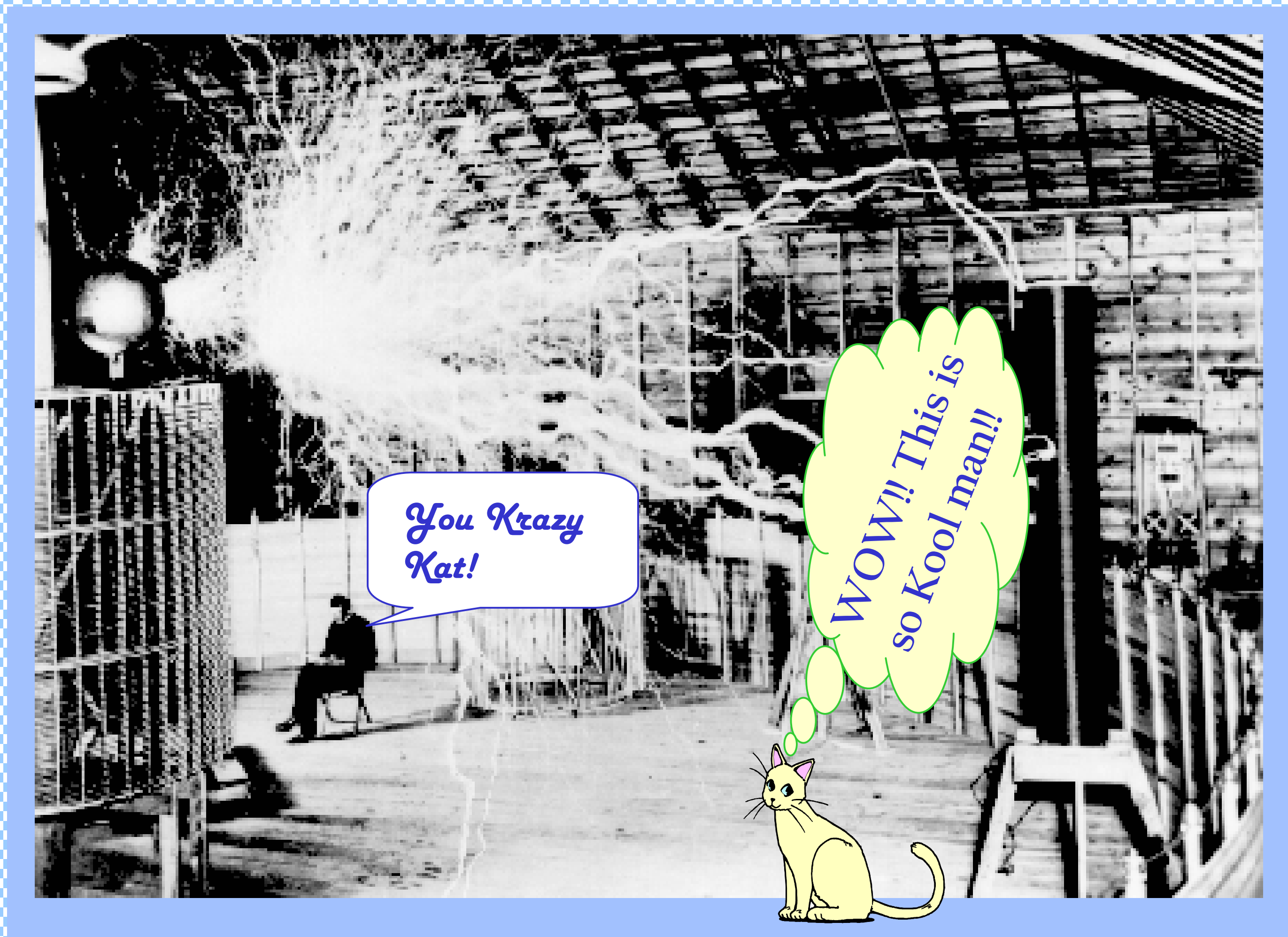
Microwave For Linear Accelerators II

October 31, 2002

Lecture 5

- RF Breakdown
- How to Accelerate Charged Particle?
- RF Components of Linear Accelerators
- RF Power Losses
- RF Power Measurements


You Krazy Kat!
WOW!! This is so Kool man!!

Breakdown depends on:

- The applied field level and local field enhancement
- The breakdown field of the medium (gas,Vacuum,solid)

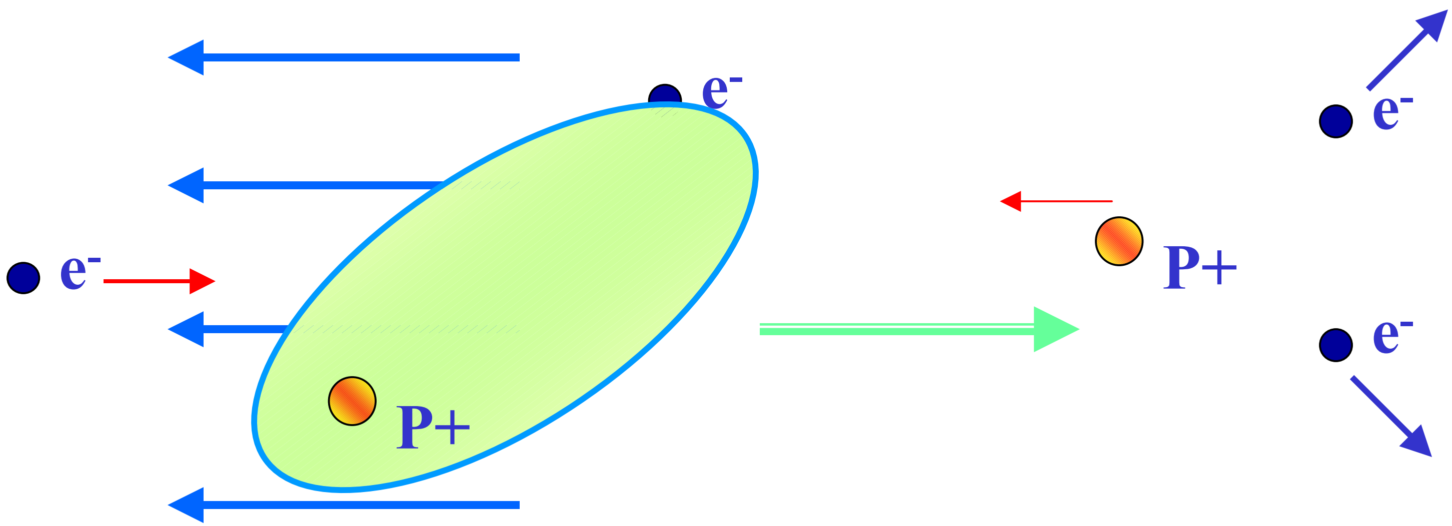
Gas	~10's V/cm - 10 kV/cm (depends on pressure and type)
Vacuum	~ 0.5 - 1MV/cm

Types:

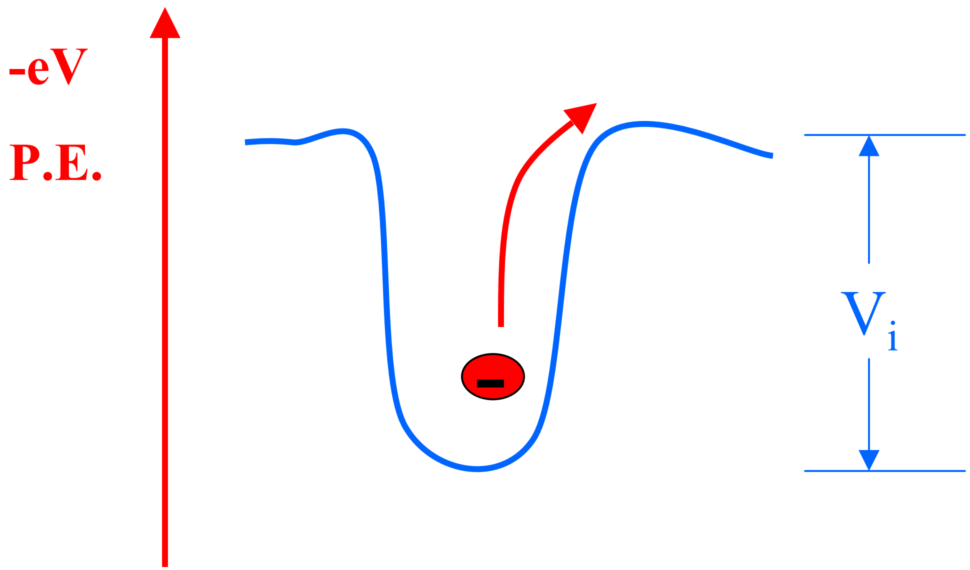
- DC Breakdown in Gas
- DC Breakdown in Vacuum
- RF Breakdown in Gas
- RF Breakdown in Vacuum

A plasma is a gas containing free charged particles. A plasma can be created by ionizing matter. Consider a single hydrogen atom consisting of a proton and an electron. Suppose there is an external electric field present that accelerates free electrons.

An individual electron can collide with the hydrogen atom. If the electron has enough energy, the impact will ionize the hydrogen atom creating a positively charged proton, a negatively charged electron, along with the original free electron. This process is called impact ionization.



In the atom, an electron is bound to the nucleus. A certain energy E_i is needed to extract the bound electron from from the potentially energy well created by the positively charged nucleus.



For atoms, ionization potential is on the order of V_i ≈10 volts

The energy per charge necessary to ionize the electron is called the ionization potential, V_i and is given by $V_i = E_i / e$

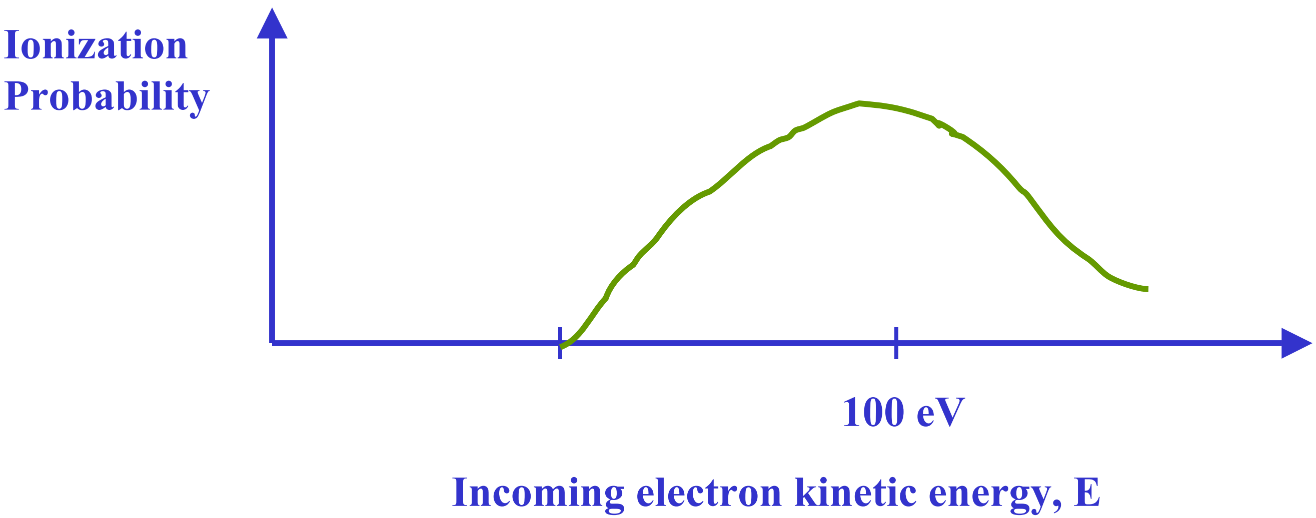
$e = 1.6 \times 10^{-19} C$

A unit of of energy for atomic processes is the electron-volt [***ev***] with

1***ev*** = 1.6×10^{-19}J. So an incoming electron must have a minimum energy

$E_i = eV_i = (1.6 \times 10^{-19} C)(10 V) = 1.6 \times 10^{-18} J = 10$ ***ev***

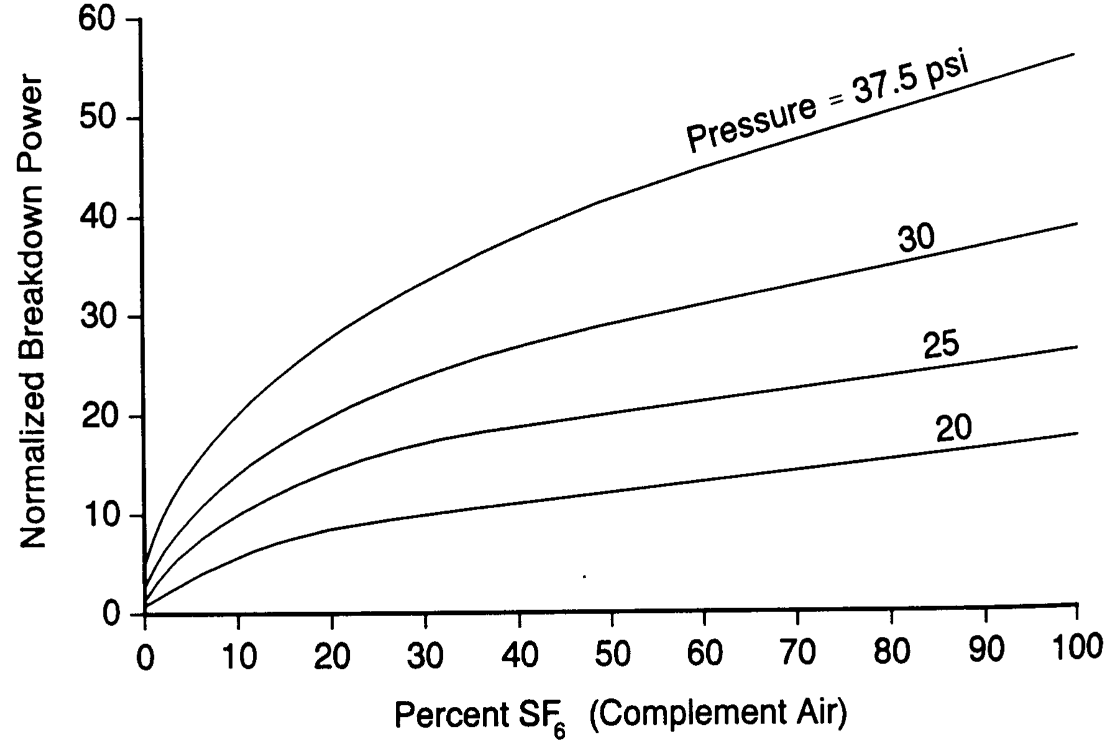
If the incoming electron has too much energy, it will go too fast and "not see the atom", effectively passing right through it.



Note: There is an optimal max. incoming energy to ionize the gas around 100 *ev* although this max. can move depending on the gas. This energy can be imparted to the incoming electron either through thermal motion or by an electric field.

RF Breakdown in Gas:

- DC breakdown field for air at atmospheric pressure is about 30 kV/m
- RF breakdown field depends on the frequency, spacing and pressure



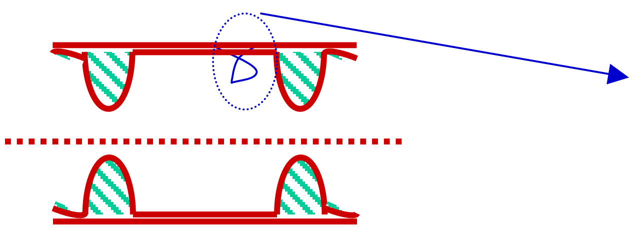
RF Breakdown in Vacuum:

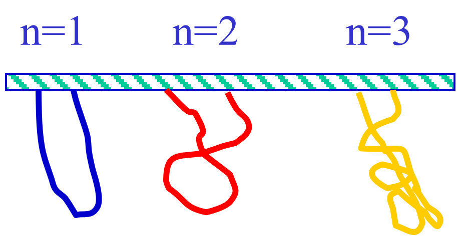
1. Kilpatrick's criterion: Relates max. field E_k[MV/m] at any frequency f[Hz];

$$f = 1.64 \times 10^6 E_k^2 \exp(-8.5 / E_k)$$

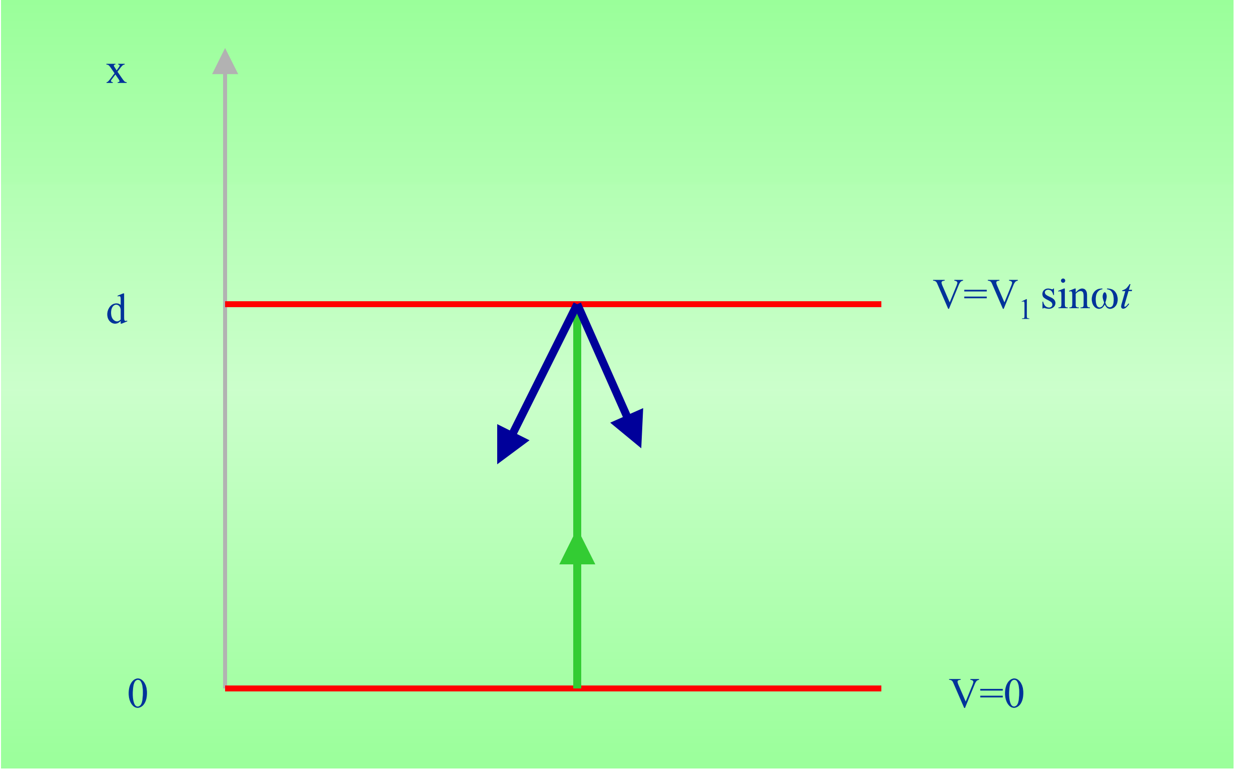
Very often, however, another king of discharge develops at voltage levels well below the Kilpatrick level. This discharge is called ***Multipactor Discharge***.

Multipacting occurs when electrons move back and forth across a gap in synchronism with an rf field. If the secondary emission ratio of the gap surface is greater than unity, then the number of electrons involved in the process build up with time and electron avalanche will be initiated and sparking might result.



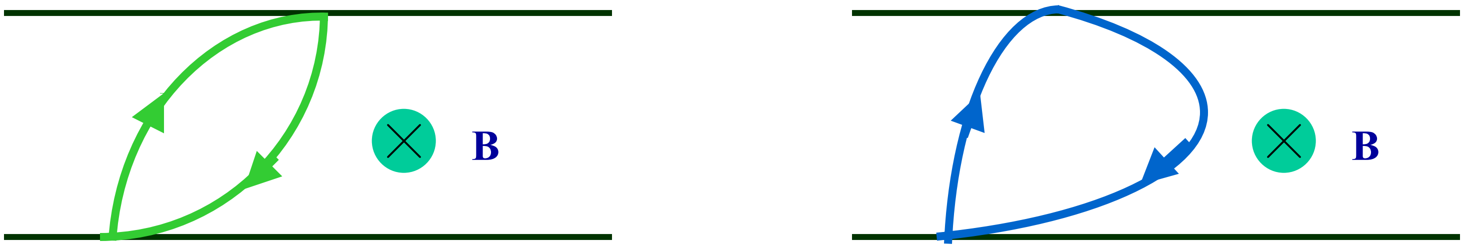


Principle of the Multipactor Discharge:

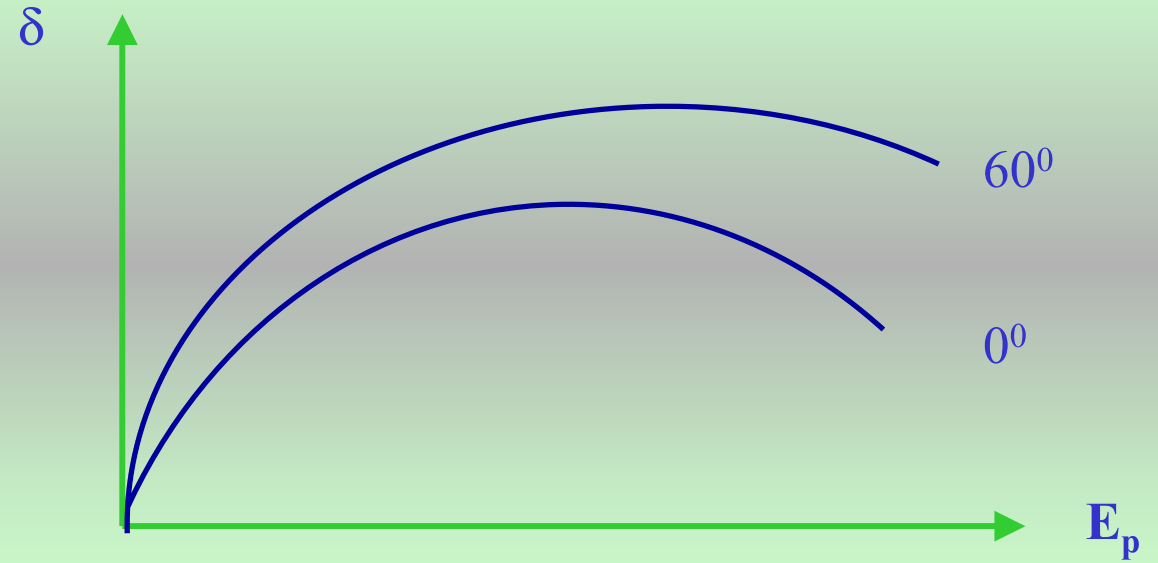


Secondary electron emission coefficient of materials used in vacuum tubes:

Material	δ_m	E_{pm}(Volts)
Copper	1.3	600
Platinum	1.8	800
Carbon	0.45	500
Alumina	2.35	500

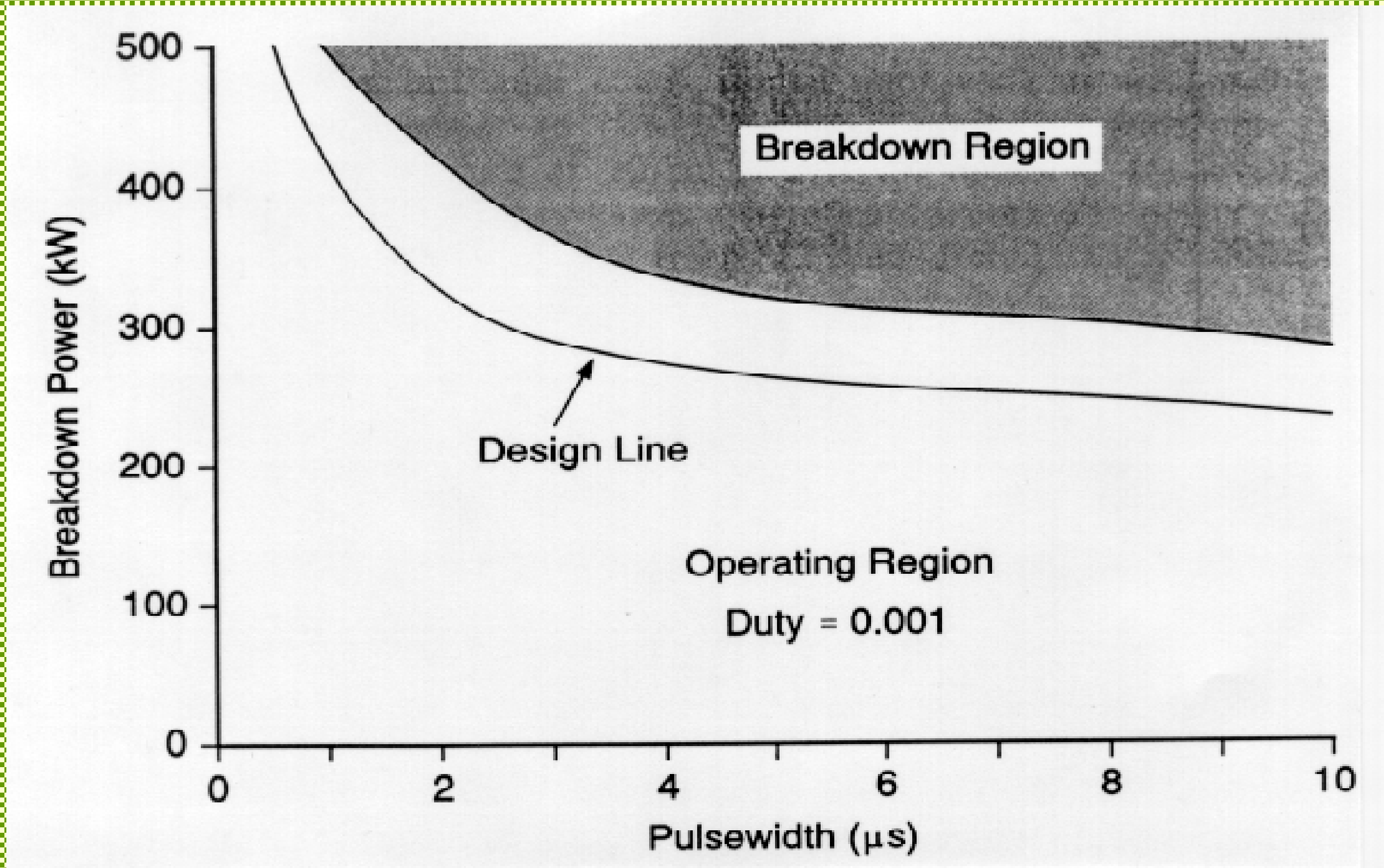


Cross-field multipactor discharges



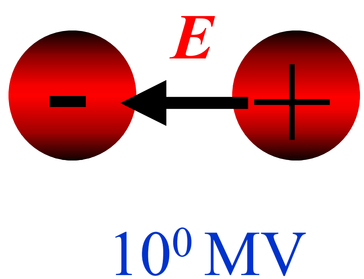
Effect of the angle of incident on secondary electron emission coefficient

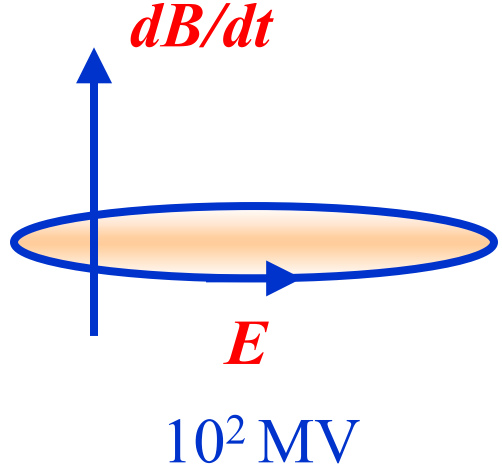
RF Conditioning with short Pulse:

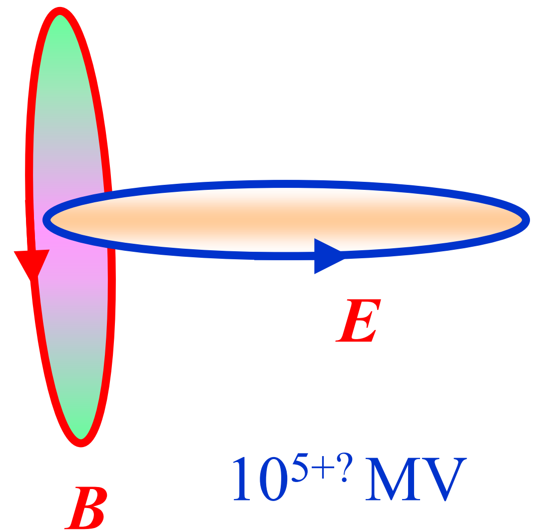


How to Accelerate?

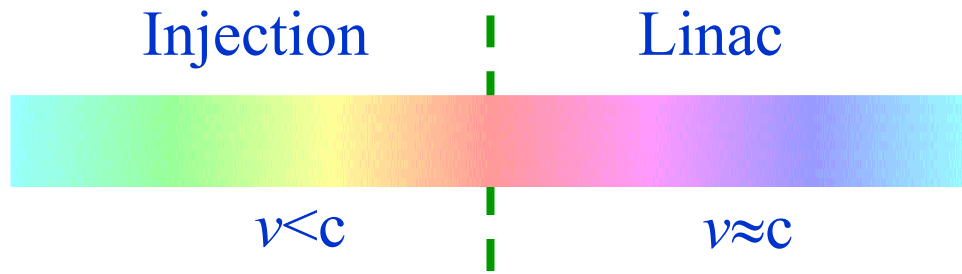
$$\frac{d\varepsilon}{dt} = q\vec{v} \bullet \vec{E}$$





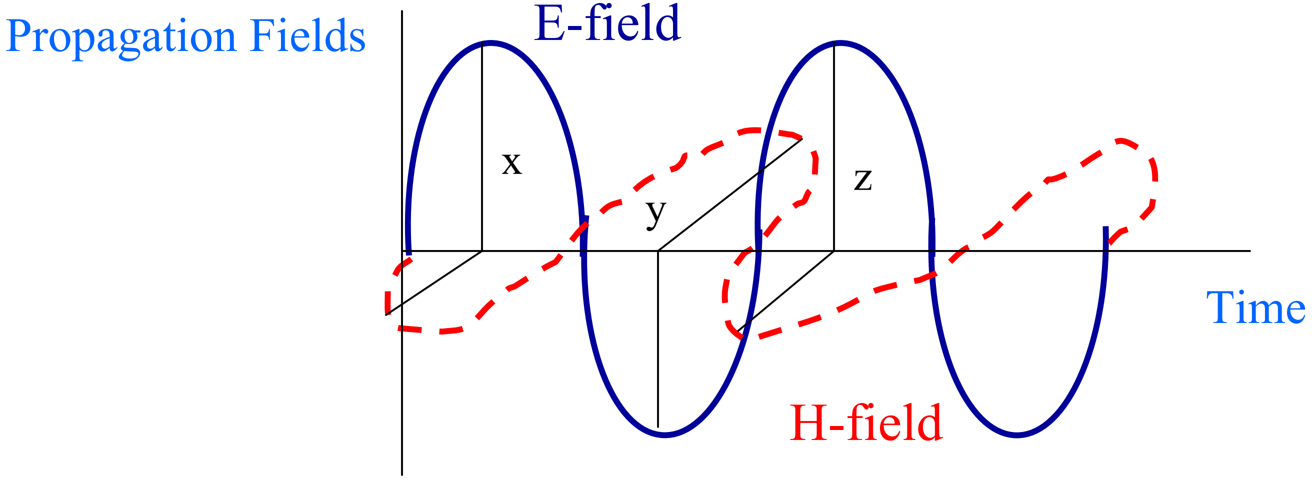


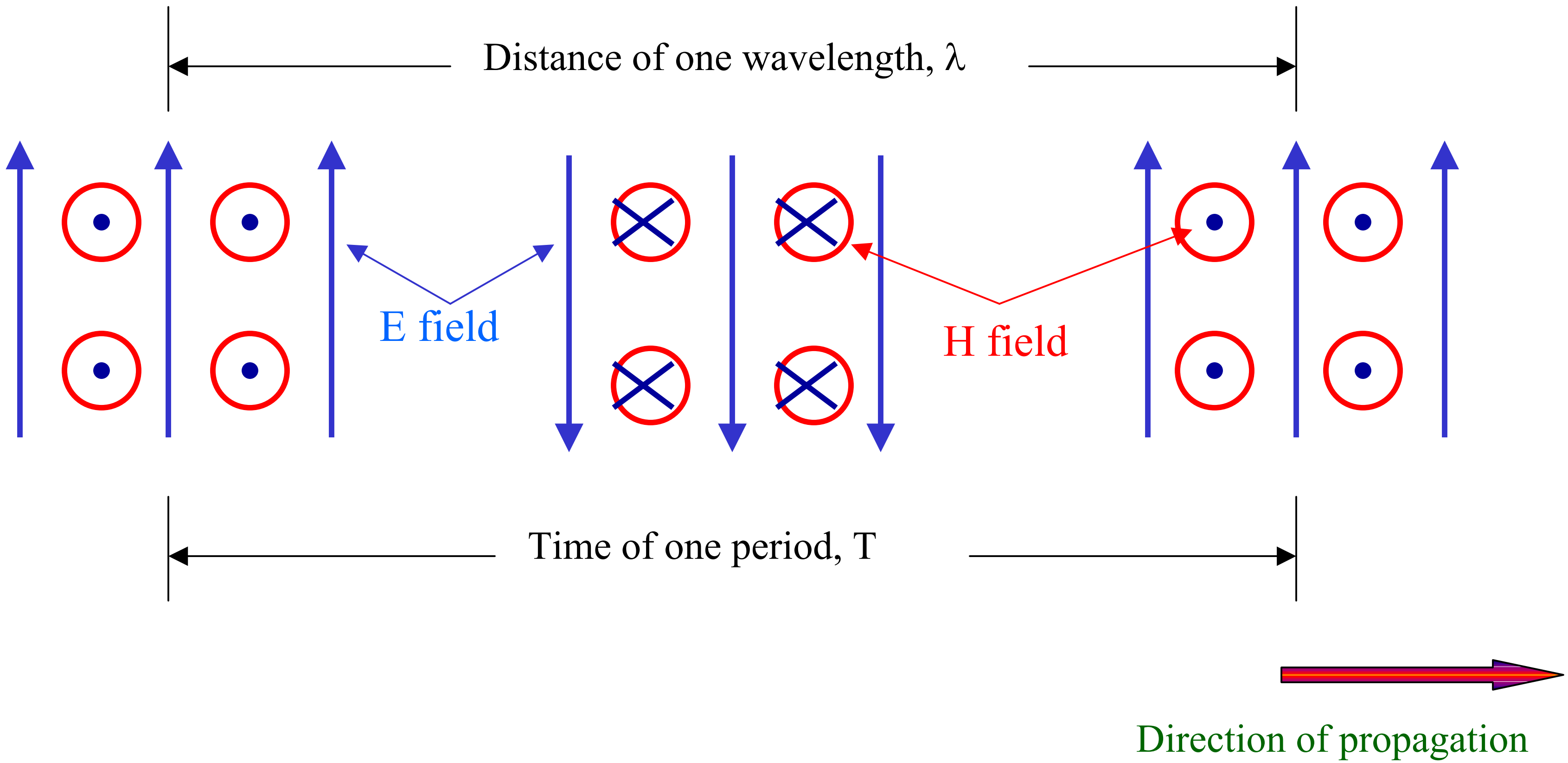
$$\Delta\varepsilon = \int dt E_0 \cos(\omega - kv)t$$



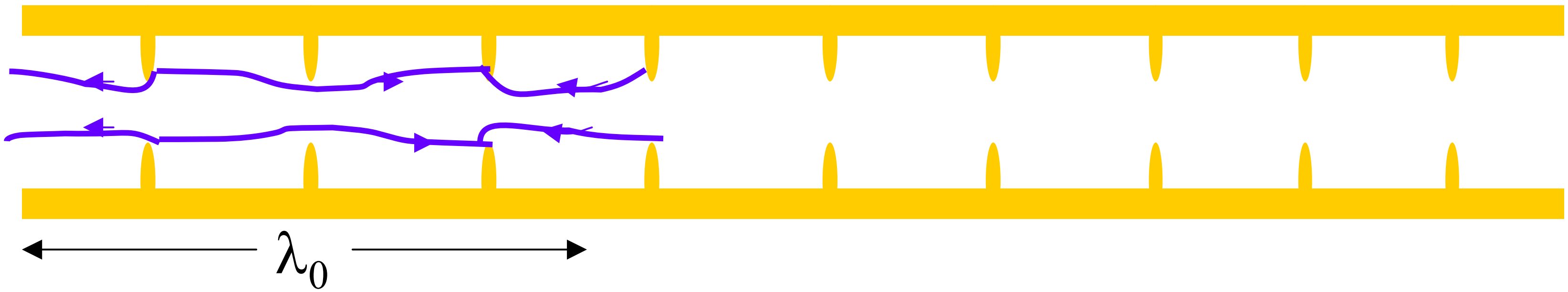
$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$c = \lambda/T = \lambda \times 1/T = f\lambda$$

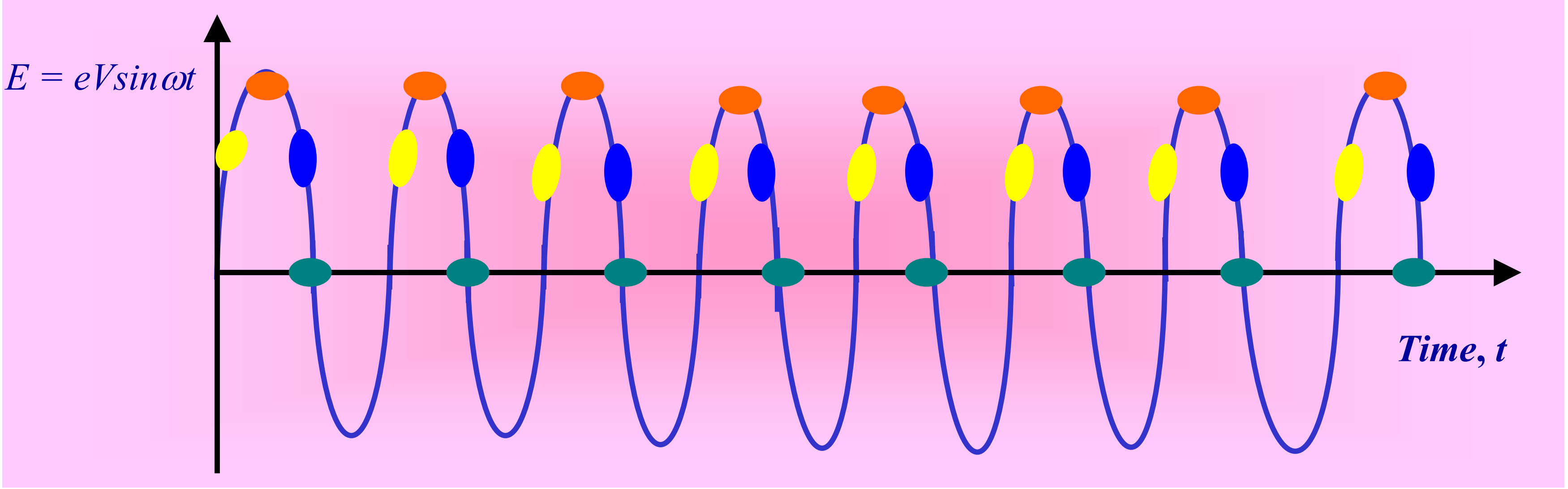


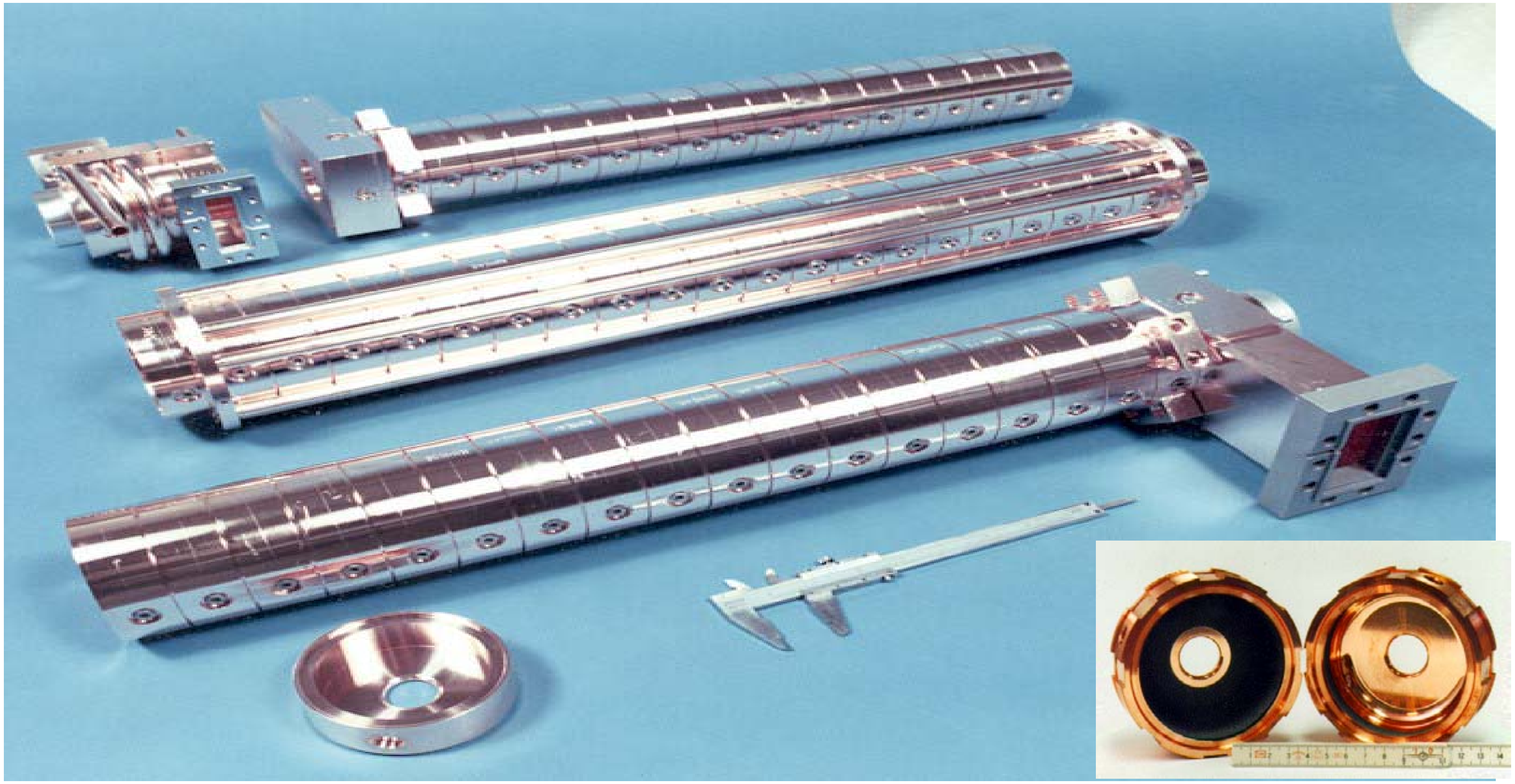

Distance of one wavelength, λ
E field
H field
Time of one period, T
Direction of propagation

Accelerating Structure

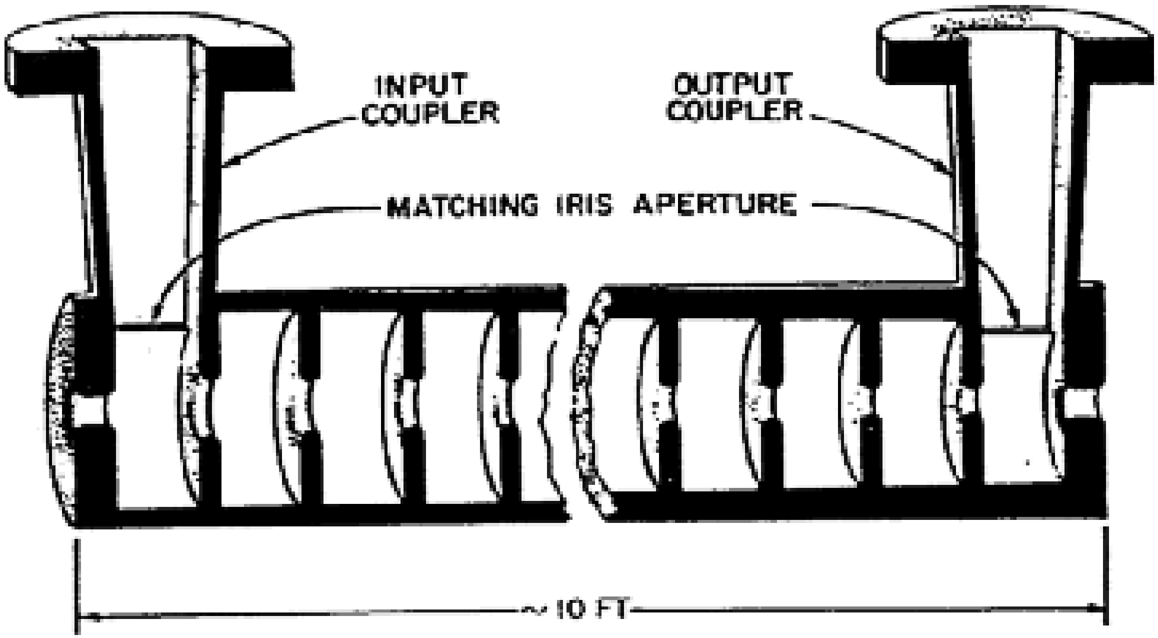


$2\pi/3$ phase shift per cell

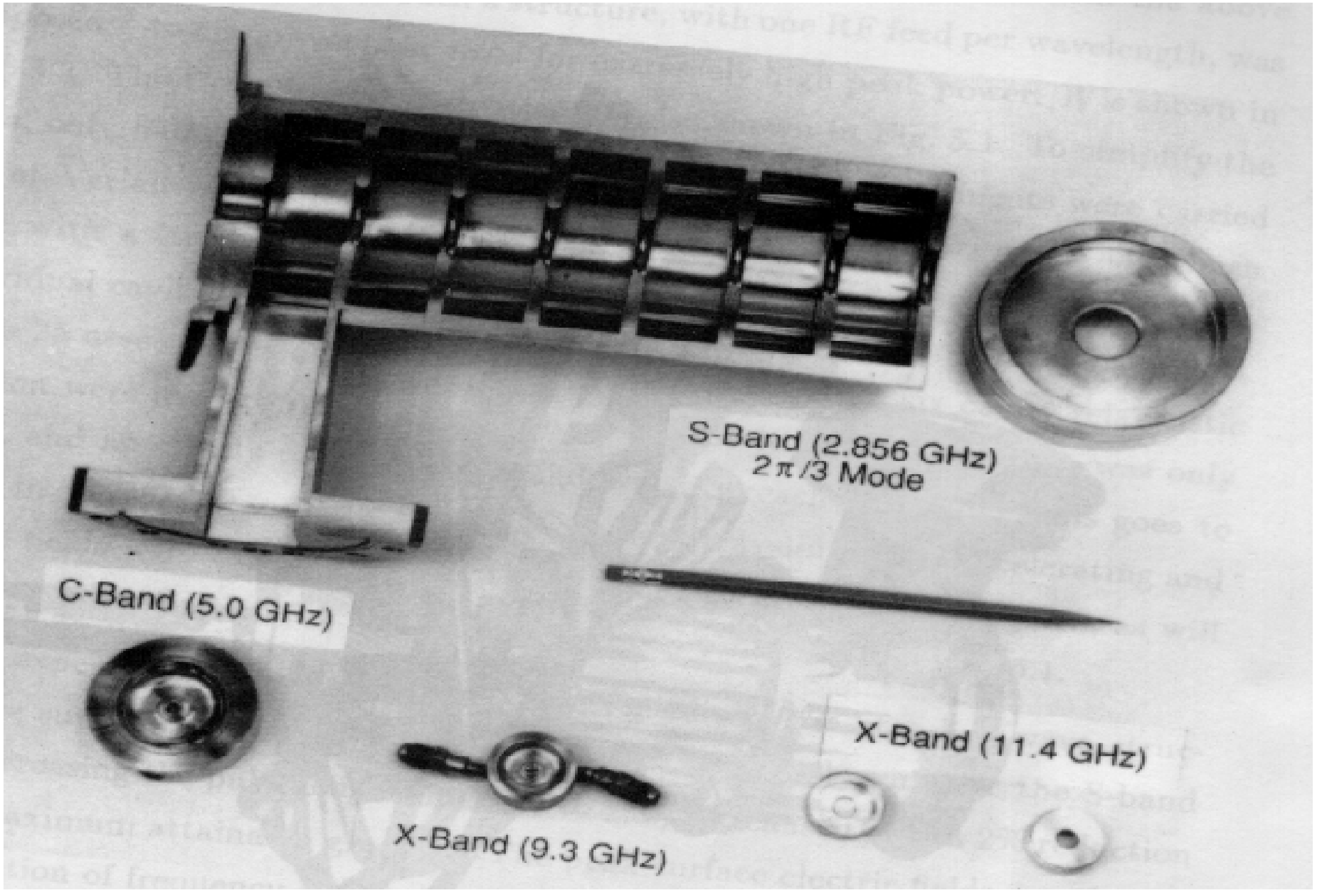


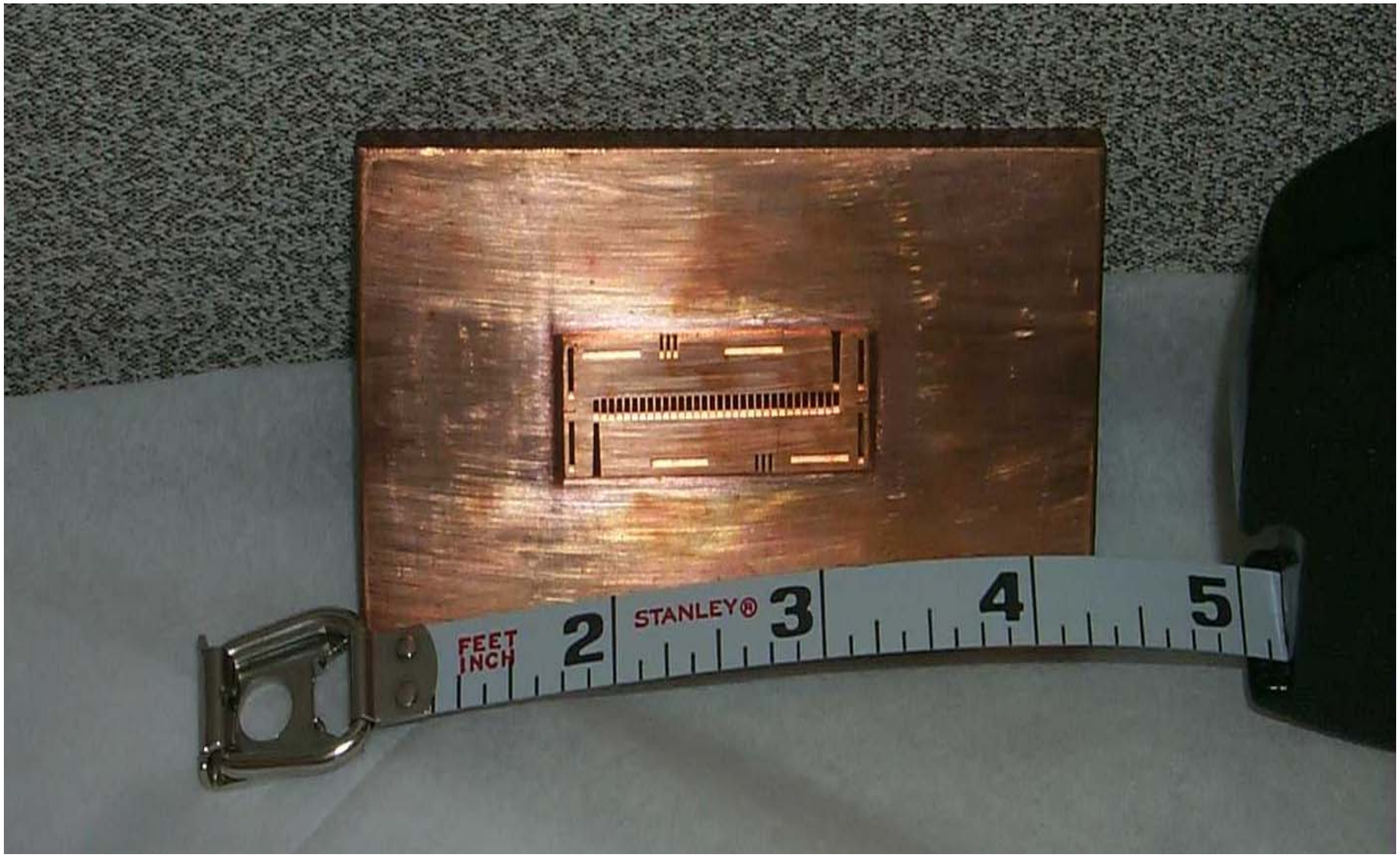


Disk-Loaded Constant Gradient S-Band Structure



S-band disk-loaded accelerating structure

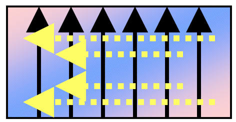

S-Band (2.856 GHz)
2π/3 Mode
C-Band (5.0 GHz)
X-Band (11.4 GHz)
X-Band (9.3 GHz)

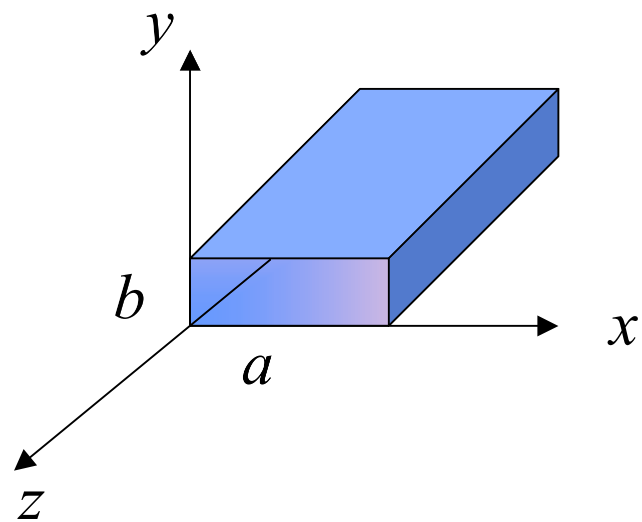


W-Band (94 GHz) Accelerating Structure

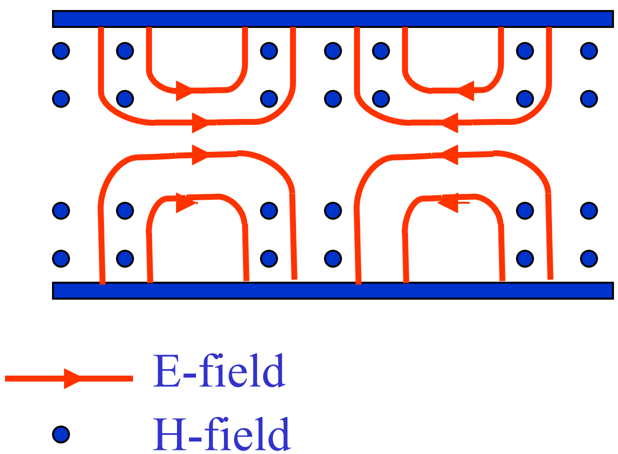
Waveguide Propagation Modes

TE - Transverse Electric Field





TM - Transverse Magnetic Field



$$\kappa = \frac{\omega}{v} = 2\pi \frac{f}{v} = \frac{2\pi}{\lambda}$$

$$\kappa_0 = \frac{2\pi}{\lambda_0}, \quad \kappa_c = \frac{2\pi}{\lambda_c}$$

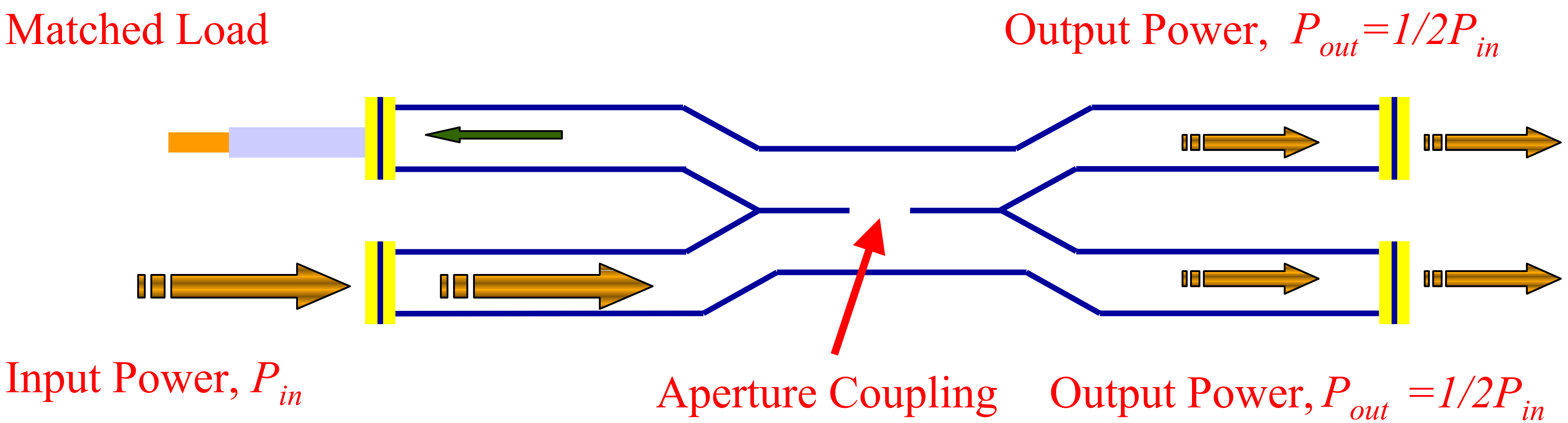
$$\beta = \left(\kappa_0{}^2 - \kappa_c{}^2\right)^{1/2}$$

$$\beta \equiv real \Rightarrow propagating \ \mathrm{mode}$$

$$\beta \equiv imaginary \Rightarrow evanescent \ \mathrm{mode}$$

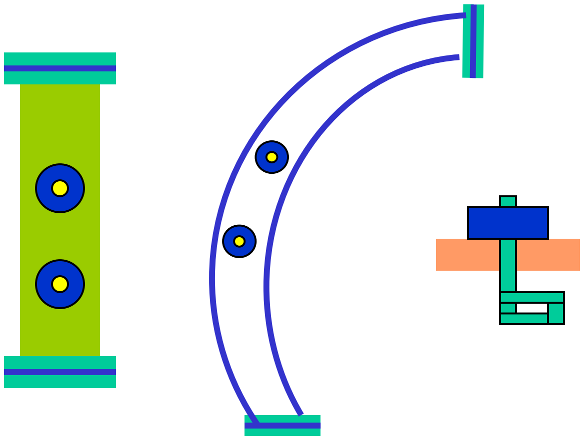
RF Components:

- Power dividers are 4-port hybrids of various coupling (I. E. a 3-dB hybrid splits the input power in half)

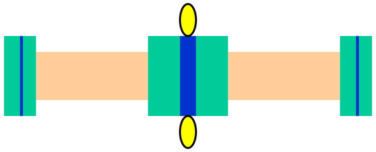


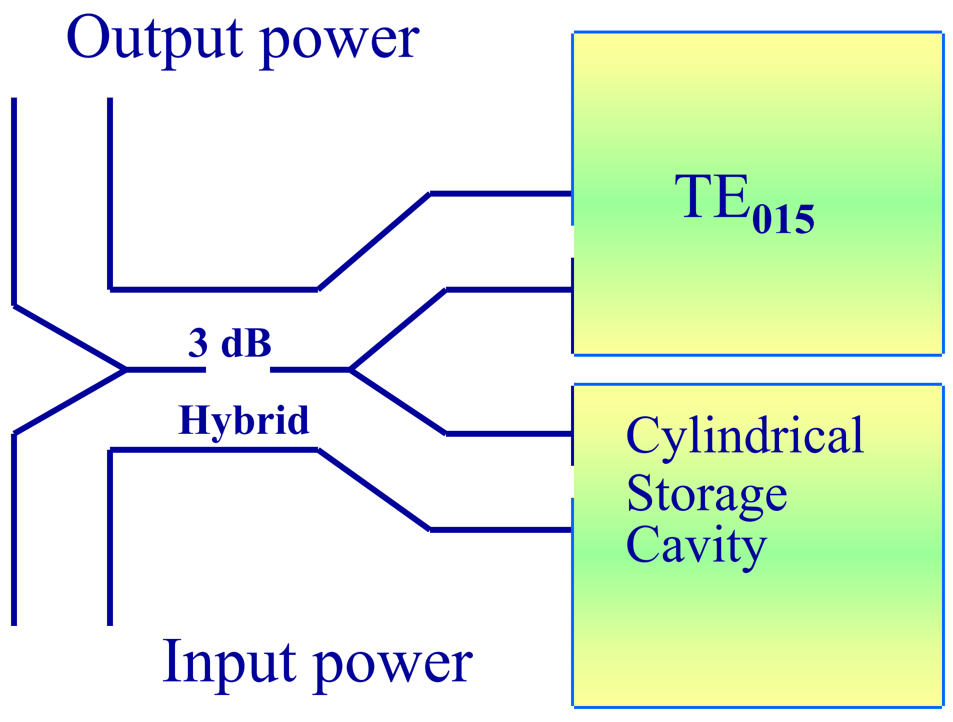
RF Components:

Couplers



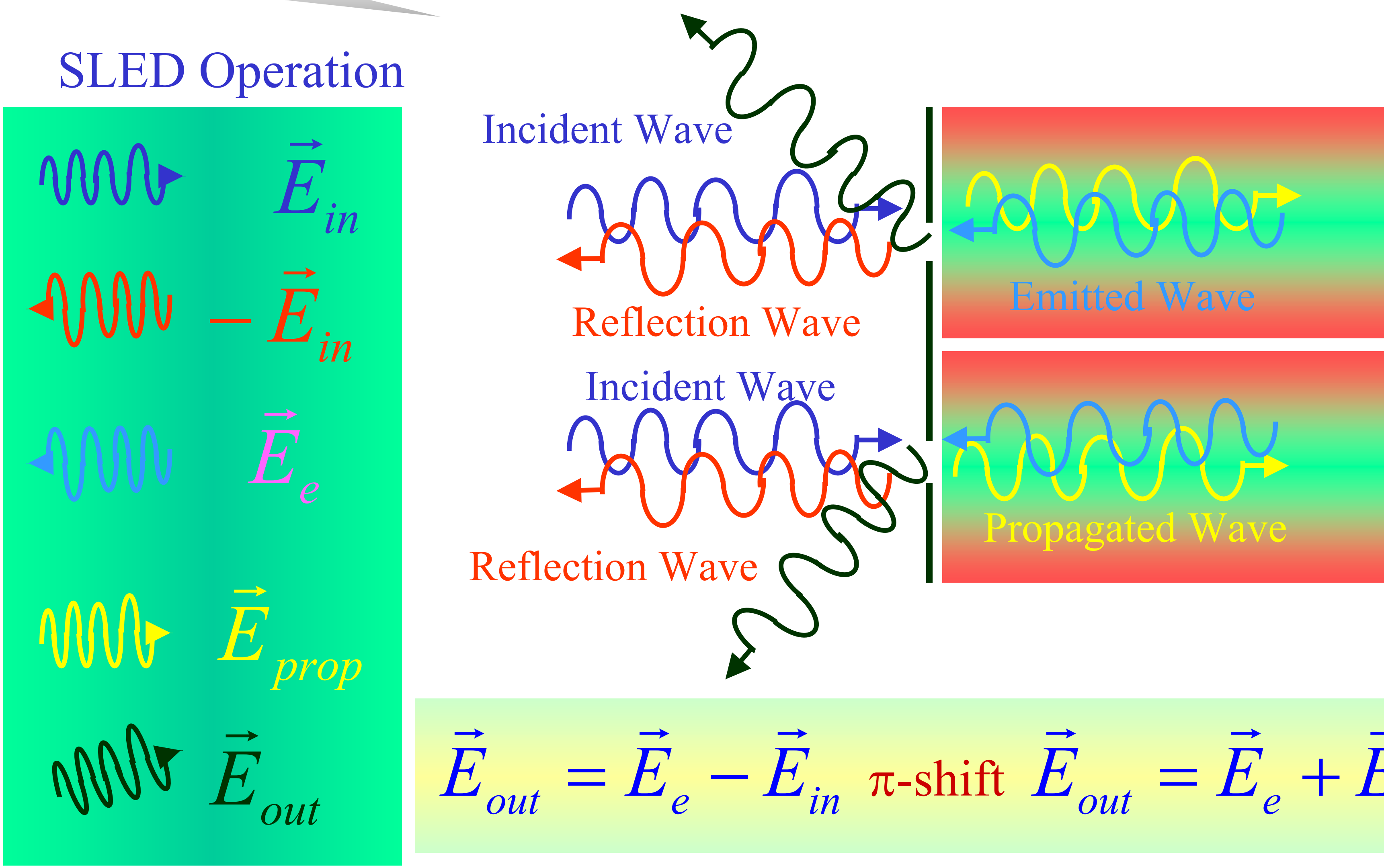
Window




Output power
TE015
3 dB
Hybrid
Cylindrical
Storage
Cavity
Input power

SLED

SLED Operation



$$\vec{E}_{out} = \vec{E}_e - \vec{E}_{in} \quad \pi\text{-shift} \quad \vec{E}_{out} = \vec{E}_e + \vec{E}_{in}$$

$$E_{\max} = E_{out}(t = t_1) = \alpha(1 - e^{-\frac{t_1}{T_c}}) + 1$$

Typical numbers :

$$\alpha = \frac{2\beta}{1+\beta} = \frac{10}{6} = 1.66$$

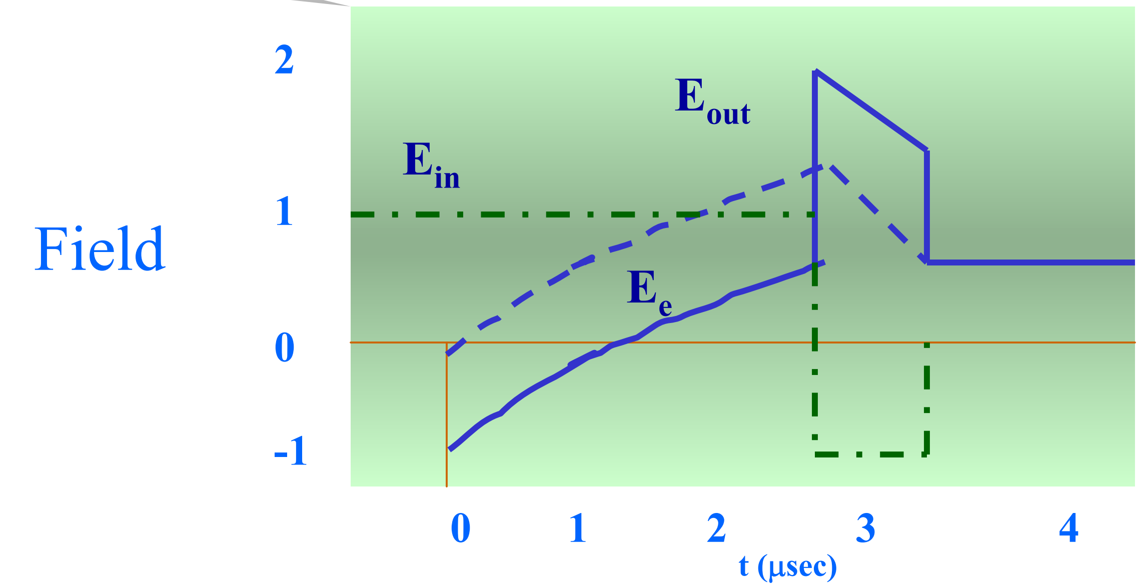
$$Q_L = \frac{Q_0}{1+\beta} = \frac{10^5}{6} \Rightarrow Q_L = 16667$$

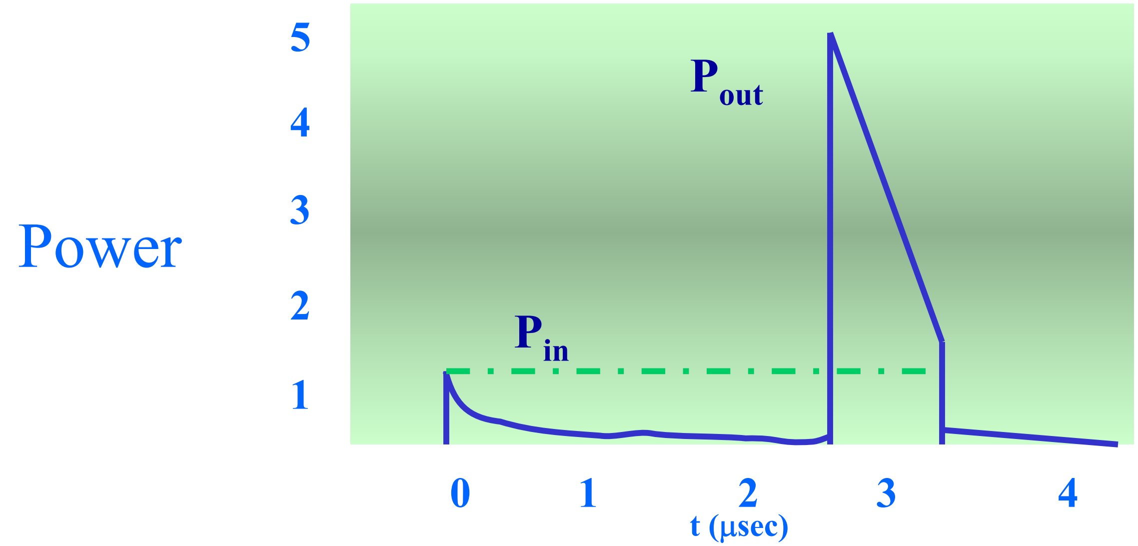
$t_2 \approx 3.5\,\mu\,\text{sec}$, Klystron Pulse Width $T_c = 1.86\,\mu\,\text{sec}$, $T_f = 0.82\,\mu\,\text{sec}$

$$t_1 = 2.68\,\mu\,\text{sec}$$

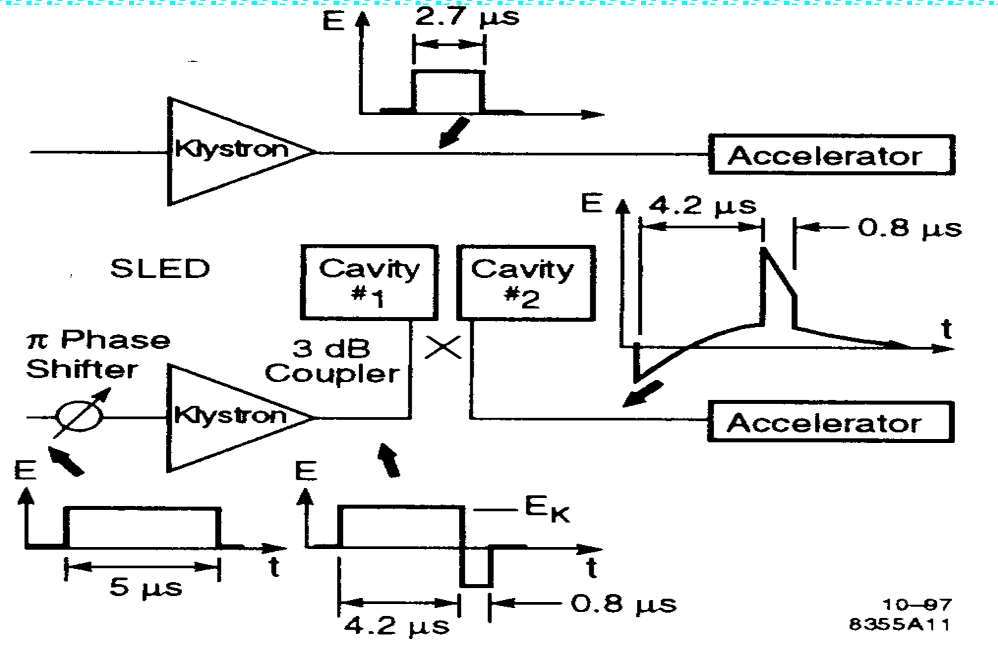
$$E_{\max} \approx 2.3$$

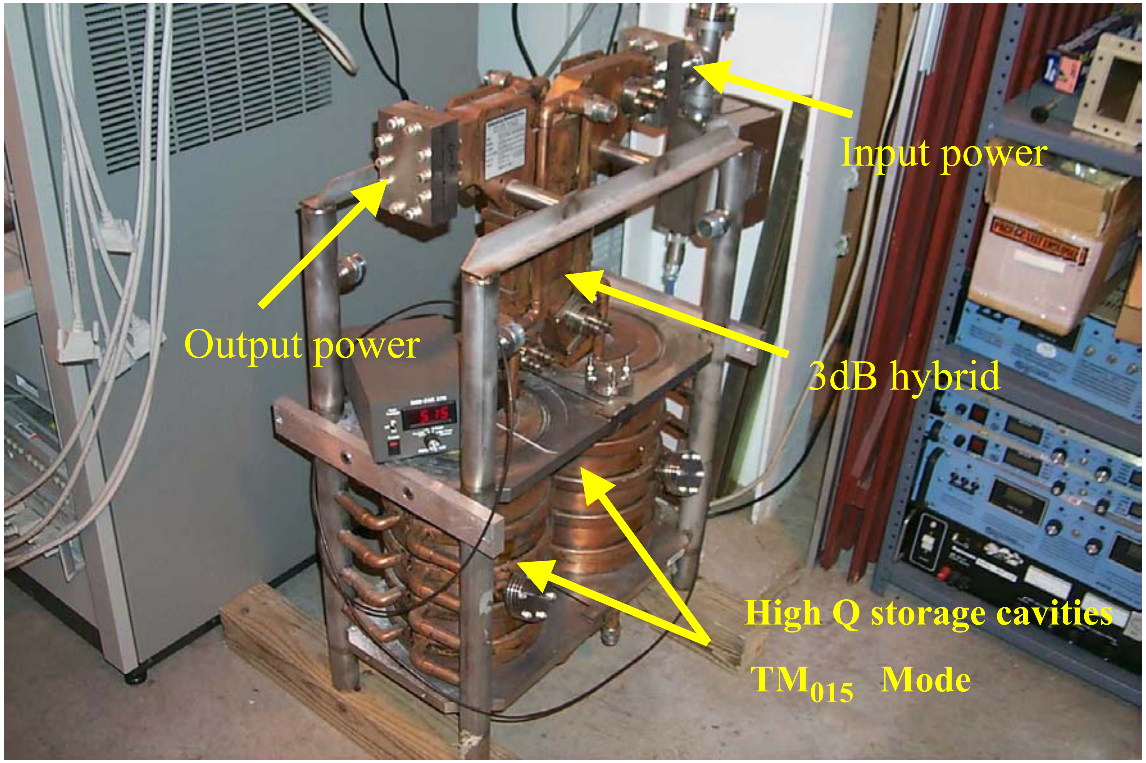
$$P \propto E_{\max}^2 \approx 5.3$$


Field
2
1
0
-1
E_{out}
E_{in}
E_e
0 1 2 3 4
t (μsec)


Power
5
4
3
2
1
P_{out}
P_{in}
0 1 2 3 4
t (μsec)

SLED


E
2.7 µs
Klystron
Accelerator
E
4.2 µs
0.8 µs
t
SLED
Cavity #1
Cavity #2
π Phase Shifter
3 dB Coupler
Klystron
Accelerator
E
E
E_K
t
t
5 µs
4.2 µs
0.8 µs
10–97
8355A11


Input power
Output power
3dB hybrid
High Q storage cavities
TM_{015} Mode

SLED UNIT

Some Basic RF Parameters of Accelerating Structures:

1. The shunt impedance per unit length is a measure of excellence of a structure as an accelerator

$$r_0 = \frac{-E_z^{\,2}}{dp/dz}$$

Higher shunt impedance is desired since it means more accelerating field for a given spent power.

2. The "unloaded" Q-factor is a measure of the merit of rf cavity as a resonator.

$$Q_0 = \frac{-\omega\, w}{dp/dz}$$

3. The ratio of r_0 / Q_0 is a very basic parameter in microwave cavities and structures.

$$r_0 / Q_0 = \frac{E^2{}_{0z}}{\omega\, w}$$

$$w \propto E^2{}_{0z} \times cross\text{-}sectional area$$

$$or$$

$$w \propto E^2{}_{0z} \times \omega^{-2}$$

$$r_0 / Q_0 \propto \omega$$

4. Group velocity, v_g , is the velocity at which rf energy flows through the accelerator. It strongly depends on the ratio of disk aperture diameter (2a) to cavity diameter (2b):

$$v_g/c \approx K(a/b)^4$$

v_g is an important parameter:

4.1. The fill time, time that is required to fill the accelerator with rf energy depends upon group velocity

$$t_f = l/v_g$$

4.2. The power flow into the structure and the energy stored per unit length of the structure are interrelated to v_g

$$w = P / v_g$$

Since $w \propto E^2_{0z}$, lower value of group velocity is preferred from the point of view of obtaining maximum accelerating fields for a given power flow.

4.3 In general, decreasing v_g, results in increasing r_0 and decreasing Q_0 which results in increasing r_0 / Q_0

Phase velocity - is the velocity of light (plane wave) in the evacuated waveguide.

$$v_p = \omega / \beta \succ \omega / \kappa = 1 / \sqrt{\mu\varepsilon}$$

This is greater than the speed of light at which the particles travel.

Need to *slow down* the phase velocity inside the structure so that it is synchronous with particle velocity.

Voltage Standing-Wave-Ratio VSWR

VSWR is defined as the ratio of $E_{max} : E_{min}$

$$E_{max} = V_i + V_r = V_i\,(1+P)$$

$$E_{min} = V_i - V_r = V_i\,(1-P)$$

$$VSWR,\ S = E_{max} / E_{min} = \frac{1+P}{1-P}$$

If p=0 (matched line), S=1

If p=1 (open or short-circuited line, $S = \infty$

Example:

A 400 W amplifier is used to drive the input cavity of the linac klystron. Lets assume that for the HV setting of 300 kV and 290 A, a klystron required 120 W to provide 25 MW of rf power. Suppose that input drive power is transmitted down a 50-Ω loss-free line and is terminated at the input cavity of the klystron which presents a 42- Ω load to the generator.

1) what is the reflected power going back to the generator?

2) What is the excitation power into the 1st cavity of the klystron

$$\text{VSWR, S} = \frac{Z_0}{R_L} = \frac{50}{42} = 1.19$$

Reflection coefficient, $P = \frac{S-1}{S+1} = \frac{0.19}{2.19} = 0.087$

Reflected Power, $P_r = P^2 \times P_i = (0.087)^2 \times 120\ W = 0.90\ W$

Transmitted power to klystron, $P_L = P_i - P_r = 120 - 0.9 = 119.1\ W$

How does one measure rf power?

- Cannot measure high peak power with any power instruments
- Need to sample a portion of the peak power so a peak power meter can be used without damage
- A waveguide coupler inserted in-line with waveguide is used for this measurement
- Coupling loops are used to sample a small portion of the peak power
- A typical forward loop coupling factor is -56 dB
- For a 30 MW peak power, this corresponds to ~75 W (SAFE)
- Attenuation elements can also be added to reduce the peak power for measurement purposes