

Course B: rf technology  
Normal conducting rf  
Part 5: Higher-order-mode damping

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## But first, a broad overview of electromagnetic simulation

Now we will look at the basic tools which are used to actually implement the concepts you have been learning.

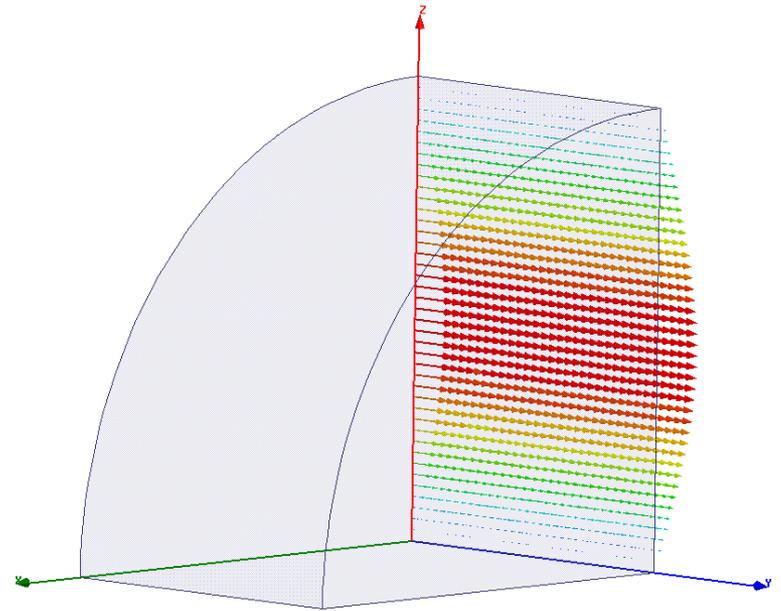
The most popular E&M codes used in the CLIC study are:

- HFSS
- GdfidL
- CST Microwave and Particle Studio
- ACE3P

But let's step back and categorize things a bit. There are three major classes simulation:

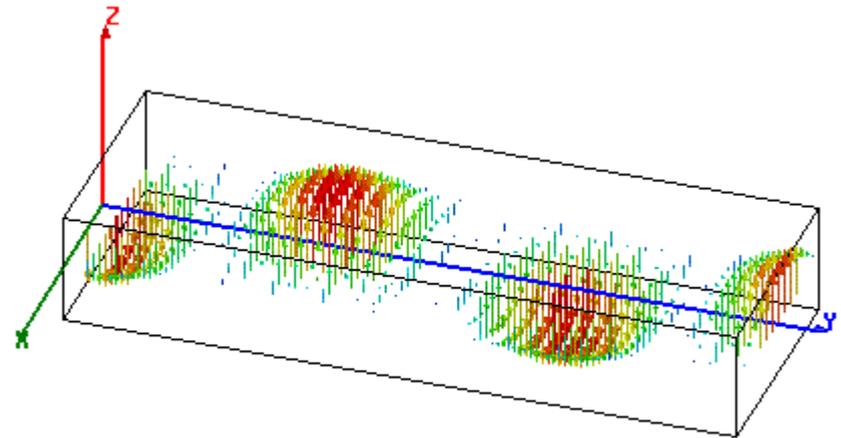
- eigenvalue
- driven solution
- time-domain

This is an eigenvalue problem:



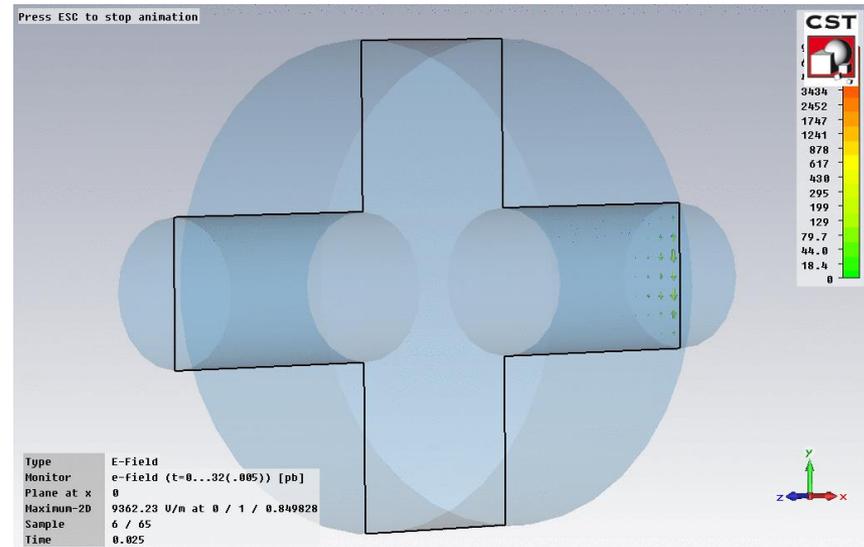
- Mostly for resonant cavities. You put in a closed geometry and get out field pattern, resonant frequency and corresponding  $Q$  factor - mode by mode.
- Used for doing detailed design work - determining your geometry to make drawings, and calculating  $f$ ,  $Q$ ,  $R/Q$ , plot dispersion curves etc.
- Used with periodic boundary conditions, you can simulate the travelling wave fields of infinitely long periodic structures.
- Can include lossy dielectrics – frequency comes out as a *complex* number.  $e^{-i\omega t}$
- Often also used to understand features seen in time domain simulations.

This is a driven problem:



- Mostly for waveguide networks. You put in a closed geometry and one or more ports. For a specified driving frequency, the field pattern of the waveguide mode(s) on that port is computed and then the fields inside the geometry are computed. You get field pattern and the scattering matrices –  $\mathbf{S}_{i,j}$ .
- You get the frequency dependence by scanning the driving frequency.
- Used for designing things like couplers, splitters, directional couplers, hybrids etc.
- You use this to eliminate mismatches, standing waves etc.

This is a time-domain problem:



- These directly compute the interaction of a beam with a geometry.
- It is useful to think of time-domain simulation as “experiments.” You can put in the whole geometry and verify that it is working like you expect.
- The primary use is for the calculating wakefields we talked about in the previous section for complicated geometries.
- If you see a resonance you didn’t expect, or frequencies that seem wrong, you can go back to the eigenvalue solver or driven solution and find out what is going on. You know where to look from time domain.
- There is also **S** parameter time domain – you get a band of frequencies all at once.

How the most popular E&M codes are used in the CLIC study :

- HFSS – Eigenvalue and driven solution. Accelerating structures, PETS and waveguide components. For understanding how fields look and very very accurate determination of solutions. Tetrahedral meshing for high accuracy. Likes computers with lots of RAM.
- GdfidL – Time-domain. Super-efficient work-horse code for wake-field calculations. Very well parallelized so well adapted to clusters of PCs. Also can do PIC.
- CST Microwave and Particle Studio – Eigenvalue, driven and wakefield. Very easy to get started doing accelerator applications with built in functions. Popular with youngsters.
- ACE3P – Supercomputer super code developed at SLAC for the ultimate calculations. Everything - eigenvalue solver, time domain, tracker (for multipactor for example) through PIC. Tricky to use, tricky to get access to... For specialists only.

\*\*\*\* Huge field and I give you only a very specific perspective from CLIC \*\*\*\*

The ultimate in computation  
(Arno Candef's slide)

The fundamental issue:

Misalignments between the beam and rf structures will result in the excitation of higher-order transverse modes. For example  $TM_{110}$ -like modes.

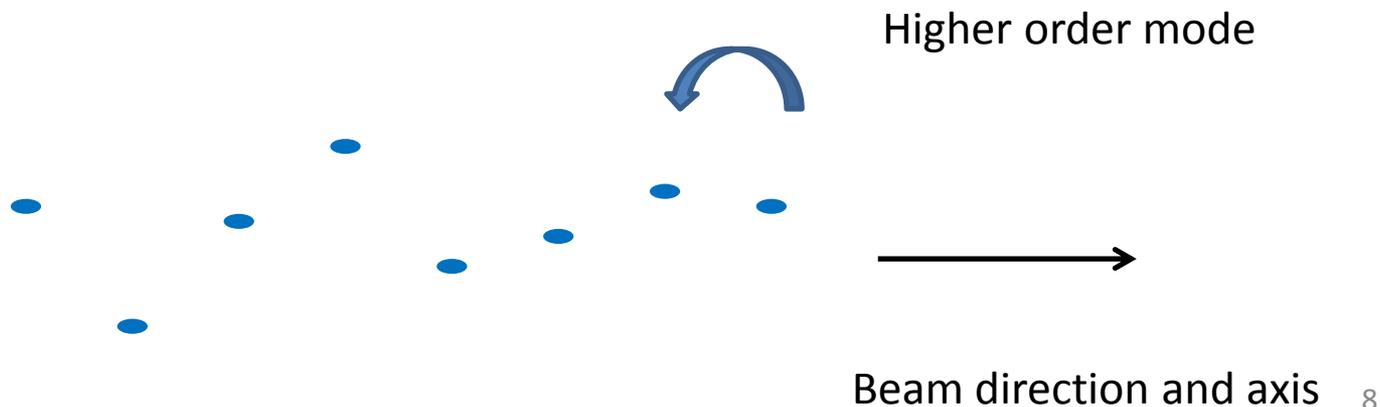
Because linear collider beams consist of trains of bunches, these modes which are excited by a bunch, will act on following bunches.

Because the modes are transverse, they will cause deflections of following bunches.

And because the beam is intense, in order to have high efficiency, this effect is quite strong.

Hence we have the potential for a transverse instability.

There are also high-order longitudinal modes which affect energy spread but we will not speak much about them – they mostly get taken care of automatically.



In order to prevent the beam instability, we need to act on the transverse mode while minimizing the effect on the fundamental, accelerating, mode.

We can do this in two ways.

1. Selectively **damp** the transverse, higher-order, modes. This means adding features to the cells which selectively couple to the unwanted modes. Lowering their  $Q$  so the amplitude of the mode is suppressed between bunches. In a linear collider this means reducing the dipole mode  $Q$ 's to values below 10.
2. Messing around with the dipole mode frequencies, while leaving the fundamental unchanged, so that bunches get kicks from different parts of the structure with different phases. This causes a net wakefield cancellation and is called **detuning**.

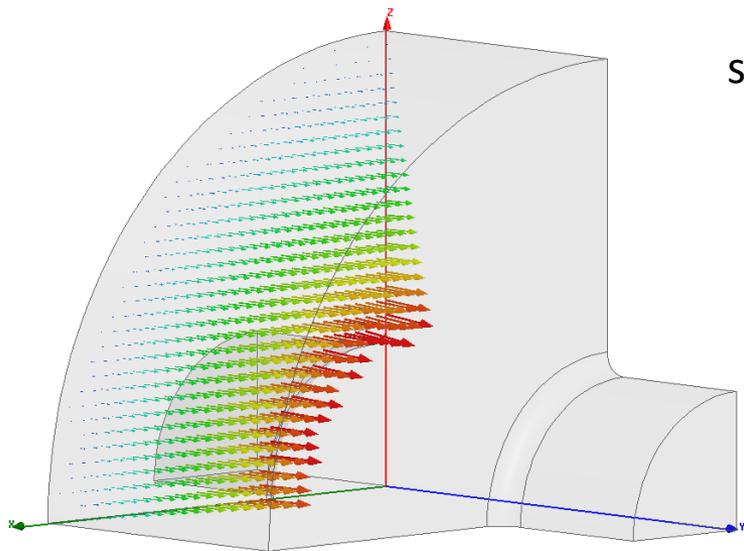
In reality we almost always do a bit of both.

In order to do this in practice we need to address the question:

How do the modes differ?

Damping first. Then detuning.

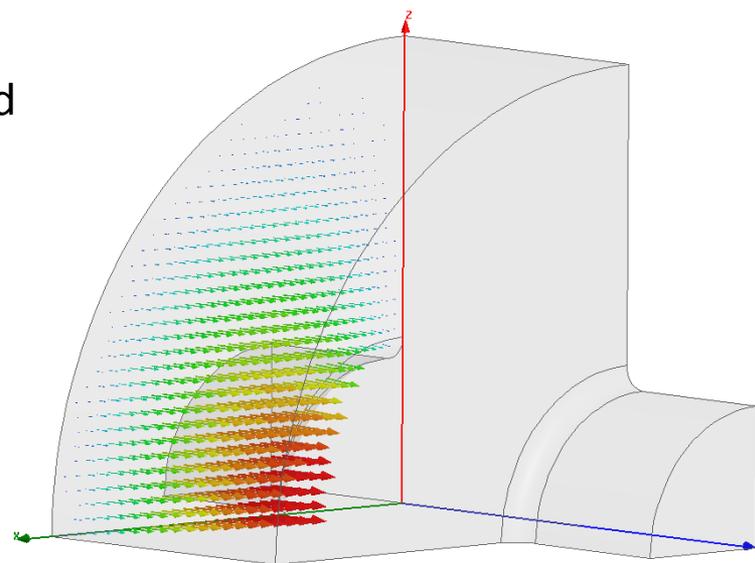
longitudinal,  $m=0$  mode



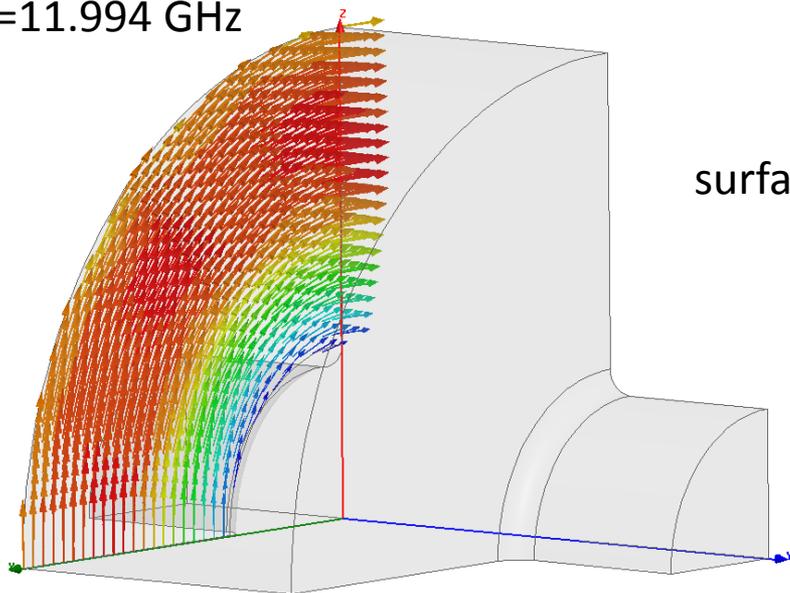
What the modes look like:

surface electric field

Transverse,  $m=1$  mode

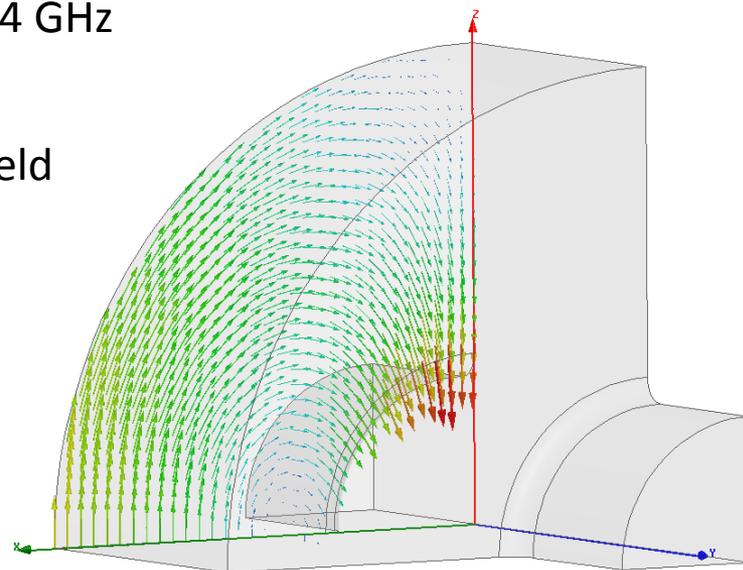


$f=11.994$  GHz



$f=18.014$  GHz

surface magnetic field

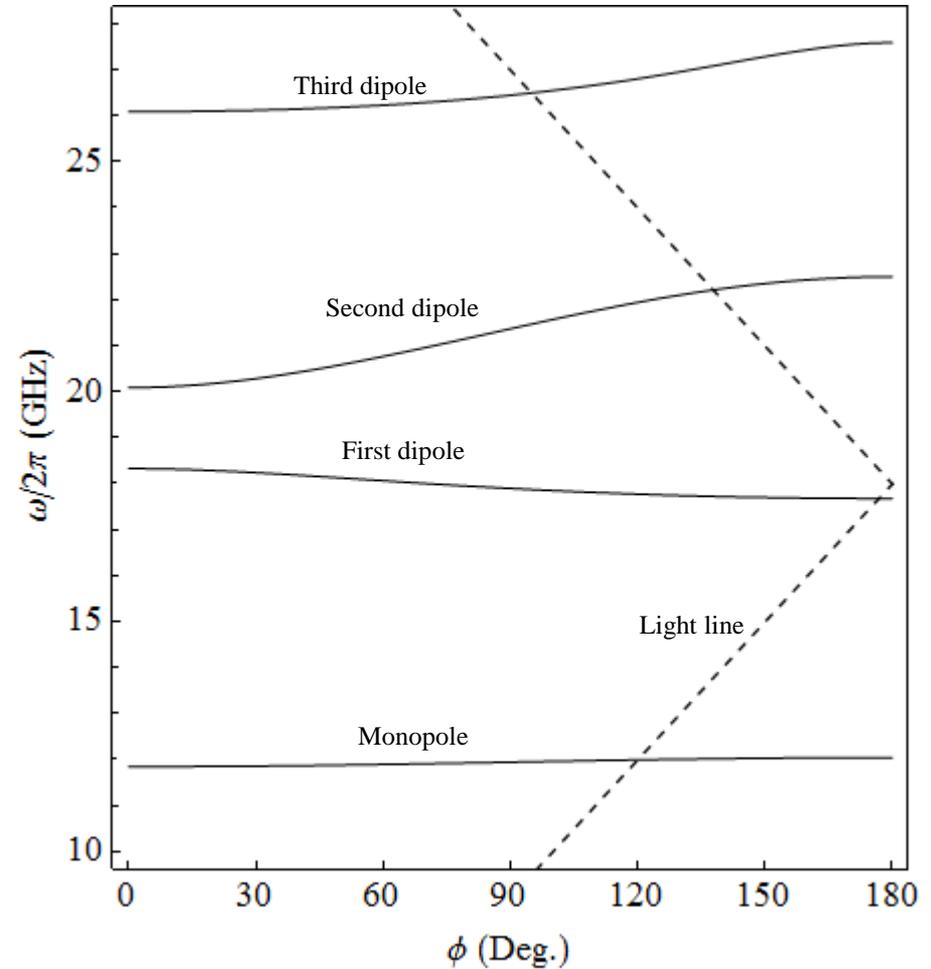


# Dispersion curves: Mid cell

We of course need to consider the beam/mode interaction in multi cell structures.

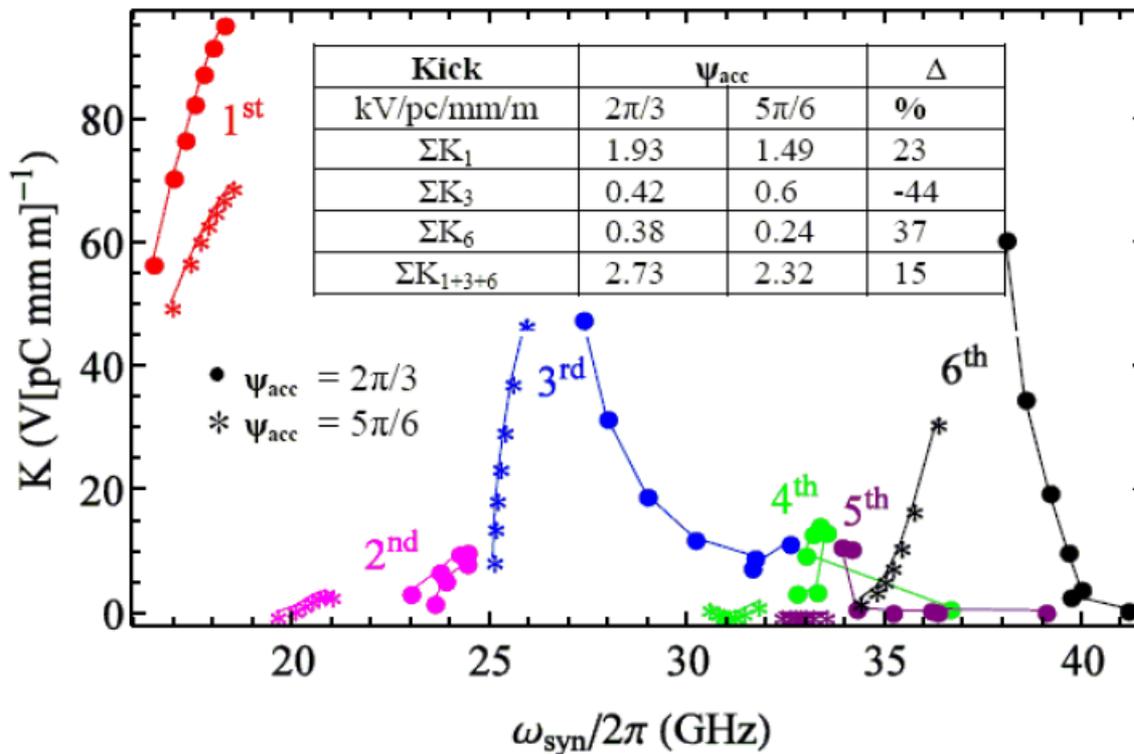
Consequently we go back to dispersion curves, Brillouin diagrams.

Here we see the synchronous crossings of the dispersion curves with the speed of light line.



Thanks to Vasim Khan for the detuning plots!

Not all of the modes kick equally. The mode characteristics of disk loaded waveguide are complicated hybrids of more TM-like and more TE-like hybrids.



The types of modes differ in both **frequency** and **symmetry**.

Lets consider their difference in frequency first.

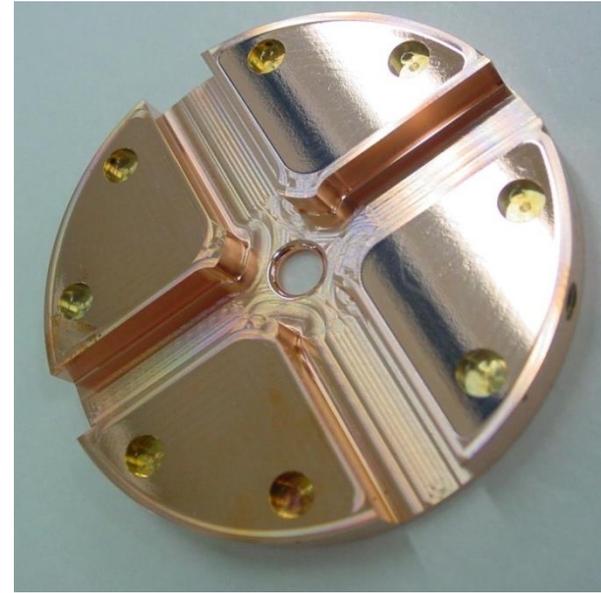
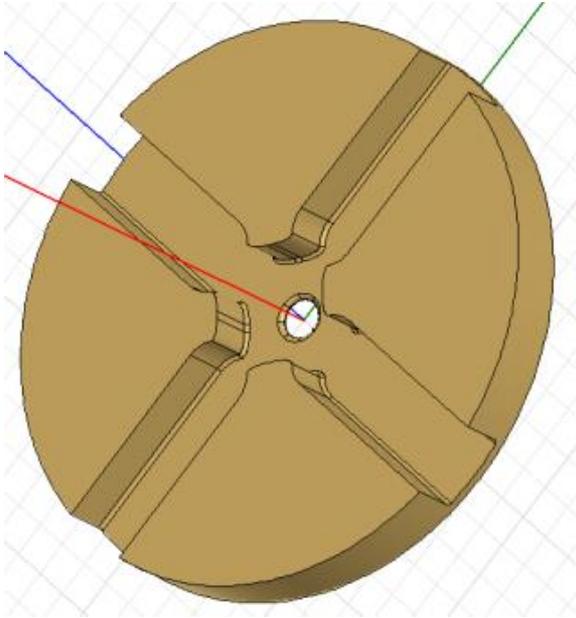
The most straightforward way of selectively damping is to introduce a waveguide into the cell which has a cutoff frequency above the fundamental mode, 12 GHz in our example, but below the lowest dipole mode, 18 GHz.

Fundamental mode power is in cut-off so does not propagate, dipole mode power does.

This is called **waveguide damping** and is used in the CLIC baseline structure.

We'll look more closely at the CLIC structure now, to get the bigger picture of a damped structure before moving on to the other types of wakefield suppression.

# Waveguide damped cell topology



The cells have 11 mm wide waveguides. This gives a cutoff frequency of 13.6 GHz for the  $TE_{1,0}$  which is given by the relation:

$$f_0 = \frac{c}{2a}$$

18 GHz propagates, 12 GHz is in cut-off. The  $Q$  of the dipole mode is around 10.

# Frequency and time behavior

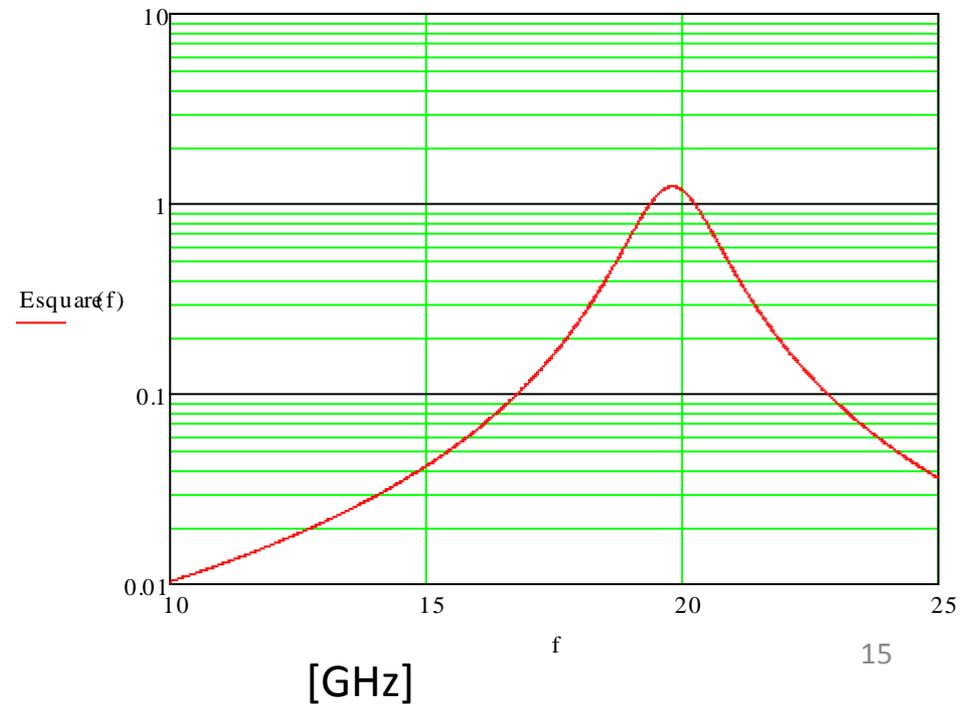
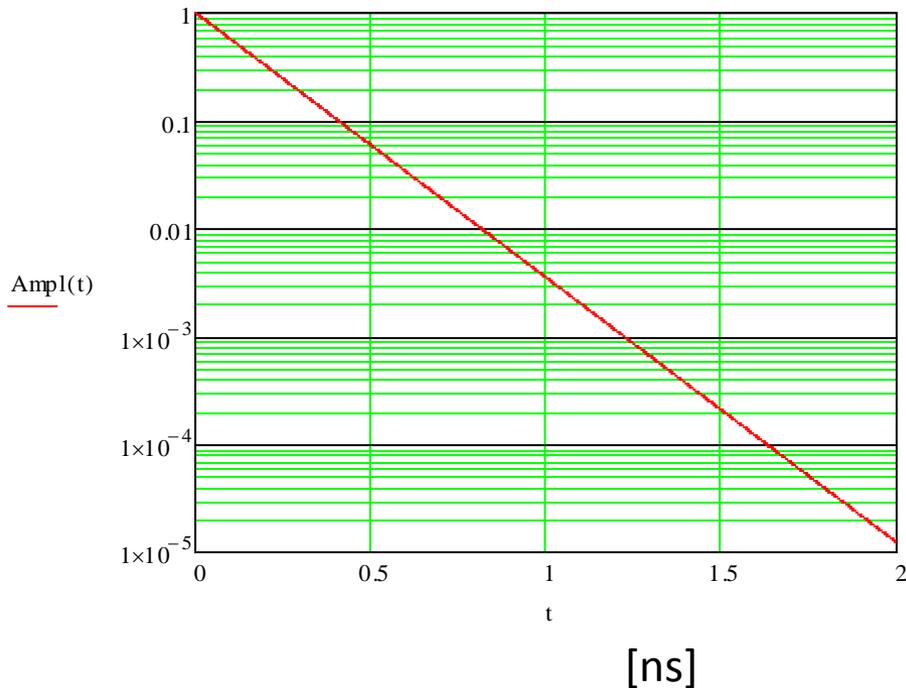
$$E(\omega) \propto e^{-\frac{\omega_0 t}{2Q}}$$

$$Q = \frac{f_0}{\Delta f}$$

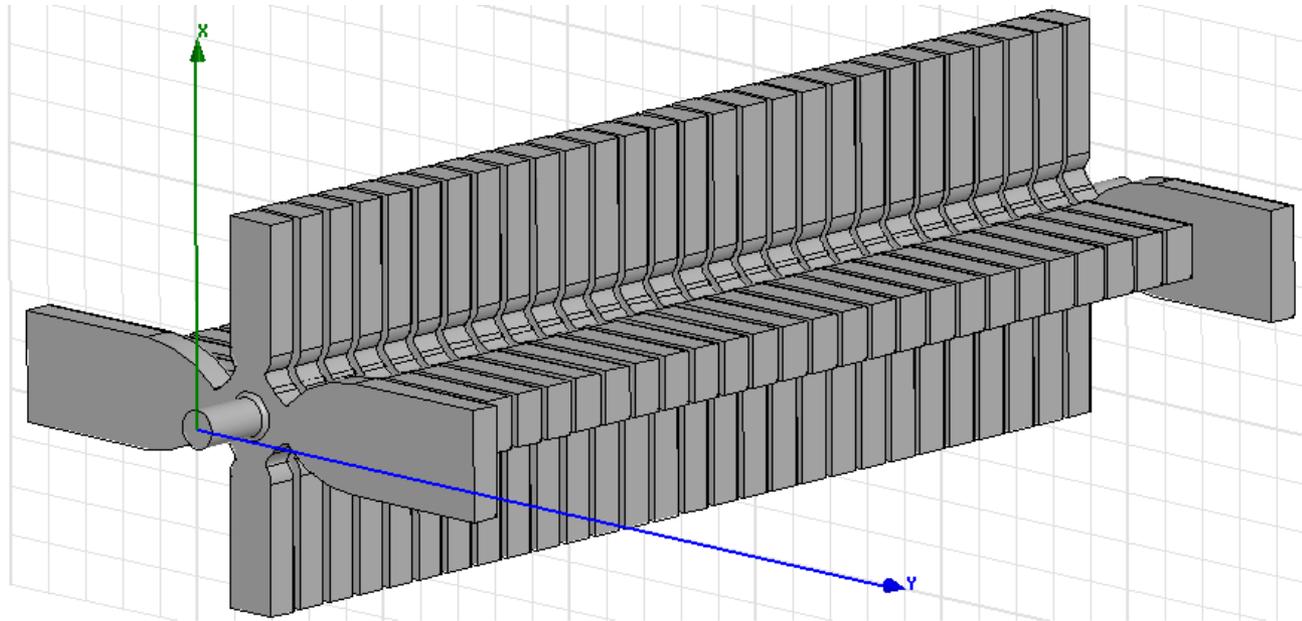
$$E^2(f) \propto \frac{1}{(f - f_0 - \Delta f)^2 + \left(\frac{f_0}{2Q}\right)^2}$$

CLIC bunch spacing  

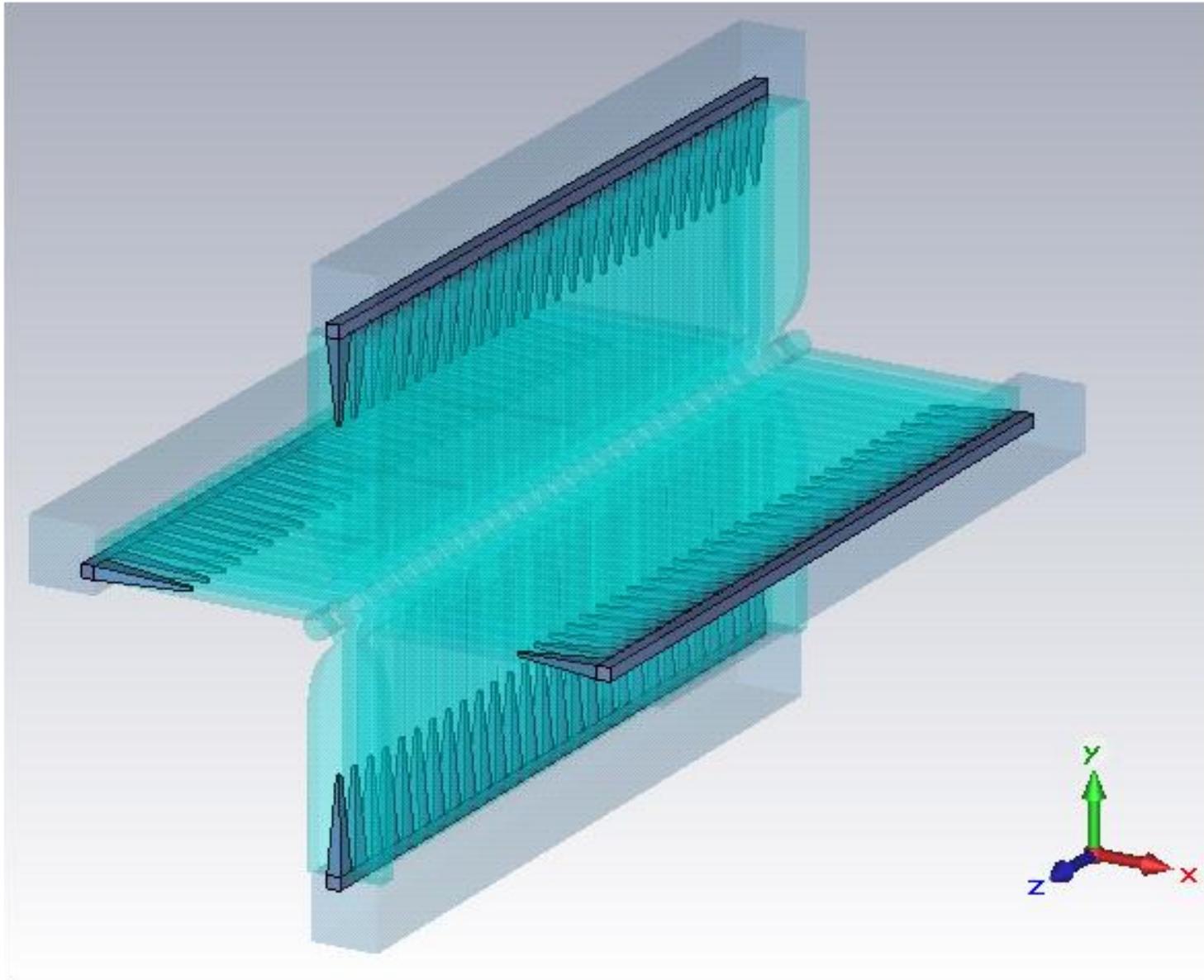

$f_0 = 18 \text{ GHz}$ ,  $Q = 10$



Every cell has to be damped in a linear collider

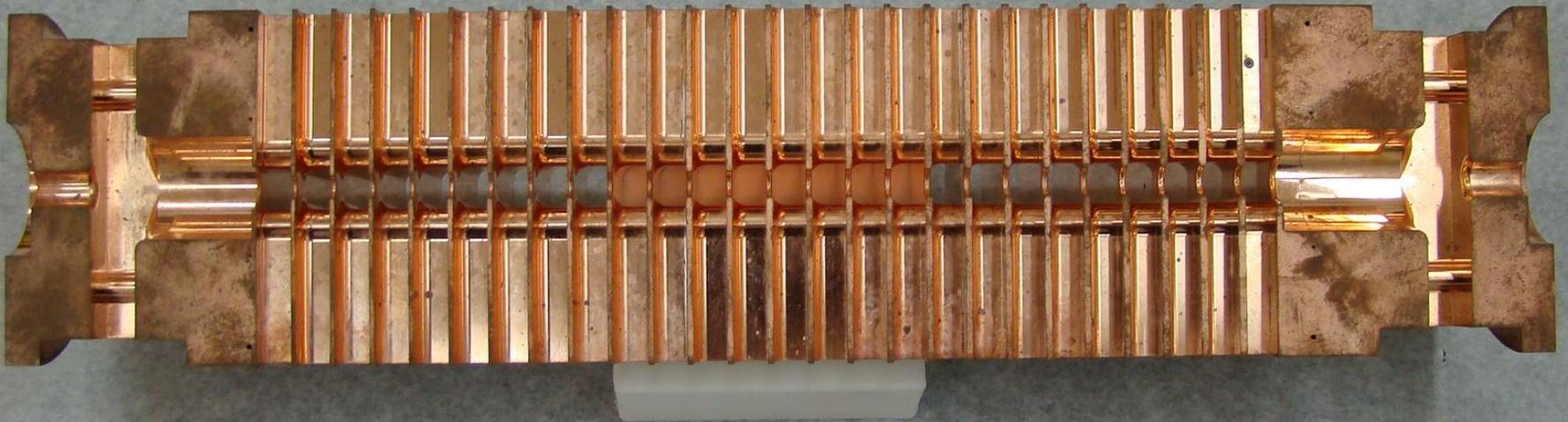


# With terminations

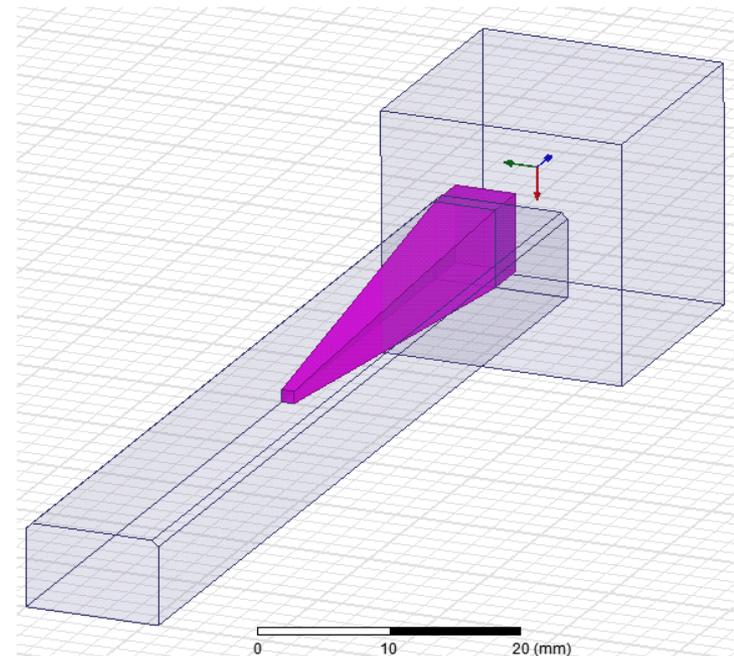
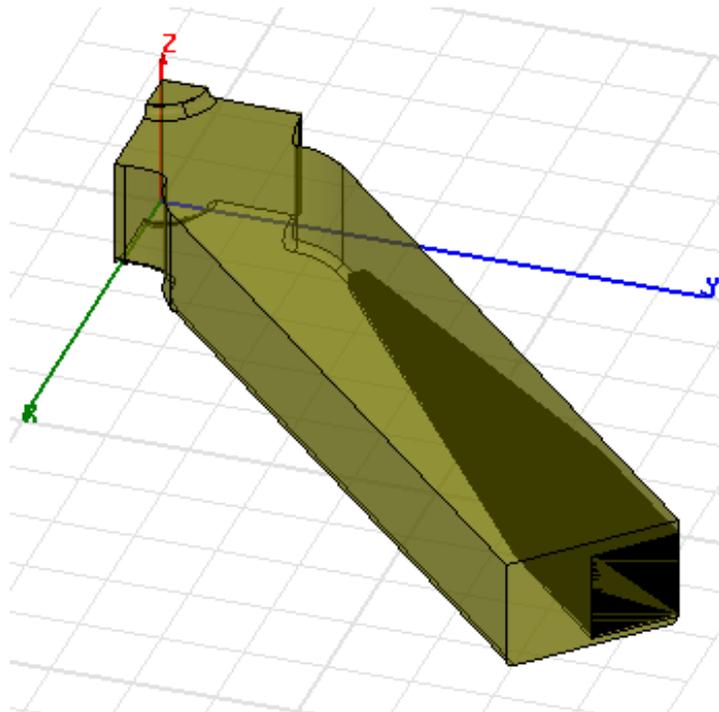
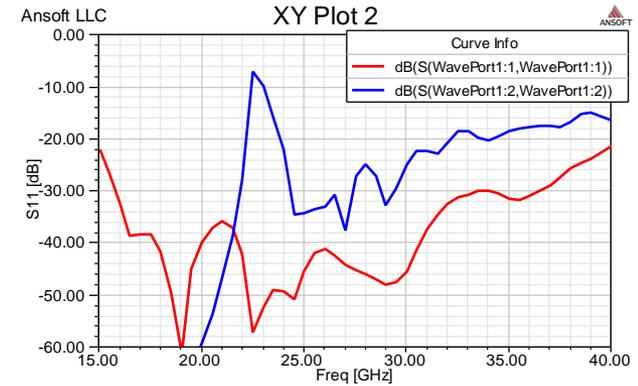
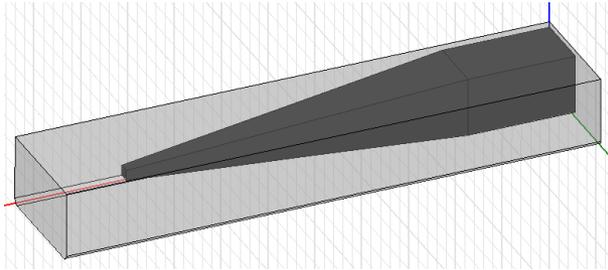




How it looks

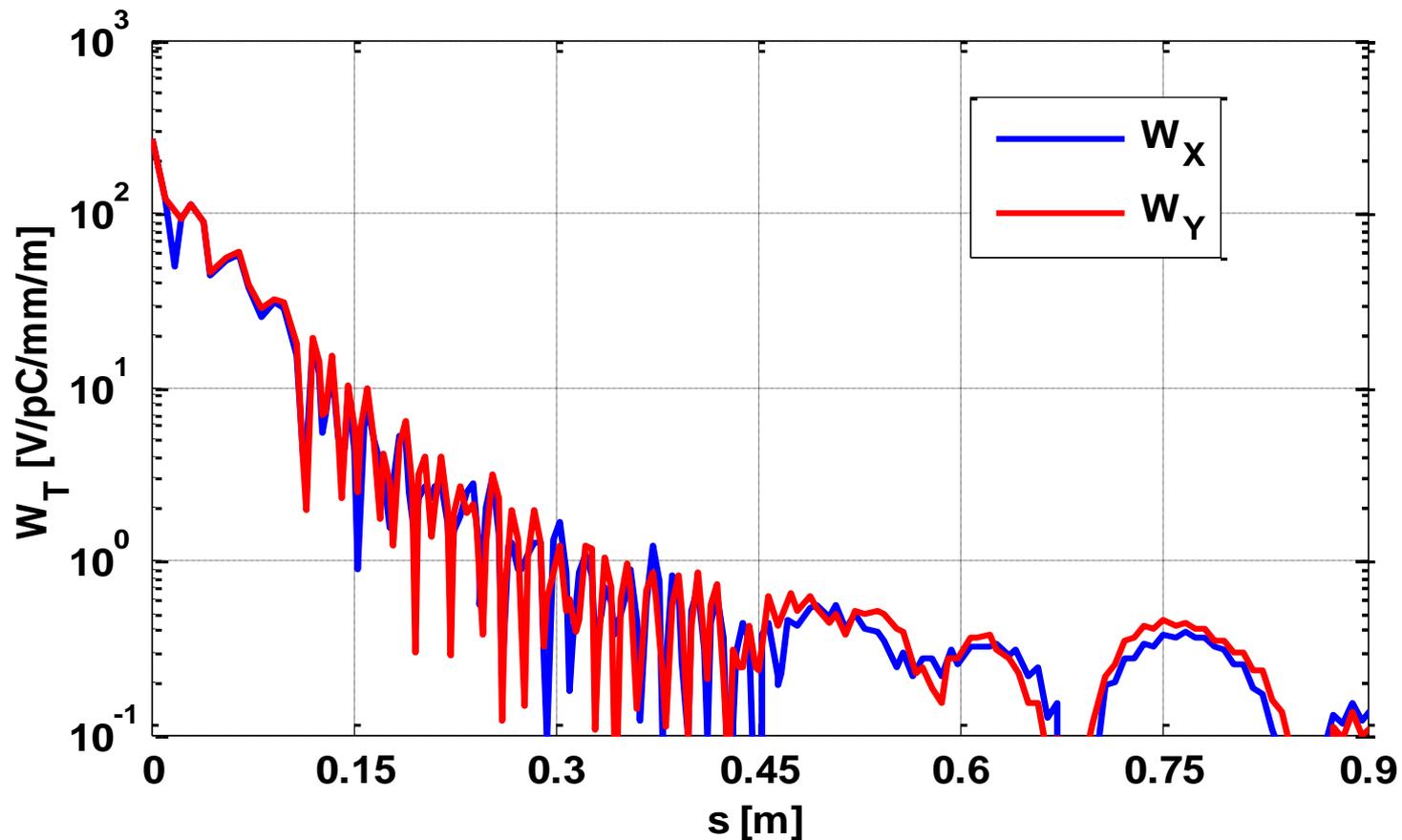


Then you need to terminate each waveguide with an absorbing load



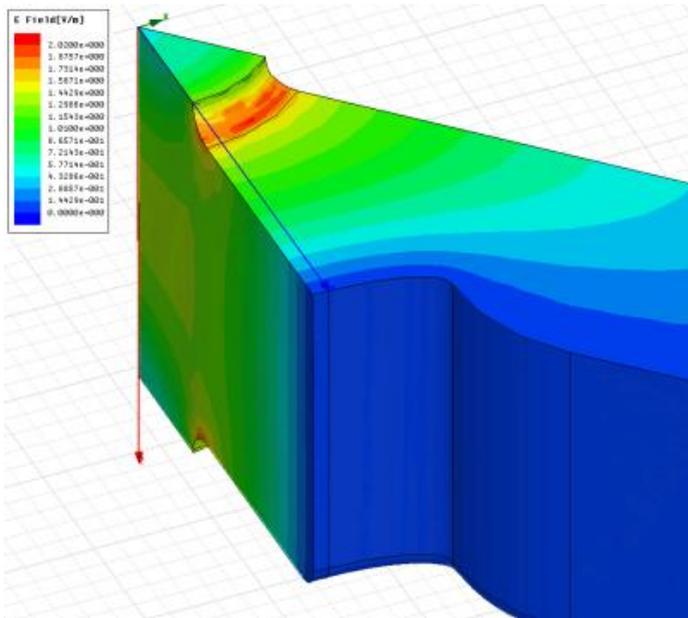
You can make a pretty good approximation to the wakefield from a heavily damped structure by getting frequencies from an undamped dispersion curve and Q's from an eigenvalue solver.

But in practice the wakefield from such a structure is solved using a time domain code.

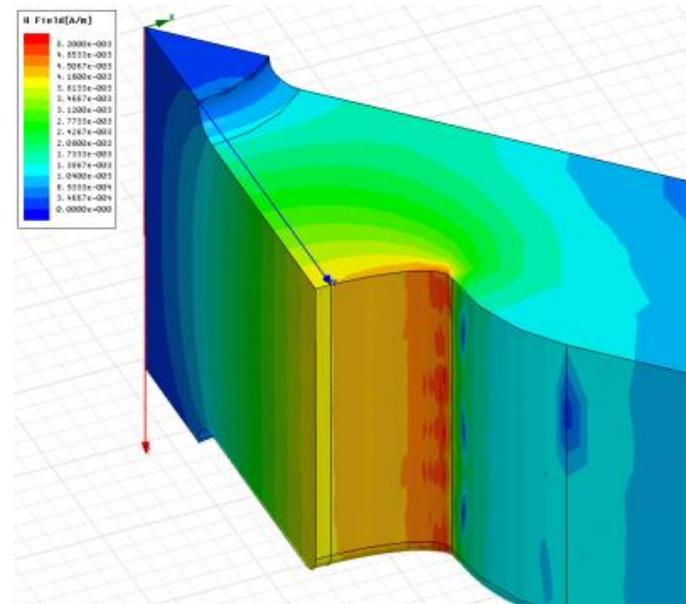


There is however a price to pay for including damping.

- You lose a bit in shunt impedance.
- There is a concentration of surface magnetic field on the outer cavity wall, which can cause problems at high power.
- Mechanical complexity – milling is required.

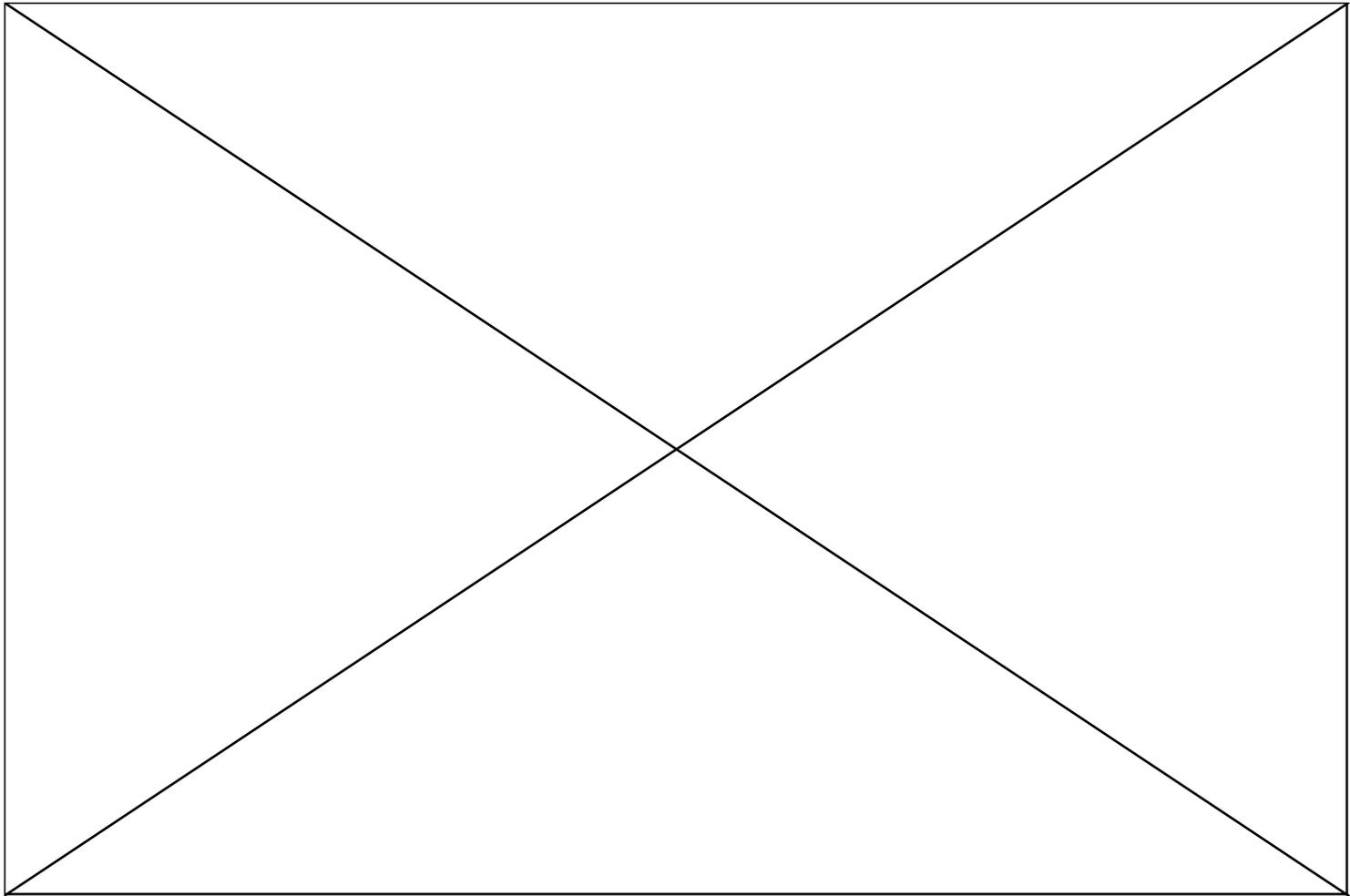


$$E_s/E_a$$



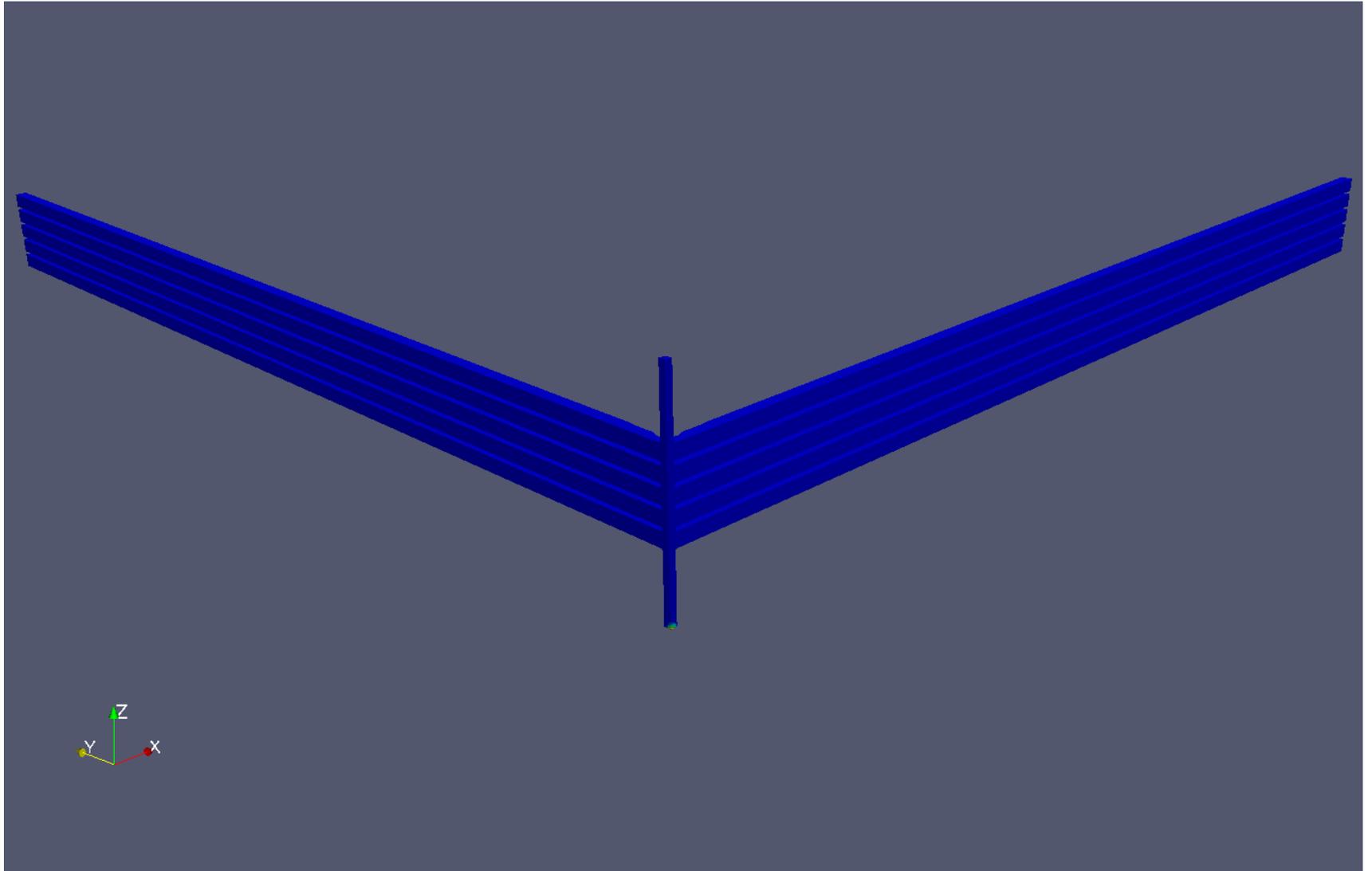
$$H_s/E_a$$

# Bunch Passage through TD26

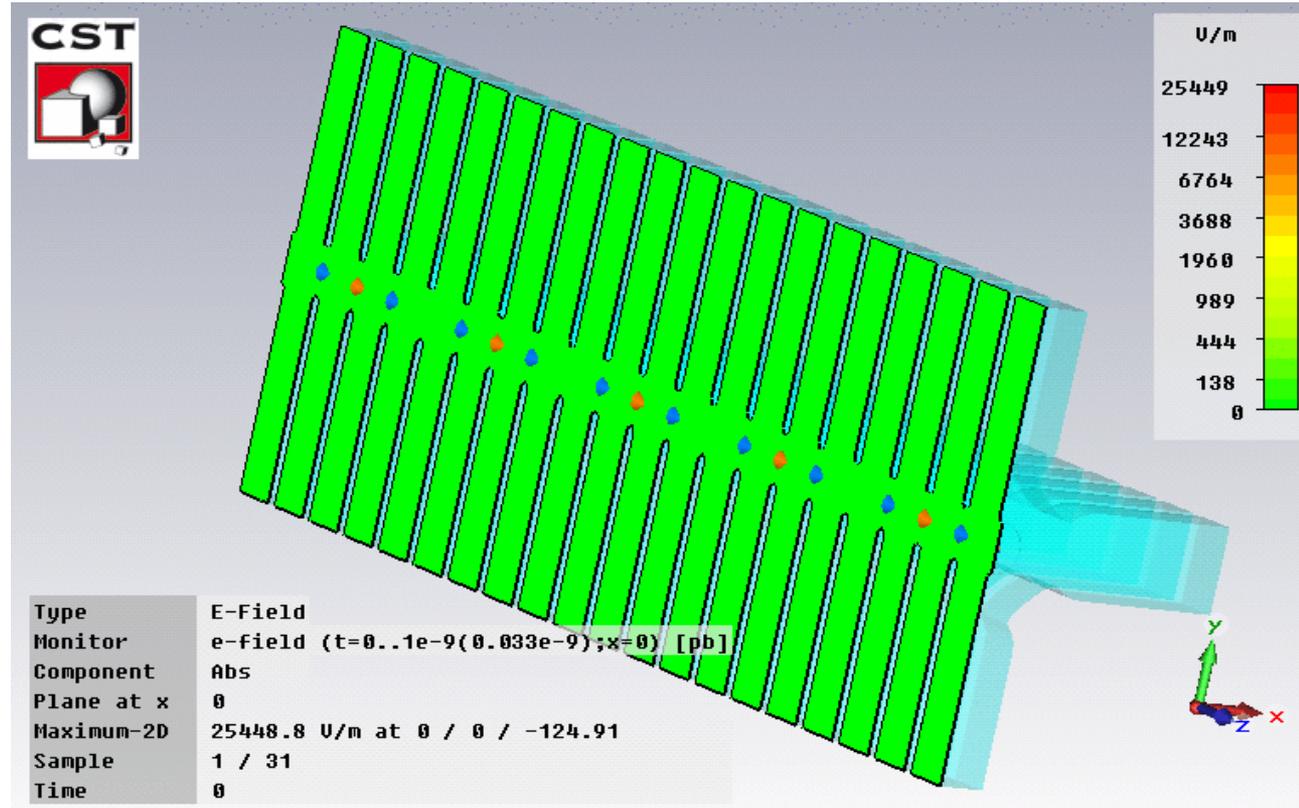


Thanks to Oleksey Kononenko

# Waveguide damping from Kyrre Sjobaek



# Another view of wakefield damping from Giovanni De Michele



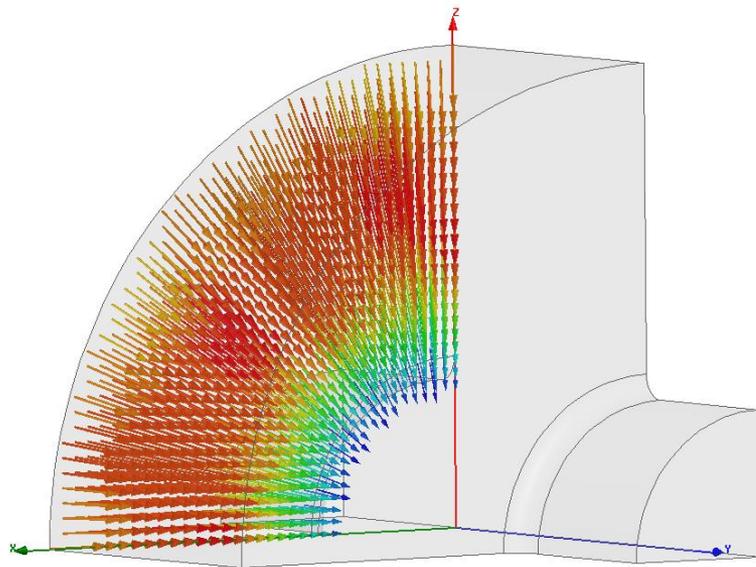
Now we will consider damping which takes advantage of the different **symmetry** of the monopole and dipole modes.

Another way of saying it is that we will take advantage of the different field patterns of the two modes.

The form of damping is called **slotted-iris damping**.

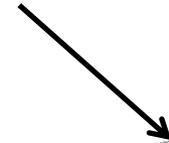
This type of damping is used in the CTF3 drive beam linac accelerating structures, in the CLIC PETS structures and has been considered as a alternative CLIC main linac structure.

# Slotted iris damping

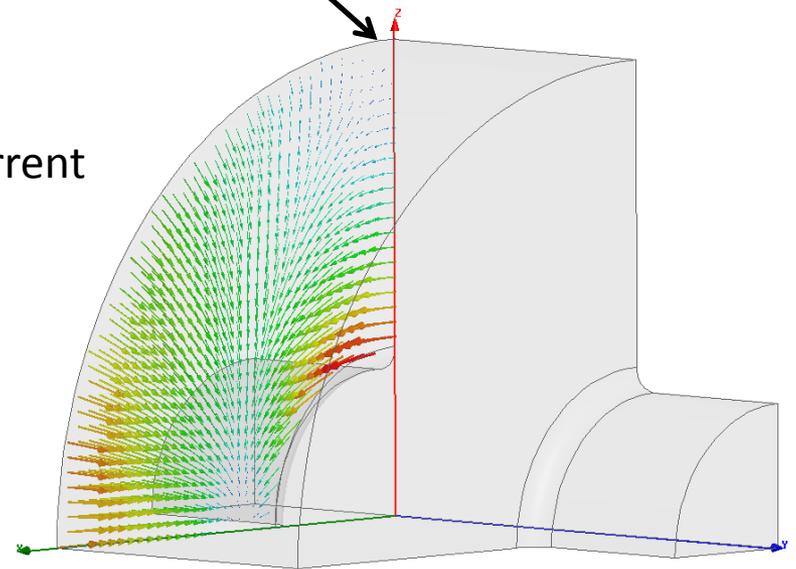


fundamental mode

put slot here



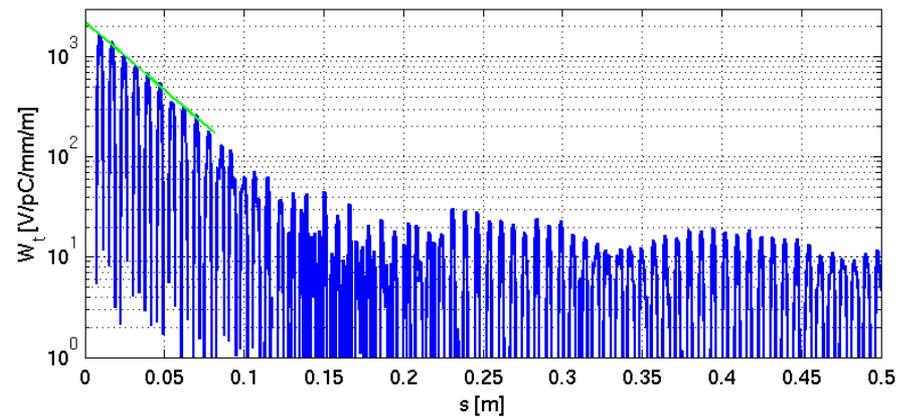
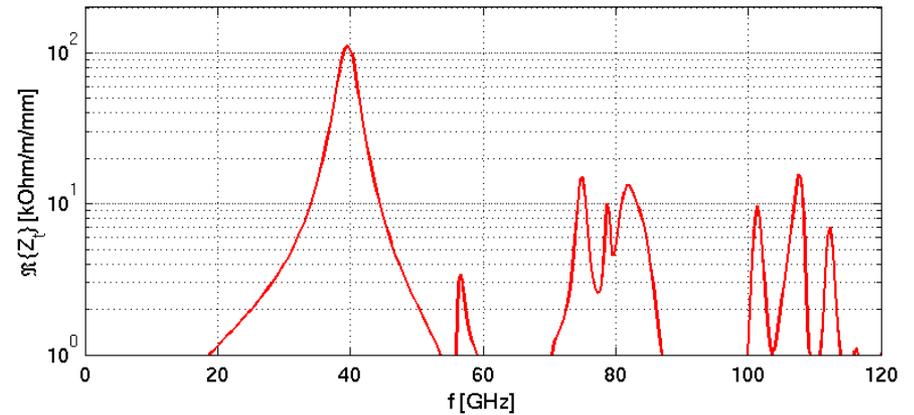
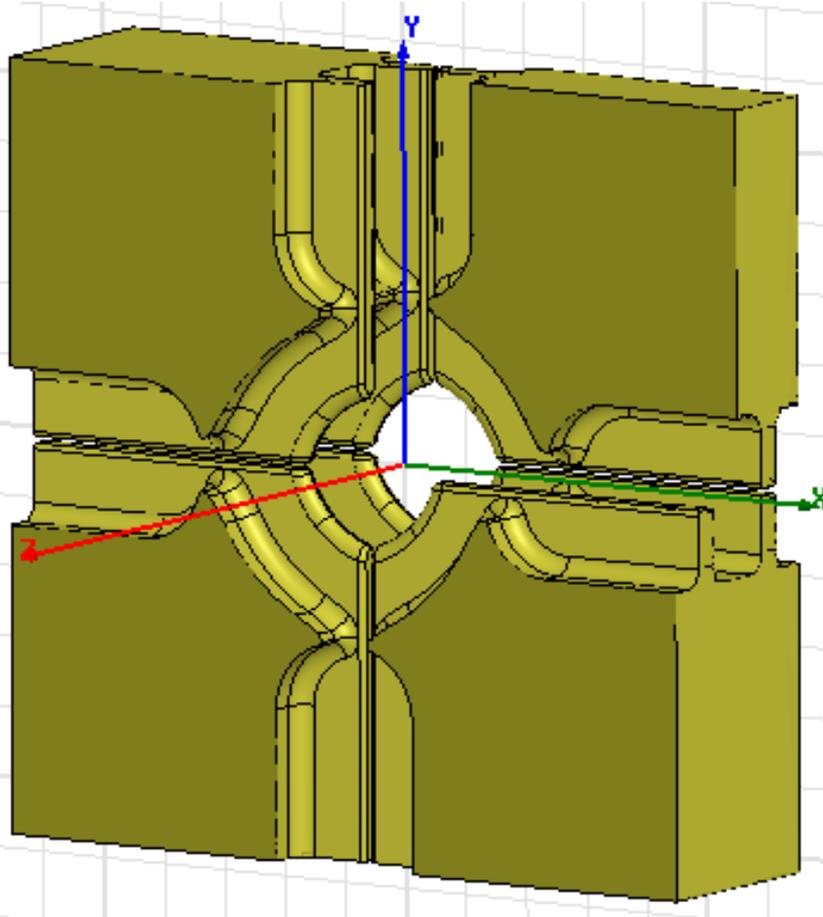
surface current



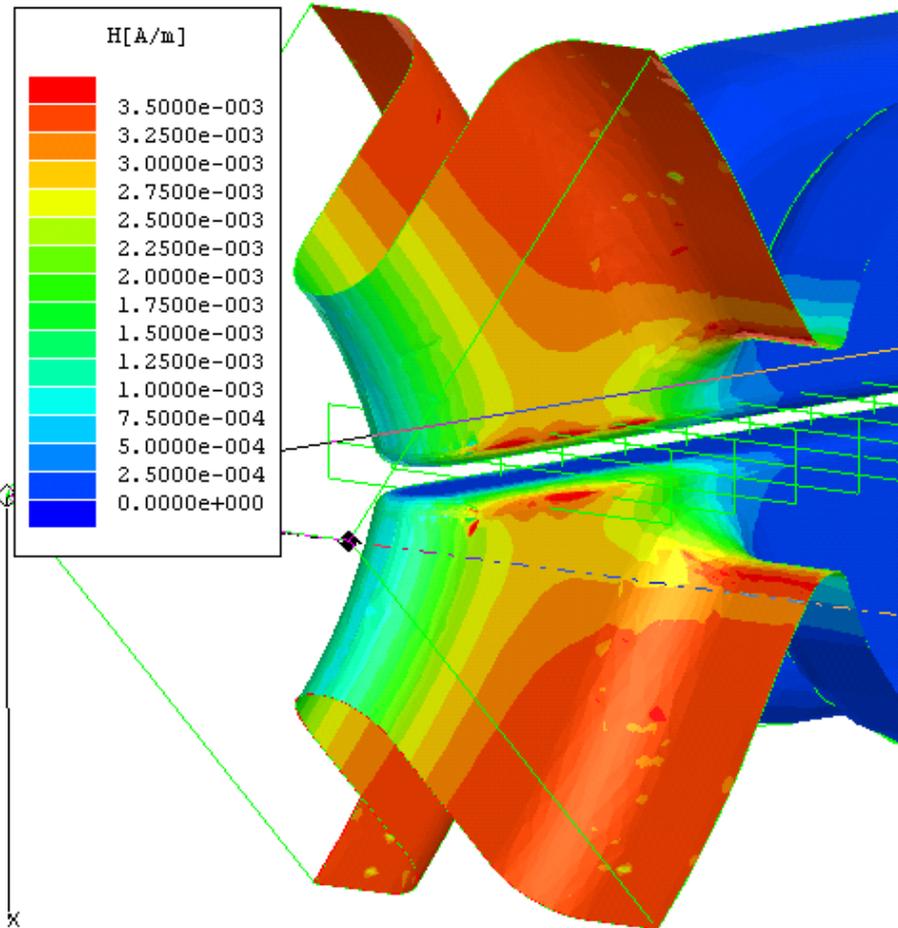
dipole mode

# Hybrid Damped Structure (HDS)

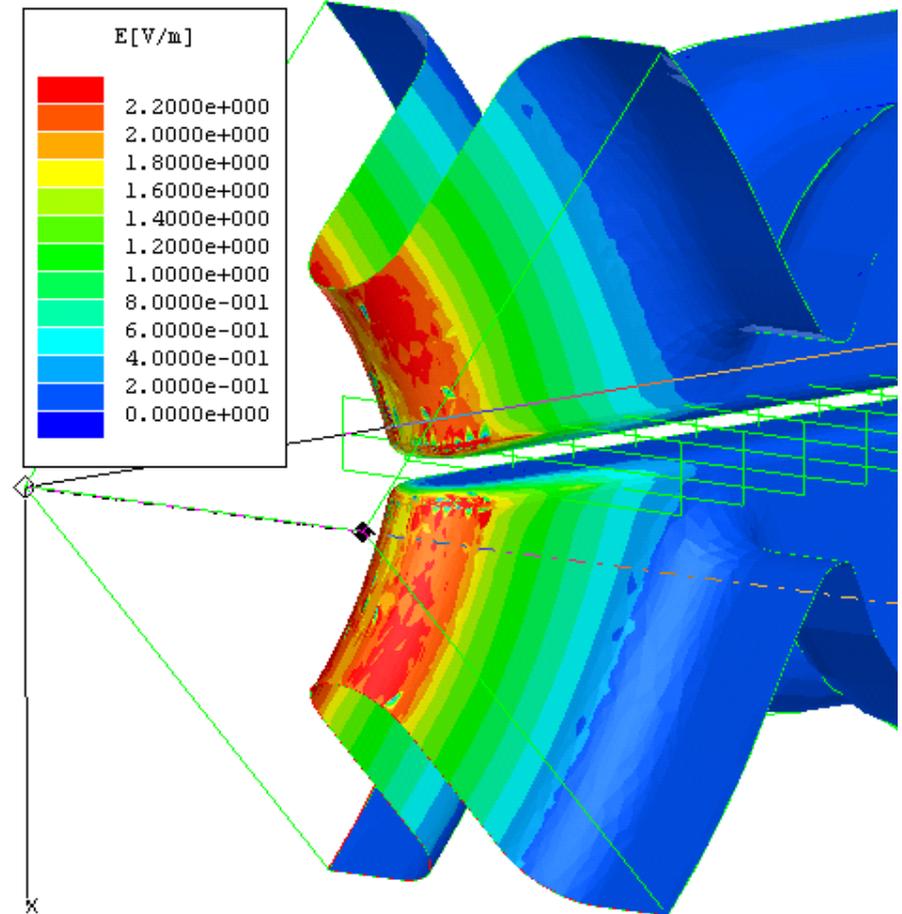
Combination of slotted iris and radial waveguide (hybrid) damping results in low Q-factor of the first dipole mode:  $\sim 10$

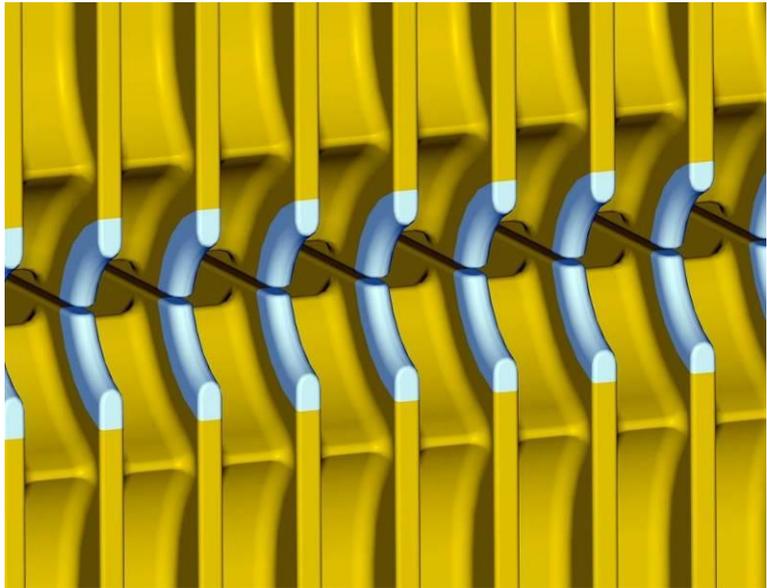
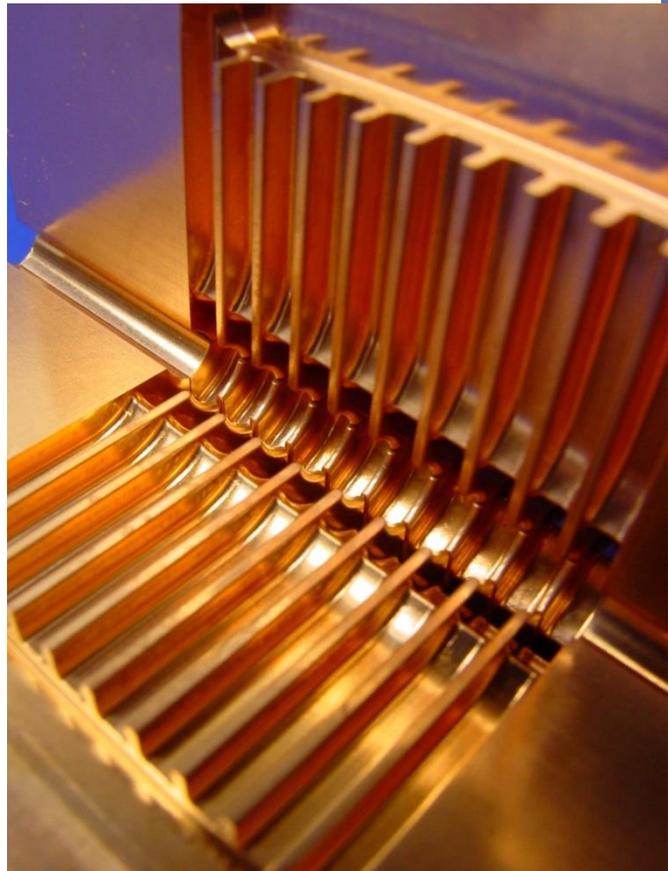
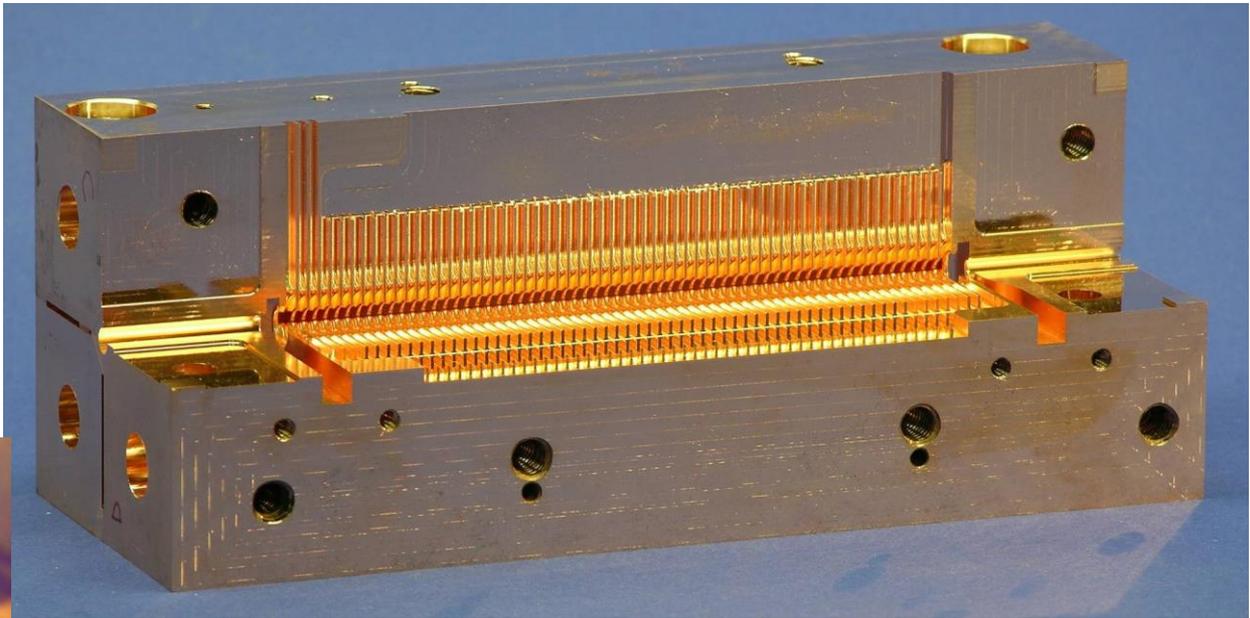


Surface magnetic field

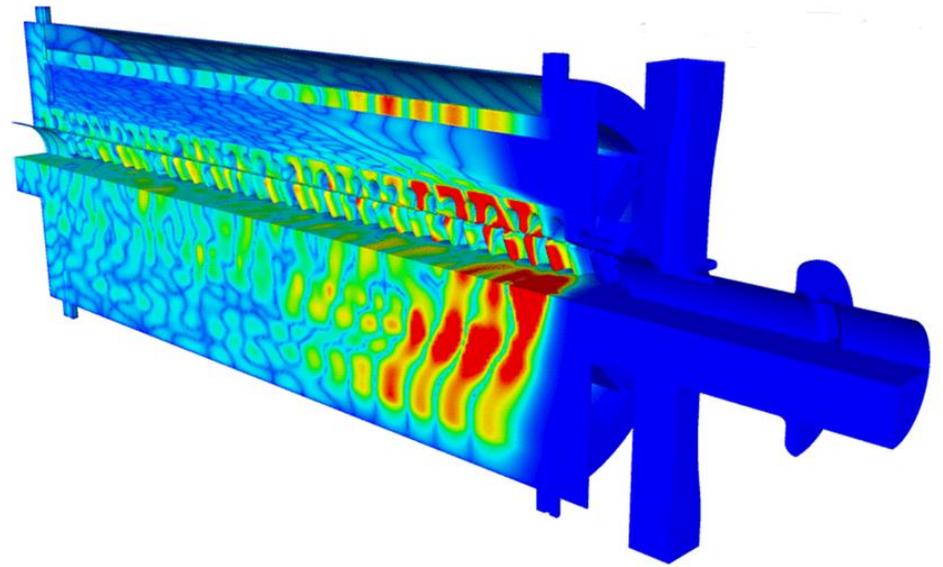
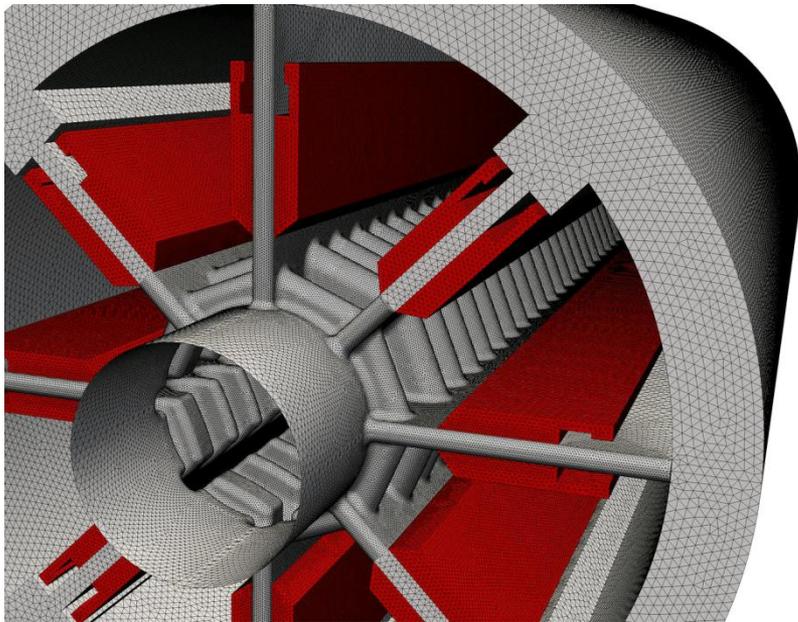


Surface electric field



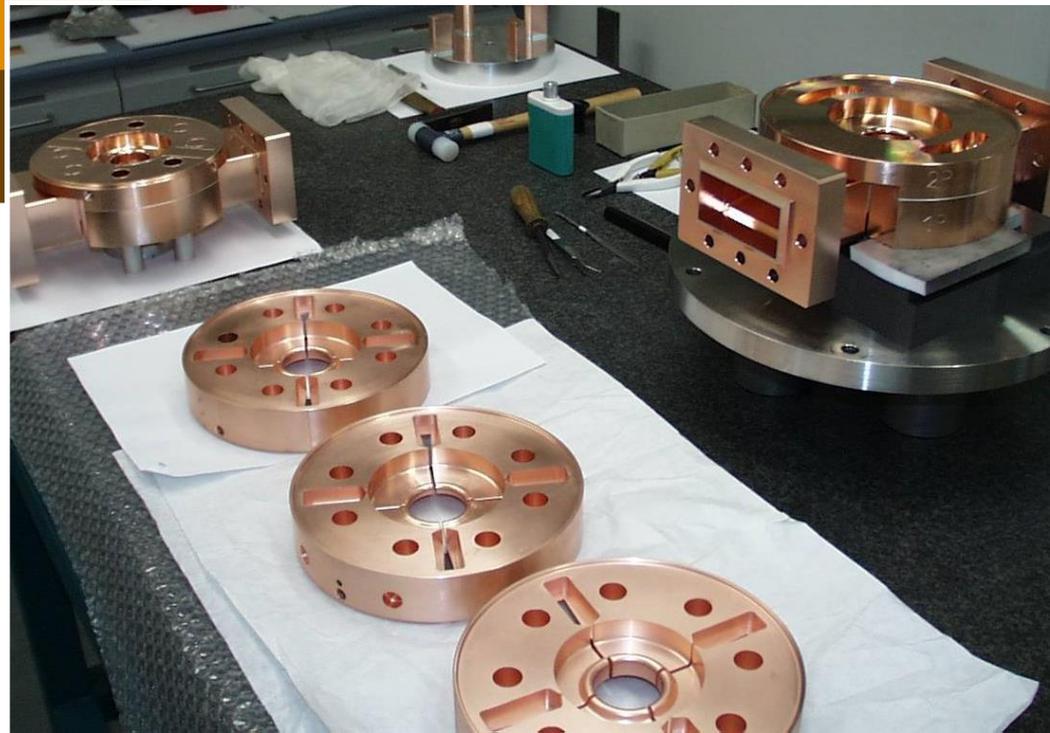


# Slotted iris damping in the CLIC PETS structures



Q's below 10

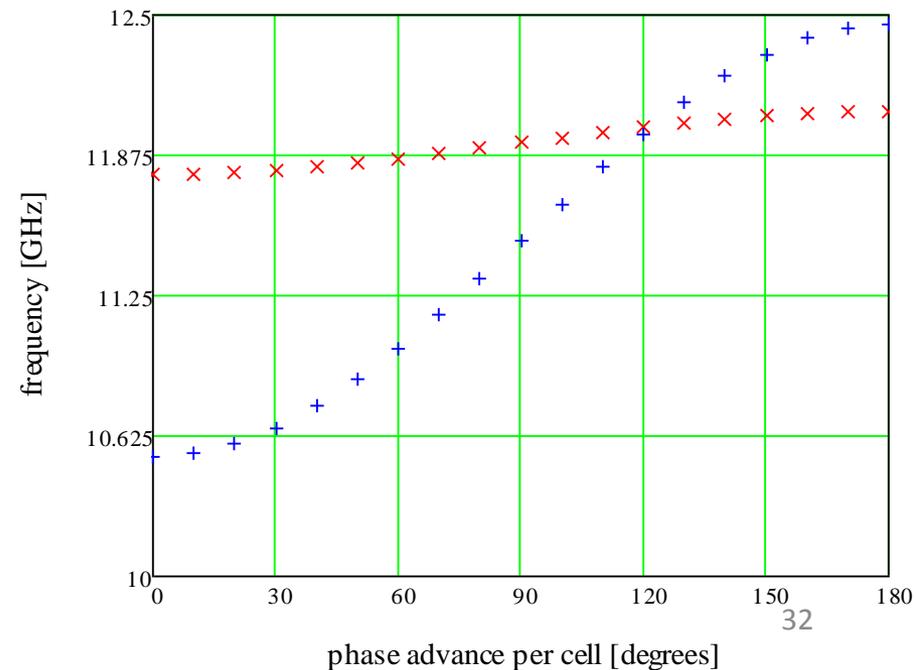
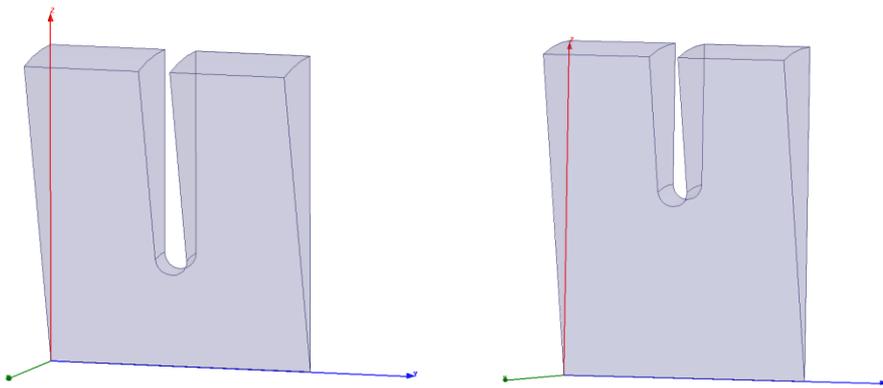
# SICA geometry. CTF3 drive beam linac



## Detuning

Introduce a variation in the dimensions of a structure such that the fundamental, accelerating mode synchronous frequency is unchanged, but higher order modes are detuned.

Remember these figures from part 1?

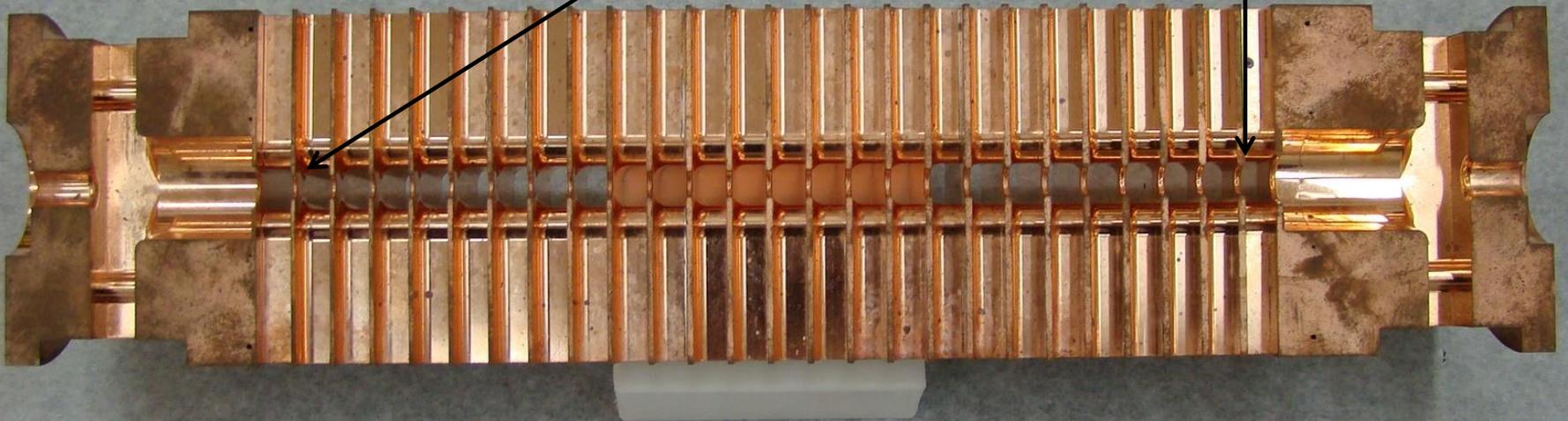




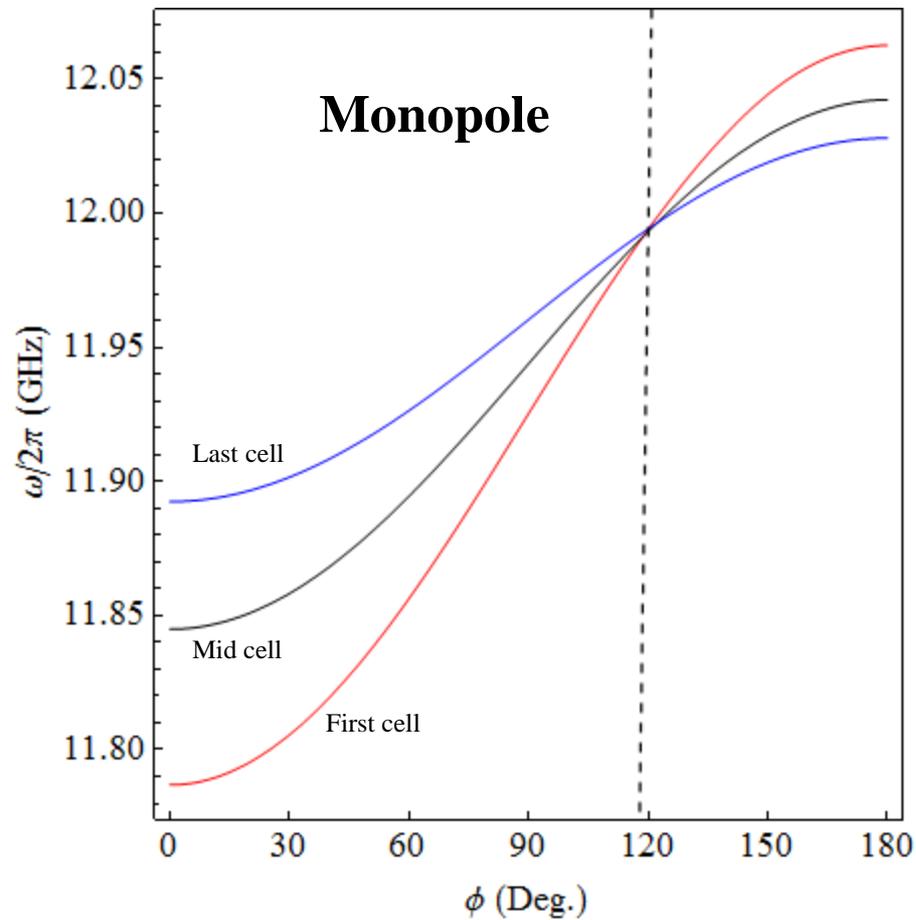
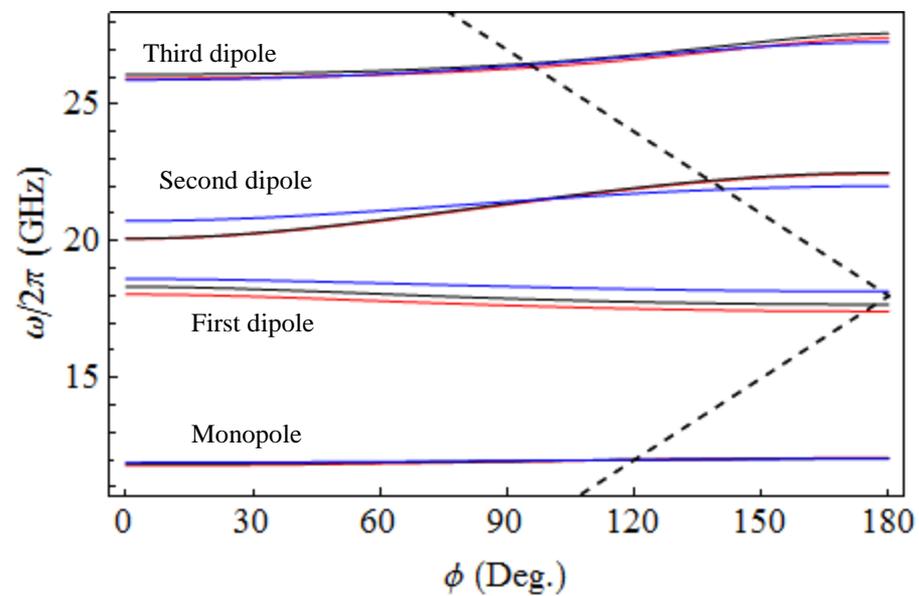
How it looks

Small iris

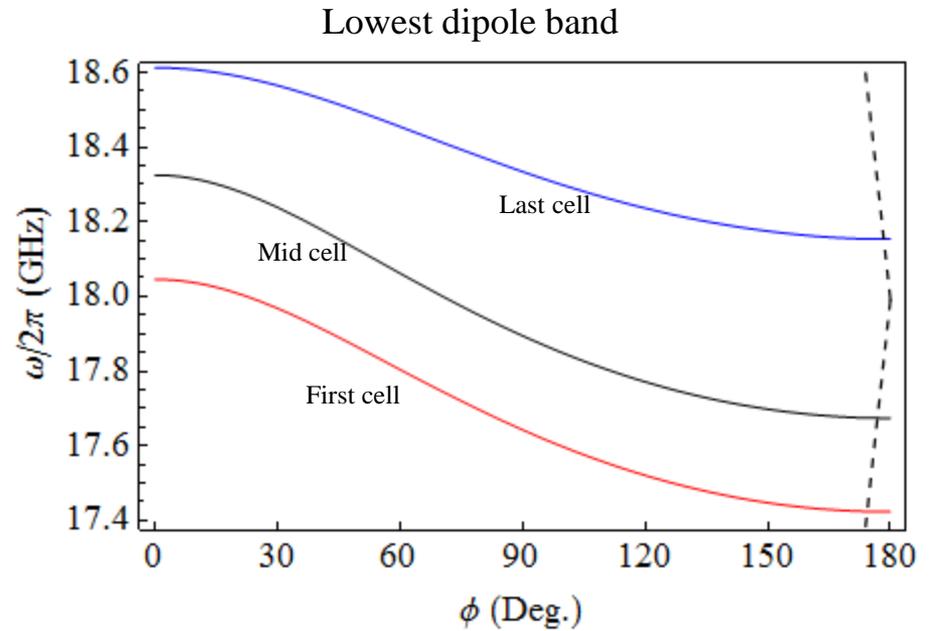
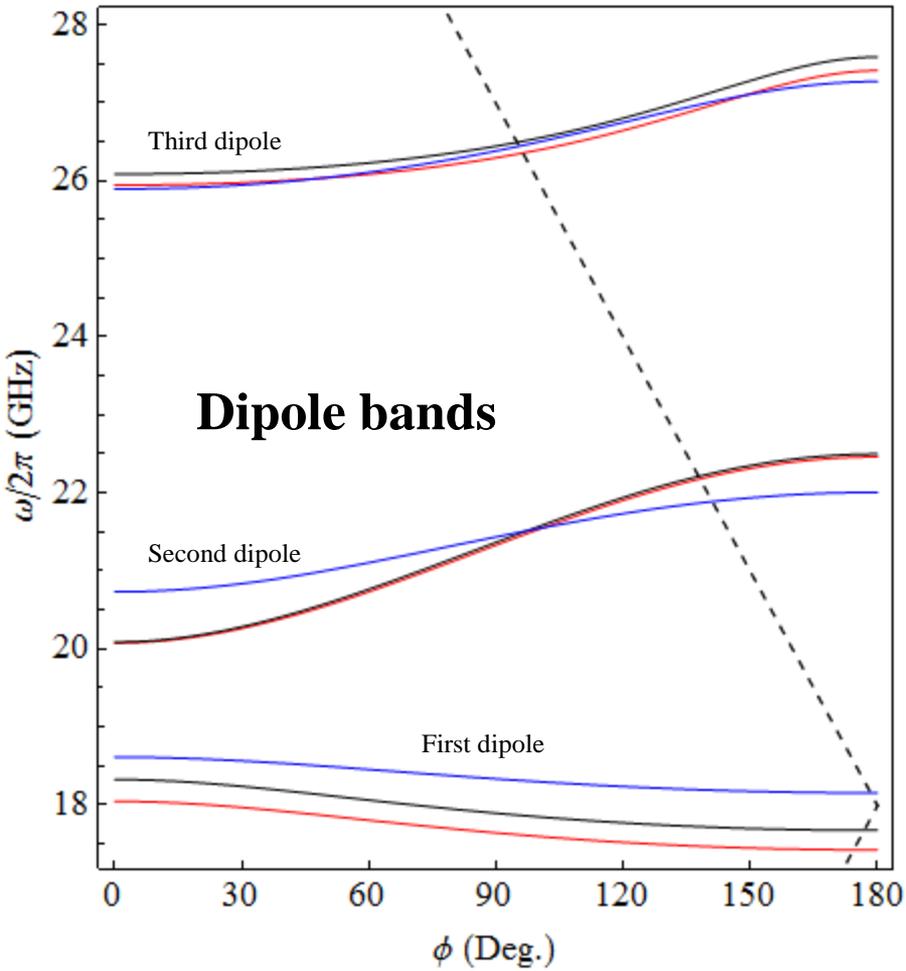
Big iris



# Detuning

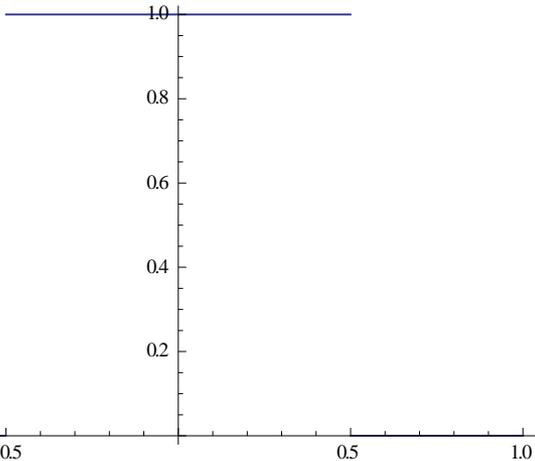


# Detuning – close upon dipole modes

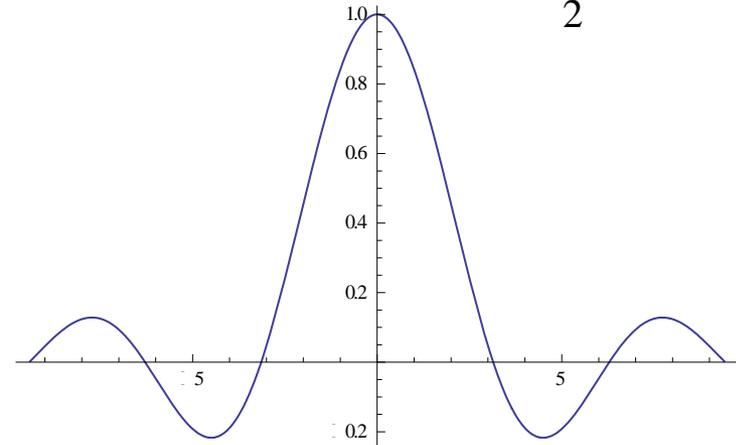


From these dispersion curves we get the frequency spectrum of the transverse modes, from which we can determine the time dependence through the Fourier transform:

$t_0$

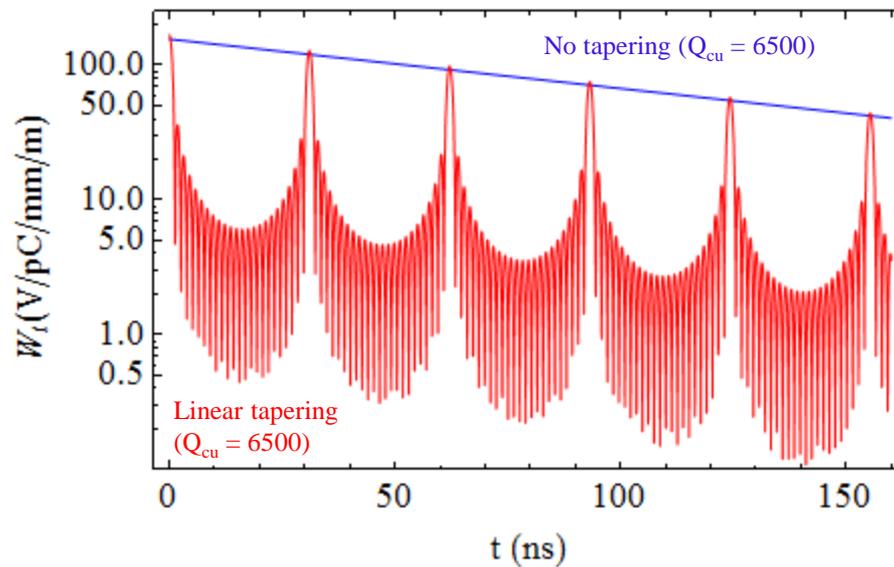
$$\frac{\sin\left(\frac{t_0}{2}\omega\right)}{\frac{t_0}{2}\omega}$$



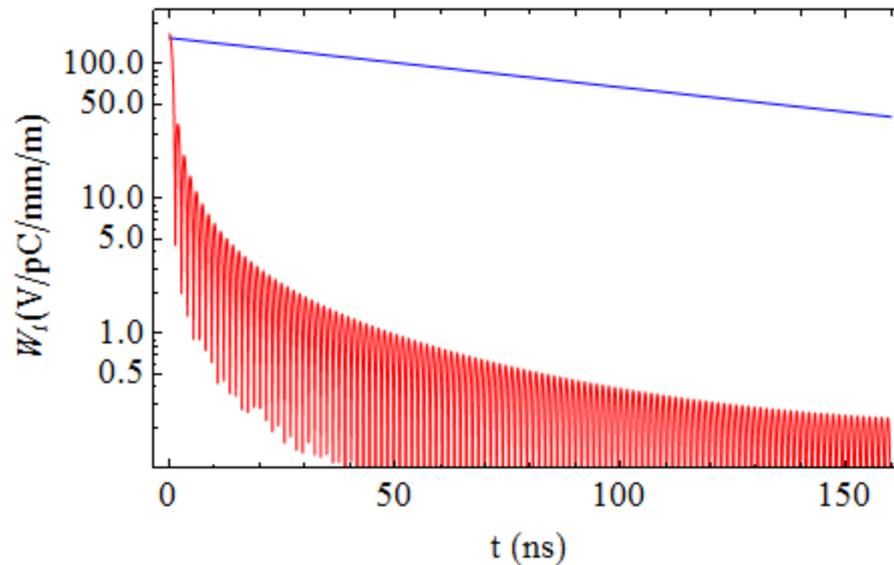
Broader spectrum gives faster roll-off.

# Lowest dipole band

No. of Cells = 24

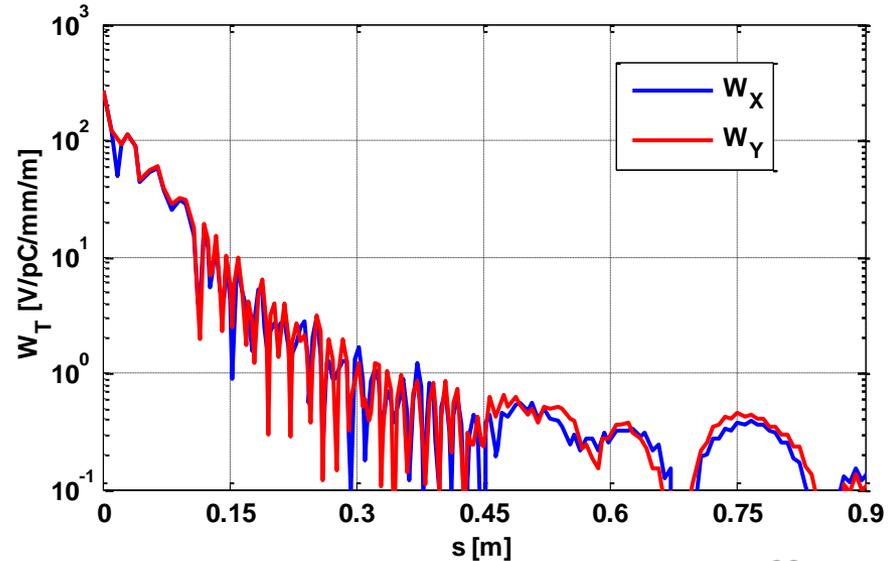
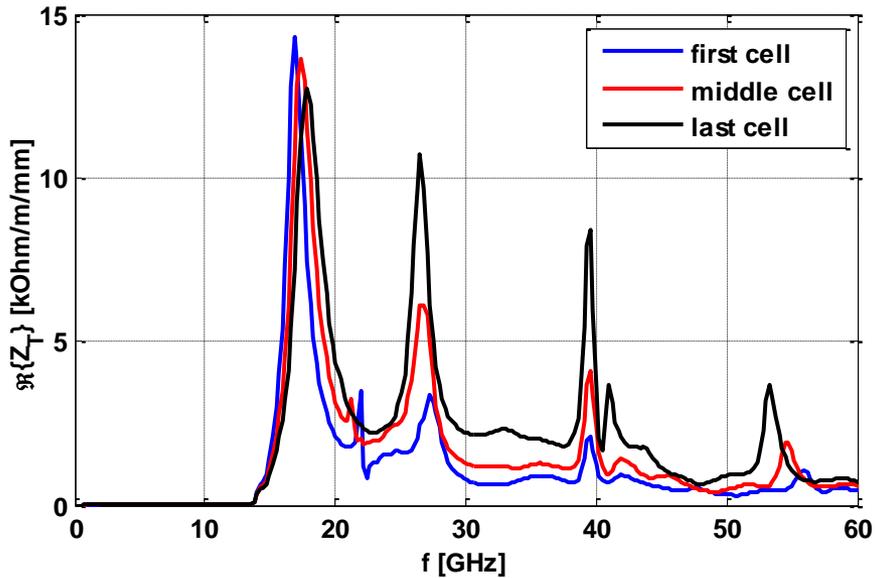


No. of Cells = 196  
(8 structures)



# Putting damping and detuning together

Cell	First	Middle	Last
$Q$ -factor	11.1	8.7	7.1
Amplitude [V/pC/mm/m]	125	156	182
Frequency [GHz]	16.91	17.35	17.80



## Additional techniques for HOM damping

Another way of taking advantage of the frequency difference – **choke mode damping**.

Basic idea:

Put in a slot around the structure to let all modes out.

Add a choke (a sort of narrow band-stop filter which acts like a short circuit) to keep the fundamental mode in.

This is another example where frequency selection is used.

Shintake, 1992

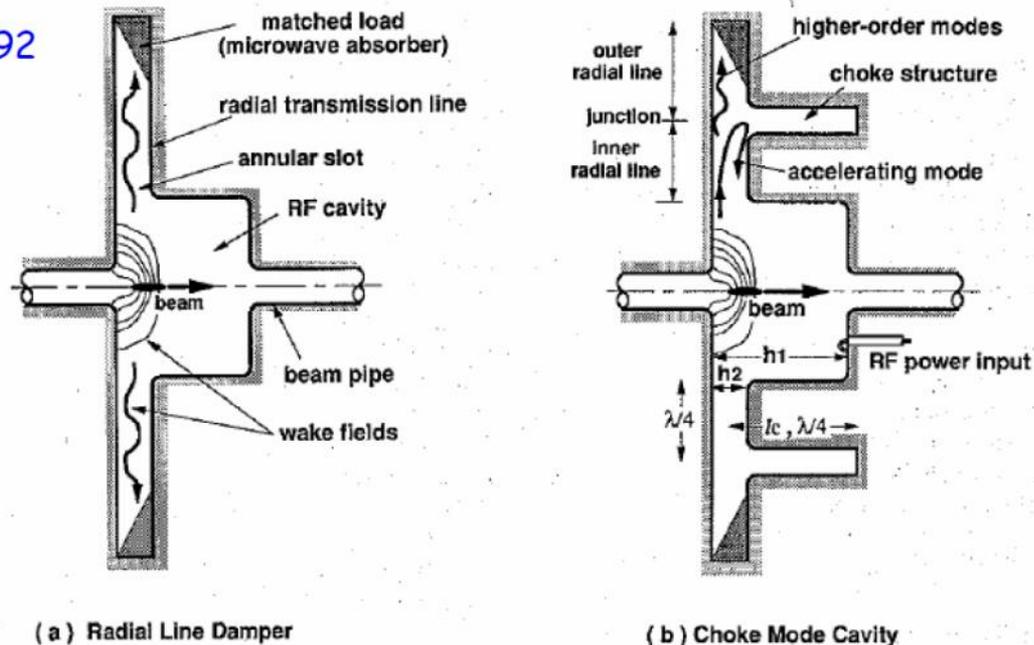
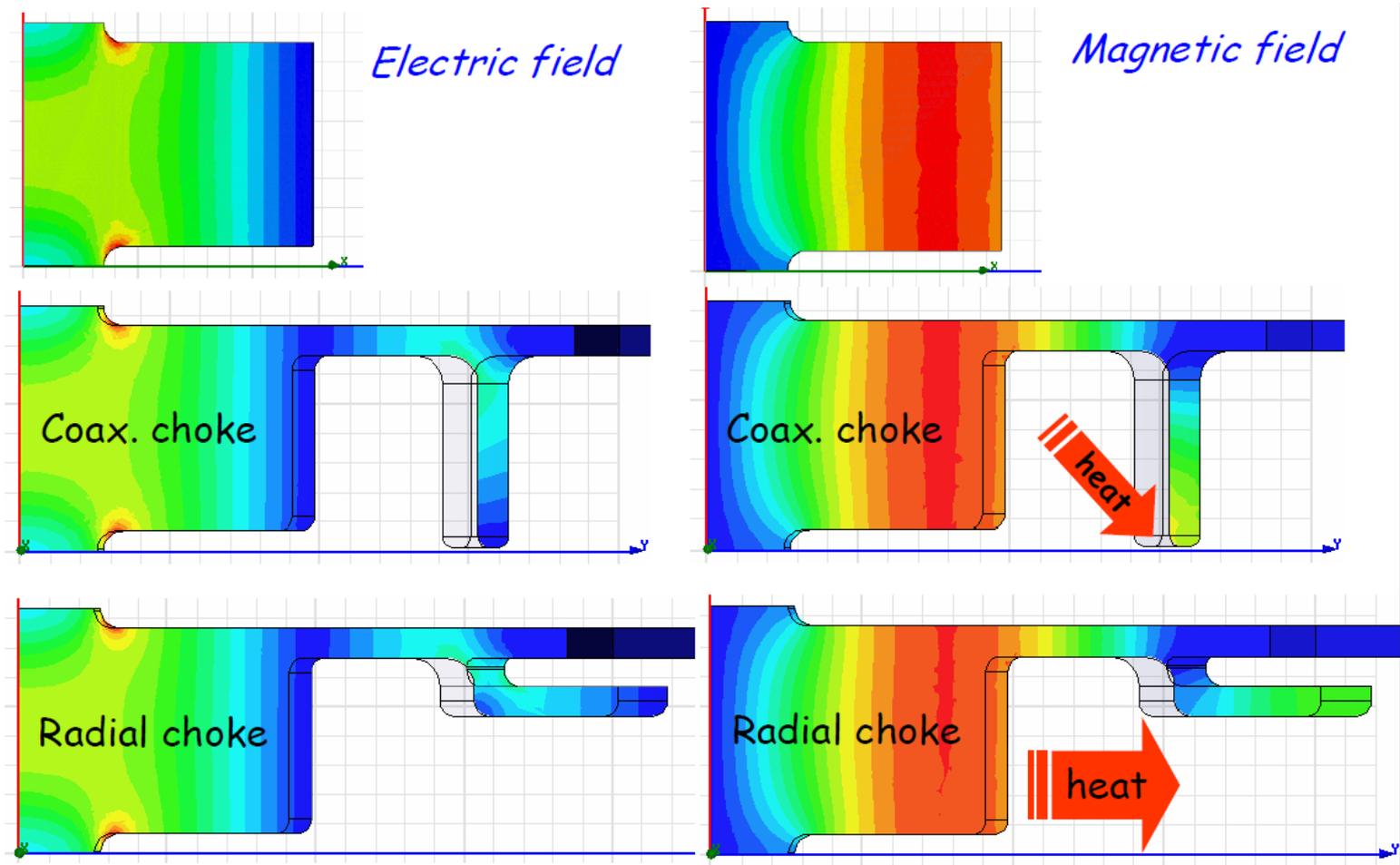


Fig. 1. Conceptual illustrations of (a) a radial line damper and (b) the choke mode cavity.

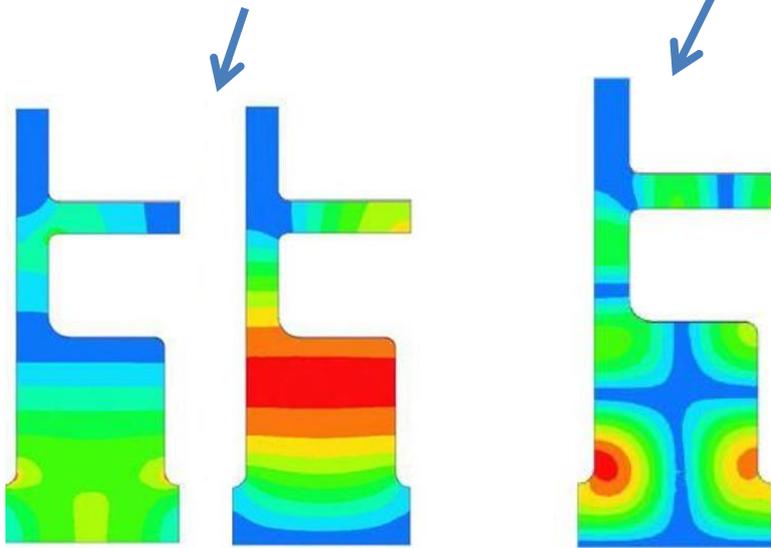
# Implementation at X-band



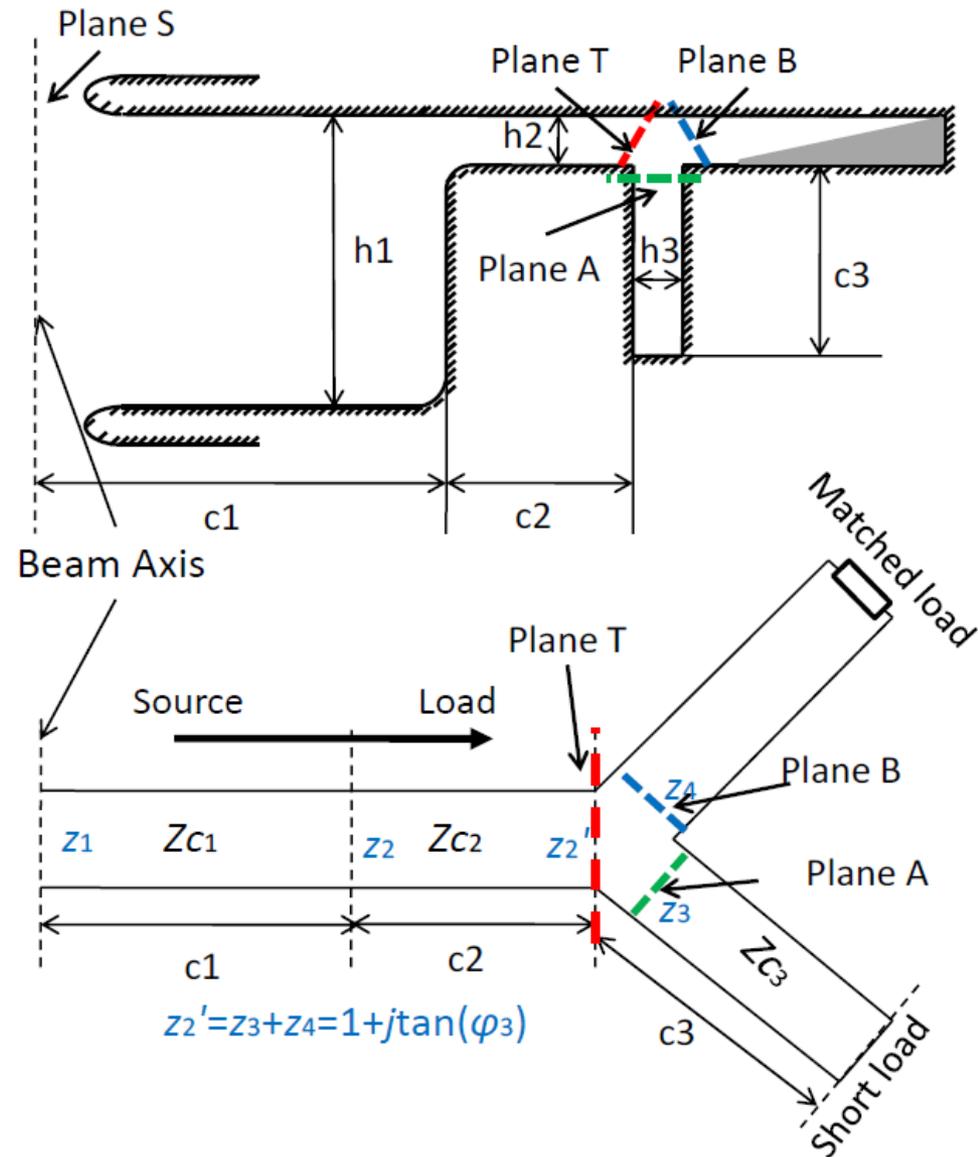
# Equivalent circuit model

For accelerating mode,  $\varphi_3 = \pi/2$ , so  $z = \infty$ . Then it is fully reflected by choke.

Some HOMs could be also fully (or mostly) reflected.



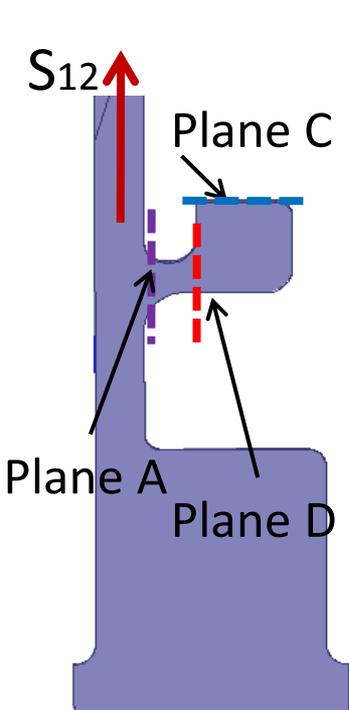
H. Zha



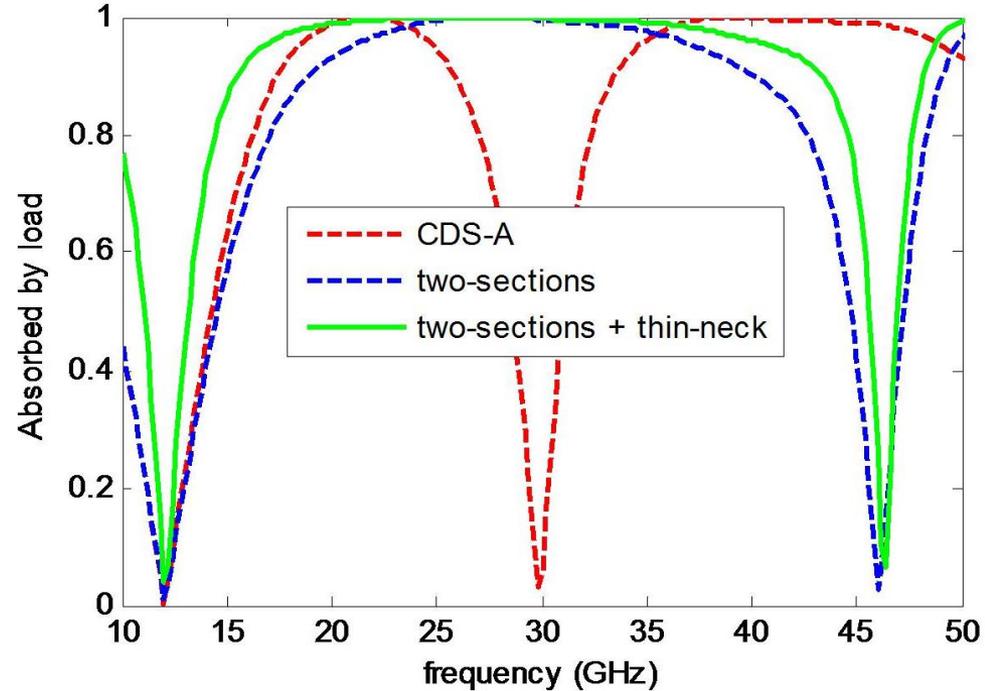
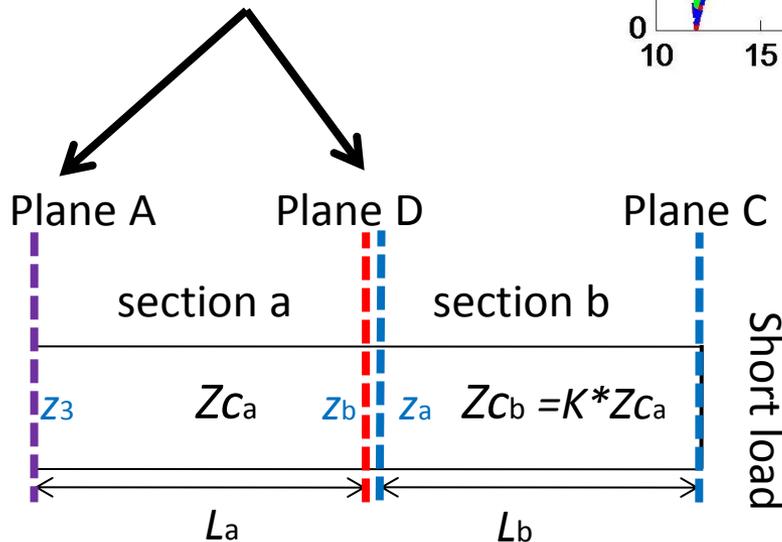
# Thin-neck choke design

Purpose of thin-neck design:

- (1) Increase the 2<sup>nd</sup> fully reflected frequency
- (2) Reduce reactance of HOMs

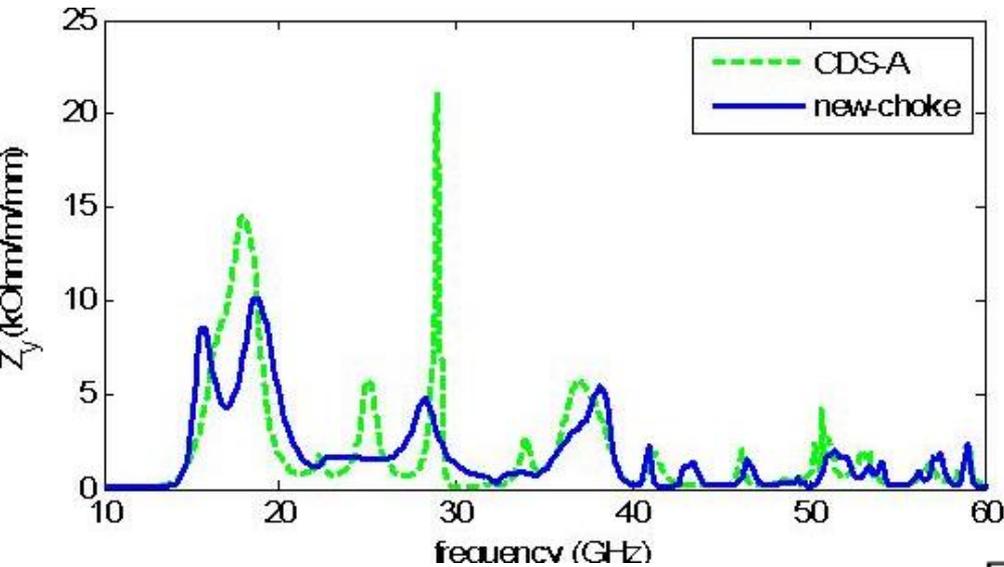


The joint planes (Plane A and Plane D) are equivalent as impedance transformers



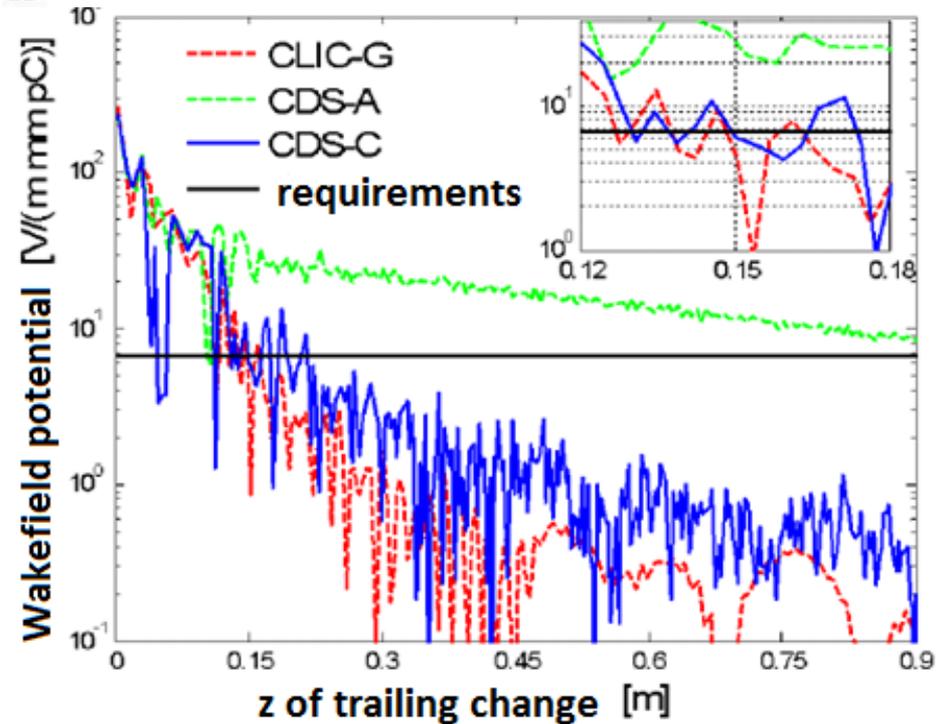
K	1	2	3	4
f2	36GHz	49GHz	60GHz	69GHz

# Wakefield simulation results

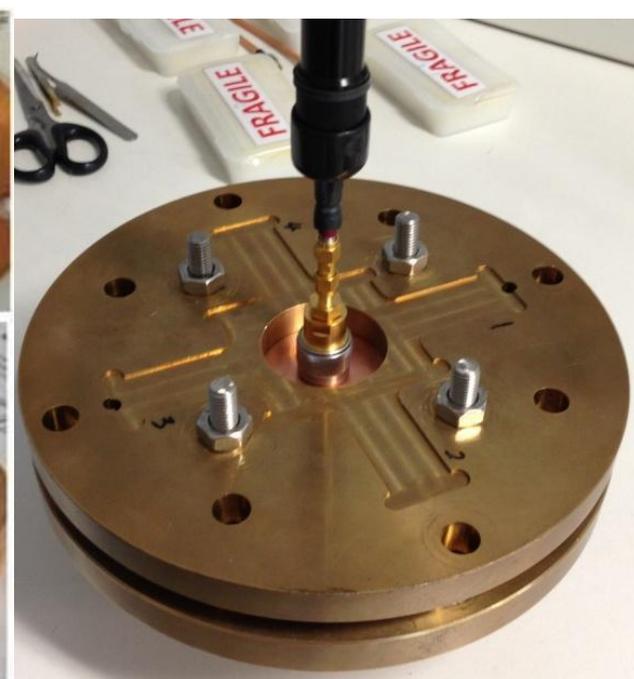
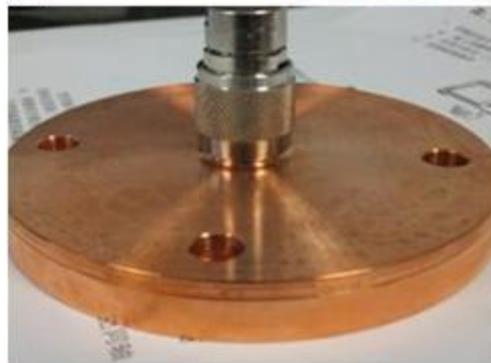
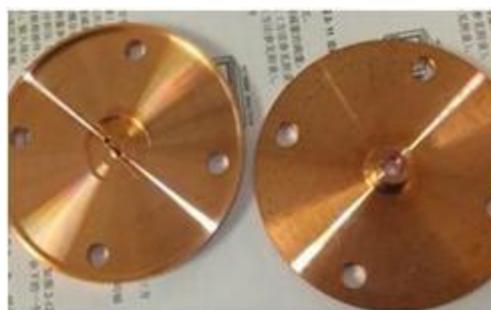
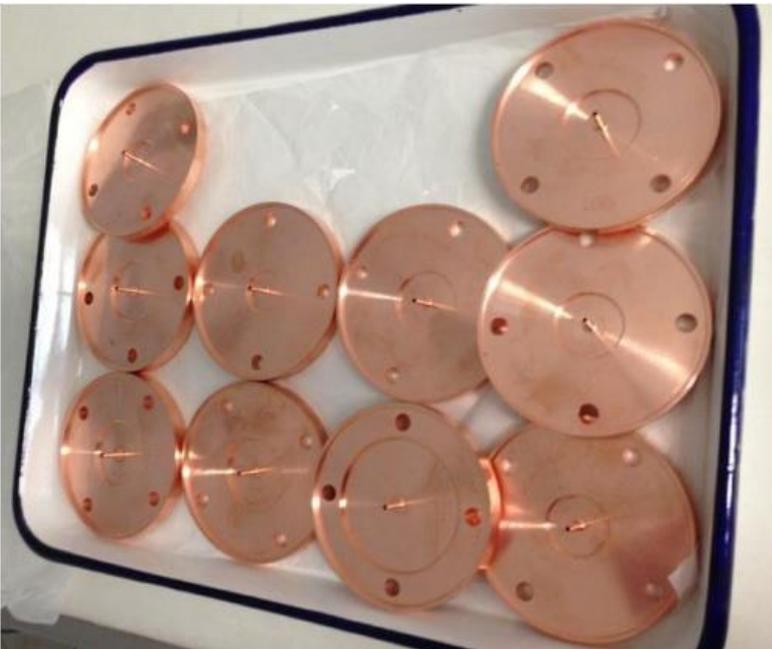
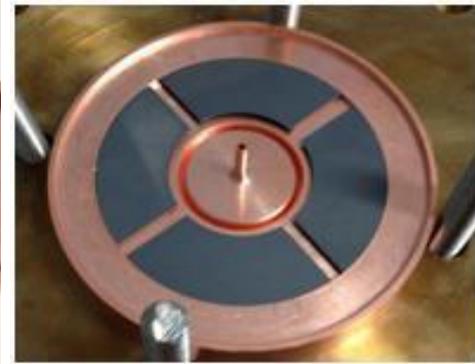
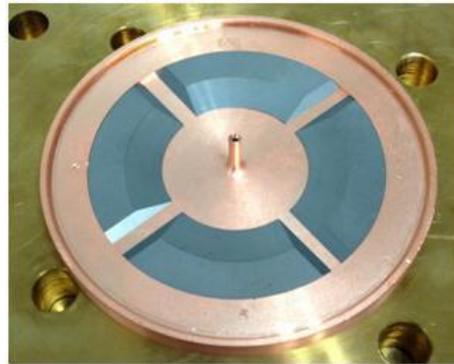
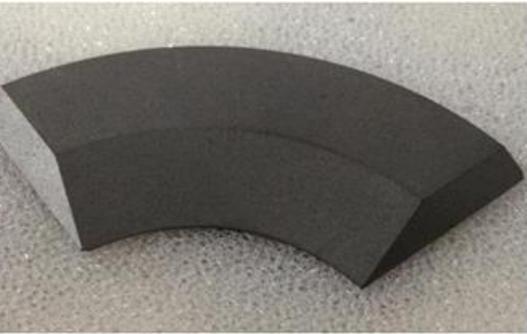


	$W_{\perp}$ (s=0.15m)
WDS	5
CDS-A	20~30
+Thin-neck	10~17
+Matching step	7~10
<b>+Dipole detuning (CDS-C)</b>	<b>5~6</b>

	CDS	WDS
$F_c$	1	1
$F_{rms}$	4	5
$F_{worst}$	25	20

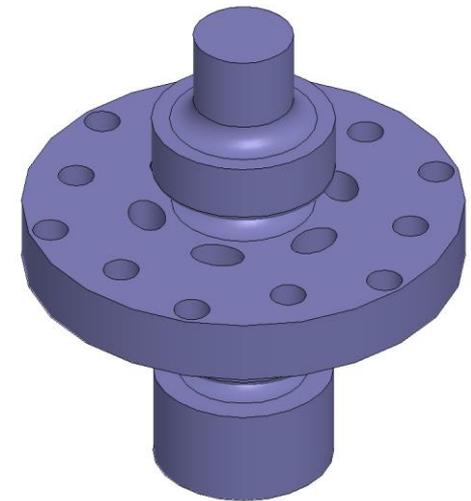


# Radial line experiments

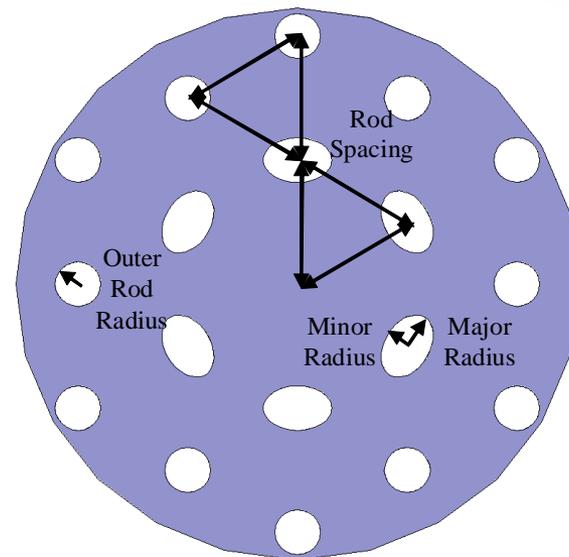


# Elliptical-rod Design at 11 GHz

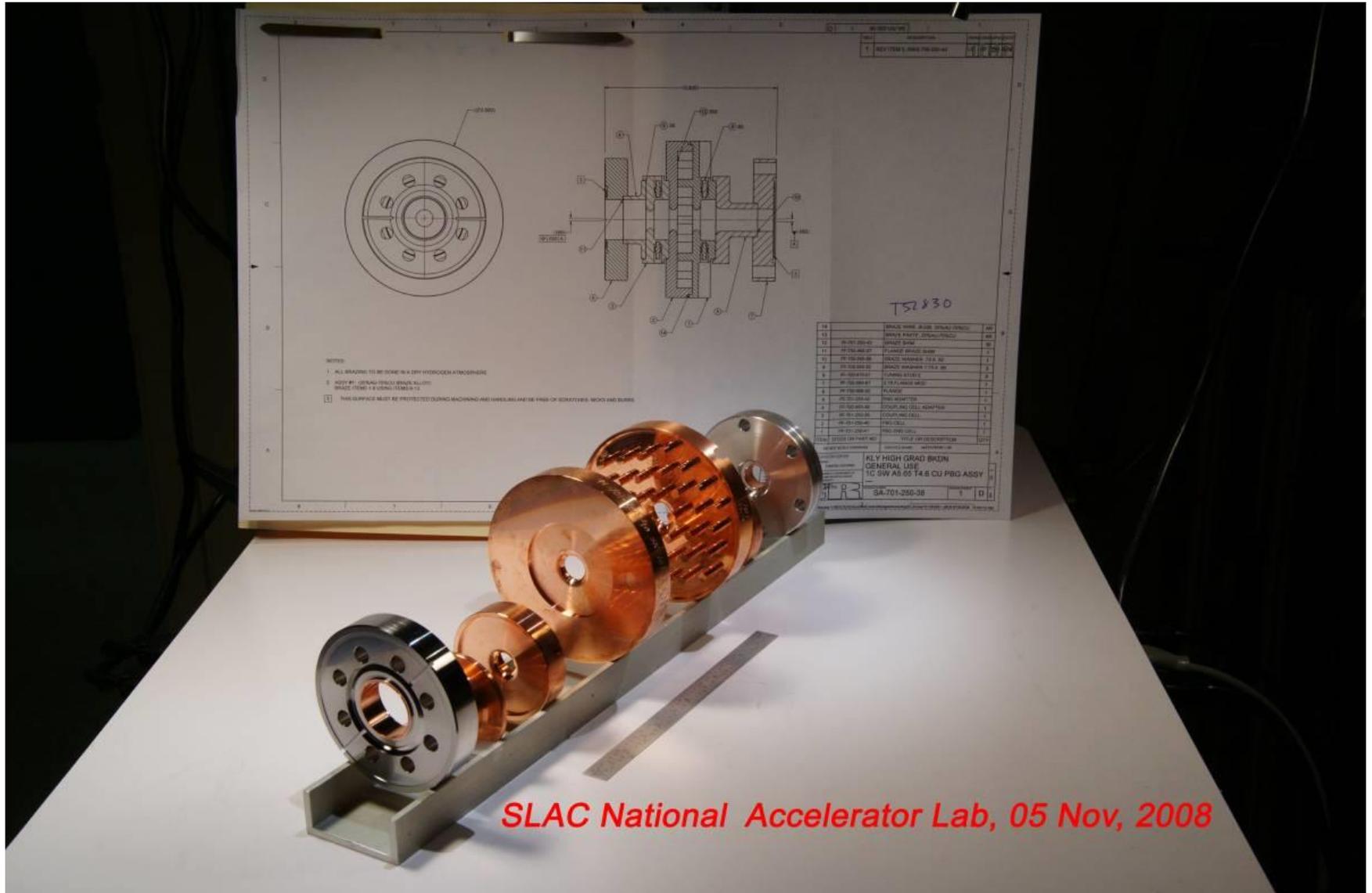
- Standing wave design with 2 matching cells, one test cell
- Axially powered via  $TM_{01}$  mode launcher
- Structure has elliptical inner rods
  - Spread large H field over larger region
  - reduce pulsed heating



Performance at 100 MV/m		
	Round	Elliptical
Power	5.9 MW	4.4 MW
Peak Surface E Field	208 MV/m	207 MV/m
Peak Surface Magnetic Field	<b>890 kA/m</b>	<b>713 kA/m</b>
Pulsed Heating for 150ns Flat Pulse	131 K	84 K



# PBG Structure Fabricated at SLAC



SLAC National Accelerator Lab, 05 Nov, 2008