HOM-based Beam Diagnostics at FLASH and the European XFEL

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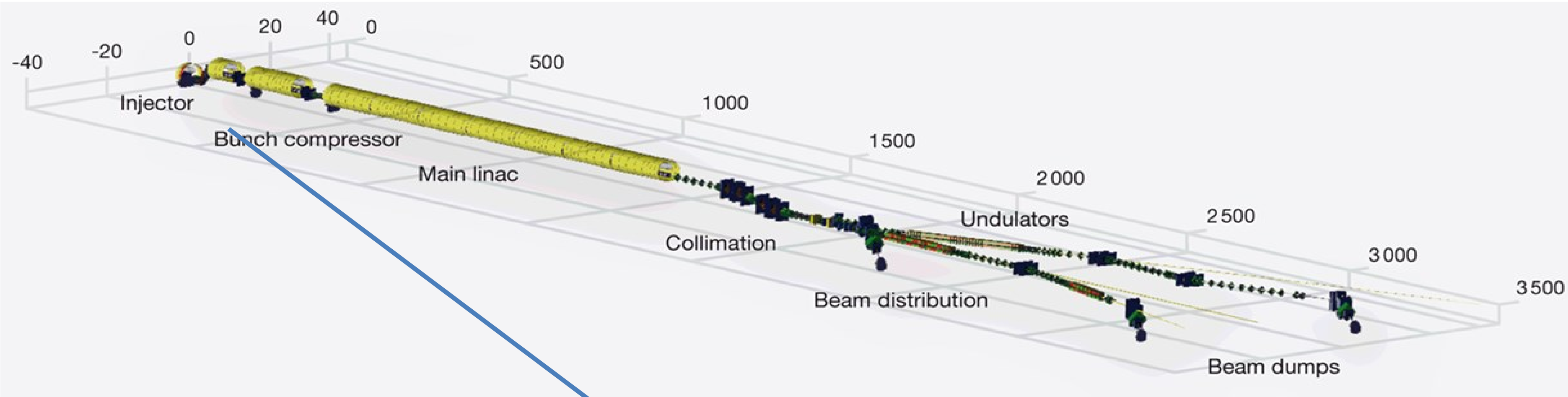
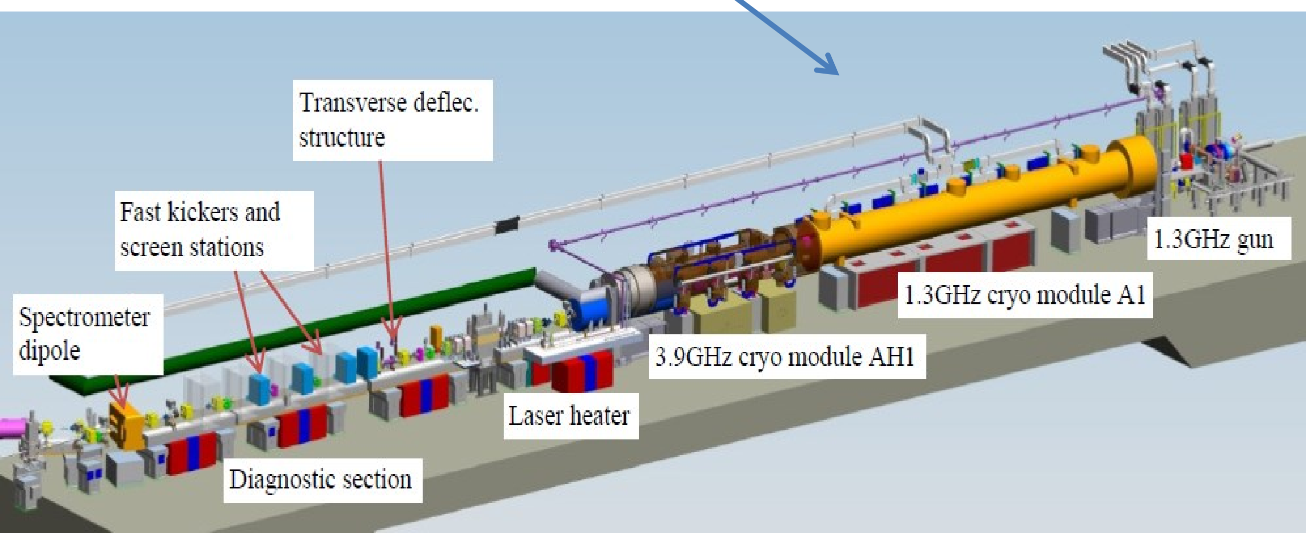
Outline

- Introduction to the European XFEL
- Wakefields and Higher Order Modes
- Beam Phase Measurements based on Monopole Modes
- Measurements based on Dipole Modes
- Overview of HOM Electronics
- Summary and Outlook.

Introduction to the European XFEL

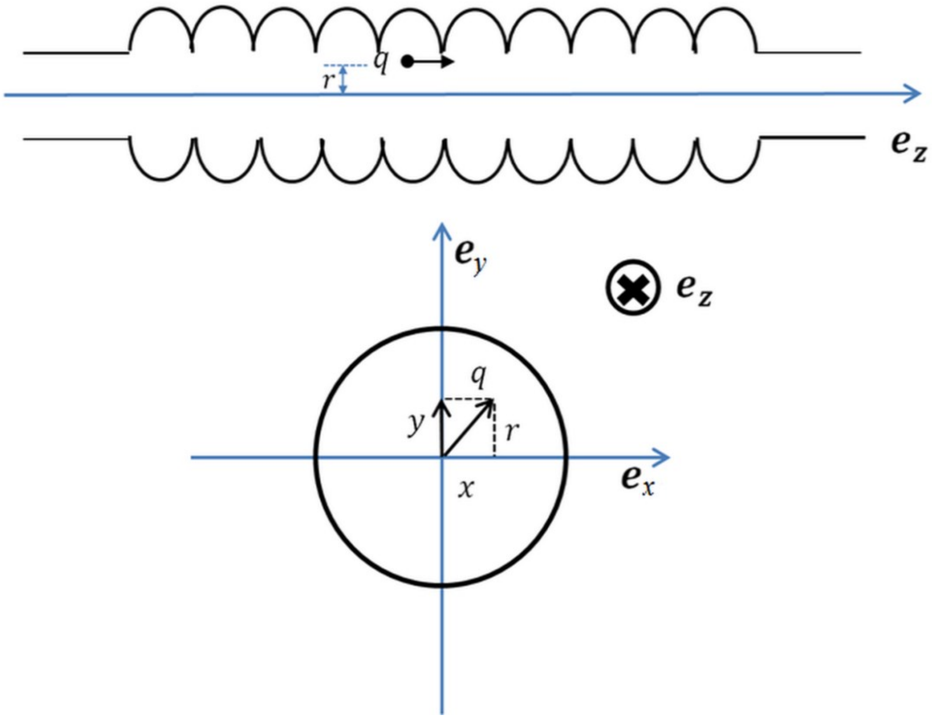


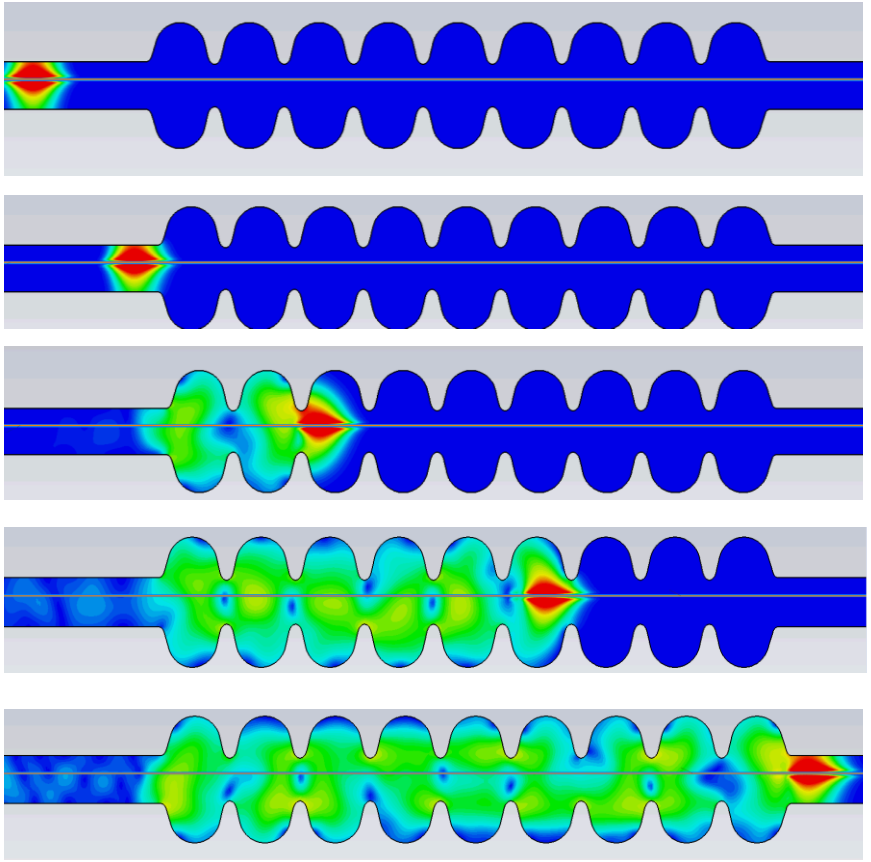


Electron Beam	
Energy (GeV)	17.5, 14, 12, 8.5
Bunch Charge (nC)	0.02-1
Bunches/ train	1-2700
Bunch spacing (µs)	0.2 (4.5 MHz)
Repetition rate (Hz)	10
Energy spread	< 1MeV

Introduction to Wakefields

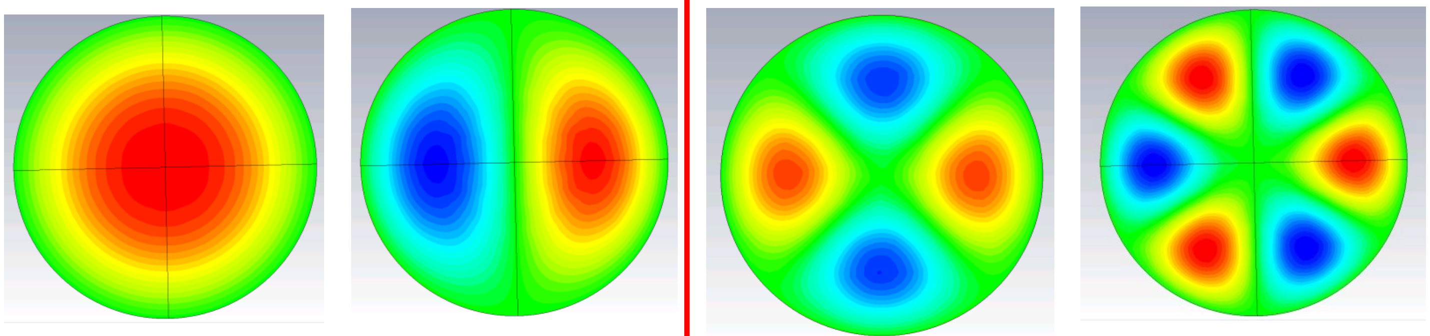
When beam transverses a cavity, wakefields are excited. These fields can be decomposed into different eigenmodes etc.





R. Wanzenberg, TESLA 2001-33, 2001.

Higher Order Modes

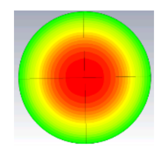
	Monopole	Dipole	Quadrupole	Sextupole	
Field distribution:					. . .
Beam moments:	n = 0 $\propto q$	n = 1 $\propto q \cdot r$	n = 2 $\propto q \cdot r^2$	n = 3 $\propto q \cdot r^3$	

- Monopole modes dominate the longitudinal wakefield:

$$\boldsymbol{W}_{\parallel} \cong -\sum_n \omega_n \left(\frac{R}{Q}\right)^n \cos\left(\frac{\omega_n s}{c}\right) H(s) \boldsymbol{e}_z$$

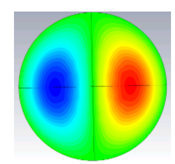
- Dipole modes dominate the transverse wakefield:

$$\boldsymbol{W}_{\perp} \cong (x\boldsymbol{e}_x + y\boldsymbol{e}_y) c \sum_n \left(\frac{R}{Q}\right)^n \sin\left(\frac{\omega_n s}{c}\right) H(s)$$



Measured Quantity $q \cdot \frac{R}{Q}$

Bunch charge

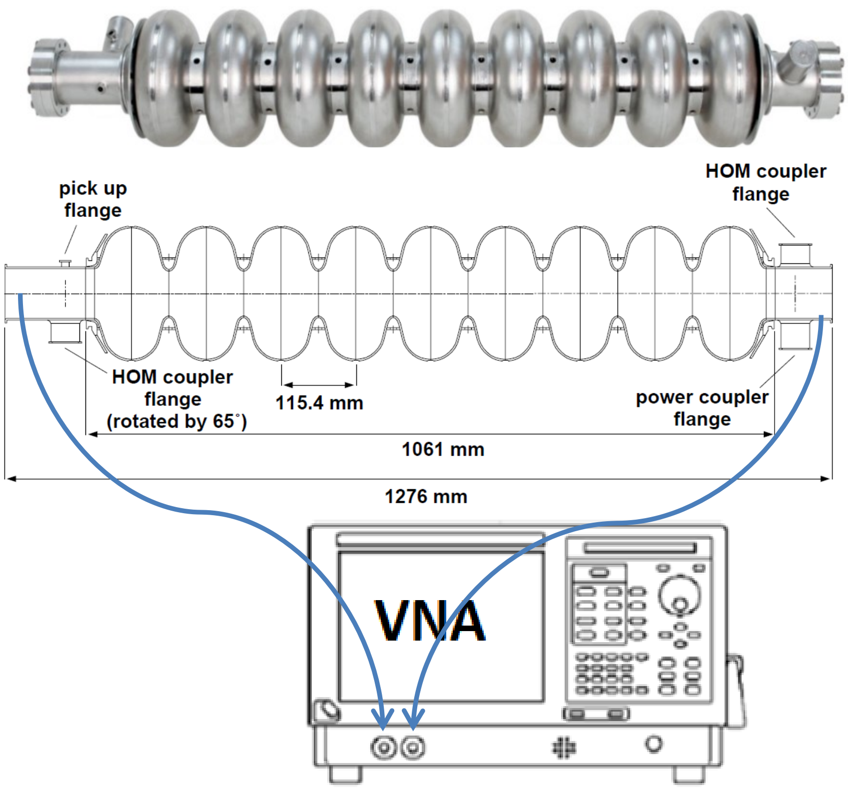


Measured Quantity $q \cdot r \cdot \frac{R}{Q}$

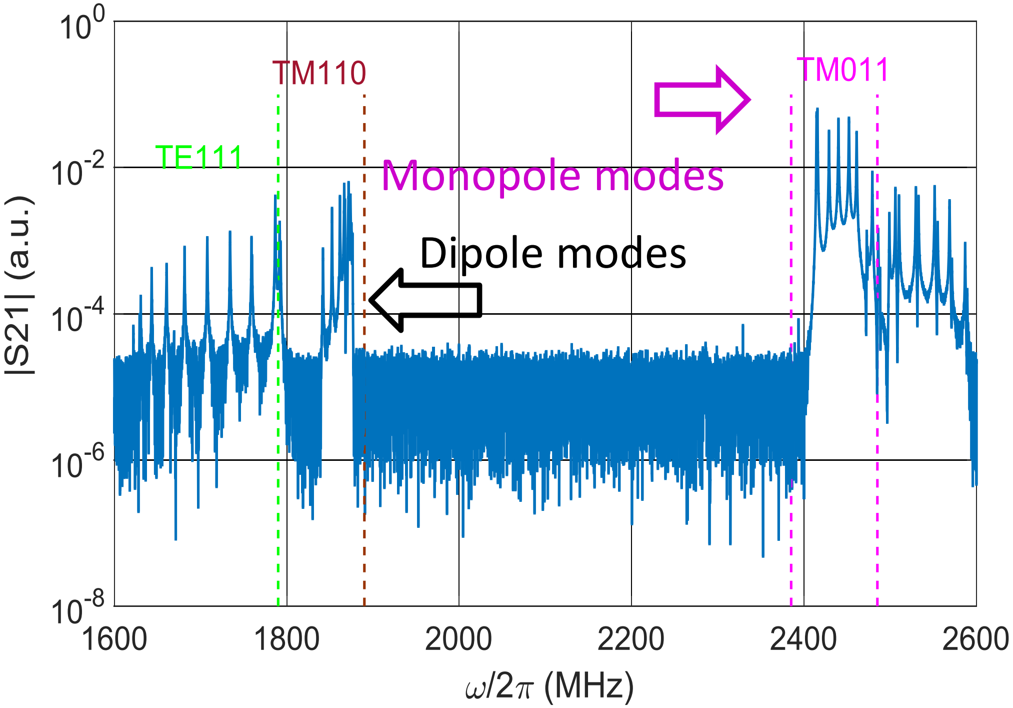
Bunch offset

TESLA Cavity HOM Spectrum

- TESLA Cavity (1.3 GHz)



- HOM Spectrum

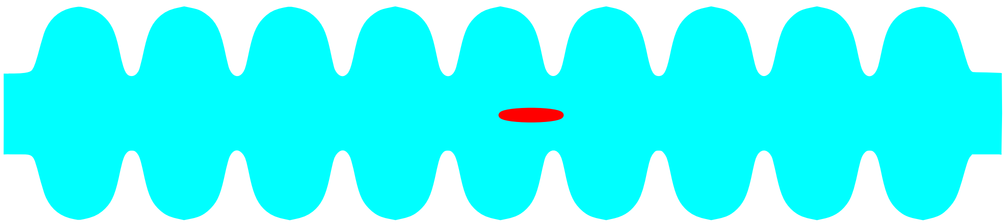


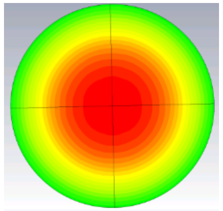
Monopole band occupies ~ 2.4 GHz with 70 MHz (2.38-2.45 GHz) bandwidth. The last two modes have higher R/Q (~ 70 Ω).

B. Aune, Phys. Rev. ST Accel. Beams 3, 092001.

Beam Phase Measurement

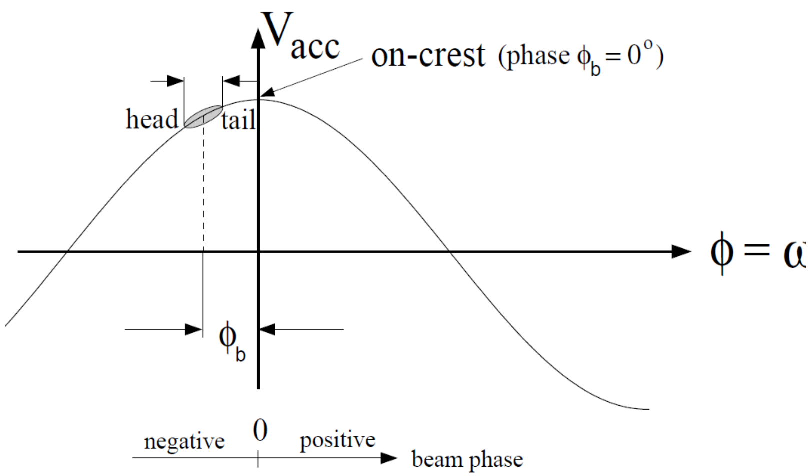
Monopole Modes

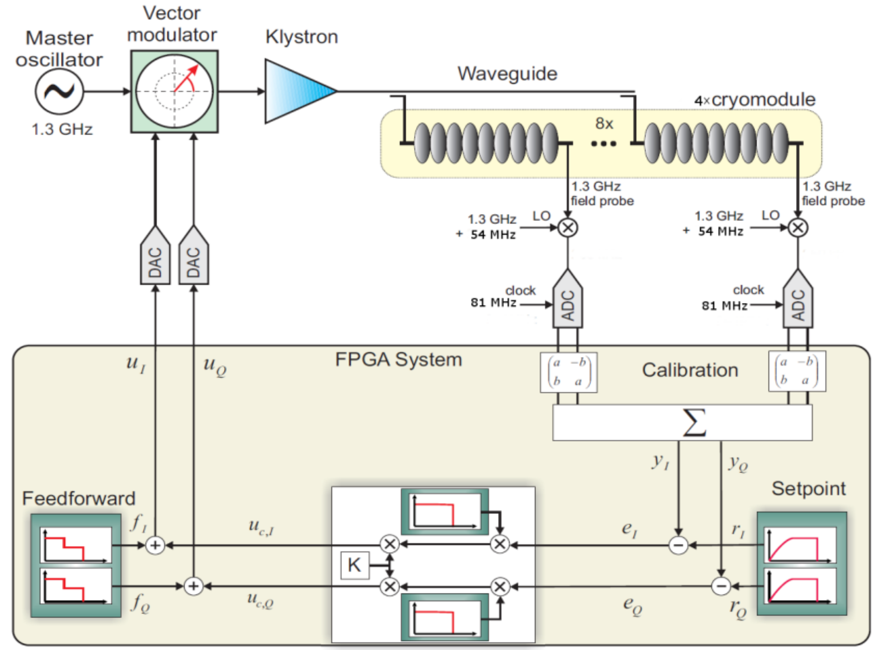




Field Control inside a Cavity

- FEL operation requires high stability of RF amplitude and phase. The requirements are derived from the beam properties:
  - ❑ Small energy spread
  - ❑ Small emittance
  - ❑ Shorter bunch length
  - ❑ Stable arrival time



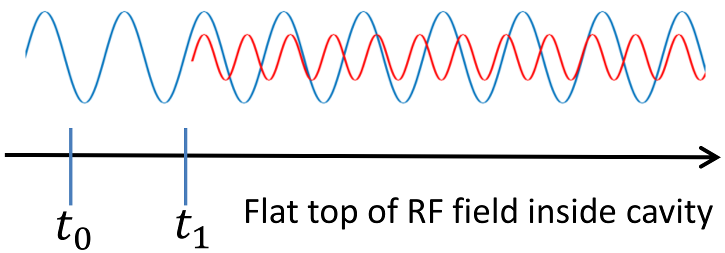


	Amp	Phase
FLASH	0.01%	0.01 degree
E-XFEL	0.01%	0.01 degree

C. Schmidt, IPAC 2013, WEPME009

How to Determine the Beam Phase?

RF_{t0} $RF_{t1} = RF_{t0} + V_b$

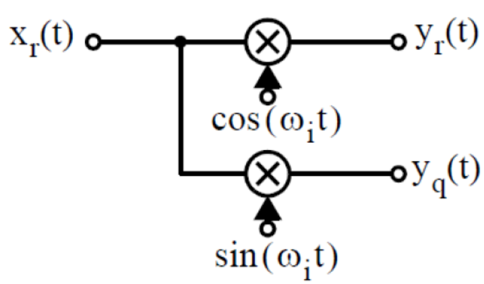


RF_{t0}: $1.3\ GHz\ signal$

V_b: $\sim 2.4\ GHz\ beam\ induced\ signal$

RF_{t1}: $1.3 + 2.4\ GHz\ signal$

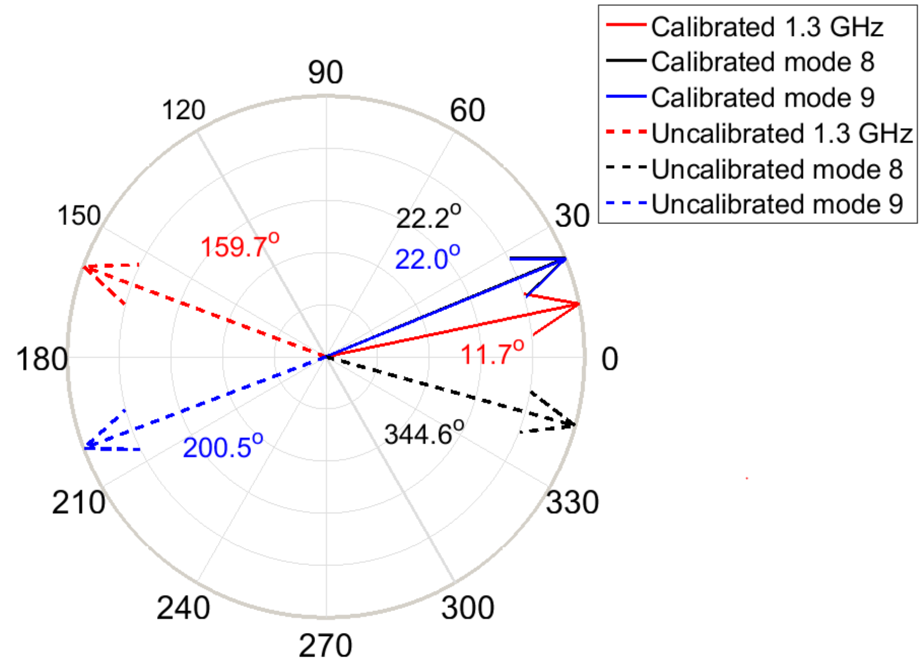
- Assume: $x_r(t) = \sum_{i=1}^{N} \cos(\omega_i t + \varphi_i)$



$$y_r(t) = \frac{\cos(2\omega_i t + \varphi_i) + \cos(\varphi_i)}{2}$$

$$y_q(t) = \frac{\sin(2\omega_i t + \varphi_i) + \sin(-\varphi_i)}{2}$$

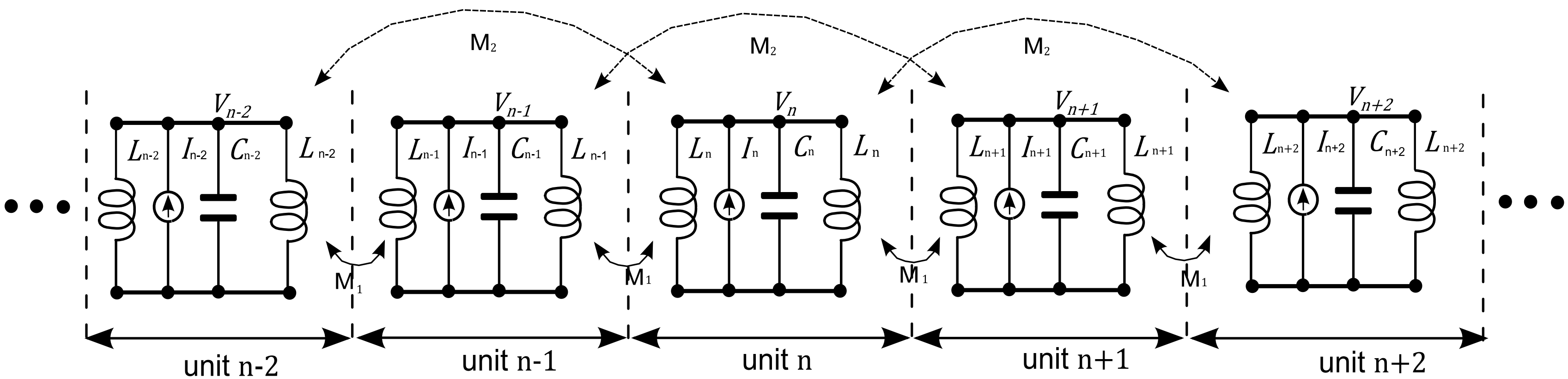
$$\tan(\varphi_i) = \frac{\int y_q(t)dt}{\int y_r(t)dt}$$

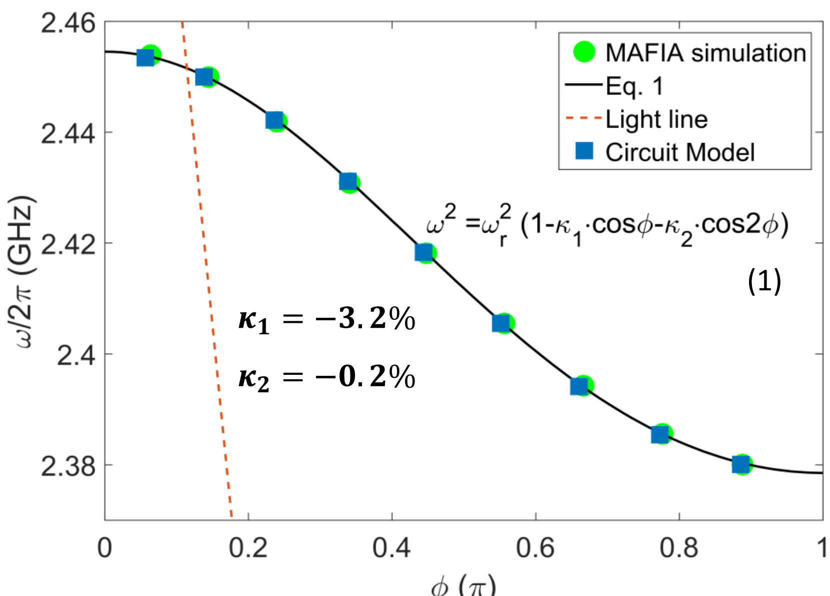


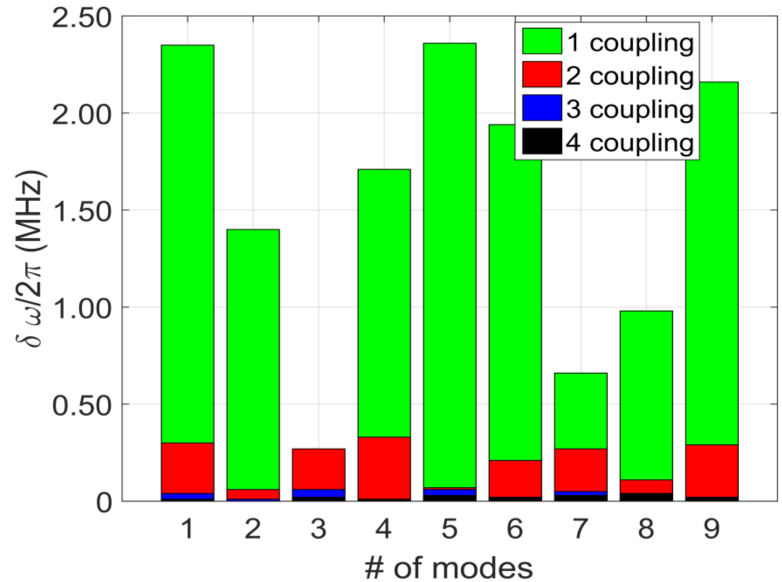
$\varphi_i s$ from HOMs can be used to define the beam arrival time t_1 and the phase relative to this time for the 1.3 GHz signal can be calculated.

A Single Chain Coupled Circuit Model

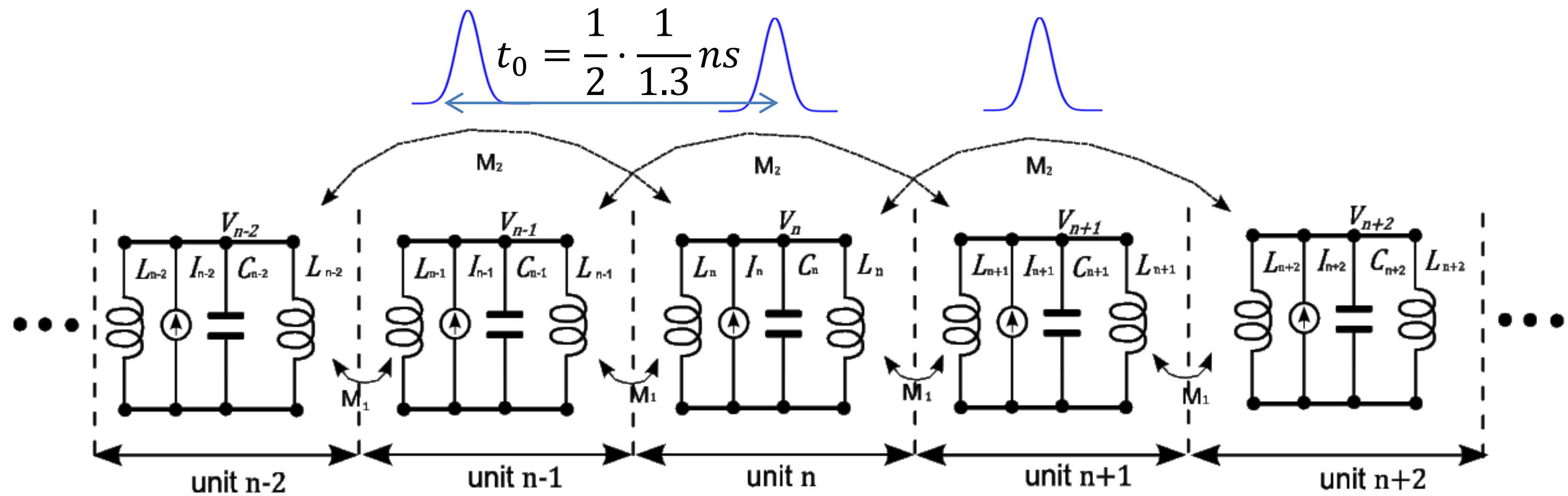
- A single chain of coupled parallel LC circuit is used to facilitate the beam phase monitor development.

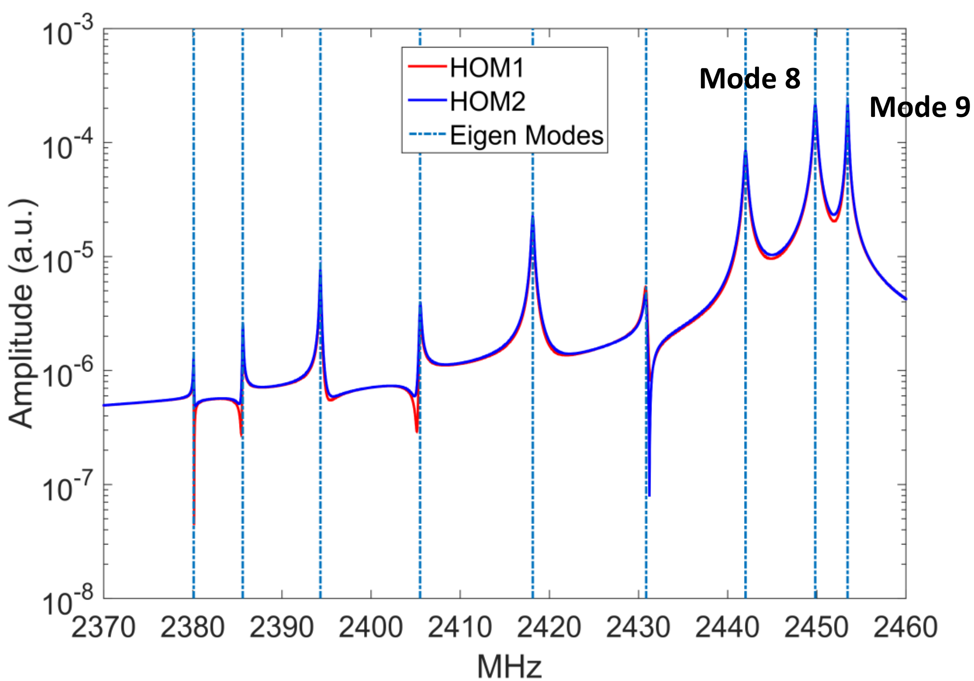






Beam driven Circuit Model

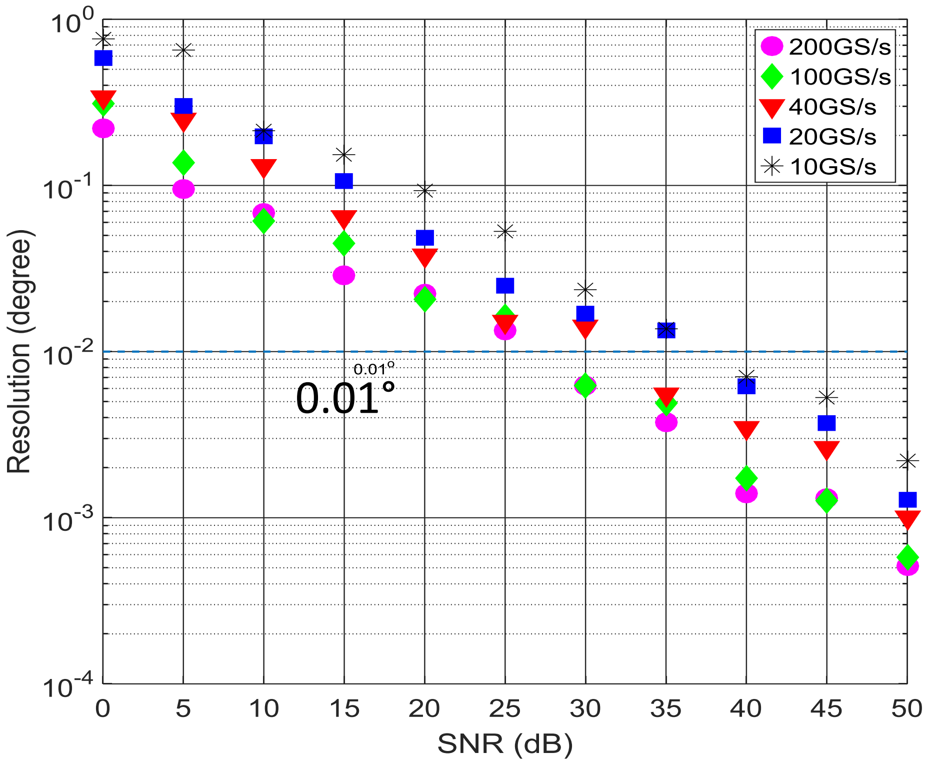




- The circuit is truncated to nine cells.
- It is then driven with delayed Gaussian pulses.
- The last two modes are excited strongly, and are used for beam phase calculation.

Resolution Study with Circuit Model

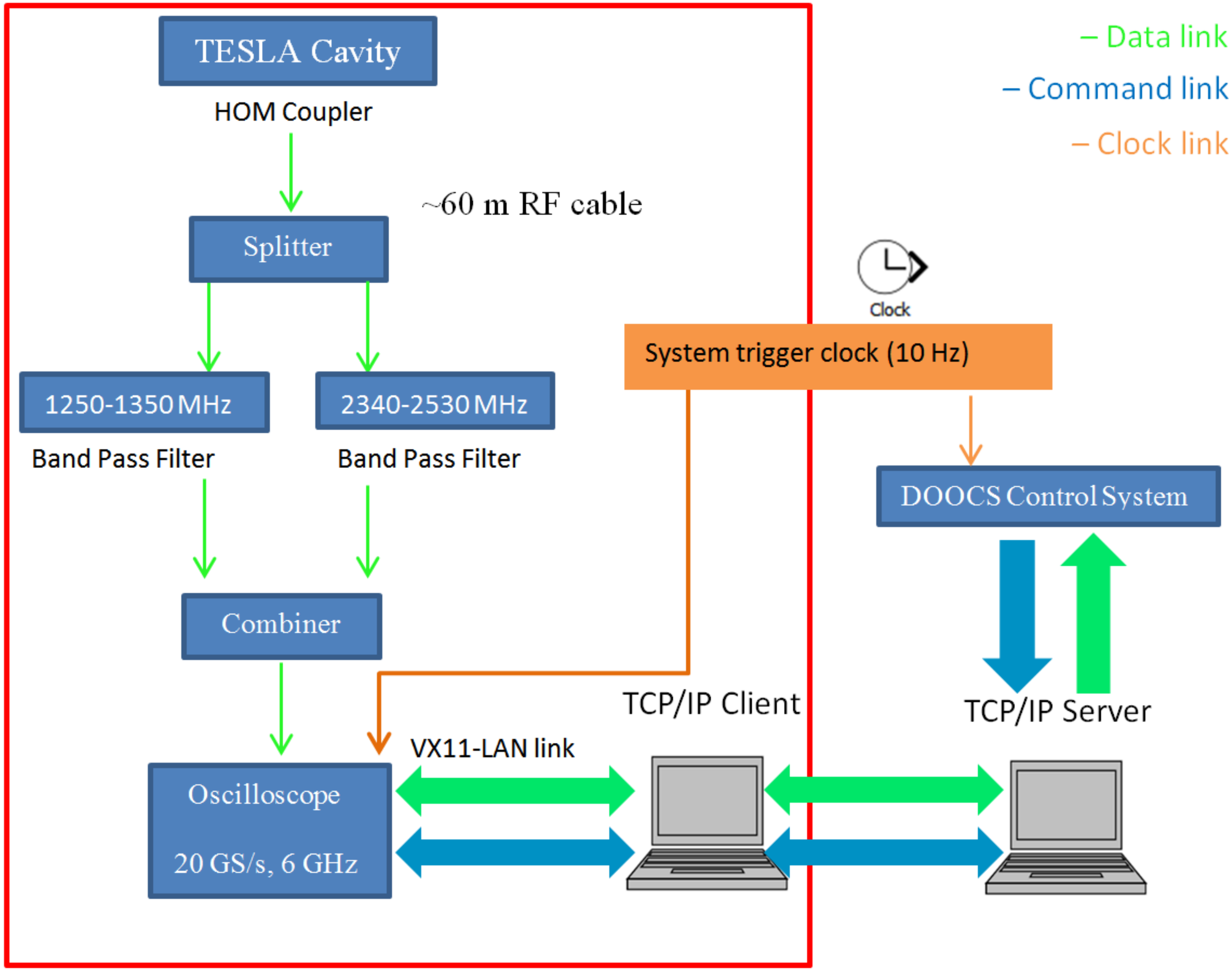
- Vary the sampling frequency, while keeping other parameters constant
- Vary the noise level, while keeping other parameters constant
- By comparing phases calculated from two HOM couplers, resolution can be estimated.



1. The resolution clearly depends exponentially on the noise present in the system.
2. The resolution also depends on the sampling frequency.
3. In order to meet the 0.01 degree requirement, the SNR should be ≥ 35 dB

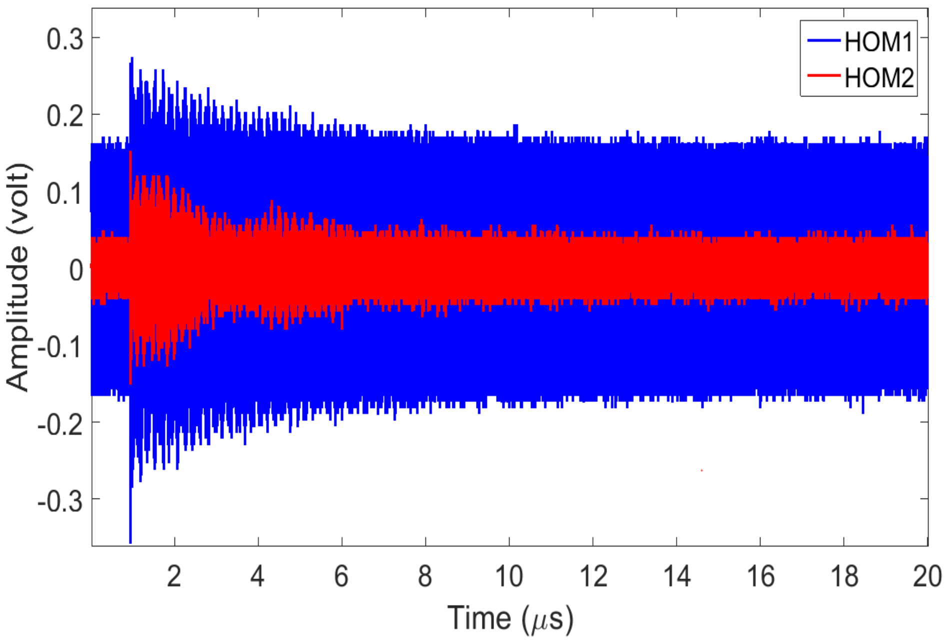
L. Shi *et al.*, IPAC2016, pp686

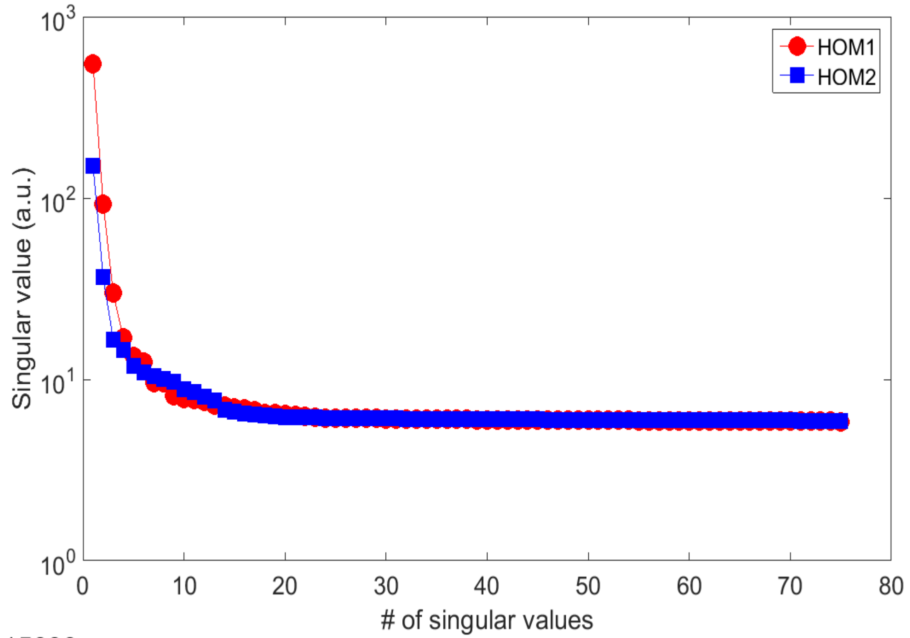
Experimental Setup

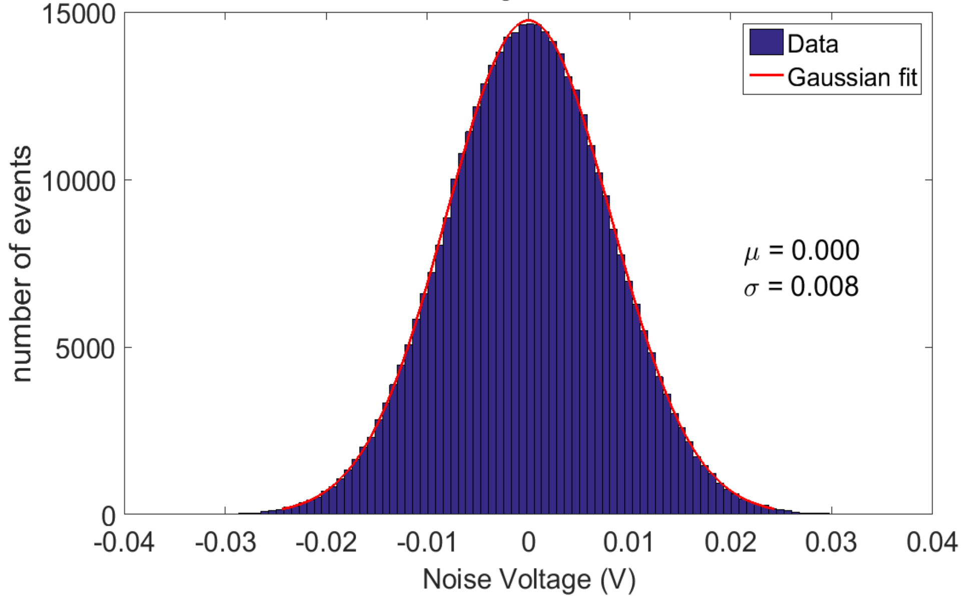


- HOM signals are available from HOM Patch panel.
- A fast scope (TDS6604B) with 20 GS/s, 6 GHz bandwidth measures from two HOM signals.
- A 10 Hz external clock is used to synchronize the measurement.
- The data from DOOCS and from scope are combined at TCP/IP Client
- Each triggered event takes ~ 20s

Estimation of Noise with SVD

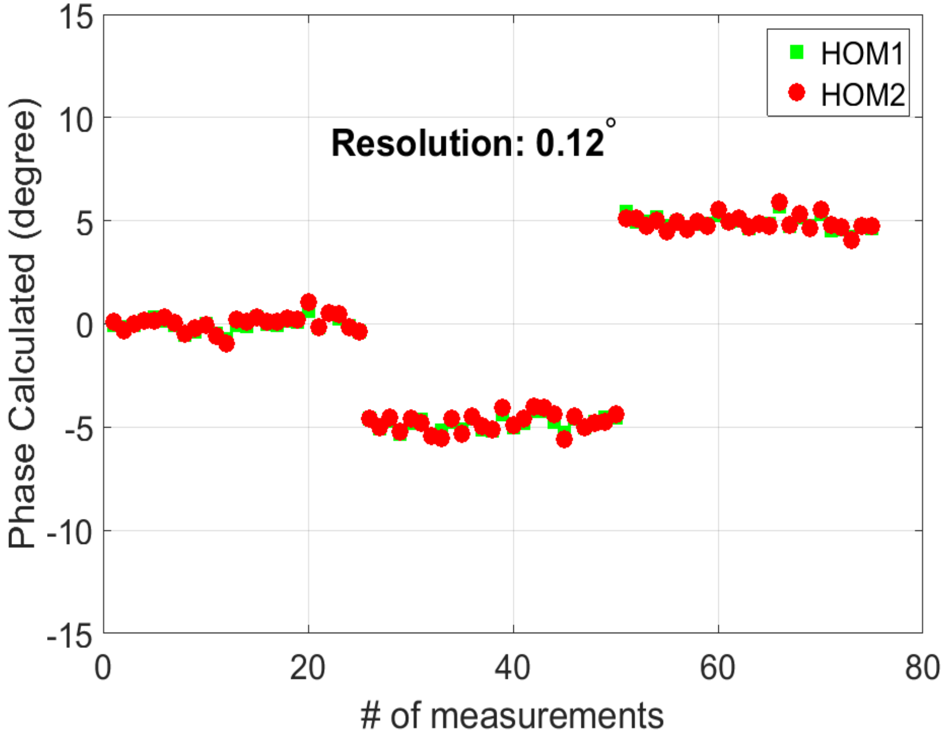




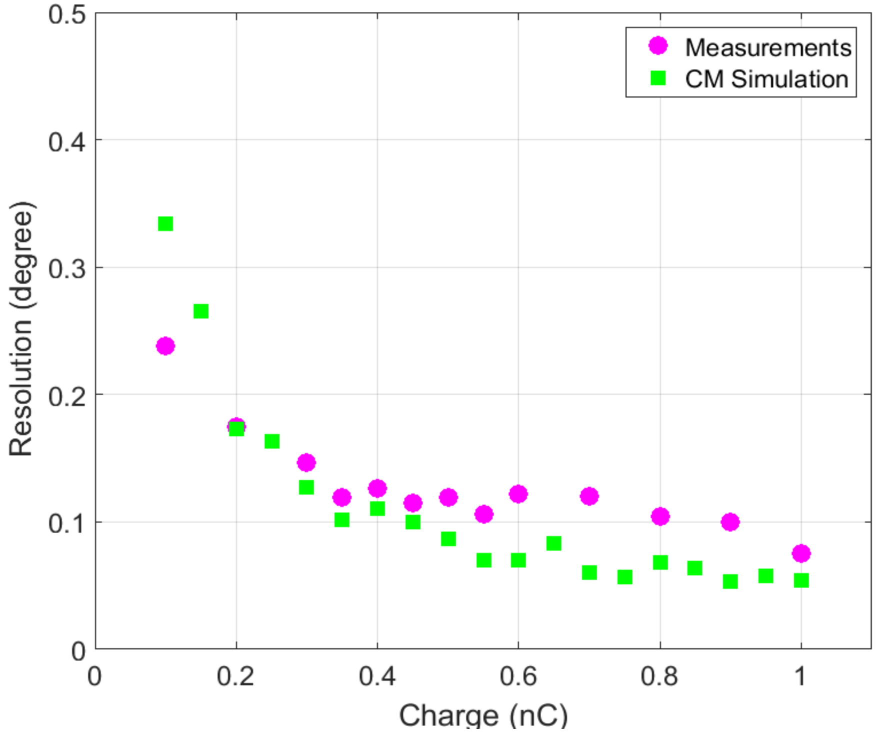


- $D = USV^T$
- S contains the singular values associated with the signal
- Top 24 singular values are used to reconstruct the signal. The rest is regarded as noise.
- The noise level is approximately 8 mV RMS. SNR is ~20 dB for HOM1 and ~10 dB for HOM2.

Resolution versus Charge

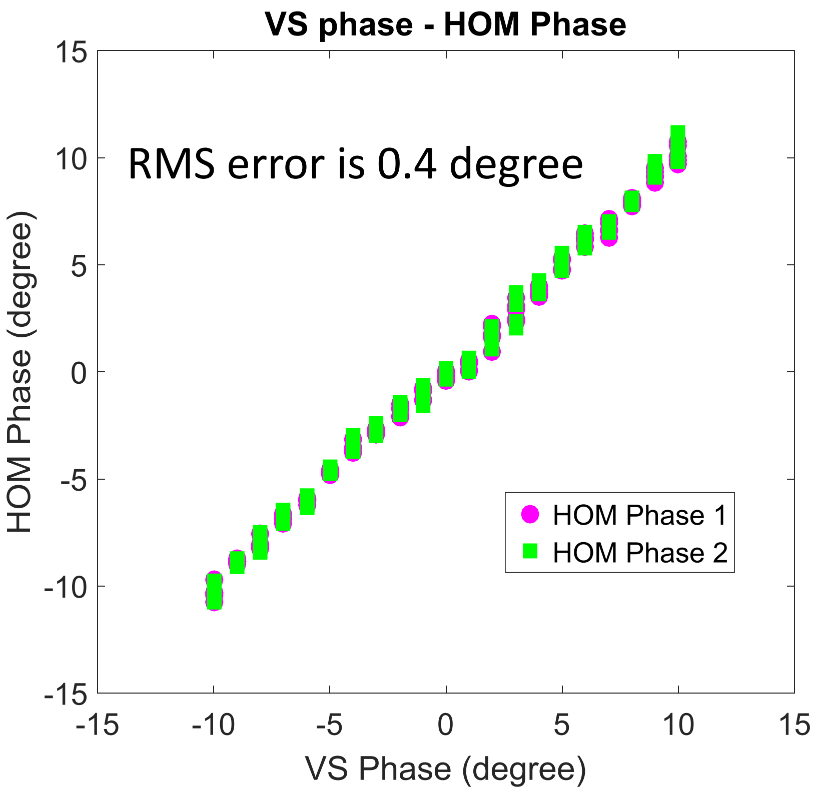


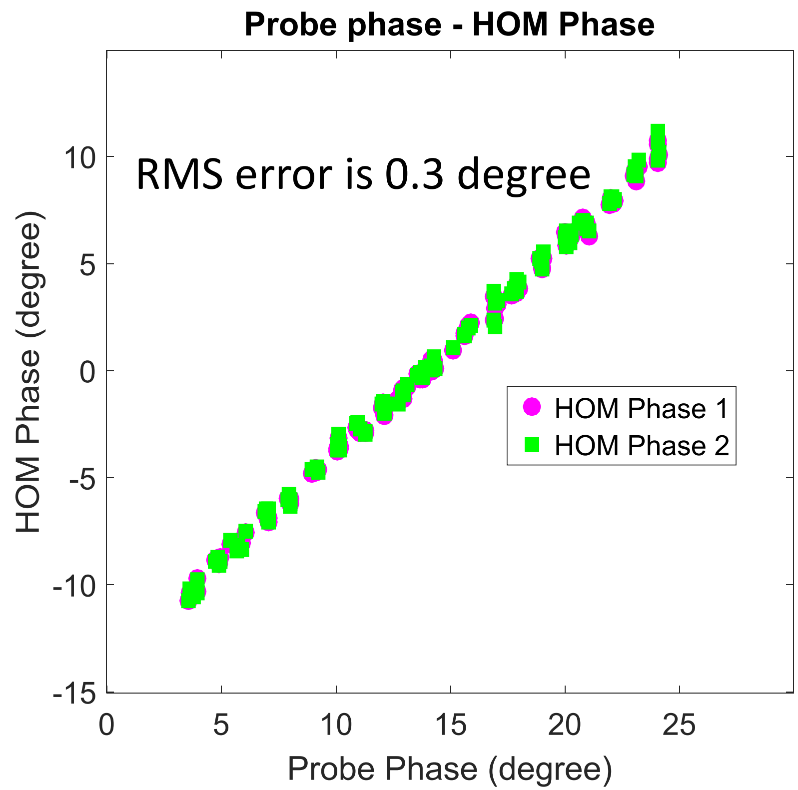
- The beam charge was varied from 0.1 to 1 nC with a step of 0.1 nC.
- The simulation data was scaled with measurements.



- Experiment（20 GS/s）@22MV/m, 0.5 nC
- Beam phase is varied at 0, -5, and 5 degree.

Comparison with Probe Phase



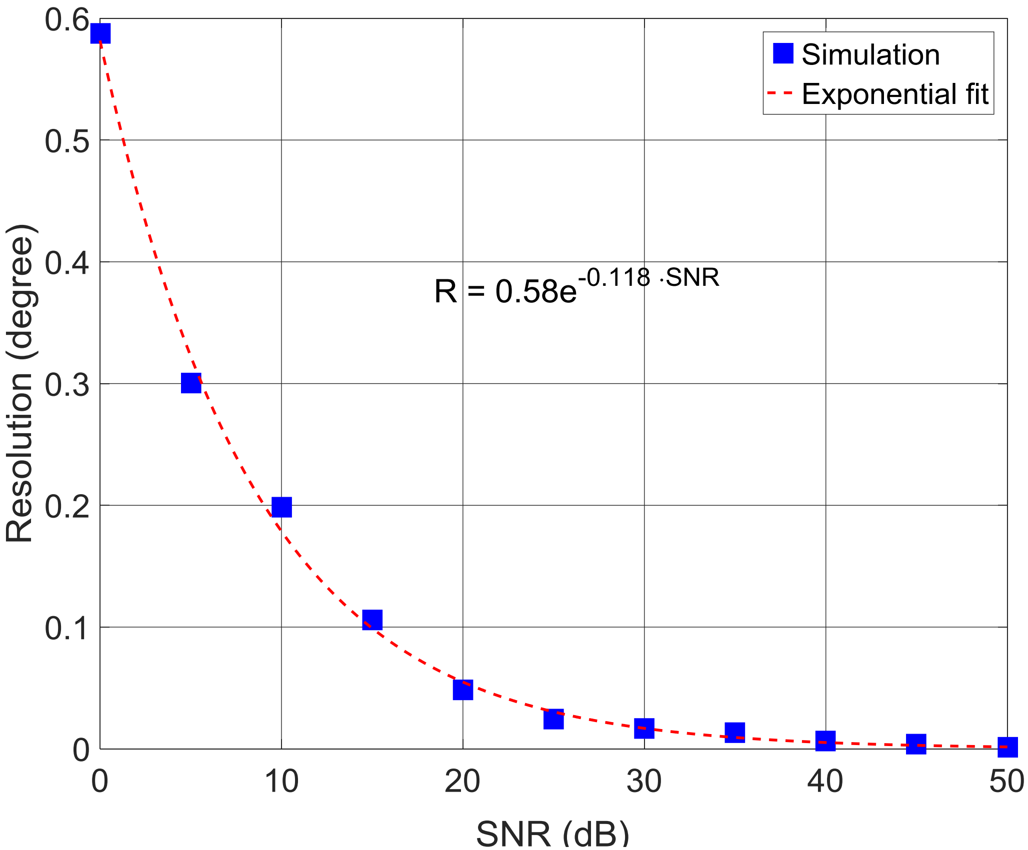


- The phase was changed from -10 to 10 degree with a step of 1 degree.
- Up to a calibration offset, the probe phase agrees with the HOM phase.

Note that the measurement system is not fully synchronized.

Resolution Limit Estimation

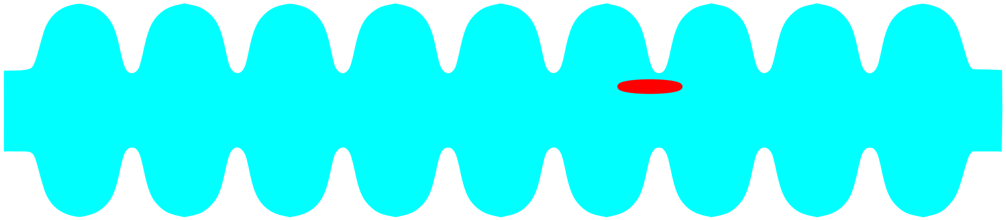
Simulation data with 0.5 nC and 20 GS/s

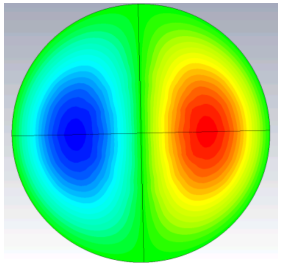


- Minimal detectable thermal noise: $U_{th} = \frac{1}{2} k_b T = 0.0129\ eV\ @\ 300K;$
- Energy deposited in a monopole mode: $kq^2 = 9.4 \cdot 10^{11}\ eV$ with 0.5 nC
- By assuming 0.5 power coupling, the SNR is approximately 136 dB, which suggests ~ 10^{-8} degree resolution.
- By scaling the power of the simulation signal based on measurements, the difference between simulation and measurement is 0.05 degree.

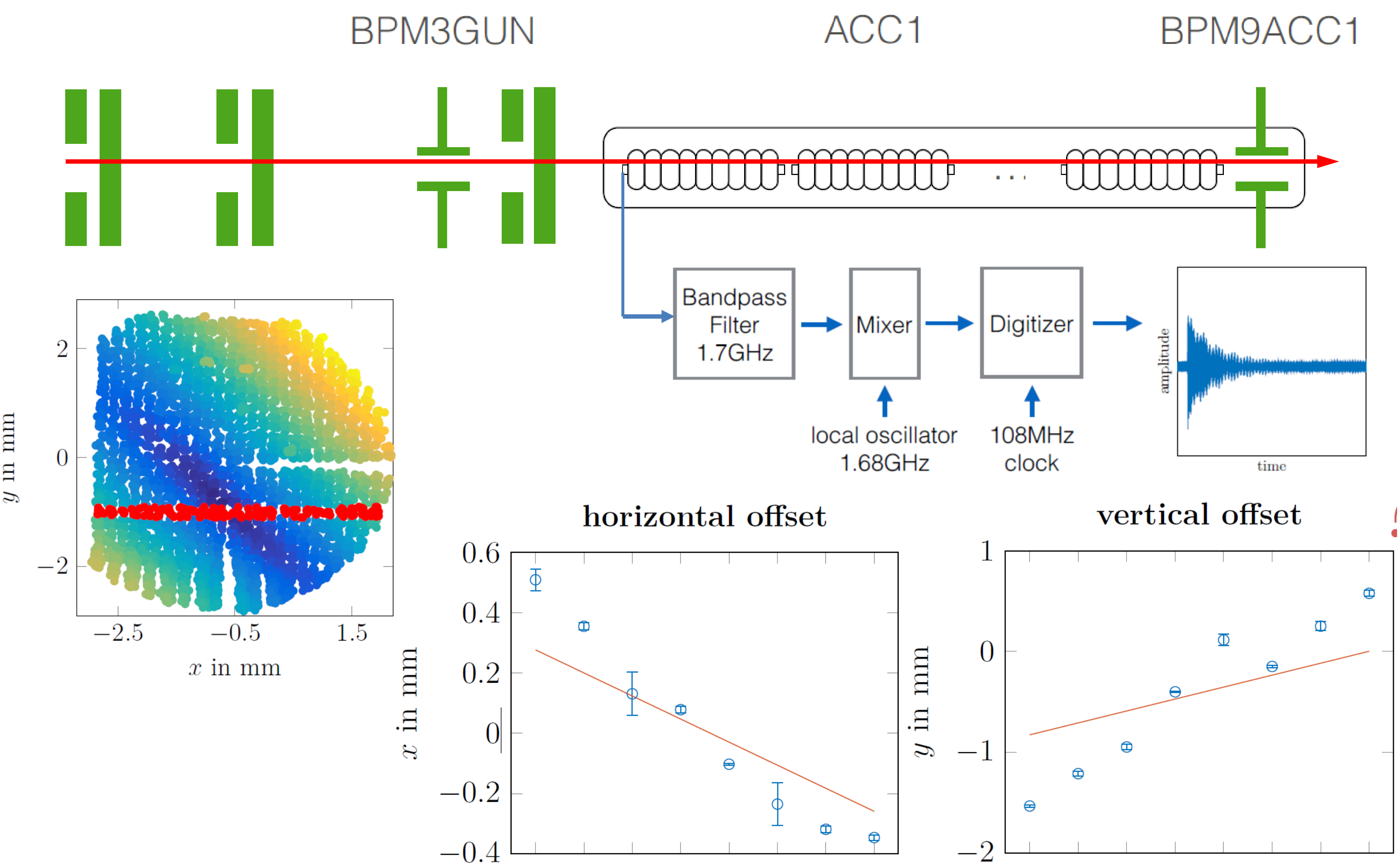
Cavity Misalignment Measurement

Dipole Modes

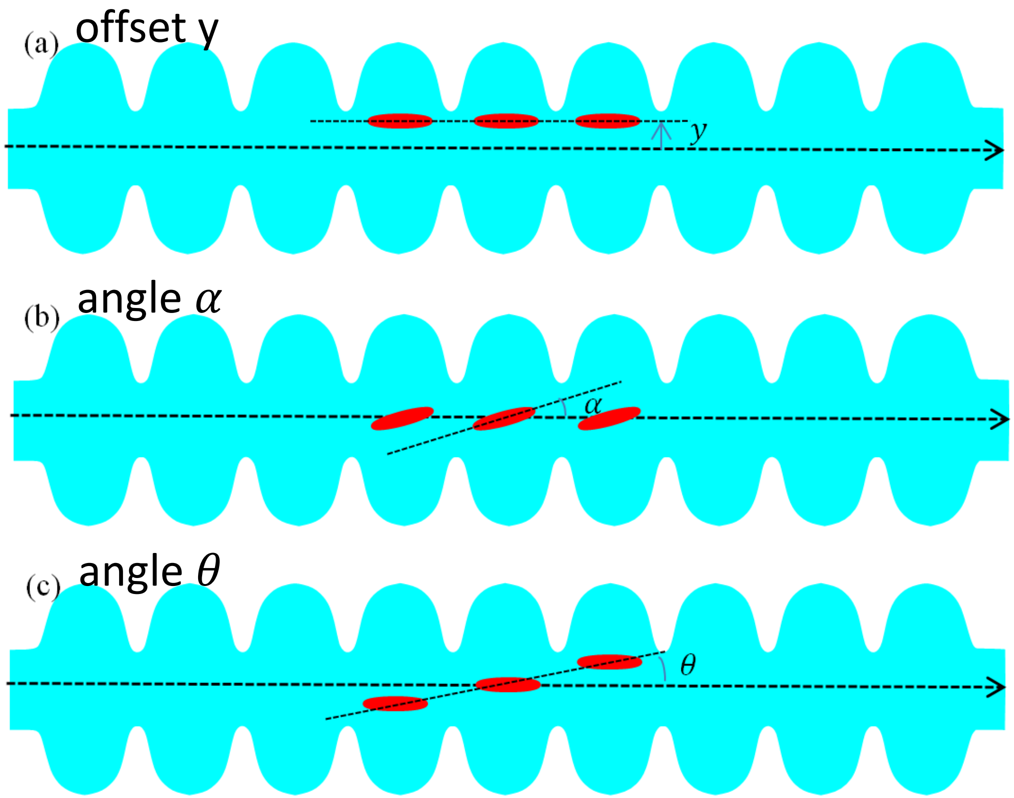




Cavity Misalignment Measurements



Wakefields for various Beam Trajectories



The amplitude depends linearly on the offset y.

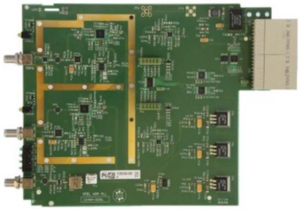
The amplitude depends linearly on α and square of bunch length

The amplitude depends linearly on θ

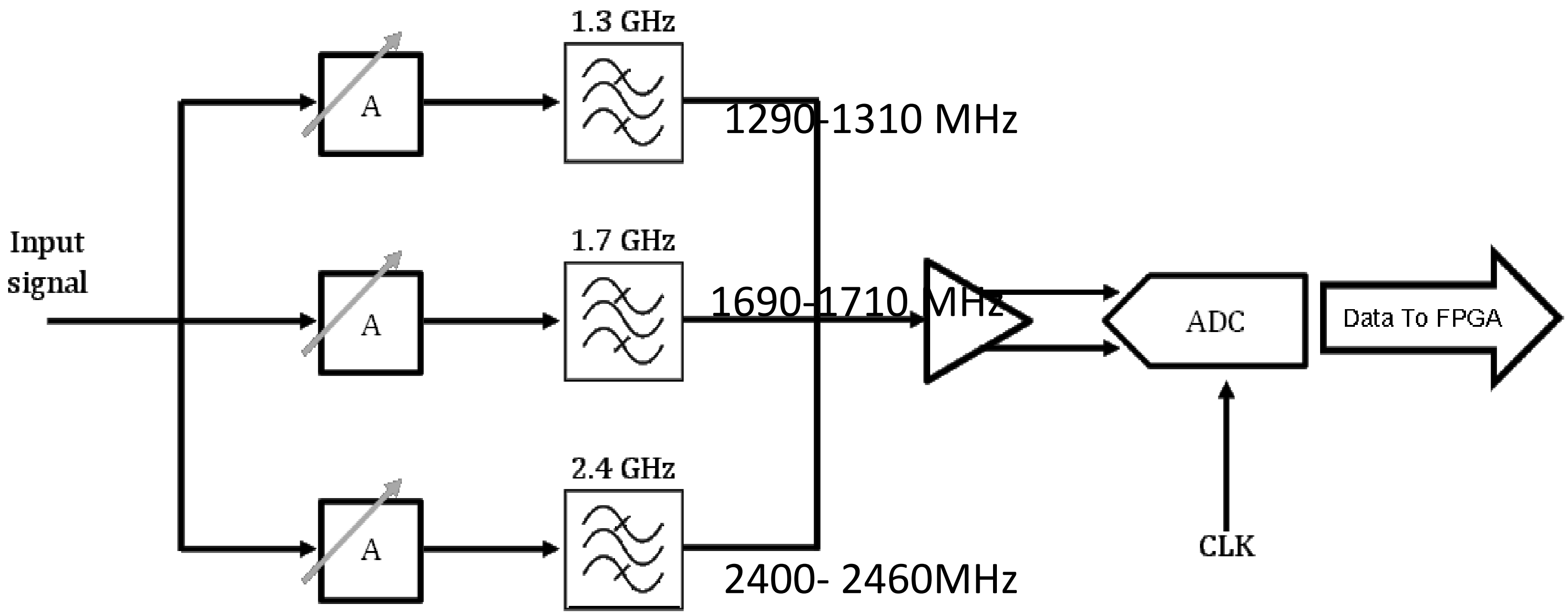
- Scenario (c) can play an important role in beam position determination.
- For scenario (a) and (c), a beam with 1 mrad angle excites a signal with the same amplitude as with ~200 µm offset.
- The maximum allowed angle (limited by beam pipe diameter) is ~ 7 mrad. The beam angle is normally a few hundred µrad.

HOM-based Beam Diagnostics

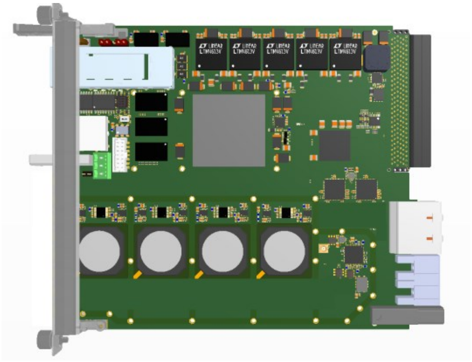
Electronics

Electronics for 1.3 GHz Cavities



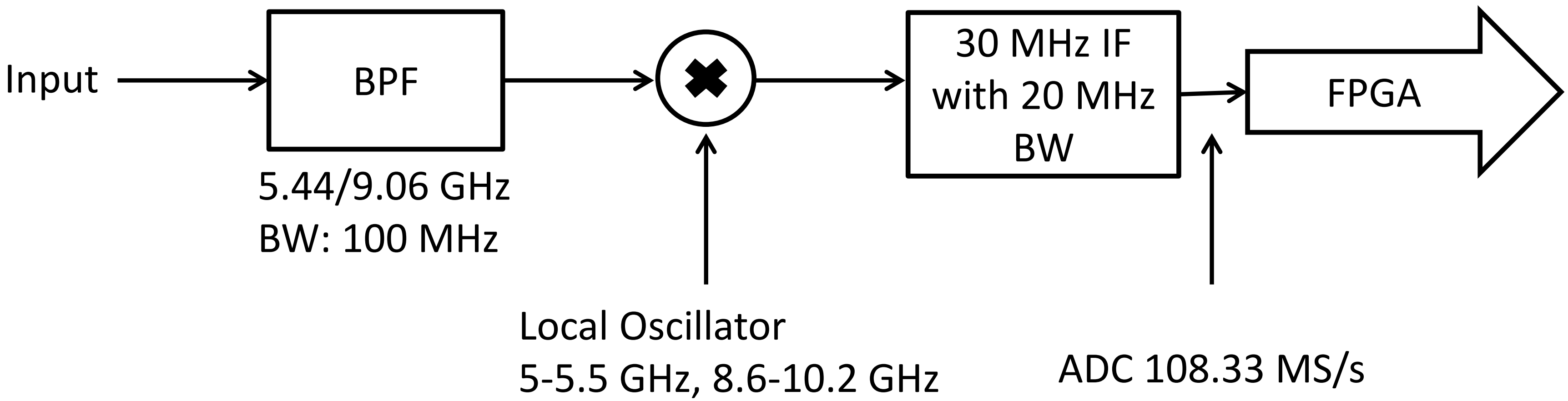
- The electronics are compact and can be used for beam phase and beam position measurements.
- They fully comply with MicroTCA.4 standard.

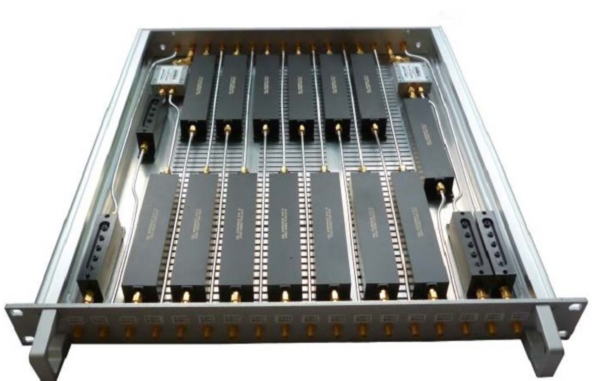


Fast digitizer

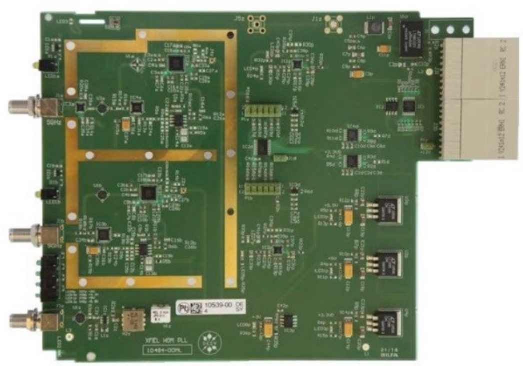
Courtesy of Uros

Electronics for 3.9 GHz Cavities





Filters



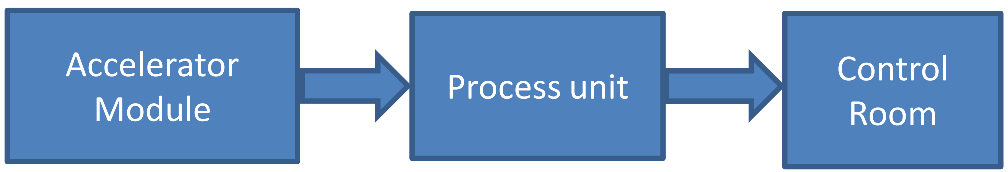
PLL card

Downconverter card

First Tests of a MICRO-TCA-Based Downconverter Electronics for 5GHz Higher Order Modes in Third Harmonic Accelerating Cavities at the XFEL, T. Warmsat, IBIC14, pp337

Possible Topologies of Final System

- Process at the front end and transmit the results over long distance.

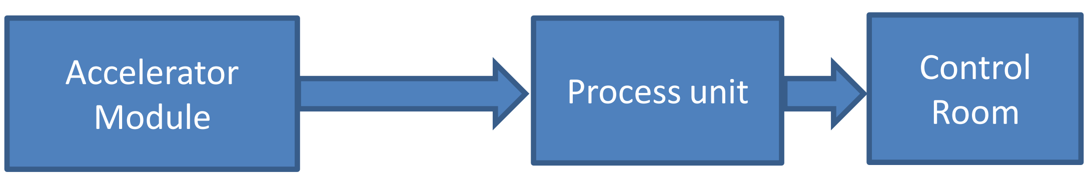


+ Less influence from the intermediate units

- Radiation protection

Vicinity of the module

- Transmit the signal over long distance and process the signal.



Longer cable
to different site

+ No need for radiation protection.

- Signal integrity issue

Summary

- **Beam Phase Measurements**

  - We routinely obtain 0.1˚ resolution with a scope setup. Simulations predict that at least **35 dB** SNR is required to achieve the 0.01 ˚ resolution.

  - Measurements are consistent with prediction from simulation and other phase monitors.

  - Electronics are under development.

- **Cavity Position Measurements**
  - The relative cavity misalignment can be measured by searching for the trajectory that minimizes the dipole mode power.

  - It is not trivial to measure the beam angle effects.

Thank you for your attention!

Cavity Misalignment Measurements