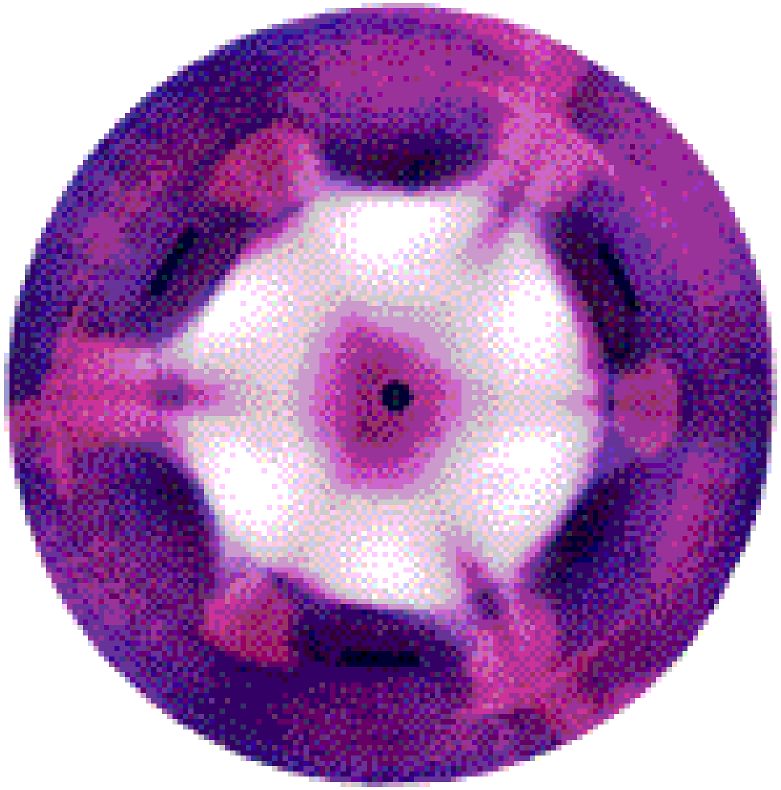
MW Discharges



EE 403/503

Introduction to Plasma Processing

November 9, 2011

$T_{e,MW}$ > $T_{e,RF}$ & $T_{e, DC}$

(5-15 eV) (1-2 eV)

0.915* GHz 2.45* GHz 300 GHz

33 cm 12.24 cm 1 mm

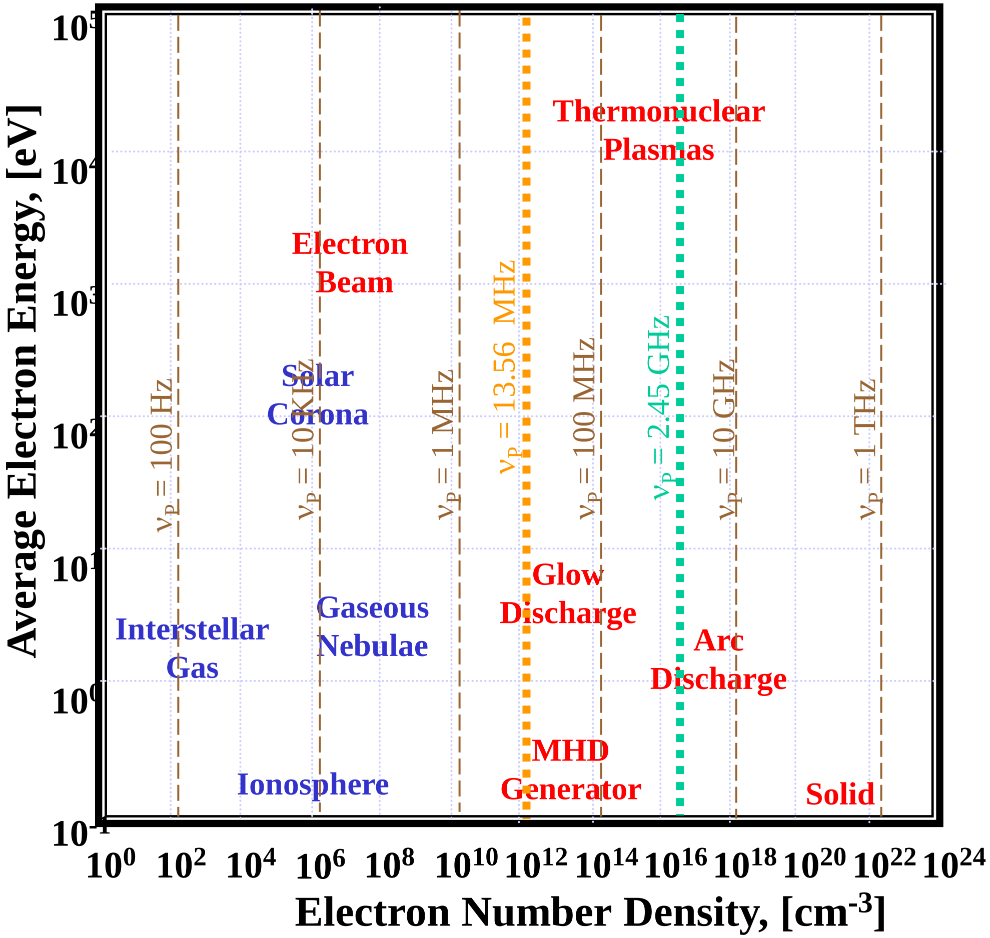
10^{-6} $Torr < pressure < 1$ atm

10 mTorr

← Magnetized ECR → Unmagnetized ECR

At frequencies above 10 GHz

--> Water absorption



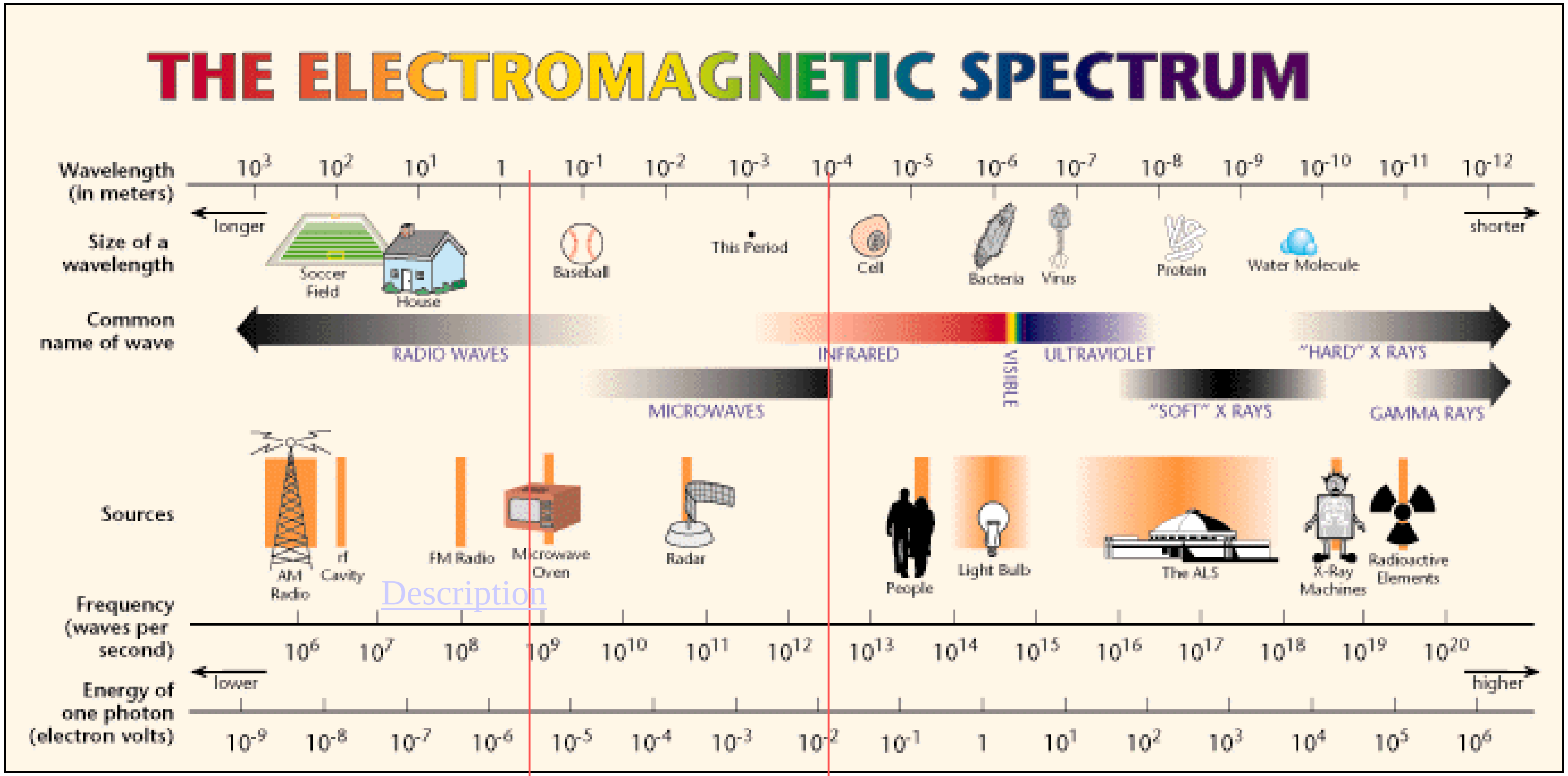
MW

↓

Collective interaction regime ⟷ **Particle interaction regime**

Radiation interact with plasma as a dielectric medium

Radiation interact with plasma as it interact with individual electrons



Description

0.915* GHz	2.45* GHz	300 GHz
33 cm	12.24 cm	1 mm

Funny Information

Advantages

- Higher electron kinetic temperatures and lower pressures
- Higher fraction of ionization and dissociation than DC and low frequency discharges
- Lower voltages across the sheath -> Less sputtering of the wall
- No electrodes -> less contamination
- More stable over a wide range of background gas pressures relative to DC & RF

Applications

ECR: for Microelectronics Plasma Processing

Fusion; for initial, steady state and high density plasmas

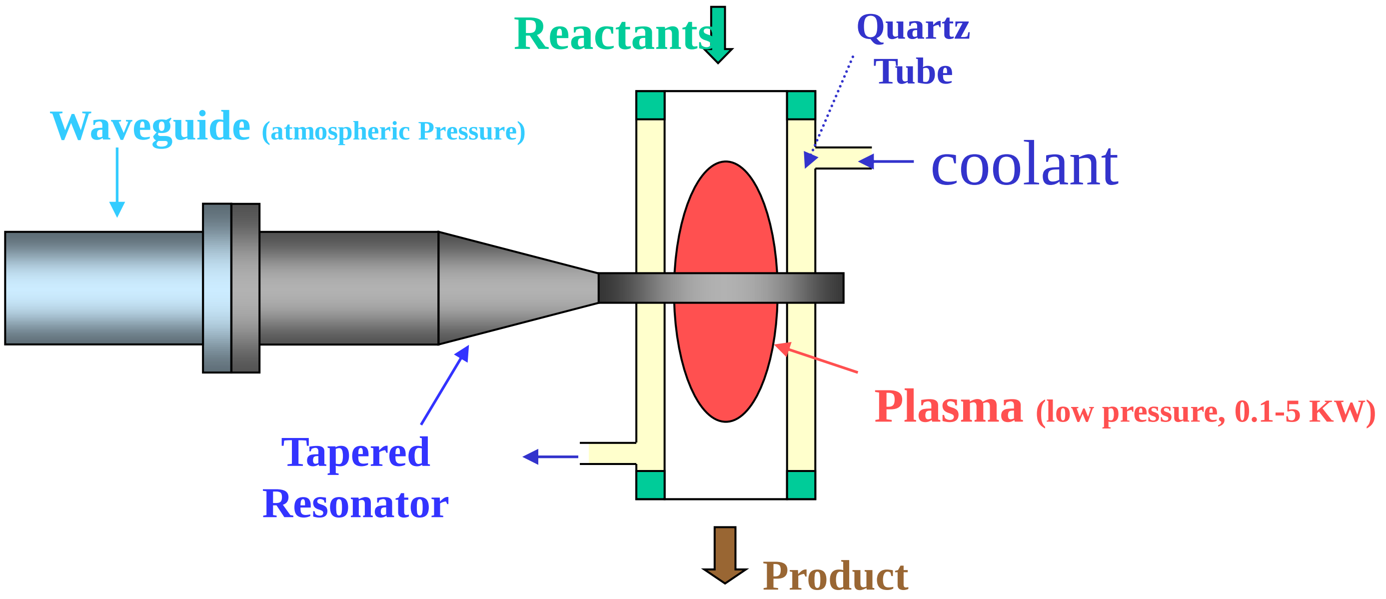
Sources: for Photons, ions, free radicals, excited atoms and dissociated neutral species

Laser: to pump laser medium

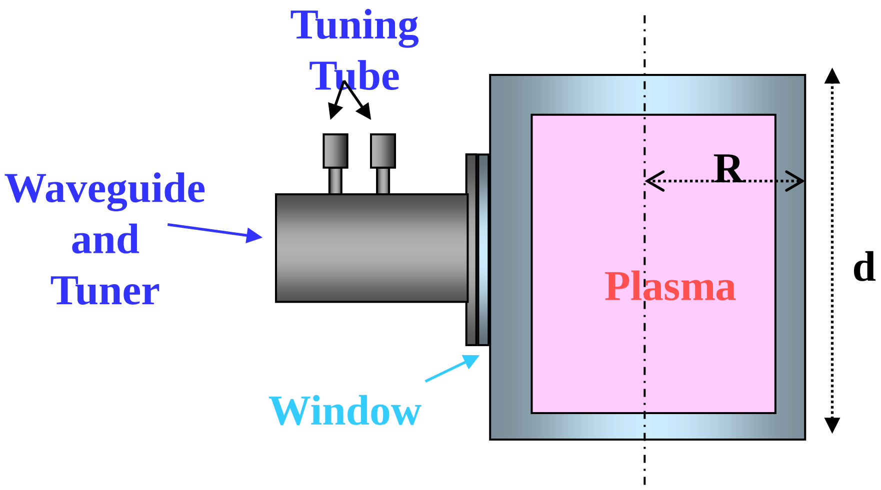
Continuous flow plasmas: Chemical reactors

Continuous Flow Non-resonant Microwave Plasma

(High electric field of radiation aligned with the axis of the tube)



Resonant or multimode cavity reactor

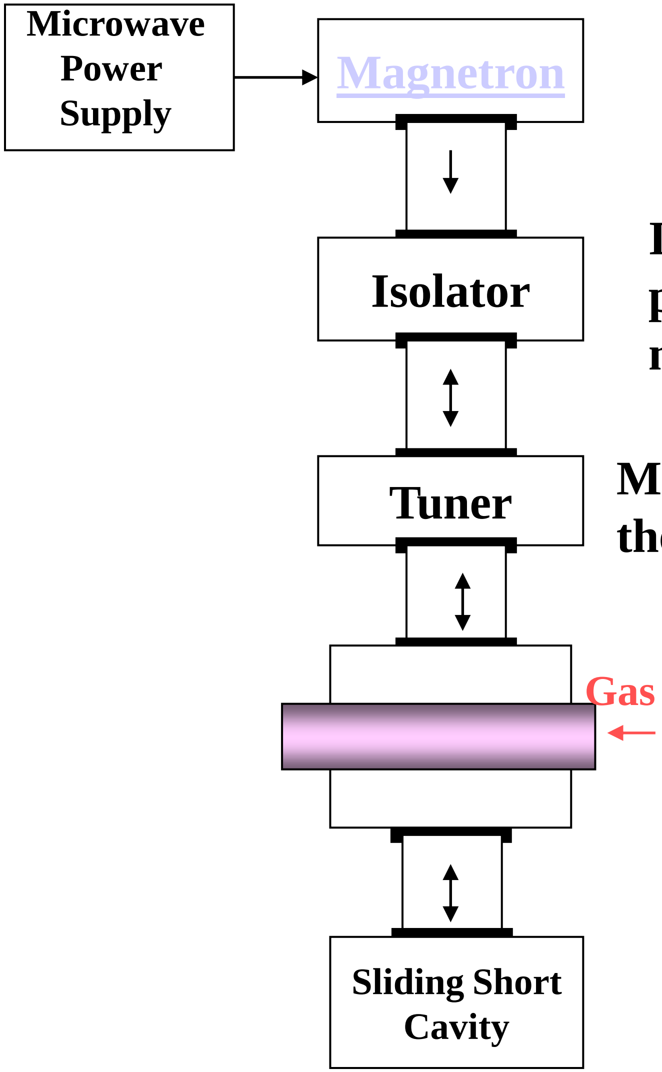


Resonant Cavity: R=λ_0; d=λ_0

Multimode Cavity: R>>λ_0; d>>λ_0

(Remember: 2.45 GHz -> 12.24 cm)

2.45 GHz, 0.4-10 KW



Microwave Power Supply

Magnetron

Isolator

Isolates the magnetron from the variable plasma load. It functions like one way valve for microwave power.

Tuner

Minimizes the reflected power, while maximizing the forward power absorbed by the load

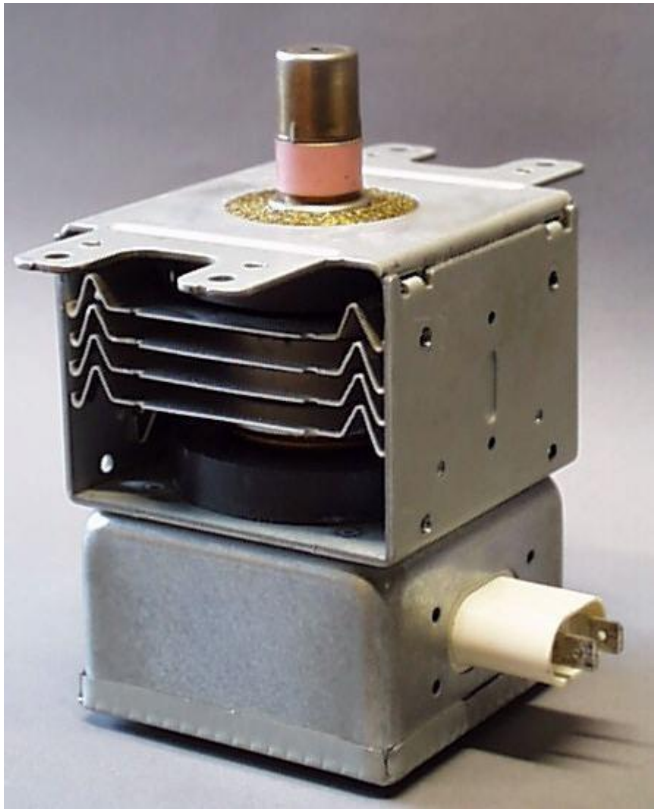
Gas

Quartz Tube separates the working gas pressue from the one within the waveguide

Sliding Short Cavity

A variable load

Magnetron



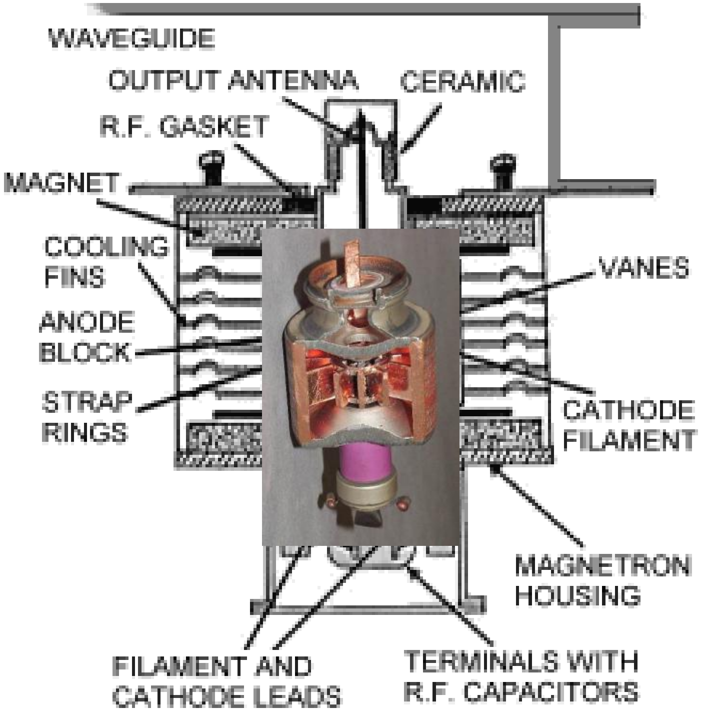


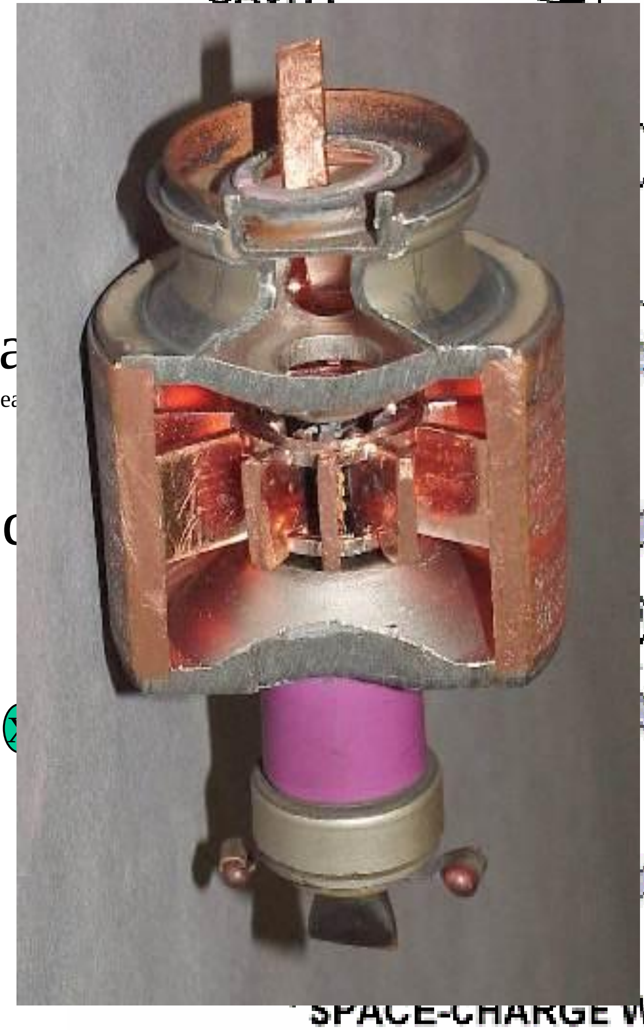
Figure 1 Sectional view of a typical magnetron
(Courtesy of Michael S. Wagner)

Ca

(hea

Anod

B



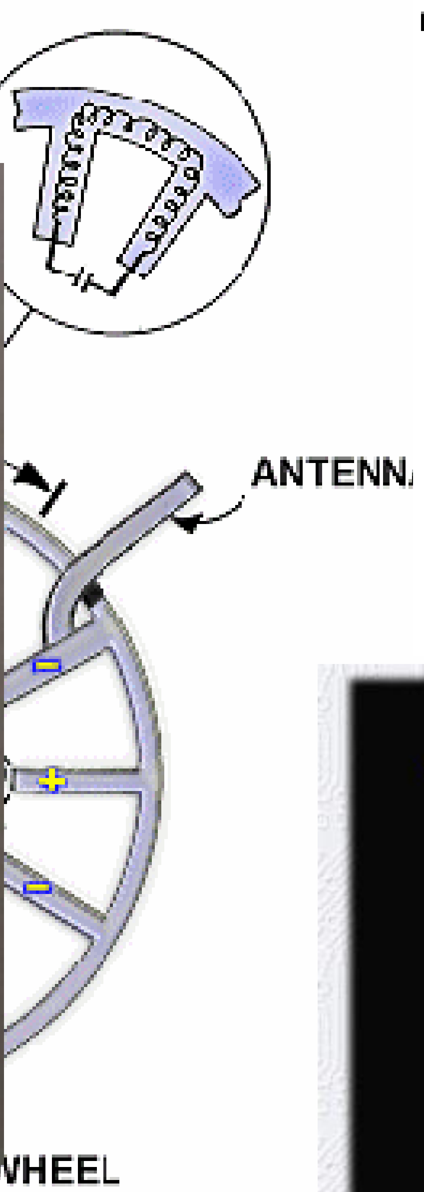


Figure 7-5 Electrons form a rotating pattern. (Wagner / Gallawa)

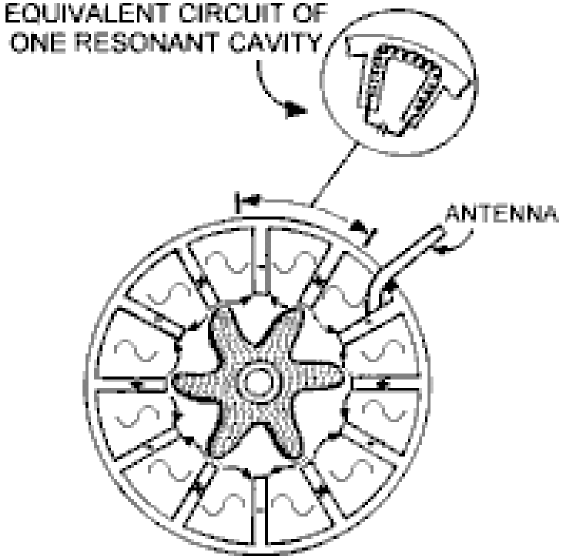
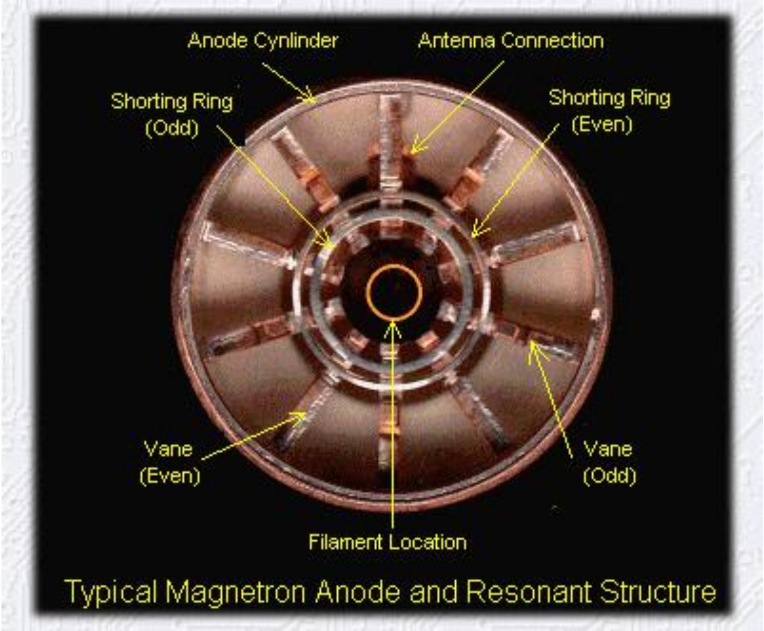
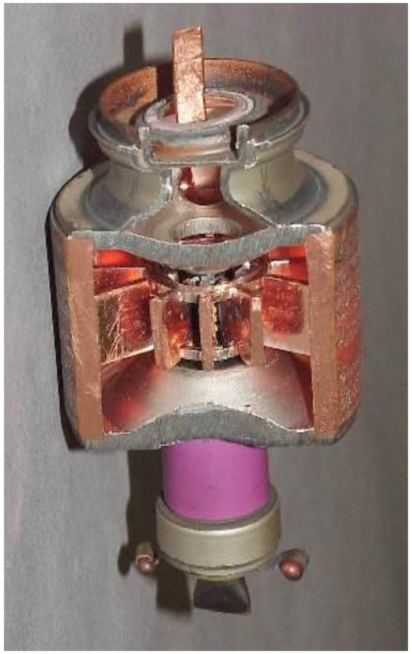


Fig. 4 Electrons form a rotating pattern (Courtesy of Michael S. Wagner)



Typical Magnetron Anode and Resonant Structure



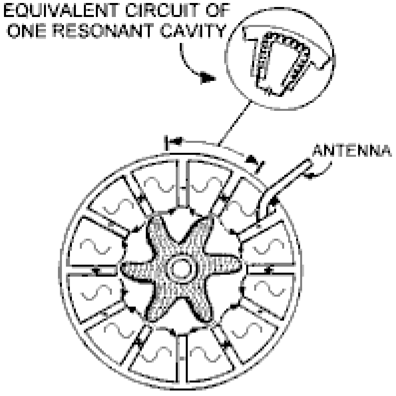
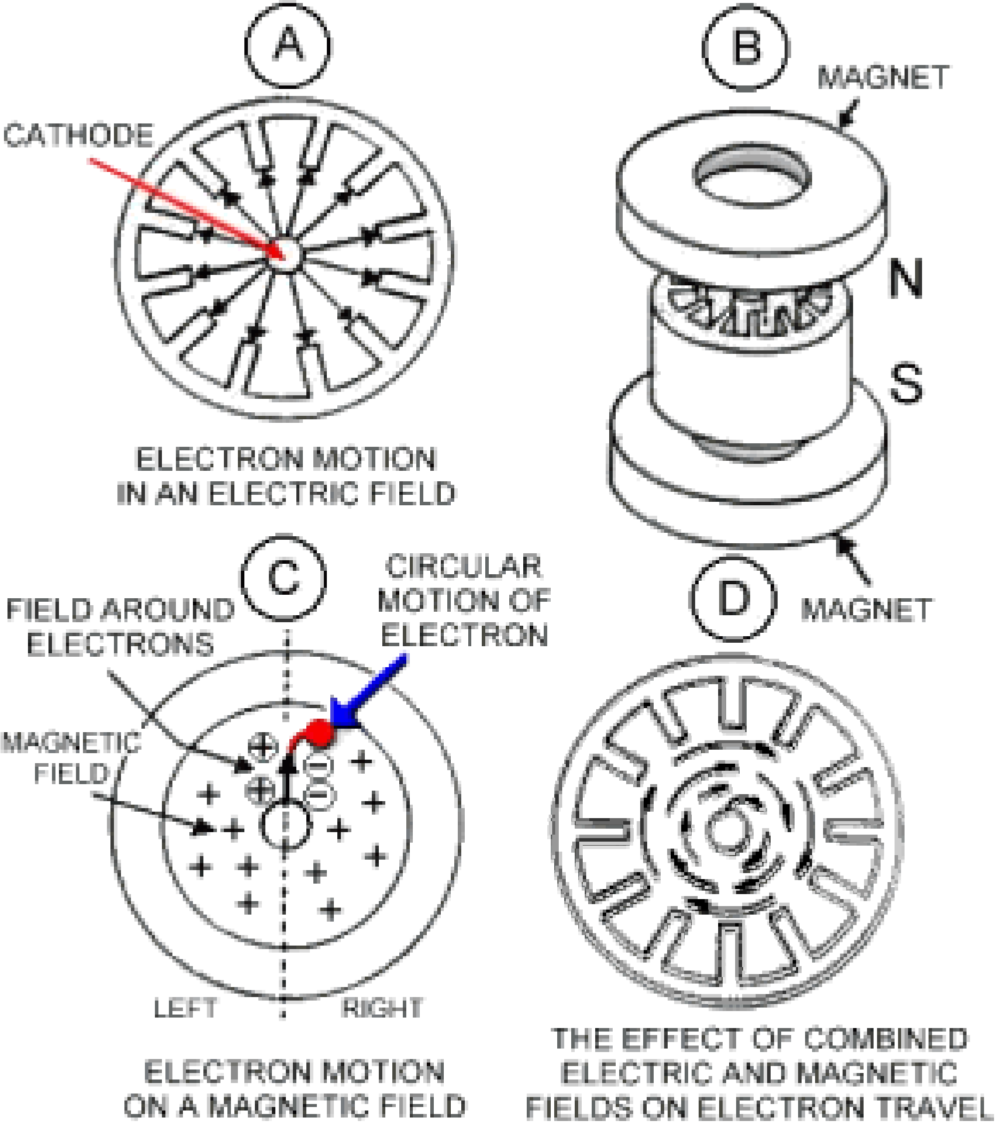


Fig. 4 Electrons form a rotating pattern (Courtesy of Michael S. Wagner)



ELECTRON MOTION IN AN ELECTRIC FIELD

ELECTRON MOTION ON A MAGNETIC FIELD

THE EFFECT OF COMBINED ELECTRIC AND MAGNETIC FIELDS ON ELECTRON TRAVEL

Figure 3 Electron motion in a magnetron tube (Courtesy of Michael S. Wagner)

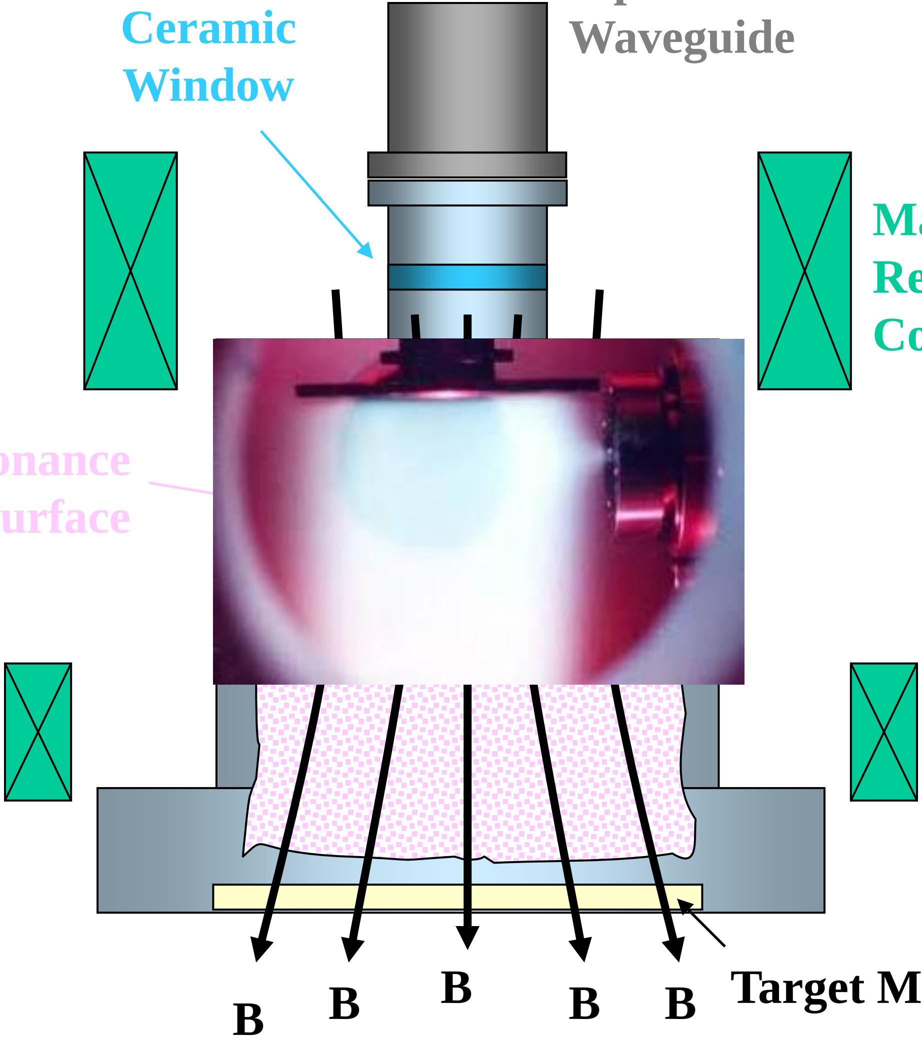
Grape Plasma 0:34

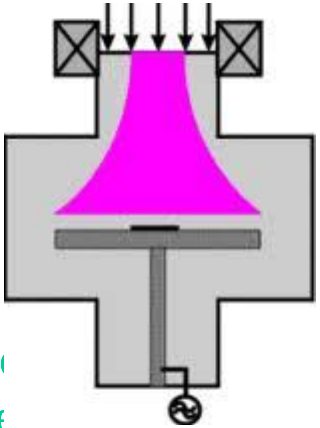
Microwave experiment plasmaball 0:57

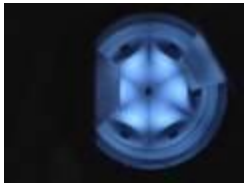
Electron Cyclotron Resonance (ECR) Plasma Reactor

$$\nu_{MW} = \nu_{gyration}$$

$$\nu_{gyration} = \frac{qB}{2\pi m}$$







Power Coupling to the Plasma (with B)

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

Energy transfer frequency

Low pressure

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

$$\left\{ \begin{aligned} \nu_{Plasma} &= 8.98\sqrt{n_e} \\ \omega_{gyro} &= 2.8\times 10^{10} B \end{aligned} \right.$$

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

High pressure

Optimum Power coupling to Plasma (with B)

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

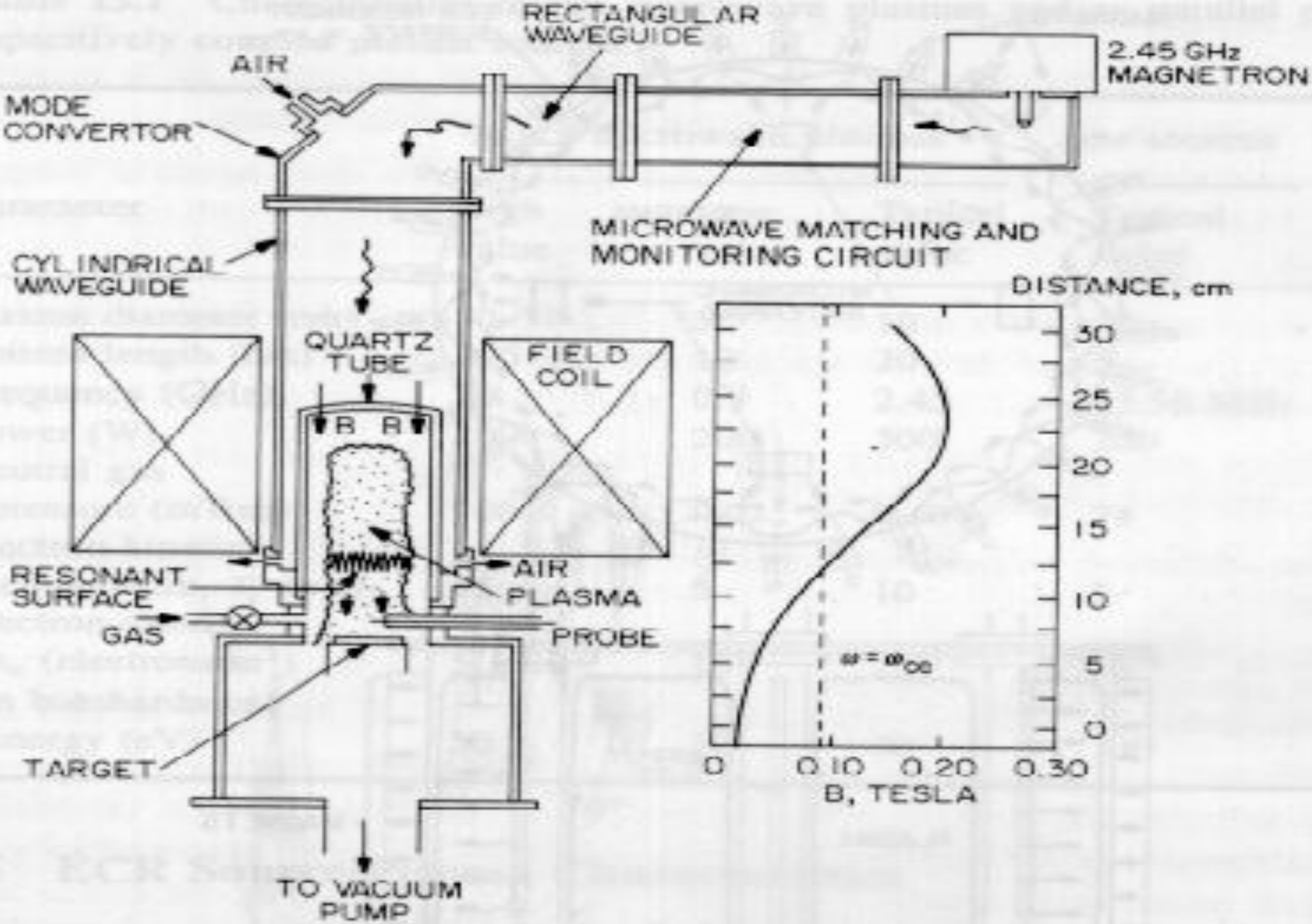
$$\frac{d\nu^*}{d\omega_g} = 0 \Rightarrow \omega_{g,opt} \approx \omega \left(1 - \frac{\nu_c^4}{\omega^2} \right)^{1/2} \approx \omega \qquad \omega \geq \frac{\nu_c}{\sqrt{3}}$$

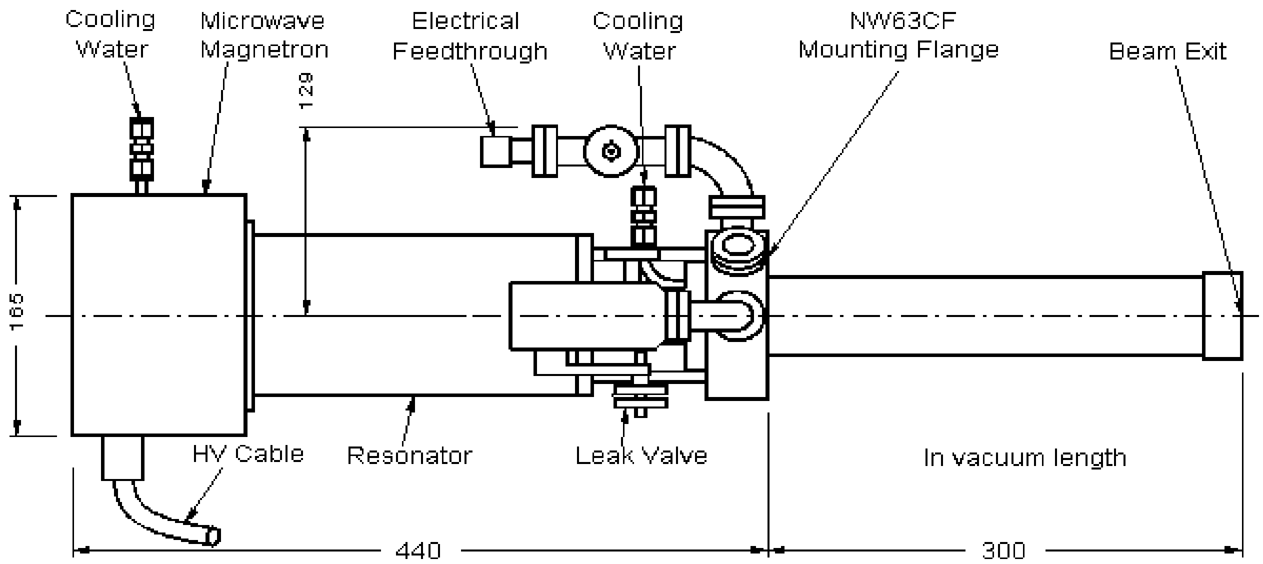
$$\frac{d\nu^*}{d\omega} = 0 \Rightarrow \omega_{opt} \approx \omega_g \left(1 - \frac{\nu_c^4}{\omega_g^4} \right)^{1/2} \approx \omega_g \qquad \begin{cases} \omega \geq \dfrac{\nu_c}{\sqrt{3}} \\ \nu << \nu_g \end{cases}$$

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

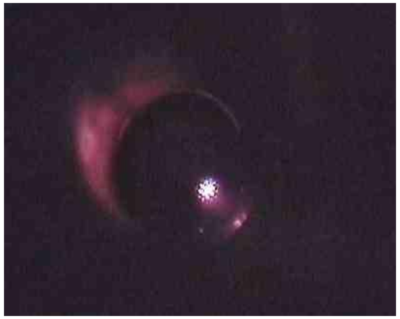
Pages 425-433

Immersed ECR System

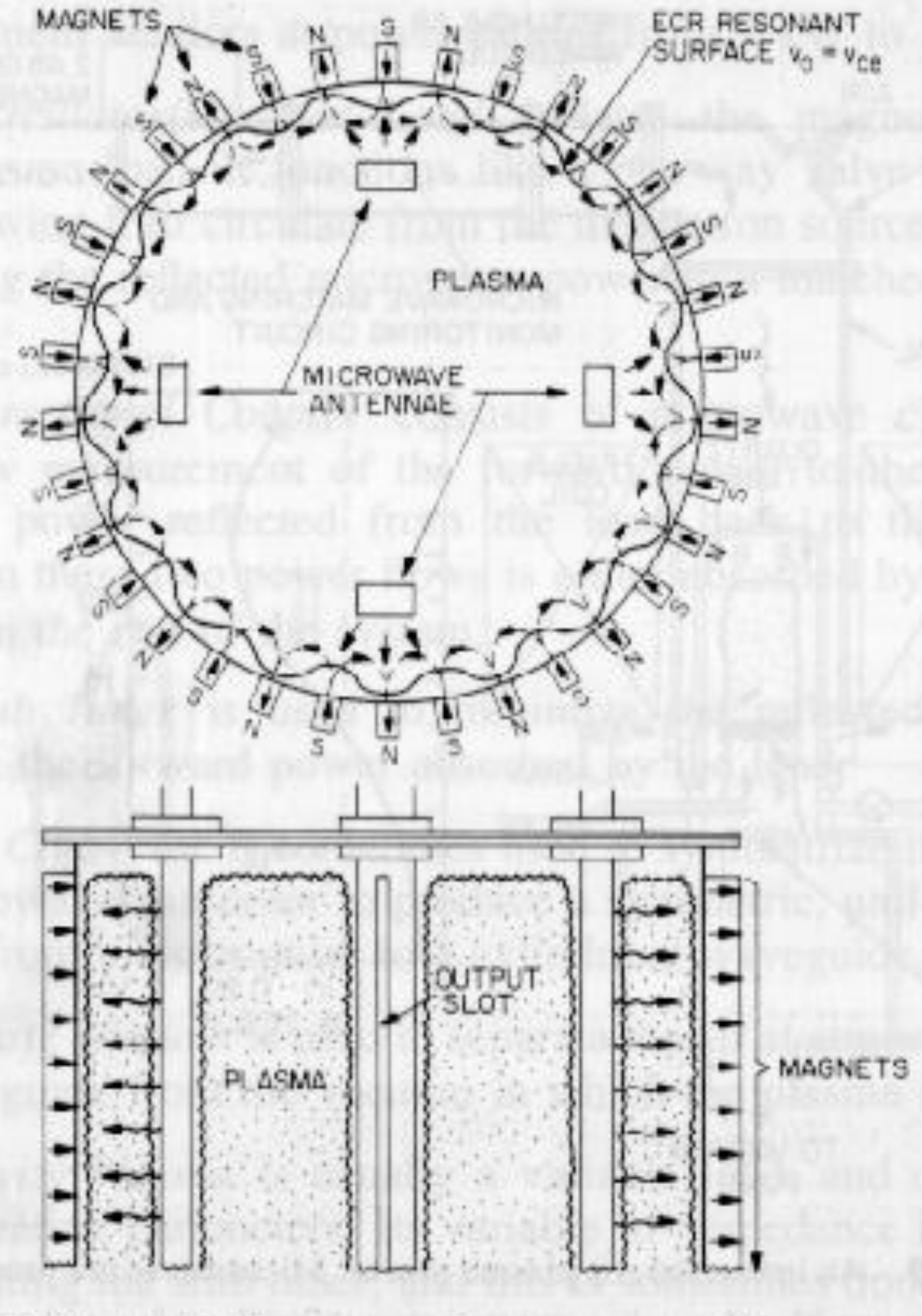



Cooling Water
Microwave Magnetron
Electrical Feedthrough
Cooling Water
NW63CF Mounting Flange
Beam Exit
129
165
HV Cable
Resonator
Leak Valve
In vacuum length
440
300

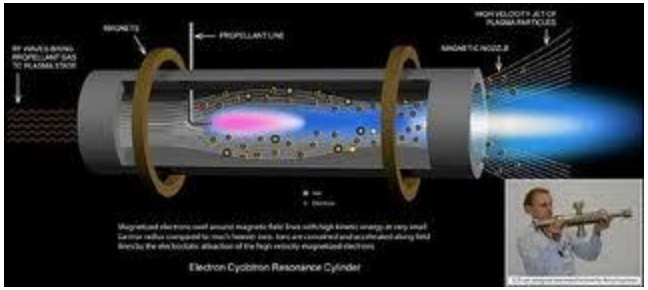

On/Off
Beam
Voltage
Plasma Ion Source
Grid Control
On/Off
Power
Plasma Ion Source
Magnetron Supply

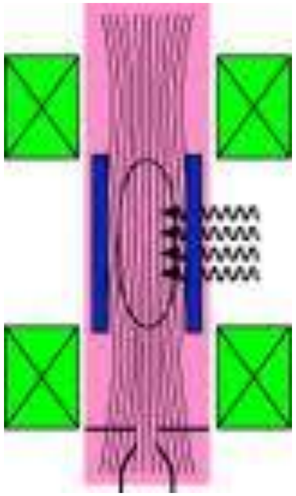


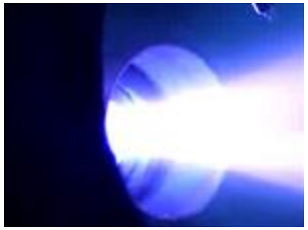
Distributed ECR System



ure 12.20 A distributed ecr plasma source. Microwave







Ion Thruster

Ion Source

Theoretical Model

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

E from radiation plus the effect of surrounding plasma

Static background magnetic field
B of radiation is neglegibly small

$$+$$

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

Maxwell Equation

Propagation Equation:

Attenuation constant $= 1/\delta$

Wave number

$$I(z,t) = I_0 \exp(-\alpha z) \exp[j(\omega t - kz)]$$

Microwave Breakdown of Gases

Breakdown
Electric Field

Free Space
Wavelength

Ionization Potential
of the Gas

$$E_b = E(\lambda, V_i, l, \Lambda)$$

Electron
Mean Free Path

Characteristic
Diffusion Length

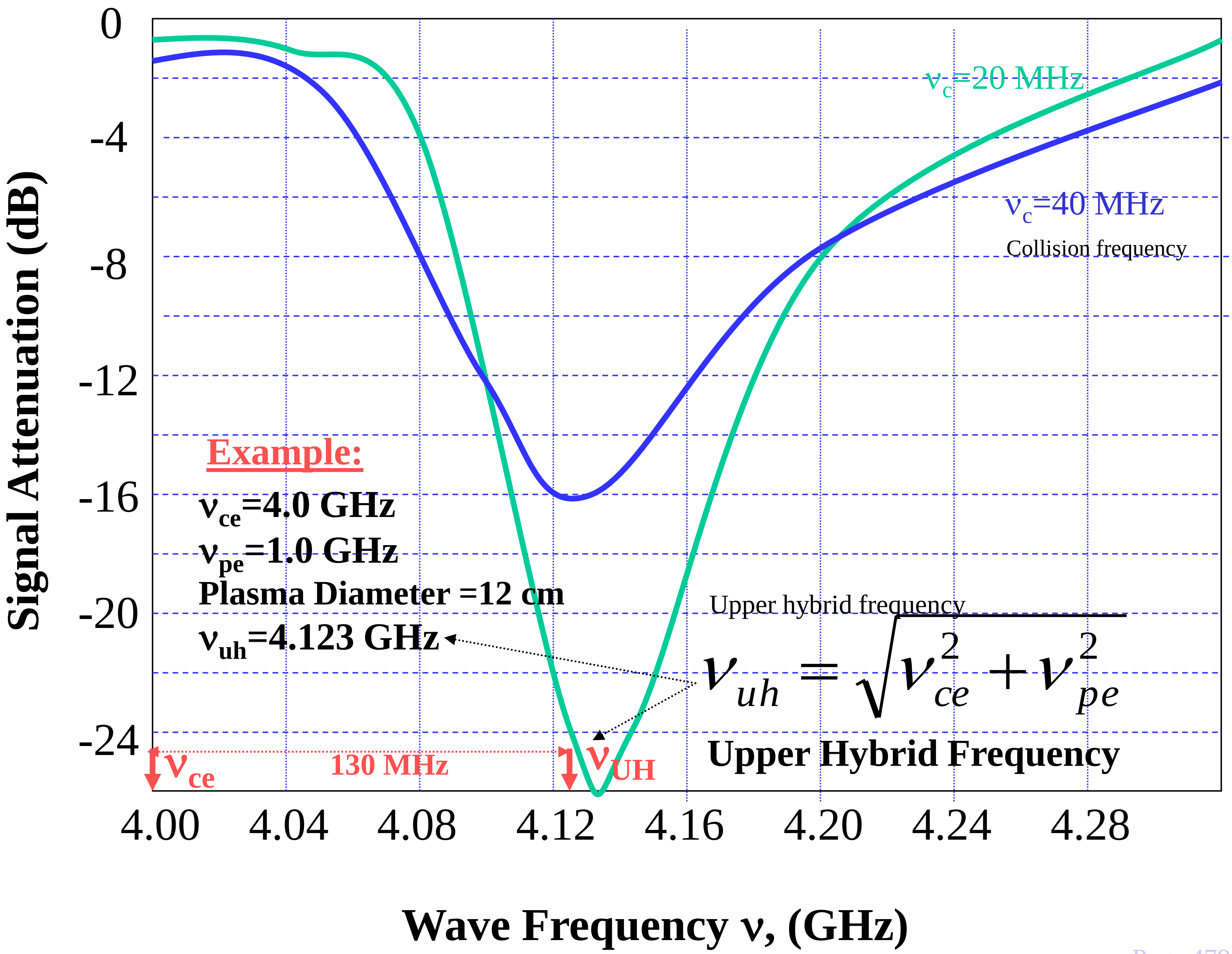
With five variables and two independent dimensions (Length and voltage), three dimensionless variables are sufficient to describe the relationship implied by the above equation

e.g. $$\frac{E\Lambda}{V_i}, \frac{\lambda}{l}, \frac{\Lambda}{l} \qquad \frac{E\lambda}{V_i}, \frac{El}{V_i}, \frac{\lambda}{\Lambda}$$

The implication is that it requires a three-dimensional surface to specify the RF and microwave breakdown conditions in the gas.

$$l \approx \frac{1}{p} \;\&\; V_i = const \Longrightarrow E\Lambda, p\lambda, p\Lambda$$

$$E\lambda, \frac{E}{p}, \frac{\lambda}{\Lambda}$$



Example:

ν_{ce}=4.0 GHz

ν_{pe}=1.0 GHz

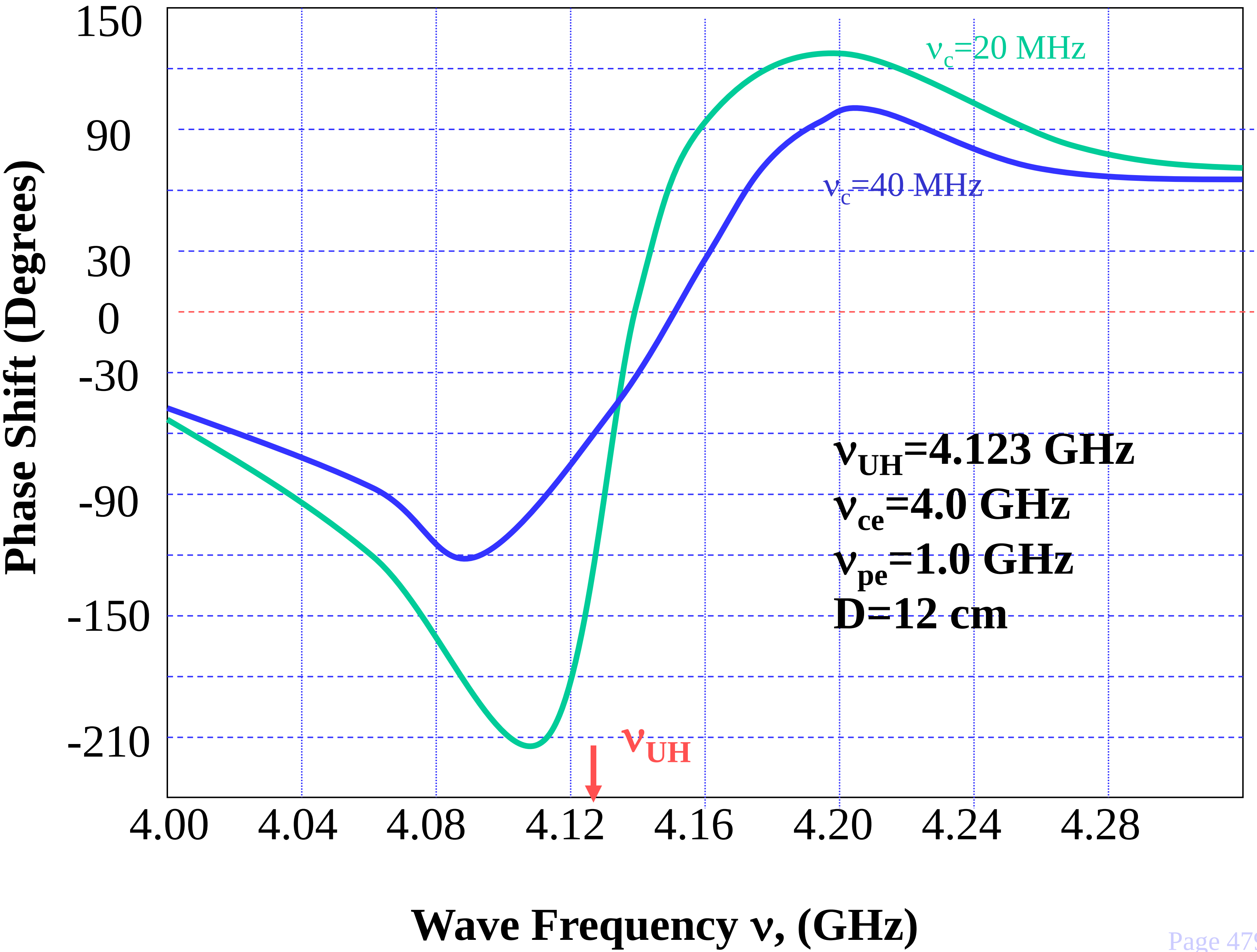
Plasma Diameter =12 cm

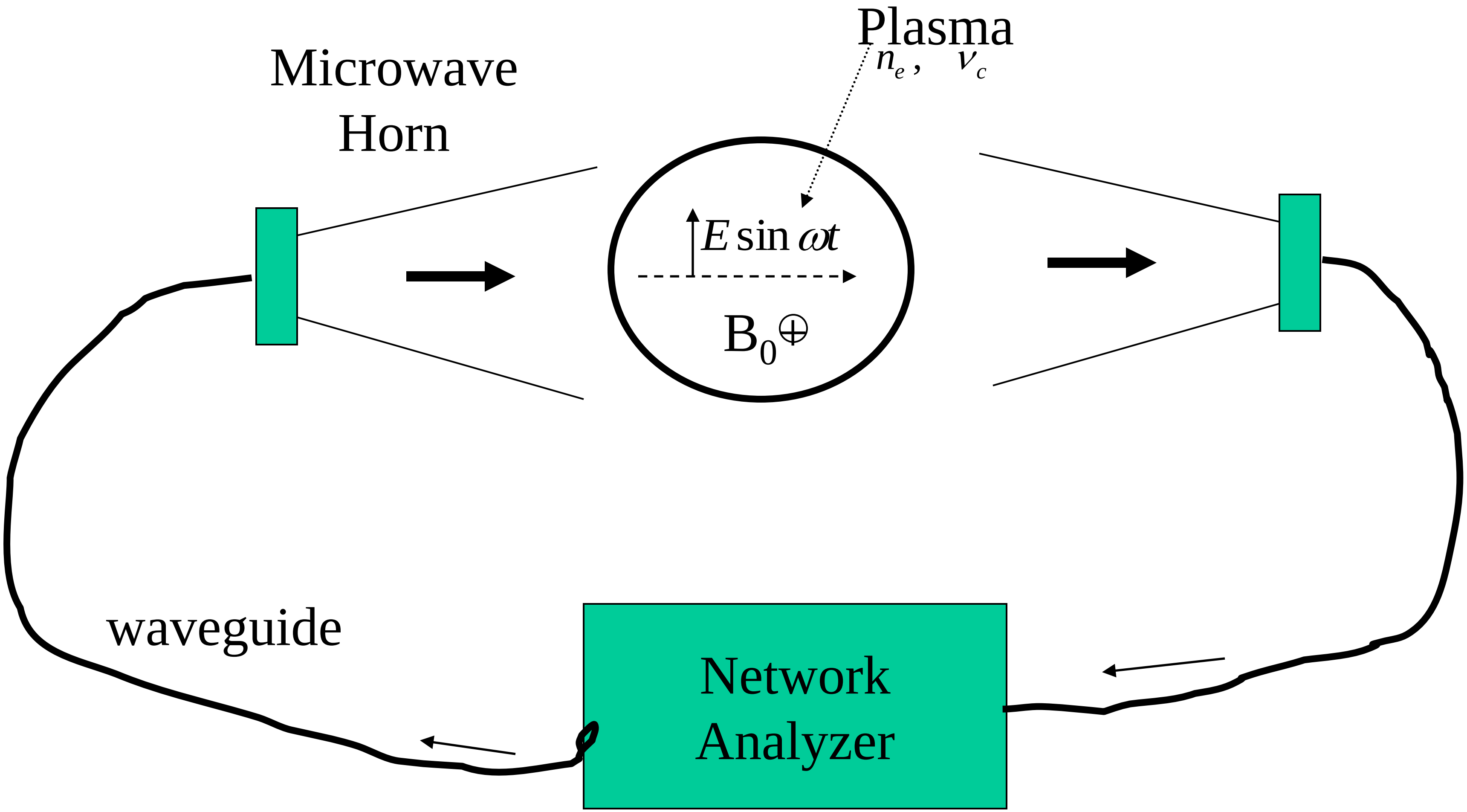
ν_{uh}=4.123 GHz

Upper hybrid frequency

$$\nu_{uh} = \sqrt{\nu_{ce}^2 + \nu_{pe}^2}$$

Upper Hybrid Frequency


ν_c=20 MHz
ν_c=40 MHz
ν_{UH}=4.123 GHz
ν_{ce}=4.0 GHz
ν_{pe}=1.0 GHz
D=12 cm
ν_{UH}
Phase Shift (Degrees)
150
90
30
0
-30
-90
-150
-210
4.00
4.04
4.08
4.12
4.16
4.20
4.24
4.28
Wave Frequency ν, (GHz)



Microwave Horn

Plasma

$n_e\,,\quad \nu_c$

$E \sin \omega t$

$B_0 \oplus$

waveguide

Network Analyzer

Pages 481-482

Heald and Wharton Propagation Equation

Complex refractive index

$$\overline{\mu} = \mu - j\chi$$

Propagation Constant $\beta = \frac{\omega}{c}\mu$

$\alpha = \frac{\omega}{c}\chi$

Real refractive index

How much the radiation is slowed down in the medium relative to propagation in vacuum

Attenuation index

How much is the wave is attenuated

1- Propagation in an unmagnetized plasma (P 472)
2- Propagation in a magnetized (B_0) plasma (P 473)
  a- θ angle between E and B_0 (P. 474)
  b- θ=0; right circularly polarized wave (P 475)
  c- θ=0; left circularly polarized wave (P 475)
  d- θ=90; B_0||E (P 476)
  e- θ=90; B_0||B (P 476)

Pages 471-476