RF Systems for the 3rd Generation Synchrotron Radiation Facilities

Lecture 10

LINAC SYSTEMS

January 28, 2003

LINAC SYSTEMS

- High Voltage
- Klystron
- Waveguides
- Accelerating Structures
  - Structure types
  - Modes
- Longitudinal Dynamics
- Breakdown

Linac RF System

High Voltage Supply - The function of the high voltage supply is to produce the high voltages required for proper modulator operation. The high voltage should be regulated , filtered and have some type of feedback of both the voltage and current. It must be protected against over-voltage and over-current conditions and be capable of withstanding high stress during normal operation as well as of a failure.

Linac RF System

High Voltage Supply – There are two basic approaches in the design of the high voltage supply. The traditional approach is what may be called the "brute force" method. In this approach, a large high voltage transformer is used with some type of rectification and filtering.

The second method is by using high frequency switching supplies. The rend is the power supply industry has been away from linear brute force and toward switching supplies.

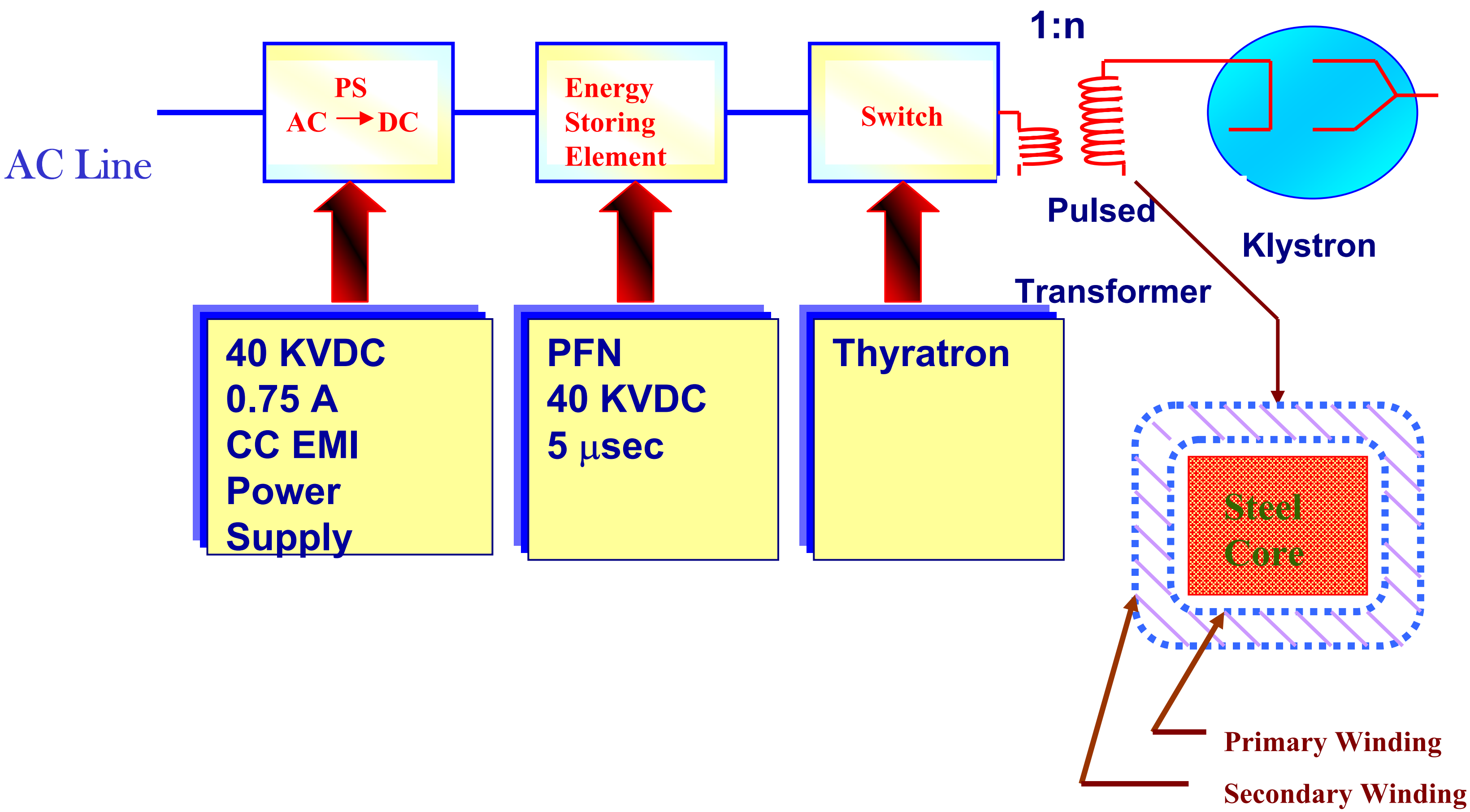
Linac RF System

High Voltage Supply - Regulation of the high voltage is important, as changes in high voltage result in changes in RF output and ultimately causes changes in the output of the linac. There are two basic ways of providing regulation. Direct regulation of the high voltage supply and post regulation on a pulse-to-pulse.

Linac RF System

Modulator – The function of the modulator is to provide high voltage pulses to the microwave transmitter (klystron). Almost every RF linac today uses some variation of the line type modulator. This design was used extensively during WWII for radar applications. The are called line modulators because the width of the output pulse is determined by an actual transmission line. Modern modulators use an artificial transmission line called a pulse-forming network (PFN).

Linac Modulator System



Modulator Operation:

1. Charging cycle – The charging inductor and capacitor of the PFN forma resonant circuit. This resonance causes the PFN to charge up to twice the voltage supplied by the high voltage supply. The charging diode keeps the PFN voltage at full until the discharge cycle.

2. The discharge cycle is initiated by conduction of the power switch (hydrogen thyratron). The discharge cycle results in a pulse to appear across the input of the pulse transformer. Typical ratio is 1:15 for the pulse transformer.

Radio Frequency System

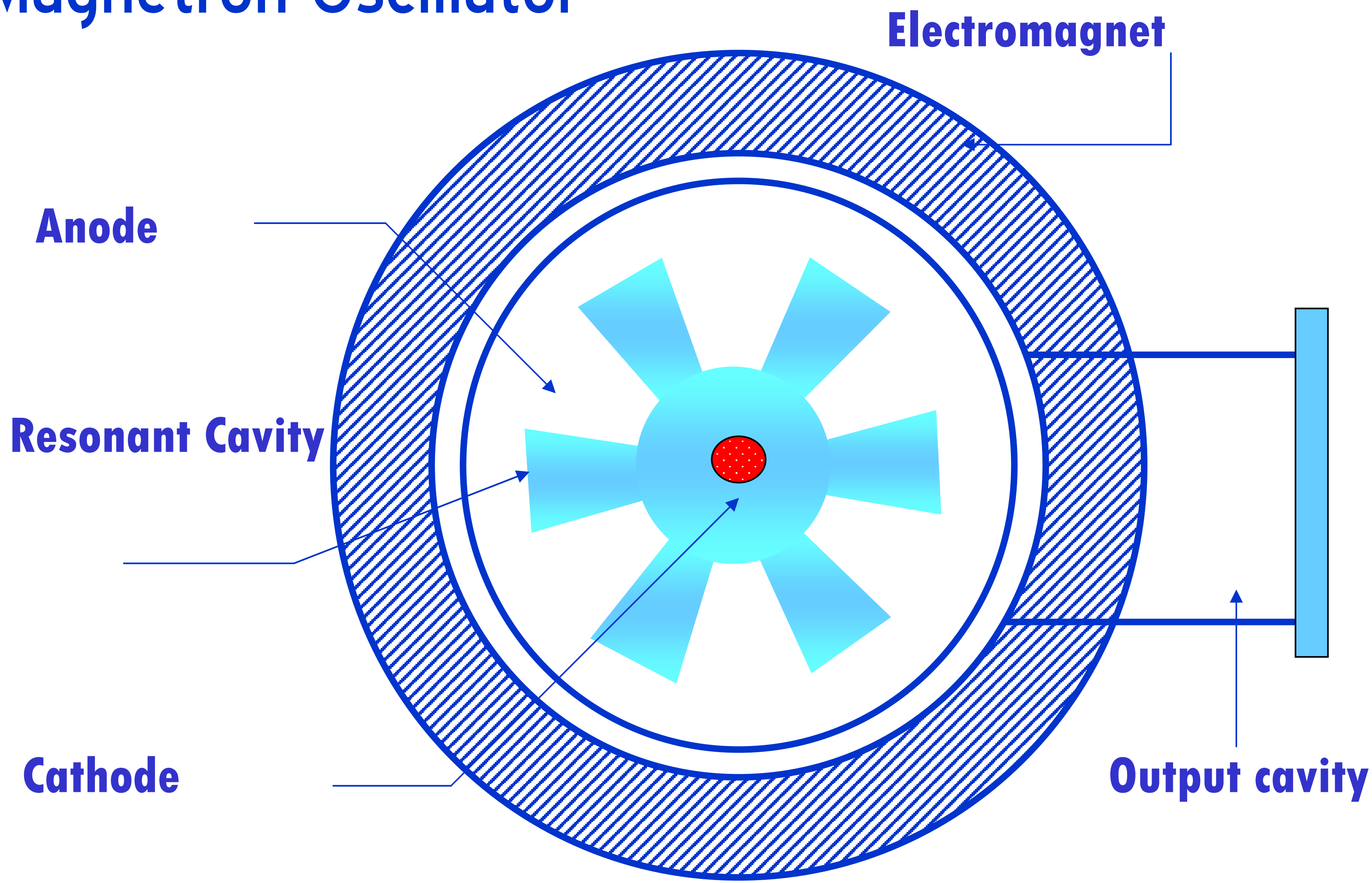
The RF system converts the high voltage pulses from the modulator into pulsed radio frequency energy. The RF pulses are sent to the accelerating structure to setup an electric field which is used for charged particle acceleration.

The main component of a RF system is the microwave source. There is a variety of microwave tubes for generating and amplifying microwave signals. The two most common ones used in linacs are magnetrons and klystrons.

Radio Frequency System

A magnetron is a microwave power oscillator which belongs to the family of electron tubes called crossed field devices. This is because it has an electric field and a magnetic field which are perpendicular to each other. The magnetron consists of a circular cathode inside a circular anode block. There are resonant cavities machined into the anode block. These cavities will resonant at microwave frequencies when excited by electrons interacting with the E and H fields.

Magnetron Oscillator

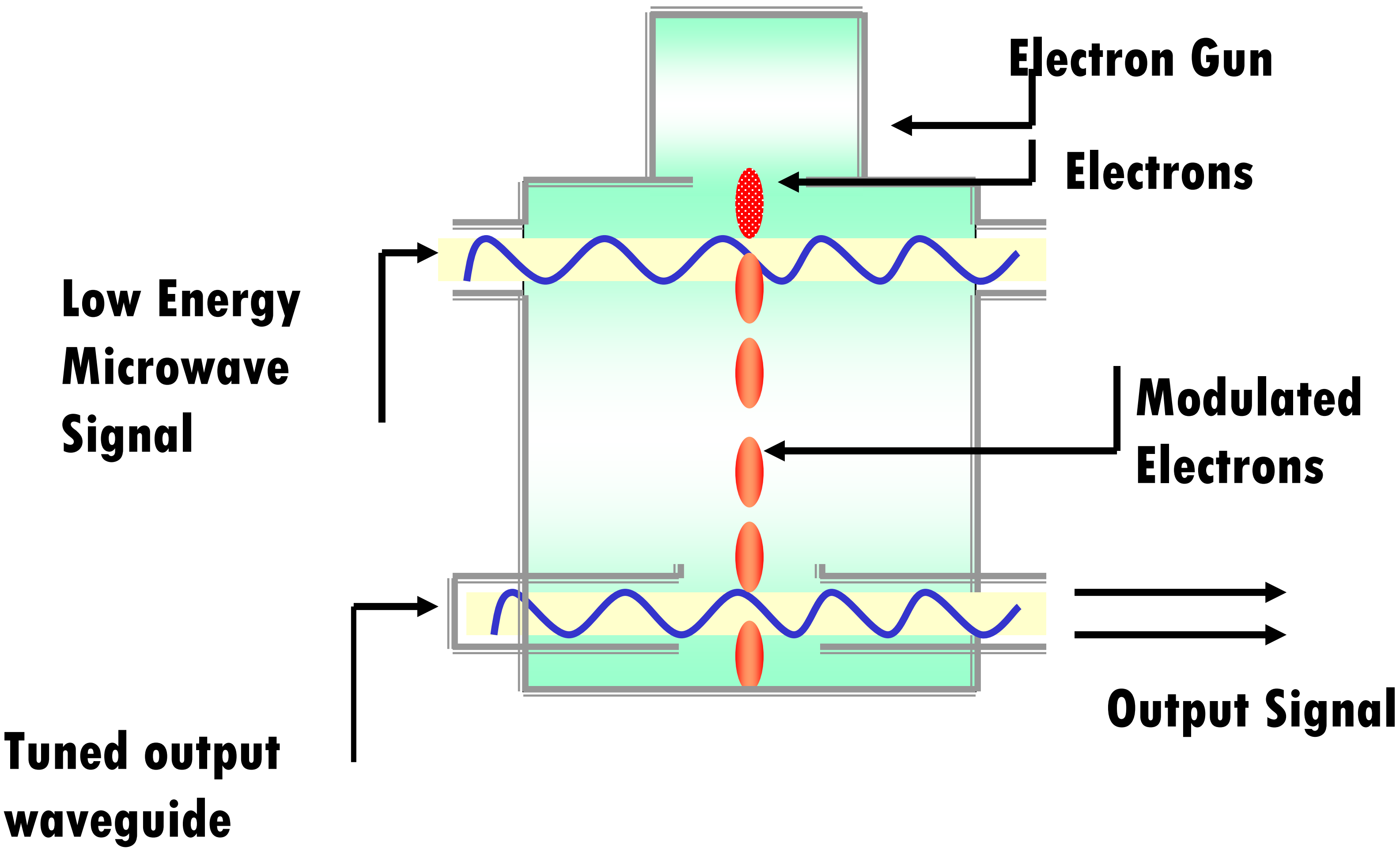


Radio Frequency System

Klystrons belong to the class of tubes called linear beam tubes. In most linac applications, the klystron is used as an amplifier, so an input signal is required. This is provided by a low power oscillator typically called an RF driver.

The choice of which type RF generator tube is used is based partially on the design requirements and partially on historical preference.

Klystron


Electron Gun
Electrons
Low Energy
Microwave
Signal
Modulated
Electrons
Output Signal
Tuned output
waveguide

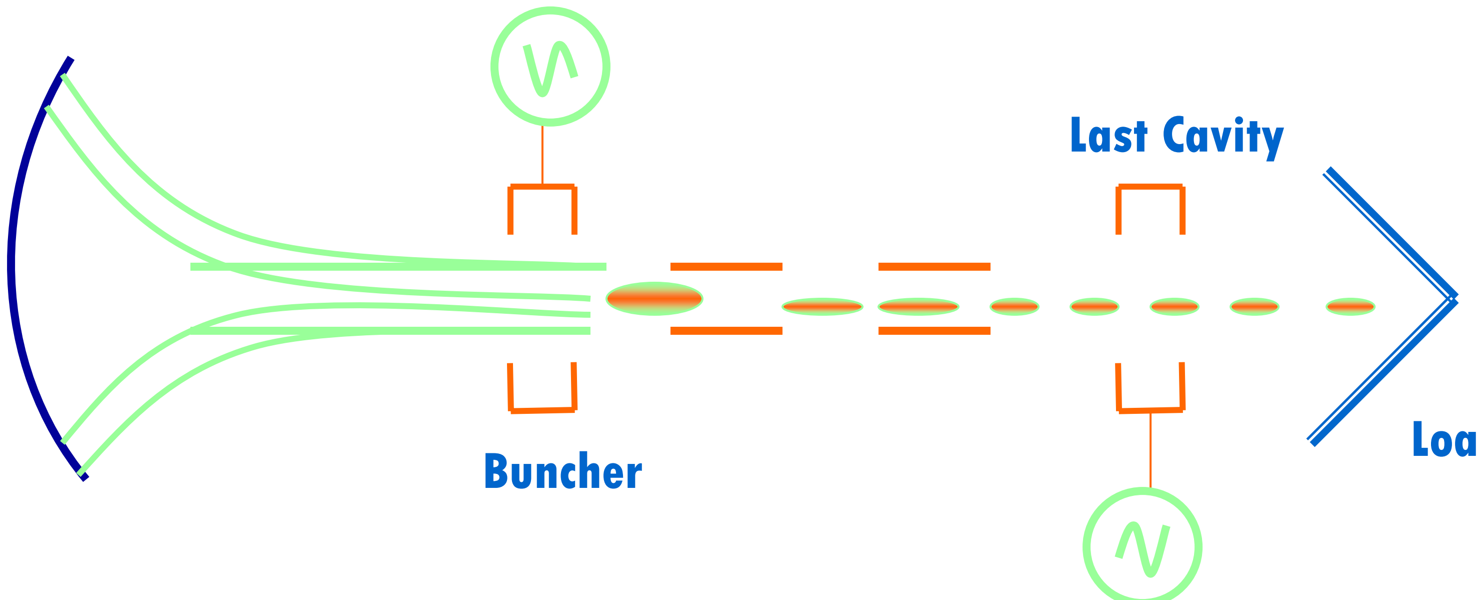
Klystrons

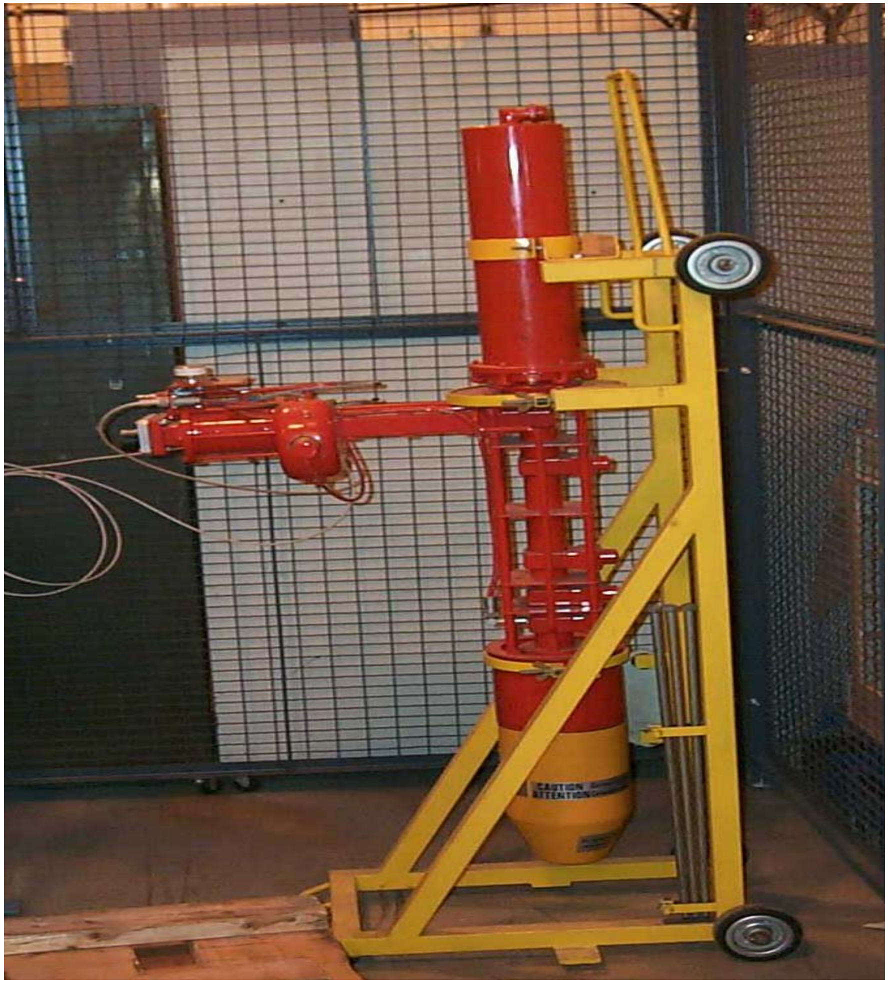
Klystron was invented at Stanford in 1937. The klystron severed as an oscillator in radar receivers during WWII. After the war, however, very high-power klystrons were built at Stanford for use in the first linear accelerators. This opened the way for the use of klystron not only in accelerators and radar, but also in UHF-TV, satellite communications, and industrial heating.

Klystrons

Klystrons are high-vacuum devices based on the interaction of well-focused pencil-like electron beam with a number of microwave cavities that it traverses, which are tuned at or near the operating frequency of the tube. The principle is conversion of the kinetic energy in the beam, imparted by high accelerating voltage, to microwave energy. Conversion takes place as a result of the amplified RF input signal, casing the beam to form "bunches." These bunches give up their energy to the high level induced RF fields at the output cavity. The amplified signal id extracted from the output cavity through a vacuum window.

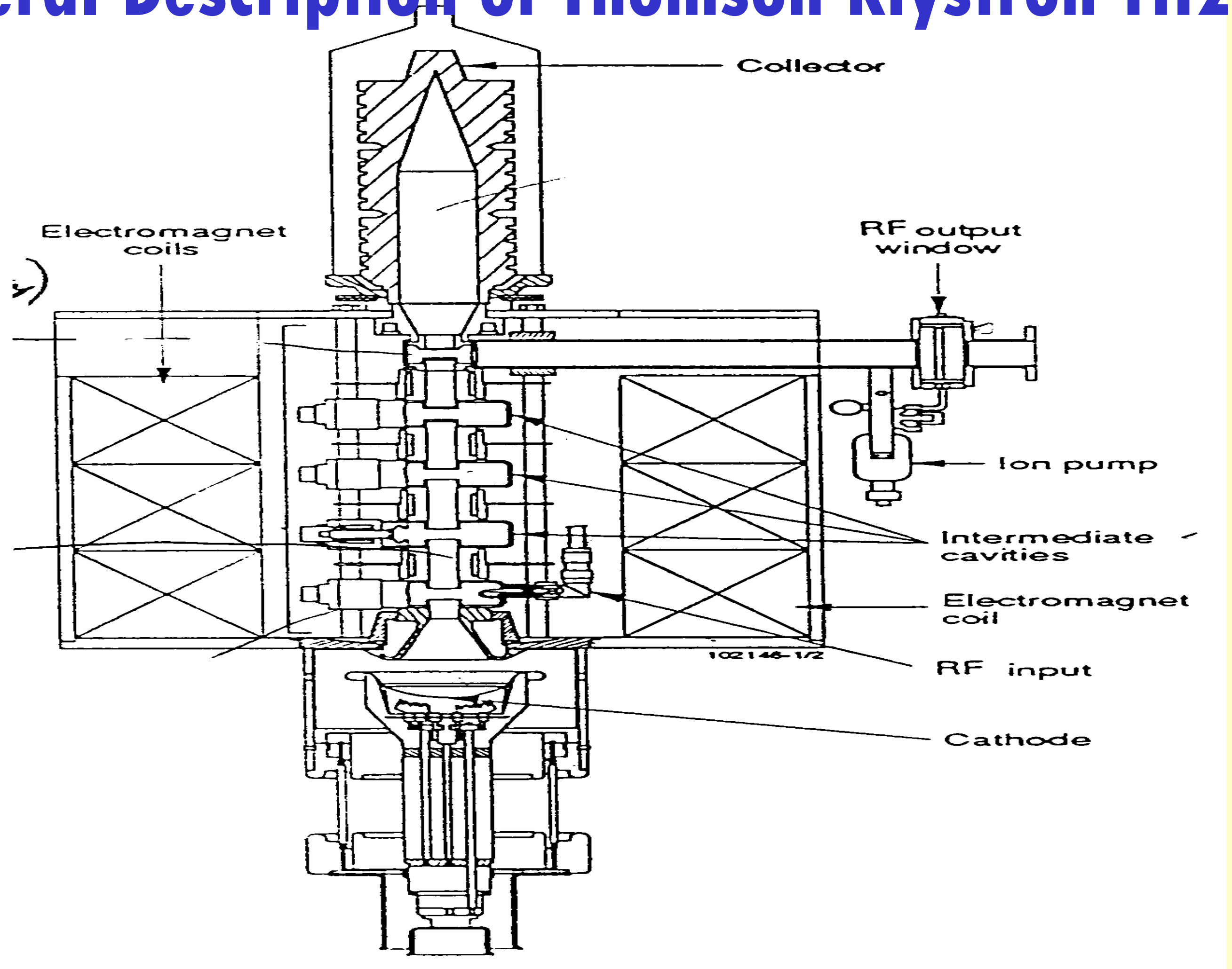
Klystron





S-Band 35 MW Klystron (TH2128)

General Description of Thomson Klystron TH2128:



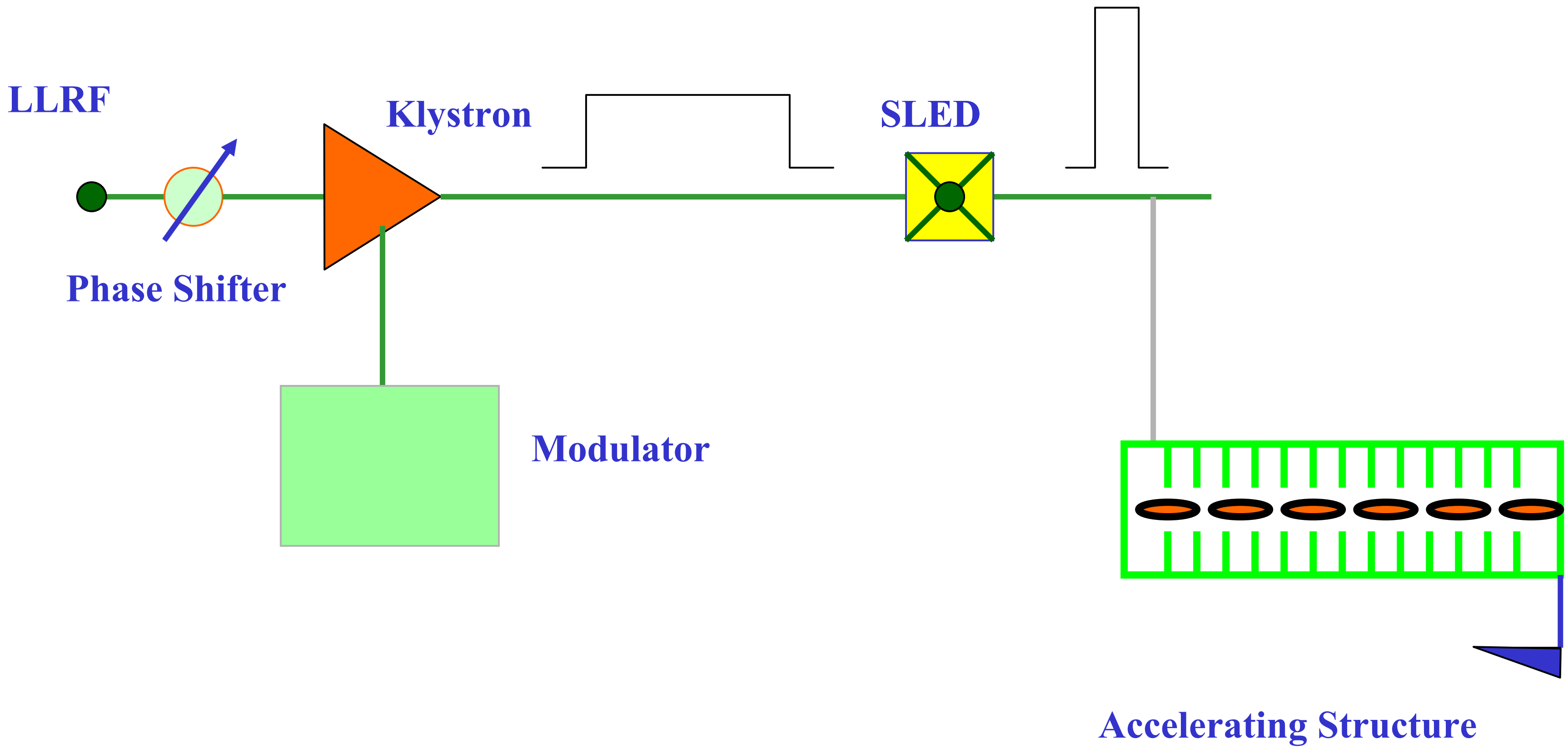
Main Parameters of TH2128 Klystron:

Frequency	2856 MHz
Peak Output Power	35 MW
Average Power	11kW
RF Pulse Duration	5μsec
Peak Beam Voltage,Max	300 kV
Peak beam Current,Max	300 A
Peak RF Drive Power, Max	200 W
Efficiency	42%
Perveance	1.9 to 2.15 $\mu A \cdot V^{-3/2}$
Filament Voltage	20 to 30 V
Hot Filament Resistance	1.1 Ω
Cold Filament Resistance	0.1 Ω

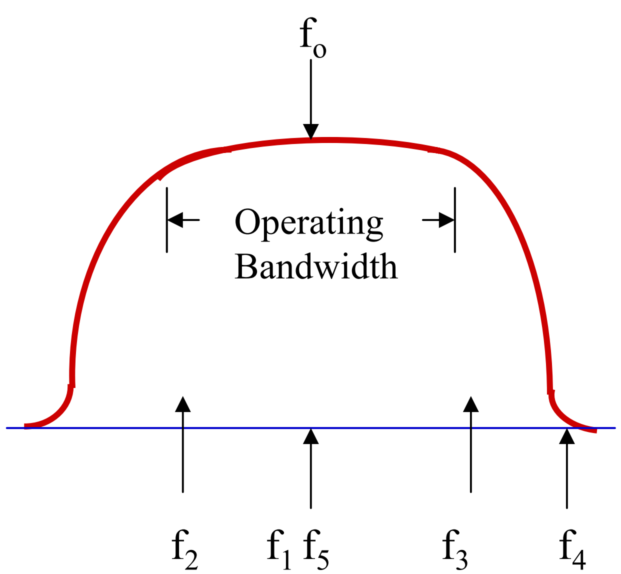
Typical Operation:

Frequency	2856 MHz
VSWR, Max.	1.1:1
Peak Beam Voltage	280 kV
Peak Beam Current	297 A
Peak RF Power	35 MW
Average Output Power	10.5 KW
RF Pulse (at -3 dB)	5 μsec
Power Dissipated on the Body	800 W

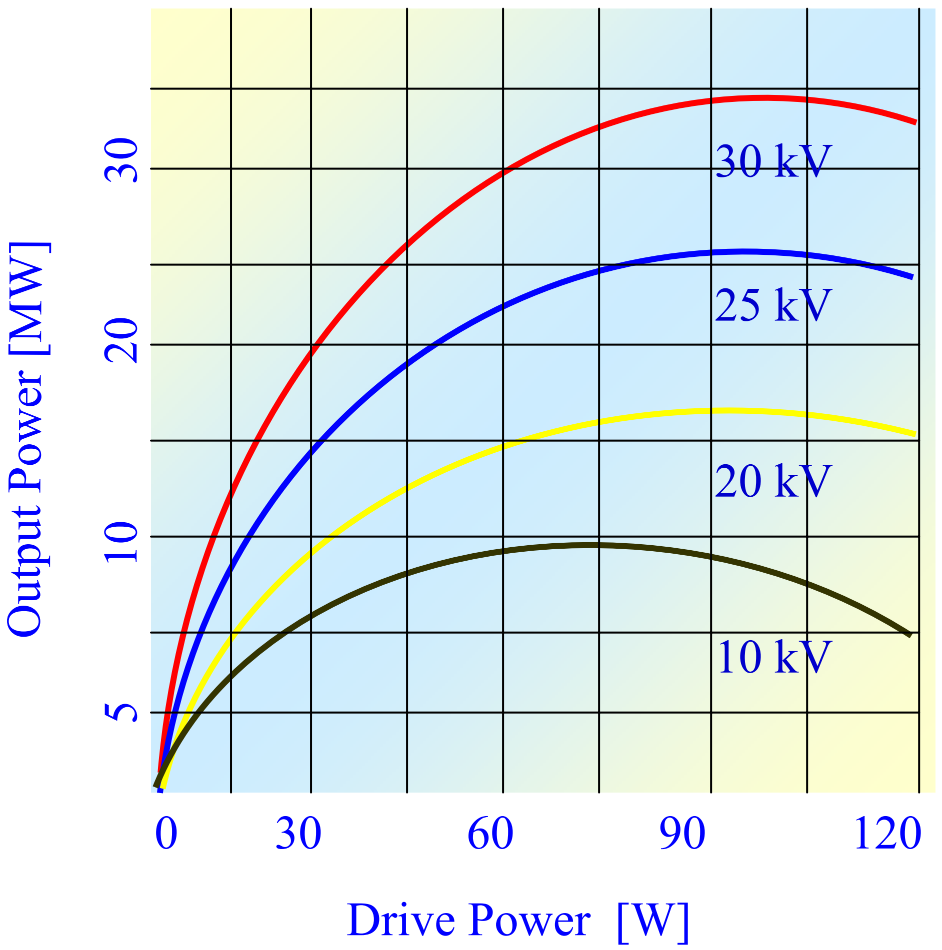
RF Power Distribution to the Accelerating Structure



Cavity Bandwidth



Typical Klystron Saturation Curves

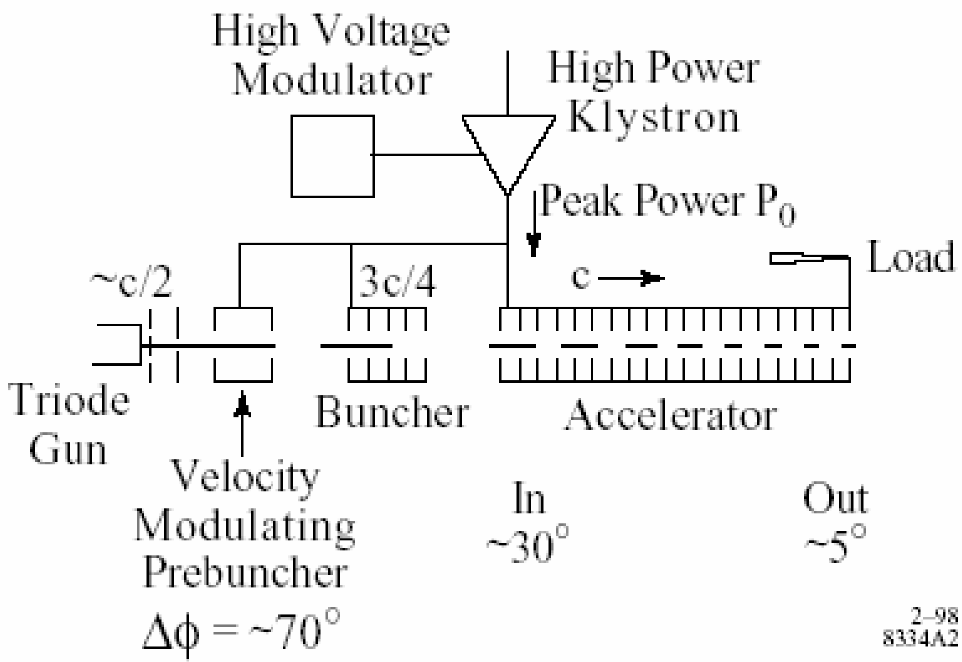


RF Components:

- 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

Accelerating Structure Requirements

- High accelerating gradient to optimize length and cost (LC, NLC)
- Control of short and long range wakefields
- Preservation of low emittance for multi-bunch beams
- Minimize HOM effects
- Beam Breakup



RF Control System

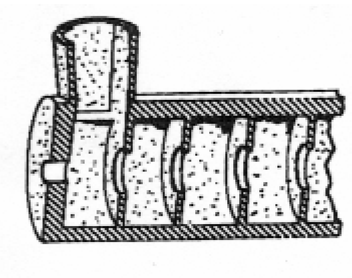
Vacuum System

Water Cooling System

Electric Power System

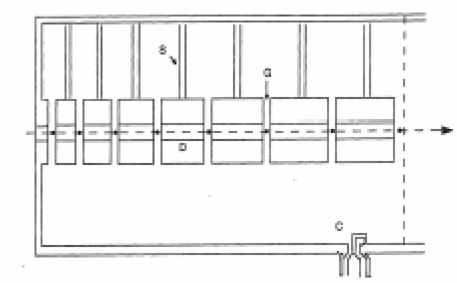
Coupled Resonator Chain – Periodic Structures

- 1947 W. Hansen (Stanford) Disk-loaded waveguide linac



DLWG

- 1955 Luis Alvarez (UC Berkeley, DTL)

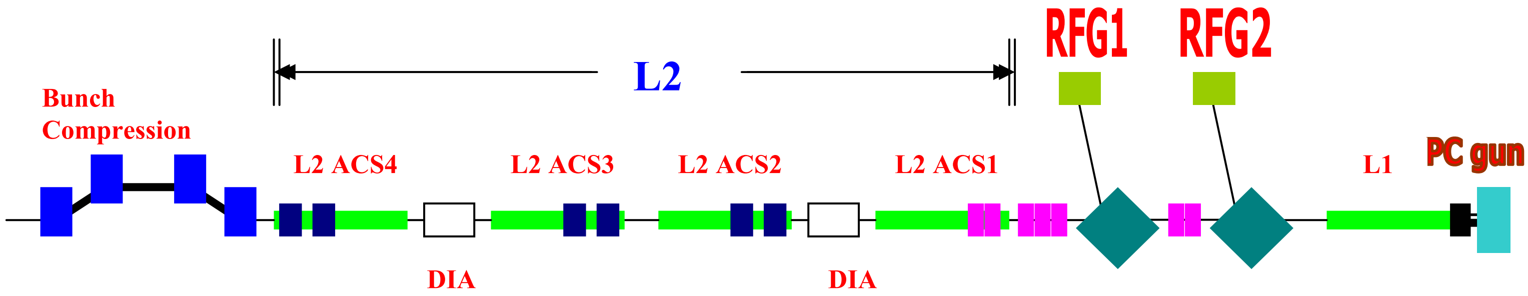


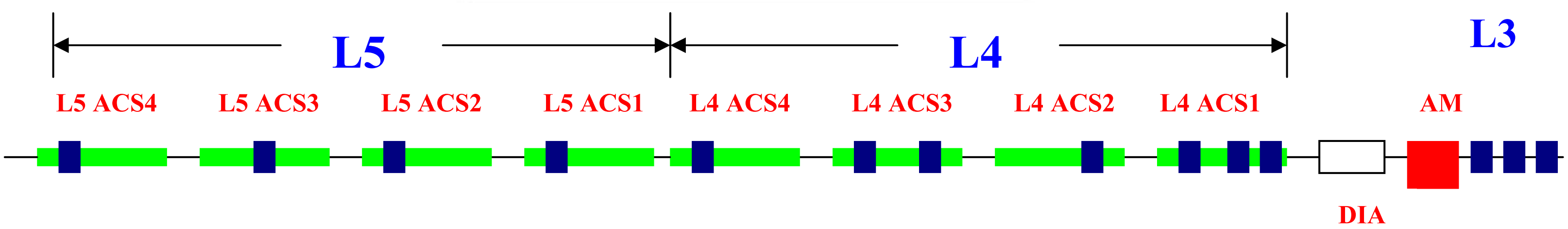
Alvarez 200MHz, 32MeV

- 1970 Radio Frequency Quadruple (RFQ)

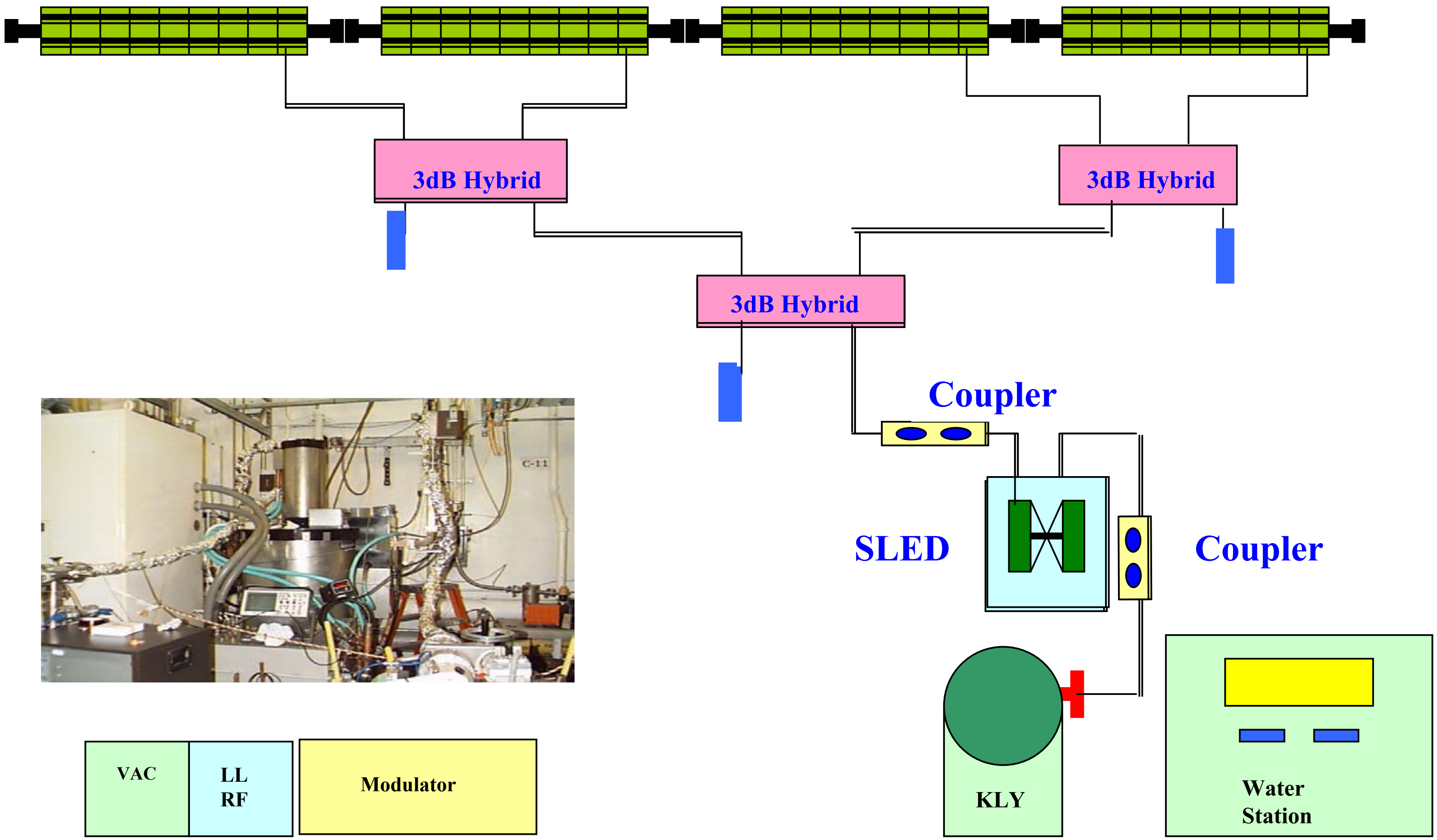
RFQ 6 - 400 MHz 0.01-0.06C

Linac RF Layout

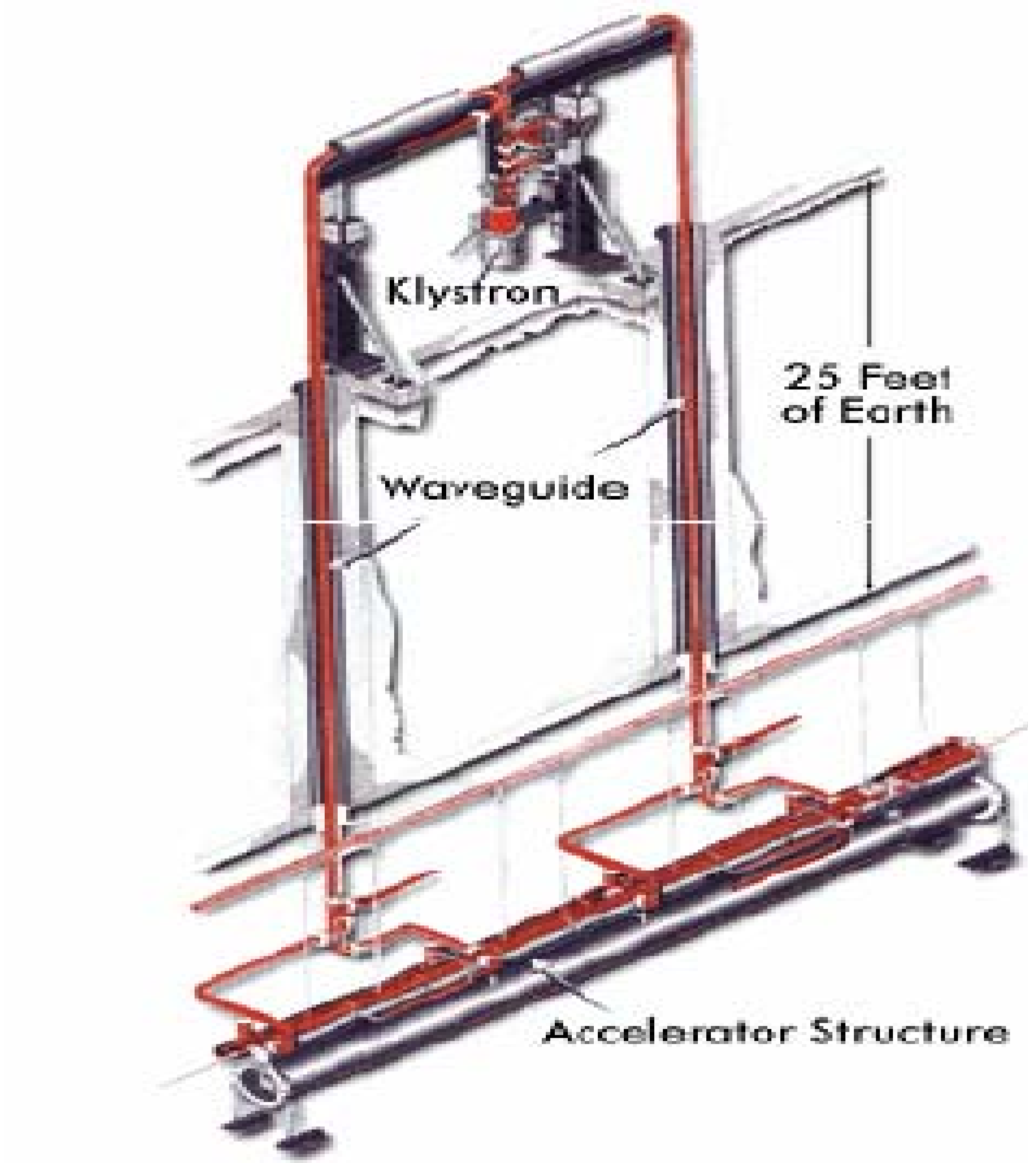




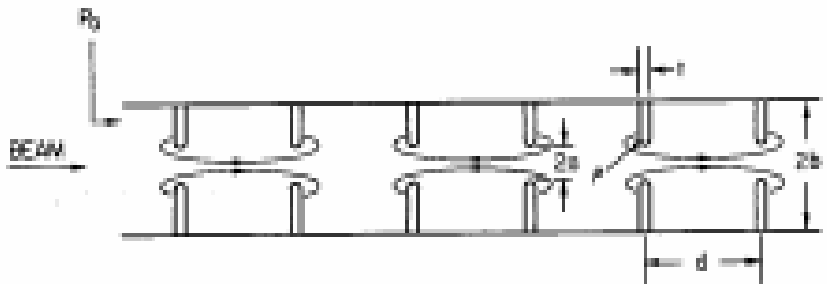
Coupled Resonator Chain – Periodic Structures



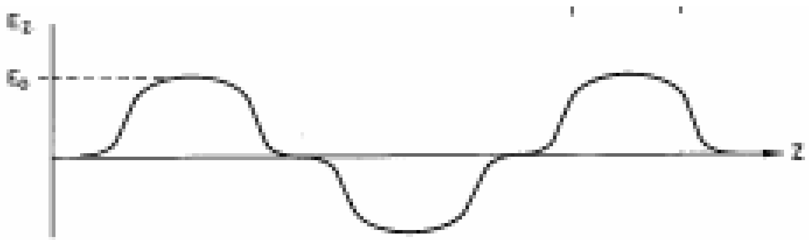
Coupled Resonator Chain - Periodic Structures



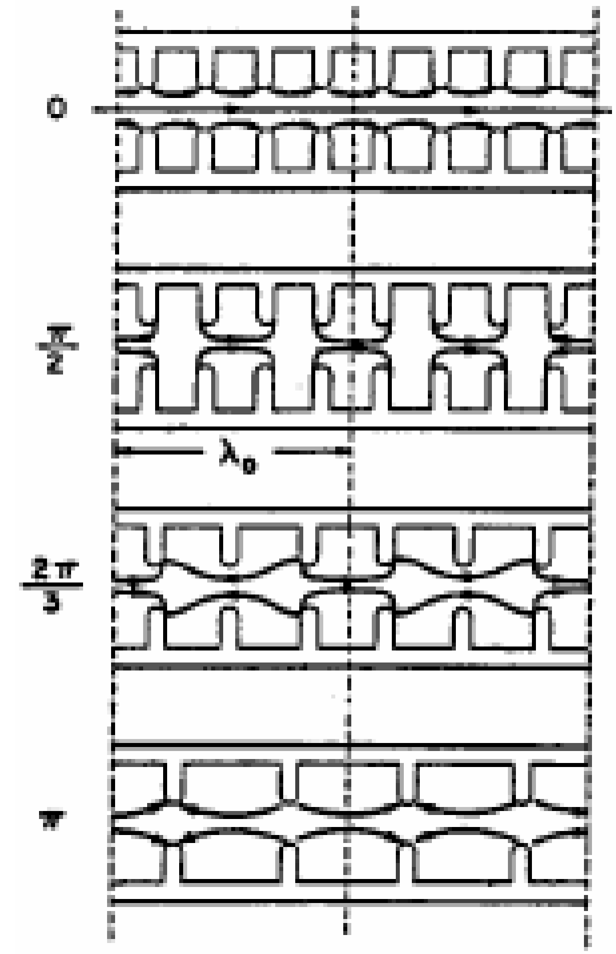
Snapshots of e-field configuration for DL structures with various phase shift per period.



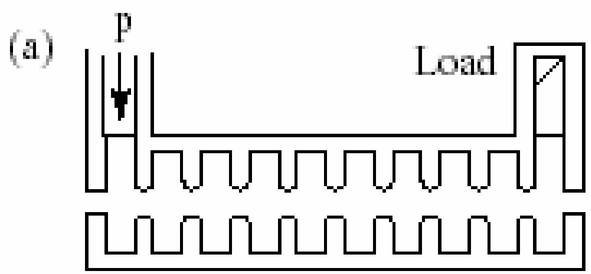
$\pi/2$ mode



Electric field amplitude along z-axis for $\pi/2$ mode

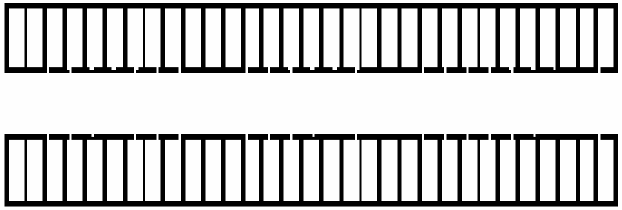


Structure Types

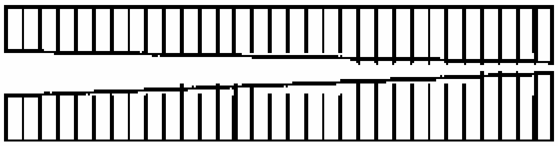


(a) Traveling Wave (TW) Structure

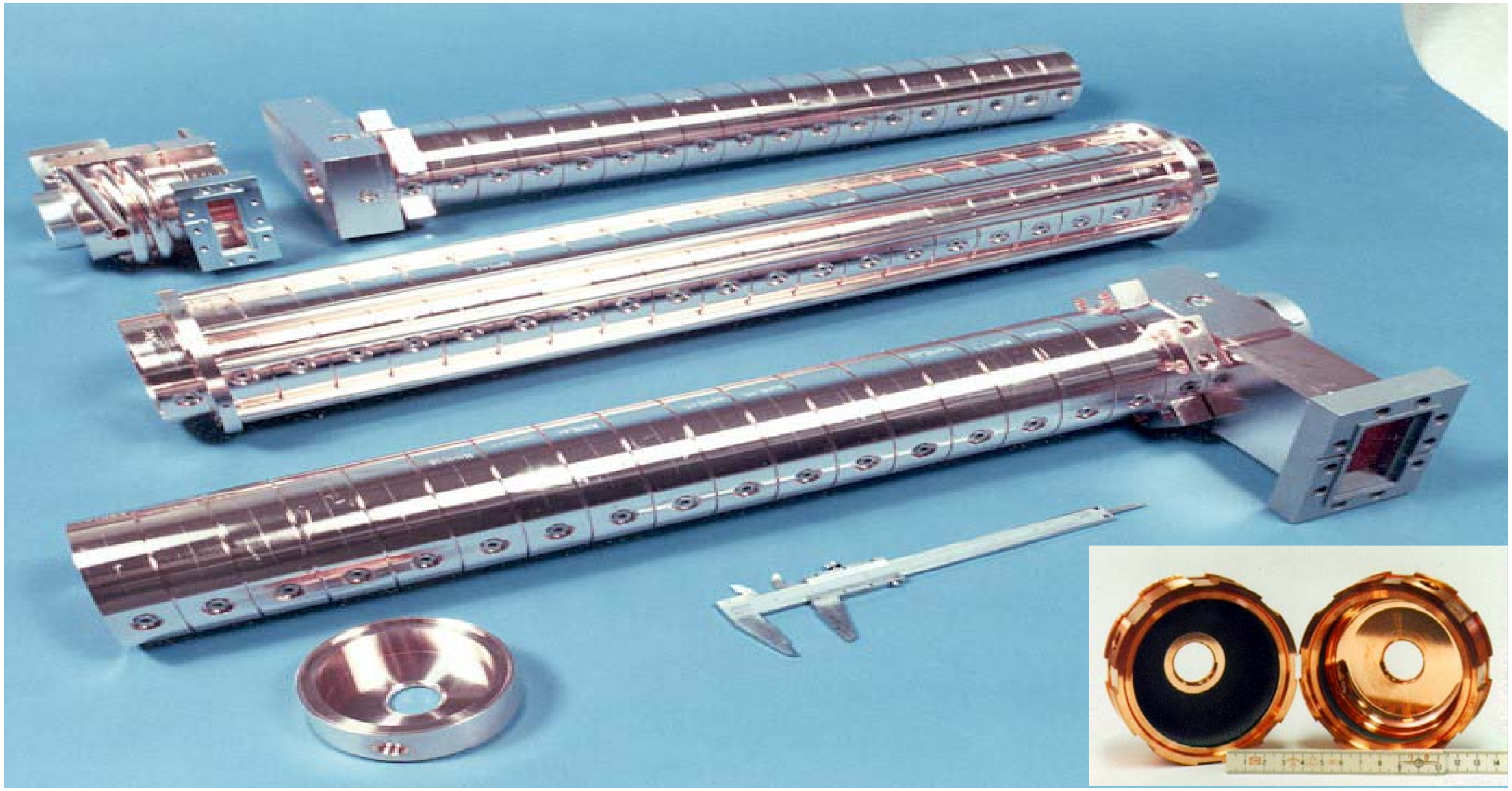
(b) Standing Wave (SW) Structure



Constant Impedance Structure (CI)

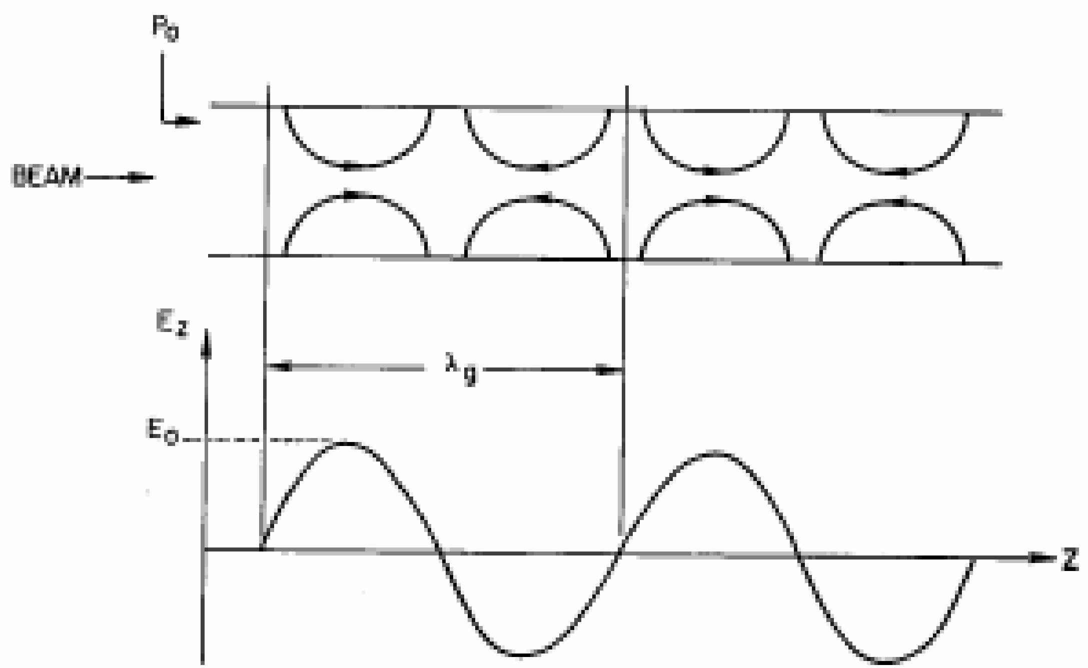


Constant Gradient Structure (CG)



Disk-Loaded Constant Gradient S-Band Structure

Circular Mode



TM_{01} mode pattern and traveling wave axial electric field in uniform cylindrical waveguide

Circular Mode

Wave equation for propagation characteristics:

$$\nabla^2 \overline{E} + k^2 \overline{E} = 0$$

$$k = \omega / c$$

K is the propagation wave number and ω is the angular frequency.

Circular Mode

For TM_{01} mode (transverse magnetic field without θ dependence – most simple accelerating mode) in cylindrical symmetric waveguide,

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \left[\left(\frac{\omega}{c}\right)^2 - \beta^2\right] E_z = 0$$

Circular Mode

The solution for TM_{01} mode is:

$$E_z = E_0 J_0(k_c r) e^{j(\omega t - \beta z)}$$

$$E_r = jE_0 \sqrt{1-(\omega_c/\omega)^2}\, J_1(k_c r)$$

$$H_\theta = j\eta J_1(k_c r) e^{j(\omega t - \beta z)}$$

β Is propagation constant and η is the intrinsic impedance of the medium, We can consider that k_c and β to be the r and z components of k of the plane wave in free space.

Circular Mode

$$k_c^2 = \left(\frac{\omega}{c}\right)^2 - \beta^2 = \left(\frac{\omega_c}{c}\right)^2$$

For a perfect metal boundary condition at wall, E_z=0 (the lowest frequency mode):

$$E_z(b) = 0 \Rightarrow J_0(k_c b) = 0$$

$$k_c b = 2.405$$

$$\omega_c = k_c c = {2.405c}/{b}$$

For any propagating wave, its frequency f must be greater than f_c, the field is in the form of $e^{j(\omega t-\beta z)}$ with $\beta>0$.

Example: **An S-band (2856 MHz) structure has a diameter of 2b=8 cm, the cut-off frequency is f_c=1.9 GHz. So a 2.856GHz can propagate as TM_{01} mode.**

Phase Velocity and Group Velocity

The phase velocity V_p is the speed of RF field phase along the accelerator, it is given by

$$v_p = \frac{\omega}{\beta}$$

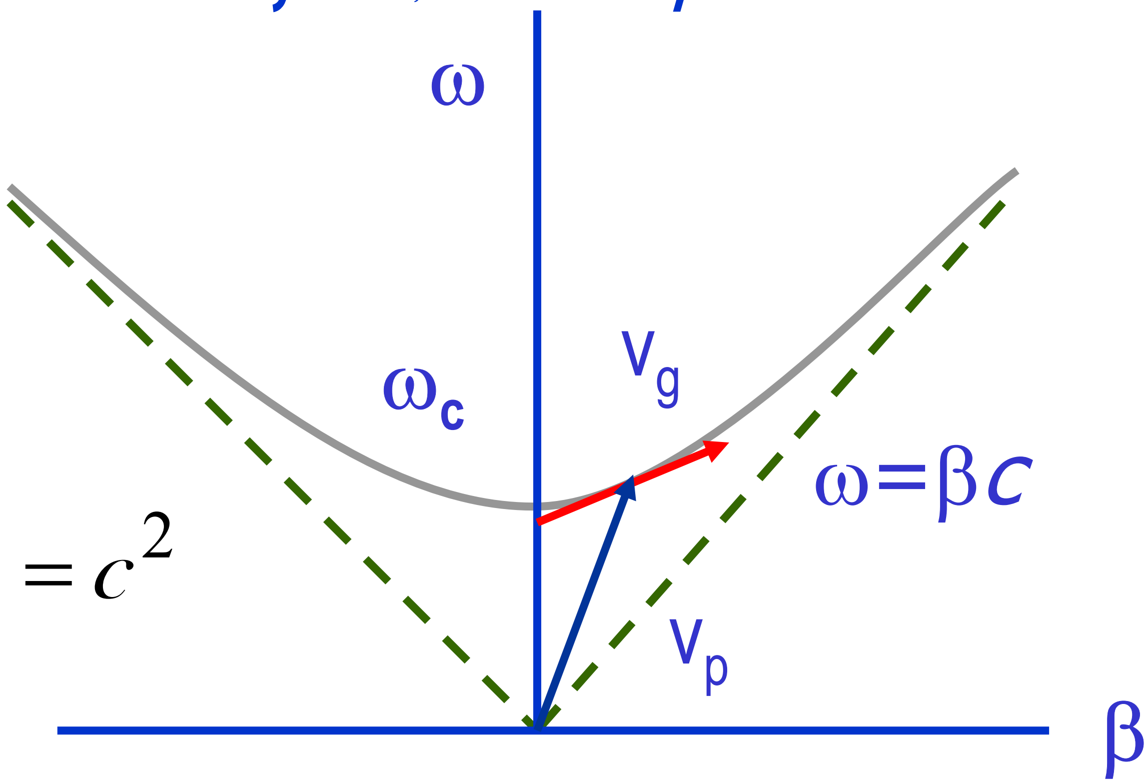
Group velocity is defined as energy propagation velocity. For waves composed of two components with different frequency ω_1 and ω_2, wave number β_1 and β_2, the wave packet travels with velocity:

$$v_g = \frac{\omega_1 - \omega_2}{\beta_1 - \beta_2} \to \frac{d\omega}{d\beta}$$

In order to use RF wave to accelerate particle beam, it is necessary to make simple cylinder "loaded" to obtain

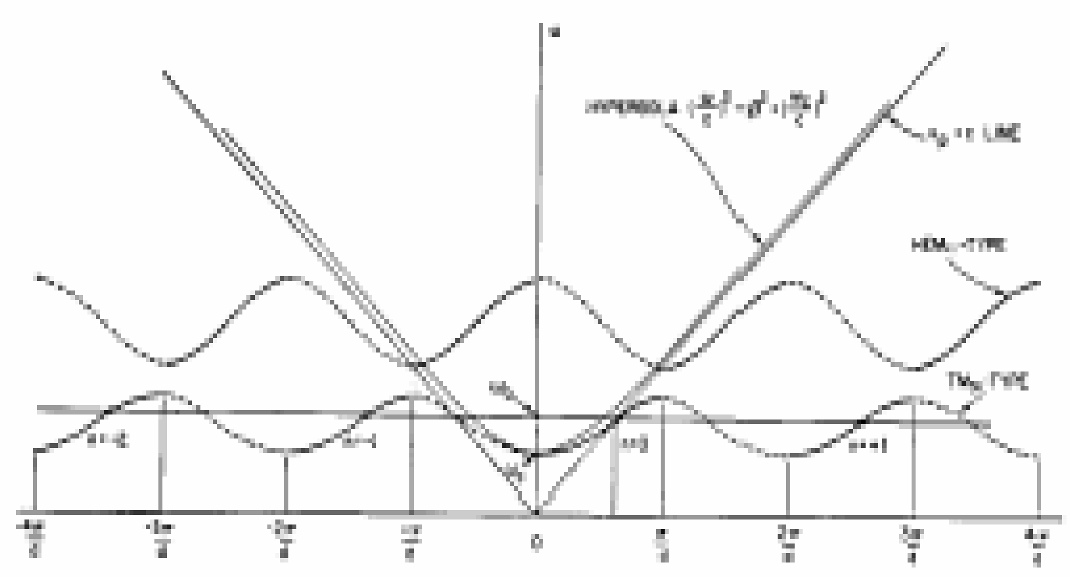
$$v_p \le c$$

For uniform waveguide, it is easy to find:



$$v_p v_g = c^2$$

Dispersion diagram for guided wave in a uniform (unloaded) waveguide.



Brillouin diagram showing propagation characteristics for uniform and periodically loaded structures with load period d.

Floquet Theorem: When a structure of infinite length is displaced along its axis by one period, it can not be distinguished from original self. For a mode with eigen frequency ω:

$$\bar{E}(\bar{r}, z+d) = e^{-j\beta d}\,\bar{E}(\bar{r}, z) \qquad \bar{r} = x\hat{x} + y\hat{y}$$

Where βd is called phase advance per period.

Make Fourier expansion for most common accelerating TM_{01} mode:

$$E_z = \sum_{-\infty}^{\infty} a_n J_0(k_n r) e^{j(\omega t - \beta_n t)}$$

Each term is called space harmonics.

The propagation constant is

$$\beta_n = \beta_0 + \frac{2\pi n}{d} = \frac{\omega}{v_{p0}} + \frac{2\pi n}{d}$$

$$k_n^2 = k^2 - \beta_n^2$$

Observations

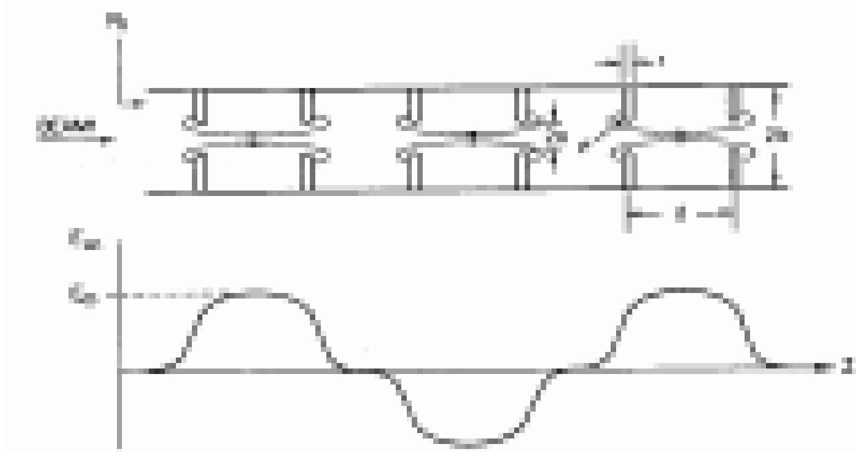
1. When the fundamental harmonic n=0 travels with v_p=c, then k_0= 0, β_0= k and $J_0(0)$=1, the acceleration is independent of the radial position for the synchronized particles.

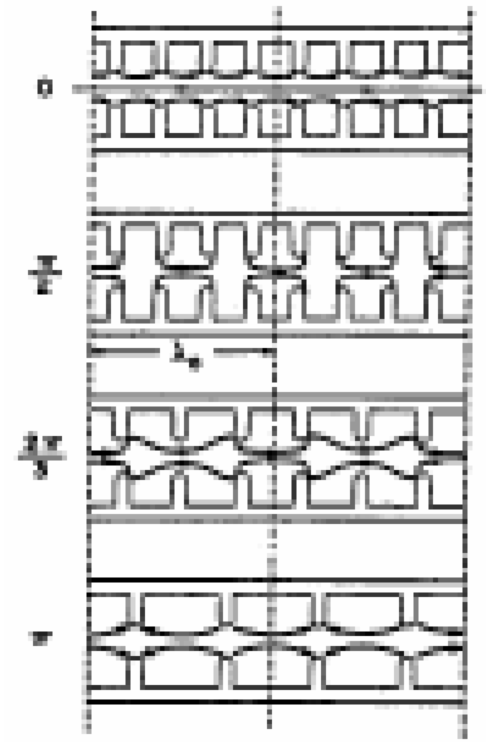
2. Each mode with specific eigenfrequency has unique group velocity.

3. Higher order space harmonics do not contribute to acceleration, but take take RF power.

- RF parameters for accelerating modes

Mode which is defined as the phase shift per structure period: $\phi=2\pi/m$ where m is the cavity number per wavelength.





Snapshots of electric field configurations for disk-loaded structures with various phase shift per period (left up for $\pi/2$ mode and right for 0, $\pi/2$, $2\pi/3$, π mode). Traveling wave axial electric field amplitude along z-axis for $\pi/2$ mode (left lower).

Shunt impedance per unit length r: is a measure of the accelerating quality of a structure

$$r = -\frac{E_a^2}{dp/dz}$$

Unit of MΩ/m or Ω/m

Where E_a is the synchronous accelerating field amplitude and dP/dz is the RF power dissipated per unit length.

$$R = \frac{V^2}{P_d}$$

Unit of MΩ or Ω

Factor of merit Q, which measures the quality of an EF structure as a resonator.

For a traveling wave structure $Q = -\frac{\omega W}{dP/dz}$ where W is the rf energy stored per unit length and ω is the angular frequency and dP/dz is the power dissipated per unit length.

For standing wave structure,

$$Q = \frac{\omega W}{P_d}$$

Group velocity V_g which is the speed of RF energy flow along the accelerator is given by

$$V_g = \frac{P}{W} = \frac{-\omega P}{Q\, {dP}/{dz}} = \frac{d\omega}{d\beta}$$

Attenuation factor τ of a constant-impedance or constant-gradient is

$$\frac{dE}{dz} = -\alpha E \qquad \frac{dP}{dz} = -2\alpha P$$

α Is the attenuation constant in nepers per unit length.

Attenuation factor τ for a traveling wave section is defined as

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

For a constant-impedance section, the attenuation is uniform,

$$\alpha = \frac{-\,{}^{dP}\!/_{dz}}{2P} = \frac{\omega}{2v_g Q} \qquad \tau = \alpha L = \frac{\omega L}{2v_g Q}$$