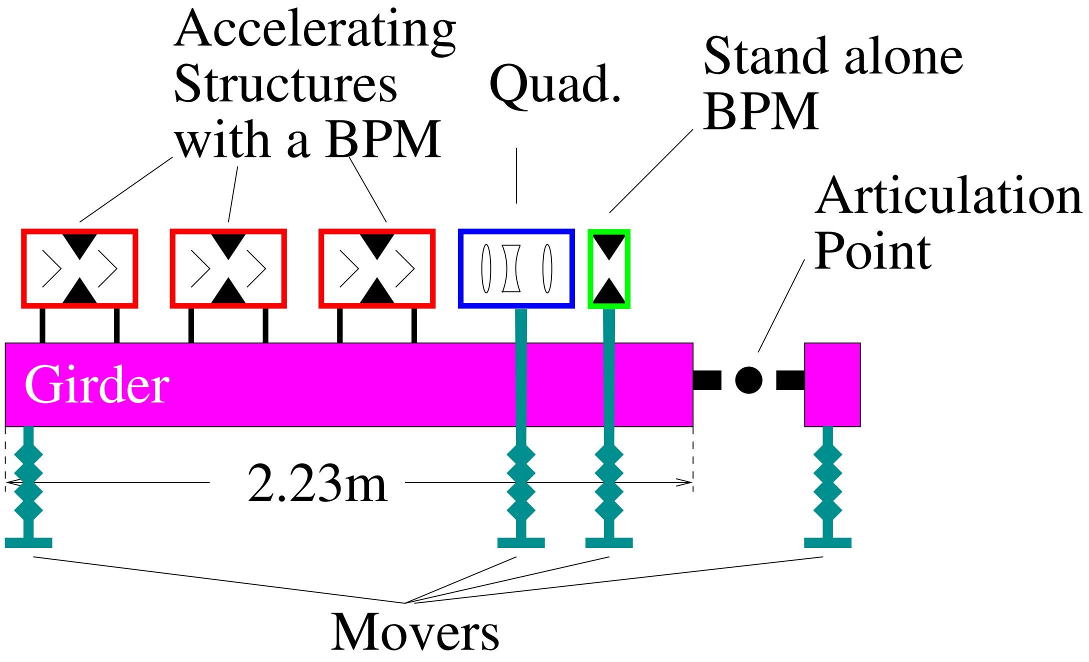
Beam Position Monitoring at CLIC

- Why and where does CLIC need beam position monitoring.
- Introduction to resonant cavity beam position monitors (BPMs).
- Single cell cavity BPM experiment in the CTF II.
- Proposition of a BPM for CLIC.
- Beam position and angle measurements with an undamped accelerating structure.
- Beam position measurement with a heavily damped accelerating structure.
- Conclusions.

presented by Jan Prochnow

Necessary Position Measurements at CLIC

CLIC main linac:



Accelerating Structures with a BPM

Quad.

Stand alone BPM

Articulation Point

Girder

2.23m

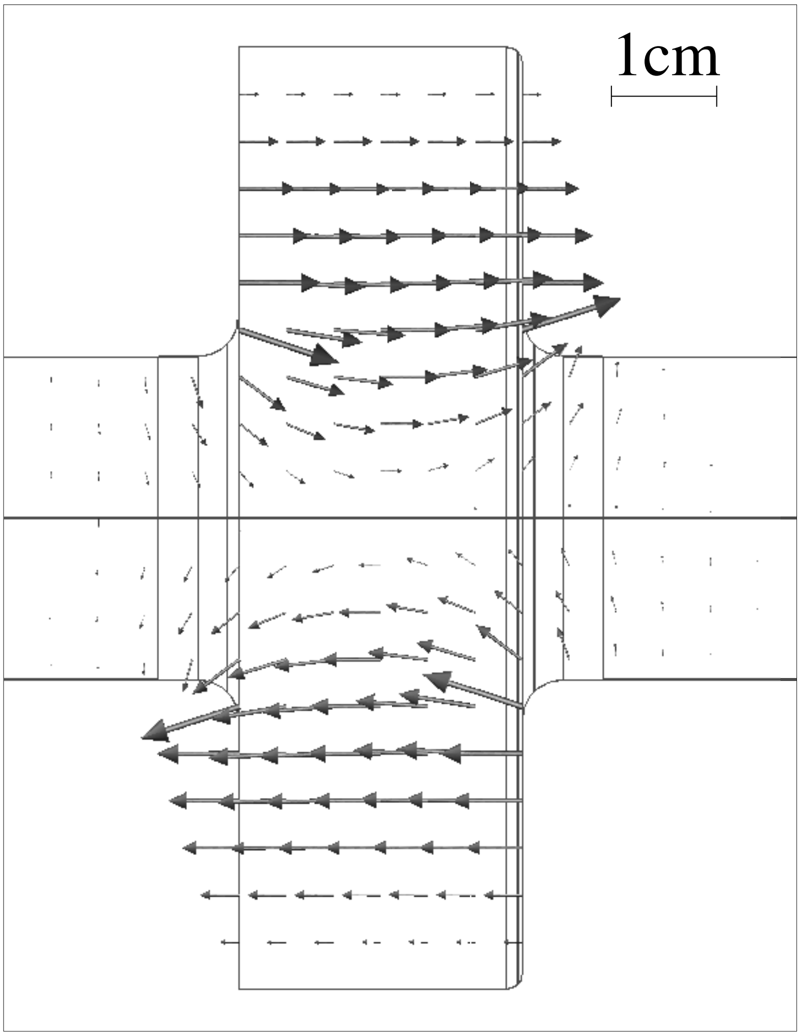
Movers

Beam Position Measurements:

Location	Motivation	Tolerances
Accelerating structure	Structure alignment to minimise and compensate transverse wakefields.	Accuracy of 10 µm with respect to the structure's centre.
Quadrupoles	Quad. alignment to avoid dispersion.	Resolution of several 100 nm.
Every ≈ 12^{th} quad. BPM (≈ 70 m)	"Anchor" for ballistic alignment.	Accuracy of 10 µm with respect to the quad.

Resonant Cavity Beam Position Monitoring

Electric Field of the TM_{11} Mode in a 30 GHz Pill Box Cavity:



The excitation by a beam is proportional to the $\vec{E}$ field component along the trajectory.

Advantages:

- no gain equalisation required like for button pick-ups.
- accelerating structures can be used as resonators.

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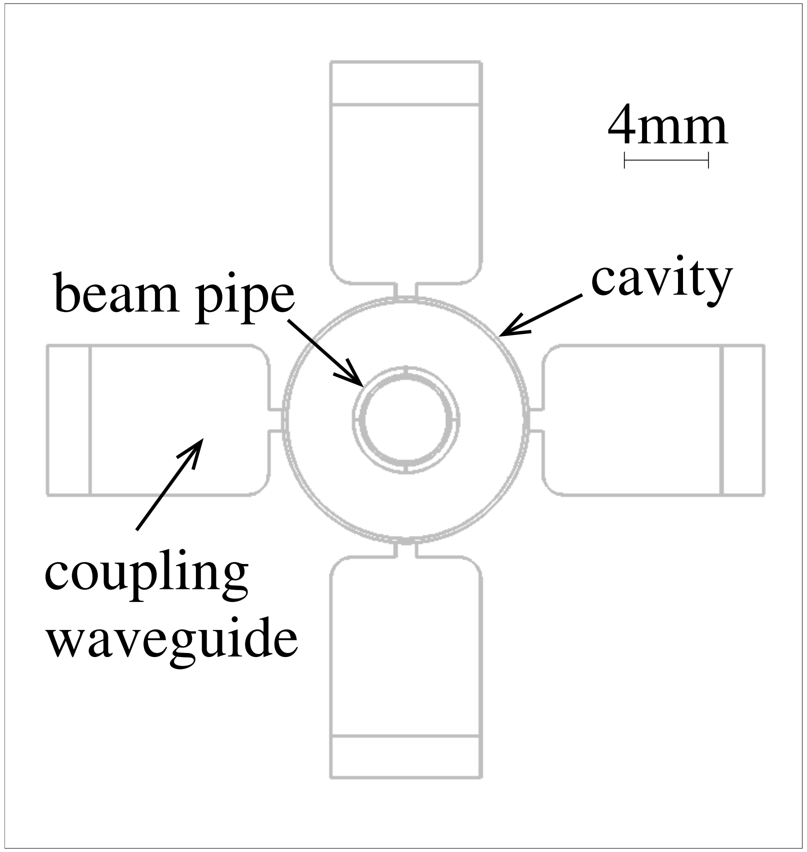
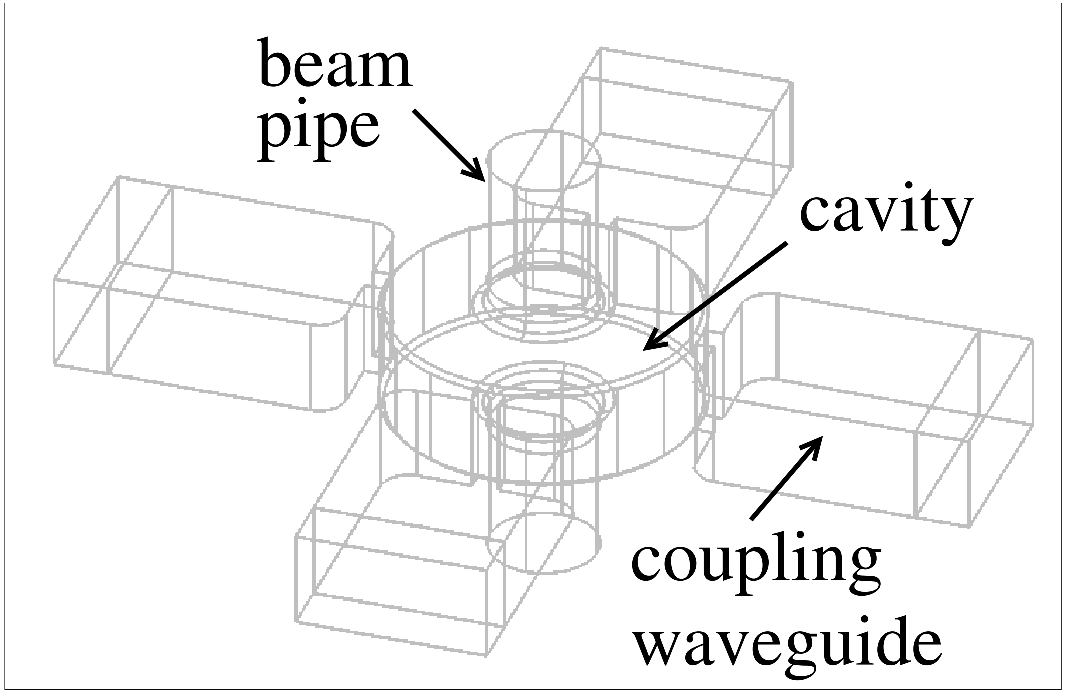
The CTF II Beam Position Monitors (I)

The excitation of the TM_{11} mode is sensed through waveguides.
The waveguides are coupled to the cavity via irises.

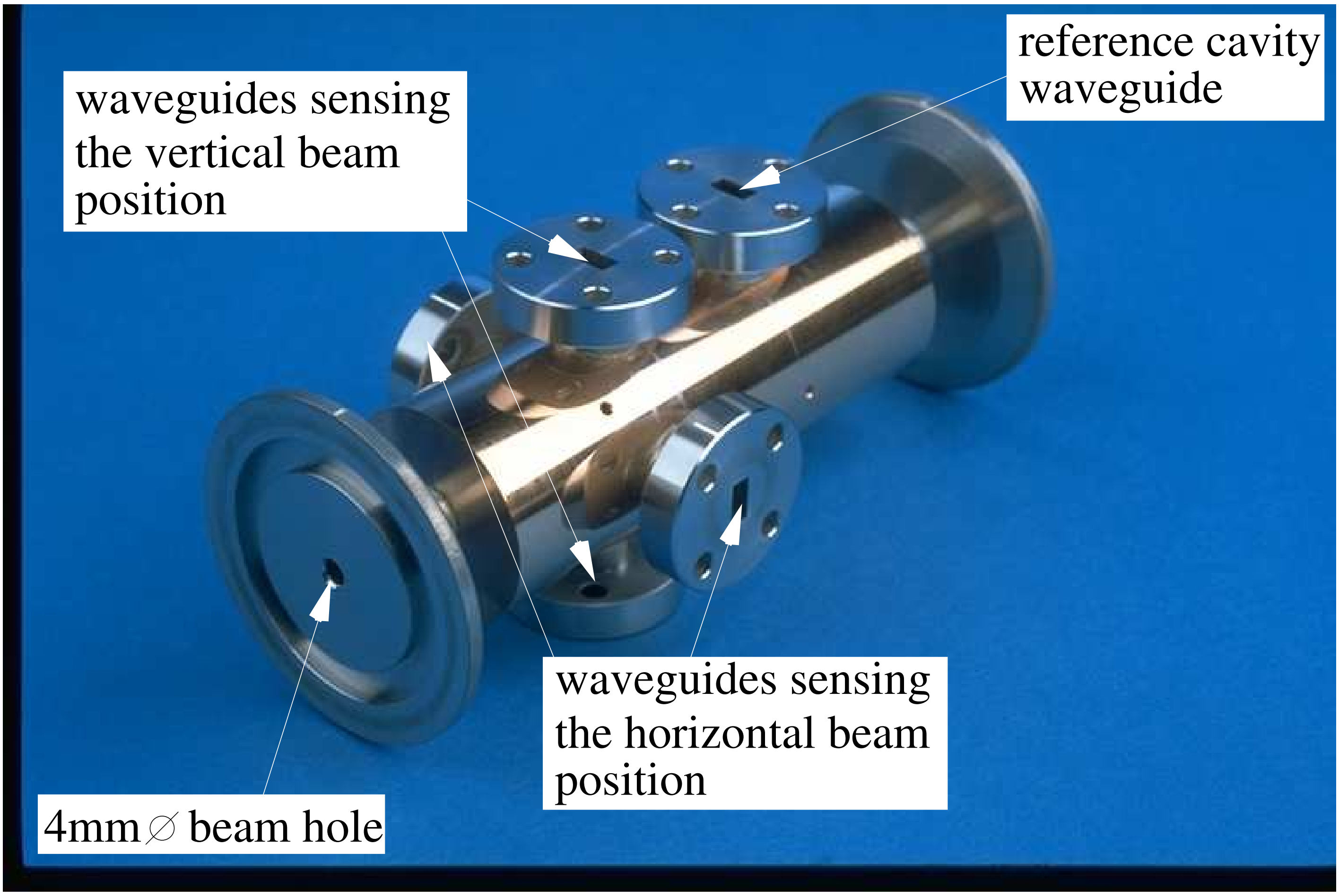




- Two waveguides for each polarisation allow external symmetry rejection.
- A reference cavity was used for charge normalisation and timing.

The CTF II Beam Position Monitors (II)

Photo:



Properties:

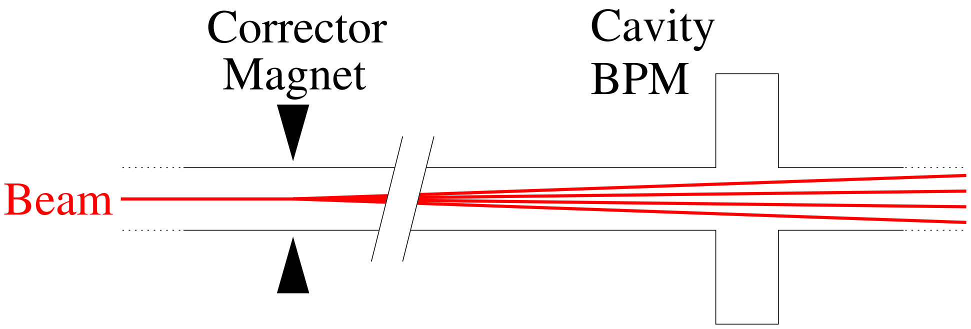
	TM_{01}	TM_{11}
f (with waveguides; with losses)	20.5603 GHz	29.9847 GHz
f (with waveguides; w/o losses)	20.5624 GHz	29.9867 GHz
f (w/o waveguides; with losses)	20.6267 GHz	30.0709 GHz
external quality factor $Q_{ext.}$	∞	499 094.
unloaded quality factor Q_o	4815.01	5381.39
loaded quality factor Q_l	4631.51	5031.08
R_s/Q @ 1 mm	61.2114 V/A	10.5725 V/A
loss factor k @ 1 mm	396.654×10^{10} V/C	99.912×10^{10} V/C

Beam Position Monitors in the CTF II

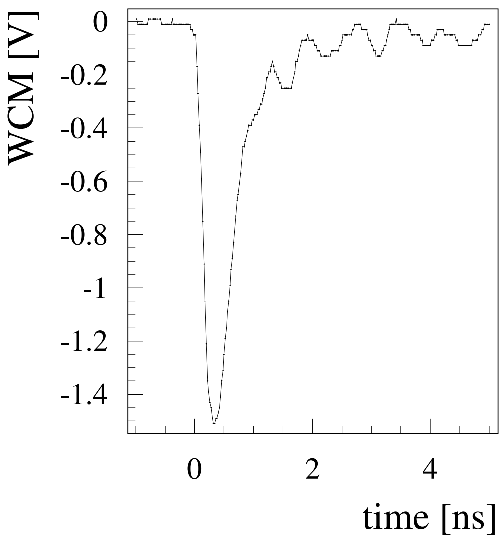
The CTF II probe beam:

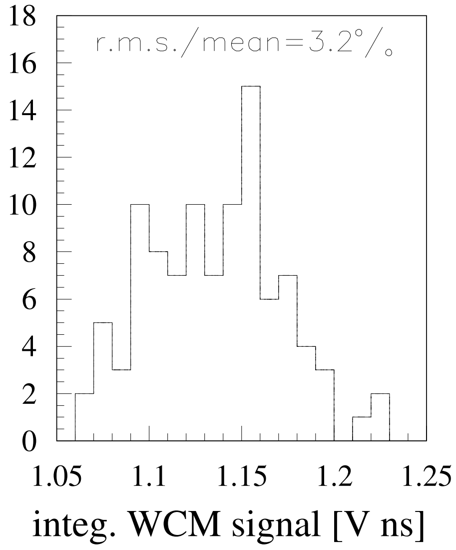
mean beam energy	62 MeV
pulse repetition frequency	5 Hz
charge per bunch	13.4 nC
total beam power	400 W
bunch length	600 µm

Experimental Setup:



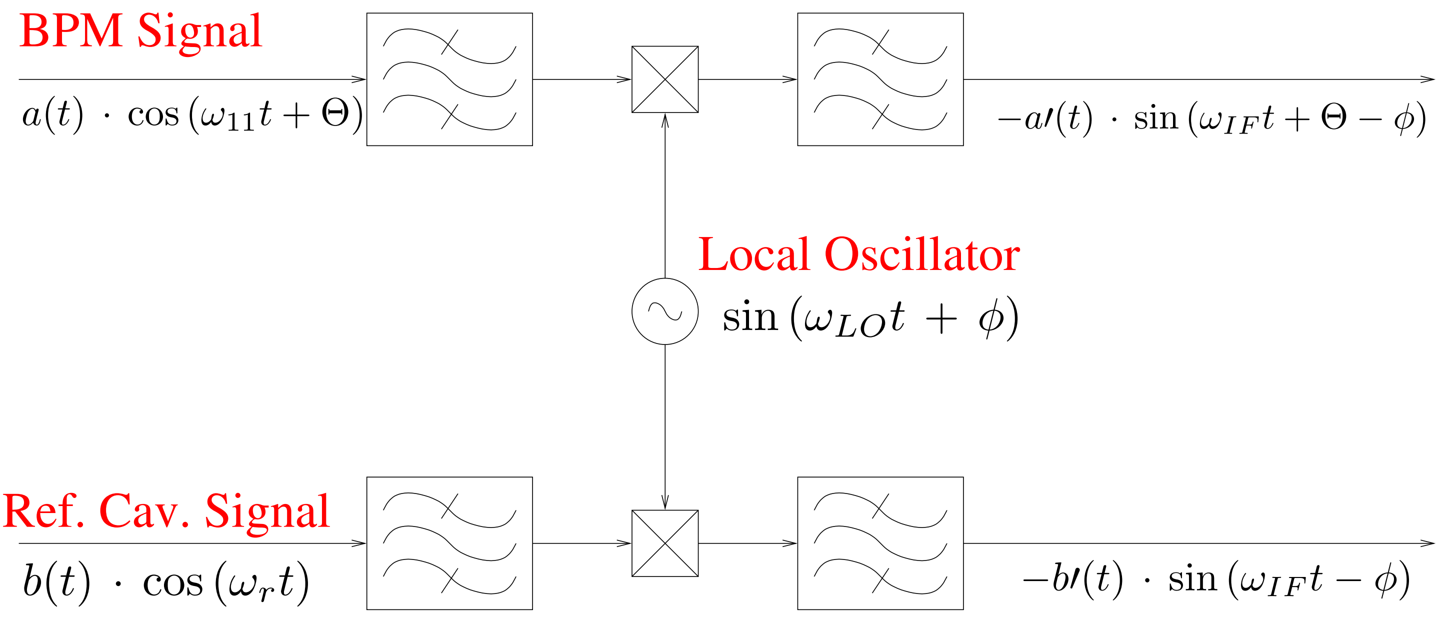
Beam current variation:





The Electronics:

Layout:



BPM Signal

$a(t) \cdot \cos(\omega_{11} t + \Theta)$

$-a\prime(t) \cdot \sin(\omega_{IF} t + \Theta - \phi)$

Local Oscillator

$\sin(\omega_{LO} t + \phi)$

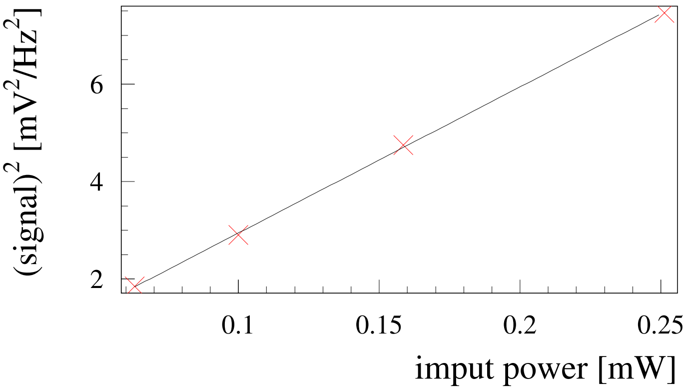
Ref. Cav. Signal

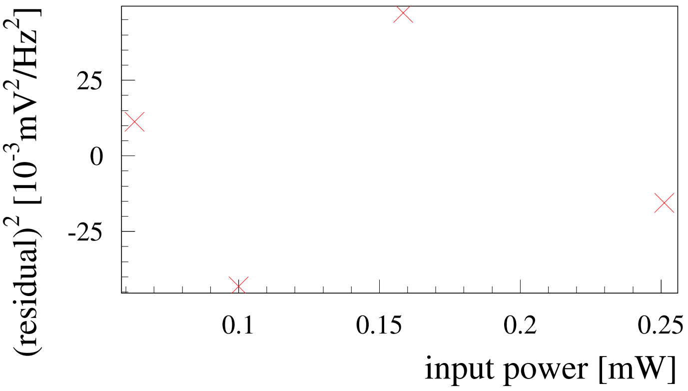
$b(t) \cdot \cos(\omega_r t)$

$-b\prime(t) \cdot \sin(\omega_{IF} t - \phi)$

f_{RF}=29.985 GHz **f_{LO}=30.105 GHz** **f_{IF}=120 MHz**

Performance:





The r.m.s. deviations from the linearity are -29.5 dBm

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The Signal from one Bunch Crossing (Measurements)

Time domain signal:

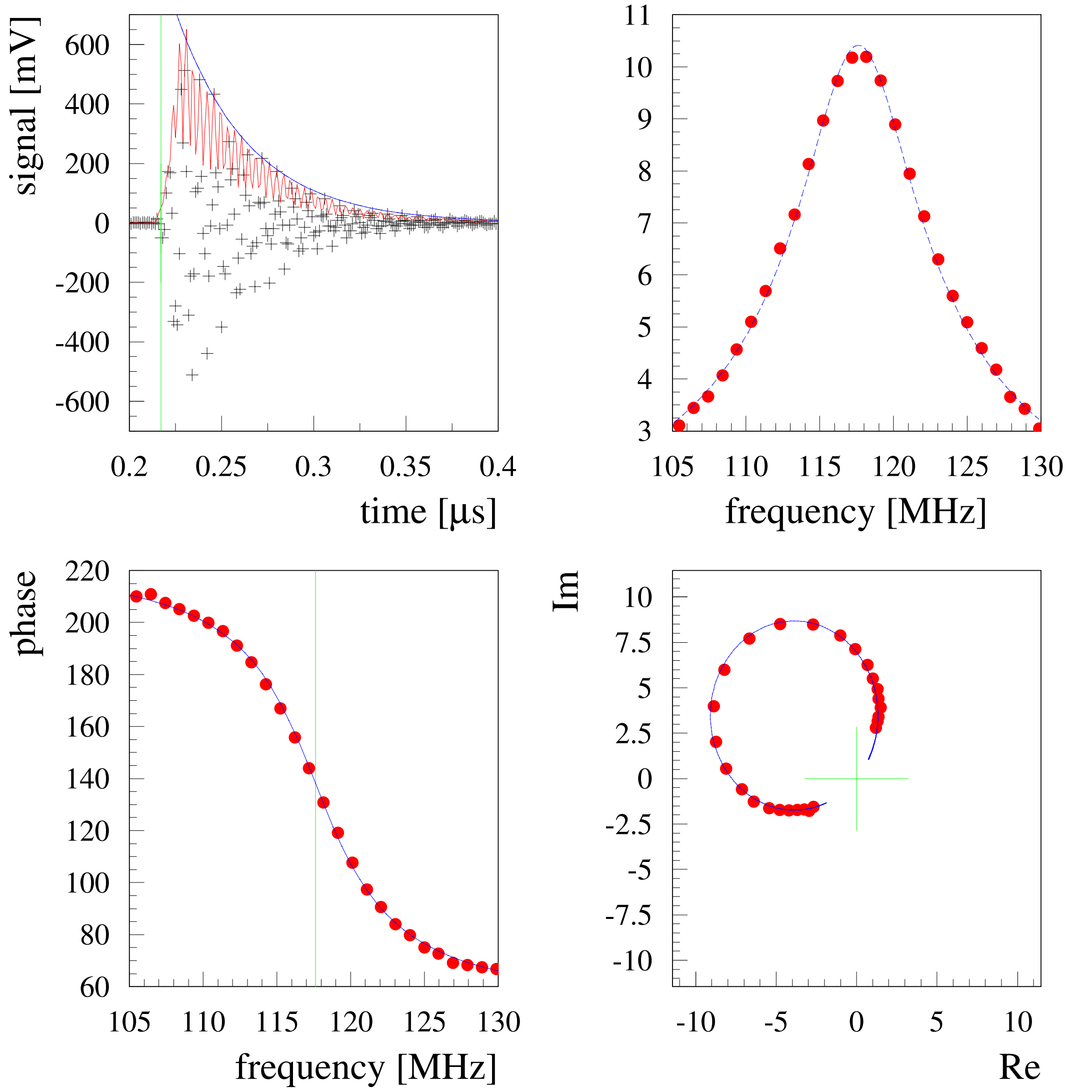
$$f(t) = 2kqxe^{-\beta_o t}\cos(\omega_o t)\Theta(t); \quad \beta_o = \frac{\omega_o}{2Q}$$

Frequency domain signal:

$$\Re\{F(\omega)\} = kqx\left(\frac{\beta_o}{\beta_o^2+(\omega-\omega_o)^2}+\frac{\beta_o}{\beta_o^2+(\omega+\omega_o)^2}\right)$$

$$\Im\{F(\omega)\} = -kqx\left(\frac{\omega-\omega_o}{\beta_o^2+(\omega-\omega_o)^2}+\frac{\omega+\omega_o}{\beta_o^2+(\omega+\omega_o)^2}\right)$$

The frequency- and time-domain signals are well described by the fits with the theoretical functions.



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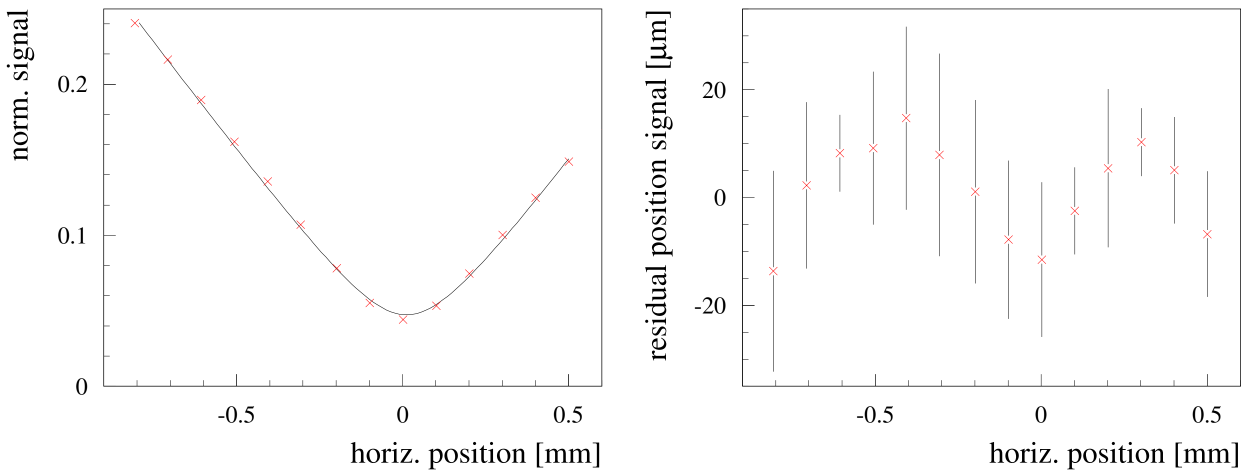
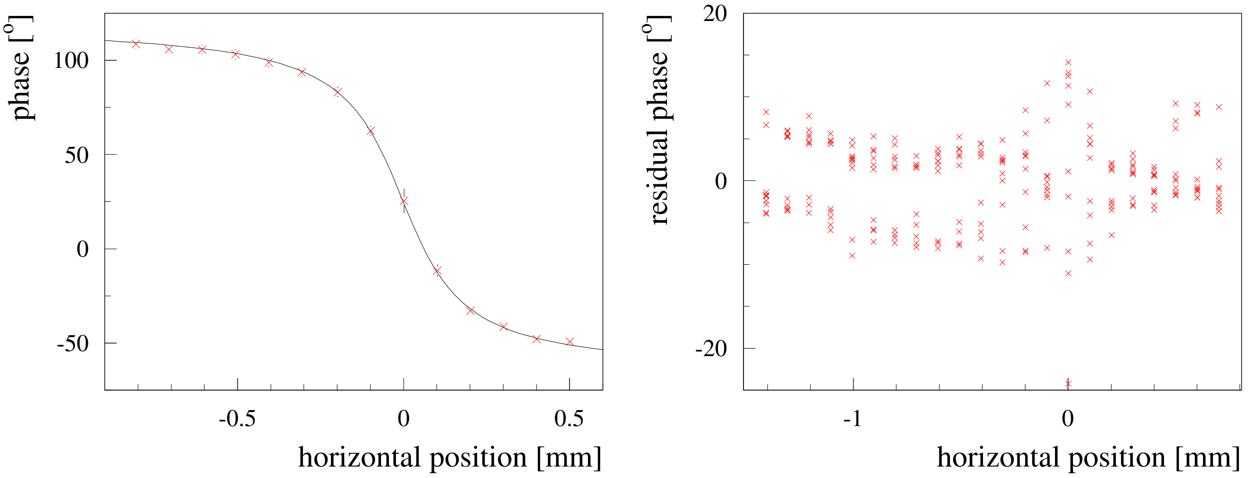
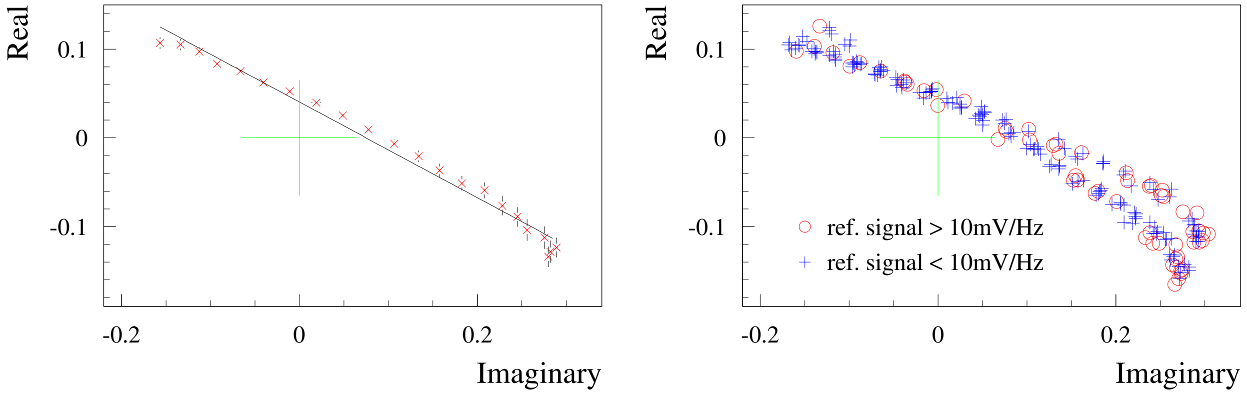
Beam Position Dependency



r.m.s. of the mean amplitude deviations is 8.4 µm.



r.m.s. of the mean phase deviations is 1.1 °.



The measurements separate into two phase states.

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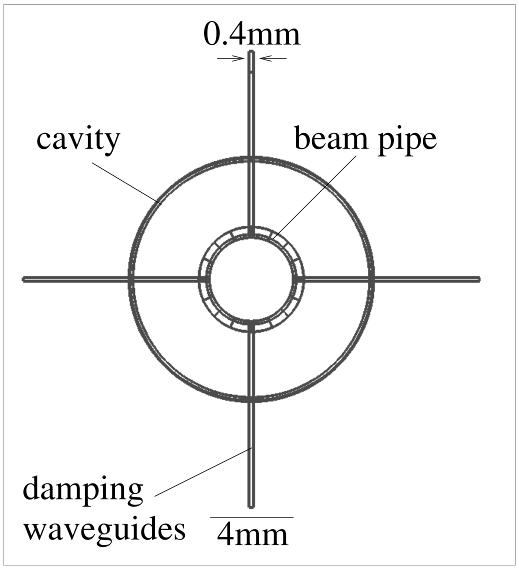
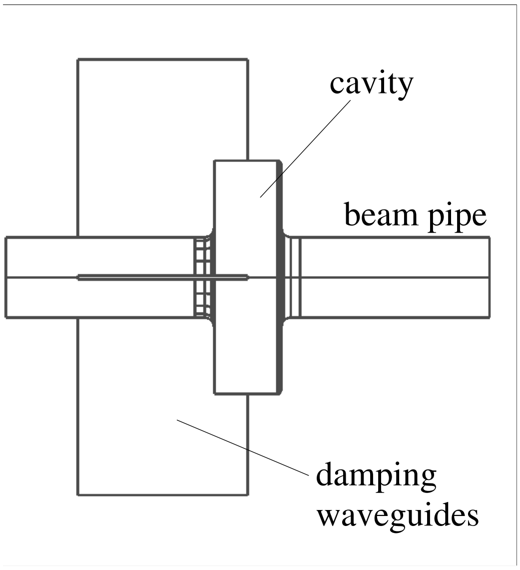
Beam Position Monitor for CLIC (I)

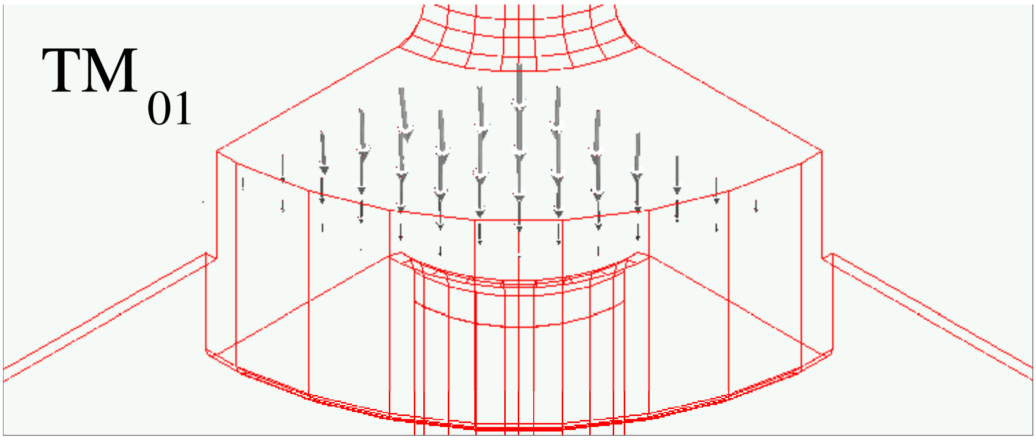
Concerns for CLIC:

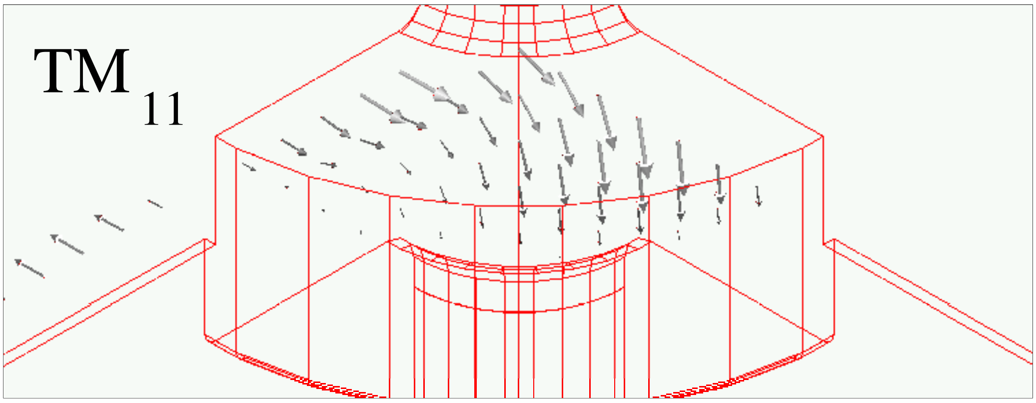
- Dipole mode damping.
- Common mode rejection.





Azimuthal electric fields induce voltages across the gap.





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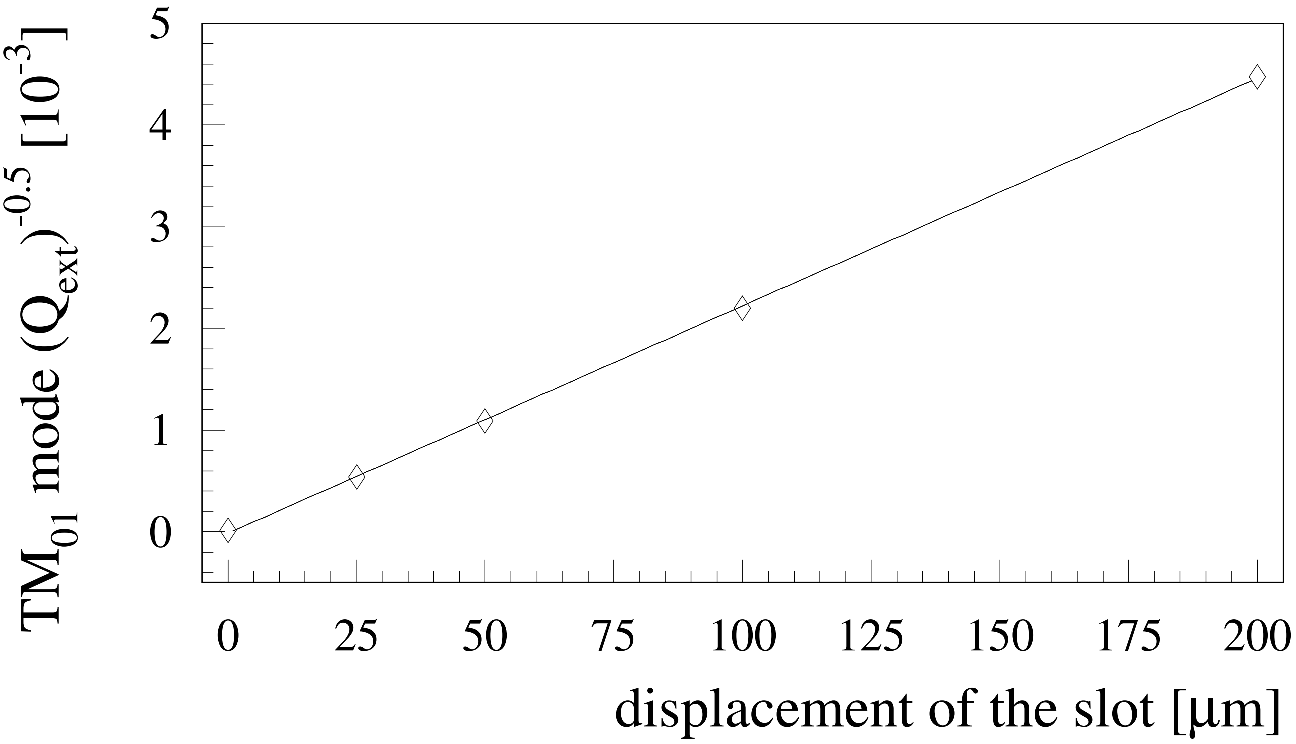
Beam Position Monitor for CLIC (II)

Properties:

	TM_{01}	TM_{11}
f (with waveguides; with losses)	20.1243 GHz	29.9984 GHz
f (with waveguides; w/o losses)	20.1257 GHz	30.0002 GHz
f (w/o waveguides; with losses)	20.1234 GHz	29.4270 GHz
external quality factor $Q_{ext.}$	∞	18.2404
unloaded quality factor Q_o	4796.64	5328.18
loaded quality factor Q_l	4771.73	18.5399
R_s/Q @ 1 mm	31.3289 V/A	5.41031 V/A
loss factor k @ 1 mm	198.060×10^{10} V/C	50.0171×10^{10} V/C

Performance:



For	manufacturing error	$<$	50µm
$\Longrightarrow$	external quality factor	$>$	8.22×10^5
$\Longleftrightarrow$	stored energy lost to wg. per cycle	$<$	1.22×10^{-6}

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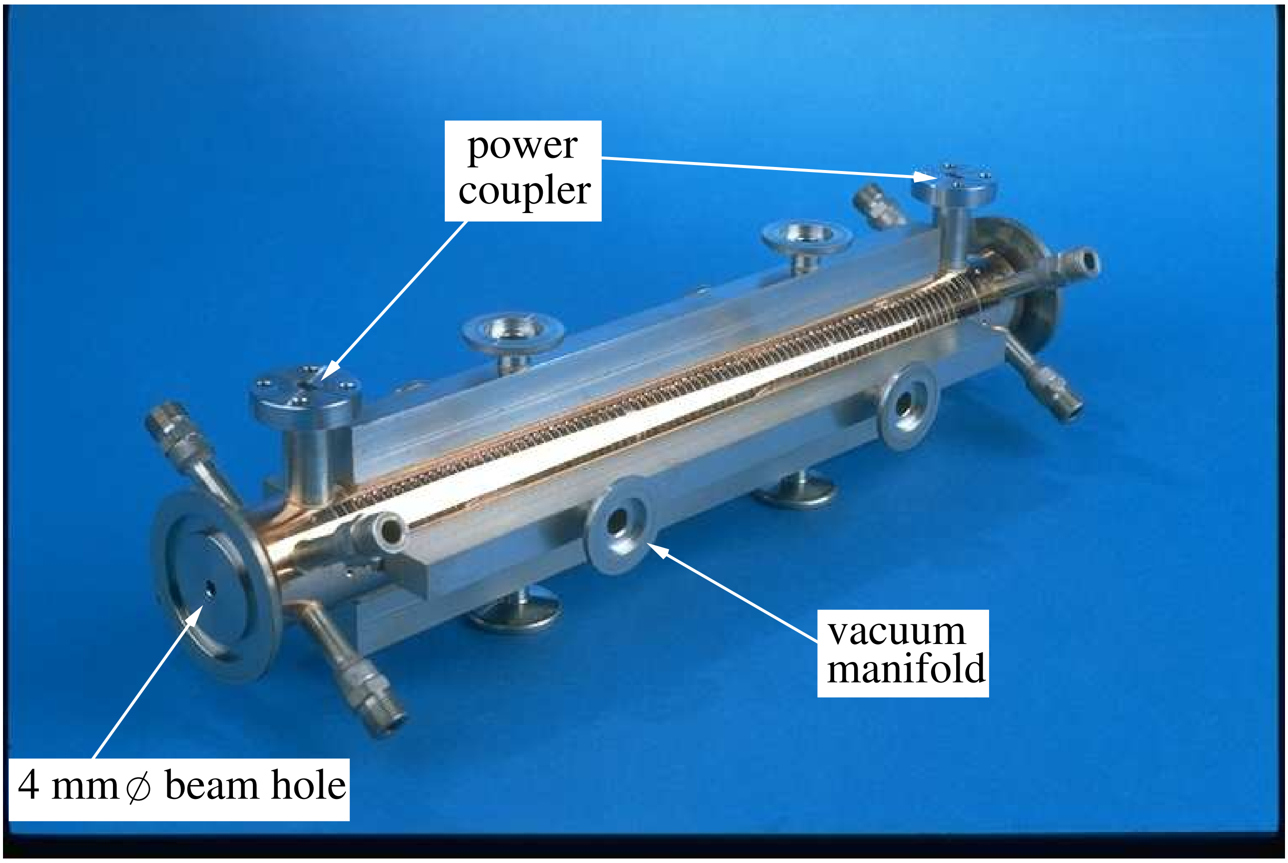
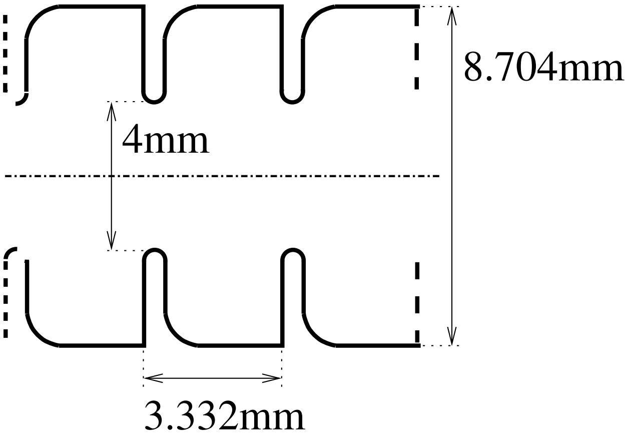
Position and Angle measurement with an undamped Accelerating Structure (I)

The CAS Accelerating Structure:





TM$_{11}$ mode:

f_o	38.5 GHz
Q	2832
v_g	3.14 % c

Position and Angle measurement with an undamped Accelerating Structure (II)

Structure response : $U(t) = U_o(x)\, e^{-\frac{\omega t}{2Q}}$; $U_o(x) = 2\,k\,q\,x$

For a ***skewed*** beam : $\mathbf{x} = \mathbf{x}_o + \alpha\,\mathbf{z}$

This results in : $U_o(t) = 2\,k\,q\,[x_o + \alpha \cdot (l - v_g\,t)]$

@ output coupler.

where x_o : beam position at the end of the structure.

α : beam angle .

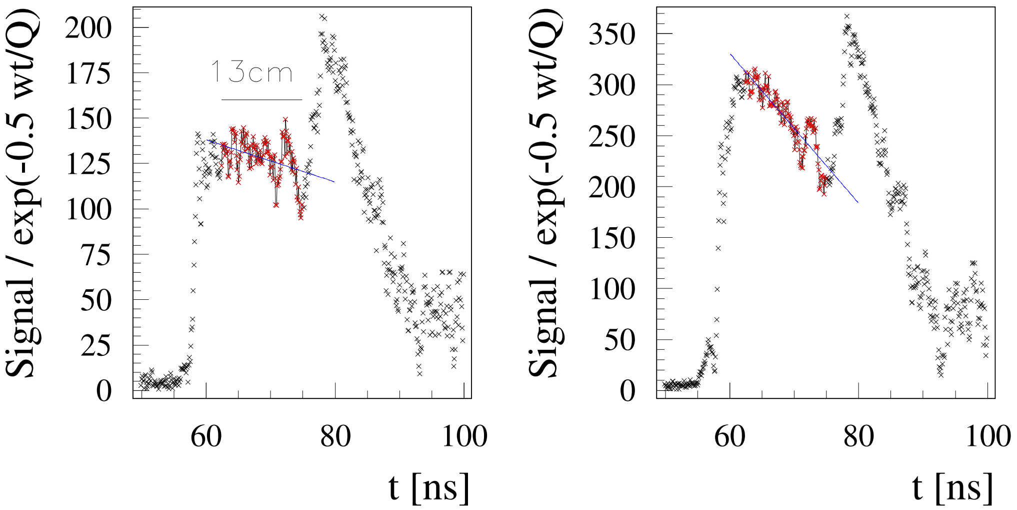
l : length of the structure (measured).

v_g : group velocity of the structure (simulated).

Fitting the function $U(t)\,/\,e^{-\frac{\omega t}{2Q}} = (p_1 + p_2\,t)$ provides both angle and offset except the charge q and loss factor k which were calibrated:

$$\alpha = -\frac{1}{2\,k\,q}\frac{p_2}{v_g} \qquad x_o = \frac{1}{2\,k\,q}\left(p_1 + \frac{l}{v_g}p_2\right)$$

Signals for 2 different trajectories:



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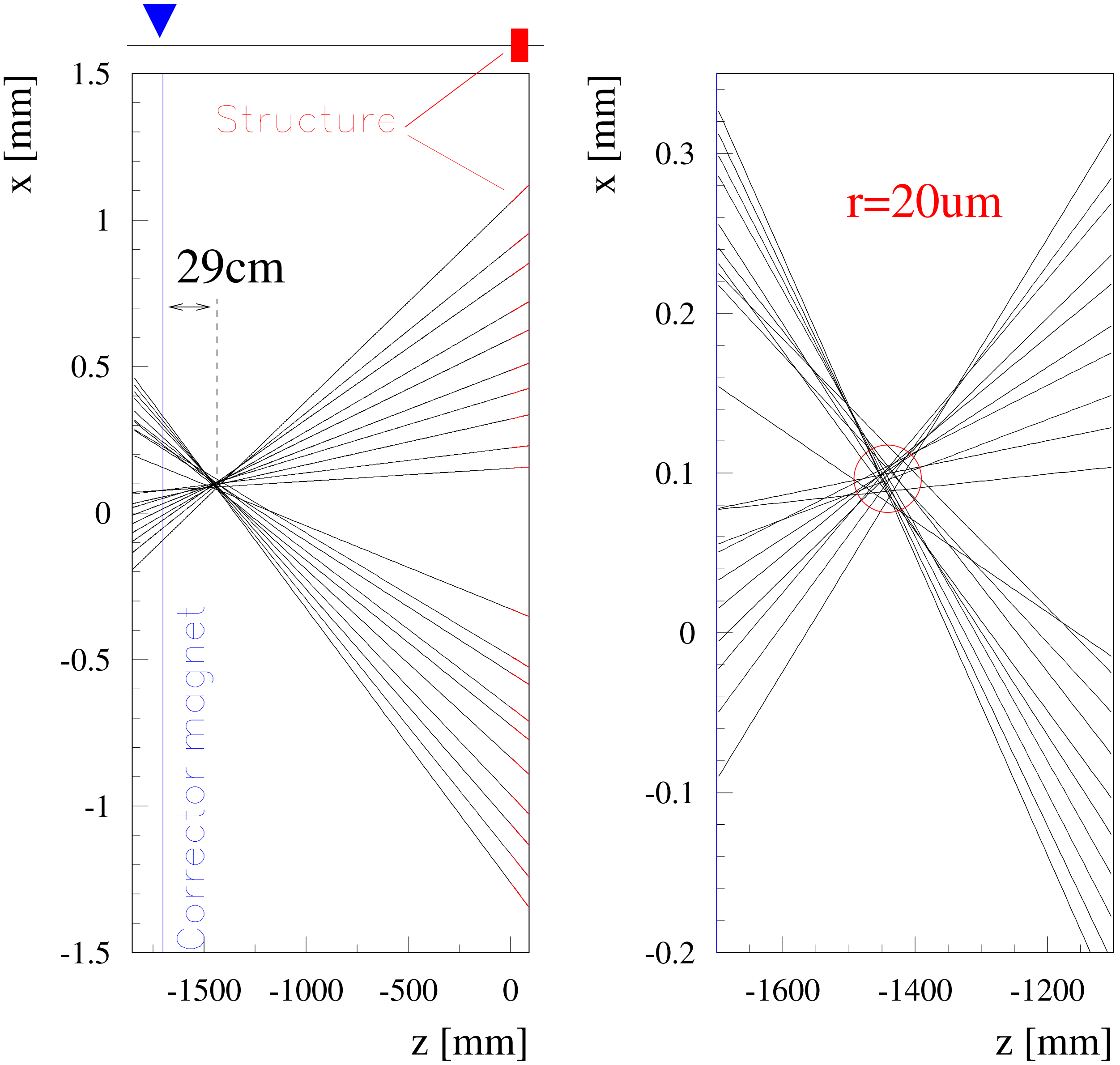
Position and Angle measurement with an undamped Accelerating Structure (III)

HFSS results: $Q = 3832$ $v_g = 3.14\,\%\,c$



Angular resolution of 7.5 µrad
Position resolution of 6.3 µm

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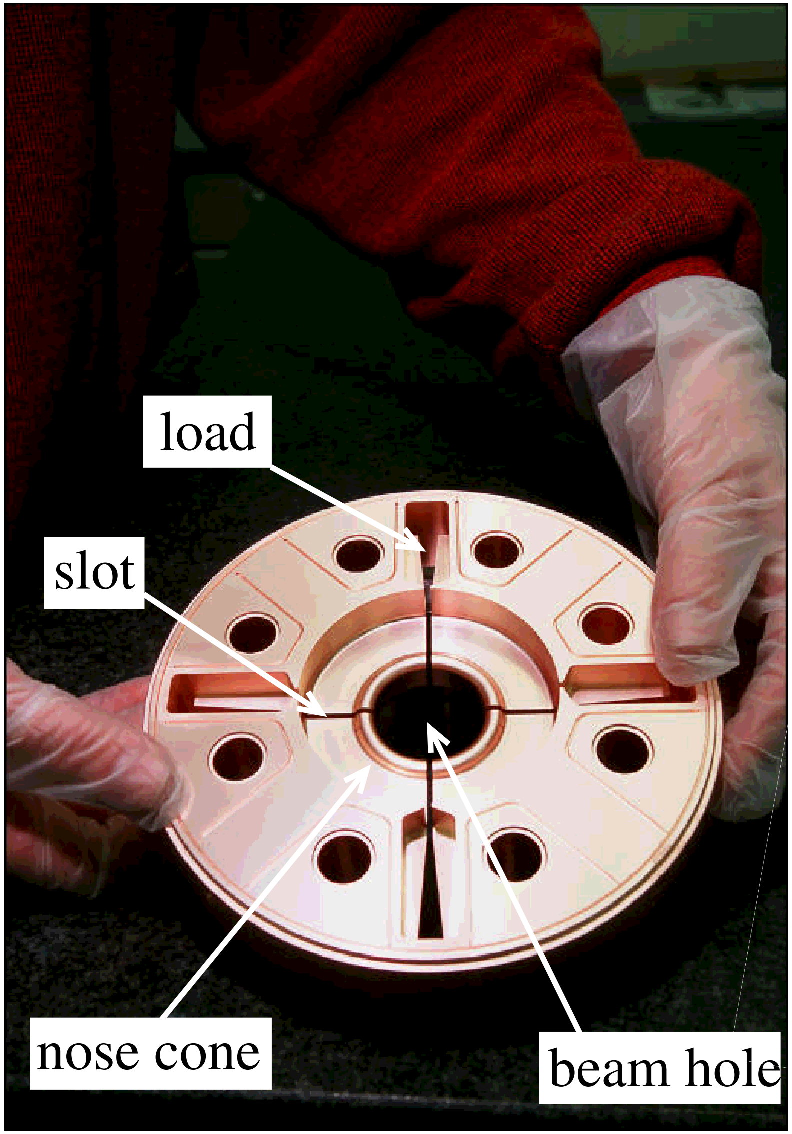
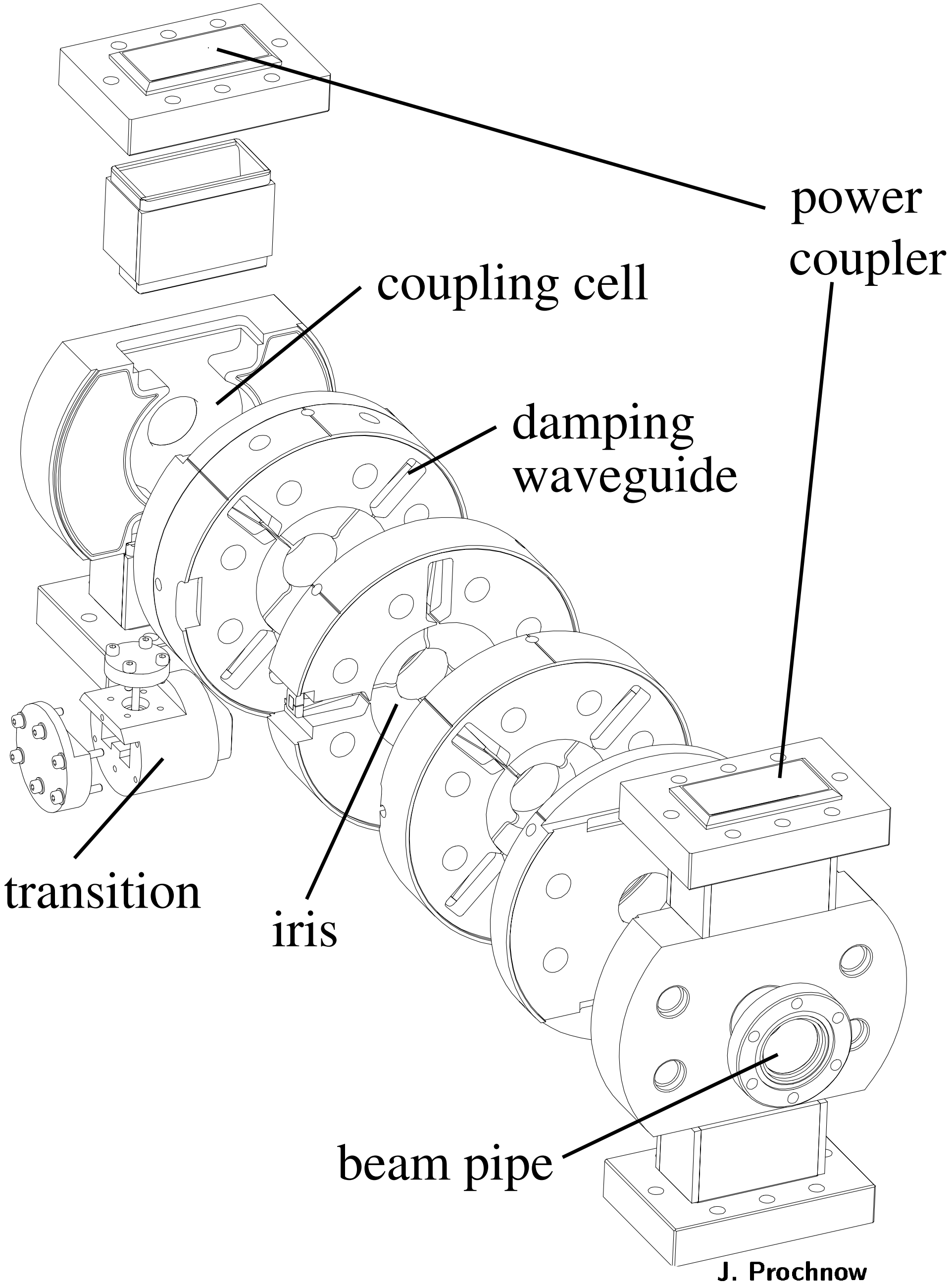
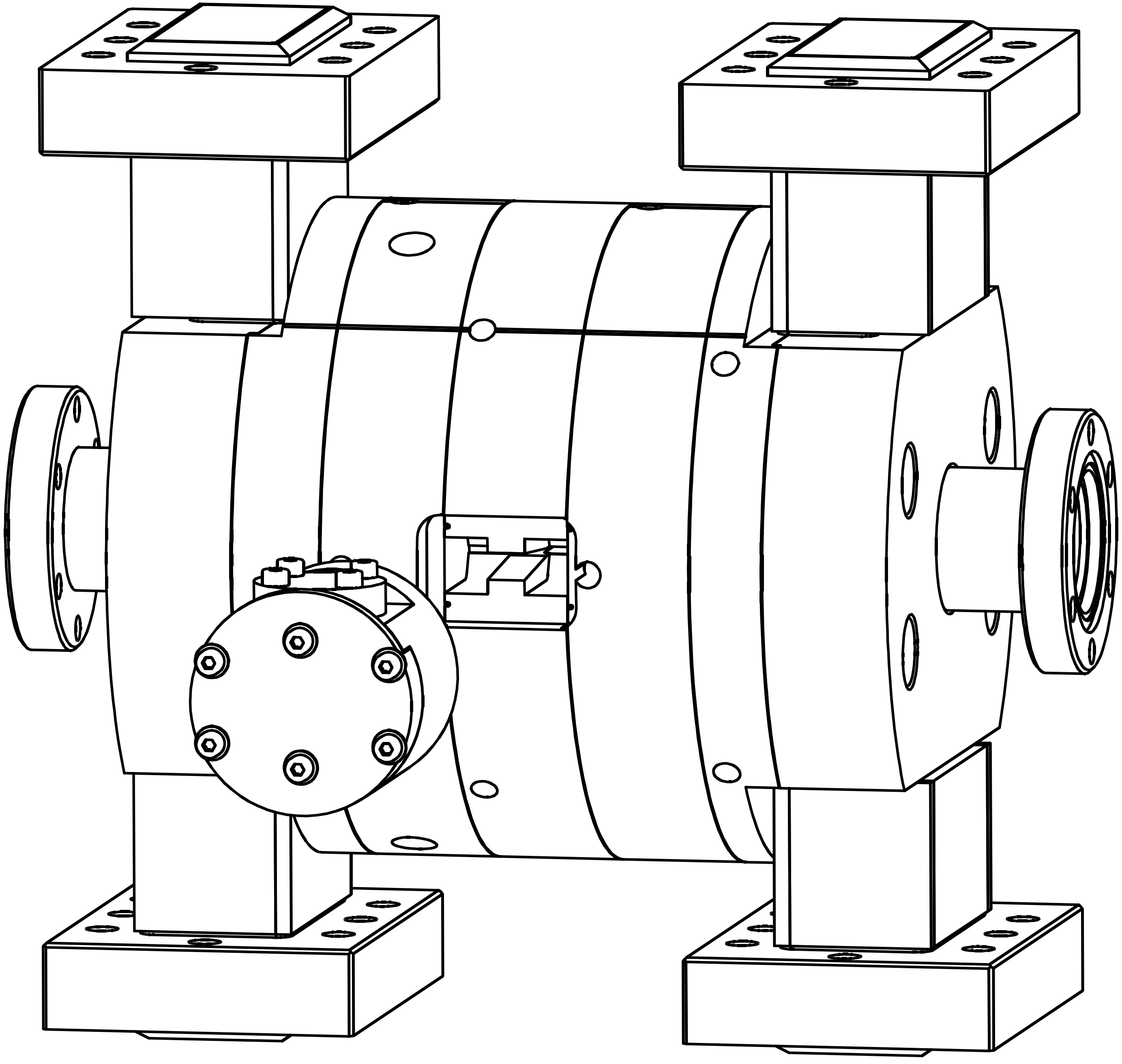
The short SICA Prototype





Sensing the Dipole Mode



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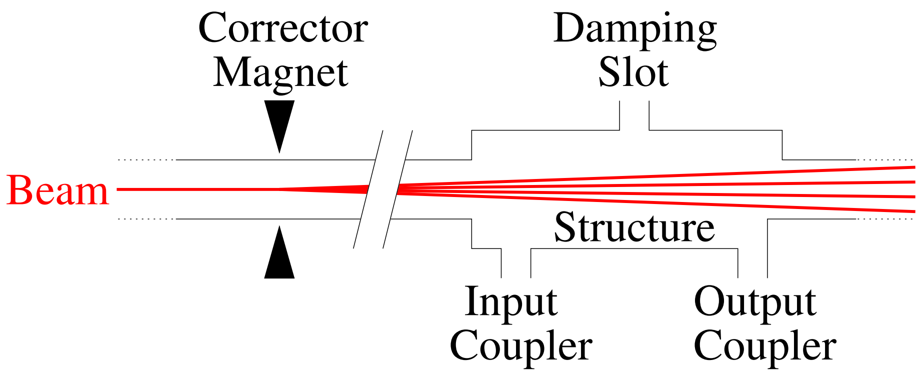
Experimental Setup



Corrector Magnet

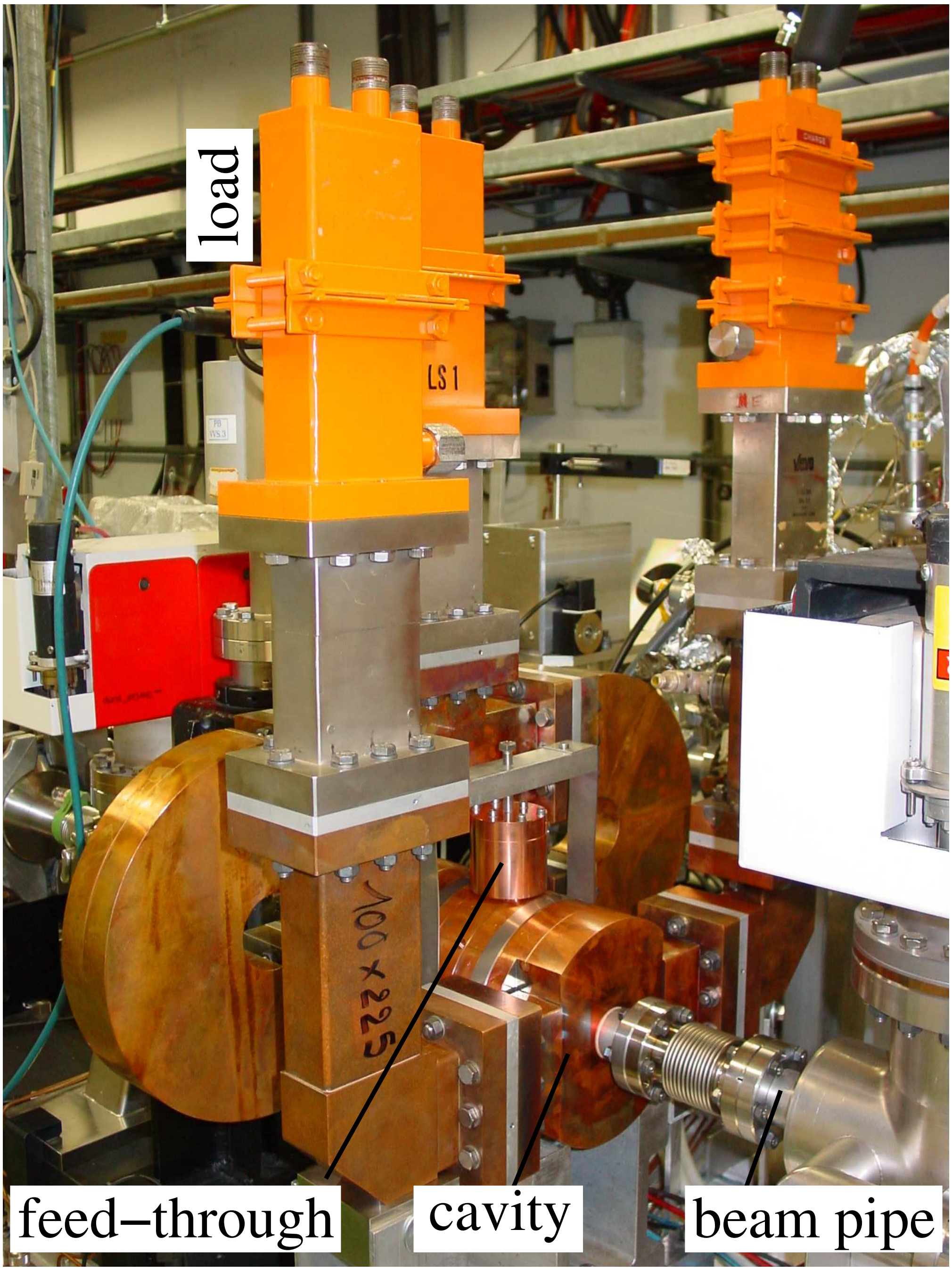
Damping Slot

Beam

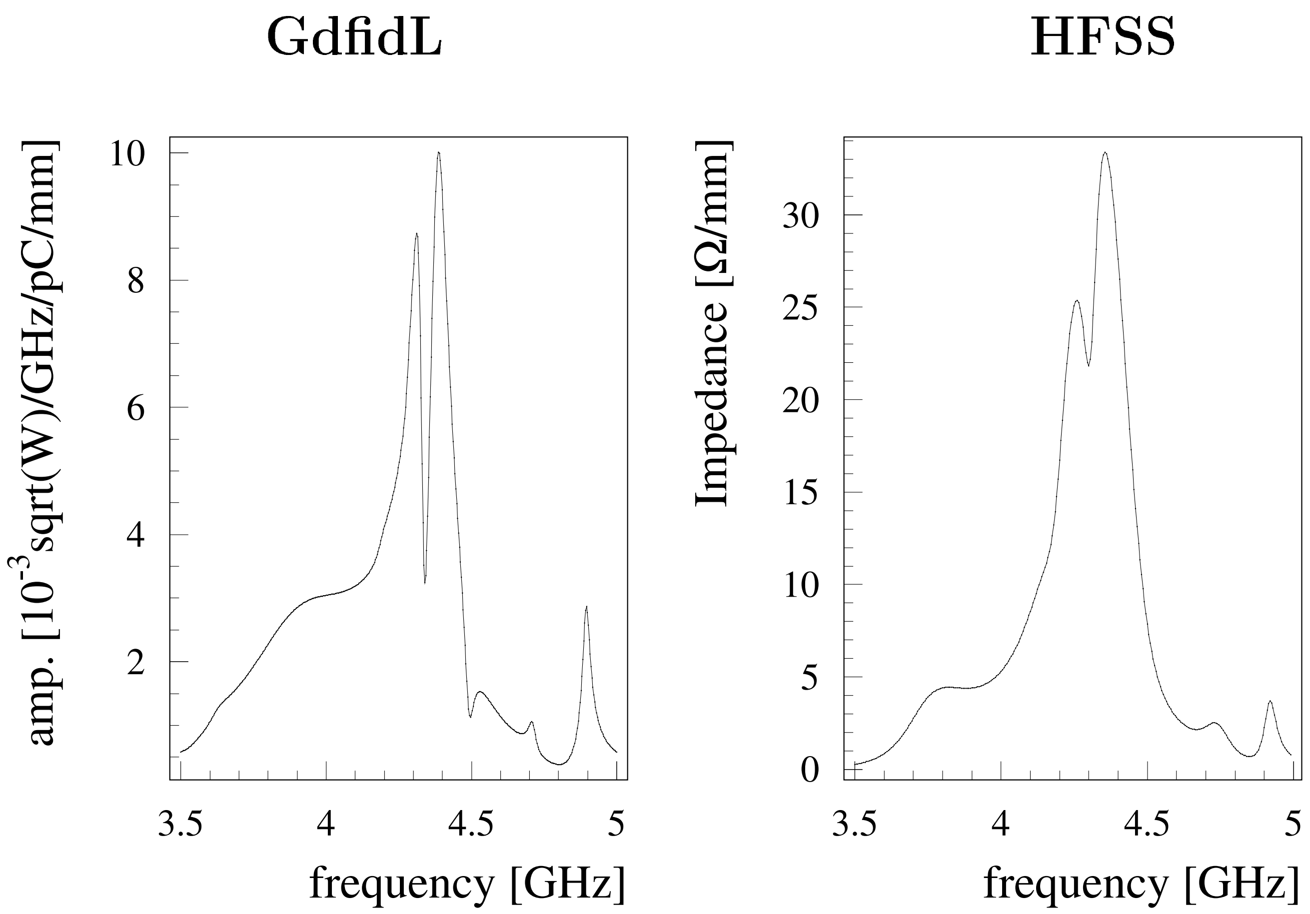
Structure

Input Coupler

Output Coupler



Benchmark of the Simulation Codes



Agreement:

- Dominant peak consisting of two peaks at 4.3 GHz.
- “Shoulder” around 3.8 GHz.
- Small peak at 4.9 GHz.

Disagreement:

- Double peaks are wider in the HFSS than in the GdfidL simulations.
- The shape of the shoulder differs.

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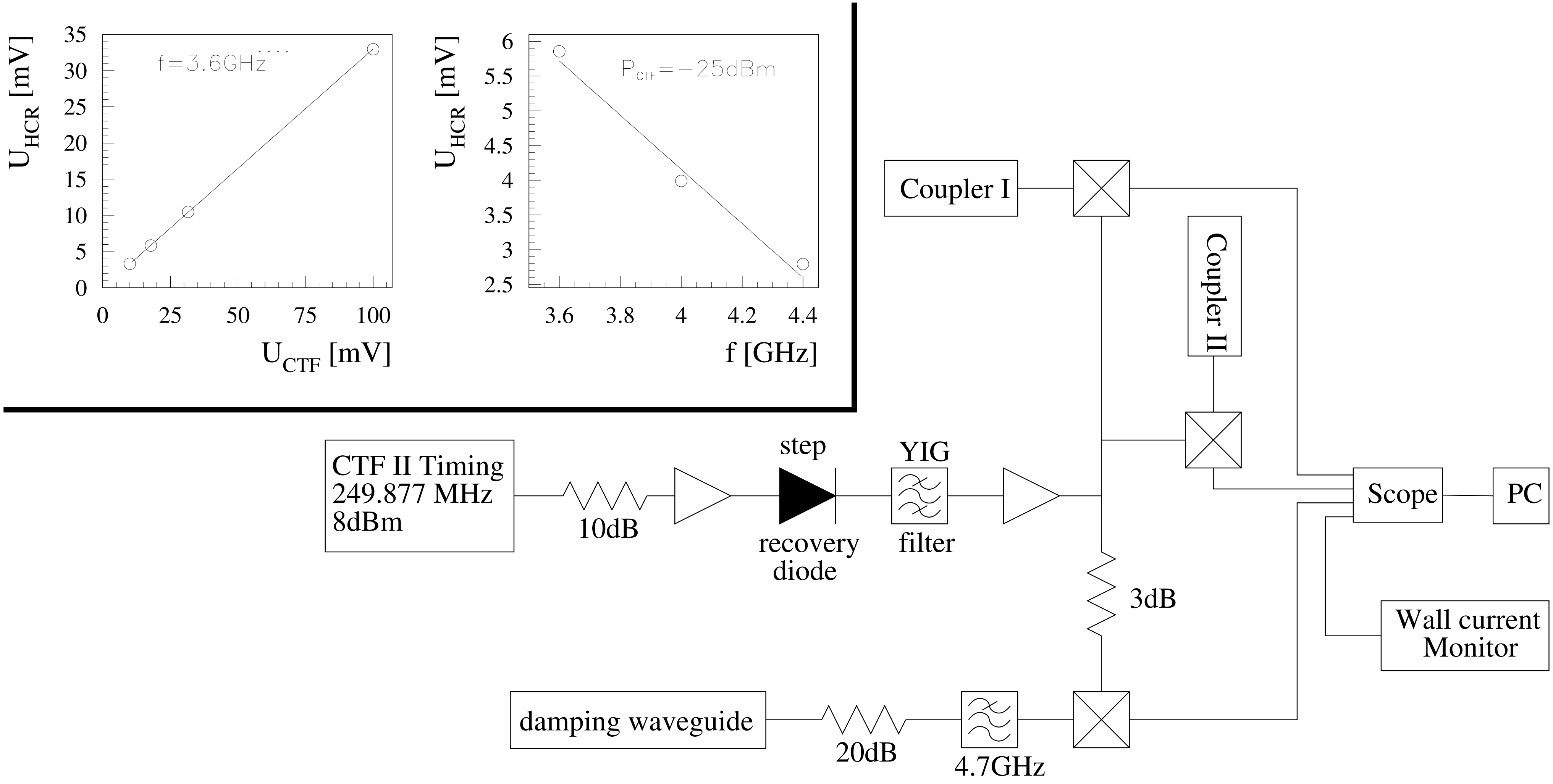
The Electronics



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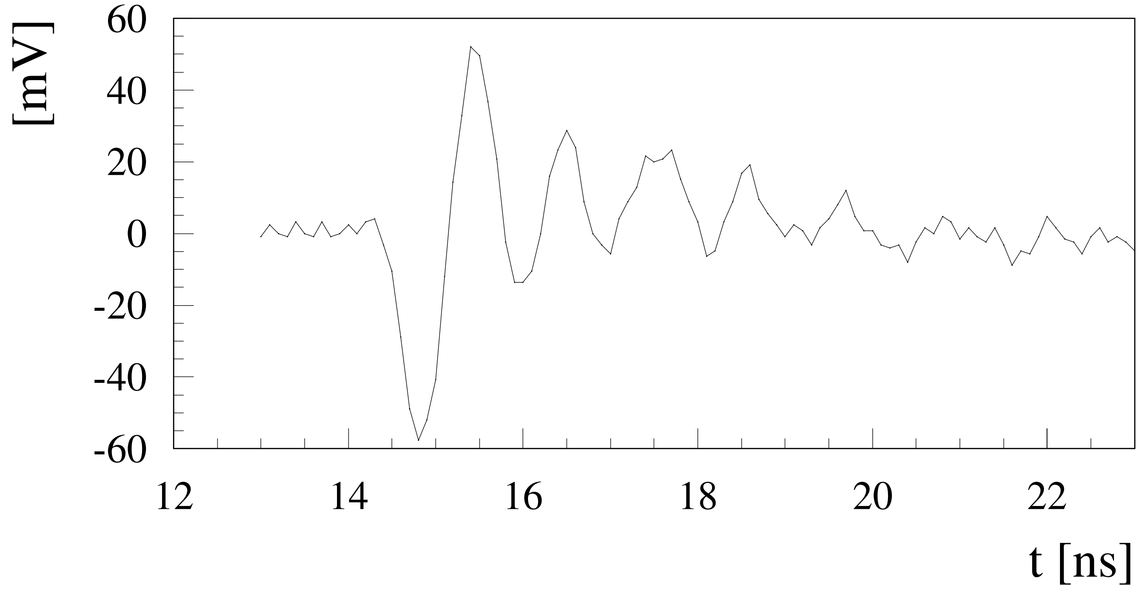
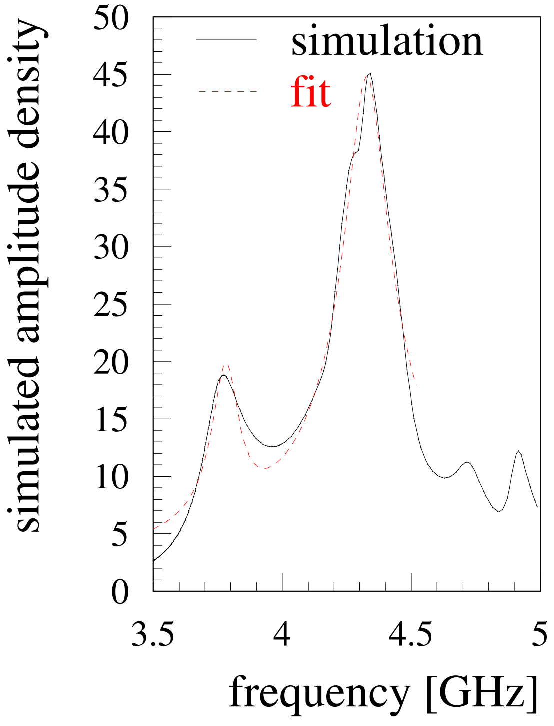
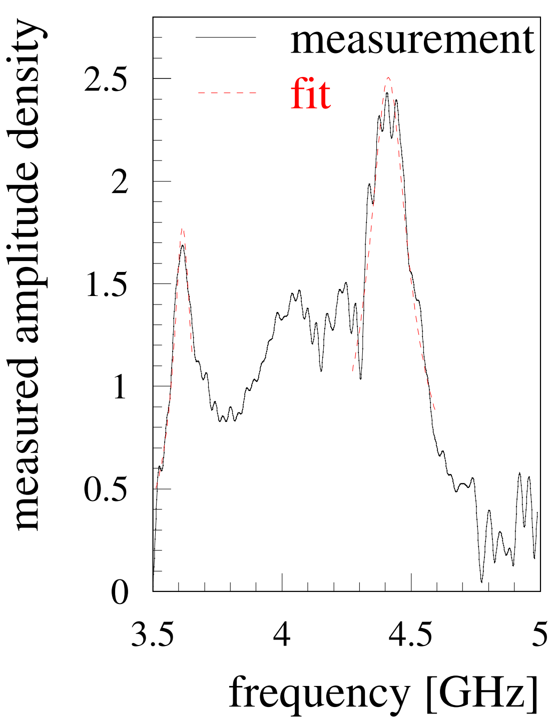
The Signal from the Damping Waveguide

Measurement:

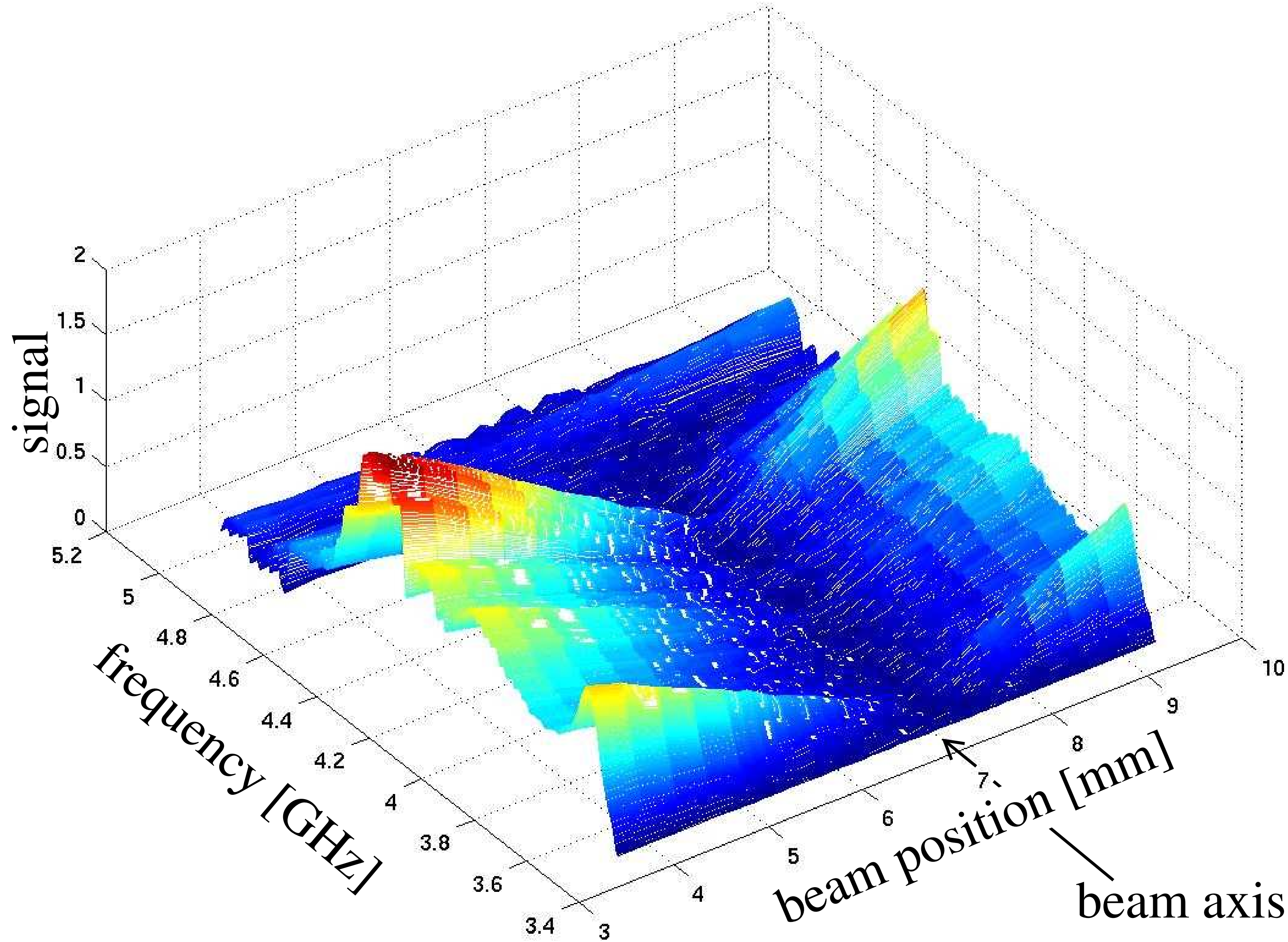






		simulation	measurement	relative deviation
1. peak	**frequency**	**3.78 GHz**	**3.62 GHz**	**4.3 %**
	quality factor	**29.4**	**58.3**	**66 %**
2. peak	**frequency**	**4.33 GHz**	**4.41 GHz**	**1.8 %**
	quality factor	**26.0**	**33.0**	**24 %**

The Beam Position Dependency (I)



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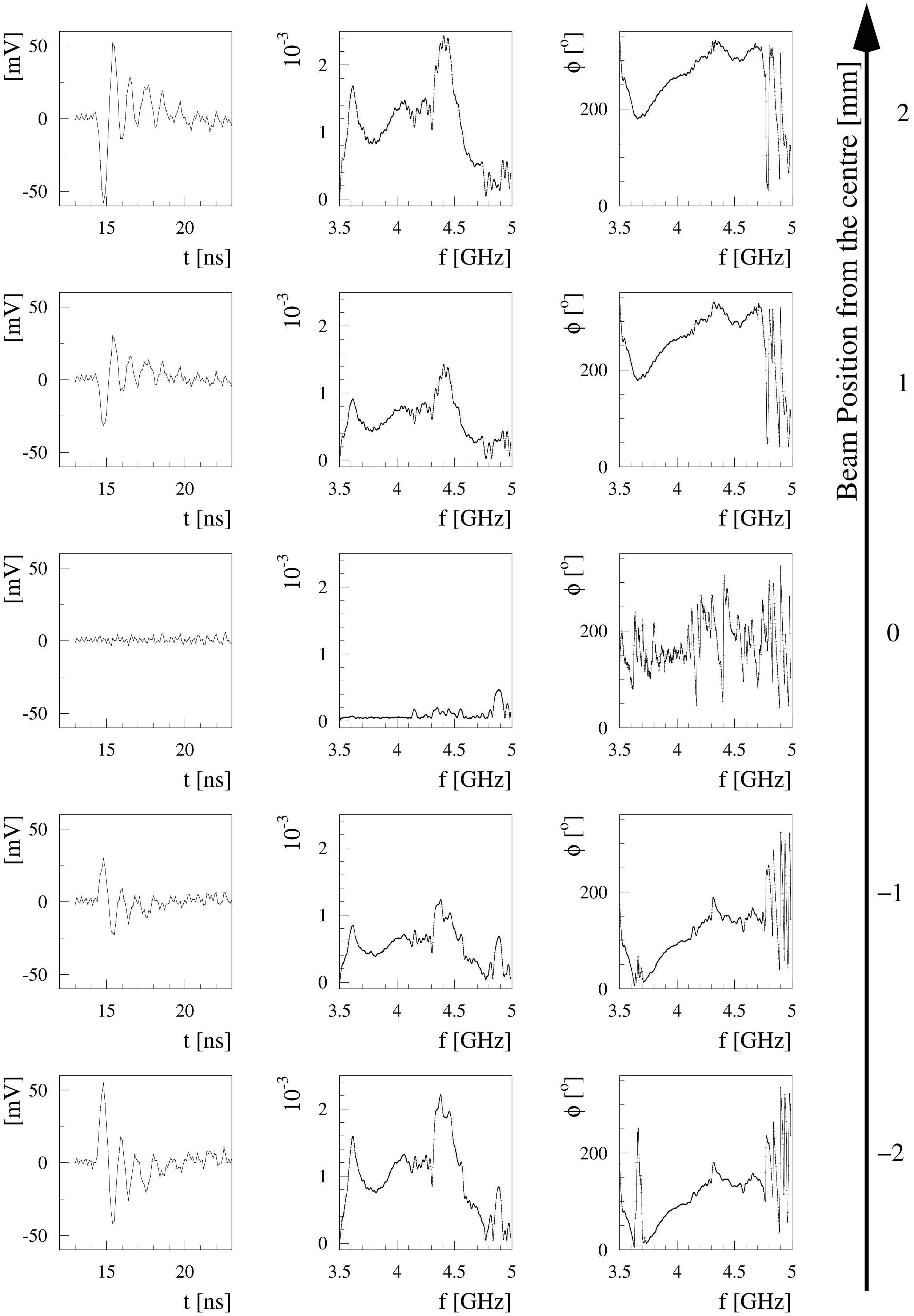
The Beam Position Dependency (II)



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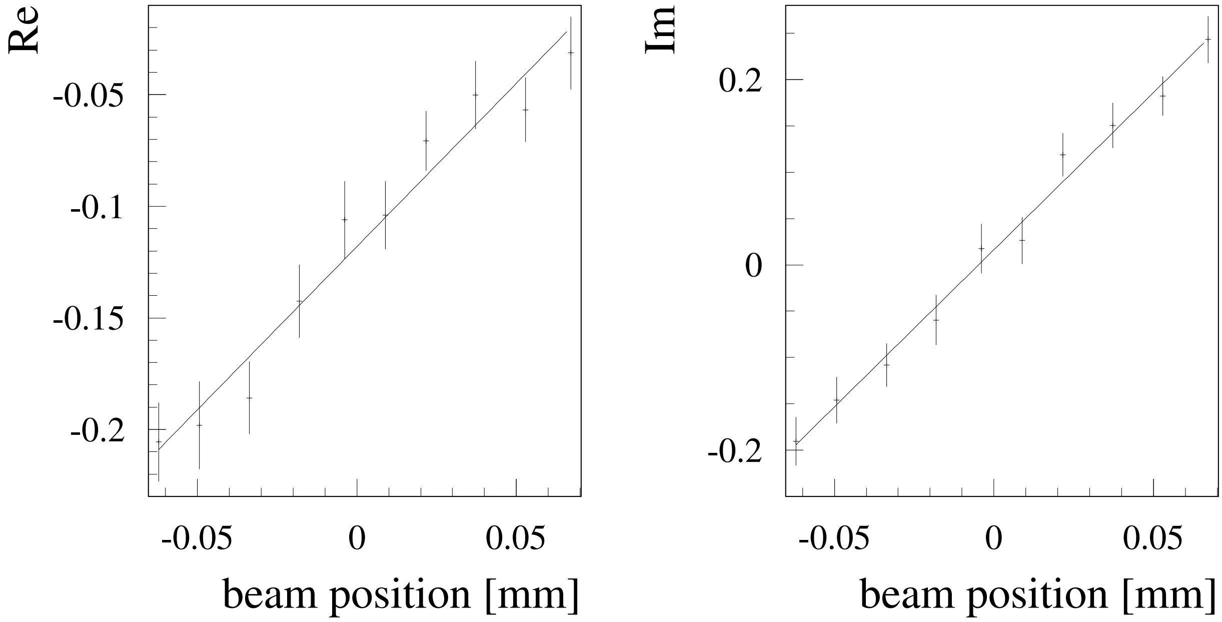
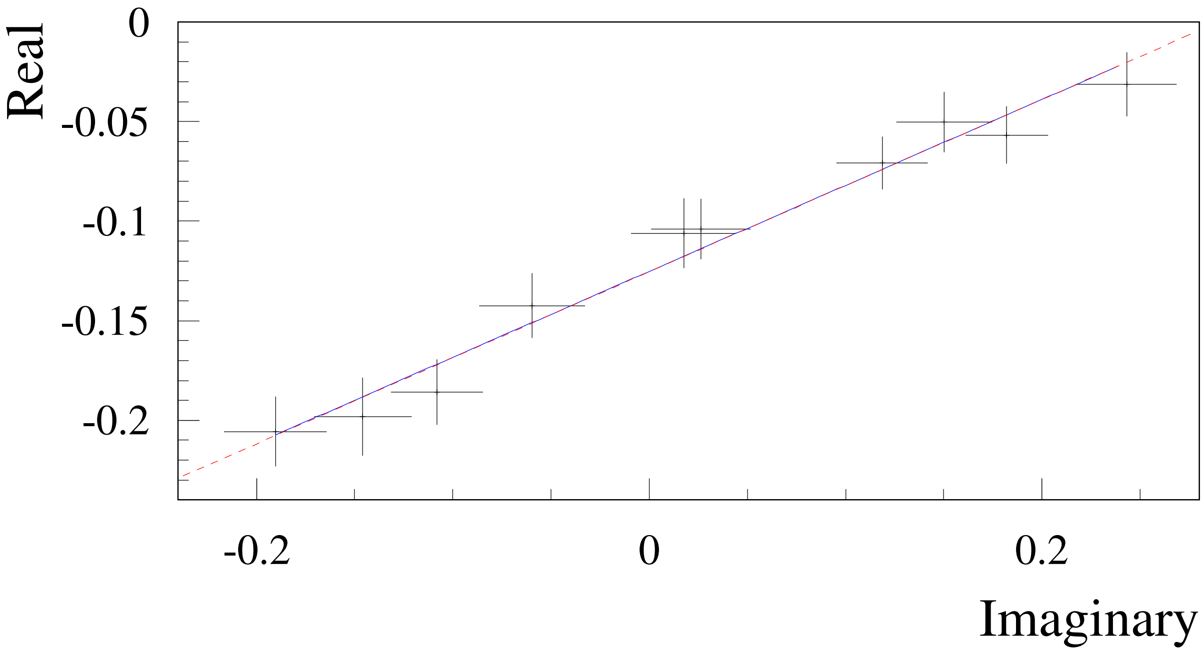
The Beam Position Dependency (III)

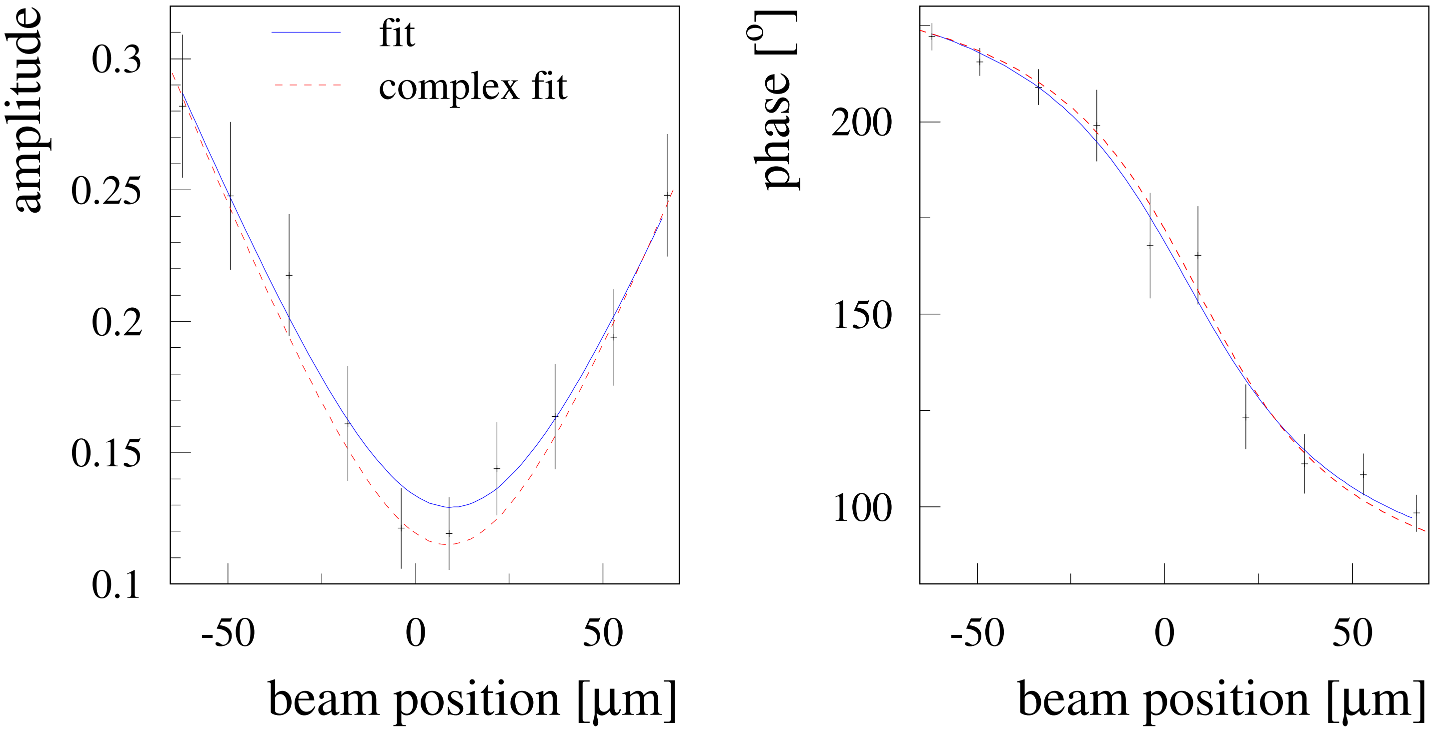
**Linear fits provide orthogonal parameters.
The fit parameters for hyperbolic and Arctangent functions are interrelated.**





The mean r.m.s of the position signal is 5.7 µm.

The Beam Position Dependency (IV)



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Jitter & Accuracy

The 5.7 µm r.m.s variations of the beam position have two sources:

- beam position jitter.
- accuracy limits on the beam position measurement.

Both effects can be disentangled by an independent position measurement with the coupler.

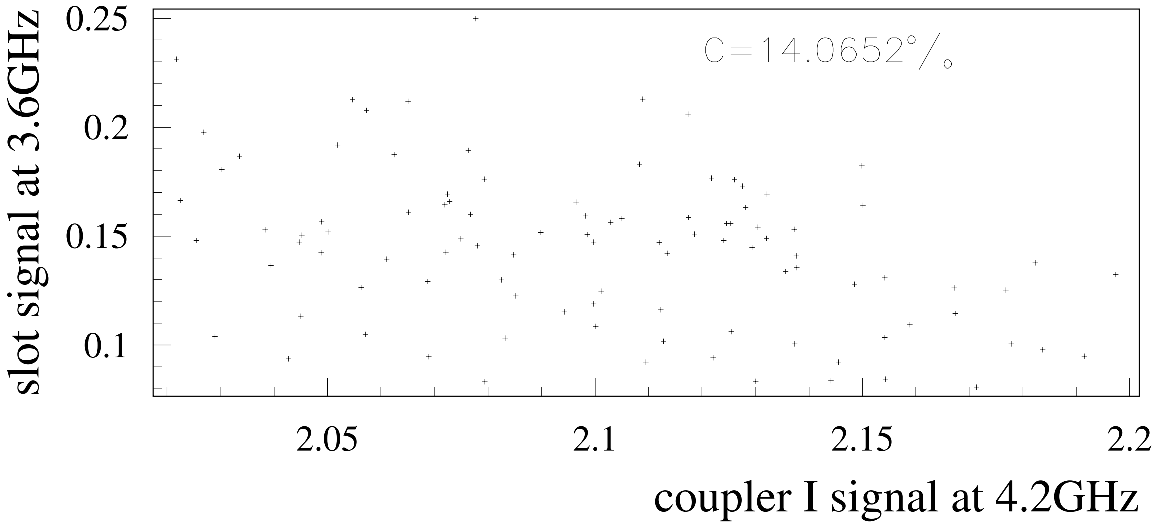
The coefficient of determination:

$C(x,y)$ indicates the proportion of variance in one variable x explained from the knowledge of the second variable y. C is defined as:

$$C = \frac{\sigma_{xy}}{\sigma_x \sigma_y}\, 100\,\% \ ,$$

σ_x, σ_y are the variances

σ_{xy} the covariance of the two variables x and y.



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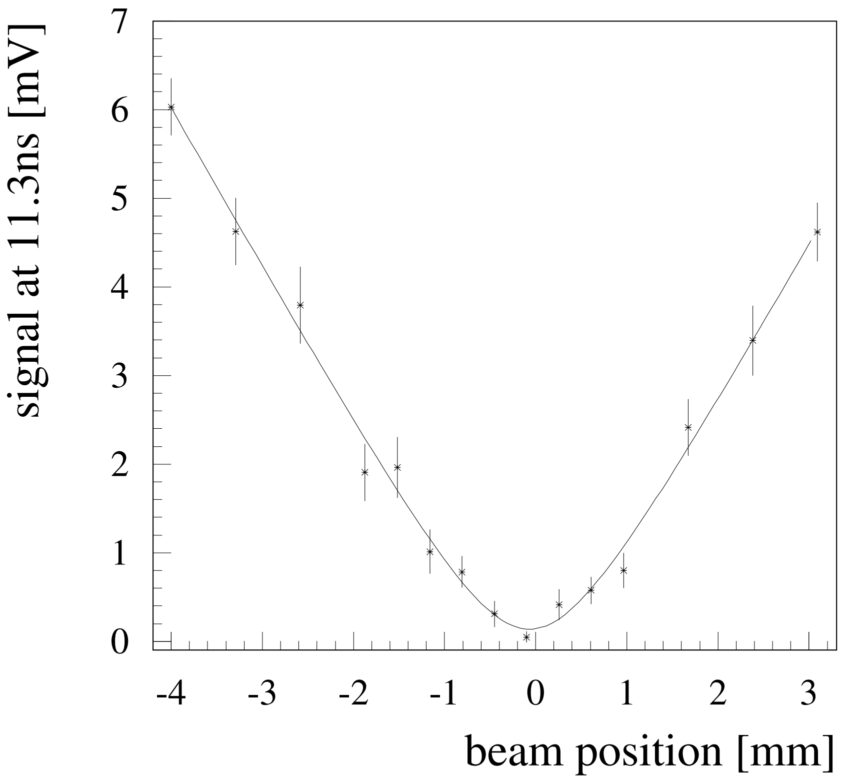
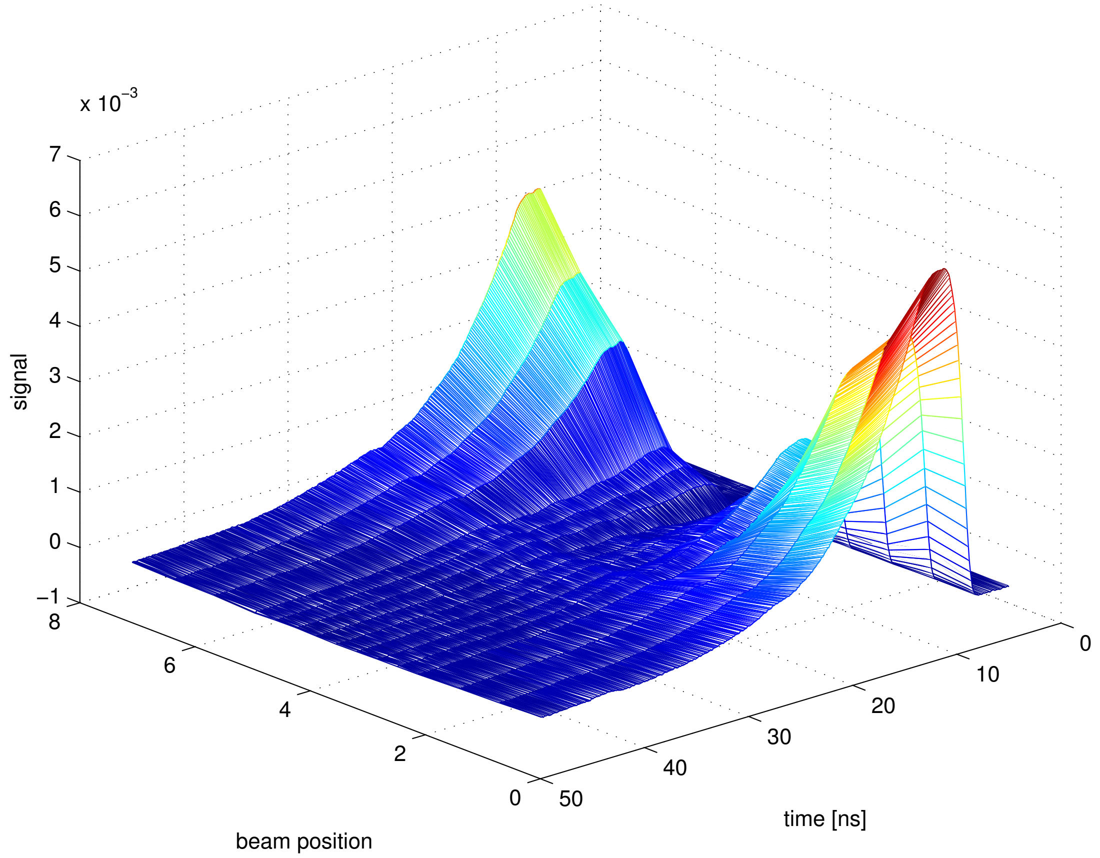
Conclusions

- Beam tests with standing wave cavities showed accuracies of better than 8.4 µm.
- Especially the phase (accuracies of 1.1 °) was found to be very valuable.
- Simulations indicate that strong damping and further common mode rejection is achievable by employing different coupling geometry.
- With an undamped accelerating structure it was possible to achieve beam position and angle resolutions of 6.3 µm and 7.5 µrad.
- First simulations with GdfidL are promising.
- Measuring the dipole mode in the damping slots was successful.
- The signal spectrum was found to agree with the simulations.
- A beam position resolution of 5.7 µm was achieved.

The signal was observed as well with a diode:





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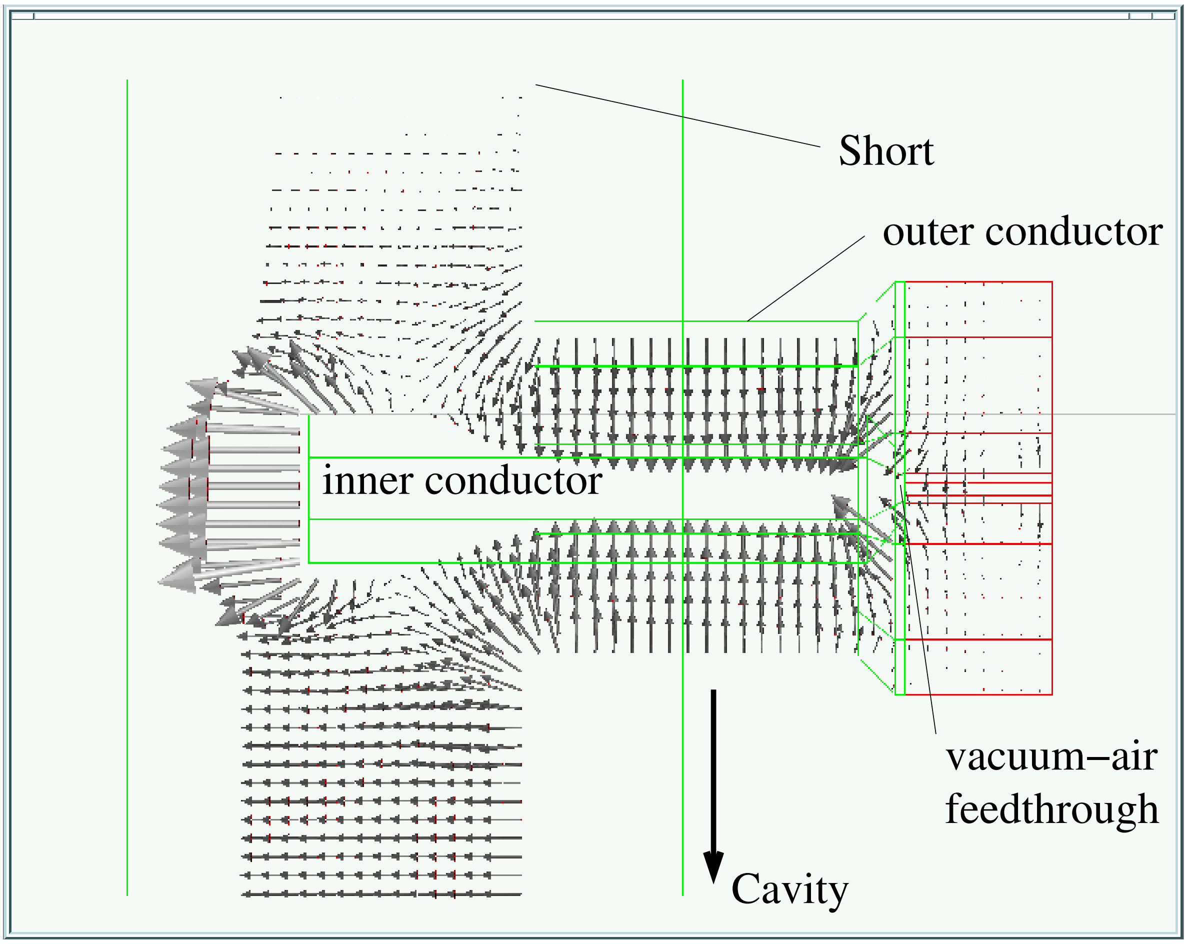
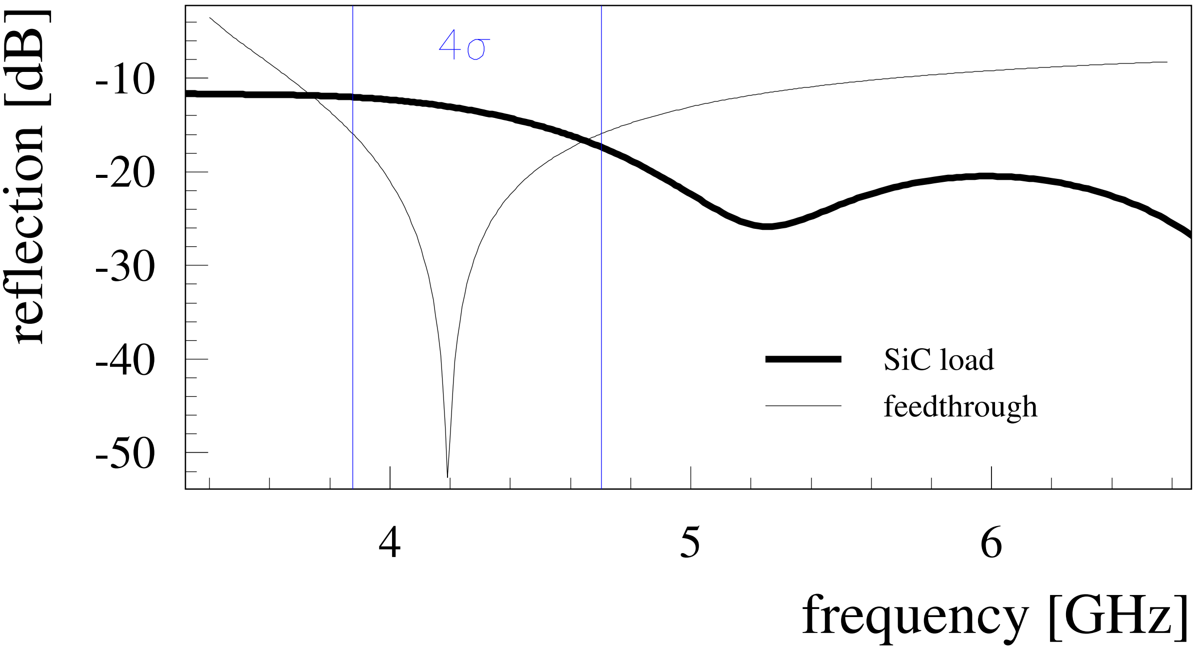
How it works and How it performs





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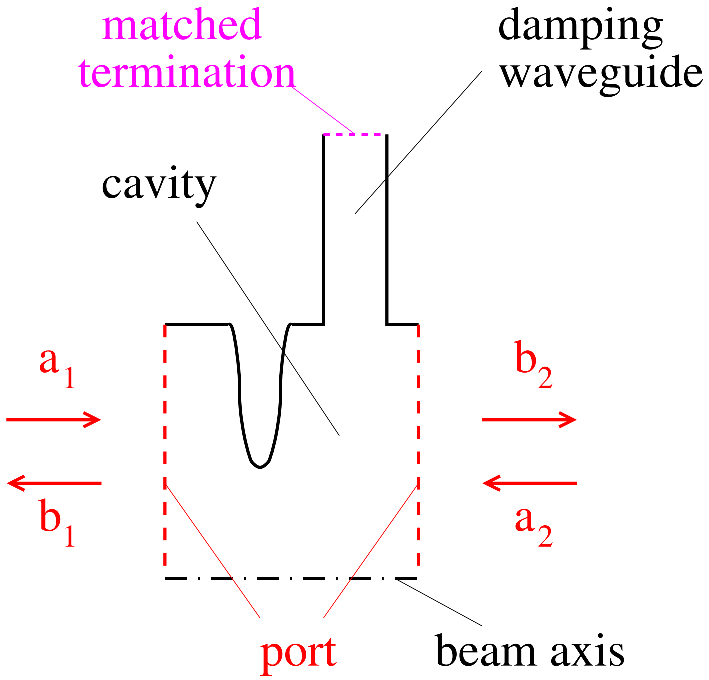
Establishing the field in one single cell such as if it was part of an infinite structure.



Transmission matrix T:

- **1 cell:**

$$\begin{pmatrix} b_1 \\ a_1 \end{pmatrix} = \mathbf{T}_{\mathbf{1\ cell}} \cdot \begin{pmatrix} a_2 \\ b_2 \end{pmatrix}$$

- **N cells:**

$$\mathbf{T}_{\mathbf{str.}} = (\mathbf{T}_{\mathbf{1\ cell}})^{\mathbf{N}} = \mathbf{V} \cdot \lambda^{\mathbf{N}} \cdot \mathbf{V}^{-1}$$

V: Eigenvector matrix

λ: Diag. matrix of the eigenvalues

$\Longrightarrow$ The periodic solutions correspond to the eigensystem of the transmission matrix. $\Longrightarrow$ The eigenvectors a_1, a_2, b_1, b_2 are the amplitudes at the position of the ports in an infinite structure. $\Longrightarrow$ The Simulation of one cell is sufficient to establish the field as it would be in an infinite structure.

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