RF Cavity Design

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CERN Accelerator School
Accelerator Physics (Advanced level)
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Overview

- DC versus RF
  - Basic equations: Lorentz & Maxwell, choice of frequency, RF breakdown, breakdown rate
- Some theory: from waveguide to pillbox
  - rectangular waveguide, waveguide dispersion, group and phase velocity, modes, equations, standing waves … waveguide resonators, round waveguides, Pillbox cavity
- Accelerating gap
  - Principle, ferrite cavity, Finemet® 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),
- Many gaps
  - Why?
  - Example: side coupled linac, LIBO
- Travelling wave structures
  - Brillouin diagram, iris loaded structure, waveguide coupling
- Superconducting Accelerating Structures
  - RF superconductivity, elliptical multi-cell cavity, low-β geometries, cryomodule
- Cavity fabrication techniques
  - Materials (Cu, Nb)
  - Forming techniques
  - joining techniques
  - Specific techniques developed for SCRF

DC VERSUS RF

DC versus RF

DC accelerator

RF accelerator

Lorentz force

- A charged particle moving with velocity $\vec{v} = \frac{\vec{p}}{m\,\gamma}$ through an electromagnetic field experiences a force $\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$.
- The total energy of this particle is $W = \sqrt{(mc^2)^2 + (pc)^2} = \gamma\, mc^2$, the kinetic energy is $W_{kin} = mc^2(\gamma - 1)$.
- The role of acceleration is to increase W.
- Change of W (by differentiation):

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

$$dW = q\vec{v} \cdot \vec{E}dt$$

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

Maxwell's equations (in vacuum)

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

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

1. Why not DC?

   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:

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

Maxwell's equations in vacuum (contd.)

Source-free:

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

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

curl (rot, $\nabla \times$) of 3rd equation and $\frac{\partial}{\partial t}$ of 1st equation:

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

Using the vector identity $\nabla \times \nabla \times \vec{E} = \nabla\nabla \cdot \vec{E} - \Delta\vec{E}$ and the 4th Maxwell equation, this yields:

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

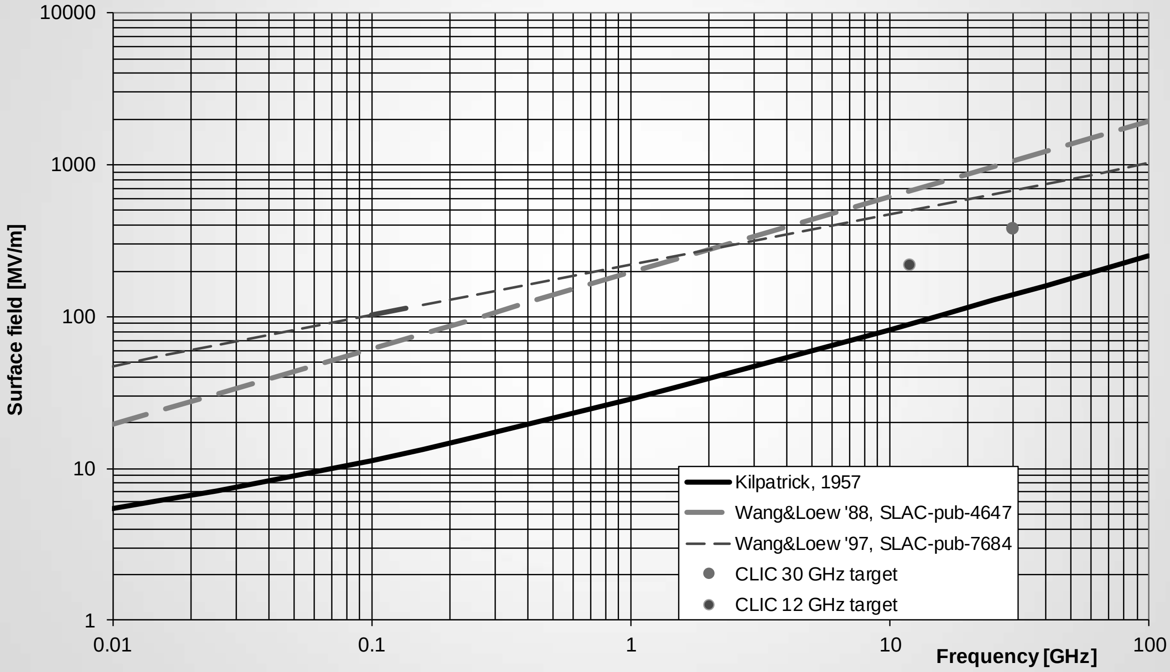
i.e. the 4-dimensional Laplace equation.

Choice of frequency

- Size:
  - Linear dimensions scale as f^{-1}, volume as f^{-3}.
  - amount of material, mass, stiffness, tolerances, …
  - Outer radius of elliptical cavity $\sim 0.45\,\lambda$.
- Beam interaction:
  - r/Q increases with f – but also for HOMs!
  - short bunches are easier with higher f.
- Technology:
  - superconducting: BCS resistance $\propto f^2$.
  - Power sources available?
  - Max. accelerating voltage?

Breakdown limit – f-dependence

surface field, in vacuum, Cu surface, room temperature

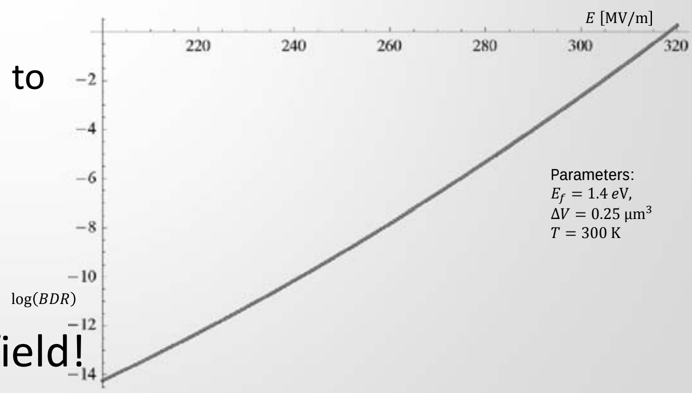


Note: More recent experimental data show much less f-dependence!

E.g.: http://prl.aps.org/abstract/PRL/v90/i22/e224801

Breakdown rate!

- In an accelerator with many structures, the breakdown rate (BDR) must be much smaller than the number of structures.
- E.g.: CLIC target $3 \cdot 10^{-7}\mathrm{m}^{-1}$(results in 1% for 30 km)
- Empirically, the breakdown rate can be described with the dependence $BDR \sim e^{\frac{\varepsilon_0 E^2 \Delta V - E_f}{k_b T}}$, where
  - E_f: **formation energy** required to form a dislocation (void),
  - ΔV: the volume change due to the dislocation.
- This is a very steep dependence on the surface field!



FROM WAVEGUIDE TO PILLBOX

Homogeneous plane wave

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

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

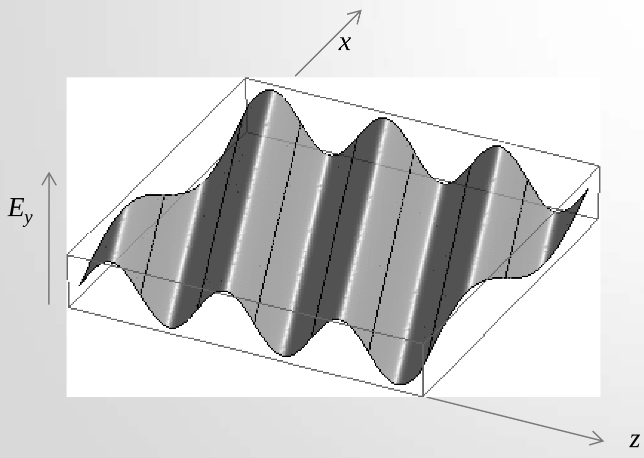
$\vec{k} \cdot \vec{r} = \frac{\omega}{c}(z \cos\varphi + x \sin\varphi)$

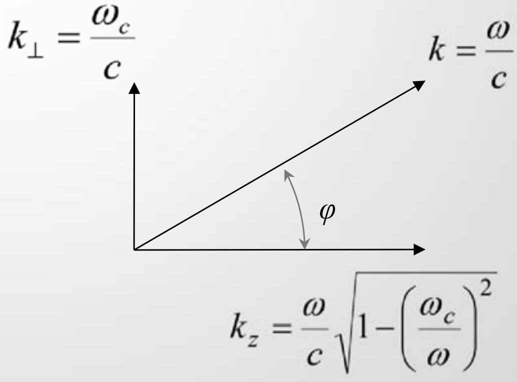
Wave vector $\vec{k}$:

the direction of $\vec{k}$ is the direction of propagation,

the length of $\vec{k}$ is the phase shift per unit length.

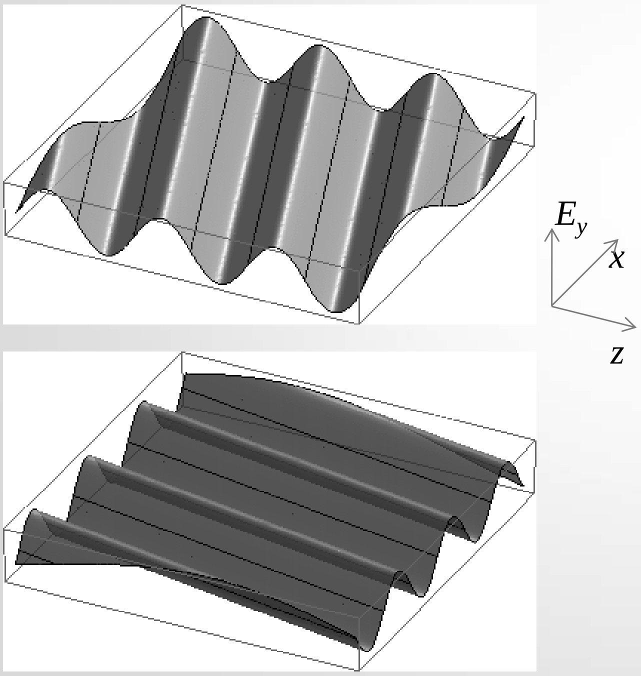
$\vec{k}$ behaves like a vector.

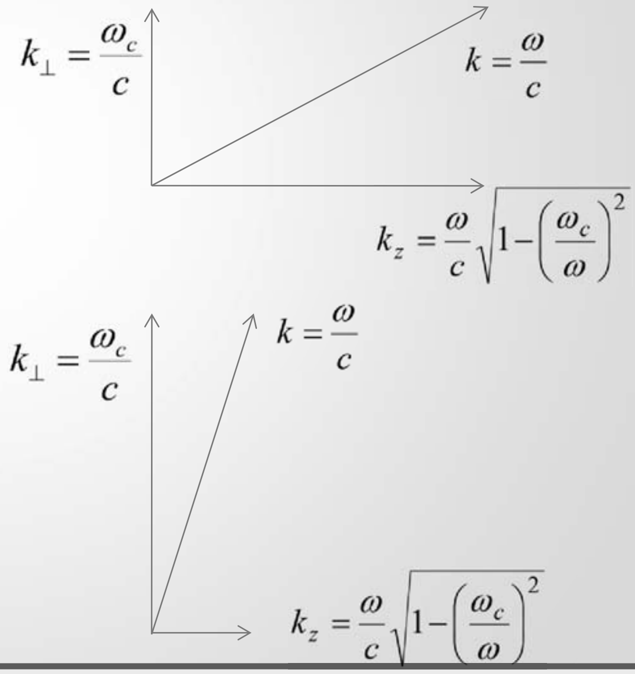




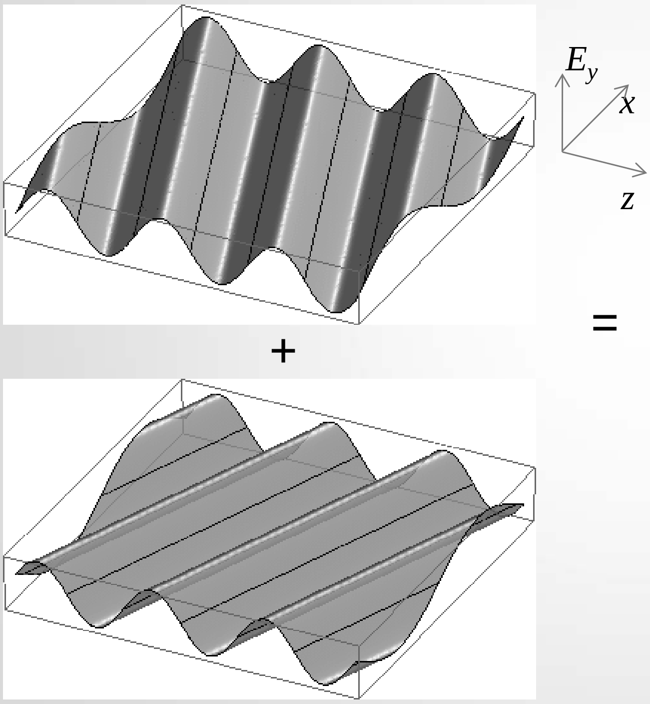
Wave length, phase velocity

- 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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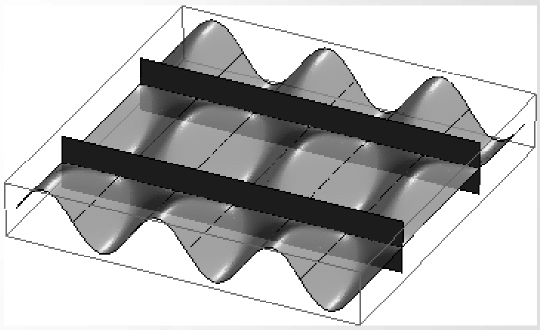


Metallic walls may be inserted where $E_y \equiv 0$

without perturbing the fields.

Note the standing wave in x-direction!

This way one gets a hollow rectangular waveguide

Rectangular waveguide

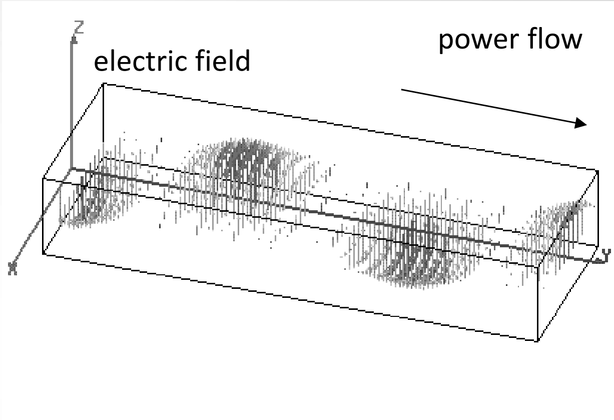
Fundamental (TE_{10} or H_{10}) mode
in a standard rectangular waveguide.

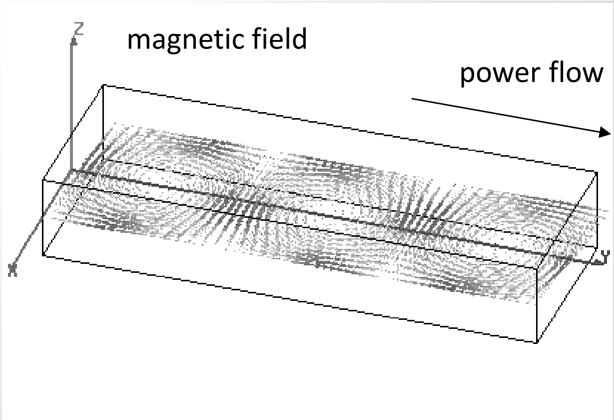
Example: "S-band" : 2.6 GHz ... 3.95 GHz,

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

Operated at $f = 3$ GHz.

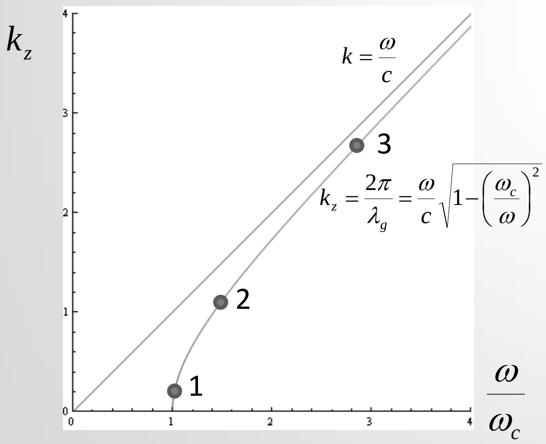
power flow: $\frac{1}{2}\mathrm{Re}\left\{\iint \vec{E} \times \vec{H}^* \cdot \mathrm{d}\vec{A}\right\}$



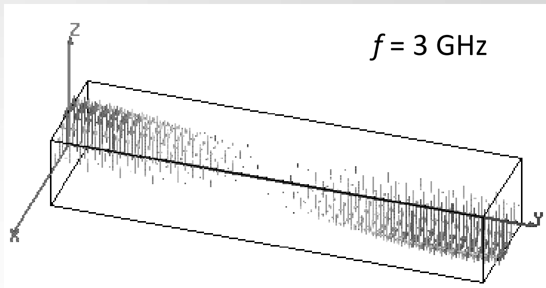


Waveguide dispersion

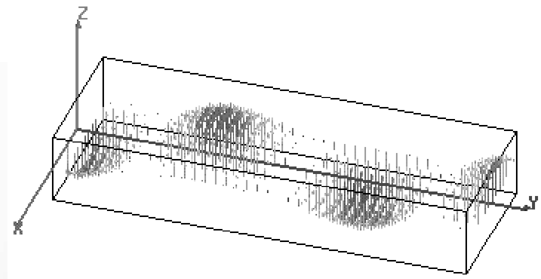
What happens with different waveguide dimensions (different width a)?



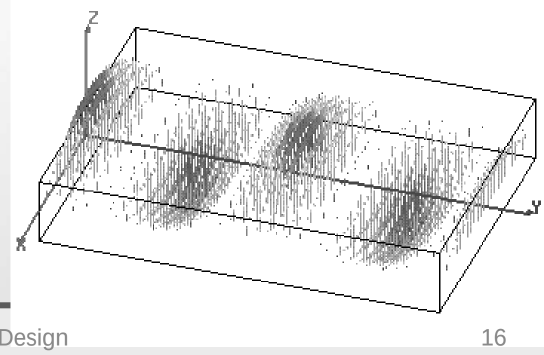
cutoff $f_c = \frac{c}{2a}$



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



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

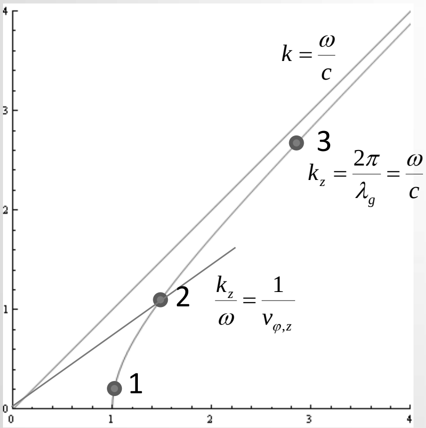


3:
a = 144.3 mm,
f/f_c = 2.88

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 $f \to \infty$, $v_{\varphi,z} \to c$!

k_z



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

$k_z = \frac{2\pi}{\lambda_g} = \frac{\omega}{c}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2} = \frac{\omega}{v_{\varphi,z}}$

$\frac{k_z}{\omega} = \frac{1}{v_{\varphi,z}}$

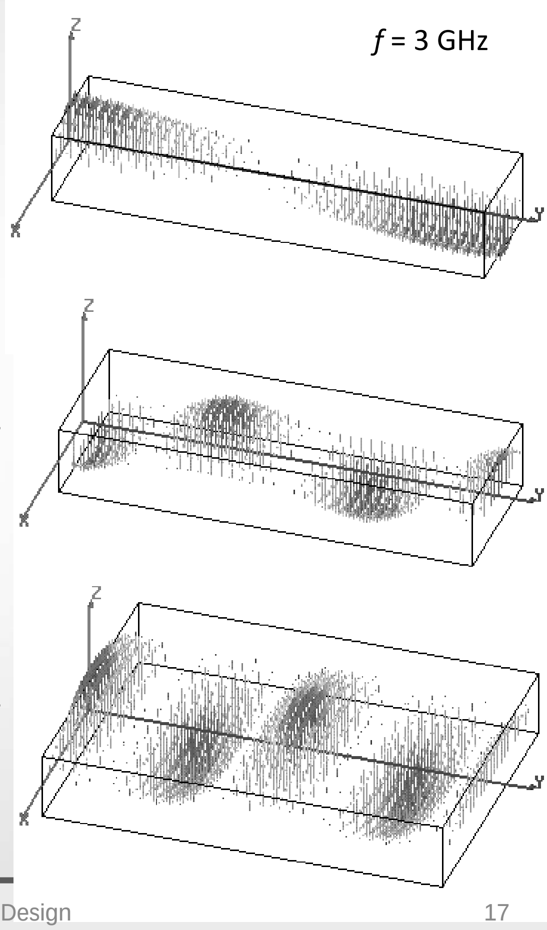
$\frac{\omega}{\omega_c}$

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

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



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:

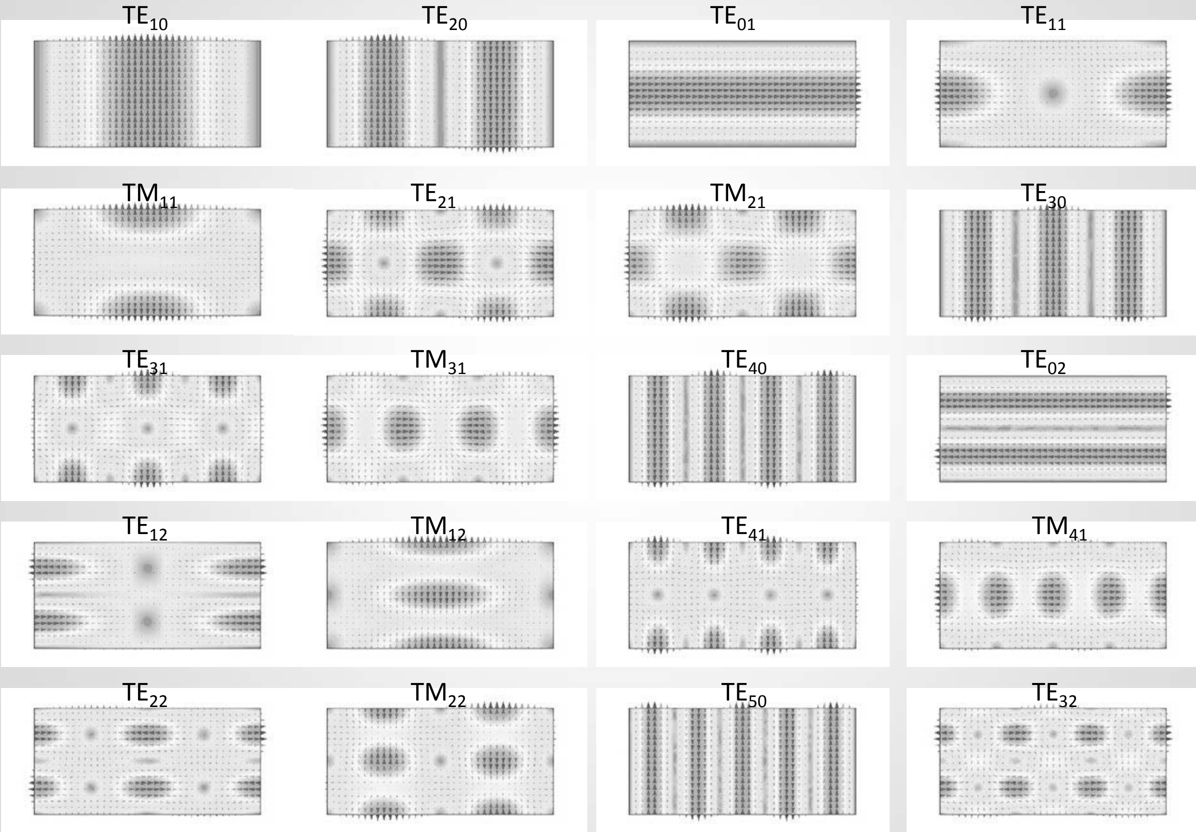
$$\gamma = \mathrm{j}\sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{\pi}{a}\right)^2}$$

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

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

In a hollow waveguide: phase velocity > c, group velocity < c

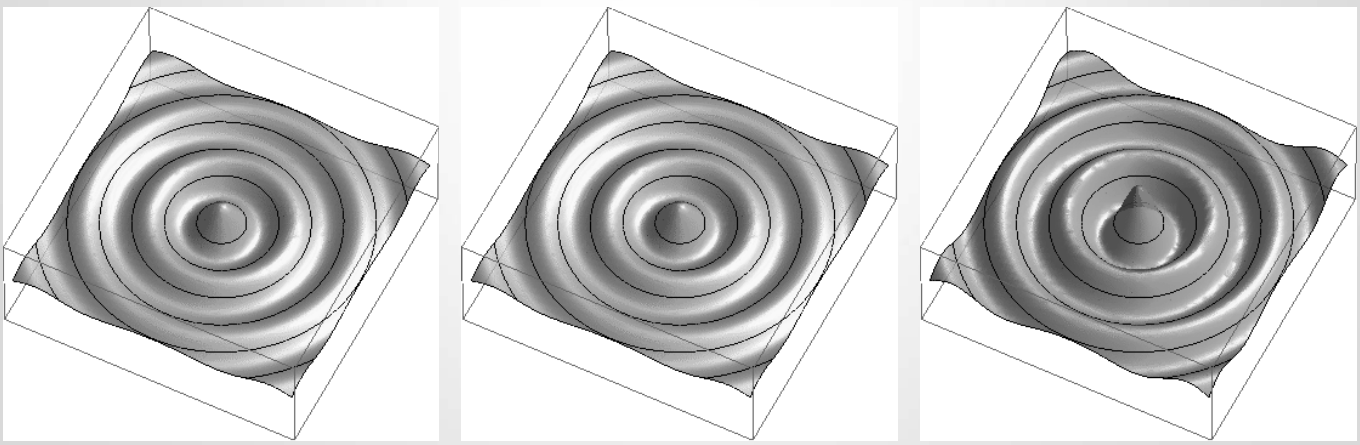
Rectangular waveguide modes



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.



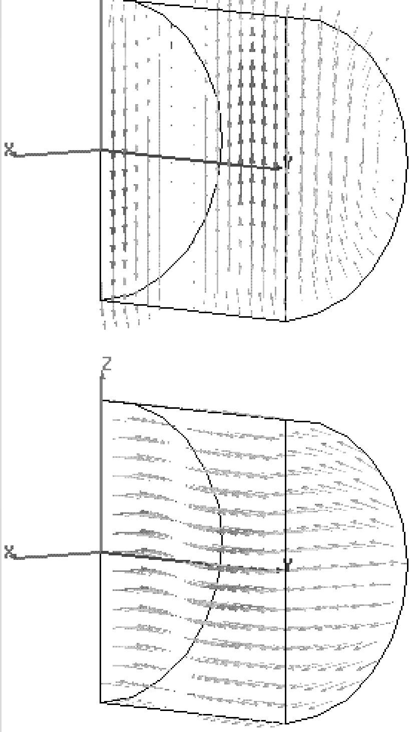
$E_z \propto H_n^{(2)}(k_\rho \rho)\cos(n\varphi)$ $E_z \propto H_n^{(1)}(k_\rho \rho)\cos(n\varphi)$ $E_z \propto J_n(k_\rho \rho)\cos(n\varphi)$

Round waveguide

$f/f_c = 1.44$

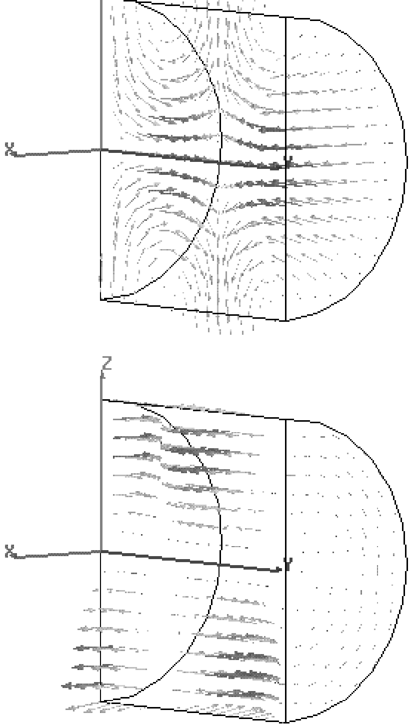
TE$_{11}$ – fundamental

$$\frac{f_c}{\text{GHz}} = \frac{87.9}{a/\text{mm}}$$



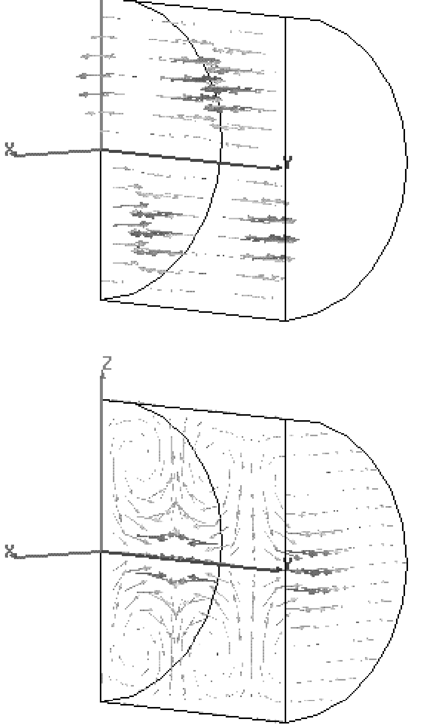
TM$_{01}$ – axial field

$$\frac{f_c}{\text{GHz}} = \frac{114.8}{a/\text{mm}}$$

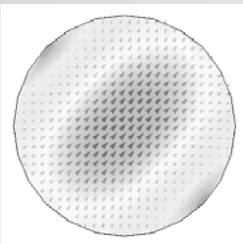


TE$_{01}$ – low loss

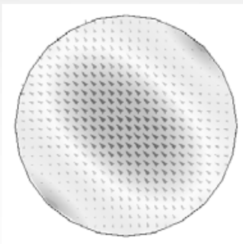
$$\frac{f_c}{\text{GHz}} = \frac{182.9}{a/\text{mm}}$$



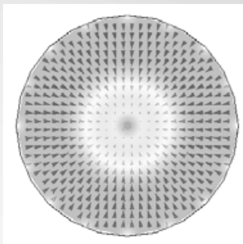
Circular waveguide modes



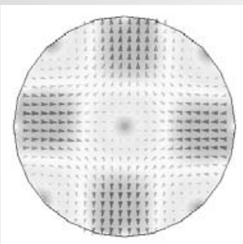
TE$_{11}$



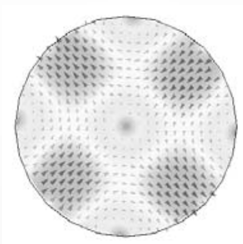
TE$_{11}$



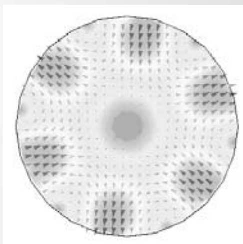
TM$_{01}$



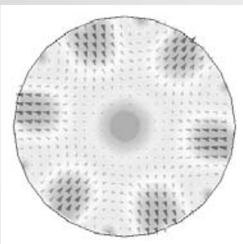
TE$_{21}$



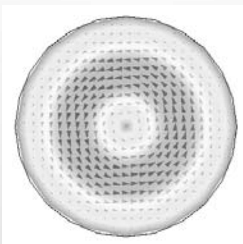
TE$_{21}$



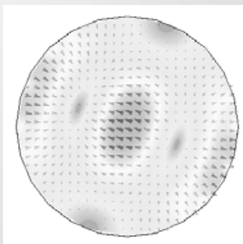
TE$_{31}$



TE$_{31}$



TE$_{01}$



TM$_{11}$

plotted: *E*-field

General waveguide equations:

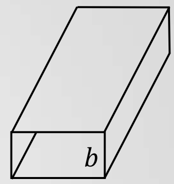
Transverse wave equation (membrane equation): $\Delta T + \left(\frac{\omega_c}{c}\right)^2 = 0.$

	TE (or H-) modes	***TM (or E-) modes***
Boundary condition:	$\vec{n} \cdot \nabla T = 0$	$T = 0$
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:	$\gamma = \mathrm{j}\frac{\omega}{c}\sqrt{1 - \left(\frac{\omega_c}{\omega}\right)^2}$	
Characteristic impedance:	$Z_0 = \frac{\mathrm{j}\omega\mu}{\gamma}$	$Z_0 = \frac{\gamma}{\mathrm{j}\omega\varepsilon}$
Ortho-normal eigenvectors:	$\vec{e} = \vec{u}_z \times \nabla T$	$\vec{e} = -\nabla T$
Transverse fields:	$\vec{E} = U(z)\vec{e}$ $\vec{H} = I(z)\,\vec{u}_z \times \vec{e}$	
Longitudinal fields:	$H_z = \left(\frac{\omega_c}{\omega}\right)^2 \frac{T\,U(z)}{\mathrm{j}\omega\mu}$	$E_z = \left(\frac{\omega_c}{\omega}\right)^2 \frac{T\,I(z)}{\mathrm{j}\omega\varepsilon}$

Special cases: rectangular and round waveguide

Rectangular waveguide: transverse eigenfunctions

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

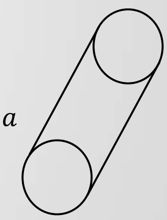


$\frac{\omega_c}{c} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$

Round waveguide: transverse eigenfunctions

TE (H-) modes:	$T_{mn}^{(H)} = \sqrt{\frac{\varepsilon_m}{\pi(\chi_{mn}'^2 - m^2)}} \frac{\mathrm{J}_m\left(\chi'_{mn}\frac{\rho}{a}\right)}{\mathrm{J}_m(\chi'_{mn})} \begin{Bmatrix}\cos(m\varphi)\\ \sin(m\varphi)\end{Bmatrix}$
TM (E-) modes:	$T_{mn}^{(E)} = \sqrt{\frac{\varepsilon_m}{\pi}} \frac{\mathrm{J}_m\left(\chi_{mn}\frac{\rho}{a}\right)}{\mathrm{J}_{m-1}(\chi_{mn})} \begin{Bmatrix}\sin(m\varphi)\\ \cos(m\varphi)\end{Bmatrix}$

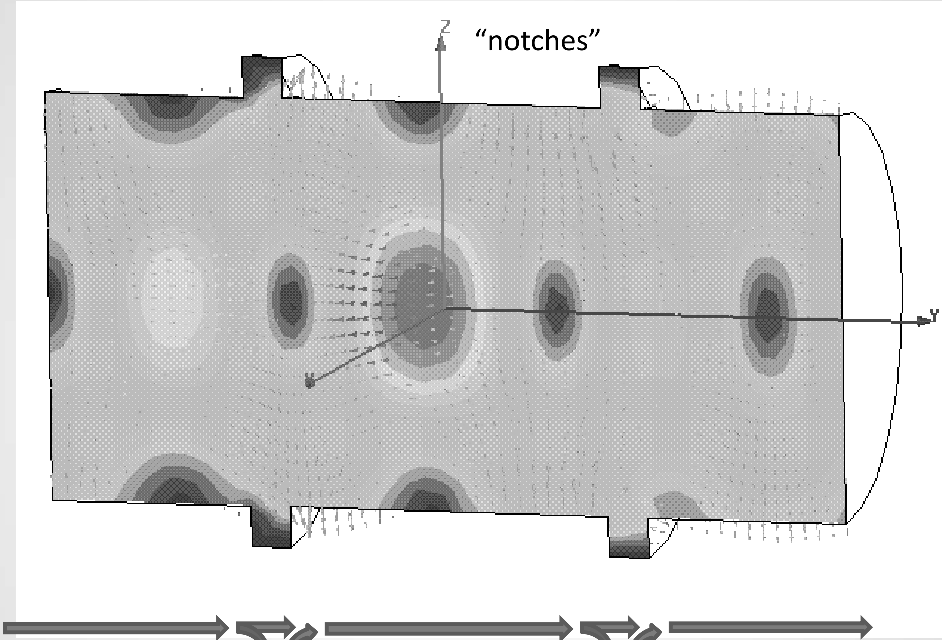
$\emptyset = 2a$



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

where in both cases $\varepsilon_i = \begin{cases}1 & \text{if} \quad i = 0\\ 2 & \text{if} \quad i \neq 0\end{cases}$

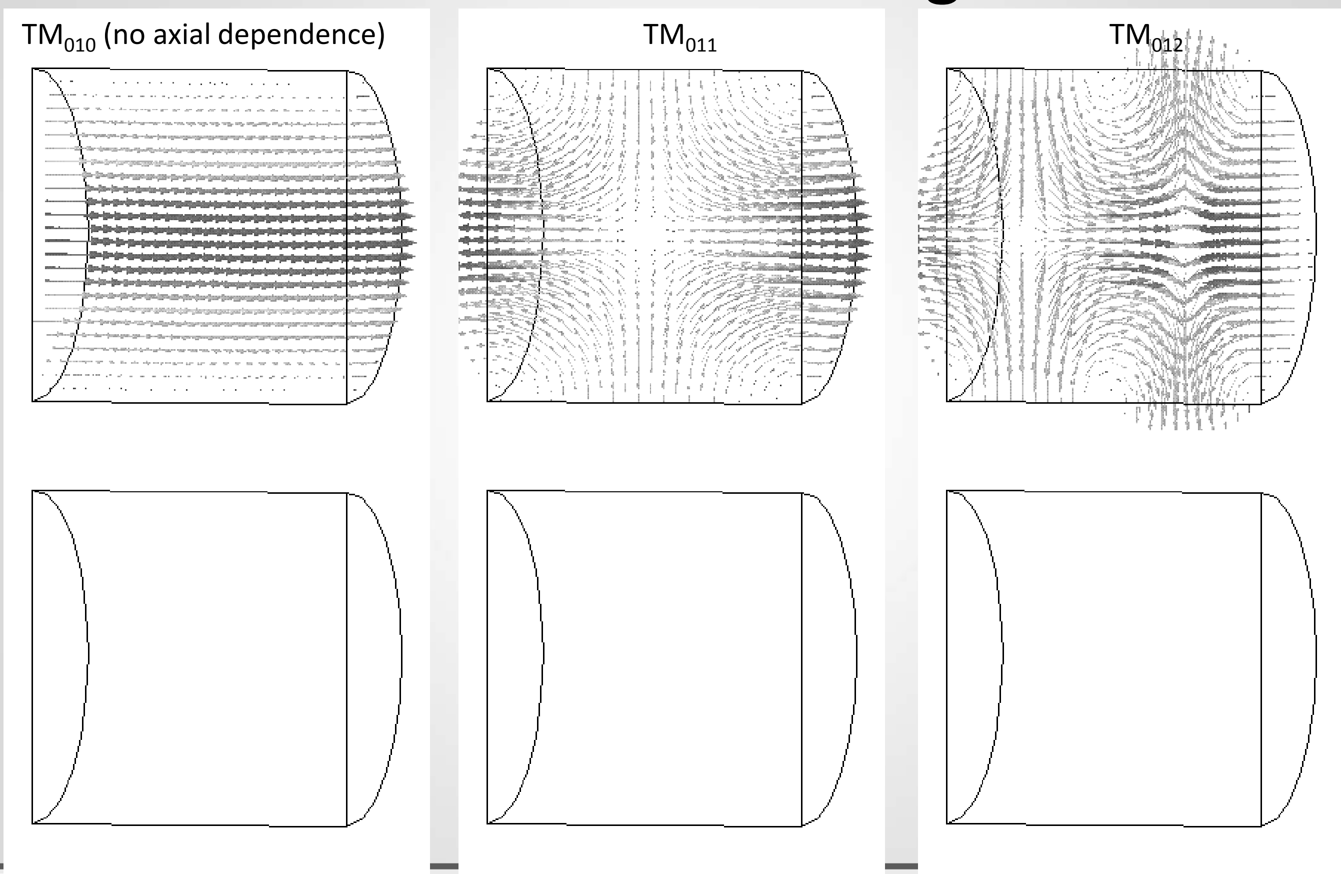
Waveguide perturbed by notches



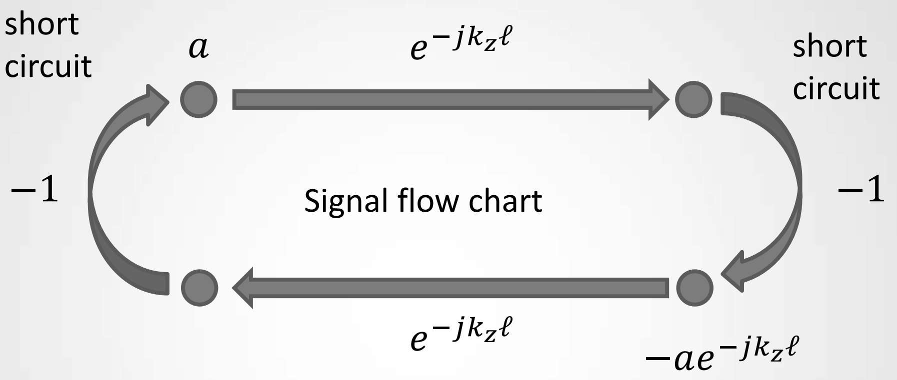
Signal flow chart

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

Short-circuited waveguide



Single WG mode between two shorts



Eigenvalue equation for field amplitude a:

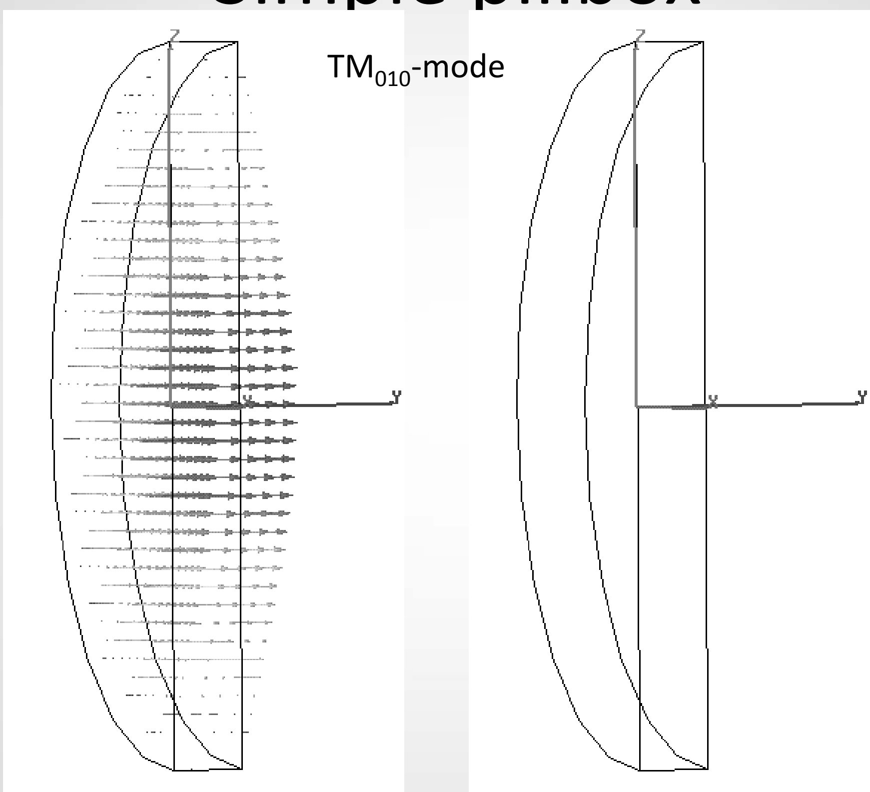
$$a = e^{-jk_z 2\ell} a$$

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

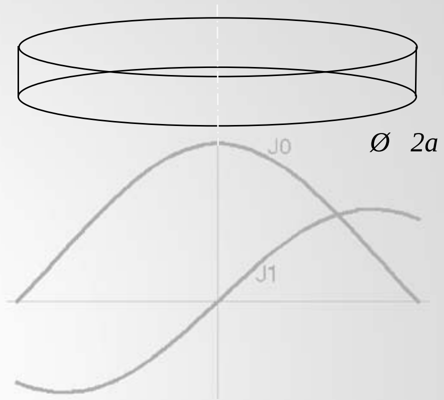
(only 1/2 shown)



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 :

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

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

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

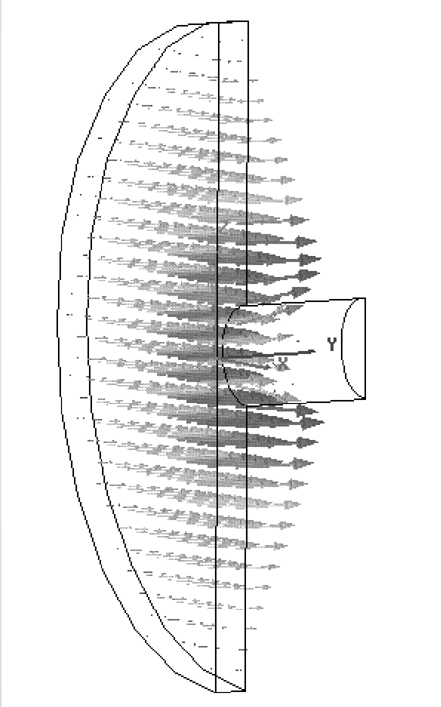
$$Q\big|_{pillbox} = \frac{\sqrt{2a\eta\sigma\chi_{01}}}{2\left(1+\frac{a}{h}\right)}$$

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

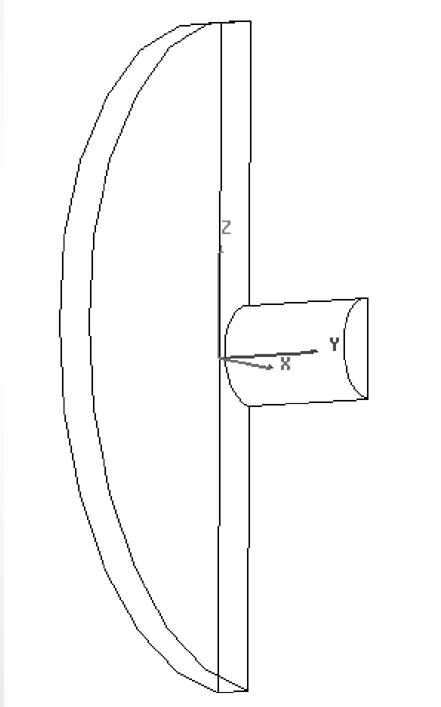
Pillbox with beam pipe

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

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



electric field

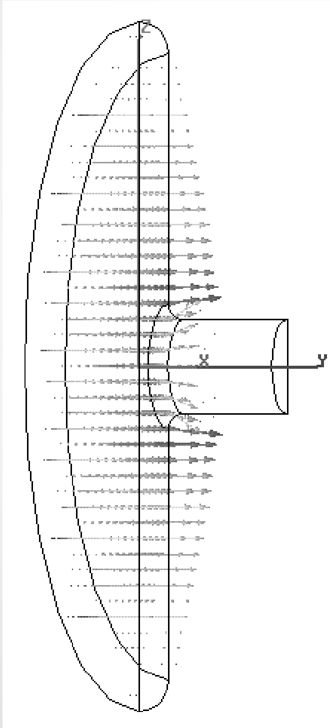


magnetic field

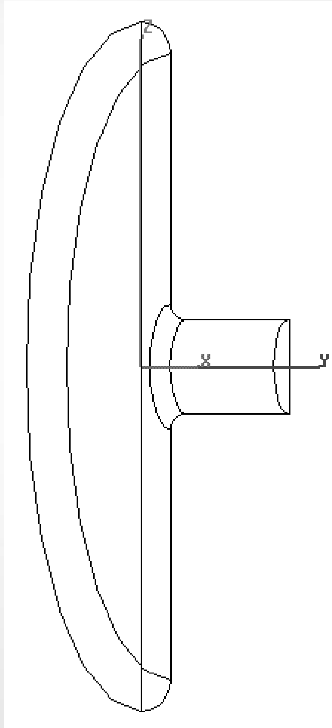
A more practical pillbox cavity

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

Round of sharp edges (to reduce field enhancement!)



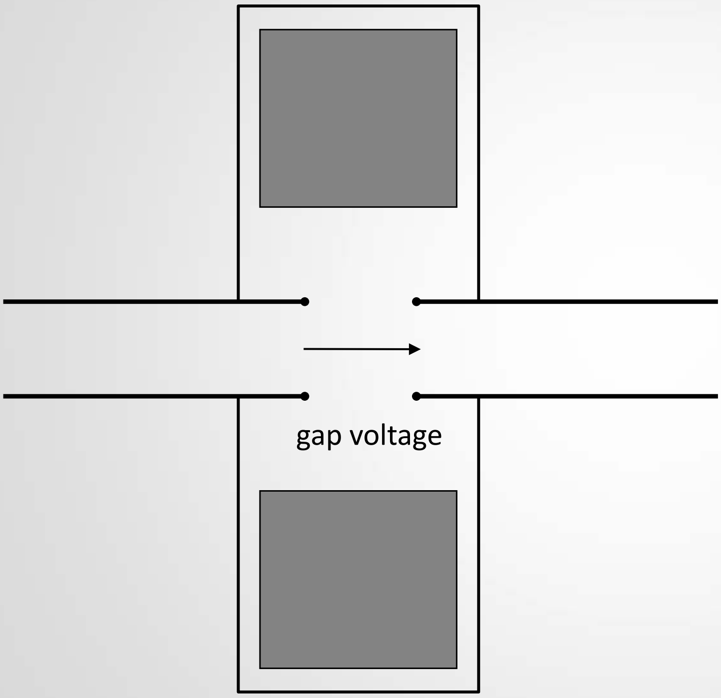
electric field



magnetic field

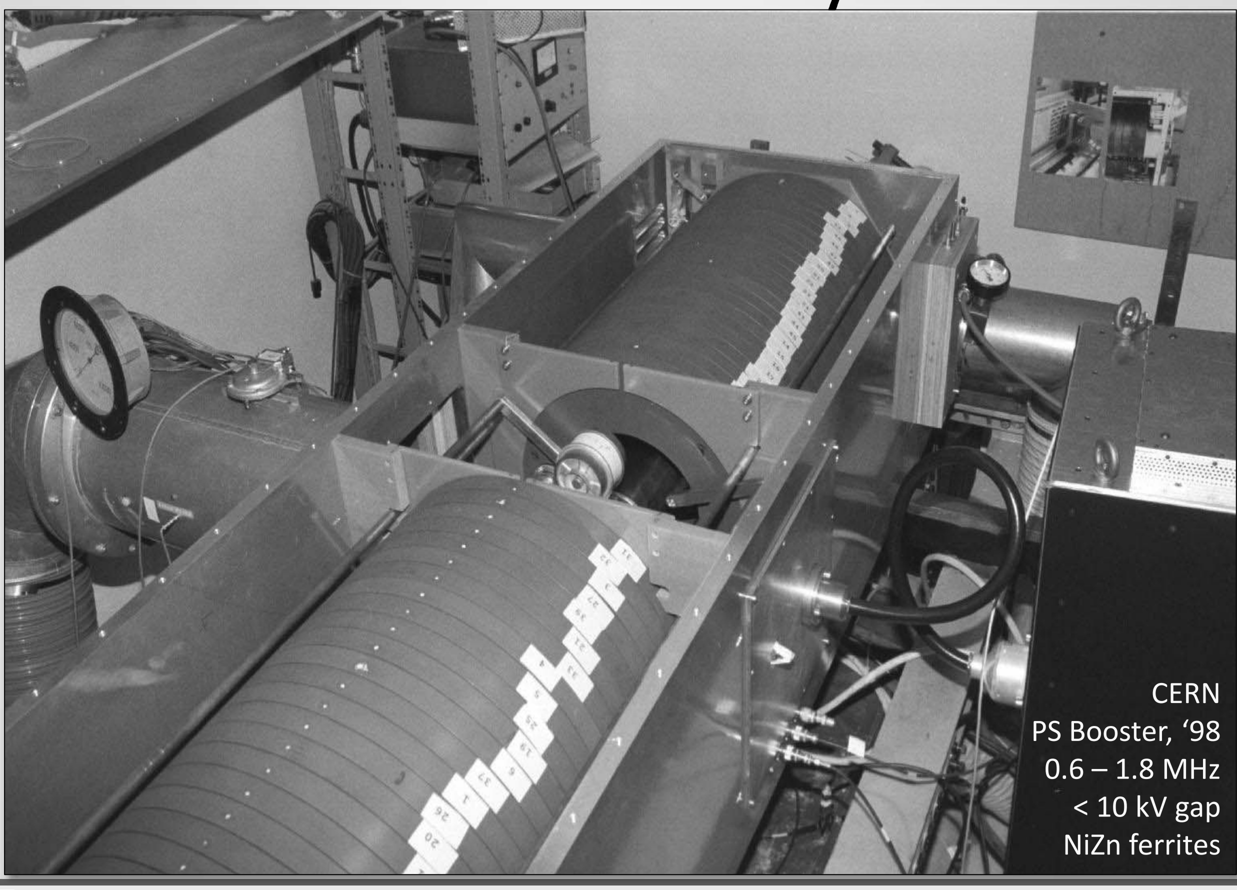
ACCELERATING GAP

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)

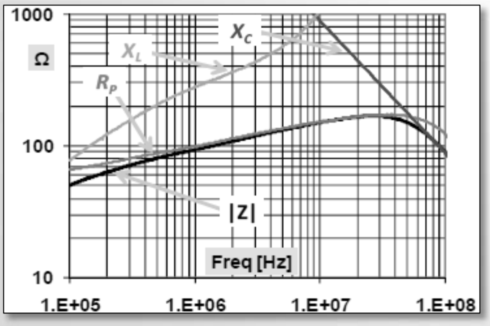
Ferrite cavity



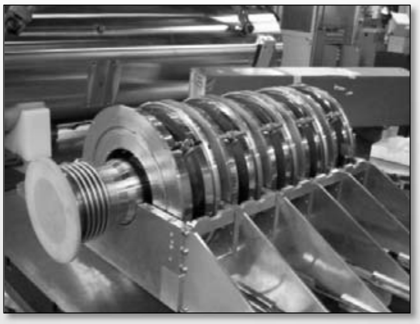
Finemet® Cavity

- Finemet® is a magnetic alloy exhibiting wideband frequency response and large magnetic field saturation level; it allows building wide-band cavities.
- Compared to ferrite cavities, no bias is needed!
- Example: the CERN PSB 5-gap system:

Single Finemet® ring on its cooling plate



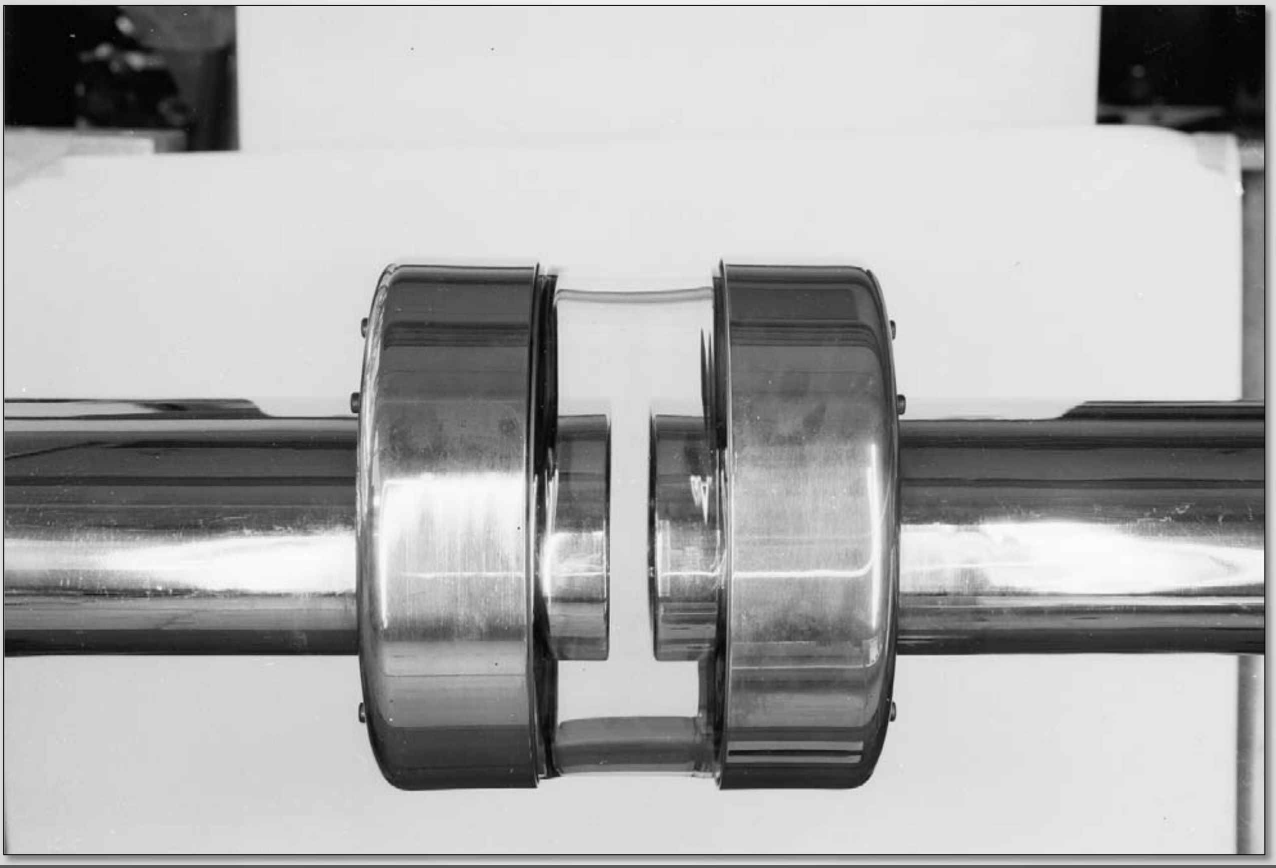
frequency response: (0.6 … 4) MHz



5 gap prototype

… installed in PSB ring 4

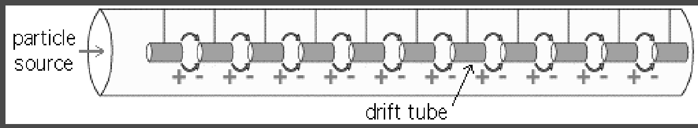
Gap of PS cavity (prototype)



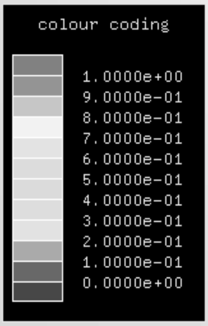
Drift Tube Linac (DTL) – how it works

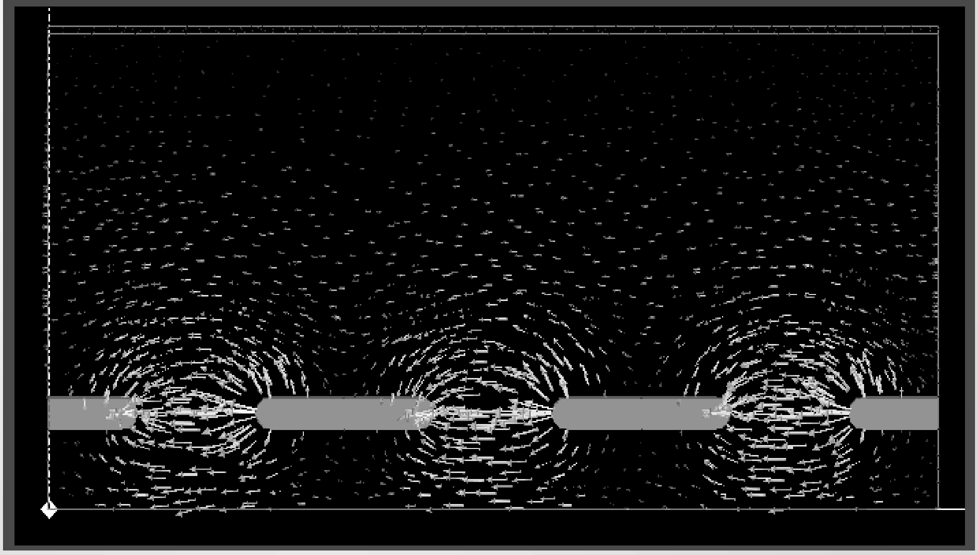
For slow particles !
E.g. protons @ few MeV

The drift tube lengths can easily be adapted.

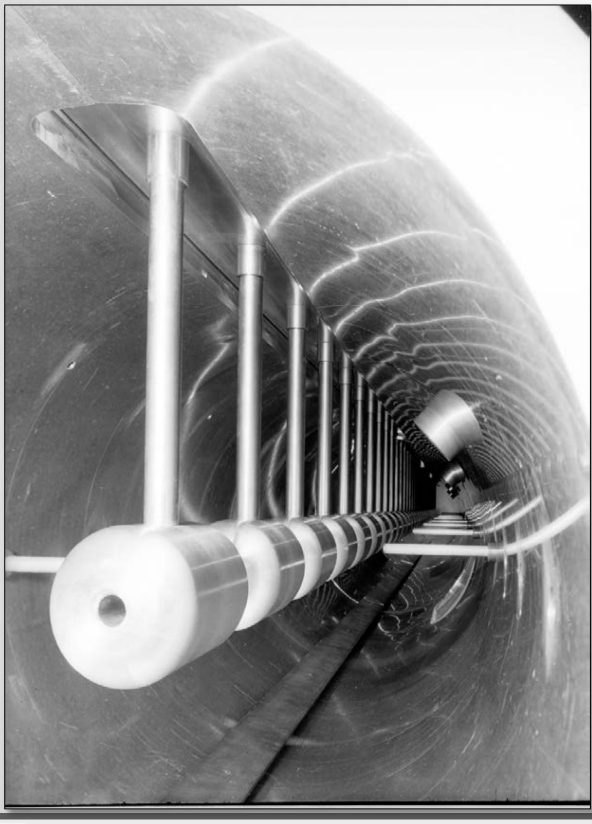


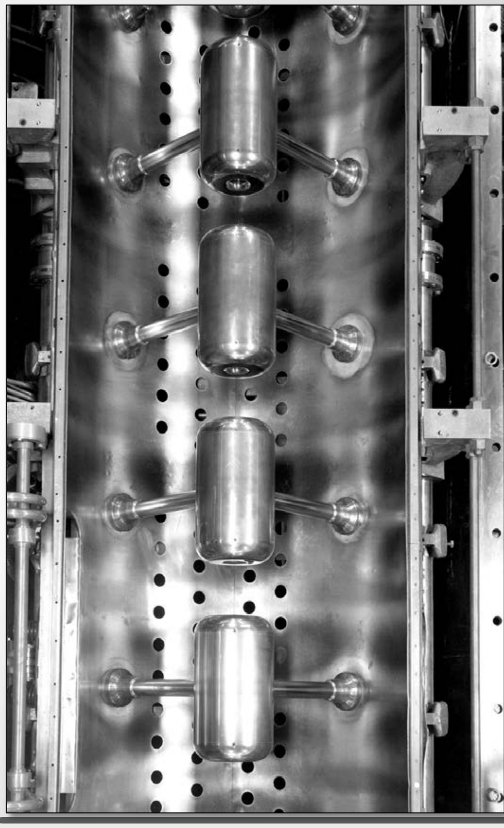
electric field





Drift tube linac – practical implementations





CHARACTERIZING A CAVITY

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

I define $V_{acc} = \int E_z e^{j\frac{\omega}{\beta c}z} \mathrm{d}z$. 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!

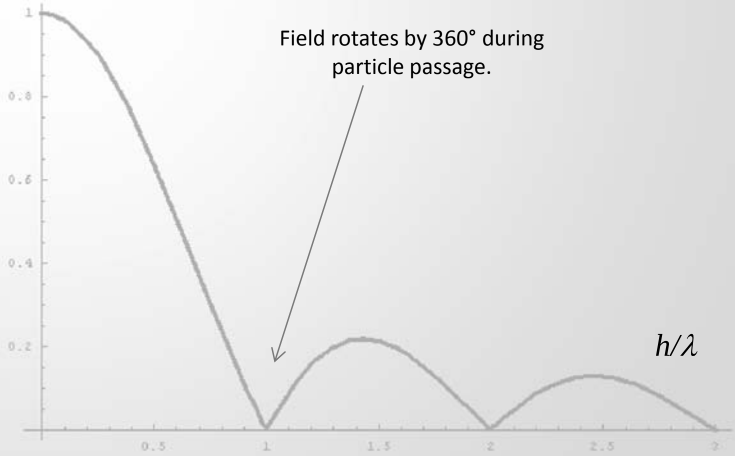
Transit time factor

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”

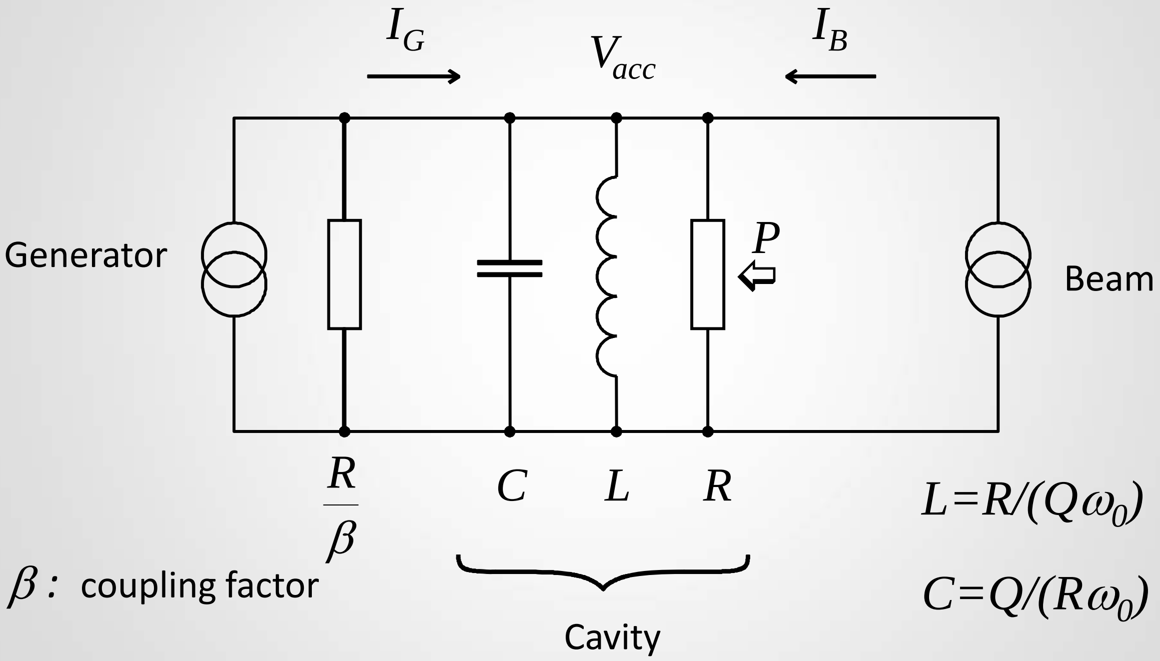
$$R = \frac{|V_{acc}|^2}{2\, P_{loss}}$$

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



$L = R/(Q\omega_0)$

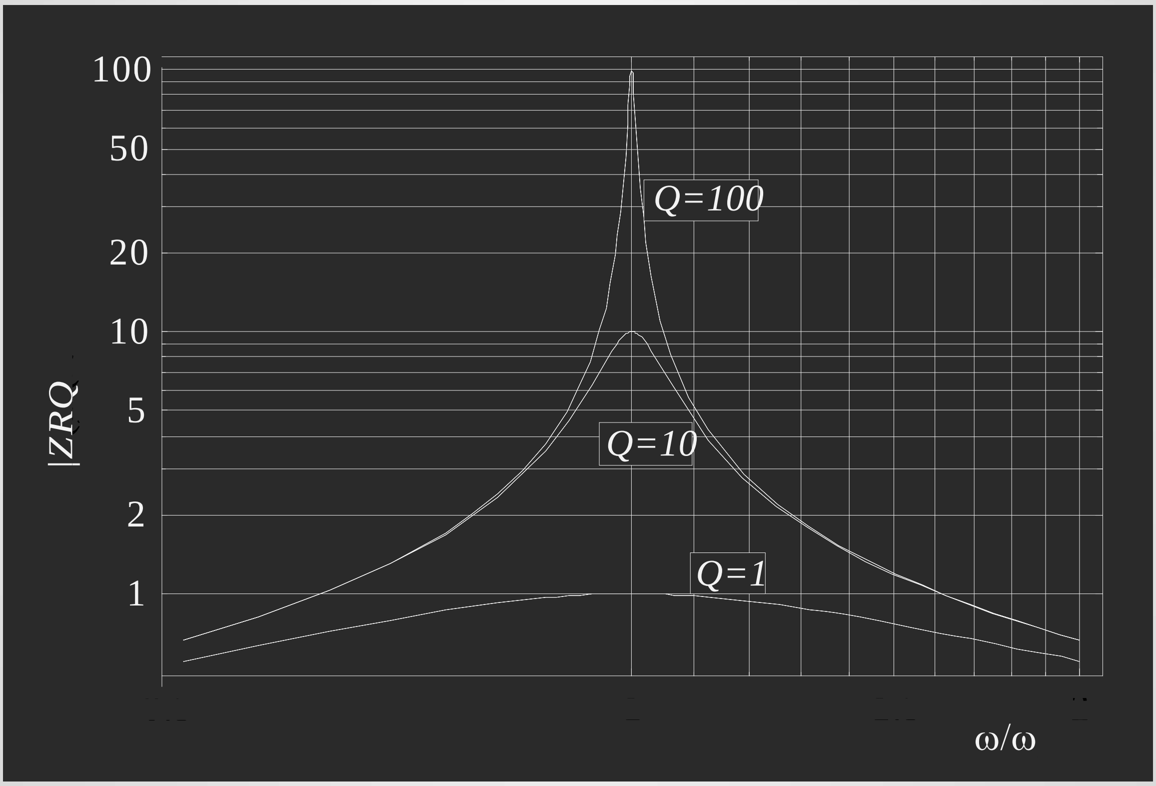
$C = Q/(R\omega_0)$

β : coupling factor

R: Shunt impedance

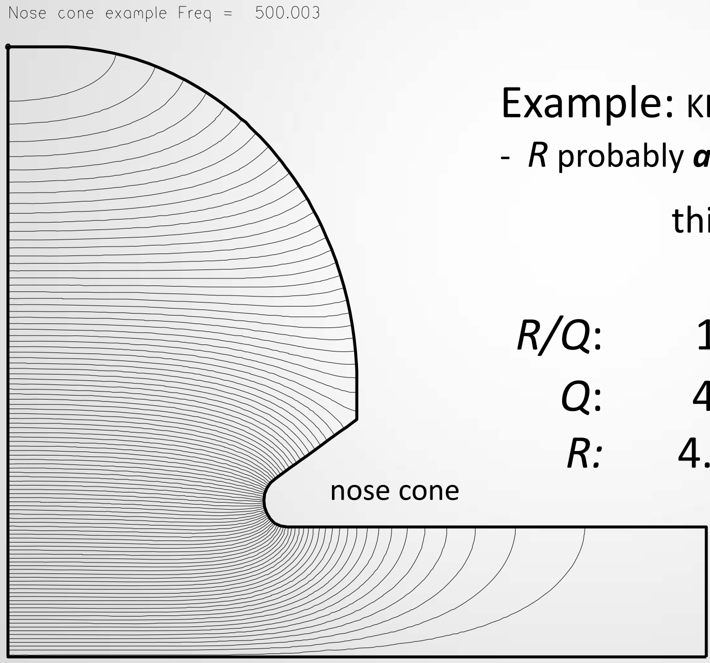
$\sqrt{L/C}$: *R*-upon-*Q*

Resonance



Reentrant cavity

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



Example: KEK photon factory 500 MHz

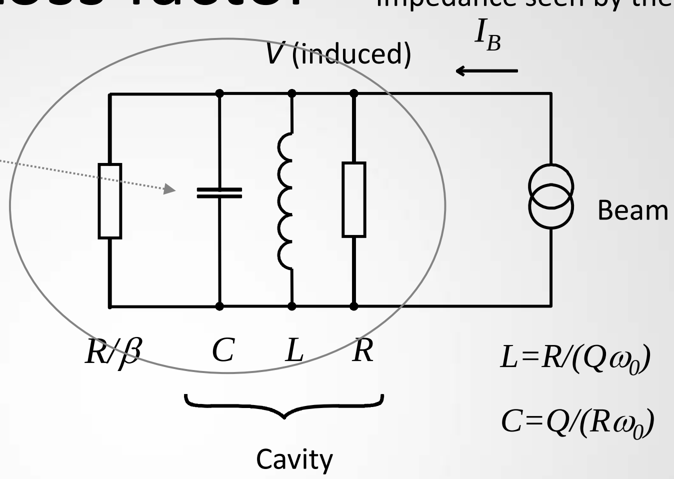
- *R* probably ***as good as it gets*** -

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

Loss factor

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

Impedance seen by the beam



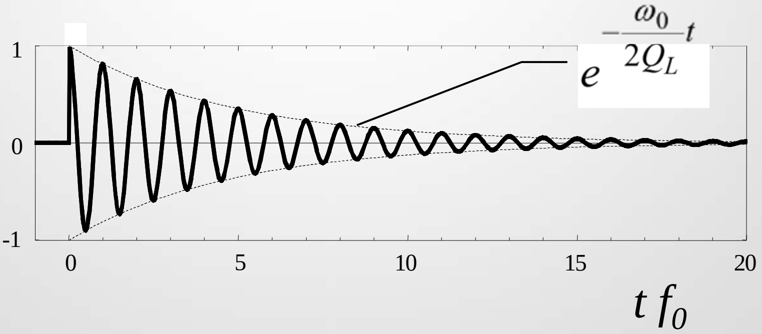
$L=R/(Q\omega_0)$

$C=Q/(R\omega_0)$

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

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

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

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

Energy stored inside the cavity

W

Power lost in the cavity walls

P_{loss}

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

***Q* factor**

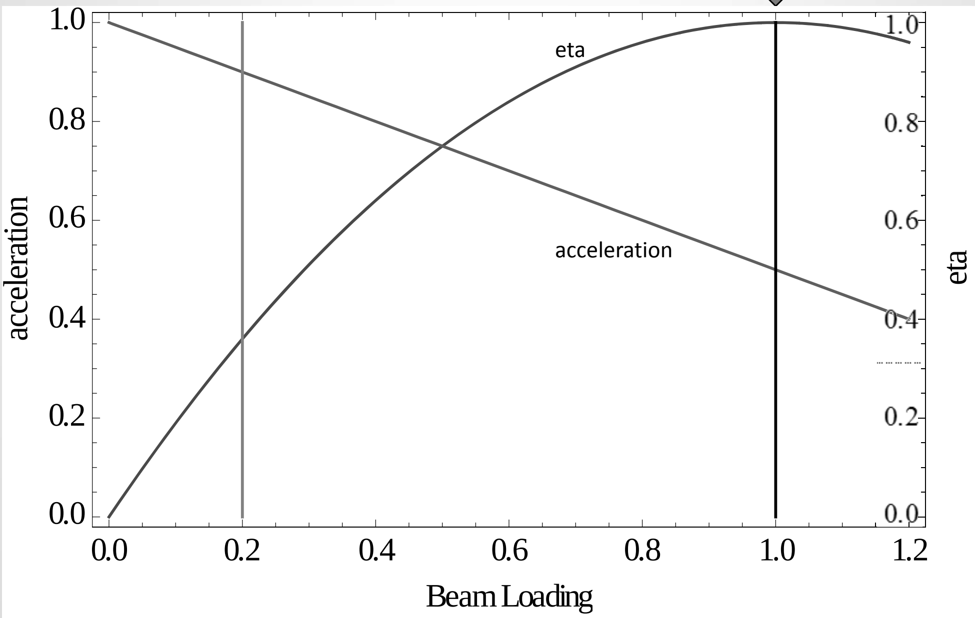
Beam loading – RF to beam efficiency

- 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 $\eta = \frac{1}{1+\frac{V_{gap}}{R\left|I_B\right|}} = \frac{\left|I_B\right|}{\left|I_G\right|}$.

Beam Loading – allows efficiency

choice for CLIC main beam

full beam loading – optimum efficiency



Characterizing cavities

- Resonance frequency $$\omega_0 = \frac{1}{\sqrt{L \cdot C}}$$
- Transit time factor

  field varies while particle is traversing the gap

$$\frac{\left| \int E_z e^{j\frac{\omega}{c}z} \mathrm{d}z \right|}{\left| \int E_z \mathrm{d}z \right|}$$

Circuit definition

Linac definition

- Shunt impedance

  gap voltage – power relation

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

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

- *Q* factor $$\omega_0 W = Q P_{loss}$$
- *R/Q*

  independent of losses – only geometry!

Circuit: $$\frac{R}{Q} = \frac{\left|V_{gap}\right|^2}{2\,\omega_0 W} = \sqrt{\frac{L}{C}}$$

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

- loss factor

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

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

Example Pillbox:

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

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

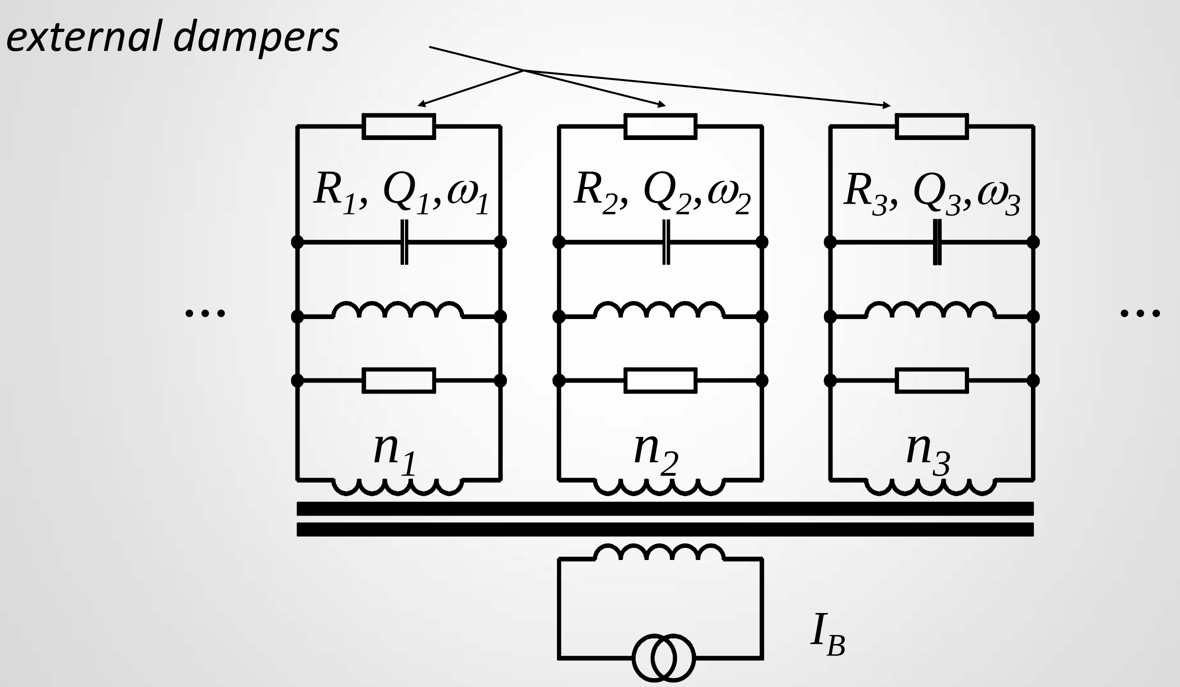
$$\frac{R}{Q}\bigg|_{pillbox} = \frac{4\eta}{\chi_{01}{}^{3}\pi\,\mathrm{J}_1^2(\chi_{01})}\,\frac{\sin^2\left(\frac{\chi_{01}}{2}\frac{h}{a}\right)}{h/a}$$

$$\chi_{01} = 2.4048$$

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

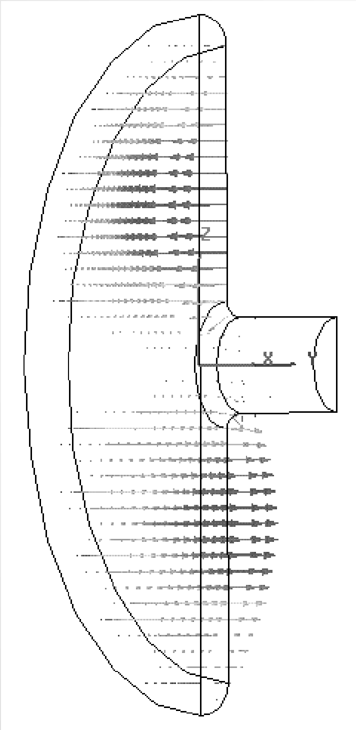
$$\sigma_{\mathrm{Cu}} = 5.8\cdot 10^7\,\mathrm{S/m}$$

Higher order modes

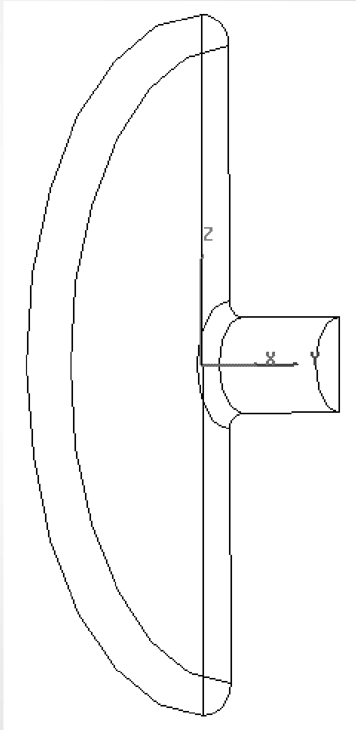


Pillbox: dipole mode

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!

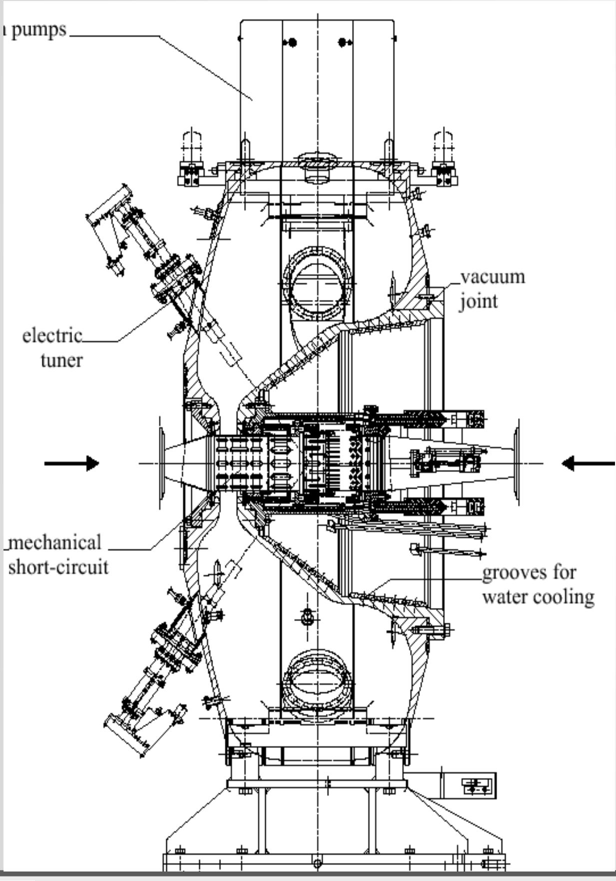
$$\mathrm{j}\frac{\omega}{c}\vec{F}_\perp = \nabla_\perp F_\parallel$$

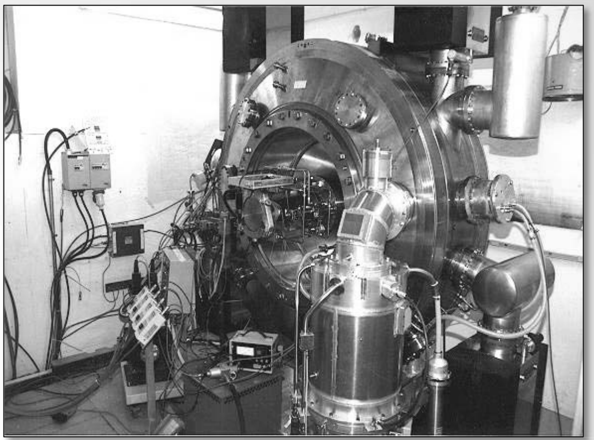
Pure TE modes: No net transverse force !

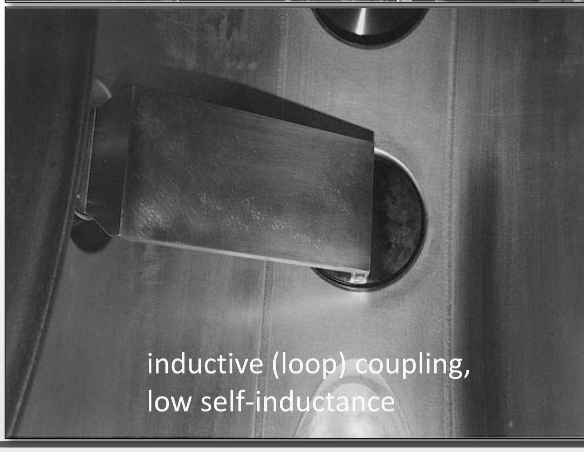
Transverse modes are characterized by
- the transverse impedance in ***ω***-domain
- the transverse loss factor (kick factor) in ***t***-domain !

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)





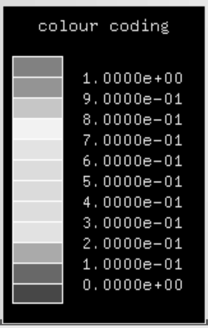


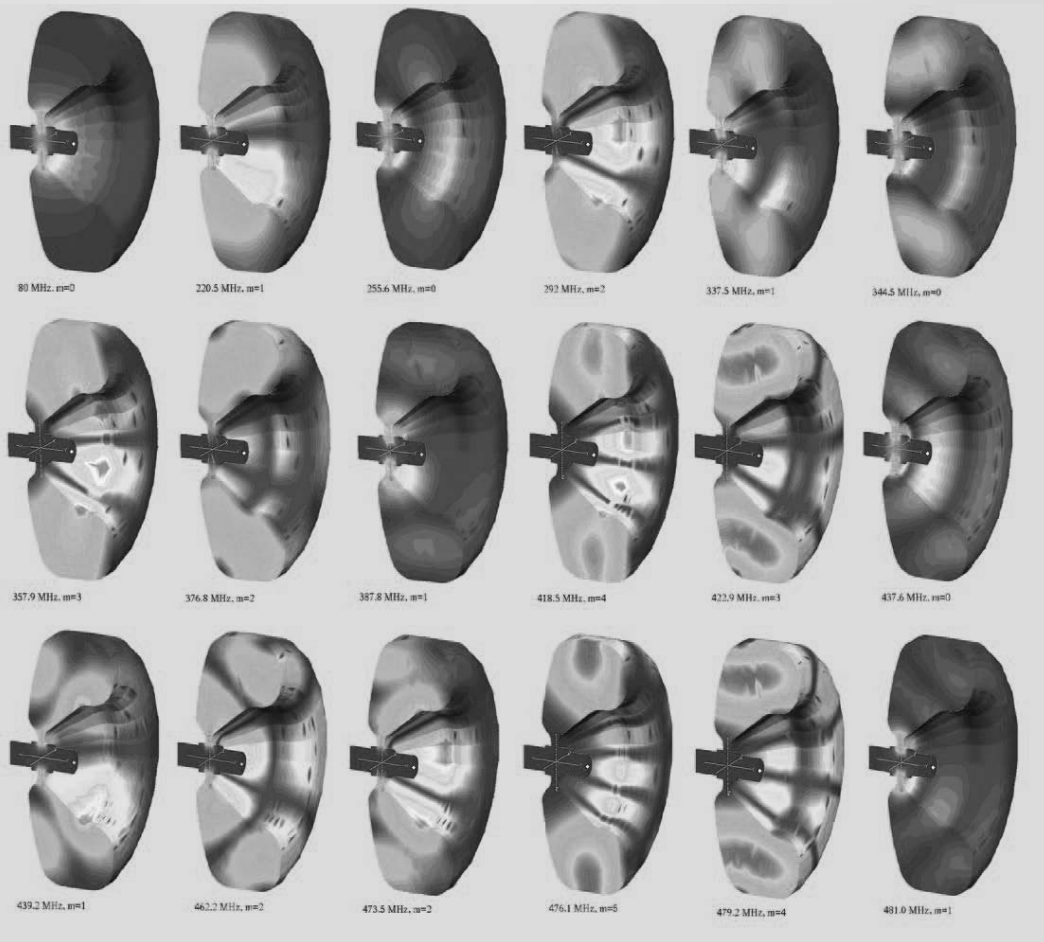
Higher order modes

Example shown: 80 MHz cavity PS for LHC.

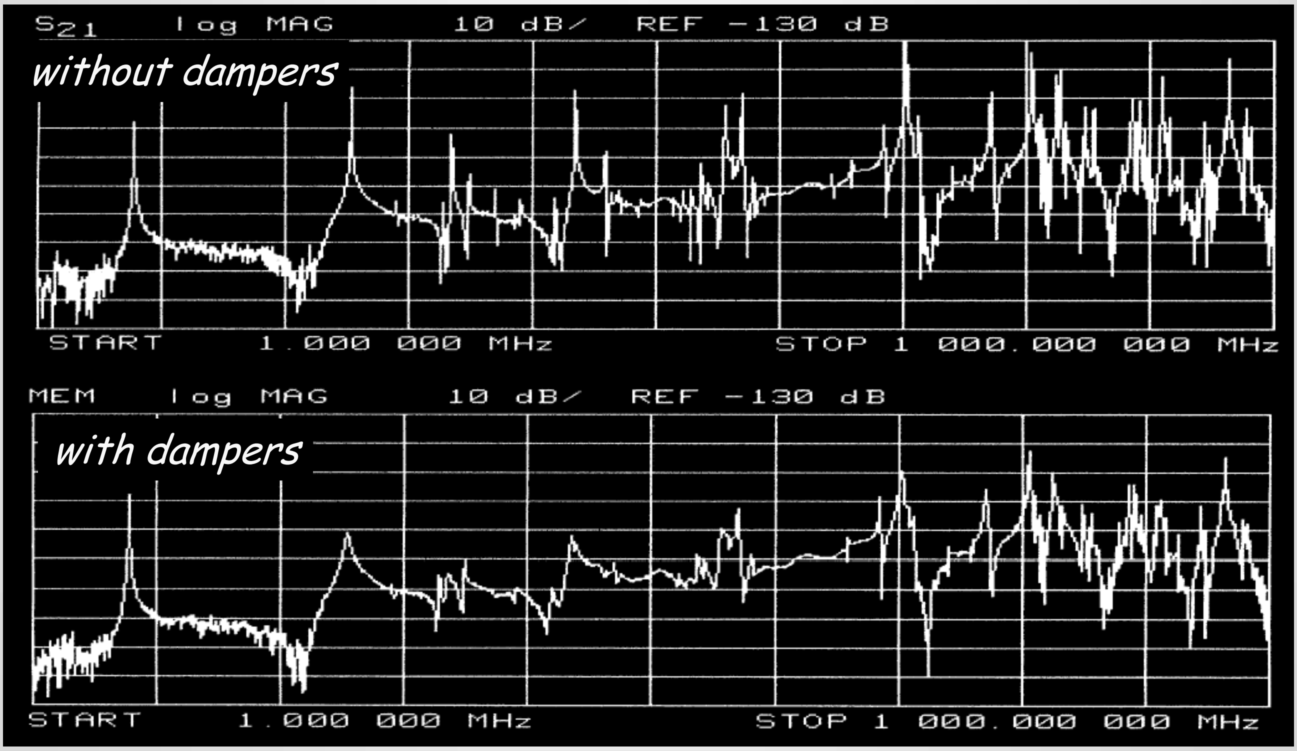
Color-coded:

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





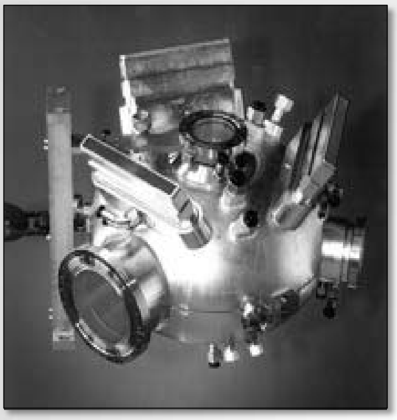
Higher order modes (measured spectrum)



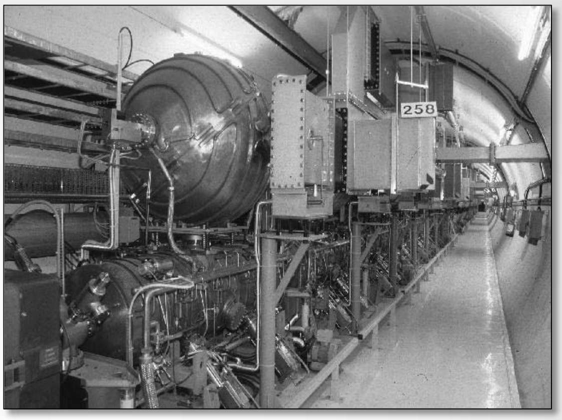
MORE EXAMPLES OF CAVITIES

PS 19 MHz cavity (prototype, photo: 1966)

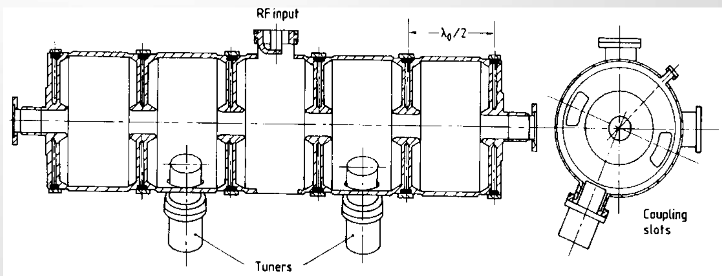
Examples of cavities



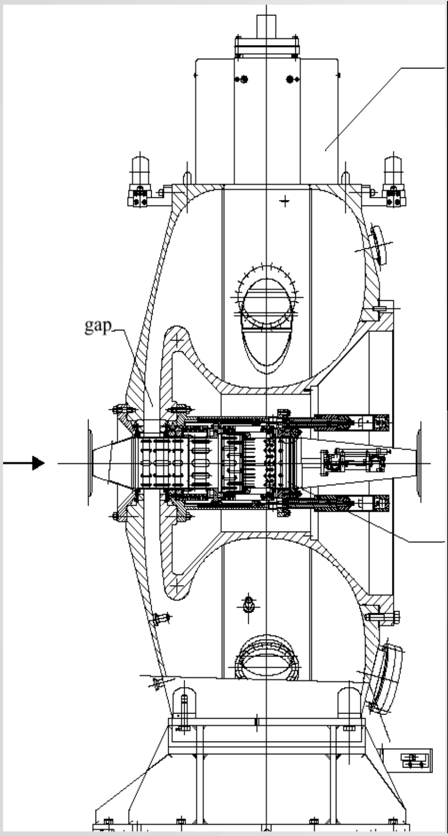
PEP II cavity
476 MHz, single cell,
1 MV gap with 150 kW,
strong HOM damping,

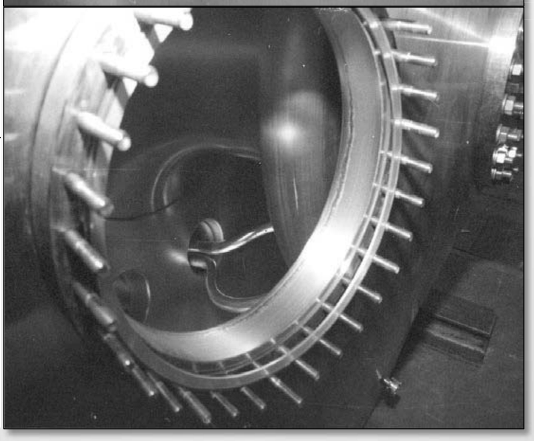


LEP normal-conducting Cu RF cavities,
350 MHz. 5 cell standing wave + spherical cavity
for energy storage, 3 MV

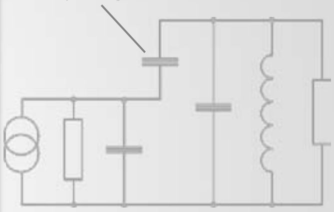


CERN/PS 40 MHz cavity (for LHC)





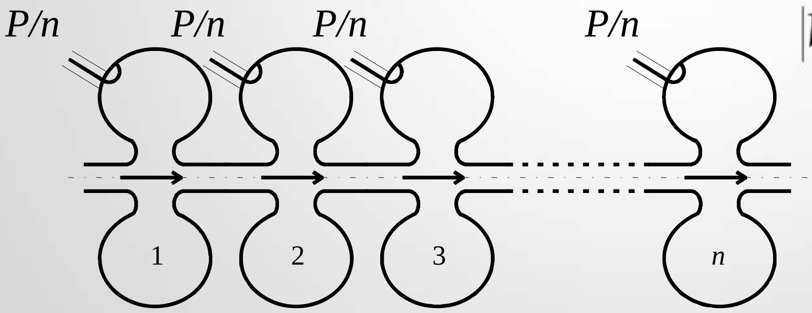
example for
capacitive coupling



MANY GAPS

What do you gain with many gaps?

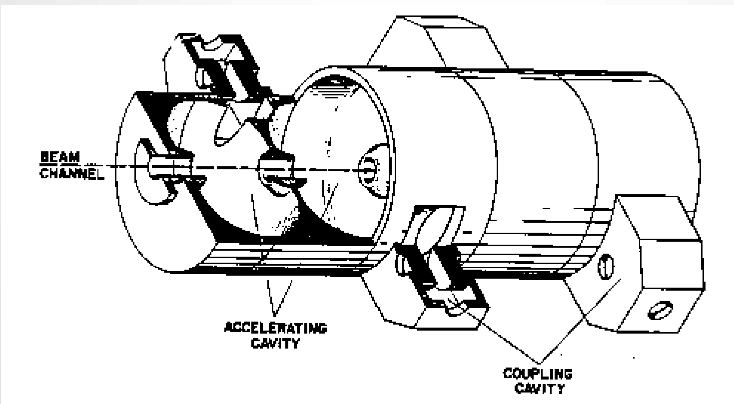
- The *R/Q* of a single gap cavity is limited to some 100 Ω.
  Now consider to distribute the available power to *n* identical cavities: each will receive *P/n*, thus produce an accelerating voltage of $\sqrt{2R\,P/n}$.
  The total accelerating voltage thus increased, equivalent to a total equivalent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



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

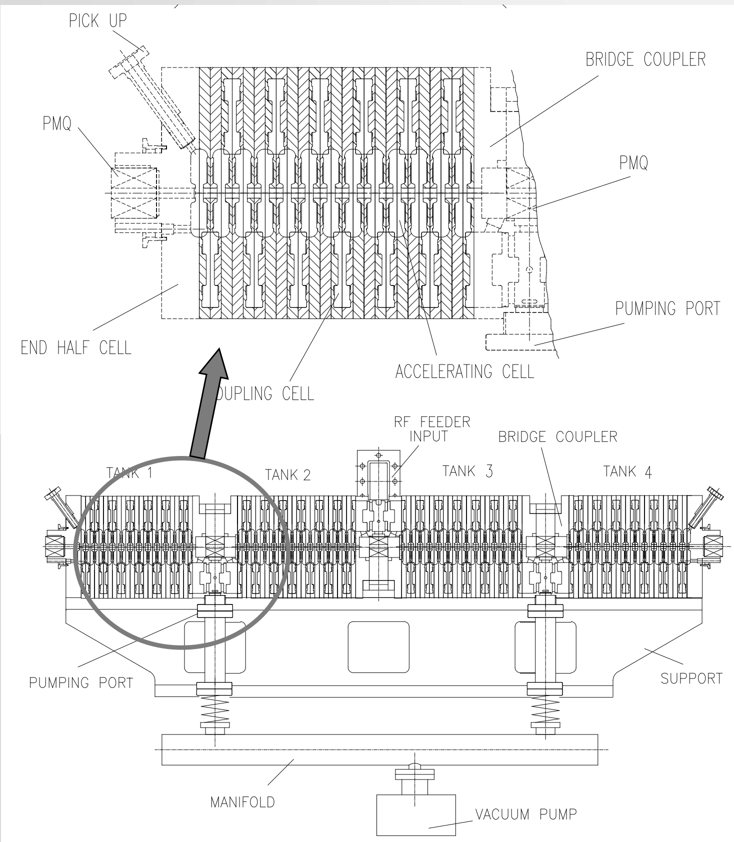
Standing wave multicell cavity

- 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)

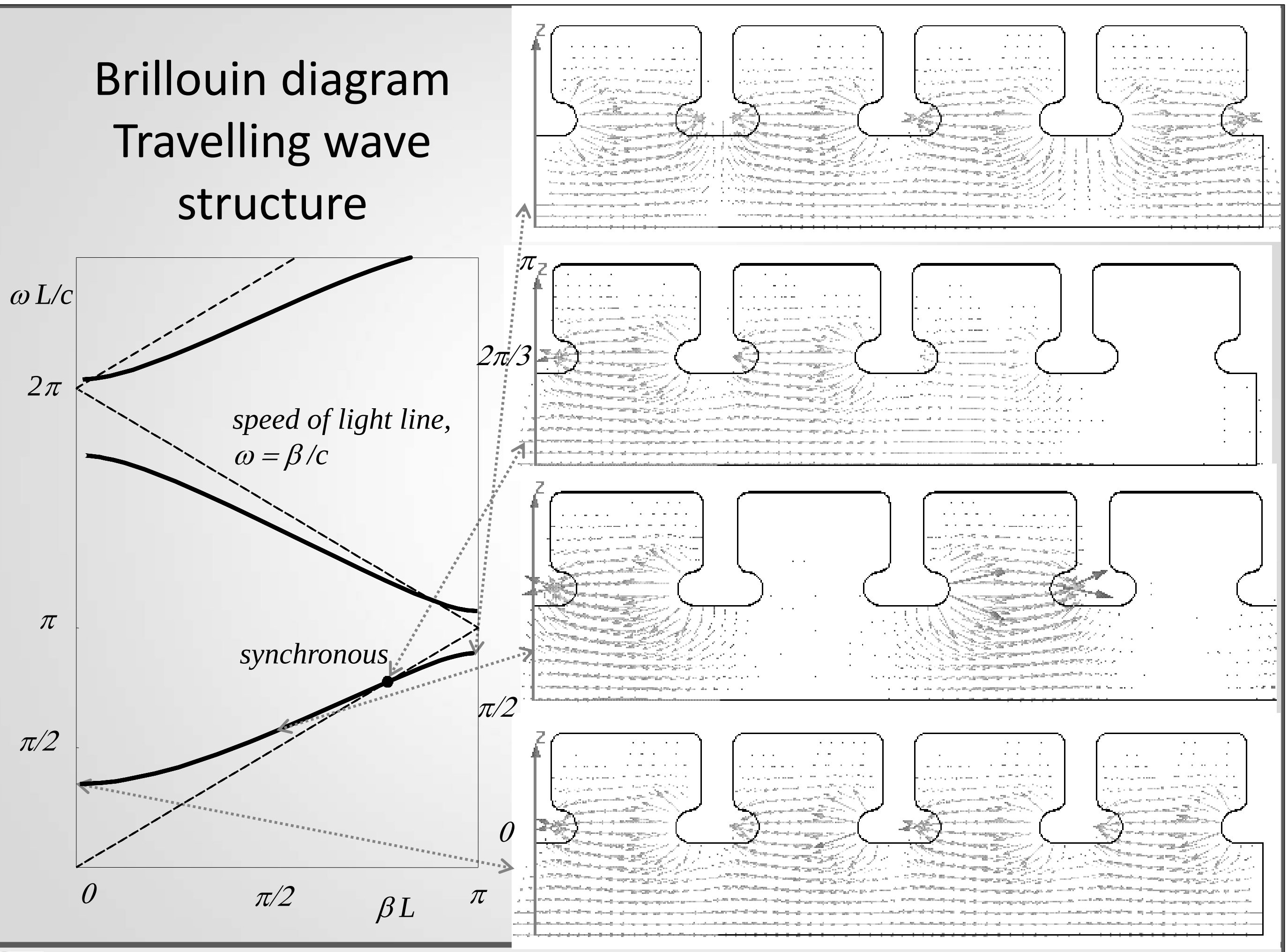
Collaboration CERN/INFN/TERA Foundation

LIBO prototype

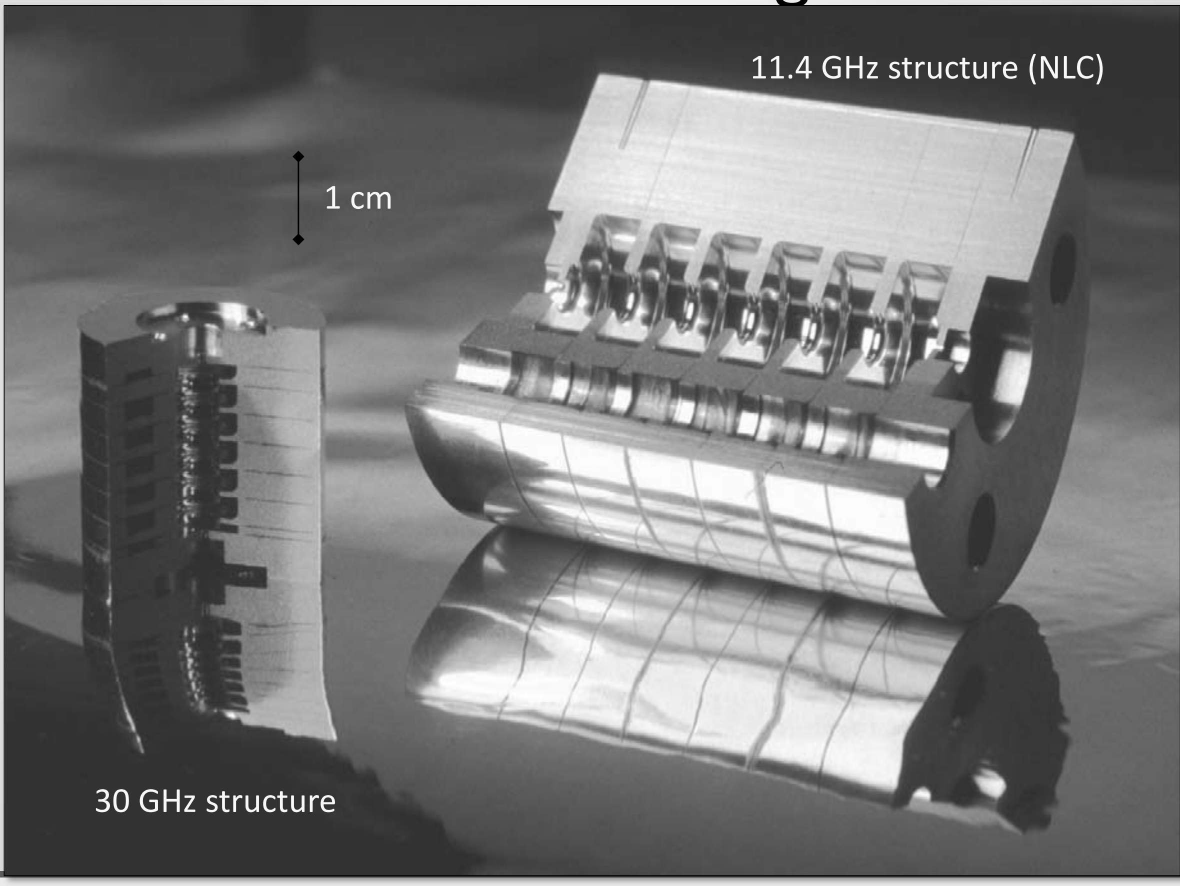
This Picture made it to the title page of CERN Courier vol. 41 No. 1 (Jan./Feb. 2001)

TRAVELLING WAVE STRUCTURES

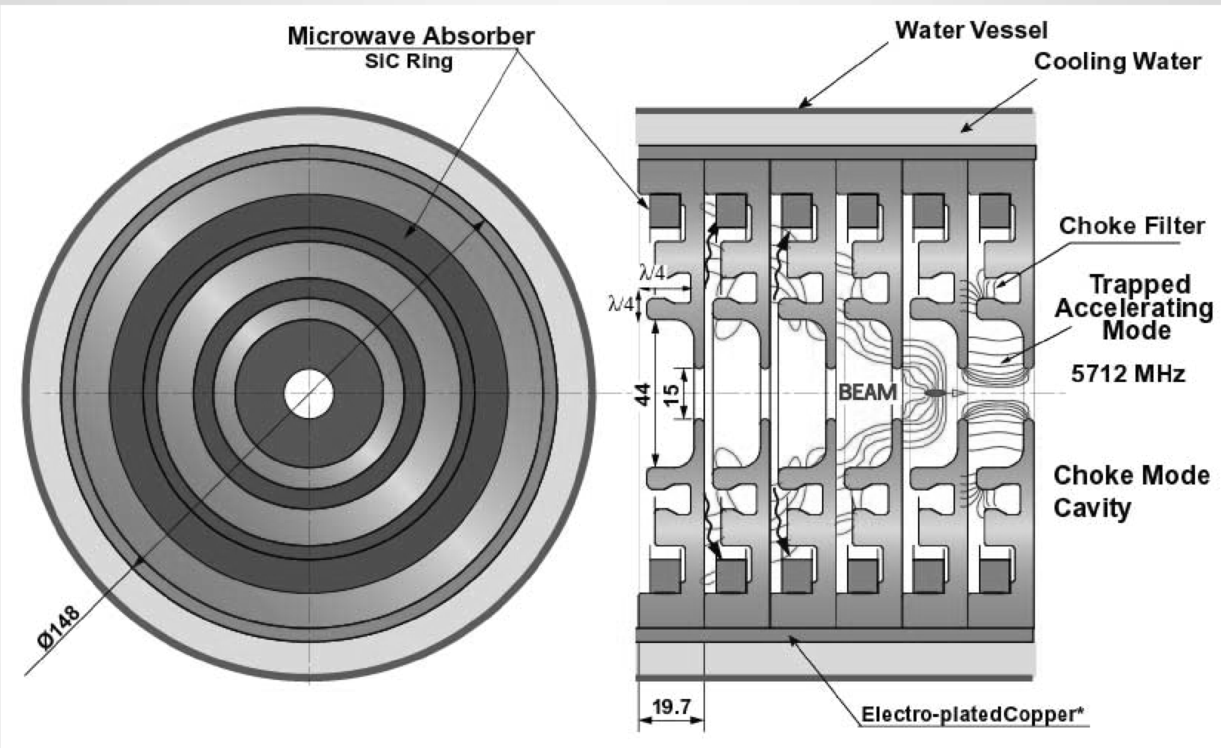
Brillouin diagram Travelling wave structure



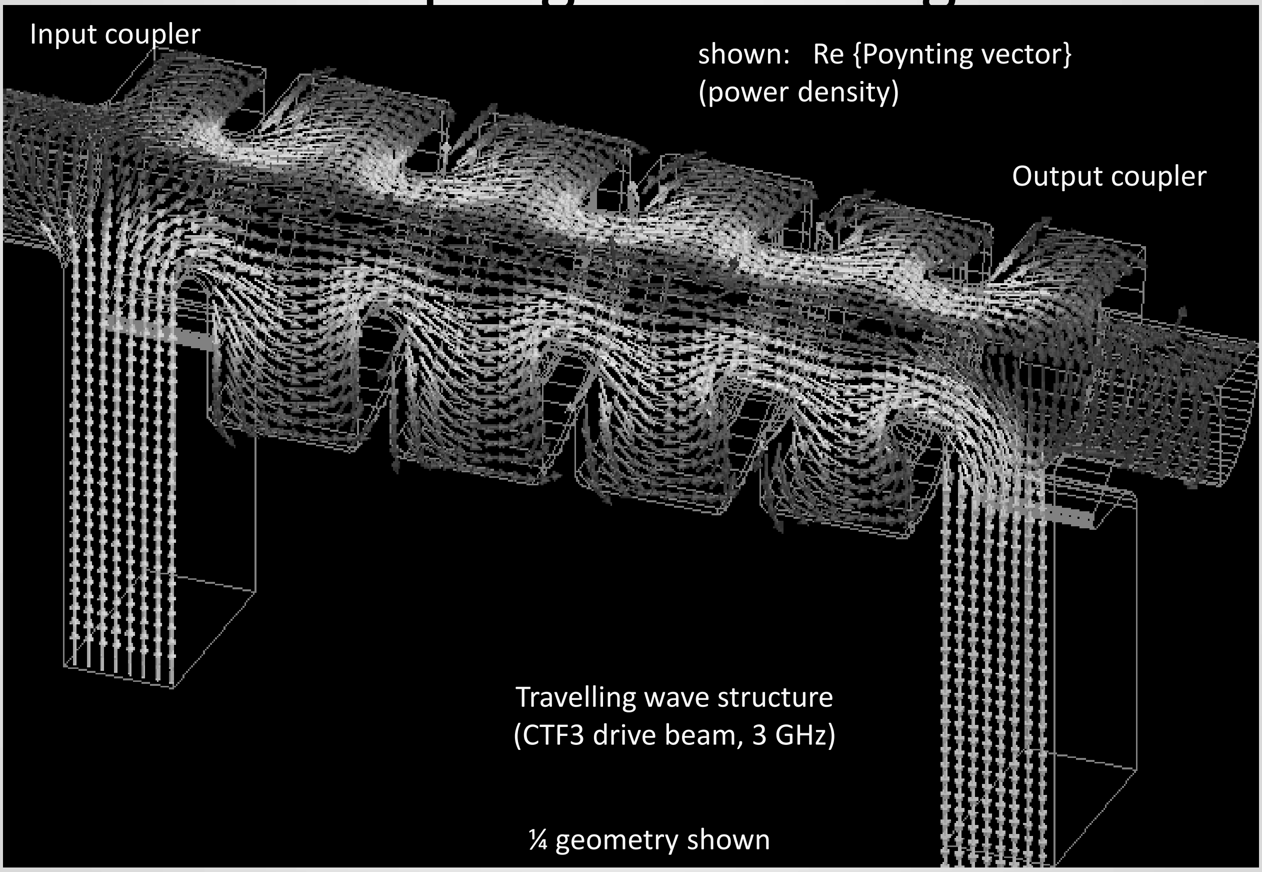
Iris loaded waveguide



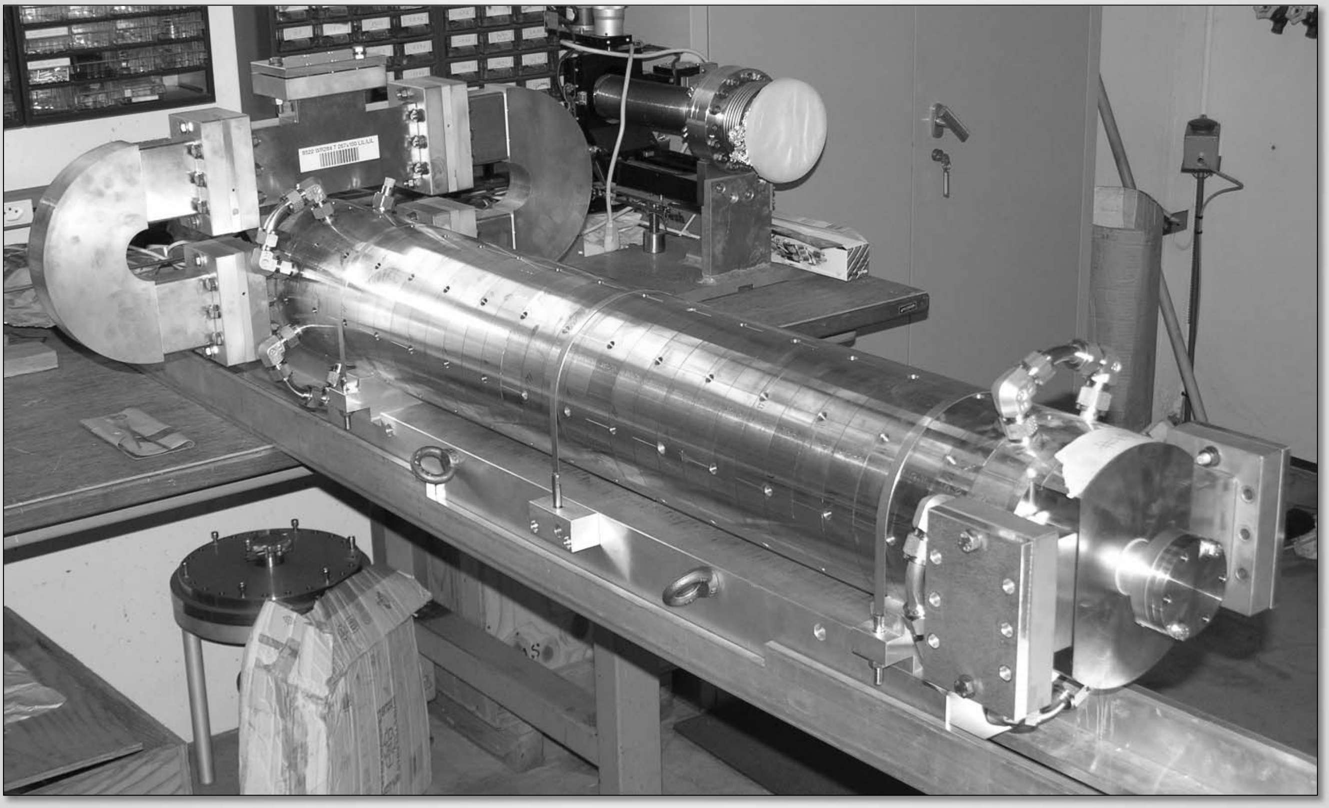
Disc loaded structure with strong HOM damping "choke mode cavity"



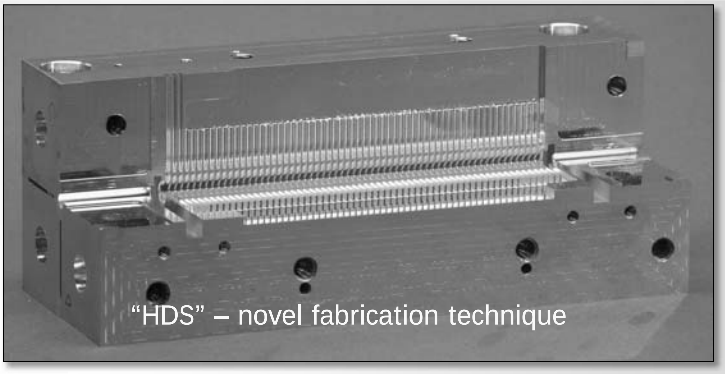
Power coupling with waveguides

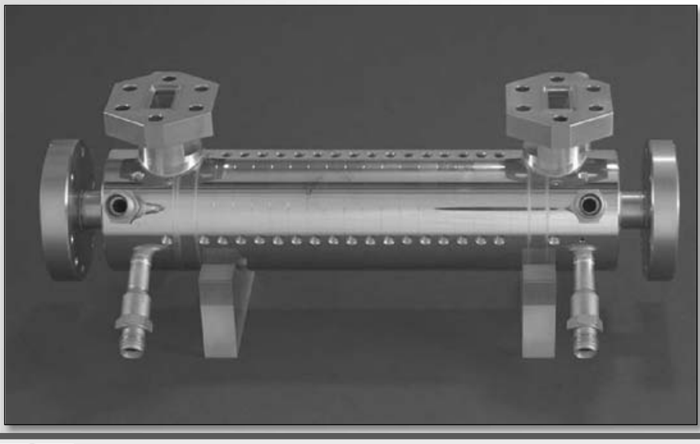


3 GHz Accelerating structure (CTF3)



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

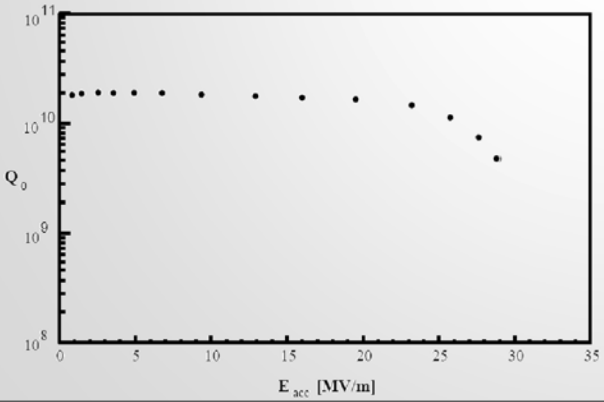




SUPERCONDUCTING ACCELERATING STRUCTURES

RF Superconductivity

- Best described by BCS (Bardeen-Cooper-Schrieffer) Theory
- $R_{BCS} \propto \frac{\omega^2}{T} \exp\left(-1.76 \frac{T_c}{T}\right)$
- Surface resistance $R = R_{BCS} + R_{res}$.
- R is not zero - Q_0 is finite.
- Good values are some 10^{10}.
- Typical performance plot of a SC cavity:



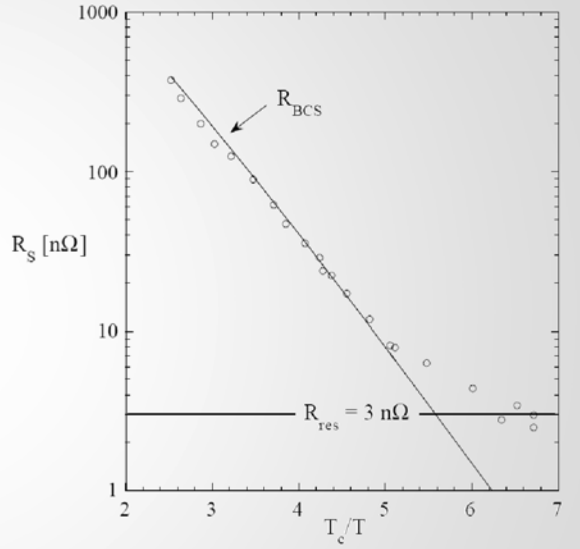
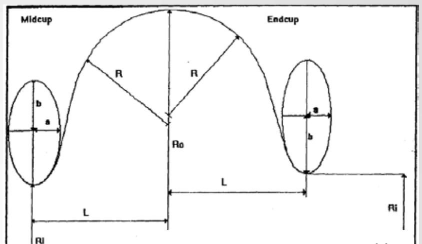


FIG. 1. The surface resistance of a 9-cell TESLA cavity plotted as a function of T_c/T. The residual resistance of 3 nΩ corresponds to a quality factor of $Q_0 = 10^{11}$.

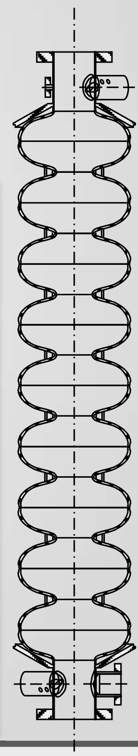
From prst-ab.aps.org/abstract/PRSTAB/v3/i9/e092001

Elliptical multi-cell cavities

- The elliptical shape was found as optimum compromise between
  - maximum gradient (E_{acc}/E_{surf})
  - suppression of multipactor
  - mode purity
  - machinability
- Operated in π-mode, i.e. cell length is exactly $\beta\lambda/2$.
- It has become de facto standard, used for ions and leptons! E.g.:
  - ILC/X-FEL: 1.3 GHz, 9-cell cavity
  - SNS (805 MHz)
  - SPL/ESS (704 MHz)
  - LHC (400 MHz*))

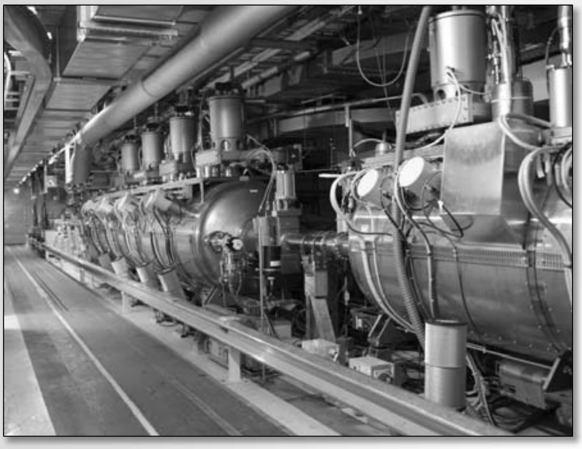


D. Proch: SRF 1993 *)

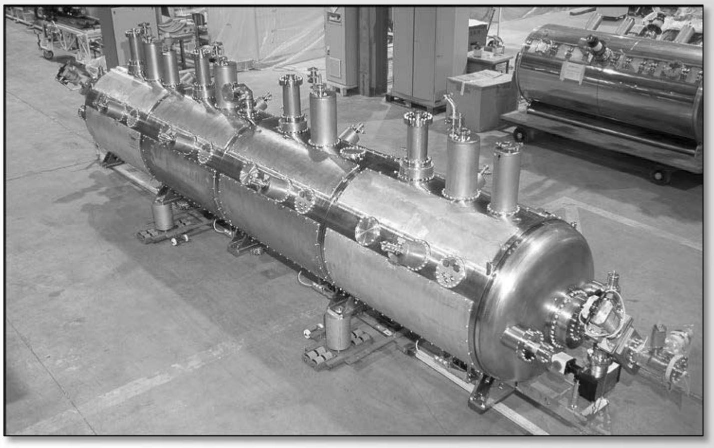


*): accelconf.web.cern.ch/accelconf/SRF93/papers/srf93g01.pdf

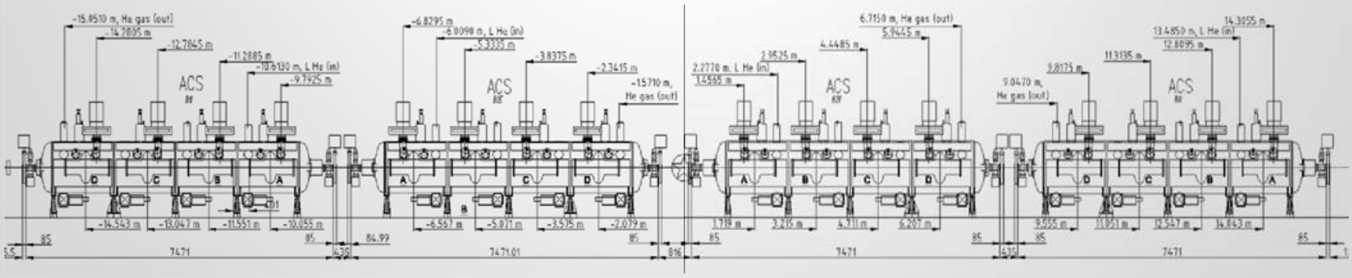
LHC SC RF, 4 cavity module, 400 MHz



installed in LHC IP4, 2 MV/cavity

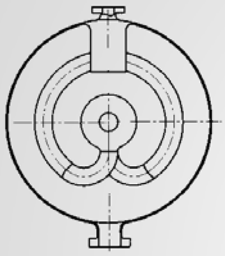


LHC spare module stored in CERN's SM18

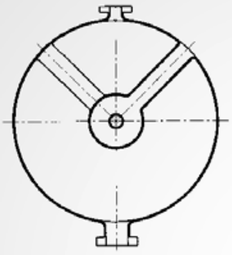


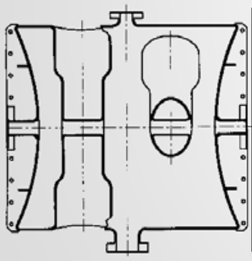
Small β superconducting cavities (example RIA, Argonne)

split ring cavity



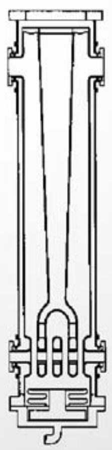
$\beta = 0.2$ "lollipop" cavity



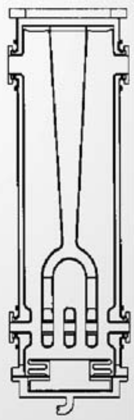


$\beta = 0.4$ spoke cavity

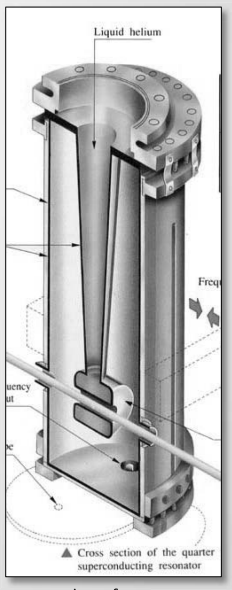
$\beta = 0.021$ fork cavity



$\beta = 0.03$ fork cavity



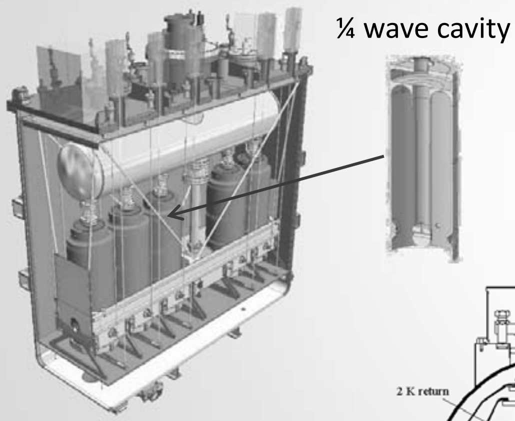
$\beta = 0.06$ QWR ¼-wave-resonator

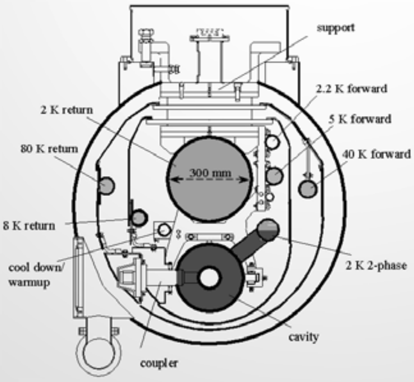


Some pictures from Shepard et al.: "Superconducting accelerating structures for a multi-beam driver linac for RIA", Linac 2000, Monterey, others from

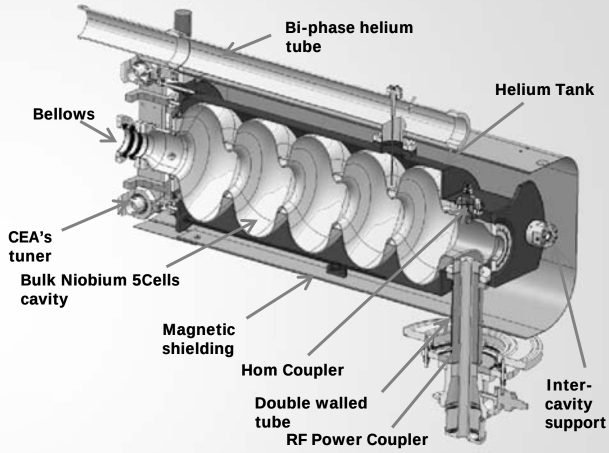
SC Cavity Cryomodule examples

HIE-Isolde (radioactive isotopes post-accelerator), 101 MHz, 5-cavity CM





SPL/ESS 704 MHz CM (partial view)

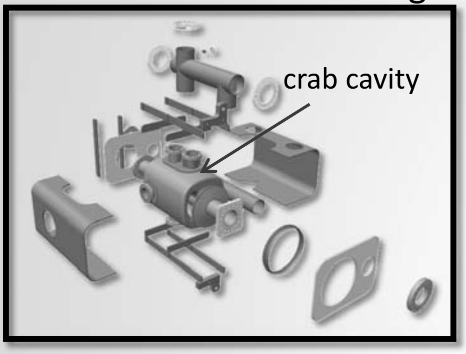


ILC/X-FEL 1.3 GHz, 8 cavity CM

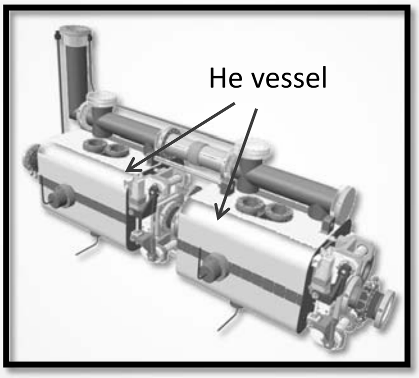
HL-LHC Crab Cavity test CM

High Luminosity LHC

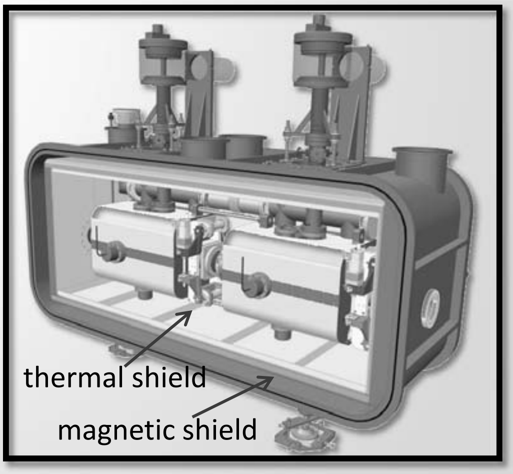
He vessel manufacturing



2-cavity string



Cryomodule



Presently under study!

T. Jones, S. Pattalwar

Science & Technology Facilities Council Daresbury Laboratory

CAVITY FABRICATION TECHNIQUES

Materials

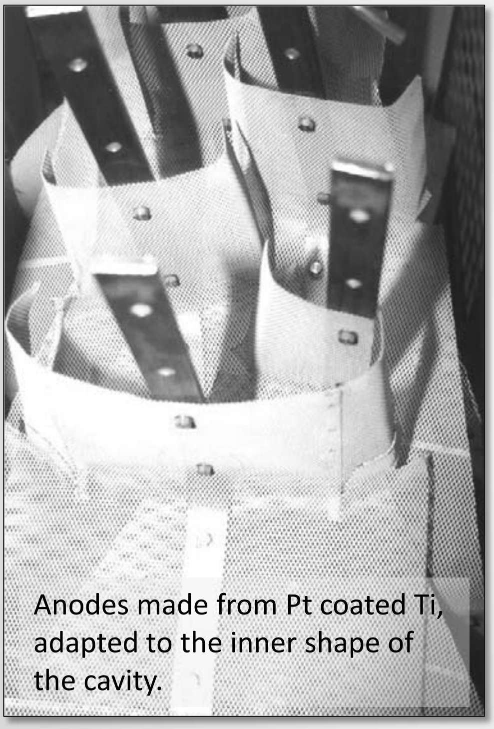
- Selection criteria
  - Electrical conductivity
  - Secondary emission yield
  - mechanical stiffness/hardness
  - thermal conductivity, thermal expansion
  - machining & joining techniques
  - vacuum tight, low outgassing rate
  - creep resistance,
  - magnetic permeability
  - radiation hardness
  - fatigue stress
  - …
- Important: specify what you need and what you can measure/control at reception!

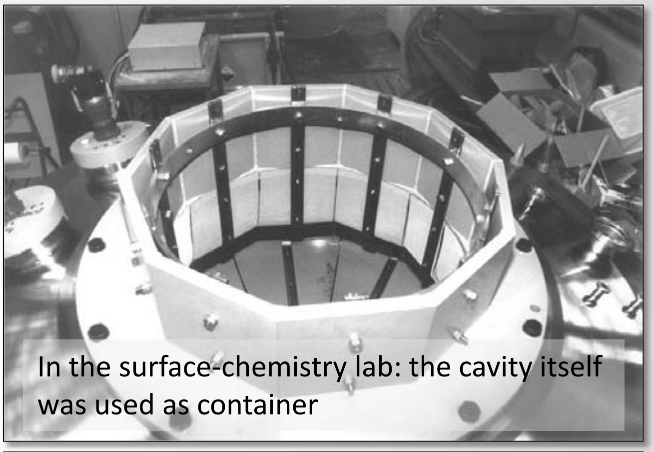
OFE copper

- Most room temperature cavities are made from copper (SLAC, CERN LEP, etc., B-factories) – (but still with plenty of exceptions, aluminium PEP).
- Solid OFE*) copper was used in LEP injector linac and the NC linear collider studies (NLC, JLC, CLIC). It is used for NC linacs today (Linac4, CLIC & CTF, linac based light sources and medical linacs).
- Copper becomes soft after annealing (or brazing). It is hardened by deformation (forging).
- The copper for the LEP storage cavities and for CERN's S-Band waveguides contain 0.1% silver (Cu-OFS), which increases the creep resistance by a factor 5.
- "official names": copper OFE Grade 1 (ASTM B224-98 oxygen free electronic, ISO 431 Cu-OFE, UNS C10100)

*) also called OFHC – oxygen free high conductivity

Galvanic Cu plating of stainless steel





Niobium

- Magnets use NbTi or Nb_3Sn, SC Cavities use mainly Nb!
- Pure Nb has a high critical magnetic field ($H_c = 200\ \mathrm{mT}$)
- Nb has a high transition temperature ($T_c = 9.3\ \mathrm{K}$).
- It is chemically inert (surface covered by oxide layer)
- It can be machined and deep-drawn
- It is available as bulk and sheet material in any size, fabricated by forging and rolling
- Large grain sizes (often favoured) obtained by e-beam melting
- Instead of bulk or sheet Nb, Nb can also be coated (e.g. by sputtering) on Cu – CERN has built the LEP, LHC and HIE-Isolde cavities with this technique. Advantages: thermal stability, material cost, optimisation of R_{BCS} possible; disadvantages: difficult technology to master, lower Q_0.

Nb ingot after EBM at Heraeus (D)

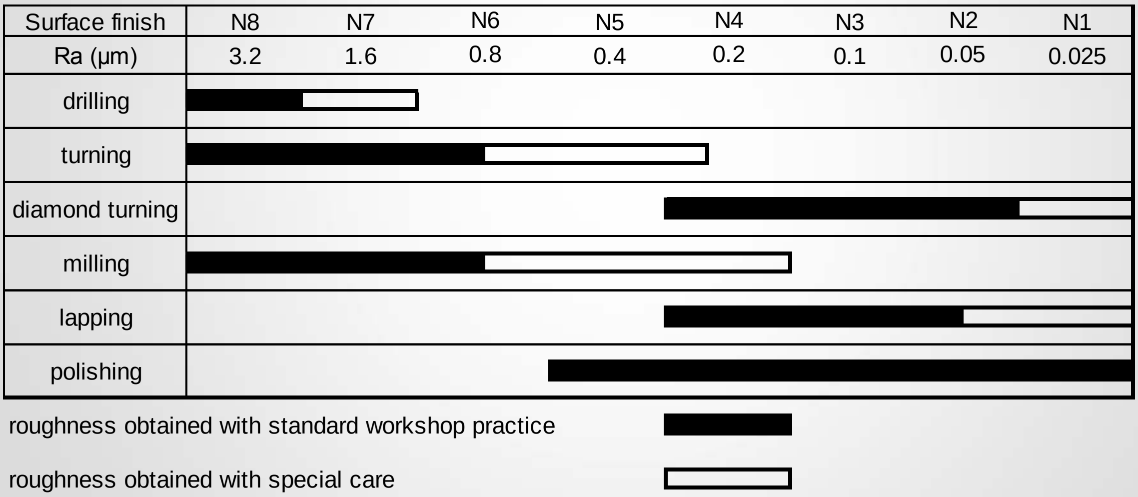
Dielectrics

- Aluminium oxide, AL_2O_3, aka Alumina, is often used in vacuum/RF windows and vacuum feed-throughs.
- Isostatically pressed AL_2O_3 is used for leak-tightness (LEP power couplers, e.g.)
- To reduce multipactor, it is often coated with titanium or titanium nitride (TiN).
- Other window materials: Sapphire, BeO, quartz, diamond …)
- Silicon carbide (SiC), C-loaded AlN have been effectively used as RF absorbers inside vacuum.
- Different ferrites are used as absorbers and to use their variable magnetic permeability.

Coax transition through alumina window with traces of breakdown

Metal forming

Typical surface finish for classical machining operations

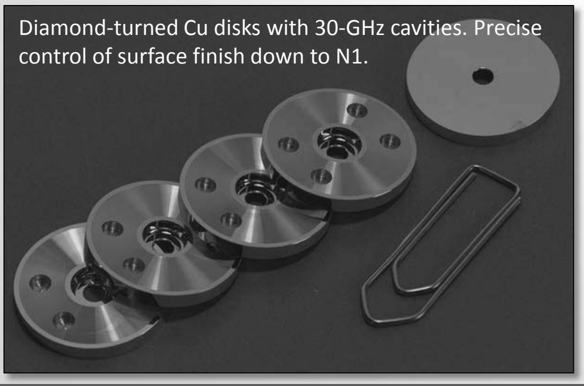


Turning

Classical industrial technique; cheap and accurate, gives excellent surface finish. Applies to a wide range of cavity dimensions (frequencies).

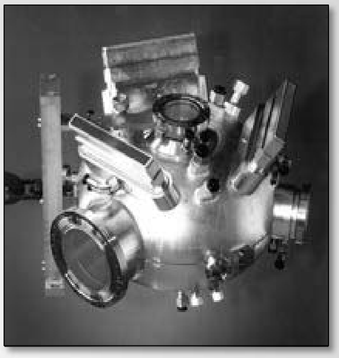
NB.:

- Cutting fluids should be oil-free and sulphur free.
- High-speed machining with diamond tools can be made with alcohol or even dry.


Diamond-turned Cu disks with 30-GHz cavities. Precise control of surface finish down to N1.


Part of the PS 40 MHz cavity after raw machining

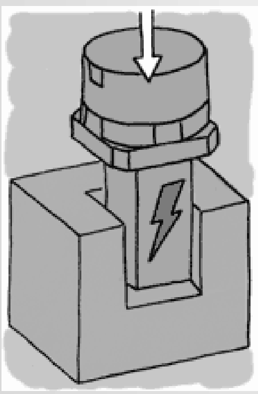
5-axis milling



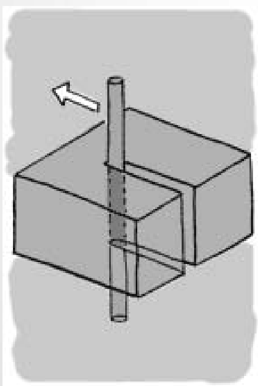
Direct 5-axis milling of cooling water circuit groove in PEPII cavity.

EDM (Electric discharge machining)

- Machines el. conductors (metals, alloys, carbides, graphite etc.) by creating sparks with temperatures of 8,000 to 12,000 °C. The part and the electrode are immersed in a dielectric liquid, usually water or mineral oil. There are two types of EDM, die sinking and wire cutting.



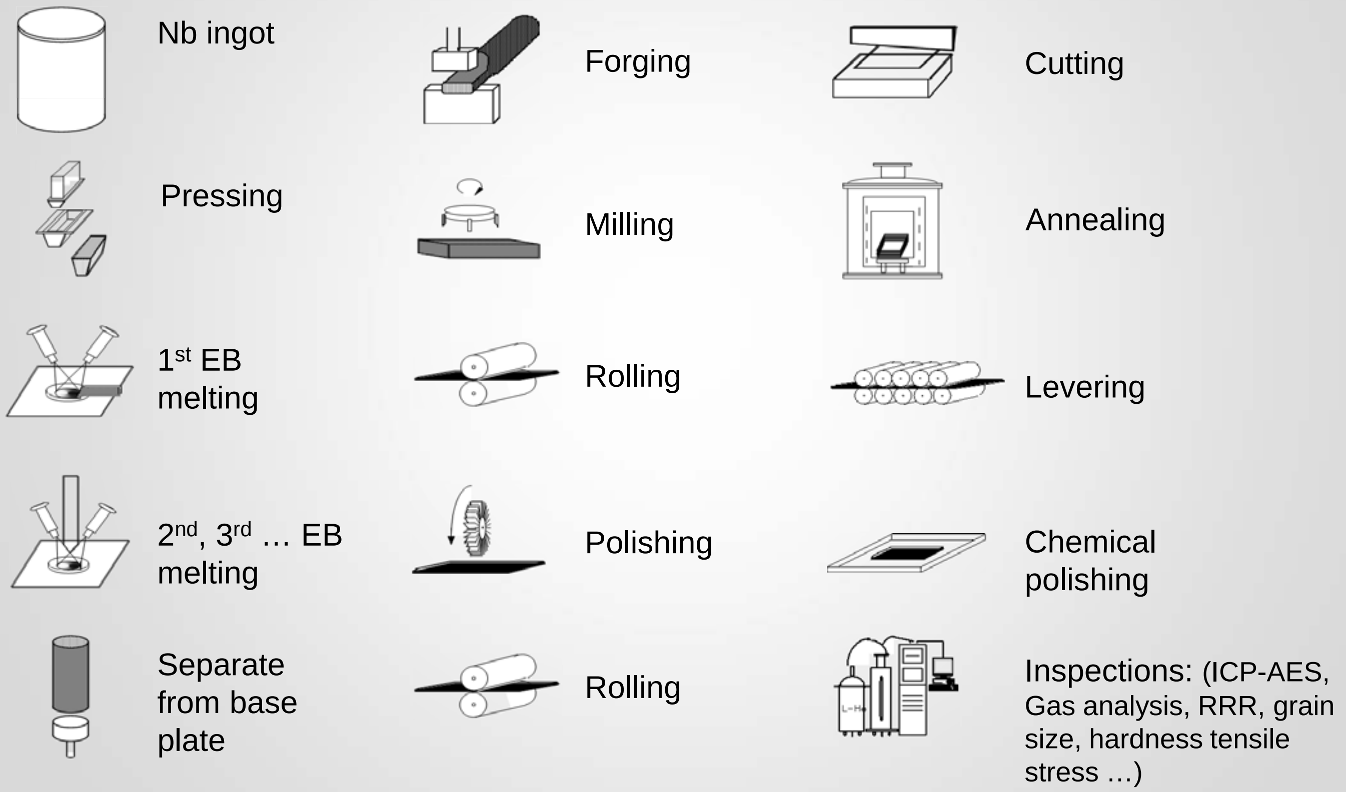
die sinking



wire cutting

wire cutting of the iris slots of SICA (slotted iris – constant aperture) disks for CERN's CTF3 drive beam accelerator

Fabrication of Nb sheets at 東京電解 Tokyo Denkai

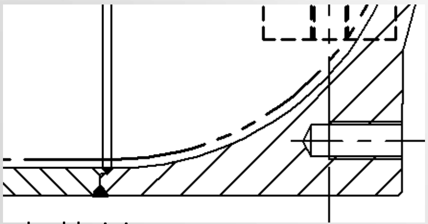


Other forming techniques

- Forging, pressing, deep drawing, …
- Spinning, planing, rolling, …
- lapping, polishing, electropolishing, …
- Electroforming, hydroforming, explosion forming
- Powder metal techniques, 3-D printing
- Sputtering
- …

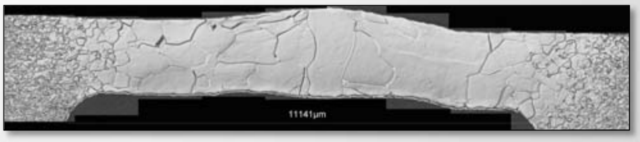
Joining techniques

TIG welding



double joint:
inner for vacuum,
out for mechanical stability

EB welding

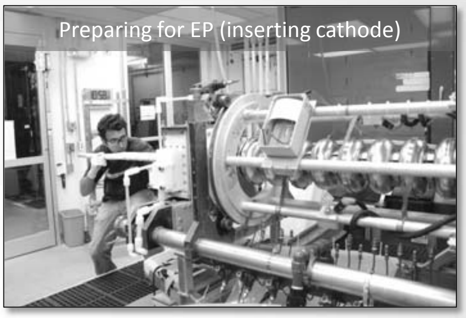


Microstructure of the EB welding area
grain size (50 ÷ 2000) µm

Advances in SCRF Technology

Step		WHY
Forming		
EB Welding		Clean welding
Ti purification		RRR enhancement
Chemical etching 100-200 µm	BCP EP	Remove contamination and damage layer
Annealing 800°C, 2h (or 600°C, 10h)		Get rid of hydrogen
Chemical etching 5-20 µm		Remove diffusion layer (O, C, N)
Specific rinsing		e.g. remove S particles due to EP
High pressure rinsing (HPR)		Get rid of dust particles
Assembling		Ancillaries : antennas, couplers, vacuum ports…
Baking, 120°C, 48h		Decrease high field losses (Q-drop)
Post processing		Get rid of "re-contamination" ?
Test RF		Cavity's performance
He processing, HPP		Decrease field emission

C. Antoine: CAS SC 2013


Preparing for EP (inserting cathode)

Photos: Rongli Geng


Clean room assembly (JLAB)

THANK YOU VERY MUCH!