EASISchool 3

Superconductivity
and its applications

Dates: 28/9/2020-9/10/2020
Genoa, Italy

Cavity Design

Elliptical and non-elliptical cavities

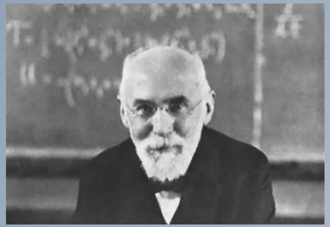
Erk JENSEN, CERN

https://cernbox.cern.ch/index.php/s/E4qimjeXzf67RLS
Password: easischool

Outline

- From waveguide to cavity
- Characterizing a cavity
- Multipactor
- Many gaps
- **Elliptical cavities**
- Higher Order Modes
- **Non-elliptical cavities**
- Power couplers
- Tuners

From Waveguide to Cavity



Hendrik A. Lorentz
1853 – 1928

Lorentz force

- A charged particle moving with velocity $\vec{v} = \frac{\vec{p}}{m\,\gamma}$ through an electromagnetic field in vacuum experiences the Lorentz force $\frac{\boldsymbol{d\vec{p}}}{\boldsymbol{dt}} = \boldsymbol{q}\big(\vec{\boldsymbol{E}} + \vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}\big)$.
- 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):

$$W dW = c^2 \vec{p} \cdot d\vec{p} = qc^2 \vec{p} \cdot \big(\vec{E} + \vec{v} \times \vec{B}\big) dt = qc^2 \vec{p} \cdot \vec{E} dt$$

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

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

James Clerk Maxwell
1831 – 1879

Maxwell's equations in vacuum

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:

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

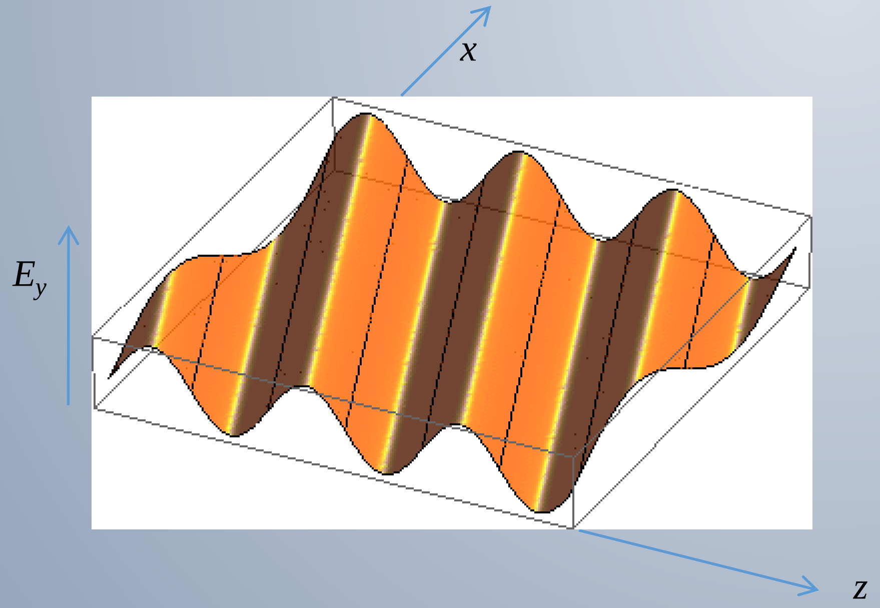
Using the vector identity $\nabla \times \nabla \times \vec{E} = \nabla\nabla \cdot \vec{E} - \nabla^2\vec{E}$ and the 4th Maxwell equation, this yields:

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

i.e. the 4-dimensional Laplace equation.

Homogeneous plane wave

$$\vec{E} \propto \vec{u}_y \cos\left(\omega t - \vec{k}\cdot\vec{r}\right)$$
$$\vec{B} \propto \vec{u}_x \cos\left(\omega t - \vec{k}\cdot\vec{r}\right)$$
$$\vec{k}\cdot\vec{r} = \frac{\omega}{c}\left(z\cos\varphi + x\sin\varphi\right)$$



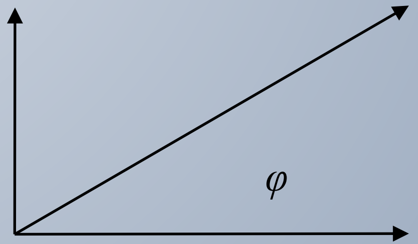
Wave vector $\vec{k}$:

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

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

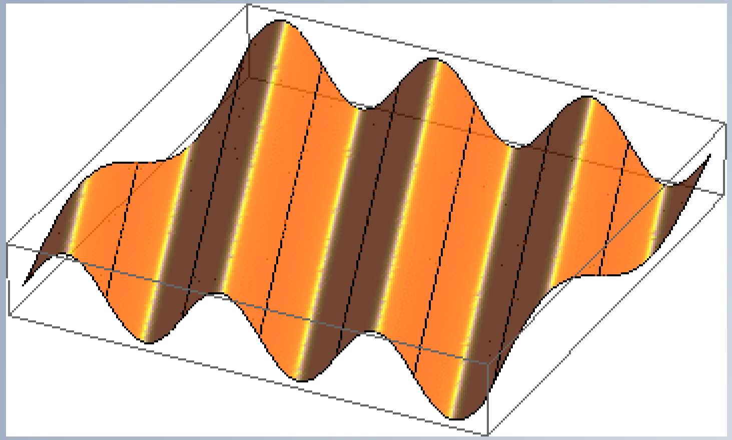
$\vec{k}$ behaves like a vector.

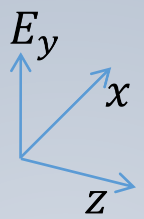
$$k_\perp = \frac{\omega_c}{c} \qquad k = \frac{\omega}{c}$$



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

Superposition of 2 homogeneous plane waves





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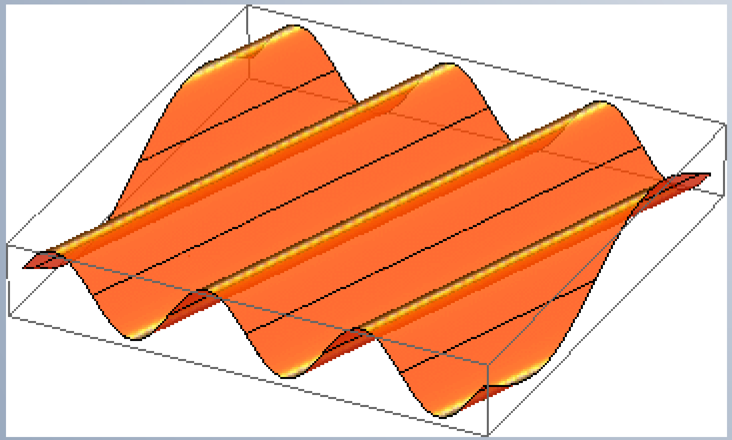

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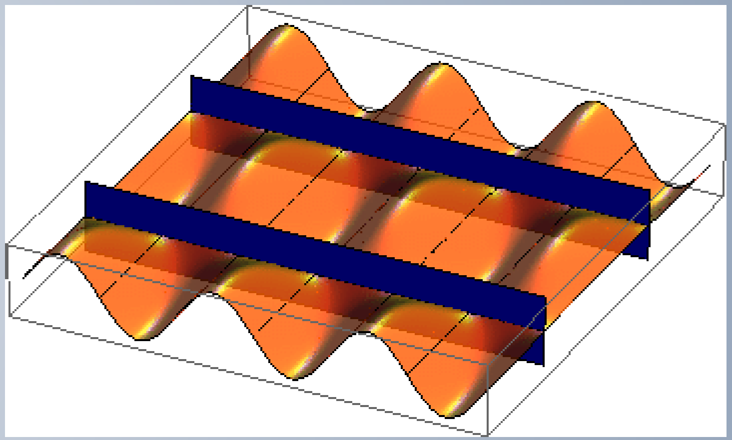


Metallic walls may be inserted where $E_y \equiv 0$

without perturbing the fields.

Note the standing wave in x-direction!

This way one gets a hollow rectangular waveguide.

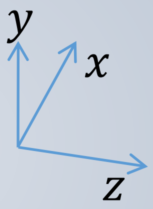

Photo:
Reidar Hahn

Rectangular waveguide

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

Example 1: "S-band": 2.6 GHz ... 3.95 GHz,

Waveguide type WR284 (2.84" wide), dimensions:
72.14 mm x 34.04 mm.
cut-off: $f_c = 2.078$ GHz.



Example 2: "L-band" : 1.13 GHz ... 1.73 GHz,

Waveguide type WR650 (6.5" wide), dimensions:
165.1 mm x 82.55 mm.
cut-off: $f_c = 0.908$ GHz.

Both these pictures correspond to operation at 1.5 f_c.

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

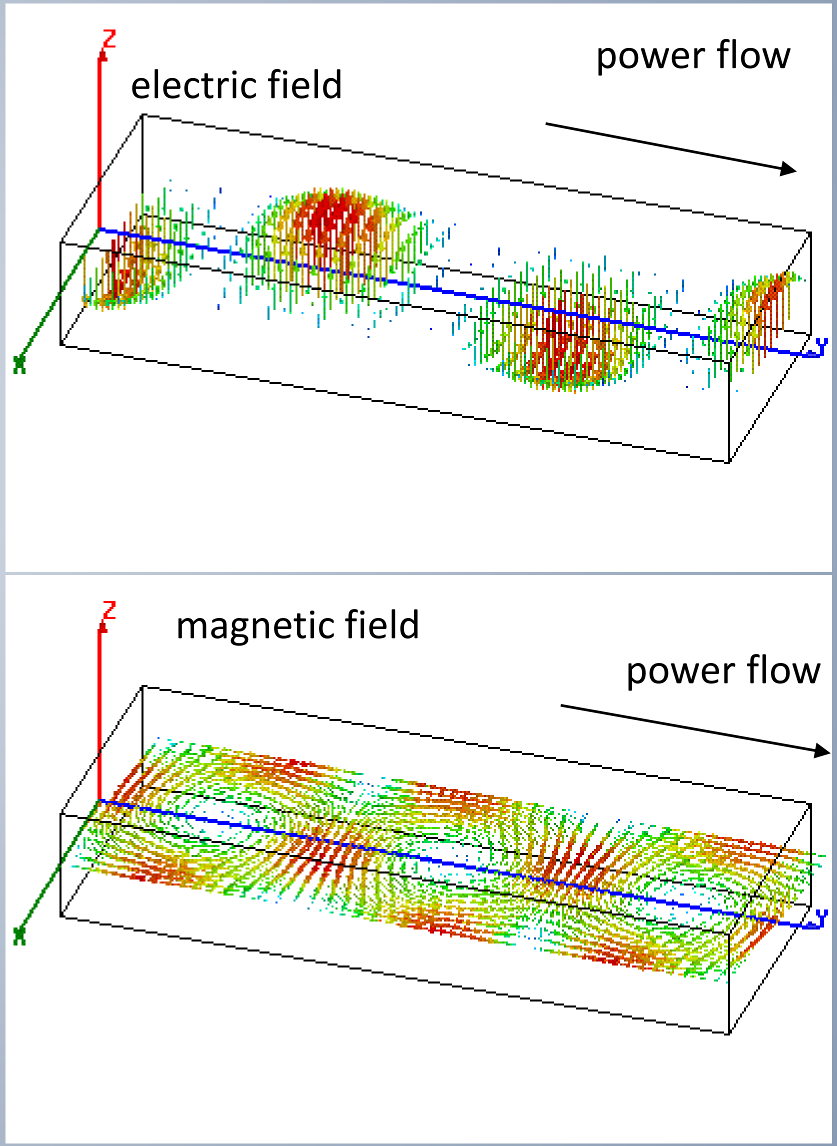
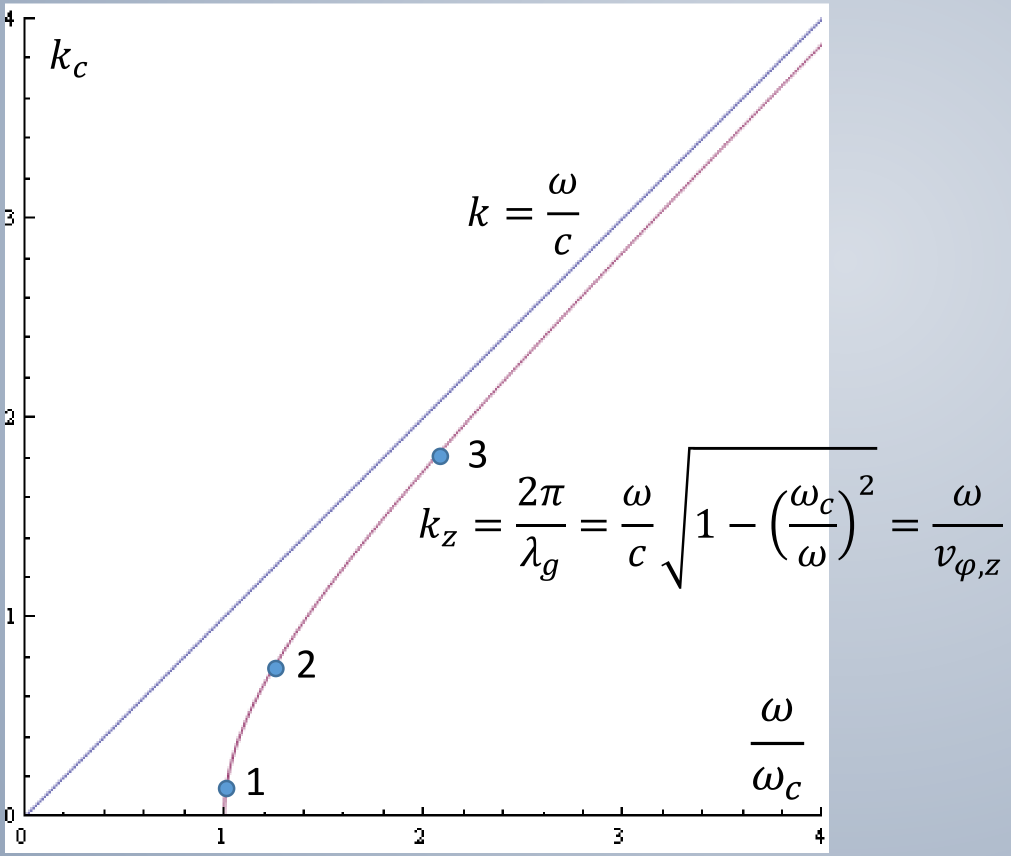


Photo: Reidar Hahn

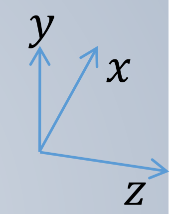
Waveguide dispersion – phase velocity $v_{\varphi,z}$

The phase velocity $v_{\varphi,z}$ is the speed at which the crest (or zero-crossing) travels in z-direction.
Note on the 3 animations on the right that, at constant f, $v_{\varphi,z} \propto \lambda_g$. Note also that at $f = f_c$, $v_{\varphi,z} = \infty$!
With $f \to \infty$, $v_{\varphi,z} \to c$!



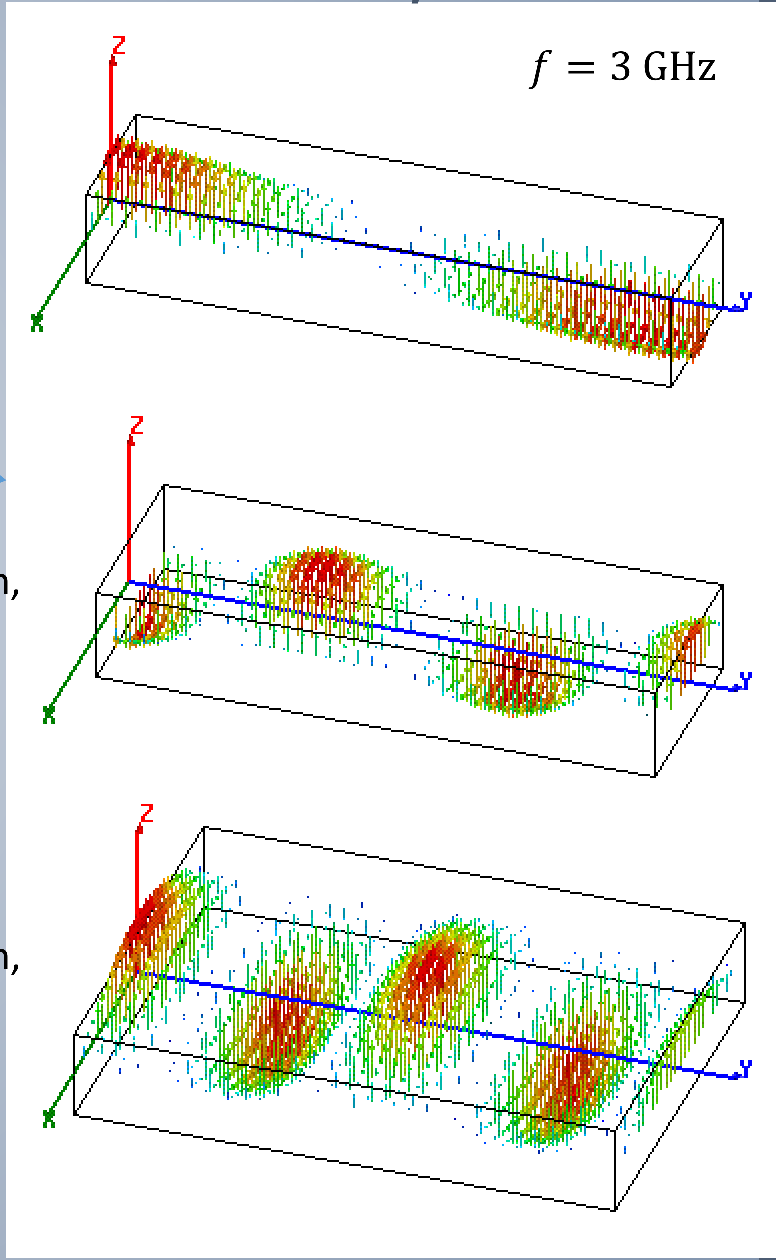
cutoff: $f_c = \frac{c}{2a}, v_{\varphi,z} = \infty$

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:

$$k_z = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_\perp^2} = \frac{\omega}{c}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}$$

Propagation in z-direction: $\propto e^{j(\omega t - k_z z)}$

$Z_0 = \frac{\omega\mu}{k_z}$ for TE, $Z_0 = \frac{k_z}{\omega\varepsilon}$ for TE

$$k_z = \frac{2\pi}{\lambda_g}$$

Example: TE10-mode in a rectangular waveguide of width a:

$$k_\perp = \frac{\pi}{a}$$

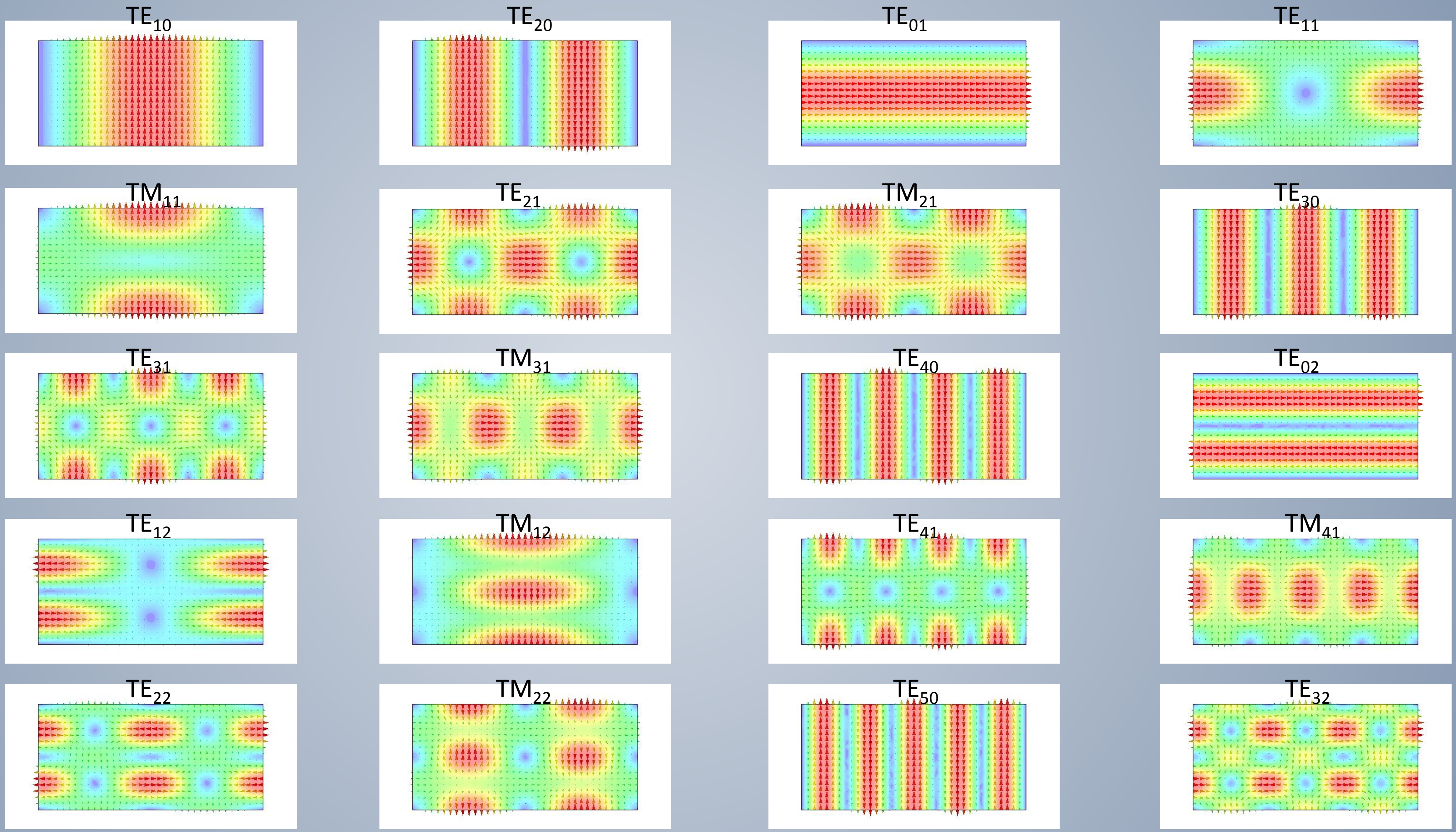
$$\gamma = \mathrm{j}\sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{\pi}{a}\right)^2}$$

$$Z_0 = \frac{\omega\mu}{k_z}$$

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

In a hollow waveguide: phase velocity $v_\varphi > c$, group velocity $v_{gr} < c$, $v_{gr} \cdot v_\varphi = c^2$.

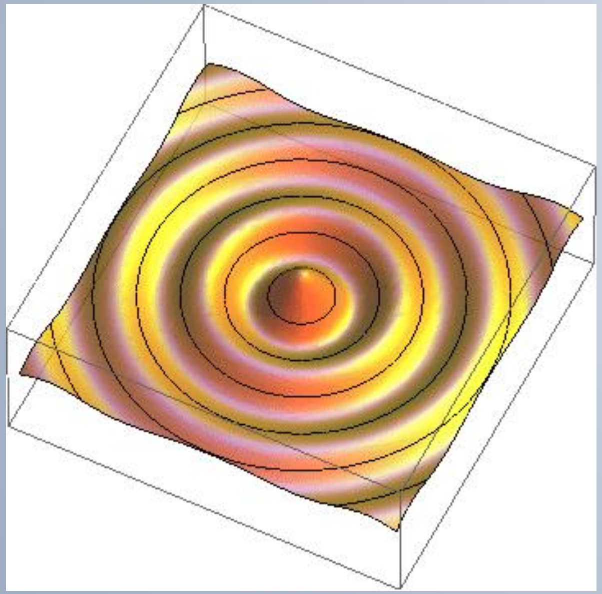
Rectangular waveguide modes



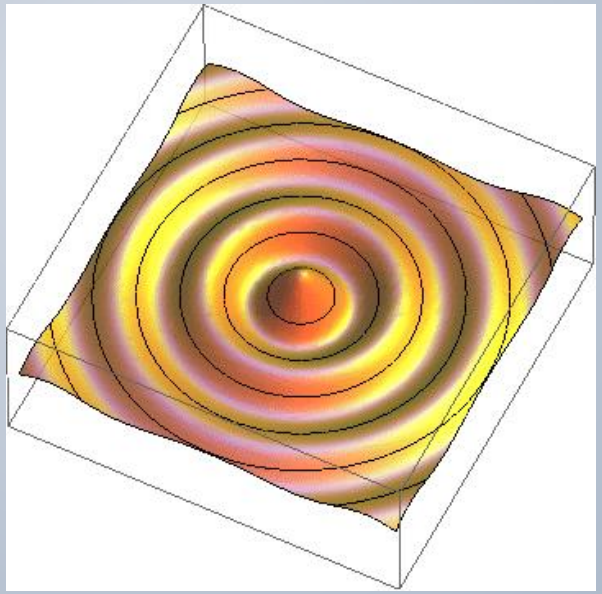
plotted: *E*-field

Radial waves

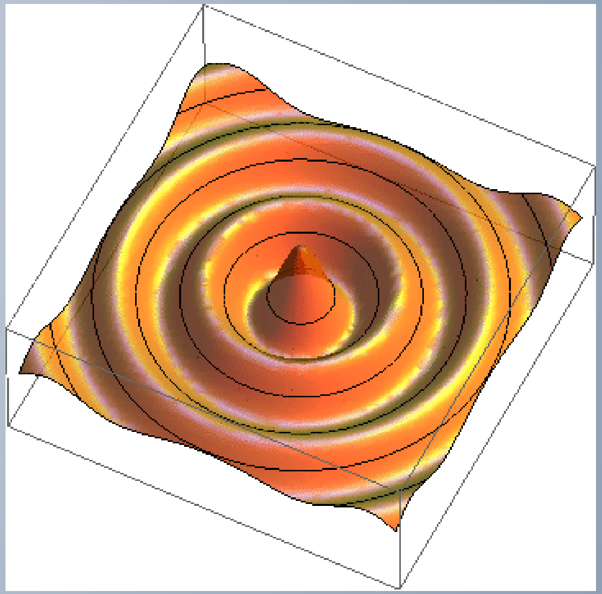
Also radial waves may be interpreted as superposition of plane waves. The superposition of an outward and an inward radial wave can result in the field of a round hollow waveguide.



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



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



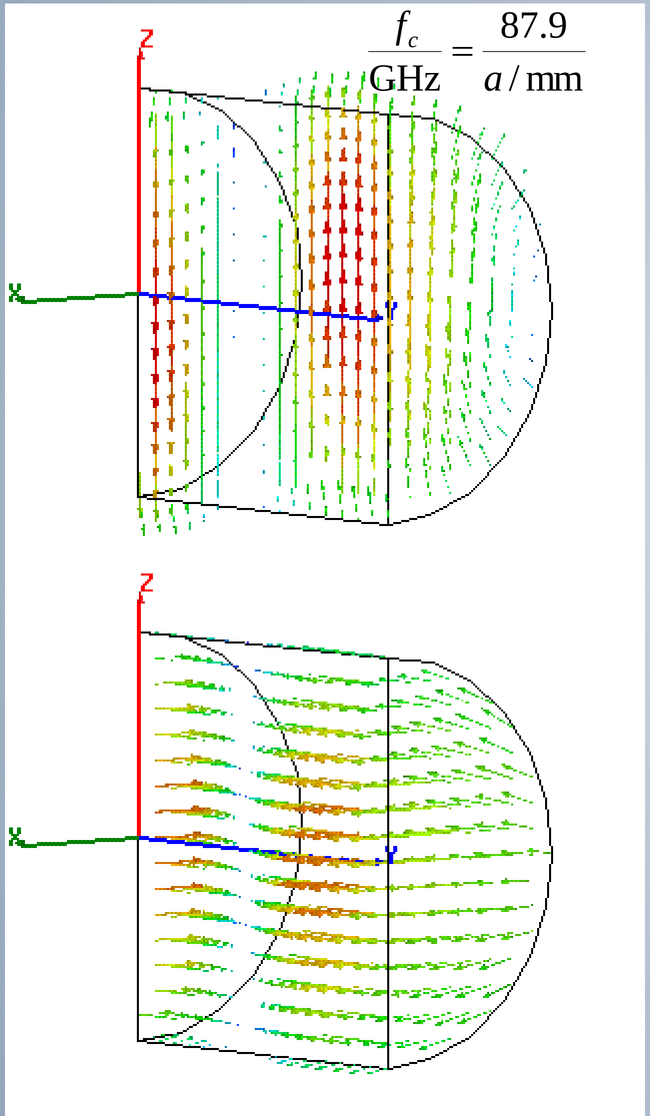
$$E_z \propto J_n(k_\rho \rho)\cos(n\varphi)$$

Round waveguide

$f/f_c = 1.44$

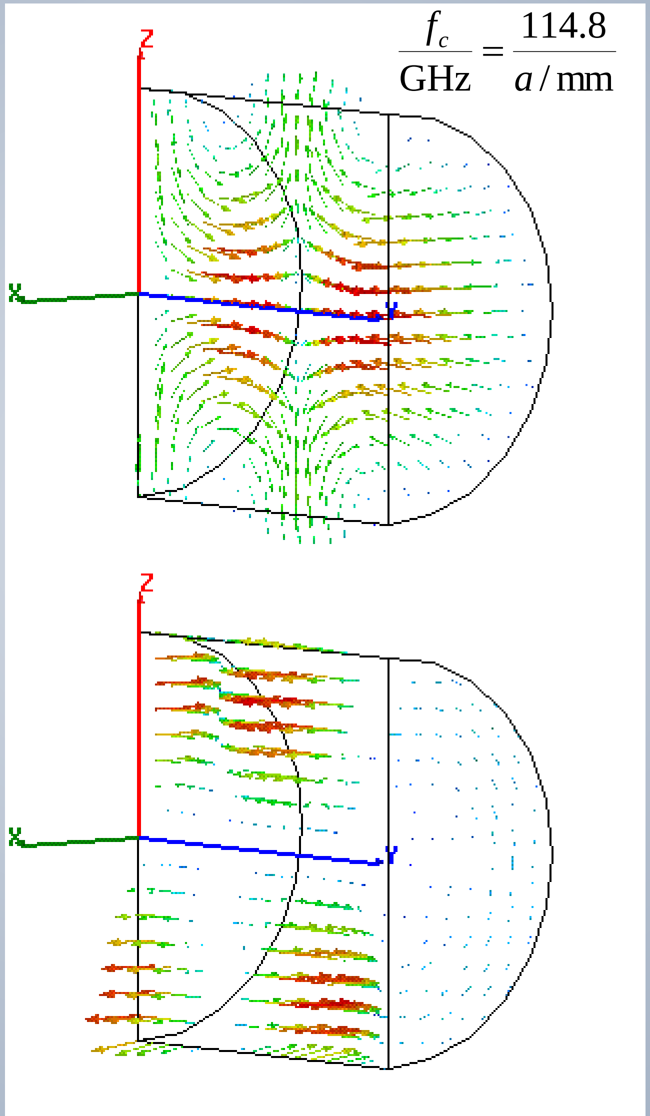
TE_{11} – fundamental

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



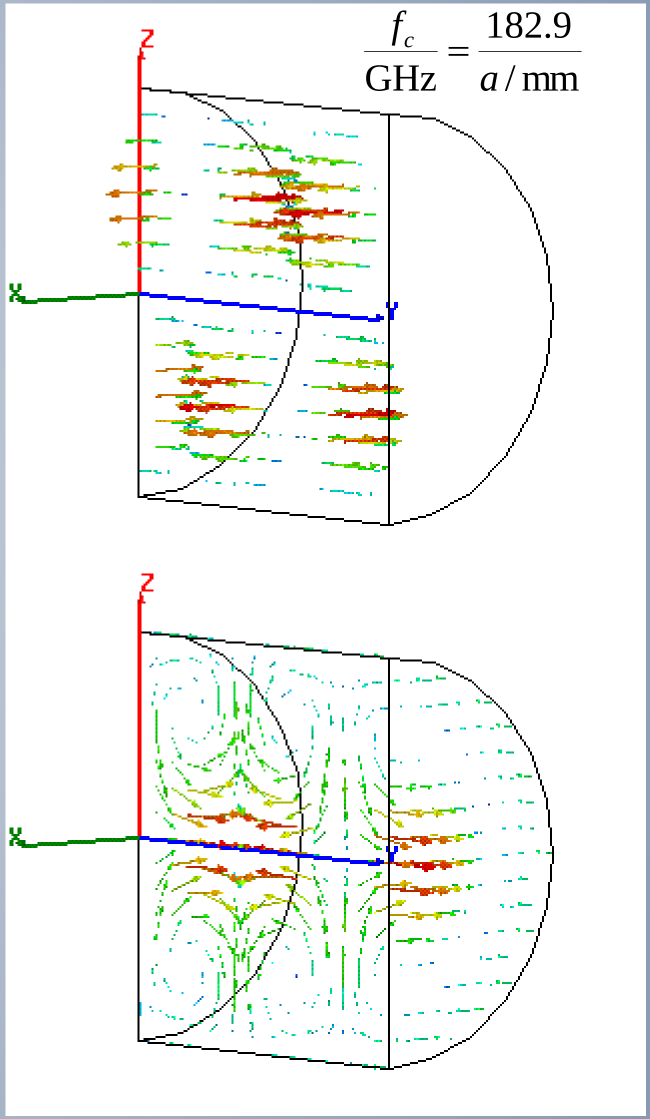
TM_{01} – axial field

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

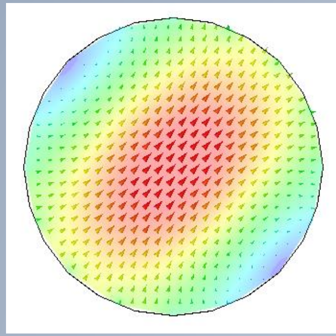


TE_{01} – low loss

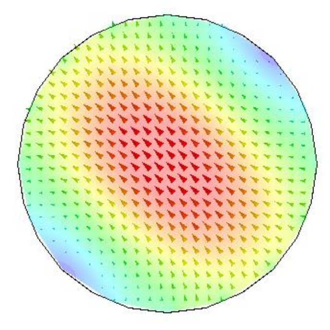
$$\frac{f_c}{\mathrm{GHz}} = \frac{182.9}{a\,/\,\mathrm{mm}}$$



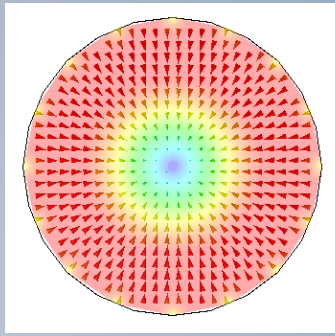
Circular waveguide modes



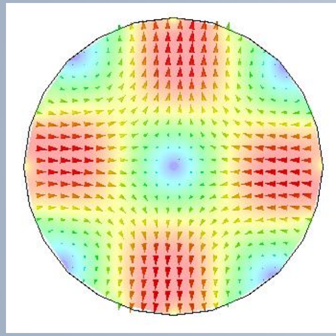
TE_{11}



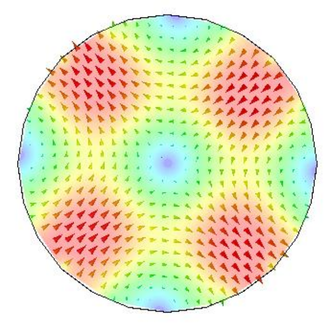
TE_{11}



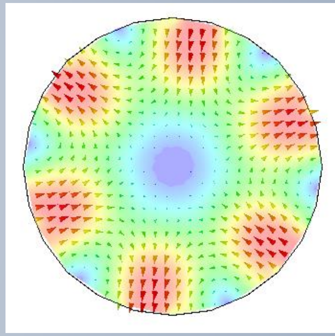
TM_{01}



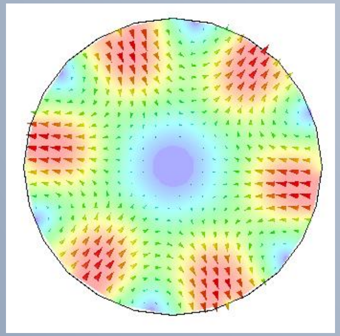
TE_{21}



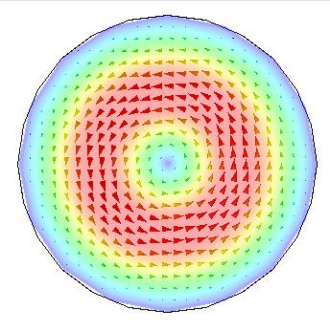
TE_{21}



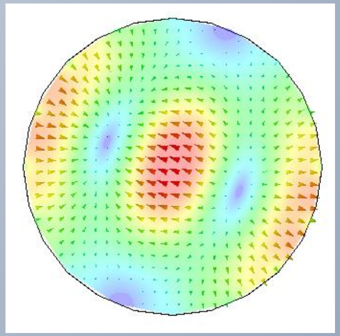
TE_{31}



TE_{31}



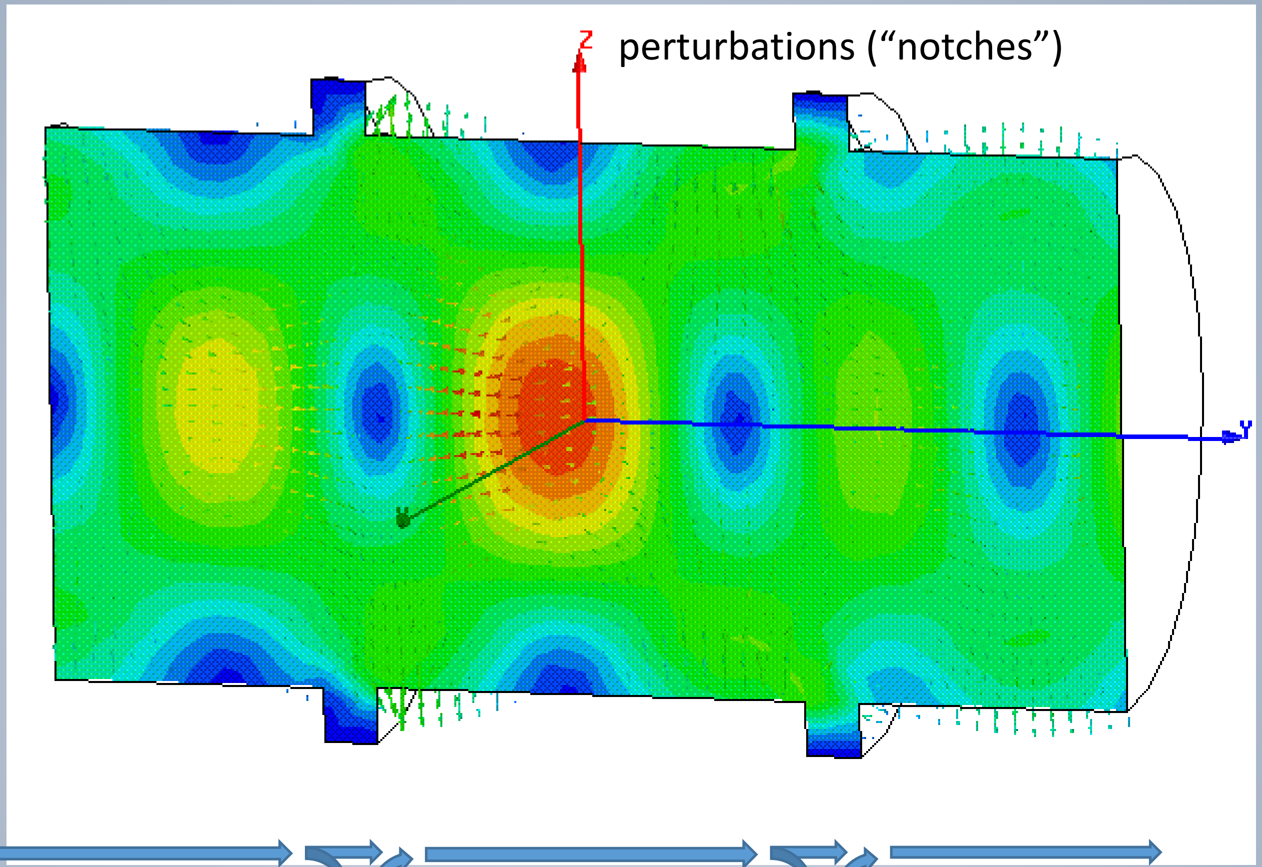
TE_{01}

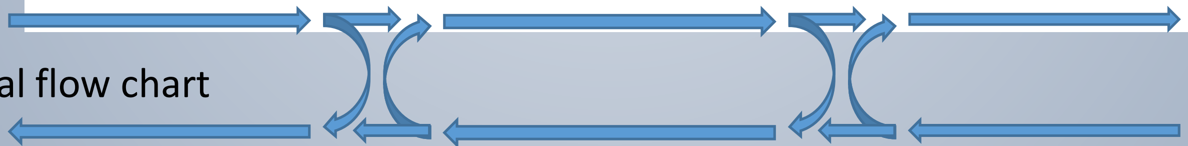


TM_{11}

plotted: *E*-field

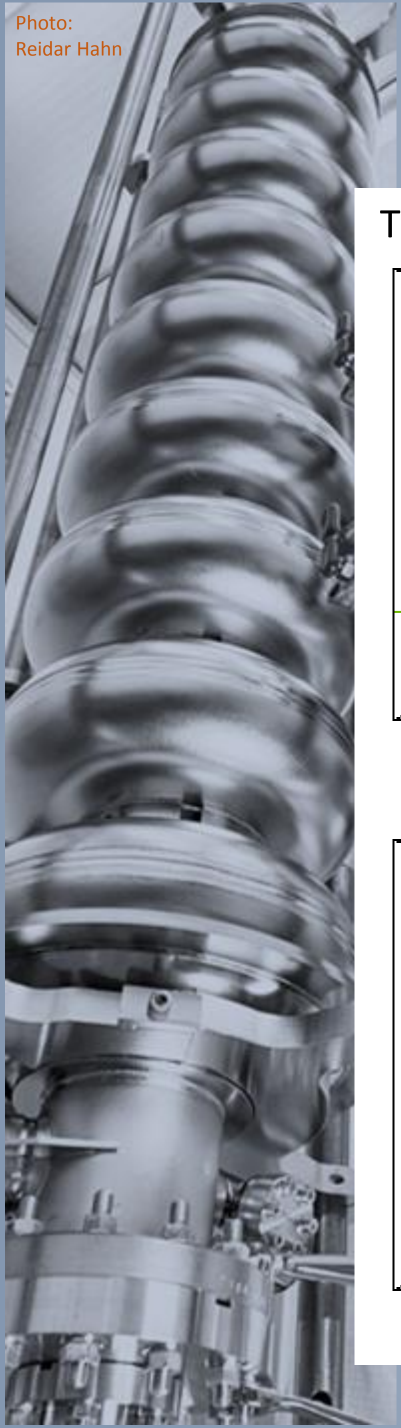
Waveguide perturbed by notches





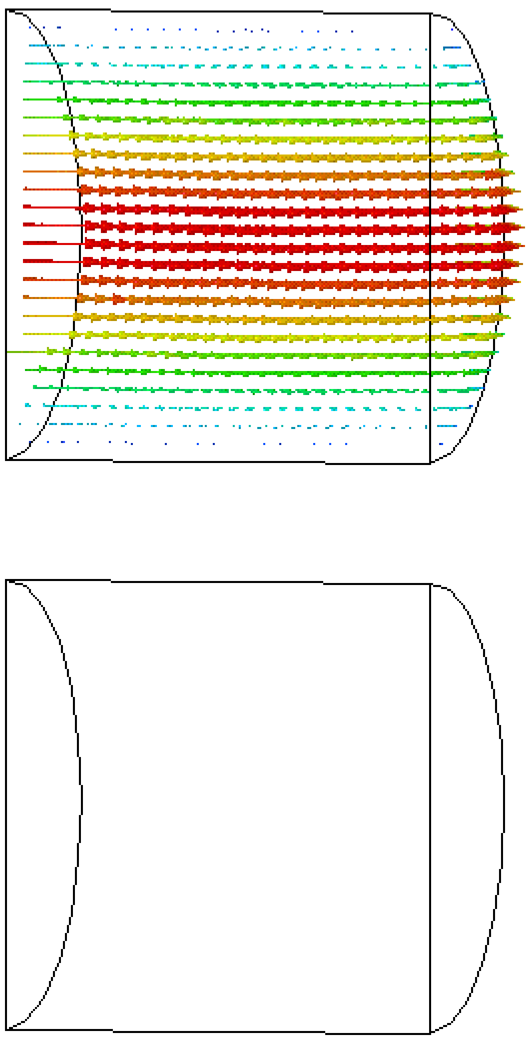
Signal flow chart

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

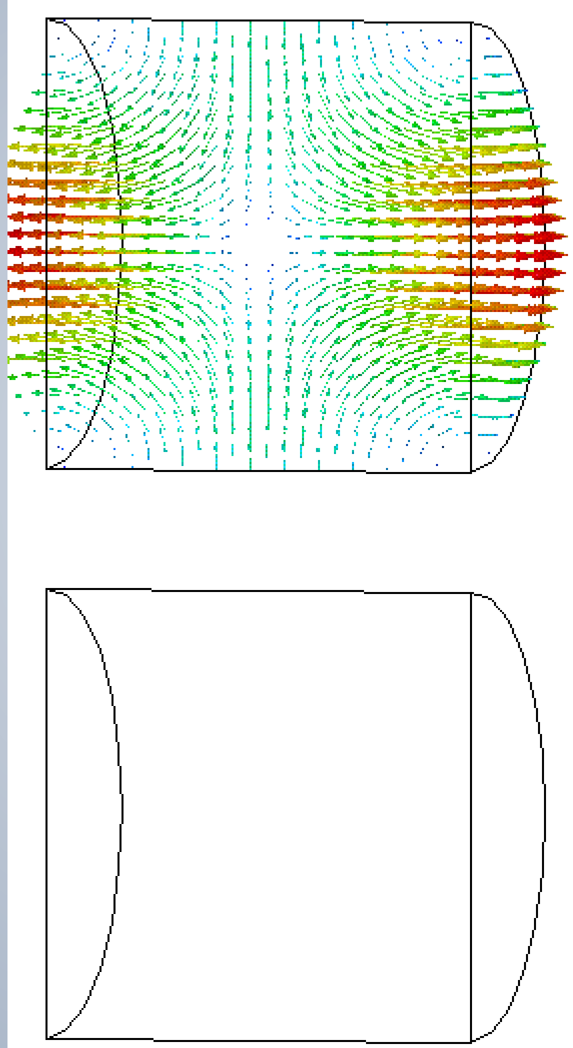


Short-circuited waveguide

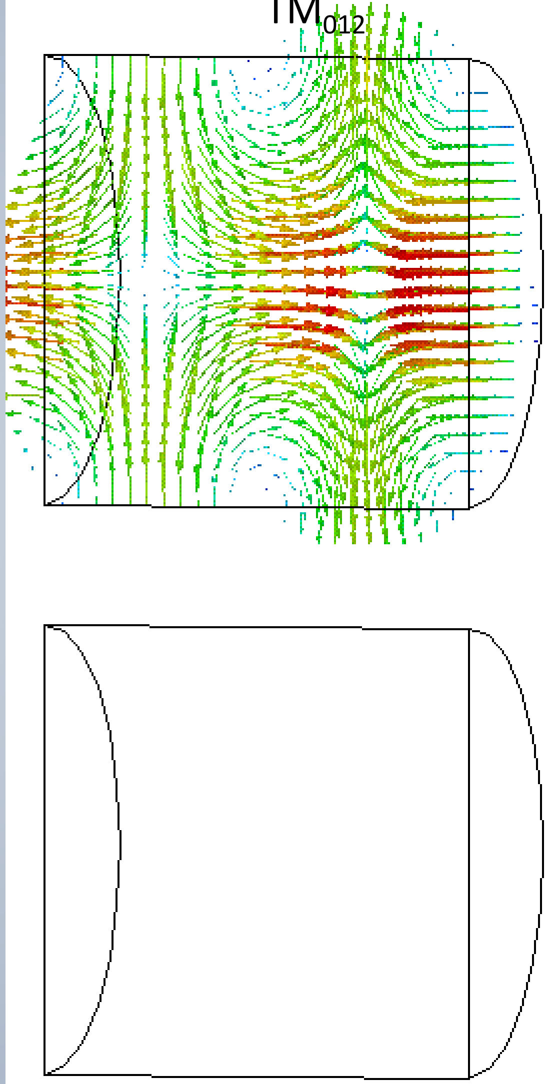
TM_{010} (no axial dependence)



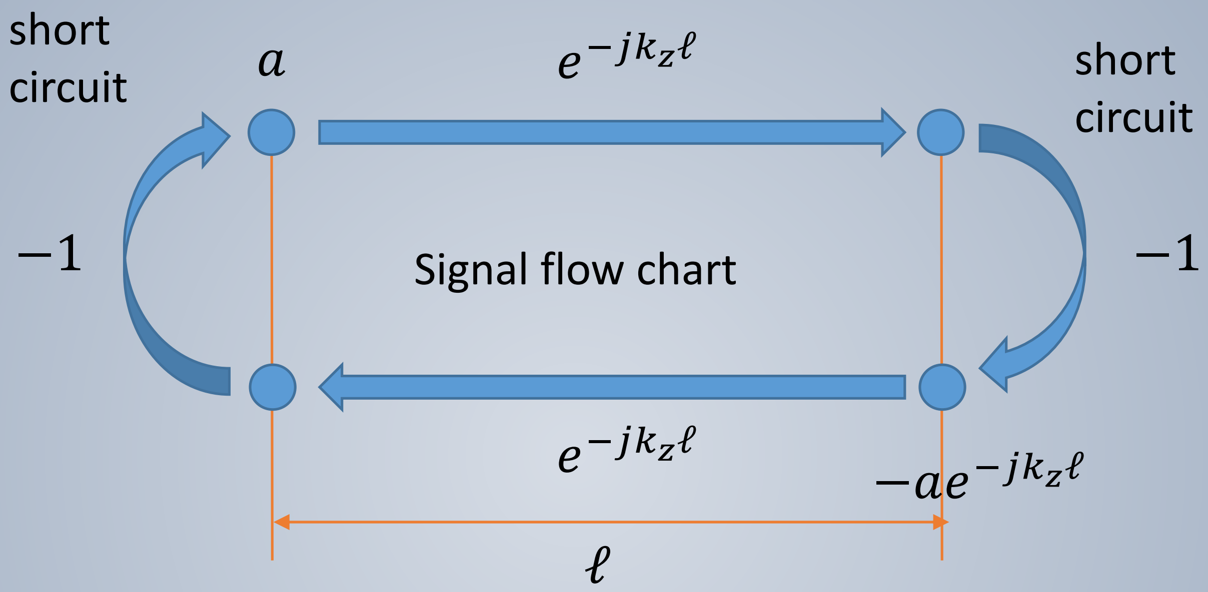
TM_{011}



TM_{012}



Single WG mode between two shorts



Eigenvalue equation for field amplitude a:

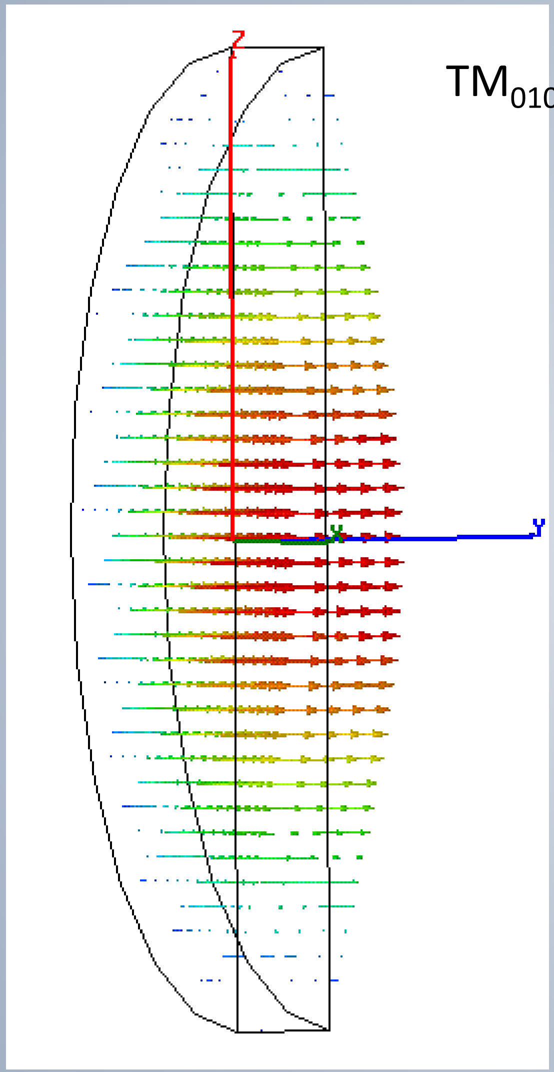
$$a = e^{-\mathrm{j}k_z 2\ell} a$$

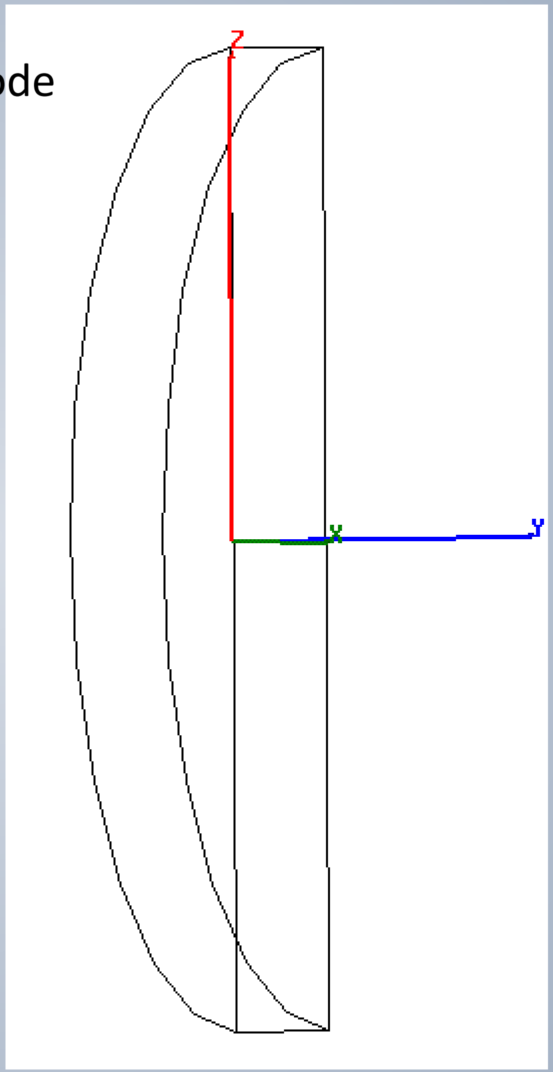
Non-vanishing solutions exist for $2k_z\ell = 2\pi m$:

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)

TM$_{010}$-mode



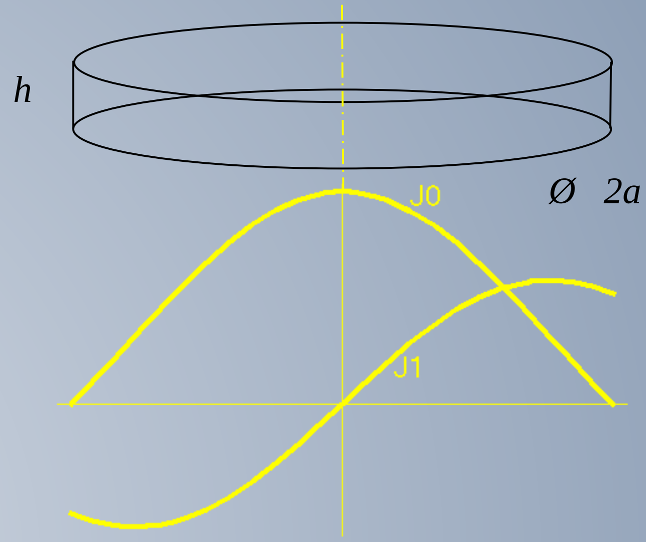


electric field (purely axial)   magnetic field (purely azimuthal)

Pillbox cavity field (w/o beam tube)

$$T(\rho,\varphi) = \sqrt{\frac{1}{\pi}}\,\frac{J_0\left(\frac{\chi_{01}\rho}{a}\right)}{\chi_{01}\,J_1\left(\frac{\chi_{01}}{a}\right)}$$

with $\chi_{01} = 2.40483\ldots$



The only non-vanishing field components :

$$E_z = \frac{1}{j\omega\varepsilon}\,\frac{\chi_{01}}{a}\,\sqrt{\frac{1}{\pi}}\,\frac{J_0\left(\frac{\chi_{01}\rho}{a}\right)}{a\,J_1\left(\frac{\chi_{01}}{a}\right)}$$

$$B_\varphi = \mu_0\sqrt{\frac{1}{\pi}}\,\frac{J_1\left(\frac{\chi_{01}\rho}{a}\right)}{a\,J_1\left(\frac{\chi_{01}}{a}\right)}$$

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

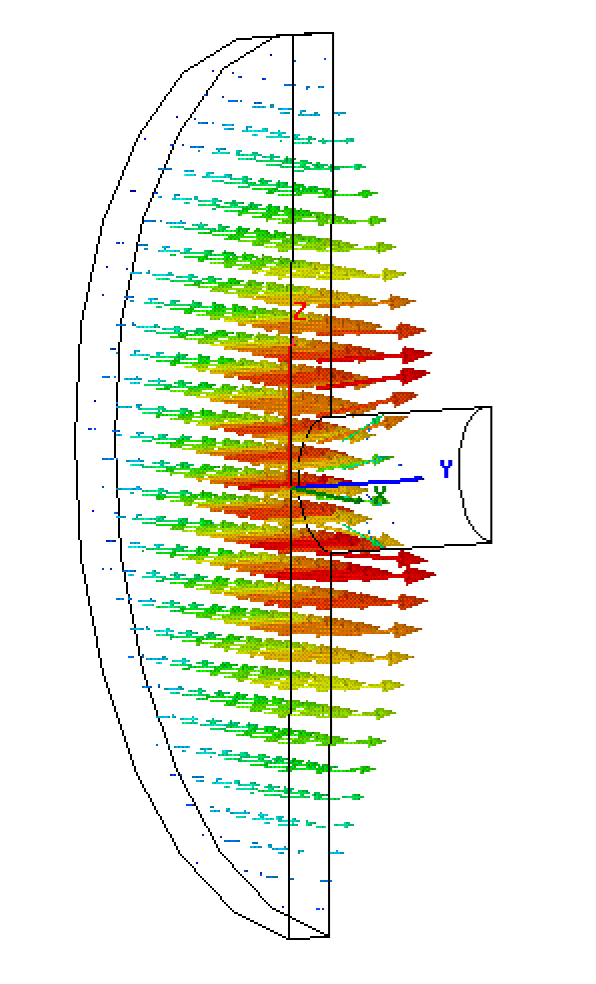
$$Q\,\bigg|_{\text{pillbox}} = \frac{\sqrt{2a\eta\sigma\chi_{01}}}{2\left(1+\frac{a}{h}\right)}$$

$$\frac{R}{Q}\bigg|_{\text{pillbox}} = \frac{4\eta}{\chi_{01}^3\pi J_1^2(\chi_{01})}\,\frac{\sin^2\left(\frac{\chi_{01}}{2}\frac{h}{a}\right)}{h/a}$$

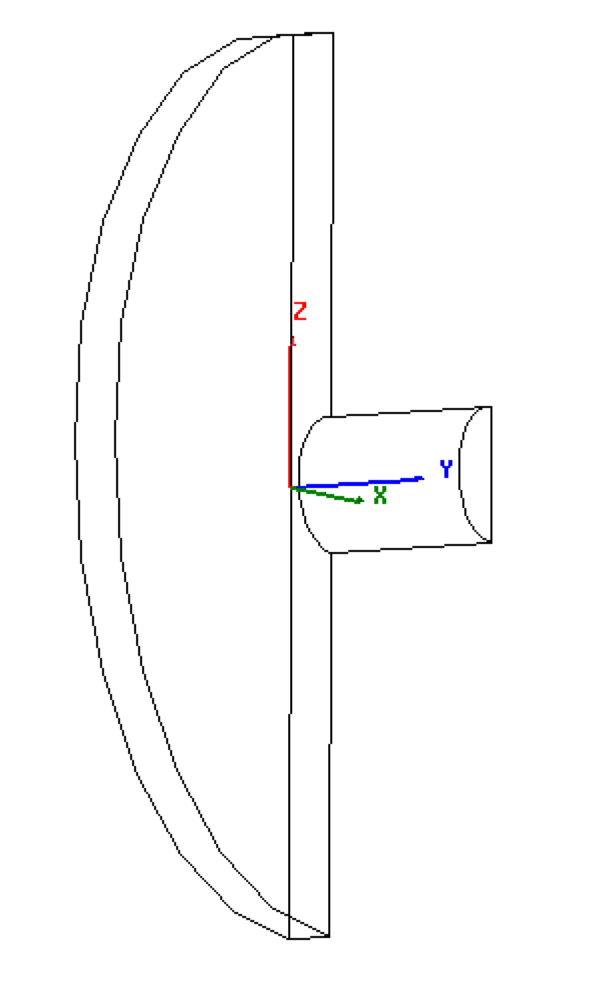
Pillbox with beam pipe

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

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



electric field

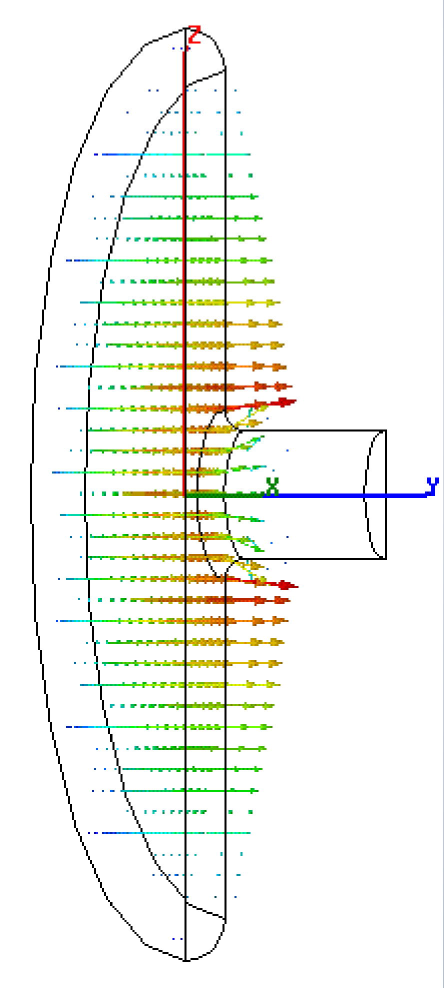


magnetic field

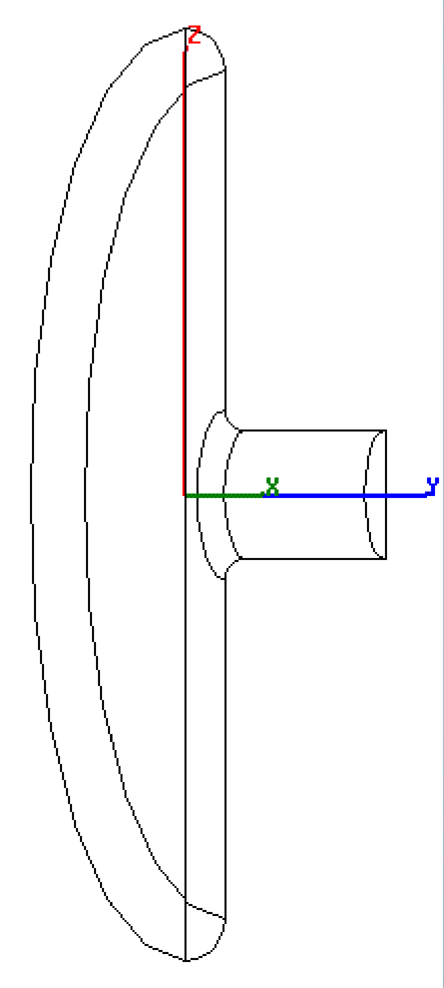
A more practical pillbox cavity

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

Rounding of sharp edges (to reduce field enhancement!)



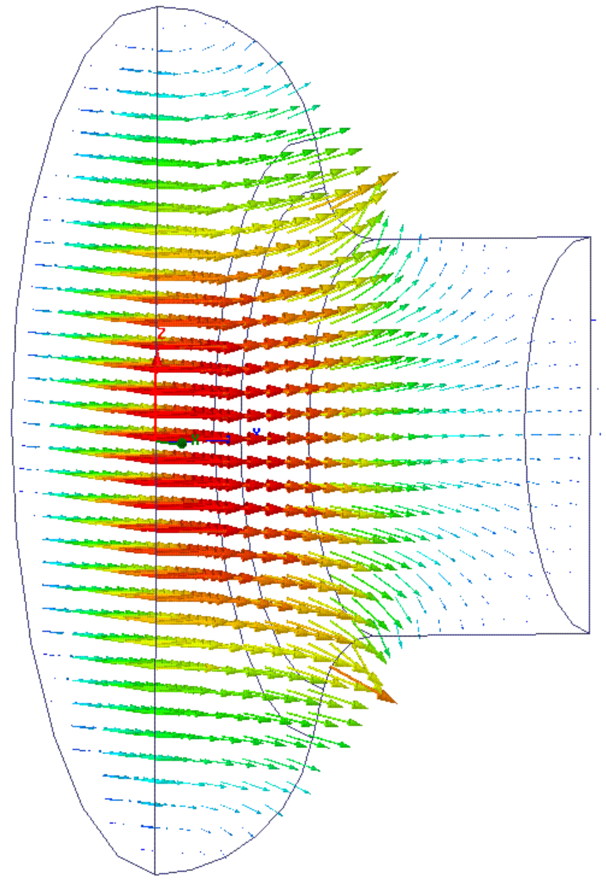
electric field



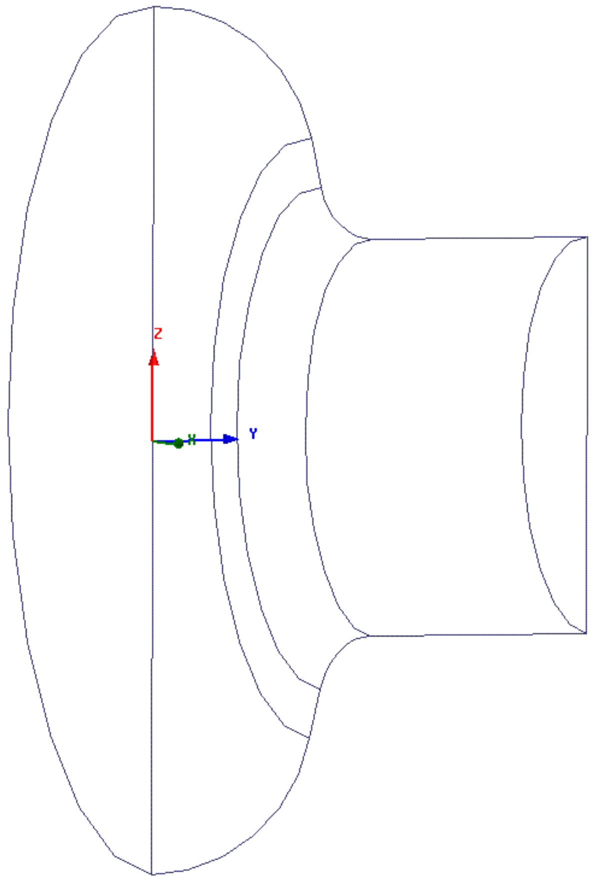
magnetic field

A (real) elliptical cavity

TM$_{010}$-mode (only 1/4 shown)



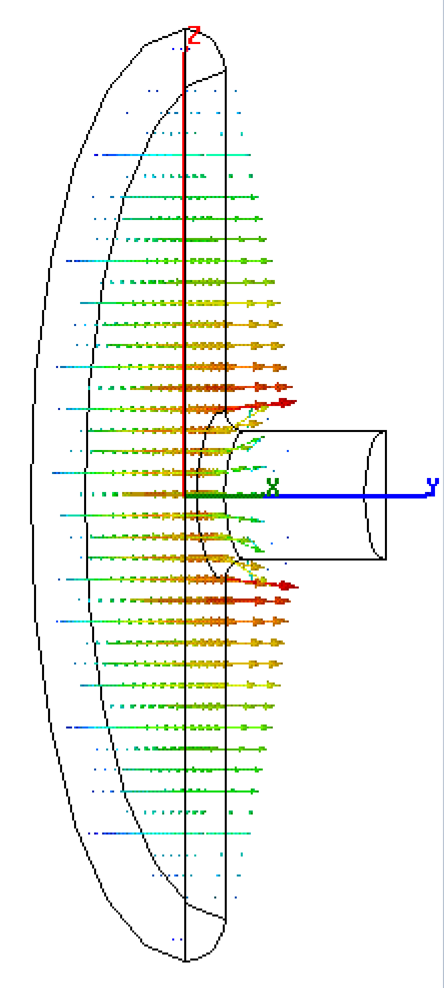
electric field



magnetic field

Characterizing a Cavity

Acceleration voltage and R/Q



electric field

- I define

$$V_{\mathrm{acc}} = \int_{-\infty}^{\infty} E_z e^{j\frac{\omega}{\beta c}z}\, dz\,.$$

- The exponential factor accounts for the variation of the field while particles with velocity βc are traversing the cavity gap.
- With this definition, V_{acc} is generally complex – this becomes important with more than one gap (cell).
- For the time being we are only interested in $|V_{\mathrm{acc}}|$.
- The square of the acceleration voltage $|V_{\mathrm{acc}}|^2$ is proportional to the stored energy W; the proportionality constant defines the quantity called "R-upon-Q":

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

- **Attention – different definitions are used in literature!**

Transit time factor

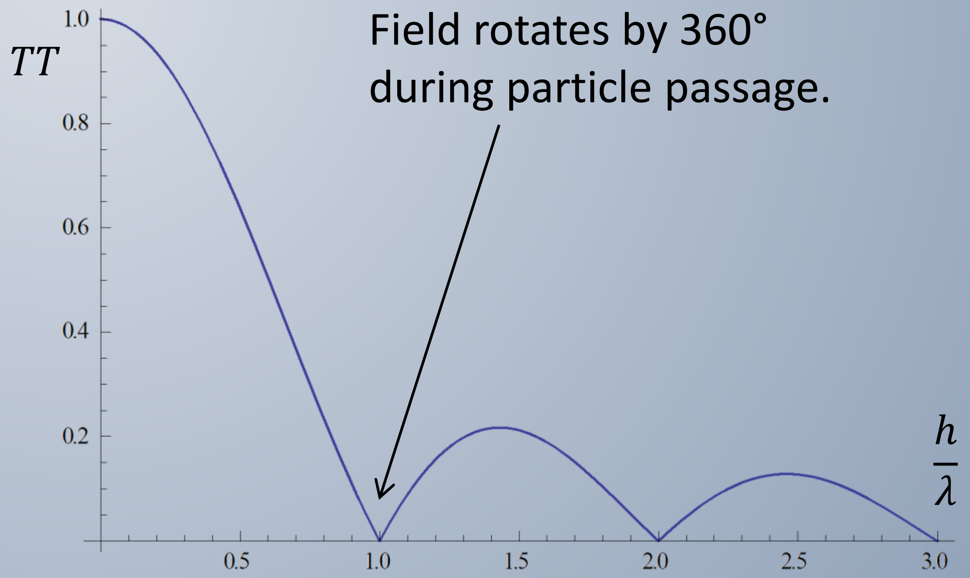
- The transit time factor is the ratio of the acceleration voltage to the (non-physical) voltage a particle with infinite velocity would see:

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

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

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

(remember: $\omega_0 = \frac{2\pi c}{\lambda} = \frac{\chi_{01} c}{a}$)



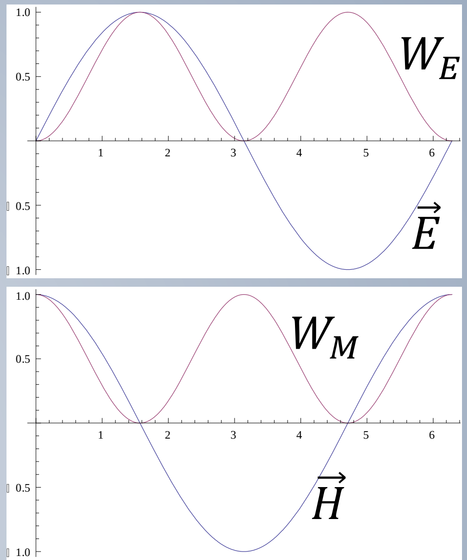
Stored energy

- The energy stored in the electric field is

$$W_E = \iiint\limits_{\text{cavity}} \frac{\varepsilon}{2} \left|\vec{E}\right|^2 dV\,.$$

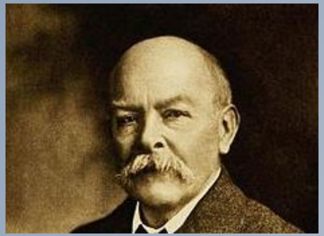
- The energy stored in the magnetic field is

$$W_M = \iiint\limits_{\text{cavity}} \frac{\mu}{2} \left|\vec{H}\right|^2 dV\,.$$



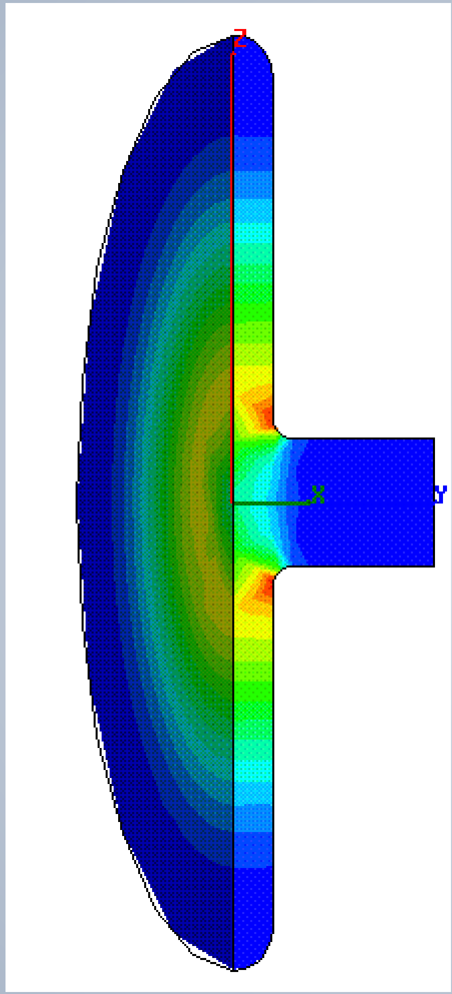
- Since $\vec{E}$ and $\vec{H}$ are $90°$ out of phase, the stored energy continuously swaps from electric energy to magnetic energy.
- On average, electric and magnetic energy must be equal.
- In steady state, the Poynting vector describes this energy flux.
- In steady state, the total energy stored (constant) is

$$W = \iiint\limits_{cavity} \left(\frac{\varepsilon}{2}\left|\vec{E}\right|^2 + \frac{\mu}{2}\left|\vec{H}\right|^2\right) dV.$$

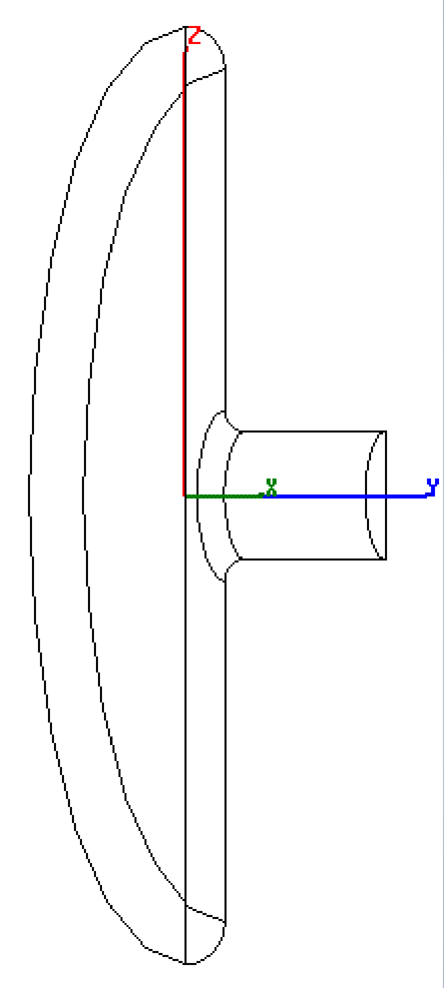


John Henry Poynting
1852 – 1914

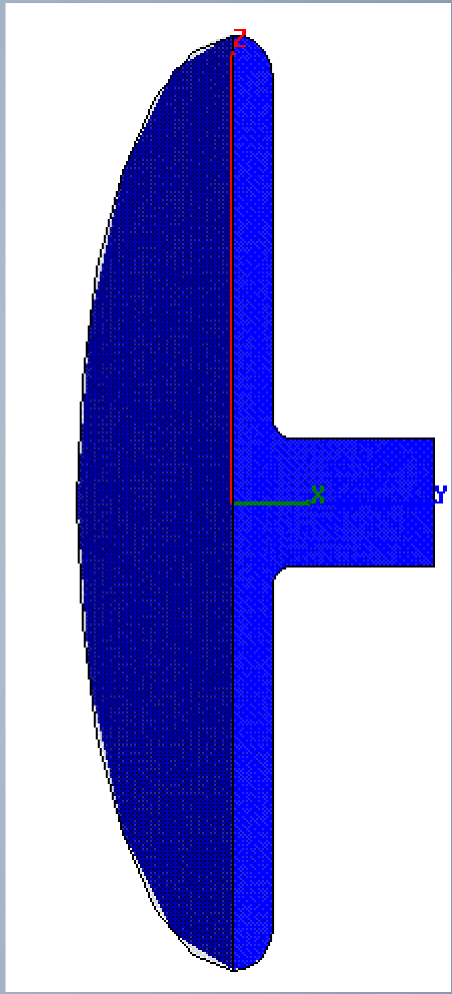
Stored energy and Poynting vector



electric field energy



Poynting vector



magnetic field energy

Wall losses & Q_0

- The losses P_{loss} are proportional to the stored energy W.
- The tangential $\vec{H}$ on the surface is linked to a surface current $\vec{J}_A = \vec{n} \times \vec{H}$ (flowing in the skin depth $\delta = \sqrt{2\,/\,(\omega\mu\sigma)}$).
- This surface current $\vec{J}_A$ sees a surface resistance R_s, resulting in a local power density $R_s|H_t|^2$ flowing into the wall.
- R_s is related to skin depth δ as $\delta\sigma R_s = 1$.
  - Cu at 300 K has $\sigma \approx 5.8 \cdot 10^7\,\text{S/m}$, leading to $R_s \approx 8\ \text{m}\Omega$ at 1 GHz, scaling with $\sqrt{\omega}$.
  - Nb at 2 K has a typical $R_s \approx 10\ \text{n}\Omega$ at 1 GHz, scaling with ω^2.
- The total wall losses result from $P_{\text{loss}} = \iint_{\text{wall}} R_s|H_t|^2\,dA$.
- The cavity Q_0 (caused by wall losses) is defined as $Q_0 = \frac{\omega_0 W}{P_{\text{loss}}}$.
- Typical Q_0 values:
  - Cu at 300 K (normal-conducting): $\mathcal{O}(10^3 \ldots 10^5)$, **should** improve at cryogenic T by a factor $\approx \sqrt{RRR}$.
  - Nb at 2 K (superconducting): $\mathcal{O}(10^9 \ldots 10^{11})$

No! Anomalous skin effect!
improves only by a factor ≈ 10!


Photo: Reidar Hahn

Shunt impedance

- Also the power loss P_{loss} is also proportional to the square of the acceleration voltage $|V_{\text{acc}}|^2$; the proportionality constant defines the "shunt impedance"

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

- **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.
- Now the previously introduced term "R-upon-Q" makes sense:

$$\left(\frac{R}{Q}\right) = R/Q$$

Geometric factor

- With

$$Q_0 = \frac{\omega_0 W}{\iint\limits_{\text{wall}} R_s |H_t|^2 \, dA},$$

and assuming an average surface resistance R_s, one can introduce the “geometric factor” G as

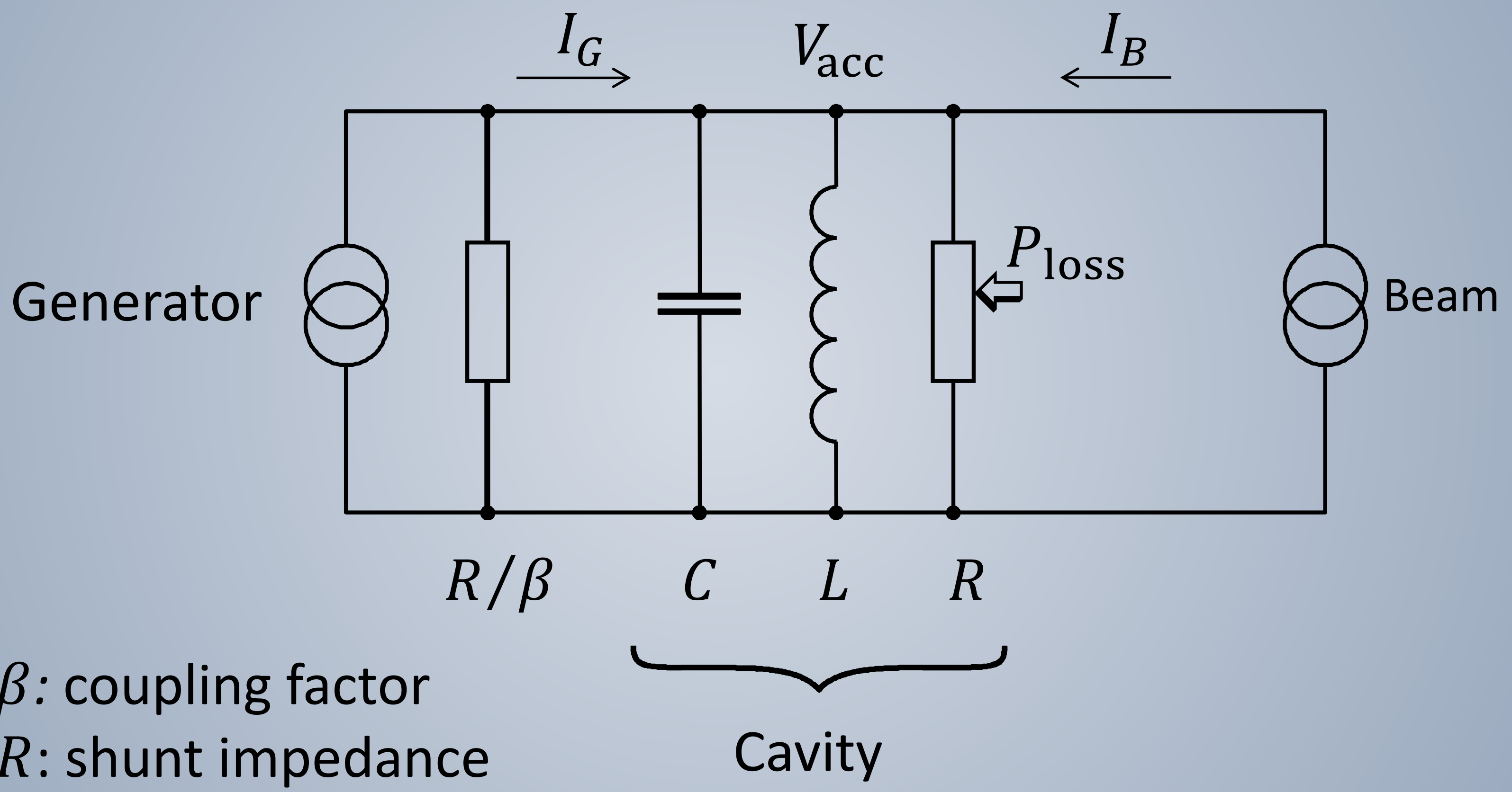
$$G = Q_0 \cdot R_s = \frac{\omega_0 W}{\iint\limits_{\text{wall}} |H_t|^2 \, dA}.$$

- G has dimension Ohm, depends only on the cavity geometry (as the name suggests) and typically is $\mathcal{O}(100\ \Omega)$.
- Note that $R_s \cdot R = G \cdot (R/Q)$ (dimension Ω^2, purely geometric)
- G is only used for SC cavities.


Photo: Reidar Hahn

Cavity resonator – equivalent circuit

Simplification: single mode



β: coupling factor
R: shunt impedance
$\sqrt{L/C} = \frac{R}{Q}$: R-upon-Q

Photo:
Reidar Hahn

Power coupling - Loaded Q

- Note that the generator inner impedance also loads the cavity – for very large Q_0 more than the cavity wall losses.
- To calculate the loaded Q (Q_L), losses have to be added:

$$\frac{1}{Q_L} = \frac{P_{\text{loss}} + P_{\text{ext}} + \cdots}{\omega_0\, W} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}} + \frac{1}{\dots}.$$

- The coupling factor β is the ratio $P_{\text{ext}}/P_{\text{loss}}$.
- With β, the loaded Q can be written

$$Q_L = \frac{Q_0}{1+\beta}.$$

- For NC cavities, often $\beta = 1$ is chosen (power amplifier matched to empty cavity); for SC cavities, $\beta = \mathcal{O}(10^4 \dots 10^6)$.

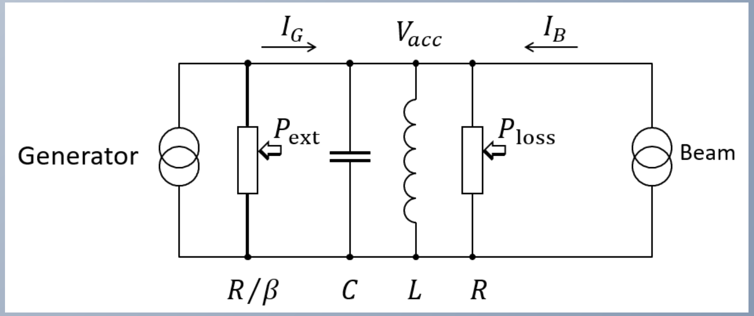
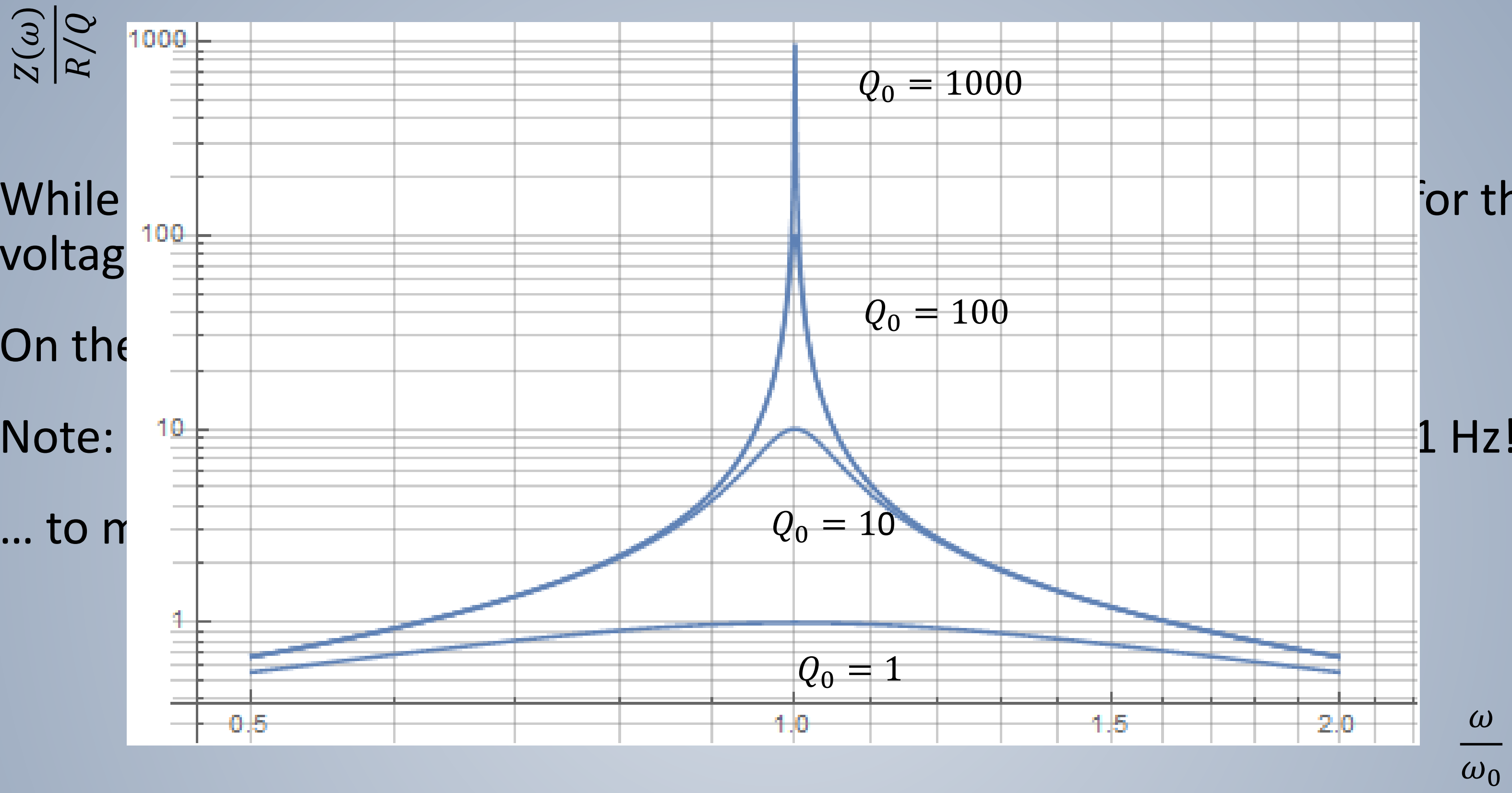


Photo:
Reidar Hahn

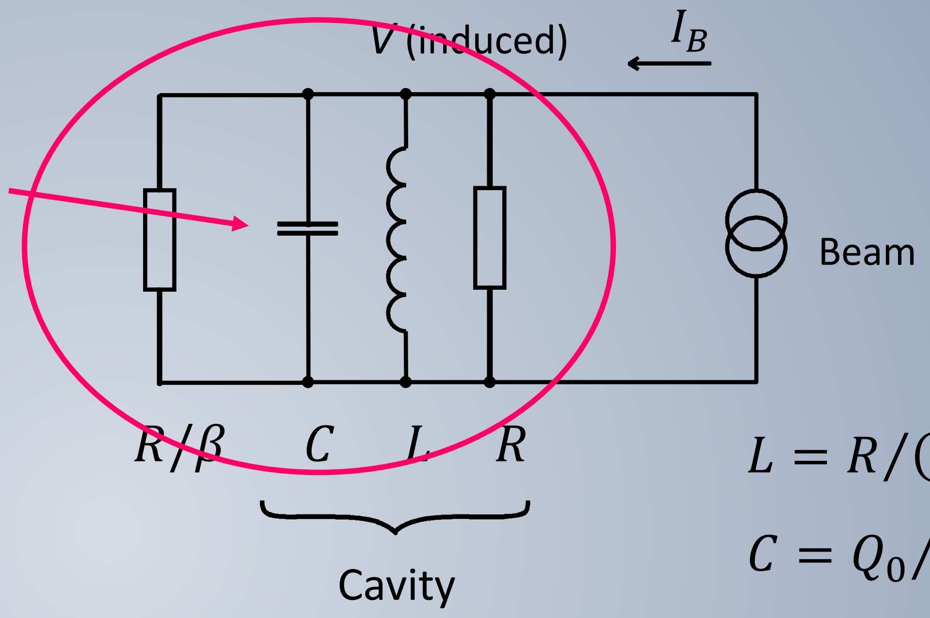
- While … for the same voltag…
- On the…
- Note: … 1 Hz!
- … to m…



Loss factor

$$k_{\mathrm{loss}} = \frac{\omega_0}{2}\left(\frac{R}{Q}\right) = \frac{|V_{\mathrm{acc}}|^2}{4\,W} = \frac{1}{2C}$$

Impedance seen by the beam



$L = R/(Q_0\,\omega_0)$

$C = Q_0/(R\,\omega_0)$

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

Voltage induced by a single charge q: $2\,k_{\mathrm{loss}} q$

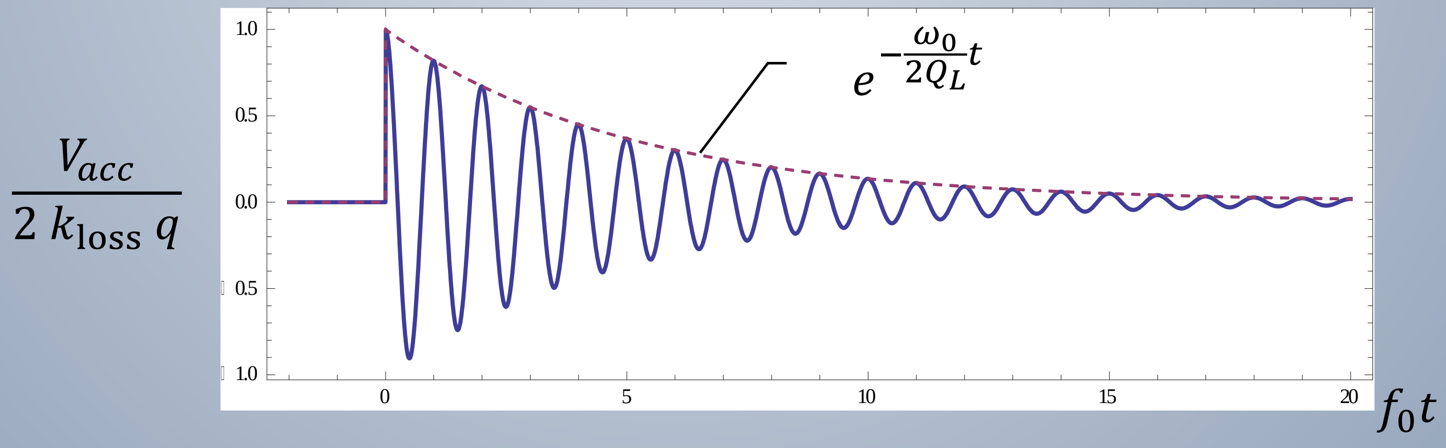



Photo: Reidar Hahn

Summary: relations V_{acc}, W and P_{loss}

Attention – different definitions are used in literature !

V_{acc}
Accelerating voltage

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

$$k_{\mathrm{loss}} = \frac{\omega_0}{2}\frac{R}{Q} = \frac{|V_{\mathrm{acc}}|^2}{4W}$$

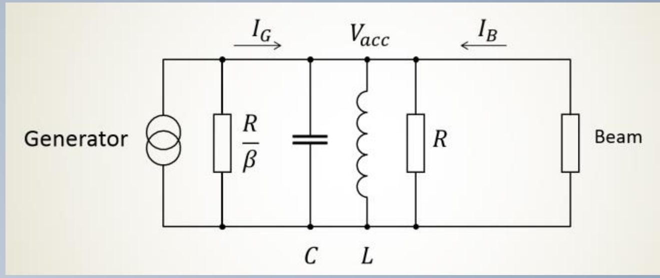
$$R = \frac{|V_{\mathrm{acc}}|^2}{2P_{\mathrm{loss}}} = \frac{R}{Q} Q_0$$

W
Energy stored

P_{loss}
wall losses

$$Q_0 = \frac{\omega_0 W}{P_{\mathrm{loss}}}$$

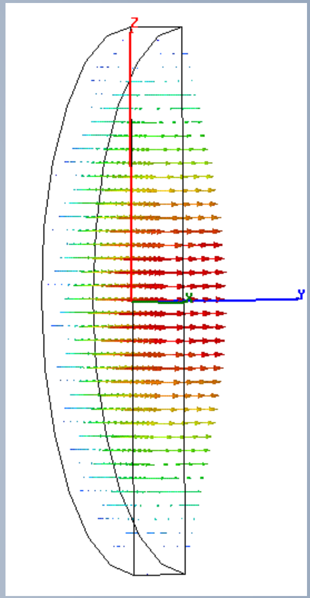
Beam loading

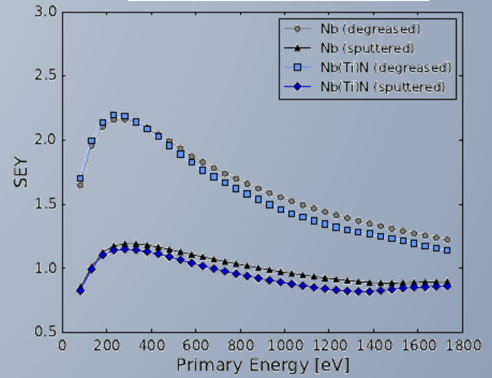


- The beam current "loads" the cavity, in the equivalent circuit this appears as an impedance in parallel to the shunt impedance.
- If the generator is matched to the unloaded cavity ($\beta = 1$), beam loading will (normally) cause the accelerating voltage to decrease.
- The power absorbed by the beam is $-\frac{1}{2}\Re\{V_{\mathrm{acc}} I_B^*\}$.
- For high power transfer efficiency RF → beam, beam loading must be high!
- For SC cavities (very large β), the generator is typically matched to the beam impedance!
- Variation in the beam current leads to **transient beam loading**, which requires special care!
- Often the "impedance" the beam presents is strongly reactive – this leads to a detuning of the cavity.

Multipactor

- The words “multipactor”, “to multipact” and “multipacting” are artificially composed of “multiple” “impact”.
- Multipactor describes a resonant RF phenomenon in vacuum:
  - Consider a free electron in a simple cavity – it gets accelerated by the electric field towards the wall
  - when it impacts the wall, secondary electrons will be emitted, described by the secondary emission yield (SEY)
  - in certain impact energy ranges, more than one electron is emitted for one electron impacting! So the number of electrons can increase
  - When the time for an electron from emission to impact takes exactly ½ of the RF period, resonance occurs – with the SEY>1, this leads to an avalanche increase of electrons, effectively taking all RF power at this field level, depleting the stored energy and limiting the field!
- For this simple “2-point MP”, this resonance condition is reached at $\frac{1}{4\pi}\frac{e}{m}V = (fd)^2$ or $\frac{V}{112\,\mathrm{V}} = \left(\frac{f}{\mathrm{MHz}}\frac{d}{\mathrm{m}}\right)^2$. There exist other resonant bands.

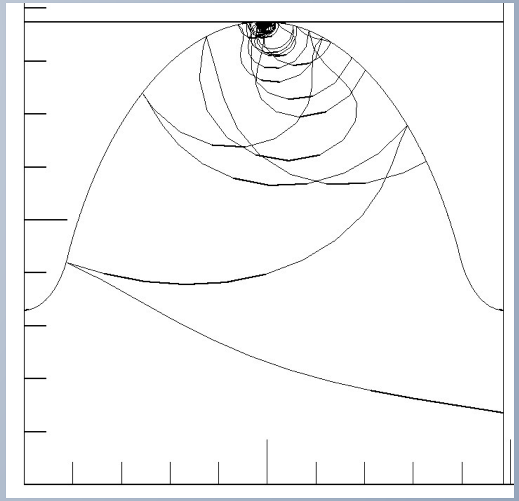




courtesy: Sarah Aull/CERN

Multipactor (contd.)

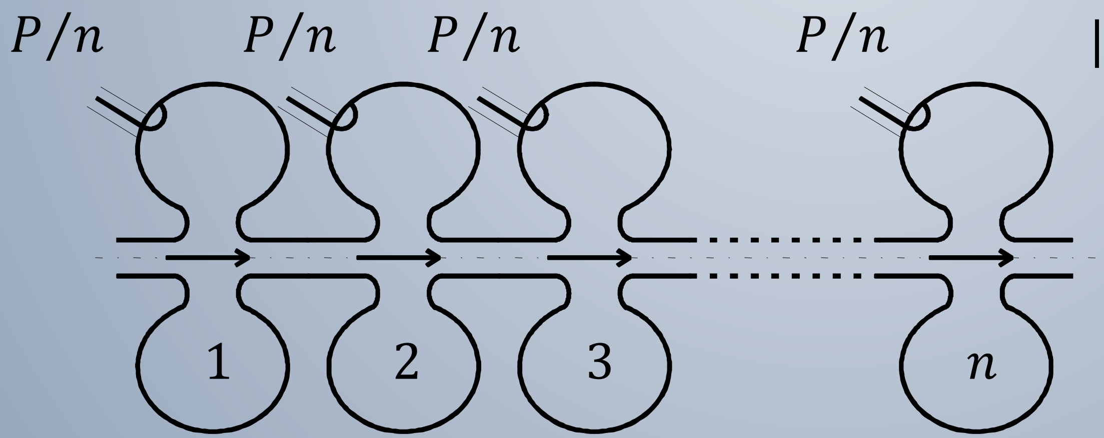
- Unfortunately, good metallic conductors (Cu, Ag, Nb) all have SEY>1!
- 1-point MP occurs when the electron impact where they were emitted
- Electron trajectories can be complex since both $\vec{E}$ and $\vec{B}$ influence them; computer simulations allow to determine the MP bands (barriers)
- To reduce or suppress MP, a combination of the following may be considered:
  - Use materials with low SEY
  - Optimize the shape of your cavity (→ elliptical cavity)
  - Conditioning (surface altered by exposure to RF fields)
  - Coating (Ti, TiN, NEG, amorphous C …)
  - Clearing electrode (for a superimposed DC electric field)
  - Rough surfaces



Many gaps

What do you gain with many gaps?

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

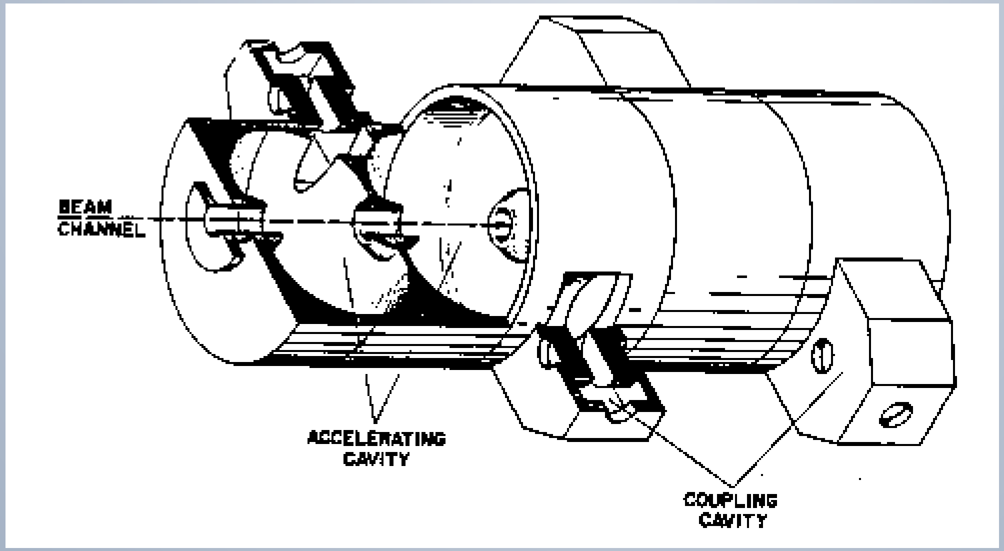


$$|V_{\mathrm{acc}}| = n\sqrt{2R\frac{P}{n}} = \sqrt{2(nR)P}$$

Standing wave multi-cell 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)

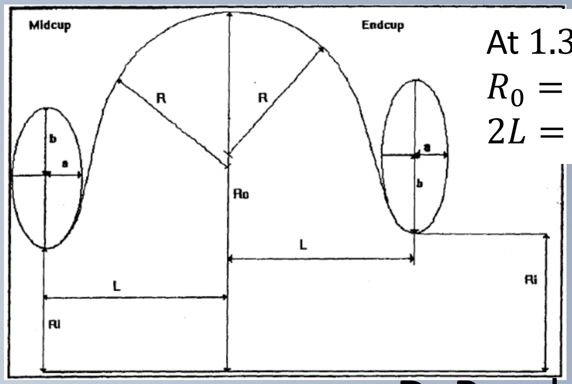


- The phase relation between gaps is important!

Photo:
Reidar Hahn

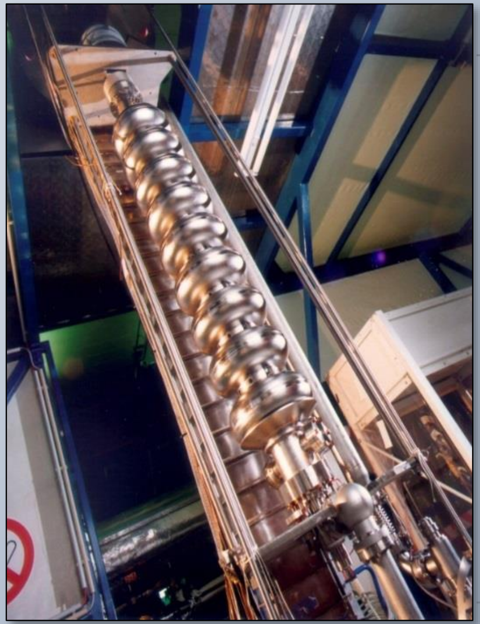
The elliptical cavity

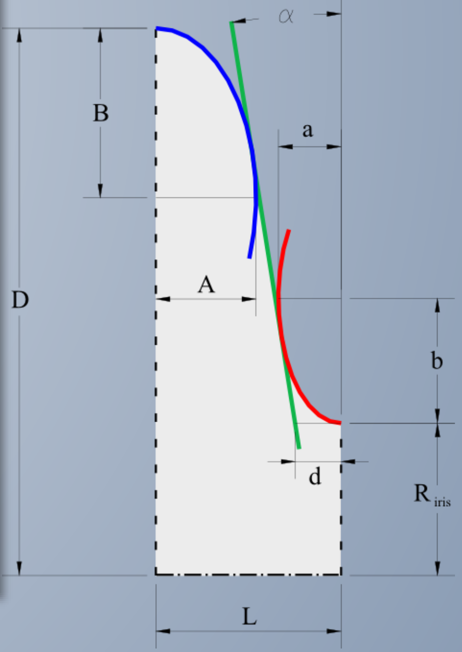
- The elliptical shape was found as optimum compromise between
  - maximum gradient ($E_{\mathrm{acc}}/E_{\mathrm{surface}}$)
  - suppression of multipactor
  - mode purity
  - machinability
- A multi-cell elliptical cavity is typically operated in π-mode, i.e. cell length is exactly $\beta\lambda/2$.
- 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)



At 1.3 GHz:
$R_0 = 103.3$ mm,
$2L = 115.3$ mm.

D. Proch, 1993 *)





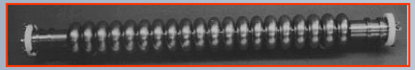
*): http://accelconf.web.cern.ch/AccelConf/SRF93/papers/srf93g01.pdf

Elliptical cavities

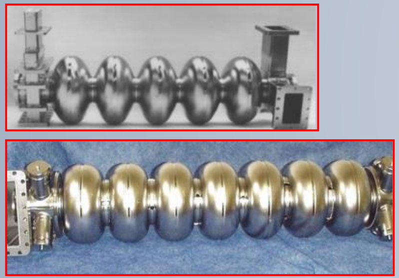
Elliptical cavities – the *de facto* standard for SRF

FERMI 3.9 GHz

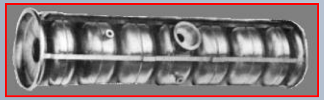
S-DALINAC 3 GHz



CEBAF 1.5 GHz

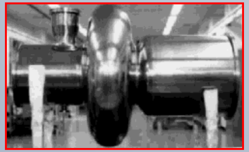


HEPL 1.3 GHz



CESR 0.5 GHz

KEK-B 0.5 GHz



TESLA/ILC 1.3 GHz

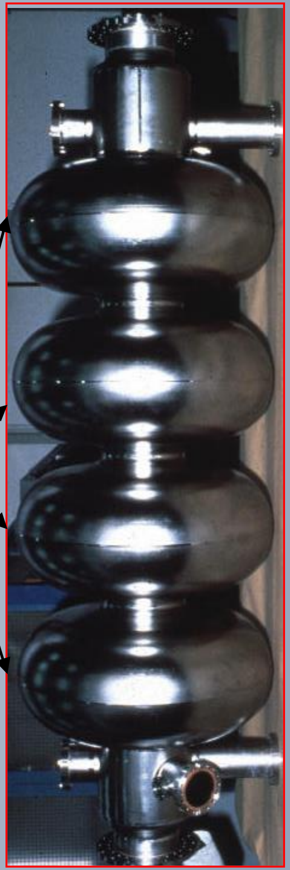
SNS $\beta = 0.61, 0.81,$ 0.805 GHz

HERA 0.5 GHz

TRISTAN 0.5 GHz

LEP 0.352 GHz

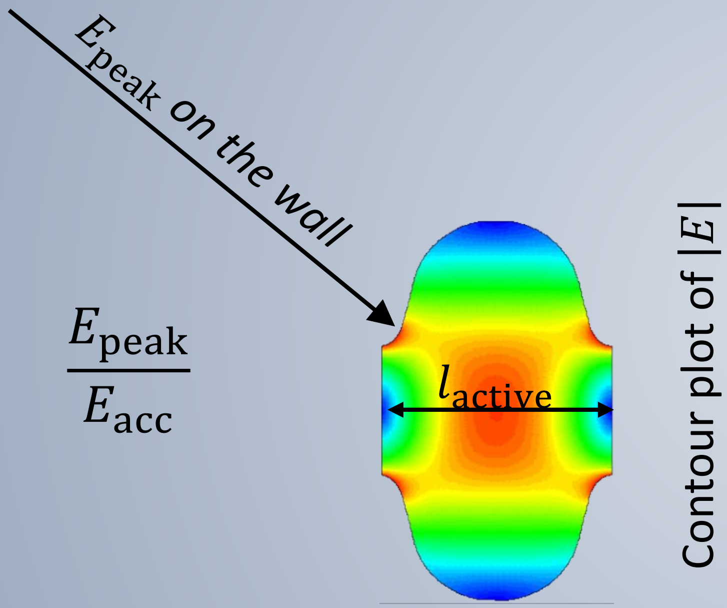
cells



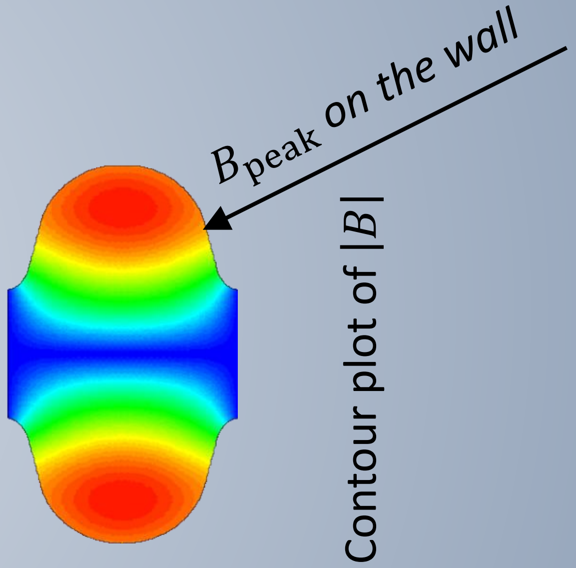
Practical RF parameters 1

- Average accelerating gradient: $E_{\text{acc}} = \dfrac{\sqrt{\omega W (R/Q)}}{l_{\text{active}}}$

$$\frac{E_{\text{peak}}}{E_{\text{acc}}}$$



$$\frac{B_{\text{peak}}}{E_{\text{acc}}}$$



The ratio shows sensitivity of the shape to the **field emission** of electrons.

The ratio shows limit in E_{acc} due to the breakdown of superconductivity (**quench**, Nb: ≈ 190 mT).

courtesy: Jacek Sekutovicz/DESY


Photo:
Reidar Hahn

Practical RF parameters 2

$$G \cdot (R/Q)$$

- Both G and R/Q are purely geometric parameters.
- Like the shunt impedance R, the product $G \cdot (R/Q)$ is a measure of the power loss for given acceleration voltage V_{acc} and surface resistance R_s.

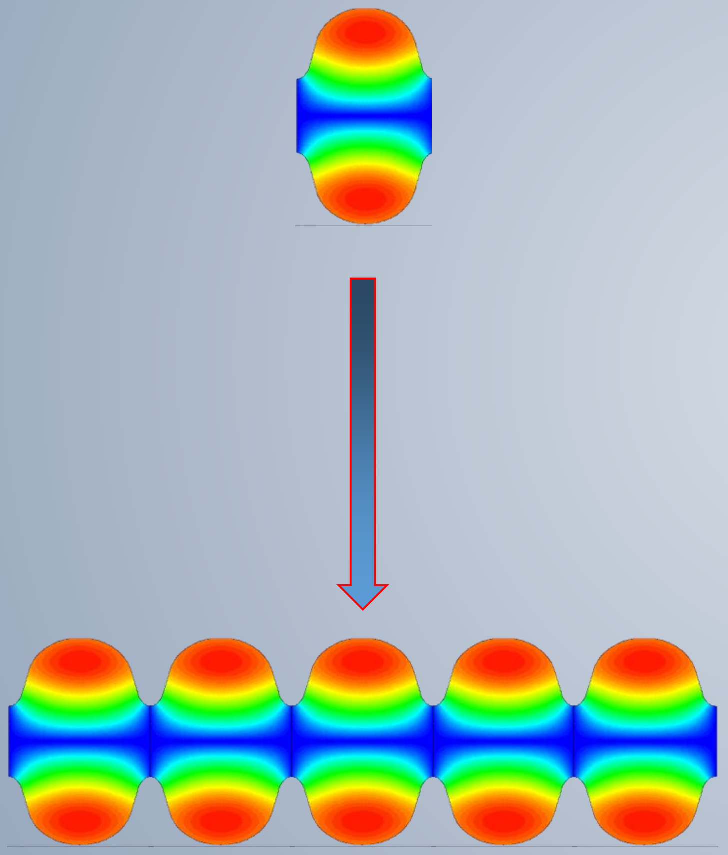
Minimize R_s:
operation at lower T,
better surface cleanliness,
lower residual resistance

$$P_{\mathrm{loss}} = \frac{|V_{\mathrm{acc}}|^2 R_s}{2\,\underbrace{G \cdot (R/Q)}}$$

Optimize geometry maximizing $G \cdot (R/Q)$.

courtesy: Jacek Sekutovicz/DESY

Single-cell versus multi-cell cavities



- Advantages of single-cell cavities:
  - It is easier to manage HOM damping
  - There is no field flatness problem.
  - Input coupler transfers less power
  - They are easy for cleaning and preparation

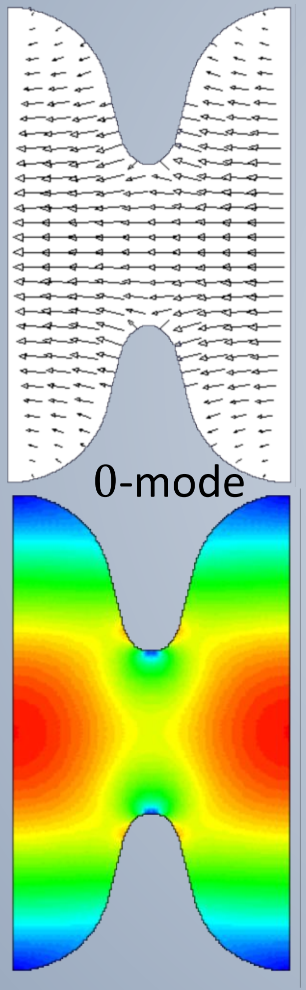
- Advantages of multi-cell cavities:
  - much more acceleration per meter!
  - better use of the power ($R \rightarrow n\ R$)
  - more cost-effective for most applications

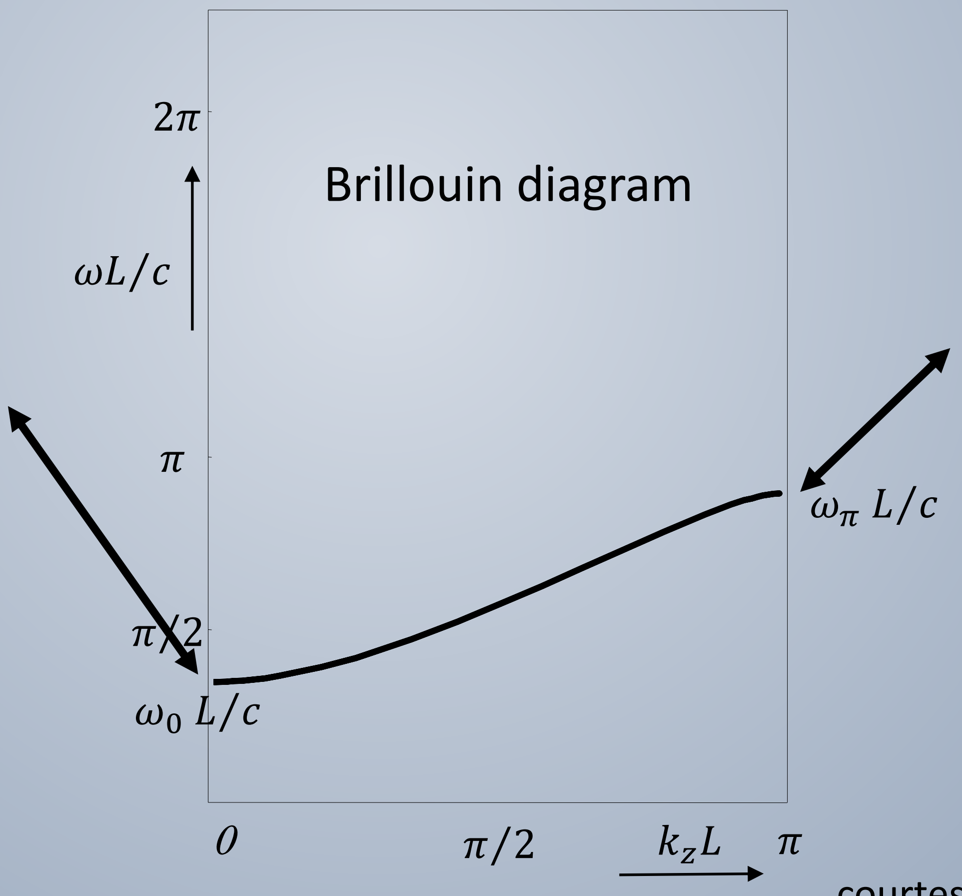
courtesy: Jacek Sekutovicz/DESY

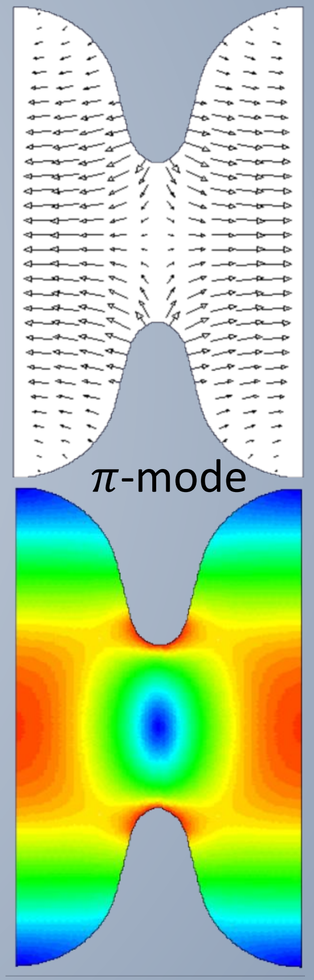
Practical RF parameters 3

- **Cell-to-cell coupling** k_{cc} will determine the width of the passbands in multi-cell cavities.

$$k_{cc} = 2\frac{\omega_\pi - \omega_0}{\omega_\pi + \omega_0}$$



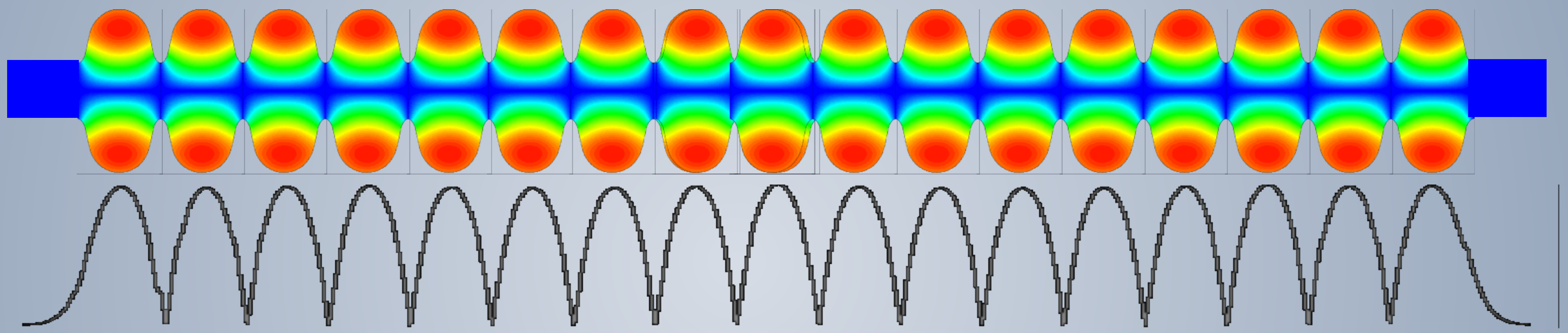




courtesy: Jacek Sekutovicz/DESY

Field flatness

- Field amplitude variation from cell to cell in a multi-cell structure
- Should be small for maximum acceleration.



- Field flatness sensitivity factor a_{ff} for a structure made of N cells:

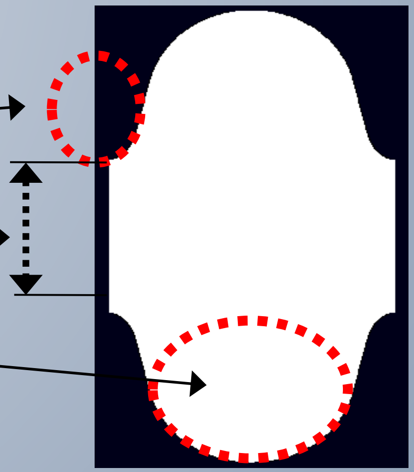
$$\frac{\Delta A_i}{A_i} = a_{ff}\,\frac{\Delta f_i}{f_i}$$

a_{ff} is related to the cell-to-cell coupling as $a_{ff} = \frac{N^2}{k_{cc}}$ and describes the sensitivity of the field flatness on the errors in individual cells.

courtesy: Jacek Sekutovicz/DESY

Criteria for Cavity Design (1)

- Here: Inner cells of multi-cell structures
- Parameters for optimization:
  - Fundamental mode: $\frac{R}{Q}$, G, $\frac{E_{\text{peak}}}{E_{\text{acc}}}$, $\frac{B_{\text{peak}}}{E_{\text{acc}}}$, k_{cc}.
  - Higher order modes: $k_\perp$, k_z.
- The elliptical cavity design has distinct advantages:
  - easy to clean (rinse)
  - little susceptible to MP – can be conditioned …
- Geometric parameters for optimization:
  - iris ellipse half axes: a, b:
  - iris aperture radius: r_i,
  - equator ellipse half axes: A, B
- Problem: 7 parameters to optimize, only 5 to play with – some compromise has to be found!



courtesy: Jacek Sekutovicz/DESY

Criteria for Cavity Design (2)

Criterion	RF parameter	Improves if	examples
high gradient operation	$E_{\text{peak}}/E_{\text{acc}}$ $B_{\text{peak}}/E_{\text{acc}}$ $\downarrow$	r_i $\downarrow$	ILC, CEBAF 12 GeV HG
low cryogenic losses	$\frac{R}{Q} \cdot G$ $\uparrow$	r_i $\downarrow$	CEBAF LL
High I_{beam}	$k_{\perp}, k_z$ $\downarrow$	r_i $\uparrow$	B-factory RHIC cooling LHeC

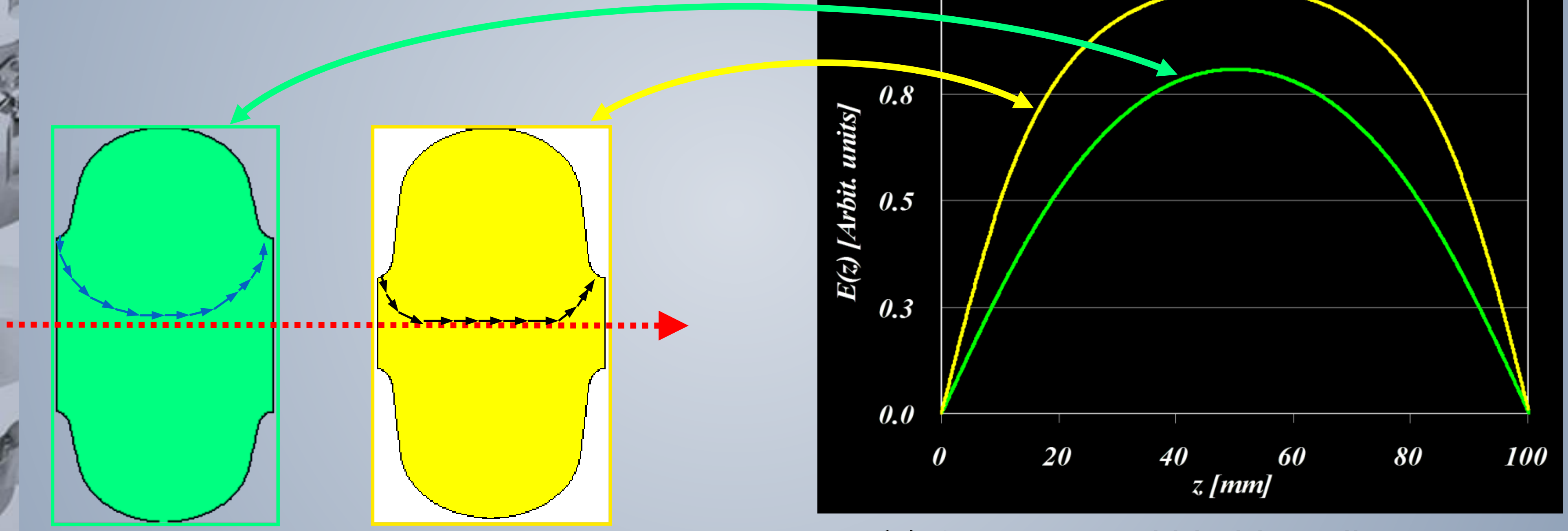
We see here that r_i is a very "powerful" variable to trim the RF-parameters of a cavity.

Of course it has to fit the aperture required for the beam!

courtesy: Jacek Sekutovicz/DESY

Effect of r_i

- Smaller r_i allows to concentrate E_z where it is needed for acceleration



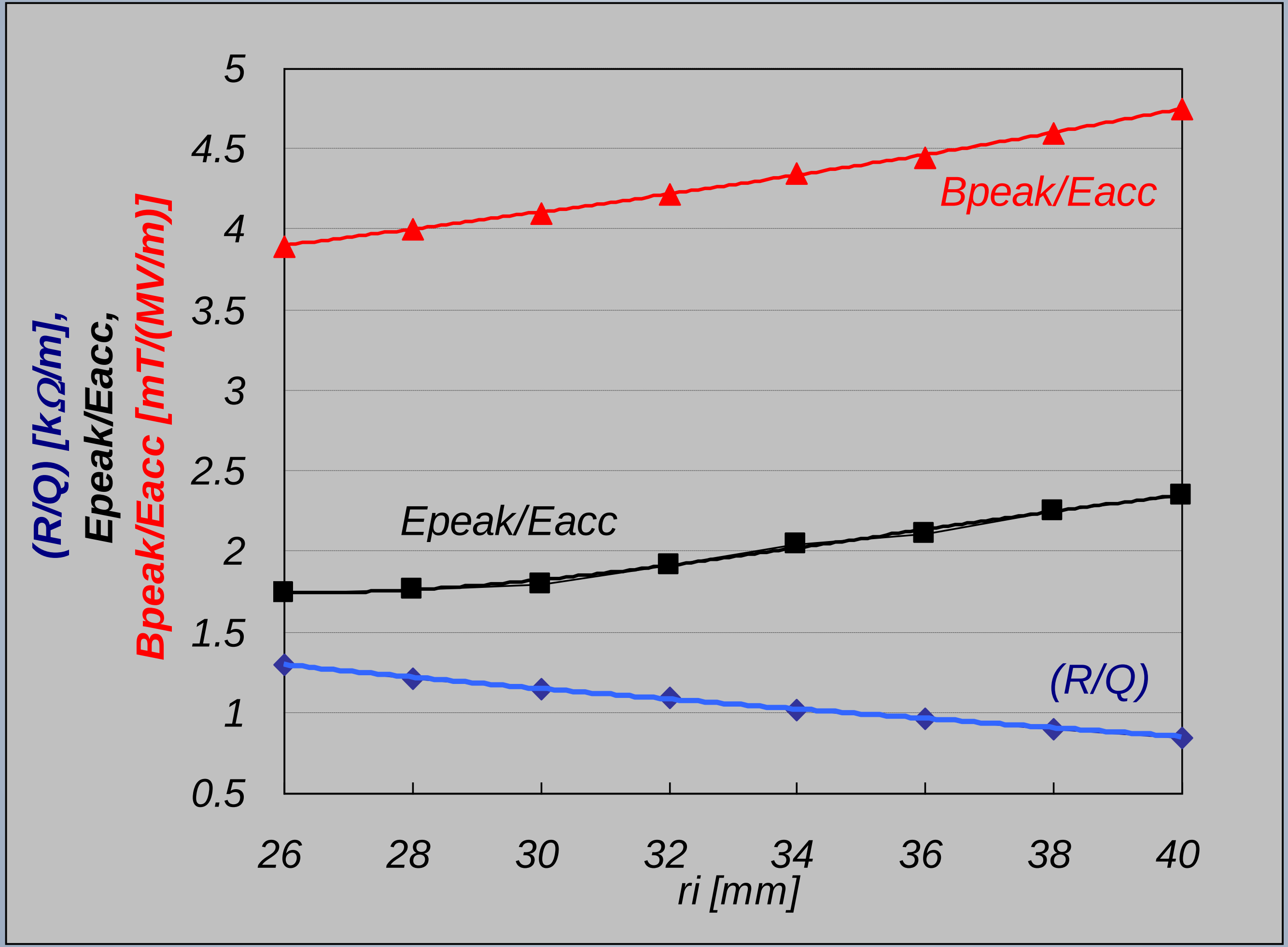
$r_i = 40$ mm

$r_i = 20$ mm

$E_z(z)$ for small and big iris radius

courtesy: Jacek Sekutovicz/DESY

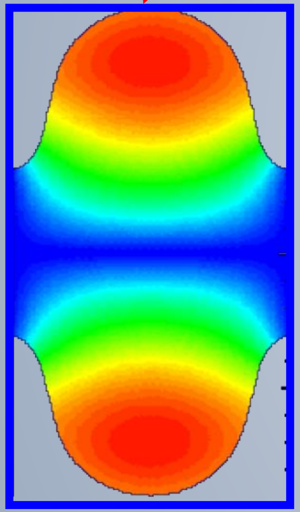
Example: cell optimization at 1.5 GHz

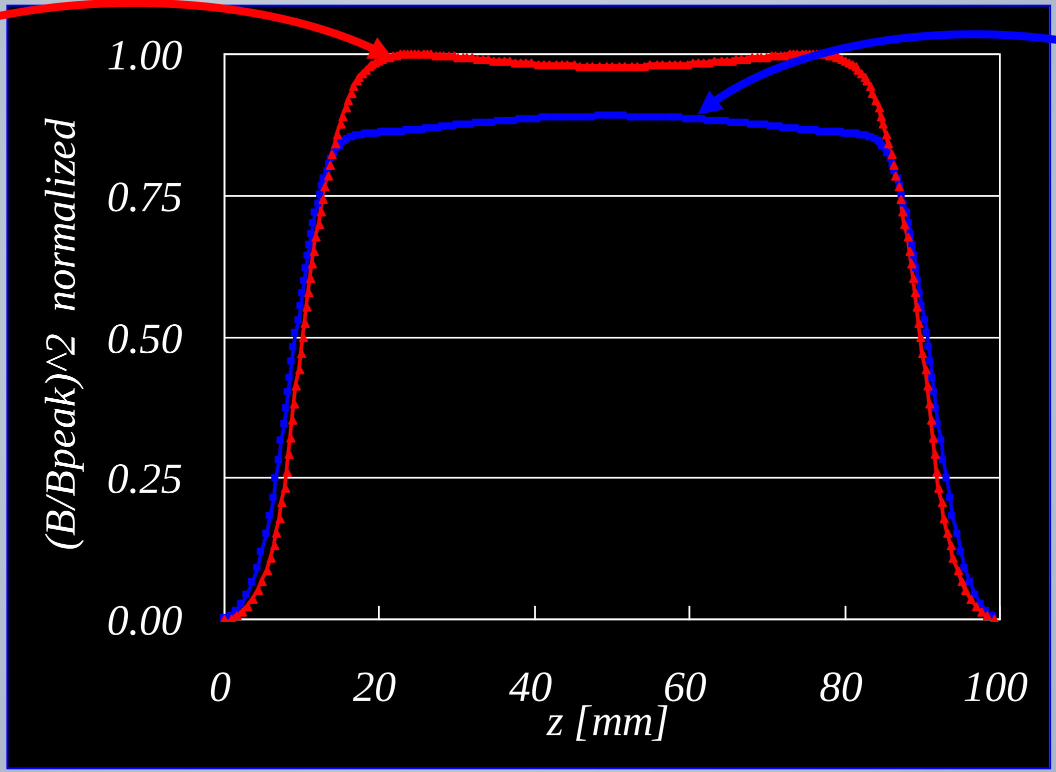


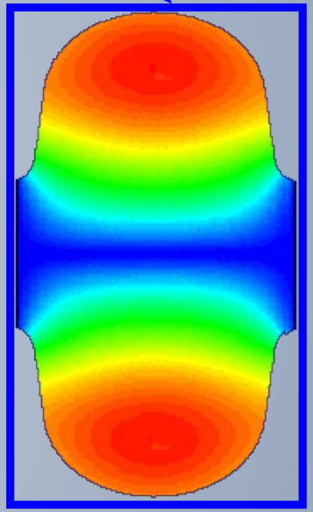
A. Mosnier, E. Haebel, SRF Workshop 1991

Equator shape optimization

- $B_{\text{peak}}/E_{\text{acc}}$ (and G) change when changing the equator shape.



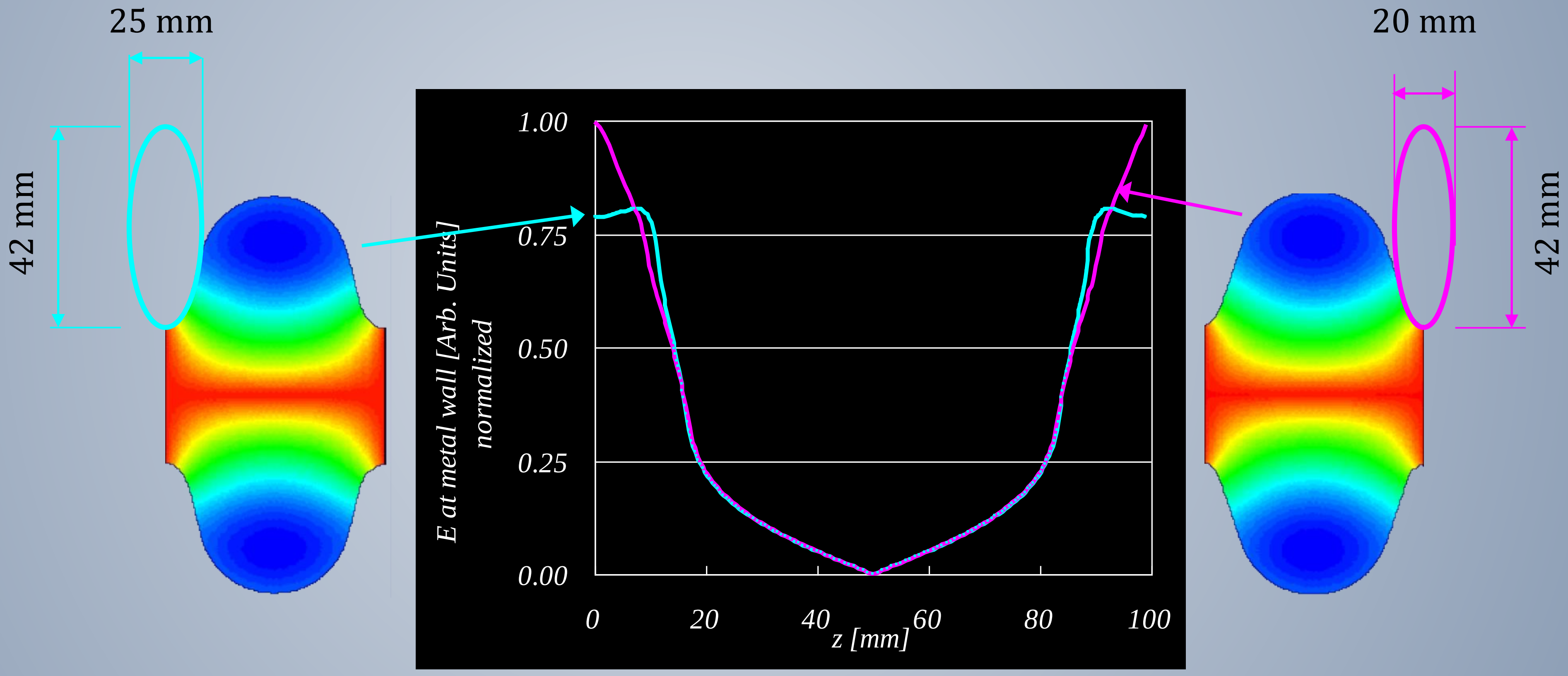




courtesy: Jacek Sekutovicz/DESY

Iris shape optimization

- $E_{\text{peak}}/E_{\text{acc}}$ changes with the iris shape



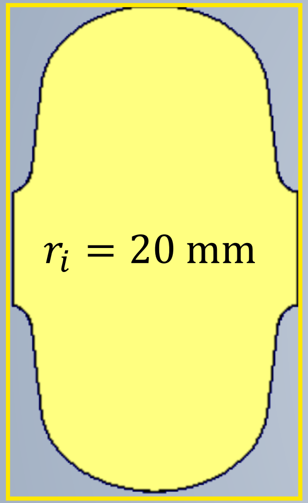
Both cells have the same: f_0, R/Q, *and* r_i.

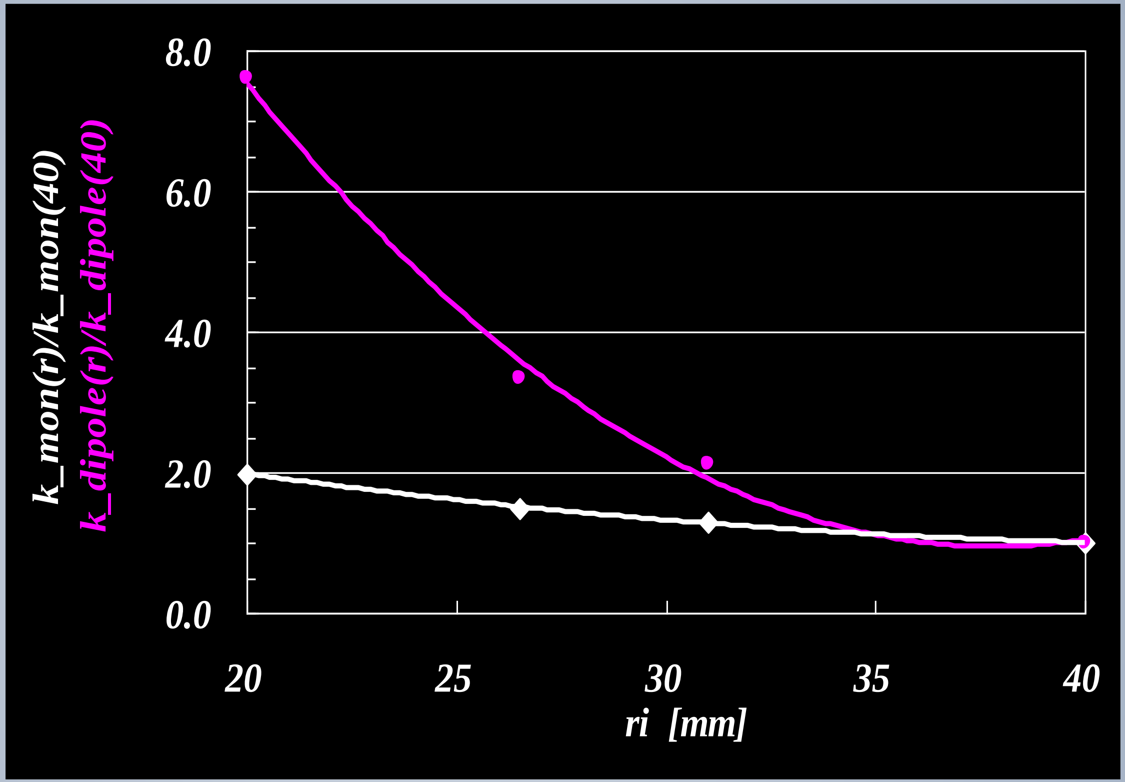
courtesy: Jacek Sekutovicz/DESY

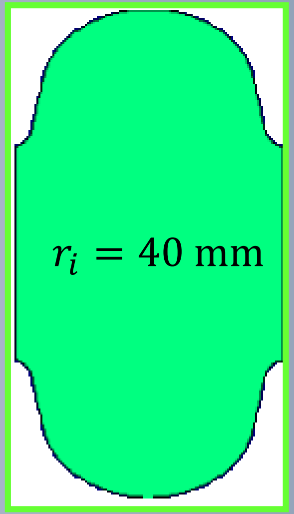
Photo: Reidar Hahn

Minimizing HOM excitation

HOMs loss factors ($k_{\mathrm{loss},\perp}$, k_{loss})





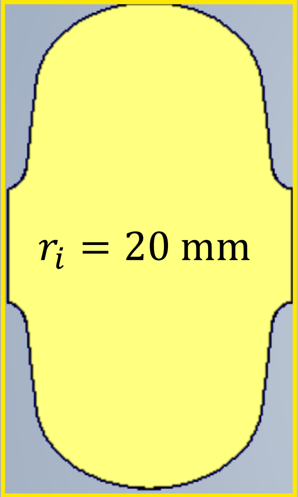


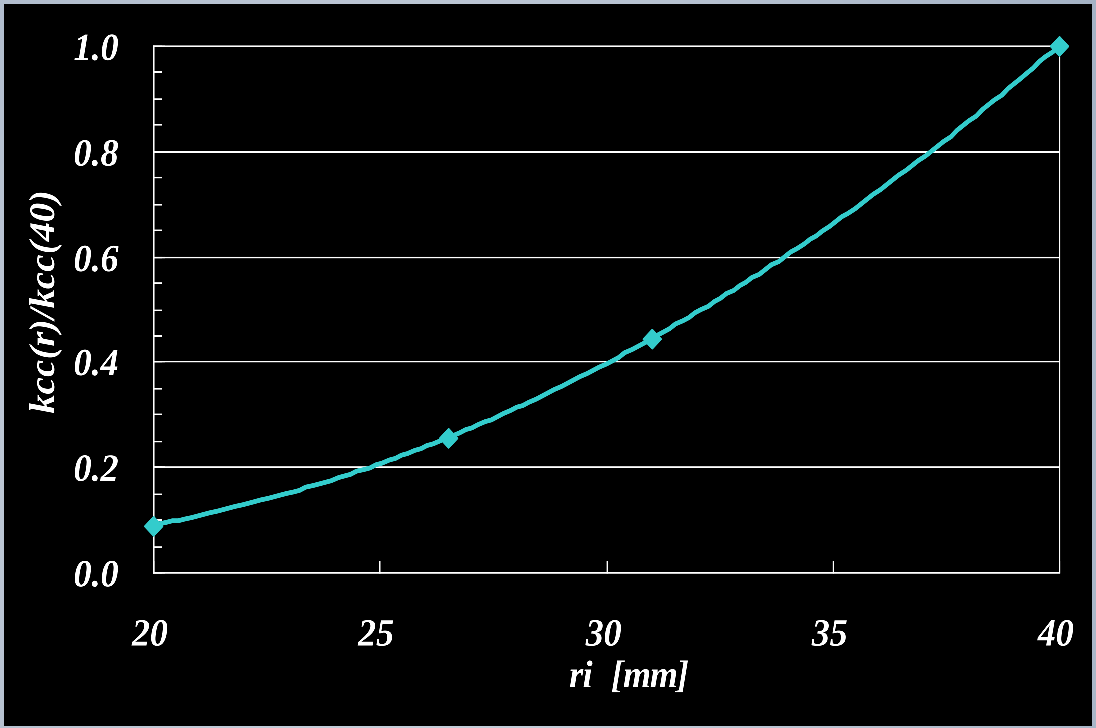
$R/Q = 152\ \Omega$
$B_{\mathrm{peak}}/E_{\mathrm{acc}} = 3.5\ \mathrm{mT}/(\mathrm{MV/m})$
$E_{\mathrm{peak}}/E_{\mathrm{acc}} = 1.9$

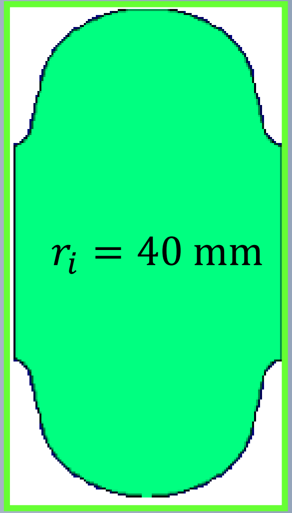
$R/Q = 86\ \Omega$
$B_{\mathrm{peak}}/E_{\mathrm{acc}} = 4.6\ \mathrm{mT}/(\mathrm{MV/m})$
$E_{\mathrm{peak}}/E_{\mathrm{acc}} = 3.2$

courtesy: Jacek Sekutovicz/DESY

Cell-to-cell coupling k_{cc}







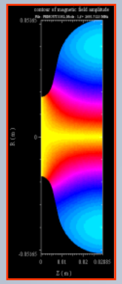
$R/Q = 152\ \Omega$
$B_{\mathrm{peak}}/E_{\mathrm{acc}} = 3.5\ \mathrm{mT/(MV/m)}$
$E_{\mathrm{peak}}/E_{\mathrm{acc}} = 1.9$

$R/Q = 86\ \Omega$
$B_{\mathrm{peak}}/E_{\mathrm{acc}} = 4.6\ \mathrm{mT/(MV/m)}$
$E_{\mathrm{peak}}/E_{\mathrm{acc}} = 3.2$

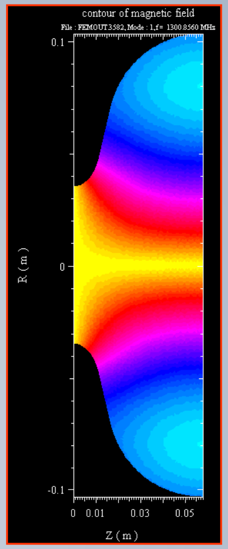
courtesy: Jacek Sekutovicz/DESY

Photo:
Reidar Hahn

Scaling the frequency



$\times\, \mathbf{2}$ $=$



f_π	[MHz]	2600
R/Q	[Ω]	57
r/Q	[Ω/m]	2000
G	[Ω]	271

f_π	[MHz]	1300
R/Q	[Ω]	57
r/Q	[Ω/m]	1000
G	[Ω]	271

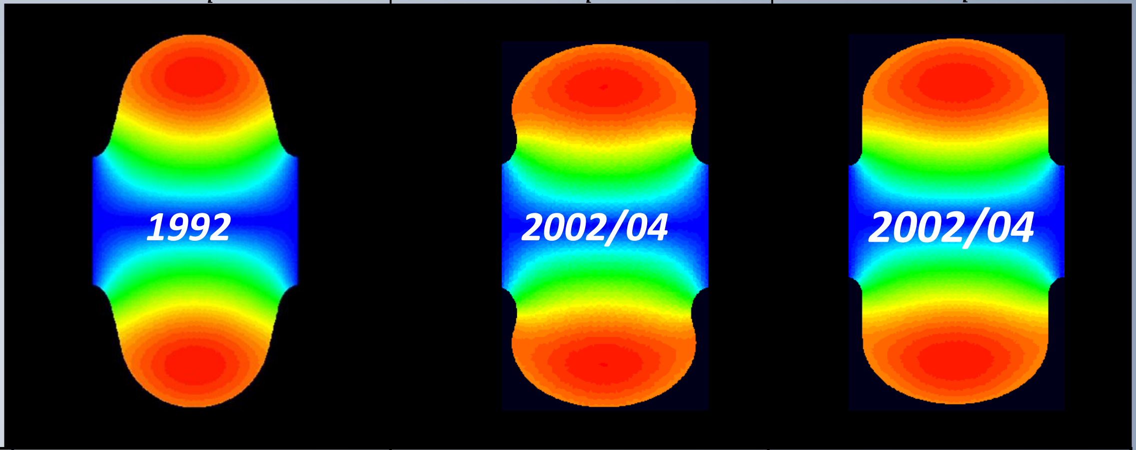
$r/Q = (R/Q)/l \propto f$ (or $(R/Q)/\lambda = \text{const}$)

courtesy: Jacek Sekutovicz/DESY

Photo: Reidar Hahn

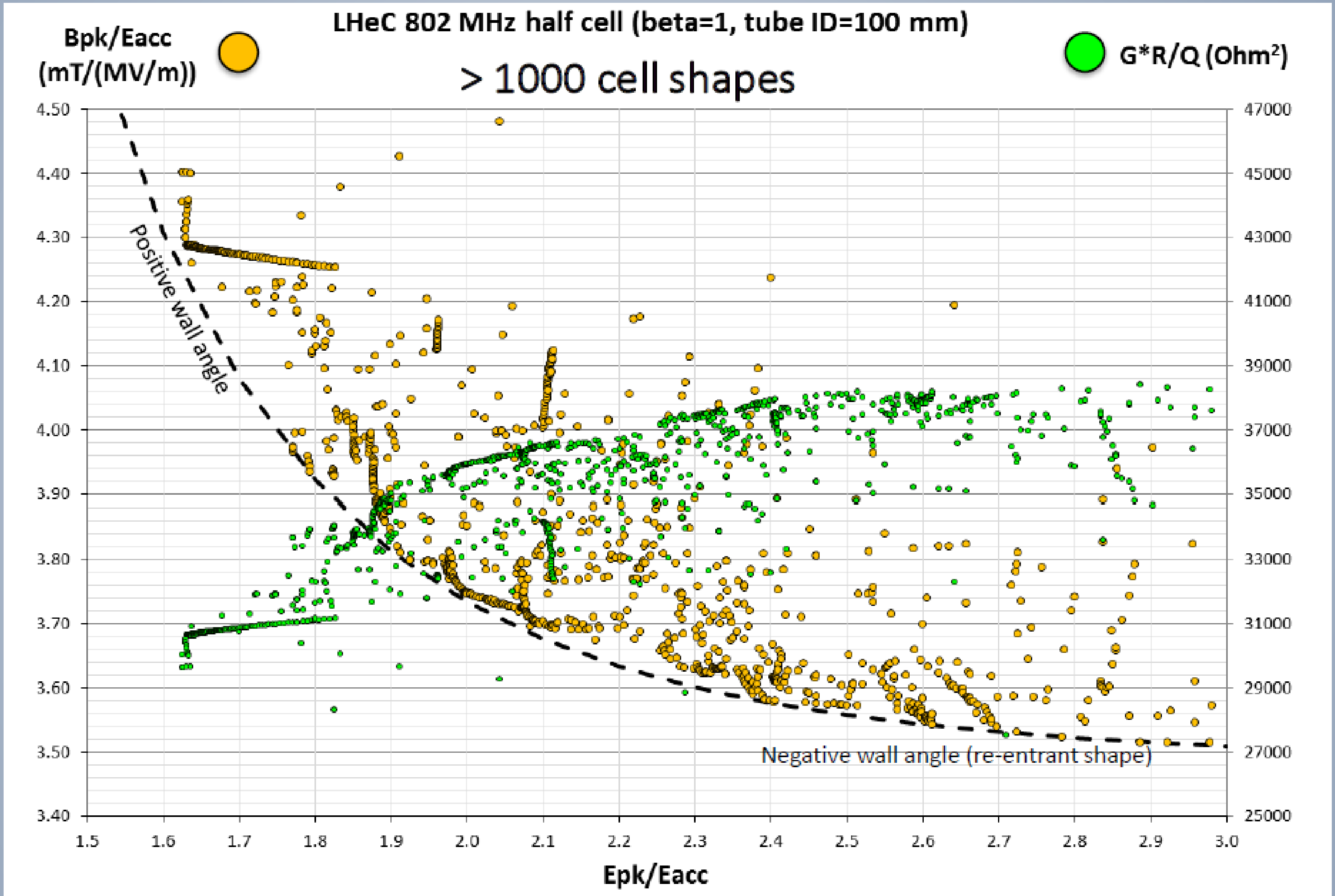
Historic evolution of inner cell geometry

Example: ILC



		TESLA, optimized E_{peak}/E_{acc}	Re-entrant, optimized B_{peak}/E_{acc}	Low-loss (LL) optimized B_{peak}/E_{acc}
r_i	[mm]	*35*	*30*	*30*
k_{cc}	[%]	*1.9*	*1.56*	*1.52*
$E_{\mathrm{peak}}/E_{\mathrm{acc}}$	-	*1.98*	*2.30*	*2.36*
$B_{\mathrm{peak}}/E_{\mathrm{acc}}$	[mT/(MV/m)]	*4.15*	*3.57*	*3.61*
R/Q	[Ω]	*113.8*	*135*	*133.7*
G	[Ω]	*271*	*284.3*	*284*
$R/Q \cdot G$	[Ω*Ω]	*30840*	*38380*	*37970*
$k_{\mathrm{loss},\perp}$ ($\sigma_z = 1$ mm)	[V/pC/cm²]	*0.23*	*0.38*	*0.38*
k_{loss} ($\sigma_z = 1$ mm)	[V/pC]	*1.46*	*1.75*	*1.72*

courtesy: Jacek Sekutovicz/DESY



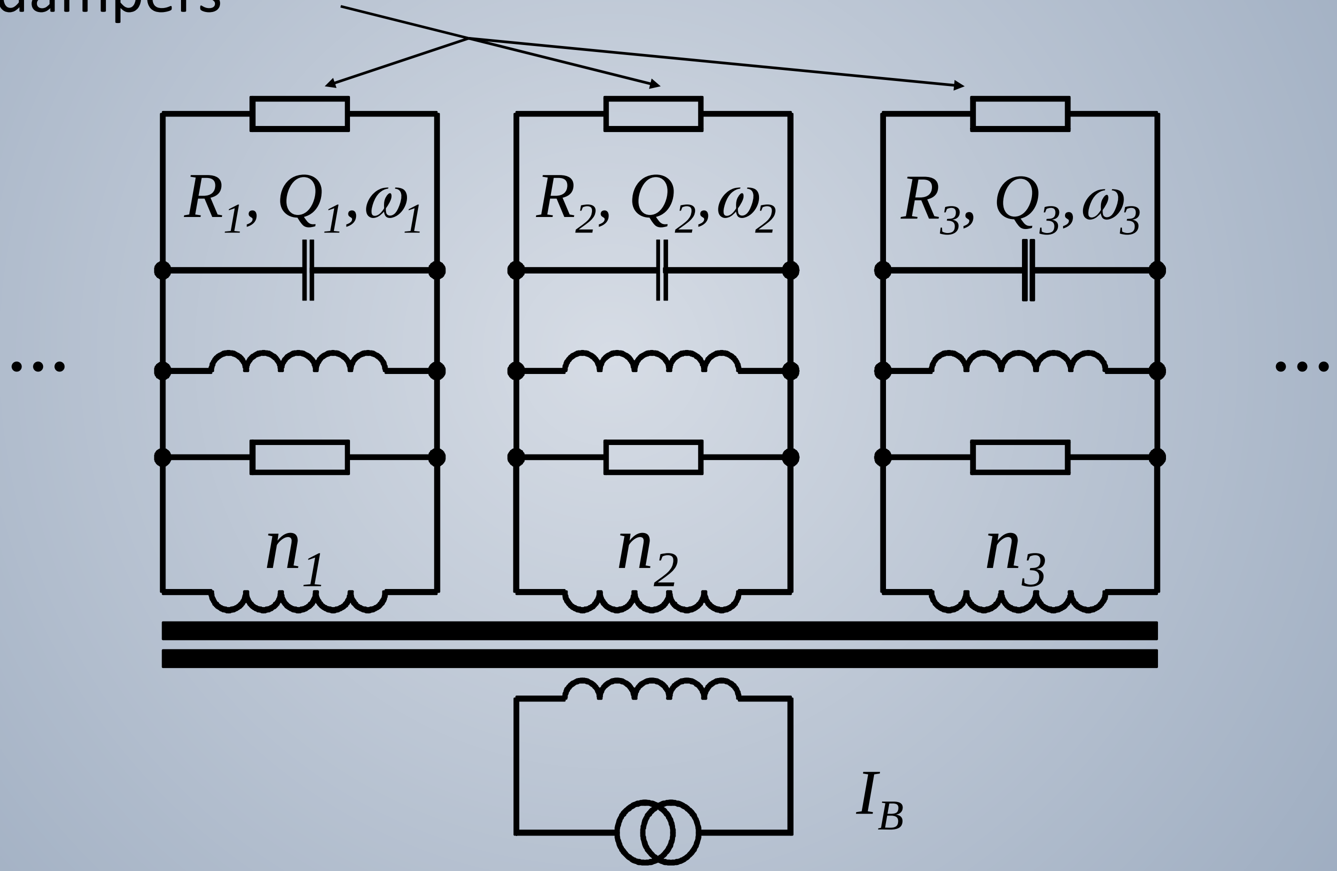
courtesy: Frank Marhauser/JLAB

Higher Order Modes

Photo: Reidar Hahn

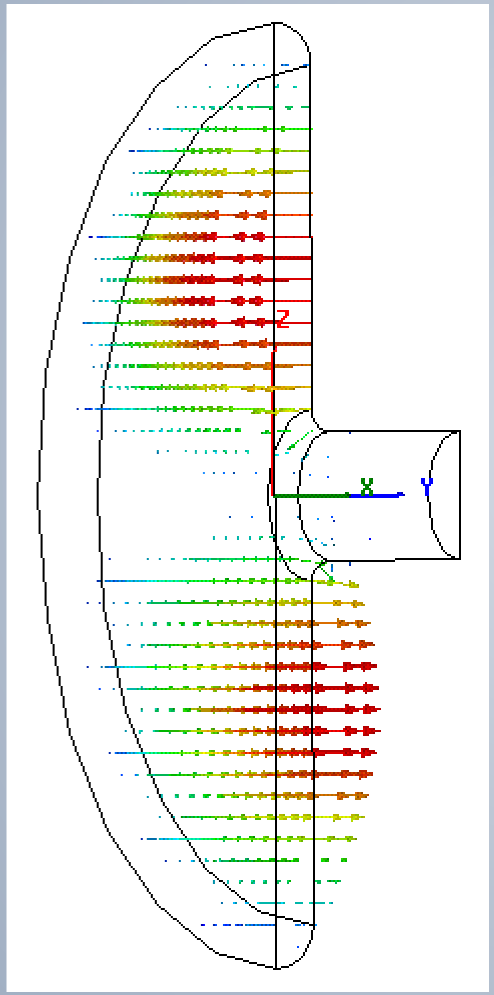
Higher order modes

external dampers

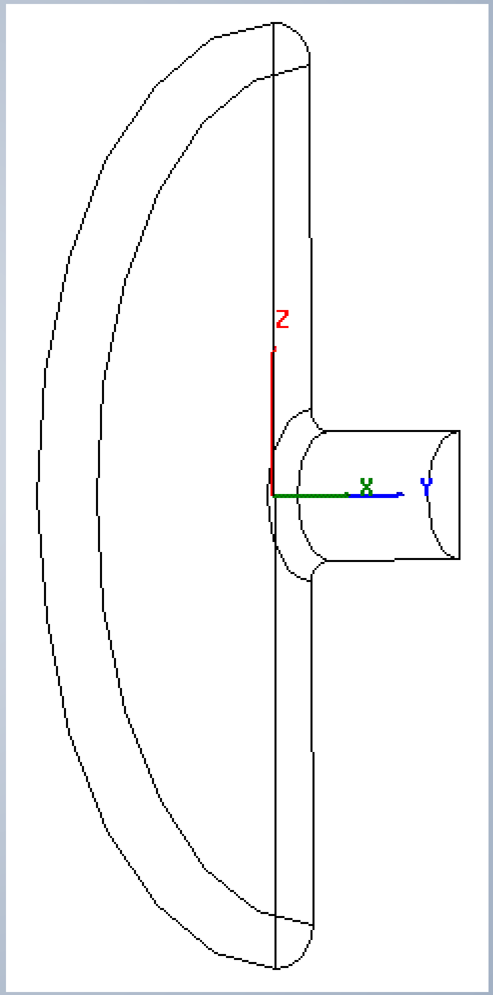


Pillbox: 1st dipole mode

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



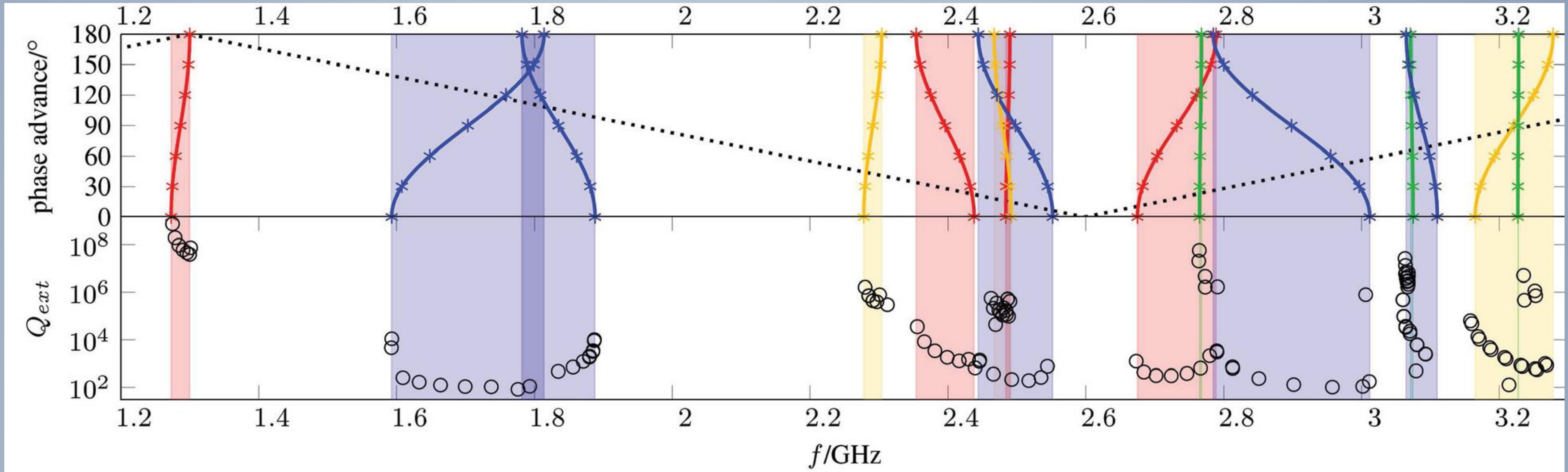
electric field



magnetic field

Photo:
Reidar Hahn

7-cell 1.3 GHz structure for bERLinPro

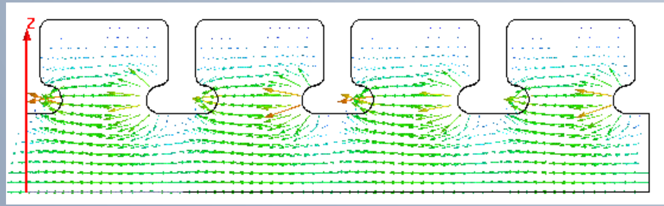


Band diagram (top) and Q-factors (bottom)

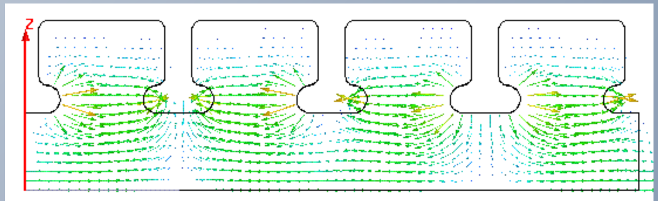
Galek et al.: IPAC2013

Reminder:

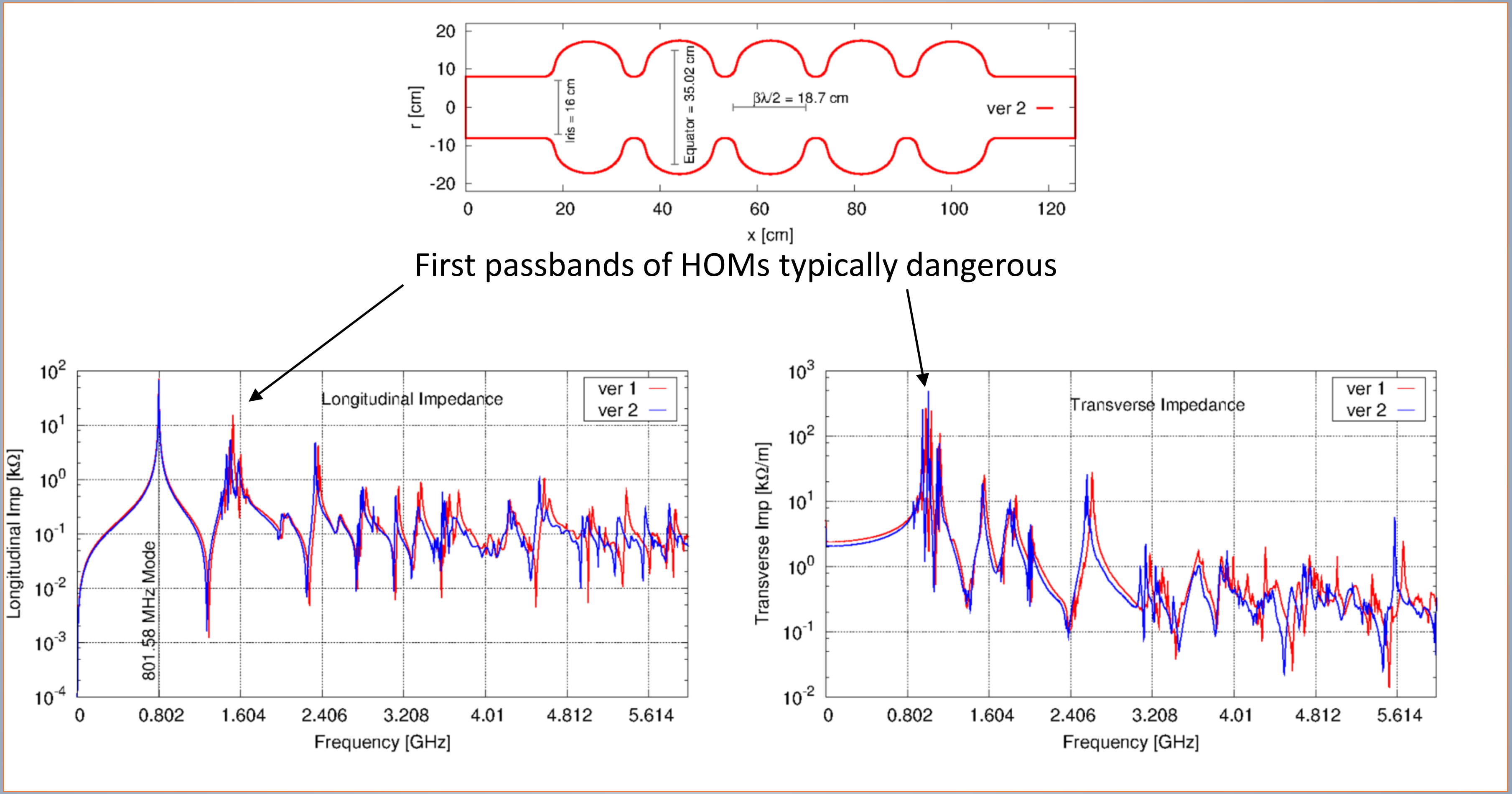
0-mode



π-mode



HOMs: Example 5-cell cavity

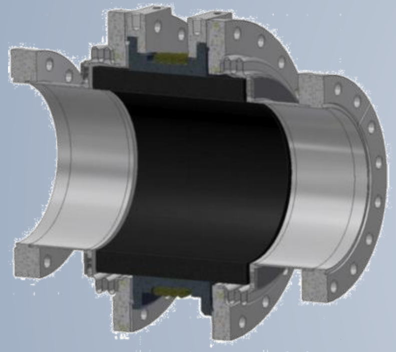


courtesy: Rama Calaga/CERN

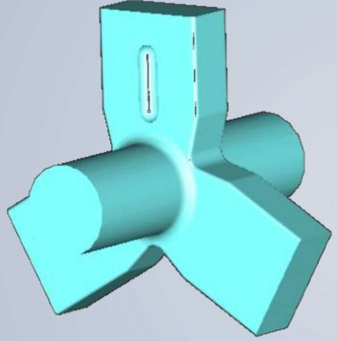
Photo:
Reidar Hahn

HOM dampers

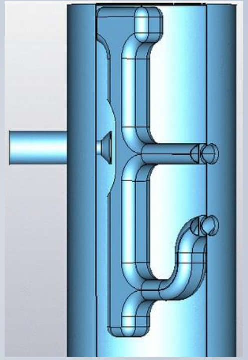
- Ferrite absorbers: broadband damper, room temperature
- Waveguides: better suited for higher frequencies (size!)
- Notch filters: narrow-band; target specific mode



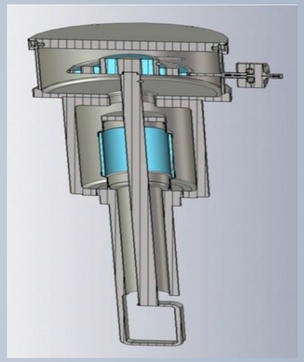
ferrite absorber



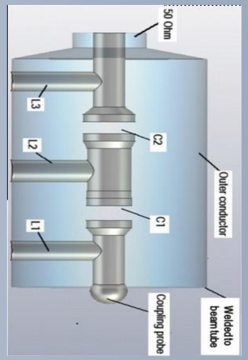
waveguides



notch filter



bandpass filter



double notch

- Multi-cell cavities require broadband dampers!

Non-elliptical cavities

Special thanks to R. Laxdal (TRIUMF) and A. Facco (INFN & FRIB)

Useful relations

Protons/H- ($A = 1, Q = 1$)

$$p = \gamma\beta m_0 c = \frac{\gamma\beta E_0}{c}$$

$$E = E_{\text{kin}} + E_0 = \gamma E_0$$

$$E_{\text{kin}} = (\gamma - 1)E_0$$

$$E_{\text{kin}} = |e| V_{\text{eff}} \cos\varphi$$

Heavy Ions (A, Q)

$$p = \gamma\beta A m_0 c = \frac{\gamma\beta A E_0}{c}$$

$$E = E_{\text{kin}} + AE_0 = \gamma A E_0$$

$$E_{\text{kin}}/A = (\gamma - 1)E_0$$

$$E_{\text{kin}}/A = (Q/A)\, V_{\text{eff}} \cos\varphi$$

Particle velocity vs. kinetic energy

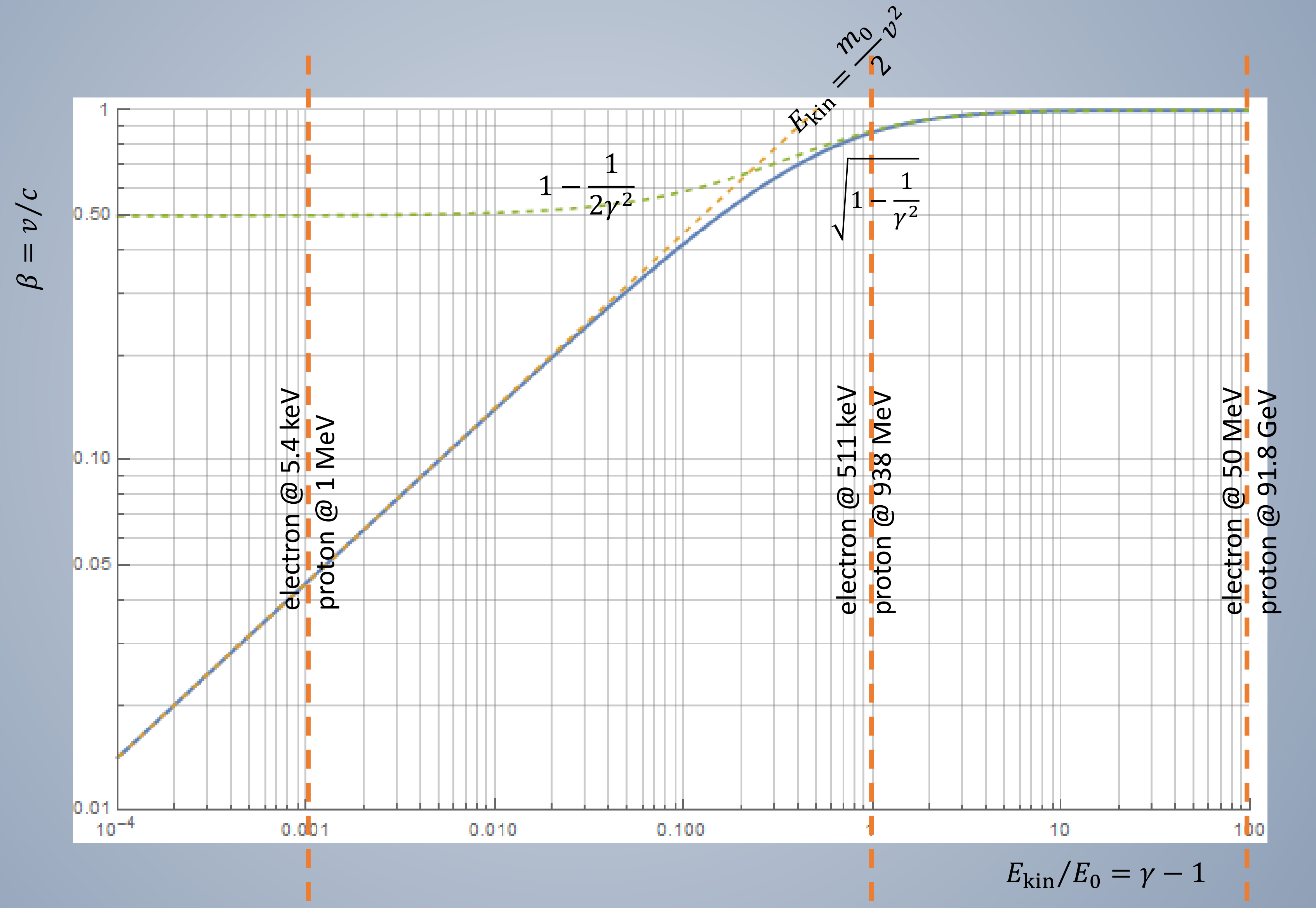


Photo:
Reidar Hahn

Accelerating electrons vs. accelerating ions

Example: a 300kV DC bias is enough to get electrons going at a relativistic speed (ie E_o=511keV so γ=1.58, v/c=β=0.78) – for protons a 300kV bias only produces v/c=β=0.025 – for A=30 v/c=β=0.005

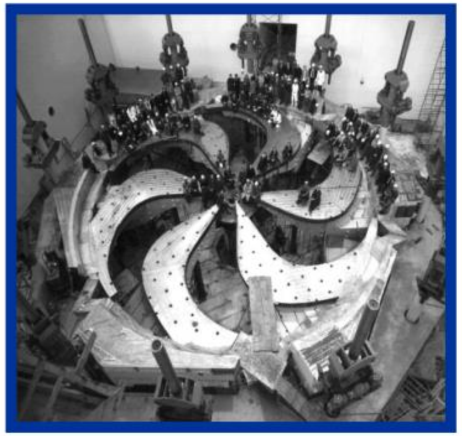
- Electron – 0.511MeV/c^2
  - 300kV - γ=1.58, v/c=β=0.78
  - 550MeV - γ=1011, v/c=β=1

8 gm

ARIEL 300kV e-gun

- Protons – 938 MeV/c^2
  - 300kV - γ=1.003, v/c=β=0.025
  - 550MeV - γ=1.58, v/c=β=0.78

160 kgm

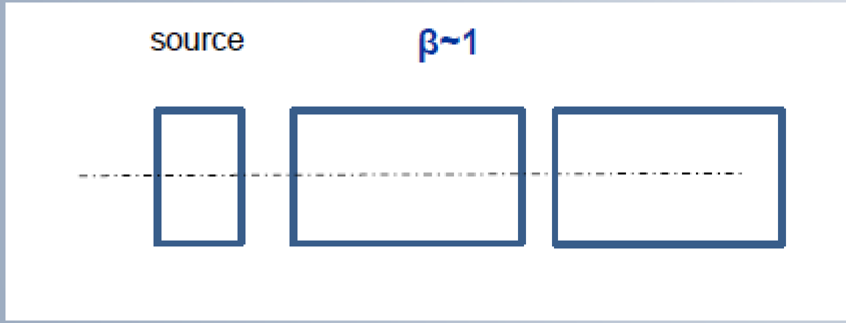


TRIUMF 500MeV cyclotron

Accelerating electrons vs. accelerating ions

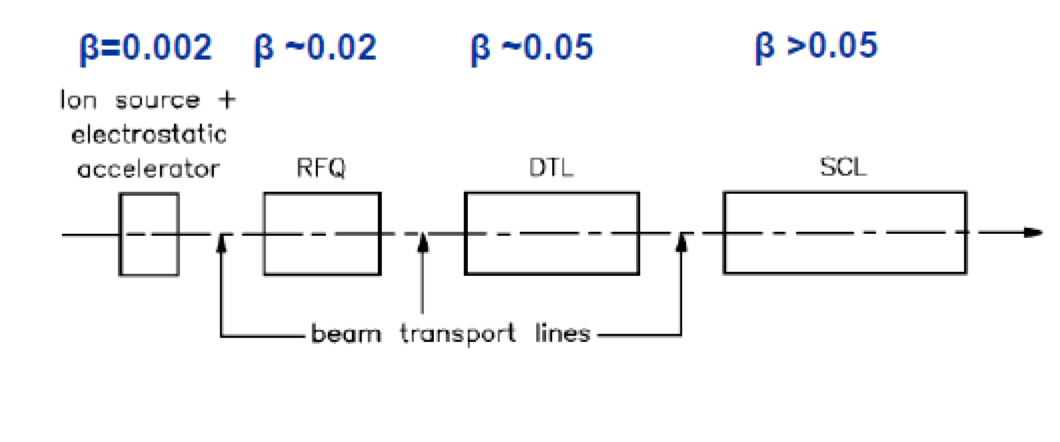
Electrons

Common building blocks – all designed for $\beta = 1$.



Ions

Various building blocks – different technologies, each optimized for a certain velocity range



Limitations of elliptical cavities

- Elliptical cavities have been designed starting at $\beta \geq 0.5$ for CW applications, for $\beta \geq 0.6$ for pulsed (SNS, ESS).
- The π-mode requires cell-to-cell distance of $\beta\lambda/2$, but outer diameter $\approx 0.9\,\lambda$, i.e. at low β the cavity looks more like bellows, sensitive to LFD!

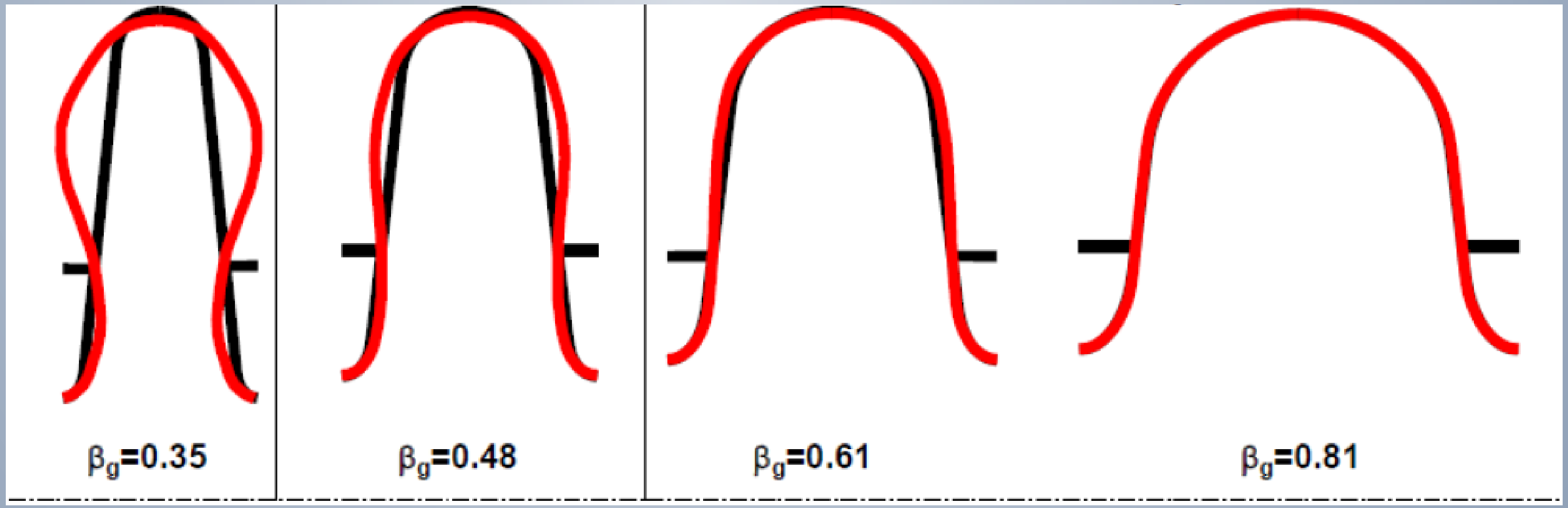
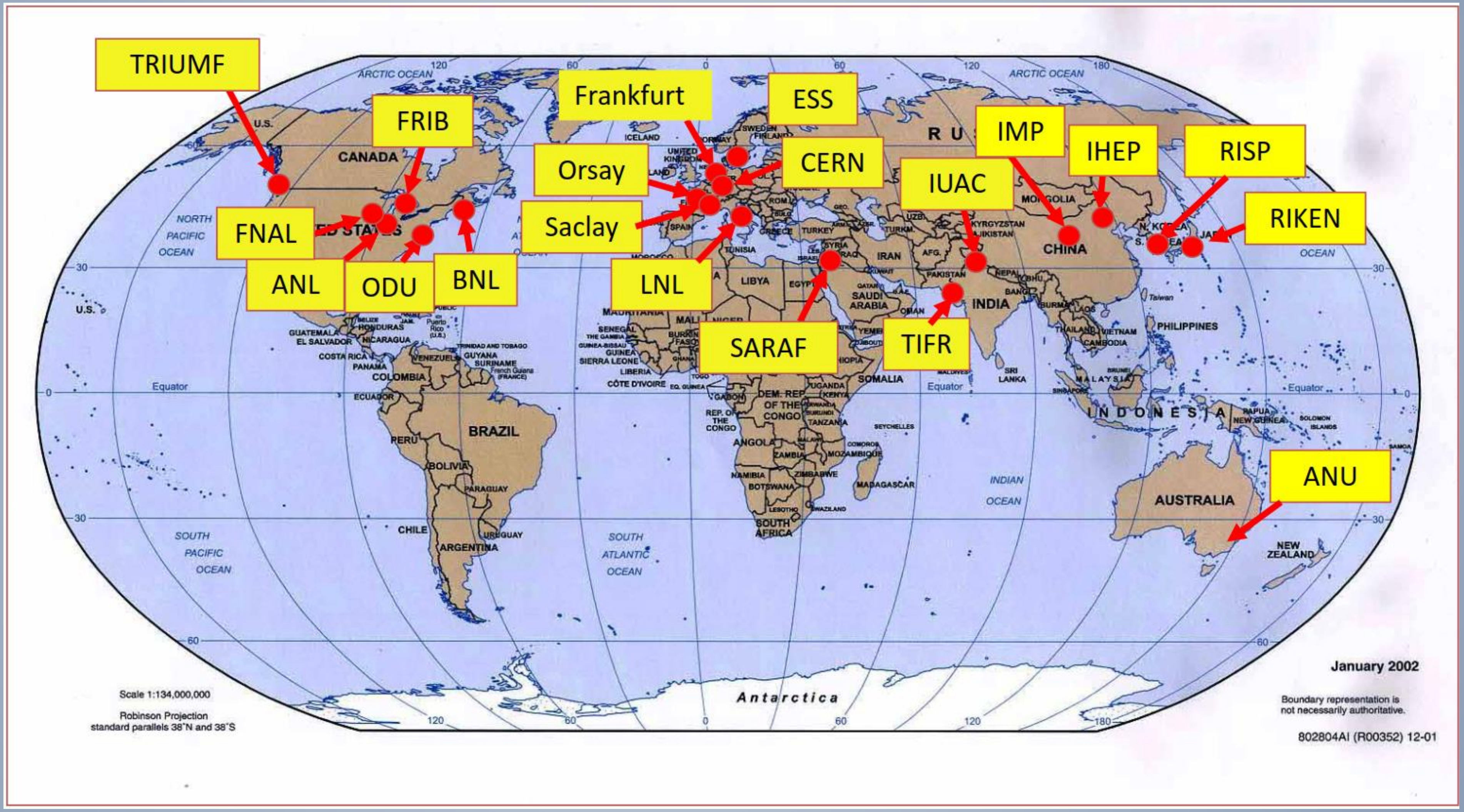


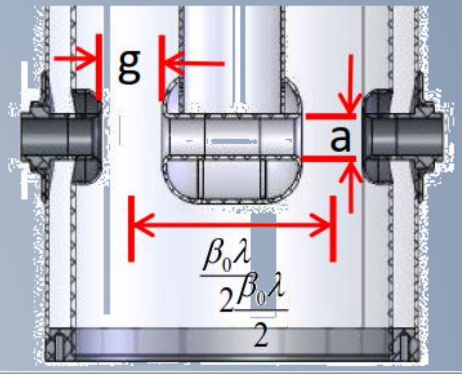
Photo:
Reidar Hahn

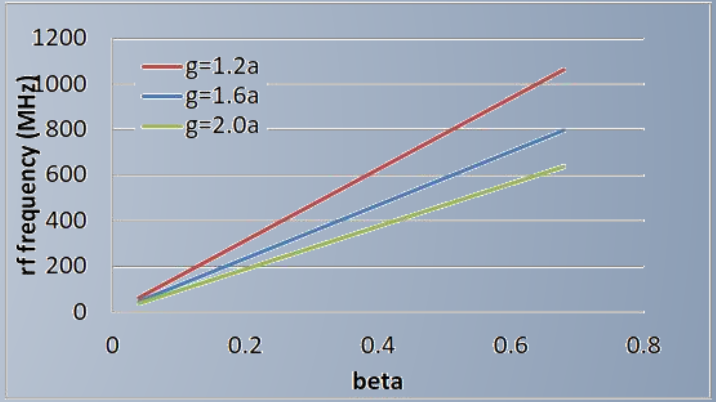
Non-elliptical SRF Community around the world

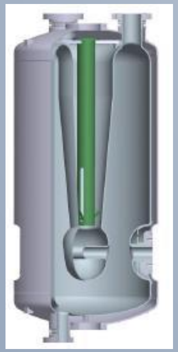


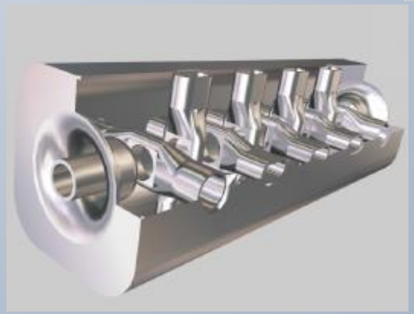
Resonator types for low beta acceleration

- Quarter wave resonator (QWR) $\beta \approx 0.04 \ \ldots 0.2$
- Half wave resonator (HWR) $\beta \approx 0.1 \ \ldots 0.5$
- Single spoke resonator (SSR) $\beta \approx 0.15 \ \ldots 0.7$
- Multi-spoke resonator (MSR) $\beta \approx 0.06 \ \ldots 1$
- For comparison: Elliptical cavities $\beta \approx 0.5 \ \ldots 1$









Coaxial resonator

- Consider a coaxial geometry with grounded end plates, an inner conductor with radius a and an outer conductor with radius b.
- A standing wave occurs with E_r vanishing on the end walls at $z = 0$ and $z = d$.
- The remaining non-zero field components are

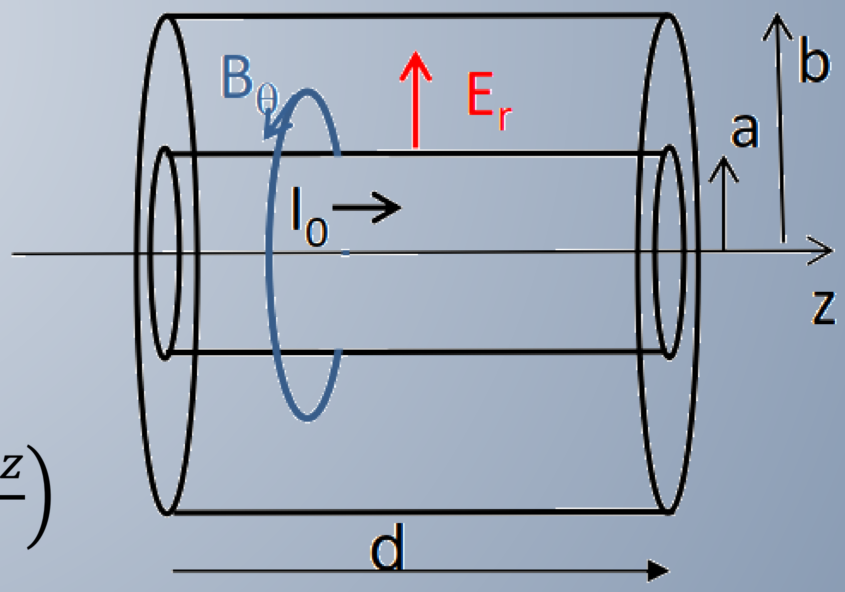
$$B_\theta = \frac{\mu_0 I_0}{\pi r}\cos\left(\frac{p\pi z}{d}\right),$$

$$E_r = -j2\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{I_0}{2\pi r}\sin\left(\frac{p\pi z}{d}\right),$$

where $\omega = \frac{p\pi c}{d}$, $p = 1,2,3,\ldots$

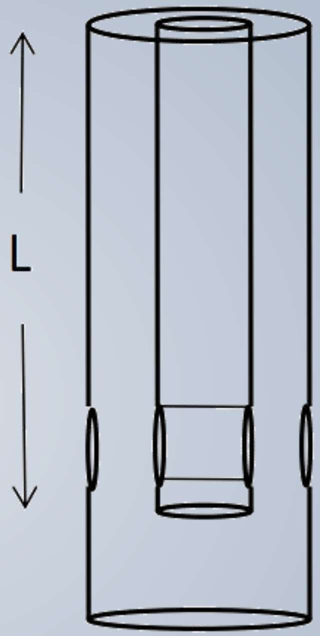
- Peak voltage:

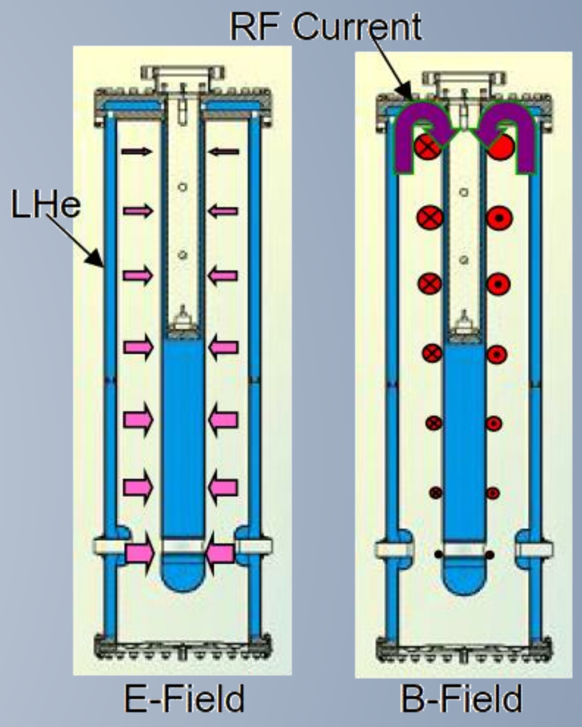
$$\hat{\mathrm{V}}(z) = \int_a^b E_r(z)\,dr = \sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{I_0}{\pi}\ln\frac{b}{a}\sin\left(\frac{p\pi z}{d}\right)$$



Quarter-wave resonator (QWR)

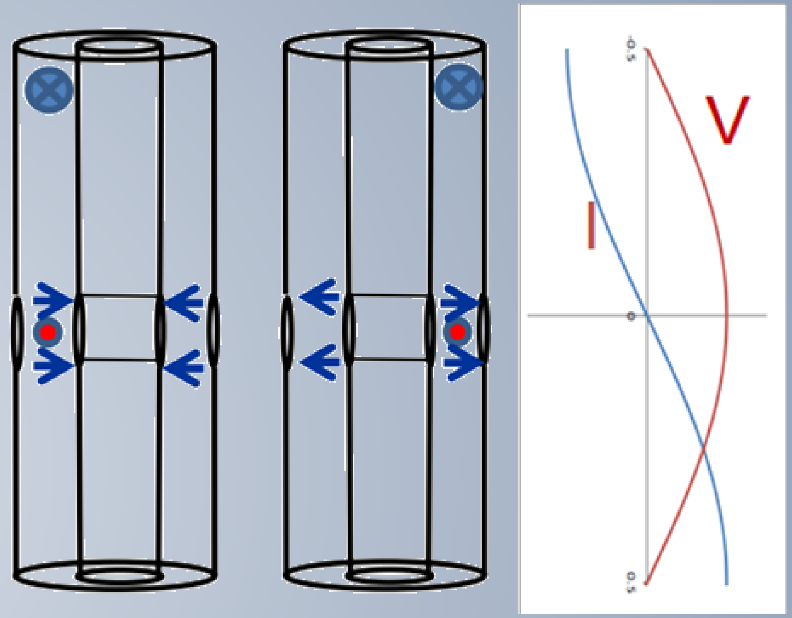
- The most popular coaxial TEM mode cavity is the quarter wave resonator – capacitively loaded $\lambda/4$ transmission line
- The inner conductor is open at one end with a resonant length of $(1+2p)\,\lambda/4$, $p = 0,1,2,\ldots$
- For acceleration, $p = 0$ is chosen.
- The maximum voltage builds up on the open tip – the maximum current at the root.
- A beam tube is arranged near the end of the tip.





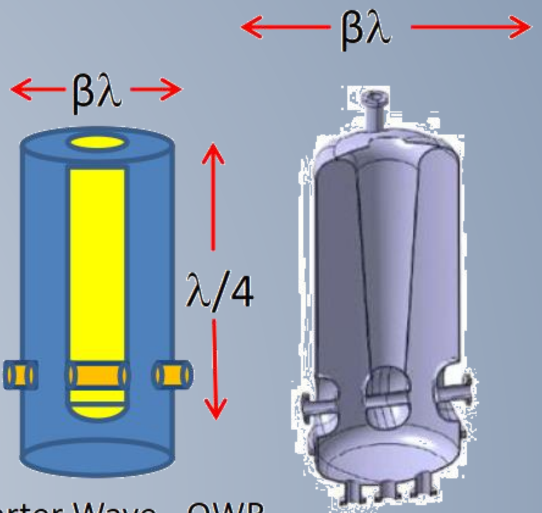
Half-wave resonator (HWR)

- In the HWR the beam port is at the centre of the inner conductor of a coaxial resonator, coincident with the maximum voltage for $p = 1$.
- Magnetic fields loop around the inner conductor with peak fields at the shorted ends.
- For acceleration, $p = 1$ is chosen.

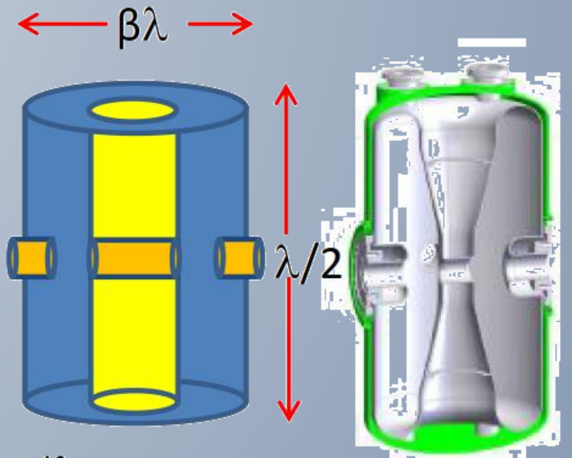


QWR vs. HWR

- QWR is the cavity of choice for low beta applications where a low frequency is needed
  - requires ~50% less structure compared to HWR for the same frequency – rf power loss is ~50% of HWR for same frequency and β_0.
  - allows low frequency choice giving larger longitudinal acceptance.
  - R/Q twice that of HWR.
  - Asymmetric field pattern introduces vertical steering especially for light ions that increases with velocity – avoid use for $\beta_0 > 0.2$.
  - Less mechanically stable than HWR due to unsupported end (microphonics).
- HWR is chosen in mid velocity range ($\beta_0 > 0.2$) or where steering must be eliminated (i.e. high intensity light ion applications)
  - produces twice rf losses for the same β_0 and λ.
  - is 2x longer for the same frequency.
  - Pluses are the symmetric field pattern and increased mechanical rigidity.



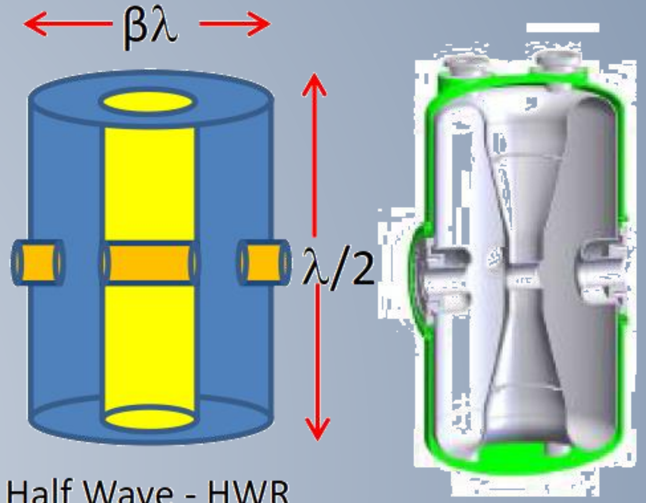
Quarter Wave - QWR



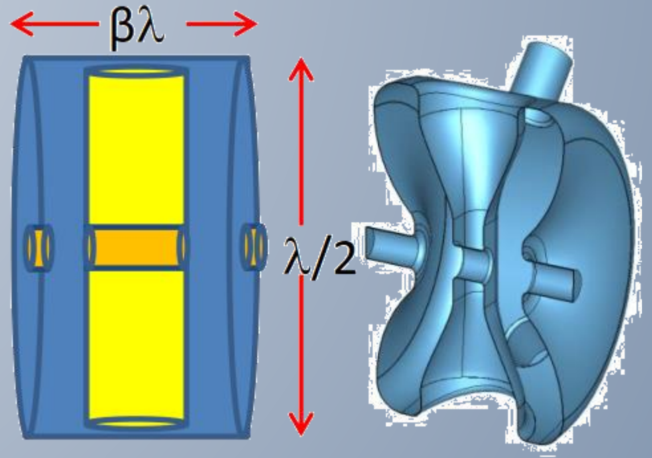
Half Wave - HWR

HWR vs. Single Spoke Resonator (SSR)

- A single spoke resonator (SSR) is another variant of the half-wave TEM mode cavity class.
- In HWR the outer conductor is coaxial with the inner conductor (with diameter $\beta_0\lambda$) while in the spoke cavities the outer cylinder is co-axial with the beam tube with diameter $\lambda/2$. It means that for $\beta_0 < 0.5$ the SSR has a larger overall physical envelop than the HWR for the same frequency.
- Thus for low beta applications $(0.1 < \beta < 0.25)$ HWRs are chosen at $\approx 160\ \mathrm{MHz}$, while SSRs are preferred at $\approx 320\ \mathrm{MHz}$.
- The spoke geometry allows an extension along the beam path to provide multiple spokes in a single resonator giving higher effective voltage, but with a narrower transit time acceptance.



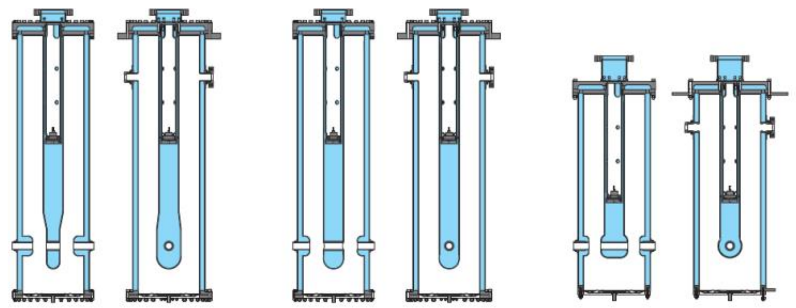
Half Wave - HWR



Single spoke - SSR

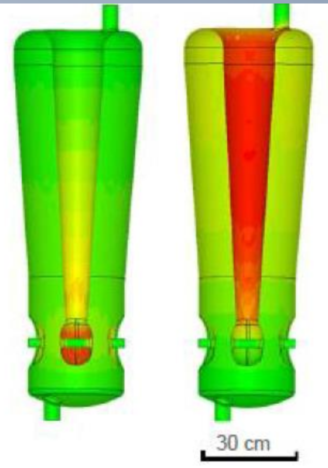
Cavity types – QWRs

TRIUMF ISAC-II Resonators

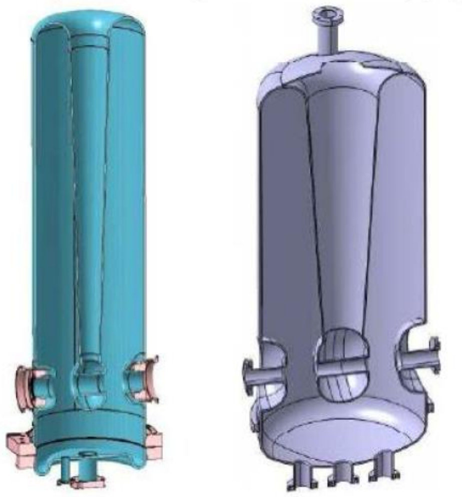


SCB low β (5.7%) 106.08 MHz | SCB medium β (7.1%) 106.08 MHz | SCC high β (11%) 141.44 MHz

FRIB β=0.041, 0.085 80.5MHz



ANL β=0.077, 0.085 72.5MHz



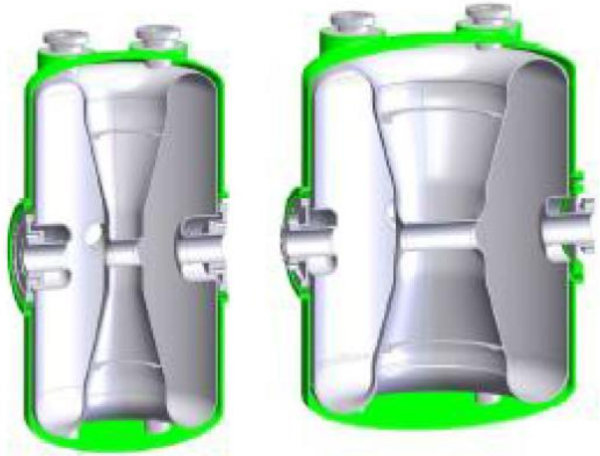
Spiral-2 β=0.007, 0.12 88.05MHz

RAON β=0.047, 81.25 MHz

Typical range:
$0.04 < \beta < 0.2$
$50\ \mathrm{MHz} \leq f \leq 160\ \mathrm{MHz}$

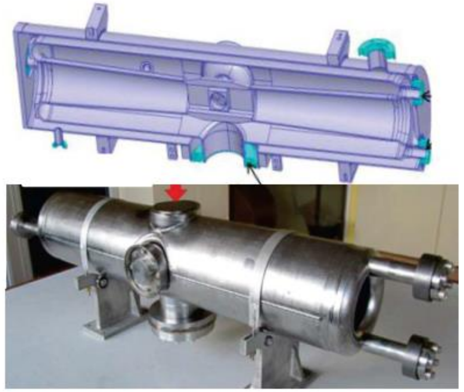
Cavity types – HWRs

IMP β=0.10, f=162.5MHz

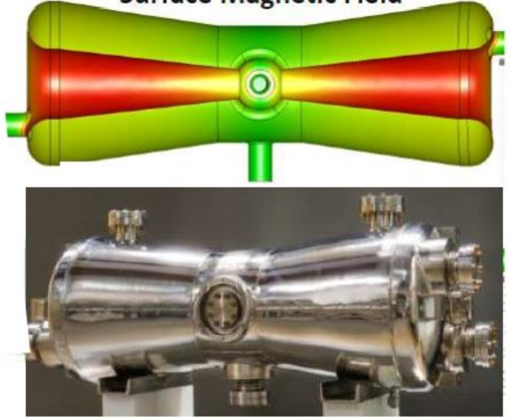


FRIB β=0.29, 0.53 f=322MHz

FRIB β=0.29, 0.53 f=322MHz



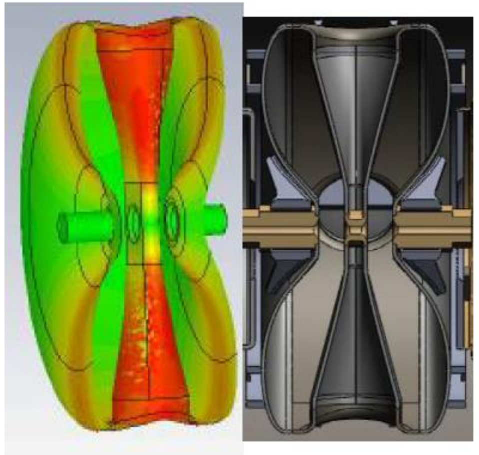
IFMIF β=0.11, f=175MHz



ANL β=0.112, f=162.5MHz

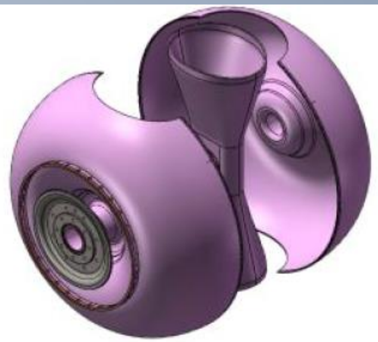
Typical range:
$0.1 < \beta < 0.5$
$140\ \mathrm{MHz} \leq f \leq 325\ \mathrm{MHz}$

Cavity types – SSRs

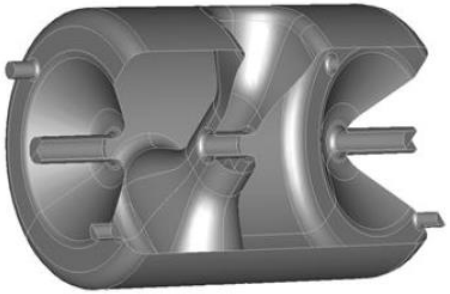


IHEP β=0.12, f=325MHz

FNAL β=0.215, f=325MHz



TRIUMF/RISP β=0.3, f=325MHz

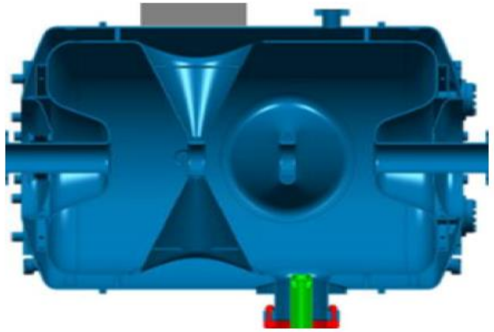


325 MHz, β_0 = 0.82
Single-Spoke Cavity

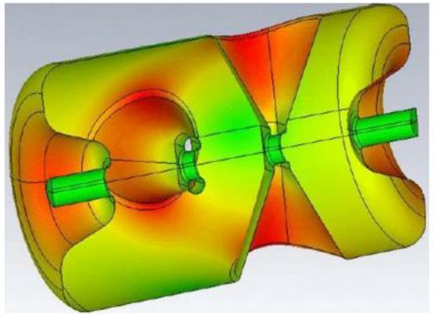
Typical range:
$0.15 < \beta < 0.7$
$320\ \mathrm{MHz} \leq f \leq 700\ \mathrm{MHz}$

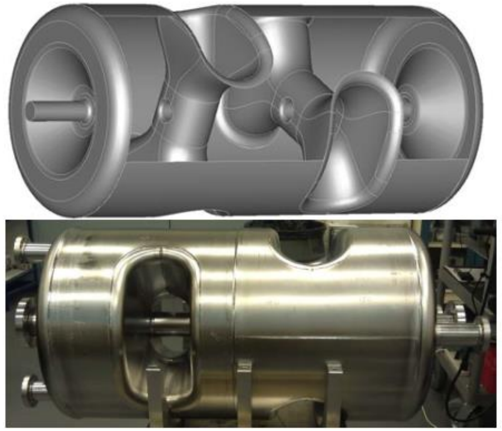
Photo:
Reidar Hahn

Cavity types – multi-cell

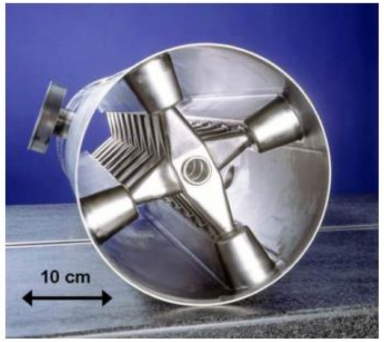


ESS/IPN β=0.50, f=352MHz

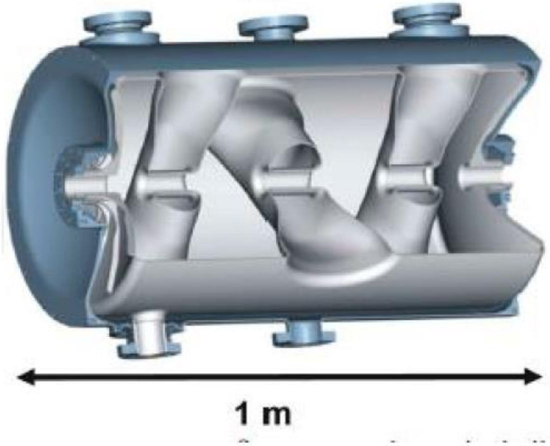




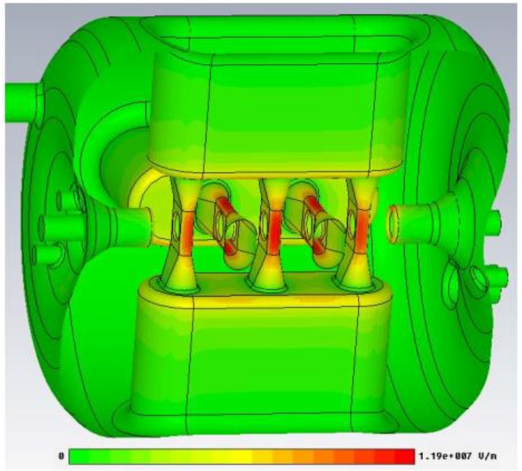
500 MHz, $\beta_0 = 1$
Double-Spoke Cavity



IAP 360 MHz, β_0~0.1
19 gap CH resonator



ANL β=0.63, f=345MHz

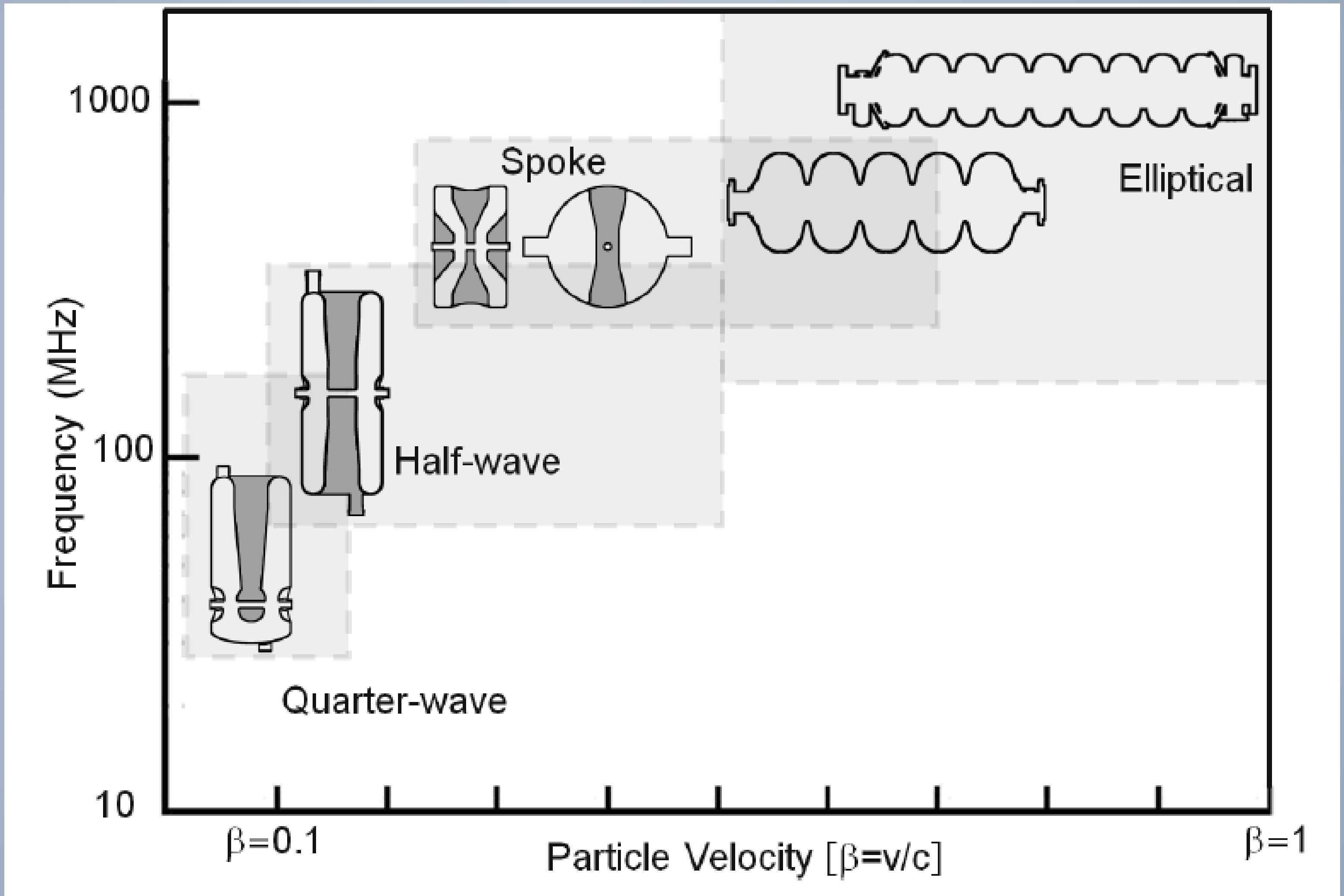


IMP CH β=0.067, f=162.5MHz

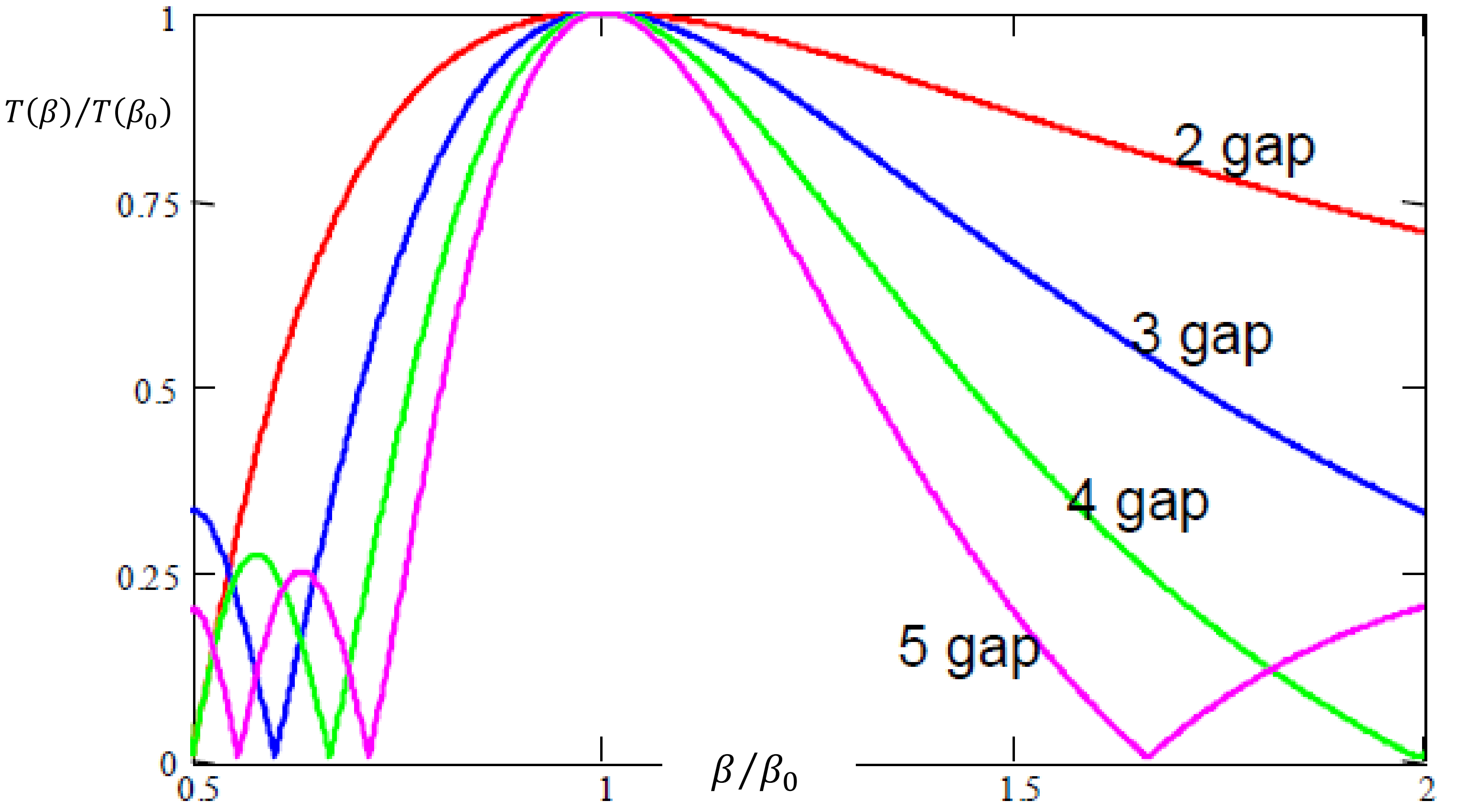
CH: Crossbar H-mode

Photo:
Reidar Hahn

Accelerating cavity velocity/frequency chart



Transit Time factor vs. β for multiple gaps



Normalized transit time factor curves vs. normalized velocity, for cavities with different number of gap

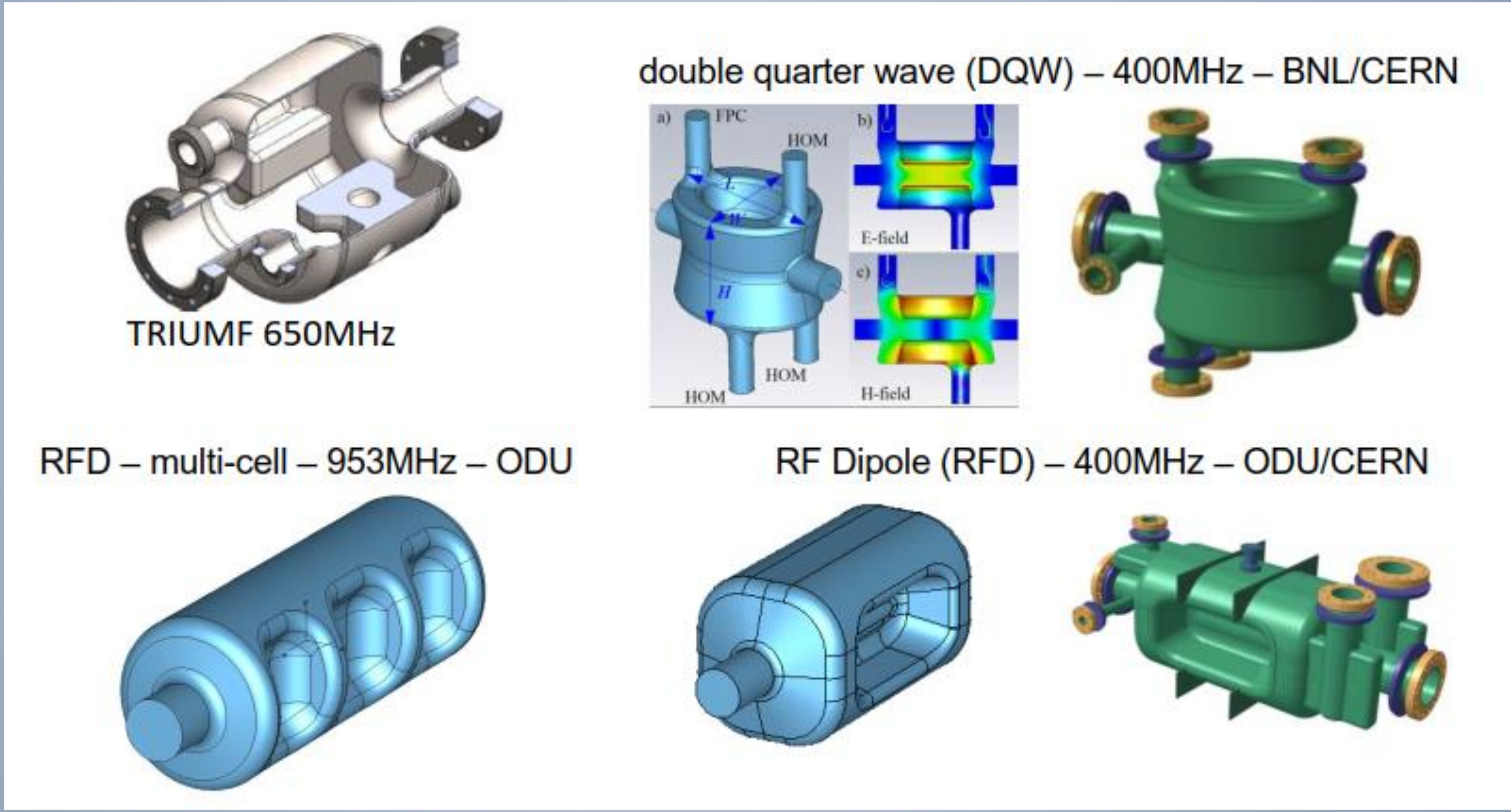
High-β spoke cavities

- High velocity spoke cavities with $\beta > 0.8$ are being designed as alternative to elliptical cavities
- Features:
  - relatively compact
    - between 20% and 50% smaller (radially) for low-β cavities
    - for high β diameter close to TM counterparts
  - allows low frequency at reasonable size
  - mechanically stable – high shunt impedance

325 MHz β=0.82 Single Spoke Cavity

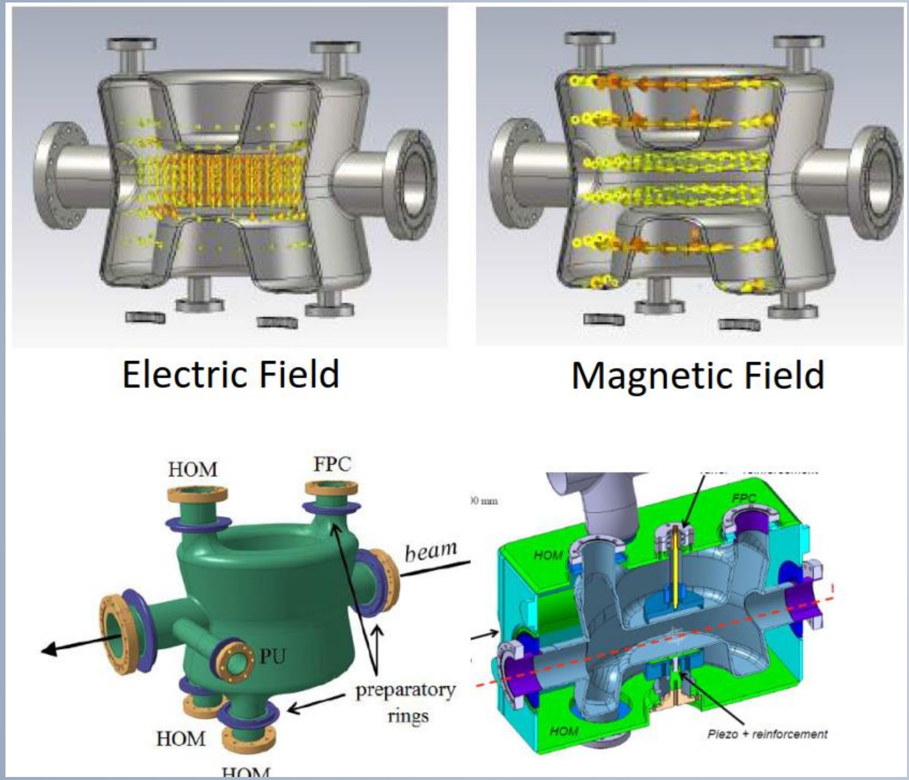
500 MHz β=1.0 Double Spoke Cavity

Deflecting mode cavities



Prototype HL-LHC Crab Cavity prototypes

“DQW” (vertical deflection)



“RFD” (vertical deflection)

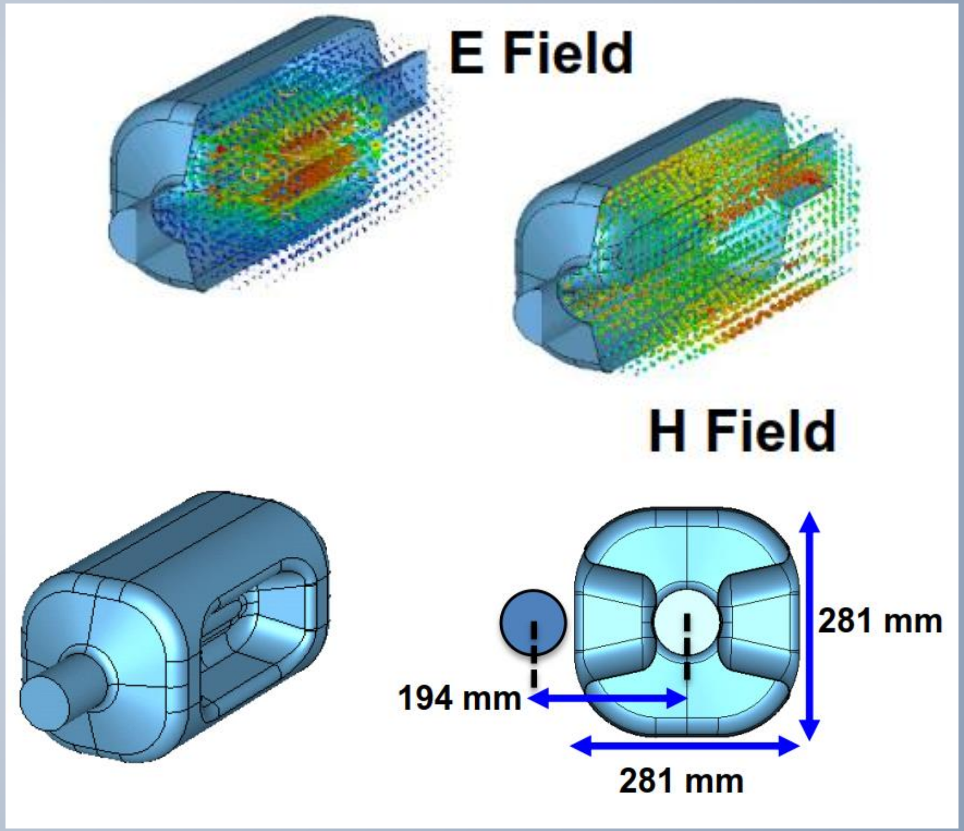
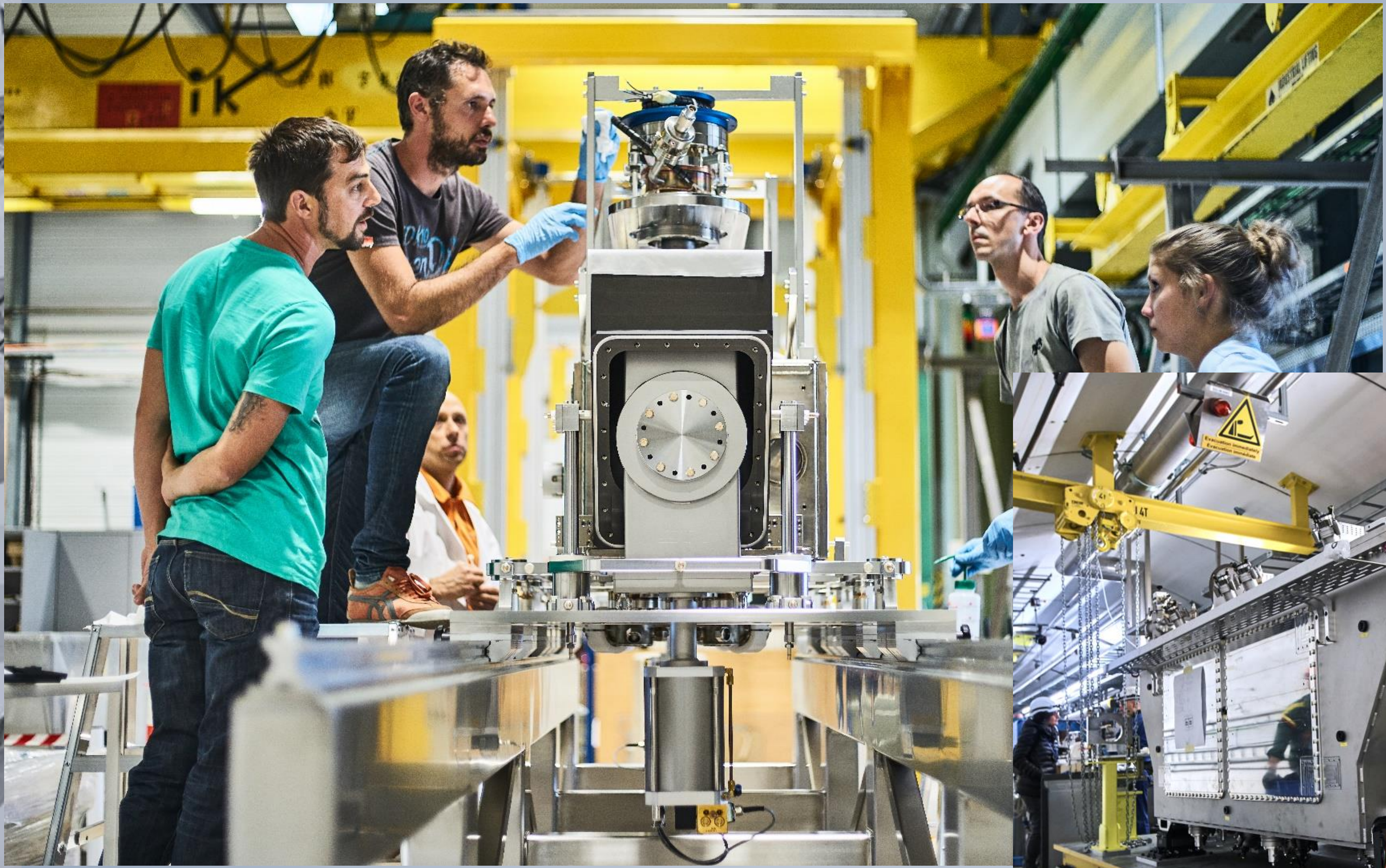
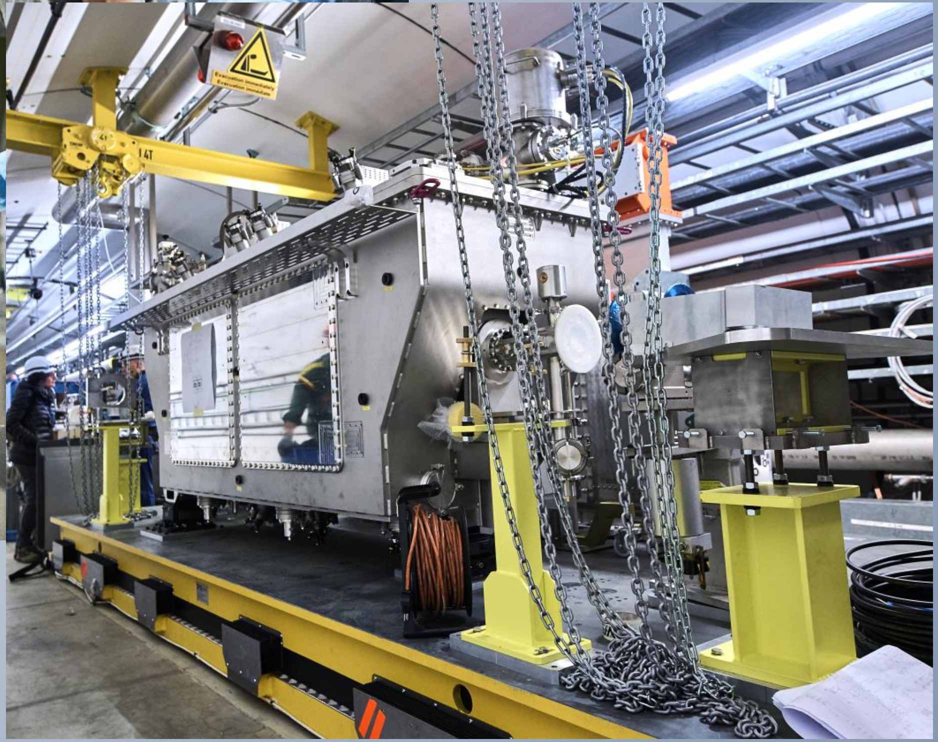



Photo:
Reidar Hahn

The real thing (HL-LHC Crab Cavity)

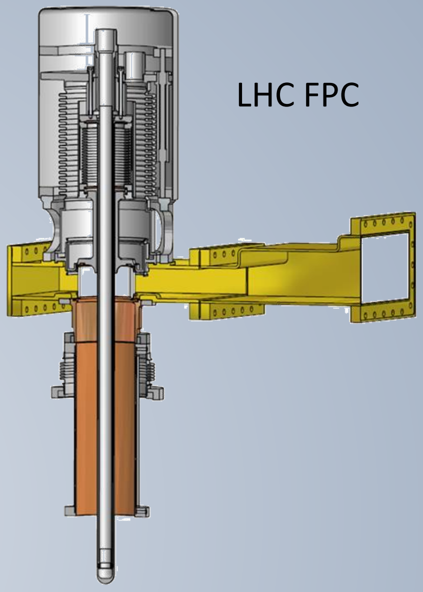

CERN-PHOTO-201708-196-10

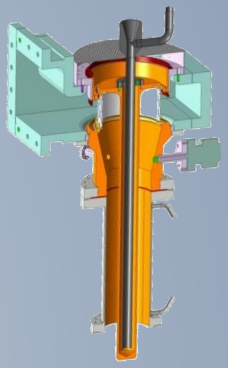

CERN-PHOTO-2018-026-5

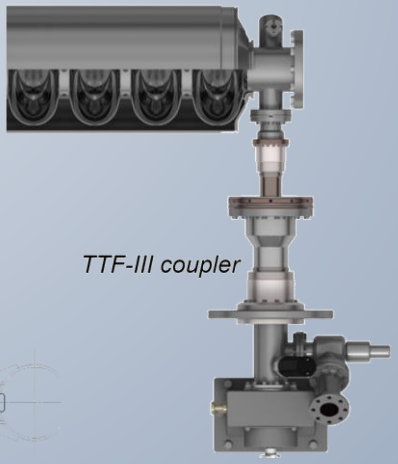
Power Couplers

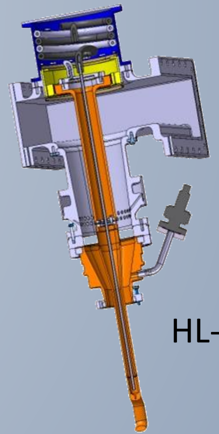
Fundamental Power Coupler – FPC

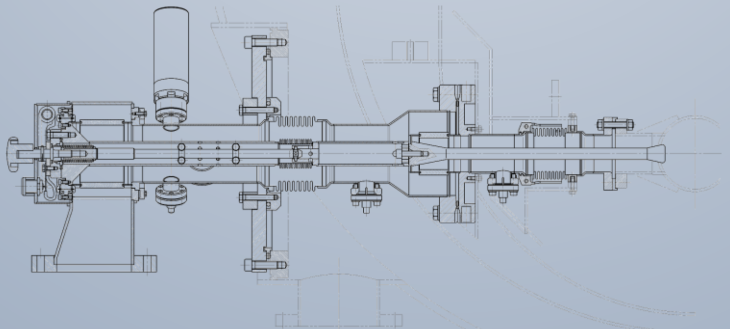
- The **Fundamental Power Coupler** is the connecting part between the RF transmission line and the RF cavity
- It is a specific piece of transmission line that also has to provide the cavity vacuum barrier.
- FPCs are amongst the most critical parts of the RF cavity system in an accelerator!
- A good RF design, a good mechanical design and a high quality fabrication are essential for an efficient and reliable operation.







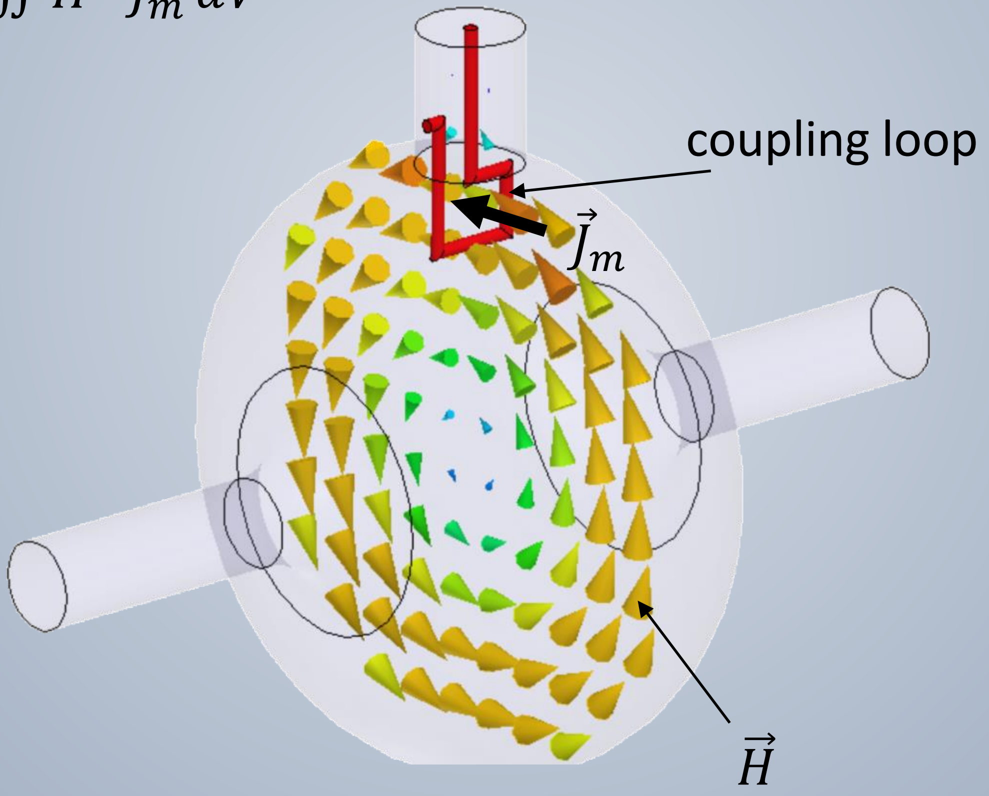




courtesy: Eric Montesinos/CERN

Magnetic (loop) coupling

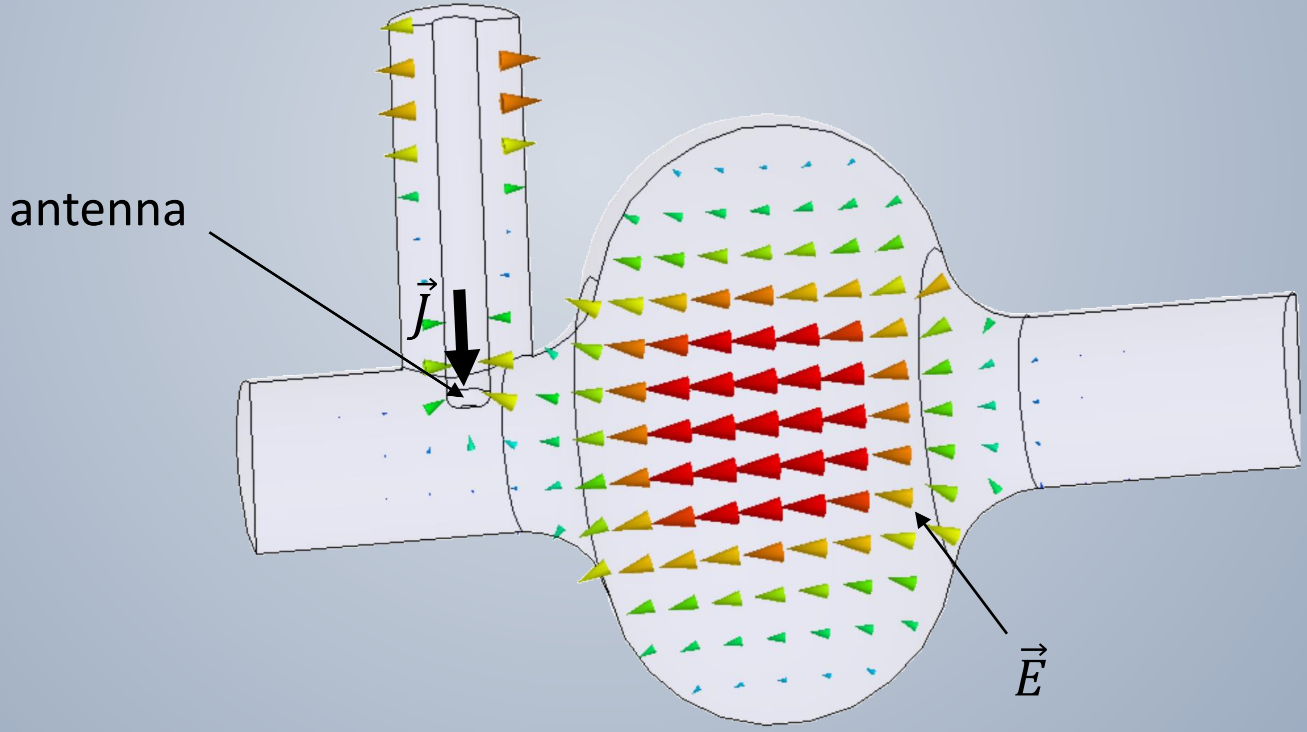
- The magnetic field of the cavity main mode is intercepted by a coupling loop
- The coupling can be adjusted by changing the size or the orientation of the loop.
- Coupling: $\propto \iiint \vec{H} \cdot \vec{J}_m \, dV$



courtesy: David Alesini/INFN

Electric (antenna) coupling

- The inner conductor of the coaxial feeder line ends in an antenna penetrating into the electric field of the cavity.
- The coupling can be adjusted by varying the penetration.
- Coupling $\propto \iiint \vec{E} \cdot \vec{J} \, dV$



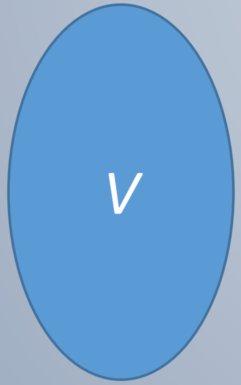
courtesy: David Alesini/INFN

Tuners

Photo:
Reidar Hahn

Small boundary perturbation

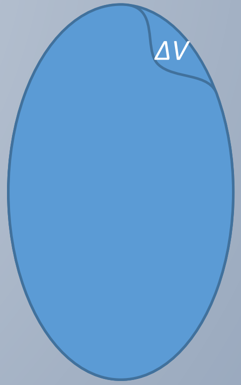
- Perturbation calculation is used to understand the basics for cavity tuning – it is used to analyse the sensitivity to (small) surface geometry perturbations.
  - This is relevant to understand the effect of fabrication tolerances.
  - Intentional surface deformation or introduced obstacles can be used to tune the cavity.
- The basic idea of the perturbation theory is use a known solution (in this case the unperturbed cavity) and assume that the deviation from it is only small. We just used this to calculate the losses (assuming H_t would be that without losses).
- The result of this calculation leads to a convenient expression for the (de)tuning:



unperturbed: ω_0

$$\frac{\omega - \omega_0}{\omega} = \frac{\iiint_{\Delta V} \left(\mu_0 |H_0|^2 - \varepsilon |E_0|^2\right) dV}{\iiint_{V} \left(\mu_0 |H_0|^2 + \varepsilon |E_0|^2\right) dV}$$

Slater's Theorem

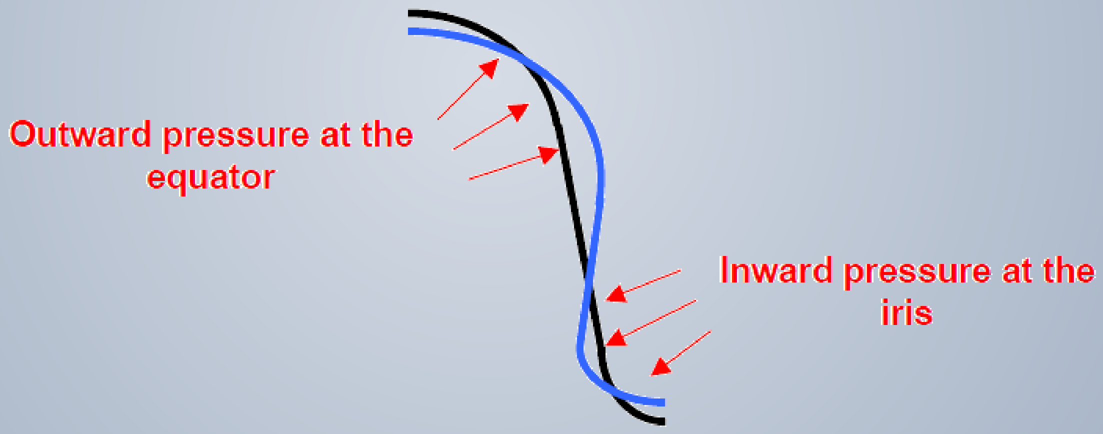


perturbed: ω

John C. Slater
1900 – 1976

Lorentz force detuning (“*LFD*”)

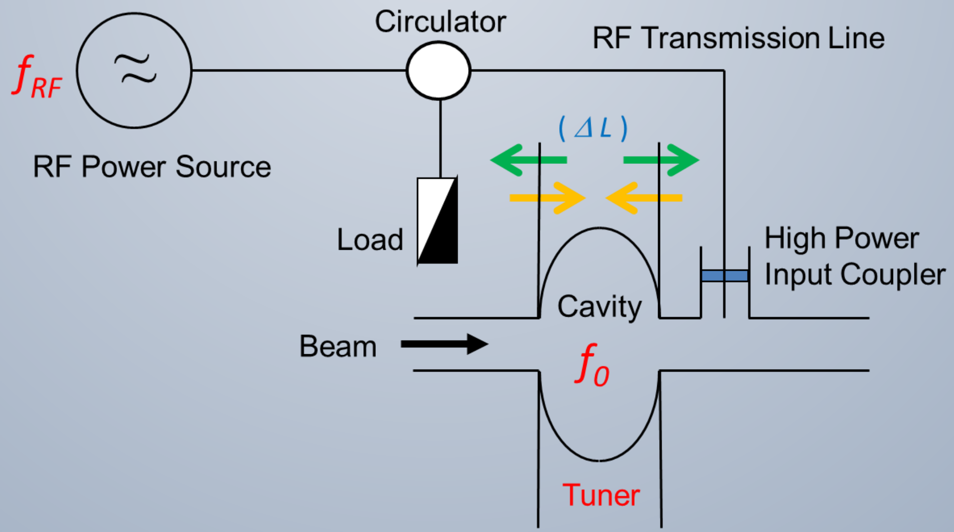
- The presence of electromagnetic fields inside the cavity lead to a mechanical pressure on the cavity.
- Radiation pressure: $P = \frac{1}{4}(\mu_0|H|^2 - \varepsilon_0|E|^2)$
- Deformation of the cavity shape:



- Frequency shift: $\Delta f = K\ L\ |E_{acc}|^2$; typical: $K\ L \approx -(1 \ldots 10)\mathrm{Hz}/\left(\frac{\mathrm{MV}}{\mathrm{m}}\right)^2$
- This requires good stiffness – and the possibility to tune rapidly!

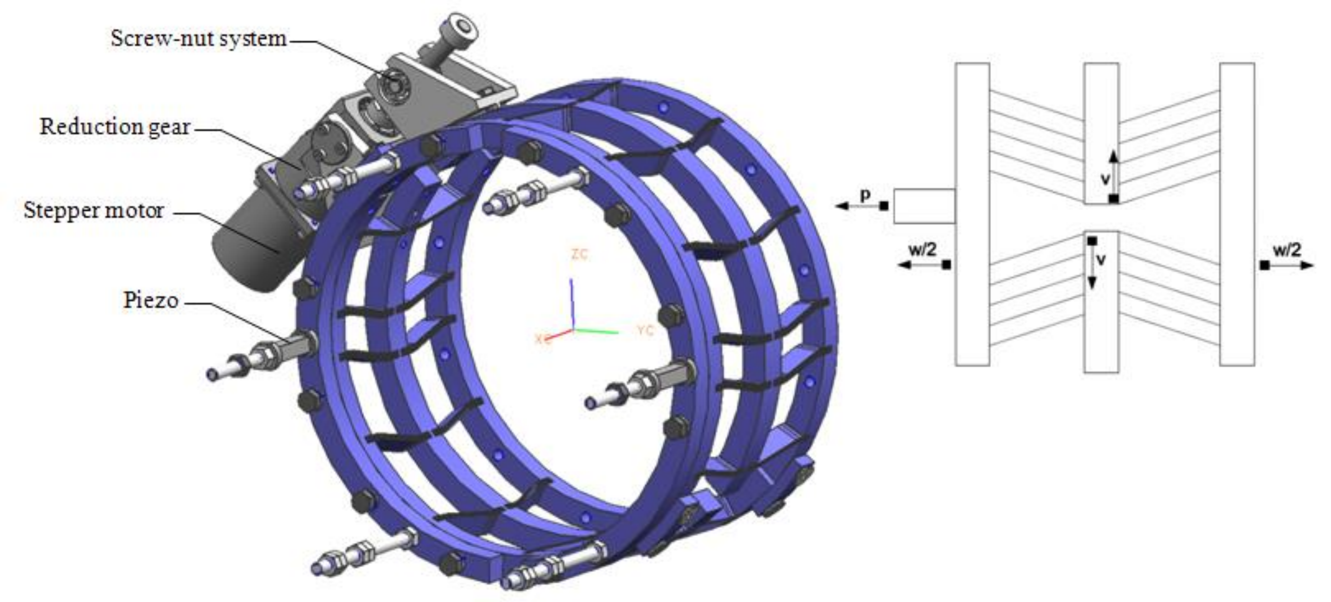
Tuner principle

- Slow tuners:
  - compensate for mechanical tolerances,
  - realized with stepper motor drives
- Fast tuners:
  - compensate Lorentz-force detuning and reactive beam loading
  - realized with piezo crystal (lead zirconate titanate – PZT)
- Tuning of SC cavities is often realized by deforming the cavity:



courtesy: Eiji Kako/KEK

Blade tuner

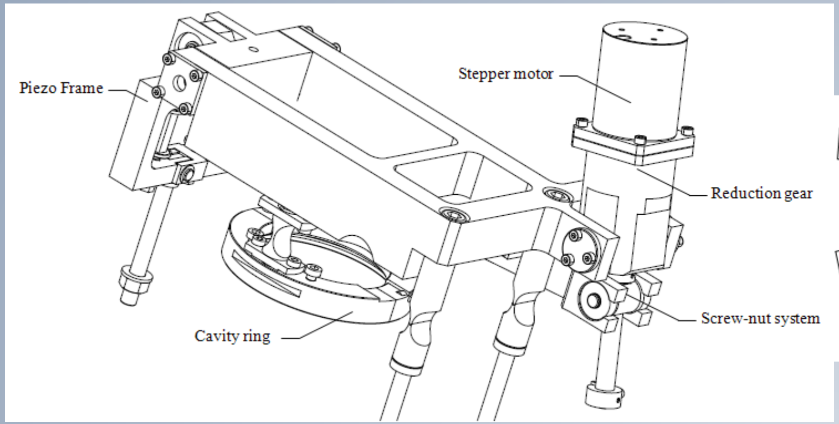


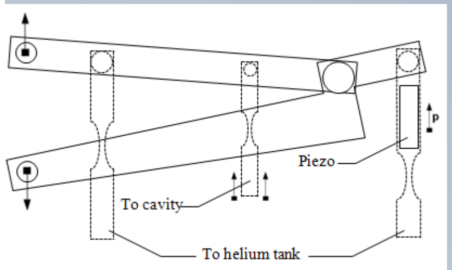
- Developed by INFN Milano
- Azimuthal motion transferred to longitudinal strain
- Zero backlash
- CuBe threaded shaft used for a screw nut system
- Stepping motor and gear combination driver
- Two piezo actuators for fast action
- All components in cold location

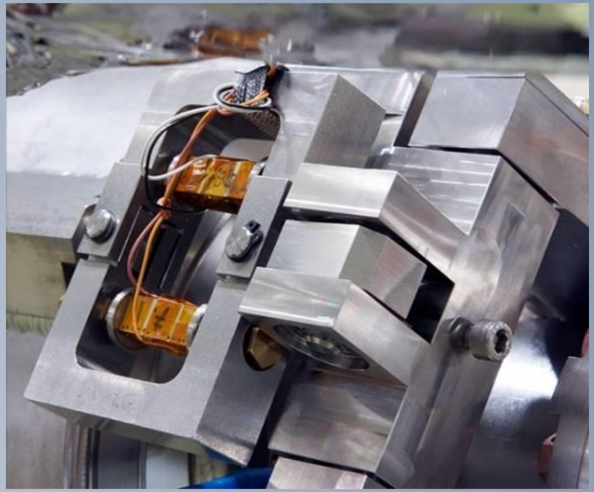
courtesy: Eiji Kako/KEK

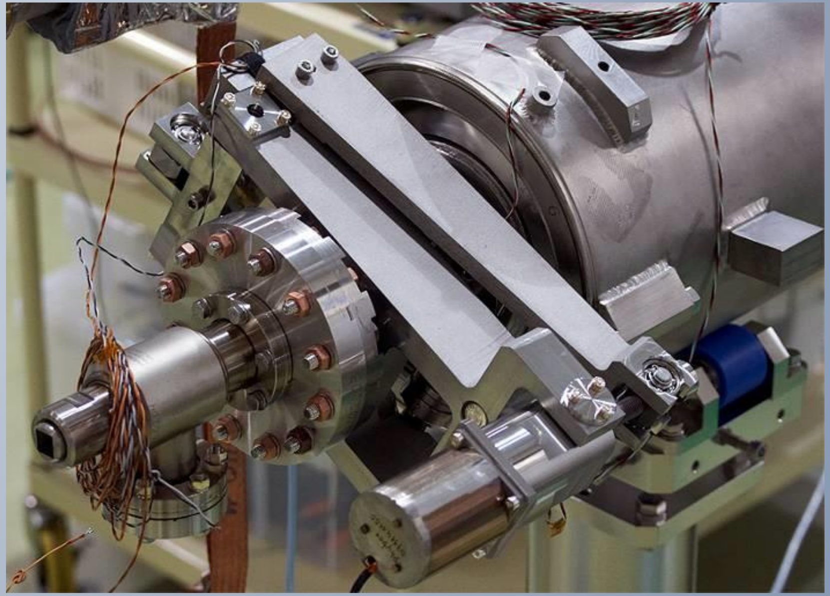
Photo:
Reidar Hahn

"Saclay" lever-arm tuner





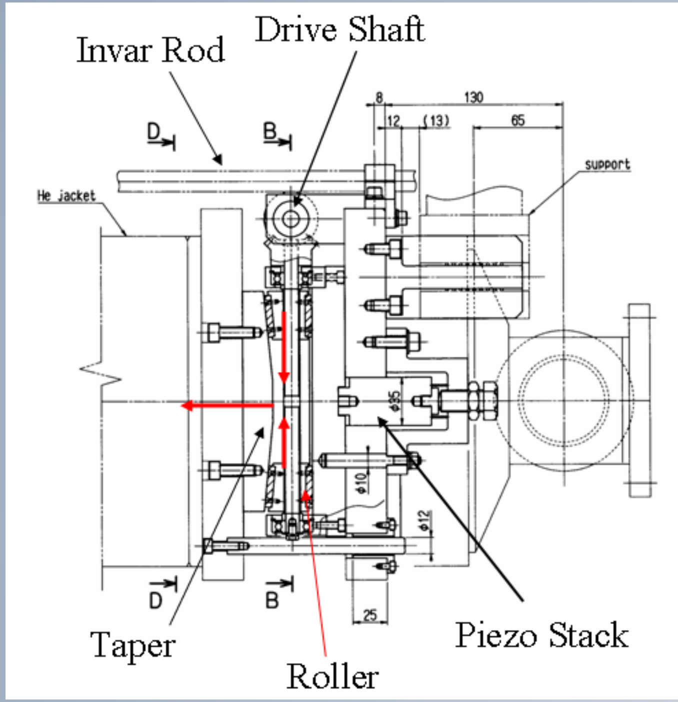


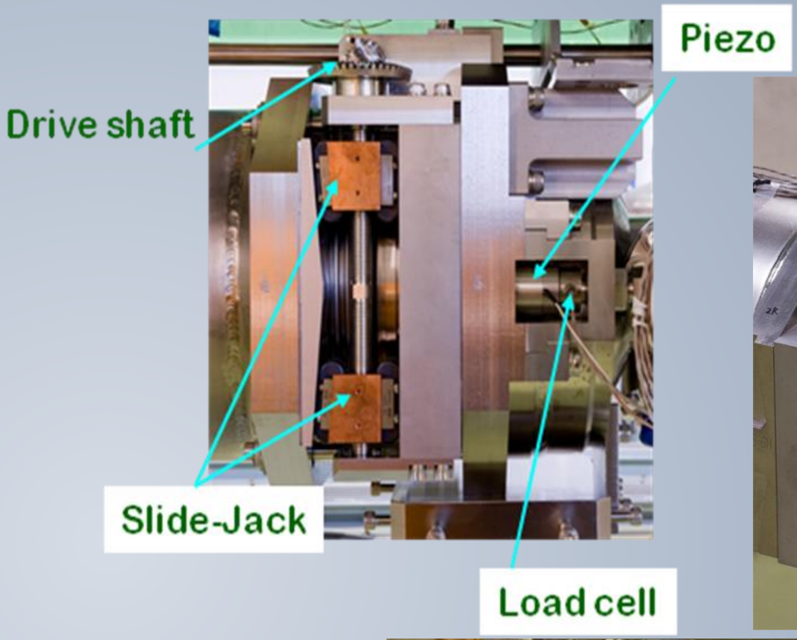


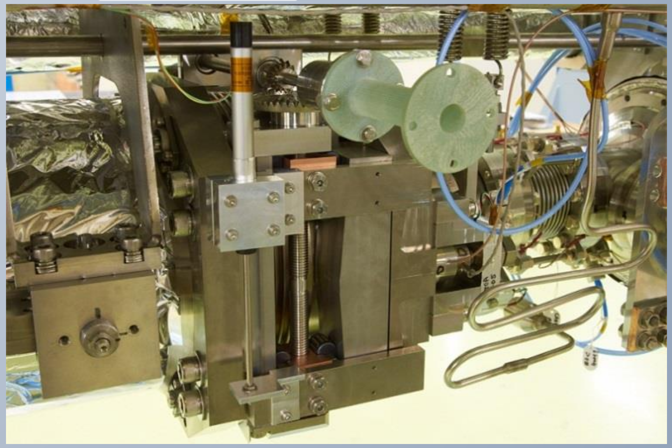
- Developed by DESY based on the Saclay design
- Double lever system (leverage 1.25)
- Cold stepping motor and gear combination
- Screw nut system
- Two piezo actuators for fast action in a preloaded frame
- All components in cold location

courtesy: Eiji Kako/KEK

Slide-jack tuner





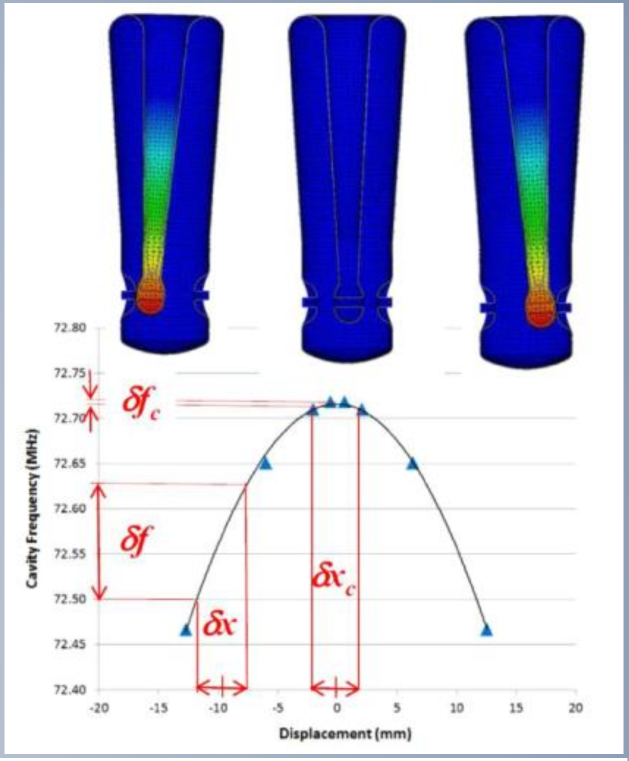


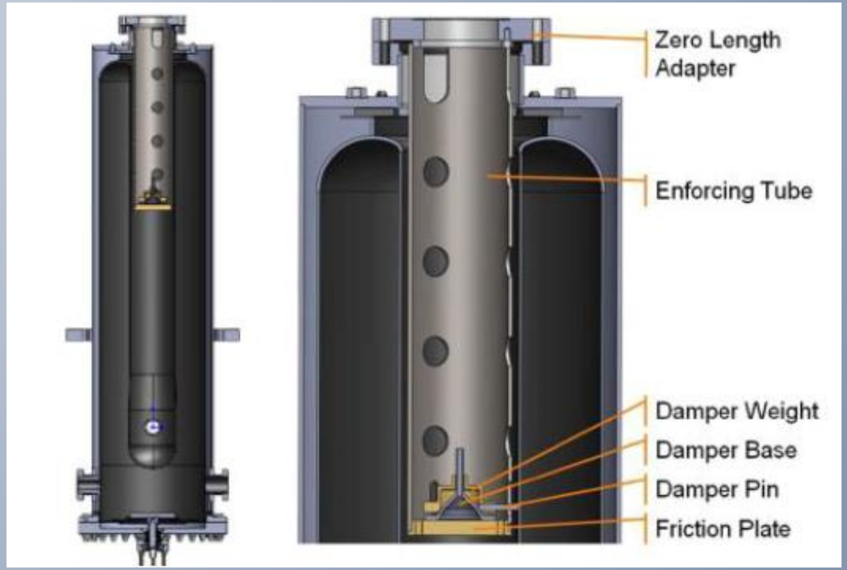
- Developed by KEK for STF cryomodule
- Slide-jack mechanism
- Single high voltage piezo actuator for fast action
- Warm stepping motor for easy maintenance
- Access port for replacing piezo

courtesy: Eiji Kako/KEK

Microphonics

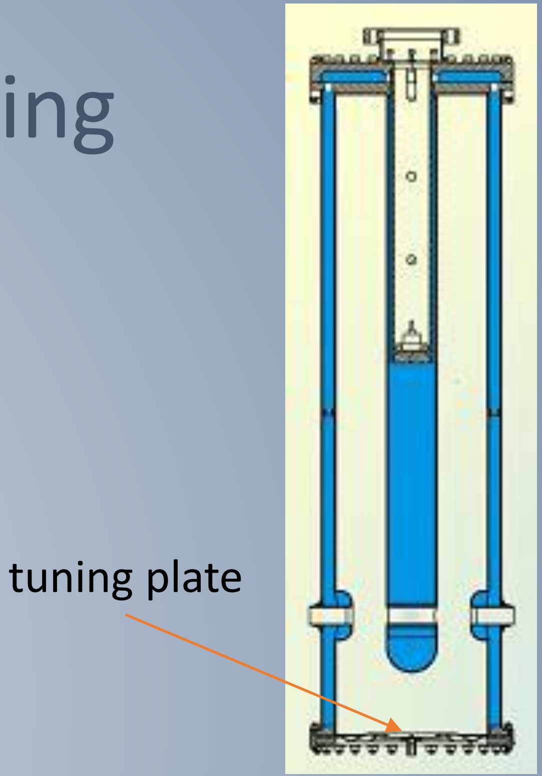
- Driven by mechanical vibration in the environment.
- QWRs are particularly problematic due to the pendulum action of the inner conductor, which can have very low mechanical frequencies ($(50 \ldots 100)$ Hz)
  - need to reduce the RMS detuning to $\ll 10\%$ of the available BW to avoid nuisance
  - the other option is to increase the BW (lower Q_L, costs power)
- Mitigation:
  - stiffening during design/manufacture
  - centring the inner conductor by plastic deformation so that $df/dx = 0$.
  - adding passive dampers
  - reduce environmental noise

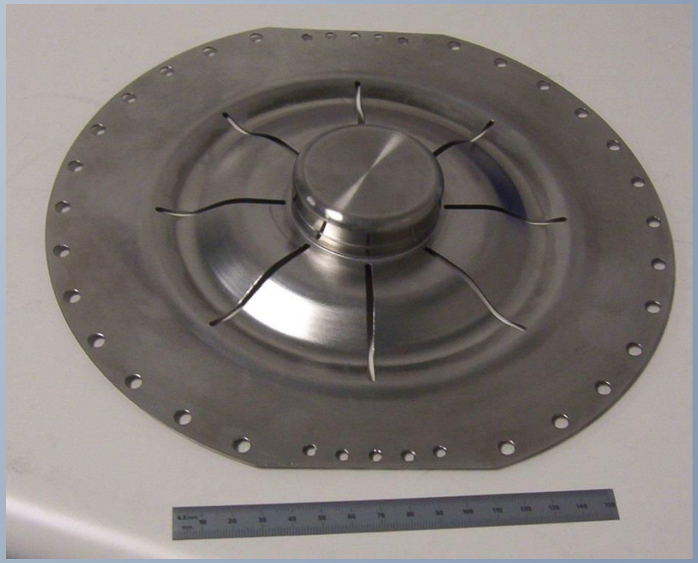




Frequency compensation/tuning

- For QWRs a tuning plate at the open end near the beam tube is generally used.
- For QWRs with removable tuning plate, a Nb puck can be welded to it – this reduces the cavity f_0 by increasing the equivalent C.
- This puck can be trimmed after final fabrication





Thank you very much!