RF Cavity Design

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CERN Accelerator School
Accelerator Physics (Intermediate level)
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Overview

- DC versus RF
  - Basic equations: Lorentz & Maxwell, RF breakdown
- Some theory: from waveguide to pillbox
  - rectangular waveguide, waveguide dispersion, group and phase velocity, standing waves … waveguide resonators, round waveguides, Pillbox cavity
- Accelerating gap
  - Principle, ferrite cavity, drift tube linac
- Characterizing a cavity
  - Accelerating voltage, transit time factor
  - Resonance frequency, shunt impedance,
  - Beam loading, loss factor, RF to beam efficiency,
  - Transverse effects, Panofsky-Wenzel, higher order modes, PS 80 MHz cavity (magnetic coupling)
- More examples of cavities
  - PEP II, LEP cavities, PS 40 MHz cavity (electric coupling),
- RF Power sources
- Many gaps
  - Why?
  - Example: side coupled linac, LIBO
- Travelling wave structures
  - Brillouin diagram, iris loaded structure, waveguide coupling
- Superconducting Accelerating Structures

DC VERSUS RF

DC versus RF

DC accelerator

RF accelerator

Lorentz force

A charged particle moving with velocity $\vec{v} = \dfrac{\vec{p}}{m\gamma}$ through an electromagnetic field experiences a force

$$\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

The total energy of this particle is $W = \sqrt{\left(mc^2\right)^2 + \left(pc\right)^2} = \gamma mc^2$, the kinetic energy is $W_{kin} = mc^2(\gamma - 1)$.

The role of acceleration is to increase the particle energy!

Change of W by differentiation:

$$W\mathrm{d}W = c^2\vec{p} \cdot \mathrm{d}\vec{p} = qc^2\vec{p} \cdot \left(\vec{E} + \vec{v} \times \vec{B}\right)\mathrm{d}t = qc^2\vec{p} \cdot \vec{E}\mathrm{d}t$$

$$\mathrm{d}W = q\vec{v} \cdot \vec{E}\mathrm{d}t$$

Note: **Only the electric field can change the particle energy!**

Maxwell's equations (in vacuum)

$$\nabla \times \vec{B} - \frac{1}{c^2}\frac{\partial}{\partial t}\vec{E} = \mu_0\vec{J} \qquad \nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} + \frac{\partial}{\partial t}\vec{B} = 0 \qquad \nabla \cdot \vec{E} = \mu_0 c^2 \rho$$

why not DC?

1) DC ($\frac{\partial}{\partial t} \equiv 0$): $\nabla \times \vec{E} = 0$ which is solved by $\vec{E} = -\nabla\Phi$

Limit: If you want to gain 1 MeV, you need a potential of 1 MV!

2) Circular machine: DC acceleration impossible since $\oint \vec{E} \cdot \mathrm{d}\vec{s} = 0$

With time-varying fields:

$$\nabla \times \vec{E} = -\frac{\partial}{\partial t}\vec{B} \qquad \oint \vec{E} \cdot \mathrm{d}\vec{s} = -\iint \frac{\partial \vec{B}}{\partial t} \cdot \mathrm{d}\vec{A}$$

Maxwell's equation in vacuum (contd.)

$$\nabla \times \vec{B} - \frac{1}{c^2}\frac{\partial}{\partial t}\vec{E} = 0 \quad \nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} + \frac{\partial}{\partial t}\vec{B} = 0 \quad \nabla \cdot \vec{E} = 0$$

curl of 3rd and $\frac{\partial}{\partial t}$ of 1st equation:

$$\nabla \times \nabla \times \vec{E} + \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E} = 0$$

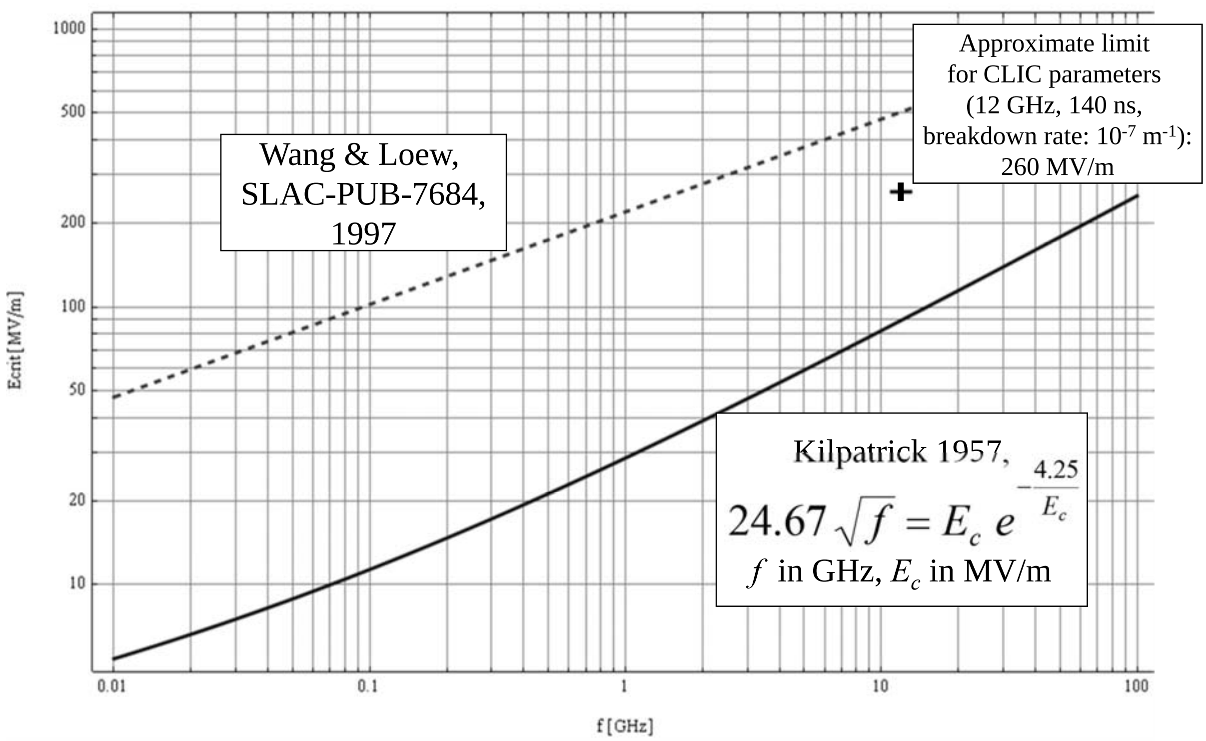
vector identity: $\nabla \times \nabla \times \vec{E} = \nabla\nabla \cdot \vec{E} - \Delta\vec{E}$

with 4th equation : $\Delta\vec{E} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E} = 0$

i.e. Laplace in 4 dimensions.

Another reason for RF: breakdown limit

surface field, in vacuum ,Cu surface, room temperature

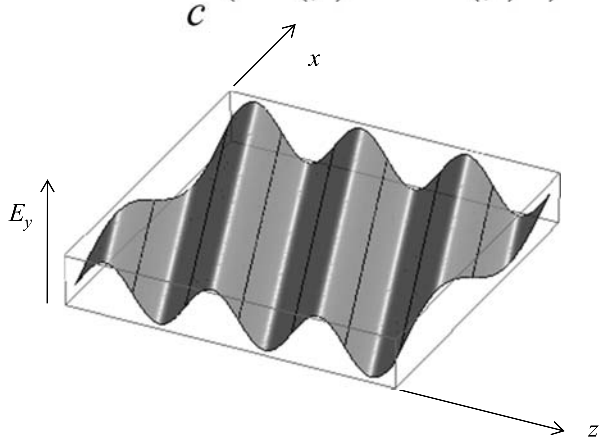


FROM WAVEGUIDE TO PILLBOX

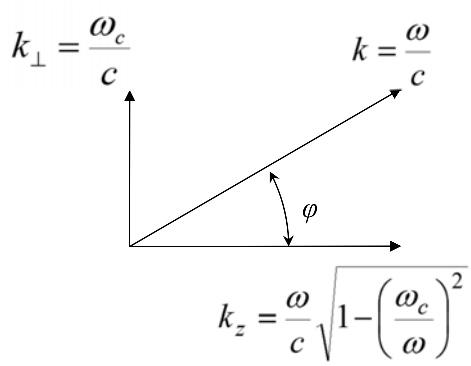
Homogeneous plane wave

$$\vec{E} \propto \vec{u}_y \cos\left(\omega t - \vec{k} \cdot \vec{r}\right)$$
$$\vec{B} \propto \vec{u}_x \cos\left(\omega t - \vec{k} \cdot \vec{r}\right)$$

$$\vec{k} \cdot \vec{r} = \frac{\omega}{c}\left(\cos(\varphi) z + \sin(\varphi) x\right)$$

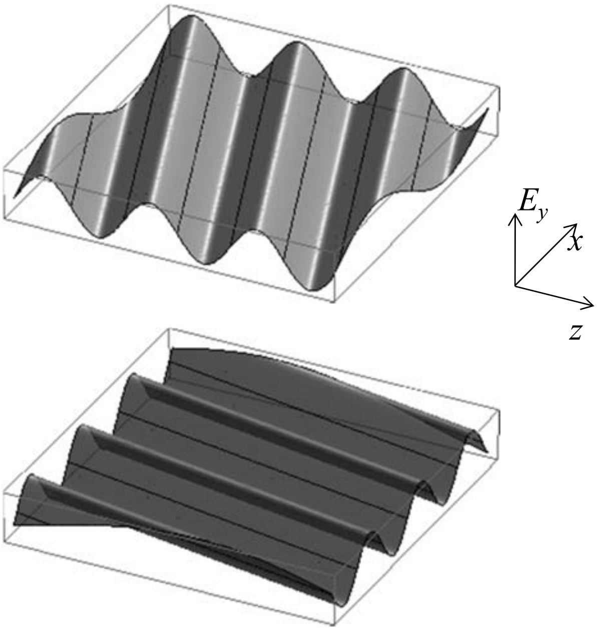


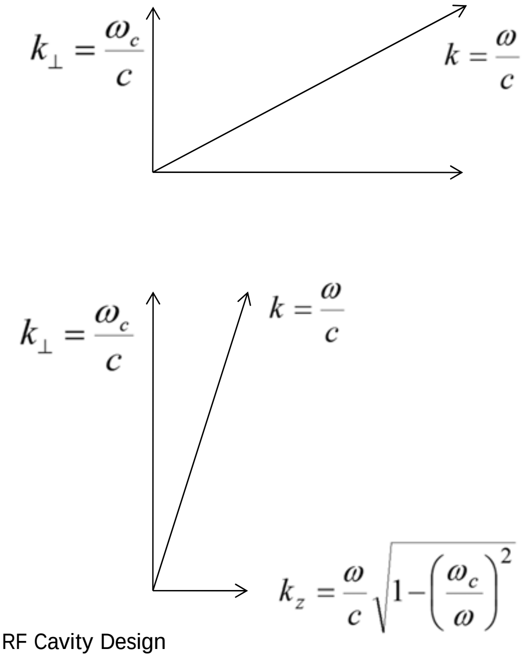
Wave vector $\vec{k}$:
the direction of $\vec{k}$ is the direction of propagation,
the length of $\vec{k}$ is the phase shift per unit length.
$\vec{k}$ behaves like a vector.



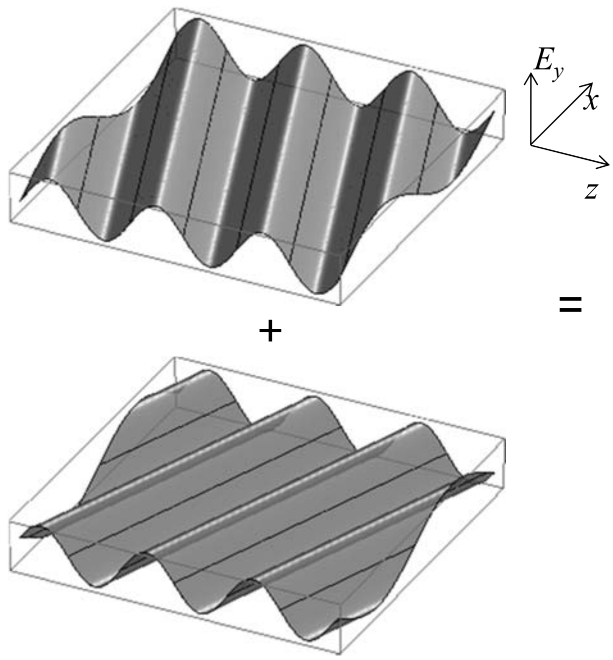
Wave length, phase velocity

- The components of $\vec{k}$ are related to the wavelength in the direction of that component as $\lambda_z = \frac{2\pi}{k_z}$ etc. , to the phase velocity as $v_{\varphi,z} = \frac{\omega}{k_z} = f\,\lambda_z$.





Superposition of 2 homogeneous plane waves



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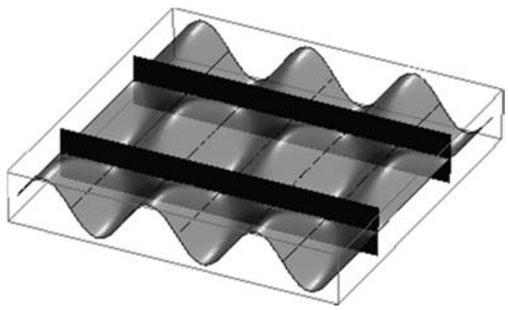


Metallic walls may be inserted where $E_y \equiv 0$ without perturbing the fields.

Note the standing wave in *x*-direction!

This way one gets a hollow rectangular waveguide

Rectangular waveguide

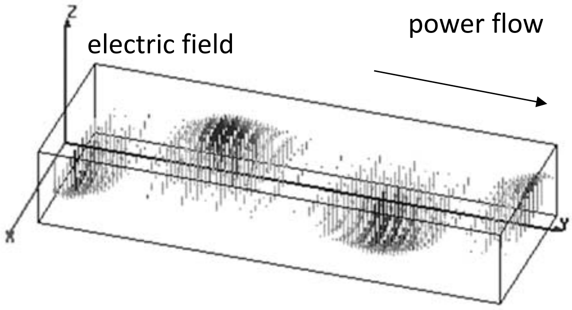
Fundamental (TE_{10} or H_{10}) mode
in a standard rectangular waveguide.

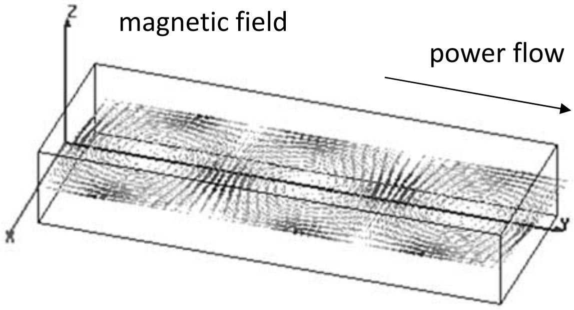
Example: "S-band" : 2.6 GHz ... 3.95 GHz,

Waveguide type WR284 (2.84" wide),
dimensions: 72.14 mm x 34.04 mm.

Operated at f = 3 GHz.

power flow: $$\frac{1}{2}\mathrm{Re}\left\{\iint_{\substack{\text{cross}\\\text{section}}} \vec{E}\times\vec{H}^{*}\cdot \mathrm{d}\vec{A}\right\}$$



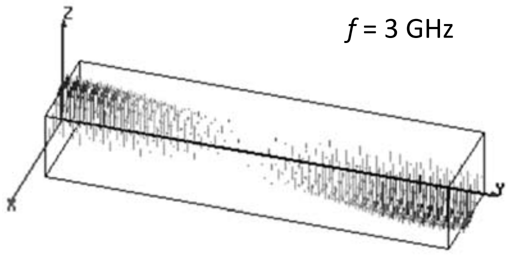


Waveguide dispersion

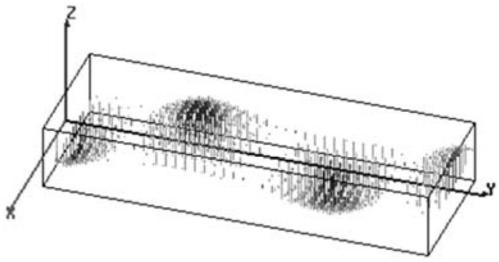
What happens with different waveguide dimensions (different width a)?

f = 3 GHz

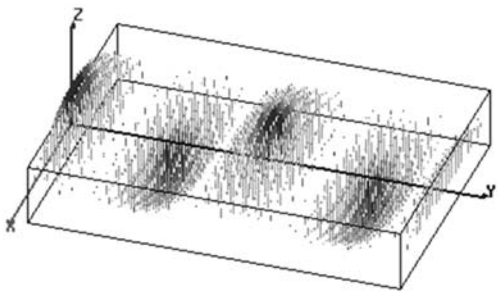
1:
a = 52 mm,
f/f_c = 1.04

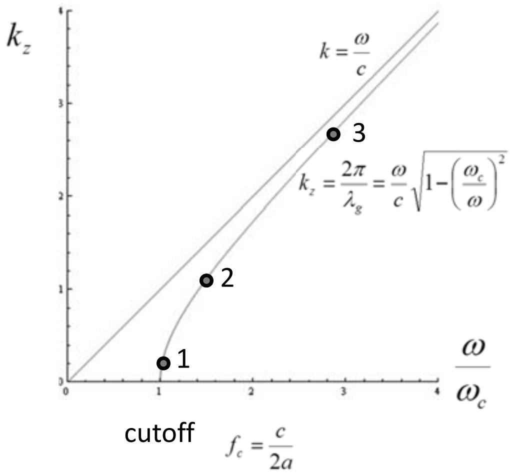


2:
a = 72.14 mm,
f/f_c = 1.44



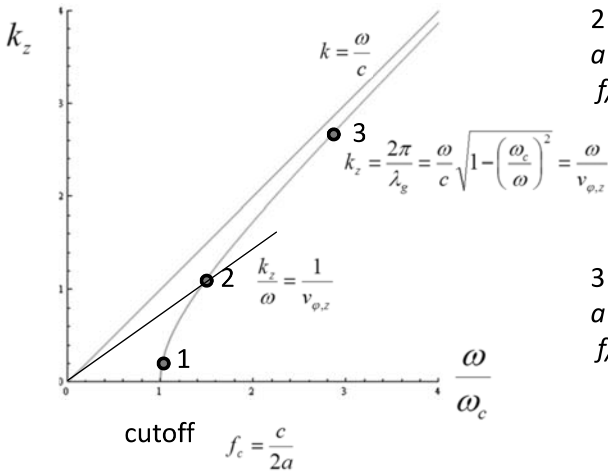
3:
a = 144.3 mm,
f/f_c = 2.88





Phase velocity

The phase velocity is the speed with which the crest or a zero-crossing travels in *z*-direction.
Note on the three animations on the right that, at constant *f*, it is $\propto \lambda_g$
Note that at $f = f_c$, $v_{\varphi,z} = \infty$!
With $f \to \infty$, $v_{\varphi,z} \to c$!



f = 3 GHz

1:
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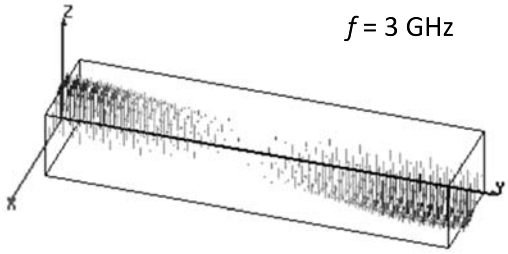

2:
a = 72.14 mm,
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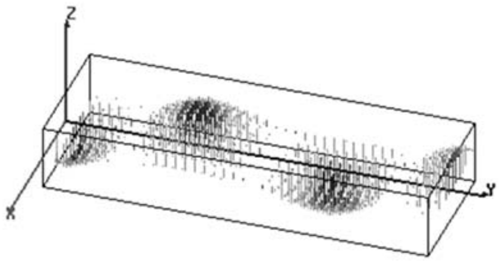
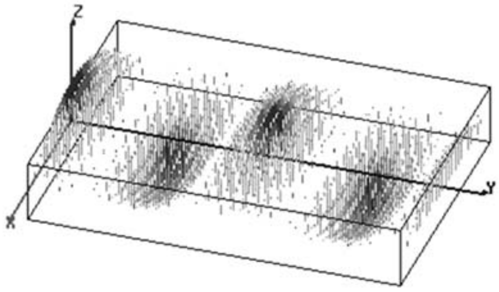


3:
a = 144.3 mm,
f/f_c = 2.88



Summary waveguide dispersion and phase velocity:

In a **general** cylindrical waveguide:

$$\gamma = \mathrm{j}\sqrt{\left(\frac{\omega}{c}\right)^2 - k_\perp{}^2}$$

$$Z_0 = \frac{\mathrm{j}\omega\mu}{\gamma} \text{ for TE}, \quad Z_0 = \frac{\gamma}{\mathrm{j}\omega\varepsilon} \text{ for TM}$$

$$k_z = \mathrm{Im}\{\gamma\} = \frac{2\pi}{\lambda_g}$$

e.g.: TE_{10}-wave in rectangular waveguide:

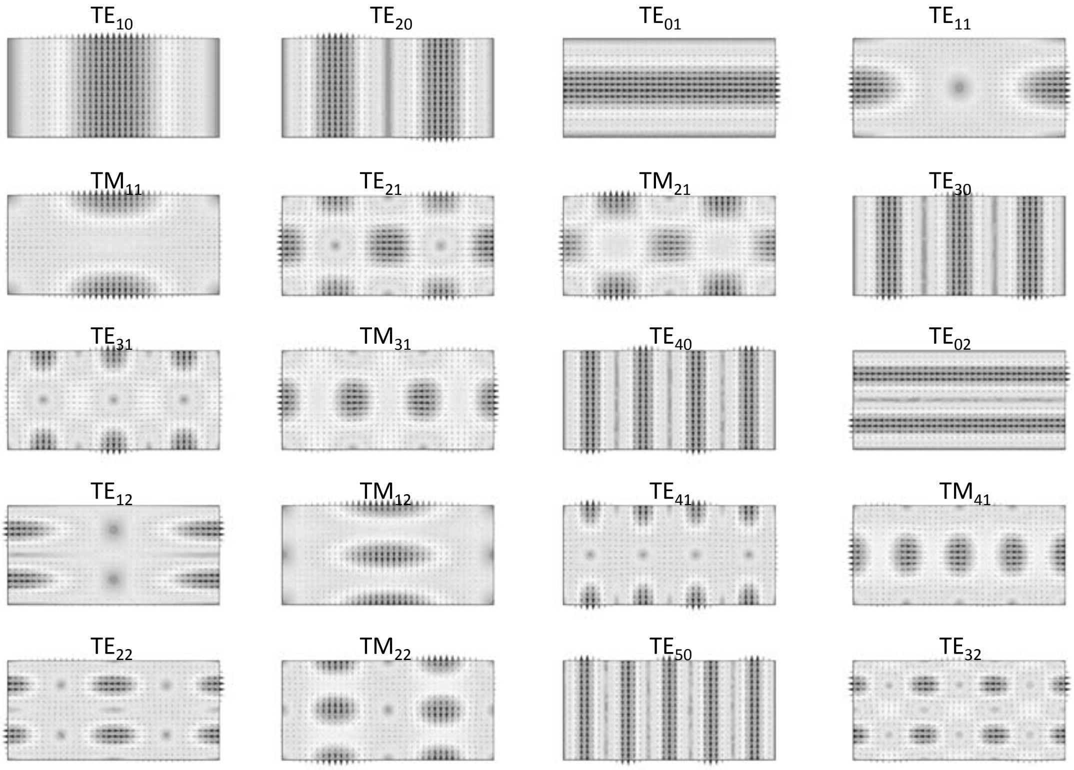
$$\gamma = \mathrm{j}\sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{\pi}{a}\right)^2}$$

$$Z_0 = \frac{\mathrm{j}\omega\mu}{\gamma}$$

$$\lambda_{\mathrm{cutoff}} = 2a$$

[redacted]

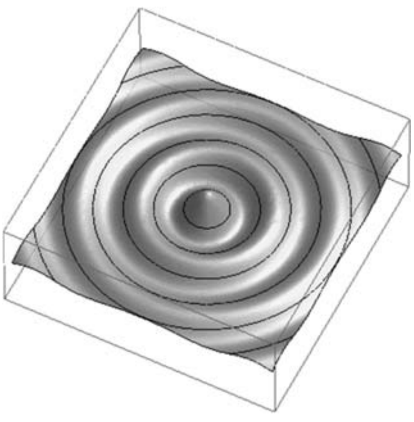
Rectangular waveguide modes



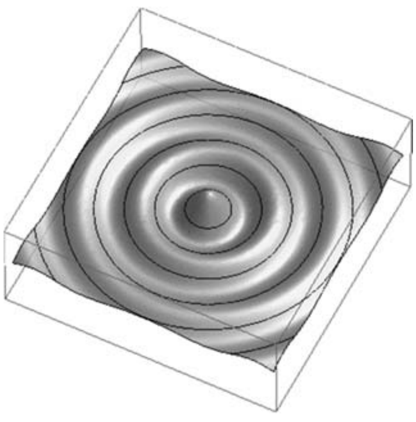
plotted: *E*-field

Radial waves

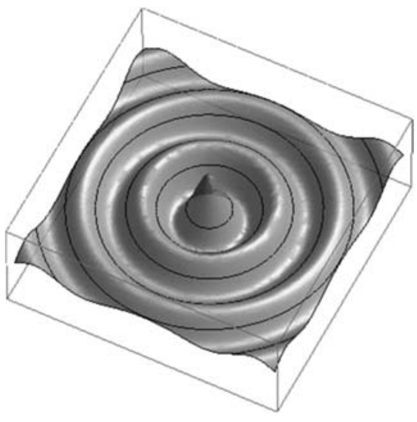
Also radial waves may be interpreted as superposition of plane waves. The superposition of an outward and an inward radial wave can result in the field of a round hollow waveguide.



$E_z \propto H_n^{(2)}(k_\rho \rho)\cos(n\varphi)$



$E_z \propto H_n^{(1)}(k_\rho \rho)\cos(n\varphi)$

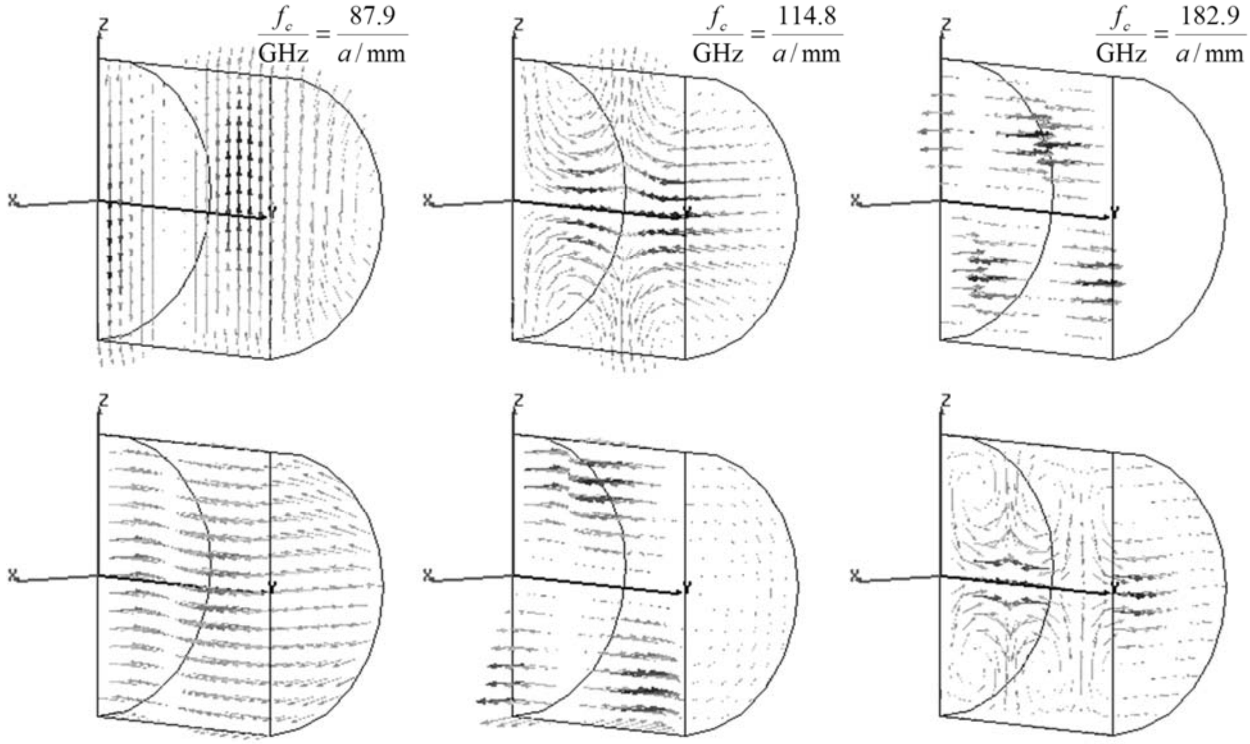


$E_z \propto J_n(k_\rho \rho)\cos(n\varphi)$

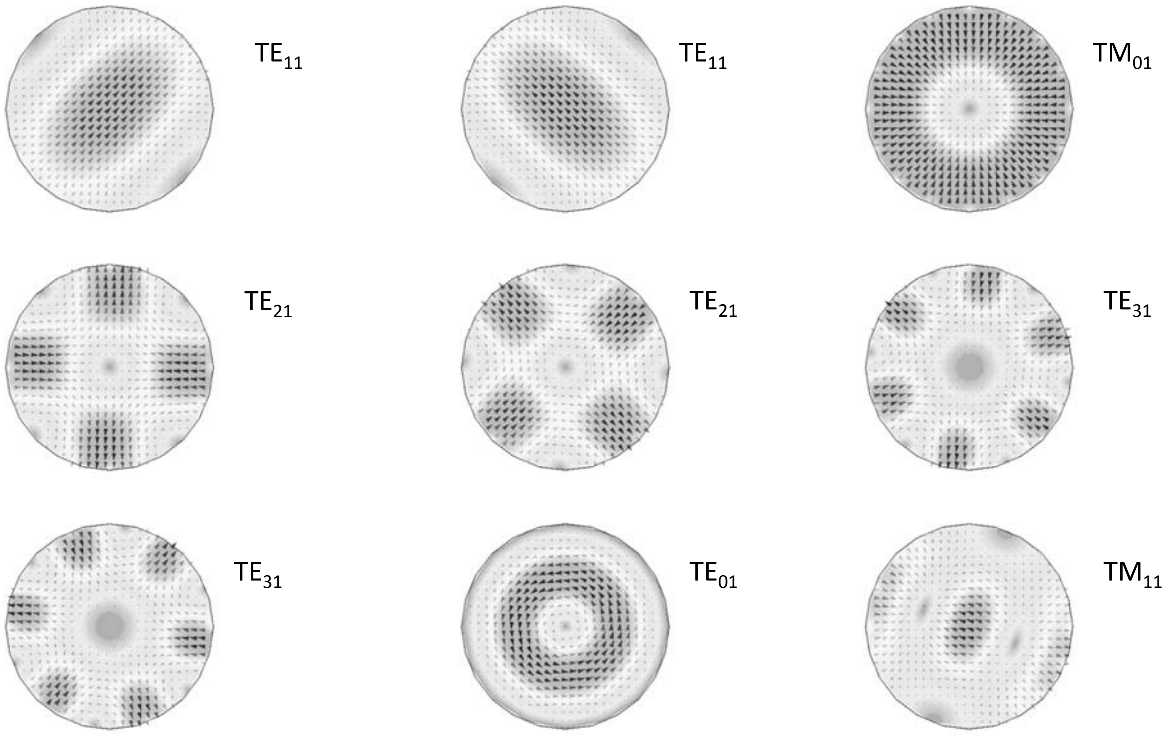
Round waveguide

f/f_c = 1.44

TE$_{11}$ – fundamental | TM$_{01}$ – axial field | TE$_{01}$ – low loss



Circular waveguide modes



plotted: *E*-field

General waveguide equations:

Transverse wave equation (membrane equation): $\Delta T + \left(\frac{\omega_c}{c}\right)^2 T = 0$

	TE (or H) modes	TM (or E) modes
boundary condition:	$\vec{n} \cdot \nabla T = 0$	$T = 0$
characteristic impedance:	$Z_0 = \frac{\mathrm{j}\omega\mu}{\gamma}$	$Z_0 = \frac{\gamma}{\mathrm{j}\omega\varepsilon}$
ortho-normal eigenvectors:	$\vec{e} = \vec{u}_z \times \nabla T$	$\vec{e} = -\nabla T$
longitudinal field:	$H_z = \left(\frac{\omega_c}{c}\right)^2 \frac{T U(z)}{\mathrm{j}\omega\mu}$	$E_z = \left(\frac{\omega_c}{c}\right)^2 \frac{T I(z)}{\mathrm{j}\omega\varepsilon}$

longitudinal wave equations (transmission line equations):

$$\frac{\mathrm{d}U(z)}{\mathrm{d}z} + \gamma Z_0 I(z) = 0$$

$$\frac{\mathrm{d}I(z)}{\mathrm{d}z} + \frac{\gamma}{Z_0} U(z) = 0$$

propagation constant:

$$\gamma = \mathrm{j}\frac{\omega}{c}\sqrt{1 - \left(\frac{\omega_c}{\omega}\right)^2}$$

transverse fields:

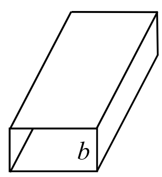
$$\vec{E} = U(z)\vec{e}$$

$$\vec{H} = I(z)\vec{u}_z \times \vec{e}$$

Rectangular waveguide: transverse eigenfunctions

TE (H) modes: $$T_{mn}^{(H)} = \frac{1}{\pi}\sqrt{\frac{ab\varepsilon_m\varepsilon_n}{(mb)^2 + (na)^2}} \cos\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)$$

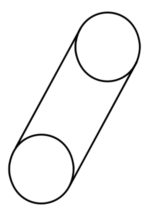
TM (E) modes: $$T_{mn}^{(E)} = \frac{2}{\pi}\sqrt{\frac{ab}{(mb)^2 + (na)^2}} \sin\left(\frac{m\pi}{a}x\right)\sin\left(\frac{n\pi}{b}y\right)$$



$$\frac{\omega_c}{c} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$$

Round waveguide: transverse eigenfunctions

TE (H) modes: $$T_{mn}^{(H)} = \sqrt{\frac{\varepsilon_m}{\pi\left(\chi_{mn}'^2 - m^2\right)}} \frac{\mathrm{J}_m\left(\chi_{mn}' \frac{\rho}{a}\right)}{\mathrm{J}_m\left(\chi_{mn}'\right)} \begin{Bmatrix}\cos(m\varphi) \\ \sin(m\varphi)\end{Bmatrix}$$

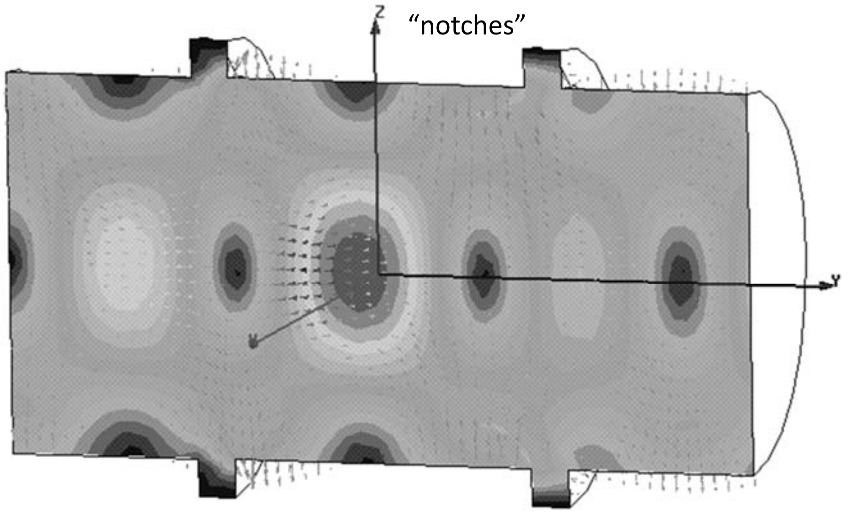


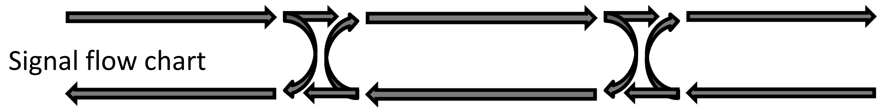
TM (E) modes: $$T_{mn}^{(E)} = \sqrt{\frac{\varepsilon_m}{\pi}} \frac{\mathrm{J}_m\left(\chi_{mn} \frac{\rho}{a}\right)}{\chi_{mn}\,\mathrm{J}_{m-1}(\chi_{mn})} \begin{Bmatrix}\sin(m\varphi) \\ \cos(m\varphi)\end{Bmatrix}$$

$$\frac{\omega_c}{c} = \frac{\chi_{mn}}{a}$$

where $$\varepsilon_i = \begin{cases} 1 & for \quad i = 0 \\ 2 & for \quad i \neq 0 \end{cases}$$

Waveguide perturbed by notches

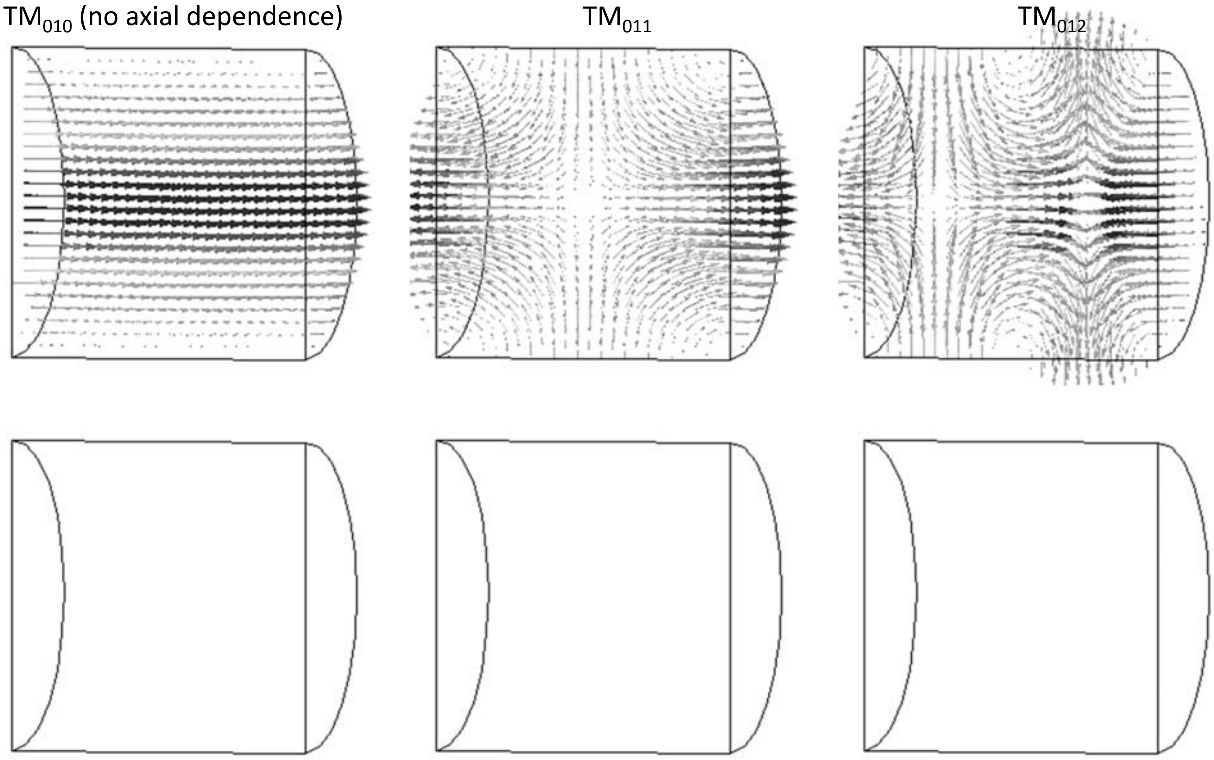




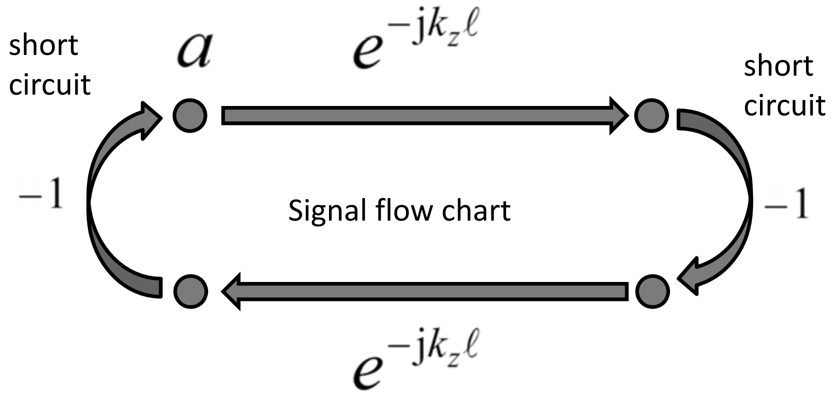
Reflections from notches lead to a superimposed standing wave pattern.
"Trapped mode"

Short-circuited waveguide

TM_{010} (no axial dependence) TM_{011} TM_{012}



Single WG mode between two shorts



Eigenvalue equation for field amplitude *a*:

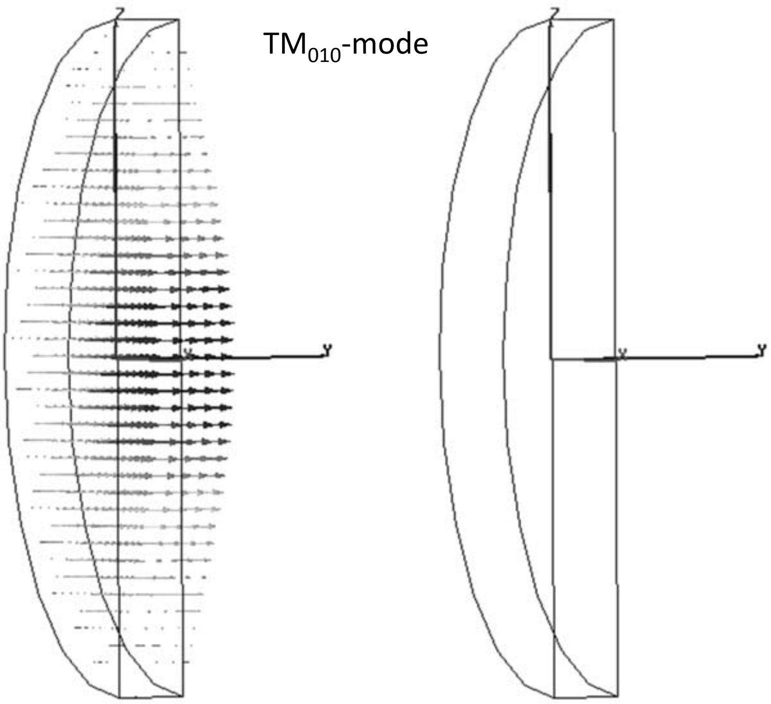
$$a = e^{-\mathrm{j}k_z 2\ell} a$$

Non-vanishing solutions exist for $2k_z\ell = 2\pi\, m$:

With $k_z = \frac{\omega}{c}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}$, this becomes $f_0^2 = f_c^2 + \left(c\frac{m}{2\ell}\right)^2$

Simple pillbox

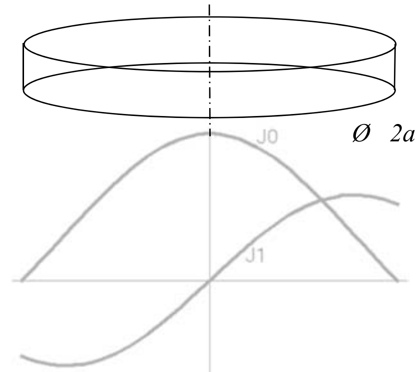
(only 1/2 shown)



electric field (purely axial) magnetic field (purely azimuthal)

Pillbox cavity field (w/o beam tube)

$$T(\rho,\varphi)=\sqrt{\frac{1}{\pi}}\,\frac{\mathrm{J}_0\left(\frac{\chi_{01}\rho}{a}\right)}{\chi_{01}\,\mathrm{J}_1\left(\frac{\chi_{01}}{a}\right)}\qquad \chi_{01}=2.40483\ldots$$



The only non-vanishing field components :

$$E_z=\frac{1}{\mathrm{j}\omega\varepsilon_0}\frac{\chi_{01}}{a}\sqrt{\frac{1}{\pi}}\,\frac{\mathrm{J}_0\left(\frac{\chi_{01}\rho}{a}\right)}{a\,\mathrm{J}_1\left(\frac{\chi_{01}}{a}\right)}$$

$$B_\varphi=\mu_0\sqrt{\frac{1}{\pi}}\,\frac{\mathrm{J}_1\left(\frac{\chi_{01}\rho}{a}\right)}{a\,\mathrm{J}_1\left(\frac{\chi_{01}}{a}\right)}$$

$$\omega_0\Big|_{pillbox}=\frac{\chi_{01}\,c}{a}\qquad \eta=\sqrt{\frac{\mu_0}{\varepsilon_0}}=377\,\Omega$$

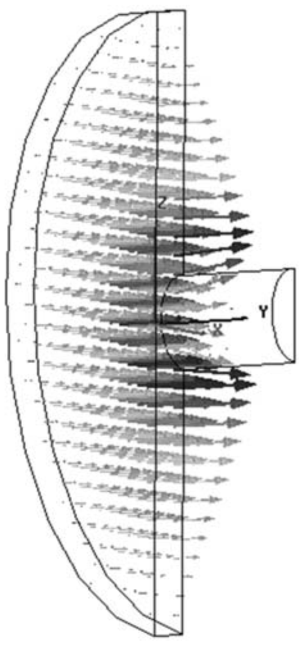
$$Q\Big|_{pillbox}=\frac{\sqrt{2a\eta\sigma\chi_{01}}}{2\left(1+\frac{a}{h}\right)}$$

$$\frac{R}{Q}\Big|_{pillbox}=\frac{4\eta}{\chi_{01}{}^3\pi\,\mathrm{J}_1^2(\chi_{01})}\,\frac{\sin^2\left(\frac{\chi_{01}}{2}\frac{h}{a}\right)}{h/a}$$

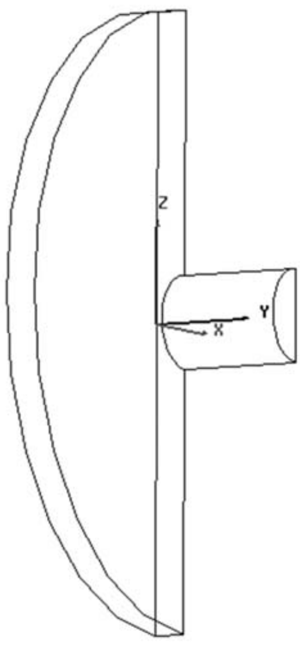
Pillbox with beam pipe

TM_{010}-mode (only 1/4 shown)

One needs a hole for the beam pipe – circular waveguide below cutoff



electric field

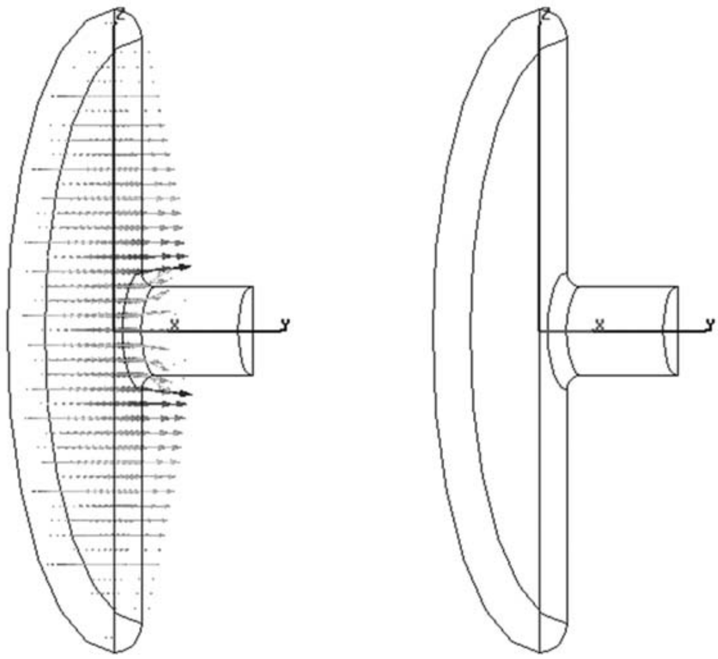


magnetic field

A more practical pillbox cavity

TM_{010}-mode (only 1/4 shown)

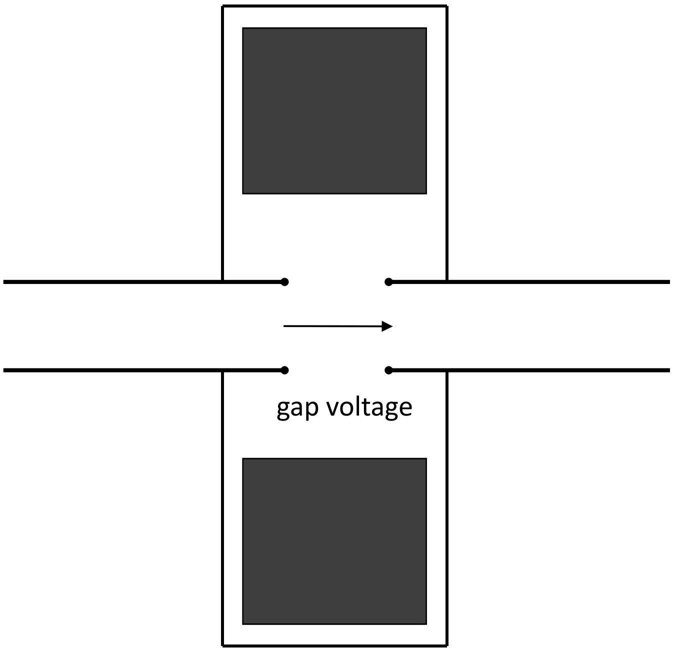
Round of sharp edges (to reduce field enhancement!)



electric field magnetic field

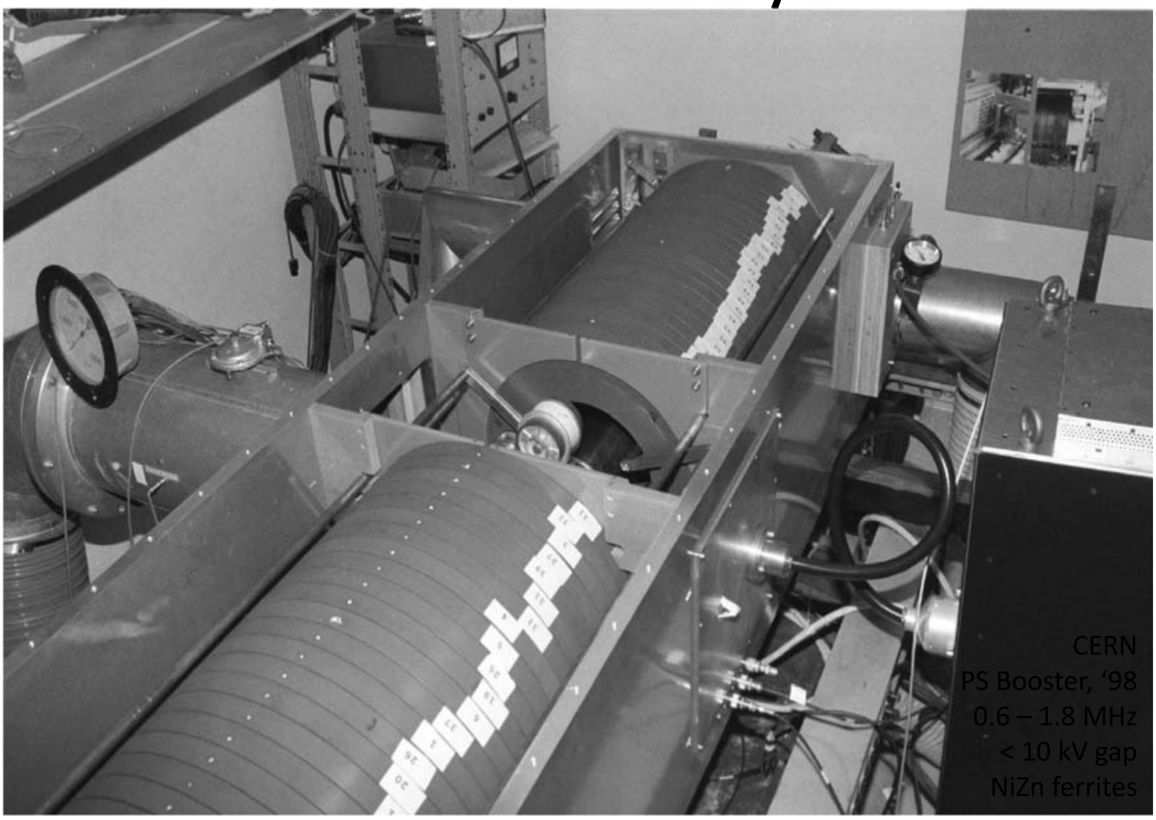
ACCELERATING GAP

Accelerating gap

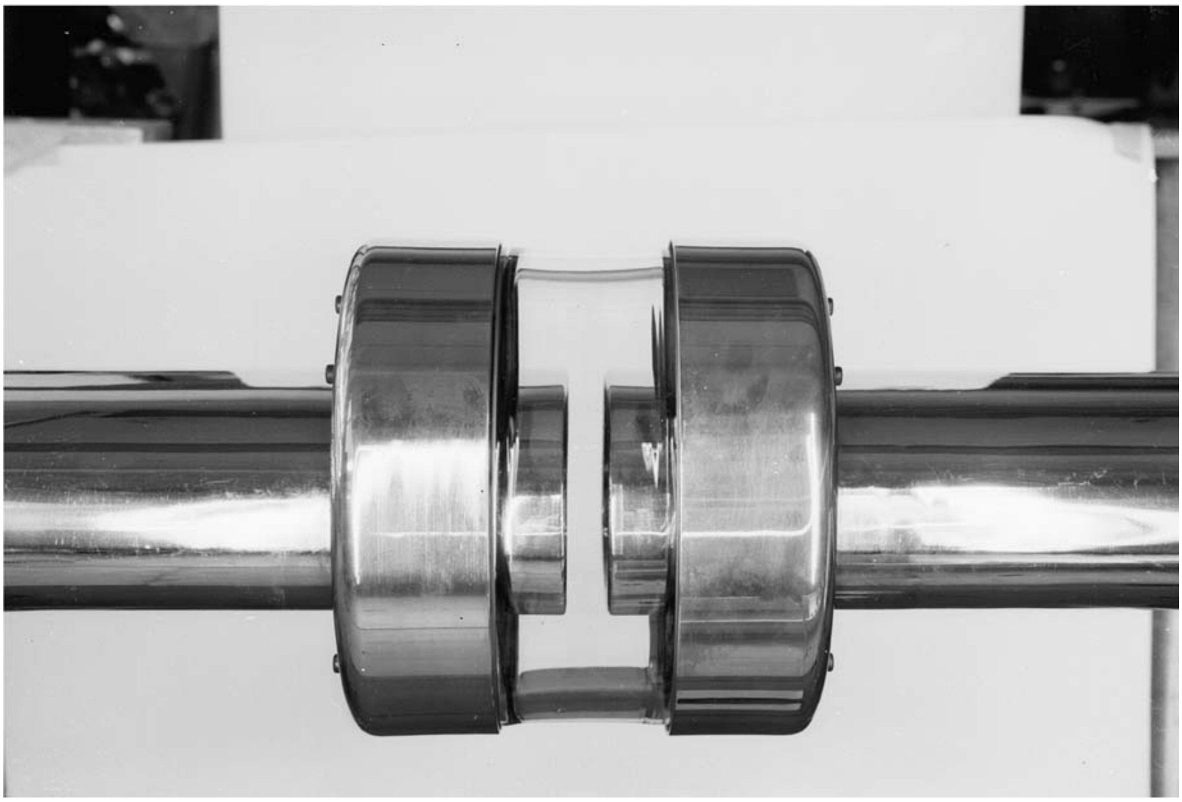


- We want a voltage across the gap!
- It cannot be DC, since we want the beam tube on ground potential.
- Use $\oint \vec{E} \cdot \mathrm{d}\vec{s} = -\iint \frac{\mathrm{d}\vec{B}}{\mathrm{d}t} \cdot \mathrm{d}\vec{A}$
- The "shield" imposes a
  - upper limit of the voltage pulse duration or – equivalently –
  - a lower limit to the usable frequency.
- The limit can be extended with a material which acts as "open circuit"!
- Materials typically used:
  - ferrites (depending on *f*-range)
  - magnetic alloys (MA) like Metglas®, Finemet®, Vitrovac®…
- resonantly driven with RF (ferrite loaded cavities) – or with pulses (induction cell)

Ferrite cavity



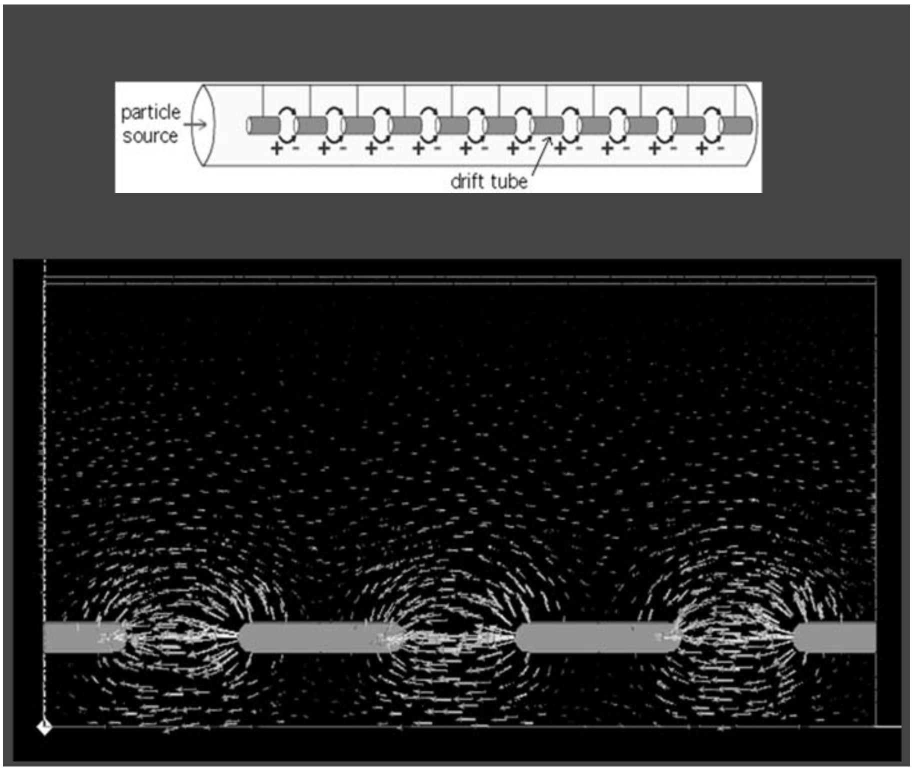
Gap of PS cavity (prototype)



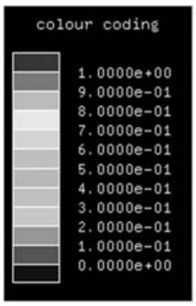
Drift Tube Linac (DTL) – how it works

For slow particles !
E.g. protons @ few MeV

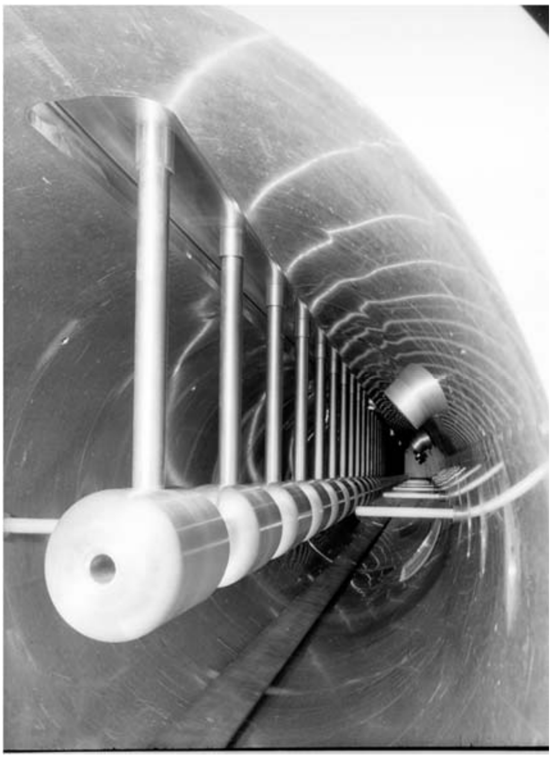
The drift tube lengths
can easily be adapted.

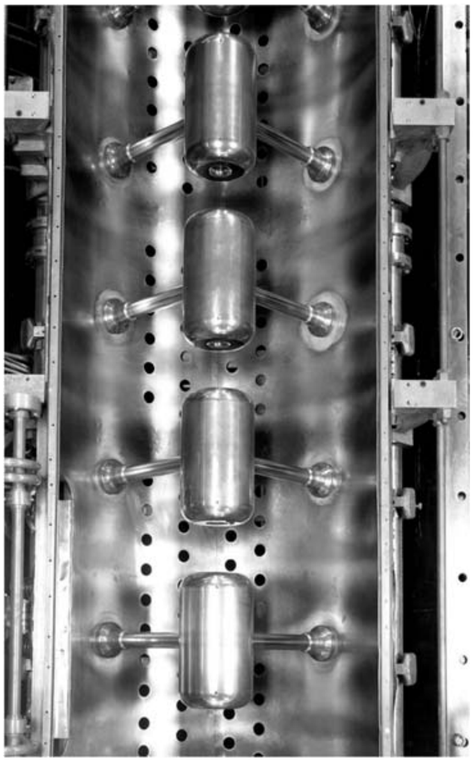


electric field



Drift tube linac – practical implementations





CHARACTERIZING A CAVITY

Acceleration voltage & *R*-upon-*Q*

I define $V_{acc} = \int E_z e^{\mathrm{j}\frac{\omega}{\beta c} z} \mathrm{d}z$. The exponential factor accounts for the variation of the field while particles with velocity βc are traversing the gap (see next page).

With this definition, V_{acc} is generally complex – this becomes important with more than one gap. For the time being we are only interested in $|V_{acc}|$.

Attention, different definitions are used!

The square of the acceleration voltage is proportional to the stored energy W. The proportionality constant defines the quantity called *R*-upon-*Q*:

$$\frac{R}{Q} = \frac{|V_{acc}|^2}{2\,\omega_0 W}$$

Attention, also here different definitions are used!

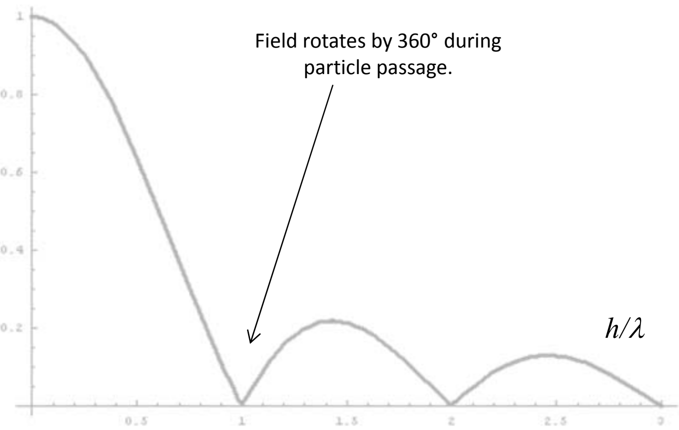
Transit time factor

The transit time factor is the ratio of the acceleration voltage to the (non-physical) voltage a particle with infinite velocity would see.

$$TT = \frac{|V_{acc}|}{\left|\int E_z \mathrm{d}z\right|} = \frac{\left|\int E_z e^{\mathrm{j}\frac{\omega}{\beta c} z} \mathrm{d}z\right|}{\left|\int E_z \mathrm{d}z\right|}$$

The transit time factor of an ideal pillbox cavity (no axial field dependence) of height (gap length) *h* is:

$$TT = \sin\left(\frac{\chi_{01} h}{2a}\right) \Big/ \left(\frac{\chi_{01} h}{2a}\right)$$



Shunt impedance

The square of the acceleration voltage is proportional to the power loss P_{loss} .

The proportionality constant defines the quantity "shunt impedance"

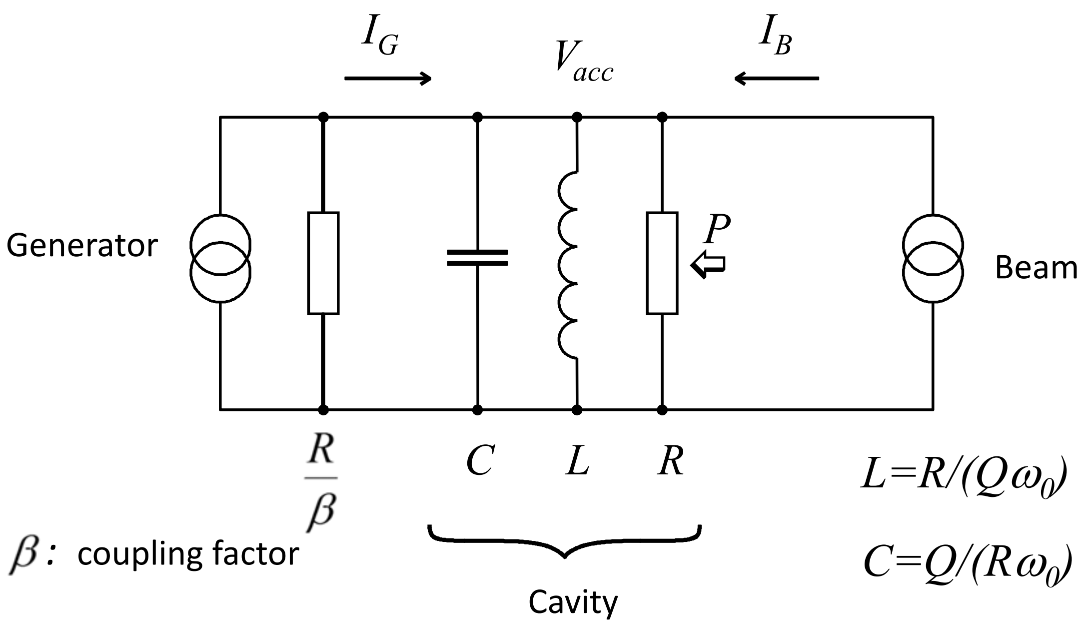
$$R = \frac{|V_{acc}|^2}{2\, P_{loss}}$$

Attention, also here different definitions are used!

Traditionally, the shunt impedance is the quantity to optimize in order to minimize the power required for a given gap voltage.

Cavity resonator - equivalent circuit

Simplification: single mode



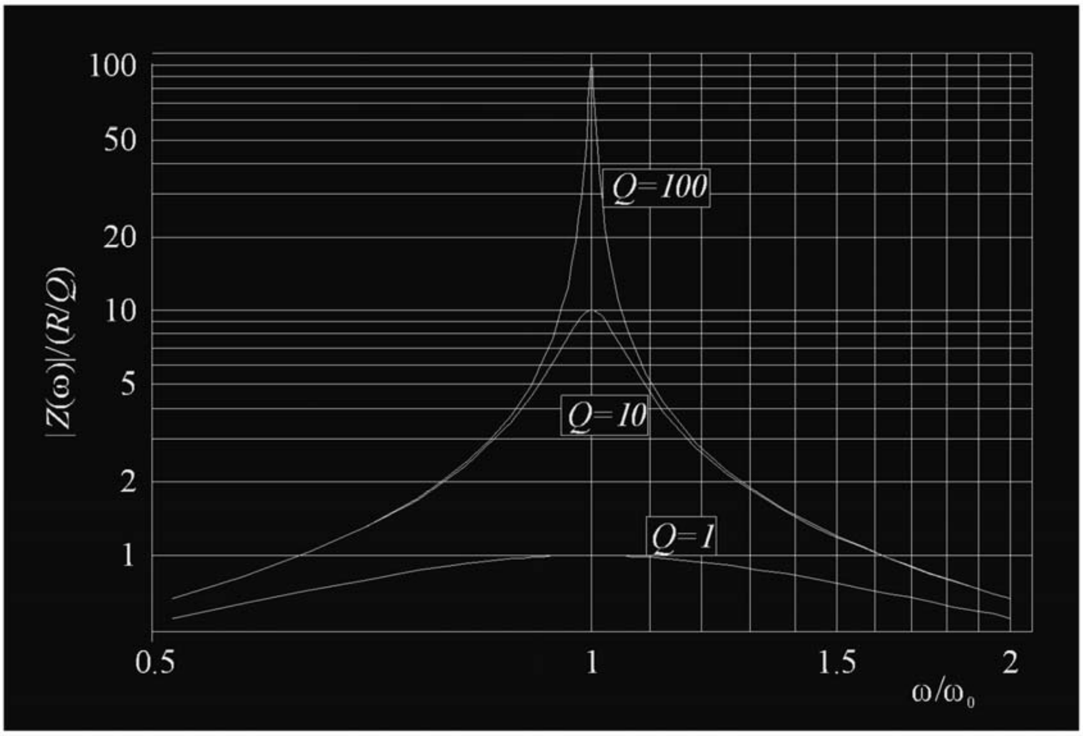
$L=R/(Q\omega_0)$

$C=Q/(R\omega_0)$

β : coupling factor

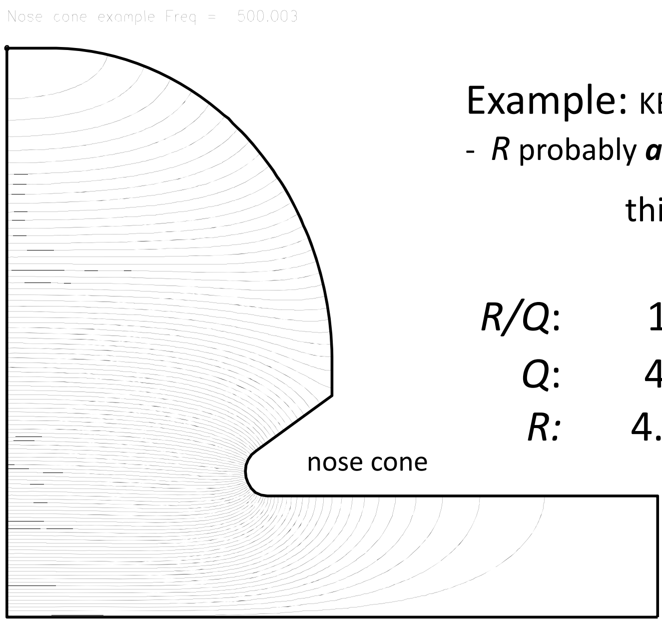
R: Shunt impedance $\sqrt{L/C}$: *R*-upon-*Q*

Resonance



Reentrant cavity

Nose cones increase transit time factor, round outer shape minimizes losses.



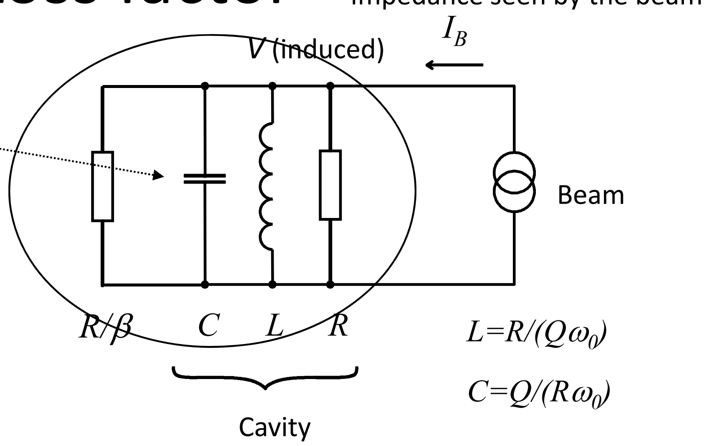
Example: KEK photon factory 500 MHz

- *R* probably ***as good as it gets*** -

	this cavity	optimized pillbox
R/Q:	111 Ω	107.5 Ω
Q:	44270	41630
R:	4.9 MΩ	4.47 MΩ

Loss factor

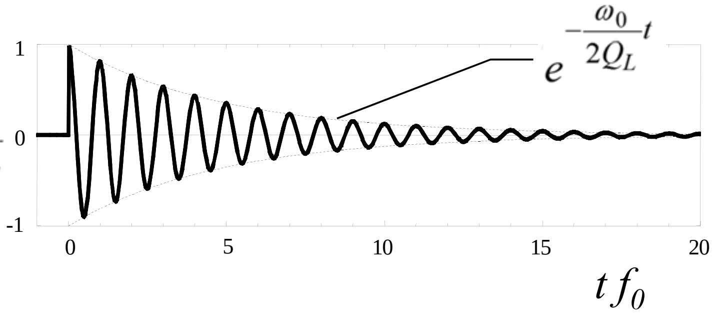
$$k_{loss} = \frac{\omega_0}{2}\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{4W} = \frac{1}{2C}$$



Energy deposited by a single charge *q*: $k_{loss}\, q^2$

Voltage induced by a single charge *q:*

$$\frac{V_{gap}}{2\,k_{loss}\,q}$$



Summary: relations V_{gap}, W, P_{loss}

R*-upon-*Q

gap voltage V_{gap}

Shunt impedance

$$\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{2\,\omega_0 W}$$

$$R_{shunt} = \frac{\left|V_{gap}\right|^2}{2\,P_{loss}}$$

$$k_{loss} = \frac{\omega_0}{2}\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{4\,W}$$

Energy stored inside the cavity W

Power lost in the cavity walls P_{loss}

$$Q = \frac{\omega_0 W}{P_{loss}}$$

***Q* factor**

Beam loading – RF to beam efficiency

- The beam current "loads" the generator, in the equivalent circuit this appears as a resistance in parallel to the shunt impedance.
- If the generator is matched to the unloaded cavity, beam loading will cause the accelerating voltage to decrease.
- The power absorbed by the beam is $-\frac{1}{2}\mathrm{Re}\left\{V_{gap}\ I_B^*\right\}$, the power loss $P = \frac{\left|V_{gap}\right|^2}{2\,R}$.
- For high efficiency, beam loading shall be high.
- The RF to beam efficiency is $\eta = \frac{1}{1+\frac{V_{gap}}{R\left|I_B\right|}} = \frac{\left|I_B\right|}{\left|I_G\right|}$.

Characterizing cavities

- Resonance frequency $\omega_0 = \frac{1}{\sqrt{L \cdot C}}$
- Transit time factor $\frac{\left|\int E_z e^{\mathrm{j}\frac{\omega}{c}z}\mathrm{d}z\right|}{\left|\int E_z \mathrm{d}z\right|}$
  - field varies while particle is traversing the gap

	Circuit definition	Linac definition
Shunt impedance gap voltage – power relation	$\left|V_{gap}\right|^2 = 2\,R_{shunt}\,P_{loss}$	$\left|V_{gap}\right|^2 = R_{shunt}\,P_{loss}$
Q factor	$\omega_0 W = Q P_{loss}$	
R/Q independent of losses – only geometry!	$\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{2\,\omega_0 W} = \sqrt{\frac{L}{C}}$	$\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{\omega_0 W}$
loss factor	$k_{loss} = \frac{\omega_0}{2}\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{4\,W}$	$k_{loss} = \frac{\omega_0}{4}\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{4\,W}$

Example Pillbox:

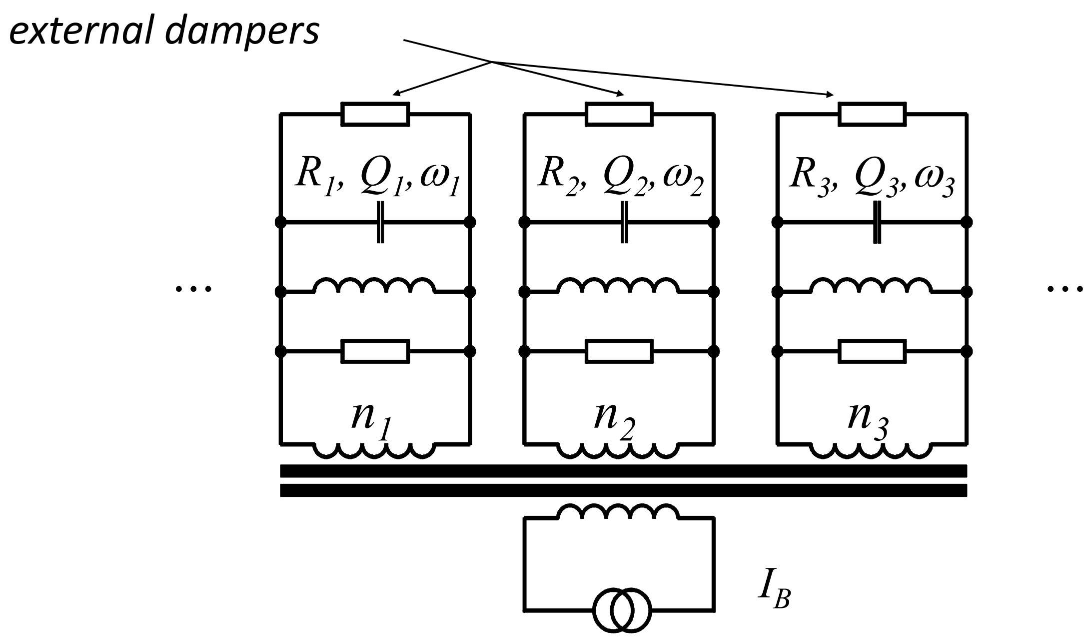
$$\omega_0\big|_{pillbox} = \frac{\chi_{01}\, c}{a} \qquad \chi_{01} = 2.4048$$

$$\eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\,\Omega$$

$$Q\big|_{pillbox} = \frac{\sqrt{2a\eta\sigma\chi_{01}}}{2\left(1+\frac{a}{h}\right)} \qquad \sigma_{\mathrm{Cu}} = 5.8\cdot10^{7}\,\mathrm{S/m}$$

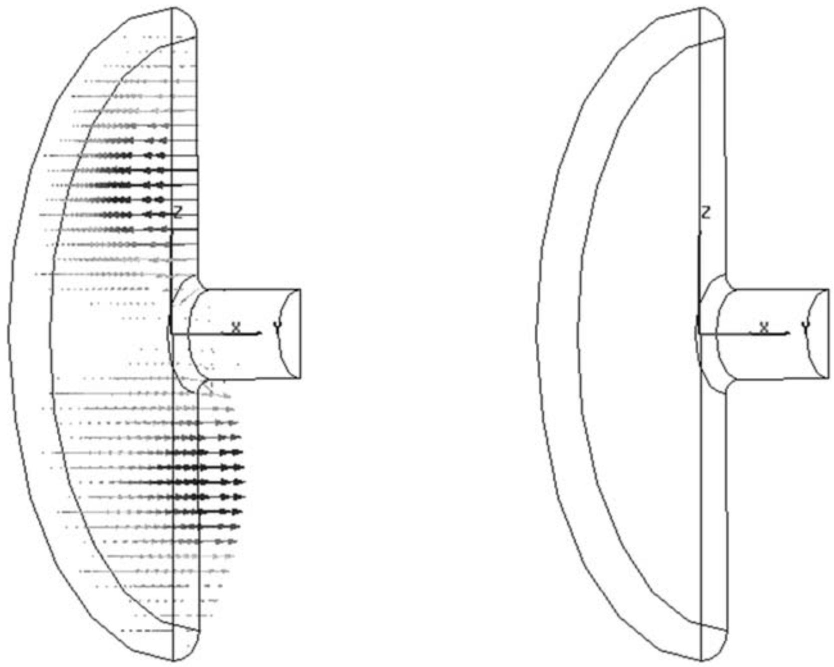
$$\left.\frac{R}{Q}\right|_{pillbox} = \frac{4\eta}{{\chi_{01}}^{3}\pi\, \mathrm{J}_1^2(\chi_{01})}\,\frac{\sin^2\left(\frac{\chi_{01}}{2}\frac{h}{a}\right)}{h/a}$$

Higher order modes



Pillbox: dipole mode

TM_{110}-mode (only 1/4 shown)



electric field magnetic field

Panofsky-Wenzel theorem

For particles moving virtually at *v=c*, the integrated transverse force (kick) can be determined from the transverse variation of the integrated longitudinal force!

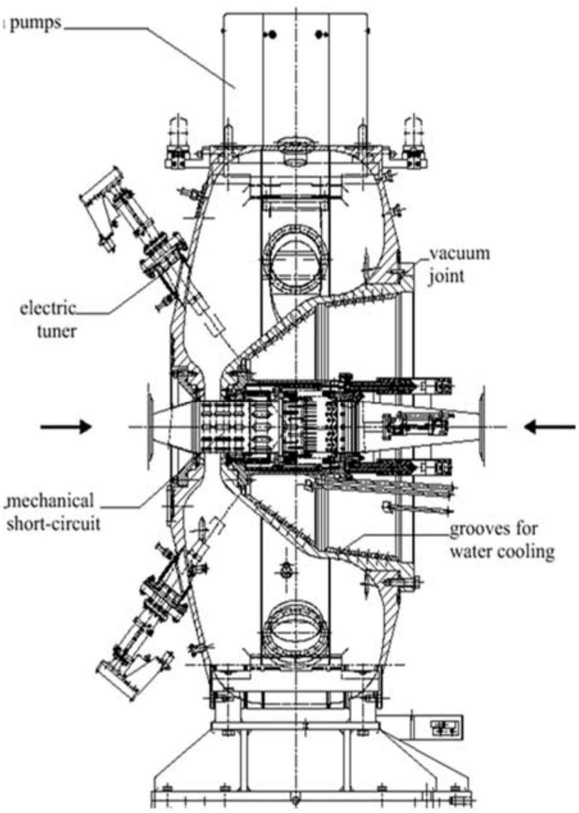
$$\mathrm{j}\frac{\omega}{c}\vec{F}_{\perp} = \nabla_{\perp} F_{\parallel}$$

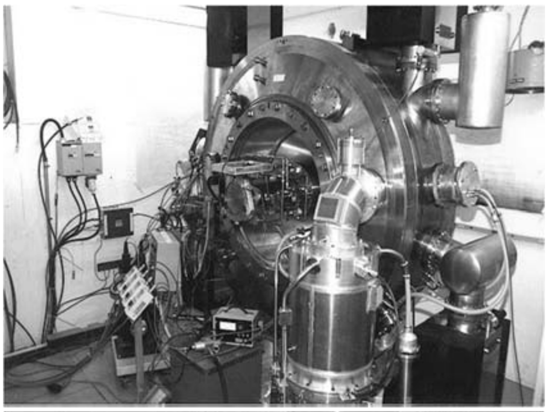
Pure TE modes: No net transverse force !

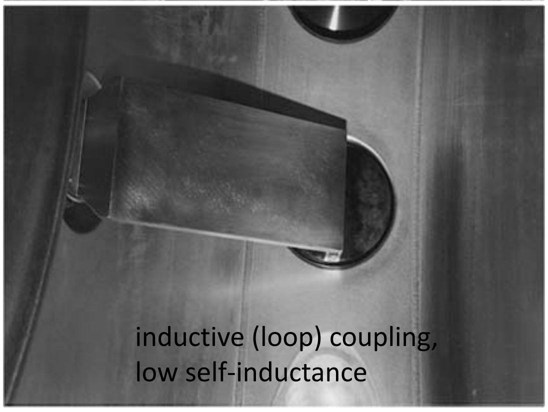
Transverse modes are characterized by
- the transverse impedance in ***ω***-domain
- the transverse loss factor (kick factor) in ***t***-domain !

W.K.H. Panofsky, W.A. Wenzel: “Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields”, RSI **27**, 1957]

CERN/PS 80 MHz cavity (for LHC)





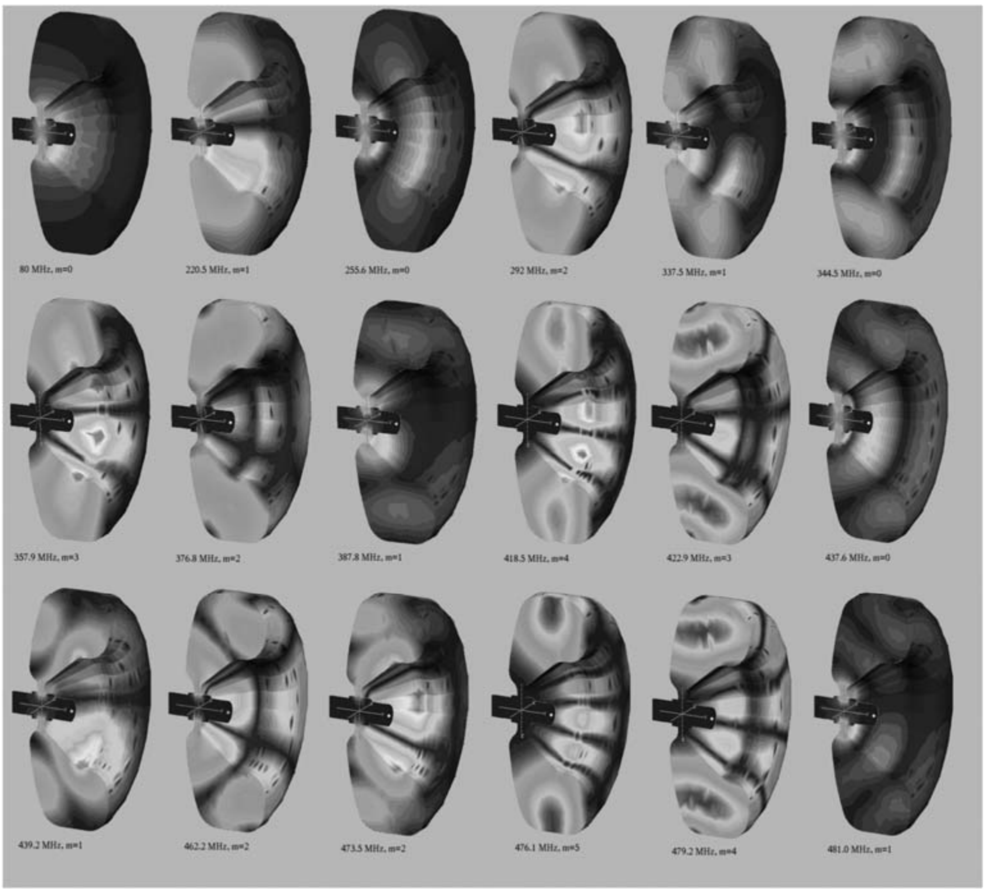


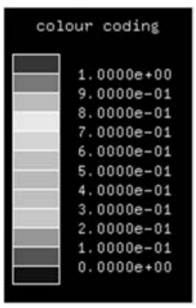
Higher order modes

Example shown: 80 MHz cavity PS for LHC.

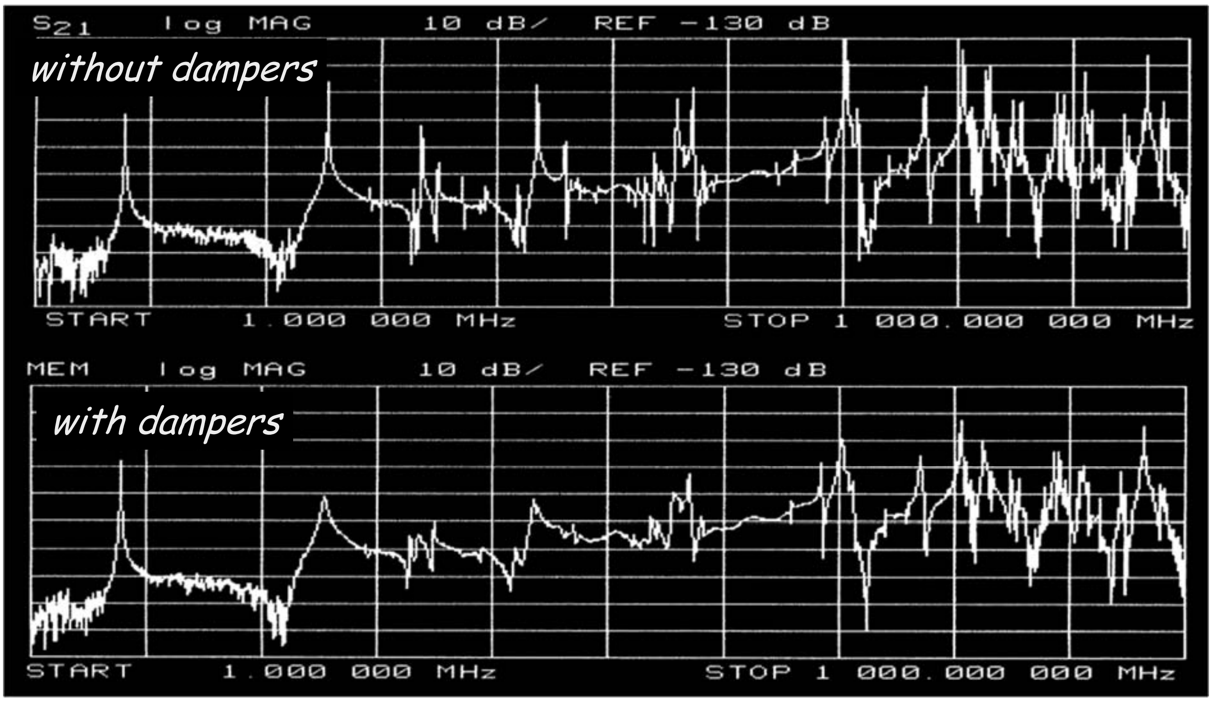
Color-coded:

$$\left|\vec{E}\right|$$





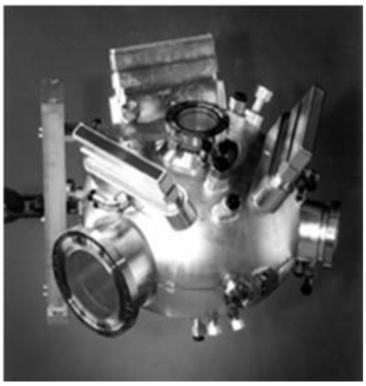
Higher order modes (measured spectrum)



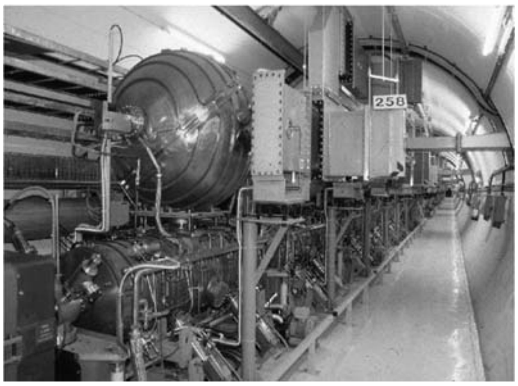
MORE EXAMPLES OF CAVITIES

PS 19 MHz cavity (prototype, photo: 1966)

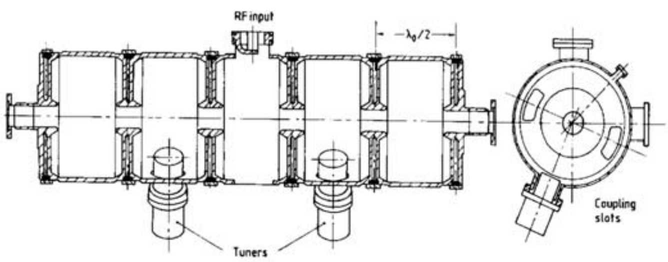
Examples of cavities



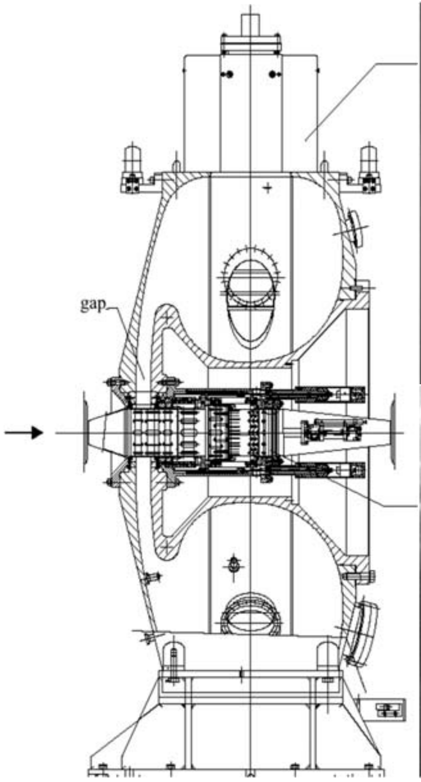
PEP II cavity
476 MHz, single cell,
1 MV gap with 150 kW,
strong HOM damping,

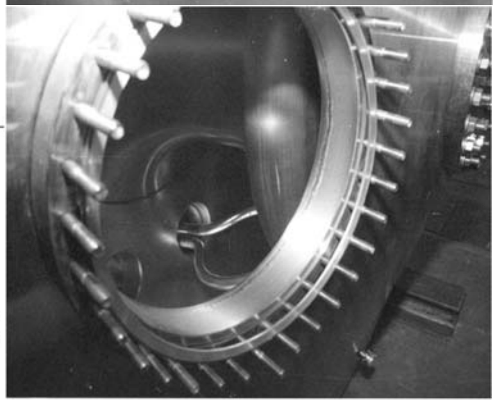


LEP normal-conducting Cu RF cavities,
350 MHz. 5 cell standing wave + spherical cavity
for energy storage, 3 MV



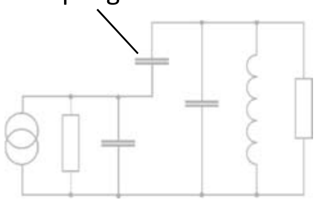
CERN/PS 40 MHz cavity (for LHC)





example for
capacitive coupling

coupling C



cavity

RF POWER SOURCES

RF Power sources

> 200 MHz: Klystrons

Thales TH1801, Multi-Beam Klystron (MBK), 1.3 GHz, 117 kV. Achieved:
48 dB gain, 10 MW peak, 150 kW average, η = 65 %

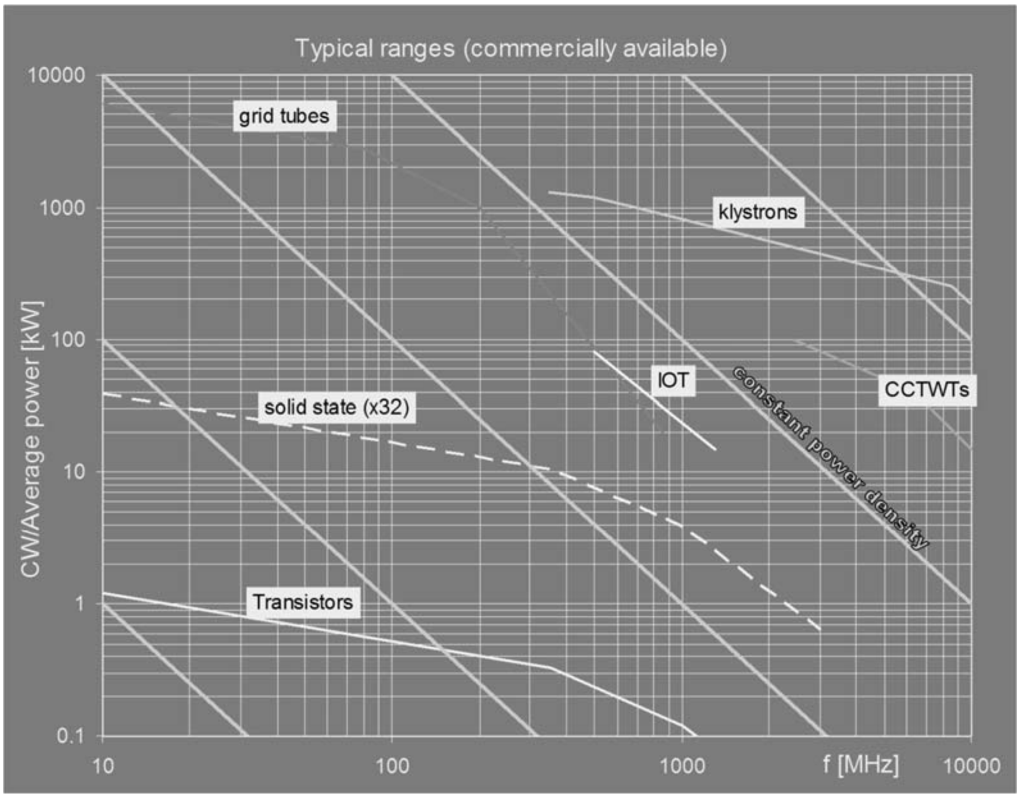
48 dB: $\frac{output\ power}{input\ power} = 10^{4.8}$

< 1000 MHz: grid tubes

pictures from http://www.thales-electrondevices.com

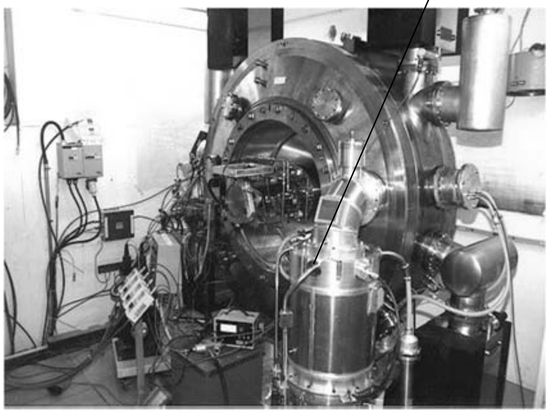
Tetrode IOT UHF Diacrode®

RF power sources



Example of a tetrode amplifier (80 MHz, CERN/PS)

400 kW, with fast RF feedback



18 Ω coaxial output (towards cavity)

22 kV DC anode voltage feed-through with $\lambda/4$ stub

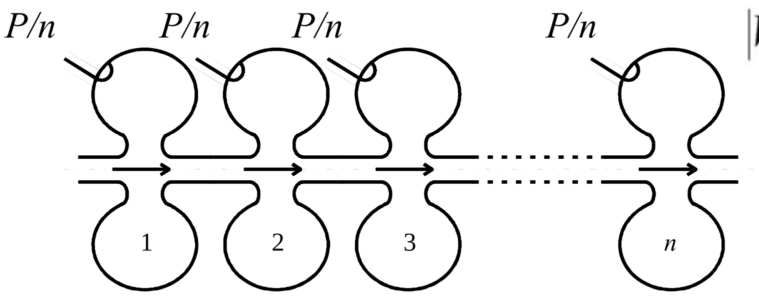
tetrode cooling water feed-throughs

coaxial input matching circuit

MANY GAPS

What do you gain with many gaps?

- The *R/Q* of a single gap cavity is limited to some 100 Ω.
  Now consider to distribute the available power to *n* identical cavities: each will receive *P/n*, thus produce an accelerating voltage of $\sqrt{2R\,P/n}$.
  The total accelerating voltage thus increased, equivalent to a total equivalent shunt impedance of nR.

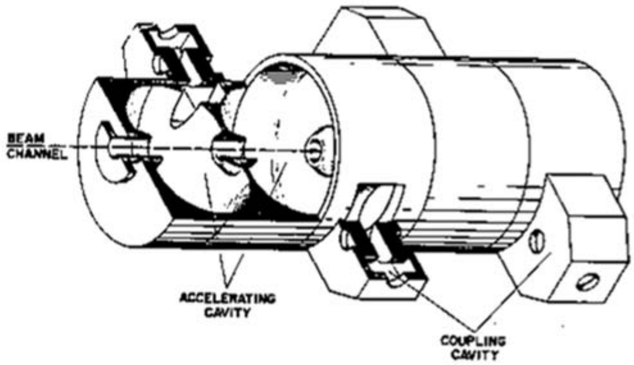


$$|V_{acc}| = n\sqrt{2R\frac{P}{n}} = \sqrt{2(nR)P}$$

Standing wave multicell cavity

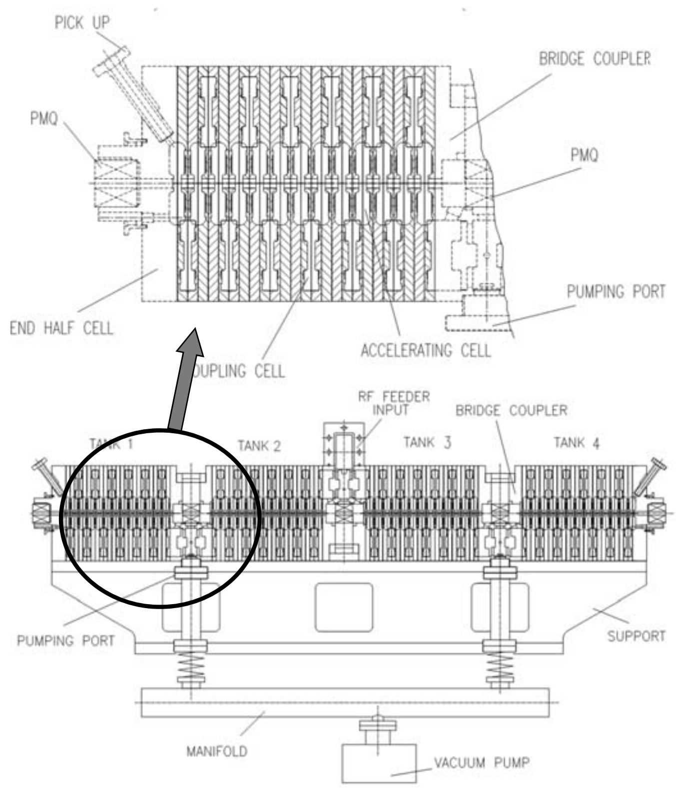
- Instead of distributing the power from the amplifier, one might as well couple the cavities, such that the power automatically distributes, or have a cavity with many gaps (e.g. drift tube linac).

- Coupled cavity accelerating structure (side coupled)



- The phase relation between gaps is important!

Example of Side Coupled Structure



LIBO (= Linac Booster)

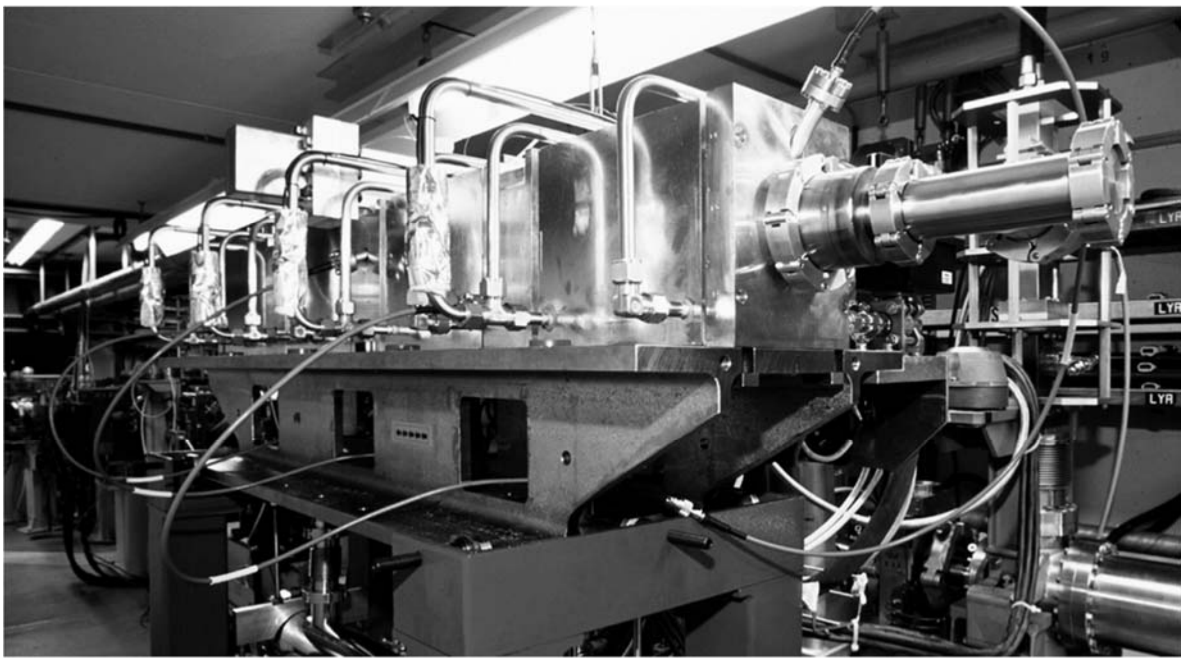
A 3 GHz Side Coupled Structure to accelerate protons out of cyclotrons from 62 MeV to 200 MeV

Medical application: treatment of tumours (proton therapy)

Prototype of Module 1 built at CERN (2000)

Collaboration CERN/INFN/TERA Foundation

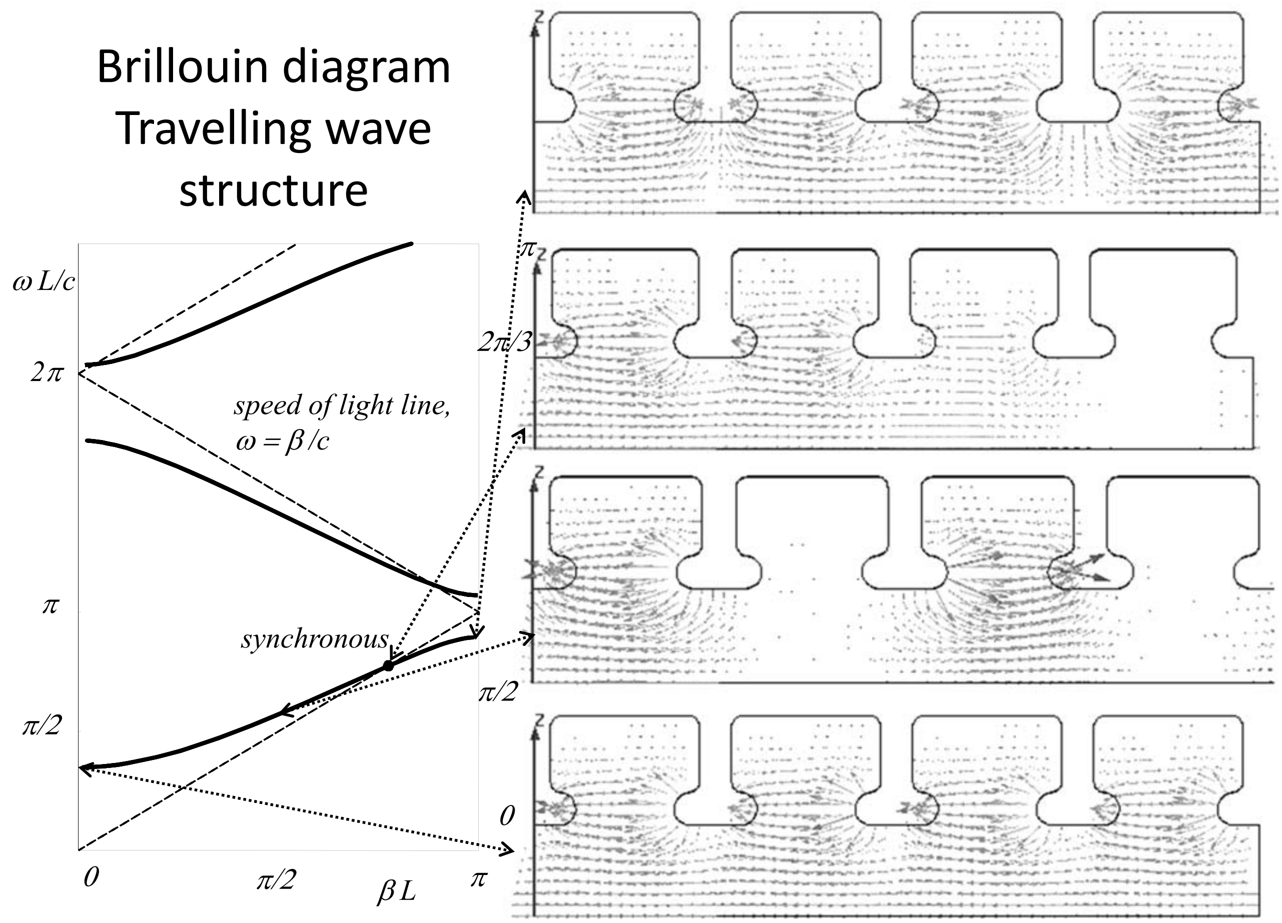
LIBO prototype



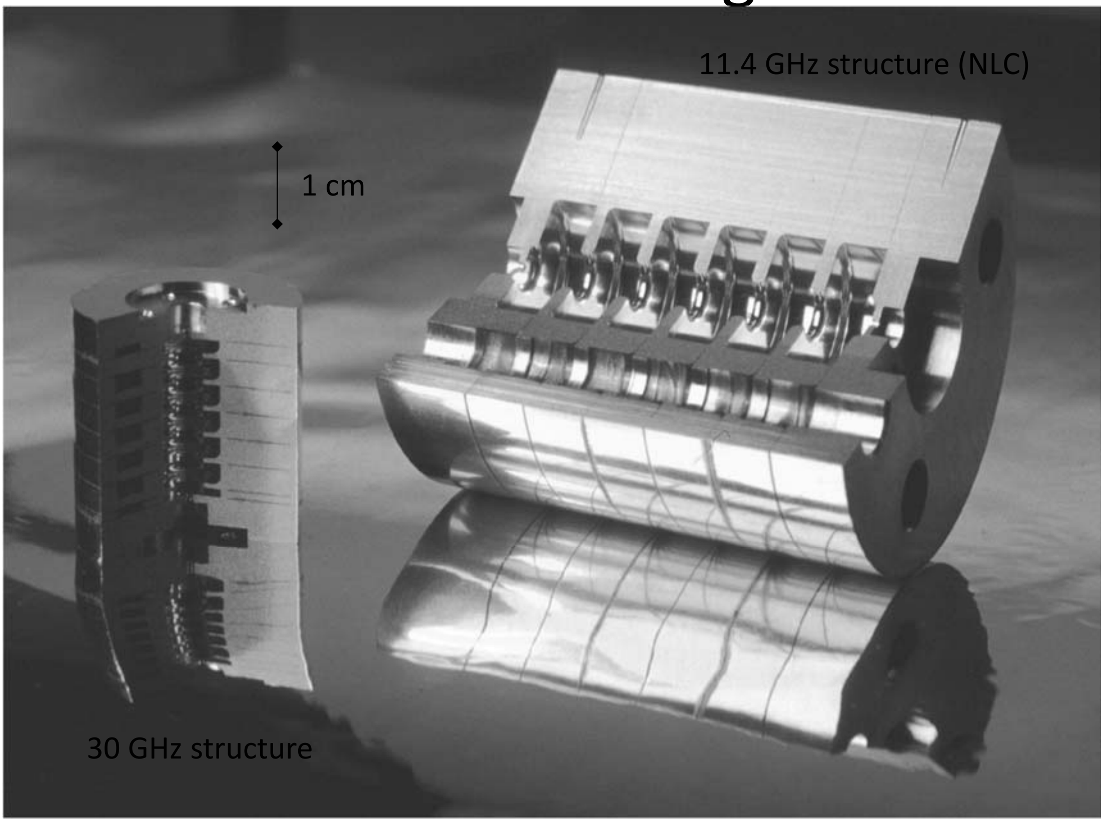
This Picture made it to the title page of CERN Courier vol. 41 No. 1 (Jan./Feb. 2001)

TRAVELLING WAVE STRUCTURES

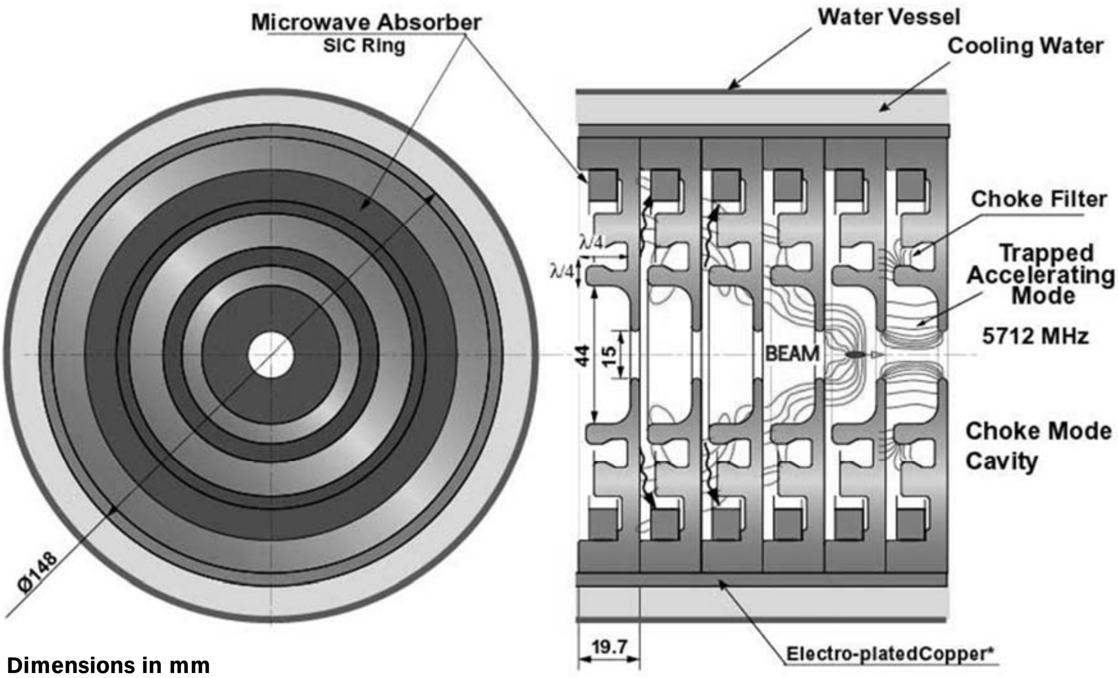
Brillouin diagram Travelling wave structure



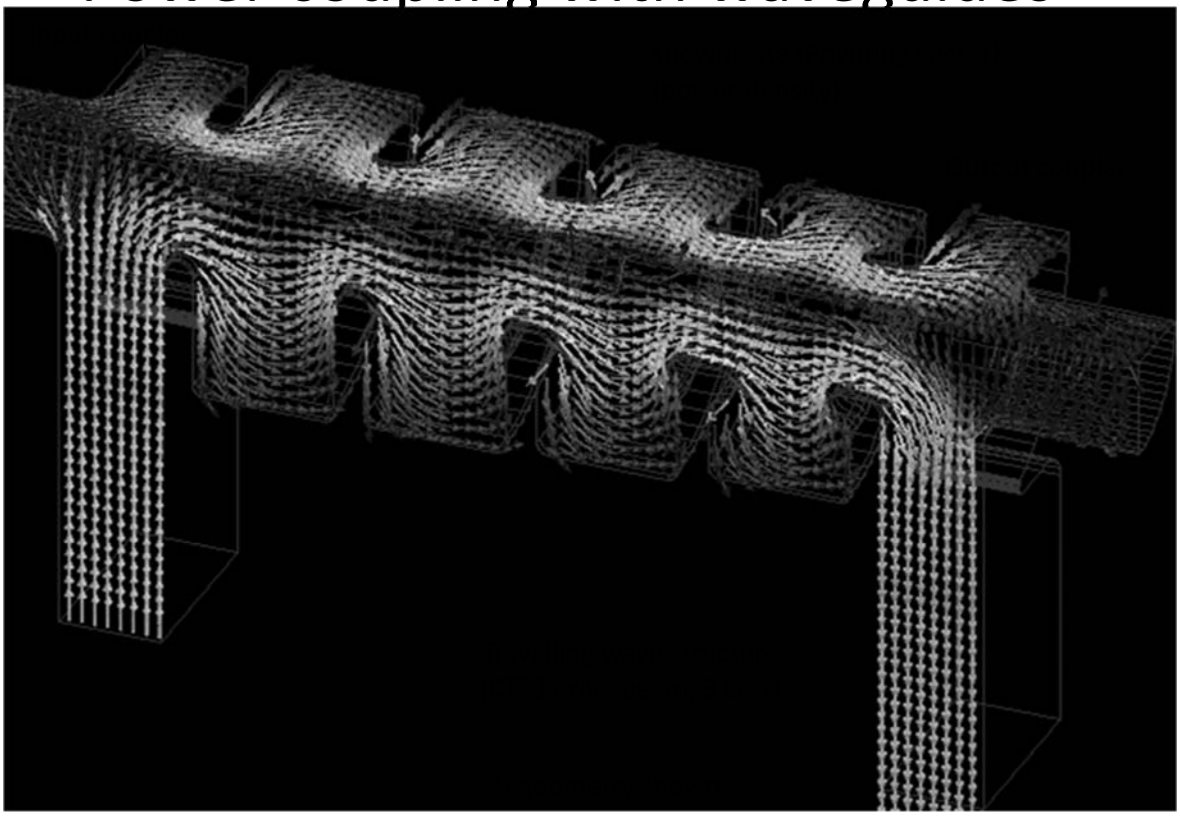
Iris loaded waveguide



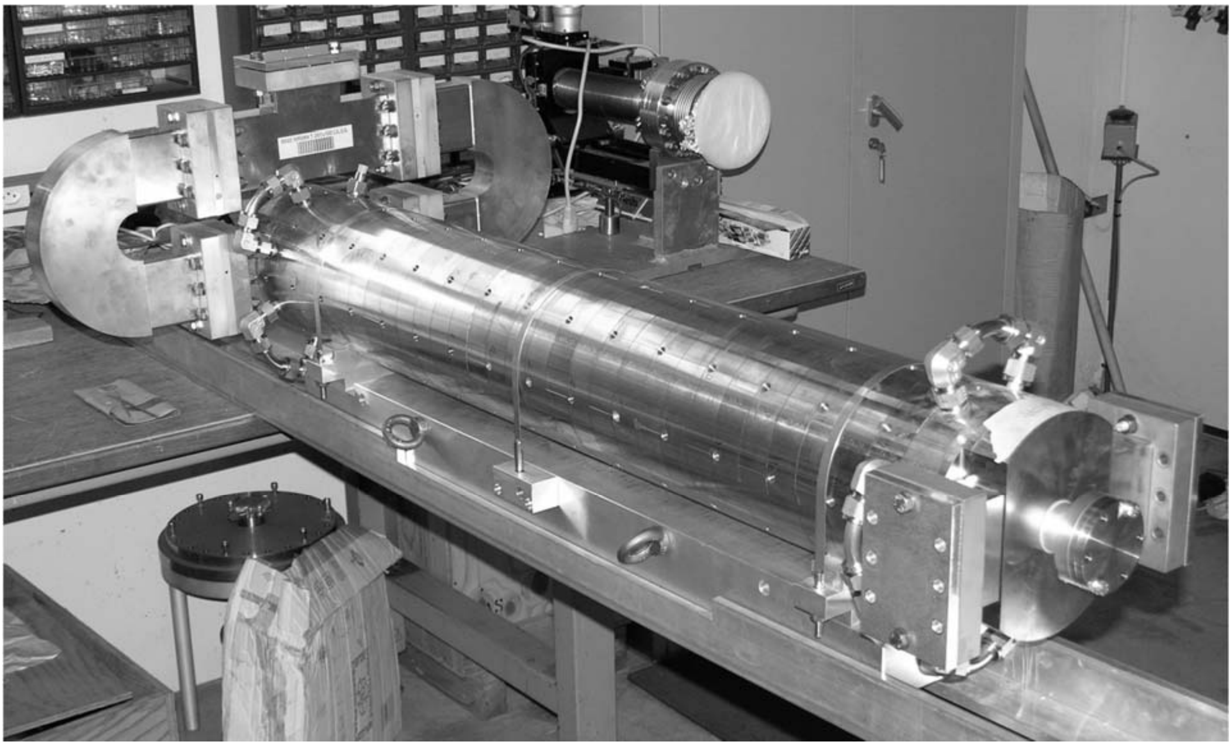
Disc loaded structure with strong HOM damping "choke mode cavity"



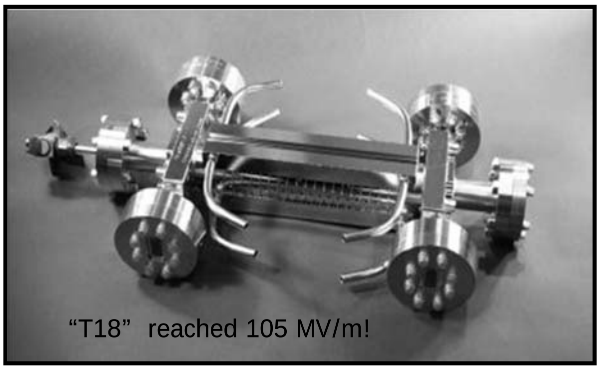
Power coupling with waveguides

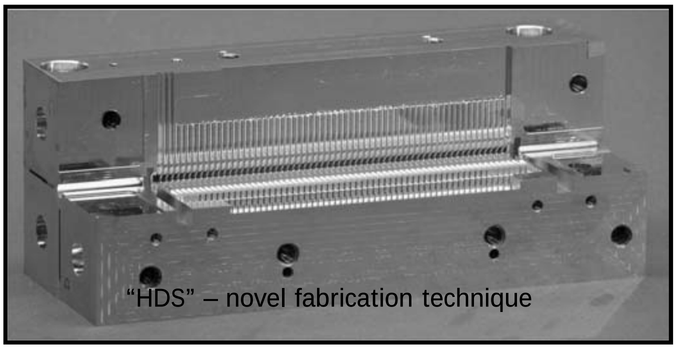


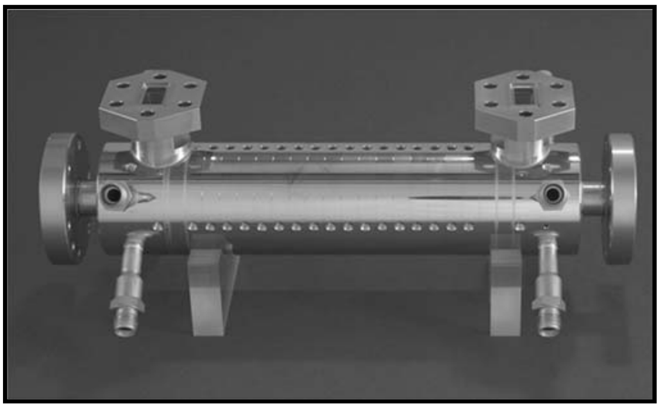
3 GHz Accelerating structure (CTF3)

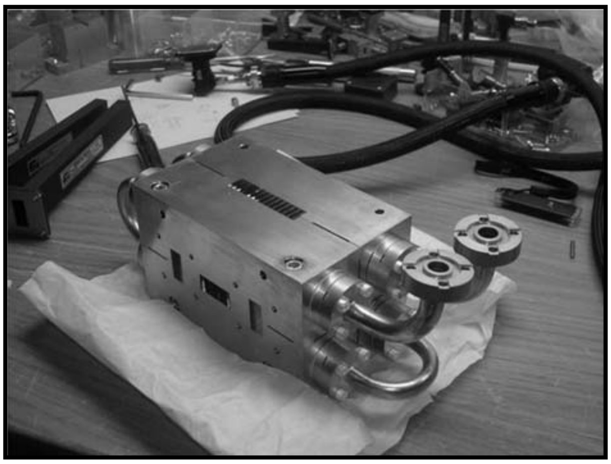


Examples (CLIC structures @ 11.4, 12 and 30 GHz)





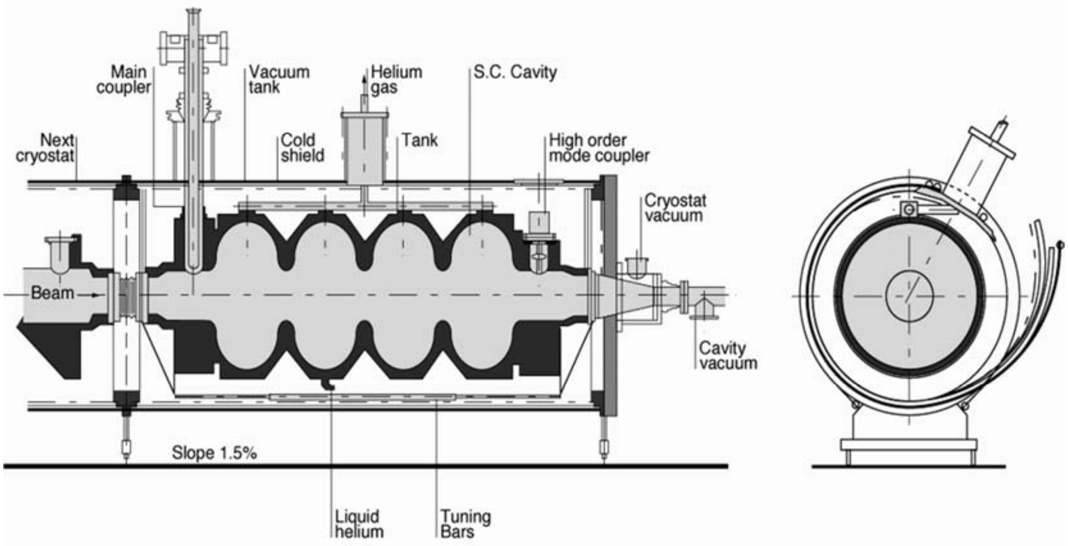




SUPERCONDUCTING ACCELERATING STRUCTURES

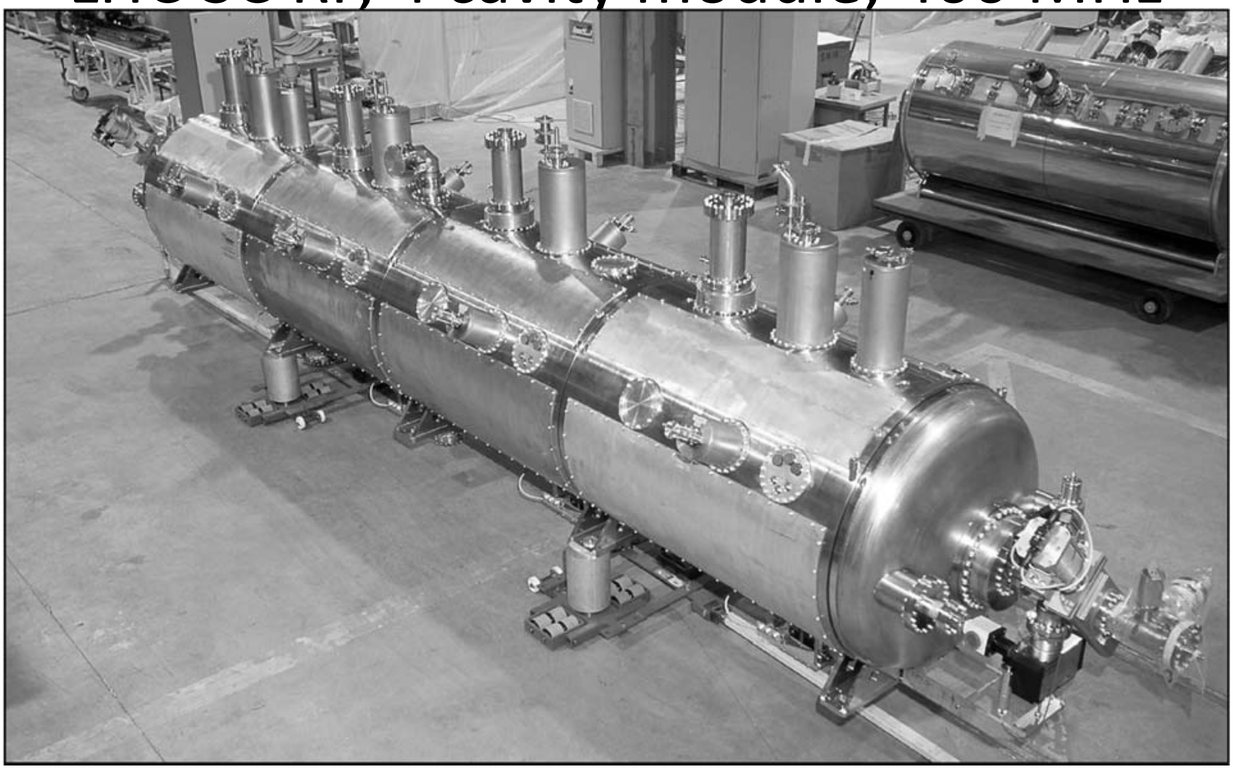
LEP Superconducting cavities

SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT

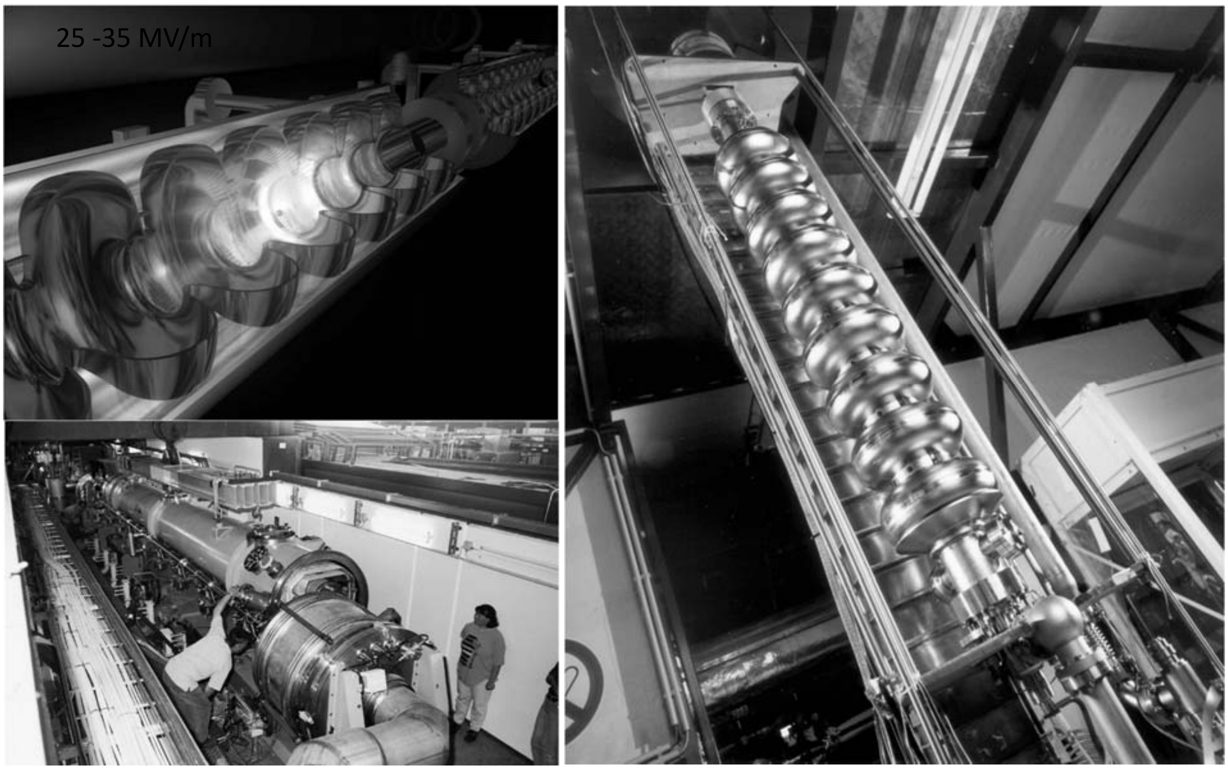


10.2 MV/ per cavity

LHC SC RF, 4 cavity module, 400 MHz

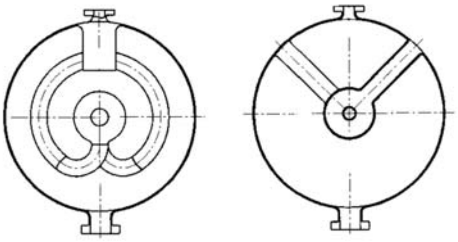


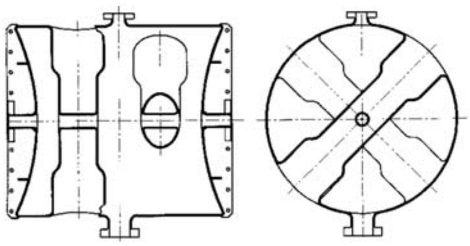
ILC high gradient SC structures at 1.3 GHz



Small β superconducting cavities (example RIA, Argonne)

115 MHz split-ring cavity, 172.5 MHz β = 0.19 "lollipop" cavity



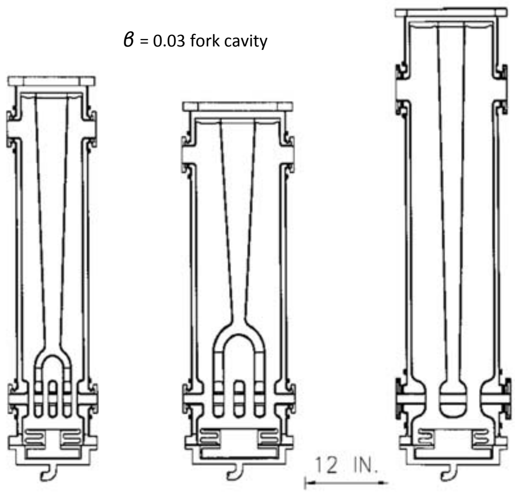


345 MHz β = 0.4 spoke cavity

57.5 MHz cavities:

β= 0.06 QWR
(quarter wave resonator)

β = 0.03 fork cavity



β = 0.021 fork cavity

pictures from Shepard et al.: "Superconducting accelerating structures for a multi-beam driver linac for RIA", Linac 2000, Monterey