Linac RF System

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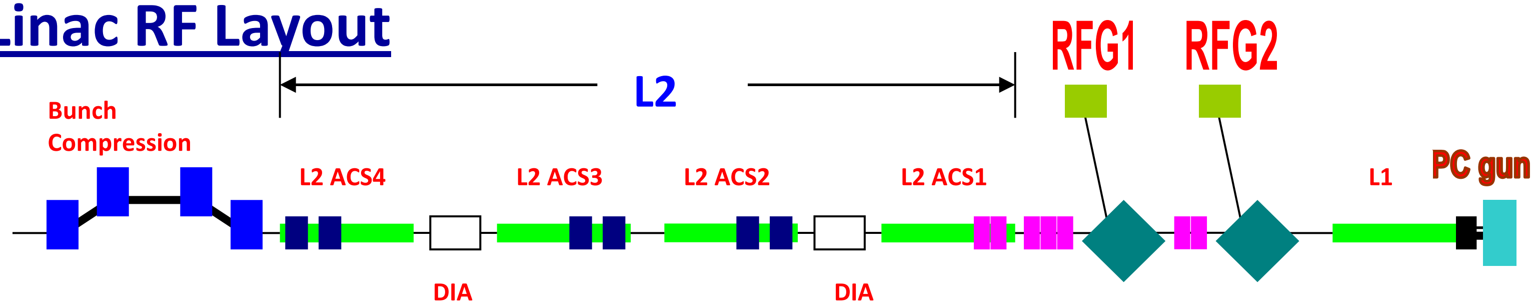
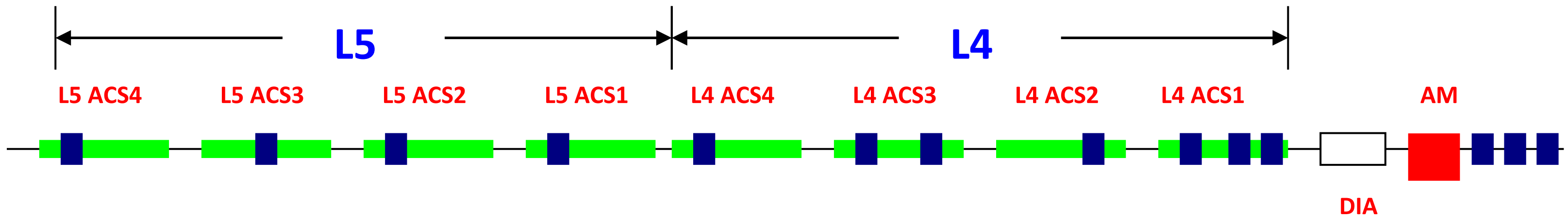
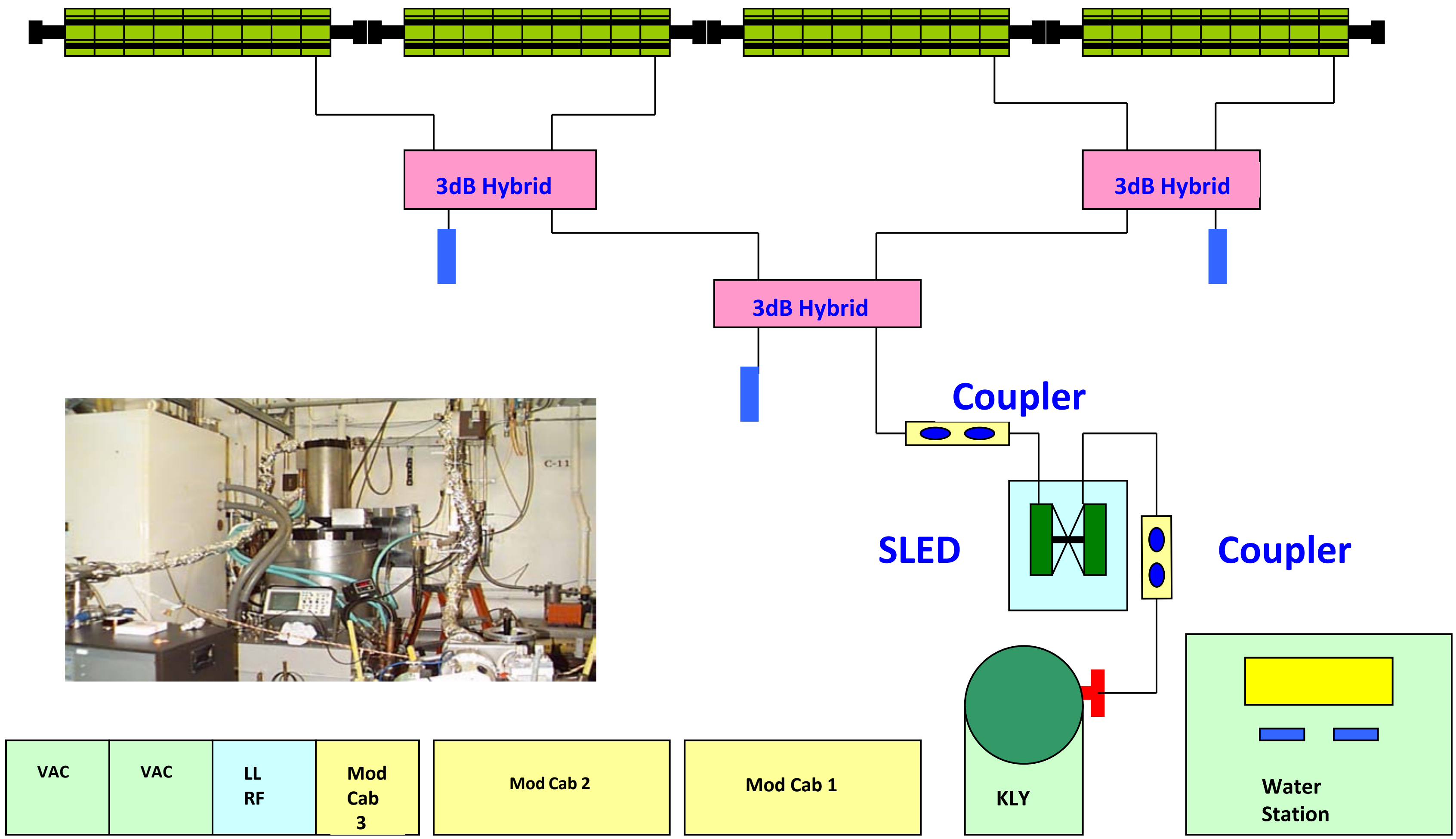
Outline:

- Linac Layout
- Power system
- Klystron Operation
- RF Components
- RF Breakdown and RF Conditioning
- Measurement Techniques
- Some Examples

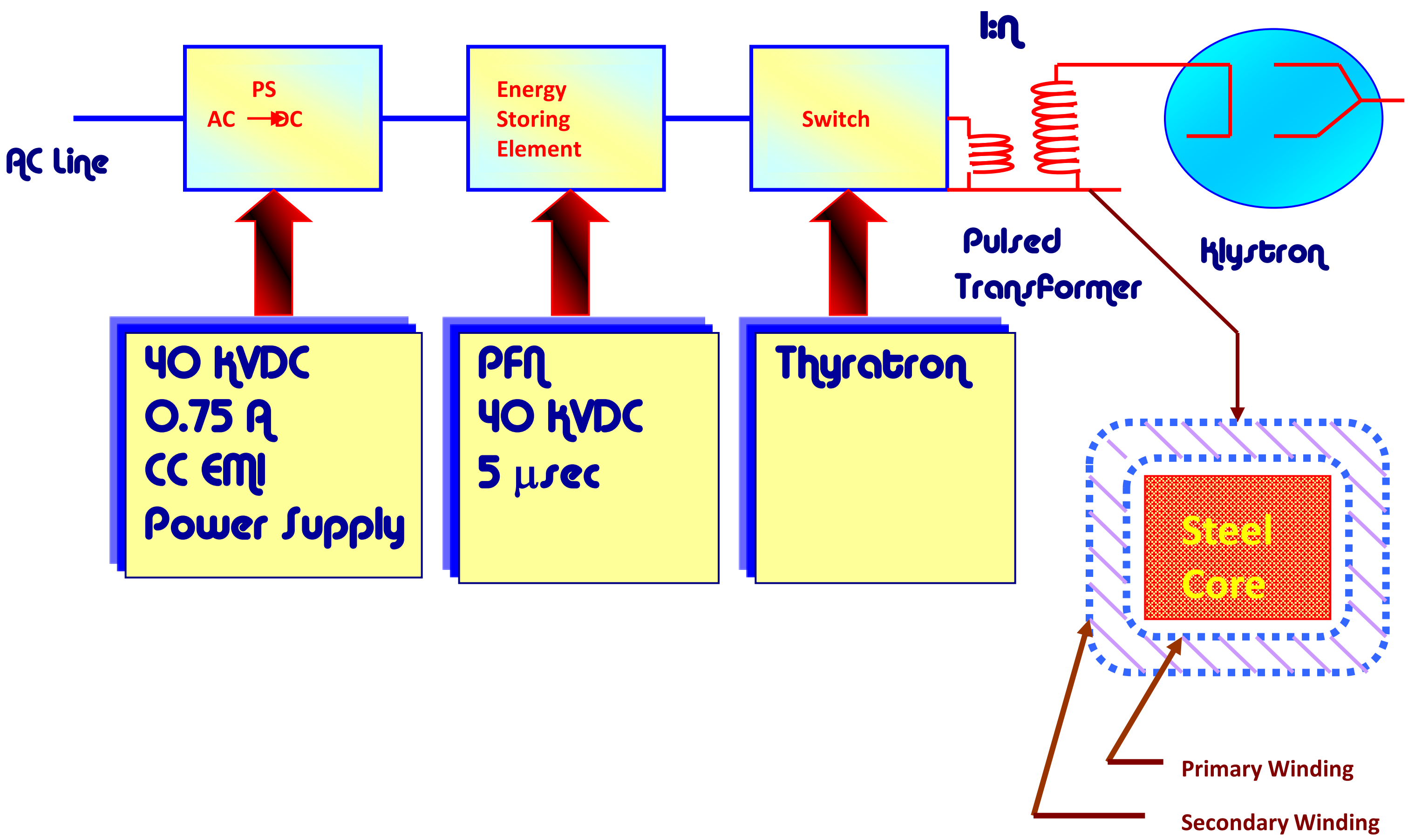
Linac RF Layout



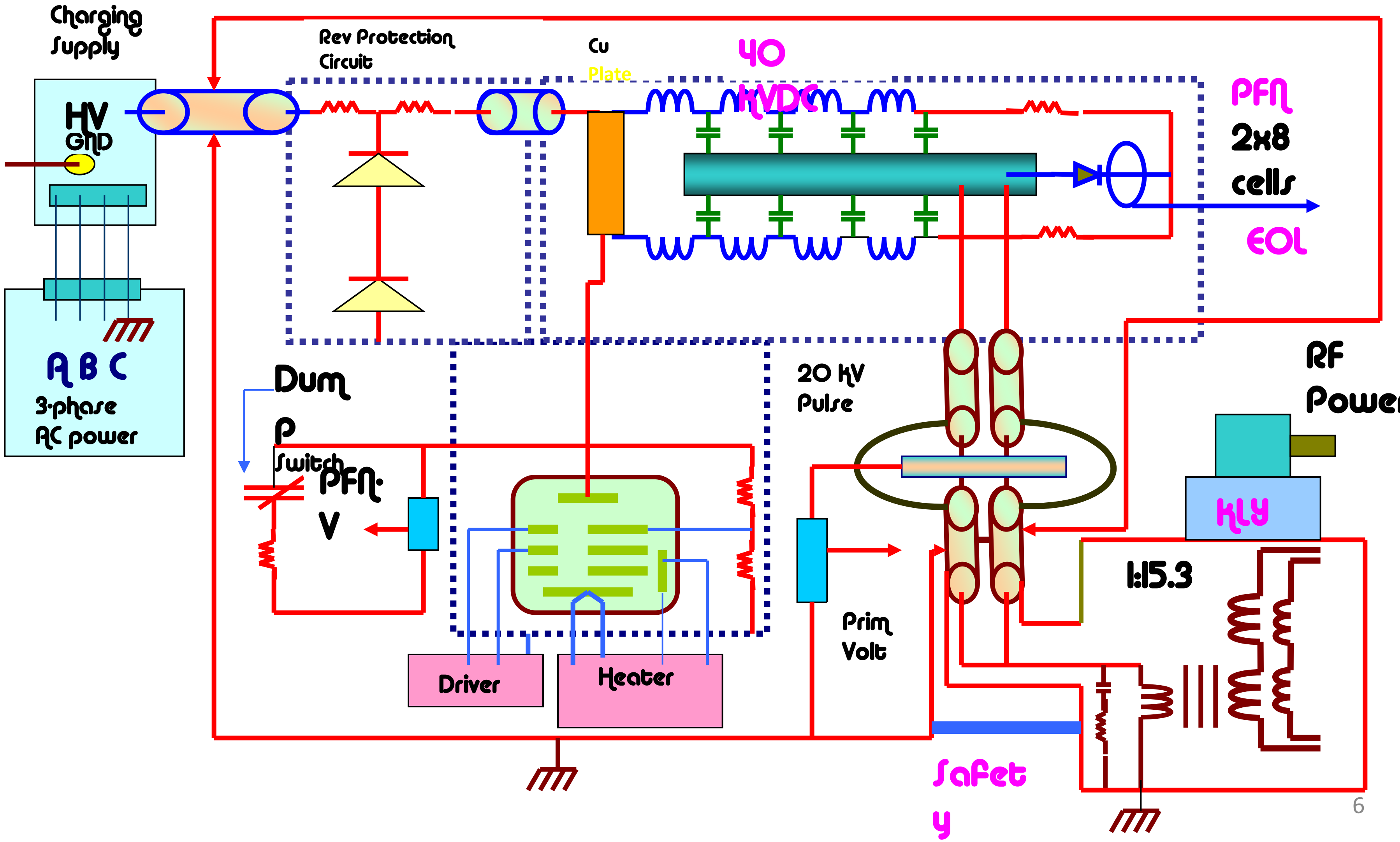


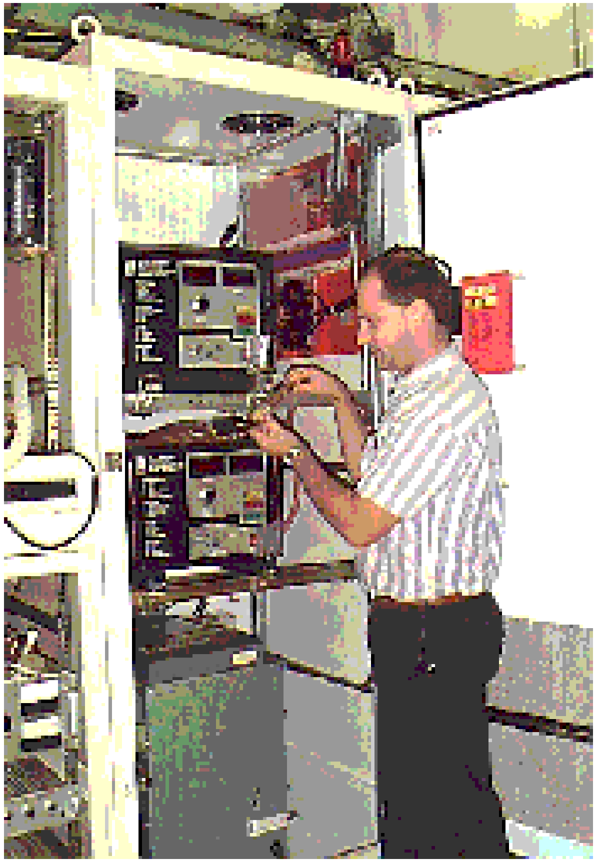

3dB Hybrid
3dB Hybrid
3dB Hybrid
Coupler
SLED
Coupler
VAC
VAC
LL
RF
Mod
Cab
3
Mod Cab 2
Mod Cab 1
KLY
Water
Station

Linac Modulator System

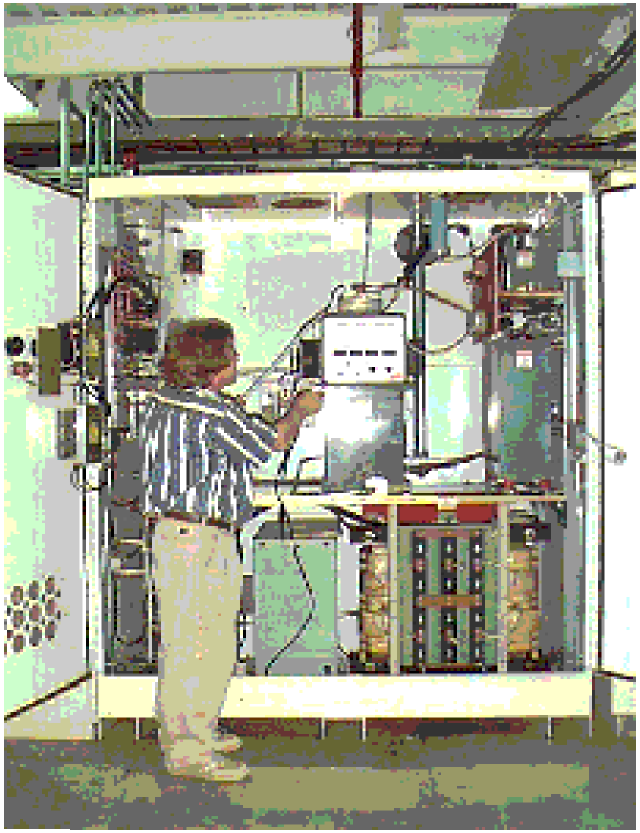


APS Linac Modulator 300 kV/300 A

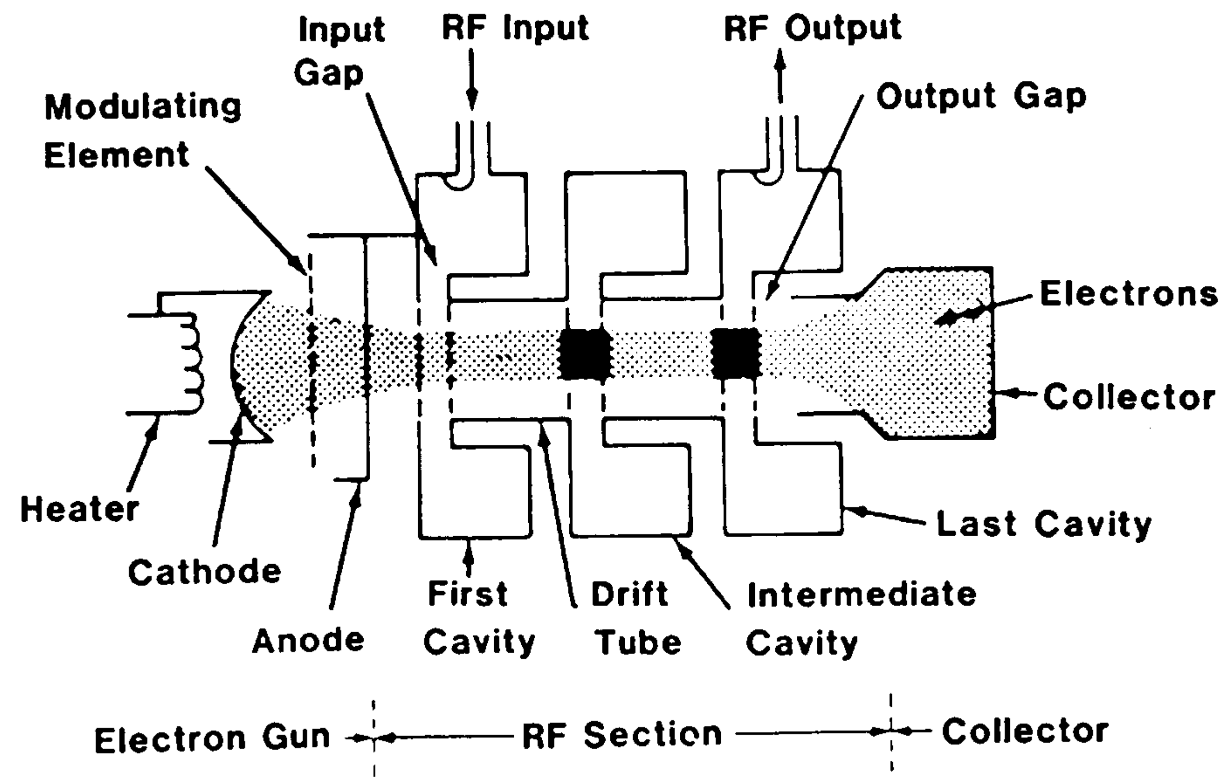




One single-width cabinet contains two constant-current power supplies.

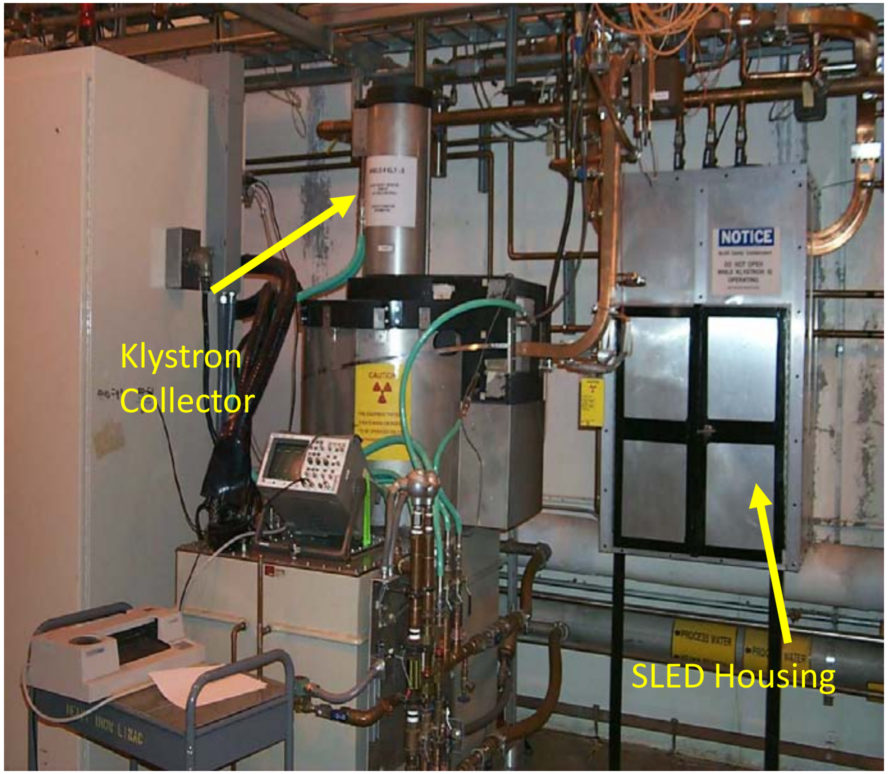


A double-width high voltage power supply cabinet contains most of the resonant-charging system.



Input Gap
RF Input
RF Output
Output Gap
Modulating Element
Electrons
Collector
Heater
Cathode
Anode
First Cavity
Drift Tube
Intermediate Cavity
Last Cavity
Electron Gun
RF Section
Collector

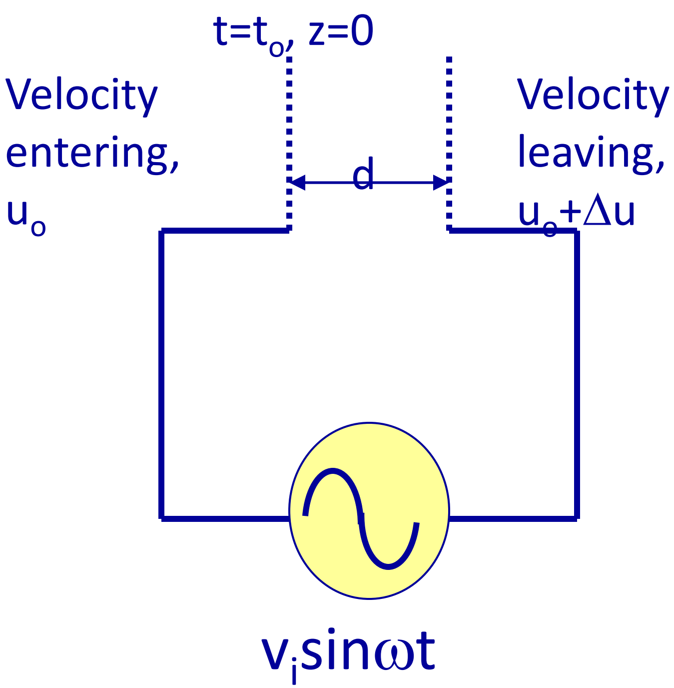
S-Band 35 MW Klystron



Klystron/SLED Unit

WG Coupler at the output of the klystron

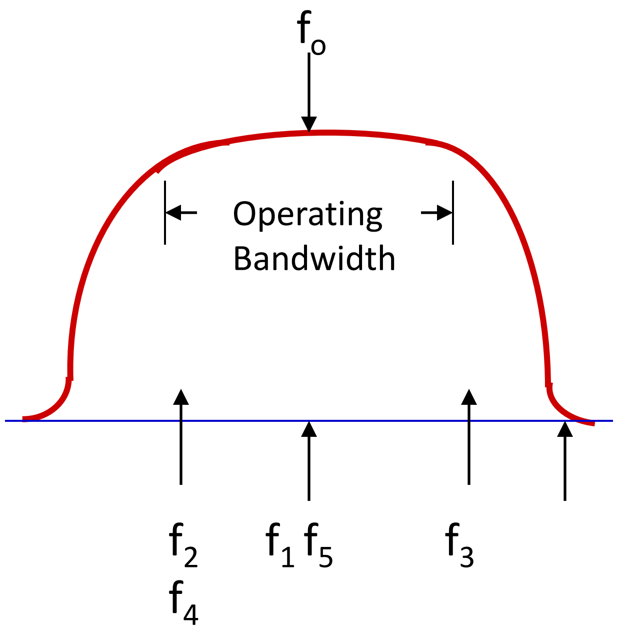
Velocity Modulation



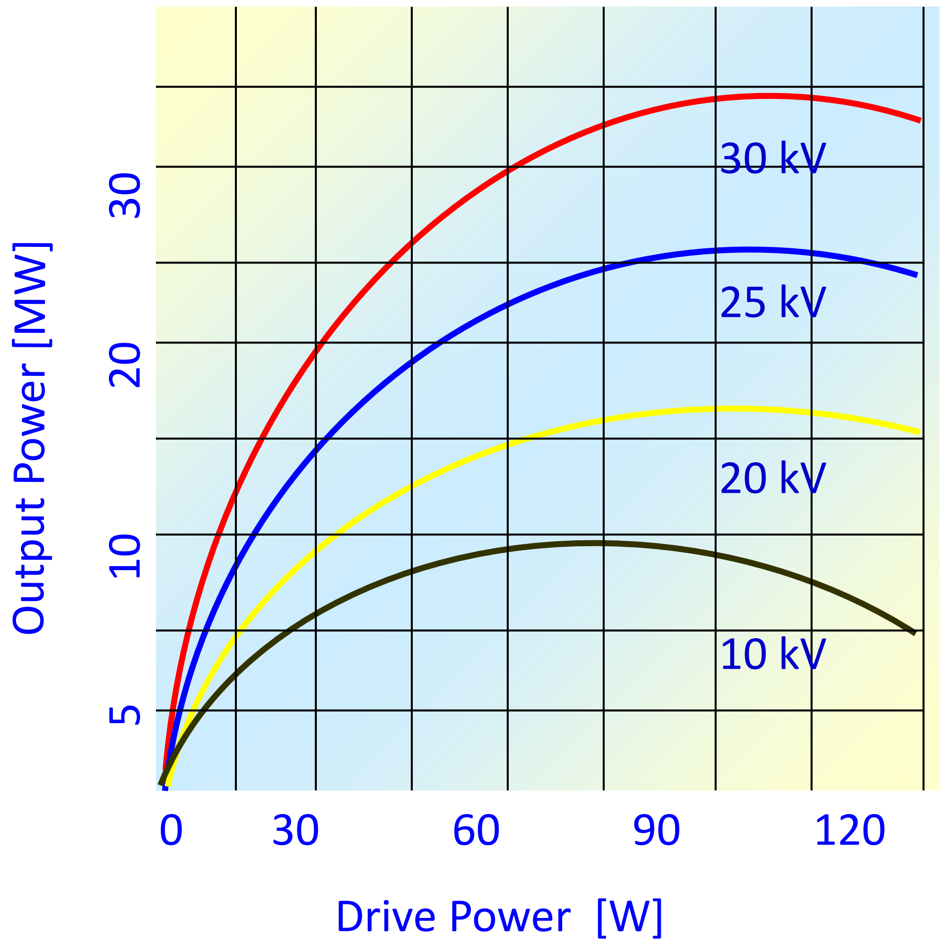
When electrons are passed through the modulating field, some electrons have their velocities increased and some will have their velocities decreases when the voltage is reversed.

As the electrons leave the gap, those with increased velocities overtake the slower electrons, as a result electron bunching (density modulation) occurs.

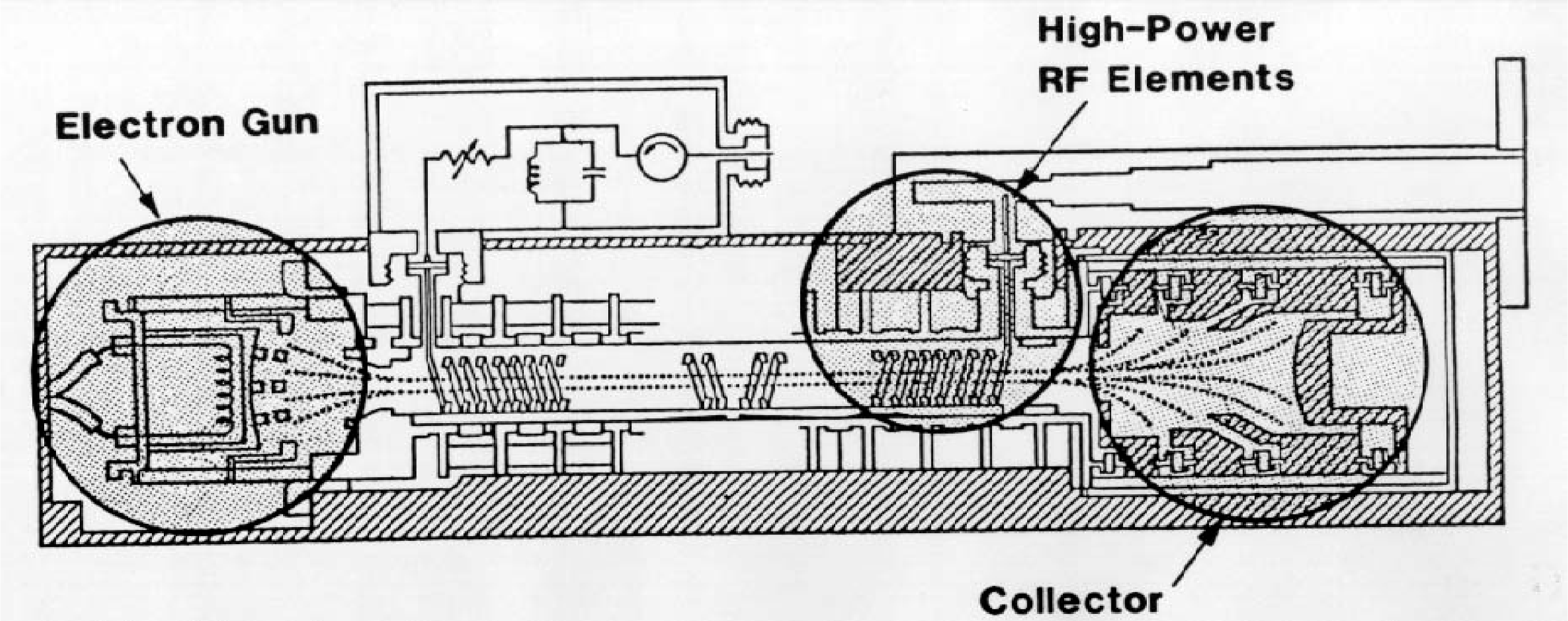
Cavity Bandwidth



Typical Klystron Saturation Curves



Breakdown and Protection



- In the gun (between electrodes,between leads or from electrodes or leads to ground)
- In the collector
- In high-power portion of the RF structure

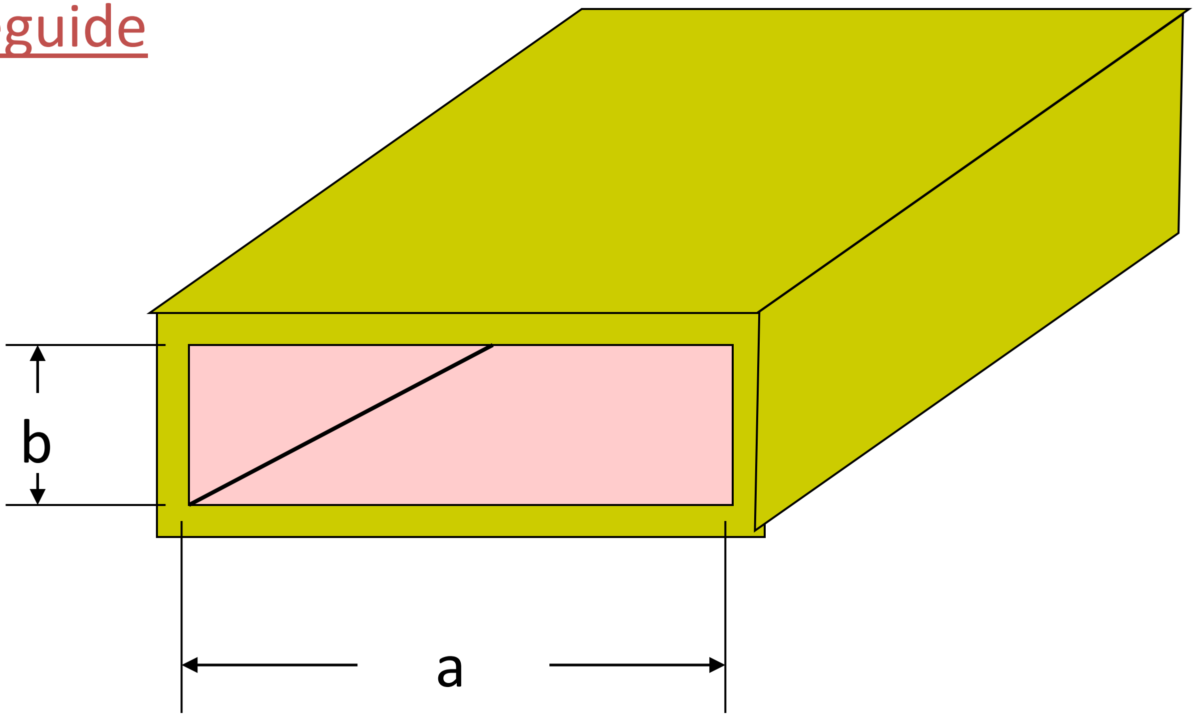
RF Components:

- Driver amplifier to power klystron
- Klystron is used to generate high peak power (A small accelerator)
- Need to transport power to the accelerating structure
- Waveguide is used (under vacuum) to propagate and guide electromagnetic fields
- Windows (dielectric material, low loss ceramic) are used to isolate sections of the waveguide
- Termination loads (water loads) are used to provide proper rf match and to absorb wasted power
- Power splitters are used to divide power in different branches of the waveguide run

Rectangular Waveguide

Cut-off frequency:

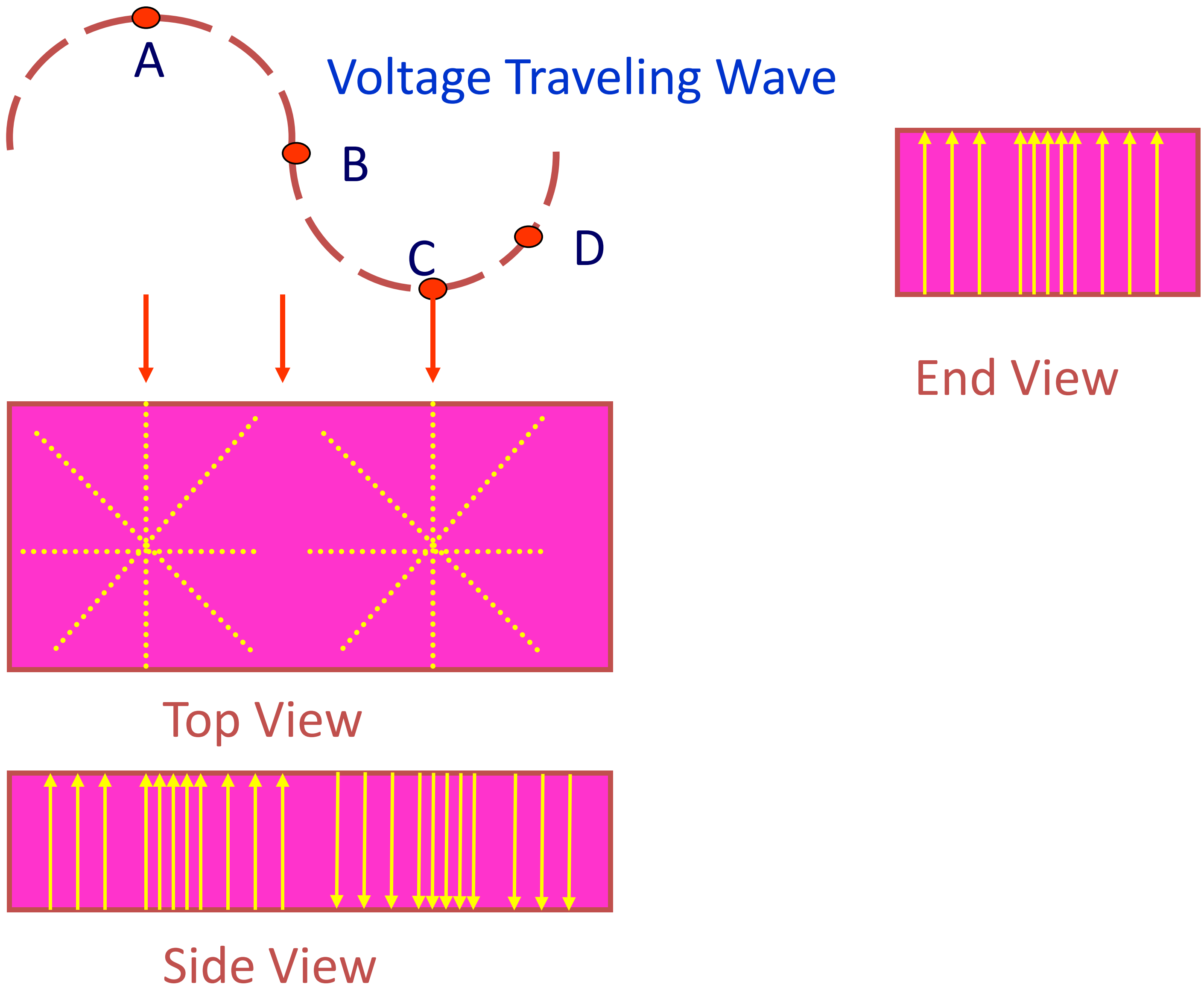
$$f_c = \frac{c}{2a}$$



For S-band:

$$a = 8\,cm$$

$$f_c = \frac{3\times10^{10}\,cm/\sec}{16cm} = 1.875\,GHz$$


A
B
C
D
Voltage Traveling Wave
End View
Top View
Side View

Guide Wavelength:

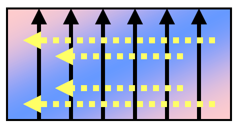
$$\lambda_g = \frac{\lambda}{\sqrt{1-\left(\frac{f_c}{f}\right)^2}}$$

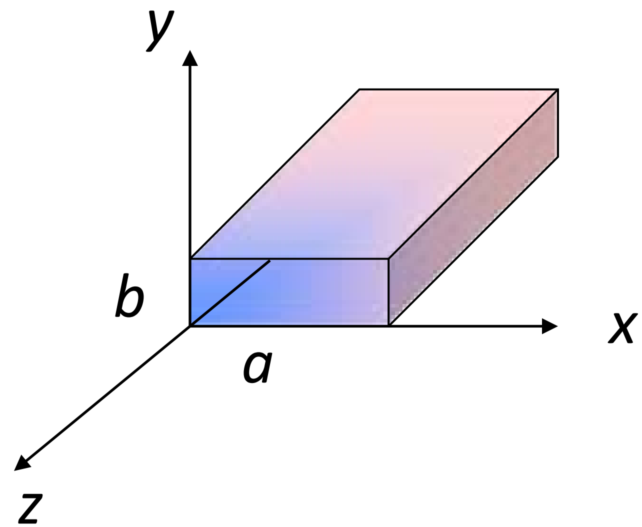
Using $f_c = 1.875\,GHz,$

$$\lambda_g = \frac{10.5\,cm}{\sqrt{1-\left(\frac{1.875\,GHz}{2.856\,GHz}\right)^2}} = 18.5\,cm$$

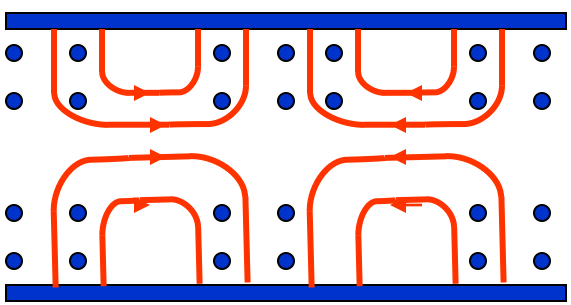
Waveguide Propagation Modes

TE - Transverse Electric Field





TM - Transverse Magnetic Field



E-field

H-field

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

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

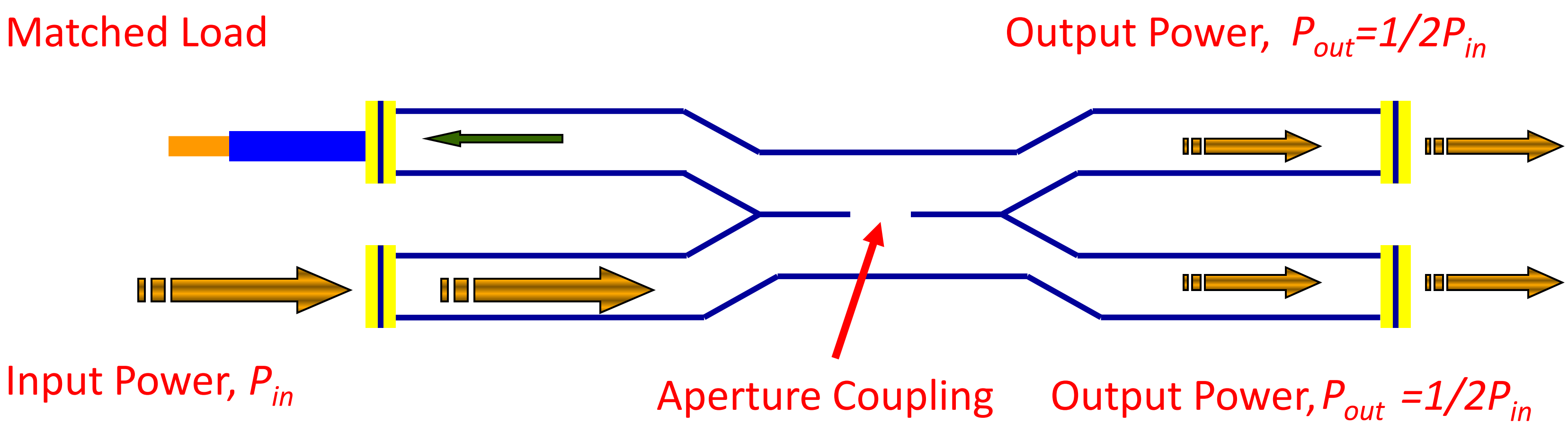
$$\beta = \left(\kappa_0{}^2 - \kappa_c{}^2\right)^{1/2}$$

$$\beta \equiv real \Rightarrow propagating \ \mathrm{mod}\, e$$

$$\beta \equiv imaginary \Rightarrow evanescent \ \mathrm{mod}\, e$$

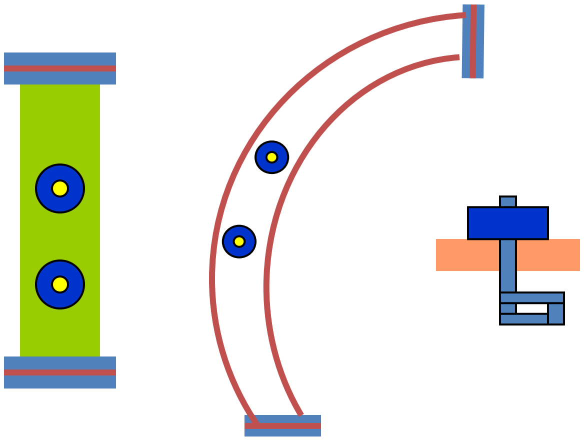
RF Components:

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

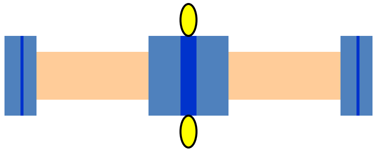


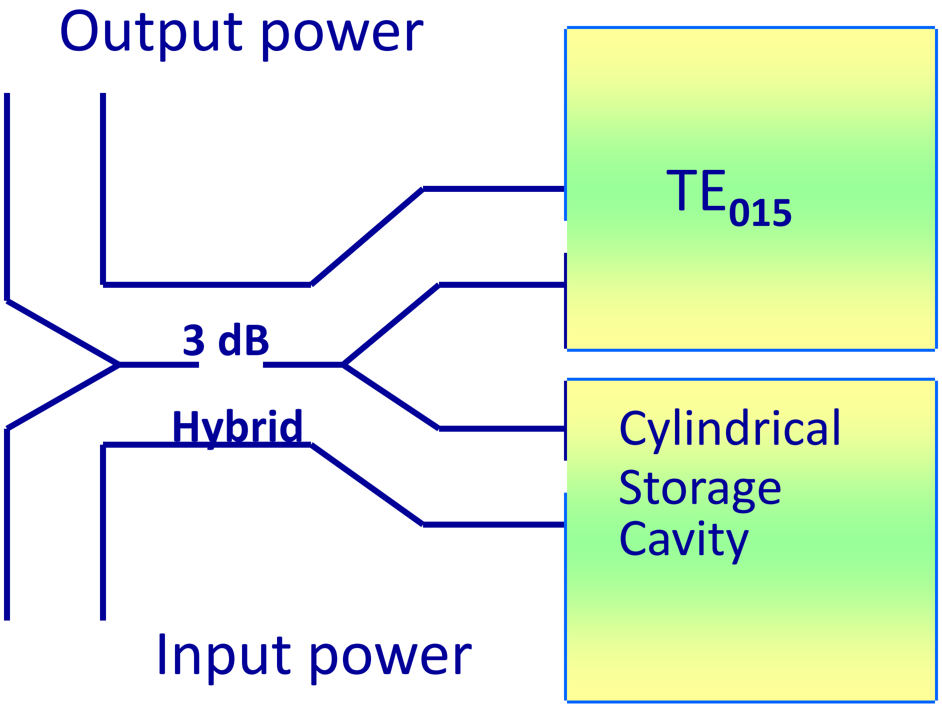
RF Components:

Couplers



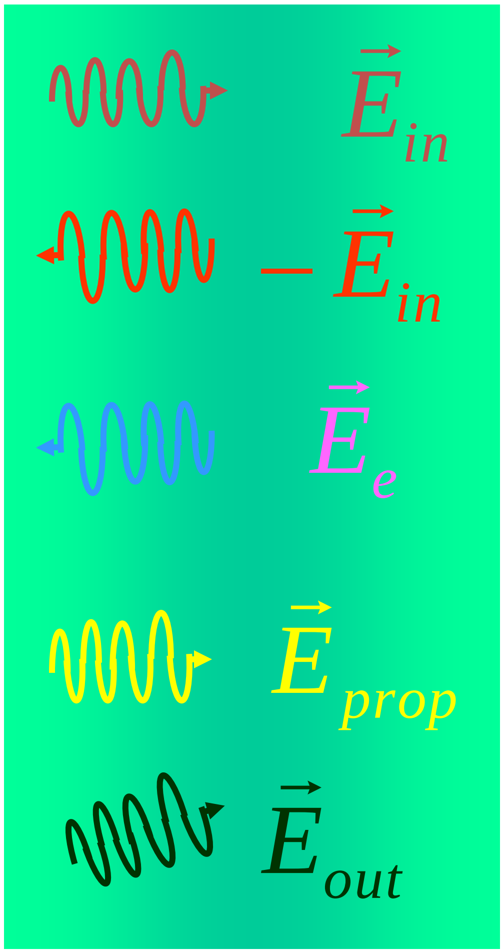
Window

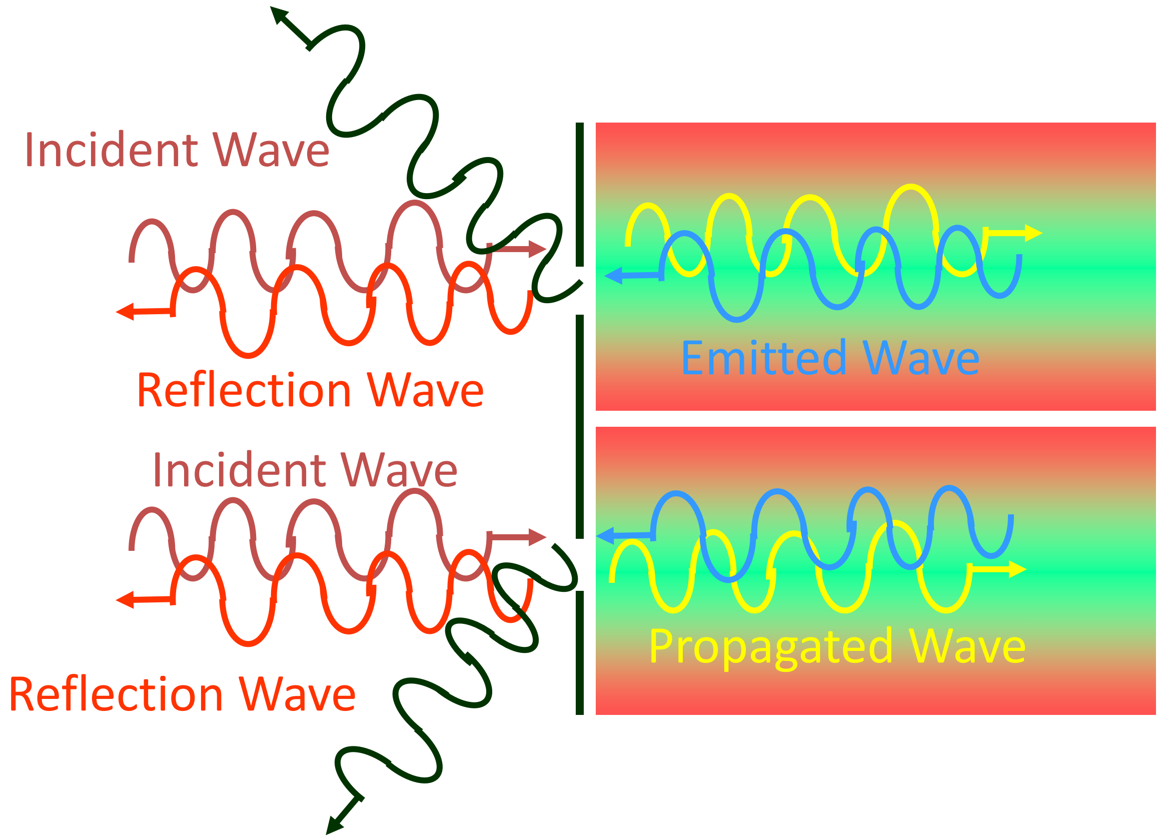



Output power
TE015
3 dB
Hybrid
Cylindrical
Storage
Cavity
Input power

SLED

SLED Operation





$\vec{E}_{out} = \vec{E}_e - \vec{E}_{in}$ π-shift $\vec{E}_{out} = \vec{E}_e + \vec{E}_{in}$

$$P_{in} = P_{out} + P_c + \frac{dU_c}{dt}$$

$$P_{in} = \kappa\, E_{in}^{\;2}$$

$$P_{out} = \kappa\,(E_e + \Gamma E_{in})^2$$

$$\text{Coupling Coeff.} \quad \beta = \frac{P_e}{P_{c(diss)}}$$

$$P_c = \frac{\kappa E_e^{\;2}}{\beta}$$

$$U_c = \frac{Q_0}{\omega} P_c = \frac{Q_0}{\omega} \frac{\kappa E_e^{\;2}}{\beta}$$

$$\frac{dU_e}{dt} = \frac{2\kappa Q_0}{\omega\beta} E_e \frac{dE_e}{dt}$$

At $t = 0, U_c = 0$

$\therefore E_e = 0$

To account for π phase shift, set $\Gamma = -1$

$$E^2{}_{in} = (E_e - E_{in})^2 + \frac{1}{\beta} E_e{}^2 + \frac{2Q_0}{\omega\beta} E_e \frac{dE_e}{dt}$$

$$E^2{}_{in} = E_e{}^2 + E_{in}^2 - 2E_e E_{in} + \frac{1}{\beta} E_e{}^2 + \frac{2Q_0}{\omega\beta} E_e \frac{dE_e}{dt}$$

$$E_{in}{}^{2} = E_e{}^{2} + E_{in}^{2} - 2E_e E_{in} + \frac{1}{\beta} E_e{}^{2} + \frac{2Q_0}{\omega\beta} E_e \frac{dE_e}{dt}$$

$$0 = E_e{}^{2} - 2E_e E_{in} + \frac{1}{\beta} E_e{}^{2} + \frac{2Q_0}{\omega\beta} E_e \frac{dE_e}{dt}$$

$$0 = 1 - 2\frac{E_{in}}{E_e} + \frac{1}{\beta} + \frac{2Q_0}{\omega\beta}\frac{1}{E_e}\frac{dE_e}{dt}$$

$$0 = E_e(1 + \frac{1}{\beta}) - 2E_e + \frac{2Q_0}{\omega\beta}\frac{dE_e}{dt}$$

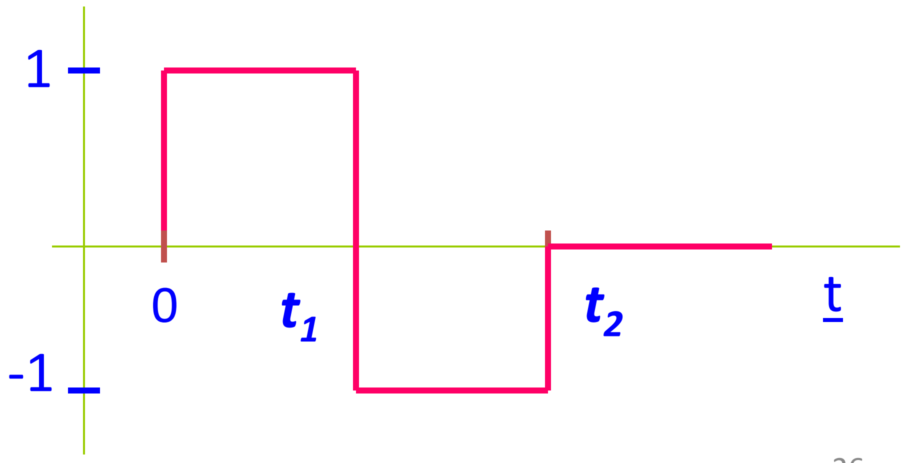
$$\boxed{\frac{dE_e}{dt} + \frac{\omega}{2Q_L} E_e = \frac{\omega\beta}{Q_0} E_{in}}, \quad Q_L = \frac{Q_0}{1+\beta}$$

Defining $T_c = \dfrac{2Q_L}{\omega}$ and $\alpha = \dfrac{2\beta}{1+\beta}$:

$$T_c \frac{dE_e}{dt} + E_e = \alpha E_{in}$$

Input to the SLED is a constant amplitude pulse with phase reversal towards the end.

$$E_{in} = \begin{cases} 1, & 0 \le t \prec t_1 \\ -1, & t_1 \le t \prec t_2 \\ 0, & t_2 \prec t \end{cases}$$



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

Typical numbers :

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

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

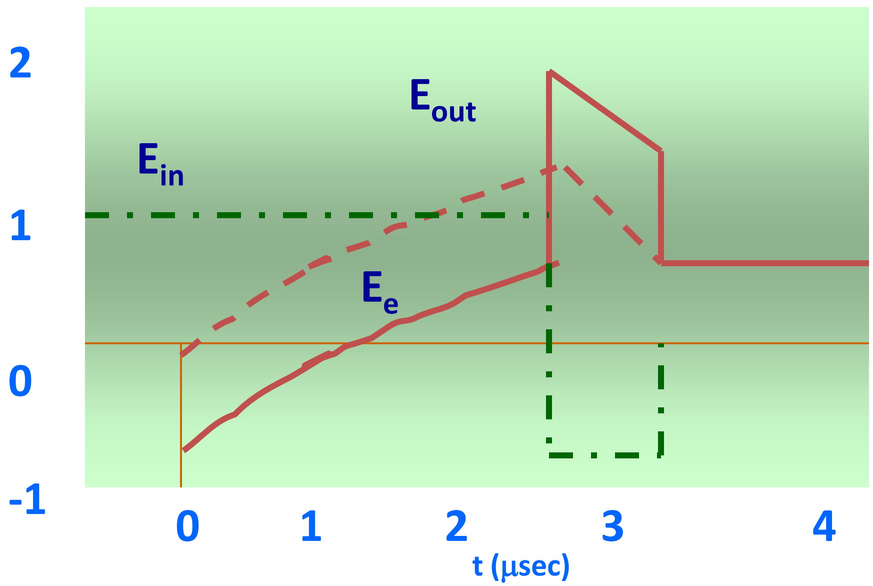
$t_2 \approx 3.5\mu\sec$, KlystronPulseWidth $T_C = 1.86\mu\sec$, $T_f = 0.82\mu\sec$

$t_1 = 2.68\mu\sec$

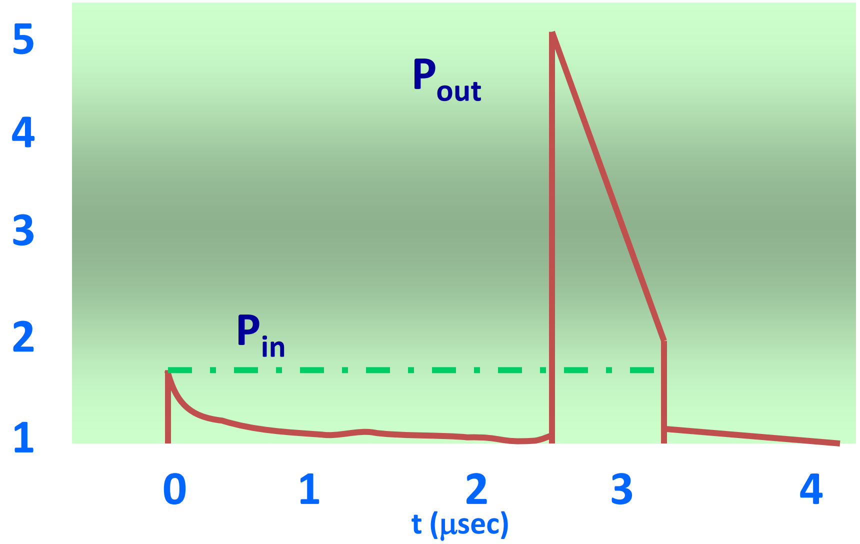
$E_{\max} \approx 2.3$

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

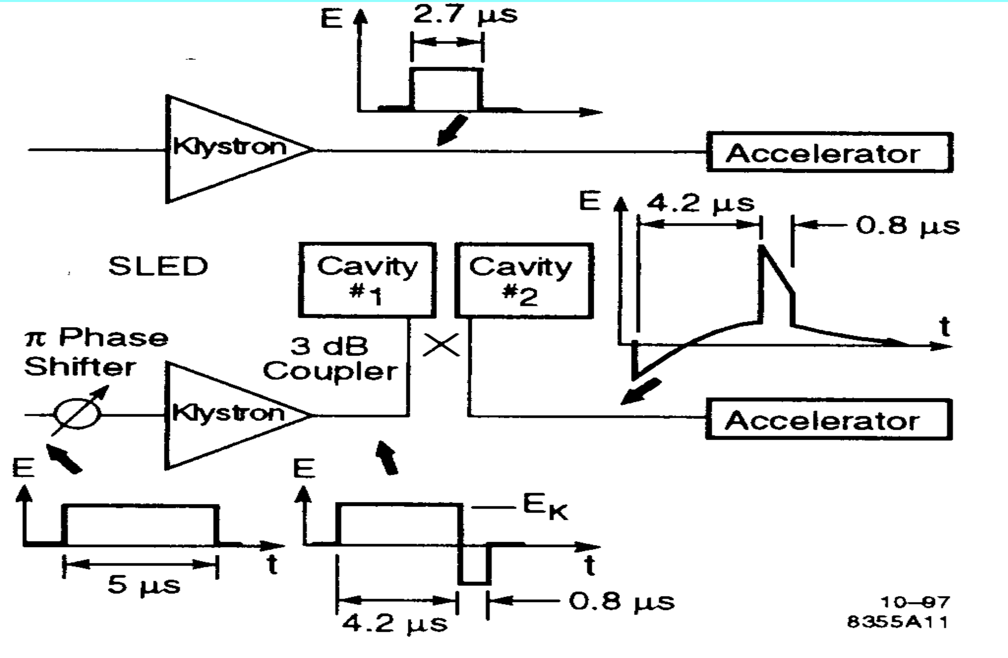
Field



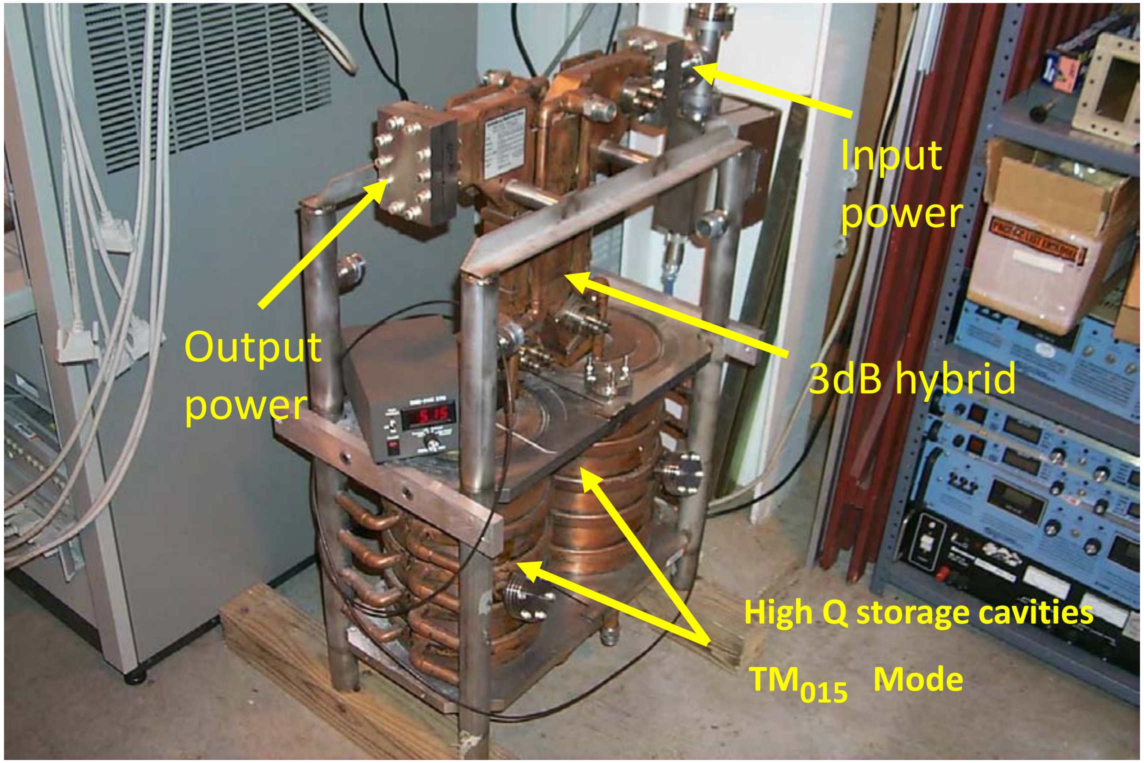
Power



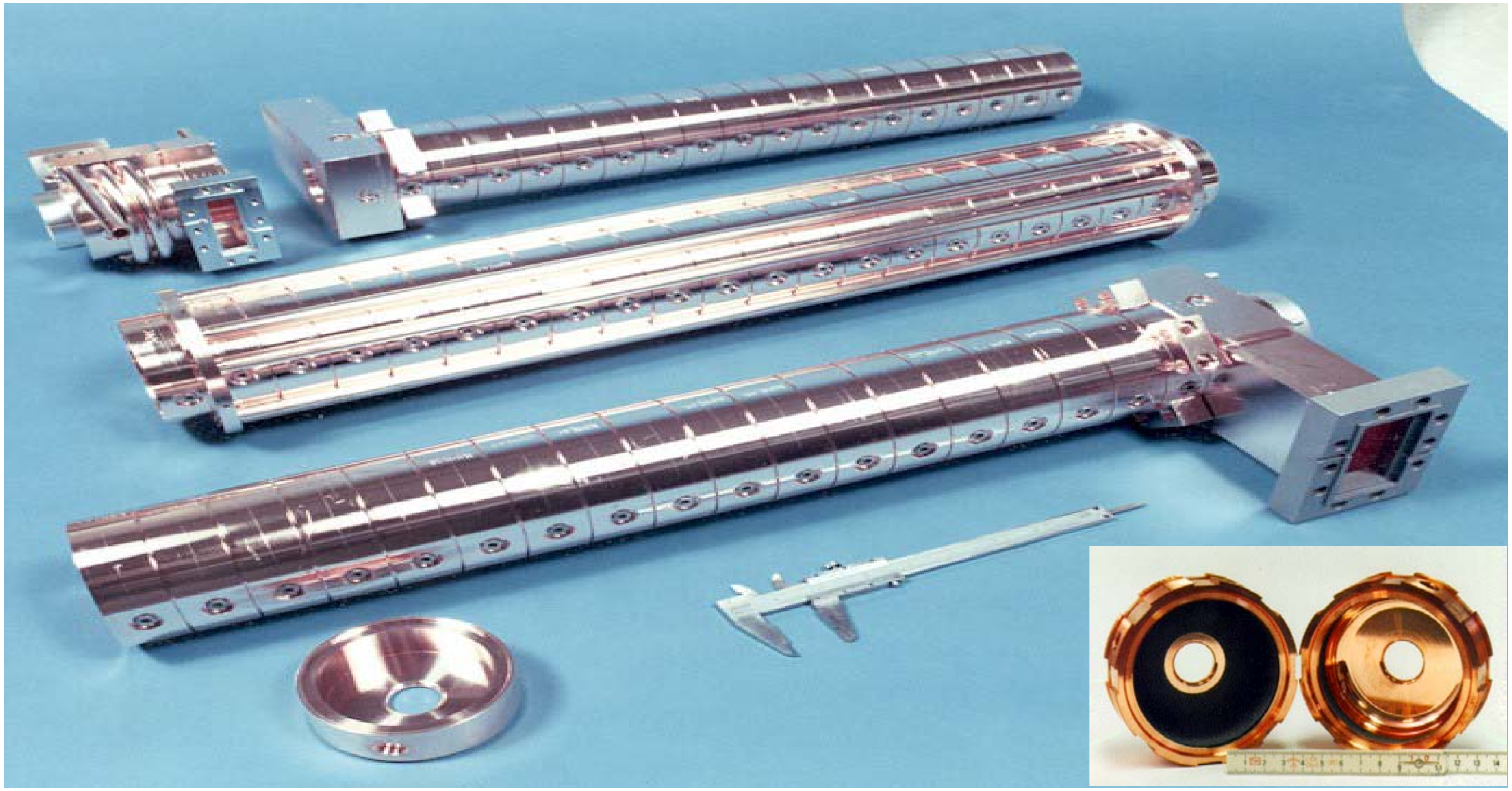
SLED



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

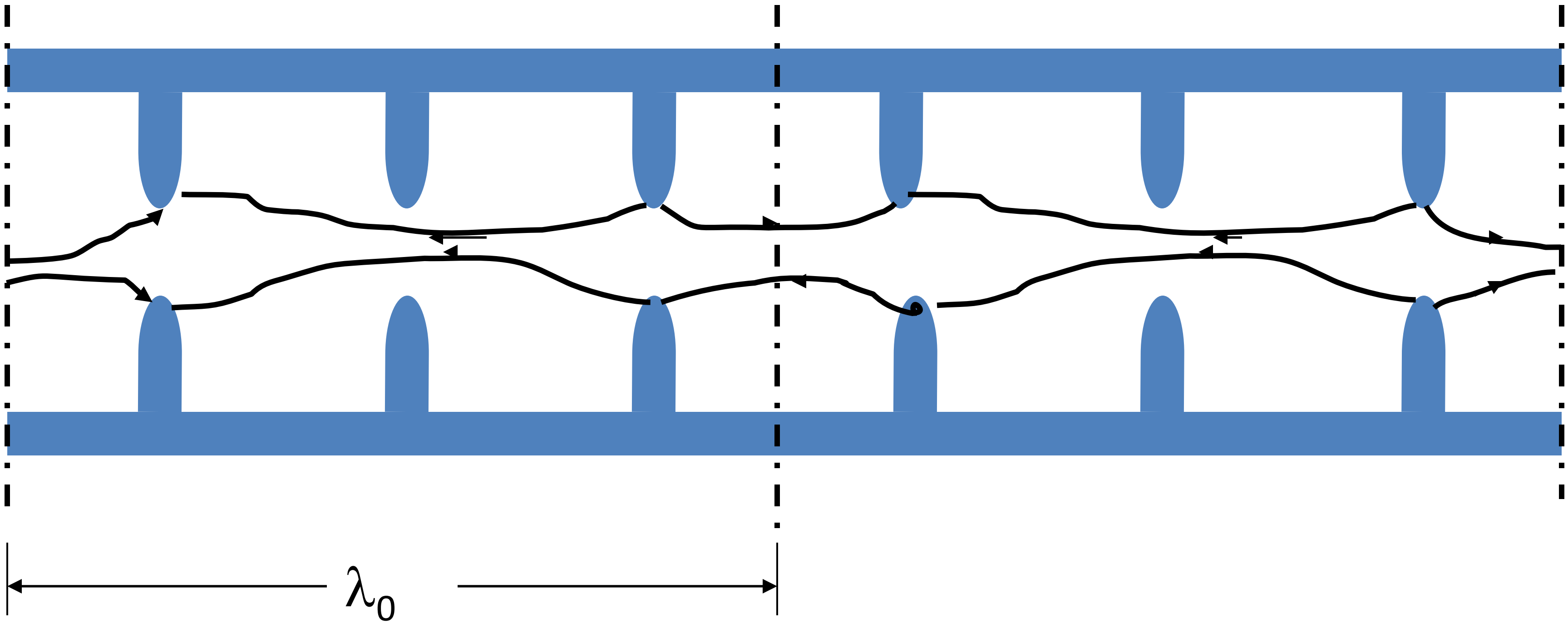

Input
power
Output
power
3dB hybrid
High Q storage cavities
TM$_{015}$ Mode

SLED UNIT

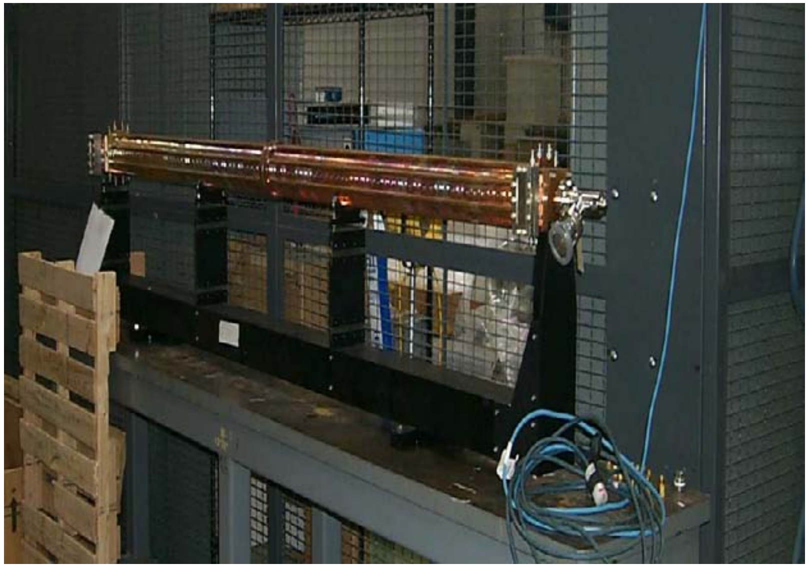


Disk-Loaded Constant Gradient S-Band Structure

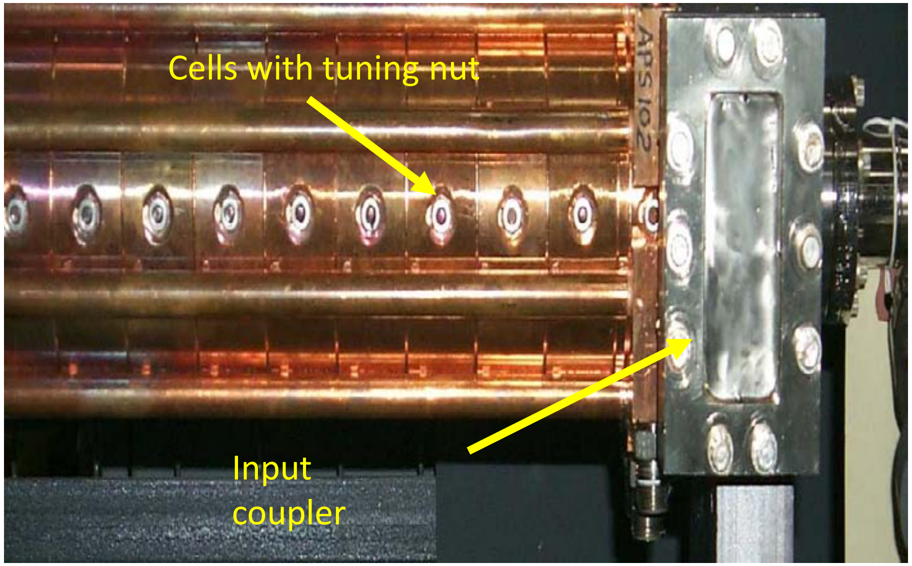
Accelerating Structure



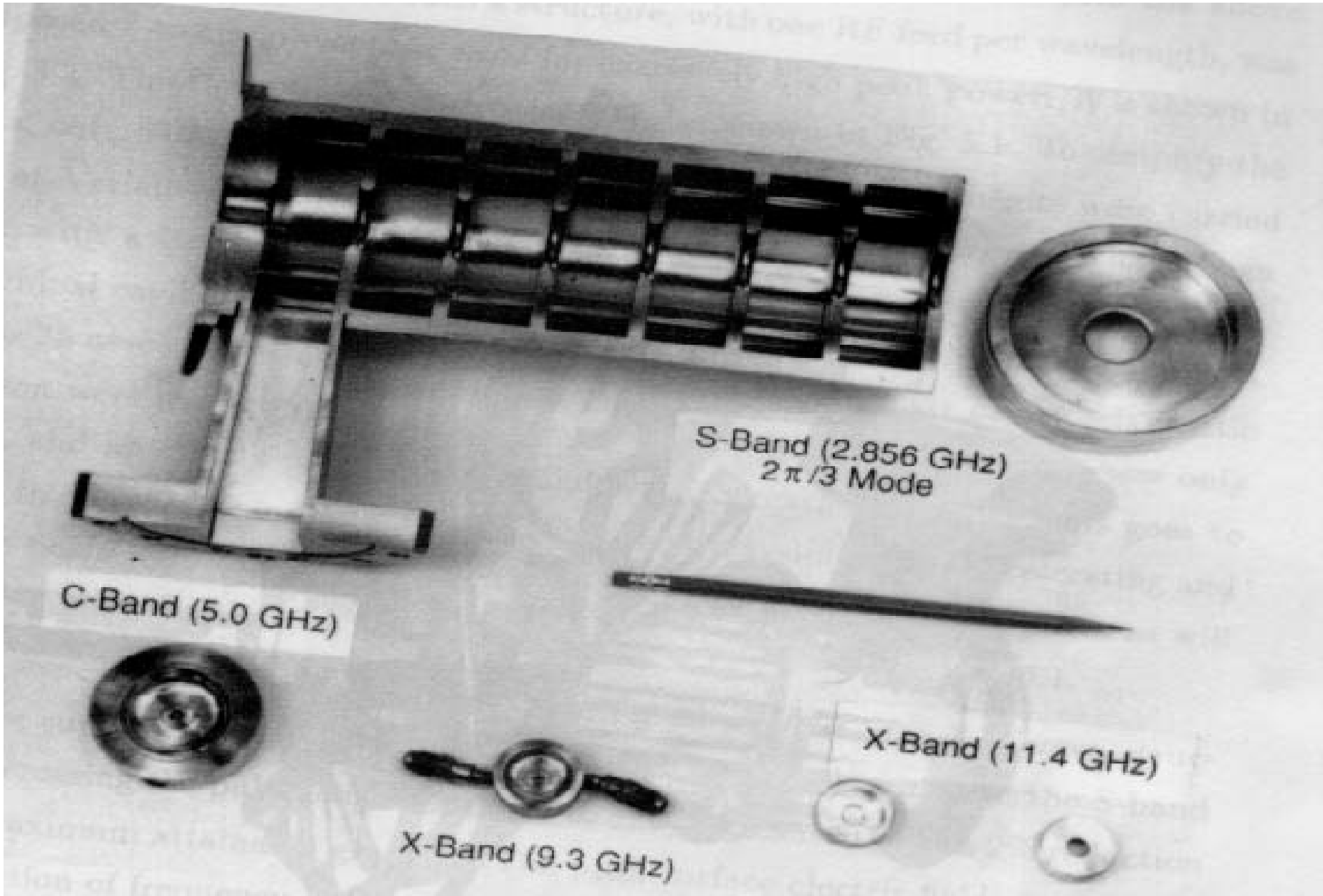
2π/3 phase shift per cell

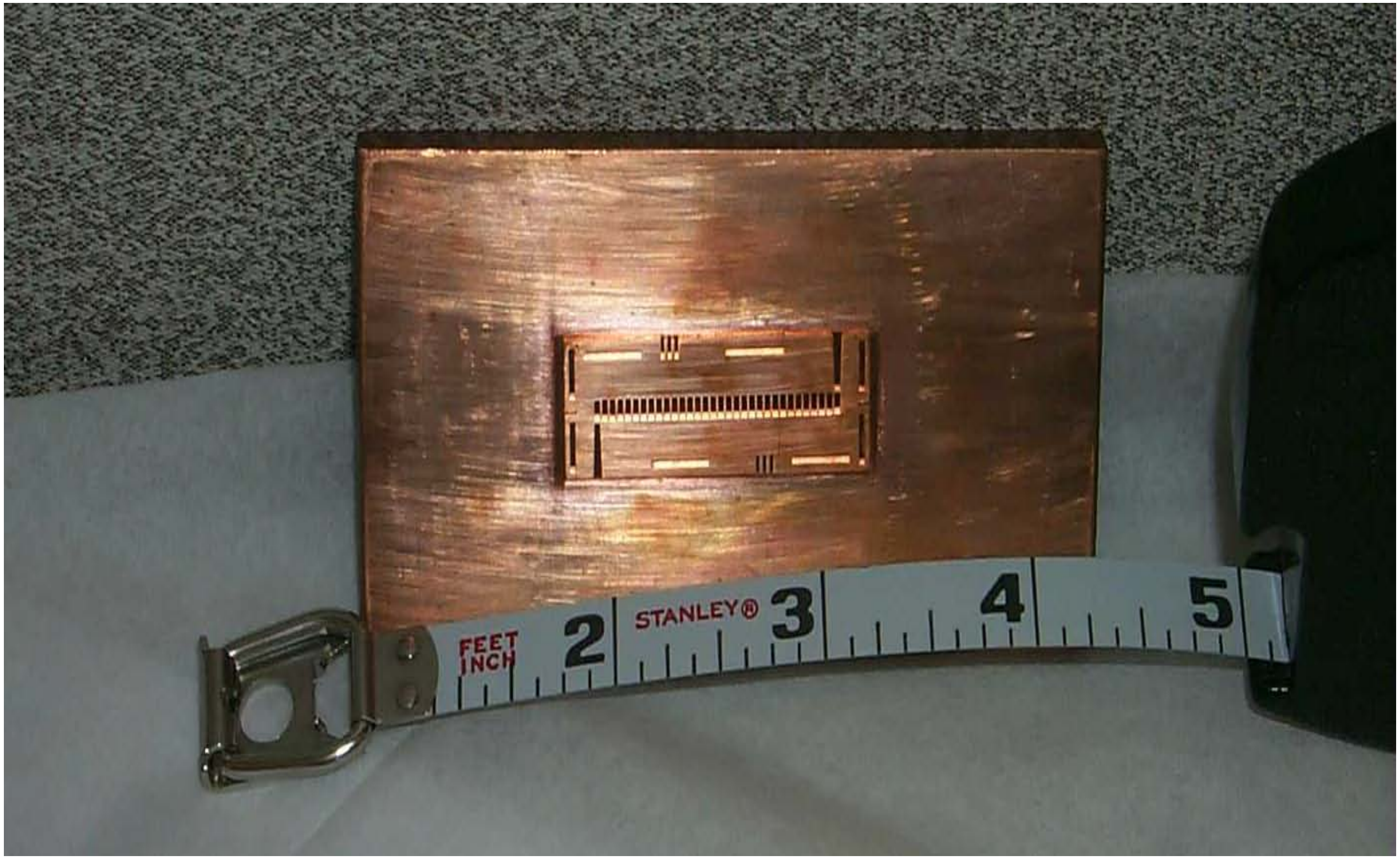


3-meters S-band Structure



Input coupling cell

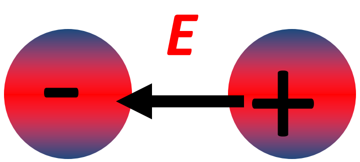

S-Band (2.856 GHz)
2π/3 Mode
C-Band (5.0 GHz)
X-Band (9.3 GHz)
X-Band (11.4 GHz)



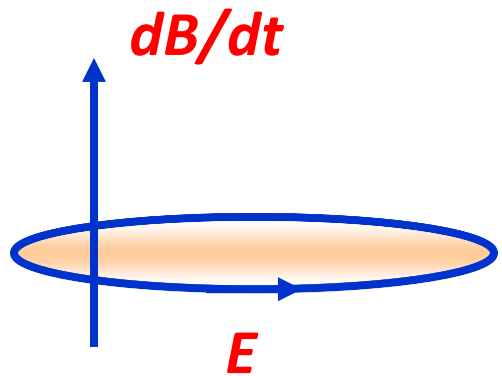
W-Band (94 GHz) Accelerating Structure

How to Accelerate?

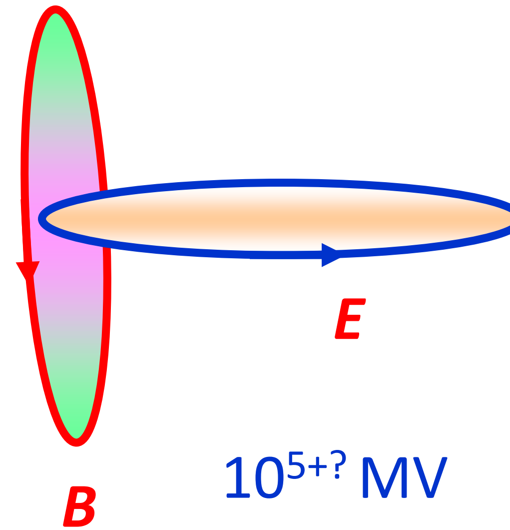
$$\frac{d\varepsilon}{dt} = q\vec{v} \bullet \vec{E}$$



10^0 MV

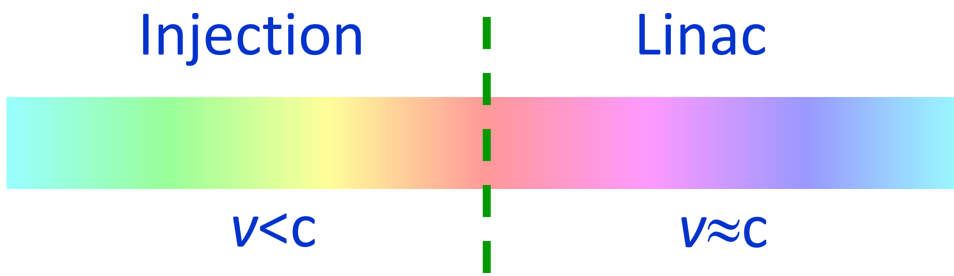


10^2 MV



$10^{5+?}$ MV

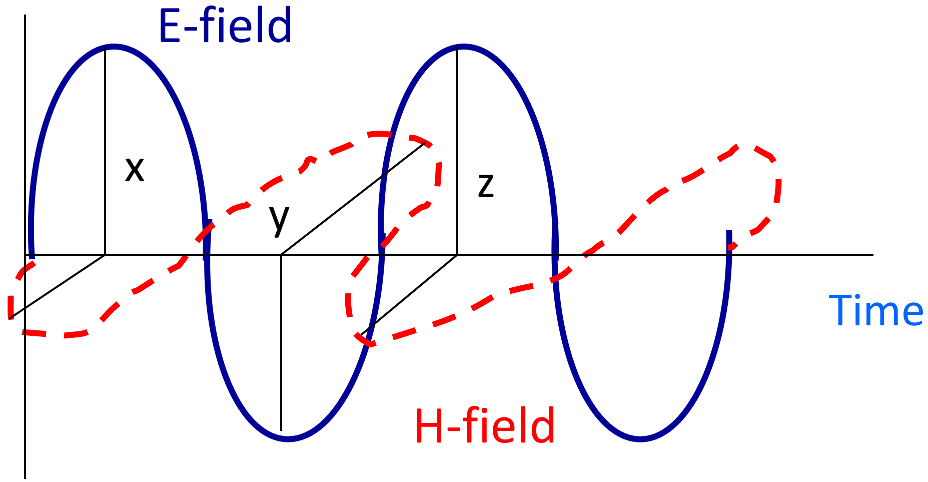
$$\Delta\varepsilon = \int dt E_0 \cos(\omega - kv)t$$

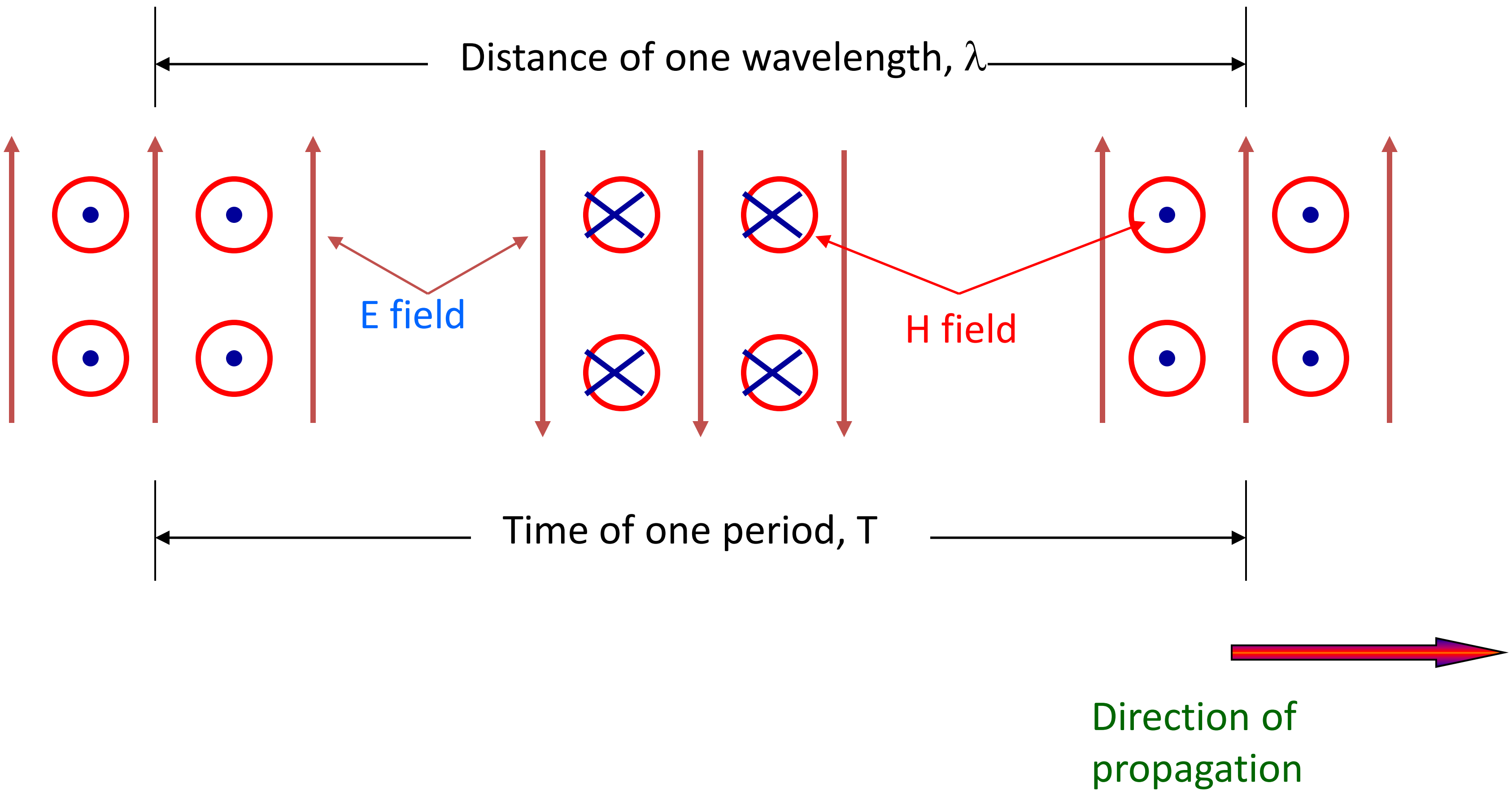


$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

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

Propagation Fields





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

Voltage Standing-Wave-Ratio VSWR

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

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

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

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

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

If p=1 (open or short-circuited line, S = ∞

Example 1:

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

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, $P_L = P_i - P_r = 120 - 0.9 = 119.1\ W$

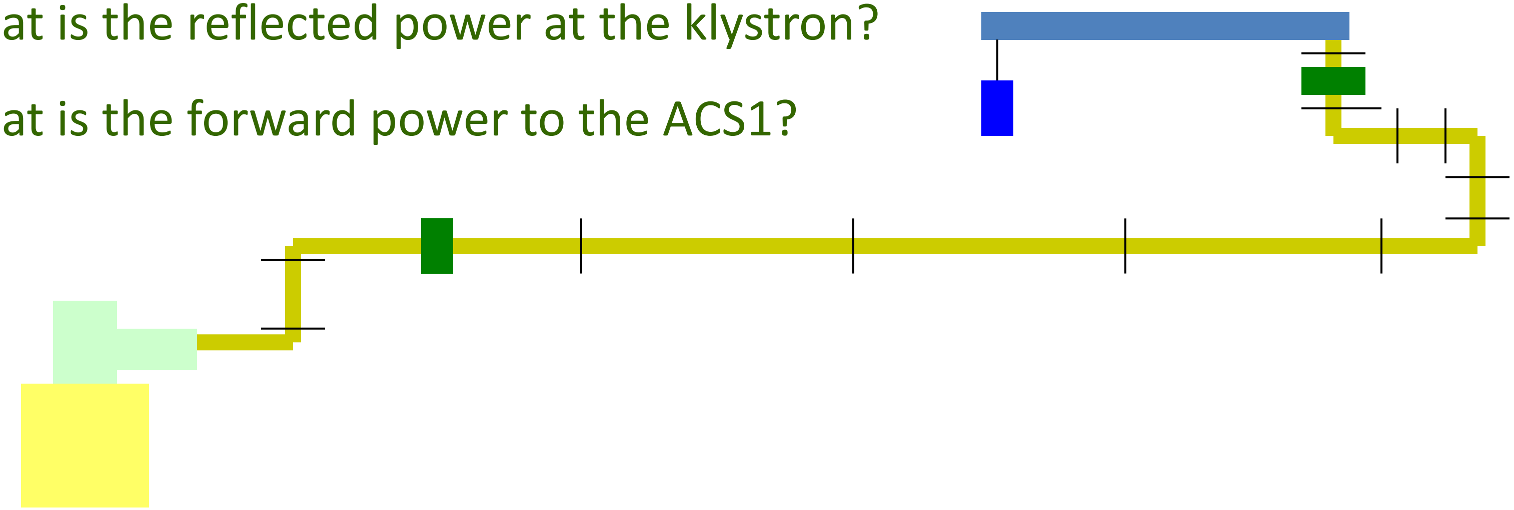
Example 2:

L1 klystron is set to generate 23 MW, measured at the klystron output coupler. The waveguide run from L1 klystron to the input of the ACS1 is roughly 75 feet. Assume that there are two windows in this run, each with a 0.12 dB loss. WR-284 waveguide has a 0.45 dB loss/100 ft. There are 12 flanges in between each with a 0.07 dB loss.

1) what is VSWR for each component?

2) what is the reflected power at the klystron?

3) what is the forward power to the ACS1?



$$loss(dB) = 20\log_{10} S$$

$$Windowloss:$$

$$0.12dB = 10\log_{10} S \Rightarrow S = 10^{0.012} = 1.03$$

$$Flangeloss:$$

$$0.07dB = 10\log_{10} S \Rightarrow S = 10^{0.007} = 1.016$$

$$Waveguideloss:$$

$$0.45dB \times \frac{75\,ft}{100\,ft} = 0.34dB$$

$$Waveguide:$$

$$0.34dB = 10\log_{10} S \Rightarrow S = 10^{0.034} = 1.1$$

$$\text{Total loss}:$$

$$\text{Windows (2)} + \text{Flanges (12)} + \text{Waveguide}$$

$$0.12dB \times 2 + 0.07db \times 12 + 0.34dB = 1.3dB$$

$$\text{Total loss }(dB) = 20\log_{10}\frac{P_t}{P_{inc}}$$

$$-1.3dB = 10\log_{10}\frac{P_t}{P_{inc}}$$

$$P_t = 0.74P_{inc} = 0.74\times 23MW = 17MW$$

$$P_{refl} = P_{inc} - P_t = 23MW - 17MW = 6MW$$

Reflected power at the klystron w indow :

$$-1.3\ dB = 10\log_{10}\frac{P_{r2}}{P_{r1}}$$

$$P_{r2} = .74P_{r1} = 0.74\times 6MW = 4.4MW$$

$$P_{window} = 6MW - 4.4MW = 1.6MW$$

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

Some Basic RF Parameters

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.

Example: A simple "back-of-the-envelop" calculation

L4 klystron is setup with 290 kV and 270 A on the modulator. L4 klystron has an efficiency of 42%. What the output power of the L4 klystron? What is the output power of the SLED? If the rf pulse length of the driver amplifier is set to 4 μsec, what is the rf pulse length of the SLED output? How long does it take to fill the SLED? What is the power level at each accelerator structure? Assume 7% loss at each power split. If the klystron and the structure are operating at 30 Hz, what is the average power dissipated in the klystron and the structure?

$$P_{DC} = 290kV \times 270A = 78.3MW$$

$$P_{rf}(kly) = 78.3MW \times 0.42 = 32.8MW$$

$$P_{rf}(SLED) = 32.8MW \times 4.1 = 134.5MW$$

$$\text{SLED rf pulse length} \approx 2\,\mu\,\text{sec}$$

$$t_{fill} = \frac{2Q_0}{(1+\beta)\omega} = \frac{2\times 10^5}{6\times\pi\times 2856\times 10^6} = 1.86\mu\,\text{sec}$$

After the first split, output power is 125.1/2 = 62.55 MW. After the second split, output power of each feed is 58.17/2 = 29 MW. So each structure receives ~29 MW rf power.

$$P_{avg}(kly) = 32.8MW \times 30 \text{ pps} \times 4\mu \sec$$

$$= 32.8 \times 10^{6} \times 30 \text{ pps} \times 4 \times 10^{-6} \sec$$

$$\approx 4kW$$

$$P_{avg}(structure) = 29MW \times 30 \text{ pps} \times 2\,\mu \sec$$

$$= 1.74kW$$

Example:

Each RF gun in the linac needs approximately 5 MW to provide a beam energy of about 1.6 MeV for injection into the linac. If the output power of L1 klystron is 23 MW, what is the maximum rf power available to each gun?

$$\frac{P_{out}}{P_{in}} = e^{-2\tau}$$

$$\tau = \frac{\omega l}{2v_g Q}$$

$$v_g / c = 0.0204 - 0.0065$$

$$Q = 14{,}000$$

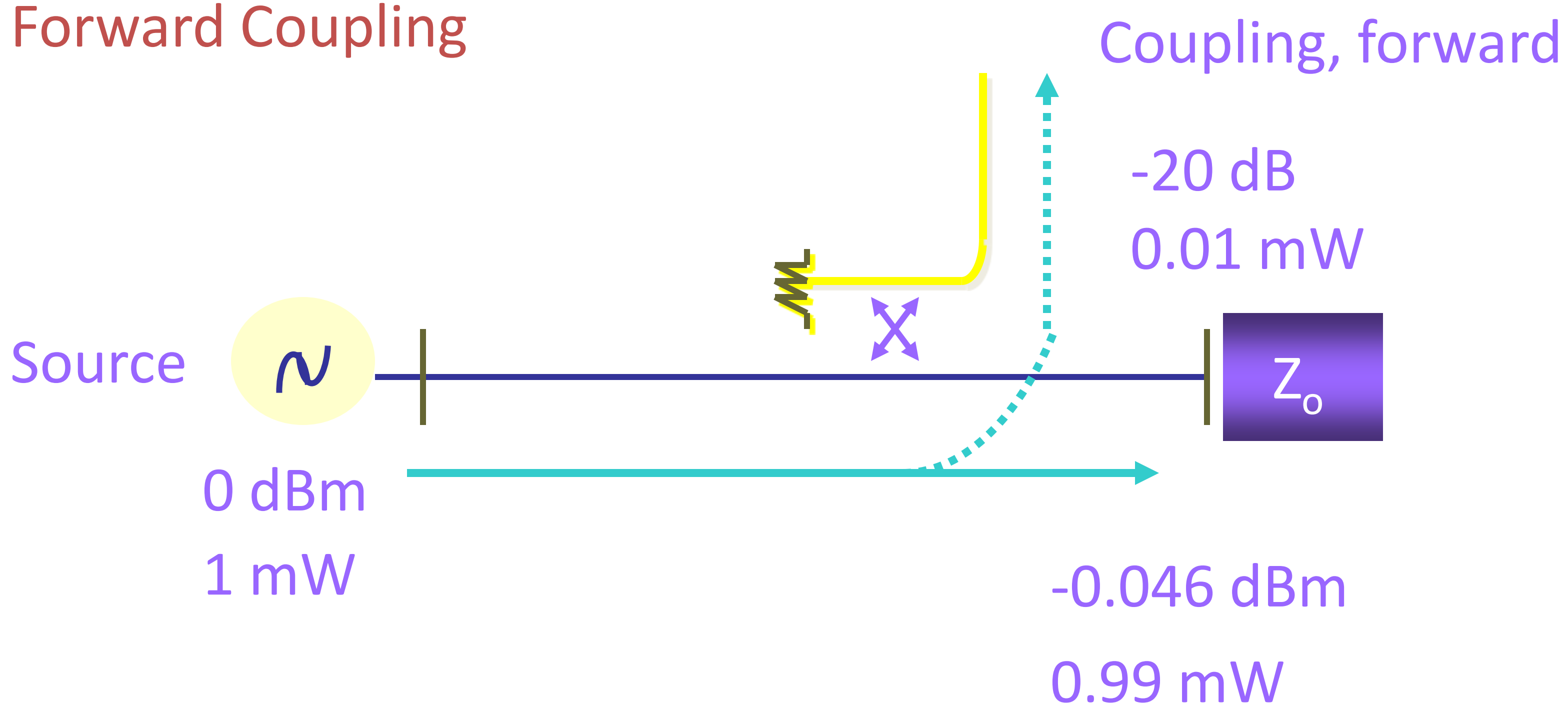
$$l = 3 \text{ meters}$$

$$\omega = 2\pi \times 2856 MHz$$

$$\tau \approx 0.48$$

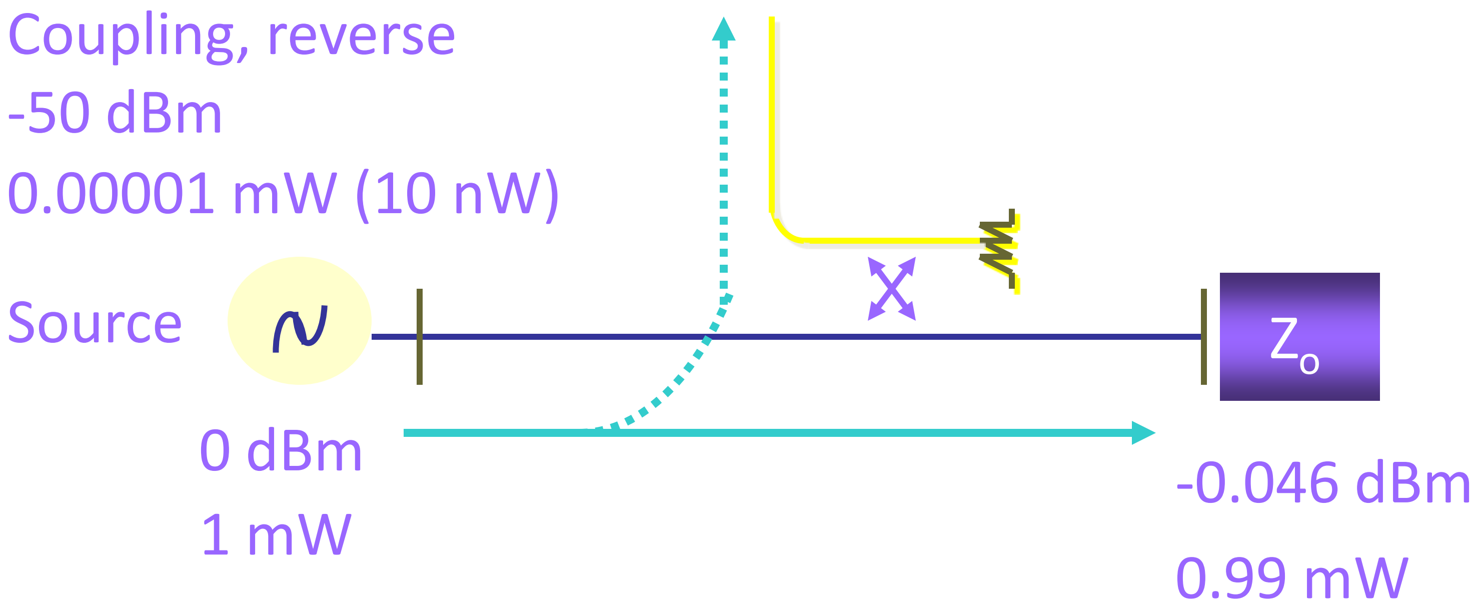
$$P_{out} = 23MW \times e^{-2\times 0.48} = 8.8MW$$

Forward Coupling



Coupling Factor (dB) = $$-10\log\frac{P_{forward}}{P_{incident}}$$

Directional Coupler Isolation

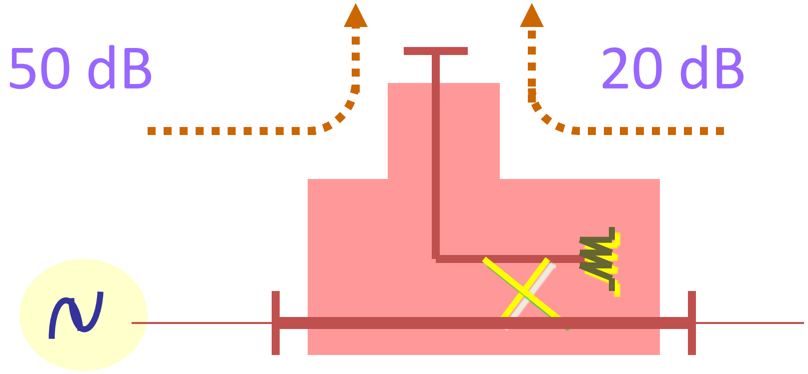


Isolation Factor (dB) = $-10\log\frac{P_{reverse}}{P_{incident}}$

Directional Coupler Directivity

$$\text{Directivity} = \frac{\text{Coupling Factor}_{(\text{fwd})} \times \text{Loss}_{(\text{througharm})}}{\text{Isolation}_{(\text{reverse})}}$$

$$\text{Directivity (dB)} = \text{Isolation(dB)} - \text{Coupling Factor(db)} - \text{Loss (dB)}$$



Directivity = 50 dB - 20 dB = 30 dB

Handy Formulas

For a constant-gradient structure:

$$\tau = \frac{\omega l}{2 v_g(z) Q} = \alpha l, \alpha = \frac{\omega}{2 v_g(z) Q}$$

$$\frac{dP}{dz} = -2\alpha(z) = const = \frac{P_{in}(1 - e^{-2\tau})}{l}$$

Fill time:

$$t_f = \frac{2Q}{\omega}\tau$$

Handy Formulas

The energy gain E of a charged particle is

$$\mathrm{E} = (2\tau)^{\frac{1}{2}}[(1-e^{-\tau})/\tau](P_{in}rl)^{\frac{1}{2}}$$

$$r = 54M\Omega/meter$$

$$Q = 14000$$

$$\tau = 0.48$$

$$E = (2\times 0.48)^{0.5}(\frac{1-e^{-0.48}}{0.48})(23MW\times 54M\Omega/m\times 3m)^{0.5}$$

$E \approx 47MeV$ in 3-meter structure

For 32 MW input to the structure,

$$E \approx 56MeV$$

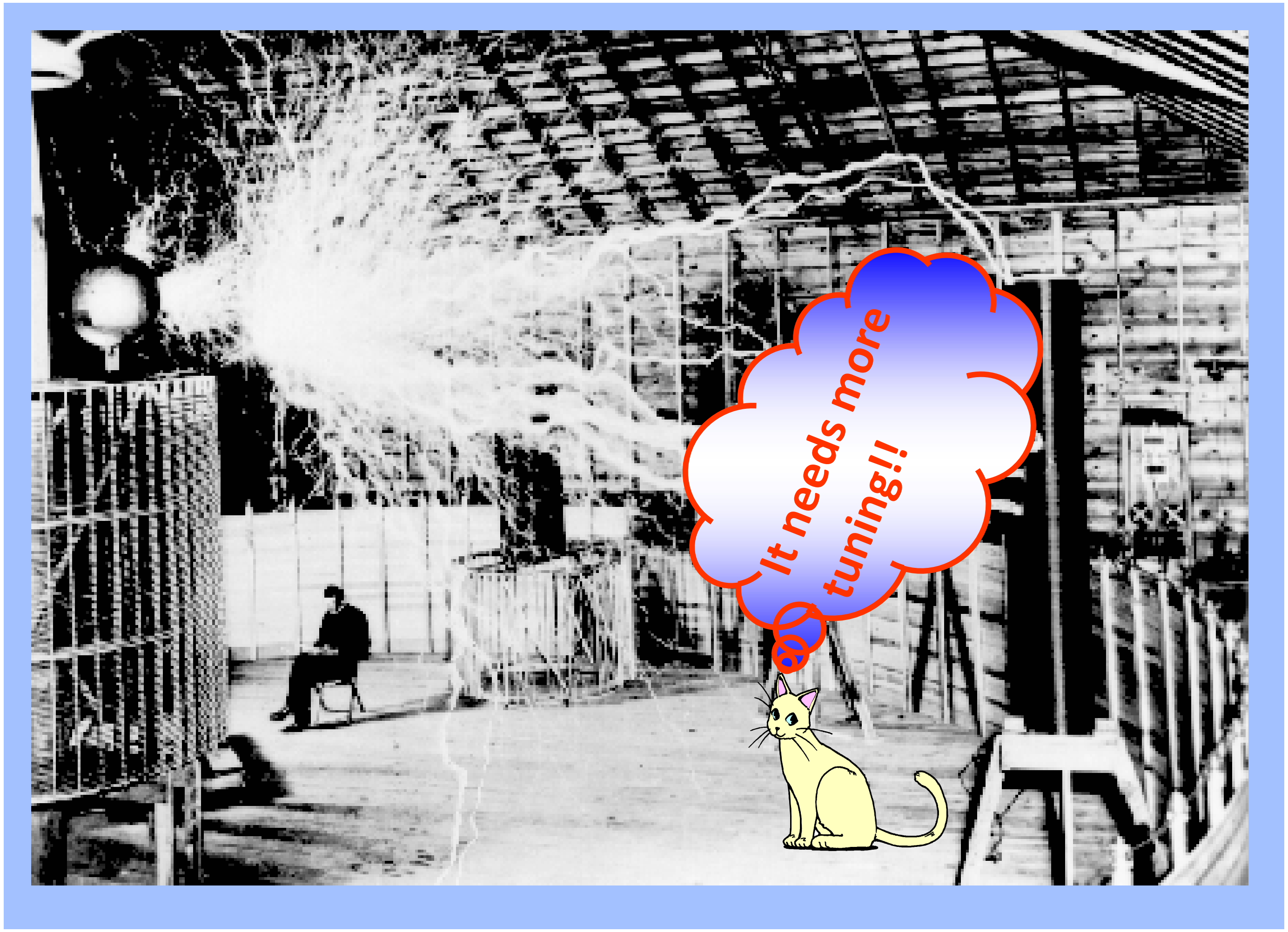
Handy Formulas

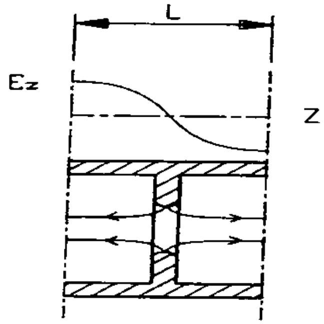
Structure efficiency:

$$\eta = \frac{\text{Stored Energy}}{\text{Energy Supplied}}$$

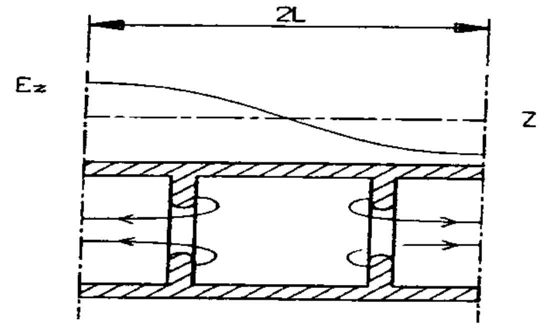
$$\eta = \frac{W}{P_{in} t_f} = \frac{1 - e^{-2\tau}}{2\tau}$$

$$\eta = \frac{1 - 0.38}{2 \times 0.48} = 0.65$$

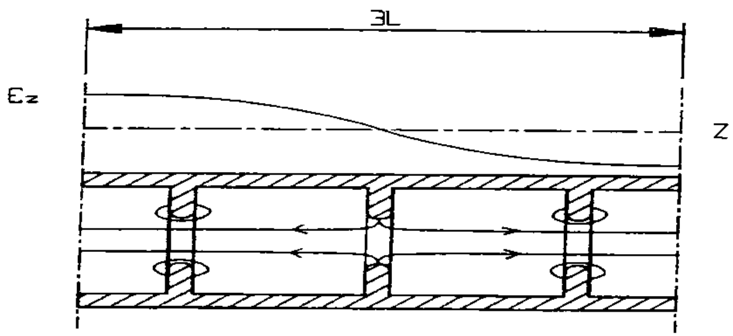

It needs more
tuning!!



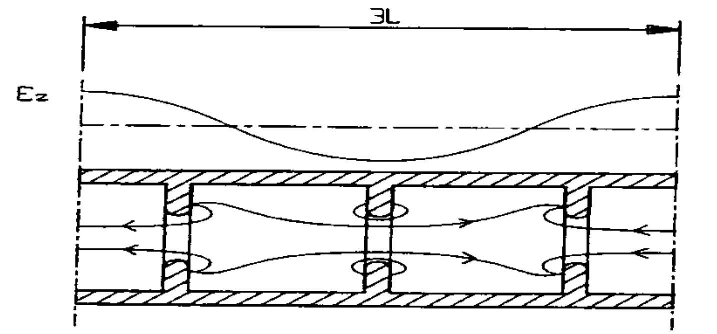
a) $\beta L = \pi$; $f_{\pi} = 2.965$ GHz



b) $\beta L = \frac{\pi}{2}$; $f_{\pi/2} = 2.947$ GHz



c) $\beta L = \frac{\pi}{3}$; $f_{\pi/3} = 2.938$ GHz



d) $\beta L = \frac{2}{3}\pi$; $f_{2/3\,\pi} = 2.957$ GHz

Breakdown depends on:

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

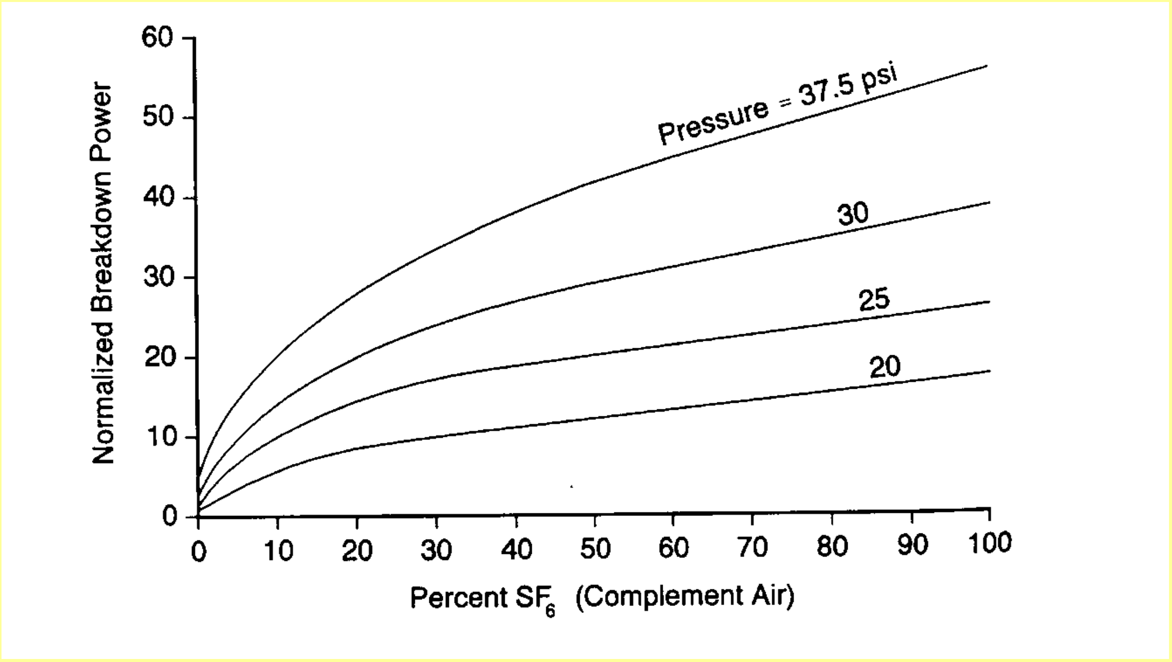
Gas	~10's V/cm - 10 kV/cm (depends on pressure and type)
Vacuum	~ 0.5 - 1MV/cm

Types:

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

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



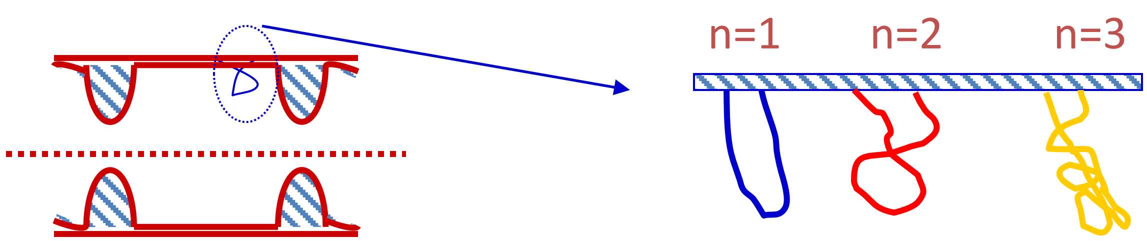
RF Breakdown in Vacuum:

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.



RF Conditioning with short Pulse: