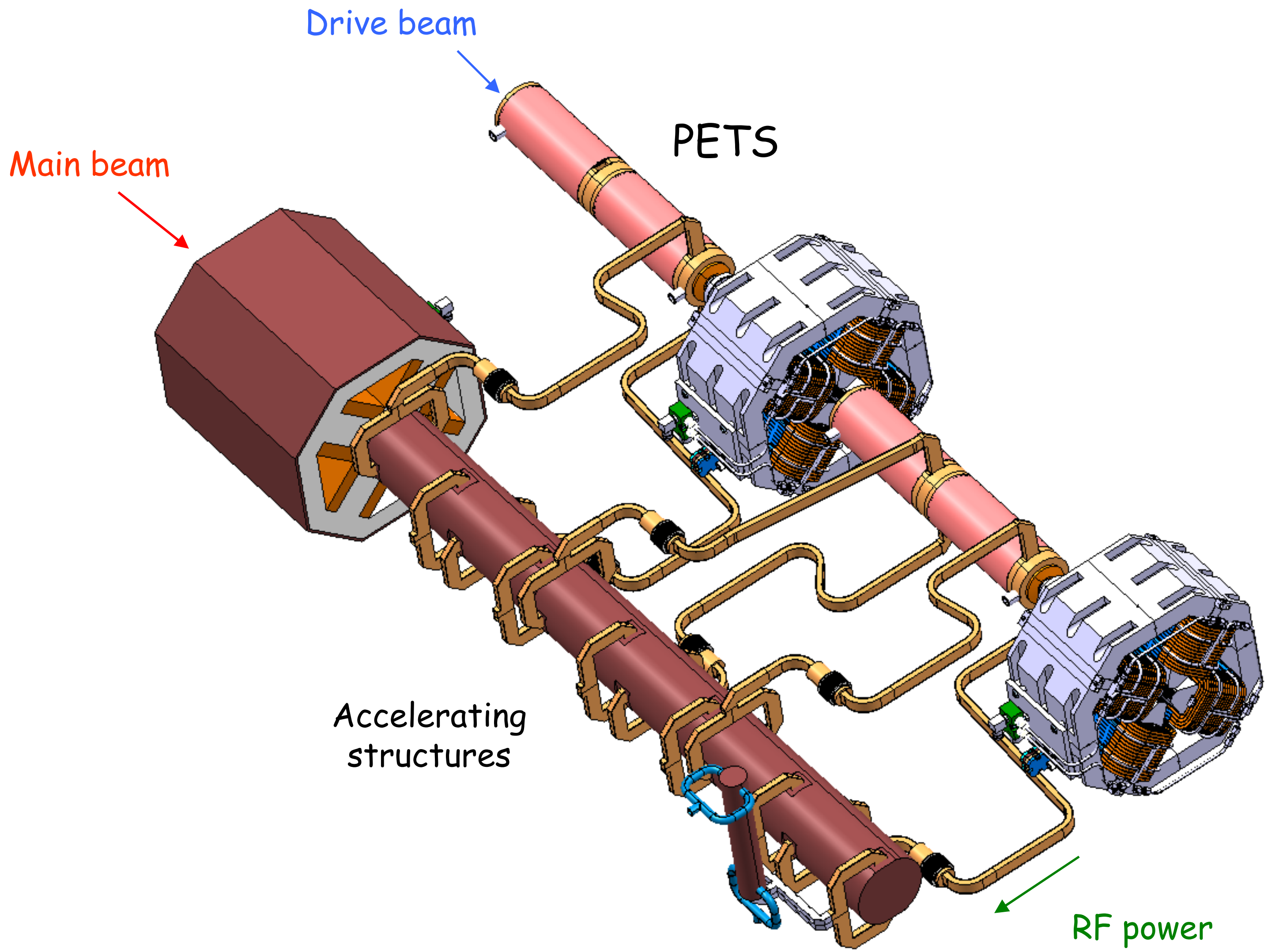
# PETS and rf network: Structure design, on/off/adjust, rf distribution, technology alternatives, high power tests results

**Igor Syratchev for the CLIC team**

A fundamental element of the CLIC concept is two-beam acceleration, where RF power is extracted from a high-current and low-energy beam in order to accelerate the low-current main beam to high energy.




I. Syratchev, 4th ACE meeting, CERN, May 2009.

# PETS design development chart

Drive beam current & energy

Extraction efficiency

On/OF capability

RF power production needs

RF power constrains

PETS design

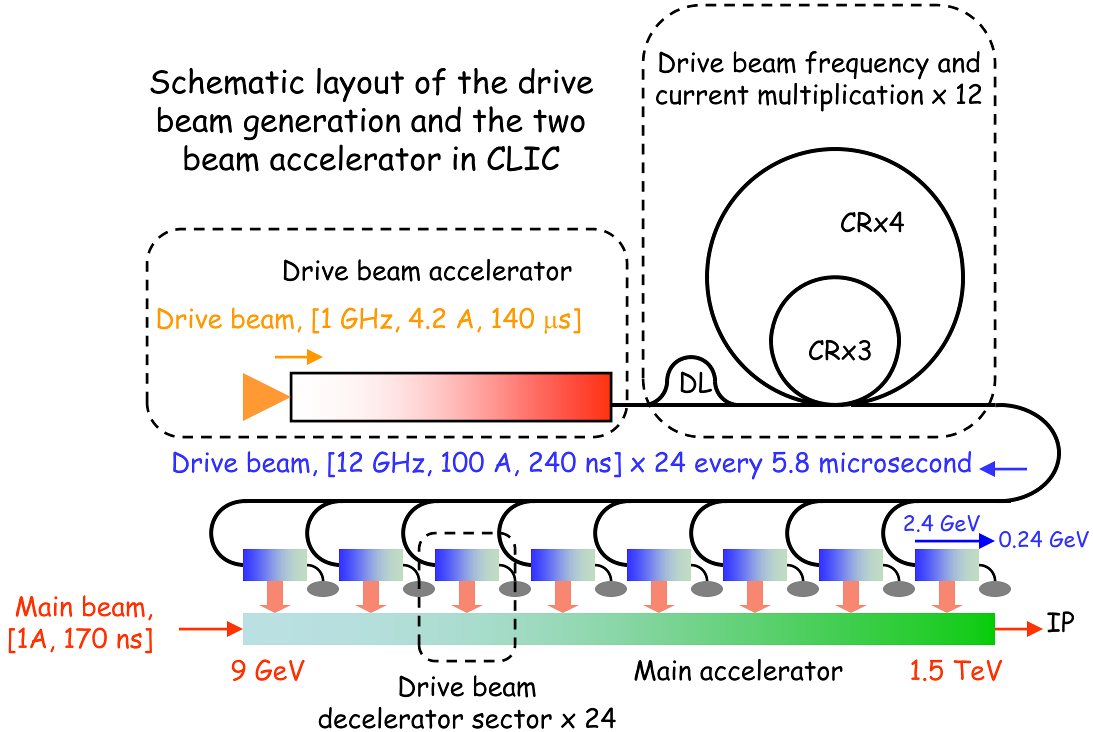
RF components

Beam transport and stability

Module layout and fabrication technology

High power tests

Schematic layout of the drive beam generation and the two beam accelerator in CLIC




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 ($P_{struct} T_{struct}$, $L_{struct}$)
- Combination factor ($N_c$)
- Drive beam energy ($E_{DB}$)
- DB extraction efficiency (~0.9) ($\eta_{DB}$)
- RF transfer efficiency (~0.94) ($\eta_{RF}$)

**In the current CLIC design $I_{DB}$ = 100 A**

For the fixed phase advance and iris thickness: $\frac{R/Q}{V_{gr}} = a^{-2} C_G$

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

$$L = \frac{(L_{struc} \times n - L_T)}{m} - L_{extr}(a)$$

$$P = P_{struc} \times \frac{n}{m} \qquad I^2 F_b^2 \omega_0 = C_I$$

$$a = B \times m^{1/2}(L_{Av} - L_{extr}(a)m)$$

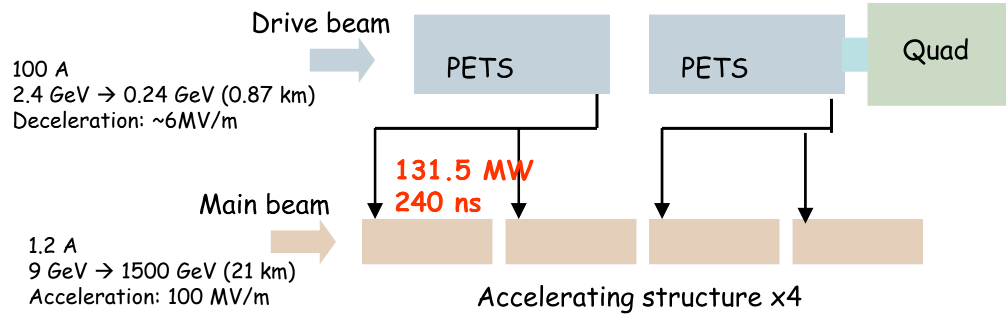
$$L_{Av} = L_{struc} \times n - L_T$$

$$B = \frac{C_I C_G}{4 P_{struc} n}$$

1. For the chosen layout ($L_{UNIT}$) and the number of PETS per unit, the aperture is uniquely defined.
2. In general the bigger aperture (longer PETS) favors the beam dynamics.
3. The longitudinal slots are mandatory to provide transverse HOM damping

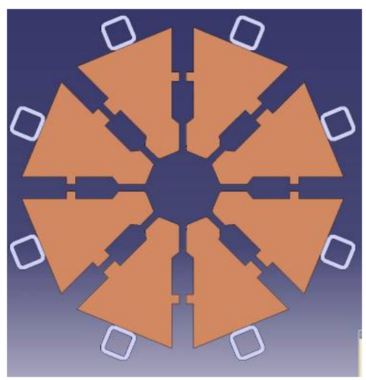
P - RF power
I - Drive beam current
L - Active length of the PETS
$F_b$ - single bunch form factor (≈ 1)

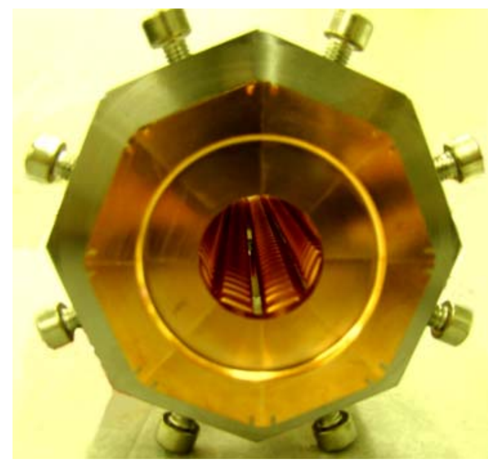
As a result of multiple compromises, the PETS aperture *a/λ* = 0.46 (m = 2) was chosen.



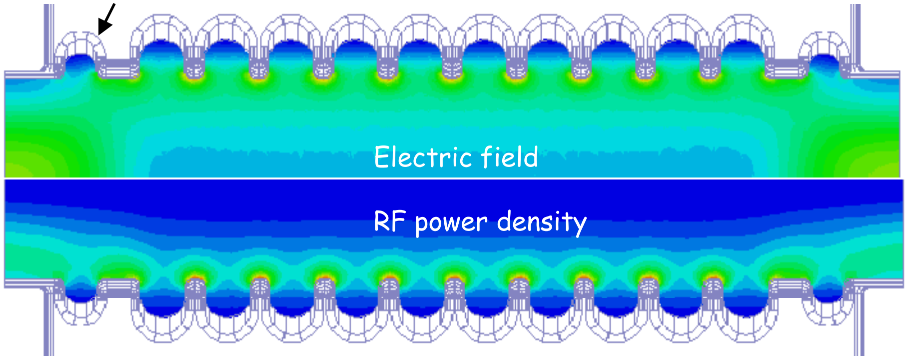

The PETS are large aperture, high-group velocity and overmoded periodic structures. In its final configuration, PETS comprises eight octants separated by 2.2 mm wide damping slots.

PETS cross-section

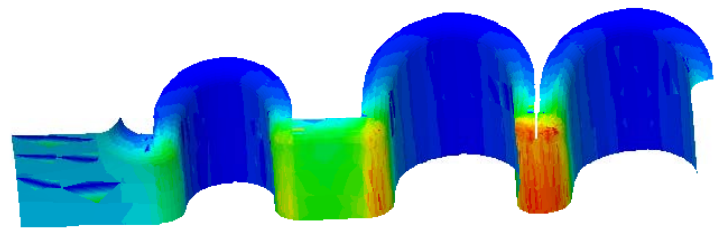




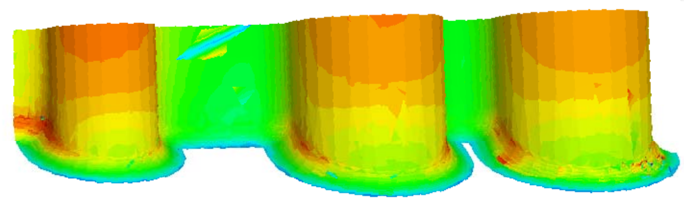
# The PETS bars

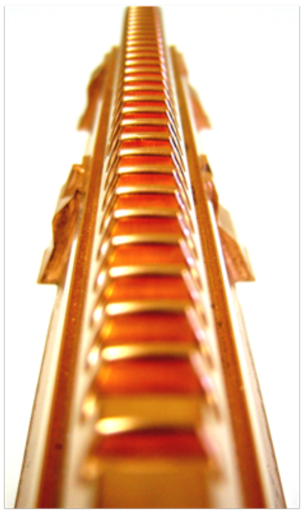


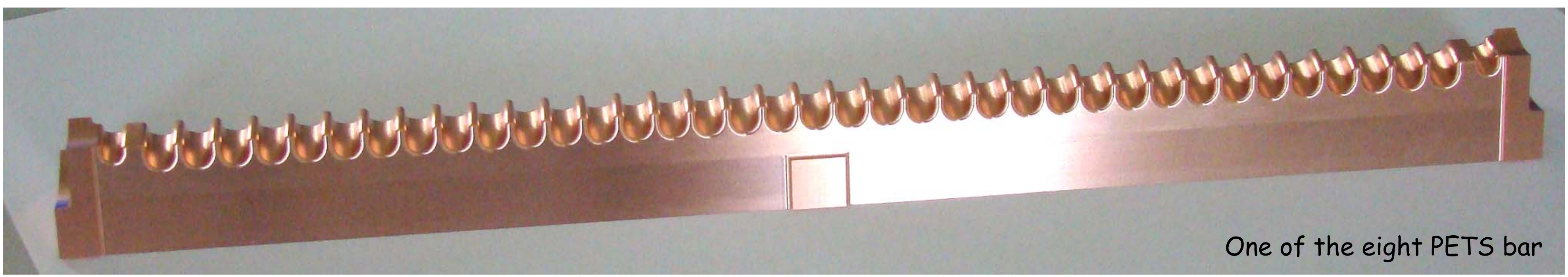

E max (135 MW)=56 MV/m



H max (135 MW)=0.08 MA/m







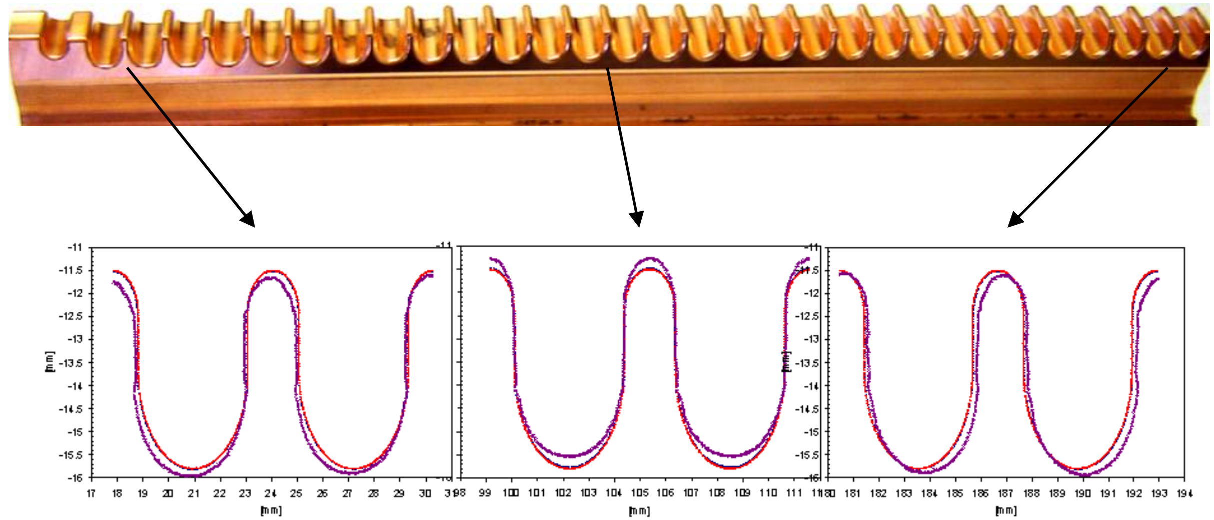
One of the eight PETS bar

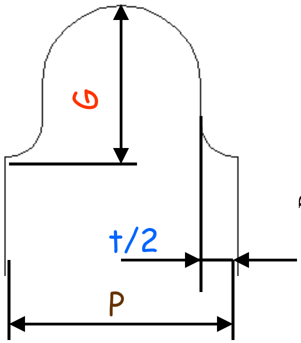
# The PETS bars

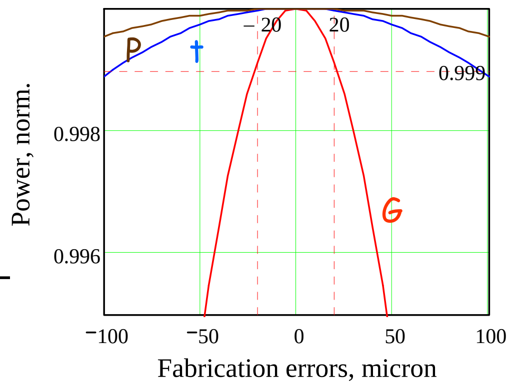
Fabrication and assembly errors can detune the PETS synchronous frequency and thus affect the power production:

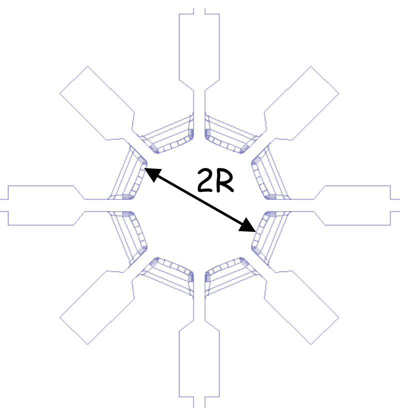
$$P = I^2 F_b^2 \omega_0 \frac{R/Q}{V_g\, 4}\left|\int_0^L \exp\left(i\frac{\Delta\omega}{2\,c}\frac{1-\beta}{\beta}z\right)dz\right|^2$$

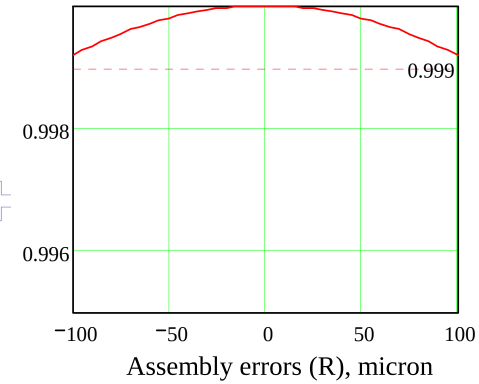
## The PETS fabrication tolerances issues





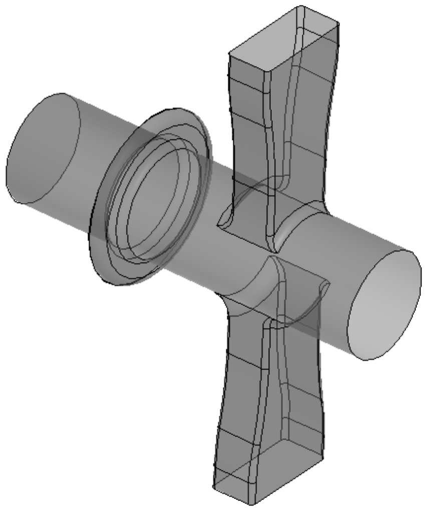



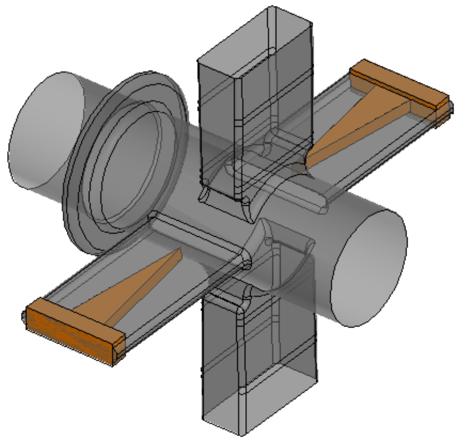

The fabrication accuracy of ± 20 μm is sufficient enough (power production efficiency >0.999) and can be achieved with a conventional 3D milling machines. Five companies worldwide are already qualified to do the job.

# PETS RF power extractor

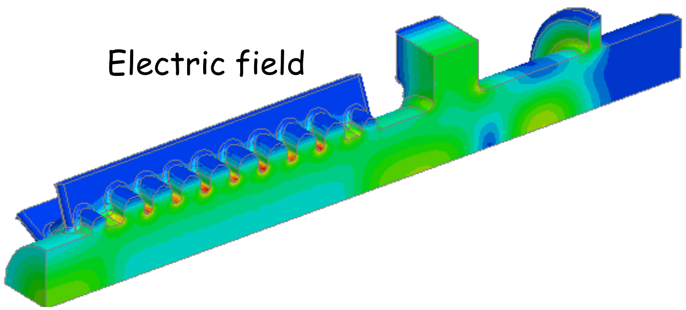
Baseline design



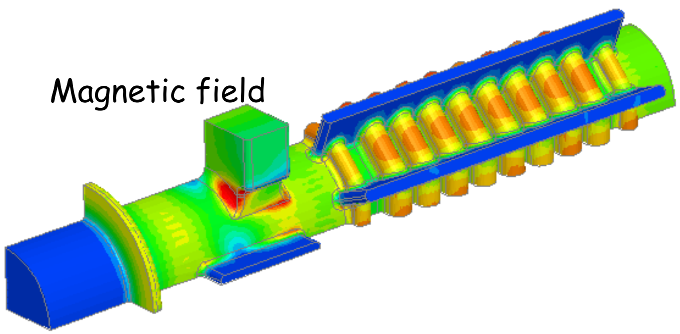
Damped modification
(in progress)

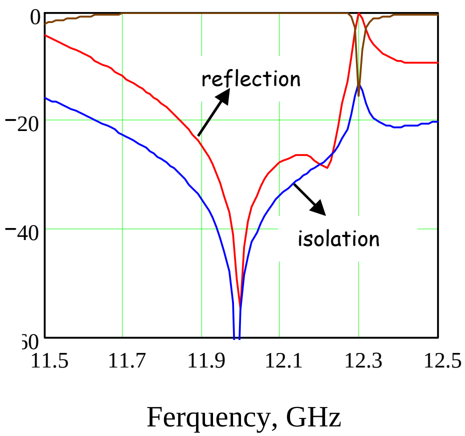


Electric field



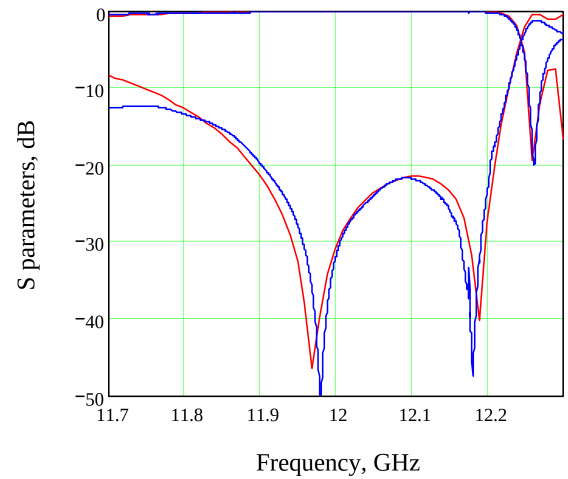
Magnetic field







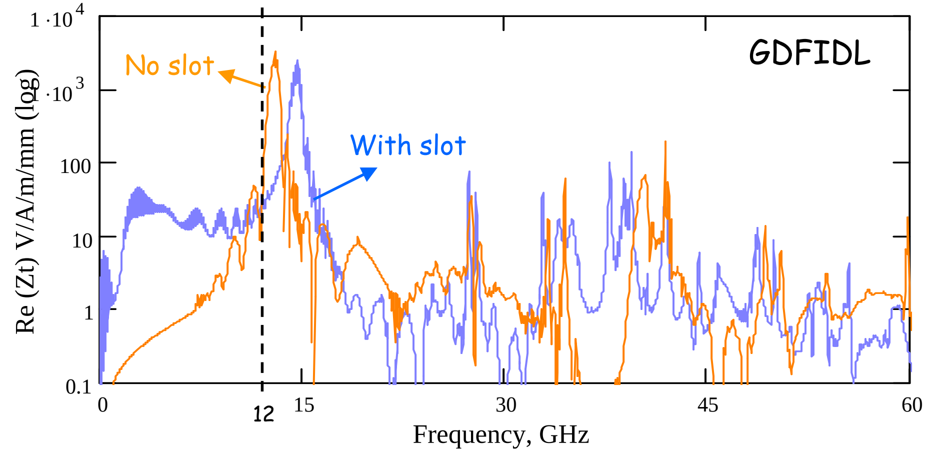
12 GHz couplers measured face-to-face (blue)
and as simulated with HFSS (red)



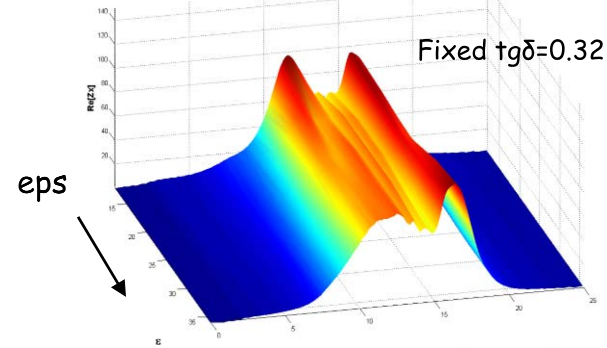
# HOM damping in PETS

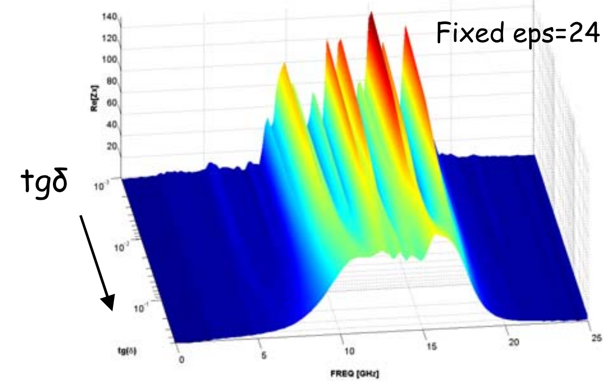
In the high group velocity structures, the frequency of the transverse mode is rather close to the operating one (13.0 GHz in our case). The only way to damp it is to use its symmetry properties – damping with the slots.

Transverse modes spectra (without loads)

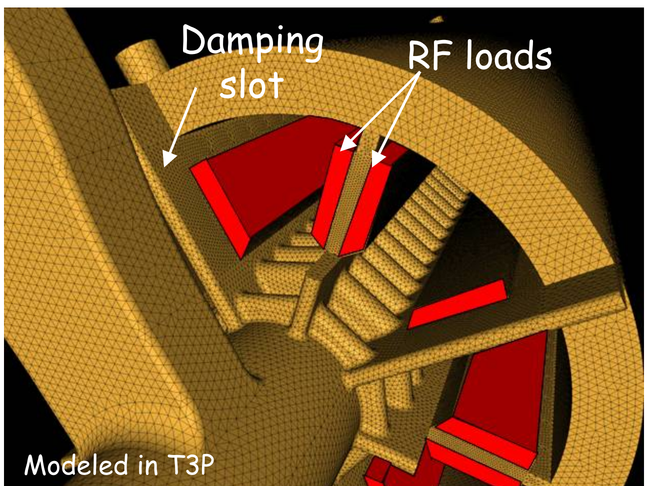



Transverse modes spectra (fixed load geometry)

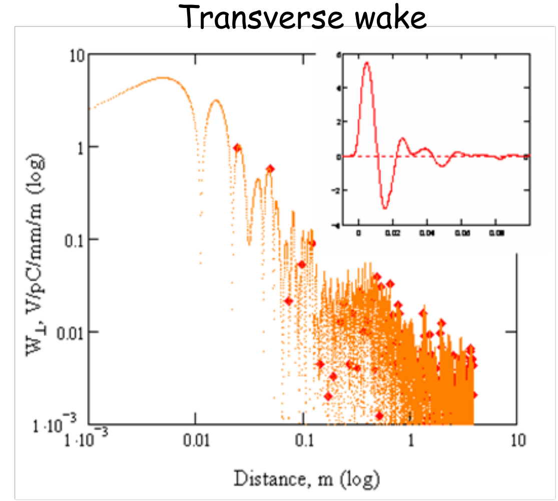



With the proper choice of the load configuration with respect to the material properties makes it possible to couple the slot mode to a number of heavily loaded modes in dielectric.

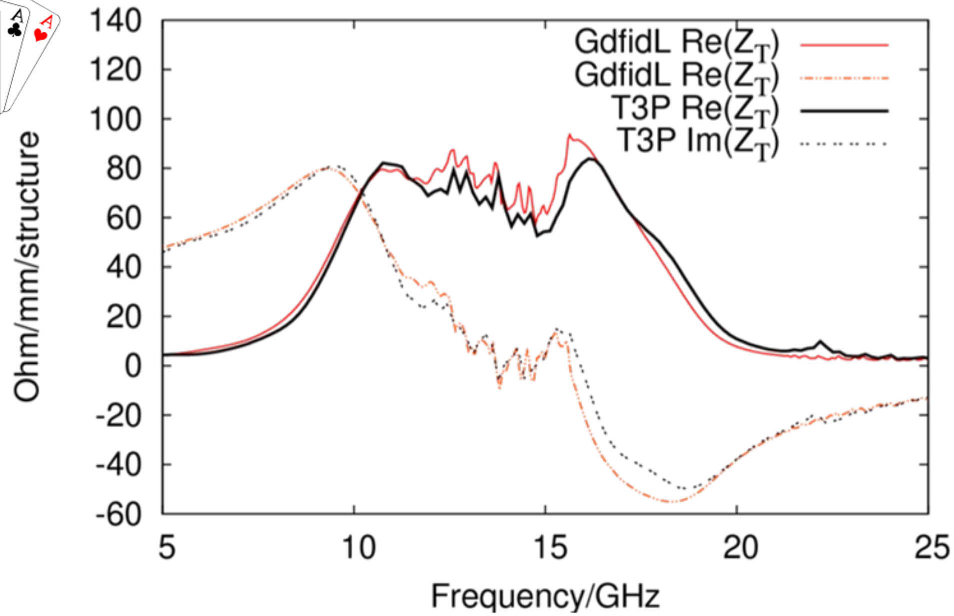



Transverse wake

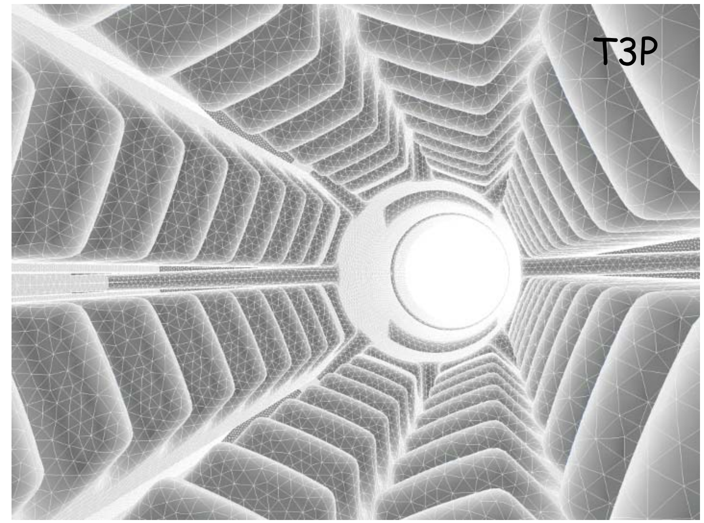


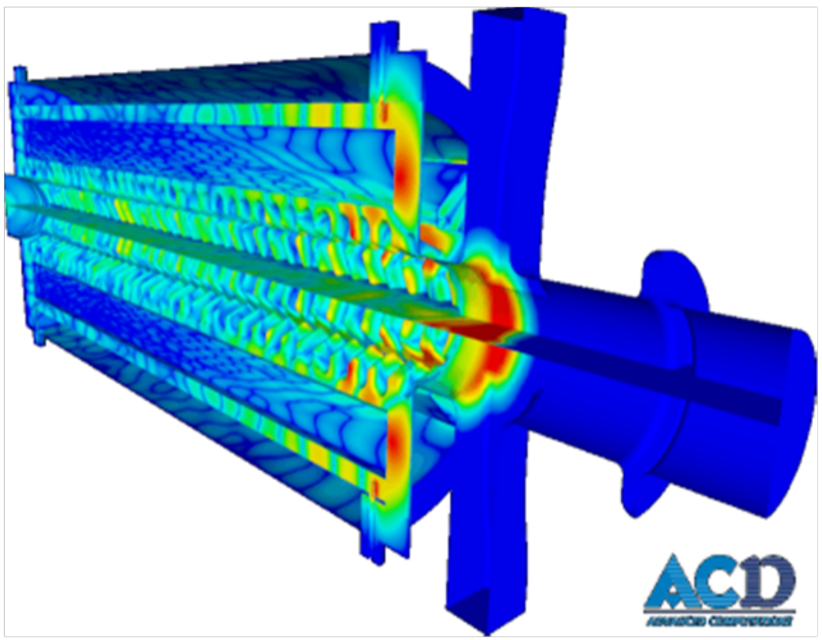
# HOM damping in PETS

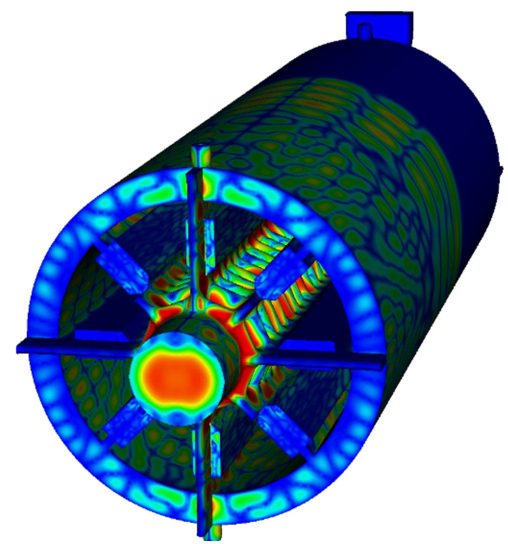
T3P vs. GDFIDL



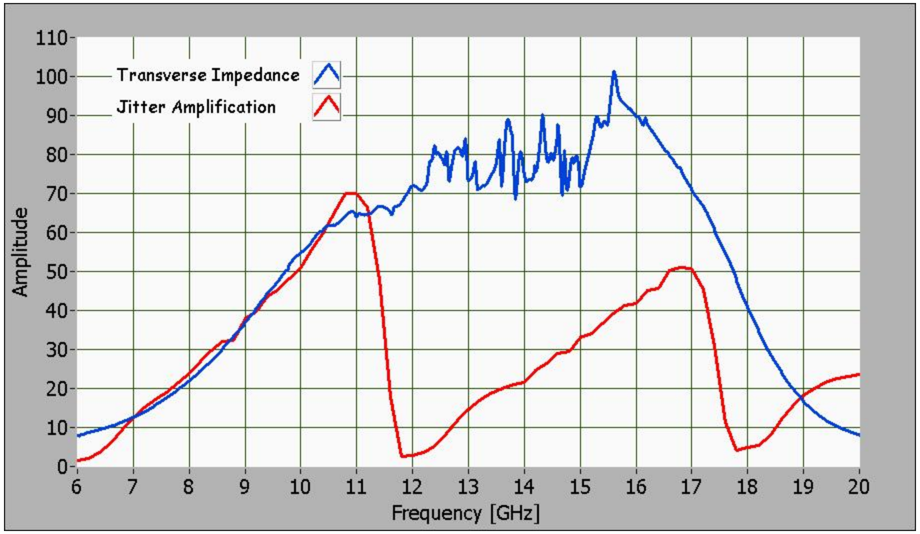

For the moment, the computer simulation is the only method to study the damping performance in the PETS. The benchmarking with the different codes is extremely beneficial.



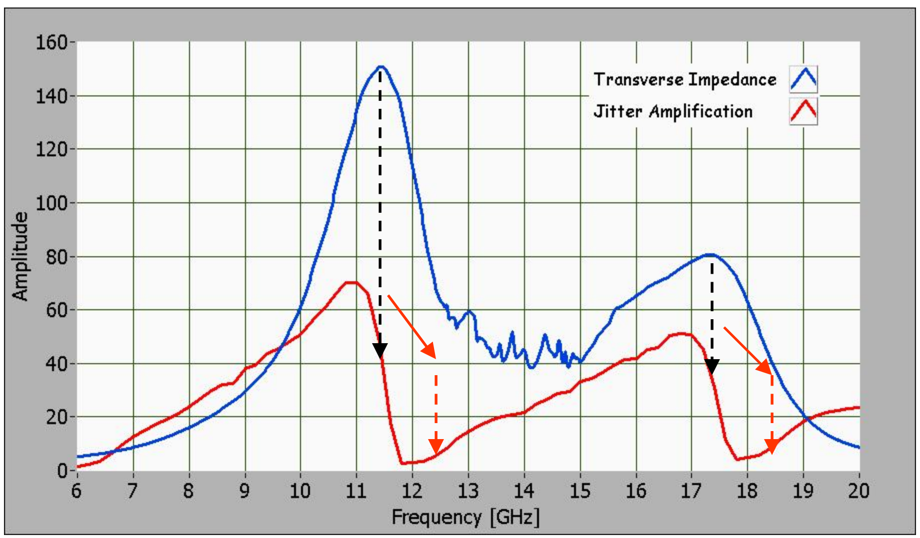



Current design:




Fast example of the spectrum modification with 4 loads being switched off:

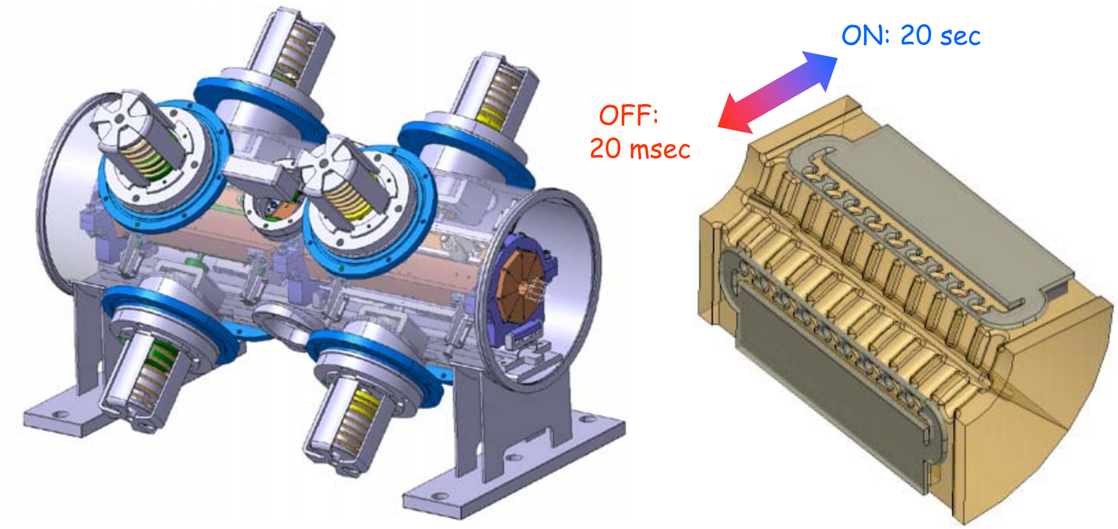



Future/ongoing development:

Based on the beam dynamic simulations in the decelerator, the damping configuration (loads geometry, position etc.) is now under new optimization round: "close" zero-crossing approach.

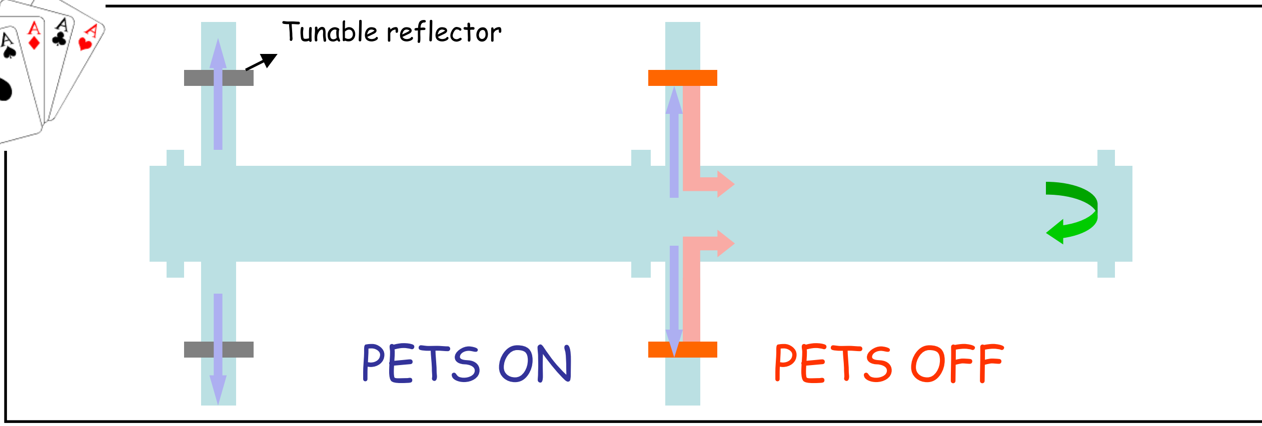
- ✓ During machine operation the accelerating structure and/or PETS will suffer from the number of RF breakdowns.
- ✓ Currently we have a little information about the actual behavior of the structures at a very low (by design: $<3\times10^{-7}$ /pulse/meter) breakdown trip rate and so it might be necessary to switch the single structure/PETS OFF and re-process it.
- ✓ In order to maintain the operation efficiency we want to do the switching OFF very fast – between the pulses (20 msec).

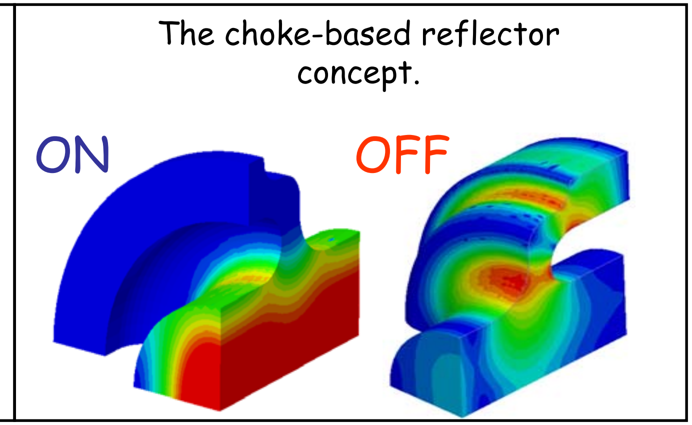
30 GHz ON/OFF design efforts. The PETS synchronous mode frequency detuning.

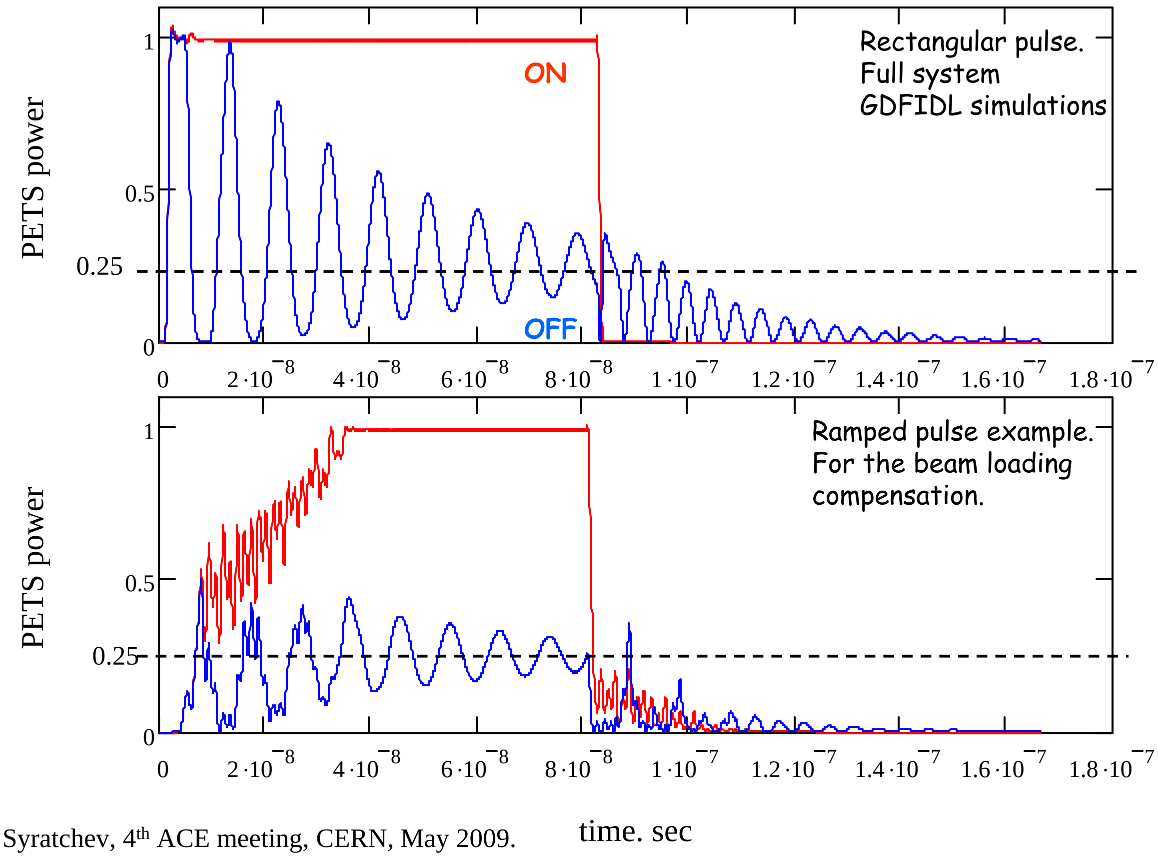



The few preliminary studies for the precise, fast and synchronous movement of the 4 blades in vacuum indicated that this system could become the cost driver for the whole PETS unite.

## ON/OFF concept with external commutation and internal re-circulation

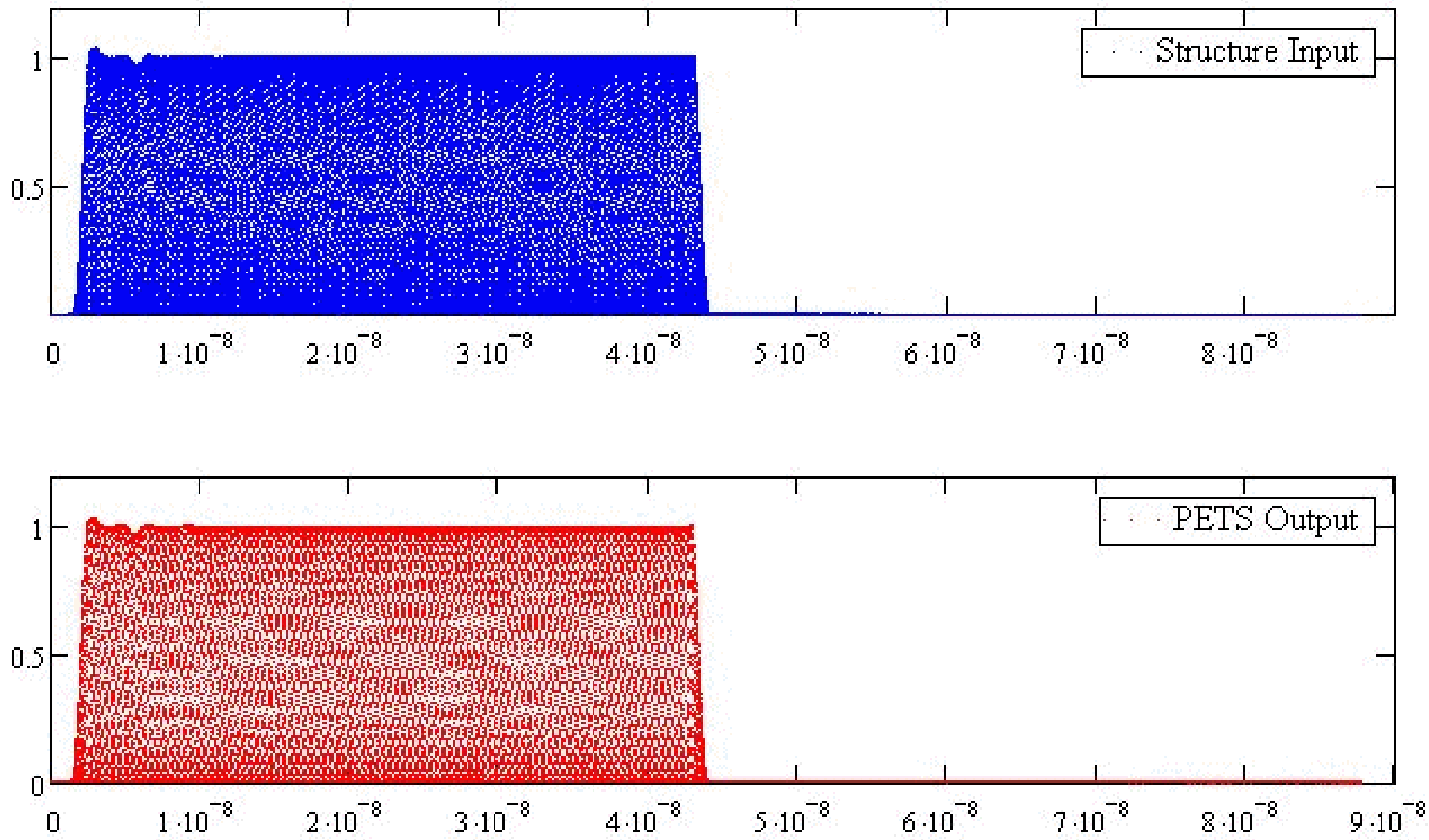


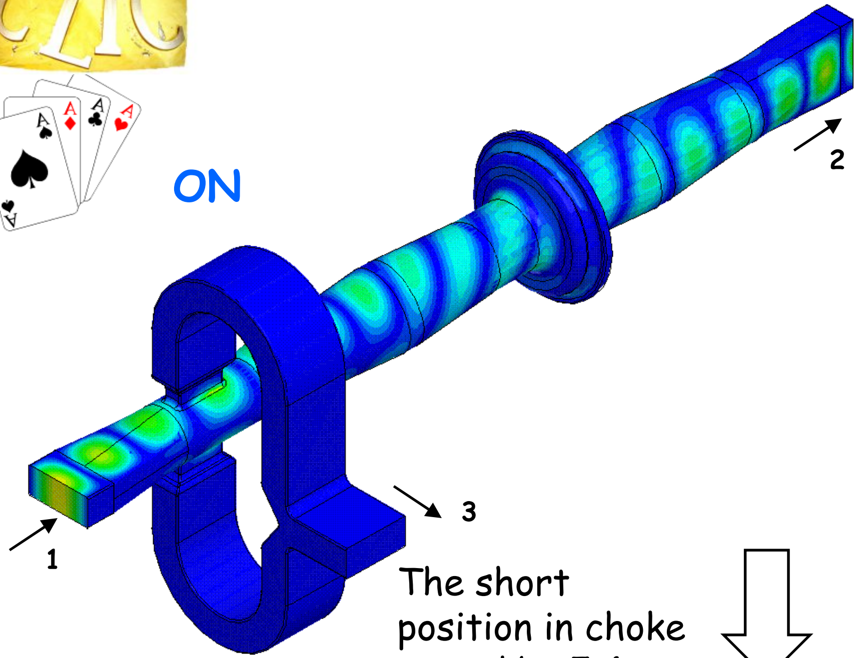

1. With proposed scheme we can guarantee the strong (< -20 dB) suppression of the RF power delivery to the accelerating structure.
2. In a case of the breakdown in PETS the RF pulse time structure and 25% saturated power allow to expect the PETS safe behavior.

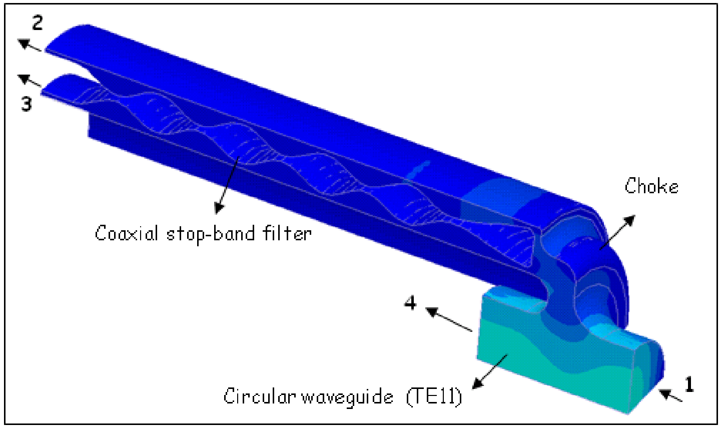
ON/OFF/adjust processes animation.



The tunable choke "proof of principle" high power tests at SLAC (autumn 2009) with klystron. The mechanical design is under way. If tests will be successful, one of the TBL PETS will then equipped with such a device

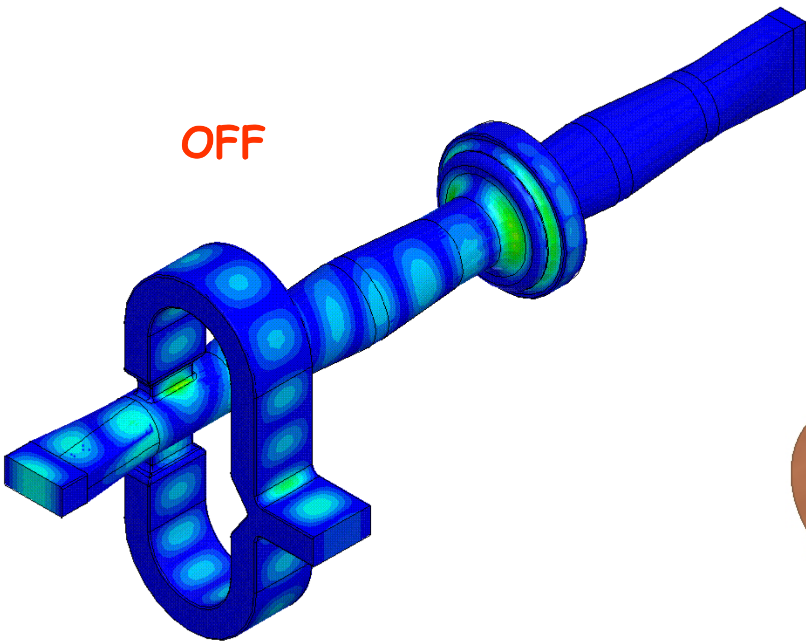
ON

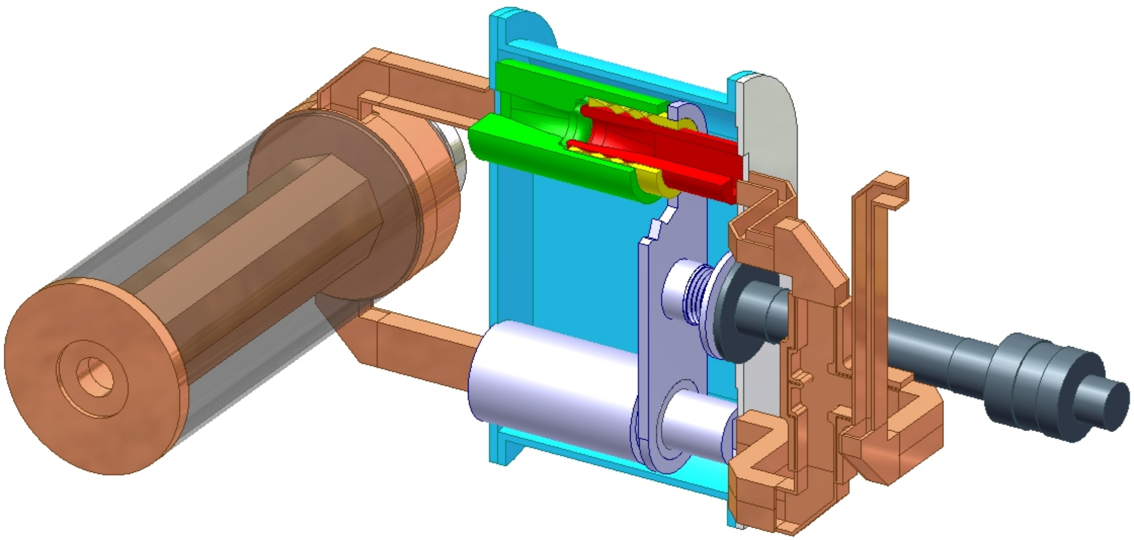



The short position in choke moved by 5.4 mm

OFF



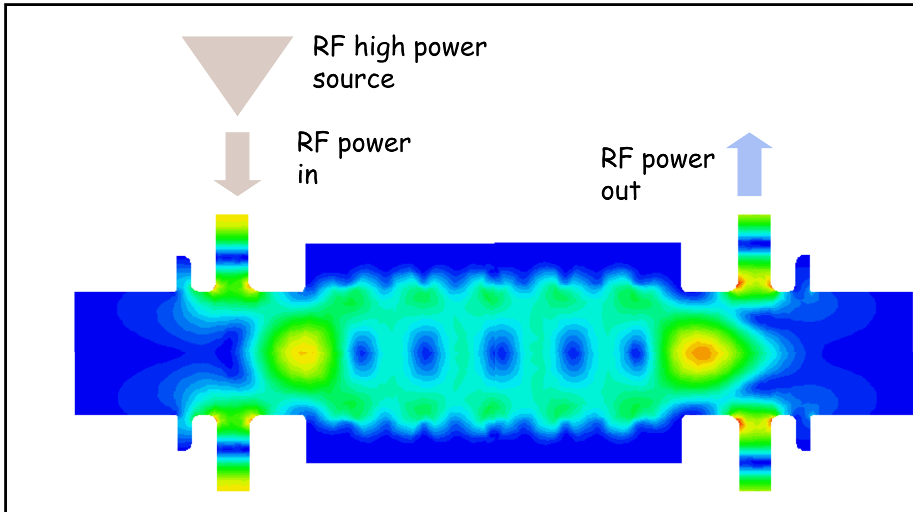


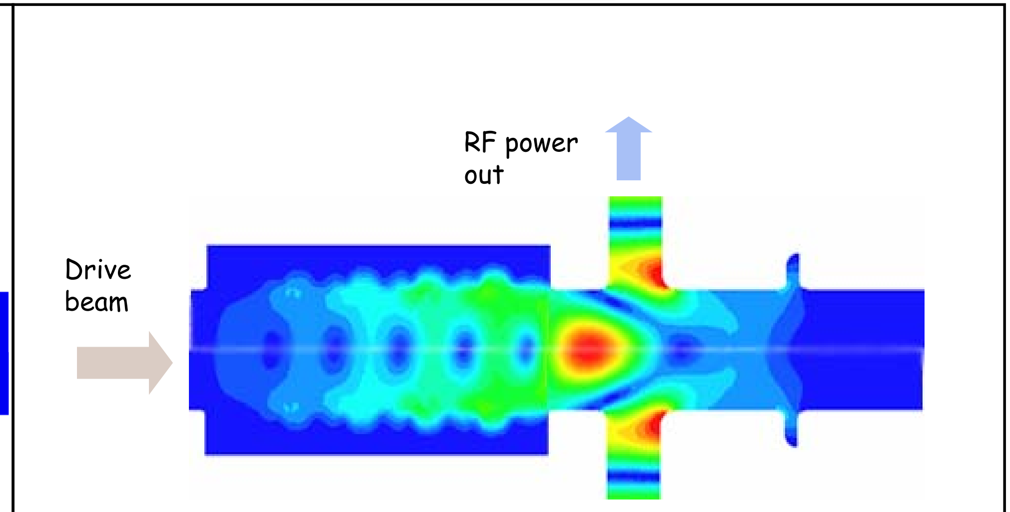
# PETS testing chart

## RF power sources

## External RF power source

## Drive beam




## ASTA (SLAC)

Objective: to understand the limiting factors for the PETS ultimate performance.

- Access to the very high power levels (300 MW) and nominal CLIC pulse length.
- High repetition rate – 60 Hz.

## CTF3 (CERN + Collaborations)

## Two beam test stand (CERN + Collaborations)

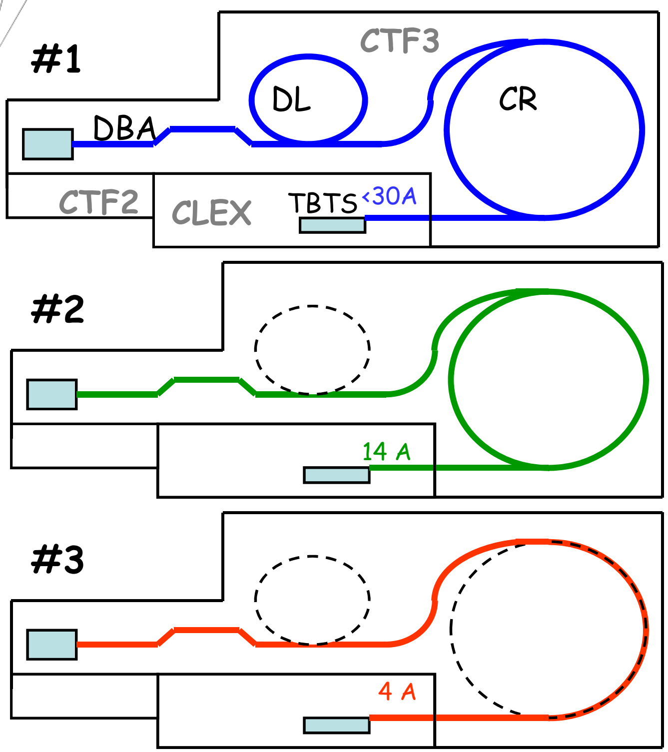
Objective: to demonstrate the reliable production of the nominal CLIC RF power level throughout the deceleration of the drive beam.

## Test beam line (CERN + Collaborations)

Objective: to demonstrate the stable, without losses, beam transportation in a presence of the strong (.50%) deceleration.

# PETS high power tests at CERN (TBTS)

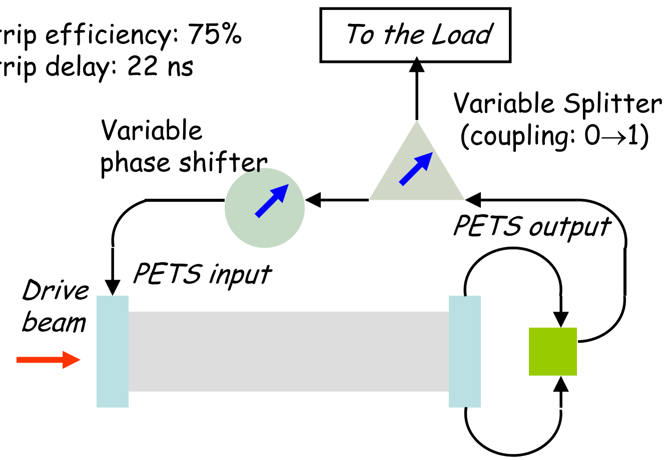
• Different scenarios of the drive beam generation in the CTF3



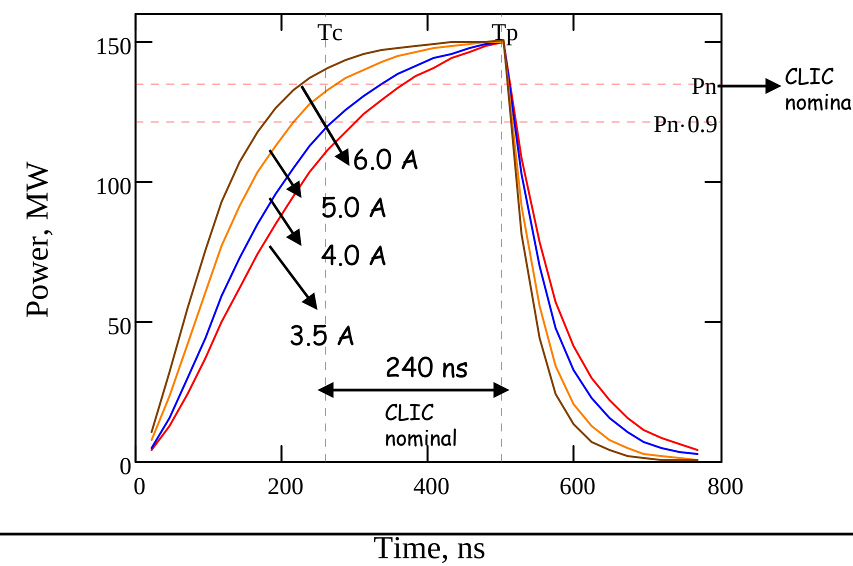

• To compensate for the lack of current, the active TBTS PETS length was significantly increased: from the original 0.215 m to 1 m.

| Operation mode | #1 | #2 | #3 | CLIC |
|---|---|---|---|---|
| Current, A | <30 | 14 | 4 | 101 |
| Pulse length, ns | 140 | <240 | <1200 | 240 |
| Bunch Frequency, GHz | 12 | 12 | 3 | 12 |
| PETS power (12 GHz), MW | <280 | 61 | 5 | 135 |

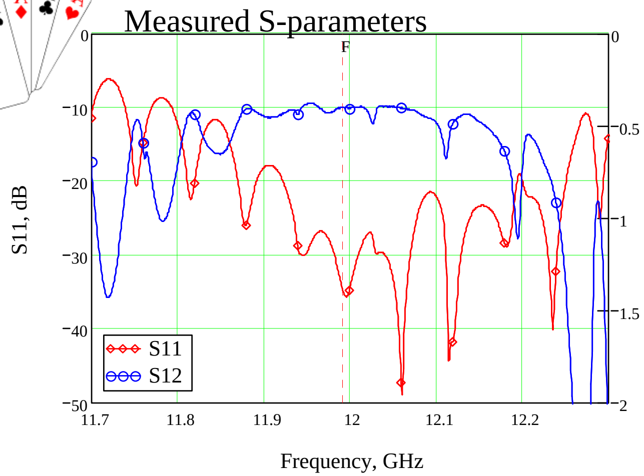
• In order to demonstrate the nominal CLIC power level and pulse length, it was decided to implement a different PETS configuration – PETS with external re-circulation.

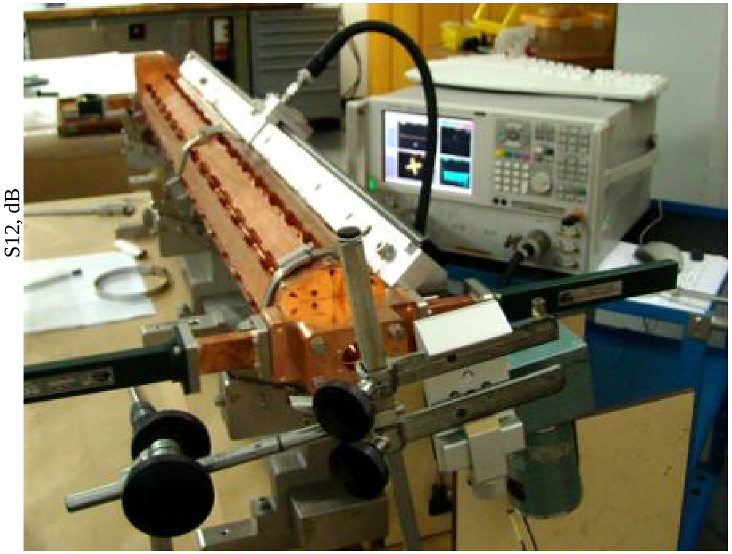


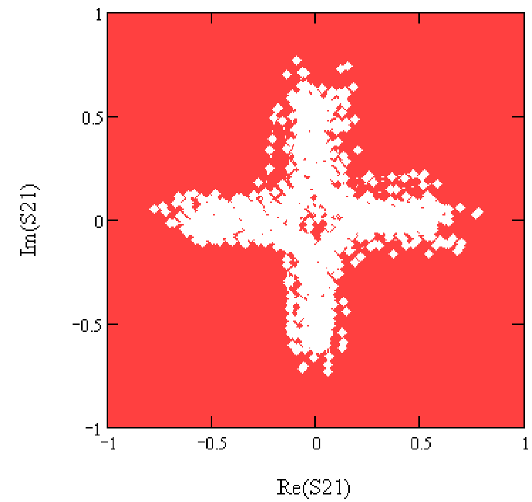

Expected PETS power production with re-circulation.
The calculation followed the measured performance of all the components



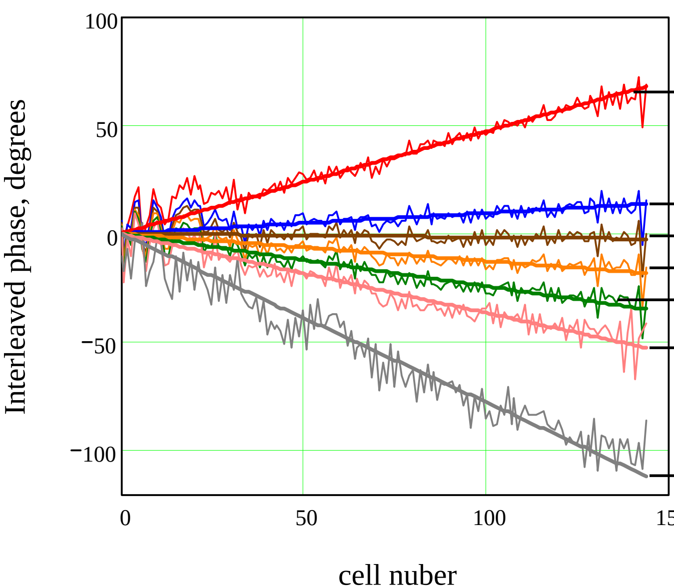
# TBTS PETS measurements



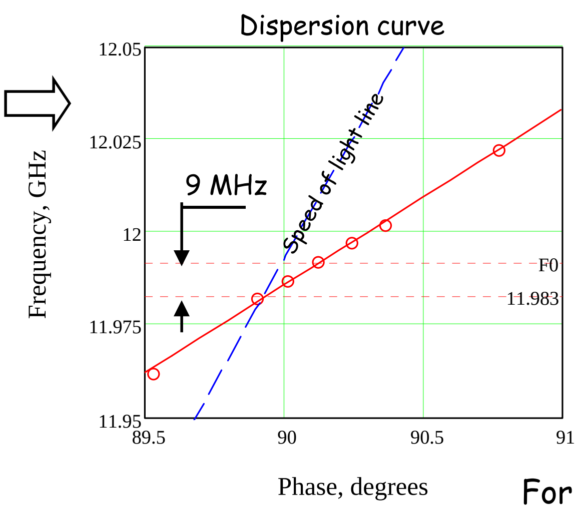





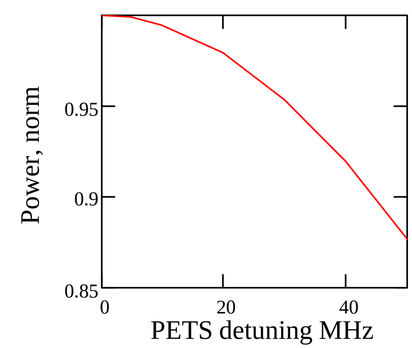

| | Measured | Calculated |
|---|---|---|
| Ohmic efficiency | 0.912 | 0.914 |
| Group delay [ns] | 7.47 | 7.35 |




| ΔF, MHz | φ/cell |
|---|---|
| -30 | 89.53 |
| -10 | 89.91 |
| -5 | 90.02 |
| 0 | 90.13 |
| +5 | 90.24 |
| +10 | 90.37 |
| +30 | 90.78 |

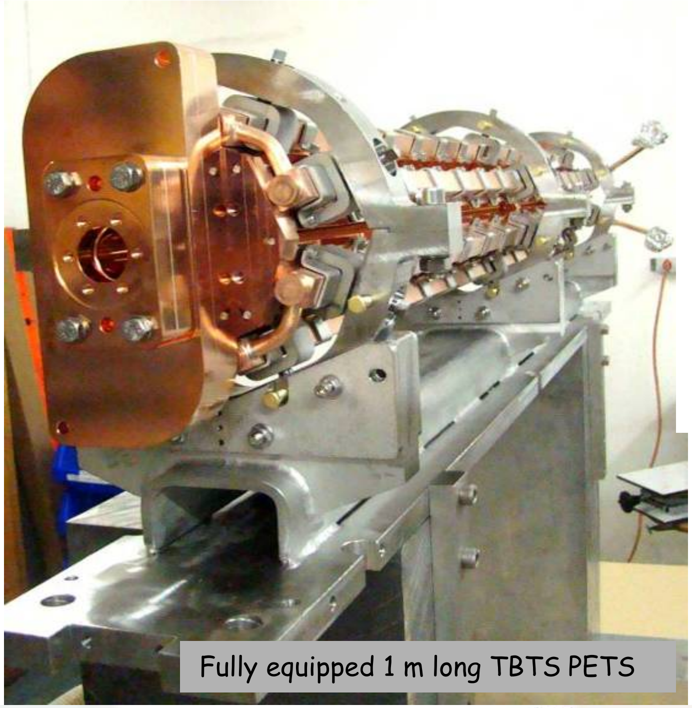



$$P = I^2 F_b^2 \omega_0 \frac{R/Q}{V_g\,4} \left| \int_0^L \exp\left( i \frac{\Delta\omega}{c} \frac{1-\beta}{\beta} z \right) dz \right|^2$$

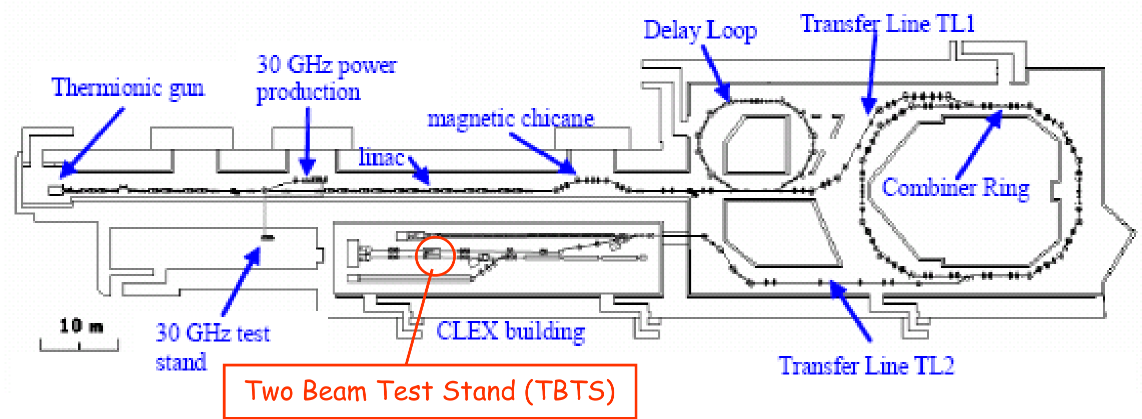



For the measured TBTS PETS detuning (9 MHz), the power production efficiency of 99.6% is expected.

# PETS high power tests at CERN (TBTS)

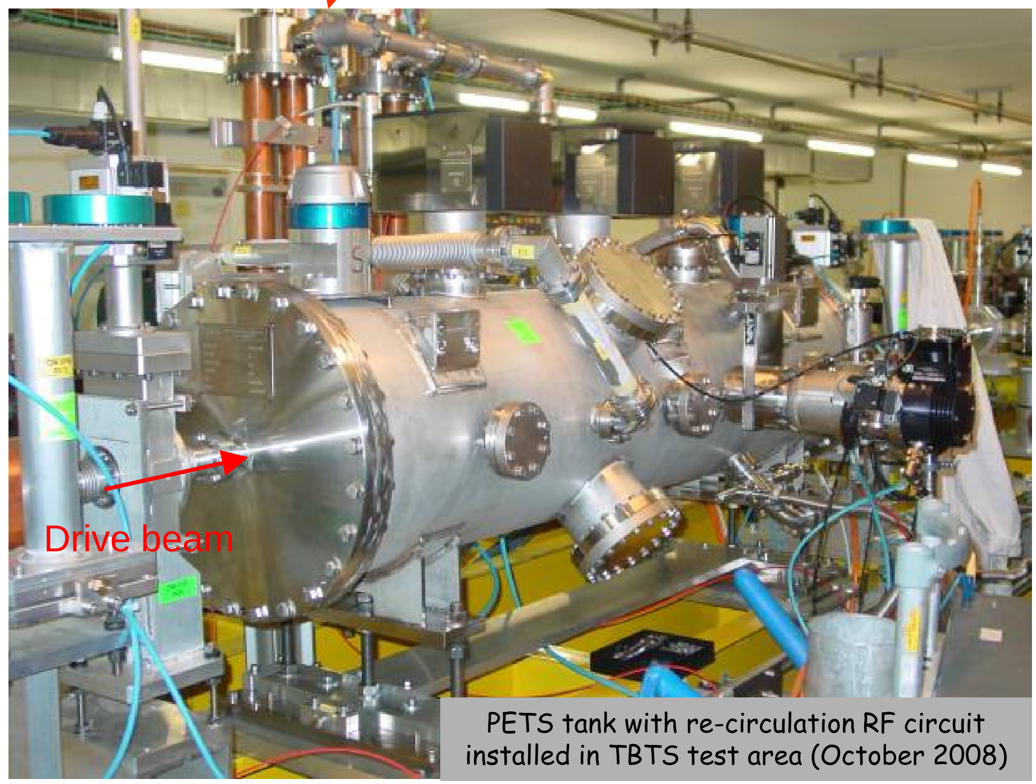


Fully equipped 1 m long TBTS PETS




Variable high power RF power splitter

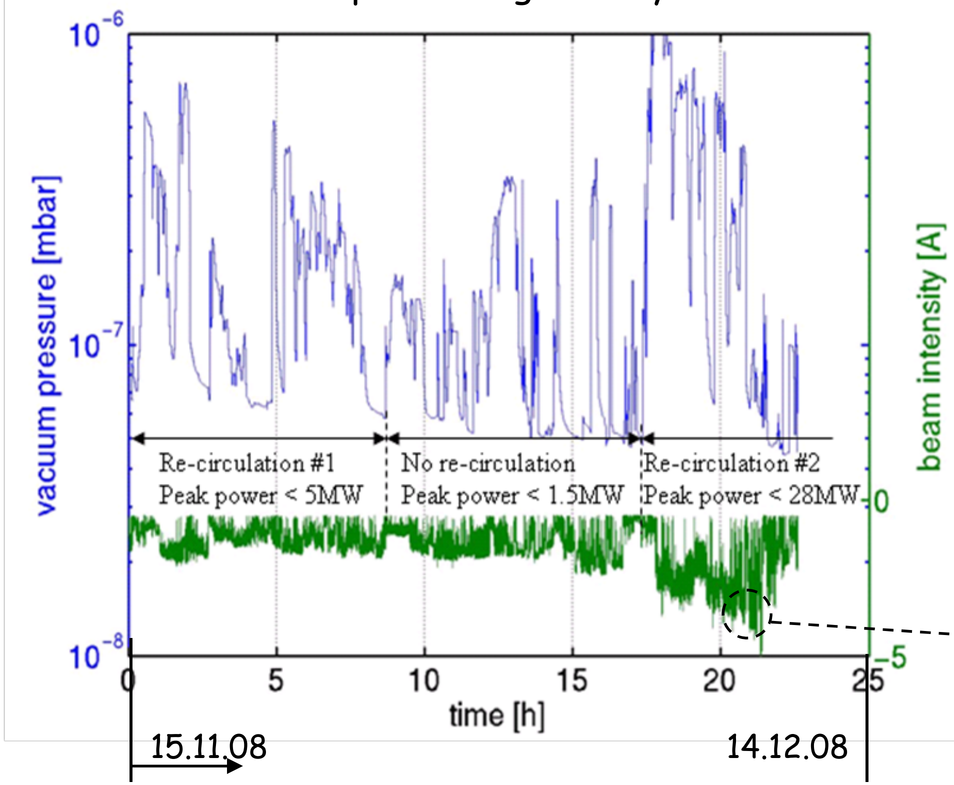
Variable high power RF phase shifter

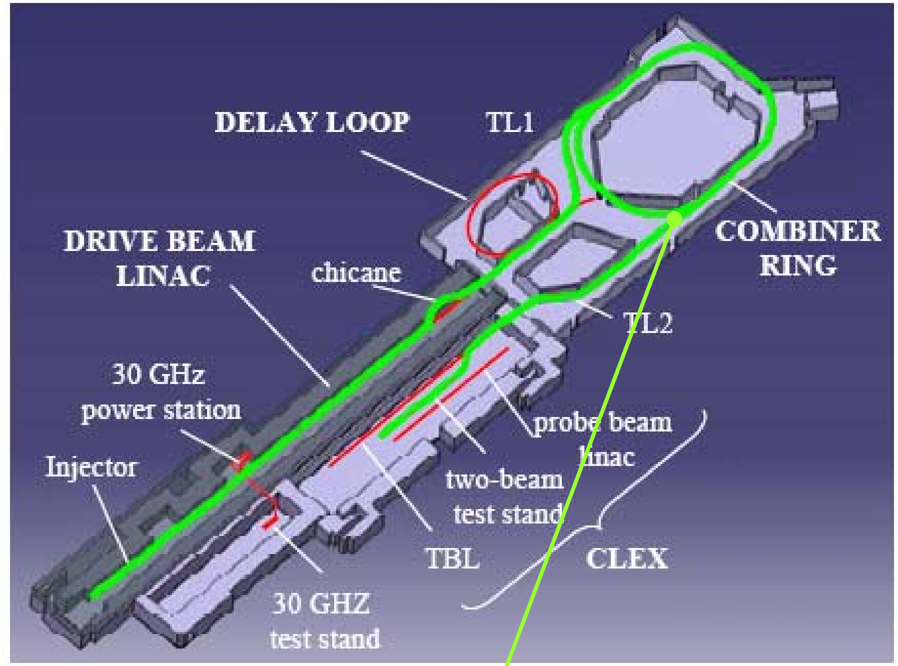


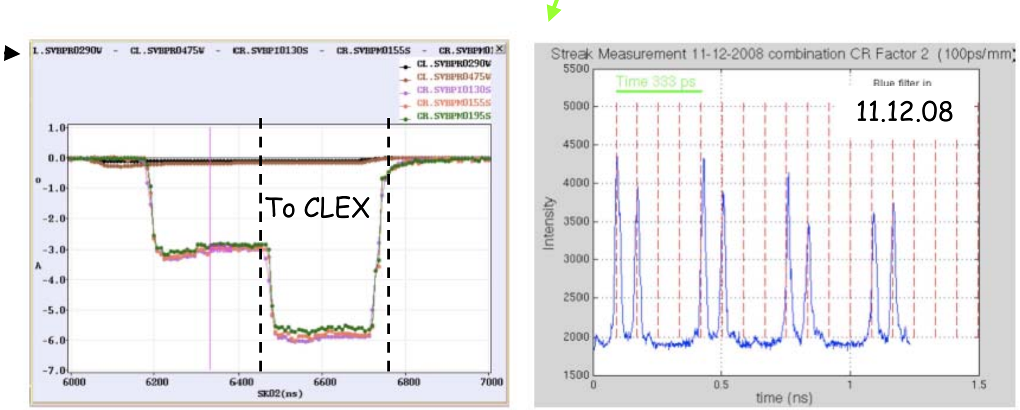

PETS tank with re-circulation RF circuit installed in TBTS test area (October 2008)

# PETS high power tests at CERN (TBTS)

PETS processing history in 2008




Example of the beam intensity and bunch train time structure after combination x2 (Mode #2) in the Combiner Ring

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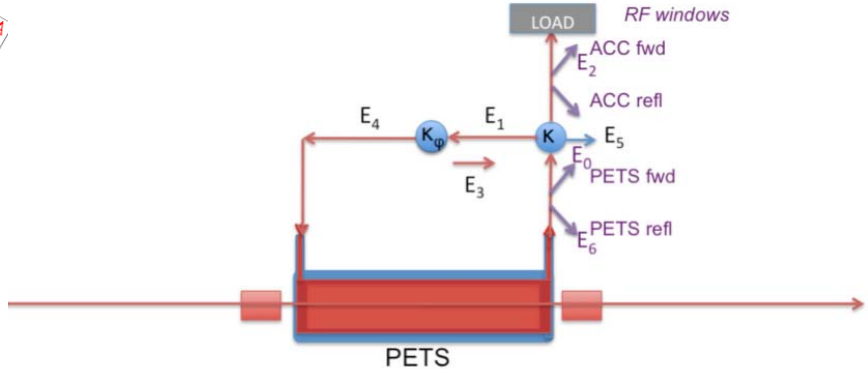
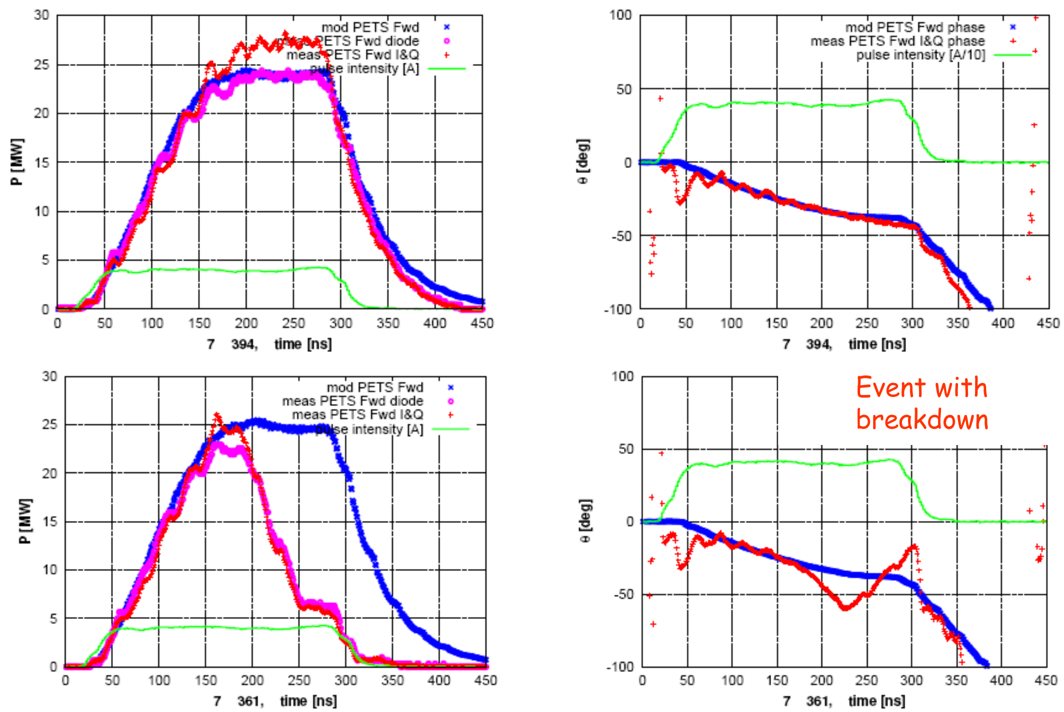
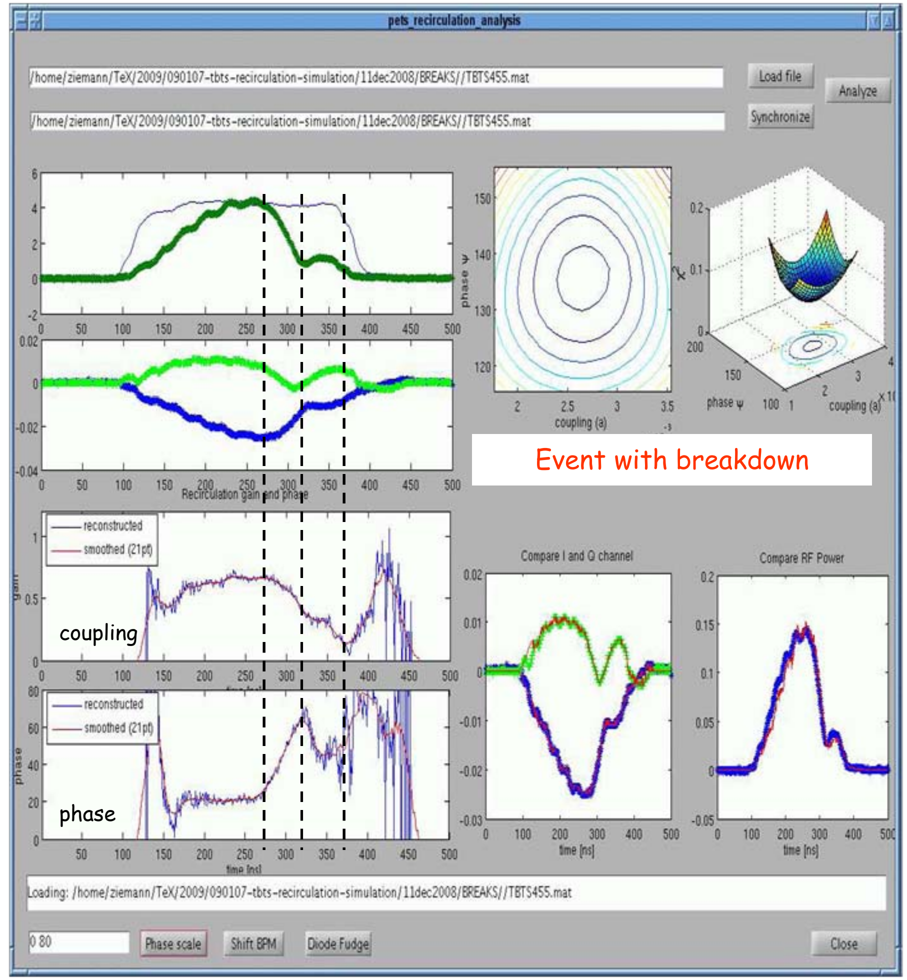



Model with constant coupling and phase

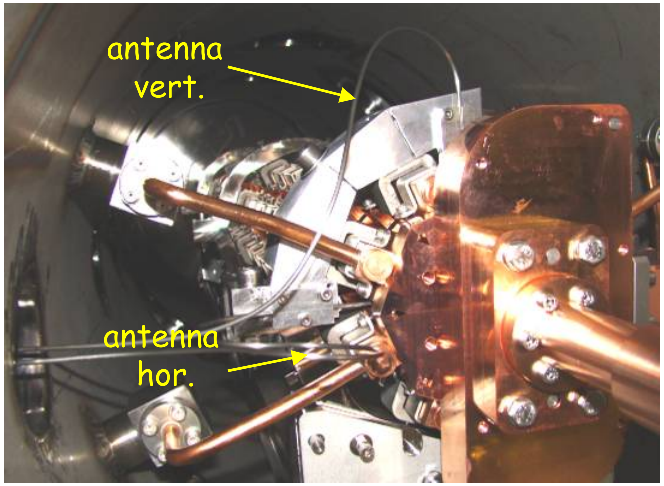


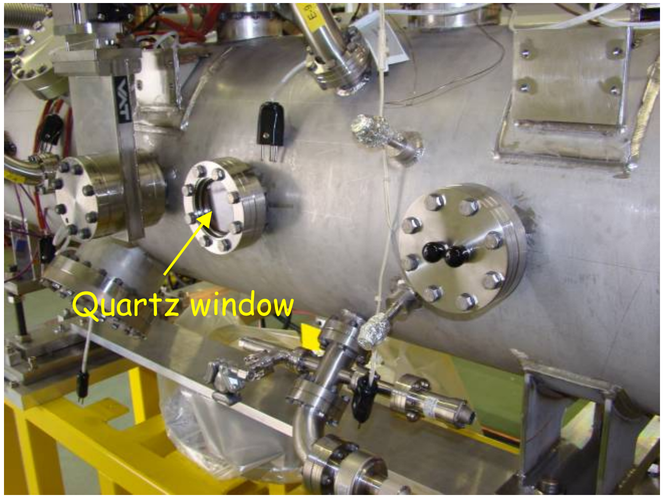

Model with time dependant coupling and phase




The full scale PETS testing will be restarted in June 2009

## TBTS PETS instrumentation upgrades in 2009




Two RF pick-ups were installed into the damping slots:

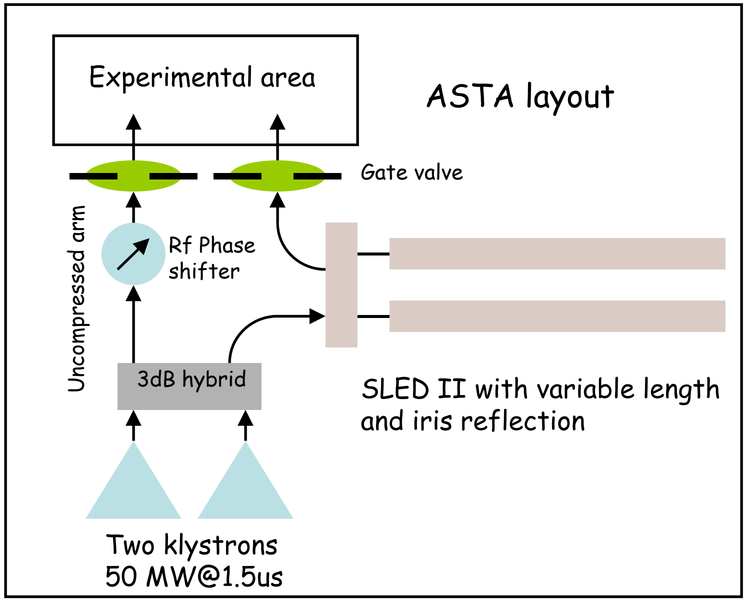
- Will allow monitoring of the beam position inside the PETS
- If happened, to measure RF signals in the slots during breakdown event.

The quartz window was installed on the PETS tank to register the light emission during breakdown event.

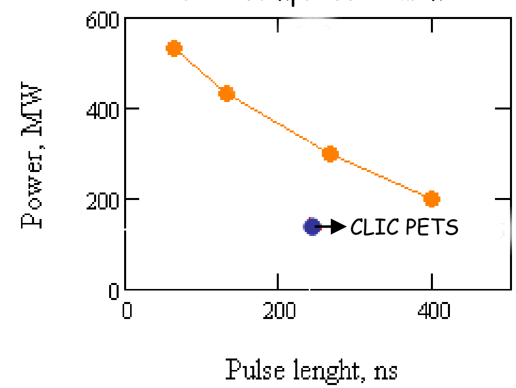
The acoustic sensors were installed on the waveguide components (attenuator and phase shifter), to localize breakdown position in a system.

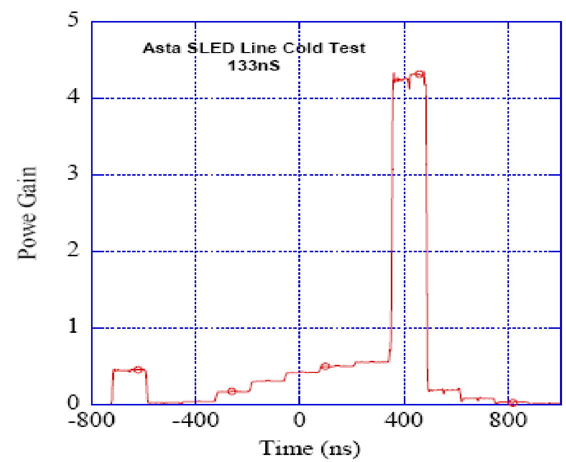
# PETS high power tests at SLAC

ASTA is a new generation general purpose test stand, which will allow processing the various types of the high power RF equipment at X-band. The facility can provide a very versatile pulse length and power level and 60 Hz repetition rate.




RF pulse @ power in the ASTA compressed arm



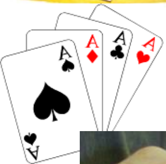




The ASTA pulse compressor with variable delay in delay-lines

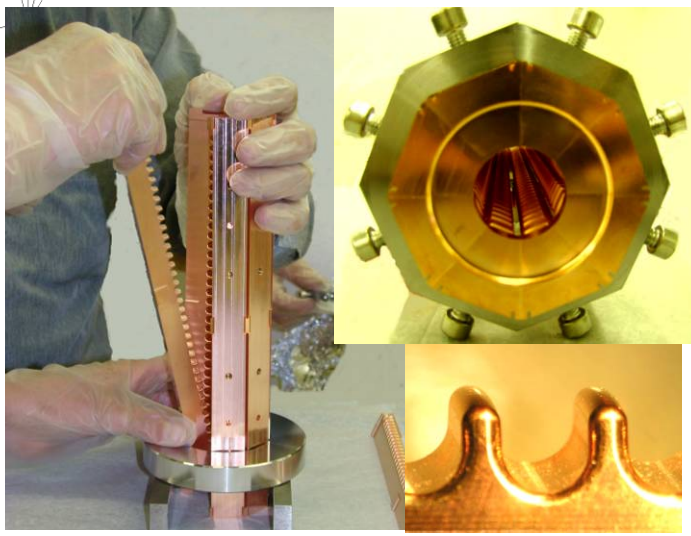
The ASTA pulse compressor with variable iris

The uncompressed arm has a variable phase shifter and a gate valve

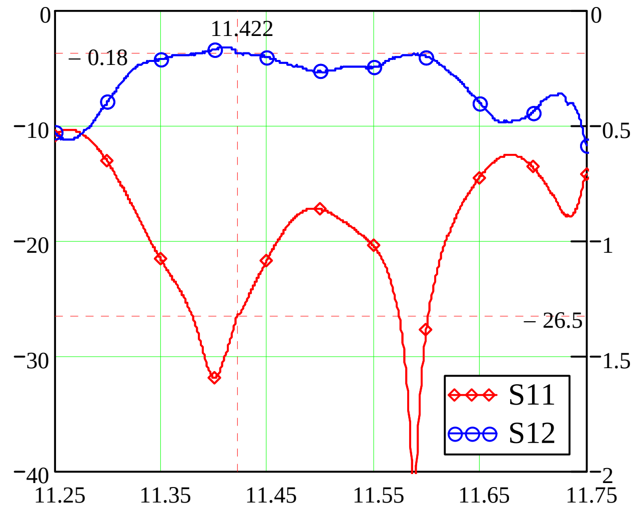
# PETS high power tests at SLAC



Assembly of the eight PETS bars.

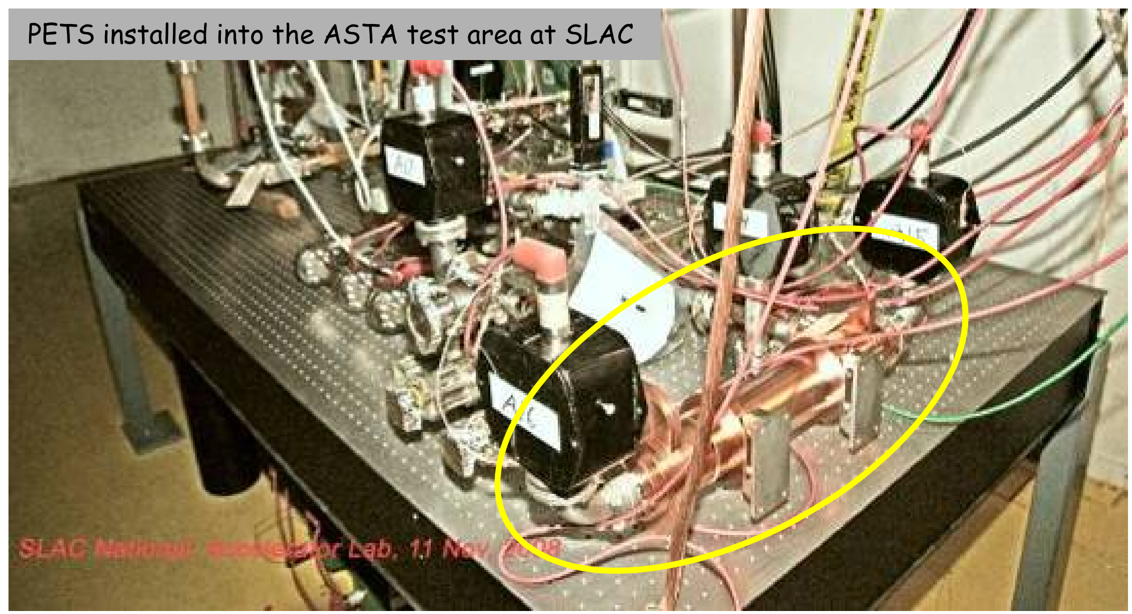


11. 424 GHz PETS measurements after final assembly



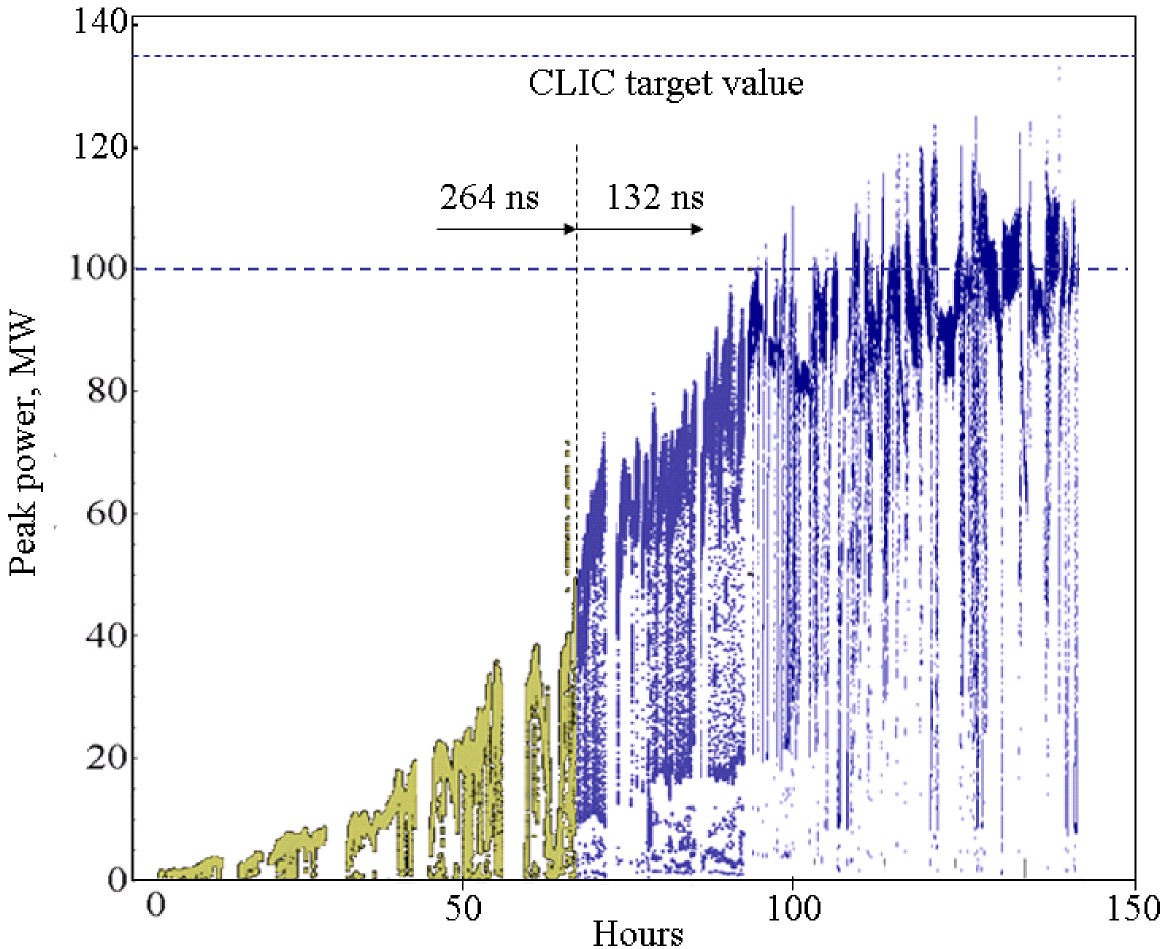

11.424 GHz PETS ready

PETS installed into the ASTA test area at SLAC



# PETS high power tests at SLAC

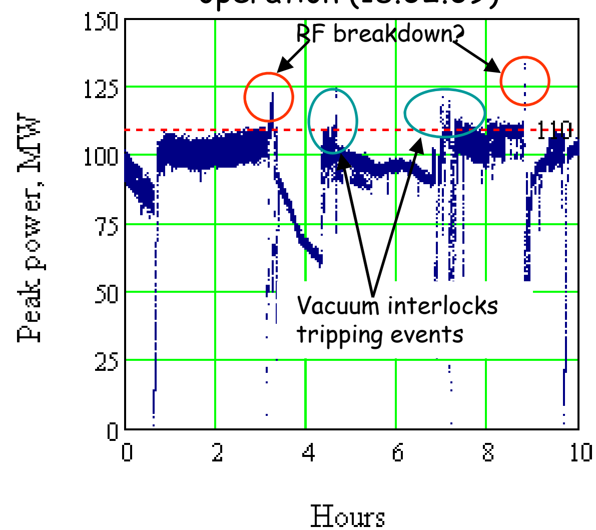
The winter 2008/09 PETS processing history in ASTA




At a peak power level above 110 MW, the processing speed was practically saturated, mostly limited by vacuum interlocks on the ion pumps, especially after the breakdown event .

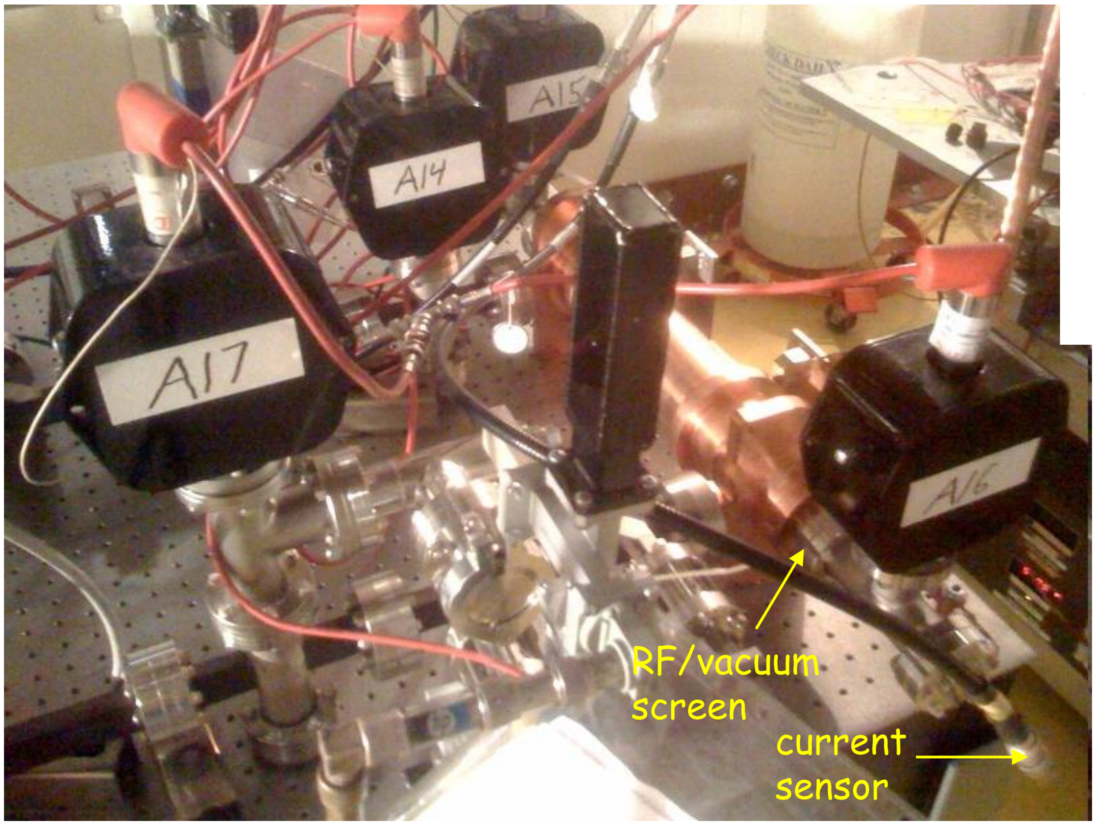
In April 2008, the PETS was removed and RF/vacuum screens were installed at the PETS extremities to avoid possible virtual vacuum activity in the pumps themselves induced by the RF power leakage out through the PETS power couplers into the pumps.

Zoom into the last 10 hours of operation (18.02.09)

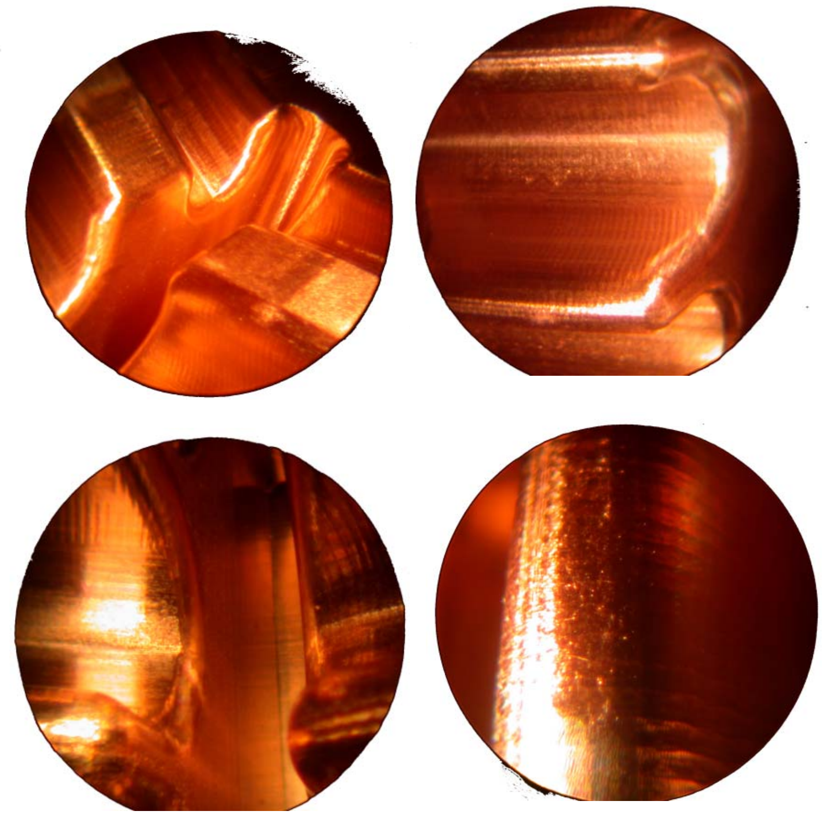


# PETS high power tests at SLAC

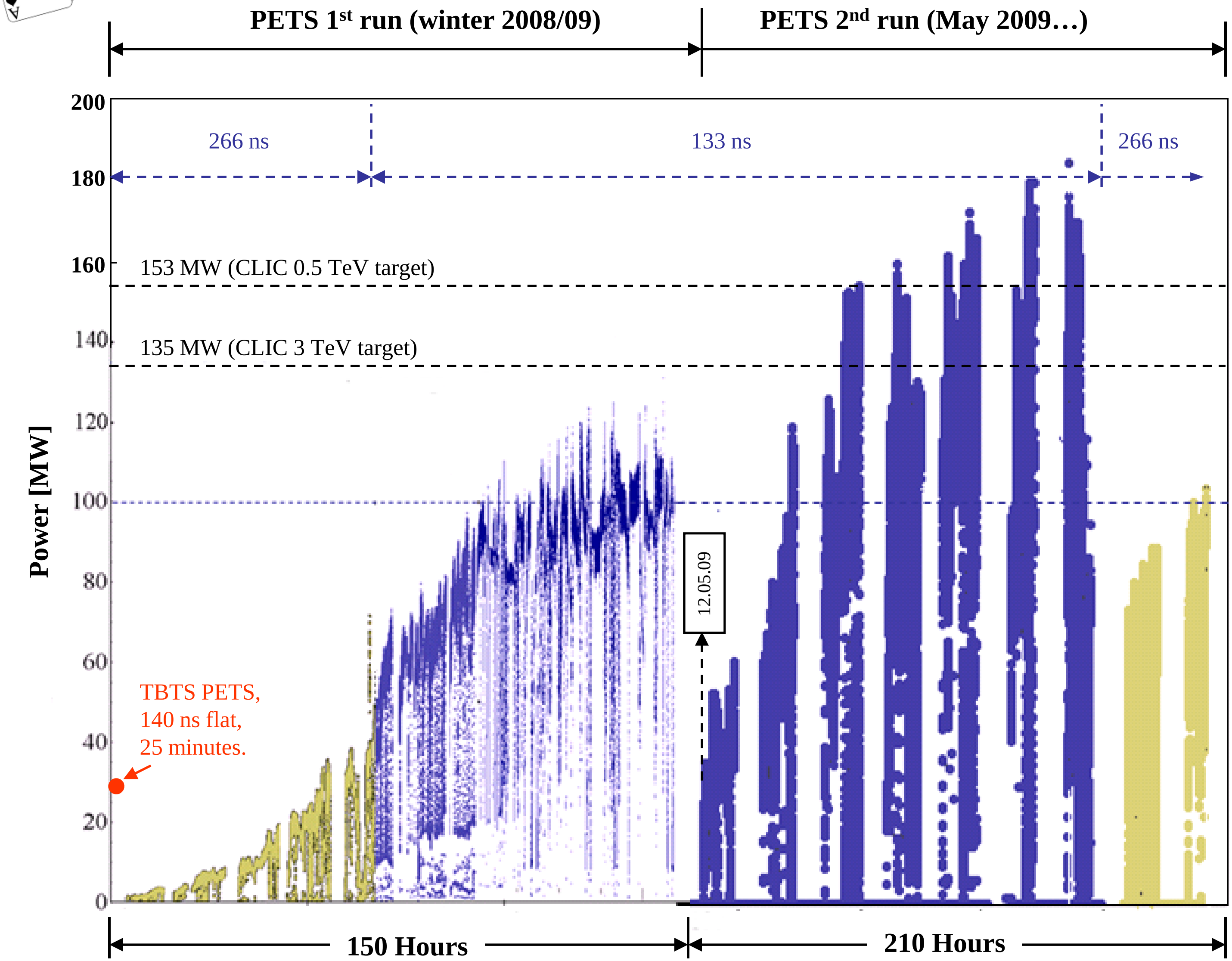
During the April shout down:
-The number of RF waveguide components were changed to improve the ASTA RF power capability.
- The RF/vacuum screens and current sensors were installed at the PETS extremities.




There we no traces of damage or surface degradation observed during visual inspection after the 1st test ran (> 100 MW x 133 ns)



# ASTA PETS processing history

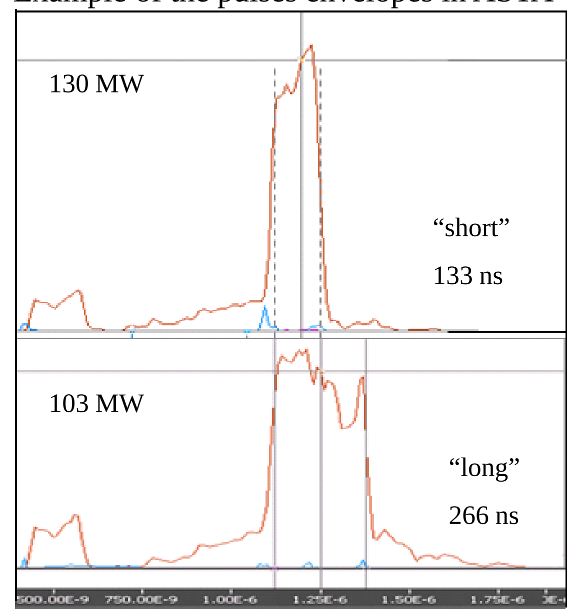



In general, the PETS has been processing up in power well.

- Beginning 12.05.09 processing of PETS with 133 ns we end up with 180MW on evening of 20.05.09
- 21.05.09 widened pulse to 266n s and have processed up to 103MW so far.
- Vacuum activity mostly in output end of PETS structure.

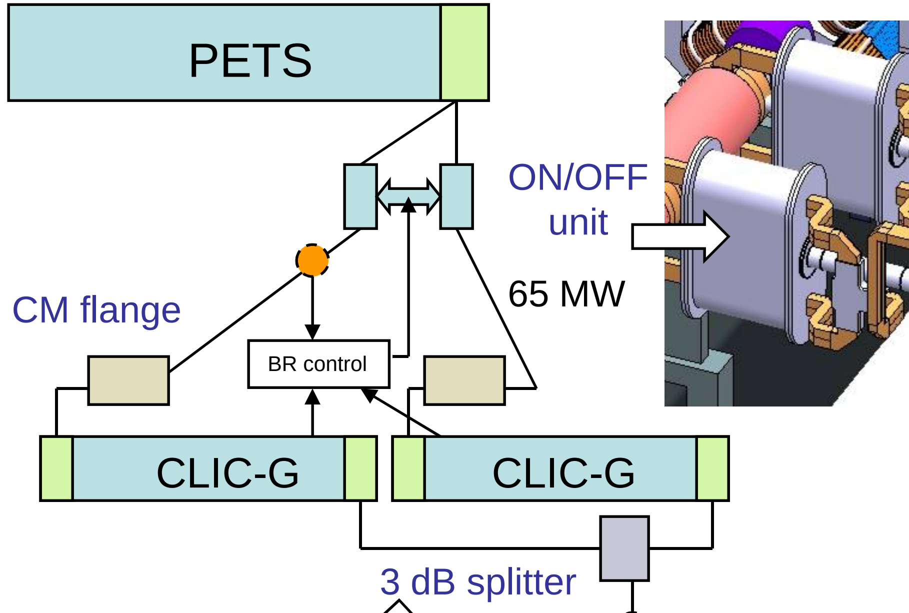
Jim Lewandowski (SLAC)

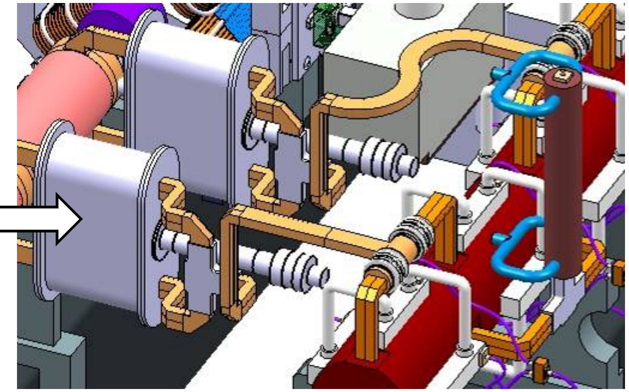
Example of the pulses envelopes in ASTA



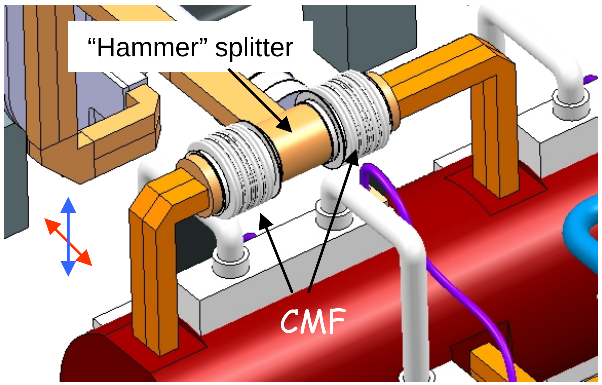

I. Syratchev, 4th ACE meeting, CERN, May 2009.

# Basic layout of the X band RF waveguide network in CLIC



To allow the independent transverse alignment of the two linacs in CLIC, the choke mode flanges (CMF) are planned to be used.

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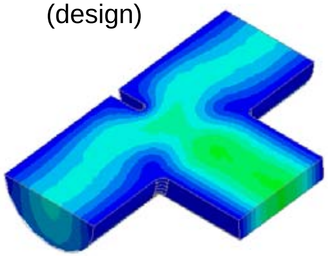
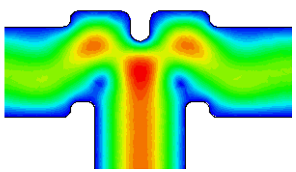
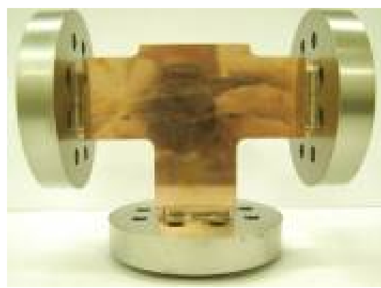
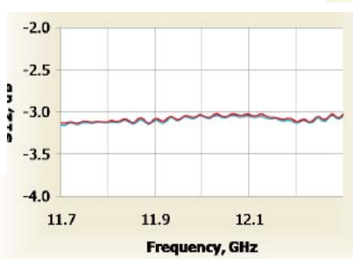
CERN

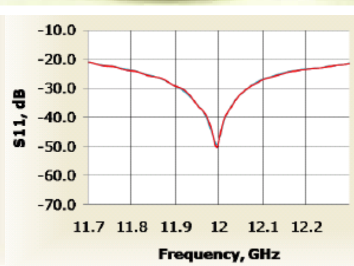
“Hammer” splitter (design)





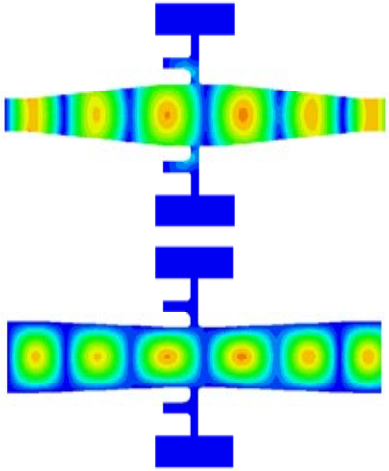





CERN

# CLIC RF waveguide network



Dynamic range for the accepted performance (S11< -45 dB)

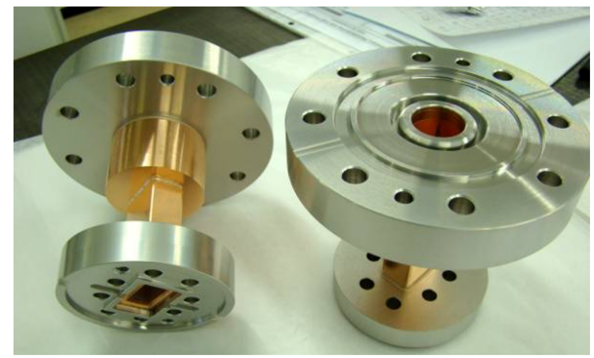
X - shift: ± 0.25 mm

Y - shift: ± 0.5 mm

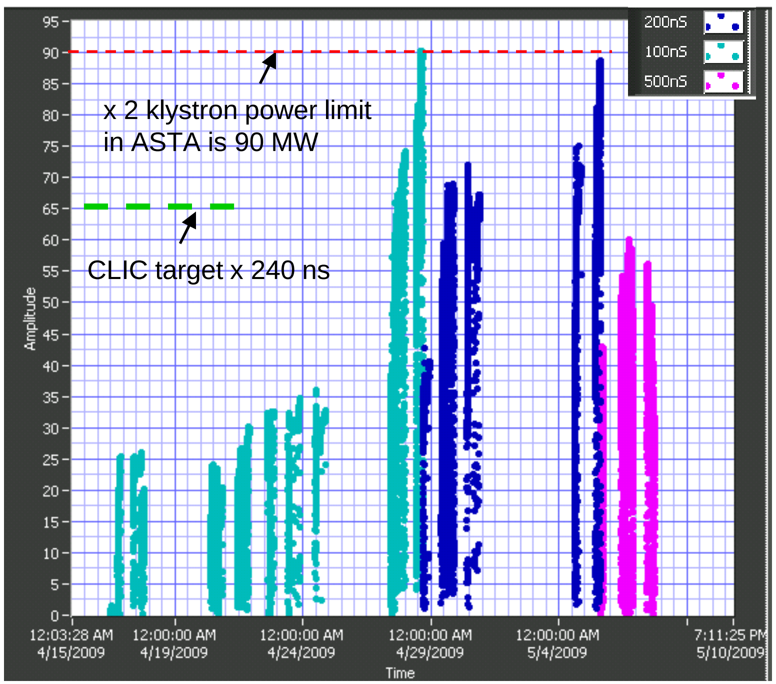
Z - shift: ± 0.5 mm

Twist: < $5^0$

11.424 GHz choke mode flange



CMF high power tests at SLAC (April/May 2009)




The choke flange performed well and we were ultimately limited by vacuum activity in the ion pumps near RF vacuum valve & phase shifter but not the choke flange itself.

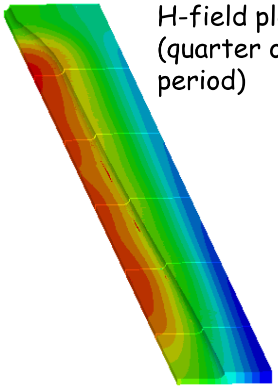
Jim Lewandowski, 08.05.2009

# CLIC RF waveguide network

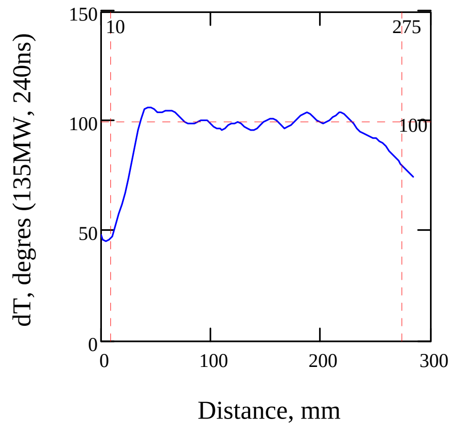
## Dry stainless steel RF load. High peak and high average power design.

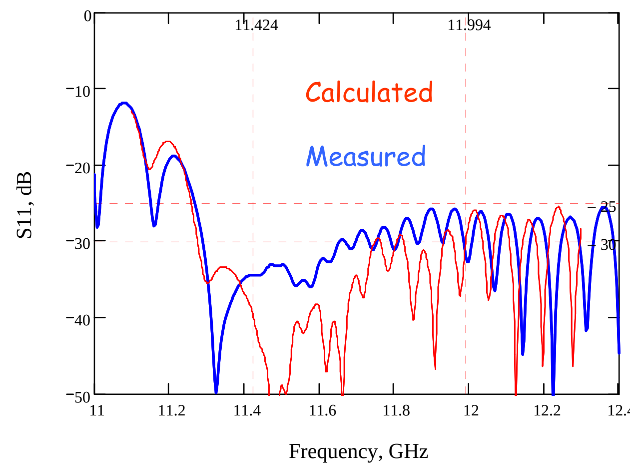
### Design specifics

H-field plot (quarter of the period)



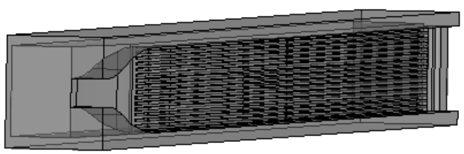
Pulsed heating distributions along the load:



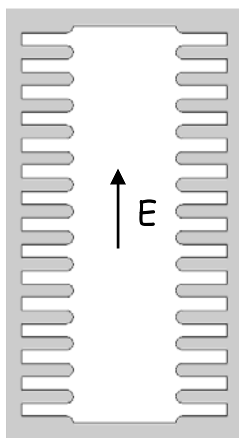




Double frequency, magnetic stainless steel 430.
Length 0.8 m.
High power tests at SLAC during summer 2009

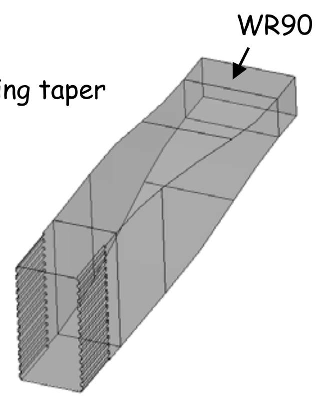
The load half



Load regular part cross section




Matching taper




For CLIC, the same technology will result in a rather compact device, about 0.35 m long