Proton and Ion Linear Accelerators

Week 2, part 2

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June 24, 2019

LA-UR-19-24574

Proton and Ion Linear Accelerators – Week 2, Part 2

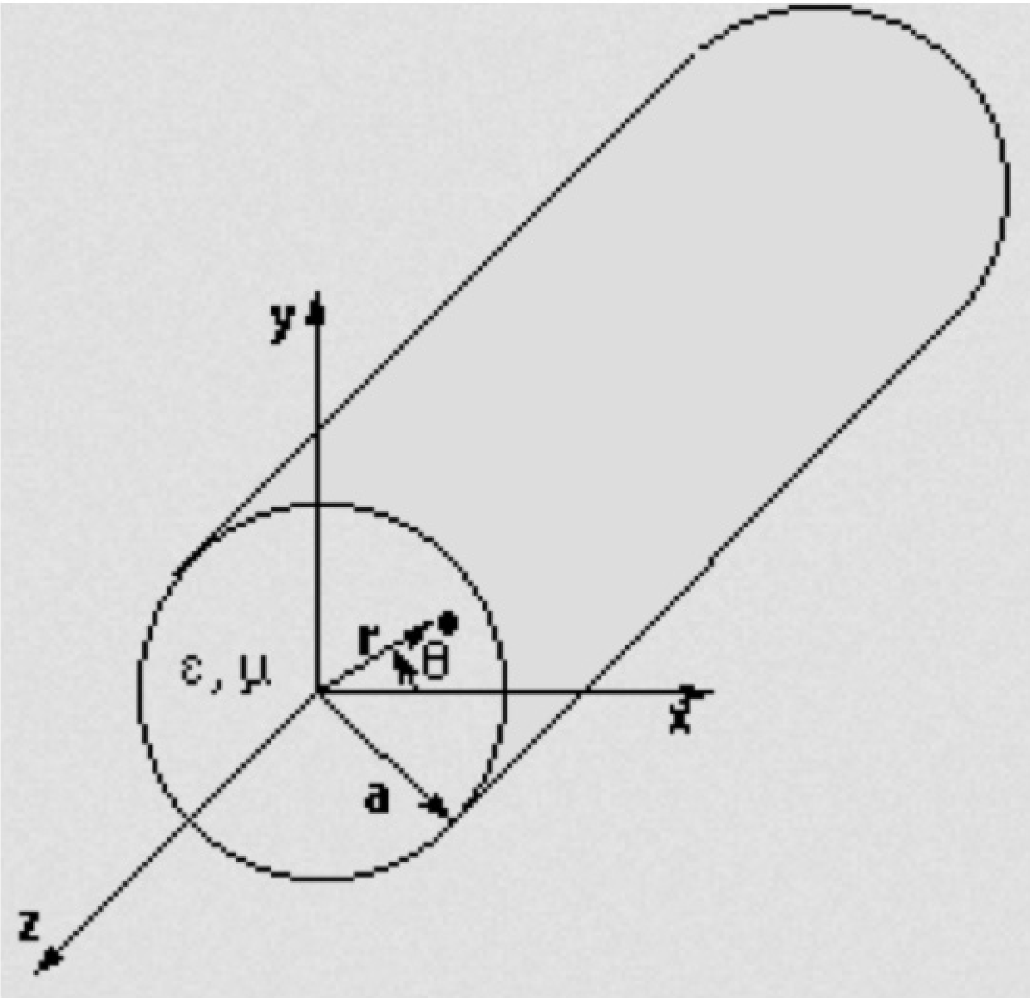
- **Why linacs & RF together?**
- **Reminder: basics of linacs**
- **RF cavities + Superfish code & exercises**
- **Accelerating structures: RFQ, DTL, CCL, etc.**
- **Electromagnetic (EM) design of accelerating structures**
- **Linac components**

Sources:

T.P. Wangler. *RF linear accelerators*, Wiley-VCH, 2nd Ed., 2008.

Handbook of Accelerator Physics and Engineering. Eds. A. Chao *et al*. World Scientific, 2013.

Uniform cylindrical waveguide



Circular waveguide.

Vacuum inside; for $\mu \neq 1$, $\varepsilon \neq 1$

$$c \to c / \sqrt{\varepsilon\mu}$$

Wave equations

$$\Delta\vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

$$\Delta\vec{B} - \frac{1}{c^2}\frac{\partial^2 \vec{B}}{\partial t^2} = 0$$

Waveguide cross section can have another shape

Waves in uniform circular cylindrical waveguide

Wave equation for electrical field

$$\Delta \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

Wave equation for E_z component in cylindrical coordinates

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 E_z}{\partial \theta^2} + \frac{\partial^2 E_z}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2} = 0$$

The solution is for TM wave:

$$E_z = R(r)\Theta(\theta)Z(z)T(t)$$

$$T(t) = T_o e^{-i\omega t} \qquad \Theta(\theta) = \Theta_o e^{-in\theta} \qquad Z(z) = Z_o e^{-ik_z z}$$

$$\frac{d^2 R}{dr^2} + \frac{1}{r}\frac{dR}{dr} + \left(\frac{\omega^2}{c^2} - k_z^2 - \frac{n^2}{r^2}\right)R = 0$$

Transverse wave number

$$k_r^2 = \frac{\omega^2}{c^2} - k_z^2$$

Wave equation can be rewritten as

$$\frac{d^2 R}{d(k_r r)^2} + \frac{1}{(k_r r)}\frac{dR}{d(k_r r)} + \left(1 - \frac{n^2}{(k_r r)^2}\right)R = 0$$

Its solution that is finite at r=0 is the Bessel function of 1st kind

$$R = AJ_n(k_r r)$$

Waves in uniform circular cylindrical waveguide – 2

Longitudinal component vanishes at the boundary of cavity

$$E_z(a) = 0 \qquad J_n(k_r a) = 0$$

Transverse wave number is determined as

$$k_r a = \upsilon_{nm}$$

ν_{nm} is the root of equation $J_{nm}(x)=0$

$$k_r = \frac{\upsilon_{nm}}{a}$$

Traveling wave in uniform waveguide

$$E_z = E_o J_n(\upsilon_{nm}\frac{r}{a})\cos n\theta e^{-i(\omega t - k_z z)}$$

Wave number $k_z = \dfrac{2\pi}{\lambda}$ and wavelength

$$k_z^2 = \frac{\omega^2}{c^2} - \frac{\upsilon_{nm}^2}{a^2} \qquad \lambda = \frac{2\pi}{k_z}$$

Cut-off frequency $k_z = 0$:

$$\omega_c = c\frac{\upsilon_{nm}}{a}$$

Phase of the wave

$$\varphi = \omega t - k_z z$$

Phase velocity of the wave in uniform homogeneous single-connected waveguide is always above the speed of light in media

$$v_{ph} = \frac{\omega}{k_z} = \frac{c}{\sqrt{1-(\frac{\omega_c}{\omega})^2}} > c$$

If $\omega < \omega_c$ in a uniform homogeneous single-connected waveguide, it is an evanescent wave: its amplitude exponentially decreases.

Dispersion diagram in uniform cylindrical waveguide

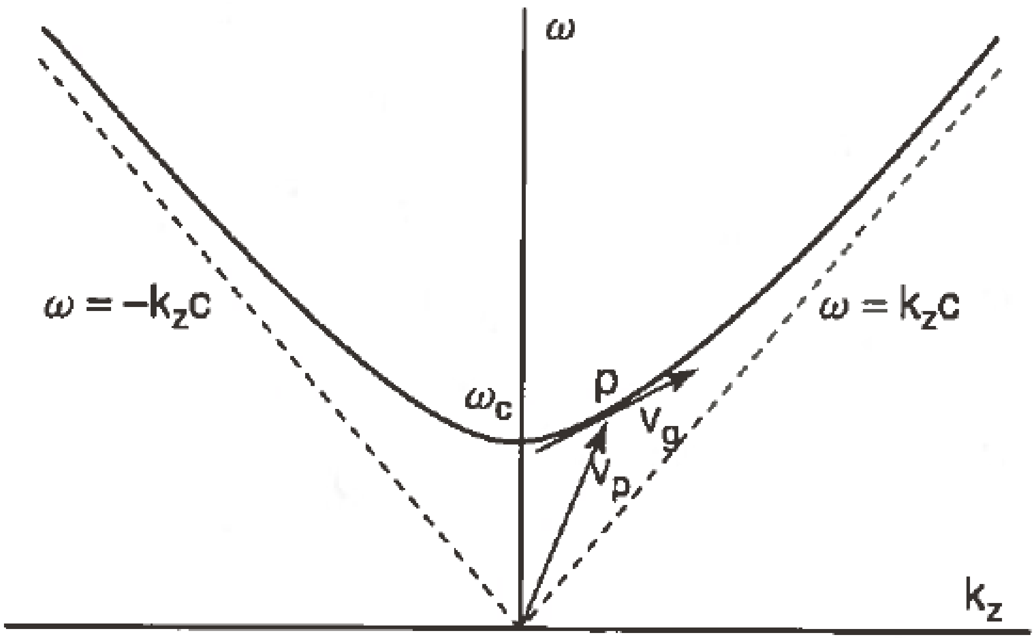


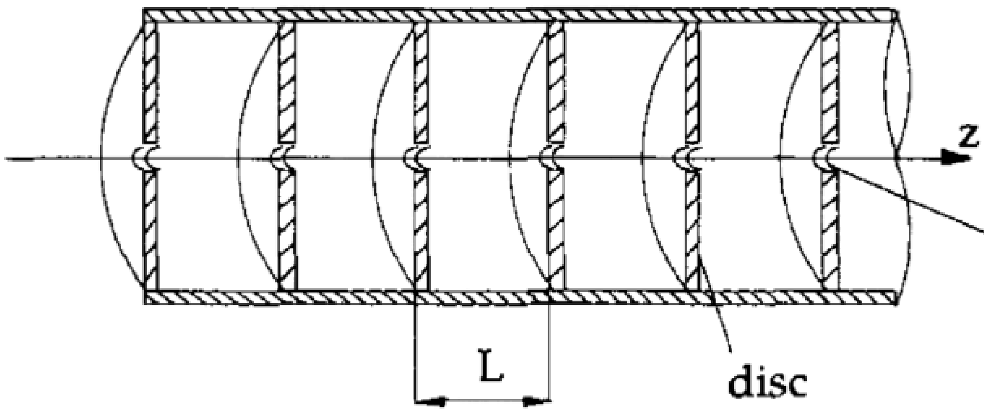
Figure 1.13 Example of dispersion curve for uniform waveguide, $\omega^2 = \omega_c^2 + (k_z c)^2$, showing graphically the meaning of phase and group velocity at the point *p* on the curve. The group velocity at point *p* is the tangent to the curve at that point. The phase velocity is the slope of the line from the origin to the point *p*.

Dispersion (Brillouin) diagram

The slope *a* of the line $\omega = a(k_z c)$ line determines the wave phase velocity:
$a > 1$ means $v_{ph} > c$.

The wave group velocity gives the speed of energy propagation along the waveguide: $v_g = d\omega/dk_z < c$.

Disk-loaded waveguide (= traveling wave structure)



Longitudinal electric field with periodic conditions

$$E_z(r,z,t) = F(r,z)e^{j(\omega t - k_0 z)} \qquad F(r, z+L) = F(r,z)$$

Expansion in Fourier series

$$F(r,z) = \sum^{n} a_n(r) e^{-j(2\pi n/L)z}$$

Substitution into wave Equation

$$e^{j\omega t} \sum^{n} e^{-j(k_0 + 2\pi n/L)z} \left[\frac{d^2 a_n(r)}{dr^2} + \frac{1}{r}\frac{da_n(r)}{dr} + K_r^2 a_n(r) \right] = 0$$

Transverse wave number

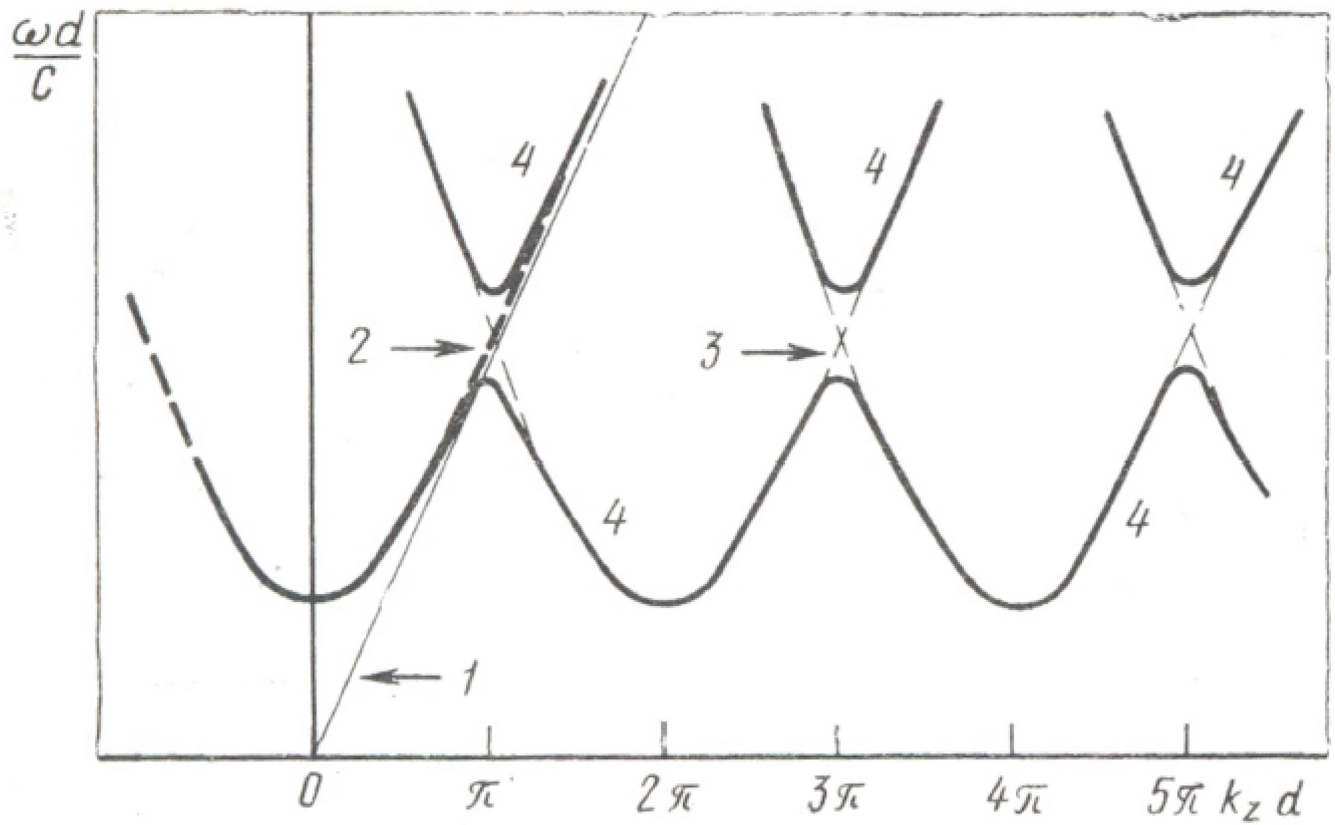
$$K_r^2 = \left(\frac{\omega}{c}\right)^2 - \left[k_0 + \frac{2\pi n}{L}\right]^2$$

Phase velocity

$$v_{ph} = \frac{\omega}{k_0 + 2\pi n/L} = \frac{\omega}{k_n}$$

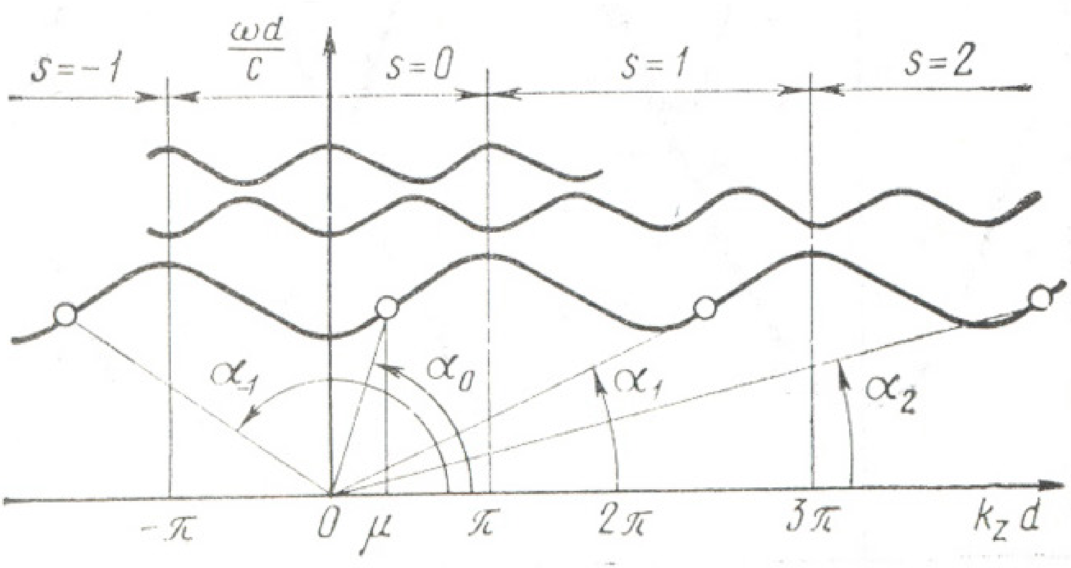
Different space harmonics have different phase velocities

Dispersion diagram of periodic waveguide

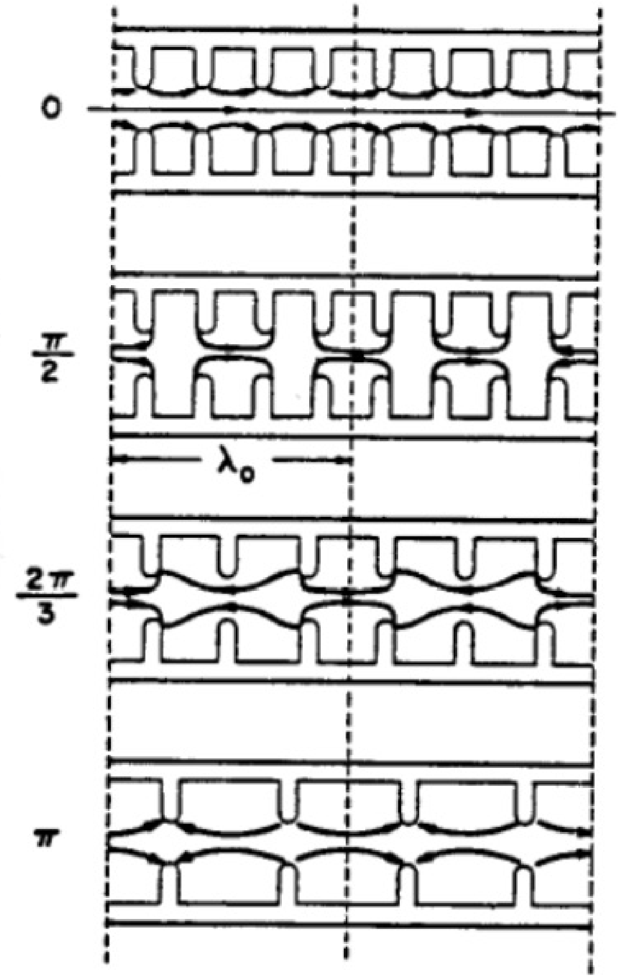


Dispersion diagram of periodic structure is a combination of diagrams for uniform waveguide periodically repeated after one period of the structure.

Traveling wave structures

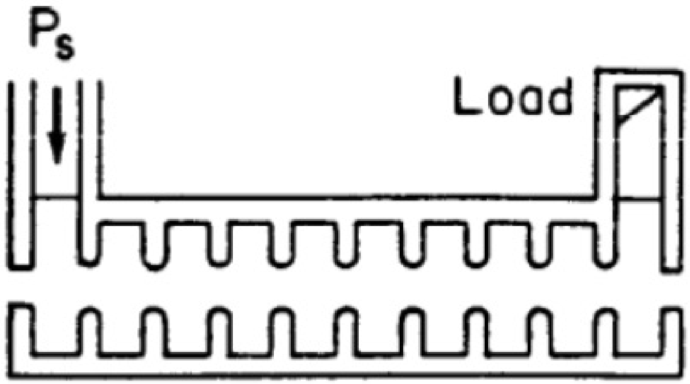


Brillouin diagram for disk-loaded waveguide. Angles α_1, α_2, ... correspond to phase velocities of various space harmonics.

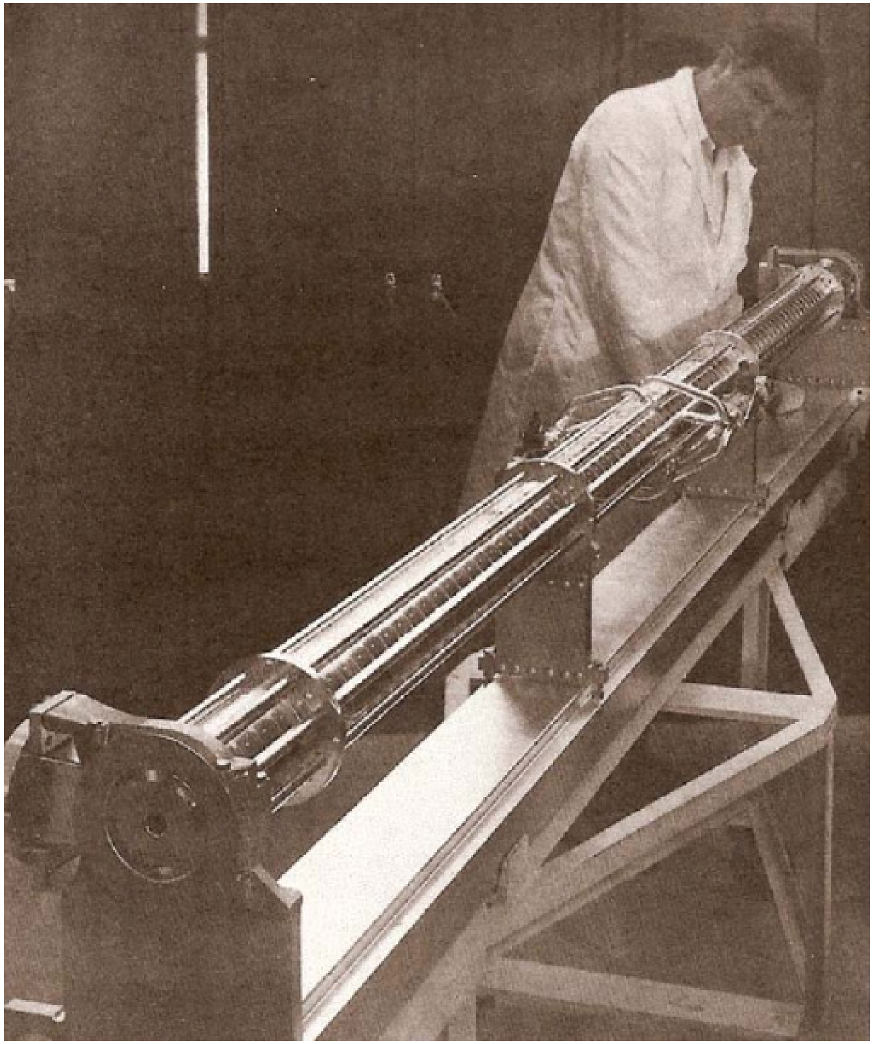


Snapshots of electric field configurations for disk-loaded structures with various phase shifts per period.

Traveling wave accelerator structures

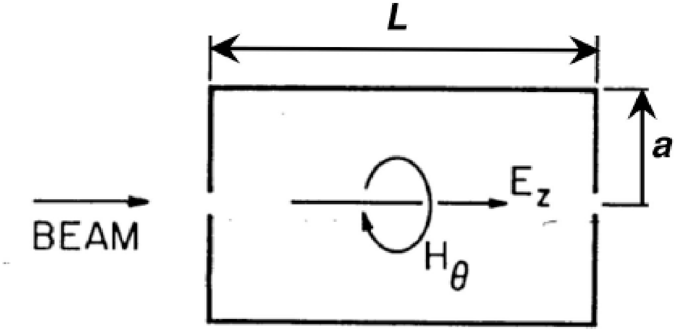


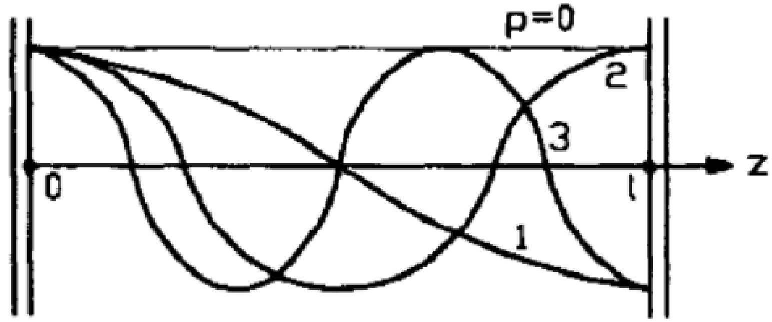
Linac with traveling wave. Primarily used for electrons.



SLAC accelerating structure: 10-foot disk-loaded, 2856 MHz, 86 cells per structure, 960 structures make up the SLAC 3-km linac.

Cylindrical resonator (pillbox)





Longitudinally integer number of half-variations can be excited

$$k_z = \frac{\pi p}{L}$$

Transverse boundary condition:

$$E_z(a) = 0 \qquad J_n(k_r a) = 0 \quad k_r = \frac{\upsilon_{nm}}{a}$$

$$\frac{\omega_o^2}{c^2} - k_z^2 = \frac{\upsilon_{nm}^2}{a^2}$$

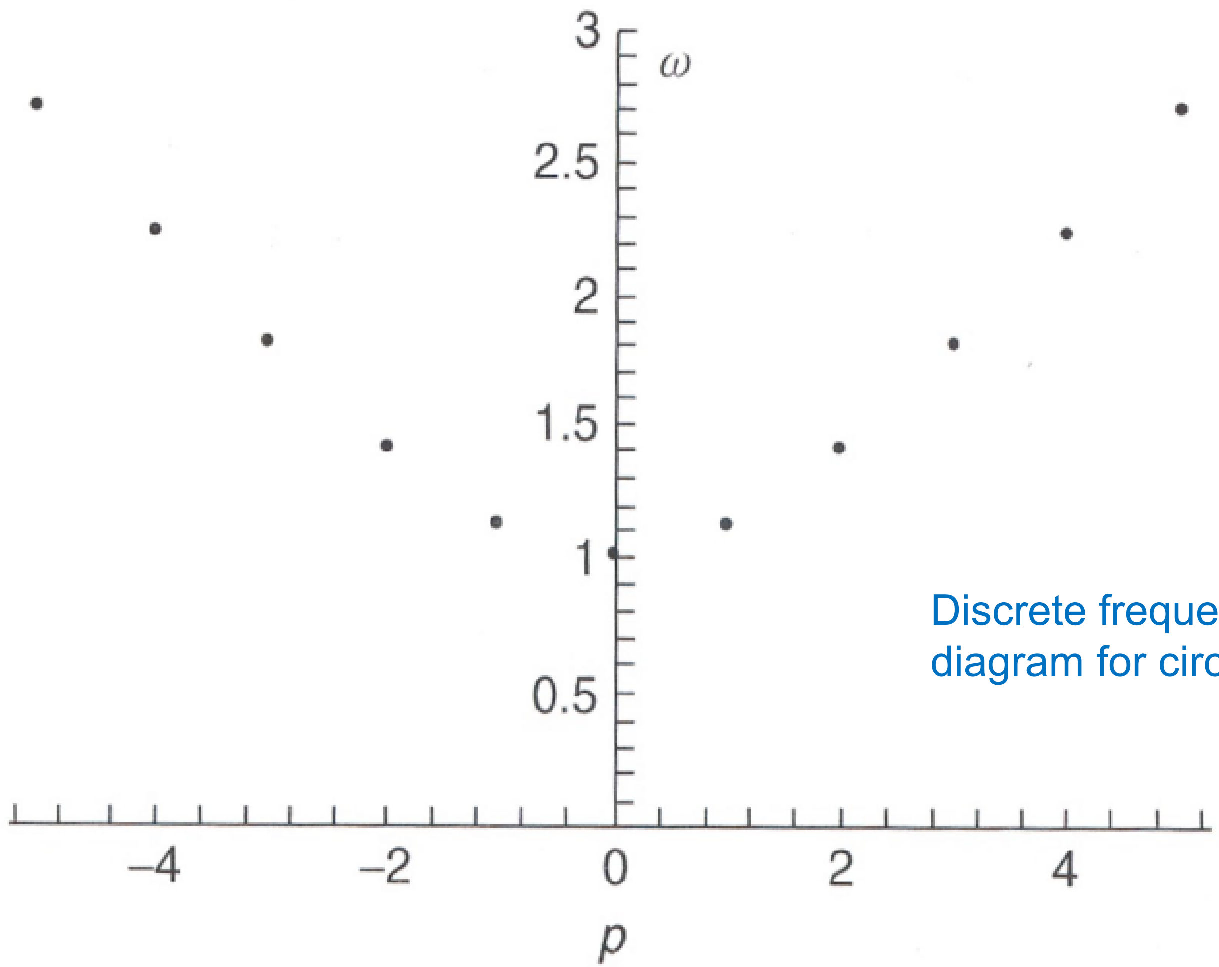
Frequency of oscillation mode is

$$\boxed{\omega_o = c\sqrt{\frac{\upsilon_{nm}^2}{a^2} + \left(\frac{\pi p}{L}\right)^2}}$$

Longitudinal component

$$E_z = E_o J_n\left(\upsilon_{nm}\frac{r}{a}\right)\cos n\theta \cos\frac{\pi p z}{L}$$

Dispersion diagram for cylindrical cavity



Discrete frequencies on the diagram for circular waveguide

Dispersion curve for the TM01p family of modes of a cylindrical circular cavity.

TM_{nmp} modes in cylindrical cavity (E modes)

Field components of TM_{nmp} modes in cylindrical cavity

$$E_z = E_o J_n(\chi r)\cos n\theta \cos \chi_z z$$

$$\chi = \frac{\upsilon_{nm}}{a} \quad \chi_z = \frac{\pi p}{L}$$

$$E_r = -E_o \frac{\chi_z}{\chi} J_n^{'}(\chi r)\cos n\theta \sin \chi_z z$$

$$E_\theta = E_o \frac{n\chi_z}{\chi^2 r} J_n(\chi r)\sin n\theta \sin \chi_z z$$

$$H_r = -iE_o \frac{n\omega_o \varepsilon_o}{\chi^2 r} J_n(\chi r)\sin n\theta \cos \chi_z z$$

$$H_\theta = -iE_o \frac{\omega_o \varepsilon_o}{\chi} J_n^{'}(\chi r)\cos n\theta \cos \chi_z z$$

$$H_z = 0$$

n – number of variation in azimuthal angle θ
m – number of variation in radius r
P – number of variation in longitudinal direction z

Example: TM_{010} mode

Field components

$$E_z = E_o J_o(\upsilon_{01}\frac{r}{a})\cos\omega_o t$$

$$B_\theta = -\frac{E_o}{c} J_1(\upsilon_{01}\frac{r}{a})\sin\omega_o t$$

Boundary condition

$$E_z(a) = 0$$

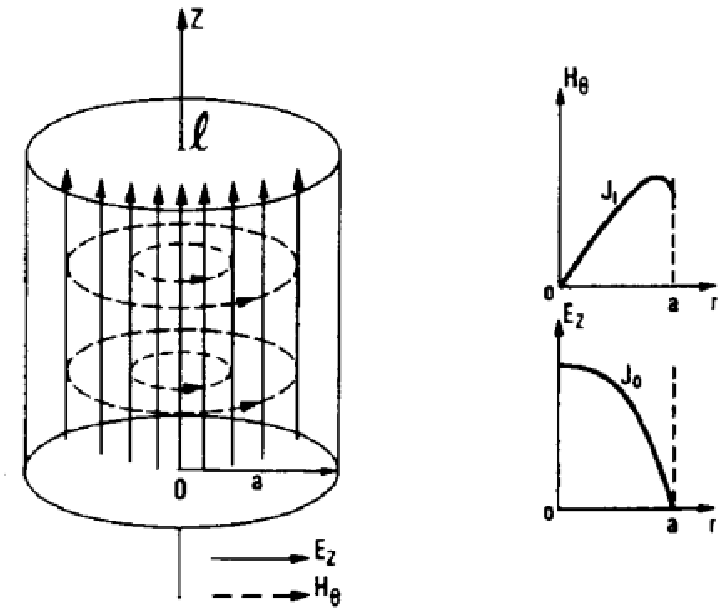
$$\upsilon_{01} = 2.405$$

Frequency of resonator

$$k_z = 0$$

$$\omega_o = 2\pi f = \frac{c\,\upsilon_{01}}{a}$$

$$\boxed{f = \frac{2.405\,c}{2\pi a}}$$

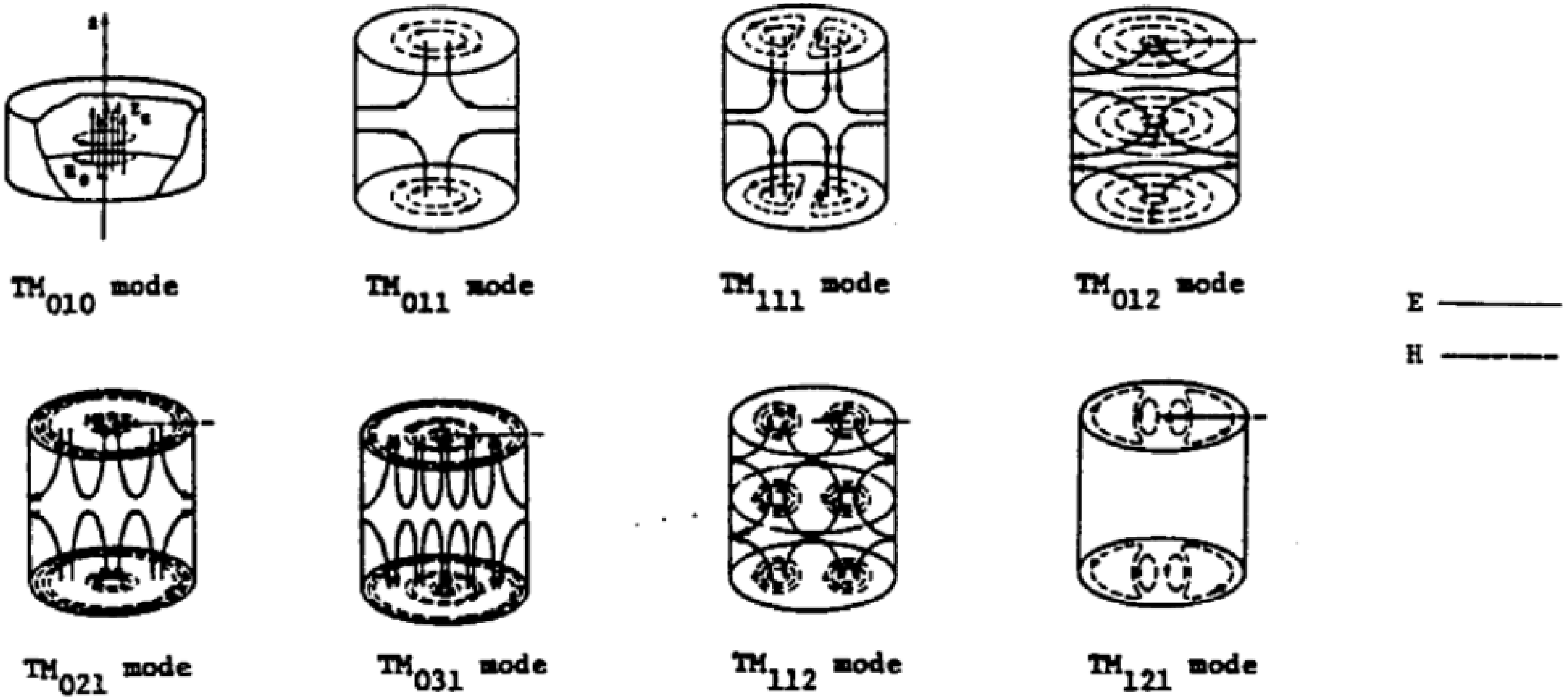


TM010 mode in a pill-box cavity.

Example: radius of resonator for *f* = 201.25 MHz:

$$a = \frac{2.405\,c}{2\pi f} = 0.57m$$

TM modes in cylindrical resonator



TM-mode field patterns in cylindrical resonator (T.Wangler, LA-UR-93-805).

TE_{nmp} modes in cylindrical cavity (H modes)

Field components of TE_{nmp} modes in cylindrical cavity

$$H_z = H_o J_n(\chi r)\cos n\theta \sin \chi_z z$$

$$H_r = H_o \frac{\chi_z}{\chi} J_n^{'}(\chi r)\cos n\theta \cos \chi_z z$$

$$H_\theta = -H_o \frac{n\chi_z}{\chi^2 r} J_n(\chi r)\sin n\theta \cos \chi_z z$$

$$E_z = 0$$

$$E_r = iH_o \frac{n\omega_o\mu_o}{\chi^2 r} J_n(\chi r)\sin n\theta \sin \chi_z z$$

$$E_\theta = iH_o \frac{\omega_o\mu_o}{\chi} J_n^{'}(\chi r)\cos n\theta \sin \chi_z z$$

$$\chi_z = \frac{\pi p}{L}$$

Boundary condition: $E_\theta(a) = 0$

$$J_n^{'}(\chi a) = 0 \qquad \chi = \frac{\upsilon_{nm}^{'}}{a}$$

$\upsilon_{nm}^{'}$ is the root of equation $J_n^{'}(x) = 0$

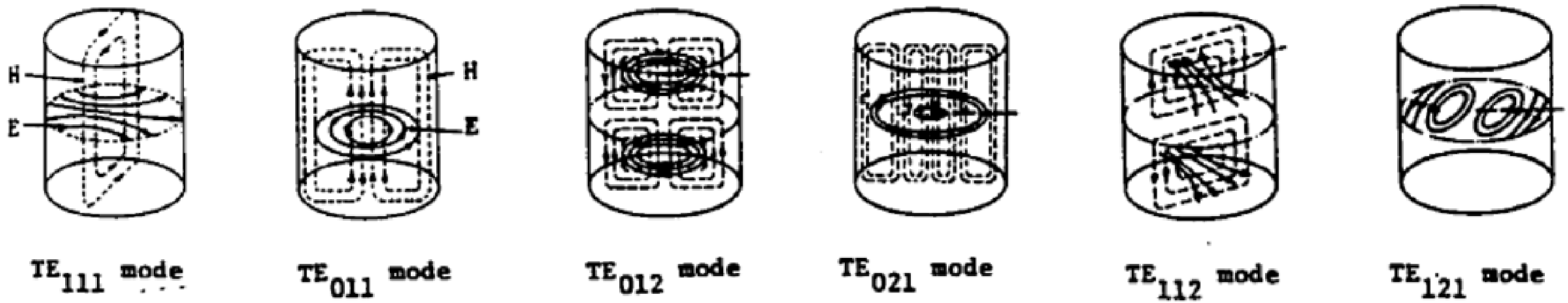
Frequency of TE_{nmp} oscillations

$$\omega_o = c\sqrt{\frac{\upsilon_{nm}^{'2}}{a^2} + \left(\frac{\pi p}{L}\right)^2}$$

Zeros $\upsilon_{nm}^{'}$ of equation $J_n^{'}(x) = 0$

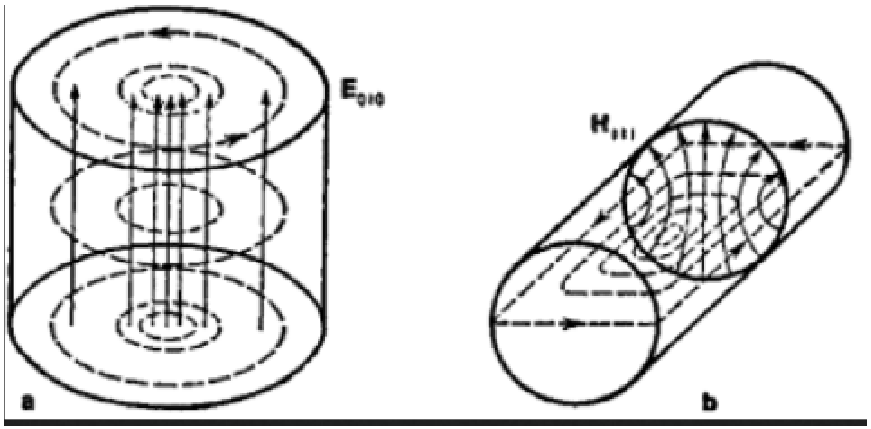
	$m = 1$	$m = 2$	$m = 3$	$m = 4$
$n = 0$	3.832	7.016	10.173	13.324
$n = 1$	1.841	5.331	8.536	11.706
$n = 2$	3.054	6.706	9.969	13.170
$n = 3$	4.201	8.015	11.346	

TE modes in cylindrical resonator



TE-mode field patterns in cylindrical resonator (T.Wangler, LA-UR-93-805).

Fundamental modes of cylindrical resonator



Oscillations TE_{111} and TM_{010} are fundamental modes which frequencies coincide if

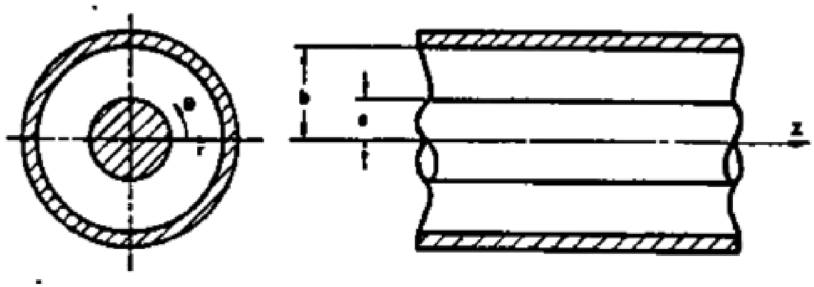
$$\frac{\upsilon_{01}^2}{a^2} = \frac{\upsilon_{11}^{'2}}{a^2} + (\frac{\pi}{L})^2$$

In this case of ratio of length of resonator to radius L/a is

$$\frac{L}{a} = \frac{\pi}{\sqrt{\upsilon_{01}^2 - \upsilon_{11}^{'2}}} = 2.03$$

For long cylinder $L/a > 2.03$ the fundamental mode is TE_{111} while for “flat” resonator $L/a < 2.03$ the fundamental mode is TM_{010}.

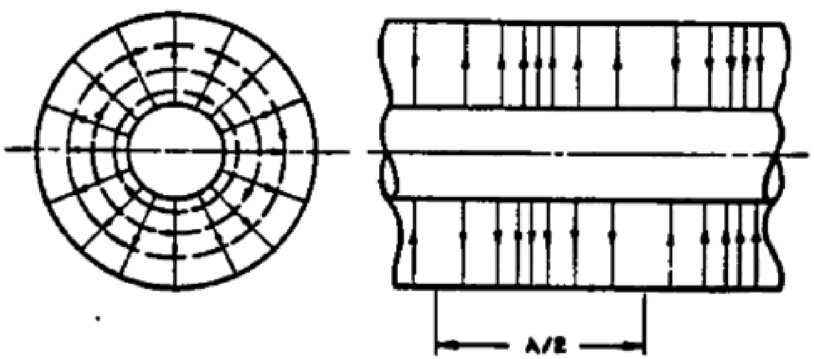
Coaxial line



A section of coaxial transmission line

Field components of TEM wave propagating in coaxial transmission line

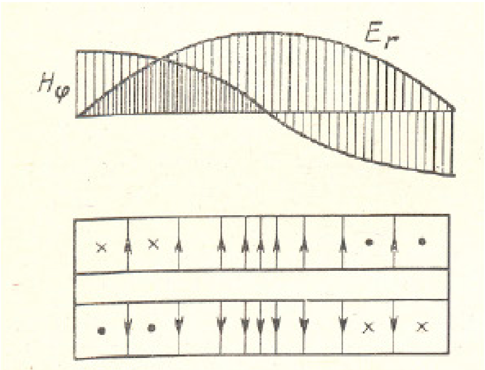
$$B_\theta = \frac{\mu_o I}{2\pi r}\exp[i(\omega t - k_z z)]$$



$$E_r = \sqrt{\frac{\mu_o}{\varepsilon_o}}\frac{I}{2\pi r}\exp[i(\omega t - k_z z)]$$

Note that unlike single-connected waveguides there is <u>no cut-off frequency</u> in coaxial lines. They can transmit waves even at very low frequencies, and the phase velocity $v_{ph}=c$.

Coaxial resonators: half-wave & quarter-wave

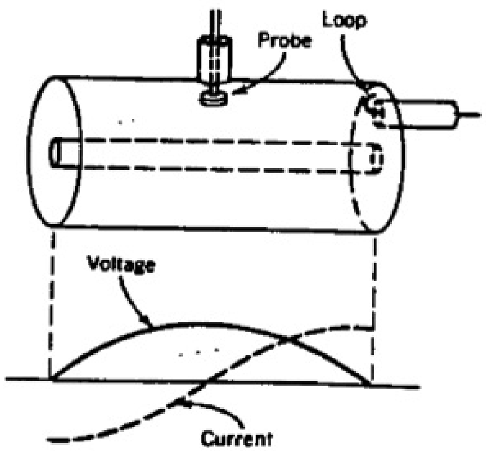


Resonance condition: $L = \frac{p\lambda}{2}$

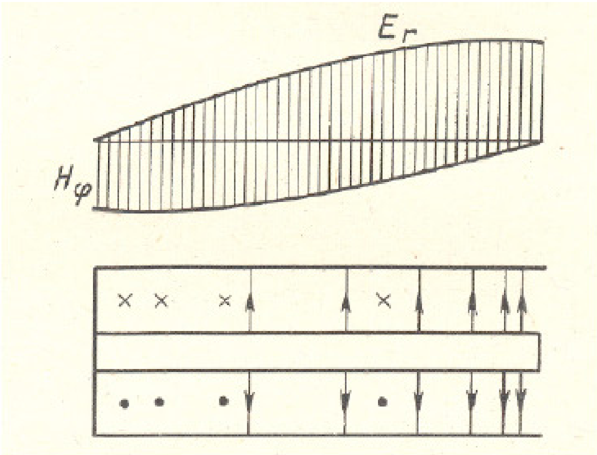
Component of RF field

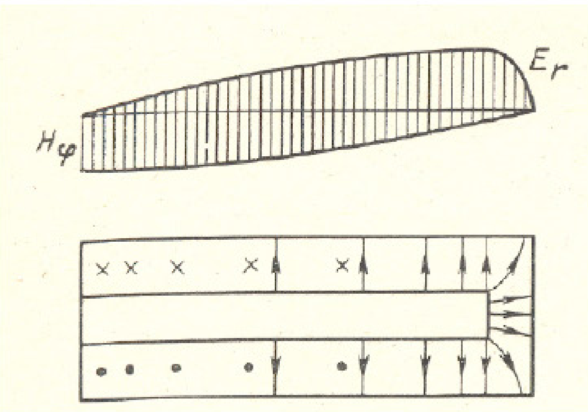
$$B_\theta = \frac{\mu_o I}{2\pi r}\cos(\frac{\pi p z}{L})\cos\omega t$$

$$E_r = \sqrt{\frac{\mu_o}{\varepsilon_o}}\frac{I}{2\pi r}\sin(\frac{\pi p z}{L})\sin\omega t$$



Coaxial resonator with voltage and current standing waves.





Quarter wave resonator

The wavelength (and frequency) of coaxial resonators is defined mainly by their length.
Note: RF coupling – magnetic loop here; ferrite loading – lowering and tuning frequency.

Field energy in RF cavities

EM energy in cavity

$$W = \frac{1}{2}\int_V (\mu_o H^2 + \varepsilon_o E^2)$$

Energy balance

$$\oint_S [\vec{E},\vec{H}]\, d\vec{S} = -\frac{d}{dt}\int_V \left(\frac{\mu_o H^2}{2} + \frac{\varepsilon_o E^2}{2}\right) dV - \int_V \vec{j}\vec{E}\, dV$$

Poynting's theorem in integral form: the rate of energy change in cavity equals the rate of work done on a charge distribution plus the energy flux through its surface.

Energy dissipation in resonator and Q factor

Dissipated power is a combination of power losses inside cavity and outside cavity

$$P = P_o + P_{ext}$$

Energy stored in cavity

$$W_o = \frac{1}{2}\int_{V_o} \mu H_m^2 dV = \frac{1}{2}\int_{V_o} \varepsilon E_m^2 dV$$

Quality factor (= 2*π**stored energy / energy loss per period)

$$Q = \frac{\omega_o W_o}{P}$$

Q-factor is a combination of unloaded quality factor of cavity and external quality (loaded Q factor)

$$\frac{1}{Q} = \frac{1}{Q_o} + \frac{1}{Q_{ext}}$$

External quality factor

$$Q_{ext} = \frac{\omega_o W_o}{P_{ext}}$$

Losses in metal with surface resistance R_s [Ohm]

$$P_o = \frac{R_s}{2}\int_S H_m^2 dS$$

$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$, where *σ* is the surface conductivity,

and *δ* is the skin depth $\delta = \sqrt{2/(\mu_0\sigma\omega)}$.

Unloaded quality factor $Q_o = \frac{\omega_o W_o}{P_o}$

$$Q_o = \frac{\omega_o}{R_s}\frac{\int_{V_o} H_m^2 dV}{\int_S H_m^2 dS}$$

Physical meaning: $Q = G\frac{V}{S\delta}$

Quality factor of TM_{010} cavity

Magnetic field

$$H_{m\theta} = -E_o \sqrt{\frac{\varepsilon_o}{\mu_o}} J_1(\upsilon_{01} \frac{r}{a})$$

Energy stored in cavity

$$W_o = \frac{1}{2} \int_{V_o} \mu_o H_{m\theta}^2 dV = \frac{\pi \varepsilon_o E_o^2 L a^2 J_1^2(\upsilon_{01})}{2} = 0.135 \pi \varepsilon_o L a^2 E_o^2$$

Loss power in cavity

$$P_o = \frac{R_s}{2} \int_S H_{m\theta}^2 dS = \pi a R_s E_o^2 \frac{\varepsilon_o}{\mu_o} J_1^2(\upsilon_{01})(L+a)$$

Unloaded quality factor

$$\boxed{Q_o = \frac{\omega_o W_o}{P} = \frac{\upsilon_{01}}{2R_s} \sqrt{\frac{\mu_o}{\varepsilon_o}} \frac{1}{(1+\frac{a}{L})} = 1.2025 \frac{376.7[Ohm]}{R_s} \frac{1}{(1+\frac{a}{L})}}$$

For ideal copper surface $\sigma = 5.8 \cdot 10^7$ Sm/m, so that $R_s = 2.6 \cdot 10^{-4} \sqrt{f(\mathrm{MHz})}\ \Omega$. At 201.25 MHz, $R_s = 3.7$ mΩ, and $Q_0 = 66500$ for $a/L = 1$. In practice, typically 10%-20% less.

Superconducting RF cavities

For RF cavities the power loss depends on the surface resistance: for normal-conducting

$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$$ scales with RF frequency as $\sqrt{f}$.

In superconducting (SC) RF cavities the surface resistance is much lower; e.g., for Nb

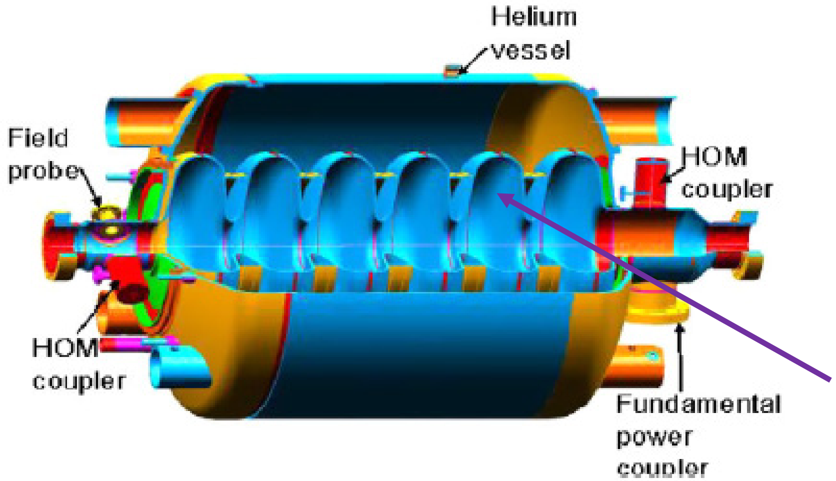
$$R_s(\Omega) = 9 \cdot 10^{-5} \frac{f^2(GHz)}{T(^\circ K)} \exp\left(-\alpha \frac{T_c}{T}\right) + R_{res},$$

where R_{res} is the residual resistance (~1-10 nΩ), α = 1.83, and T_c = 9.2 K is the critical temperature.

SC R_s is ~10^{-5} of that in copper, and so are the cavity surface losses!

For ideal copper surface, typical $Q_0 = 10^4$-10^5. In SC cavities, typical $Q_0 = 10^8$-10^{10}, so it is especially advantageous to use SC RF cavities in CW machines (operating at 100% RF duty factor).

SC cavity assembly for SNS linac



6-cell Nb 805-MHz elliptical RF cavity

Quality factor of coaxial resonator

Azimuthal magnetic field

$$H_{m\theta} = \frac{I_m}{2\pi r} \cos \frac{p\pi z}{L}$$

Integral over volume

$$\int_{V_o} H_m^2 dV = \pi L \left(\frac{I}{2\pi}\right)^2 \ln \frac{R_2}{R_1}$$

Integral over surface

$$\int_{V_o} H_m^2 dS = \pi \left(\frac{I}{2\pi}\right)^2 \left[4 \ln \frac{R_2}{R_1} + L\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\right]$$

Unloaded quality factor

$$Q_o = \frac{p\pi}{R_s} \sqrt{\frac{\mu_o}{\varepsilon_o}} \frac{\ln \frac{R_2}{R_1}}{4 \ln \frac{R_2}{R_1} + L\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}$$

Filling time of resonator

Power losses is a rate of decrease of stored energy

$$P = -\frac{dW_o}{dt}$$

Substitution into equation $Q = \frac{\omega_o W_o}{P}$ gives equation for decrease of stored energy

$$\frac{dW_o}{dt} = -\frac{\omega_o W_o}{Q}$$

Solution

$$W_o = W_o(0)e^{-\frac{\omega_o}{Q}t}$$

Electrical field changes with two times smaller rate:

$$\alpha = \frac{\omega_o}{2Q}$$

Electric field

$$E = E_m e^{-i\omega_o t} e^{-\frac{\omega_o}{2Q}t}$$

Filing time of the cavity

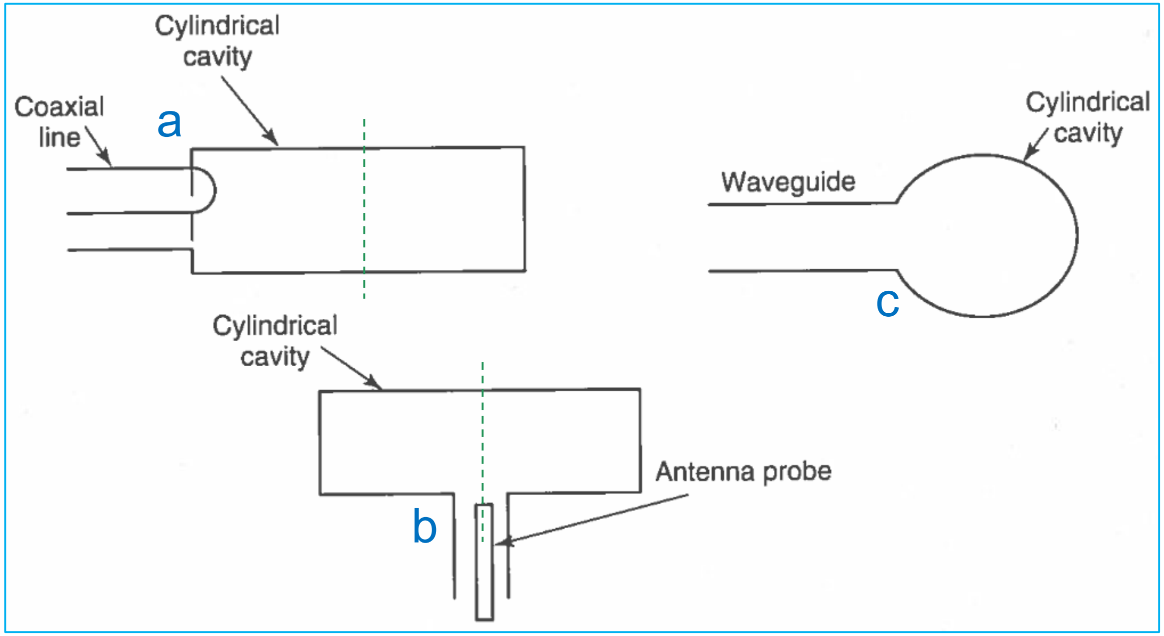
$$t_f = \frac{2Q}{\omega_o}$$

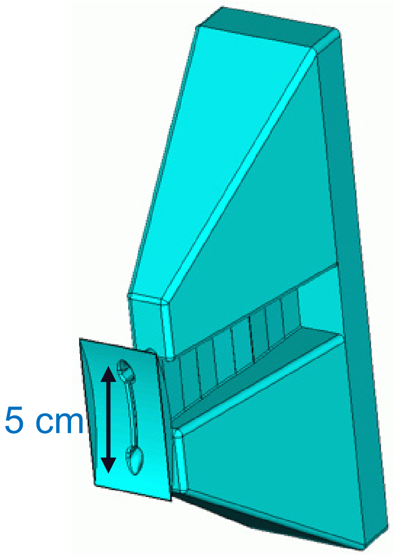
Note: filling time $t_f = QT_{RF}/\pi$

Sometimes it is convenient to use complex frequency of cavity

$$\dot{\omega}_o = \omega_o\left(1 + i\frac{1}{2Q}\right)$$

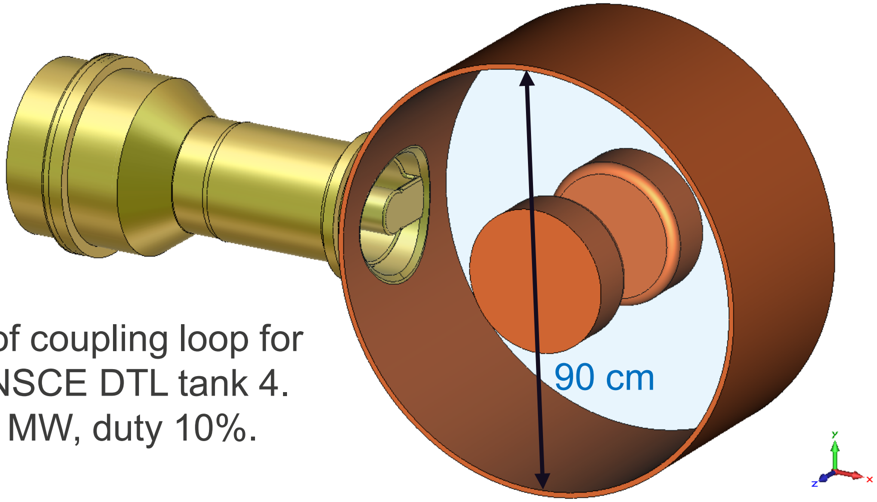
Coupling RF power to cavities





“Dog-bone” coupling iris for high-power FEL photoinjector. Up to 0.5 MW at 100% duty.

Methods of coupling to RF cavities:
(a) magnetic – current loop;
(b) electric – antenna;
(c) magnetic – iris WG-cavity



Model of coupling loop for the LANSCE DTL tank 4. Up to 3 MW, duty 10%.

Filling time with external load

The cavity coupling coefficient is defined as $\beta \equiv \frac{P_{ext}}{P_0} = \frac{Q_0}{Q_{ext}}$.

When the power source is matched to the resonant structure through a coupling loop, such that no power is reflected toward the source, then the loaded Q

$$Q = \frac{Q_o}{1+\beta}$$

where β is the coupling coefficient. For negligible beam current β = 1.

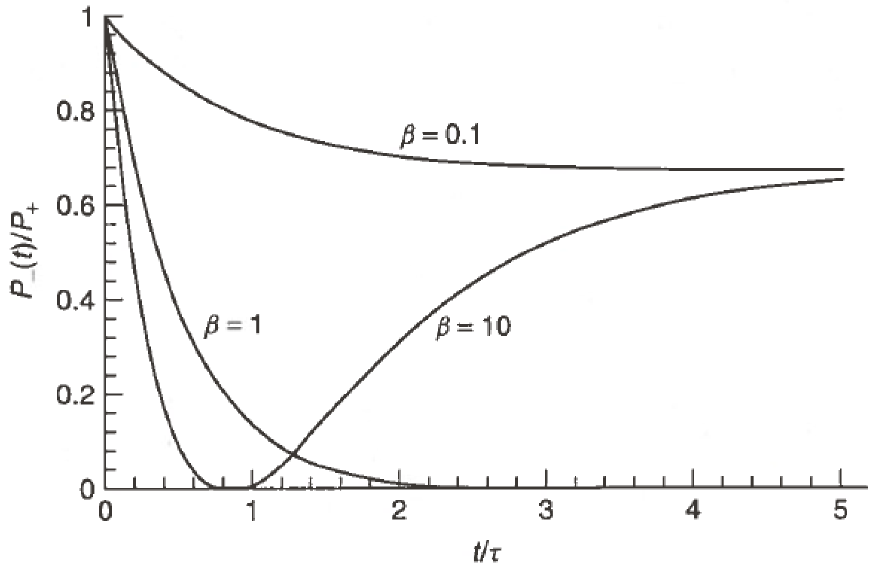
The filling time becomes

$$t_f = \frac{2Q}{\omega_o} = \frac{2Q_o}{\omega_o(1+\beta)}$$

During the filling time, the transient effect exists when reflected power cannot be avoided.

RF coupling and reflected power

When coupling coefficient $\beta = 1$, the cavity is matched to RF feed (critically coupled); $\beta > 1$ – over-coupled, and $\beta < 1$ – under-coupled.



Backward (reflected) power vs time for different values of *β.* Here $\tau = t_f$ – cavity filling time.

The cavity RF coupling is usually designed such that

$$\beta = \frac{P_0 + P_{beam}}{P_0}.$$

In this case no RF power is reflected back to the RF source when the cavity is operating with the beam.

Figures of merit for accelerating structures

Quality factor (stored energy *U*, averaged power loss *P*) $$Q = \frac{\omega U}{P}$$

Shunt impedance (total cavity voltage V_0) $$R_{sh} = \frac{V_0^2}{P}$$

Effective shunt impedance (effective voltage V_0T) $$R_{eff} = R_{sh}T^2$$

Shunt impedance per unit length (voltage $V_0 = E_0L$) $$Z = \frac{E_0^2}{P/L}$$

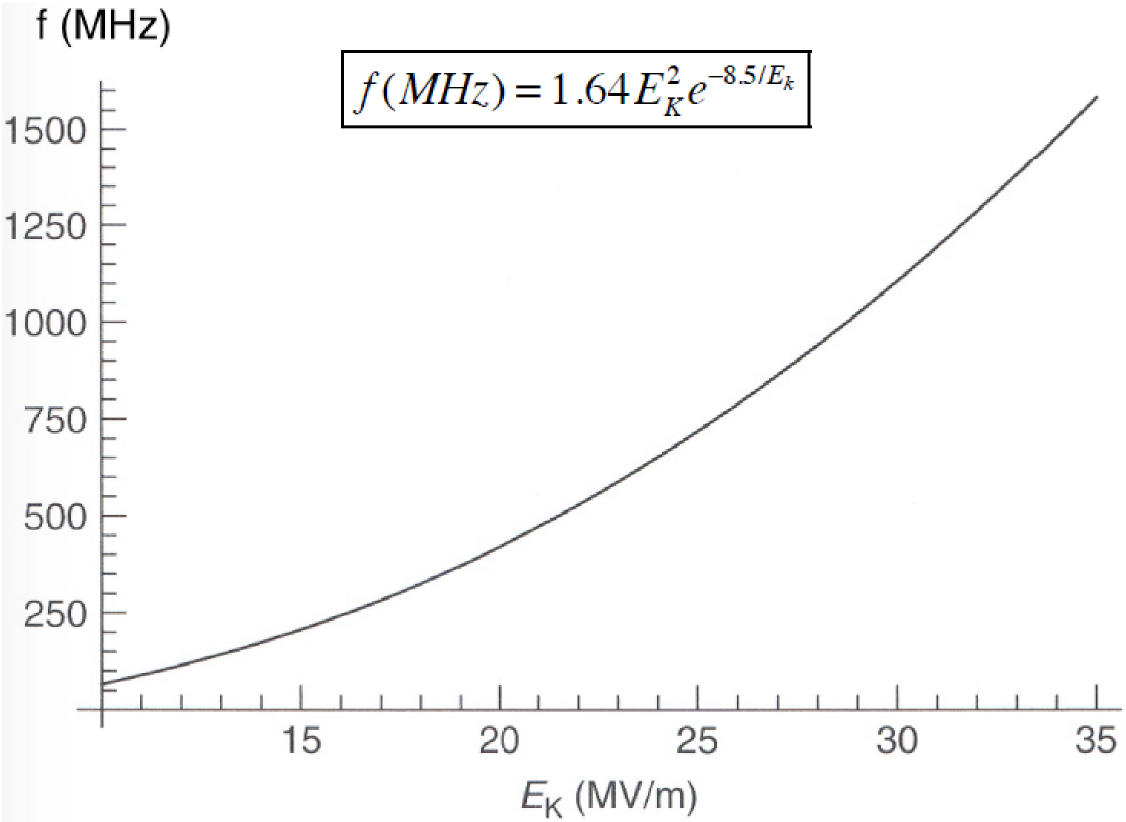
Effective shunt impedance per unit length (Z_{eff}) $$ZT^2 = \frac{(E_0T)^2}{P/L}$$

Ratio R_{eff}/Q is independent of surface losses and depends only on the cavity (structure) geometry $$\frac{R_{eff}}{Q} = \frac{(V_0T)^2}{\omega U}$$

Ratios E_{max}/E_{acc} ($E_{acc}=E_0T$) and B_{max}/E_{acc} – lower is better. The latter is very important for SC cavities.

Cavity RF electric breakdowns: Kilpatrick criterion

RF breakdowns – uncontrolled discharges in cavities – limit the cavity max electric fields.



The maximal surface field also depends on the RF pulse length. The cavity design fields are typically (1.3-2)E_K for pulses longer then 1 ms. For very short pulses, below 1 μs, they can be higher and scale as

$$E_s \propto f^{1/2} / t^{1/4}.$$

The critical value of the surface electric field (E_K – Kilpatrick field) versus RF frequency (empirical, conservative).

Other deleterious electron-related effects in RF cavities: multipacting (usually occurs at low RF field levels) and electron RF loading. In SC RF cavities – quench (→NC).

RF cavity design issues

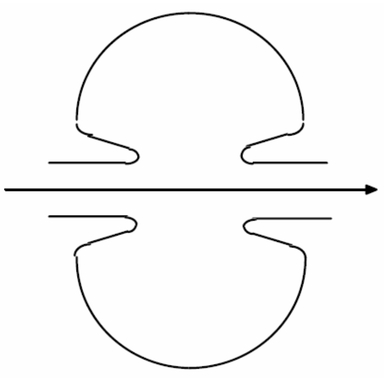
Cavity design goals depend on many factors including its application and the cavity type: maximize accelerating gradient, minimize losses (NC), minimize max surface fields, etc.

Frequency dependence of cavity parameters: *a ~ 1/f*,

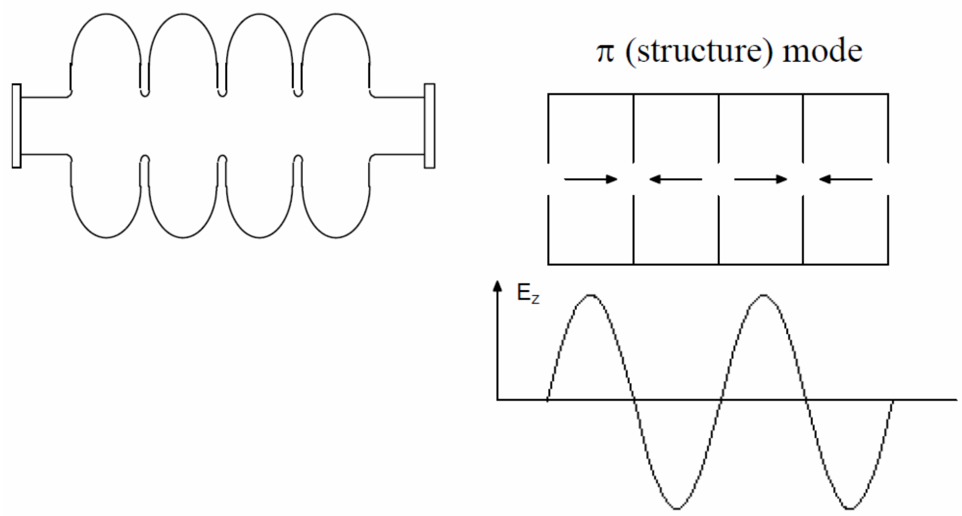
$$P \propto \begin{Bmatrix} f^{-1/2}, & \text{NC} \\ f, & \text{SC} \end{Bmatrix} \qquad Q \propto \begin{Bmatrix} f^{-1/2}, & \text{NC} \\ f^{-2}, & \text{SC} \end{Bmatrix} \qquad ZT^2 \propto \begin{Bmatrix} f^{1/2}, & \text{NC} \\ f^{-1}, & \text{SC} \end{Bmatrix}$$

Frequency choice also depends on available RF sources and beam parameters.

Changing cavity shape is the common way of achieving the design goals. Examples:



Nose-cone cavity



4-cell elliptical cavity (SC)

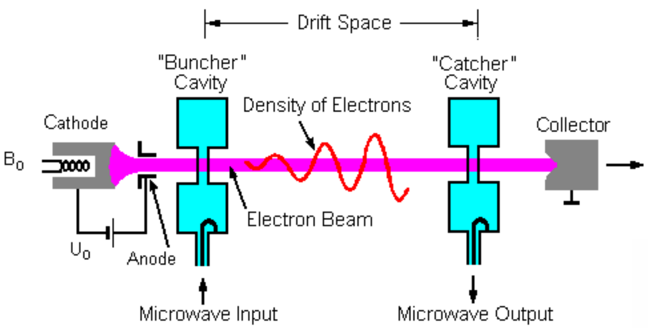
RF power sources

<u>High-power vacuum-tube amplifiers</u>: gridded <u>tubes</u> (triodes, tetrodes – below 300 MHz, pulsed) and <u>klystrons</u> (300 MHz – 10s GHz; from 1 μs pulses to CW operation).

Klystrons were invented in 1937 (Varian). Peak power up to 60 MW, average 50 kW (SLAC).

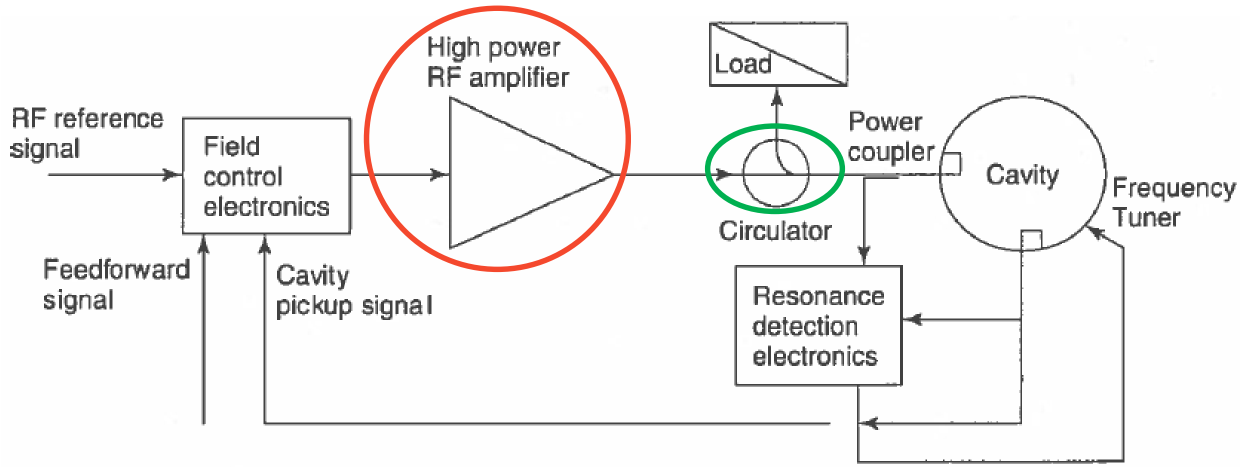
Power gain up to 50-60 dB, efficiency 40-60%.

Reliable: MTBF > 30000 h.



Klystron principle

Scheme of RF system for accelerator cavity



- The choice depends on application (pulsed or CW), frequency, peak and average power, efficiency, and cost. The RF cost is typically the largest part of linac cost.
- Magnetrons are rarely used (cheaper but lack phase stability).
- More recently – multi-beam klystrons, solid-state amplifiers, and inductive-output tubes (IOTs).

Summary of part 2

RF waveguide, cavity, and power source basics are reviewed.