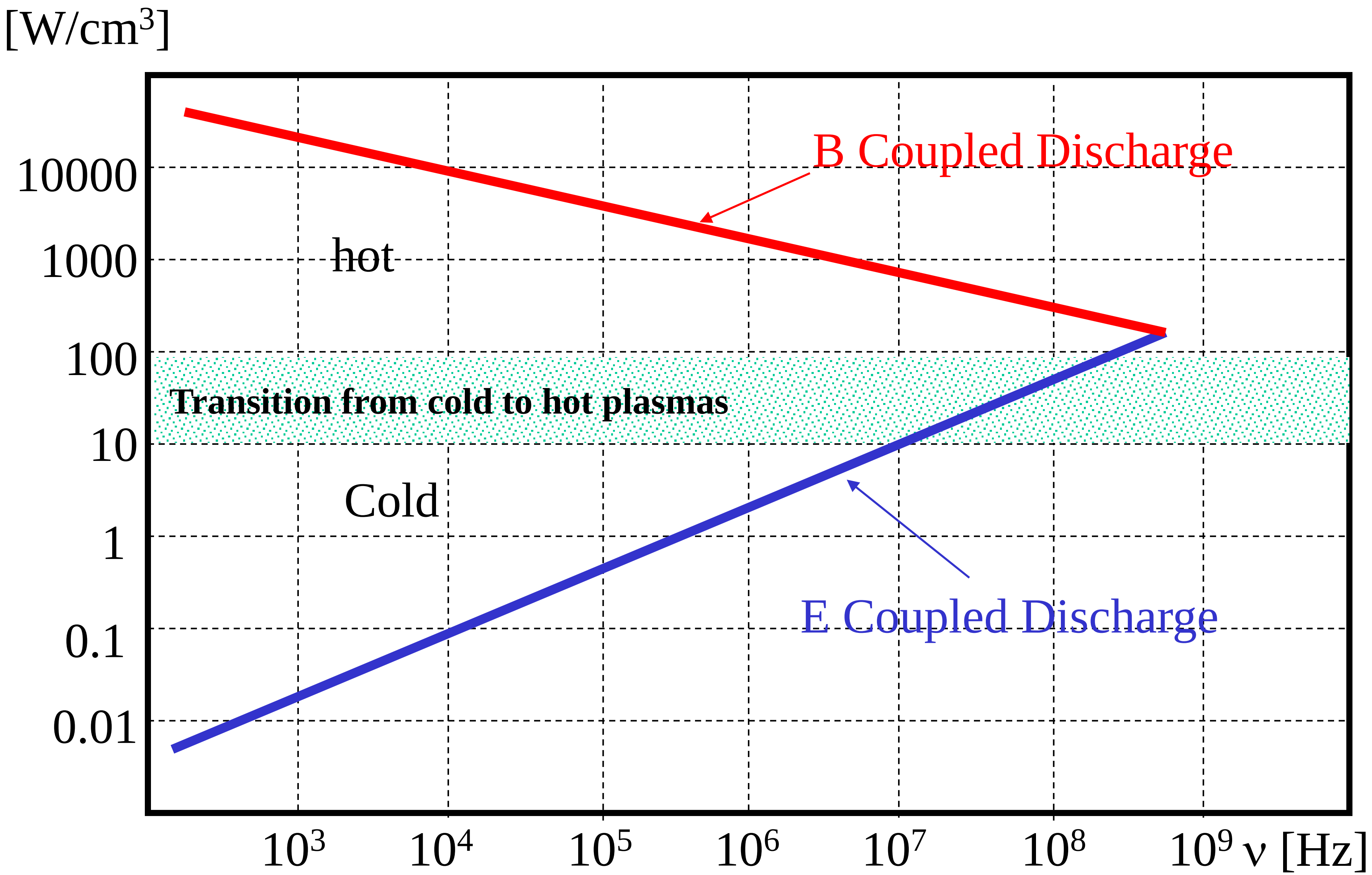
(10 KHz-30MHz)



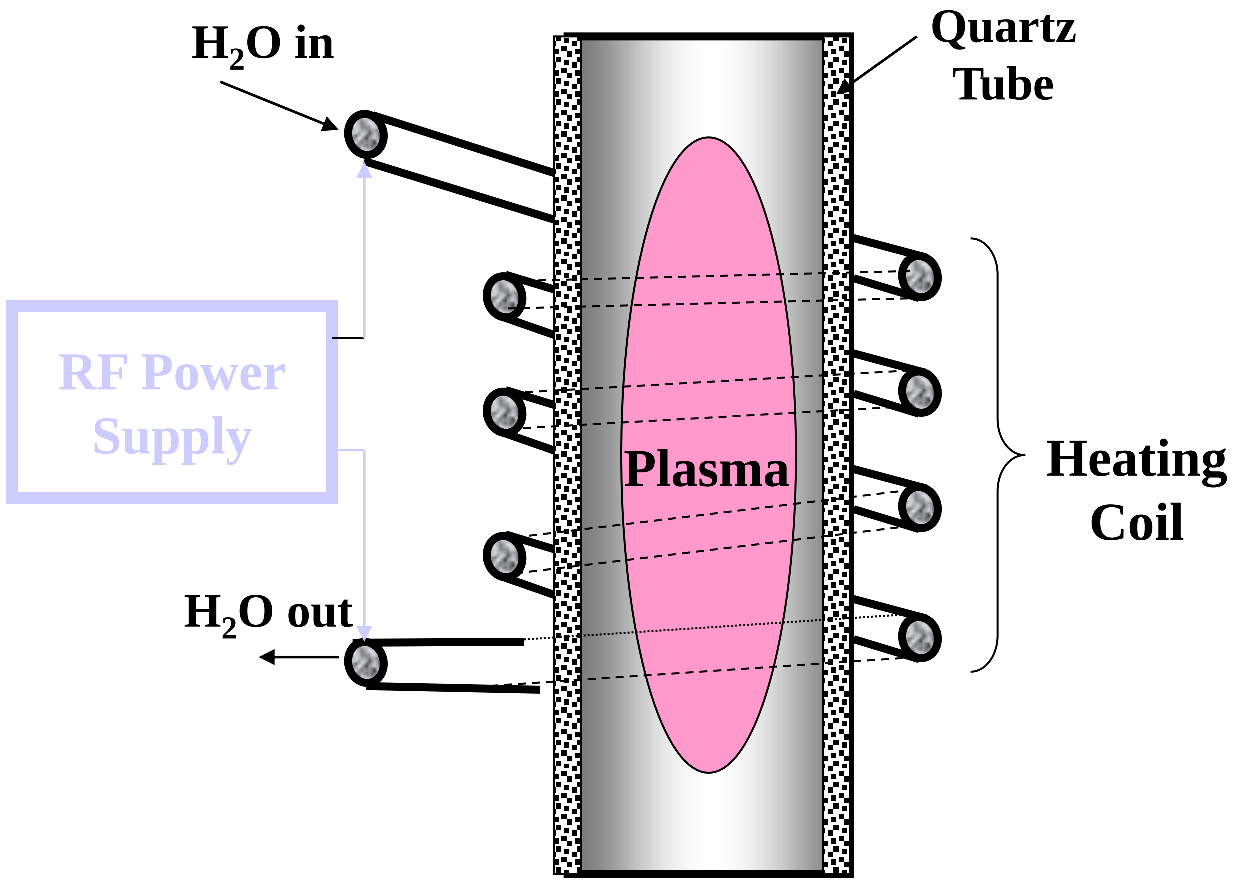
Inductive Coupling

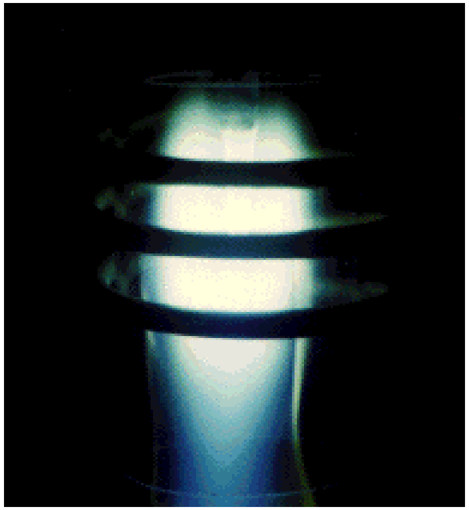
Capacitive Coupling

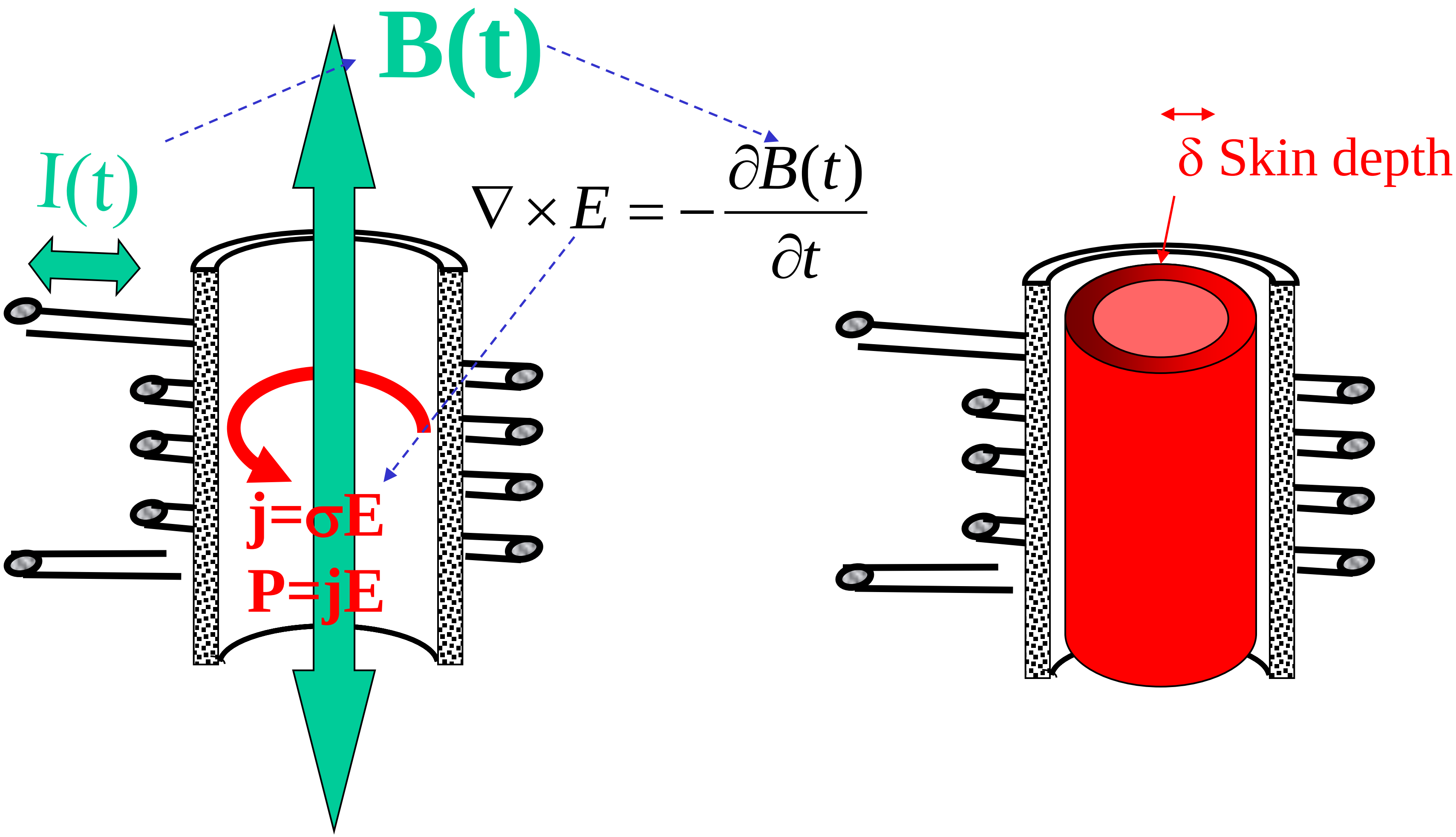
Special Types of RF Discharges



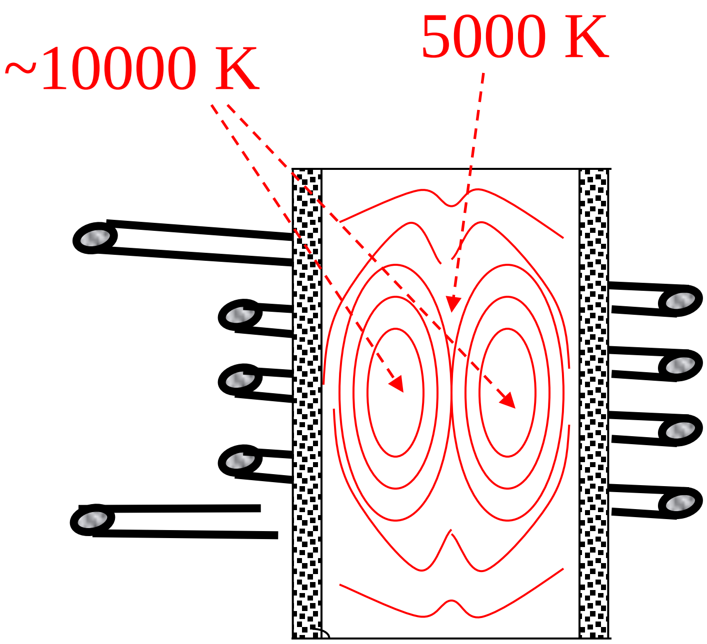
RF Inductive Plasmas

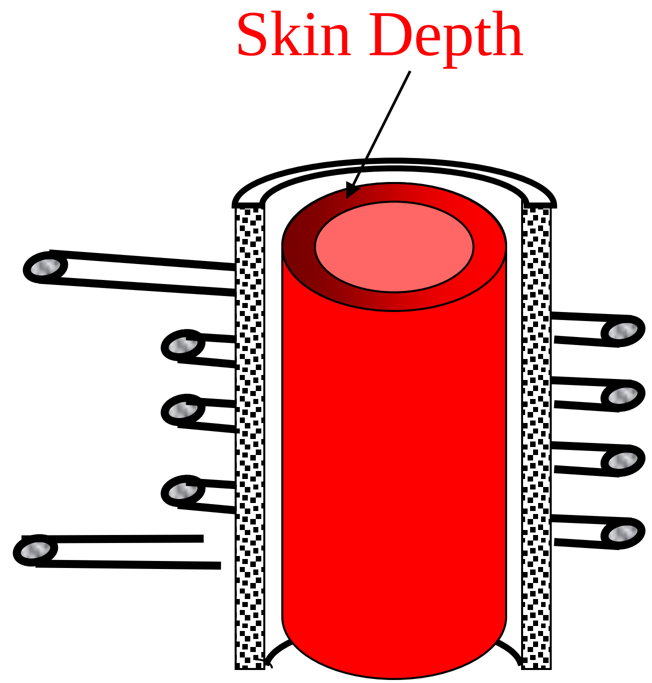




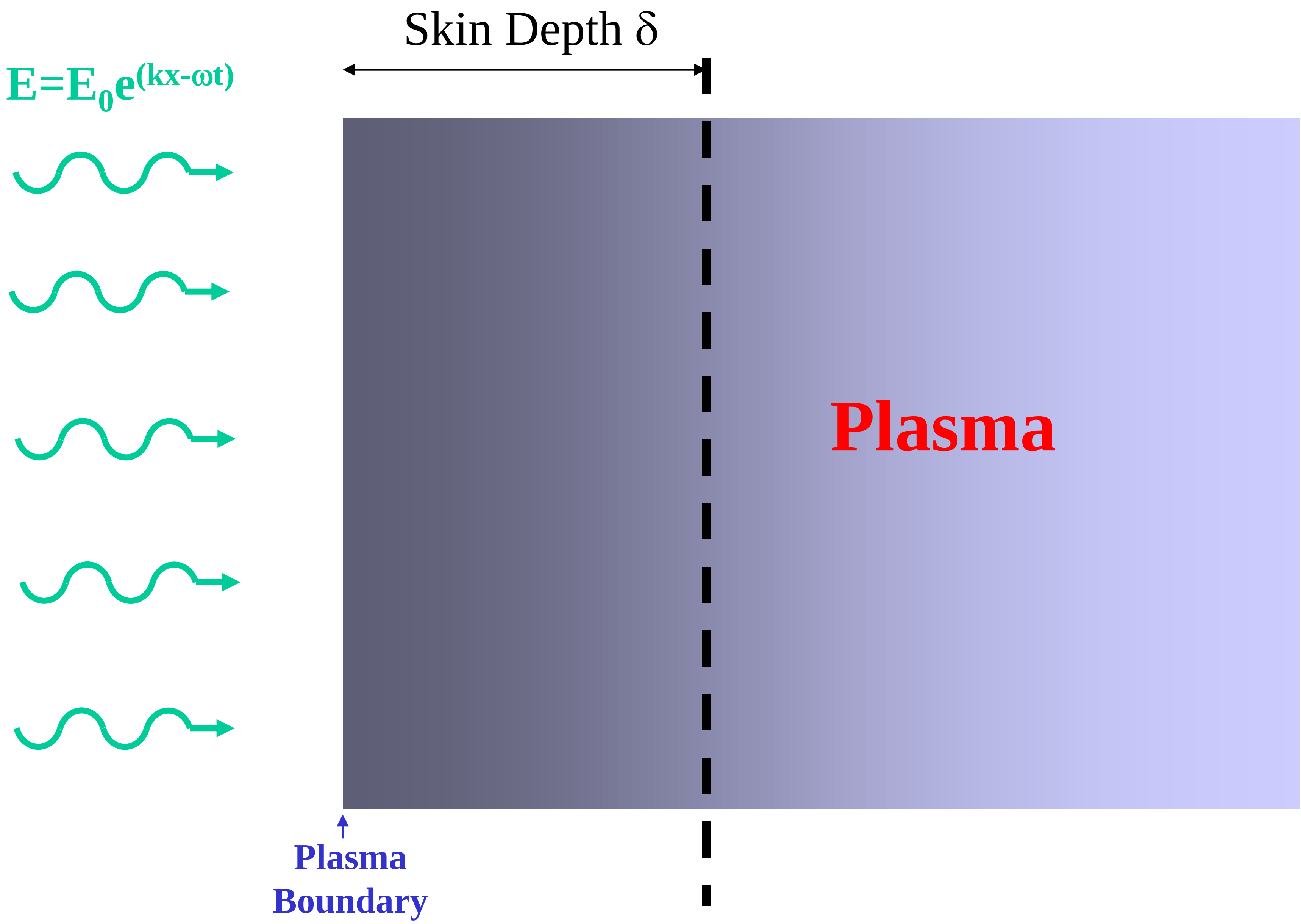


RF Discharge


~10000 K
5000 K


Skin Depth

EM Wave Plasma Interaction



Background I

Maxwell's Equations

$$D = \varepsilon_0 E + \cancel{P}$$
$$B = \mu_0 (H + \cancel{M})$$

$$\nabla \cdot D = \rho$$
$$\nabla \cdot B = 0$$
$$\nabla \times E = -\frac{\partial B}{\partial t}$$
$$\nabla \times H = j + \frac{\partial D}{\partial t}$$

$$\nabla \cdot E \approx 0$$
$$\nabla \cdot B = 0$$
$$\nabla \times E = -\frac{\partial B}{\partial t}$$
$$\nabla \times B = \mu_0 j + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

$$j = \sigma E$$

$\nabla \times$

$$\nabla \times (\nabla \times E) = \nabla(\nabla . E) - \nabla^2 E \sim -\nabla^2 E$$

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

$$\nabla^2 E = \mu_0 \sigma \frac{\partial E}{\partial t} + \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2}$$

$$\nabla^2 E = \mu_0 \sigma \frac{\partial E}{\partial t} + \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2}$$

One Dimensional

$$E = E_0 e^{[i(kx - \omega t)]}$$

$$\frac{\partial^2 E}{\partial x^2} - \mu_0 \sigma \frac{\partial E}{\partial t} - \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2} = 0$$

$$(k^2 + i\omega\mu_0\sigma + \mu_0\varepsilon_0\omega^2)E = 0$$

$$c = \sqrt{\frac{1}{\varepsilon_0 \mu_0}}$$

$$k^2 = \left(\alpha + \frac{i}{\delta}\right)^2 = \frac{\omega^2}{c^2} + i\frac{\omega\sigma}{c^2\varepsilon_0}$$

$$k = \sqrt{\frac{\sigma\mu_0\omega}{2}}\left[\frac{\omega\varepsilon_0}{\sigma} - \sqrt{1 + \left(\frac{\omega\varepsilon_0}{\sigma}\right)^2}\right]^{1/2} + i\sqrt{\frac{\sigma\mu_0\omega}{2}}\left[\sqrt{1 + \left(\frac{\omega\varepsilon_0}{\sigma}\right)^2} - \frac{\omega\varepsilon_0}{\sigma}\right]^{1/2}$$

Oscillation of EM field

Damping of EM in surface layer; $\left(= \frac{1}{\delta}\right)$

Skin Depth

$$k = \sqrt{\frac{\sigma\mu_0\omega}{2}}\left[\frac{\omega\varepsilon_0}{\sigma} - \sqrt{1+\left(\frac{\omega\varepsilon_0}{\sigma}\right)^2}\right]^{1/2} + i\sqrt{\frac{\sigma\mu_0\omega}{2}}\left[\sqrt{1+\left(\frac{\omega\varepsilon_0}{\sigma}\right)^2} - \frac{\omega\varepsilon_0}{\sigma}\right]^{1/2}$$

Damping of EM in surface layer; $\left(=\frac{1}{\delta}\right)$

$$\frac{\omega\varepsilon_0}{\sigma} << 1$$

In most Industrial Plasmas

$$\sigma = \frac{e^2 n_e}{m_e \nu_c} = \frac{\varepsilon_0 \omega_p^2}{\nu_c}$$

Electrical Conductivity

$$\delta = 3\times 10^6 \sqrt{\frac{\nu_{collision}}{n_e \nu_{Power}}} \quad (m)$$

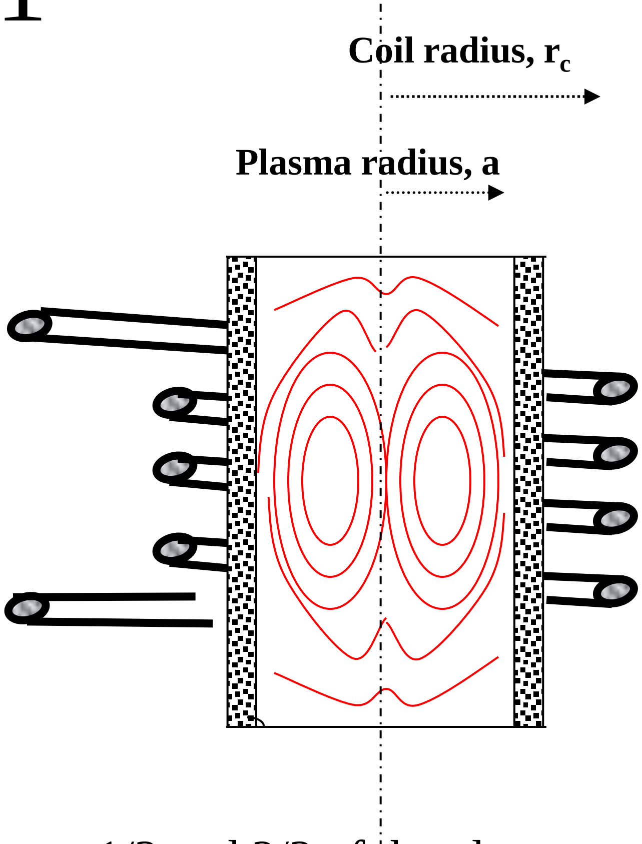
Energy Coupling Parameter η_c

$$\left(\eta_c = \frac{\text{Discharge Power}}{\text{Reactive Power}}\right)$$

$$0 \leq \eta_c \leq 1$$

$$\eta_c \equiv f\left(\frac{a}{r_c}, \kappa\right)$$

Coupling parameter $\kappa \equiv \sqrt{2}\,\frac{a}{\delta}$



Maximum power transfer: when skin depth (δ) is between 1/3 and 2/3 of the plasma radius or κ is between approximately 2 to 4.

Background II

$$\nu_{Power}$$

$$\nu_{Plasma} = 8.98\sqrt{n_e}$$ ← $1/m^3$

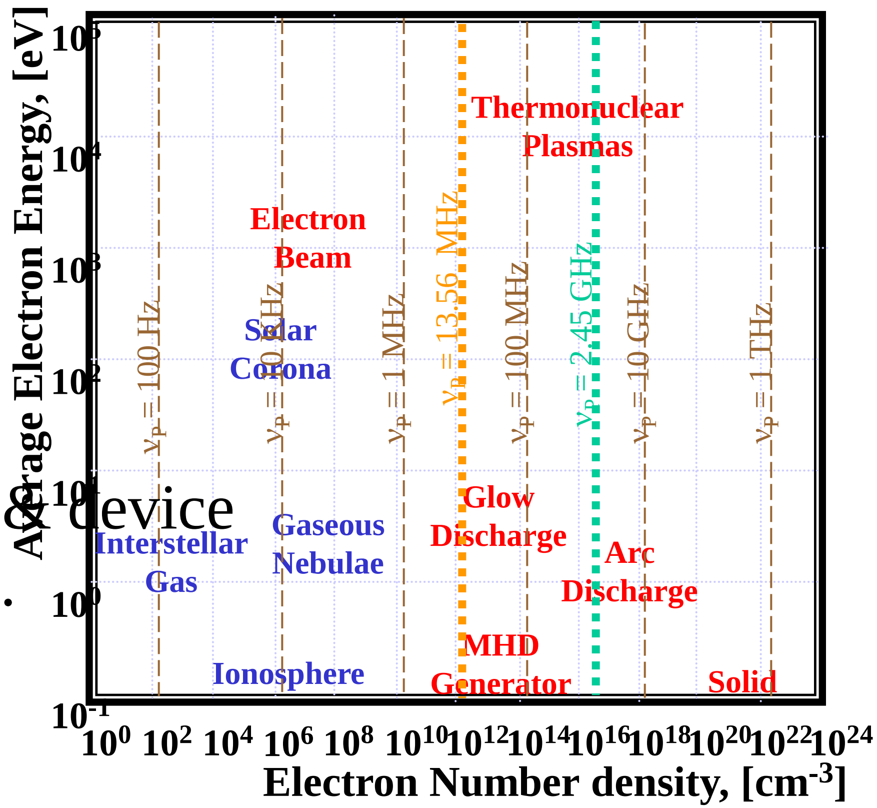
$$\nu_{gyro} = 2.8\times10^{10} B$$ ← Tesla

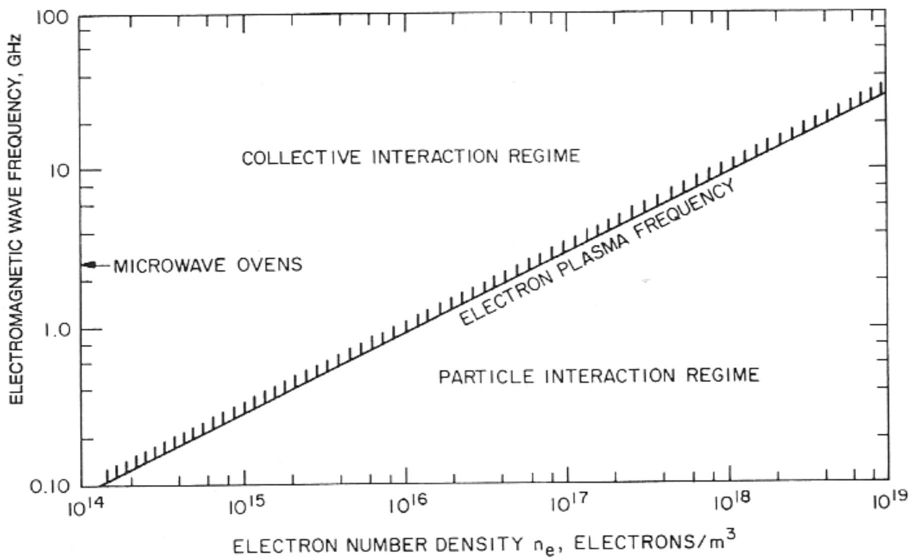
$$\nu_{collision} = 2.8\times10^{-8}\times\frac{n_e}{\sigma_{cond}}$$

Plasma properties & device properties missing.

Energy transfer frequency $\left(p = \sigma E^2 = \frac{1}{2}\varepsilon_0 E^2 \nu^*\right)$

$$\nu^* = \frac{8\pi^2\nu_{Plasma}^2}{\nu_{colission}} = \frac{2\sigma_0}{\varepsilon_0}$$





The electron plasma frequency, in gigahertz, as a function of the electron number density in electrons per cubic meter. In the particle interaction regime, below the electron plasma frequency, individual electrons can respond to the electric field of the electromagnetic wave; above the electron plasma frequency, the inertia of the individual electrons causes them to respond collectively.

Particle interaction Regime

(Absorption or Reflection)

$$\nu_{Power} < \nu_{Plasma}$$

Magnetized Plasma

$$\nu_{gyro} < \nu_{Plasma}$$

Collective Interaction Regime

(Interaction weak)

$$\nu_{Power} > \nu_{Plasma}$$

$$\nu_{gyro} > \nu_{Plasma}$$

GEC Reference Cell