RF Systems

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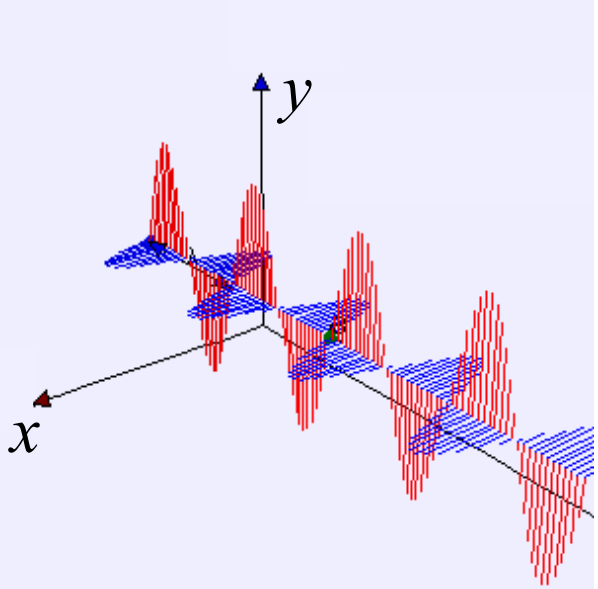
Many thanks to Erk Jensen
from whom I inherited the course
for using much of his material

- Waves in waveguides and modes in cavities
- Types of cavities
  - Standing wave and travelling wave structures
- Cavity parameters:
  - Shunt impedance, transit time factor, quality factor, filling time
- Higher Order Modes and Wakefields
- Power and coupling to cavities
- RF systems and feedback loops

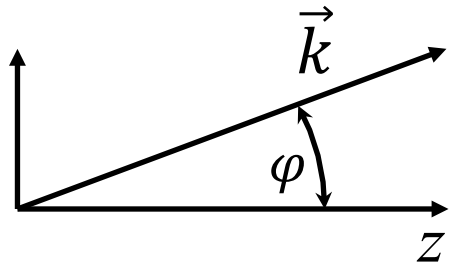
Introduction to Accelerator Physics
Budapest, 2-14/10/2016

Electromagnetic Homogeneous Plane Wave



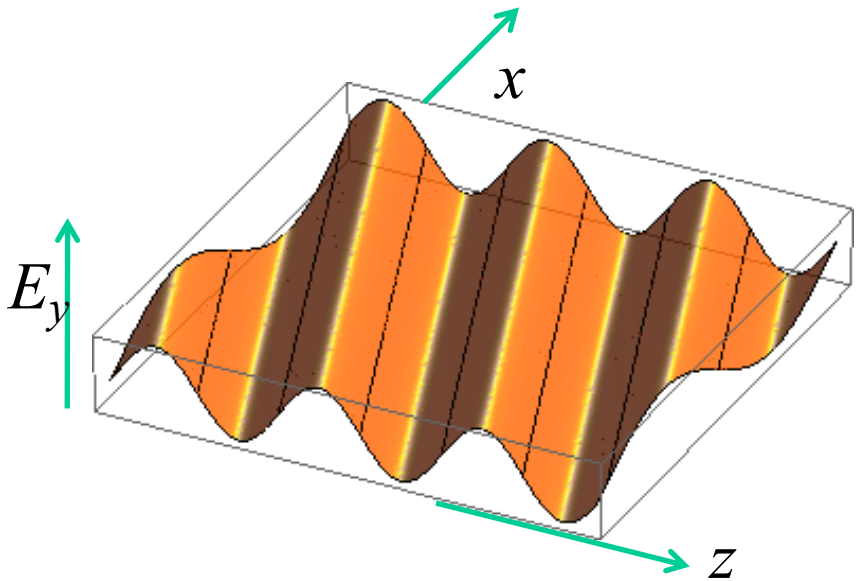
Courtesy: http://weelookang.blogspot.ch/2011/10/ejs-open-source-propagation-of.html

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



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

$$k = |\vec{k}| = \frac{\omega}{c} = \frac{2\pi}{\lambda}$$



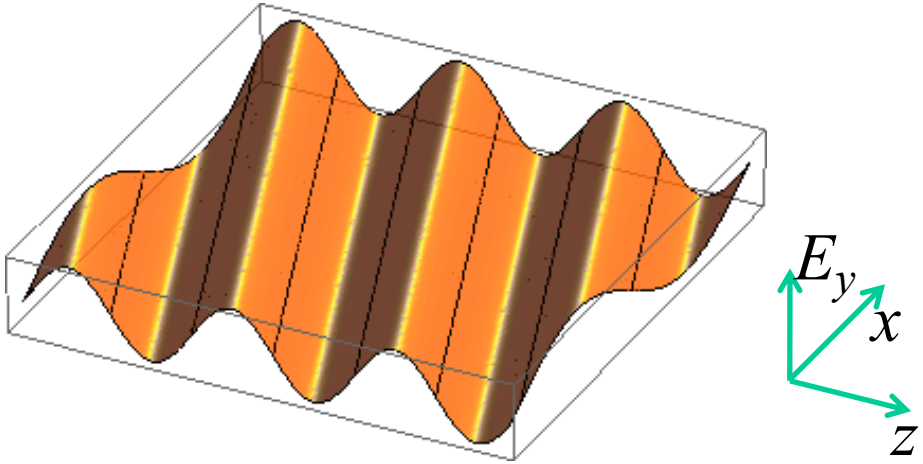
Wave vector $\vec{k}$:

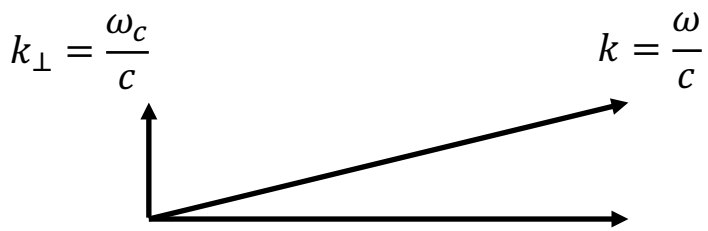
- orthogonal to phase front
- the direction of $\vec{k}$ is (usually) the direction of propagation
- the length of $\vec{k}$ is the phase shift per unit length
- $\vec{k}$ behaves like a vector.

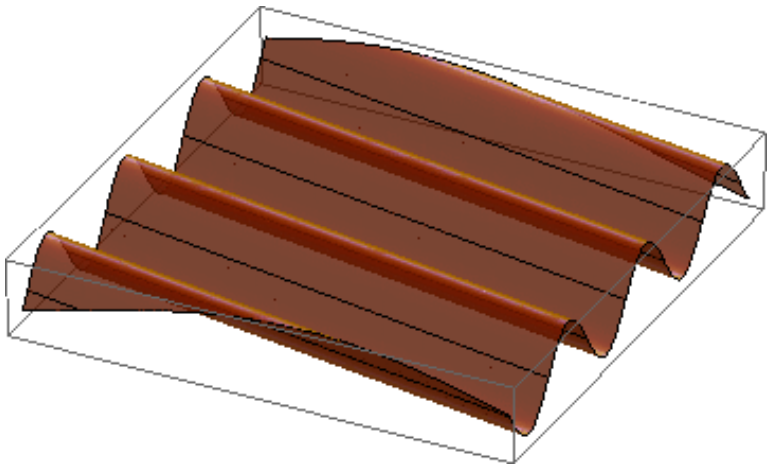
Wave length, phase velocity

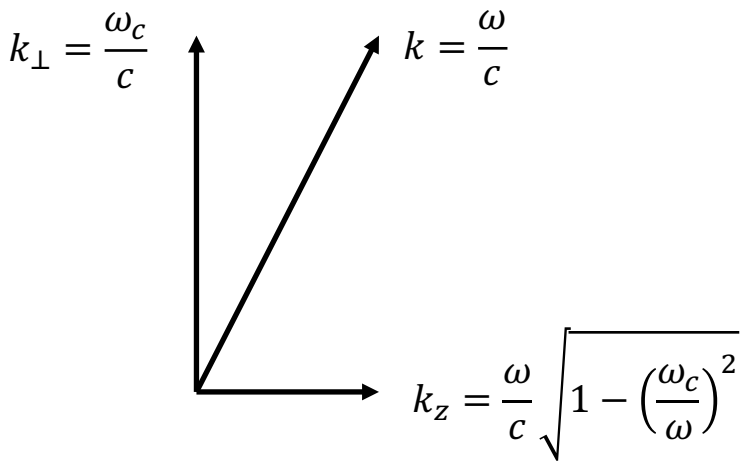
The components of $\vec{k}$ are related to

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

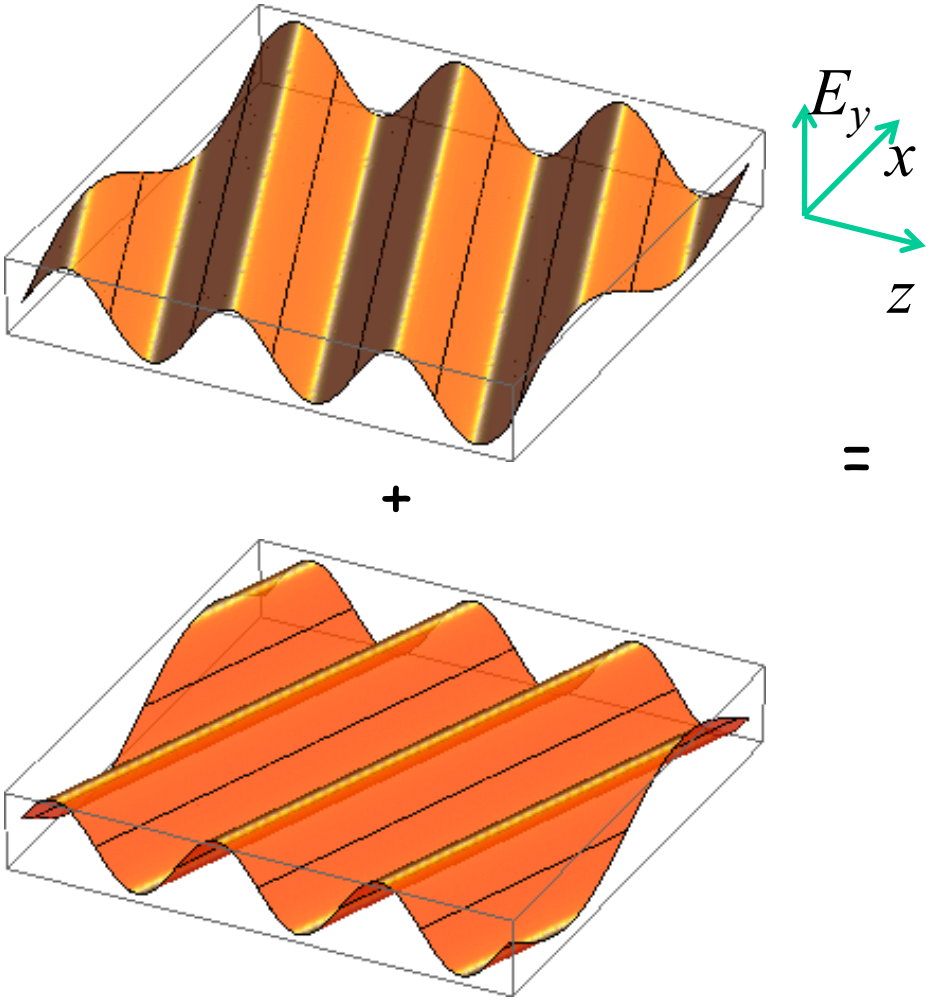








Superposition of 2 homogeneous plane waves



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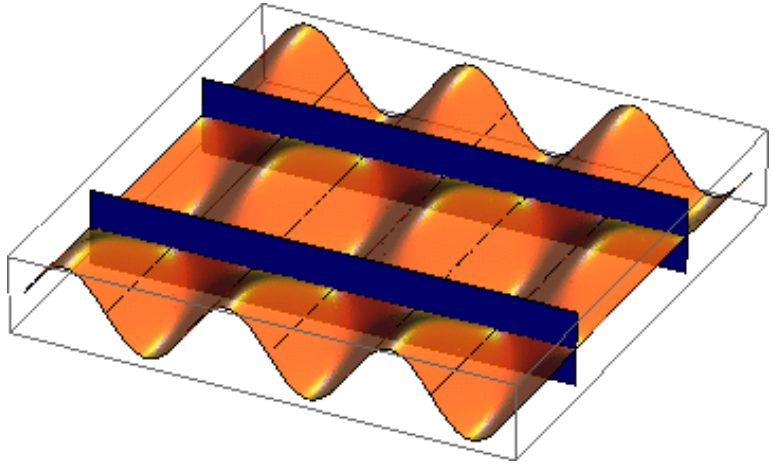
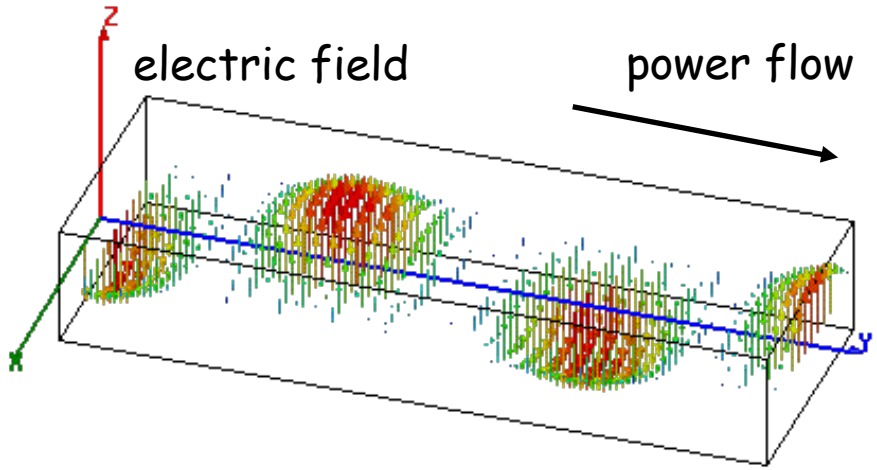


Metallic walls may be inserted where $E_y=0$ without perturbing the fields. Note the standing wave in x-direction!

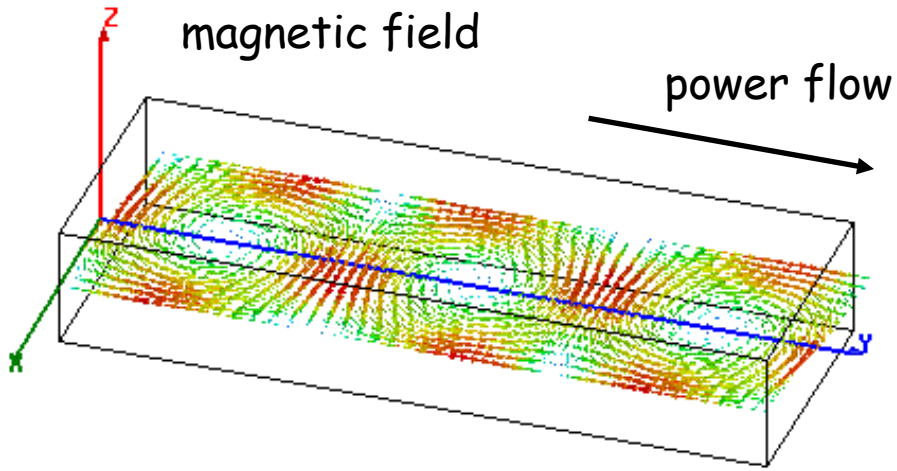
This way one gets a hollow rectangular waveguide!

Rectangular waveguide

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

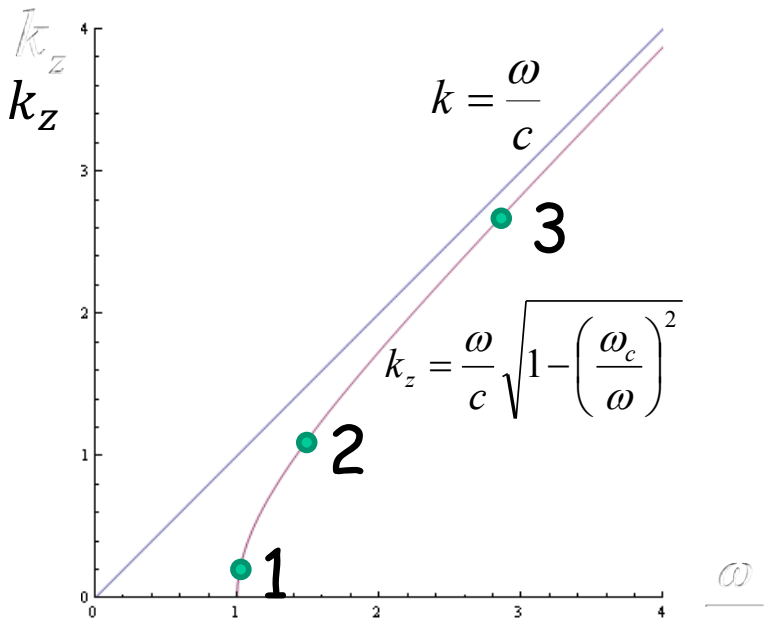


power flow: $\frac{1}{2}\mathrm{Re}\left\{\iint \vec{E}\times\vec{H}^{*}dA\right\}$



Waveguide dispersion

What happens with different waveguide dimensions (different width a)?
The "guided wavelength" λ_g varies from ∞ at f_c to λ at very high frequencies.

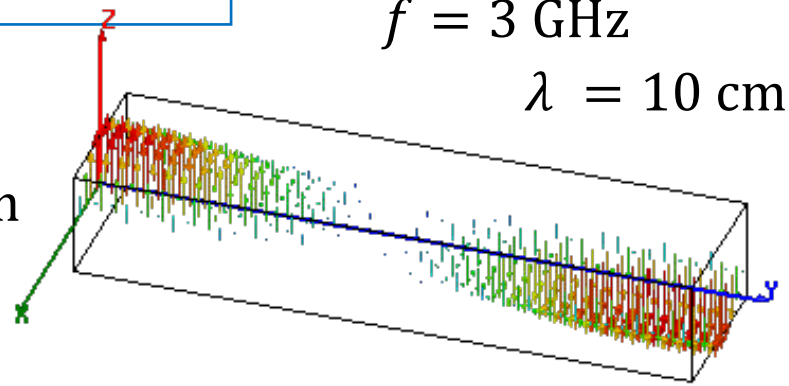


cutoff: $f_c = \frac{c}{2\,a}$

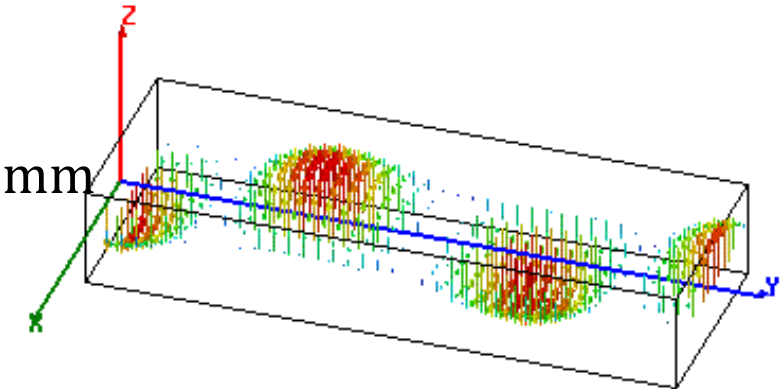
$f = 3$ GHz

$\lambda = 10$ cm

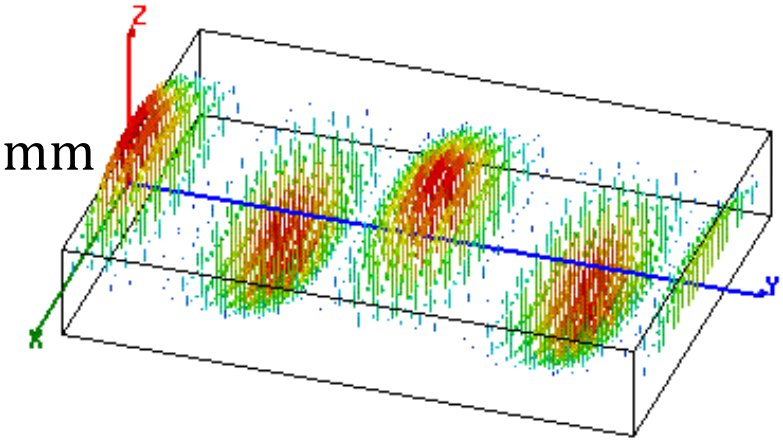
1:
$a = 52$ mm
$\frac{f}{f_c} = 1.04$



2:
$a = 72.14$ mm
$\frac{f}{f_c} = 1.44$



3:
$a = 144.3$ mm
$\frac{f}{f_c} = 2.88$

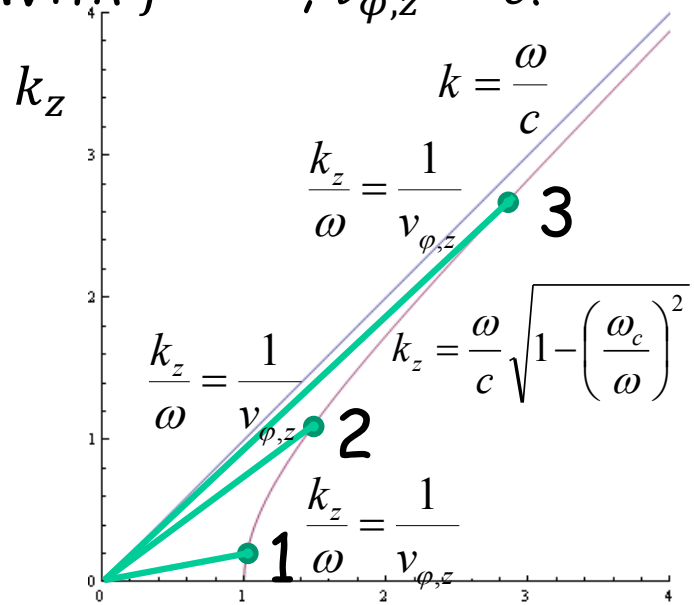


Phase velocity $v_{\varphi,z}$

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

Note that at $f = f_c$, $v_{\varphi,z} = \infty$!

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



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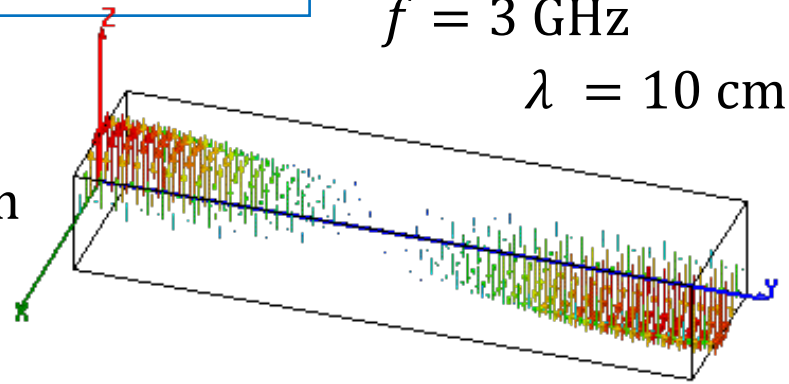

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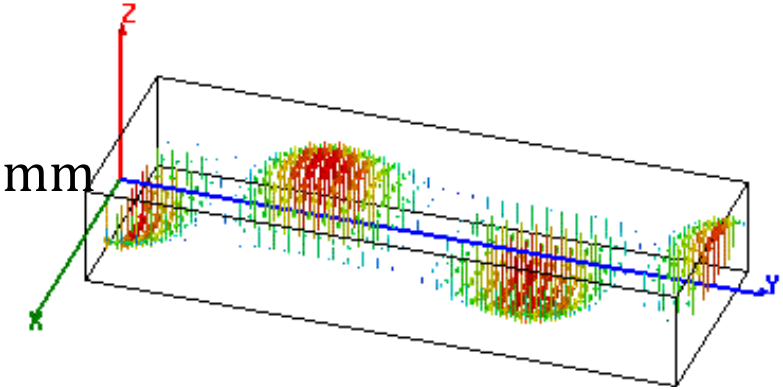

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$a = 144.3$ mm

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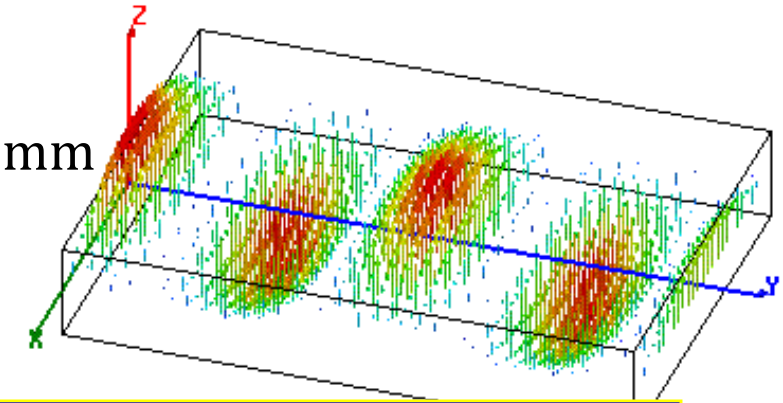
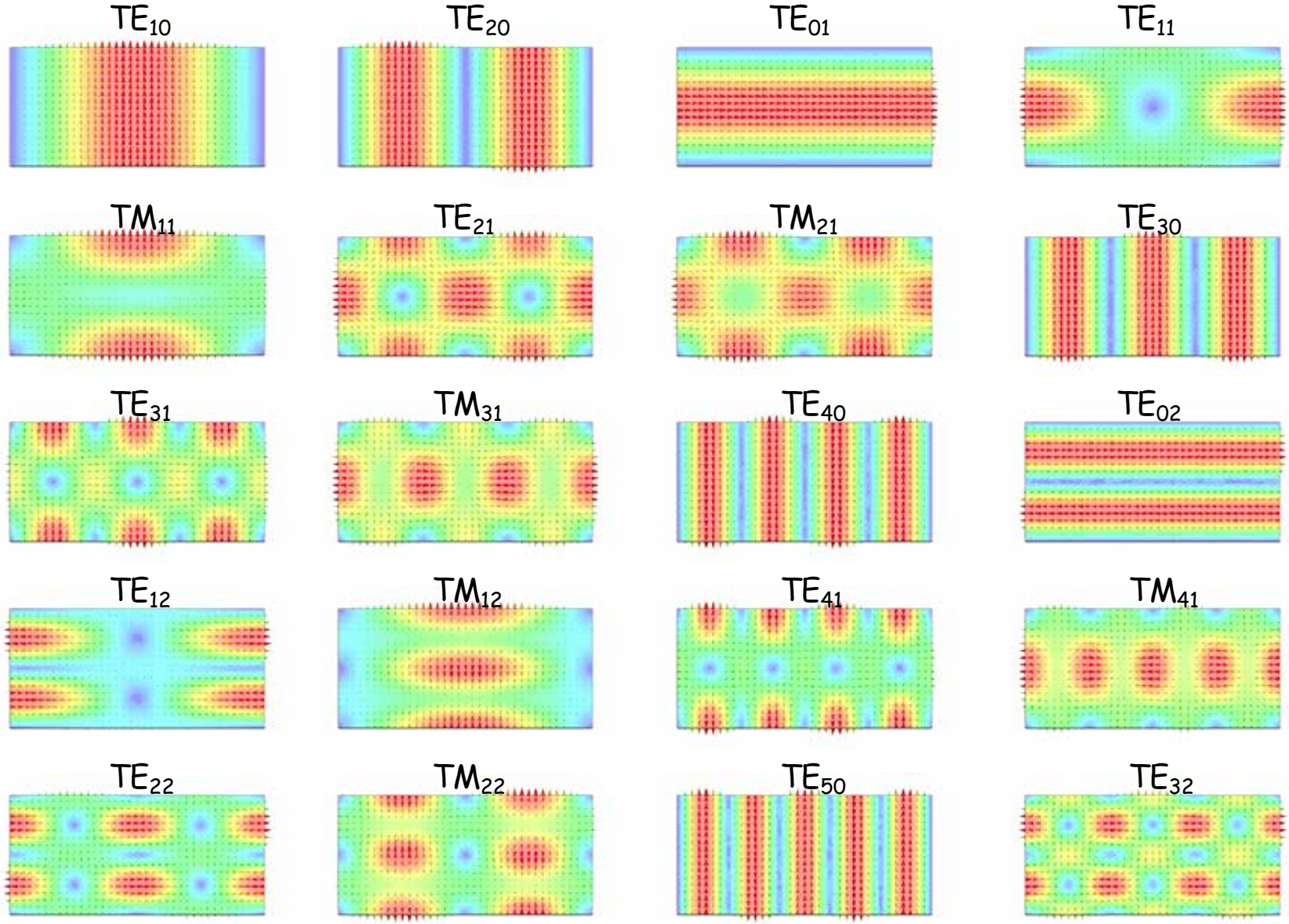


In a hollow waveguide: phase velocity $v_\varphi > c$, group velocity $v_{gr} < c$, $v_{gr} \cdot v_\varphi = c^2$.

Rectangular waveguide modes

Indices indicate number of half-waves in transverse directions.

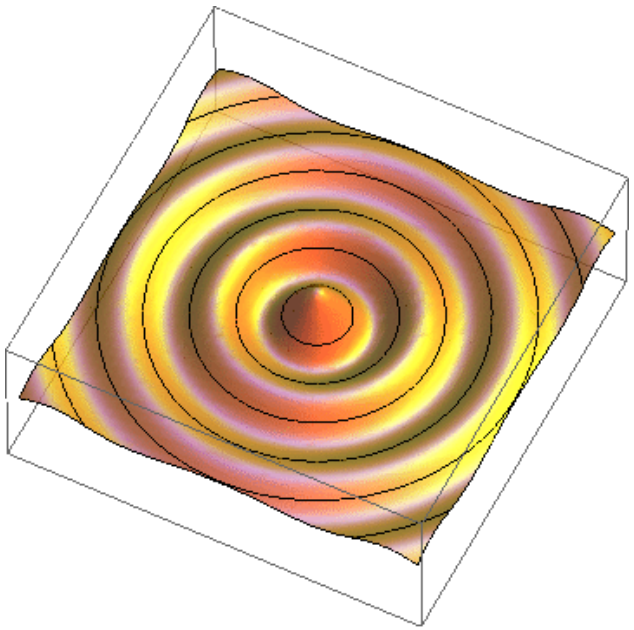


plotted: *E*-field

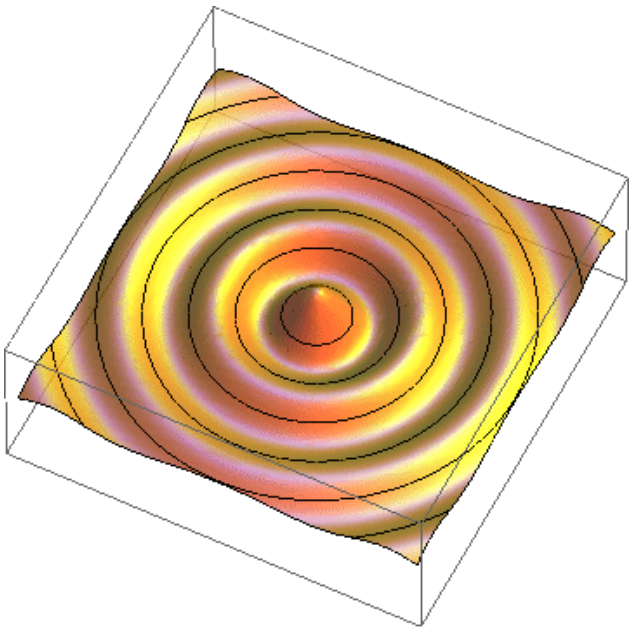
Radial waves

Also radial waves may be interpreted as superposition of plane waves.

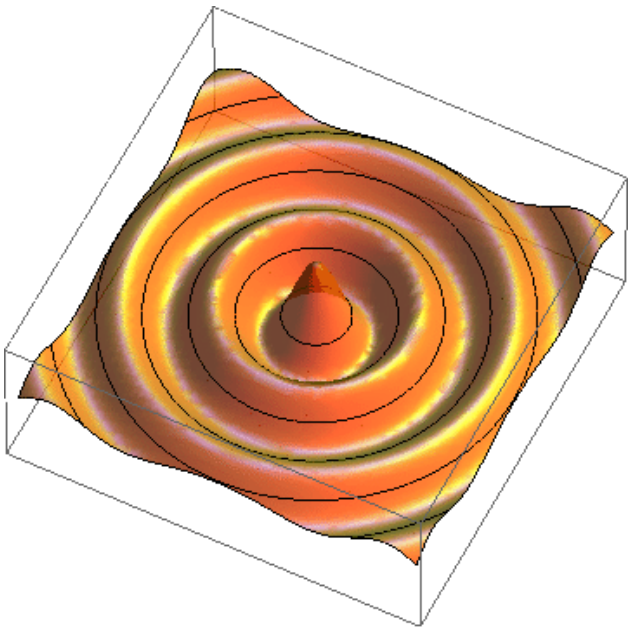
The superposition of an outward and an inward radial wave can result in the field of a round hollow waveguide.



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



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



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

Round waveguide modes

TE_{11} – fundamental

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

TM_{01} – axial field

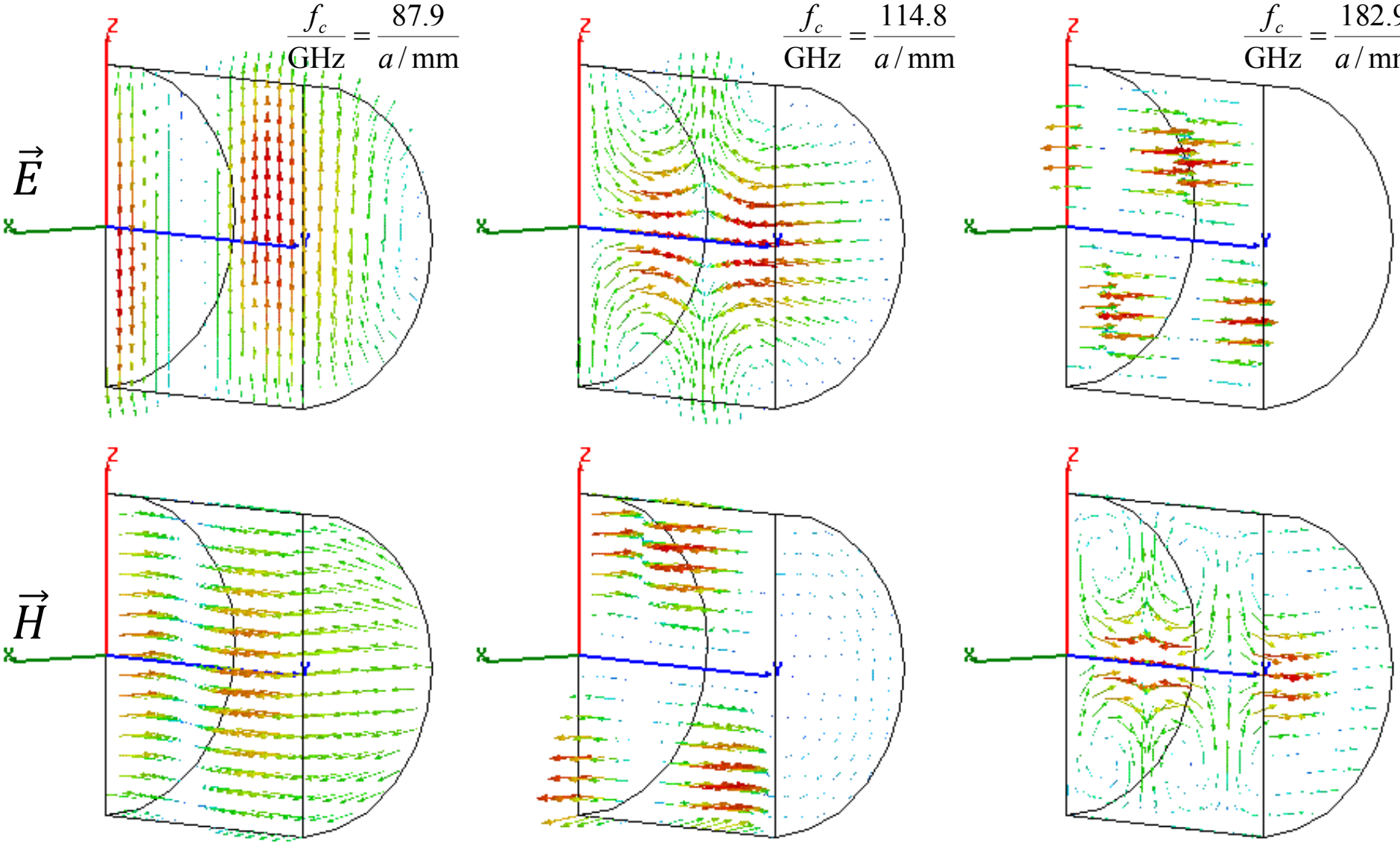
$$\frac{f_c}{\text{GHz}} = \frac{114.8}{a/\text{mm}}$$

TE_{01} – low loss

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

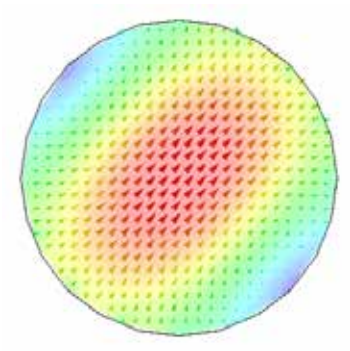
$\vec{E}$

$\vec{H}$

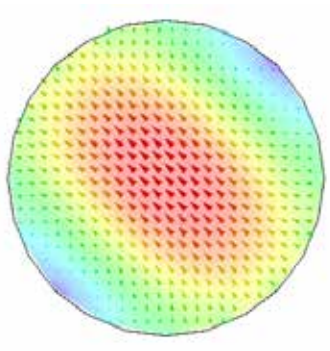


Circular waveguide modes

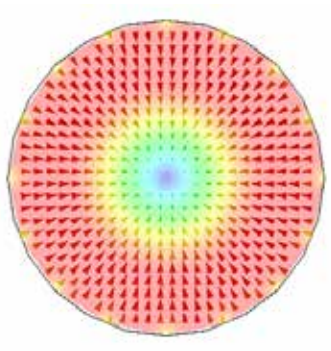
Indices linked to the number of field knots in polar co-ordinates φ, r



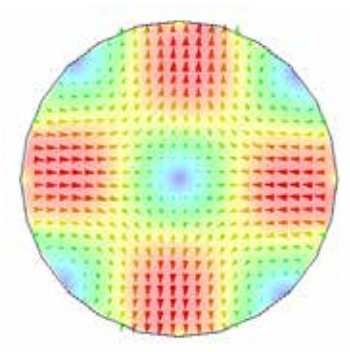
TE_{11}



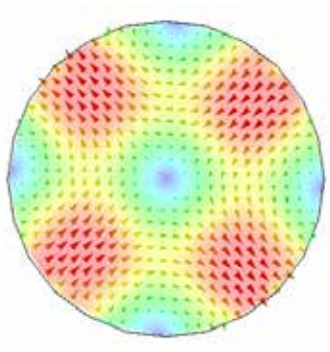
TE_{11}



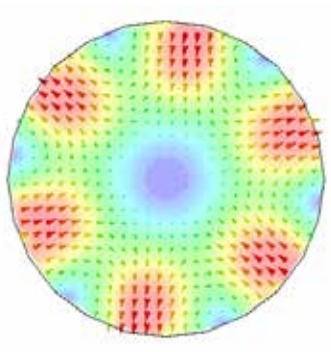
TM_{01}



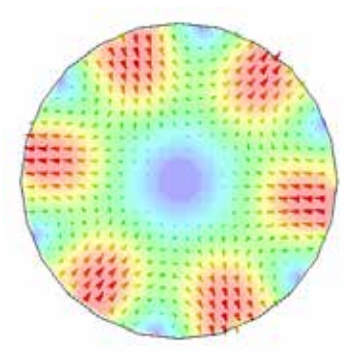
TE_{21}



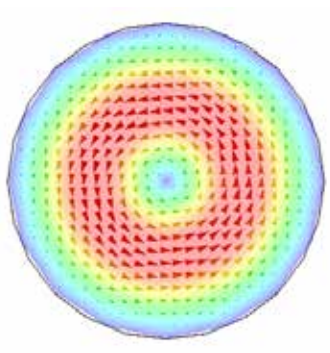
TE_{21}



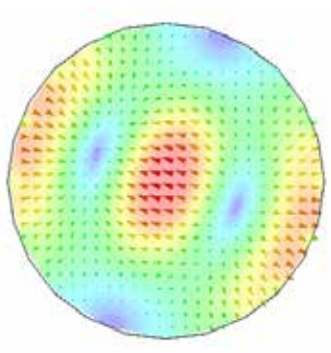
TE_{31}



TE_{31}



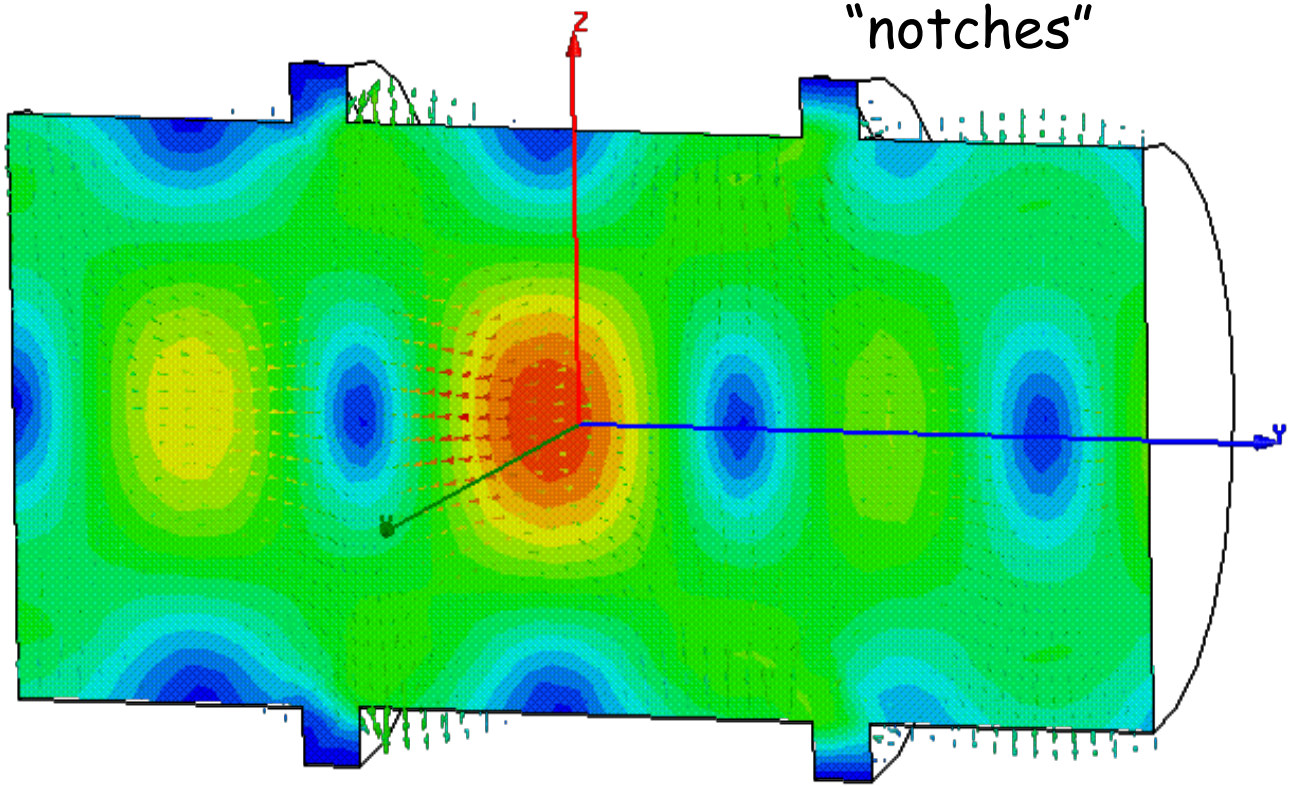
TE_{01}



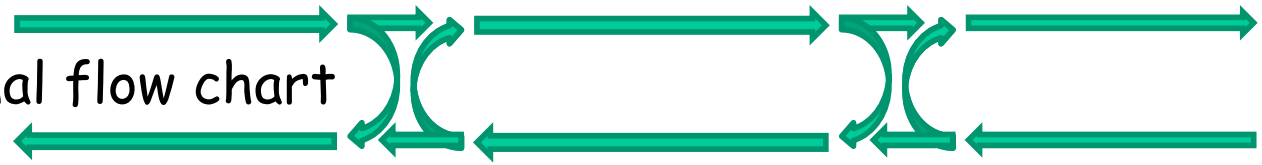
TM_{11}

plotted: *E*-field

Waveguide perturbed by discontinuities (notches)



Signal flow chart

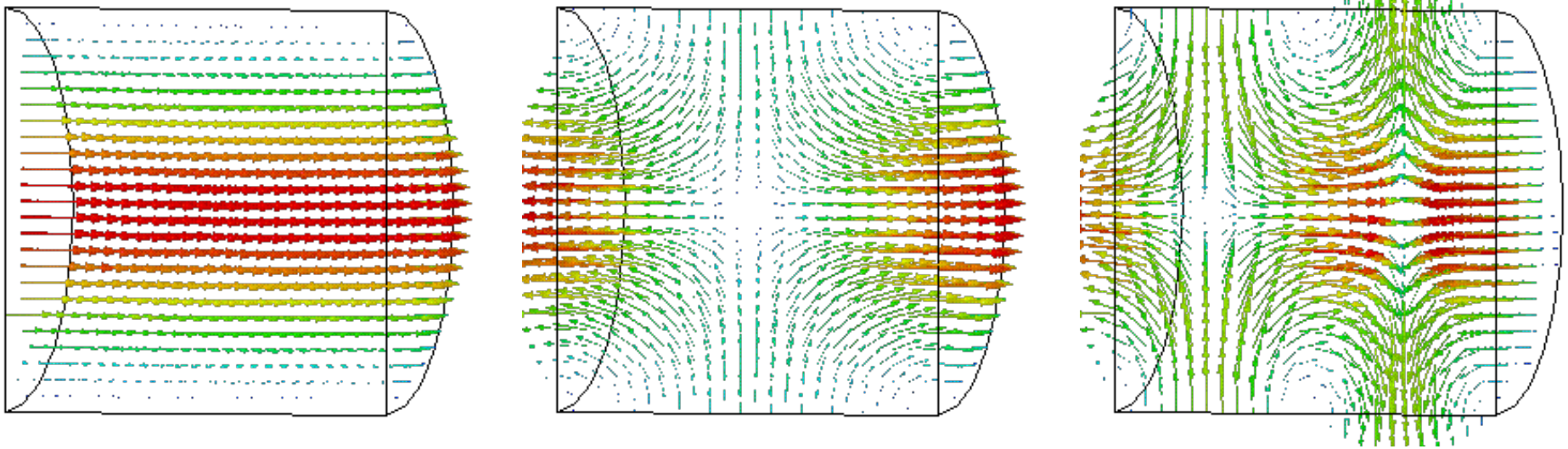


Reflections from notches lead to a superimposed standing wave pattern.
"Trapped mode"

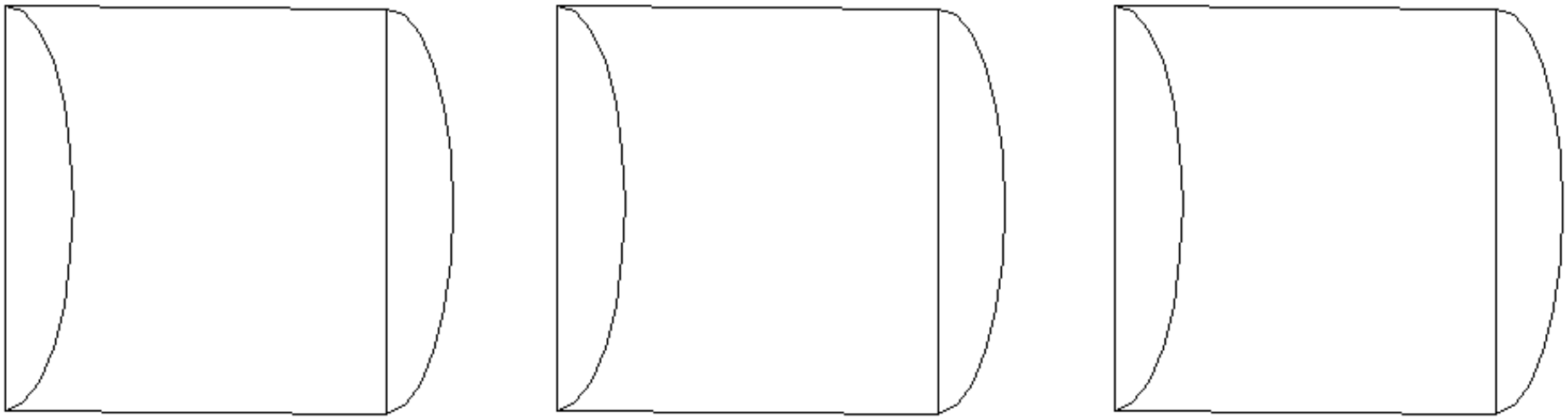
Short-circuited waveguide

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

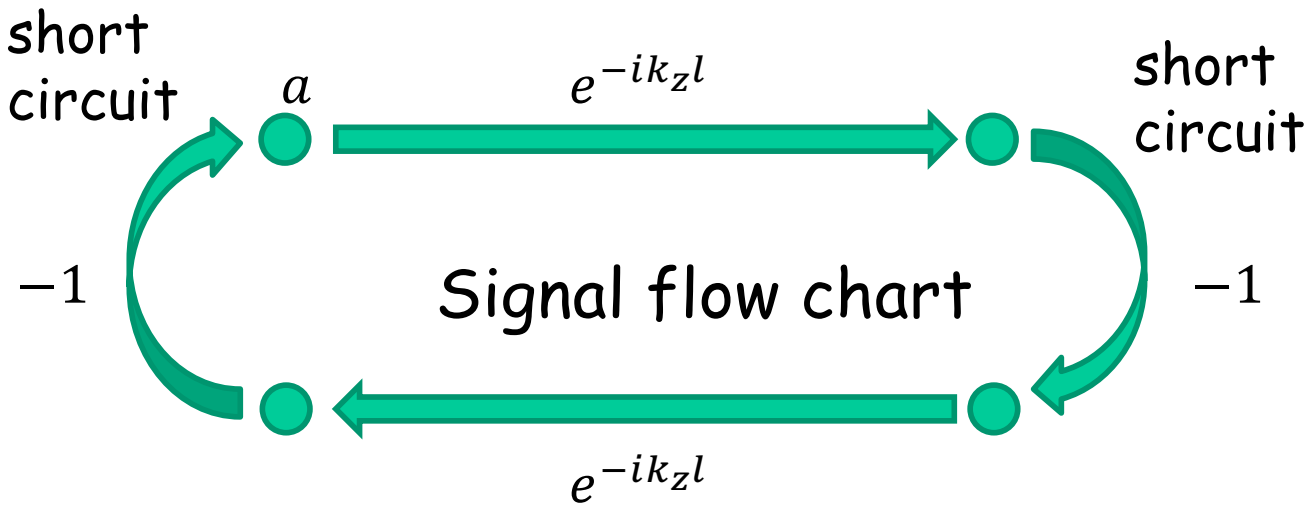
$\vec{E}$



$\vec{H}$



Single waveguide mode between two shorts



Eigenvalue equation for field amplitude a:

$$a = a\, e^{-ik_z 2l}$$

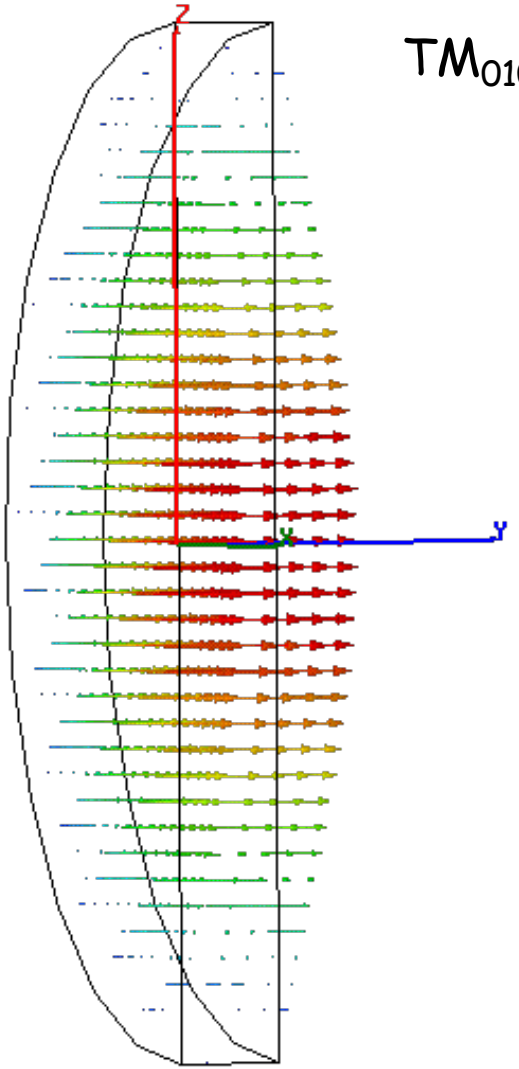
Non-vanishing solutions exist for $2k_z l = 2\,\pi m$.

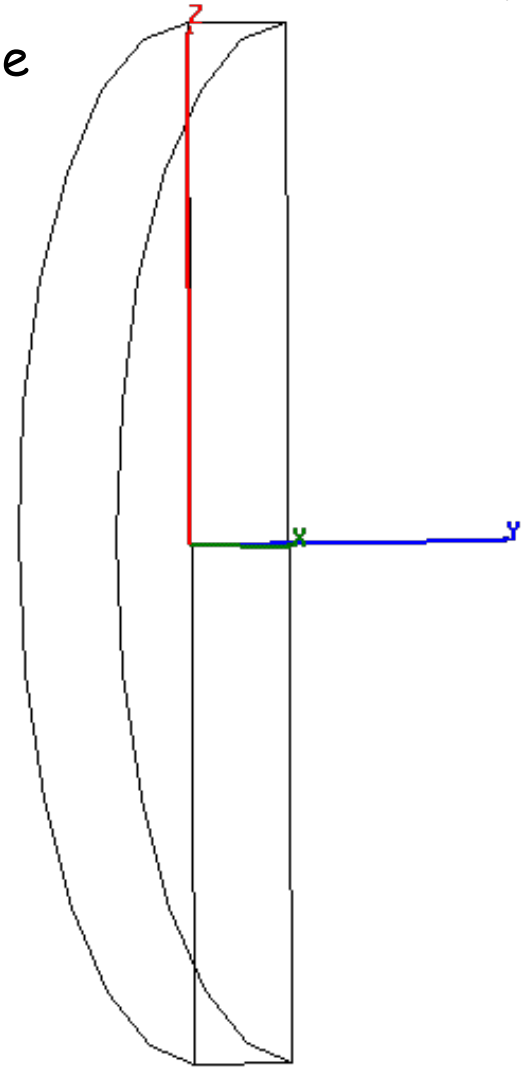
With $k_z = \frac{\omega}{c}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}$, this becomes $f_0^2 = f_c^2 + \left(c\,\frac{m}{2l}\right)^2$.

Simple pillbox cavity

(only 1/2 shown)

TM_{010}-mode



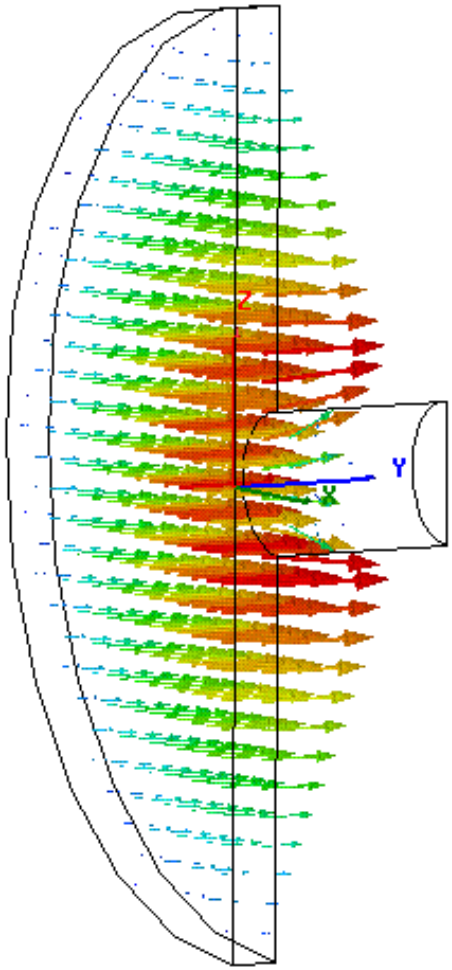


electric field (purely axial) magnetic field (purely azimuthal)

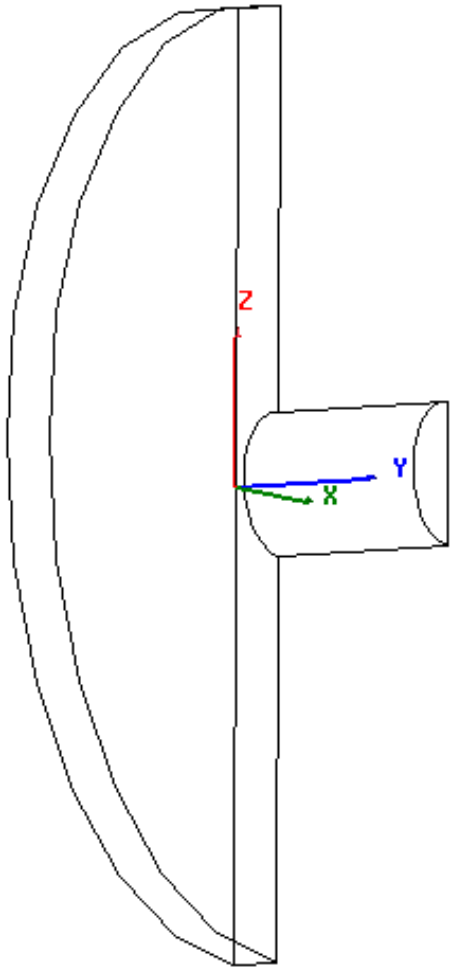
Pillbox with beam pipe

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

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



electric field

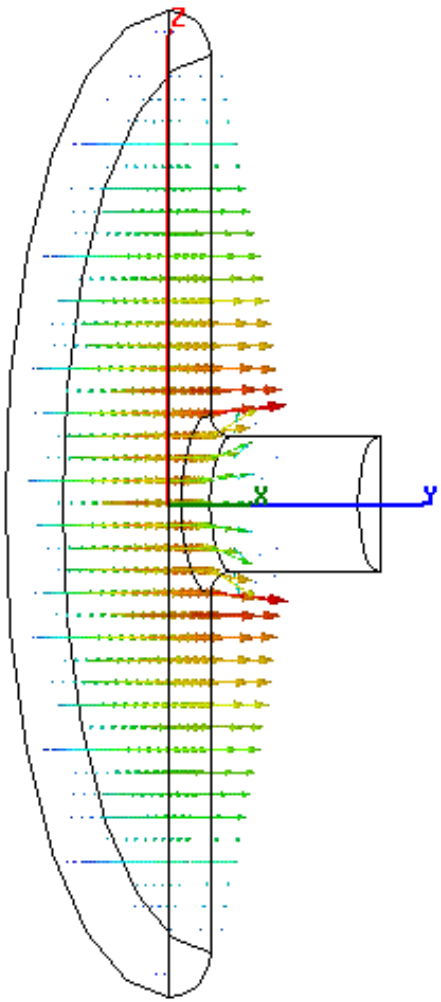


magnetic field

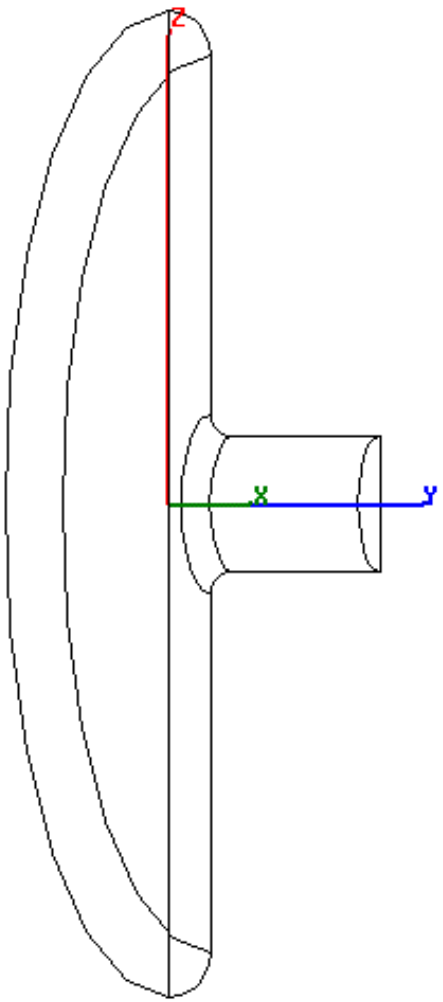
A more practical pillbox cavity

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

Round off sharp edges (field enhancement!)



electric field

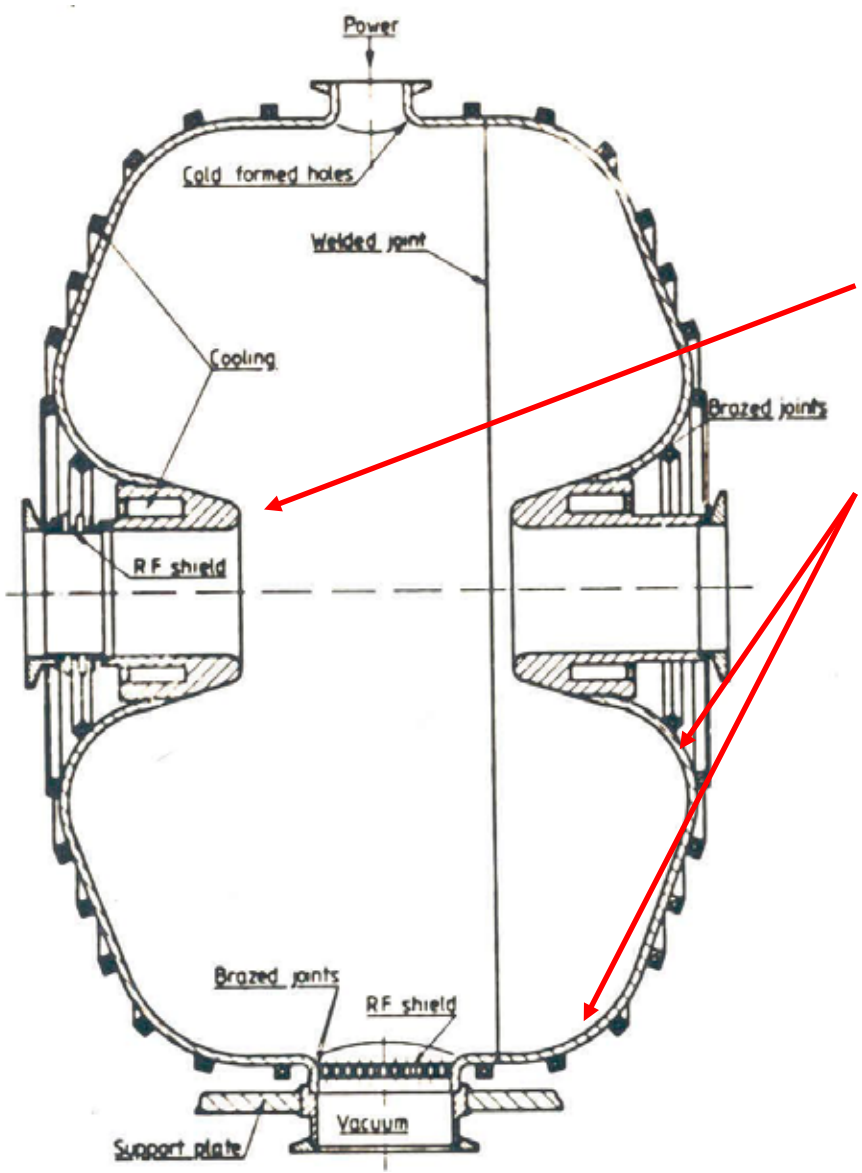


magnetic field

Some real "pillbox" cavities

CERN PS 200 MHz cavities

The Pill Box Cavity -> Real Cavity



The design of a cavity can be sophisticated in order to improve its performances:

- A nose cone can be introduced in order to concentrate the electric field around the axis

- Round shaping of the corners allows a better distribution of the magnetic field on the surface and a reduction of the Joule losses.
It also prevents from multipactoring effects (e- emission and acceleration).

A good cavity efficiently transforms the RF power into accelerating voltage.

Simulation codes allow precise calculation of the properties.

Transit time factor

The accelerating field varies during the passage of the particle
=> particle does not always see maximum field => effective acceleration smaller

Transit time factor defined as:

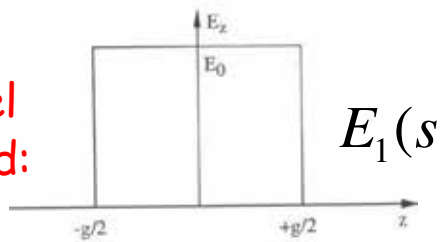
$$T_a = \frac{\text{energy gain of particle with } v = \beta c}{\text{maximum energy gain (particle with } v \to \infty)}$$

In the general case, the transit time factor is:

$$T_a = \frac{\left| \int_{-\infty}^{+\infty} E_1(s,r) \cos\left(\omega_{RF} \frac{s}{v}\right) \mathrm{d}s \right|}{\int_{-\infty}^{+\infty} E_1(s,r)\, \mathrm{d}s}$$

for $E(s,r,t) = E_1(s,r) \cdot E_2(t)$

Simple model uniform field:

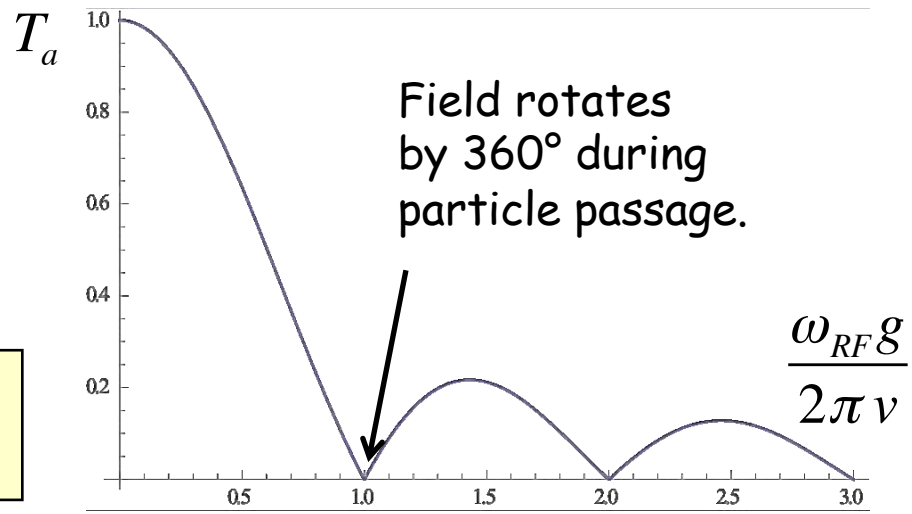


$$E_1(s,r) = \frac{V_{RF}}{g}$$

follows:

$$T_a = \left| \sin \frac{\omega_{RF} g}{2v} \Big/ \frac{\omega_{RF} g}{2v} \right|$$

$0 < T_a < 1$, $T_a \to 1$ for $g \to 0$, smaller ω_{RF}
Important for low velocities (ions)

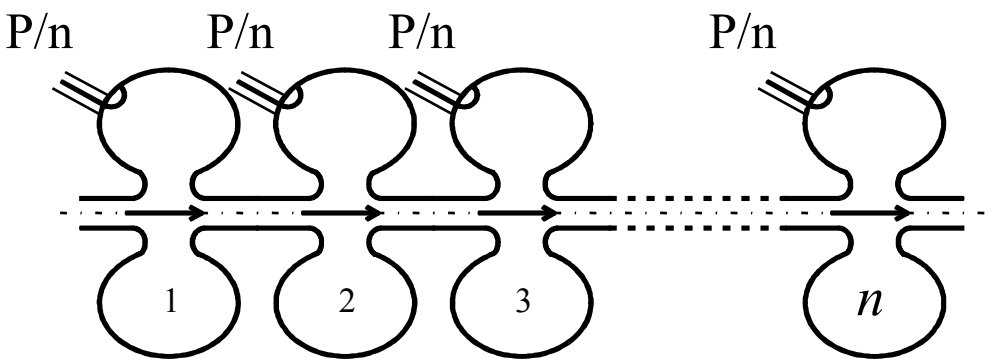


Multi-Cell Cavities

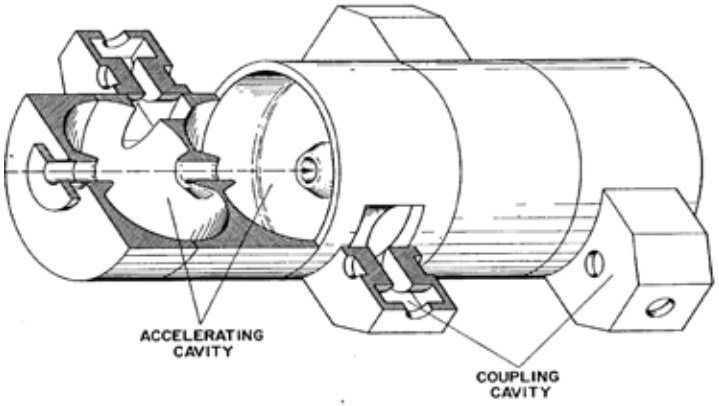
Acceleration of one cavity limited => distribute power over several cells

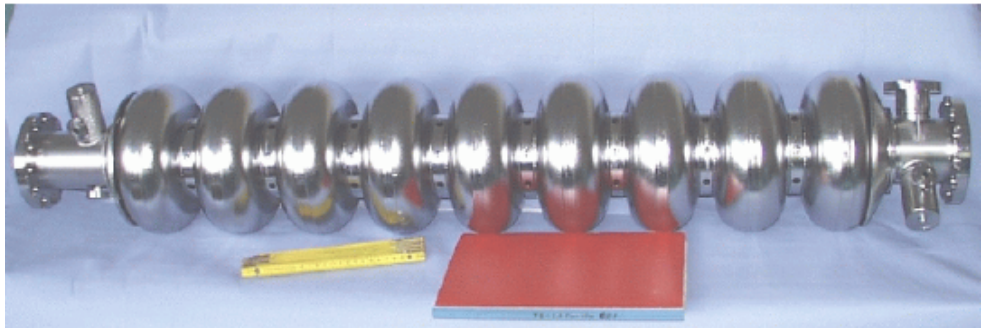
Each cavity receives P/n

Since the field is proportional √P, you get $\sum E_i \propto n\sqrt{P/n} = \sqrt{n}E_0$



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).





Multi-Cell Cavities - Modes

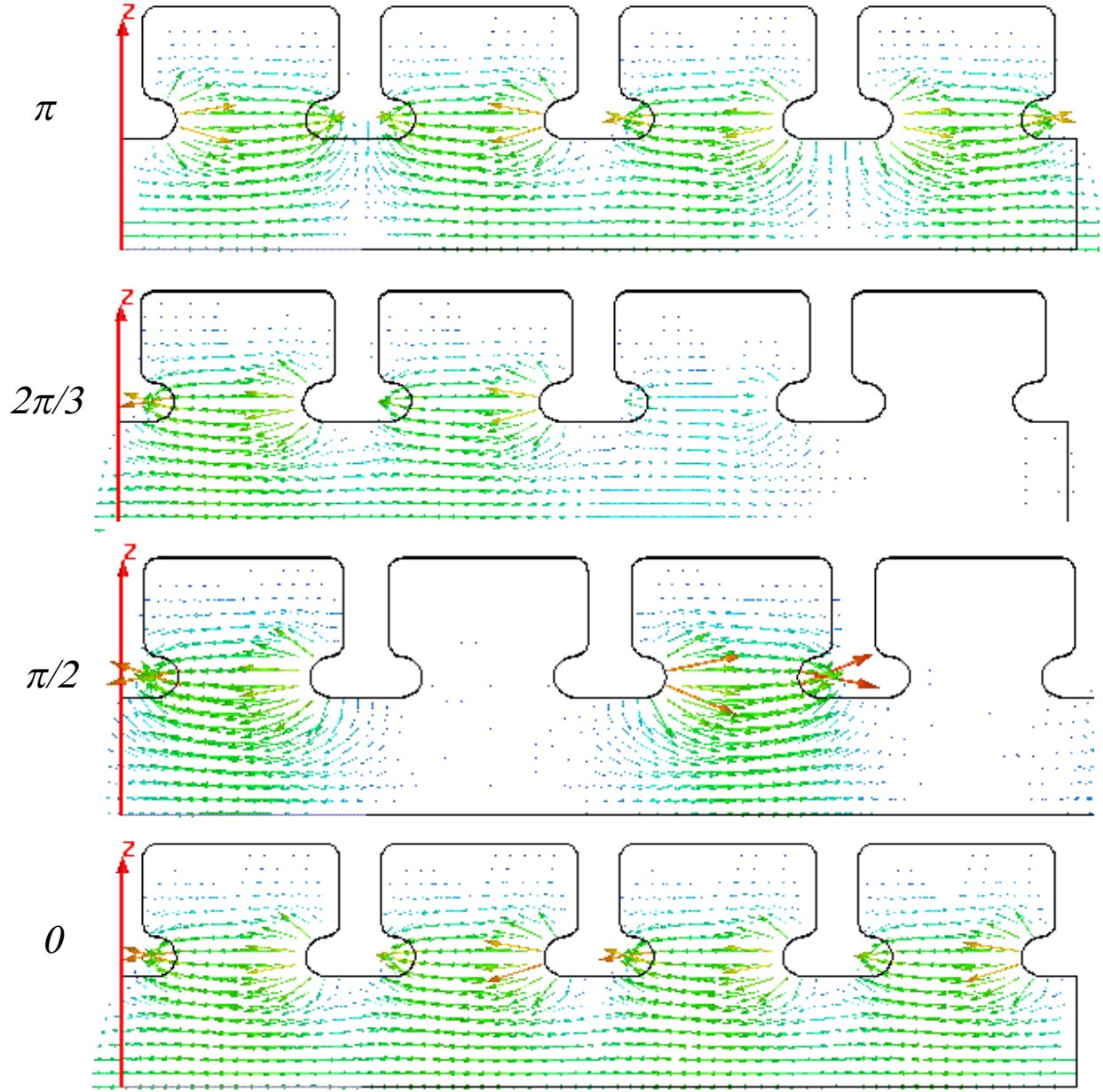
The phase relation between gaps is important!

Coupled harmonic oscillator

=> Modes, named after the phase difference between adjacent cells.

Relates to different synchronism conditions for the cell length L

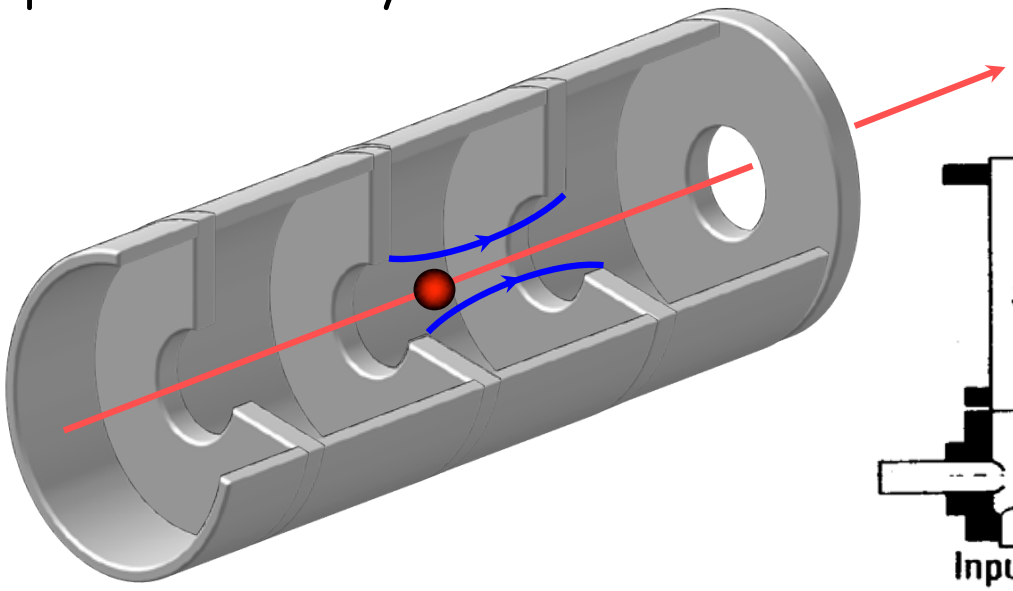
Mode	L
0 (2π)	βλ
π/2	βλ/4
2π/3	βλ/3
π	βλ/2

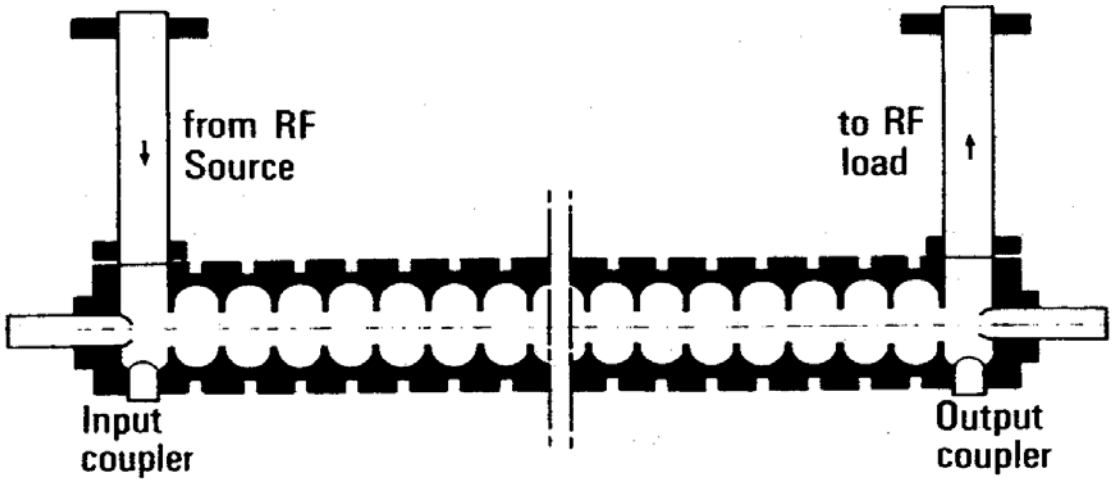


Disc-Loaded Traveling-Wave Structures

When particles get ultra-relativistic (v~c) the drift tubes become very long unless the operating frequency is increased. Late 40's the development of radar led to high power transmitters (klystrons) at very high frequencies (3 GHz).

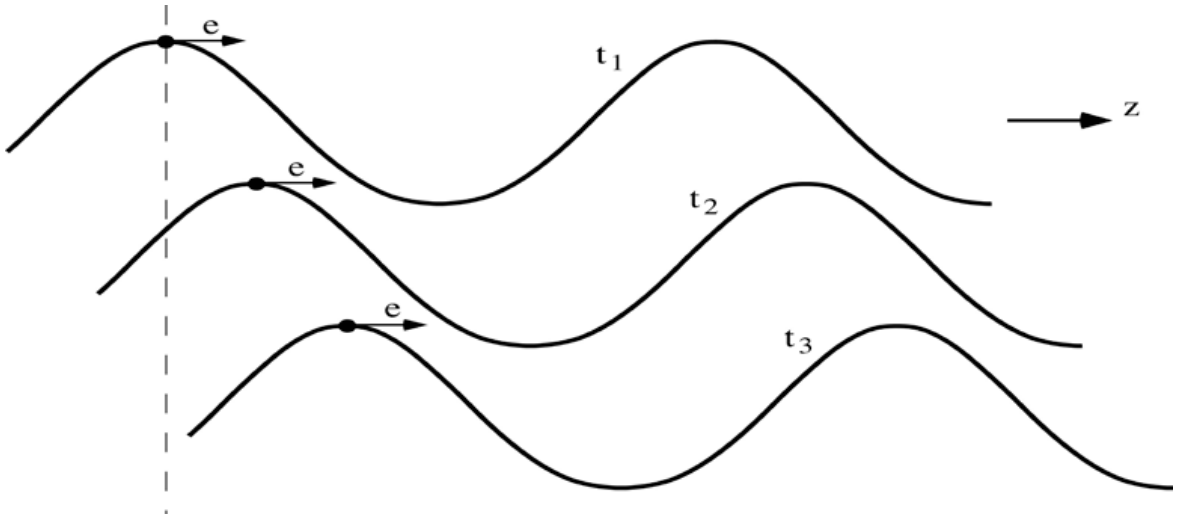
Next came the idea of suppressing the drift tubes using traveling waves.
A wave guide has always a phase velocity $v_\varphi > c$. However to get a continuous acceleration the phase velocity of the wave needs to be adjusted to the particle velocity.





solution: slow wave guide with irises ==> iris loaded structure

The Traveling Wave Case



$$E_z = E_0 \cos\left(\omega_{RF} t - kz\right)$$

$$k = \frac{\omega_{RF}}{v_\varphi} \qquad \text{wave number}$$

$$z = v(t - t_0)$$

v_φ = phase velocity
v = particle velocity

The particle travels along with the wave, and k represents the wave propagation factor.

$$E_z = E_0 \cos\left(\omega_{RF} t - \omega_{RF} \frac{v}{v_\varphi} t - \phi_0\right)$$

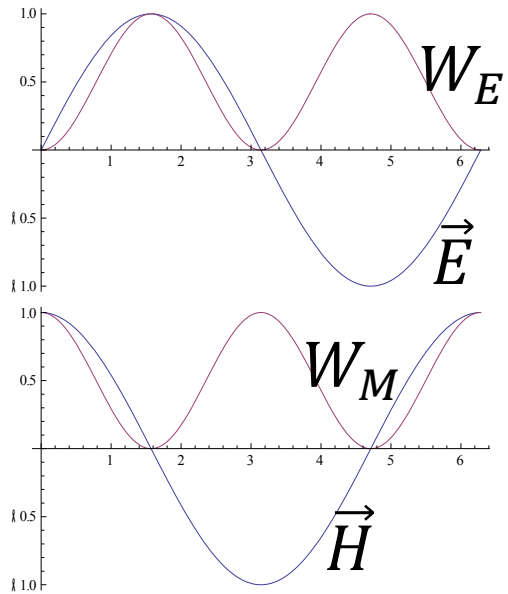
If synchronism satisfied: $v = v_\varphi$ and $E_z = E_0 \cos\phi_0$

where Φ_0 is the RF phase seen by the particle.

Stored energy

The energy stored in the electric field is

$$W_E = \iiint_{cavity} \frac{\varepsilon}{2} \left|\vec{E}\right|^2 dV.$$



The energy stored in the magnetic field is

$$W_M = \iiint_{cavity} \frac{\mu}{2} \left|\vec{H}\right|^2 dV.$$

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.

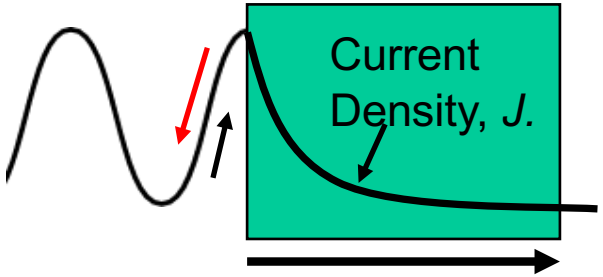
In steady state, the total energy stored (constant) is

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

Wall losses

The losses P_{loss} are proportional to the stored energy W.

The tangential magnetic field on the metallic surface is linked to a surface current $\vec{J}_A = \vec{n} \times \vec{H}$ (flowing in the skin depth).



This surface current $\vec{J}_A$ sees a surface resistance

$R_A = \sqrt{\frac{\omega\mu}{2\sigma}}$, resulting in a local power density

flowing into the wall of $\frac{1}{2} R_A |H_t|^2$.

R_A is related to skin depth δ as $\delta\sigma R_A = 1$.

- Cu at 300 K has $\sigma \approx 5.8 \cdot 10^7$ S/m, leading to $R_A \approx 8$ mΩ at 1 GHz, scaling with $\sqrt{\omega}$.
- Nb at 2 K has a typical $R_A \approx 10$ nΩ at 1 GHz, scaling with ω^2.

The total wall losses P_{loss} during one RF period result from

$$P_{loss} = \frac{1}{2} \iint_{wall} R_A |H_t|^2 \, dA$$

Cavity Parameters: Quality Factor Q

- Quality Factor Q (caused by wall losses) defined as

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

Ratio of stored energy W and dissipated power P_{loss} on the walls in one RF cycle

The Q factor determines the maximum energy the cavity can fill to with a given input power.
Larger Q => less power needed to sustain stored energy.

The Q factor is 2π times the number of rf cycles it takes to dissipate the energy stored in the cavity (down by 1/e).

- function of the geometry and the surface resistance of the material:
  superconducting (niobium) : Q= 10^{10}
  normal conducting (copper) : Q=10^4

Important Parameters of Accelerating Cavities

- Accelerating voltage V_{acc}

$$V_{acc} = \int_{-\infty}^{\infty} E_z e^{-i\frac{\omega z}{\beta c}} dz$$

Measure of the acceleration

- R upon Q

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

Relationship between acceleration V_{acc} and stored energy W

independent from material!

Attention: Different definitions are used!

- Shunt Impedance R

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

Relationship between acceleration V_{acc} and wall losses P_{loss}

depends on
- material
- cavity mode
- geometry

Important Parameters of Accelerating Cavities (cont.)

- Fill Time t_F

  - **standing wave cavities**:

$$P_{loss} = -\frac{dW}{dt} = \frac{\omega}{Q} W$$

Exponential decay of the stored energy W due to losses

$$t_F = \frac{Q}{\omega}$$

time for the field to decrease by 1/e after the cavity has been filled

measure of how fast the stored energy is dissipated on the wall

Several fill times needed to fill the cavity!

  - **travelling wave cavities**:

time needed for the electromagnetic energy to fill the cavity of length L

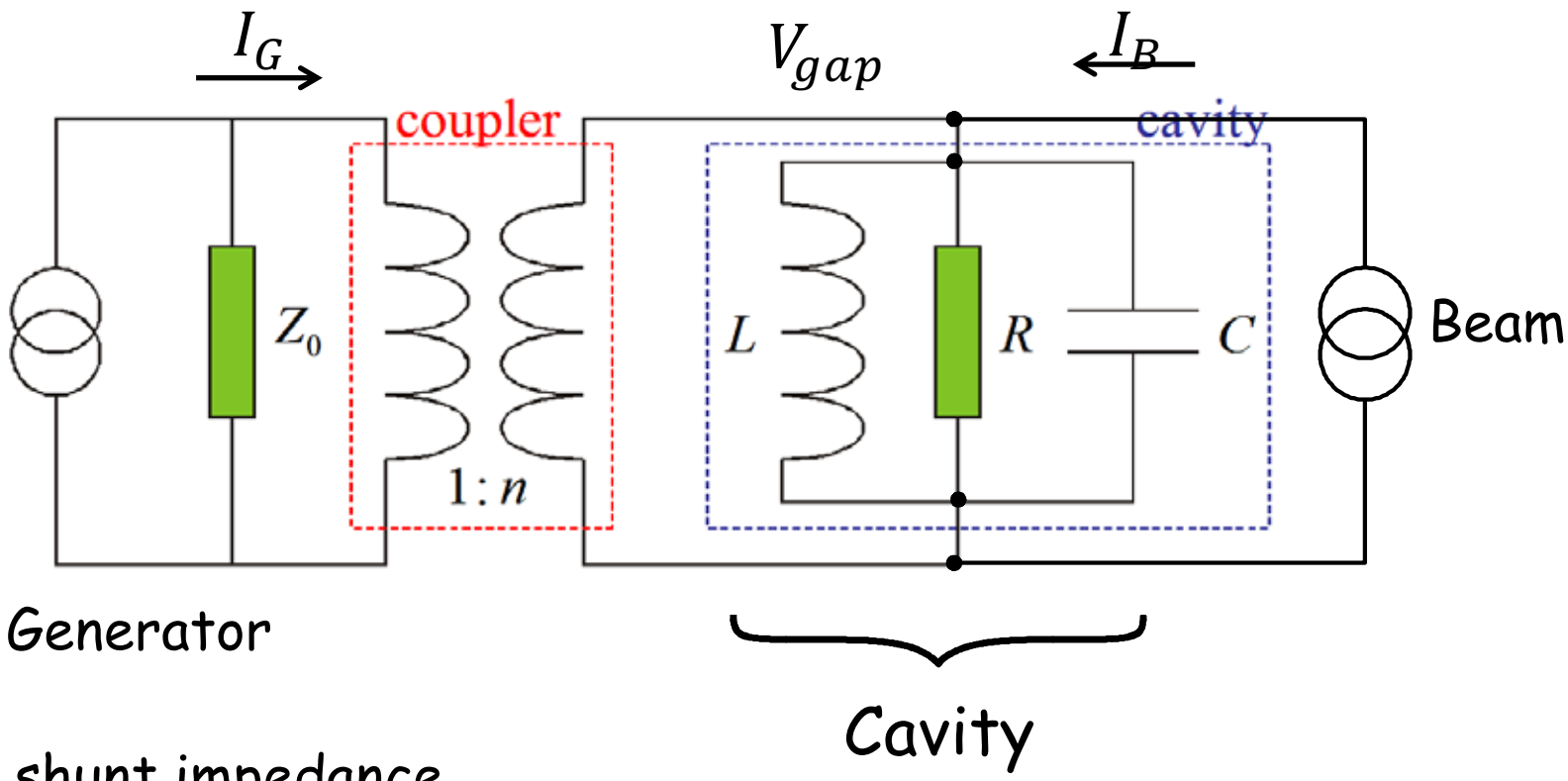
$$t_F = \int_0^L \frac{dz}{v_g(z)}$$

v_g: velocity at which the energy propagates through the cavity

Cavity is completely filled after 1 fill time!

SW Cavity resonator – equivalent circuit

Simplification: single mode



R: shunt impedance

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

$$\omega_0 = \frac{1}{\sqrt{L \cdot C}}$$

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), the losses have to be added:

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

The coupling factor β is the ratio P_{ext}/P_{loss}.

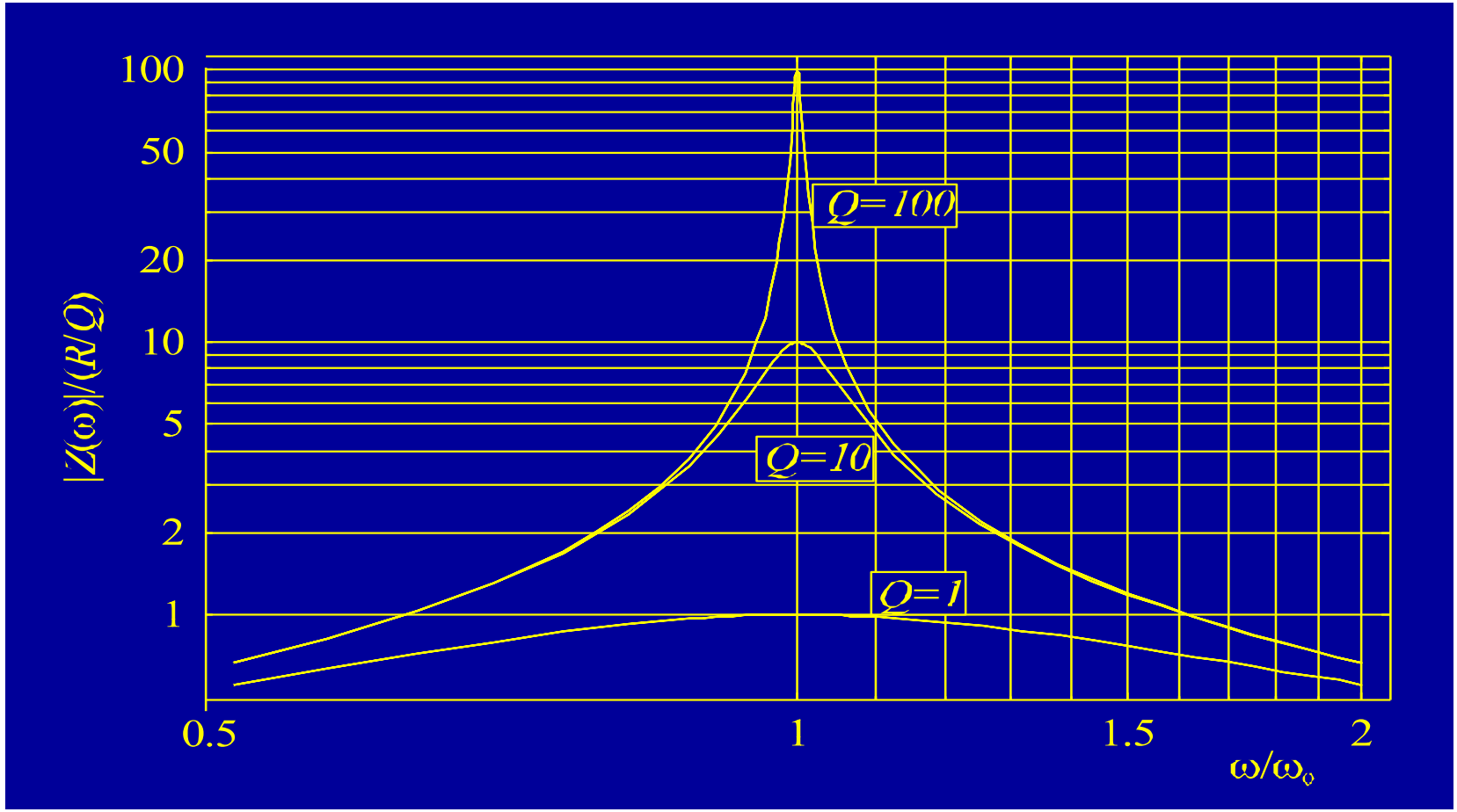
$$\beta = \frac{P_{ext}}{P_{loss}} = \frac{Q_0}{Q_{ext}}$$

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, $\beta = \mathcal{O}(10^4 \ldots 10^6)$.

Resonance



A high Q_0: small wall losses => less power needed for the same voltage.

But the bandwidth becomes very narrow.

Note: a 1 GHz cavity with a Q_0 of 10^{10} has a natural bandwidth of 0.1 Hz!

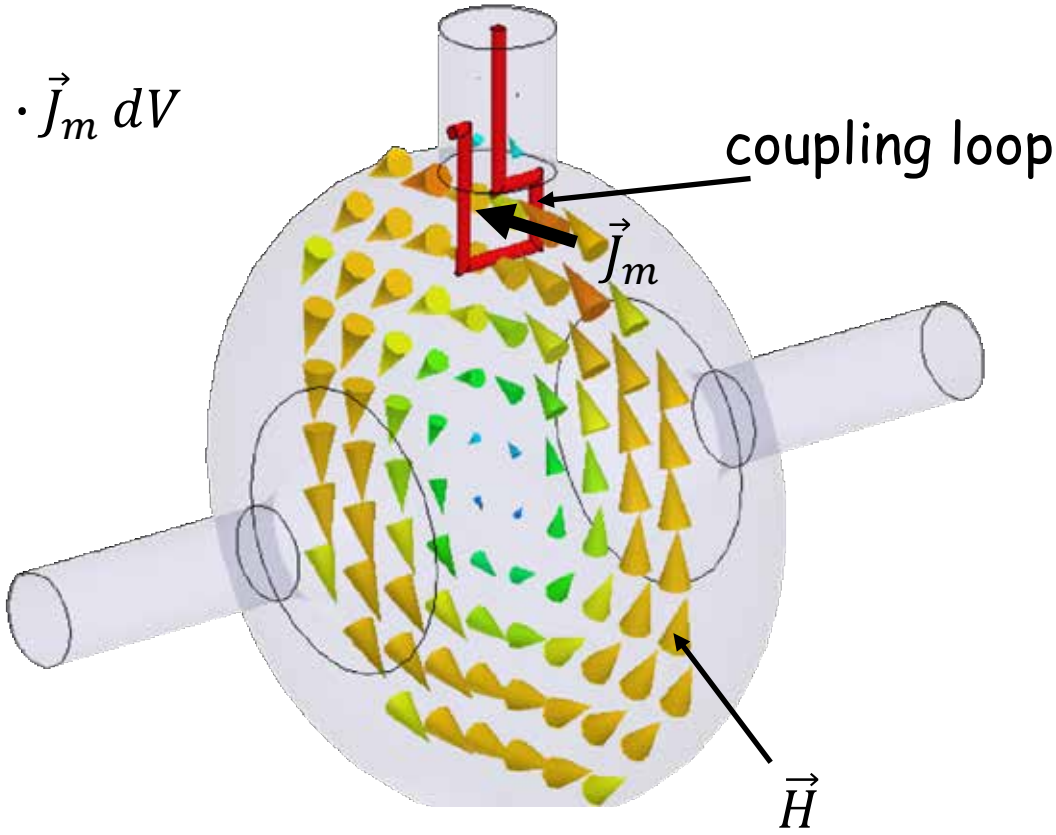
… to make this manageable, Q_{ext} is chosen much smaller!

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: $\propto \iiint \vec{H} \cdot \vec{J}_m \, dV$



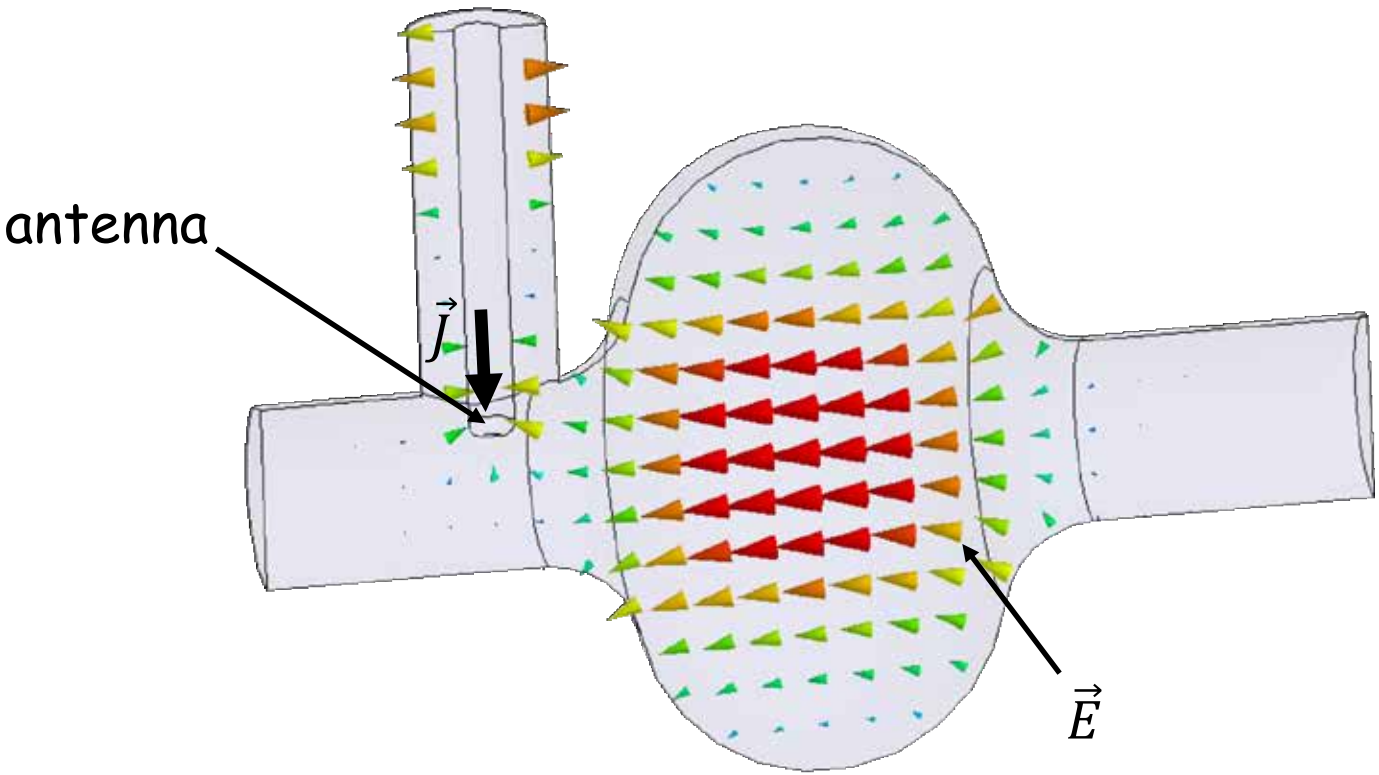
courtesy: David Alesini/INFN

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

Cavity parameters

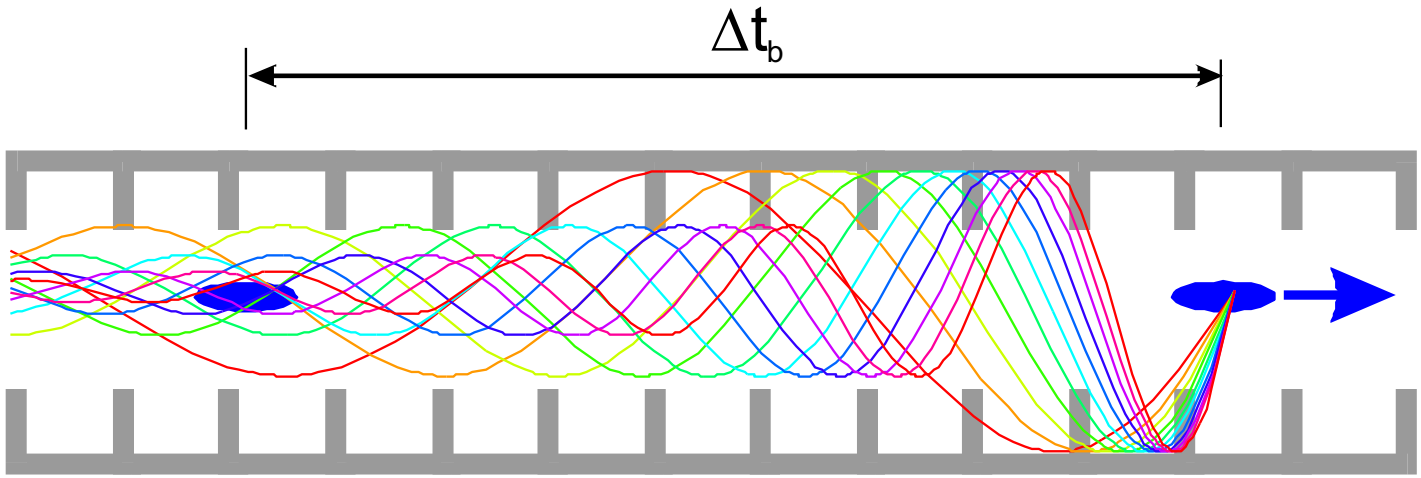
Resonance frequency	$\omega_0 = \frac{1}{\sqrt{L \cdot C}}$	
Transit time factor	$TT = \frac{\left\lvert \int E_z e^{i\frac{\omega}{\beta c}z}\, dz \right\rvert}{\left\lvert \int E_z\, dz \right\rvert}$	
Q factor	$\omega_0 W = Q\, P_{loss}$	
	Circuit definition	***Linac definition***
Shunt impedance	$\lvert V_{gap} \rvert^2 = 2\, R\, P_{loss}$	$\lvert V_{gap} \rvert^2 = R\, P_{loss}$
R/Q (R-upon-Q)	$\frac{R}{Q} = \frac{\lvert V_{gap} \rvert^2}{2\, \omega_0 W} = \sqrt{L/C}$	$\frac{R}{Q} = \frac{\lvert V_{gap} \rvert^2}{\omega_0 W}$
Loss factor	$k_{loss} = \frac{\omega_0}{2}\frac{R}{Q} = \frac{\lvert V_{gap} \rvert^2}{4W} = \frac{1}{2C}$	$k_{loss} = \frac{\omega_0}{4}\frac{R}{Q} = \frac{\lvert V_{gap} \rvert^2}{4W}$

Wakefields and Beam Loading

The cavities' electric field accelerates the beam.

But the beam will also act on the fields inside the cavities

- Accelerating field will be reduced (energy conservation!)
  => Beam Loading (longitudinal wakefield)
- Beam can excite perturbing cavity modes (Higher Order Modes – HOM) and deflect following bunches
  => (transverse) Wakefields



Transverse wakefields

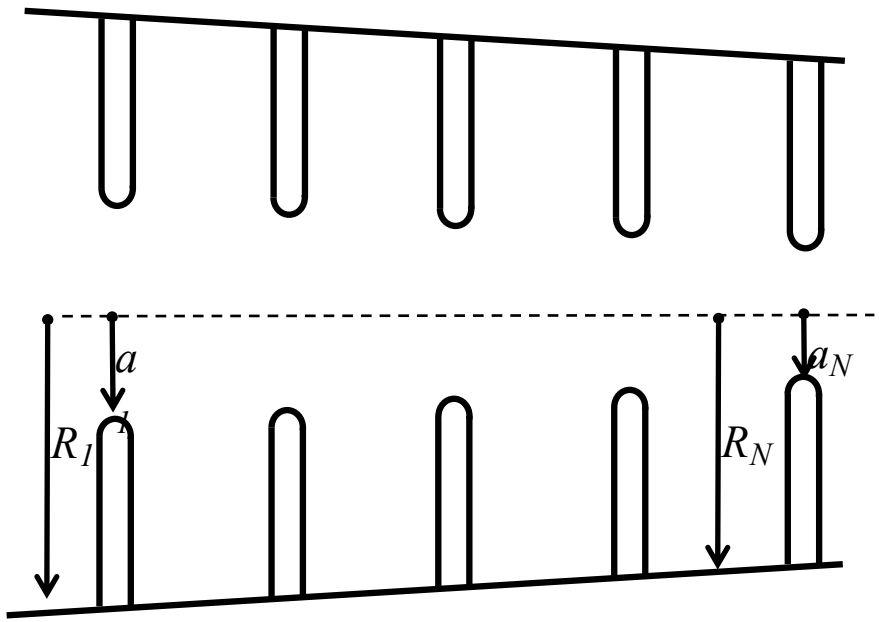
Effect depends on a/λ (a iris aperture) and structure design details

transverse wakefields roughly scale as $W_\perp \propto f^3$

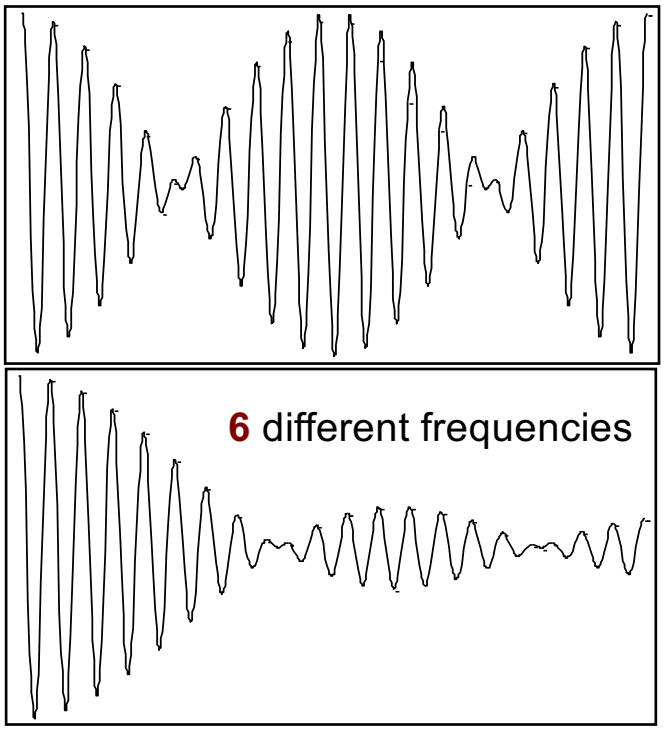
=> less important for lower frequency

Long-range minimised by structure design

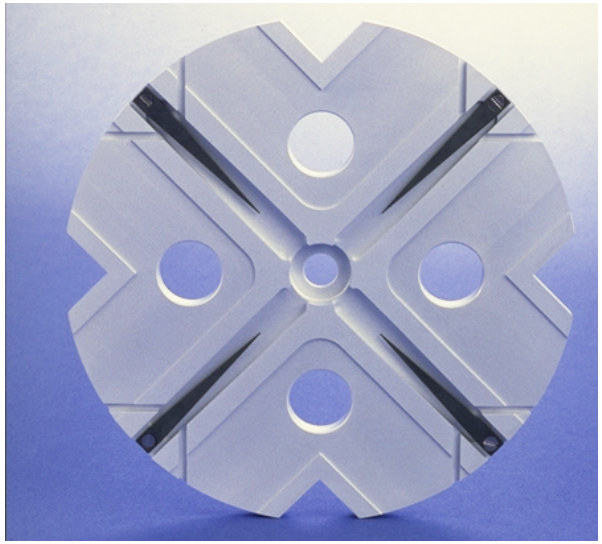
Dipole mode detuning

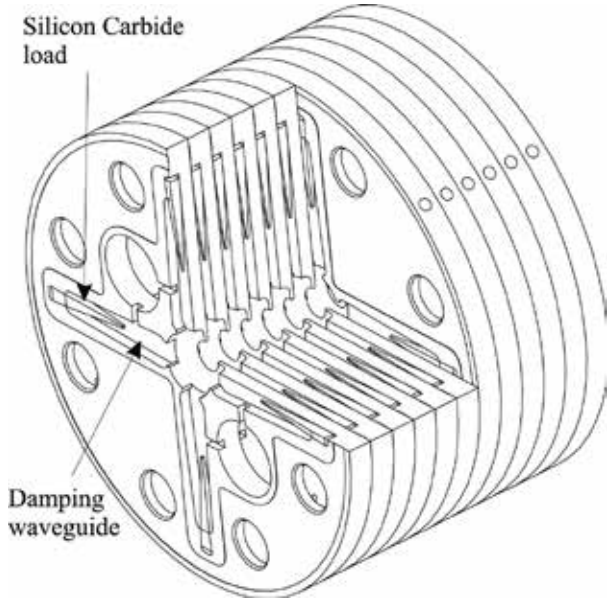


Long range wake of a dipole mode spread over **2** different frequencies

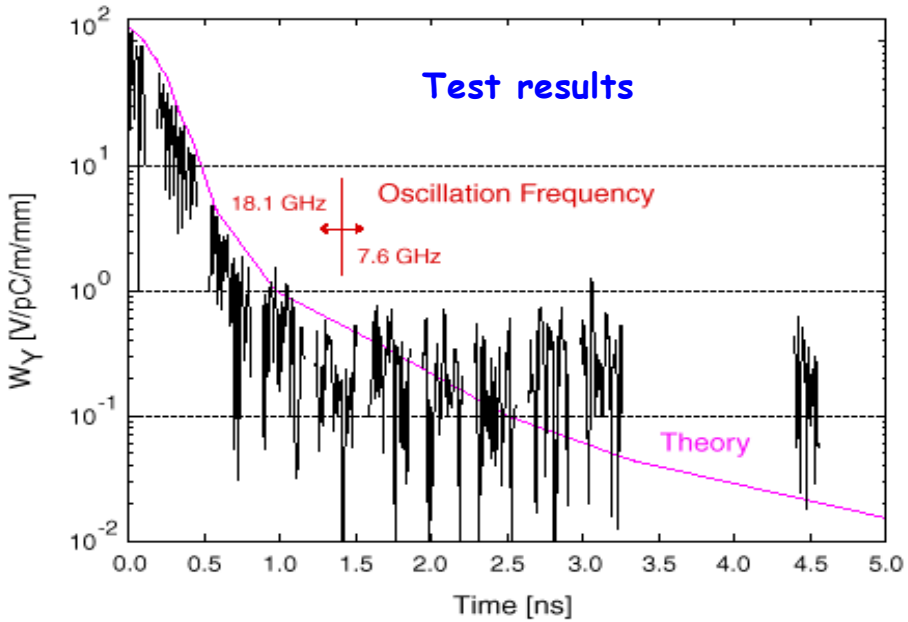


HOM damping – TW structures



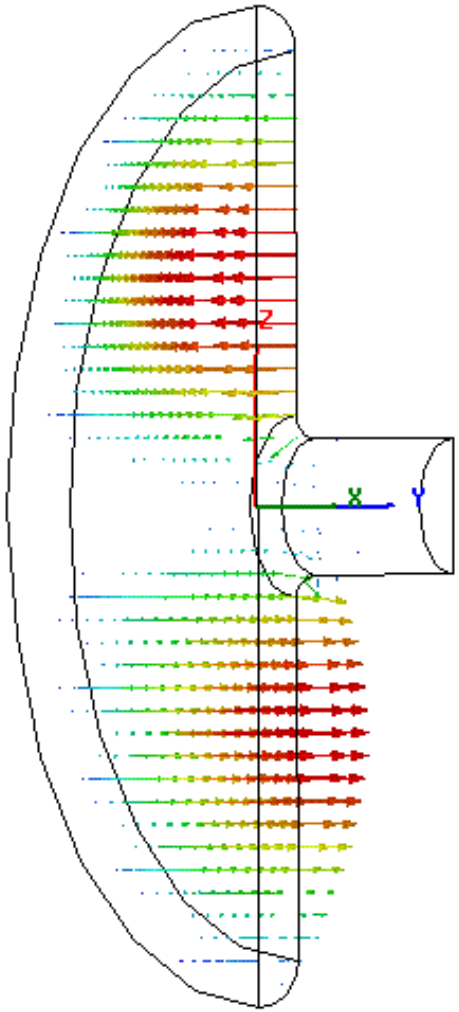


- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- HOM enter WG
- Long-range wake efficiently damped

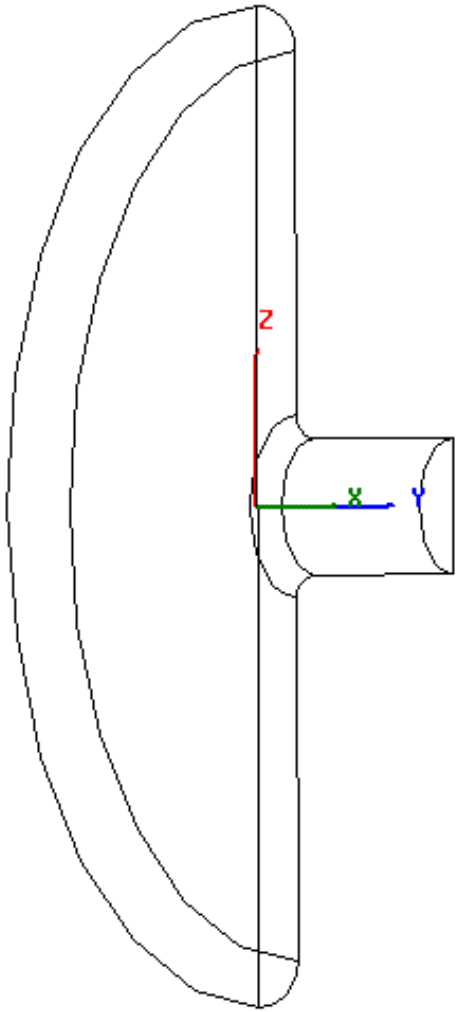


Dipole mode in a pillbox

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

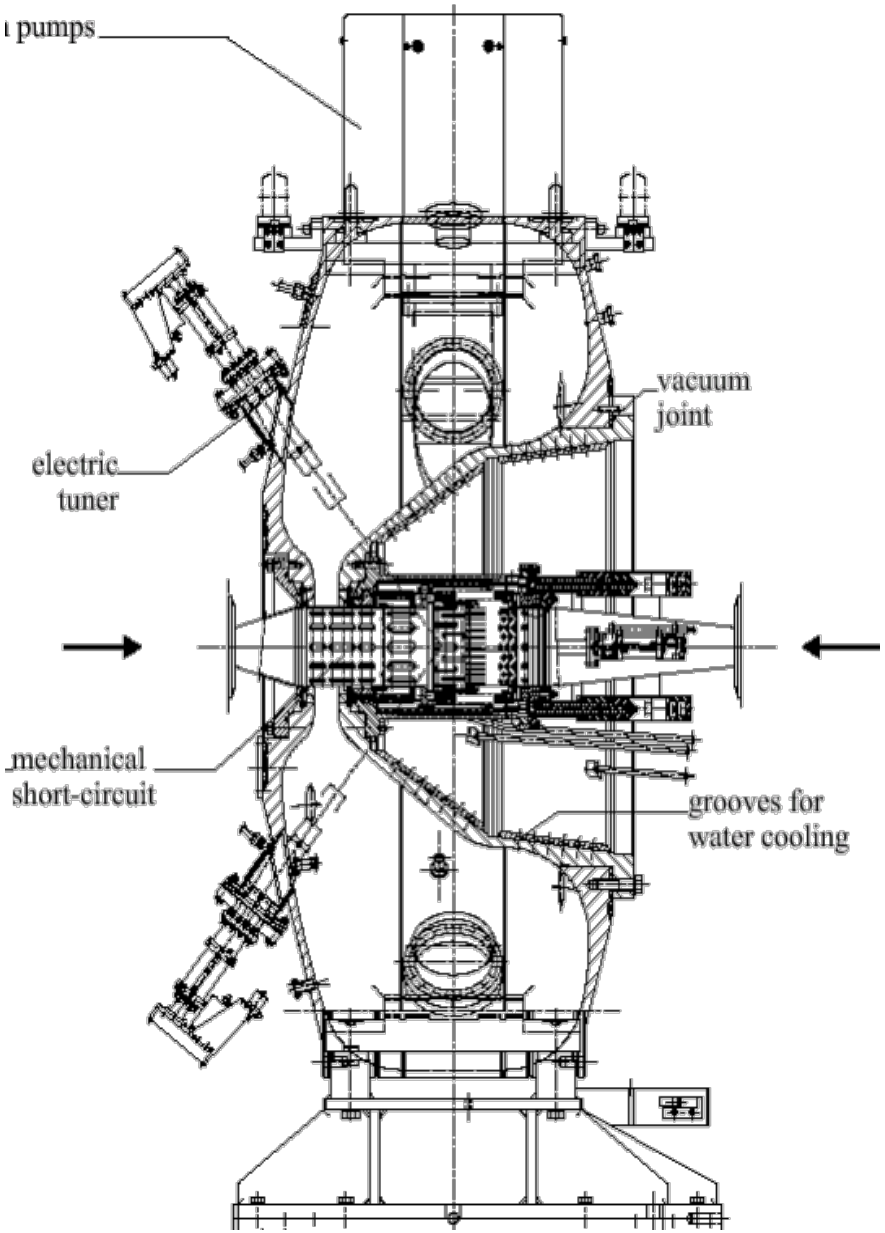


electric field



magnetic field

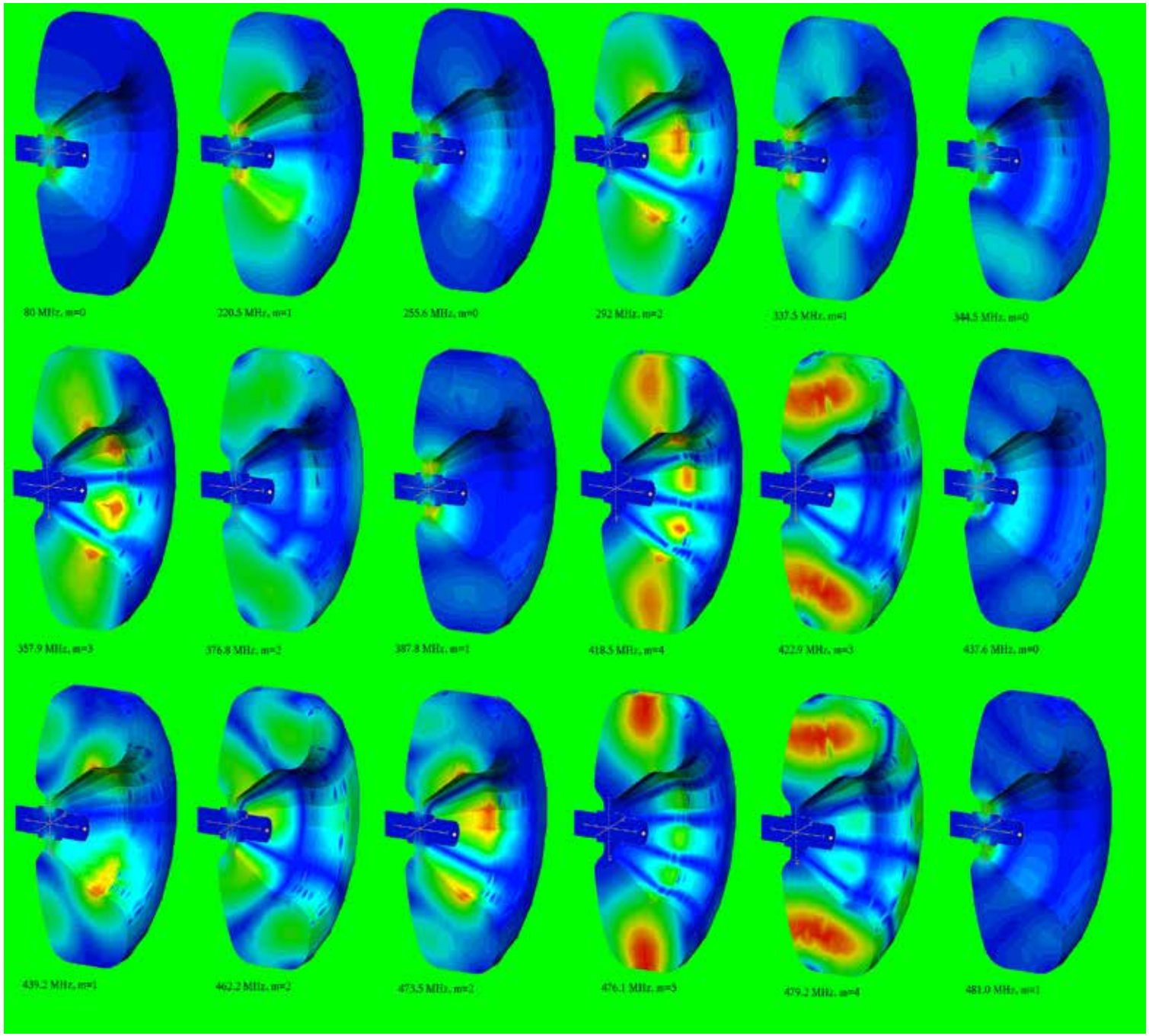
CERN/PS 80 MHz cavity (for LHC)



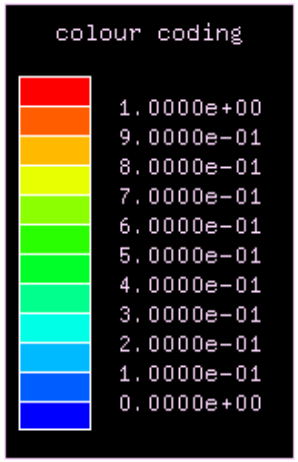
HOM's

Example shown:

CERN/PS 80 MHz cavity

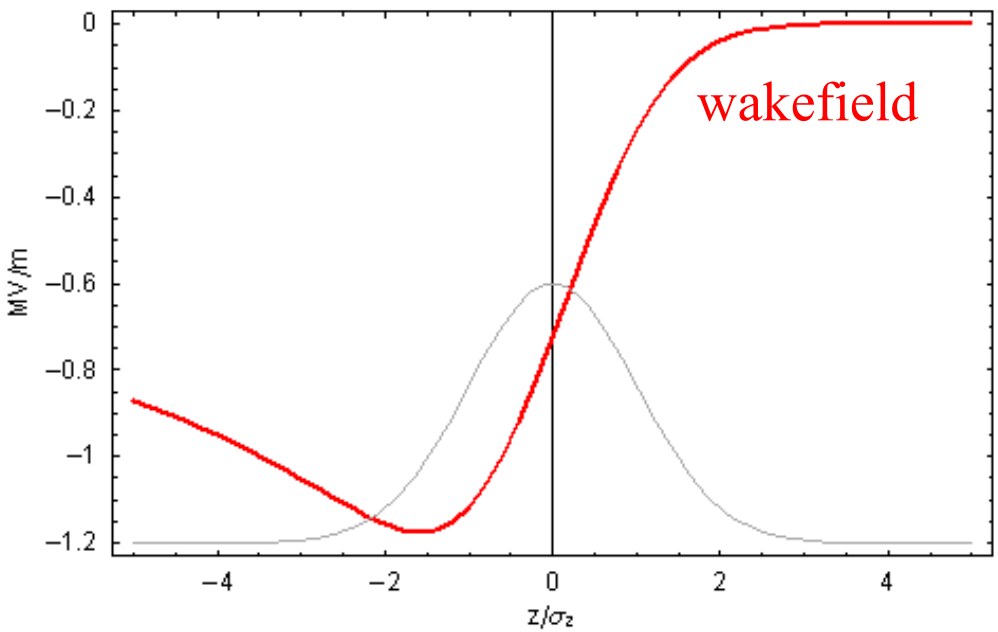


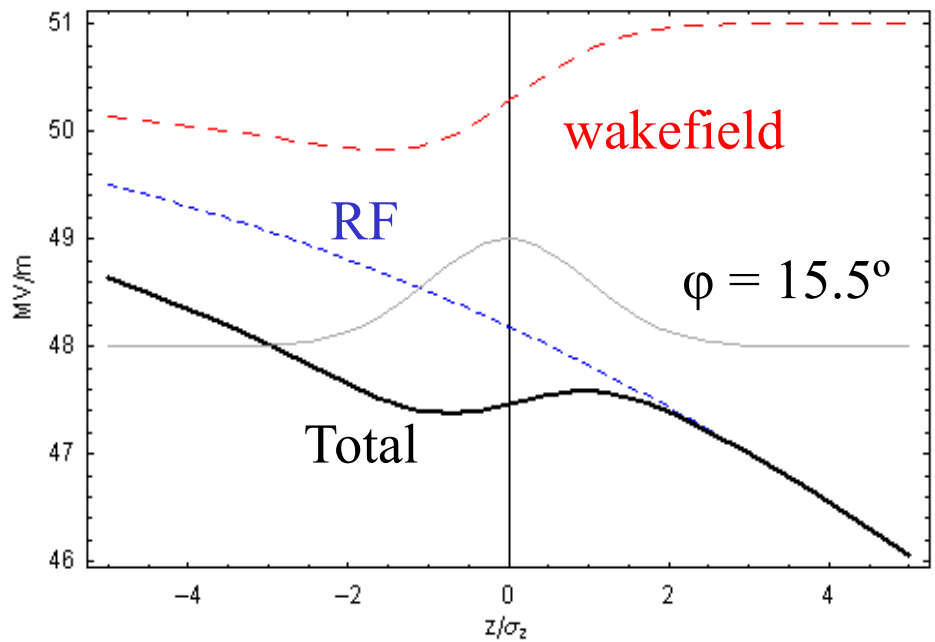
Colour coding: $|\vec{E}|$



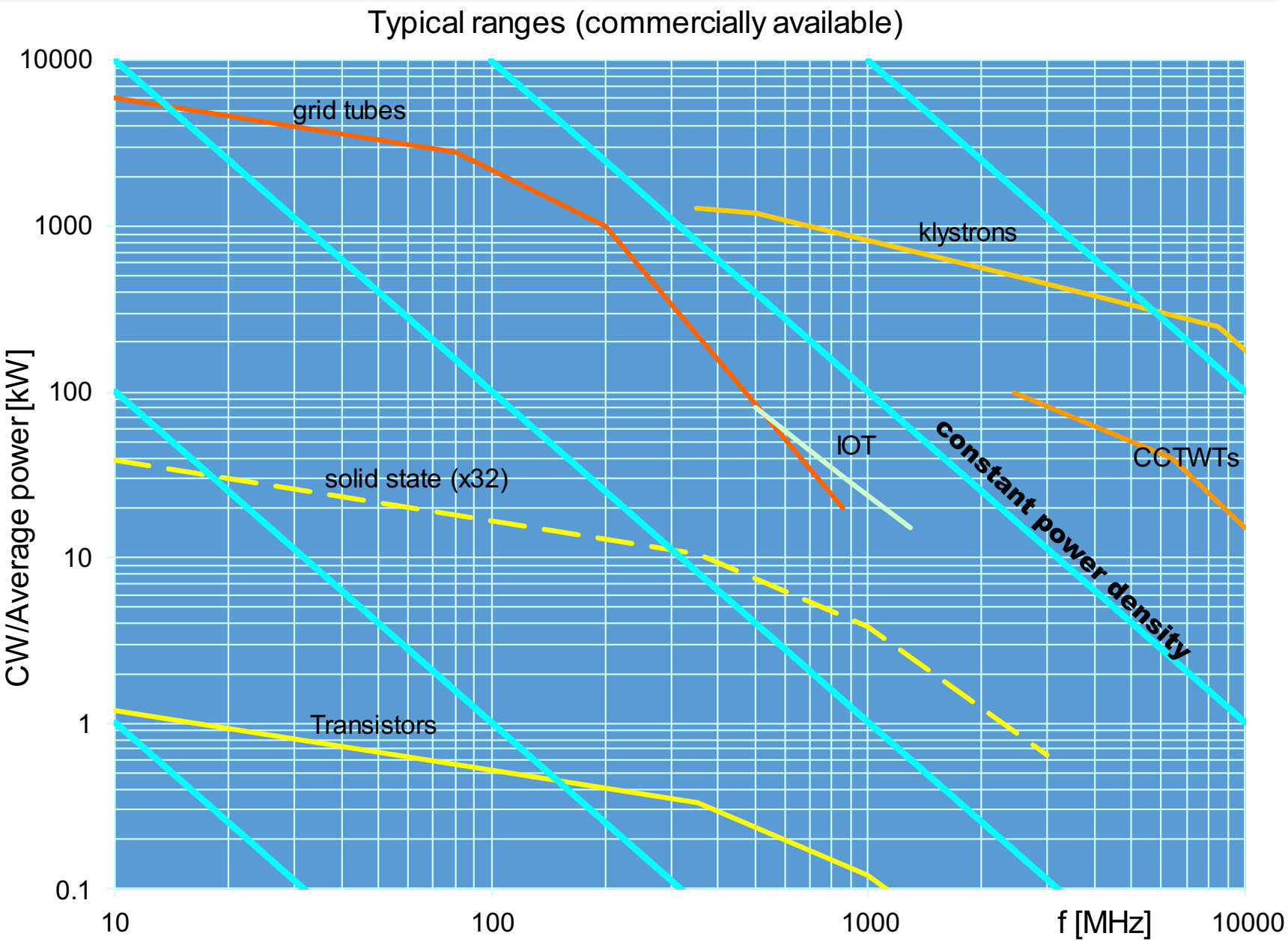
Longitudinal Wakefield – Beam Loading

- Beam absorbs RF power ⇒ decreasing RF field in cavities
- Single bunch beam loading: longitudinal wake field
- Particles within a bunch see a decreasing field
  ⇒ energy gain different within a bunch
- Run off-crest and use RF curvature to compensate single bunch beam-loading
- Reduces the effective gradient





RF power sources

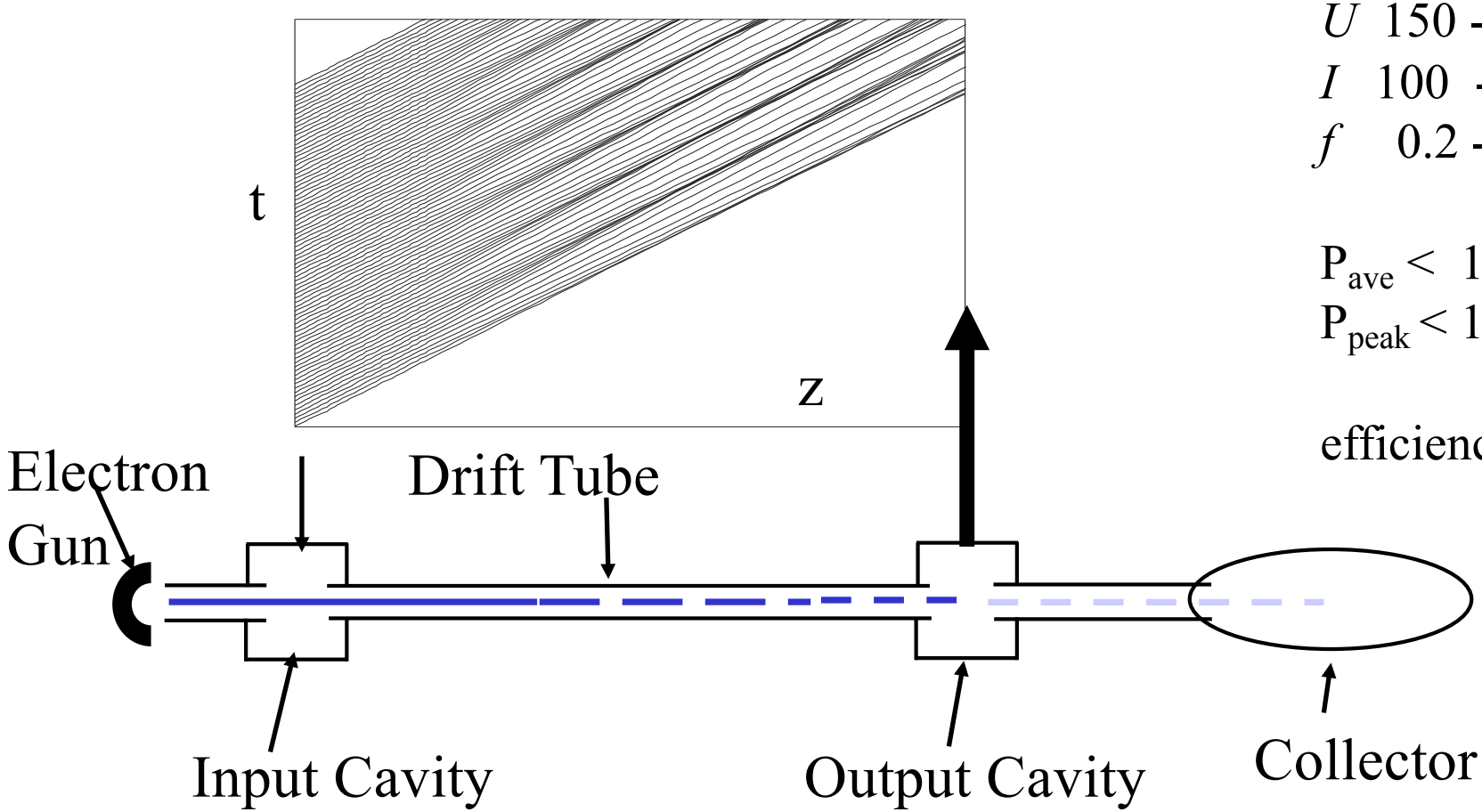


Klystrons

low-power RF signal at the design frequency excites input cavity

Velocity modulation of electron beam -> density modulation

Bunched beam excites output cavity



U 150 -500 kV
I 100 -500 A
f 0.2 -20 GHz

$P_{ave} <$ 1.5 MW
$P_{peak} <$ 150 MW

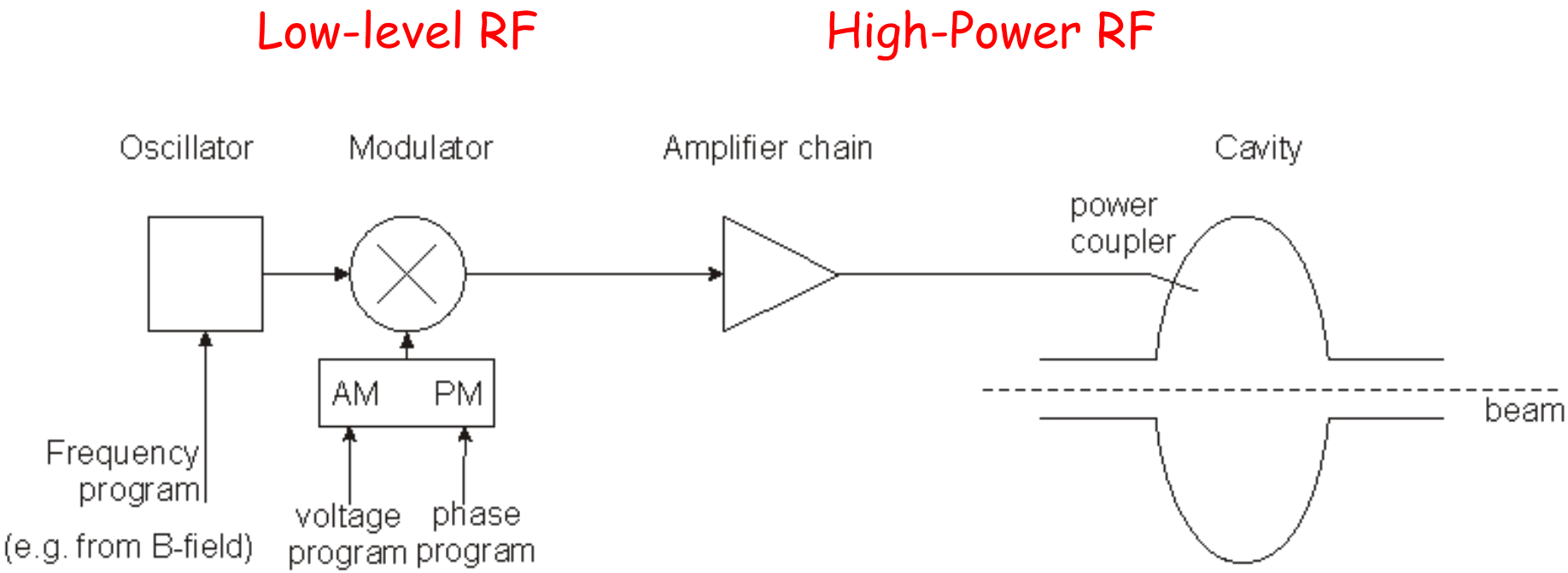
efficiency 40-70%

Klystrons

CERN CTF3 (LIL):
3 GHz, 45 MW,
4.5 μs, 50 Hz, η 45 %

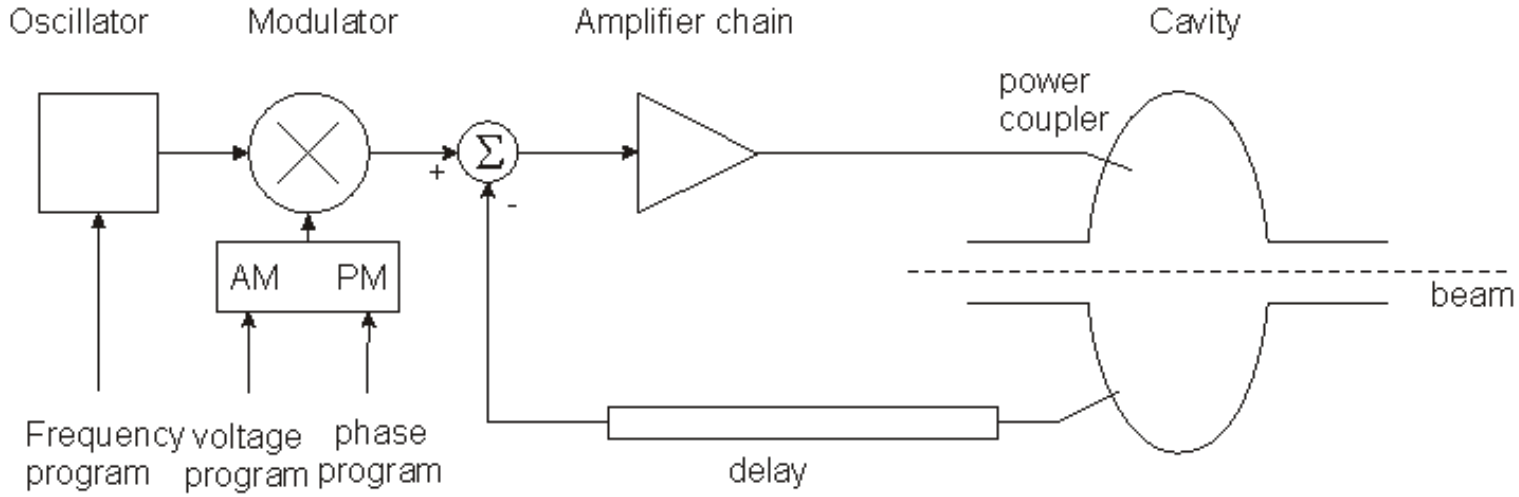
CERN LHC:
400 MHz, 300 kW,
CW, η 62 %

Minimal RF system (of a synchrotron)



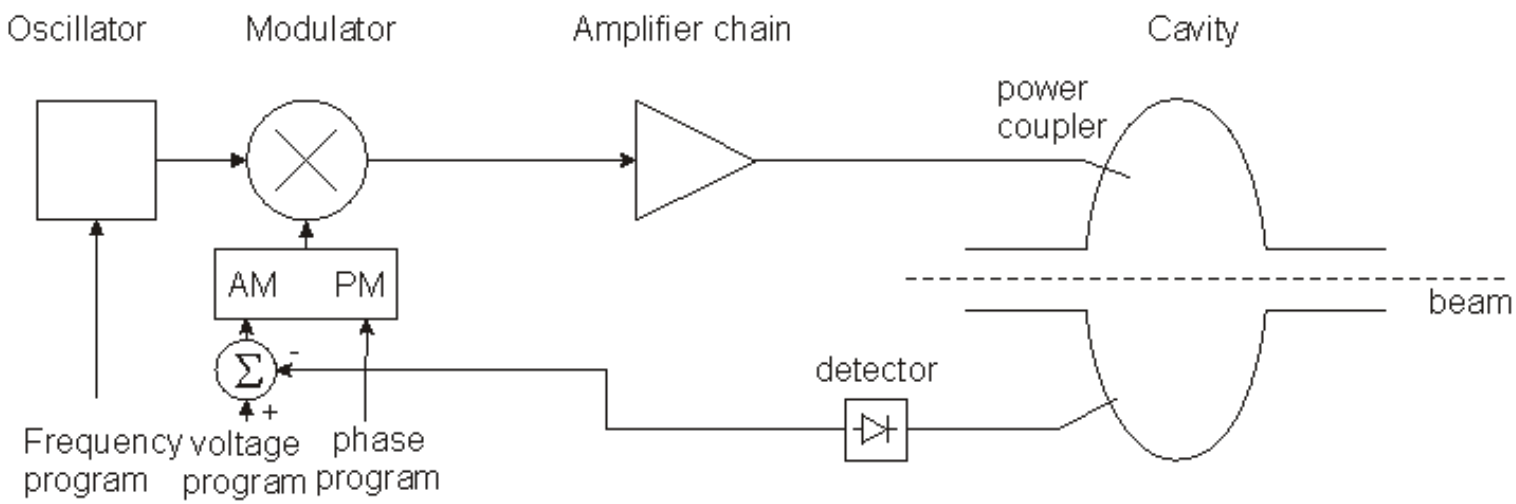
- The frequency has to be controlled to follow the magnetic field such that the beam remains in the centre of the vacuum chamber.
- The voltage has to be controlled to allow for capture at injection, a correct bucket area during acceleration, matching before ejection; phase may have to be controlled for transition crossing and for synchronisation before ejection.

Fast RF Feed-back loop



- Compares actual RF voltage and phase with desired and corrects.
- Rapidity limited by total group delay (path lengths) (some 100 ns).
- Unstable if loop gain $= 1$ with total phase shift $180\,°$ – design requires to stay away from this point (stability margin)
- The group delay limits the gain·bandwidth product.
- Works also to keep voltage at zero for strong beam loading, i.e. it reduces the beam impedance.

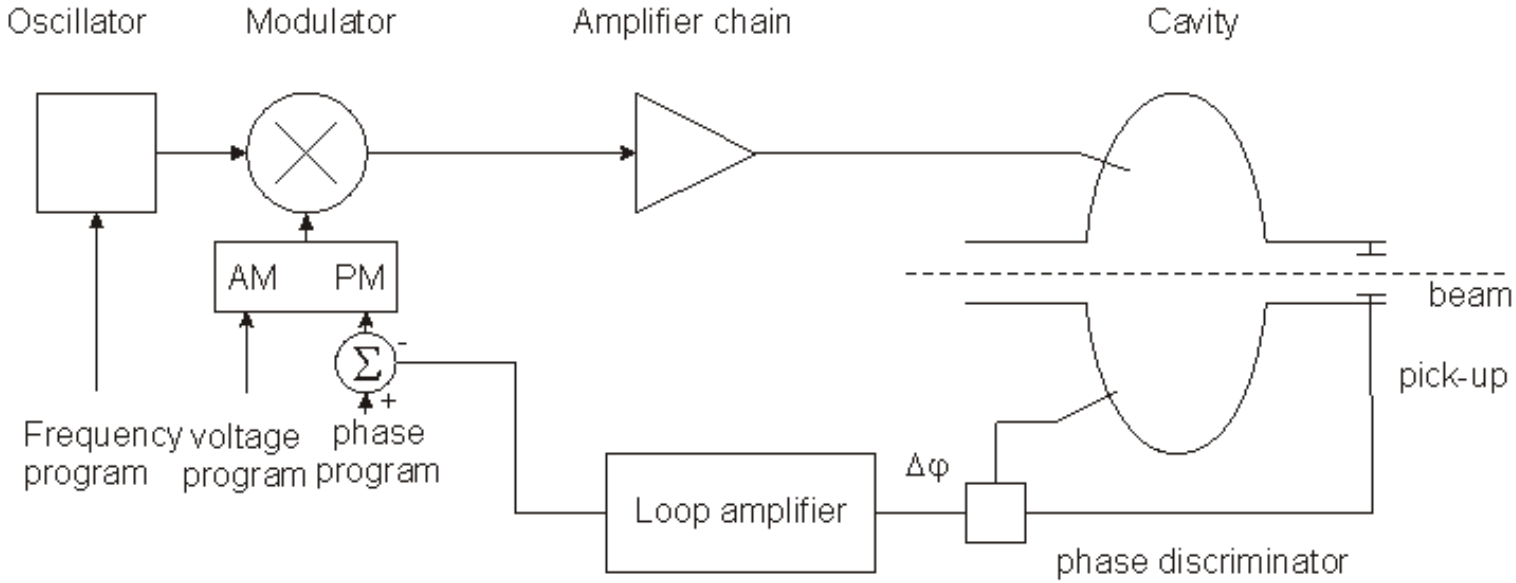
Field amplitude control loop (AVC)



- Compares the detected cavity voltage to the voltage program. The error signal serves to correct the amplitude
- The speed of the "fast RF feedback" is limited by the group delay

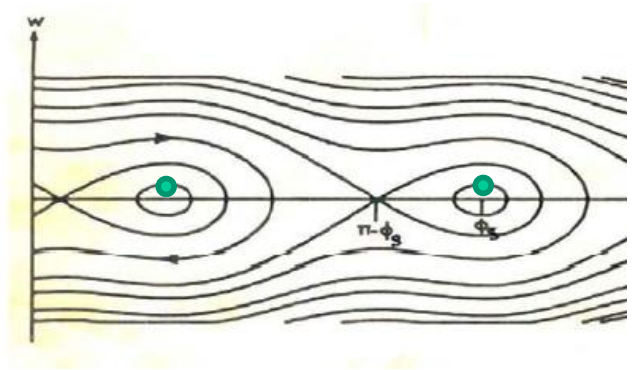
- 1-turn delay: extend the group delay to exactly 1 turn + comb filter
- -> stabilize at multiple harmonics of the revolution frequency

Beam phase loop



- Longitudinal motion: $\frac{d^2(\Delta\phi)}{dt^2} + \Omega_s^2(\Delta\phi)^2 = 0.$
- Loop amplifier transfer function designed to damp synchrotron oscillation.

  Modified equation: $\frac{d^2(\Delta\phi)}{dt^2} + \alpha\frac{d(\Delta\phi)}{dt} + \Omega_s^2(\Delta\phi)^2 = 0$



Other loops

Radial loop:

Detect average radial position of the beam,
Compare to a programmed radial position,
Error signal controls the frequency.

Synchronisation loop (e.g. before ejection):

1st step: Synchronize f to an external frequency (will also act on radial position!).

2nd step: phase loop brings bunches to correct position.

...

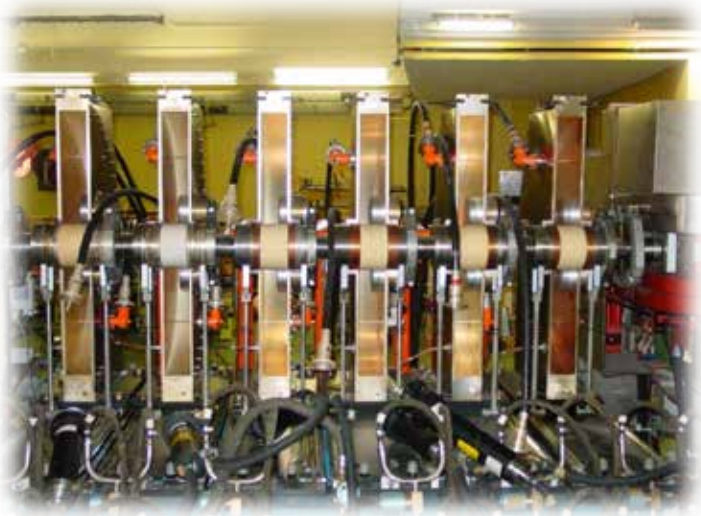
CERN PS RF Systems

10 MHz system, *h*=7…21

13/20 MHz system, *h*=28/42

40 MHz system, *h*=84

80 MHz system, *h*=168



200 MHz system

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I would like to thank everyone for the material that I have used.

In particular (hope I don't forget anyone):

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- Joël Le Duff
- Graeme Burt
- David Alesini
- Fu-Kwun Hwang and Lookang Lawrence Wee

…

Homework at the spa: