Lecture 7
RF linacs

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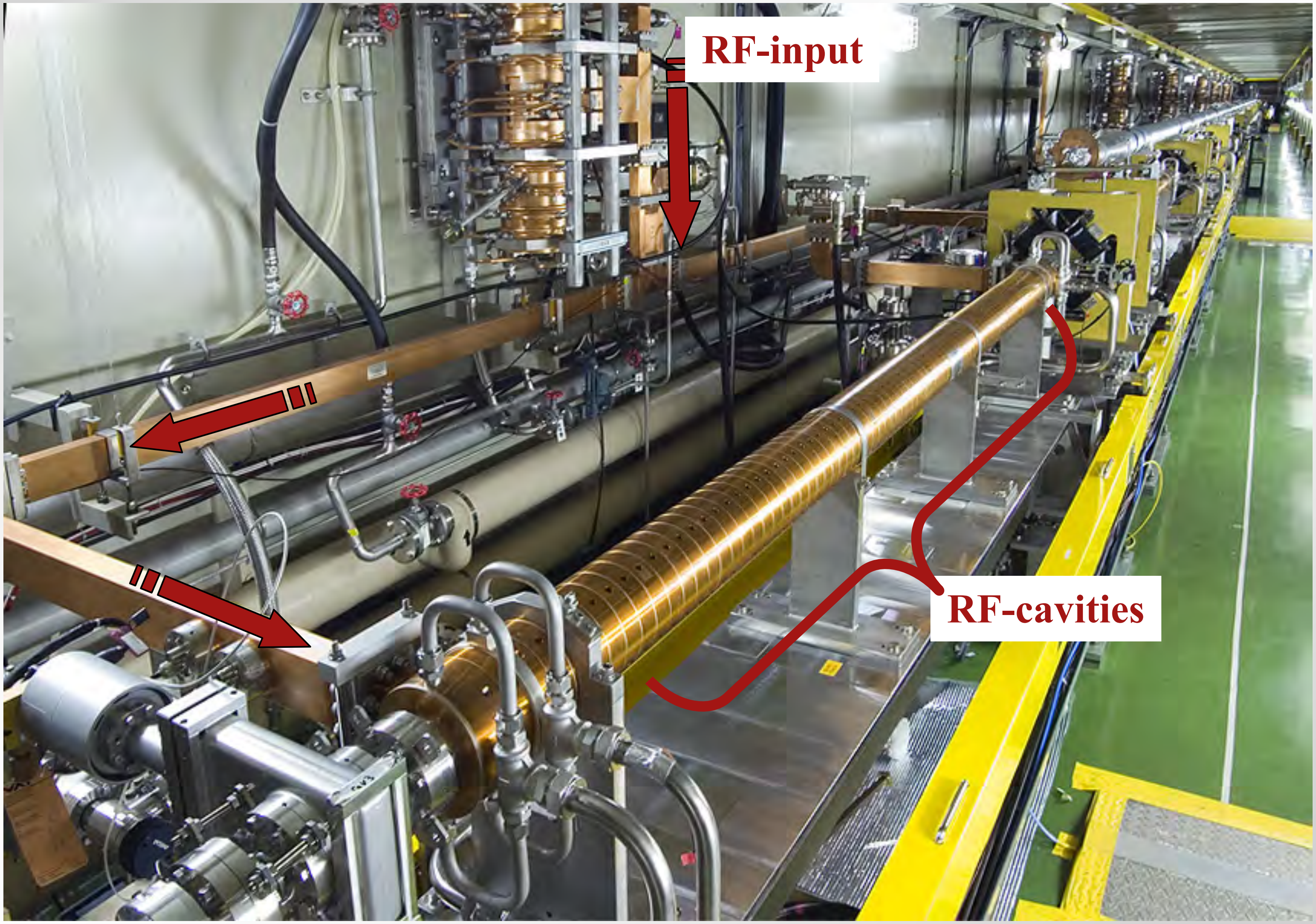
S-band (~3 GHz) RF linac



Translate circuit model to a cavity model: Directly driven, re-entrant RF cavity

Outer region: Large, single turn Inductor

$$L = \frac{\mu_o \pi a^2}{2\pi(R+a)}$$

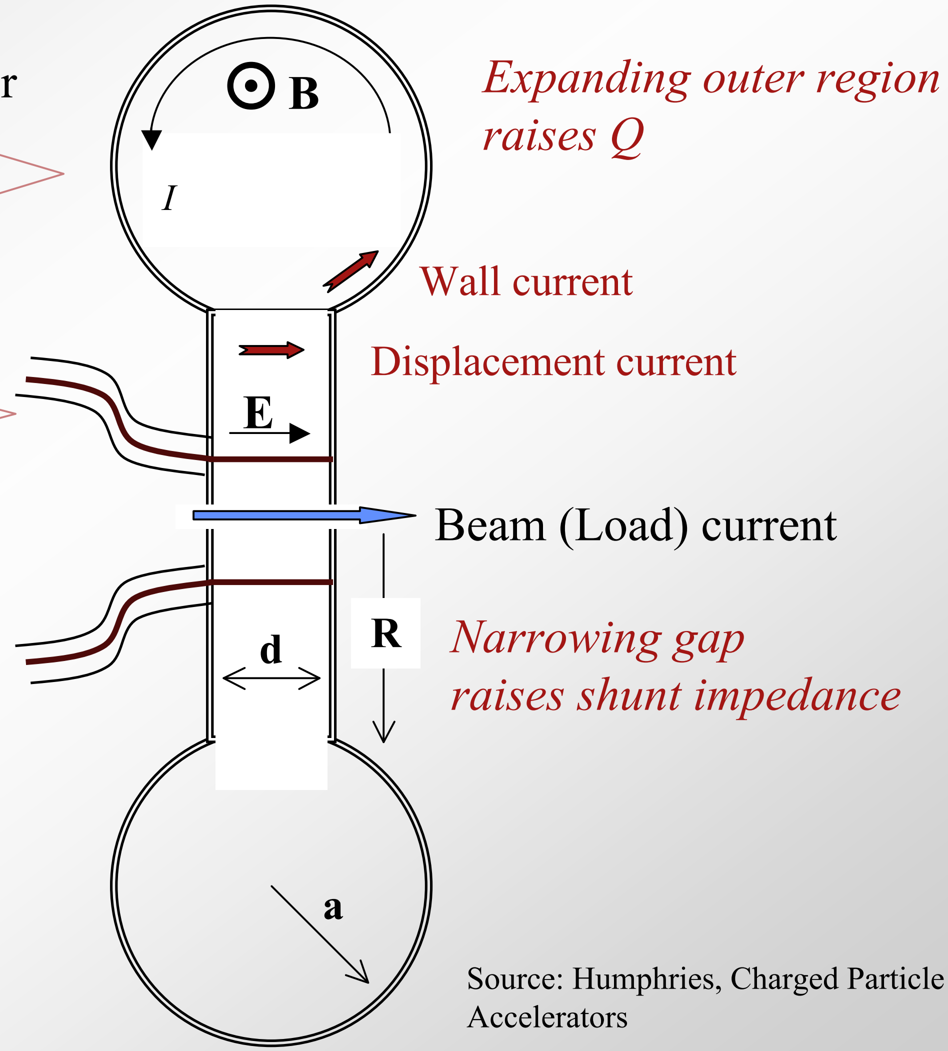
Central region: Large plate Capacitor

$$C = \varepsilon_o \frac{\pi R^2}{d}$$

$$\omega_o = 1\Big/\sqrt{LC} = c\left[\frac{2((R+a)d}{\pi R^2 a^2}\right]^{1/2}$$

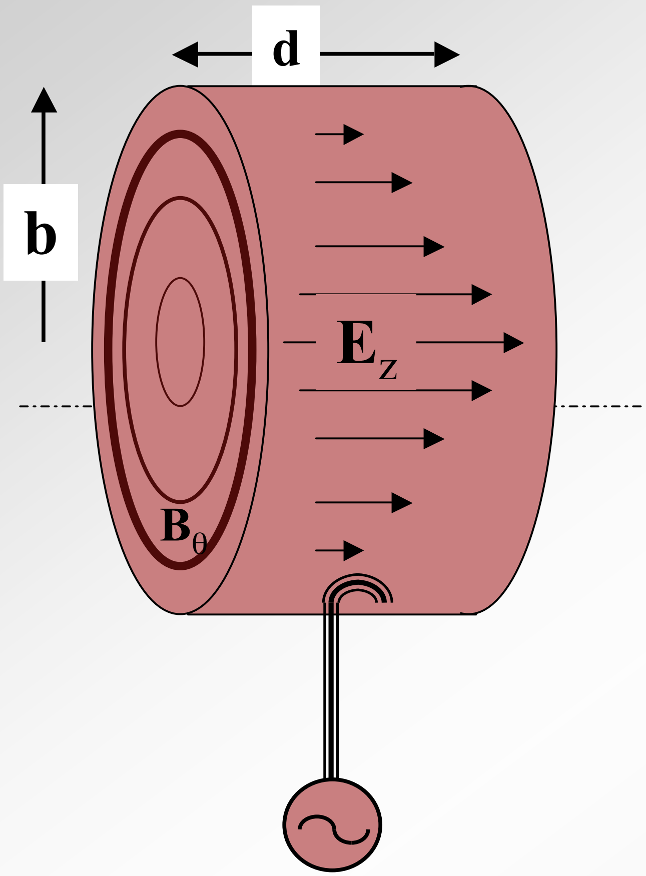
Q – set by resistance in outer region

$$Q = \sqrt{L/C}\Big/R$$



Source: Humphries, Charged Particle Accelerators

Properties of the RF pillbox cavity



$$\sigma_{walls} = \infty$$

- We want lowest mode: with only $\mathbf{E}_z$ & $\mathbf{B}_\theta$
- Maxwell's equations are:

$$\boxed{\frac{1}{r}\frac{\partial}{\partial r}(rB_\theta) = \frac{1}{c^2}\frac{\partial}{\partial t}E_z \quad \text{and} \quad \frac{\partial}{\partial r}E_z = \frac{\partial}{\partial t}B_\theta}$$

- Take derivatives

$$\frac{\partial}{\partial t}\left[\frac{1}{r}\frac{\partial}{\partial r}(rB_\theta)\right] = \frac{\partial}{\partial t}\left[\frac{\partial B_\theta}{\partial r} + \frac{B_\theta}{r}\right] = \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2}$$

$$\frac{\partial}{\partial r}\frac{\partial E_z}{\partial r} = \frac{\partial}{\partial r}\frac{\partial B_\theta}{\partial t}$$

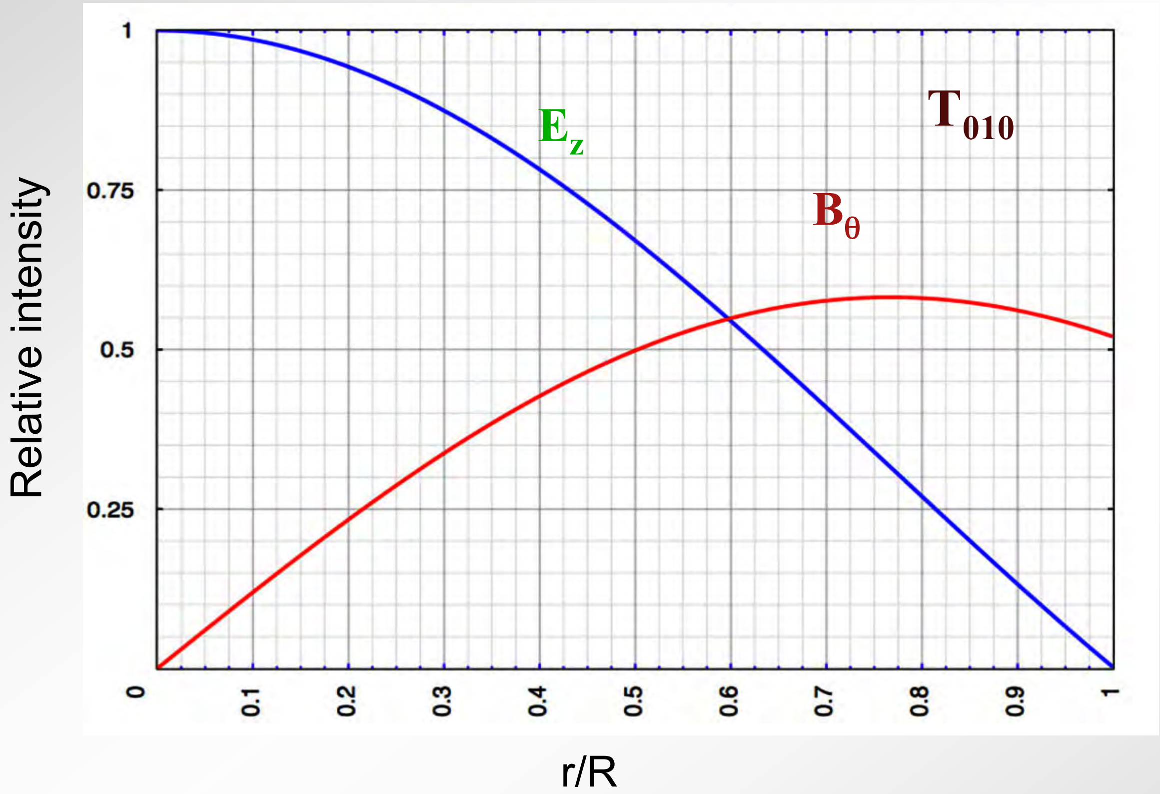
==> $$\boxed{\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} = \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2}}$$

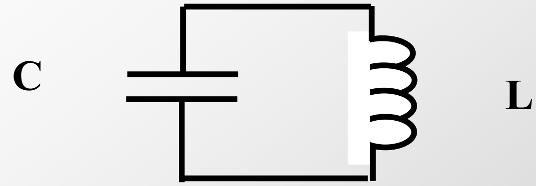
For a mode with frequency ω

- $$E_z(r,t) = E_z(r)\ e^{i\omega t}$$
- Therefore, $$E_z'' + \frac{E_z'}{r} + \left(\frac{\omega}{c}\right)^2 E_z = 0$$
  - (Bessel's equation, 0 order)
- Hence, $$\boxed{E_z(r) = E_o\ J_o\left(\frac{\omega}{c} r\right)}$$
- For conducting walls, $E_z(R) = 0$, therefore

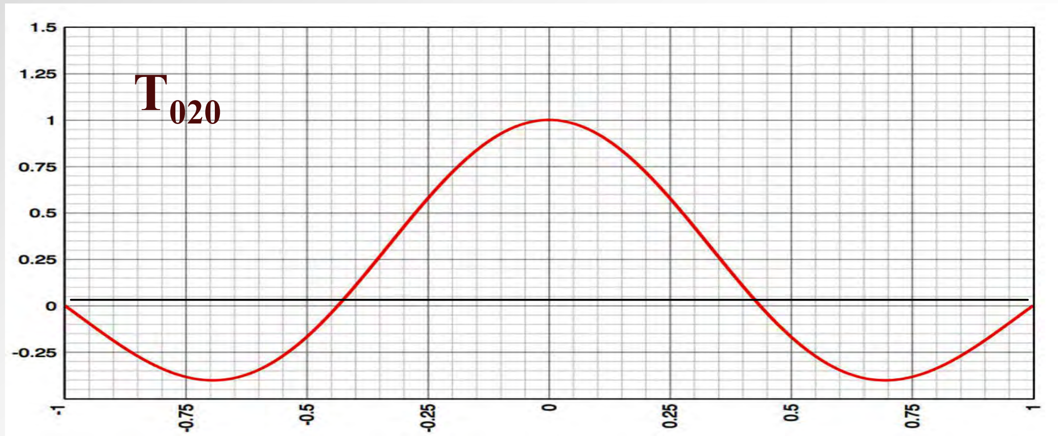
$$\frac{2\pi f}{c} b = 2.405$$

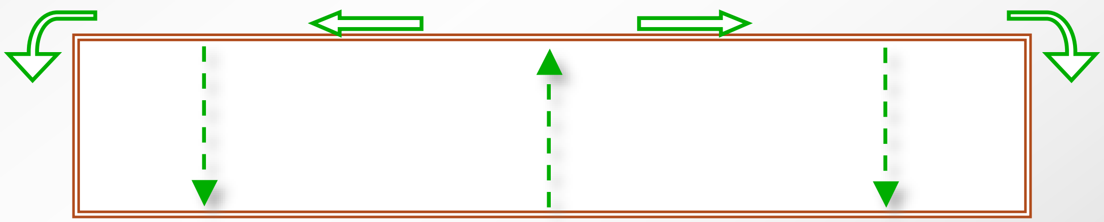
E-fields & equivalent circuit: T_{on1o} mode

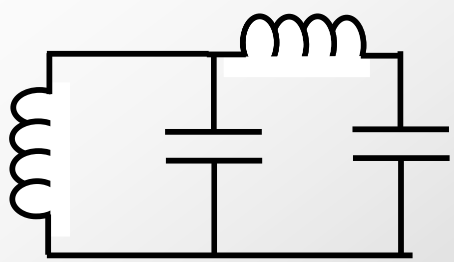




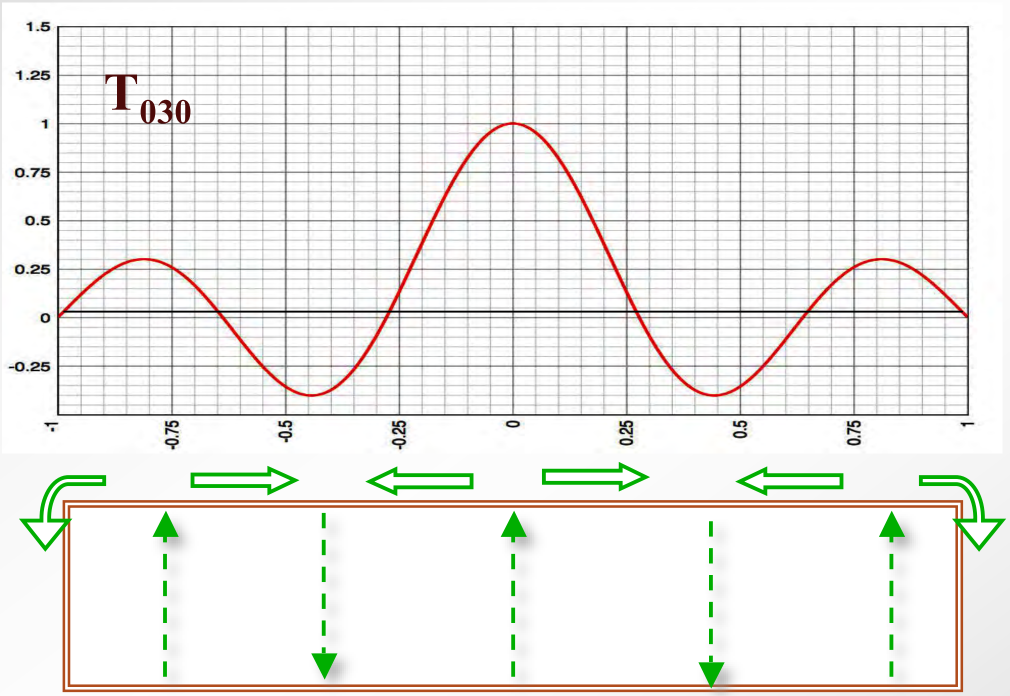
E-fields & equivalent circuits for T_{020} modes

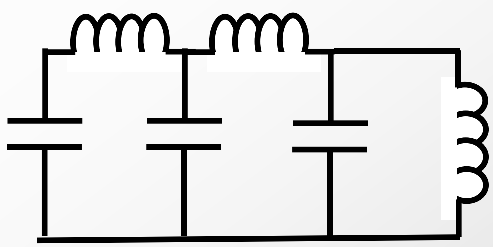






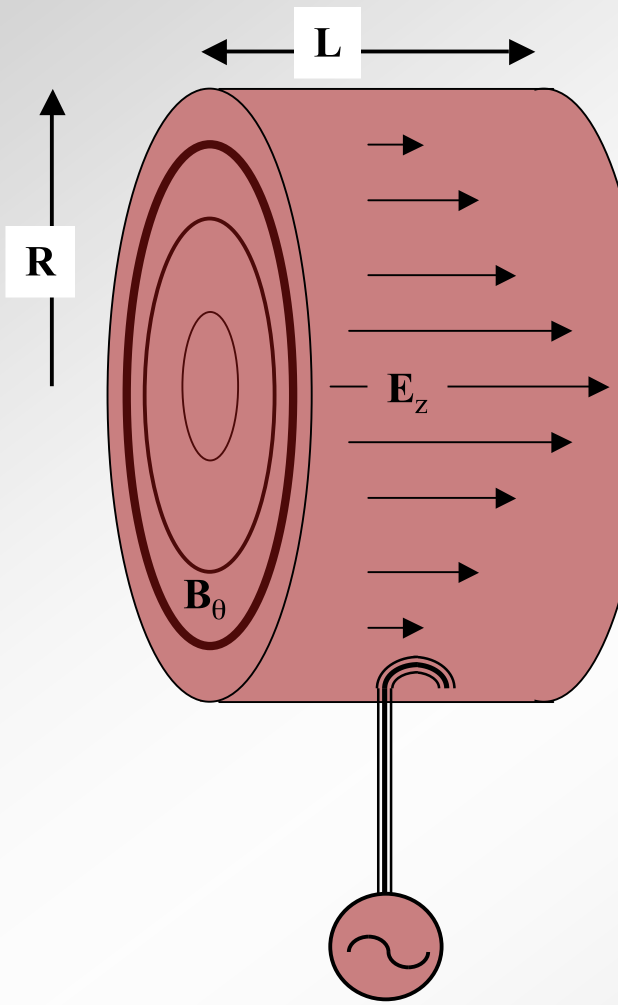
E-fields & equivalent circuits for T_{ono} modes





T_{0n0} has n coupled, resonant circuits; each L & C reduced by 1/n

Simple consequences of pillbox model

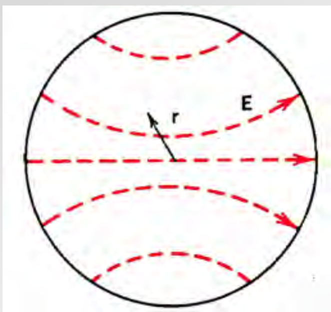


- Increasing R lowers frequency
  ==> Stored Energy, $\mathscr{E} \sim \omega^{-2}$
- $\mathscr{E} \sim E_z^2$
- Beam loading lowers E_z for the next bunch
- Lowering ω lowers the fractional beam loading
- Raising ω lowers $Q \sim \omega^{-1/2}$
- If time between beam pulses,
  $T_s \sim Q/\omega$
  almost all $\mathscr{E}$ is lost in the walls

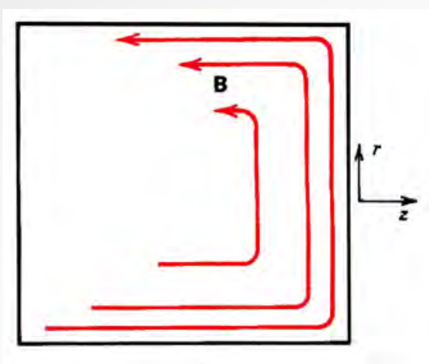
Keeping energy out of higher order modes

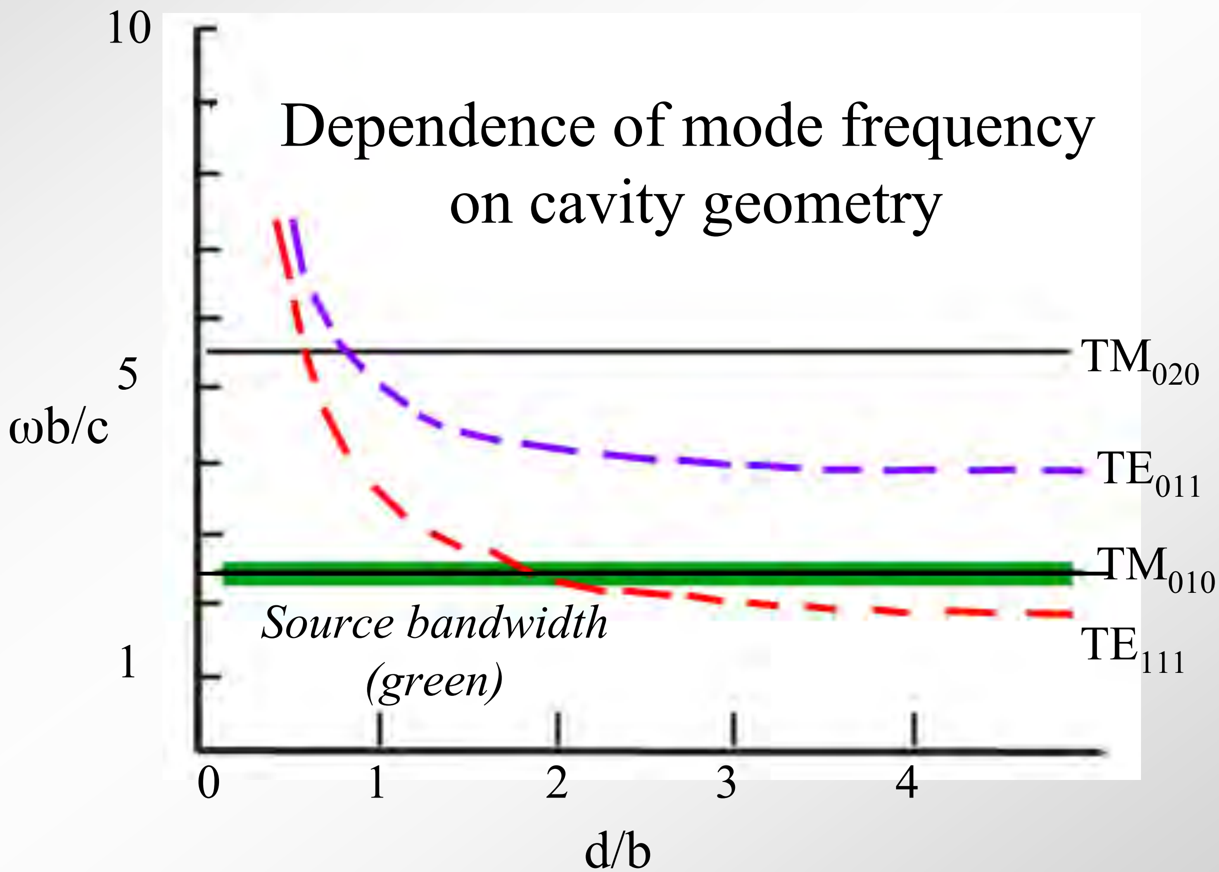
TE_{111} mode

End view



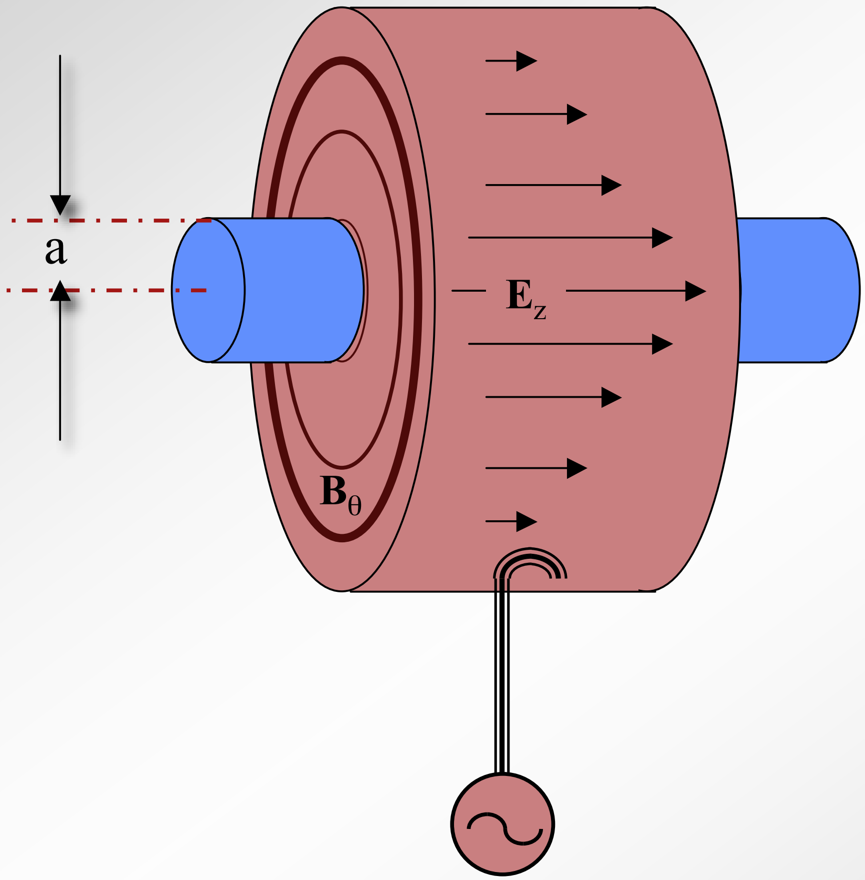
Side view





Choose cavity dimensions to stay far from crossovers

The beam tube makes the field modes (& cell design) more complicated



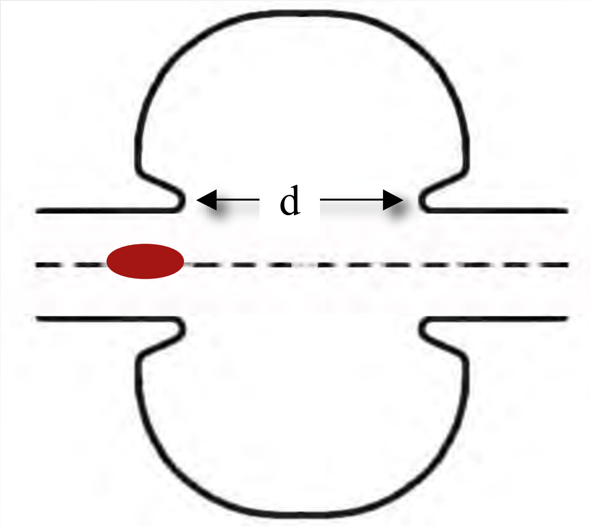
- Peak E no longer on axis
  - $E_{pk} \sim 2 - 3 \times E_{acc}$
  - FOM = E_{pk}/E_{acc}
- ω_o more sensitive to cavity dimensions
  - Mechanical tuning & detuning
- Beam tubes add length & €'s w/o acceleration
- Beam induced voltages $\sim a^{-3}$
  - Instabilities

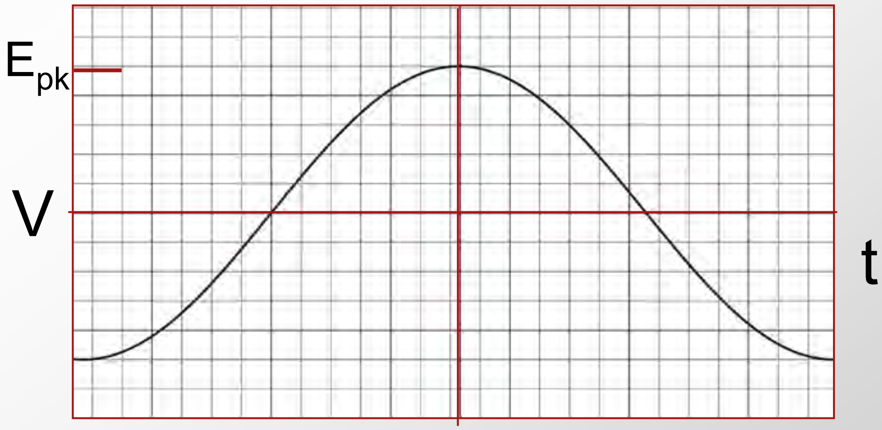
Cavity figures of merit

Figure of Merit: Accelerating voltage

- The voltage varies during time that bunch takes to cross gap
  - reduction of the peak voltage by Γ (transt time factor)

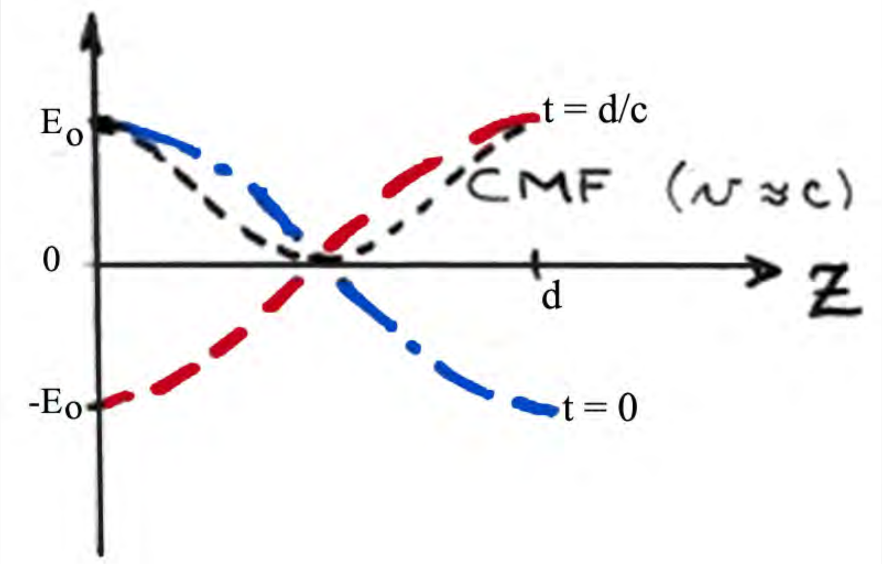
$$\Gamma = \frac{\sin\left(\vartheta/2\right)}{\vartheta/2} \quad \text{where} \quad \vartheta = \omega d/\beta c$$





For maximum acceleration $T_{cav} = \frac{d}{c} = \frac{T_{rf}}{2}$ ==> Γ = 2/π

Compute the voltage gain correctly



The voltage gain seen by the beam can computed in the co-moving frame, or we can use the transit-time factor, Γ & compute V at fixed time

$$V_o^2 = \Gamma \int_{z_1}^{z_2} E(z)dz$$

Figure of merit from circuits - Q

$$Q = \frac{\omega_o \circ \ Energy\ stored}{Time\ average\ power\ loss} = \frac{2\pi \circ Energy\ stored}{Energy\ lost\ per\ cycle}$$

$$\mathscr{E} = \frac{\mu_o}{2} \int_v |H|^2 dv = \frac{1}{2} L\, I_o I_o^*$$

$$\langle \mathscr{P} \rangle = \frac{R_{surf}}{2} \int_s |H|^2 ds = \frac{1}{2} I_o I_o^* R_{surf}$$

$$R_{surf} = \frac{1}{Conductivity \circ Skin\ depth} \sim \omega^{1/2}$$

$$\therefore \quad Q = \frac{\sqrt{L/C}}{R_{surf}} = \left(\frac{\Delta\omega}{\omega_o} \right)^{-1}$$

Measuring the energy stored in the cavity allows us to measure Q

- We have computed the field in the fundamental mode

$$U = \int_0^d dz \int_0^b dr\, 2\pi r \left(\varepsilon E_o^2 \big/ 2 \right) J_1^2(2.405 r/b)$$
$$= b^2 d \left(\varepsilon E_o^2 /2 \right) J_1^2(2.405)$$

- To measure Q we excite the cavity and measure the E field as a function of time

- Energy lost per half cycle = UπQ

- Note: energy can be stored in the higher order modes that deflect the beam

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Figure of merit for accelerating cavity: Power to produce the accelerating field

Resistive input (shunt) impedance at ω_o relates power dissipated in walls to accelerating voltage

$$R_{in} = \frac{\langle V^2(t) \rangle}{\mathscr{P}} = \frac{V_o^2}{2\mathscr{P}} = Q\sqrt{L/C}$$

Linac literature commonly defines "shunt impedance" without the "2"

$$\mathscr{R}_{in} = \frac{V_o^2}{\mathscr{P}} \sim \frac{1}{R_{surf}}$$

Typical values 25 - 50 MΩ

Computing shunt impedance

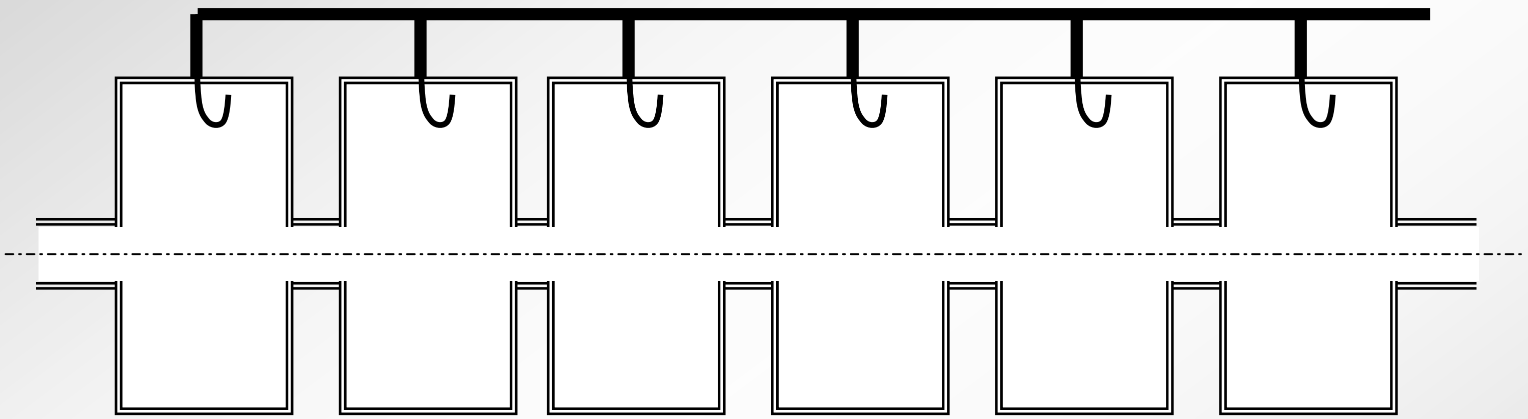
$$\mathscr{R}_{in} = \frac{V_o^2}{\mathscr{P}}$$

$$\langle \mathscr{P} \rangle = \frac{R_{surf}}{2} \int_s |H|^2 ds$$

$$R_{surf} = \frac{\mu\omega}{2\sigma_{dc}} = \pi Z_o \frac{\delta_{skin}}{\lambda_{rf}} \quad \text{where } Z_o = \sqrt{\mu_o / \varepsilon_o} = 377\Omega$$

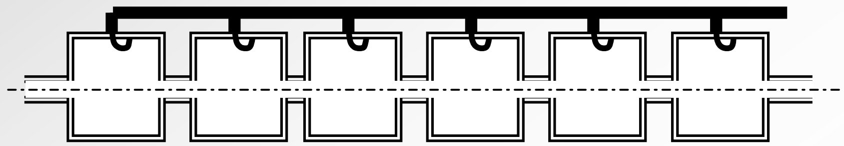
The on-axis field E and surface H are generally computed with a computer code such as SUPERFISH for a complicated cavity shape

Make the linac out of many pillbox cavities

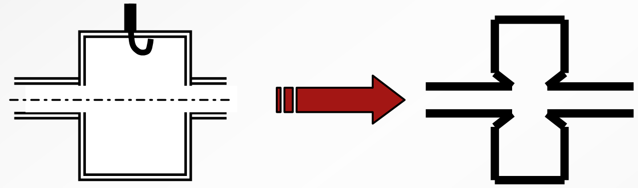


Power the cavities so that $E_z(z,t) = E_z(z)e^{i\omega t}$

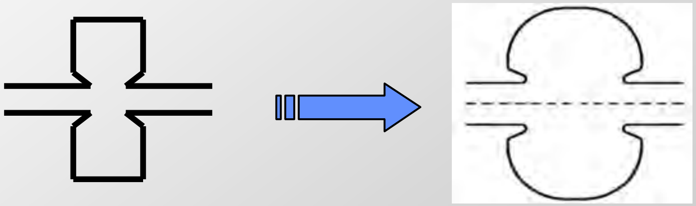
How can we improve on an array of pillboxes?



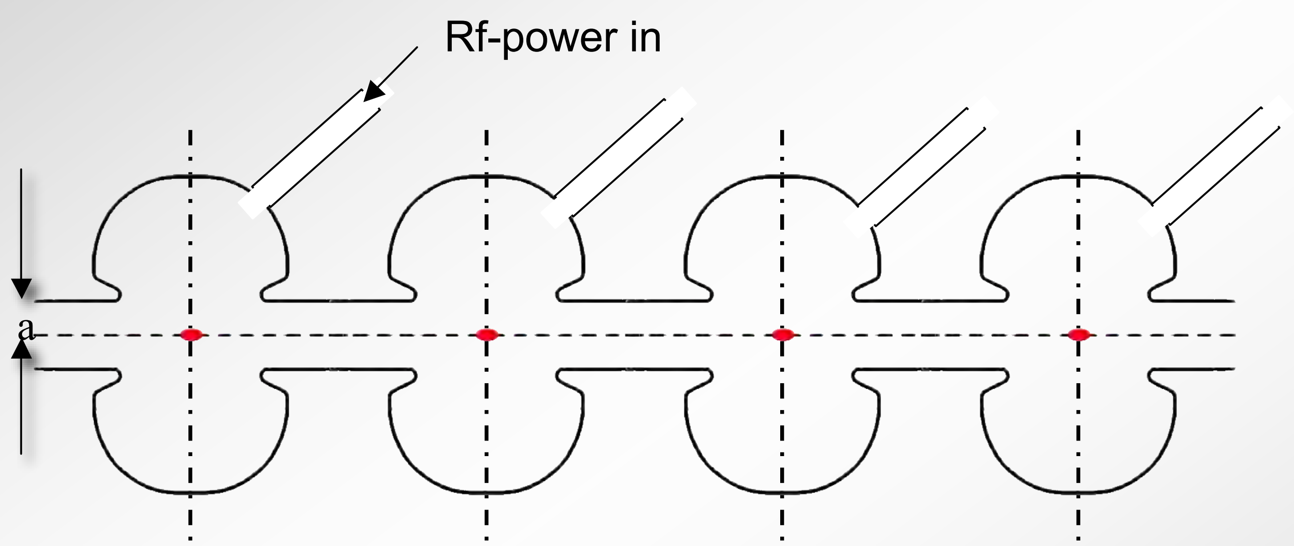
- ❖ Return to the picture of the re-entrant cavity



- ❖ Nose cones concentrate E_z near beam for fixed stored energy
- ❖ Optimize nose cone to maximize V^2; I.e., maximize R_{sh}/Q
- ❖ Make H-field region nearly spherical; raises Q & minimizes P for given stored energy



Thus, linacs can be considered to be an array of distorted pillbox cavities…

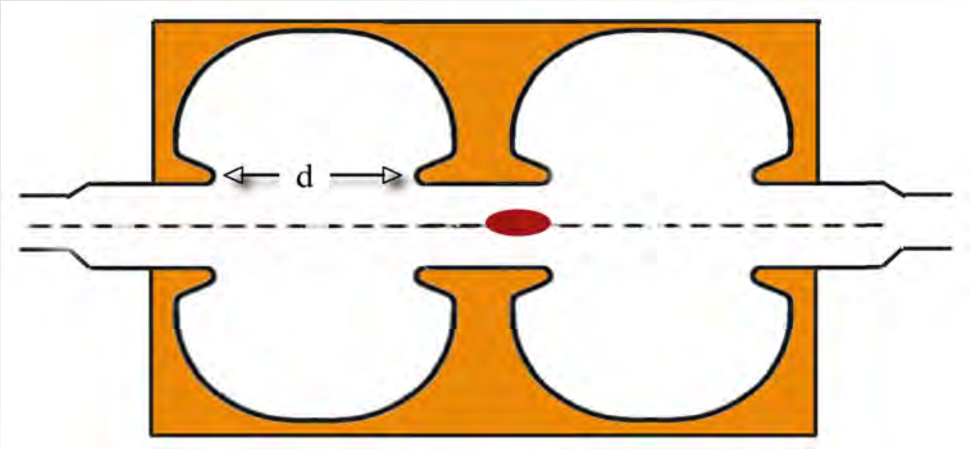


In warm linacs “nose cones” optimize the voltage per cell with respect to resistive dissipation

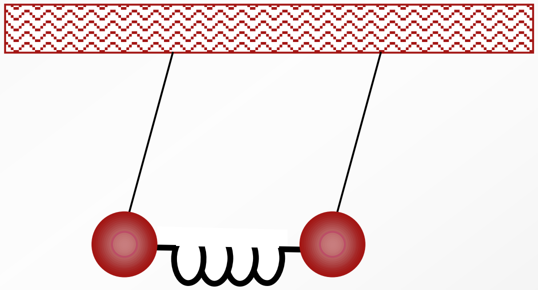
$$Q = \frac{\sqrt{L/C}}{\mathscr{R}_{surface}}$$

Usually cells are feed in groups not individually…. and

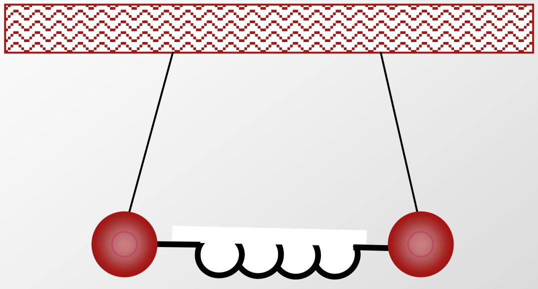
Linacs cells are linked to minimize cost



==> coupled oscillators ==>multiple modes

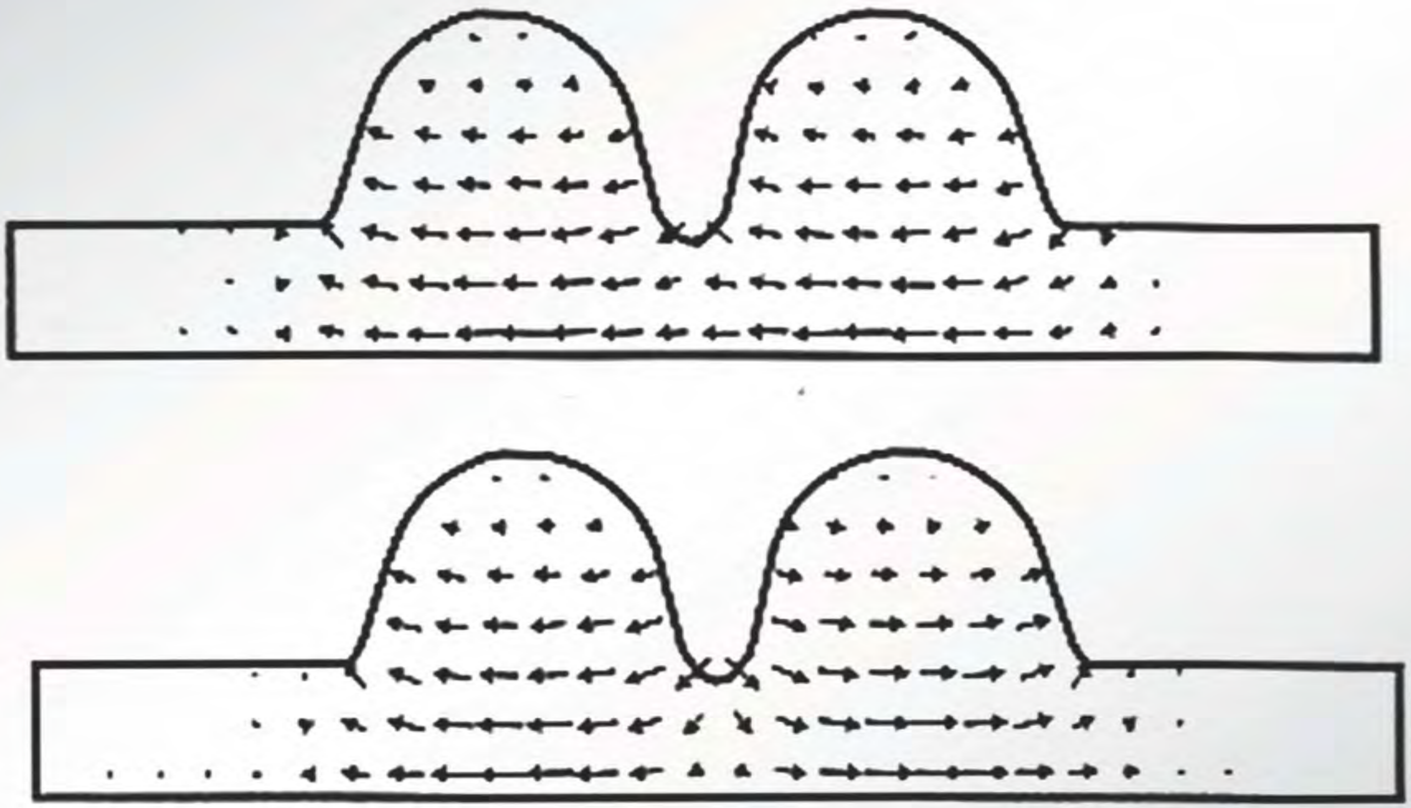


Zero mode

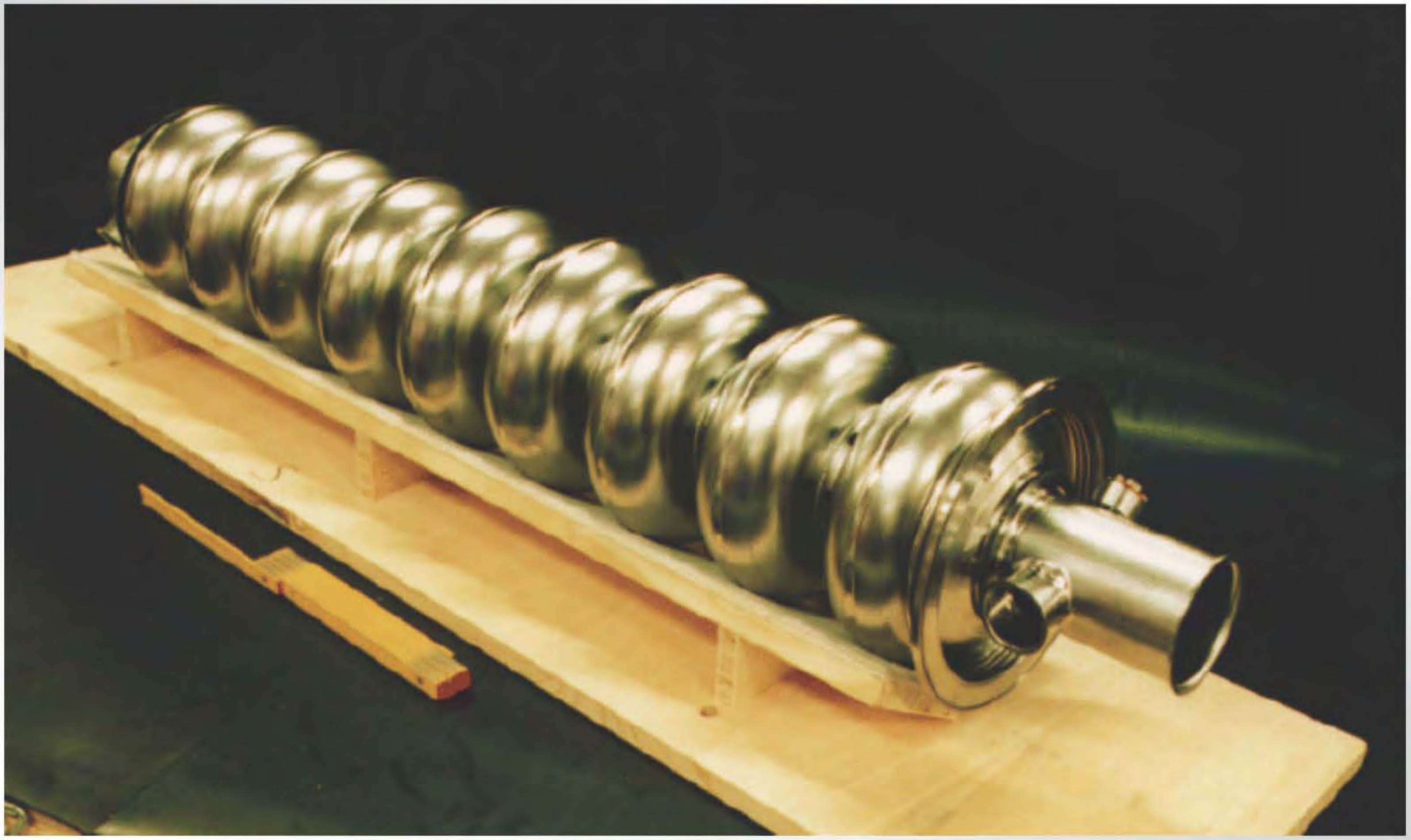


π mode

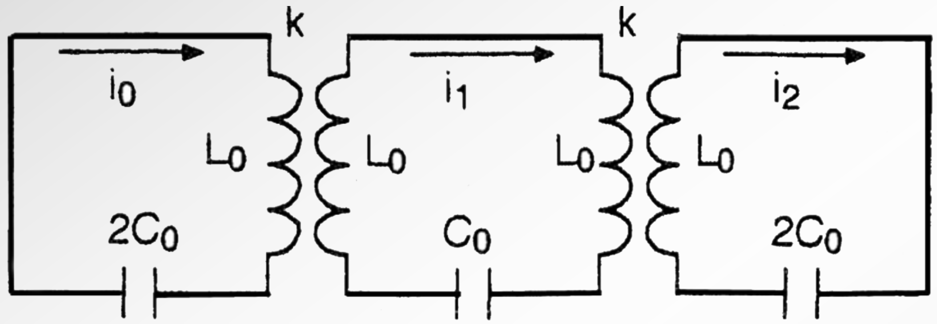
Modes of a two-cell cavity



9-cavity TESLA cell



Example of 3 coupled cavities



$$x_0\left(1-\frac{\omega_0^2}{\Omega^2}\right)+x_1 k=0 \qquad \text{oscillator } n=0$$

$$x_1\left(1-\frac{\omega_0^2}{\Omega^2}\right)+(x_0+x_2)\frac{k}{2}=0 \qquad \text{oscillator } n=1$$

$$x_2\left(1-\frac{\omega_0^2}{\Omega^2}\right)+x_1 k=0 \qquad \text{oscillator } n=2$$

$x_j = i_j\sqrt{2L_o}$ and $\Omega =$ normal mode frequency

Write the coupled circuit equations in matrix form

$$\mathbf{L}\mathbf{x}_q = \frac{1}{\Omega_q^2}\mathbf{x}_q \quad \text{where} \quad \mathbf{L} = \begin{pmatrix} 1/\omega_o^2 & k/\omega_o^2 & 0 \\ k/2\omega_o^2 & 1/\omega_o^2 & k/2\omega_o^2 \\ 0 & k/\omega_o^2 & 1/\omega_o^2 \end{pmatrix} \quad \text{and} \quad \mathbf{x_q} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}$$

- Compute eigenvalues & eigenvectors to find the three normal modes

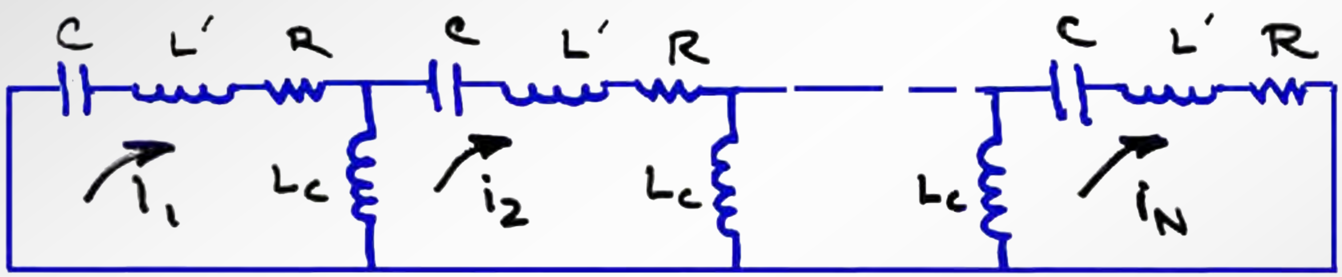
$$\text{Mode q} = 0: \text{ zero mode} \quad \Omega_0 = \frac{\omega_o}{\sqrt{1+k}} \quad \mathbf{x_0} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\text{Mode q} = 1: \ \pi/2 \text{ mode} \quad \Omega_1 = \omega_o \quad \mathbf{x}_1 = \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}$$

$$\text{Mode q} = 2: \ \pi \text{ mode} \quad \Omega_2 = \frac{\omega_o}{\sqrt{1-k}} \quad \mathbf{x}_2 = \begin{pmatrix} 1 \\ -1 \\ 1 \end{pmatrix}$$

For a structure with N coupled cavities

- ==> Set of N coupled oscillators
  - N normal modes, N frequencies
- From the equivalent circuit with magnetic coupling

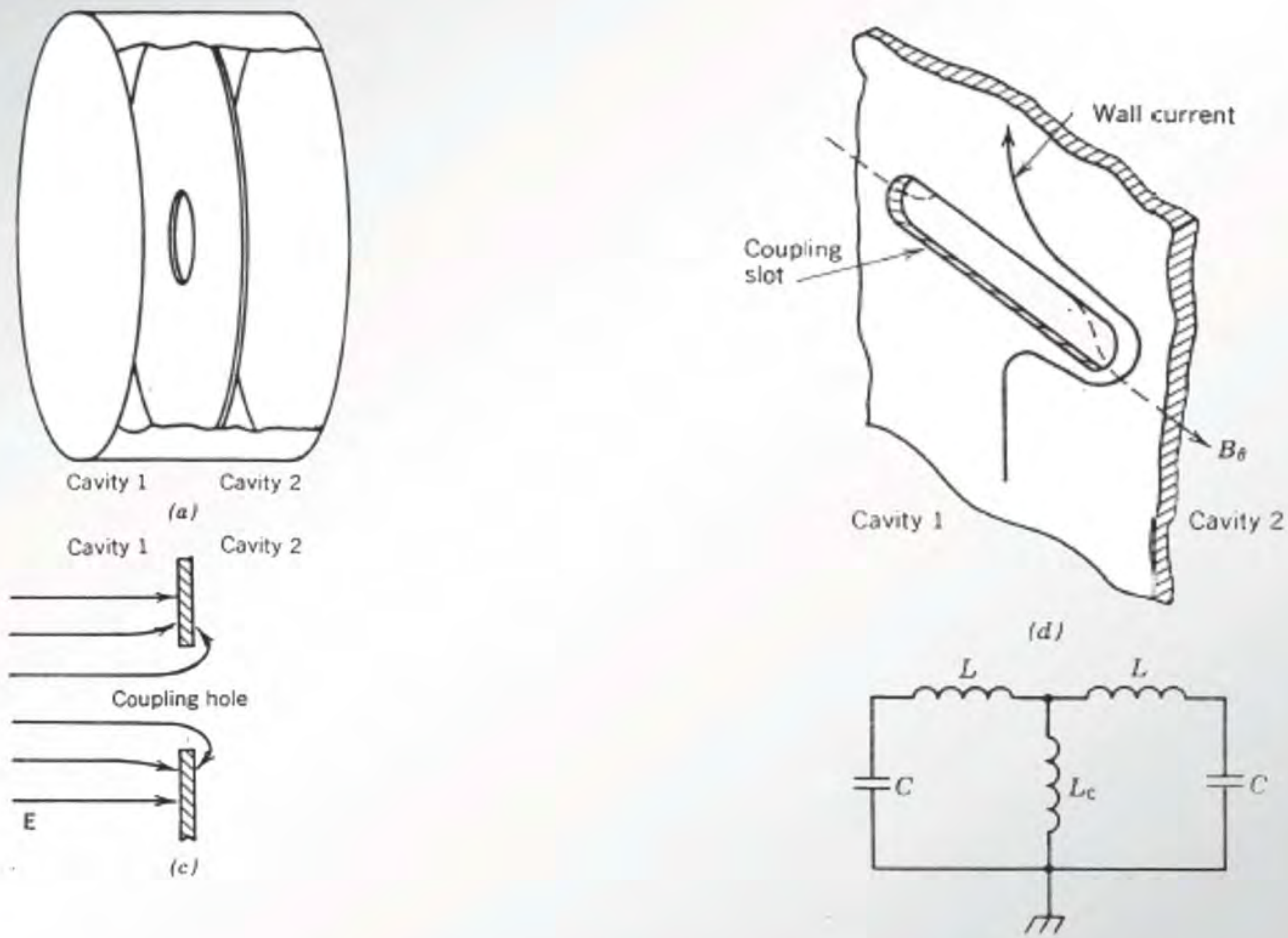


$$\omega_m = \frac{\omega_o}{\left(1 - B\cos\frac{m\pi}{N}\right)^{1/2}} \approx \omega_o\left(1 + B\cos\frac{m\pi}{N}\right)$$

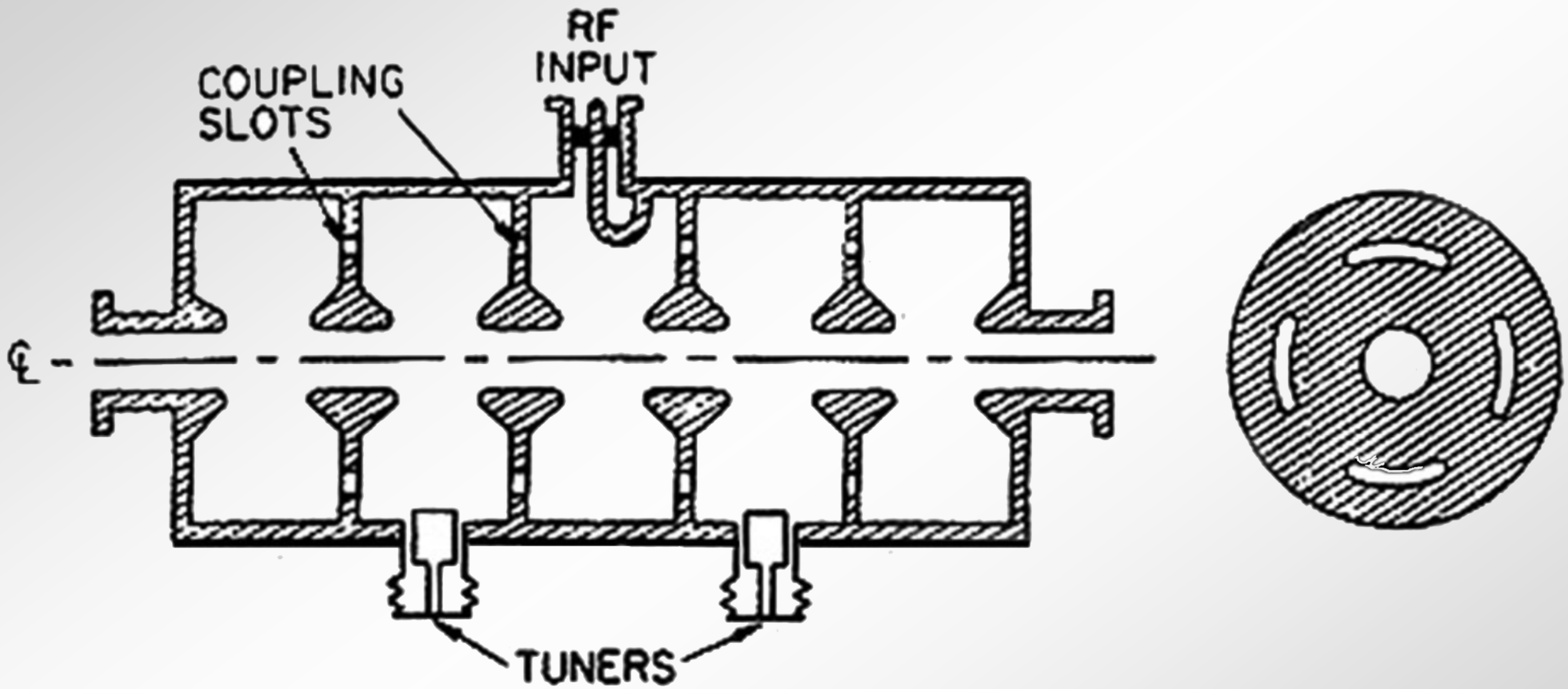
where B= bandwidth (frequency difference between lowest & high frequency mode)

- Typically accelerators run in the π-mode

Magnetically coupled pillbox cavities



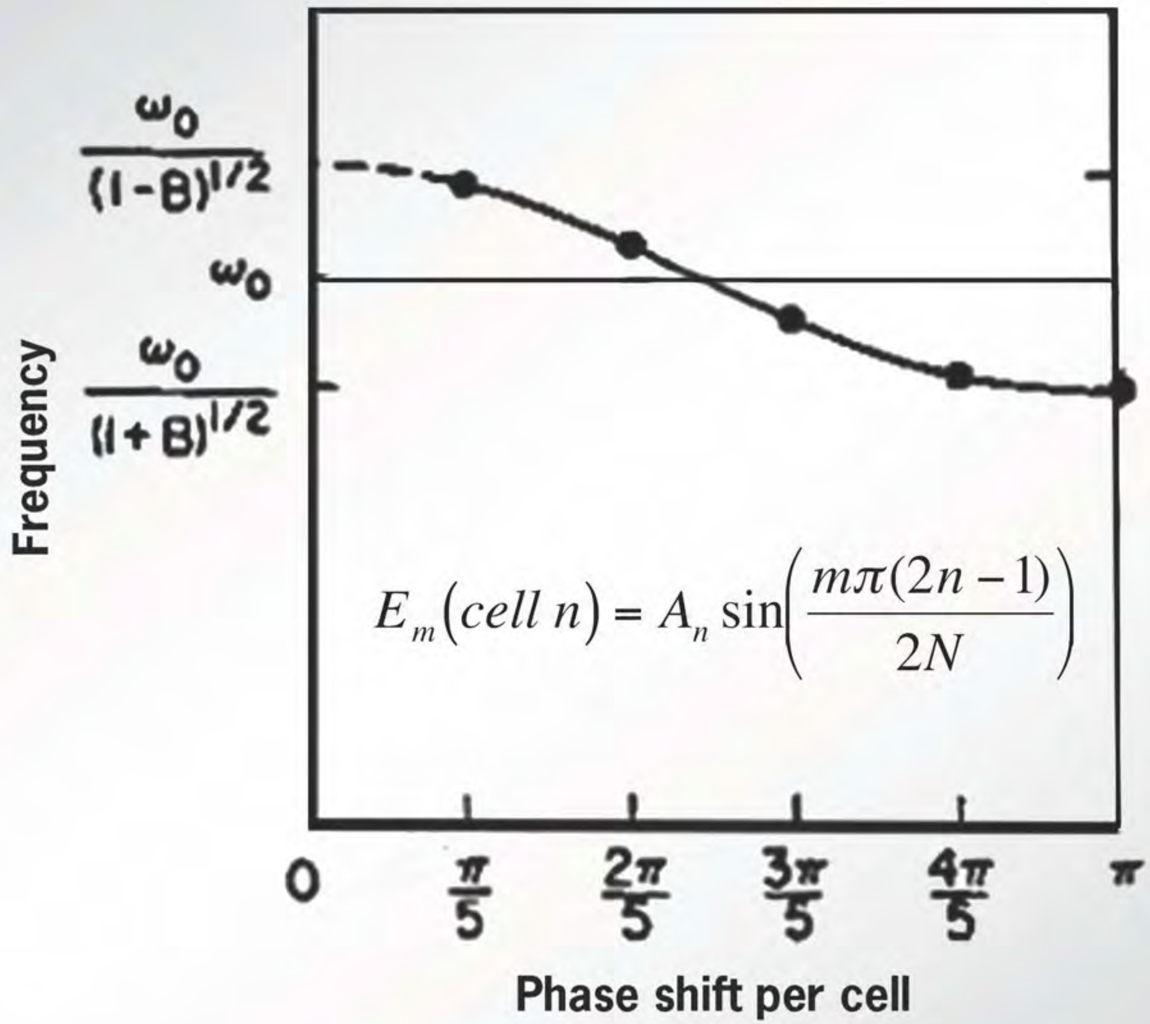
5-cell π-mode cell with magnetic coupling



The tuners change the frequencies by perturbing wall currents ==> changes the inductance ==> changes the energy stored in the magnetic field

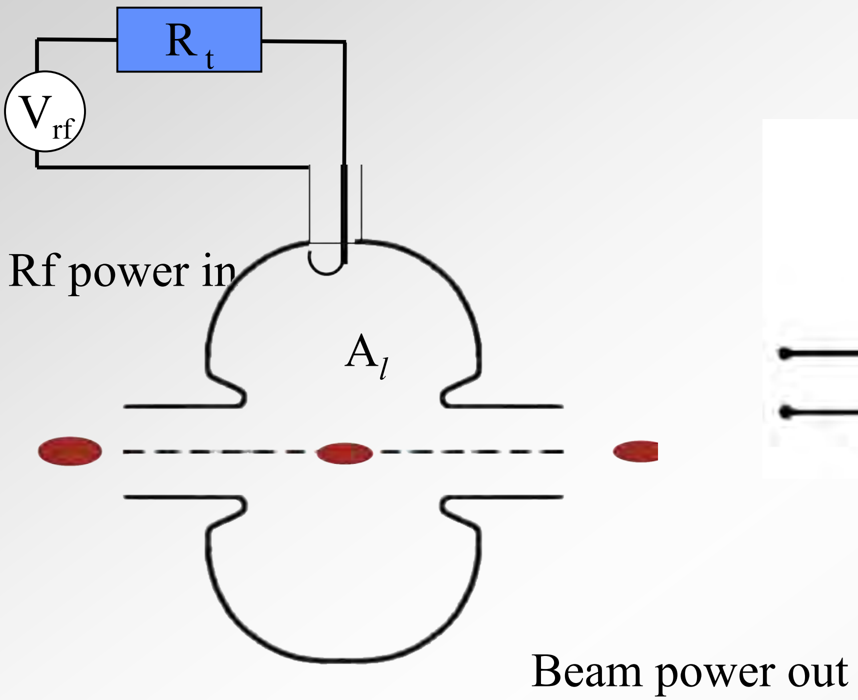
$$\frac{\Delta\omega_o}{\omega_o} = \frac{\Delta U}{U}$$

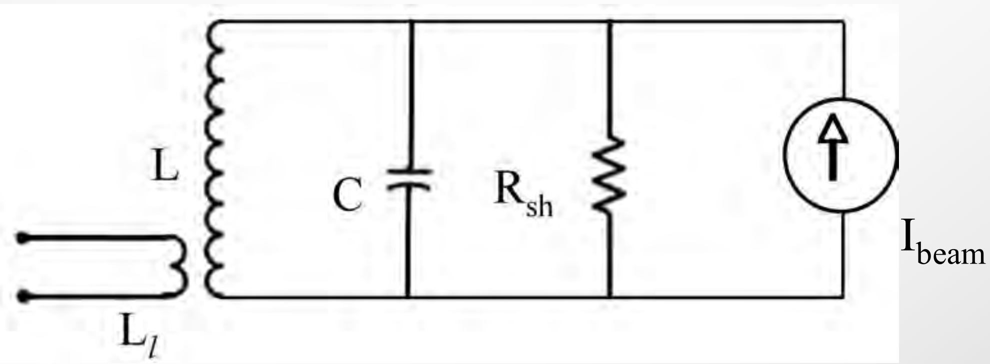
Dispersion diagram for 5-cell structure



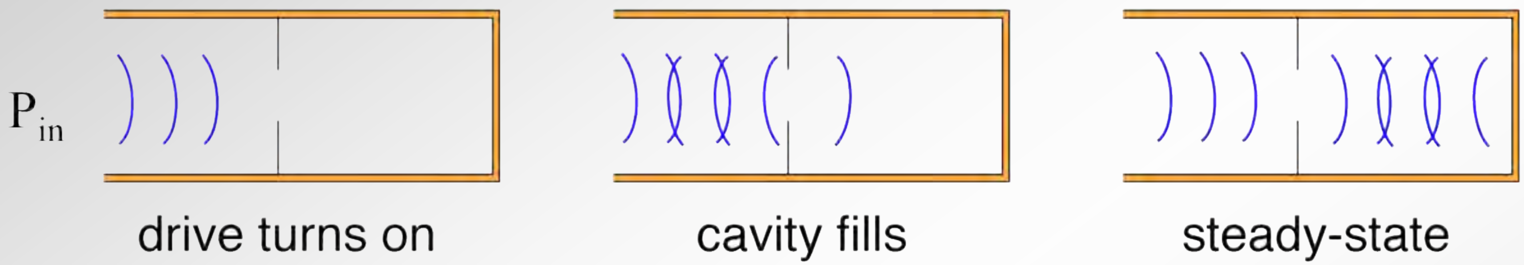
$$E_m(cell\ n) = A_n \sin\left(\frac{m\pi(2n-1)}{2N}\right)$$

Power exchange with resonant cavities





Effects of wall-losses & external coupling on stored energy, U



- Define "wall quality factor", Q_w, & "external" quality factor, Q_e
- Power into the walls is $P_w = \omega U/ Q_w$.
- If P_{in} is turned off, then the power flowing out $P_e = \omega U/Q_e$
- Net rate of energy loss $= \omega U/ Q_w + \omega U/Q_e = \omega U/ Q_{loaded}$

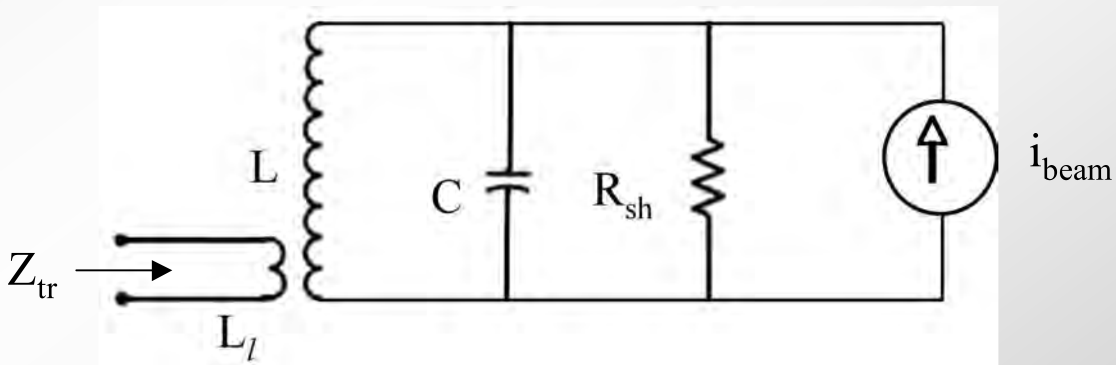
Till time & coupling

- Loaded fill time

$$T_{fill} = 2Q_L/\omega$$

- Critically coupled cavity: $P_{in} = P_w \implies 1/Q_e = 1/Q_w$

- In general, the coupling parameter $\beta = Q_w / Q_e$



Effects of the rf source & beam at resonance

- Voltage produced by the generator is

$$V_{gr} = \frac{2\sqrt{\beta}}{1+\beta} \cdot \sqrt{R_{shunt} P_{gen}}$$

- The voltage produced by the beam is

$$V_{b,r} = \frac{i_{beam}}{Z_{tr}(1+\beta)} \approx \frac{I_{dc} R_{shunt}}{(1+\beta)}$$

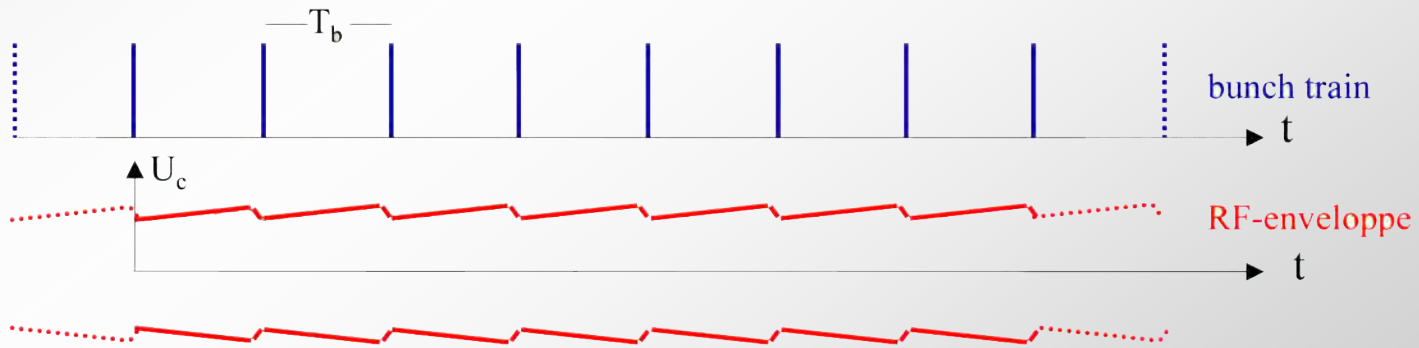
Effects of the rf source & beam at resonance

- The accelerating voltage is the sum of these effects

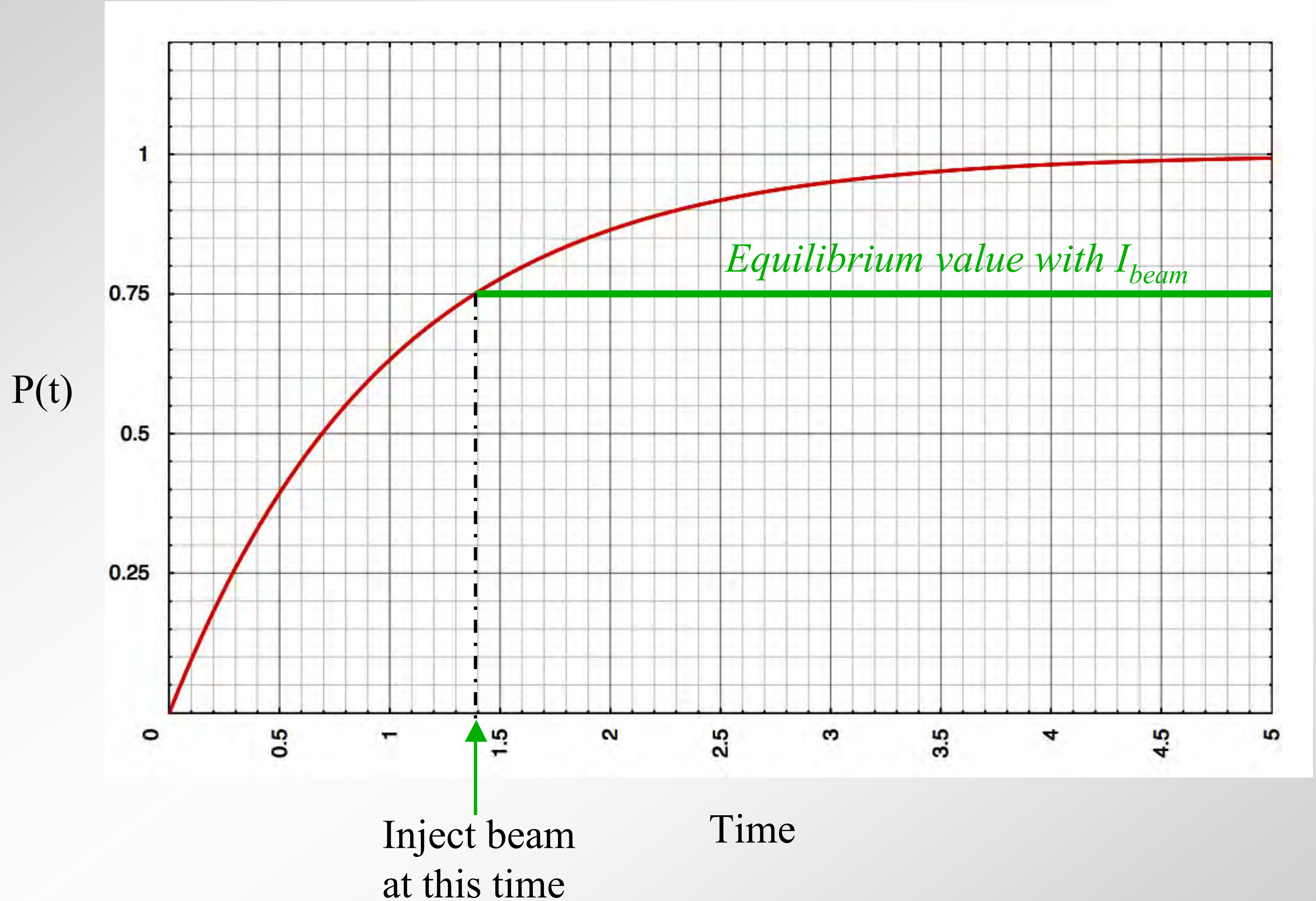
$$V_{accel} = \sqrt{R_{shunt} P_{gen}} \left[\frac{2\sqrt{\beta}}{1+\beta} \left(1 - \frac{K}{\sqrt{\beta}} \right) \right] = \sqrt{R_{shunt} P_{wall}}$$

$$\text{where } \mathrm{K} = \frac{I_{dc}}{2} \sqrt{R_{shunt} / P_{gen}} \quad \text{is the "loading factor"}$$

- ==> V_{acc} decreases linearly with increasing beam current

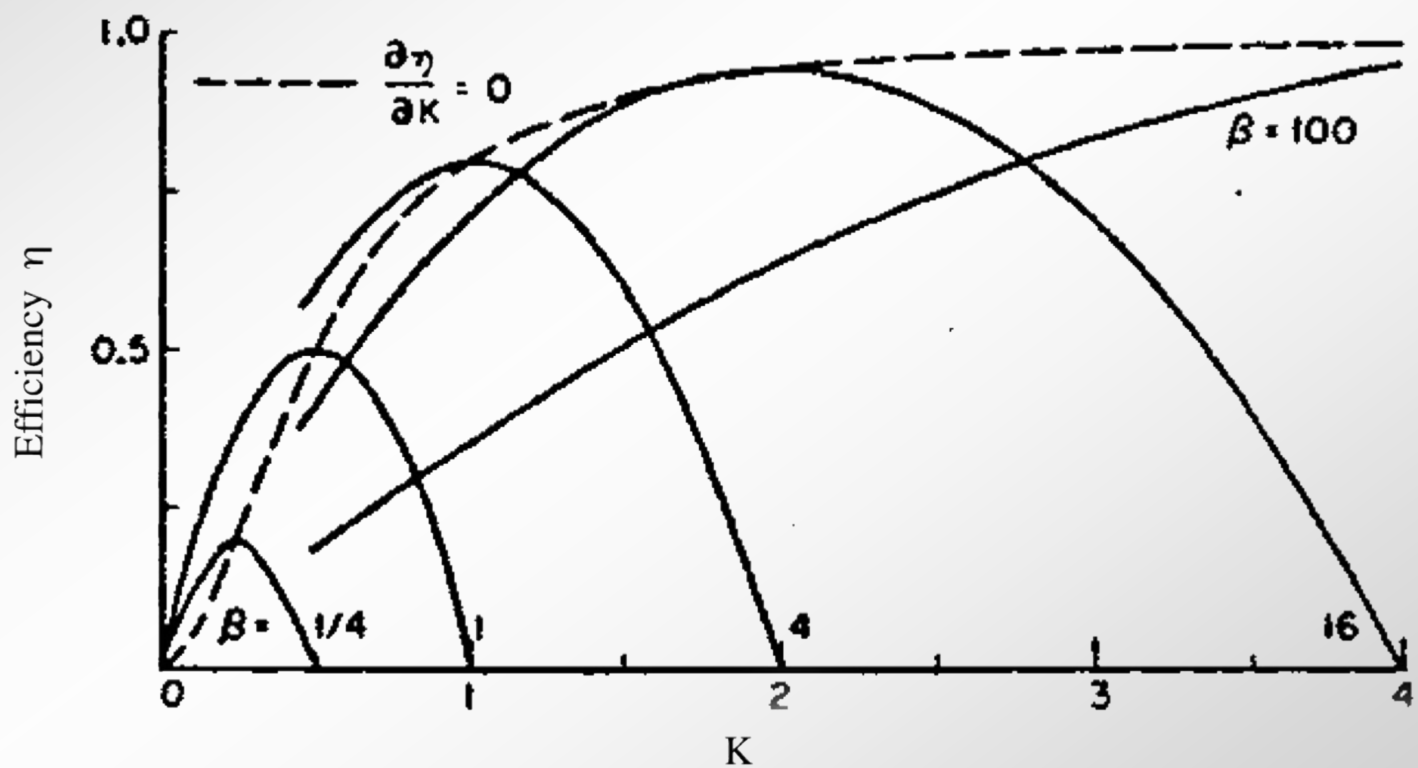


Power flow in standing wave linac

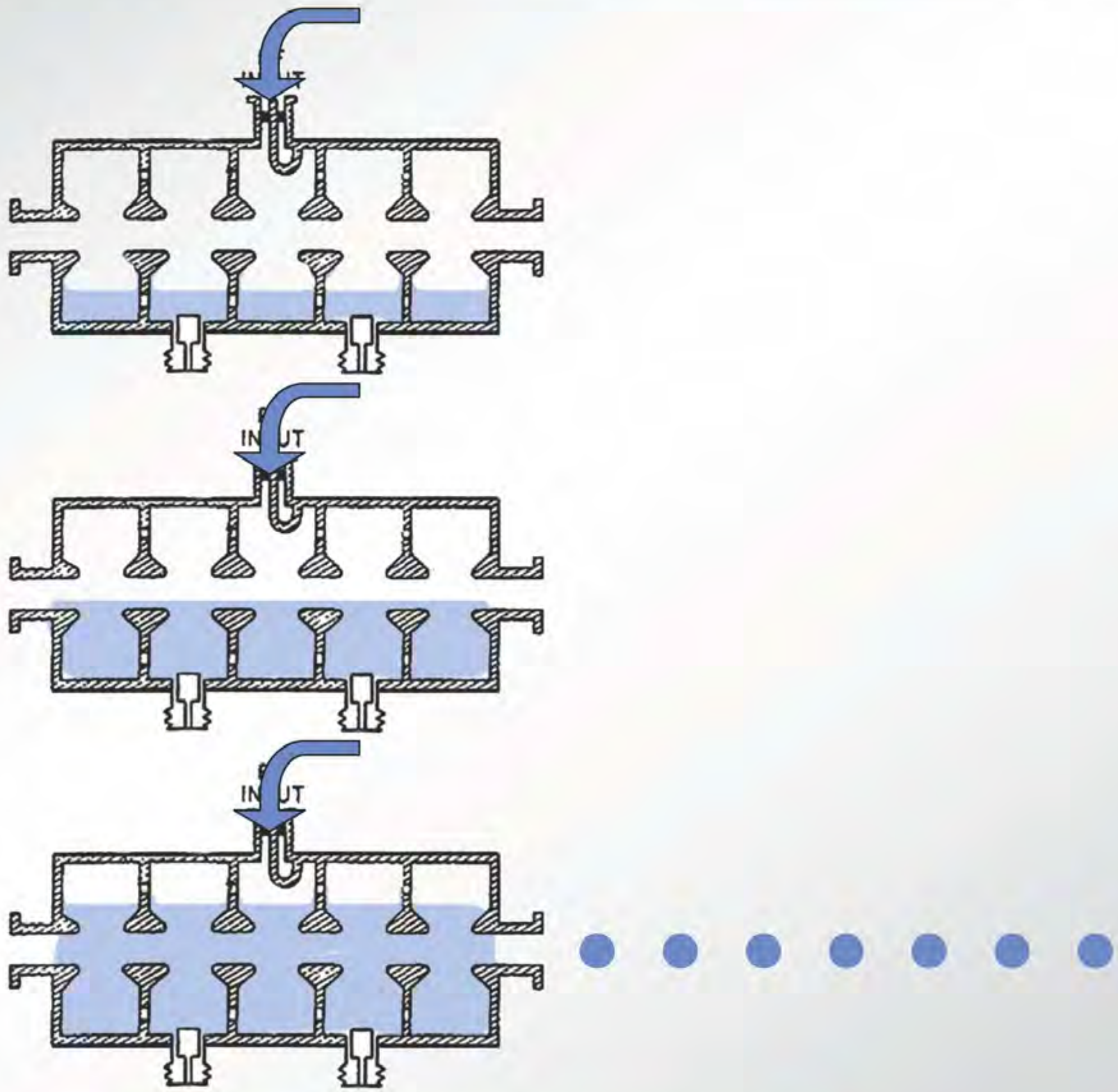


Efficiency of the standing wave linac

$$\eta = \frac{I_{dc}V_{acc}}{P_{gen}} = \frac{2\sqrt{\beta}}{1+\beta}\left[2K\left(1-\frac{K}{\sqrt{\beta}}\right)\right]$$



Schematic of energy flow
in a standing wave structure



What makes SC RF attractive?

Comparison of SC and NC RF

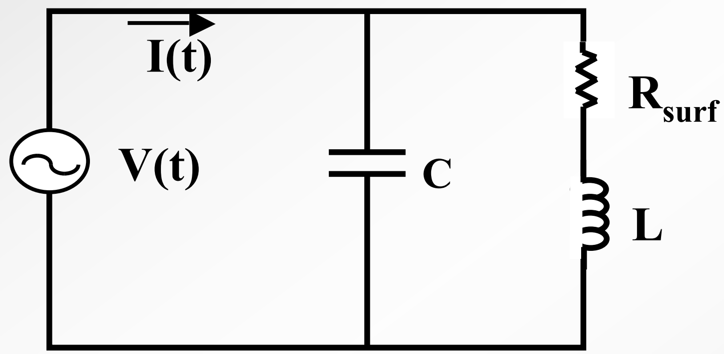
Superconducting RF

- High gradient
  ==> 1 GHz, meticulous care
- Mid-frequencies
  ==> Large stored energy, $\mathscr{E}_s$
- Large $\mathscr{E}_s$
  ==> very small $\Delta E/E$
- Large Q
  ==> high efficiency

Normal Conductivity RF

- High gradient
  ==> high frequency (5 - 17 GHz)
- High frequency
  ==> low stored energy
- Low $\mathscr{E}_s$
  ==> ~10x larger $\Delta E/E$
- Low Q
  ==> reduced efficiency

Recall the circuit analog



As R_{surf} ==> 0, the Q ==> ∞.

In practice,

$$Q_{nc} \sim 10^4 \qquad\qquad Q_{sc} \sim 10^{11}$$

Figure of merit for accelerating cavity:
Power to produce the accelerating field

Resistive input (shunt) impedance at ω_o relates power dissipated in walls to accelerating voltage

$$R_{in} = \frac{\langle V^2(t) \rangle}{\mathscr{P}} = \frac{V_o^2}{2\mathscr{P}} = Q\sqrt{L/C}$$

Linac literature more commonly defines "shunt impedance" without the "2"

$$\mathscr{R}_{in} = \frac{V_o^2}{\mathscr{P}} \sim \frac{1}{R_{surf}}$$

For SC-rf $\mathscr{P}$ is reduced by orders of magnitude

BUT, it is deposited @ 2K

Traveling wave linacs

Electromagnetic waves

From Maxwell equations, we can derive

$$\boxed{\nabla^2 E_i = \frac{\partial^2 E_i}{\partial x^2} + \frac{\partial^2 E_i}{\partial y^2} + \frac{\partial^2 E_i}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2 E_i}{\partial t^2} \qquad i = x, y, z}$$

for electromagnetic waves in free space (no charge or current distributions present).

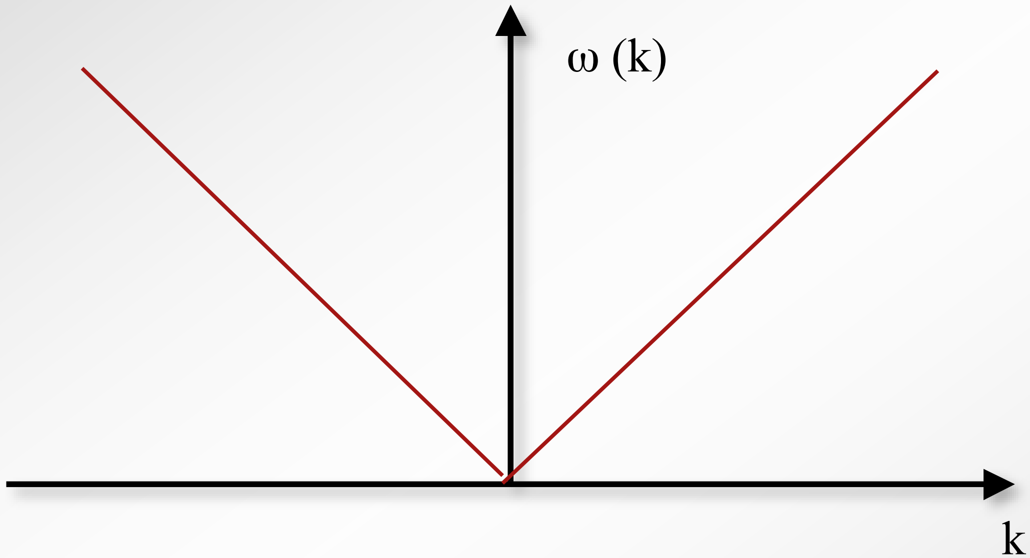
The plane wave is a particular solution of the EM wave equation

$$\overline{E} = \overline{E}_o e^{i(\omega t - ks)} = \overline{E}_o \left[\cos\left(\underbrace{\omega t - ks}_{\text{Phase of the wave } =\phi}\right) + i \sin\left(\omega t - ks\right)\right]$$

when

$$\omega = c\, k$$

Dispersion (Brillouin) diagram:
monochromatic plane wave



The phase of this plane wave is constant for

$$\frac{d\phi}{dt} = \omega - k\frac{ds}{dt} \equiv \omega - kv_{ph} = 0$$

or

$$v_{ph} = \frac{\omega}{k} = c$$

Plane wave representation of EM waves

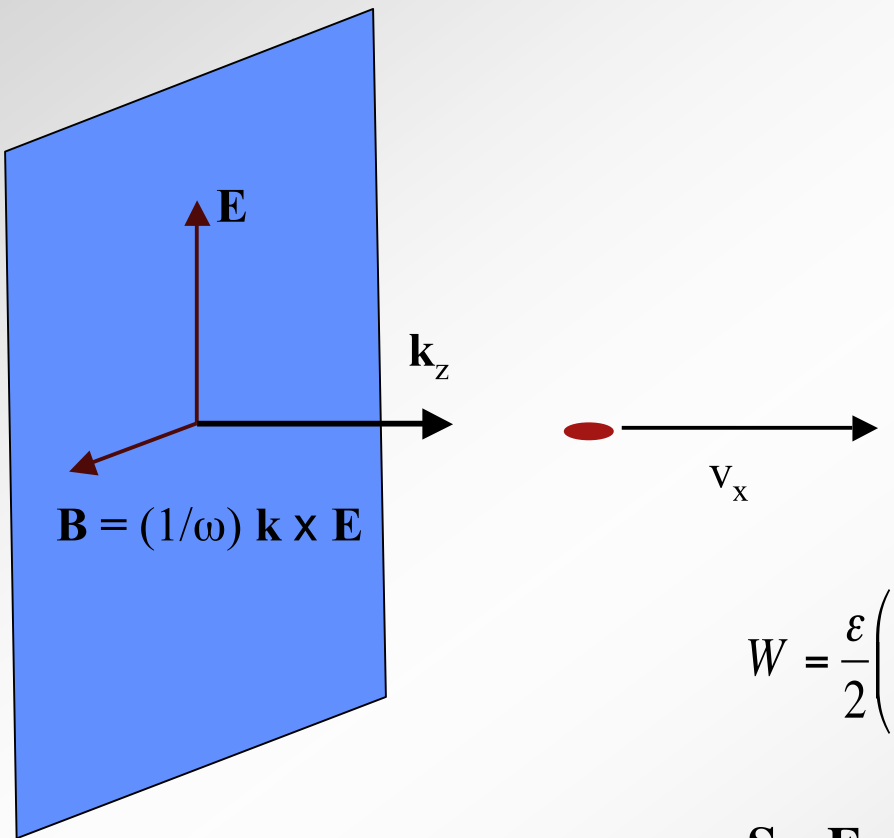
- In more generality, we can represent an arbitrary wave as a sum of plane waves:

$$\overline{E} = \sum_{n=-\infty}^{\infty} \overline{E}_{no} e^{i(n\omega_0 t - ks)} \qquad \overline{E} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dt\, f(\omega) e^{i(\omega t - ks)}$$

Periodic Case

Non-periodic Case

Exercise: Can the plane wave accelerate the particle in the x-direction?



$$W = \frac{\varepsilon}{2}\left(E^2 + \frac{1}{\varepsilon\mu}B^2\right) = \frac{\varepsilon}{2}\left(E^2 + c^2B^2\right) = \varepsilon E^2$$

$$\mathbf{S} = \mathbf{E}\times\mathbf{H} = \frac{1}{\mu}\mathbf{E}\times\mathbf{B} = \frac{1}{\mu c}E^2 = \sqrt{\frac{\varepsilon}{\mu}}E^2$$

Can accelerating structures be smooth waveguides?

- Assume the answer is "yes"
- Then $\mathbf{E} = \mathbf{E}(r,\theta)\, e^{i(\omega t-kz)}$ with $\omega/k = v_{ph} < c$
- Transform to the frame co-moving at $v_{ph} < c$
- Then,
  - The structure is unchanged (by hypothesis)
  - E is static (v_{ph} is zero in this frame)

  ==> By Maxwell's equations, H =0

  ==> $\nabla \circ \mathbf{E} = 0$ and $\mathbf{E} = -\nabla\phi$

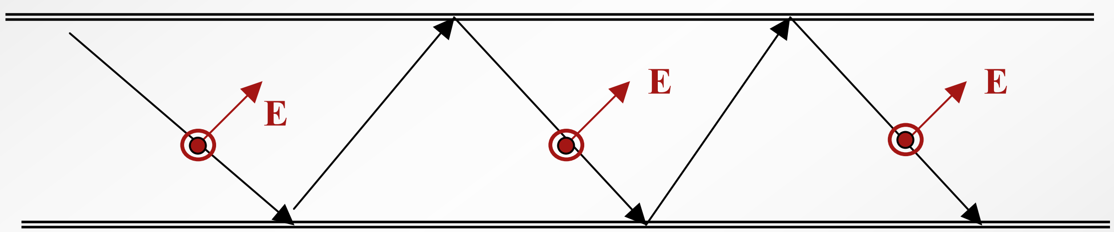
  - But ϕ is constant at the walls (metallic boundary conditions)

  ==> $\mathbf{E} = 0$

The assumption is false, smooth structures have $v_{ph} > c$

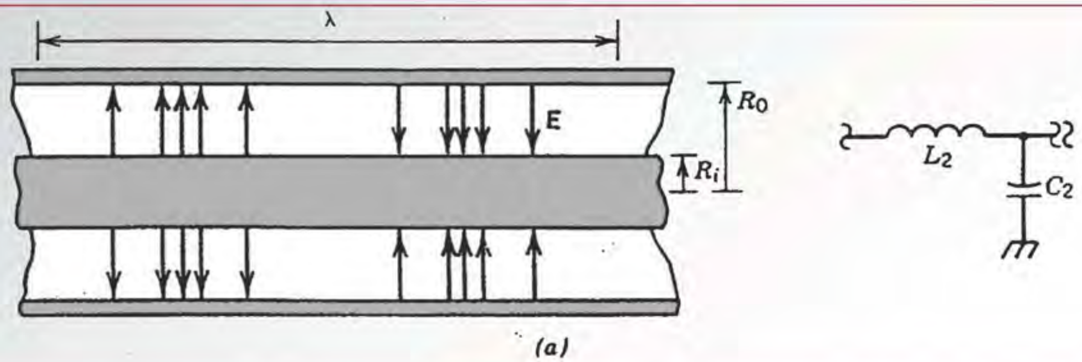
We need a longitudinal E-field
to accelerate particles in vacuum

- Example: the standing wave structure in a pillbox cavity
- What about traveling waves?
  - Waves guided by perfectly conducting walls can have E_{long}

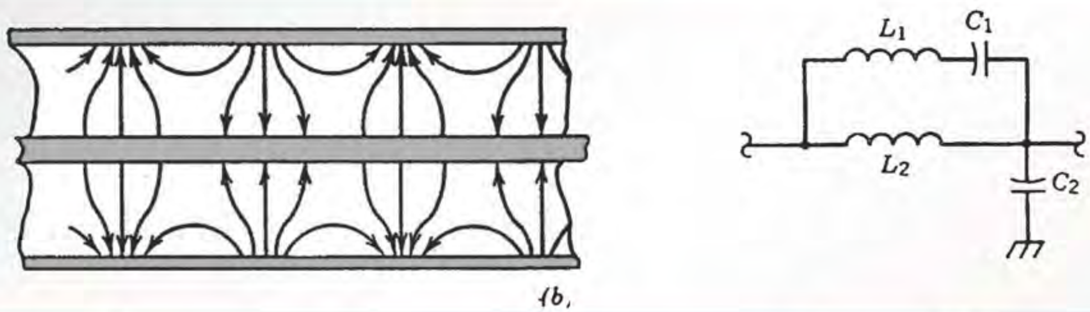


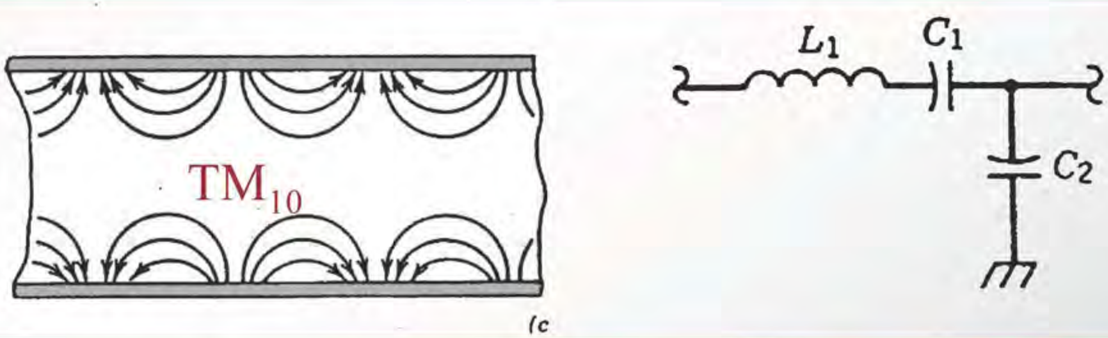
- But first, think back to phase stability
  - To get continual acceleration the wave & the particle must stay in phase
  - Therefore, we can accelerate a charge with a wave with a synchronous phase velocity, $v_{ph} \approx v_{particle} < c$

Propagating modes & equivalent circuits



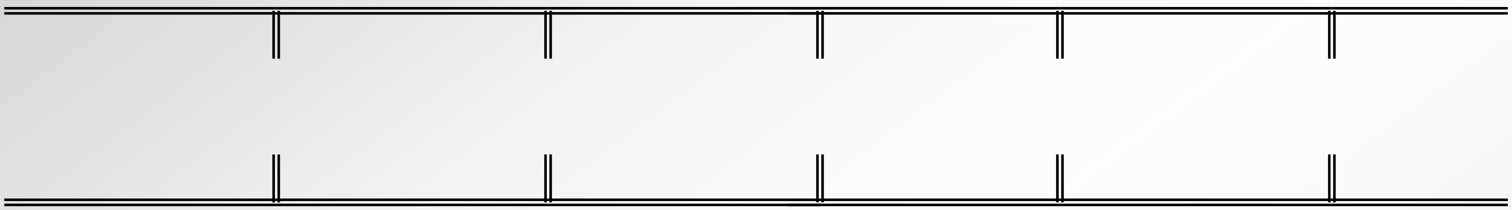
All frequencies can propagate





Propagation is cut-off at low frequencies

To slow the wave, add irises



In a transmission line the irises

a) Increase capacitance, C

b) Leave inductance ~ constant

c) ==> lower impedance, Z

d) ==> lower v_{ph}

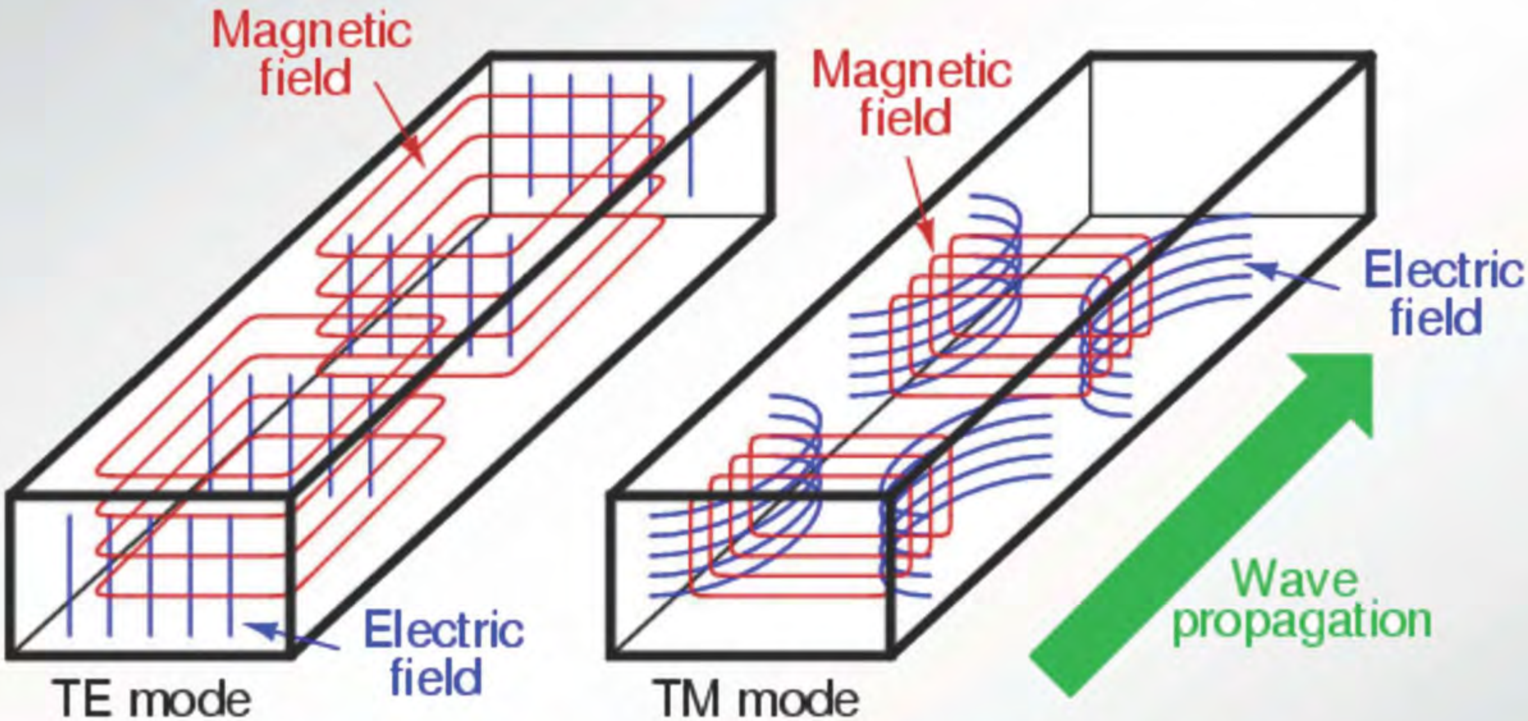
Similar for TM01 mode in the waveguide

$$\frac{\omega}{k} = \frac{1}{\sqrt{LC}}$$

$$Z = \frac{L}{C}$$

Fields in waveguides

University of Ljubljana
FACULTY OF ECONOMICS



Magnetic flux lines appear as continuous loops
Electric flux lines appear with beginning and end points

Figure source: www.opamp-electronics.com/tutorials/waveguide
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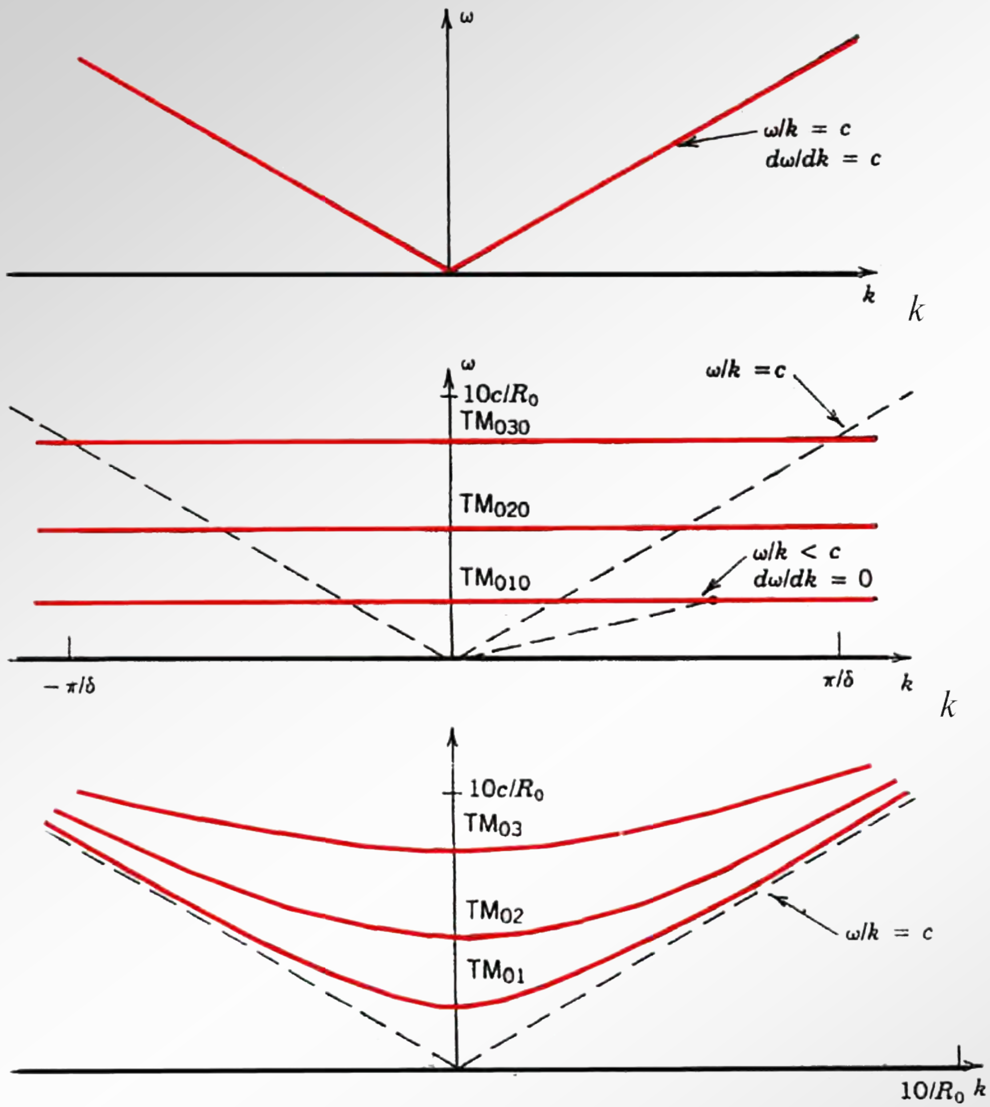
Dispersion diagrams

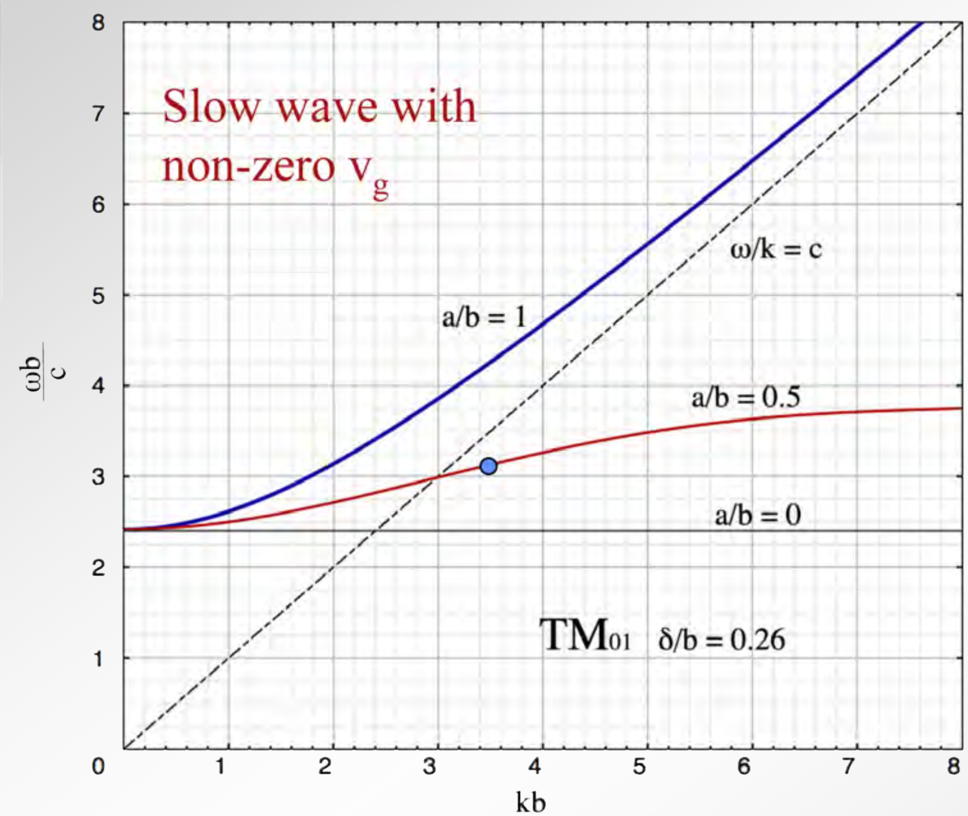


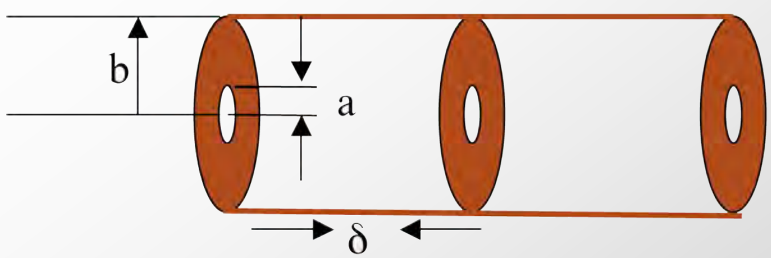
Transmission line
TEM mode

Weakly coupled pillboxes
TM_{0n0} modes

Smooth waveguide,
TM_{0n} modes

Dispersion relation for SLAC structure





Small changes in *a* lead to large reduction in v_g

Notation

$\beta_g = v_g/c$ = Relative group velocity

E_a = Accelerating field (MV/m)

E_s = Peak surface field (MV/m)

P_d = Power dissipated per length (MW/m)

P_t = Power transmitted (MW/m)

w = Stored energy per length (J/m)

Structure parameters for TW linacs

$$r_{shunt} = \frac{E_a^2}{\left|dP_t/dz\right|} \quad (\mathrm{M\Omega/m})$$

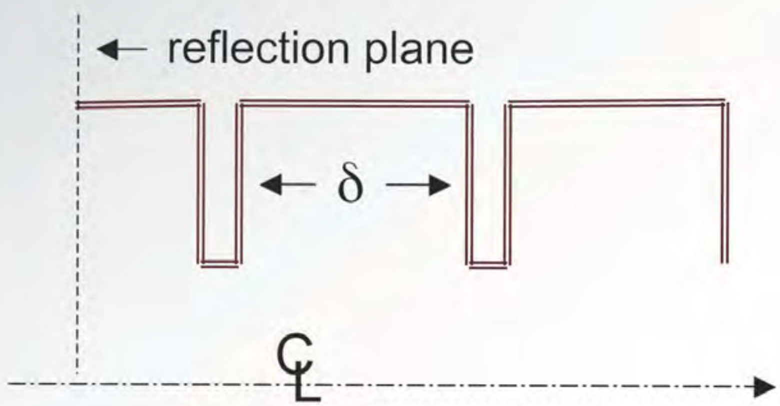
$$Q = \frac{w\omega}{\left|dP_t/dz\right|}$$

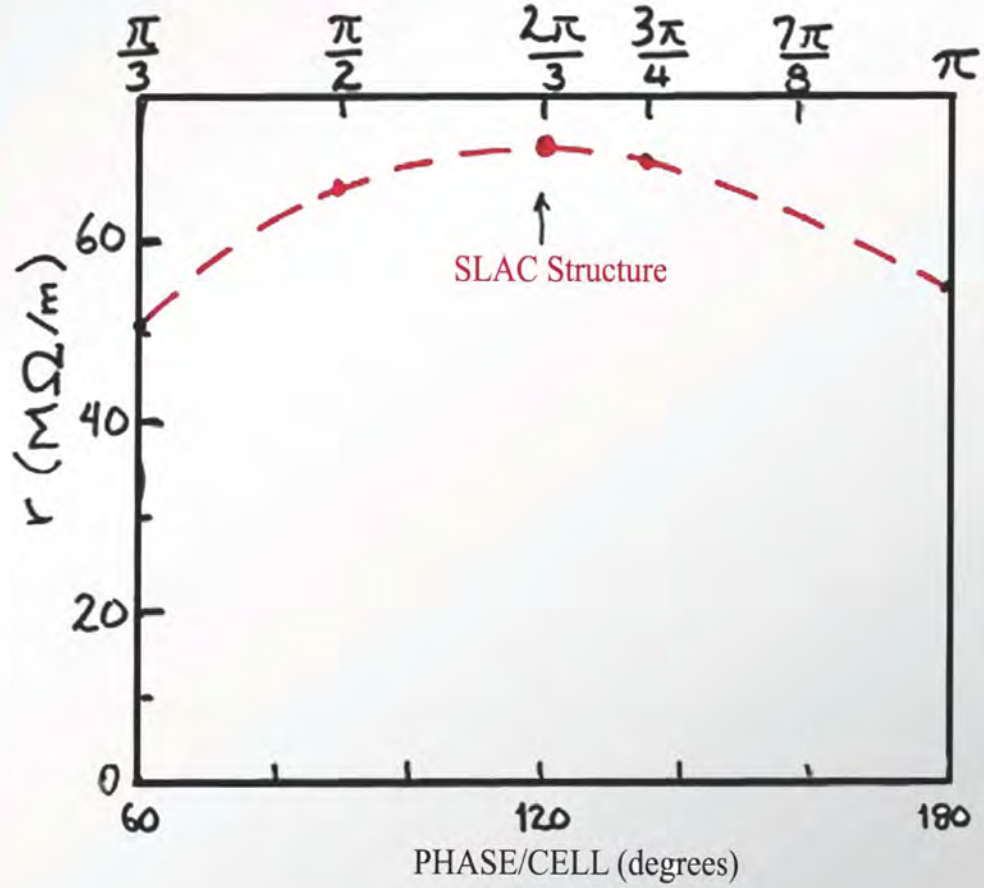
$$\frac{r_{shunt}}{Q} = \frac{E_a^2}{w\omega}$$

$$s = \frac{E_a^w}{w} = \text{ Elastance } (\mathrm{M\Omega/m/\mu s})$$

$$W_{acc} = \text{ emergy/length for acceleration}$$

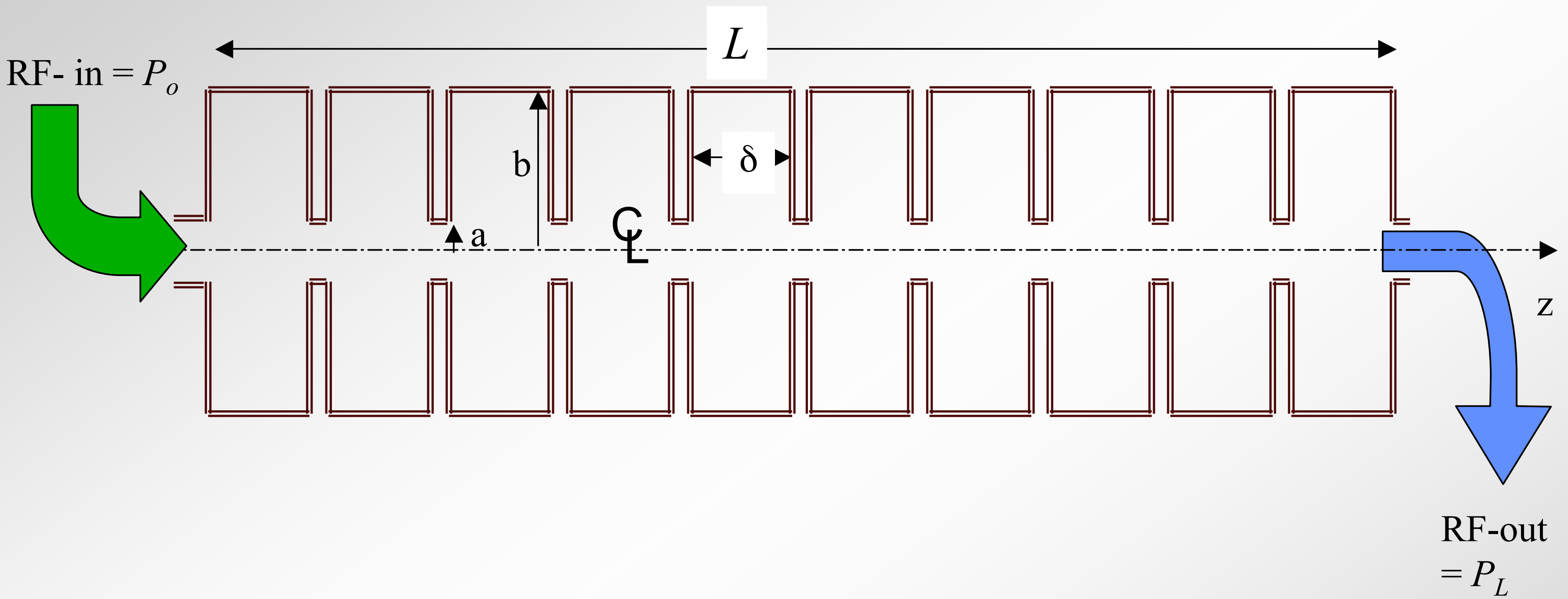
Variation of shunt impedance
with cell length





Calculations by D. Farkas (SLAC)

The constant geometry structure

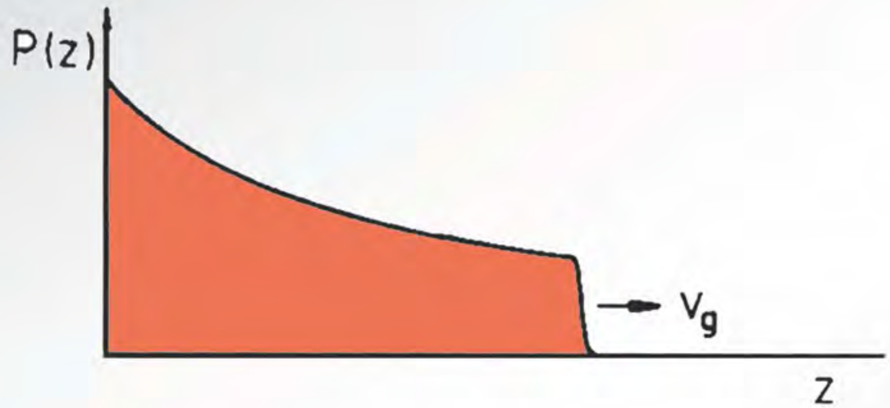


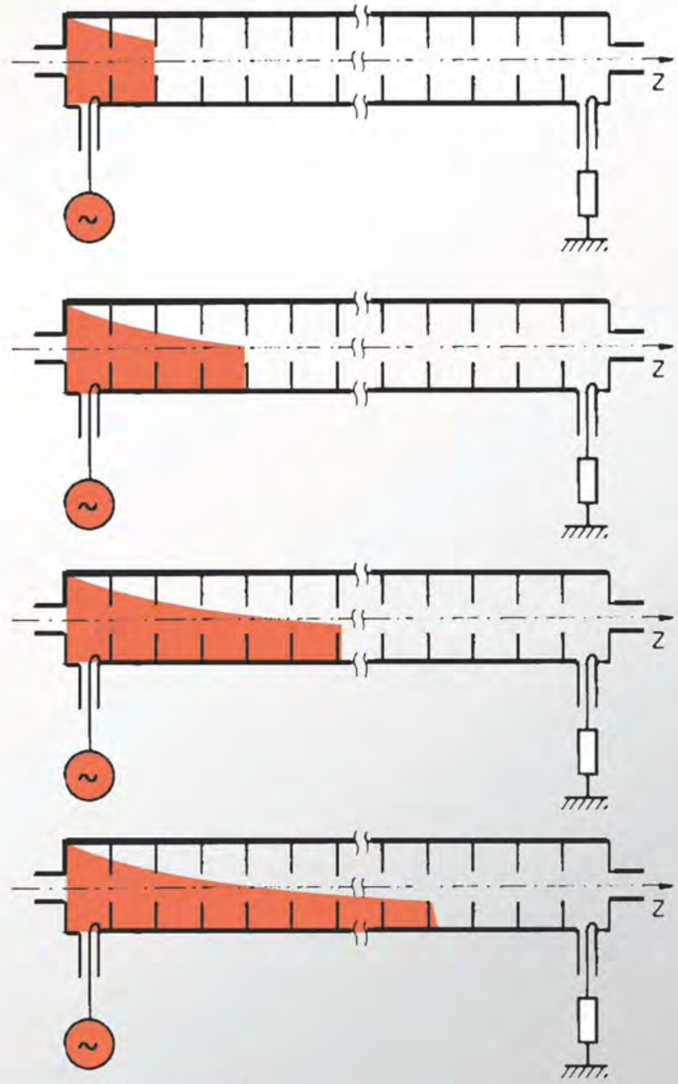
In a structure with a constant geometry,

the inductance & capacitance per unit length are constant

==> **constant impedance structure**

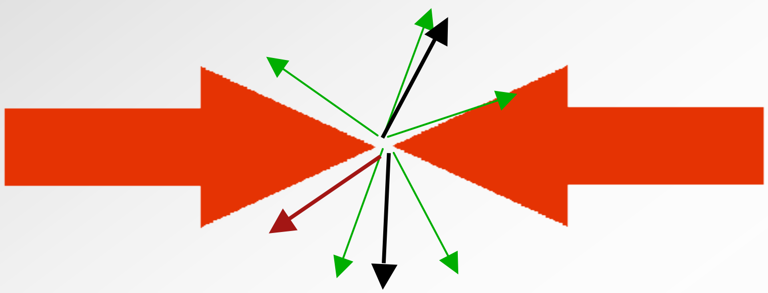
Filling the traveling wave linac





Why do we need beams?

Collide beams



FOMs: Collision rate, energy stability, Accelerating field

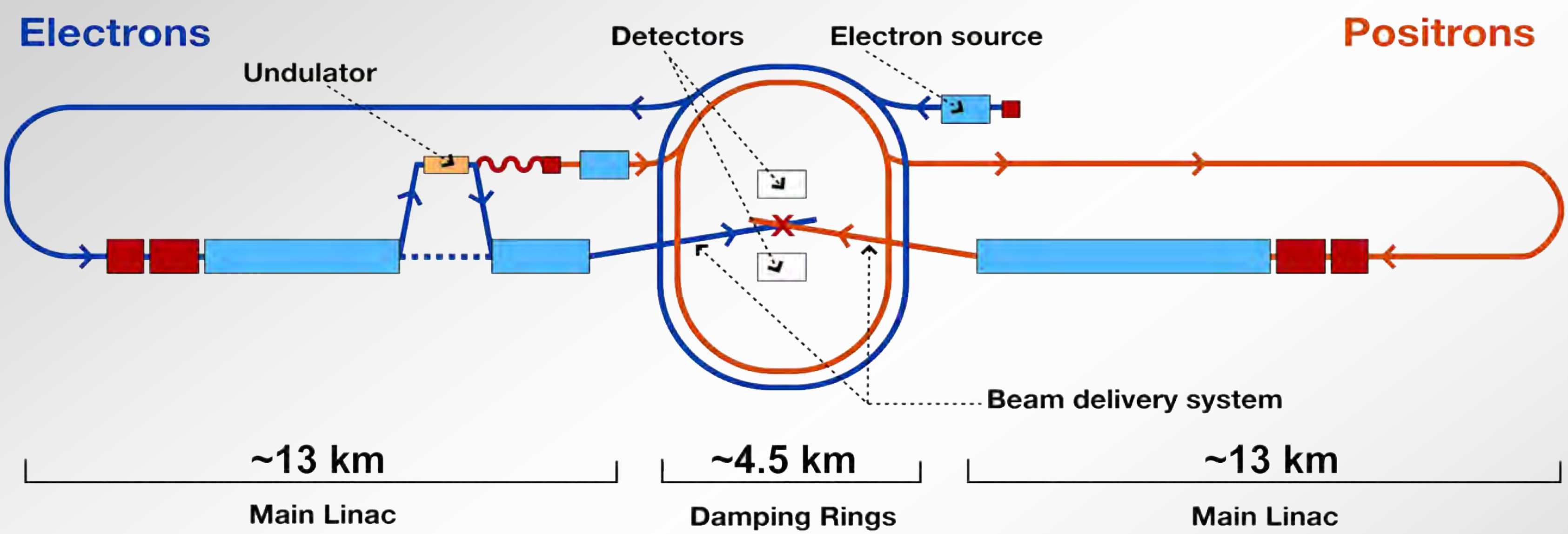
Examples: LHC, ILC, RHIC

In LHC storage rings…

- Limited space & Large rf trapping of particles
  - V/cavity must be high
- Bunch length must be large (≤ 1 event/cm in luminous region)
  - RF frequency must be low
- Energy lost in walls must be small
  - R_{surf} must be small

SC cavities were the only practical choice

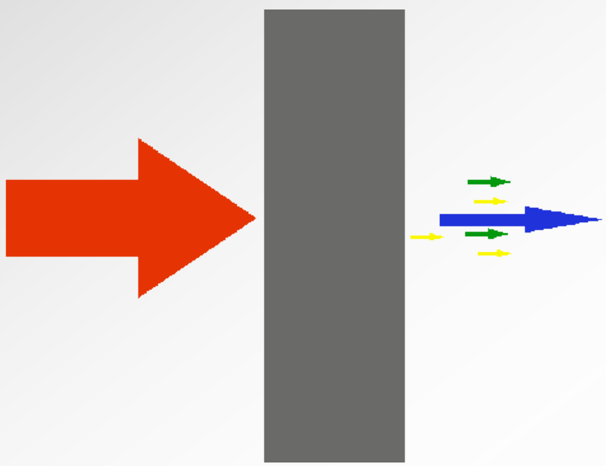
For ILC, SC rf provides high power, low ε beams at high efficiency

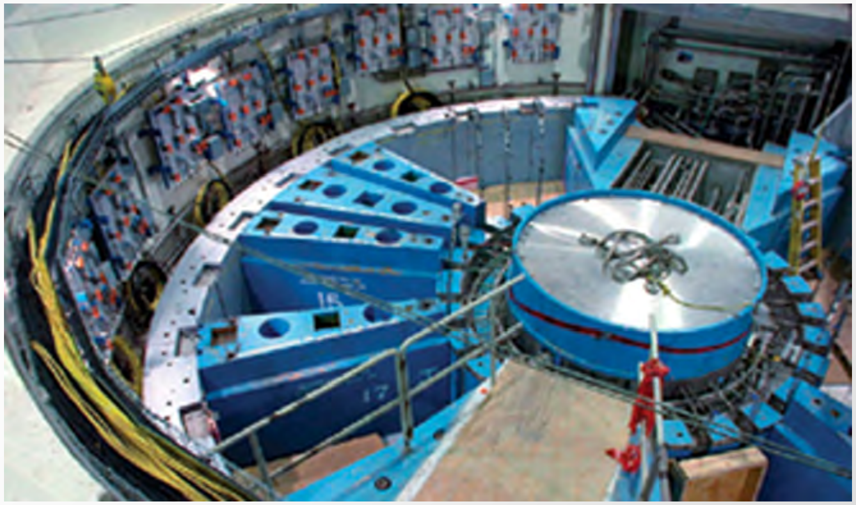


- **To deliver required luminosity (500 fb^{-1} in 4 years) ==>**
  - powerful polarized electron & positron beams (11 MW /beam)
  - tiny beams at collision point ==> minimizing beam-structure interaction
- **To limit power consumption** ==> high "wall plug" to beam power efficiency
  - Even with SC rf, the site power is still 230 MW !

Why do we need beams?

Intense secondary beams





1 MW target at SNS

FOM: Secondaries/primary
Examples: spallation neutrons,
neutrino beams

The Spallation Neutron Source

- 1 MW @ 1GeV (compare with ILC 11 MW at 500 GeV (upgradeable to 4 MW)

==> miniscule beam loss into accelerator

==> large aperture in cavities ==> large cavities

==> low frequency

==> high energy stability

==>large stored energy

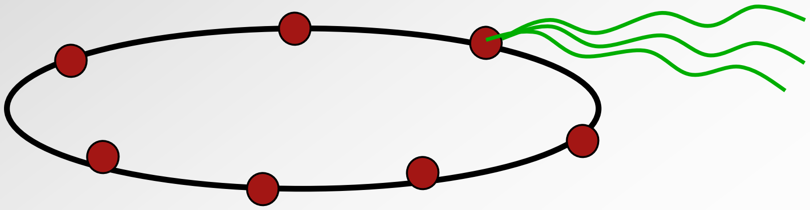
==> high efficiency at E_z

==> SC RF

Matter to energy: Synchrotron radiation science

Synchrotron light source

(pulsed incoherent X-ray emission)



FOM: Brilliance v. λ

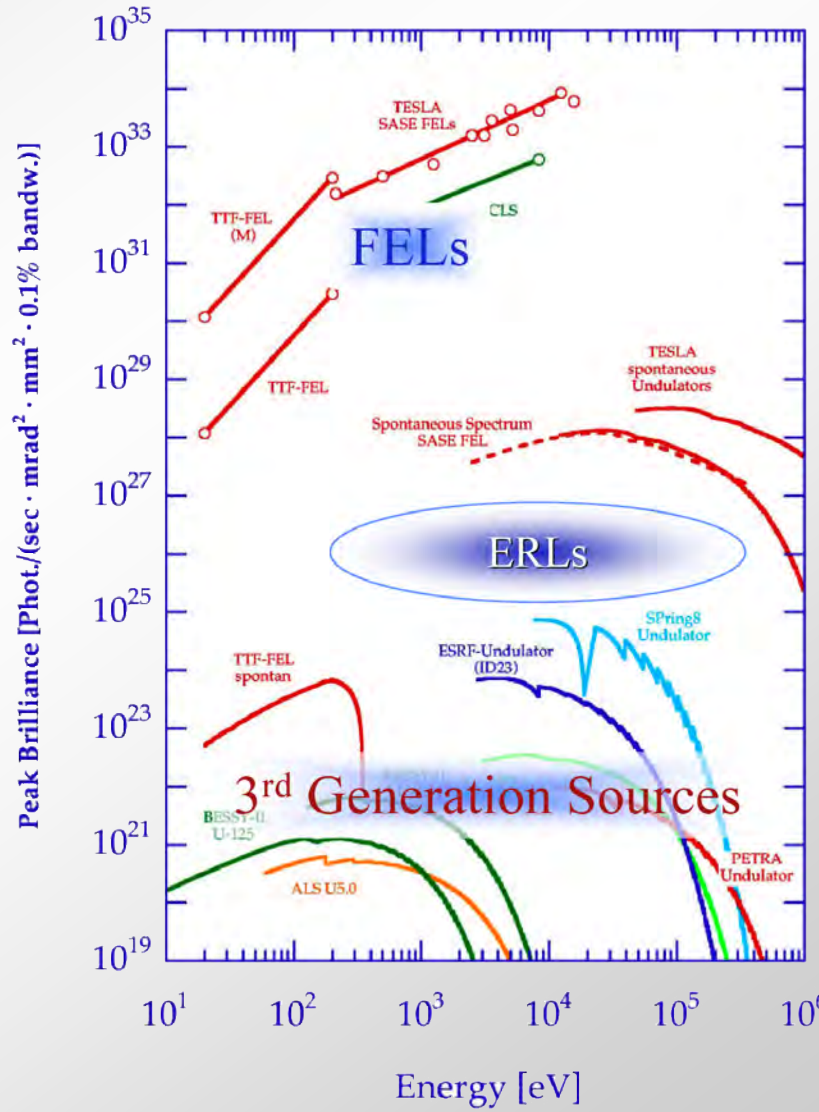
$B = \text{ph/s/mm}^2\text{/mrad}^2\text{/0.1\%BW}$

Pulse duration

Science with X-rays

Imaging

Spectroscopy



Matter to energy: Energy Recovery Linacs

Hard X-rays ==> ~5 GeV

Synchrotron light source
(pulsed incoherent X-ray emission)

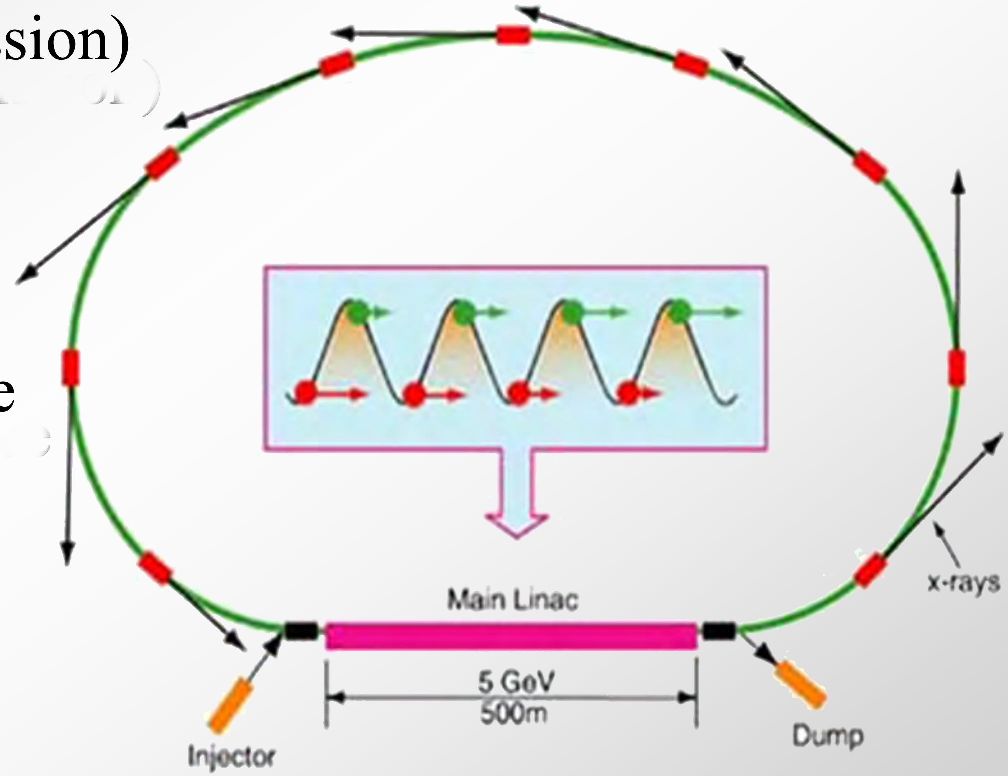
Pulse rates – kHz => MHz

X-ray pulse duration ≤ 1 ps

High average e-beam brilliance
& e-beam duration ≤ 1 ps

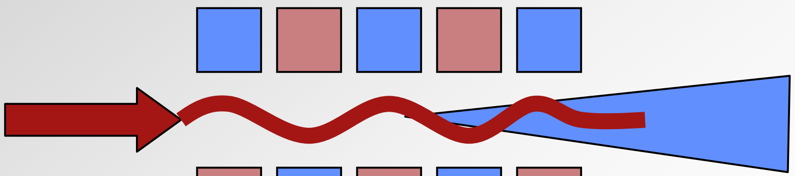
⇒ One pass through ring
⇒ Recover beam energy
⇒ High efficiency

⇒ SC RF

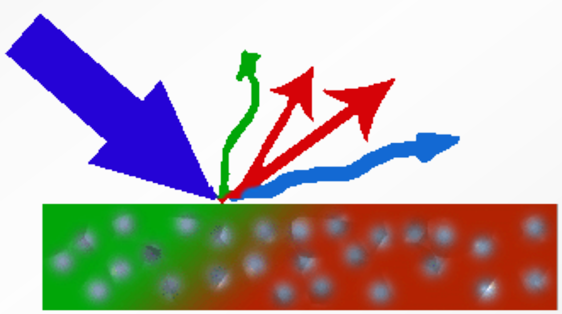


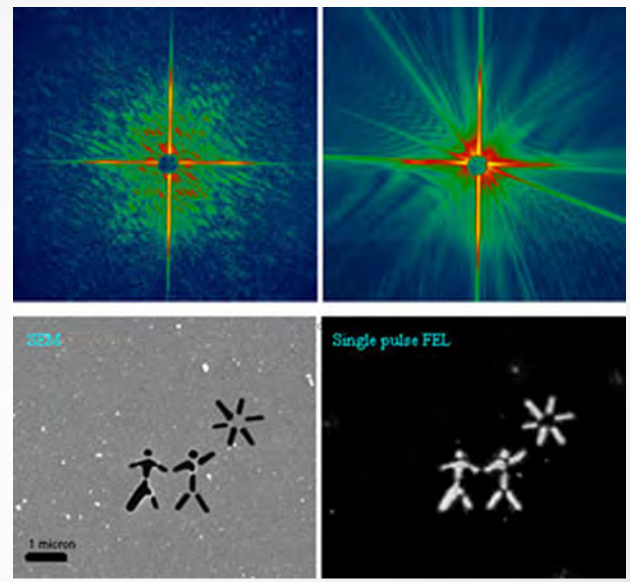
Even higher brightness requires coherent emission ==> FEL

Free electron laser



FOM: Brightness v. λ
Time structure





Full range of FEL-based science requires…

- Pulses rates 10 Hz to 10 MHz (NC limited to ~ 100 Hz)
  - High efficiency
- Pulse duration 10 fs - 1 ps
- High gain
  - Excellent beam emittance

    ==> Minimize wakefield effect

    ==> large aperture

    ==> low frequency
  - Stable beam energy & intensity

    ==> large stored energy in cavities

    ==> high Q

===> SC RF