CLIC Power Extraction and Transfer Structure (PETS) Design & Computation.

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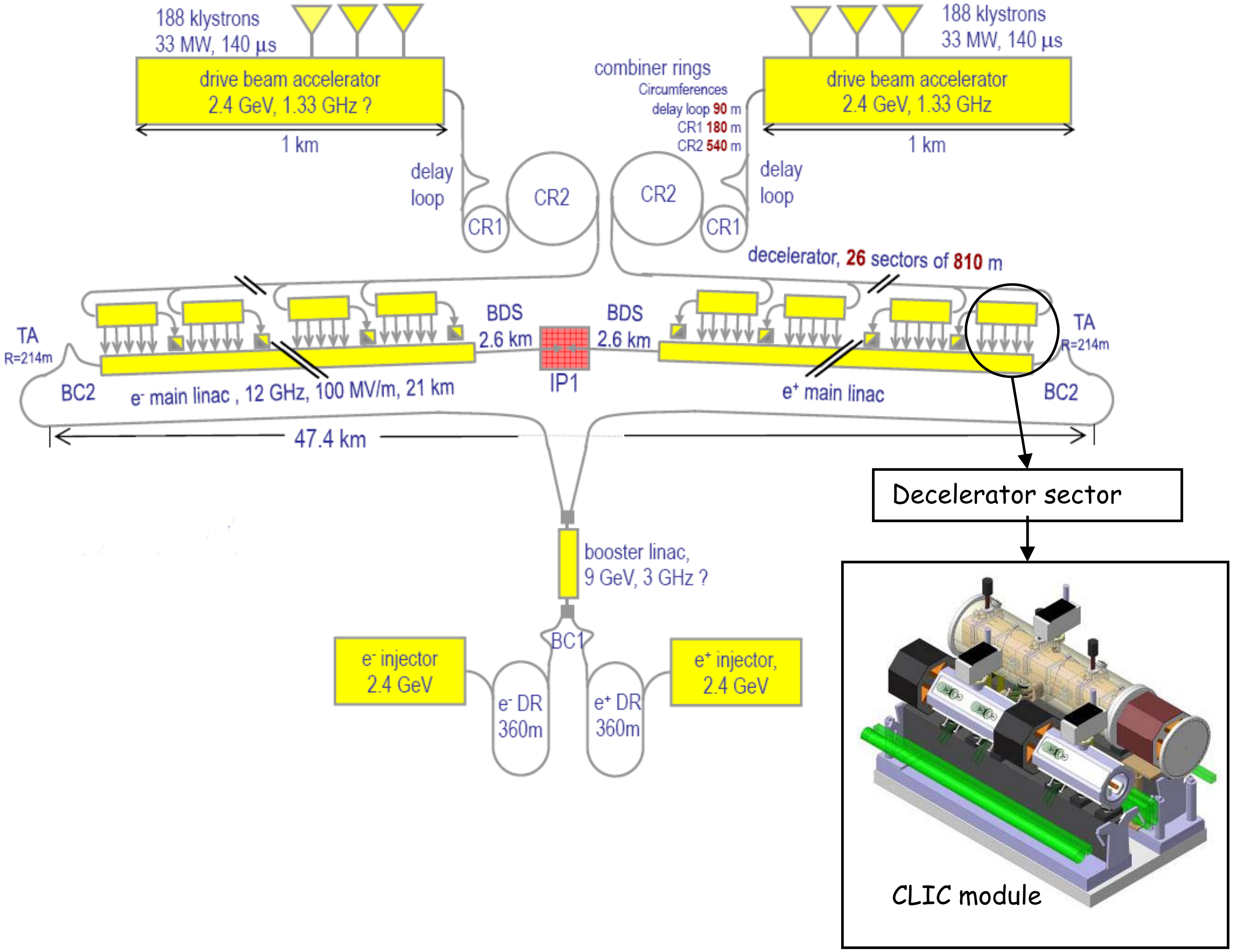
Introduction

The CLIC Power Extraction and Transfer Structure (PETS) is a passive microwave device in which bunches of the drive beam interact with the impedance of the periodically loaded waveguide and generate RF power for the main linac accelerating structure.

3 TeV CLIC



The power produced by the bunched (ω_0) beam in a constant impedance structure:

Design input parameters

PETS design

$$P = I^2 L^2 F_b{}^2 \omega_0 \frac{R/Q}{V_g\,4}$$

P – RF power, determined by the accelerating structure needs and the module layout.
I – Drive beam current
L – Active length of the PETS
F_b – single bunch form factor (≈ 1)

Introduction

#1. Drive beam current

For the given drive beam initial and final energies, the drive beam current is almost uniquely defined by the accelerating structure performance and DB generation arithmetic:

Number of decelerating sectors in the linac:

$$N_{\sec} = \frac{E_{cm}}{G_{effective}\ \eta\ cT_p N_c}$$

$$E_{DB} = 2.4\,GeV$$

(Limited by radiation losses in combiner rings)

$$I_{DB} = \frac{L_{Linac} P_{struct}}{N_{\sec} L_{struct}\ E_{DB}\eta_{DB}\eta_{RF}} = \frac{P_{struct} T_{struct}\ N_c c}{L_{struct}\ E_{DB}\eta_{DB}\eta_{RF}}$$

Accelerating structure

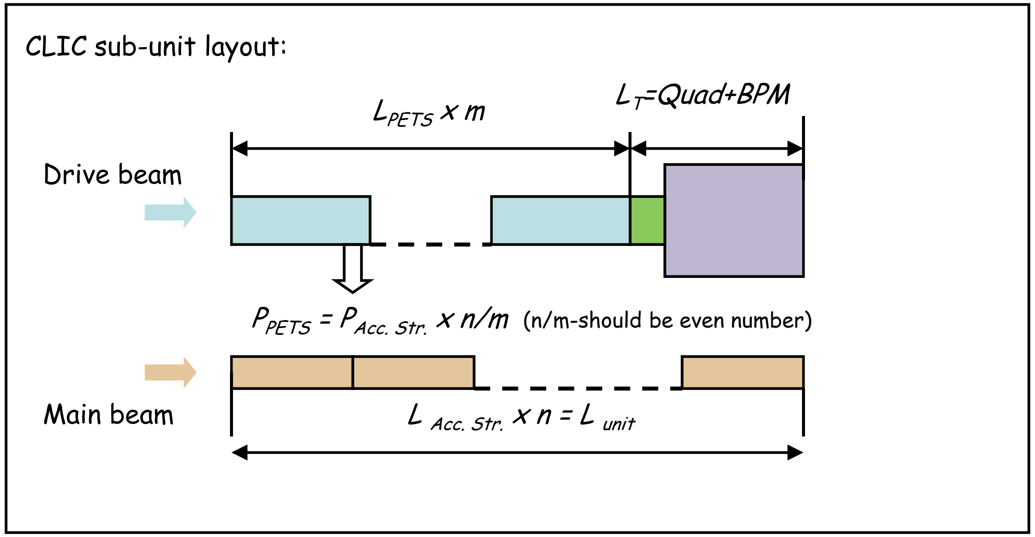
Combination factor

Drive beam energy

DB extraction efficiency (~0.9)

RF transfer efficiency (~0.94)

#2. PETS Power and length



The CLIC sub-unit general issues:

-The CLIC sub-unit length is defined by the decelerator FODO lattice period. In turn, it is tuned to be equal to the even number of the accelerating structures length.

-The space reserved for the PETS should satisfy:

$$(L_{PETS} \times m) + L_T \leq L_{unit}$$

to ensure the highest effective gradient.

- For any sub-unit layout chosen (m), the PETS active length should be maximized to reduce the impedance and thus to provide more stable beam transportation.

#3. PETS aperture

The equation for the power production now can be rewritten in terms of the PETS parameters (for simplicity the extraction length is taken = 0):

$$\frac{R/Q}{\beta_{gr}} = \frac{4P_{struct}\,(n/m)\lambda}{2\pi I^2 F_b^2\,((L_{unit} - L_T)/m)^2\,\eta_{RF}}$$

In the periodical structure, for the fixed iris thickness and phase advance:

$$\frac{R/Q}{\beta_{gr}} = a^{-2}G$$

where a- radius of the structure and G – geometrical parameter.

Now the PETS aperture can expressed as:

$$a = I(L_{unit} - L_T)F_b\left[\frac{2\pi\eta_{RF}}{G4P_{struct}n\lambda\,m}\right]^{1/2} = C_d m^{-1/2}$$

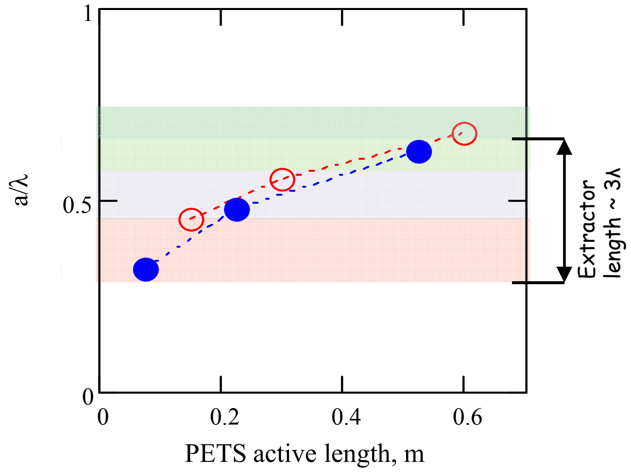
#3. PETS aperture (continued)

Following the CLIC accelerating structure development (CLIC_G), simulations of the beam dynamics in the DB decelerator and the design considerations for the DB quadrupole and BPM, the following parameters were used to finalize the PETS design:

Accelerating structure length:	0.25 m
RF power per structure:	63.8 MW
Transfer efficiency:	0.94
Sub-unit Length = 4xL structure:	1.0 m
Quad. +BPM length:	0.4 m
Combination factor (Nc)	12
Drive beam current:	100 A

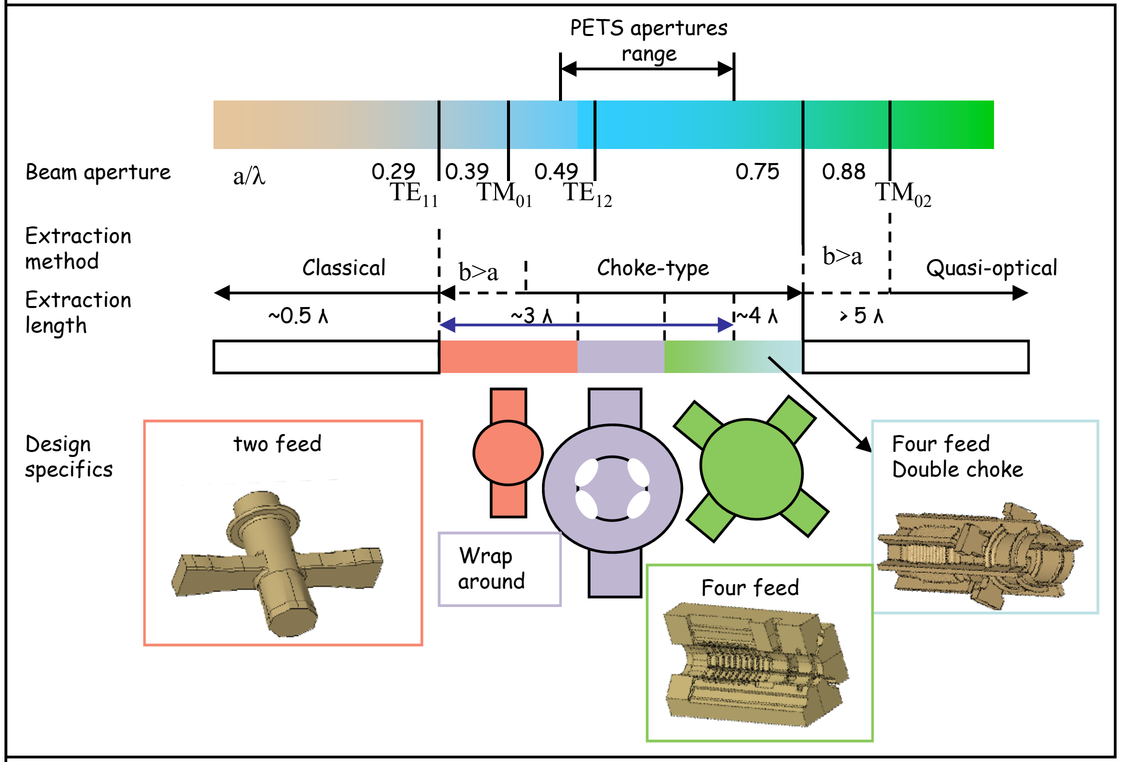
Accordingly, the tree possible sub-unit layouts can be envisaged: m **= 1,2 and 4,** and the PETS active length:

$$L_{active} = (L_{unit} - L_T)/m = 0.6/m \quad [\mathrm{m}]$$



#4 RF power extraction (aperture)

The choice of the PETS aperture to a great extent, strictly determine the type of the RF power extraction method. The only constrain should be applied to the extractor aperture: $b \geq a$.



For the range of the specified PETS apertures, the power extraction length should be ~ 3λ. Now the PETS active lengths can be re-iterated:

$$L_{active} = (L_{unit} - L_T)/m - 3\lambda = 0.6/m - 0.075 \quad [\mathrm{m}]$$

#5 RF constrains (aperture)

RF breakdown and pulsed surface heating (rf) constraints:

- $\Delta T^{max}(H_{surf}^{max}, t_p) < 36$ and 60 K
- $E_{surf}^{max} < 220$, 260 and 300 MV/m
- $P_{in}t_p^{1/3}/C_{in} = 18$ MW·ns$^{1/3}$/mm @ X-band

Grudiev A.
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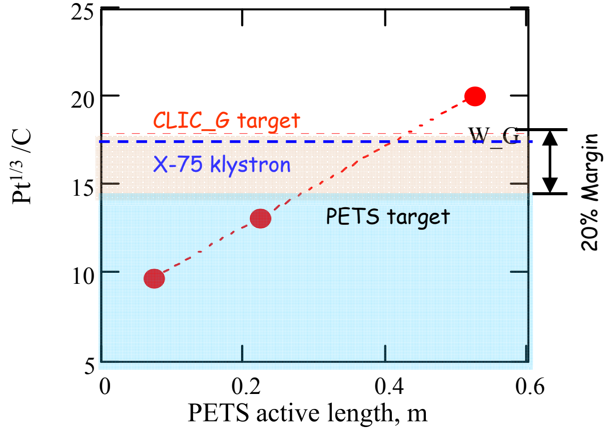
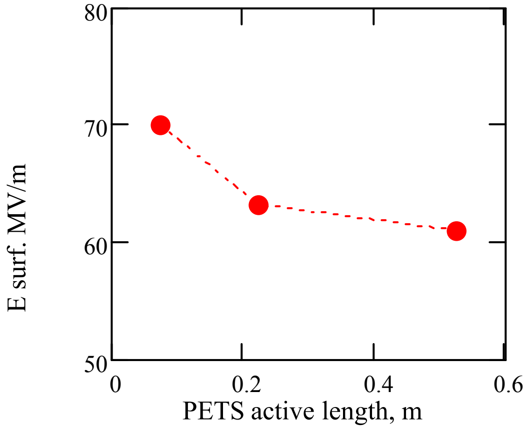




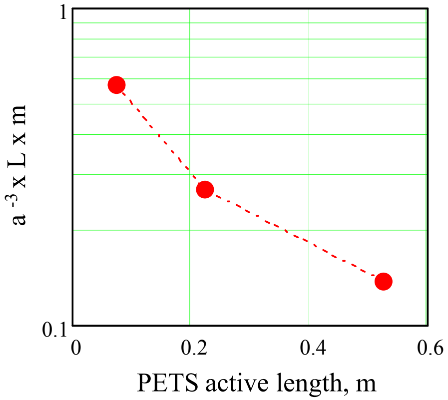
#6 Beam stability (aperture)

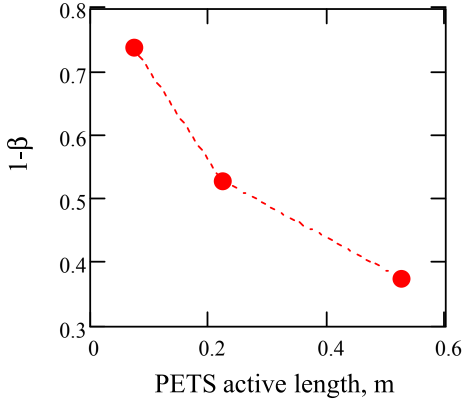
The transfers wakes can significantly distort the drive beam and cause heavy beam losses. The wake potential in a finite length structure with a high group velocity is:

$$W_\perp(z) = 2q \times K_\perp \sin\left(\frac{\omega z}{c}\right) e^{-\frac{\omega z}{2Q(1-\beta)c}} \times \left\{1 - \frac{\beta z}{L(1-\beta)}\right\}$$

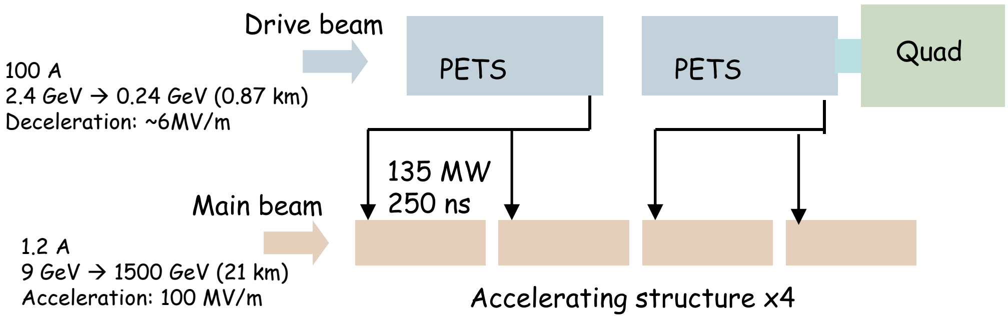
$$W_\perp(z) = 0, \quad z > L\frac{1-\beta}{\beta}$$

The best scenario to suppress wake field effects will be to reduce the wake amplitude and to increase the group velocity. In a periodical structure the wake effect ~ $a^{-3} \times L$ and the group velocity ~ a.





Finally, as a result of multiple compromises, the PETS aperture $a/\lambda = 0.46$ was chosen.


Drive beam

100 A
2.4 GeV → 0.24 GeV (0.87 km)
Deceleration: ~6MV/m

PETS
PETS
Quad

135 MW
250 ns

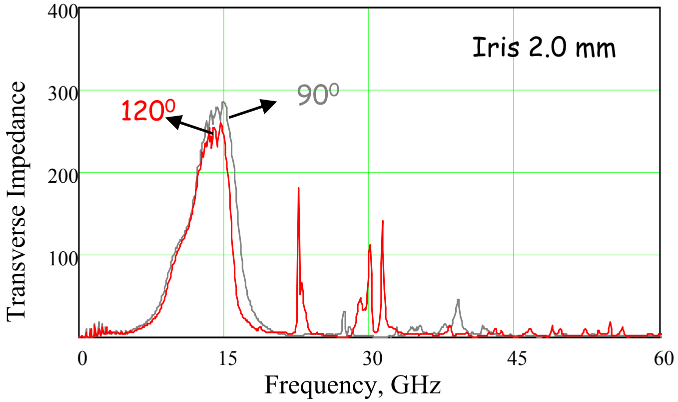
Main beam

1.2 A
9 GeV → 1500 GeV (21 km)
Acceleration: 100 MV/m

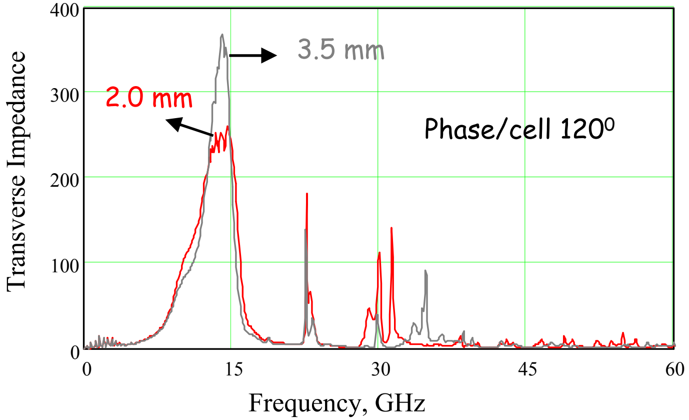
Accelerating structure x4

Introduction

#7 Phase advance

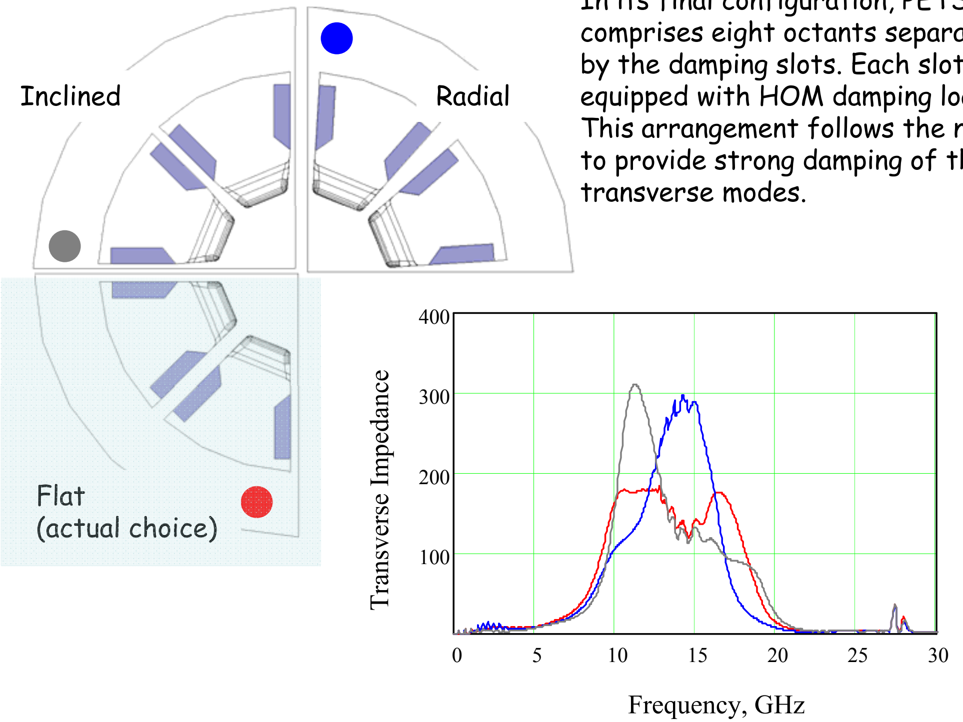


#8 Iris thickness



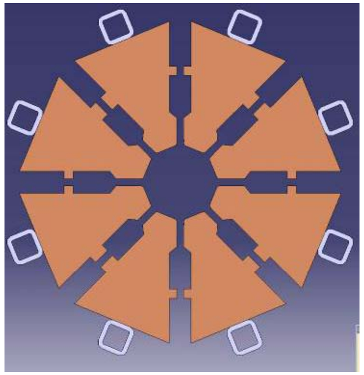
The lower phase advances and thinner irises favor the beam stability

#9 PETS cross-section and slot configuration



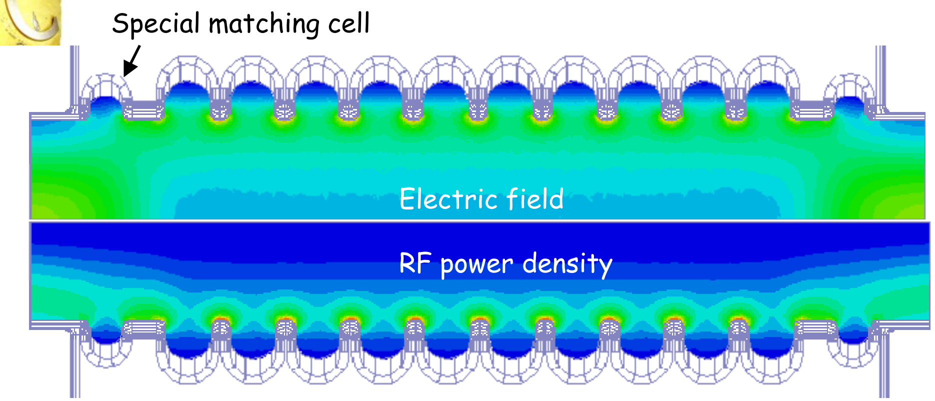
In its final configuration, PETS comprises eight octants separated by the damping slots. Each slot is equipped with HOM damping loads. This arrangement follows the need to provide strong damping of the transverse modes.

PETS parameters:



- Frequency = 11.9942 GHz
- Aperture = 23 mm
- Active length = 0.213 (34 cells)
- Period = 6.253 mm (90^0/cell)
- Iris thickness = 2 mm
- Slot width = 2.2 mm
- R/Q = 2222 Ω/m
- V group= 0.459C
- Q = 7200
- $Pt^{1/3}/C$ = 13.4
- E surf. (135 MW)= 56 MV/m
- H surf. (135 MW) = 0.08 MA/m (ΔT max (240 ns, Cu) = 1.8 C^0)

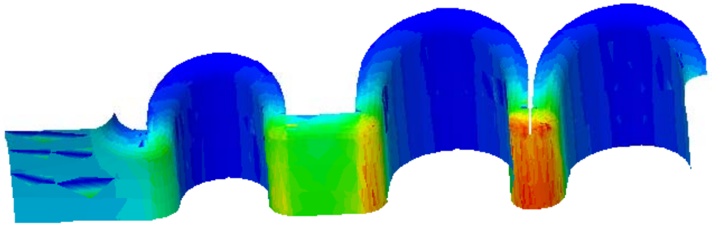
PETS regular iris shape and matching cell



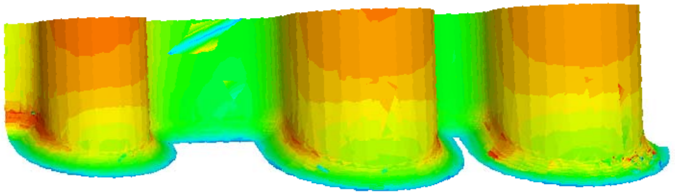
To reduce the surface field concentration in the presence of the damping slot, the special profiling of the iris was introduced. As a result, compared to the circularly symmetric geometry, the 20% field amplification was achieved.

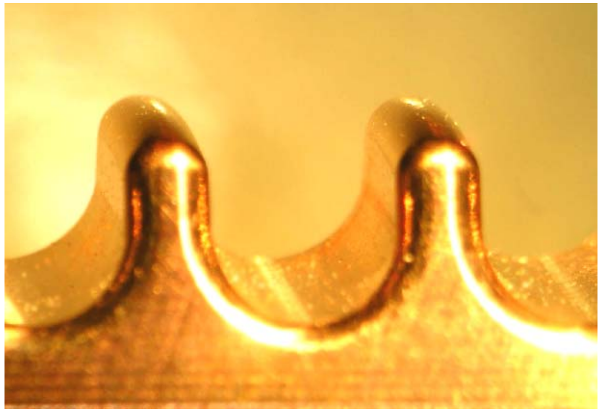
The special matching cell was designed to provide the most compact and efficient connection between the regular PETS part and the RF power extractor.

E max (135 MW)=56 MV/m



H max (135 MW)=0.08 MA/m

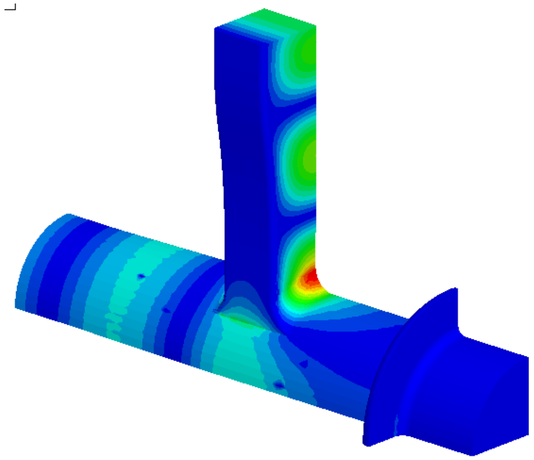




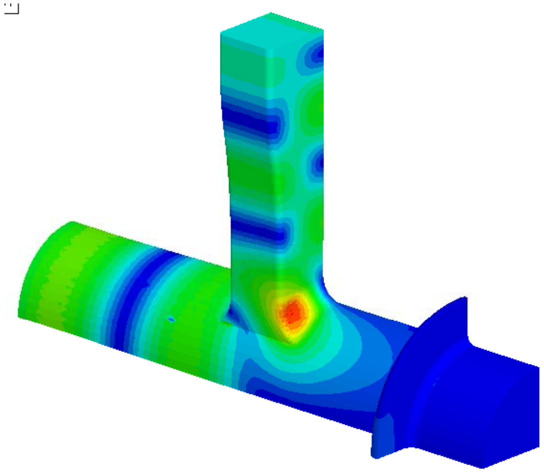
PETS machining test bar

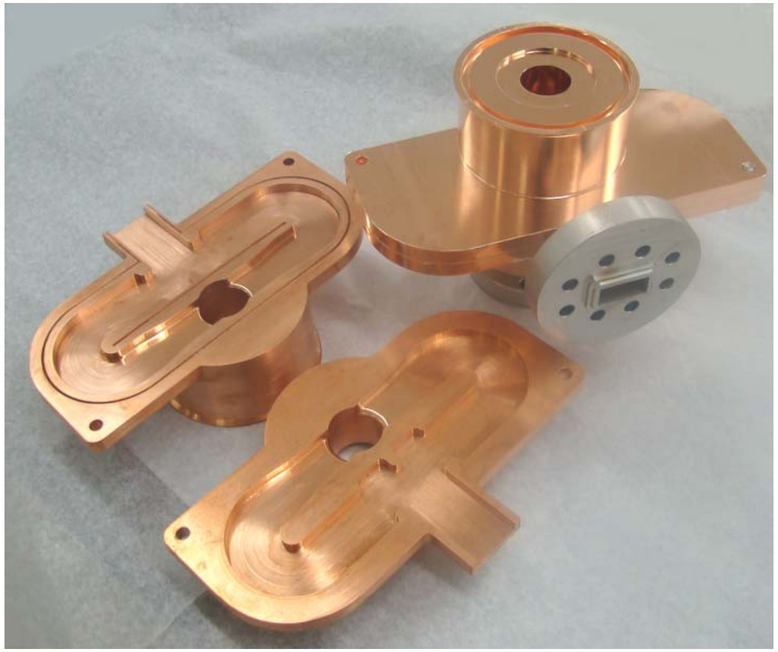
PETS RF power extractor

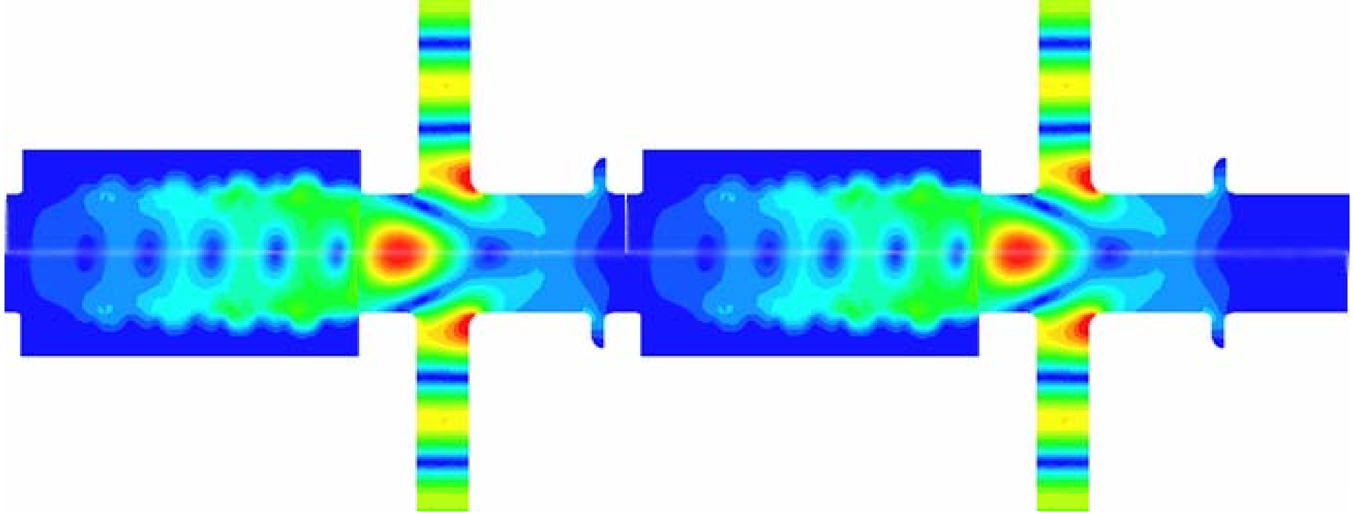
E max (135 MW)=41.7 MV/m



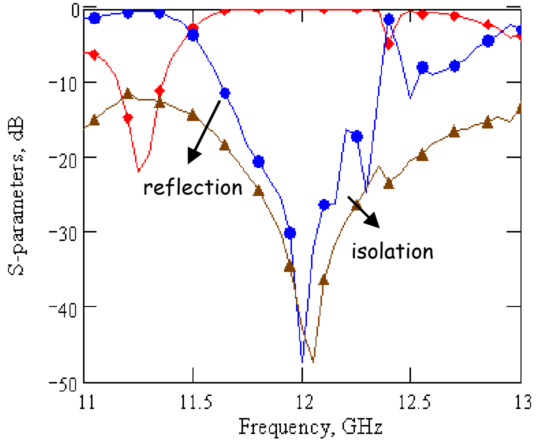
H max (135 MW)=0.07 MA/m







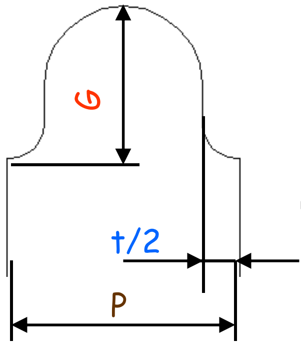
HFSS simulations

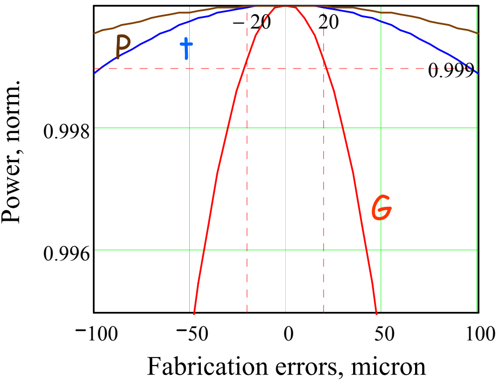


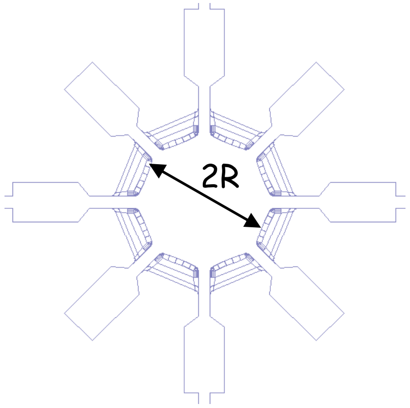
The PETS tolerances issues

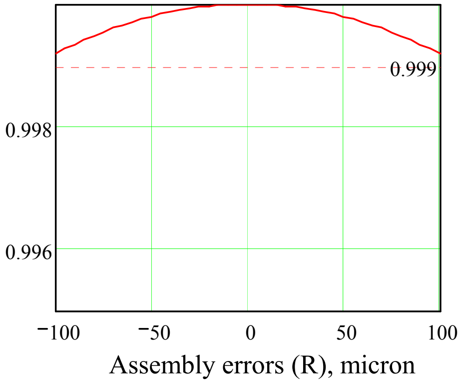
Fabrication and assembly errors can detune the PETS synchronous frequency and thus affect the power production:

$$P = I^2 F_b^2 \omega_0 \frac{R/Q}{V_g 4}\left|\int_0^L \exp\left(i\frac{\Delta\omega}{2c}\frac{1-\beta}{\beta}z\right)dz\right|^2$$

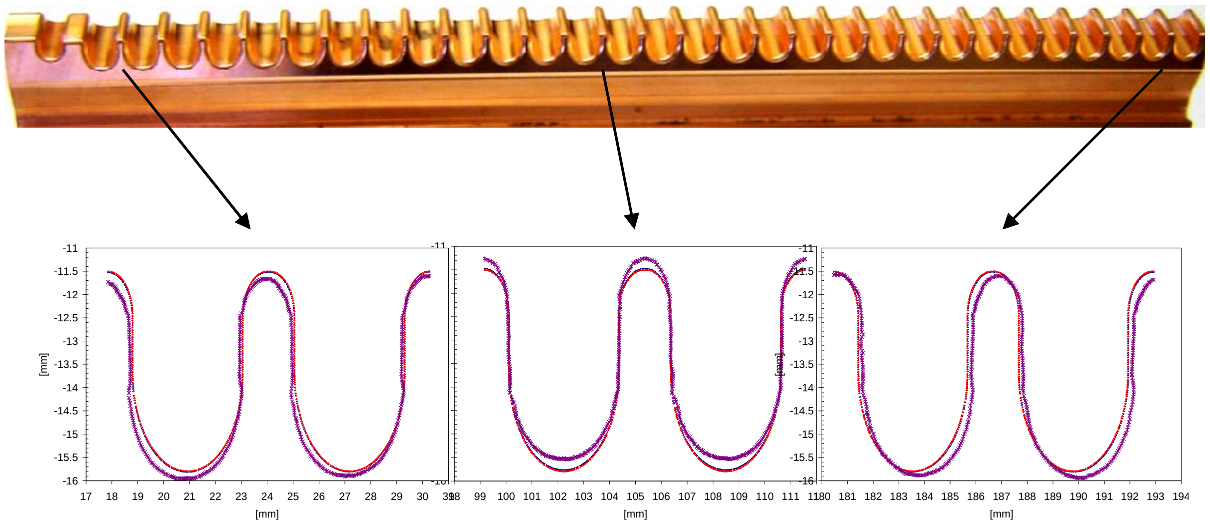




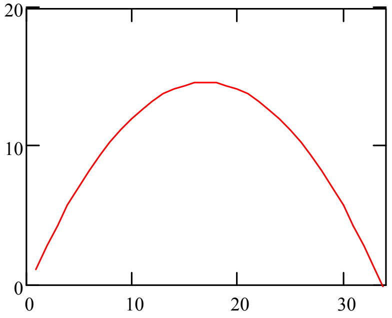




PETS machining test bar fabricated in IMP (Italy)



Metrology results translated into the frequency error:

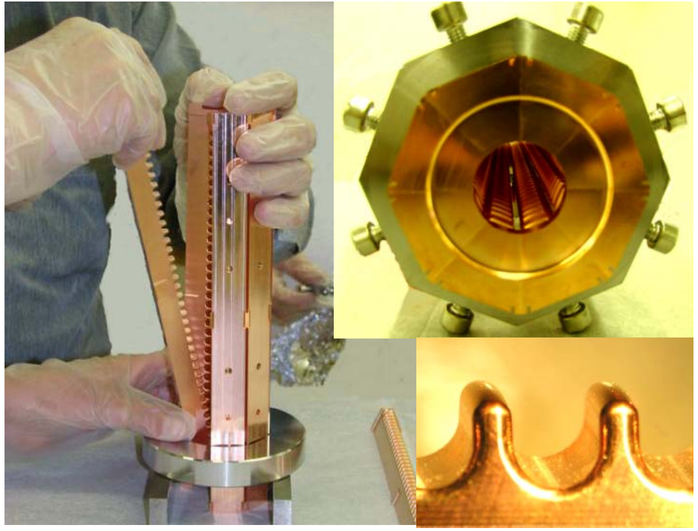


If the hypothetical PETS will be constructed of such 8 identical bars, the expected power losses will be 0.03%.

The fabrication accuracy of ± 20 μm is sufficient enough and can be achieved with a conventional 3D milling machines.

11.424 GHz PETS (design scaled from the CLIC 12 GHz PETS).

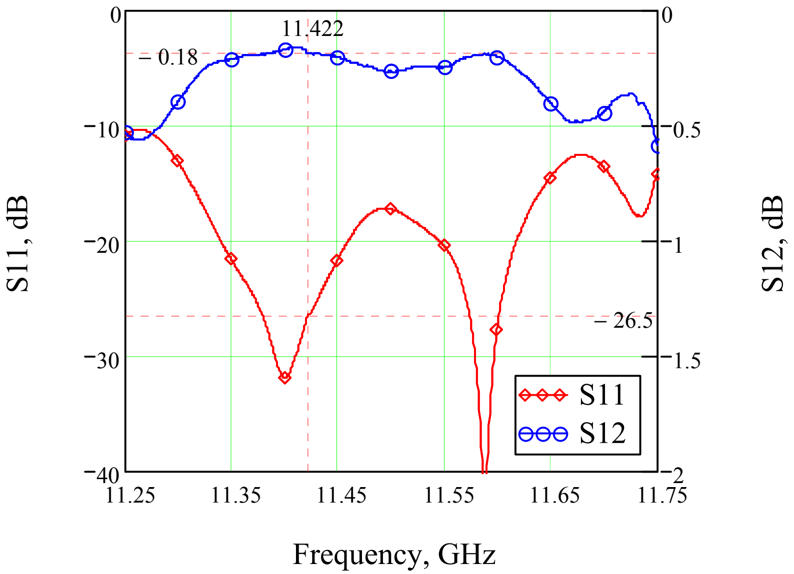
Assembly of the eight PETS bars.



PETS during RF check

PETS before the last EB welding

11. 424 GHz PETS measurements after final assembly

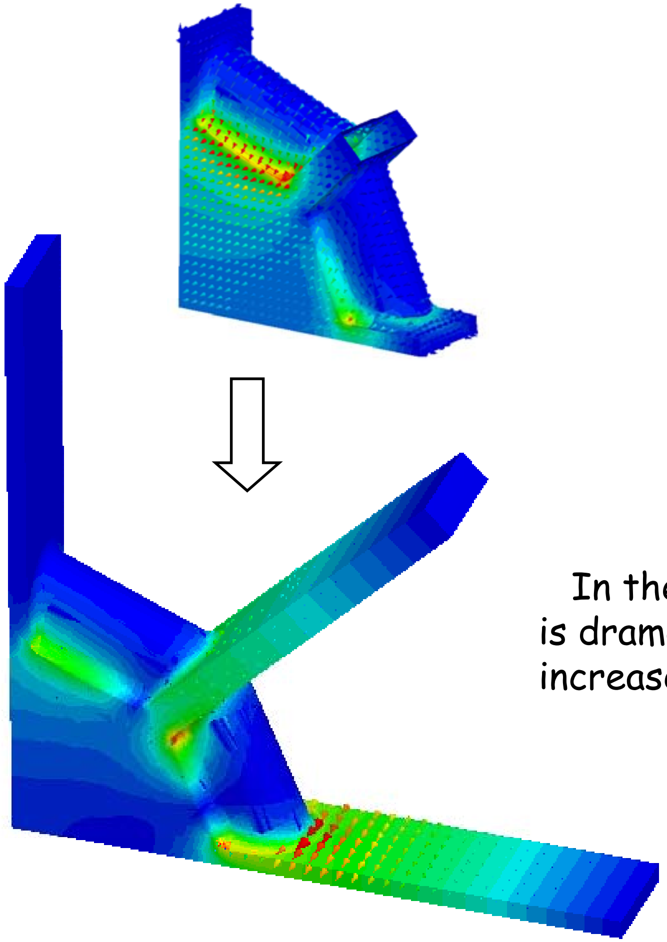


Transverse modes damping in PETS.

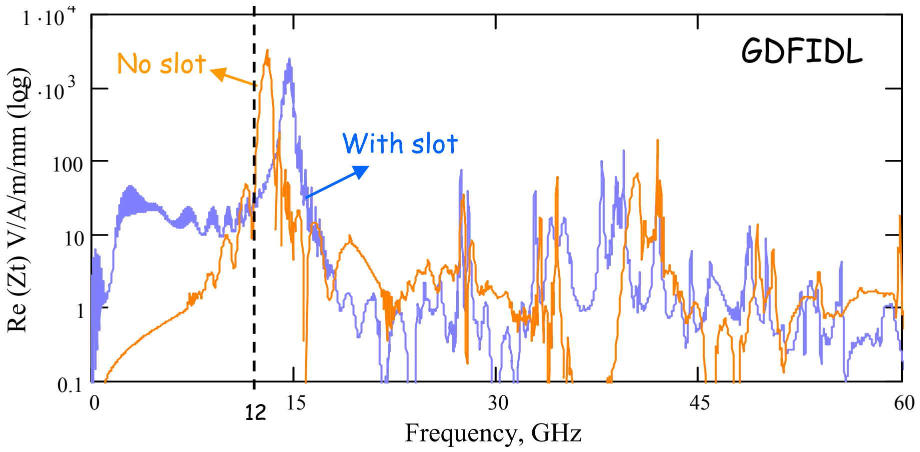
In the high group velocity structures, the frequency of the transverse mode is rather close to the operating one. The only way to damp it is to use its symmetry properties – damping with the slots .

HFSS

E-field (color maps) and pointing vectors (arrows):



Transverse modes spectra

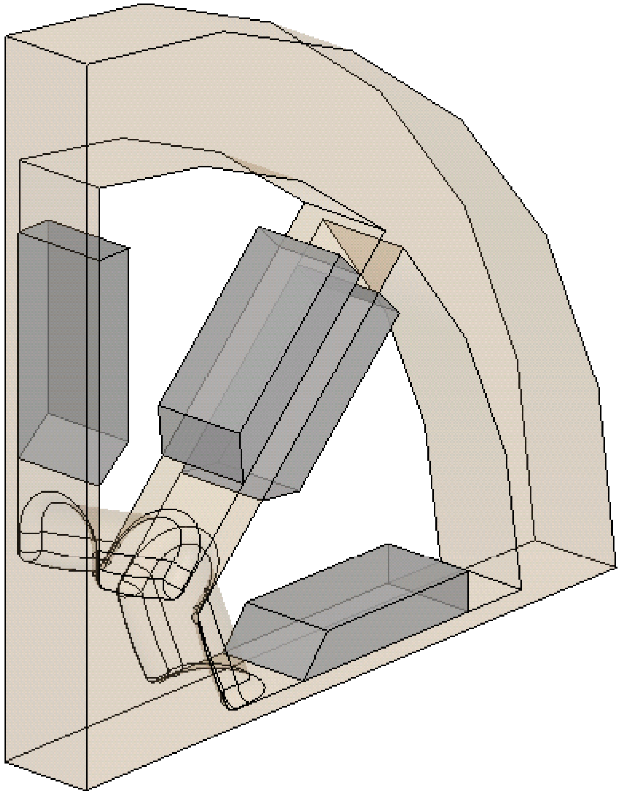


$$W_\perp(z) = 2q \times K_\perp \sin\left(\frac{\omega z}{c}\right) e^{-\frac{\omega z}{2Q(1-\beta)c}} \times \left\{1 - \frac{\beta z}{L(1-\beta)}\right\}$$

$$W_\perp(z) = 0, \quad z > L\frac{1-\beta}{\beta}$$

In the presence of the longitudinal slots, the transverse mode field pattern is dramatically distorted. The new, TEM-like nature of the mode significantly increases the group velocity, in our case from 0.52*c* to almost 0.73*c*.

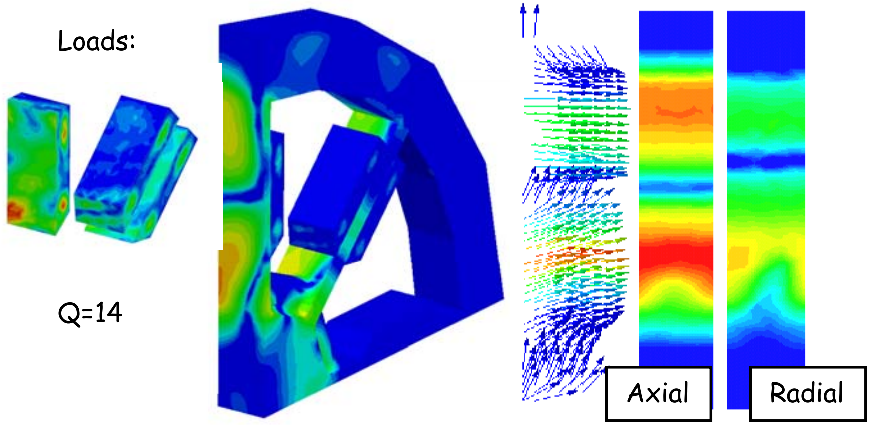
However there is practically no damping in this configuration. To do that we must to introduce the radial impedance gradient in the slot - to create the radial component of the pointing vector.



With introduction of the lossy dielectric material close to the slot opening, the situation changes. The proper choice of the load configuration with respect to the material properties makes it possible to couple the slot mode to a number of heavily loaded modes in dielectric. This gives a tool to construct the broad wakefields impedance.

The transverse wake damping in PETS

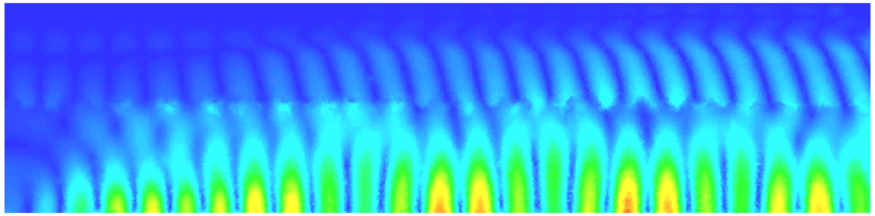
HFSS: 16 GHz coupled mode example (ε=24 tgδ=0.32):



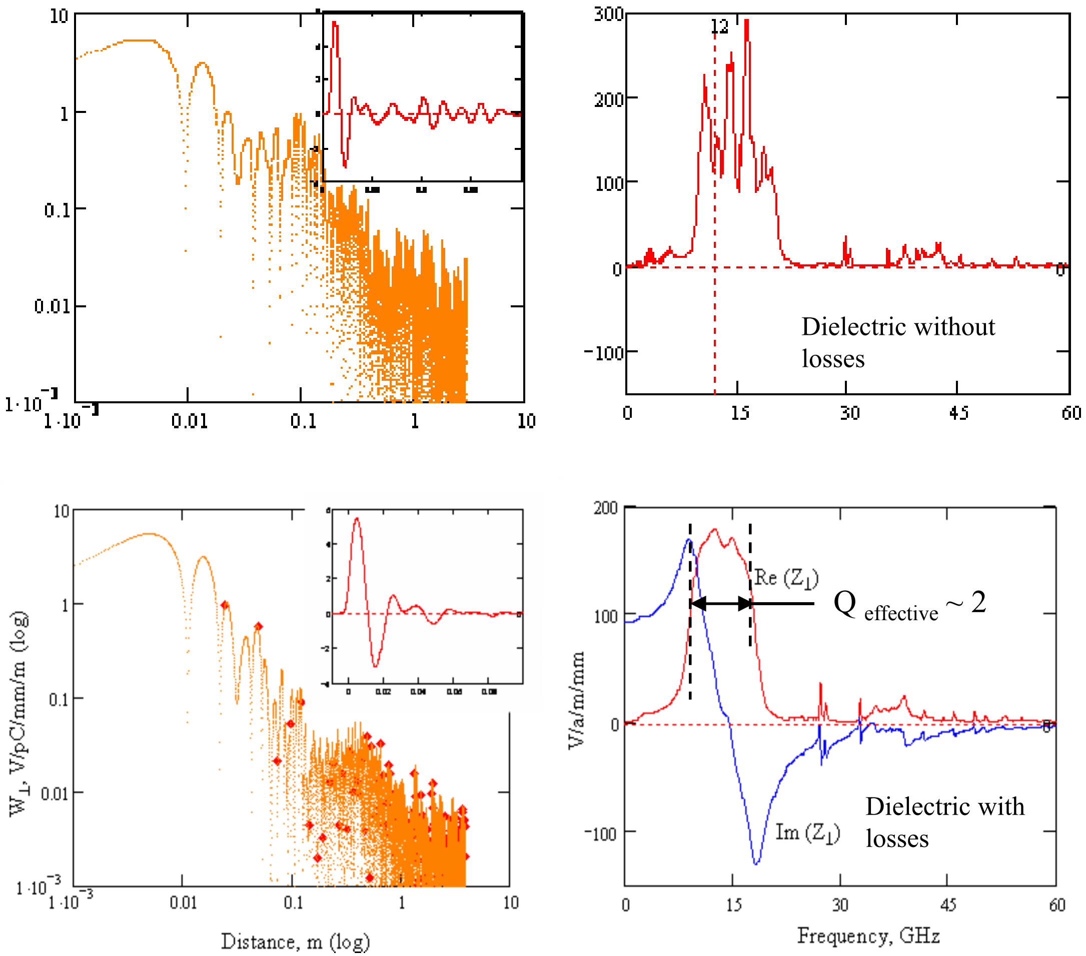
Electric field (log scale) Vector Pointing components

$$\beta_{gr}^{//} = \frac{P^{//}L}{W} = 0.542; \quad \beta_{gr}^{\perp} = \frac{P^{\perp}L}{W} = 0.115$$

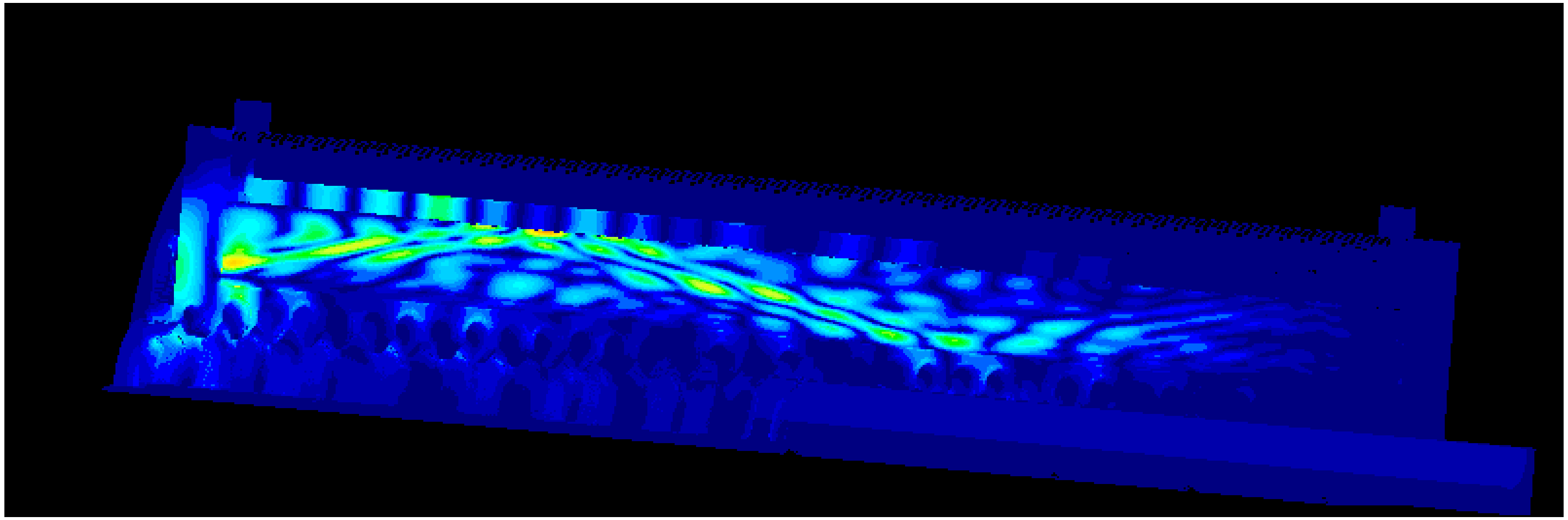
Qualitative study using the steady state beam simulation with HFSS.



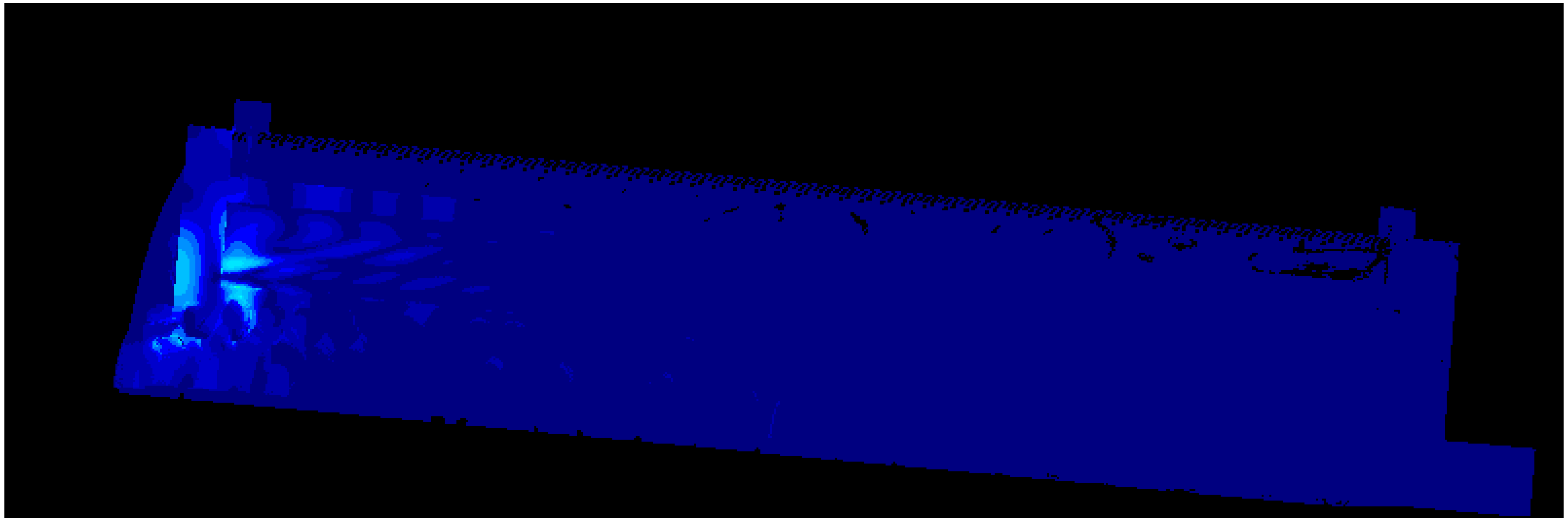
GDFIDL



The PETS equipped with ceramic loads without losses (tgδ=0)

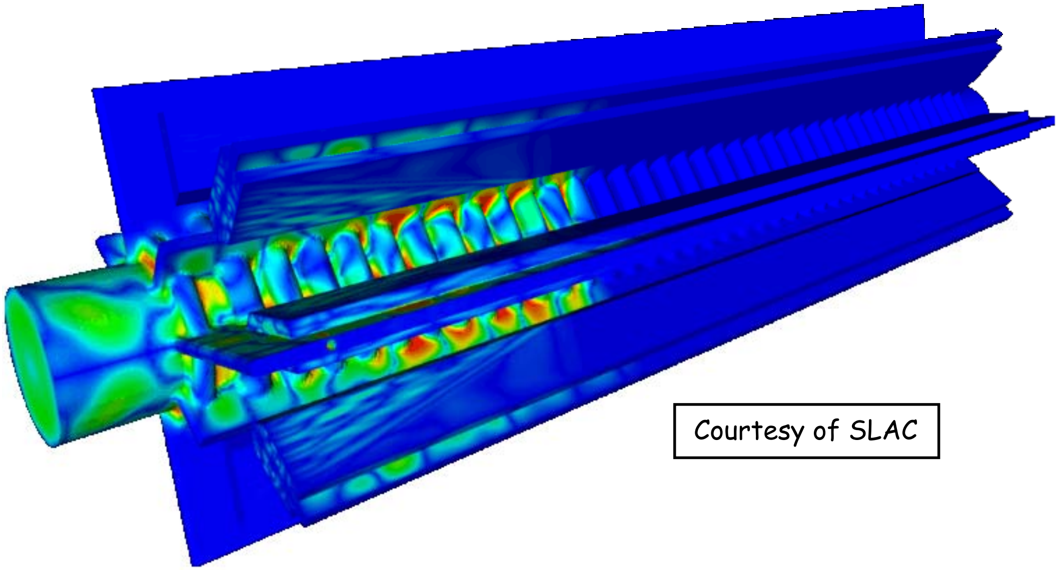


The PETS equipped with ceramic loads with losses (tgδ=0.32)

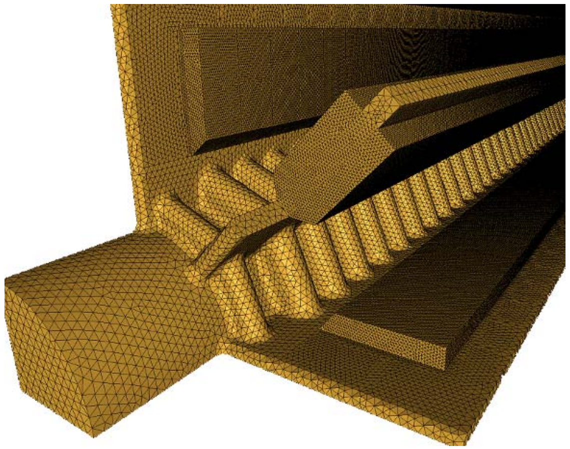


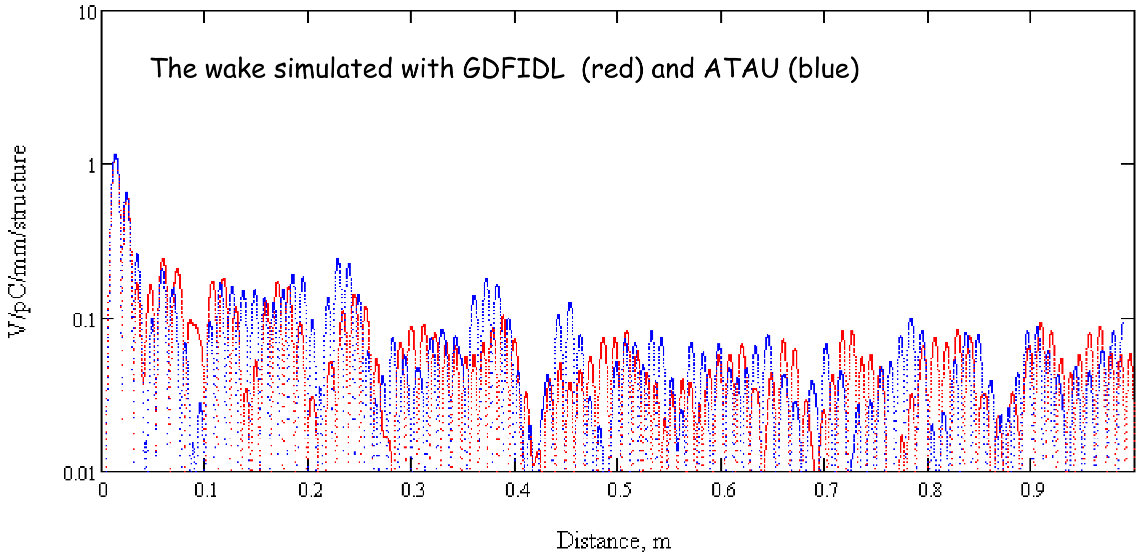
PETS computations expansion. ATAU (SLAC)

For the moment, the computer simulation is the only method to study the damping performance in the PETS. The benchmarking with the different codes is extremely beneficial.

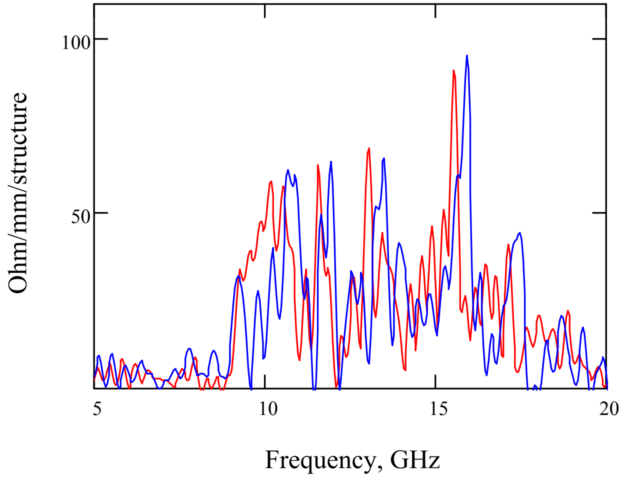


Courtesy of SLAC





The wake simulated with GDFIDL (red) and ATAU (blue)



Open requests for the collaborations:

1. Technical issues

The PETS damping circuit design is very much dependant on the material properties. Currently we do not have preferred /defined candidate. We propose to establish a dedicated collaborating efforts to develop new or to characterize existing RF absorbing materials both for the high and low RF power applications.

2. Design

The PETS design is well established for the moment. Although we are still lacking the high power tests results. We certainly welcome the new / alternative ideas and possible improvements for the PETS and couplers designs.

3. PETS damping and Computations

The massive computer simulations with different codes and methods are very important to confirm the mechanisms of the transverse wakes damping in the PETS. Please bring new approaches if possible (even tests with a beam?).