HOM-based Beam Diagnostics at the European XFEL

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Outline

– Introduction to the European XFEL

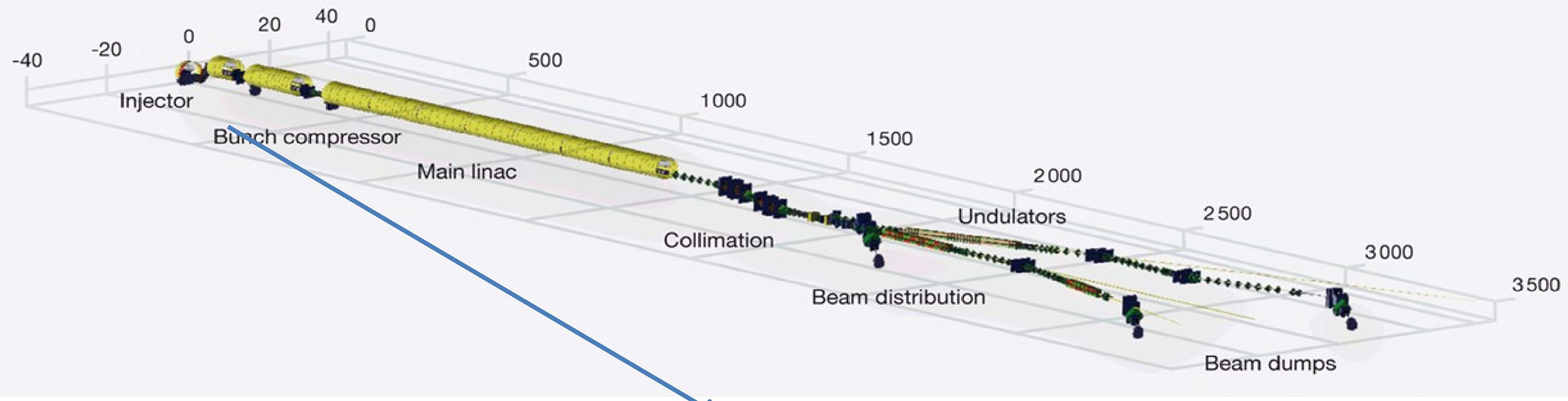
– Wakefields and Higher Order Modes

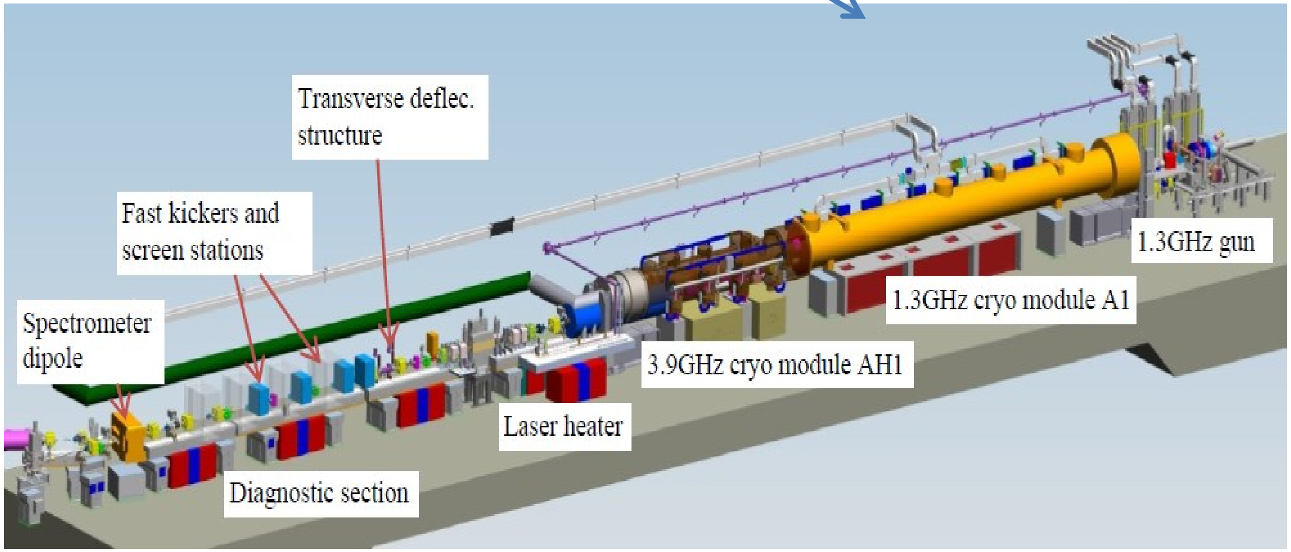
– HOM-based Beam Phase Monitor

– HOM-based Beam Position Monitor

– Summary and Outlook.

Introduction to the European XFEL



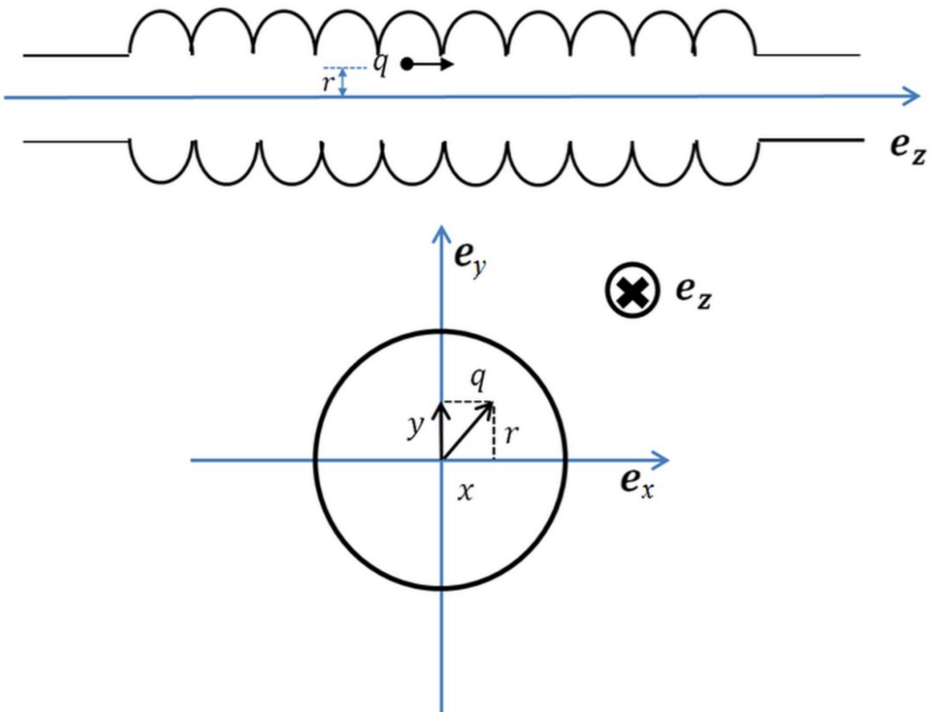


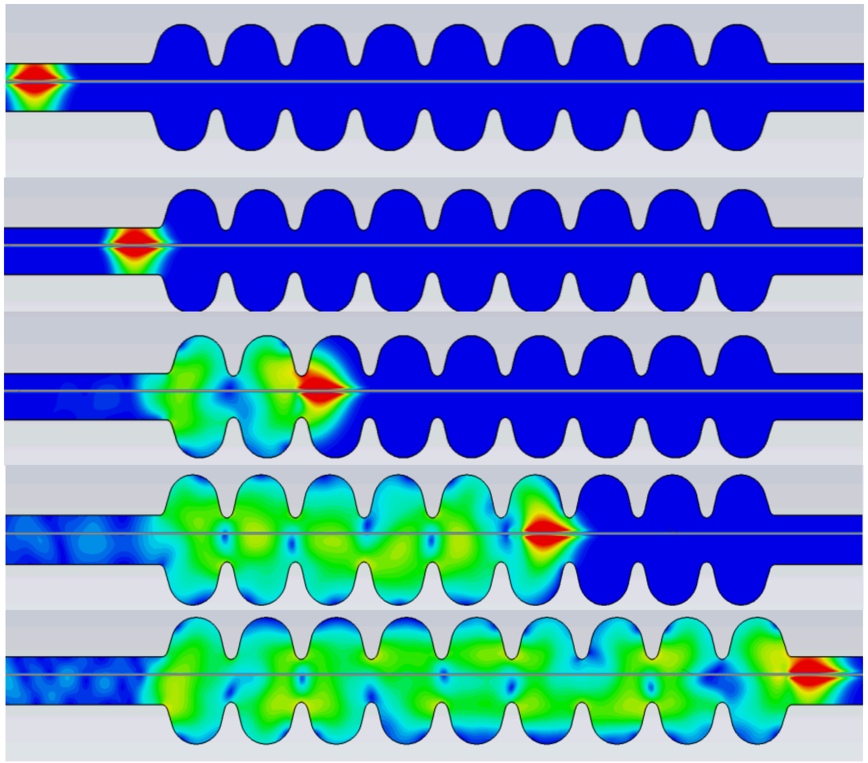
Electron Beam

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 are classified into monopole, dipole, quadrupole modes etc.

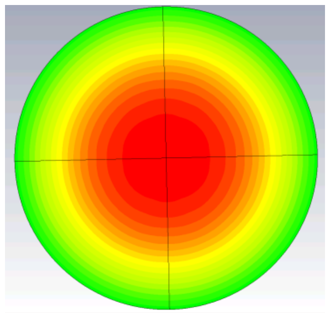
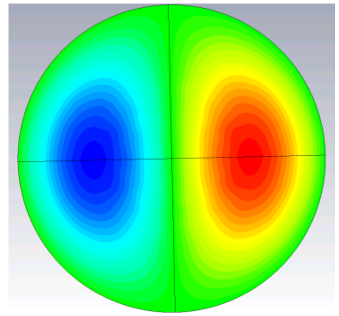
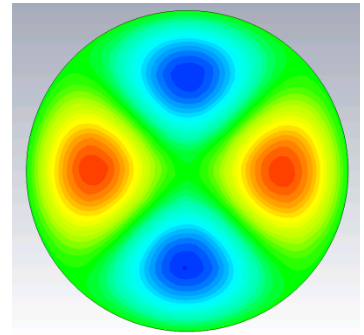
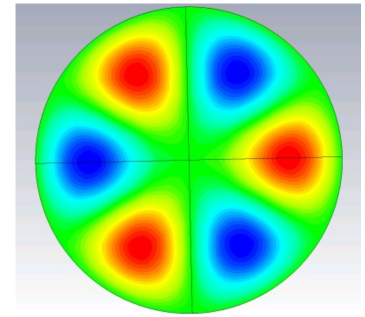




$$\widetilde{\boldsymbol{E}}(r,\theta,z) = \sum_{m=0}^{\infty}\left(E_r^{(m)}(r,z)\cos(m\theta)\,\boldsymbol{e_r} + E_\theta^{(m)}(r,z)\sin(m\theta)\,\boldsymbol{e_\theta} + E_z^{(m)}(r,z)\cos(m\theta)\,\boldsymbol{e_z}\right)$$

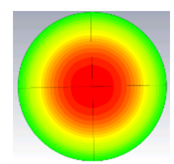
R. Wanzenberg, TESLA 2001-33, 2001.

Higher Order Modes

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

- Monopole modes dominate the longitudinal wake potential:

$$\boldsymbol{W}_{\parallel} \cong -\sum_n \omega_{0n} \left(\frac{R}{Q}\right)^{0n} \cos\left(\frac{\omega_{0n} s}{c}\right) H(s) \boldsymbol{e}_z$$

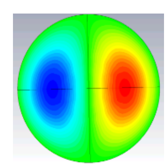


Measured Quantity $\propto q \cdot \frac{R}{Q}$

Bunch charge

- Dipole modes dominate the transverse wake potential:

$$\boldsymbol{W}_{\perp} \cong (x\boldsymbol{e}_x + y\boldsymbol{e}_y) c \sum_n \left(\frac{R}{Q}\right)^{0n} \sin\left(\frac{\omega_{0n} s}{c}\right) H(s)$$

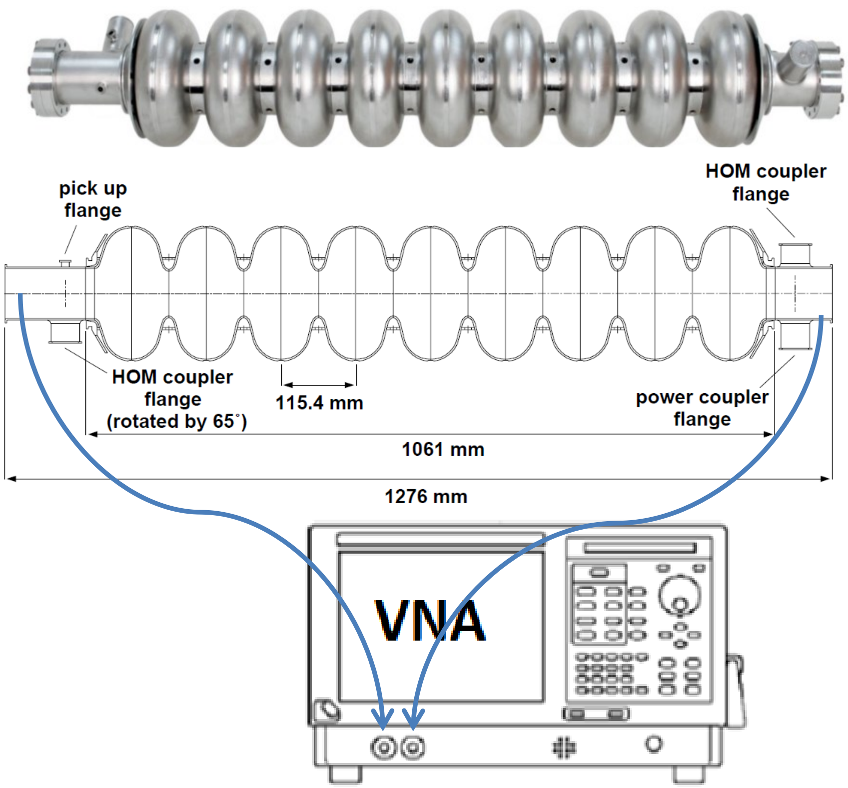


Measured Quantity $\propto q \cdot r \cdot \frac{R}{Q}$

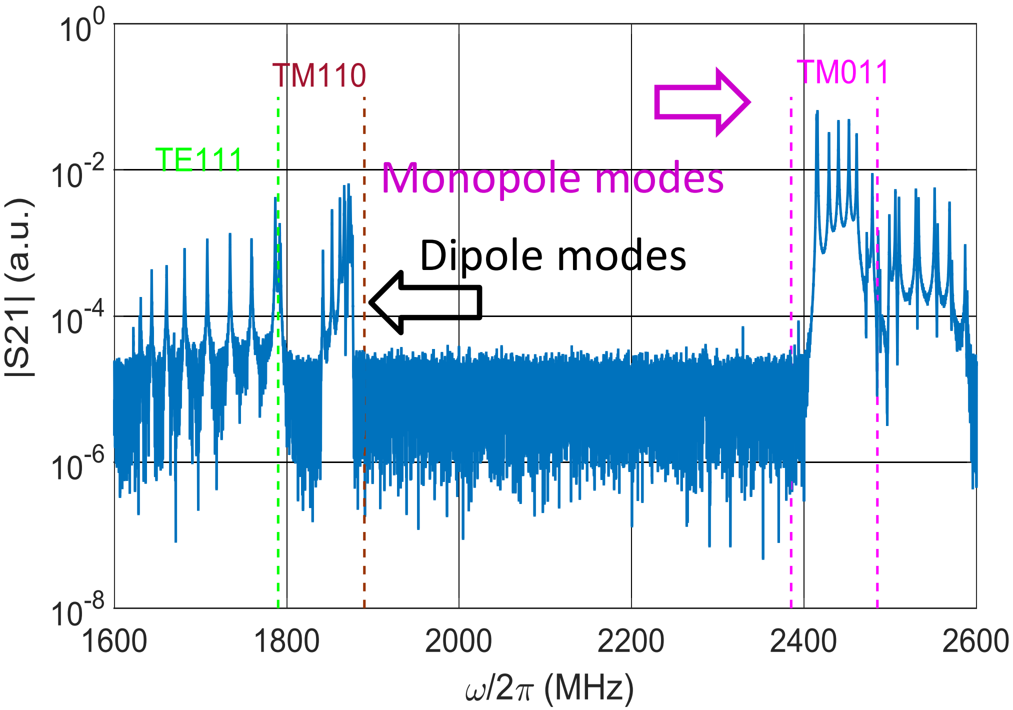
Bunch offset

TESLA Cavity and HOM spectrum

- TESLA Cavity (1.3 GHz)



- HOM Spectrum

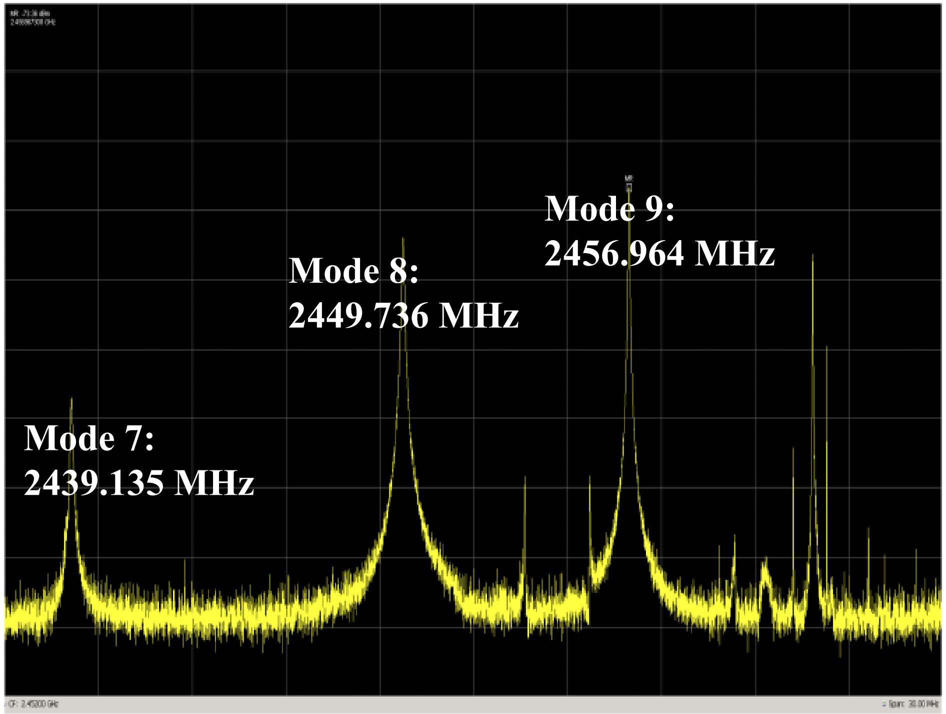


Monopole band occupies ~ 2.4 GHz with 70 MHz (2.38-2.45 GHz) bandwidth.

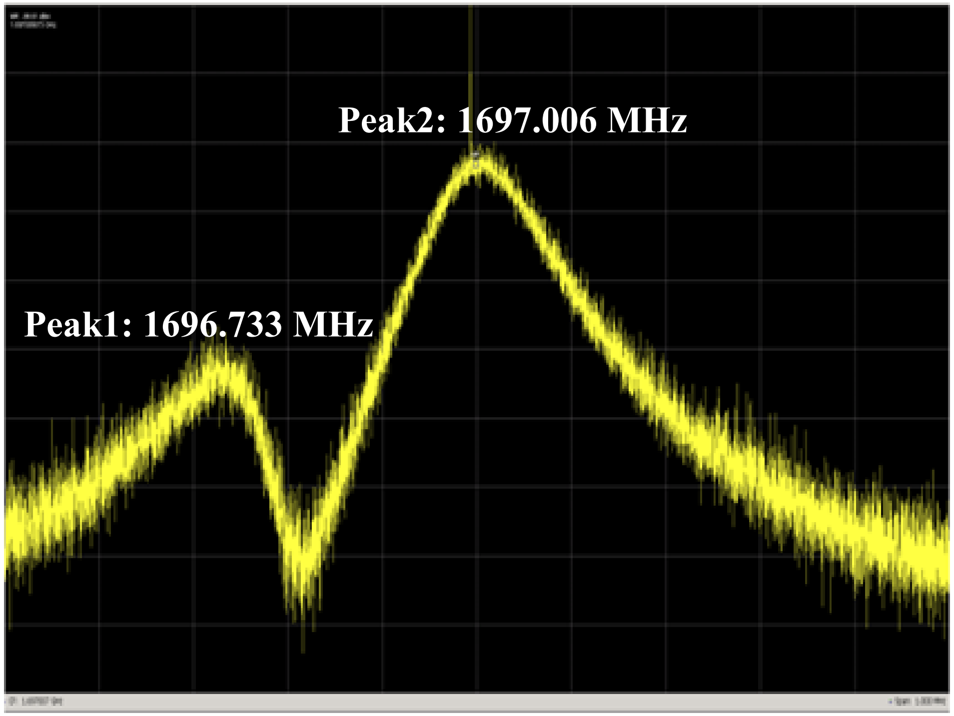
B. Aune, Phys. Rev. ST Accel. Beams 3, 092001.

Beam-excited HOM

- Monopole modes TM011



- Dipole mode TE111-6

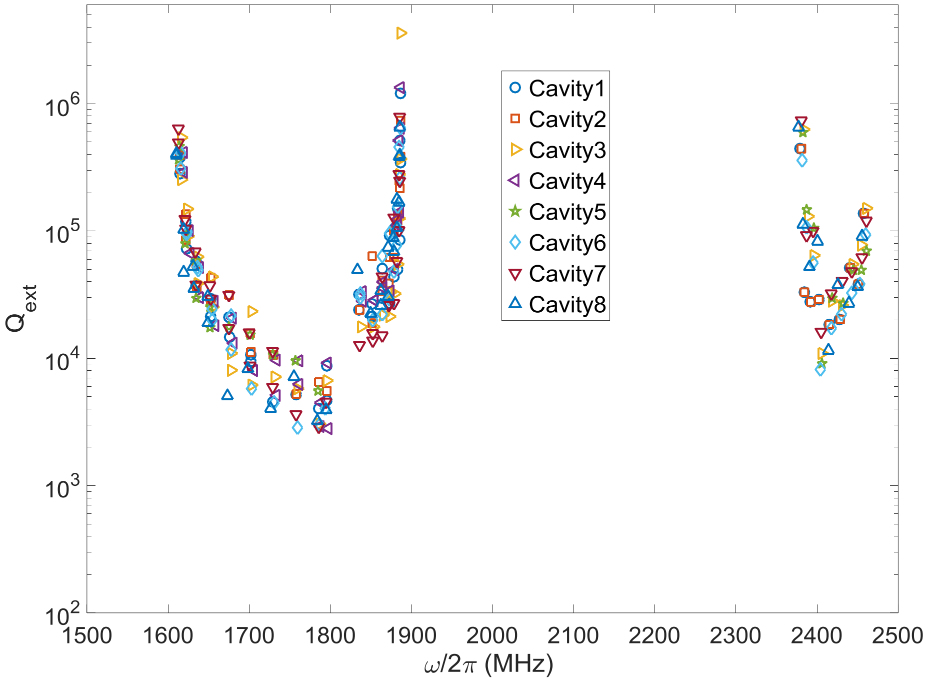


- Each peak can be described by Lorentzian distribution: $y = \sum_i \frac{a_{0i}}{1+\left(\frac{x-a_{1i}}{a_{2i}}\right)^2}$
- The quality factor: $Q_i = \frac{a_{1i}}{2a_{2i}}$

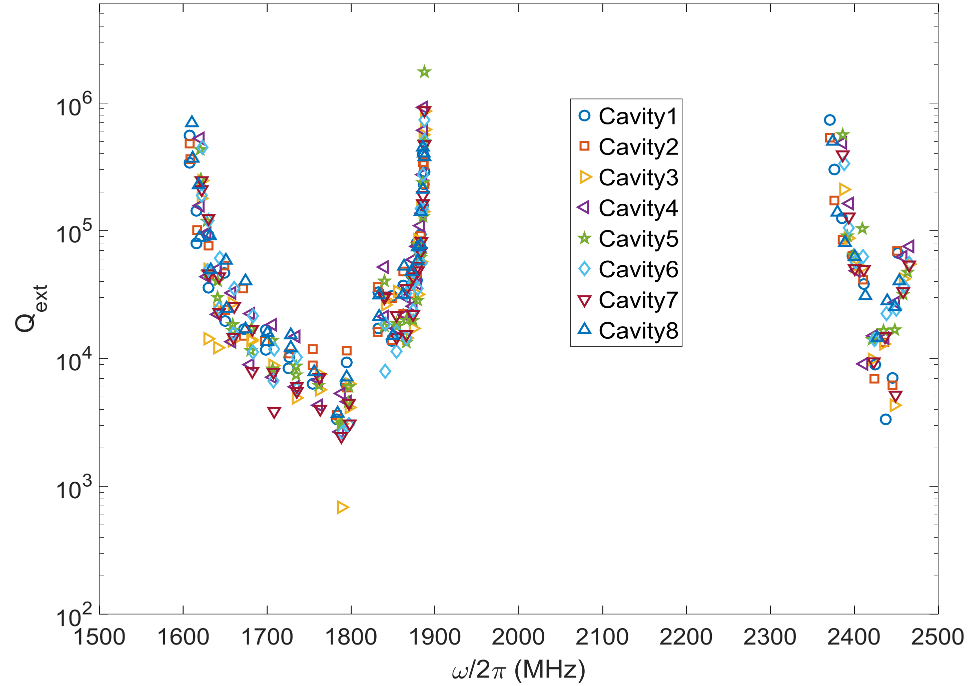
The last two modes are with higher R/Q (~ 70 Ω).

Monopole and Dipole Mode Characteristics

- Fifth module (FLASH)



- Injector module (E-XFEL)

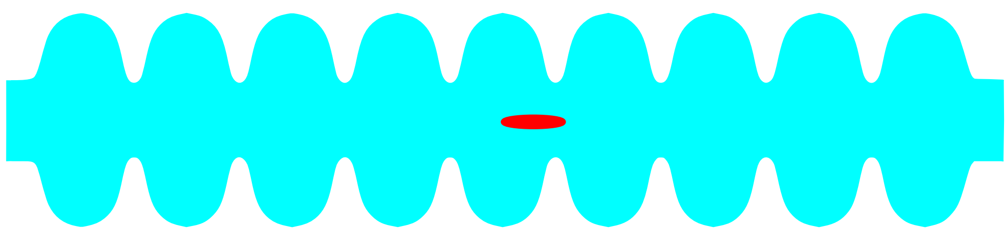


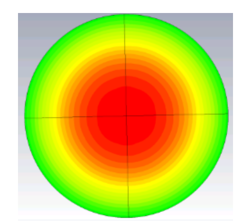
		TE111-6 Polarization 1	TE111-6 Polarization 2	TM011-8	TM011-9
FLASH	Min(MHz)	1700.719	1698.130	2449.731	2455.682
	Max(MHz)	1705.536	1705.536	2455.188	2461.127
E-XFEL	Min(MHz)	1698.015	1698.170	2445.412	2450.865
	Max(MHz)	1707.819	1708.475	2459.042	2459.042

- FLASH: 5 and 7 MHz for TE111-6 and 5 MHz for TM011-8,9.
- E-XFEL: 10 MHz for TE111-6 and 15 MHz for TM011-8,9.

Beam Phase Measurement

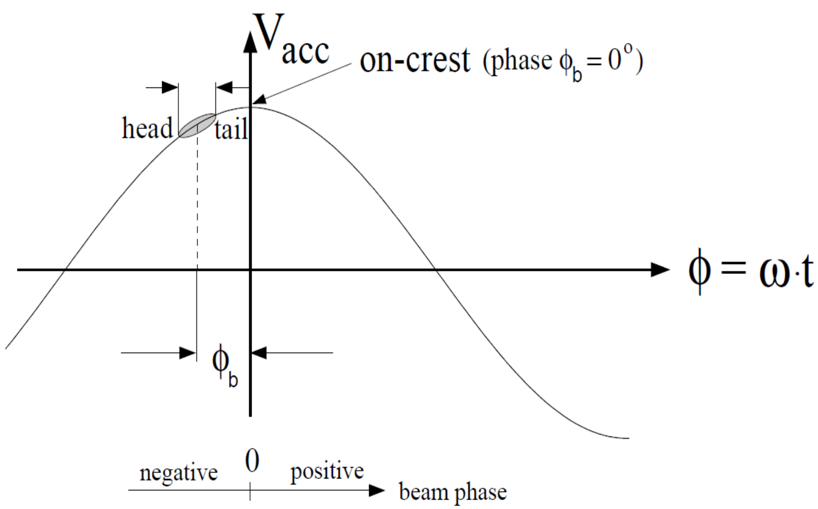
Monopole Modes

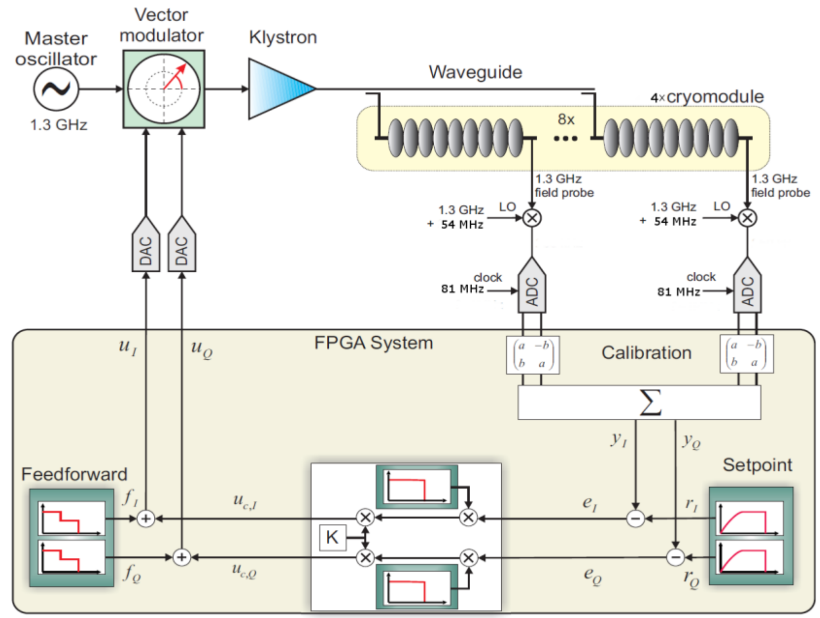




Field Control inside a cavity

- FEL operation requires high stability of RF amplitude and phase. Requirements are derived from beam properties:
  - ❑ Energy spread
  - ❑ Emittance
  - ❑ Bunch length
  - ❑ Arrival time

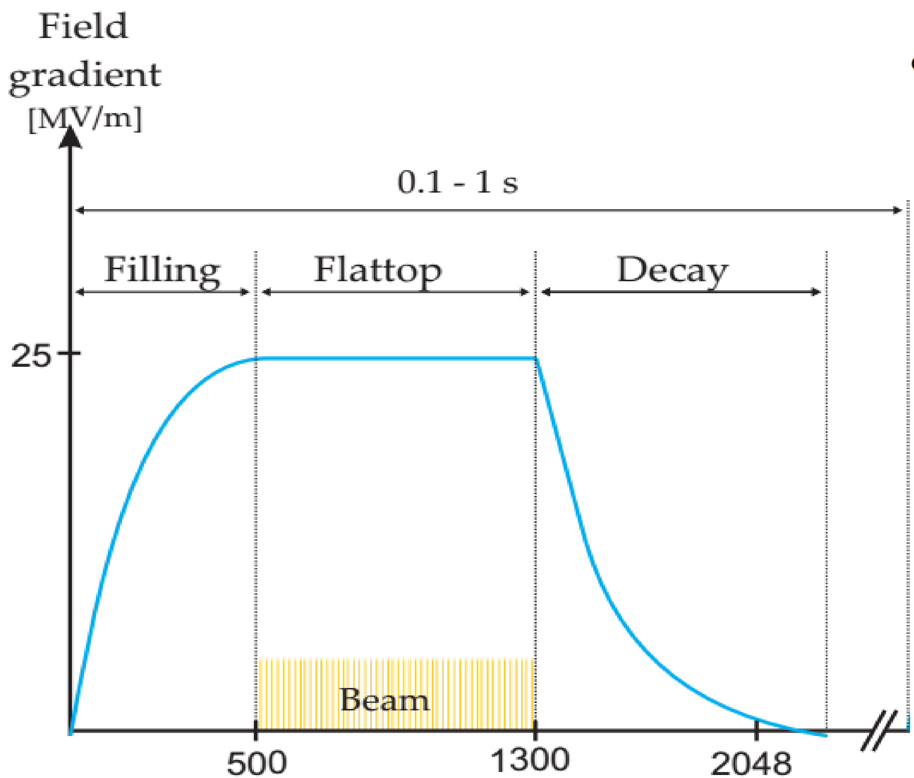


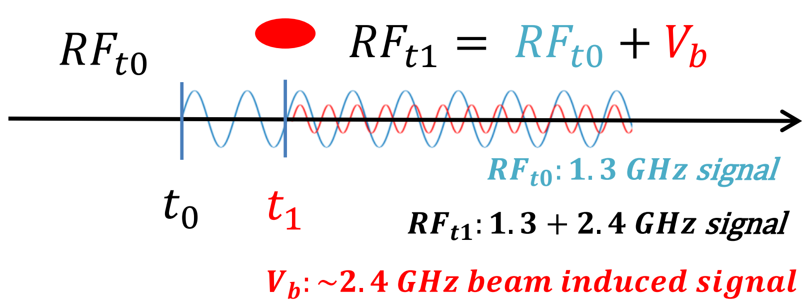


	Amp.	Phase
FLASH	0.01%	0.01˚
E-XFEL	0.01%	0.01˚

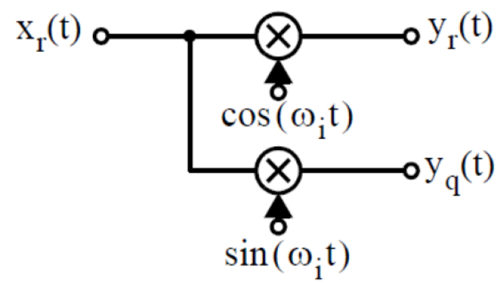
C. Schmidt, IPAC 2013, WEPME009

How to determine the beam phase?





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



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

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

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

✓ Digital down convert signal $x(t)$

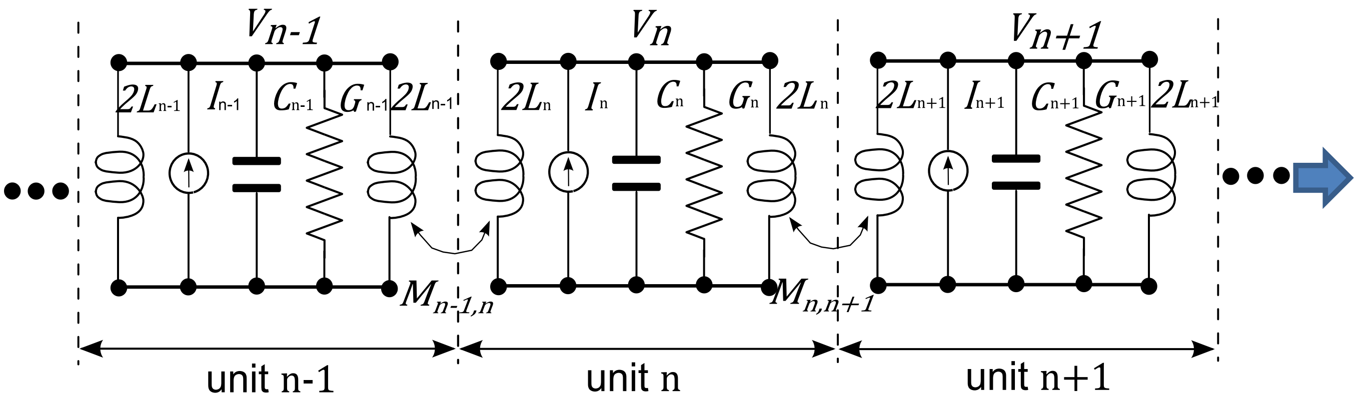
✓ Calculate phase φ_i for each mode

✓ Convert φ_i to beam arrival time t_1 and obtain the beam phase

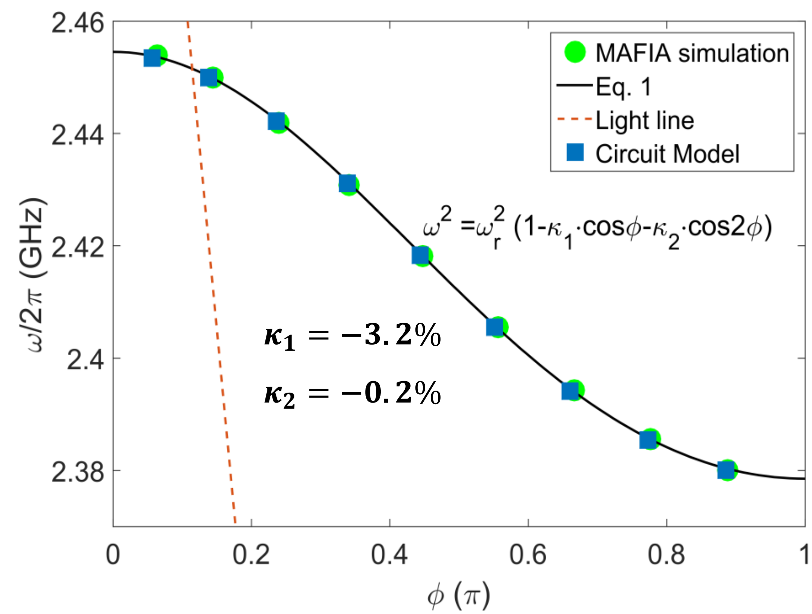
L.Shi, *et al., "Beam phase retrieval based on the higher order modes in cylindrical SRF cavities", to be published, 2017.*

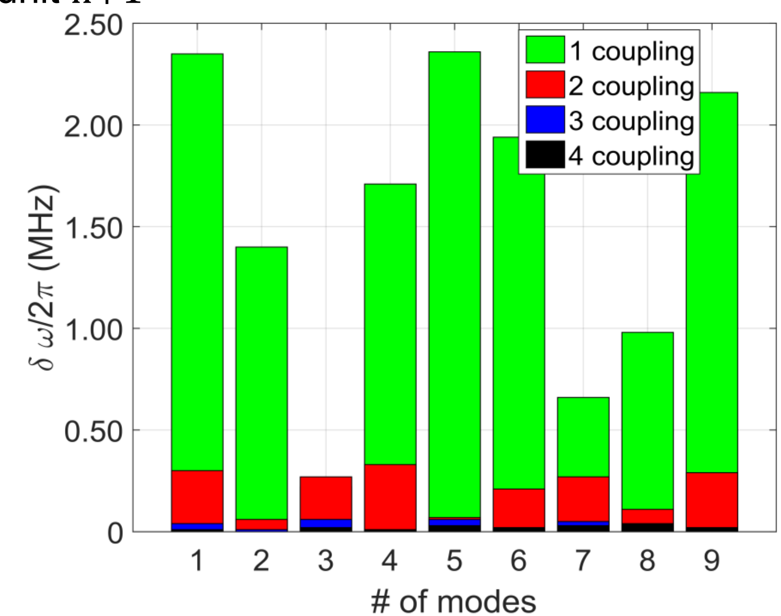
A single chain coupled circuit model

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

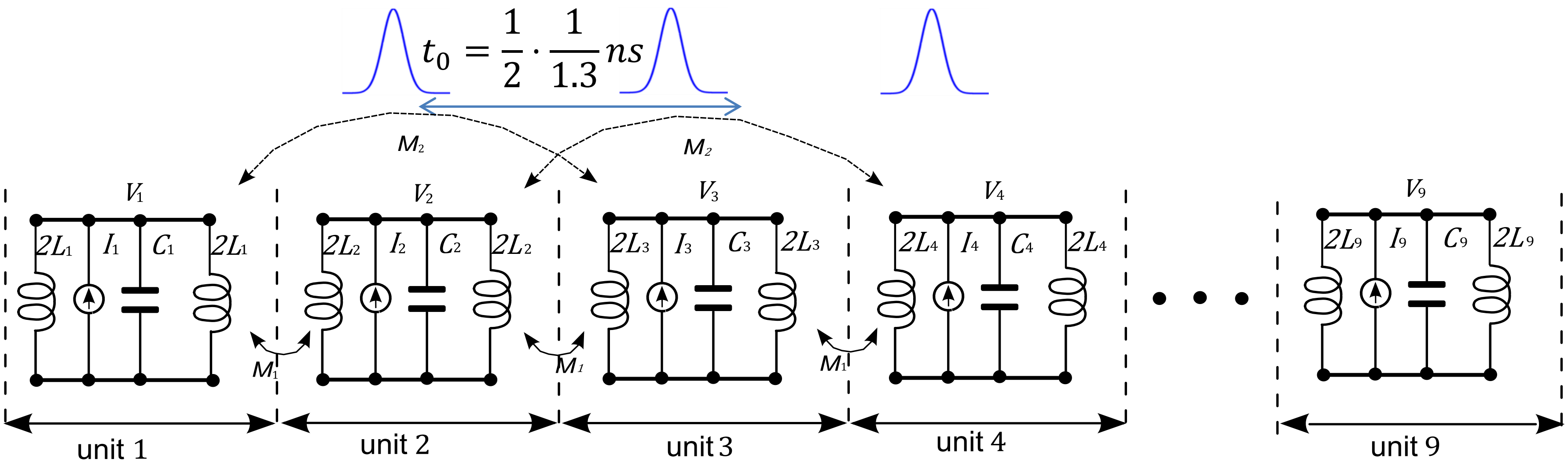


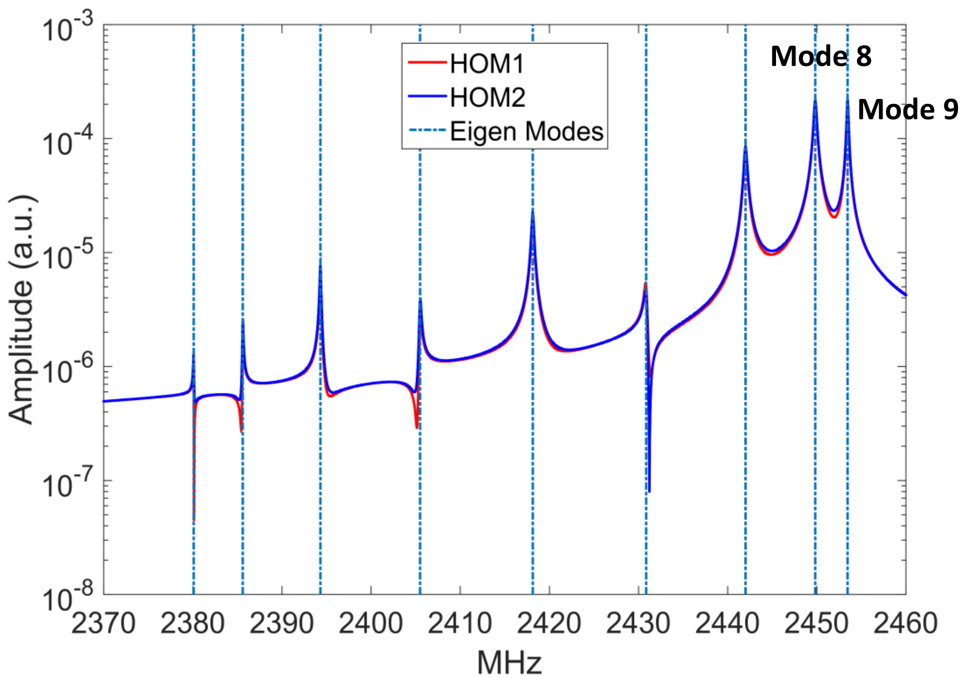
$$\omega^2 = \omega_r^2\left(1 - \sum_{i=1}^{N} \kappa_i \cos(i\phi)\right)$$





Beam-driven circuit model

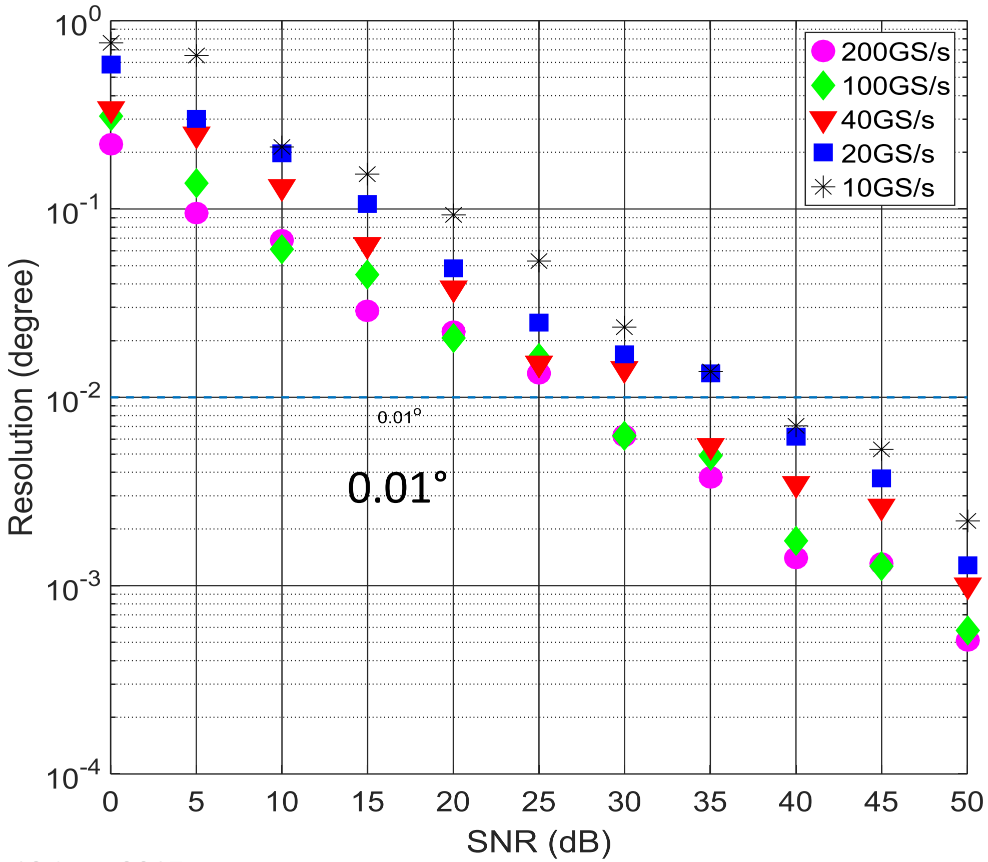




- Infinite circuit model is truncated to nine cells.
- It is then driven with delayed Gaussian pulses.
- The last two modes are excited strongly, and are used for beam phase calculation.

Resolution study - Circuit model

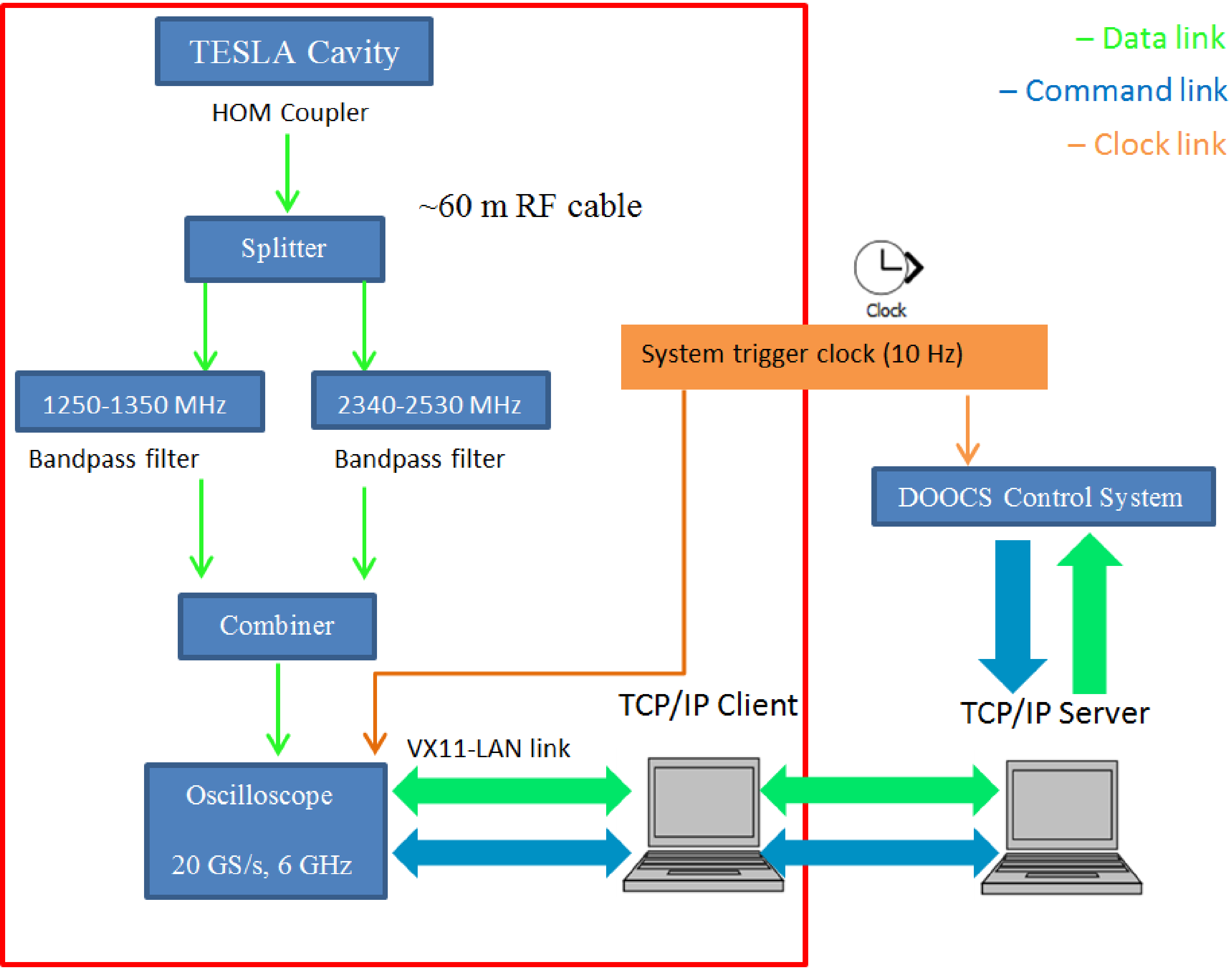
1. Vary the sampling frequency, while keeping other parameters constant
2. Vary the noise level, while keeping other parameters constant
3. Resolution is estimated for each setting



1. The resolution 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˚ requirement, the SNR is at least 35 dB

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

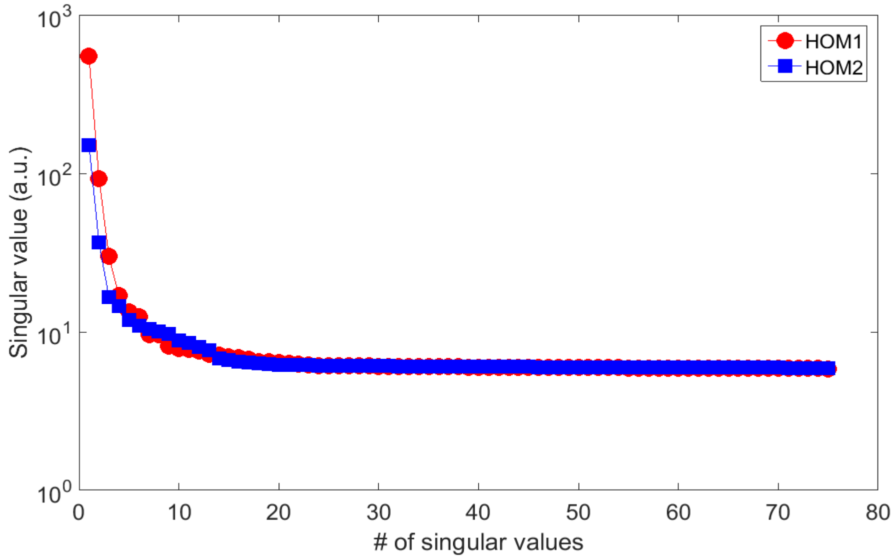
Experimental Setup

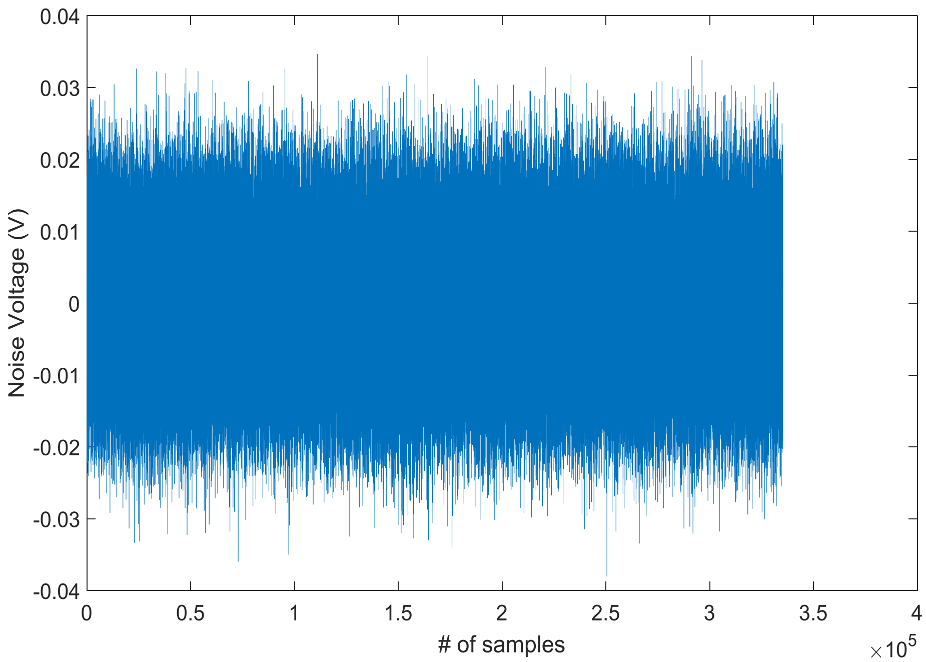


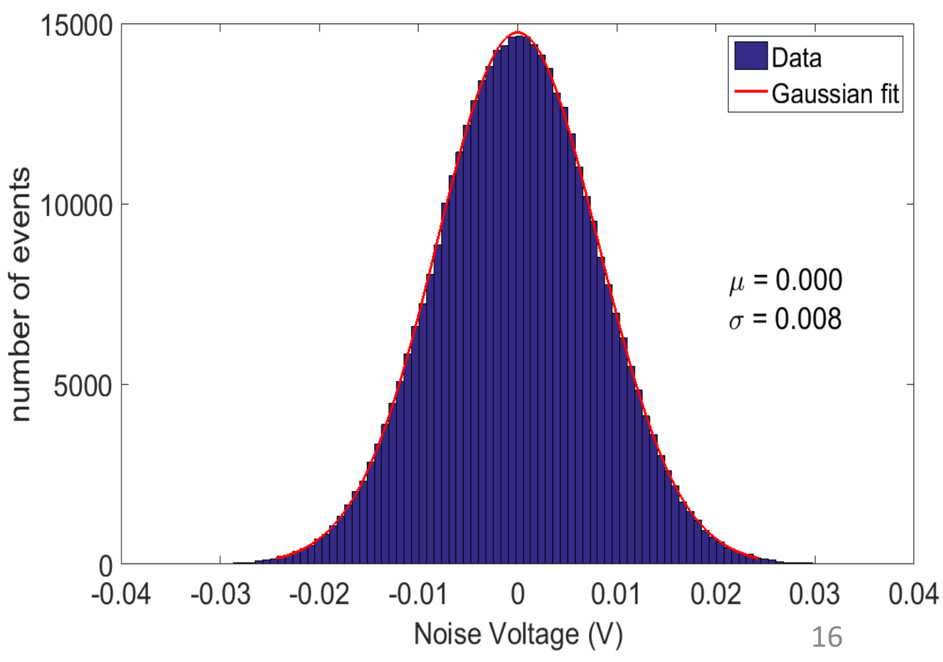
- ❑ HOM signals are available from HOM Patch panel.
- ❑ A fast scope (TDS6604B) with 20 GS/s, 6 GHz bandwidth is connected for two channels for HOM signals.
- ❑ A 10 Hz external clock is used to synchronize the measurement.
- ❑ The data from DOOCS and from scope are combined at TCP/IP Client
- ❑ Each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

Estimation of Noise based on SVD

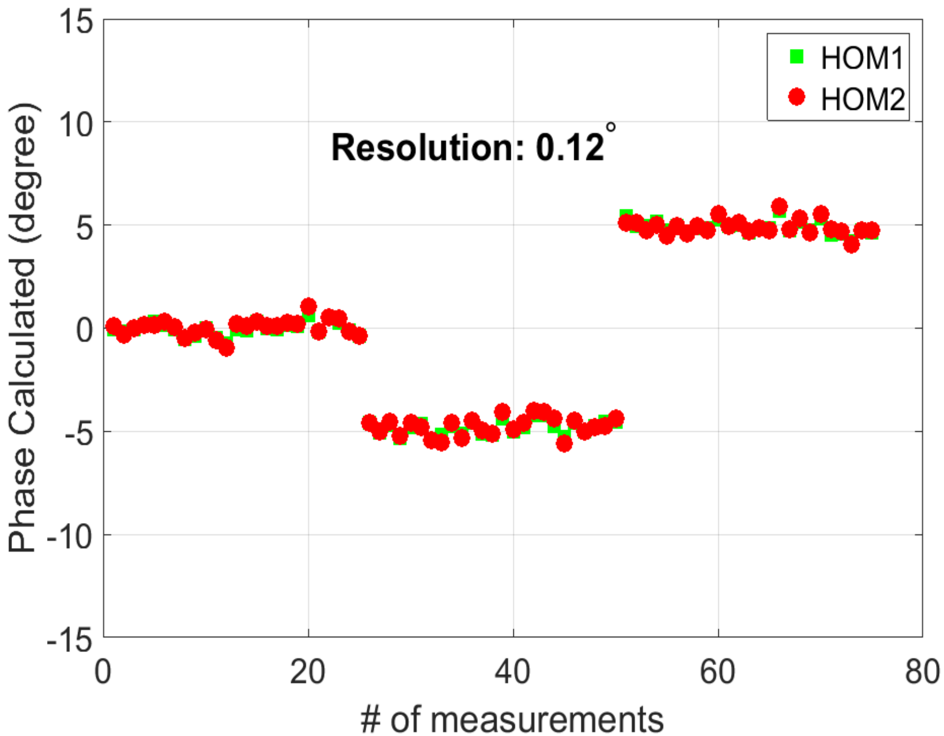
- $D = USV^T$
- S contains the singular values associated with the signal
- Top 24 singular values are used to reconstruct the signal. The rest is regarded as noise.
- The noise level is approximately 8 mV in RMS. SNR is ~20 dB for HOM1 and ~10 dB for HOM2.



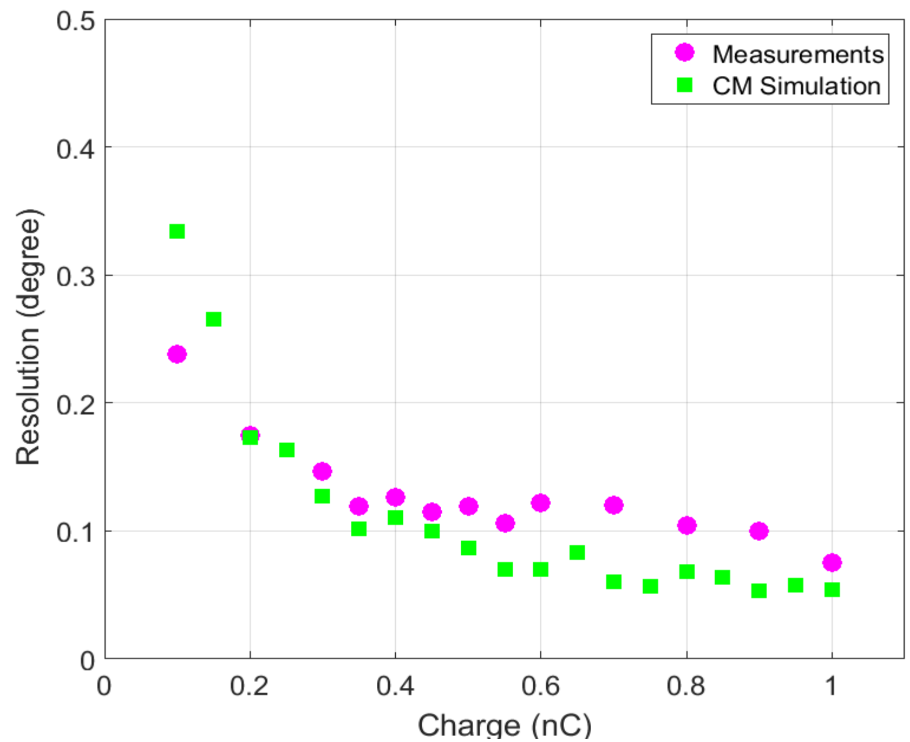




Resolution over charge

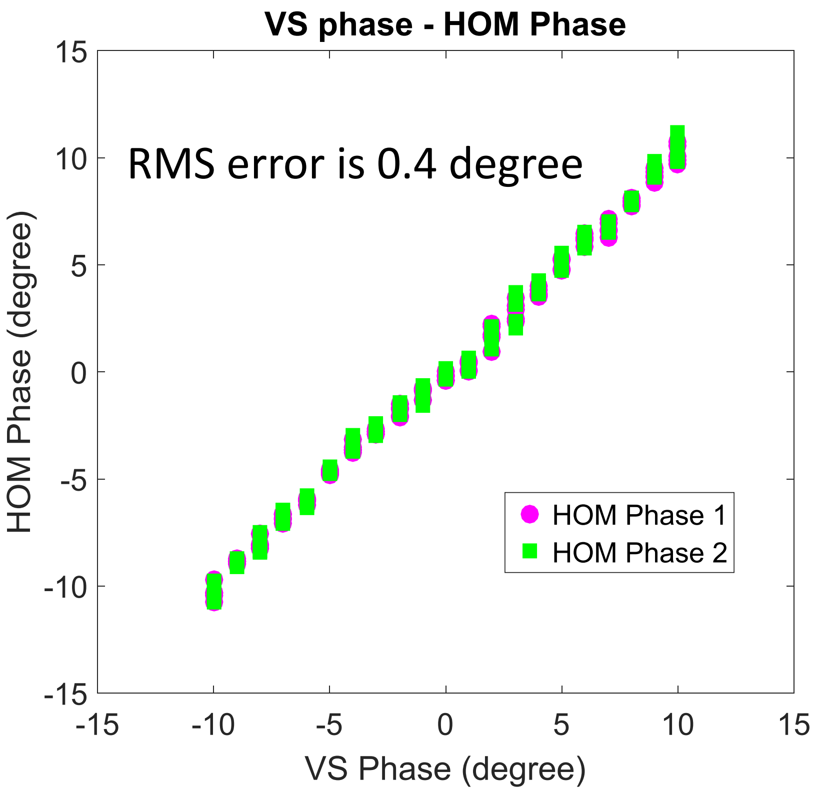


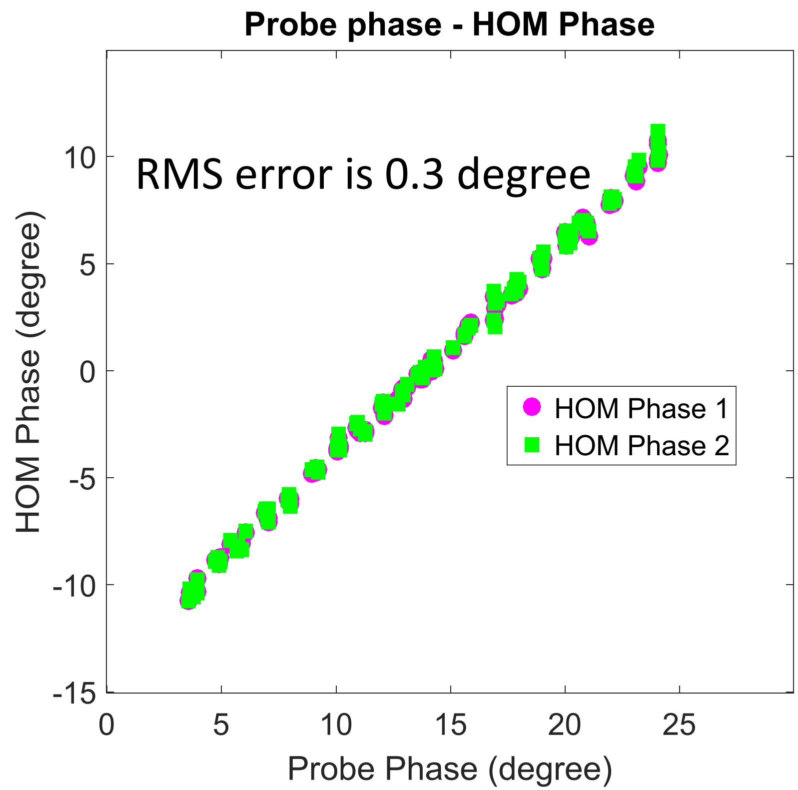
- The beam charge was varied from 0.1 to 1 nC.
- The simulation data was scaled with real measurements based on estimated SNR.



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

HOM Phase vs LLRF result



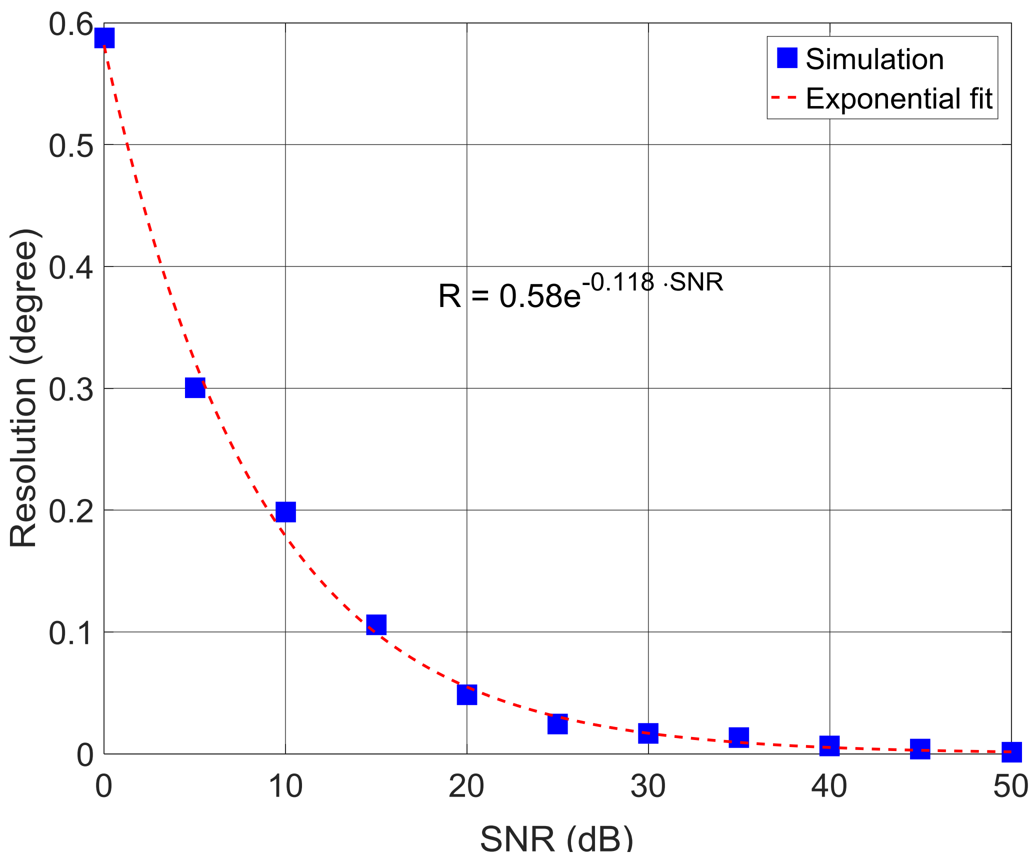


- Phase was changed from -10 to 10 degree with a step of 1 degree.
- Up to a calibration offset, the probe phase agrees with the phase from HOM.

Note the measurement system is not fully synchronized.

Resolution limit estimation

Simulation data with 0.5 nC and 20 GS/s



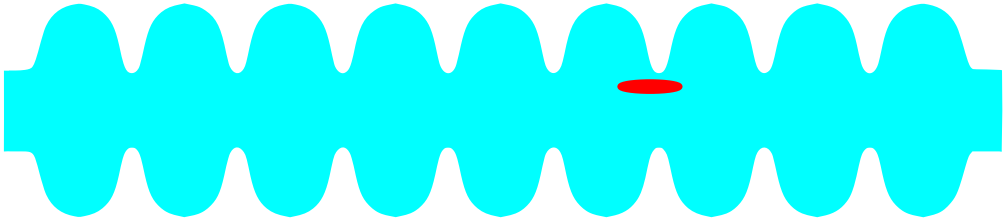
- Minimal detectable thermal noise:
$$U_{th} = \frac{1}{2} k_b T$$
- Energy deposited in a monopole mode: $9.4 \times 10^{11}\ eV$ with 0.5 nC charge
- By assuming 0.5 power coupling, the SNR is approximately **136 dB**, which suggests 6×10^{-8} degree resolution.
- The best resolution obtained so far is 0.03˚, while the prediction based on the fitted curve is ~0.04˚, with the SNR estimated to be 22dB.

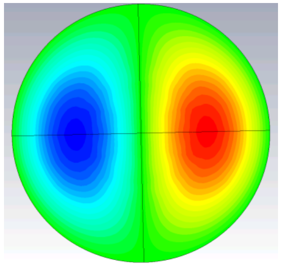
Summary

- Circuit model aids the development of beam phase monitor. At least 35 dB SNR is required to achieve 0.01˚ resolution.
- SVD method is used to estimate the signal strength and noise level.
- Measurements are performed with the proposed setup. The results are consistent with simulation and LLRF system.

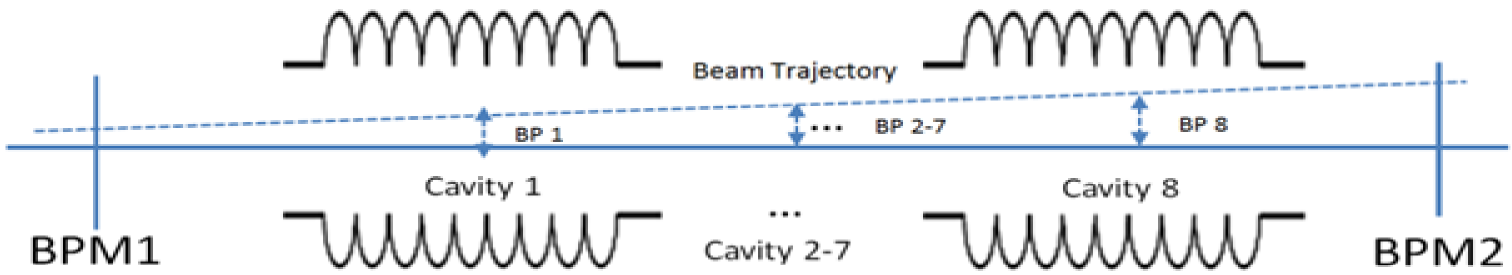
Beam Position Measurement

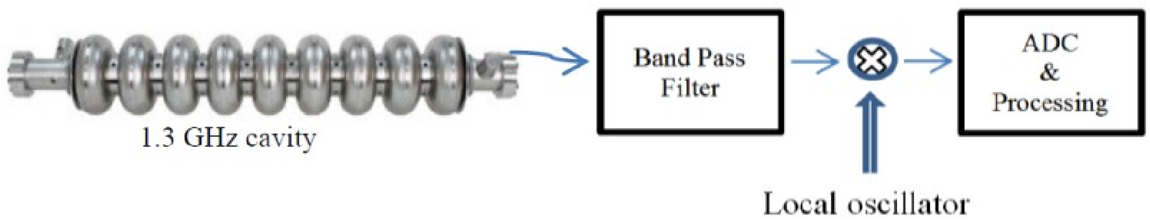
Dipole Modes





HOM-based BPM





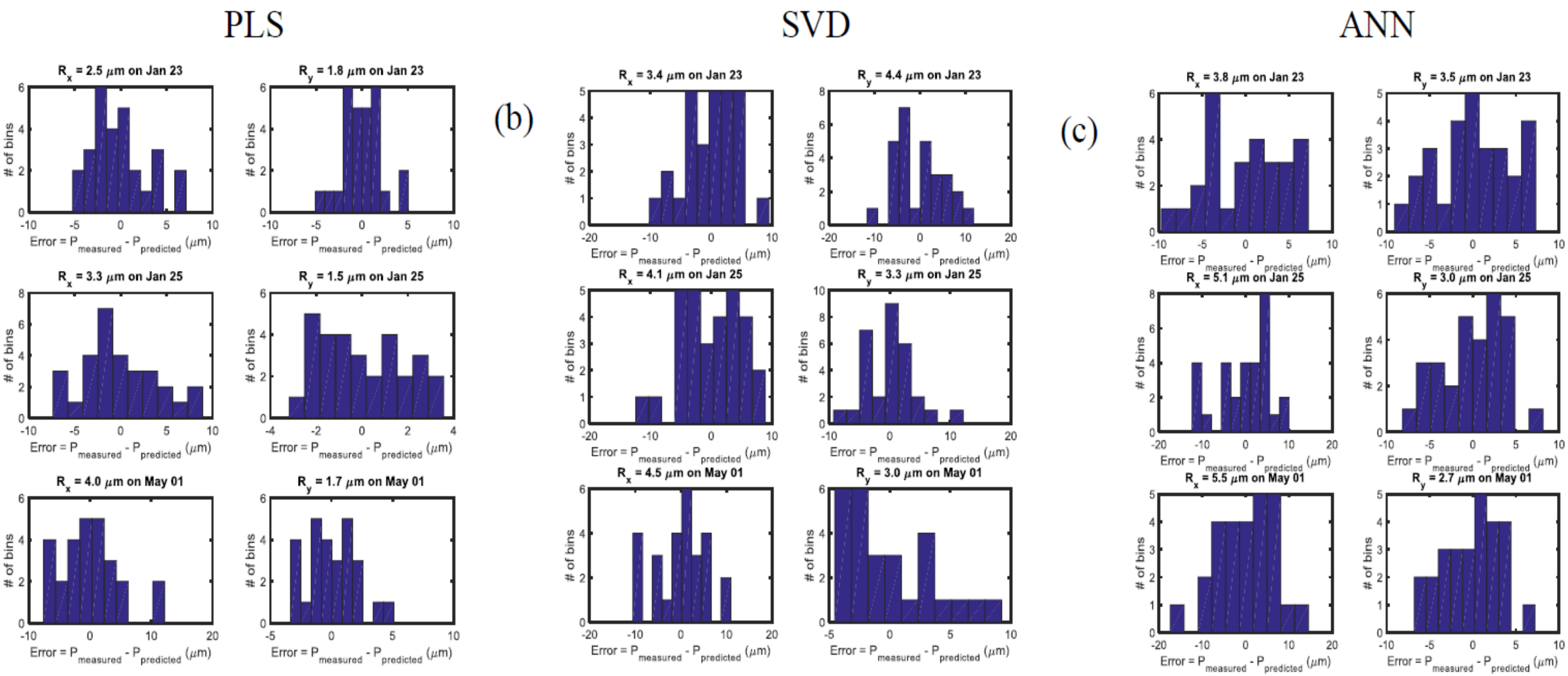
1. Beam position inside each cavity is interpolated from two BPMs.
2. Dipole signals are measured via each HOM port.
3. The correlation between dipole signal and beam positions can be established.

$$\begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{m1} & \cdots & d_{mn} \end{bmatrix} \begin{bmatrix} C_{11} & C_{12} \\ \vdots & \vdots \\ C_{n1} & C_{n2} \end{bmatrix} = \begin{bmatrix} X_{11} & Y_{11} \\ \vdots & \vdots \\ X_{m1} & Y_{m1} \end{bmatrix}$$

Dipole data

Beam position data

HOMBPM at FLASH - 1.3 GHz cavities

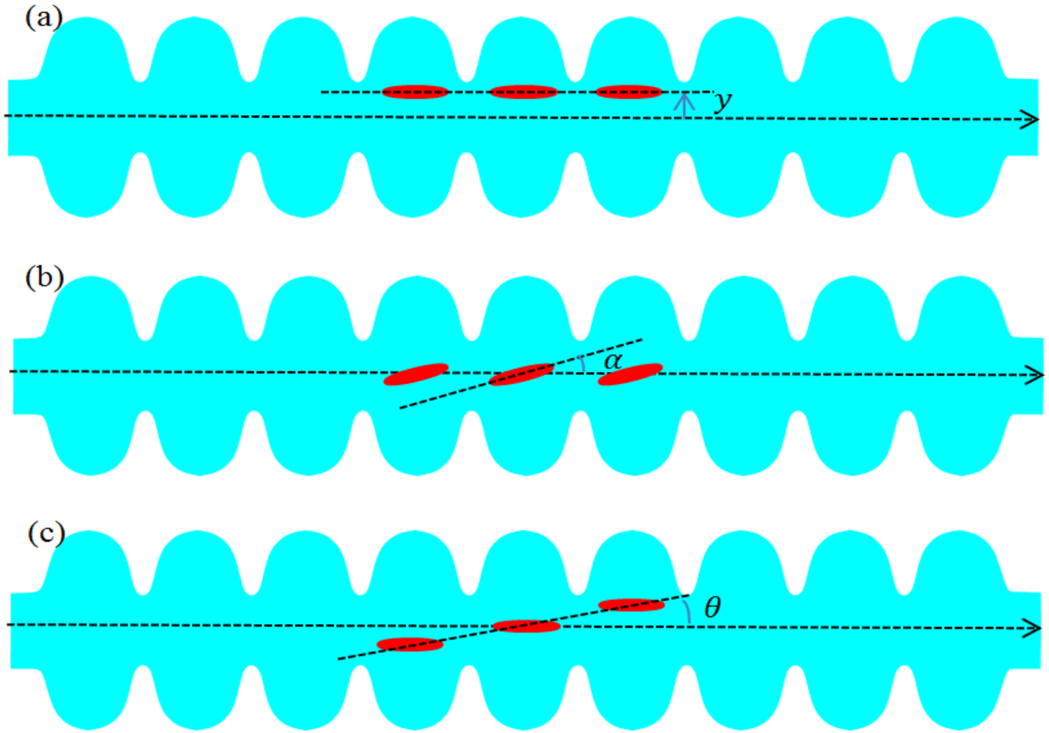


PLS: Partial Least Square
SVD: Singular Value Decomposition
ANN: Artificial Neural Network

Most of the results obtained are below 5 microns.

L. Shi *et al*, *Physics Procedia* 77 (2015) 42-49

Beam-excited Angular Wakefields



(a) Offset y: $V_y(t) \propto y e^{-\frac{t}{\tau}} \sin(\omega t)$

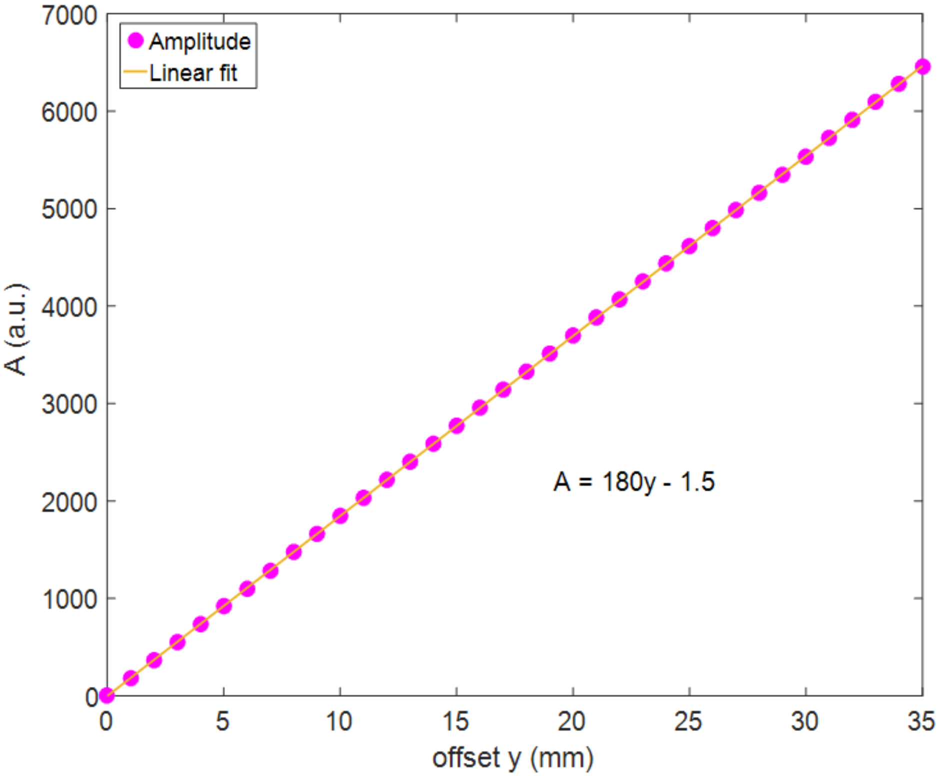
(b) Angle α: $V_\alpha(t) \propto -\alpha\sigma_z^2 e^{-\frac{t}{\tau}} \cos(\omega t)$

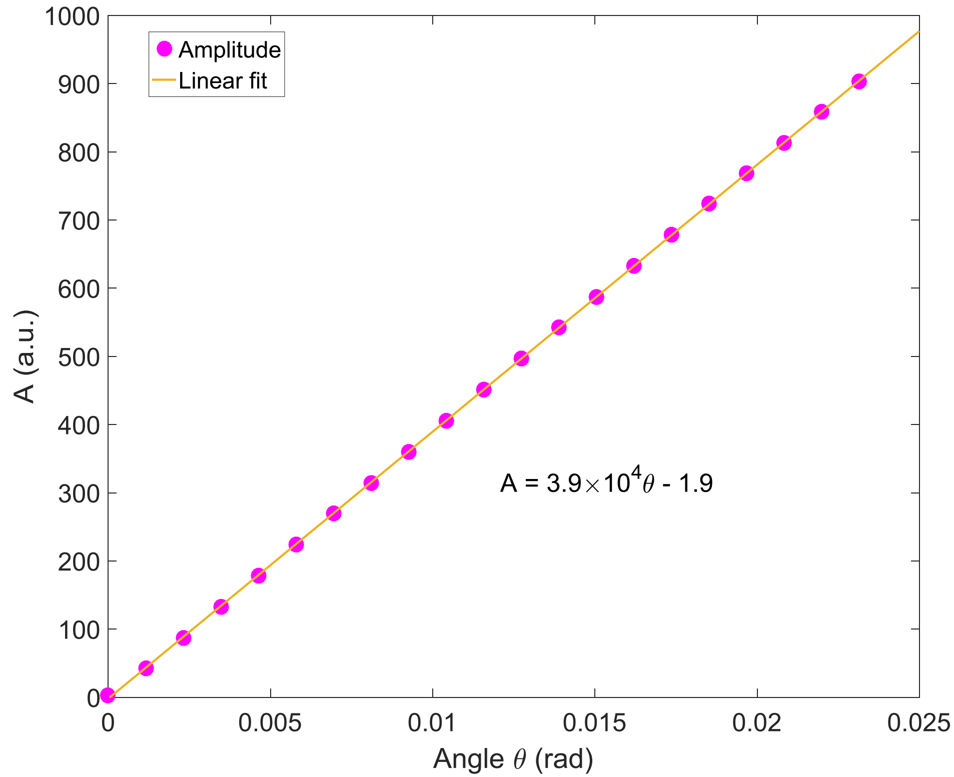
(c) Angle θ $V_\theta(t) \propto -\theta e^{-\frac{t}{\tau}} \cos(\omega t)$

- Scenario (c) can play an important role in beam position determination.

- The maximum allowed angle (set by beam pipe) is ~ 7 mrad. The beam angle is normally a few hundred μrad.

Beam-excited Angular Wakefields

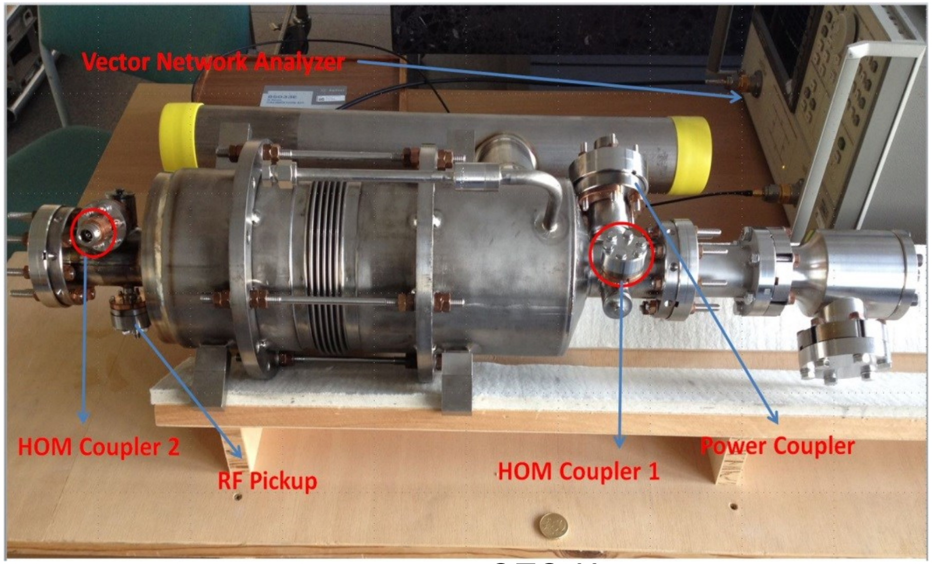




- For scenario (a) and (c), beam with 1 mrad angle excites signal with the same amplitude as with 214 μm offset.

S21 measurements for single cavity

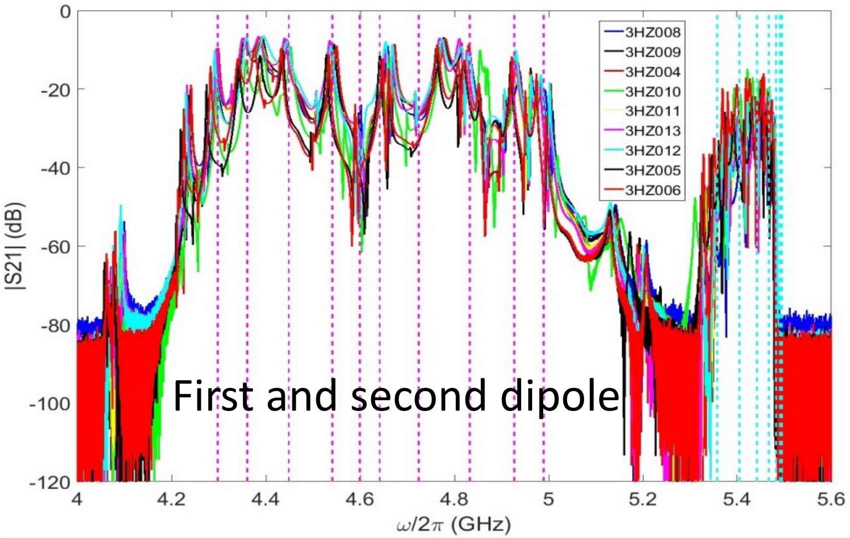
Experimental setup:

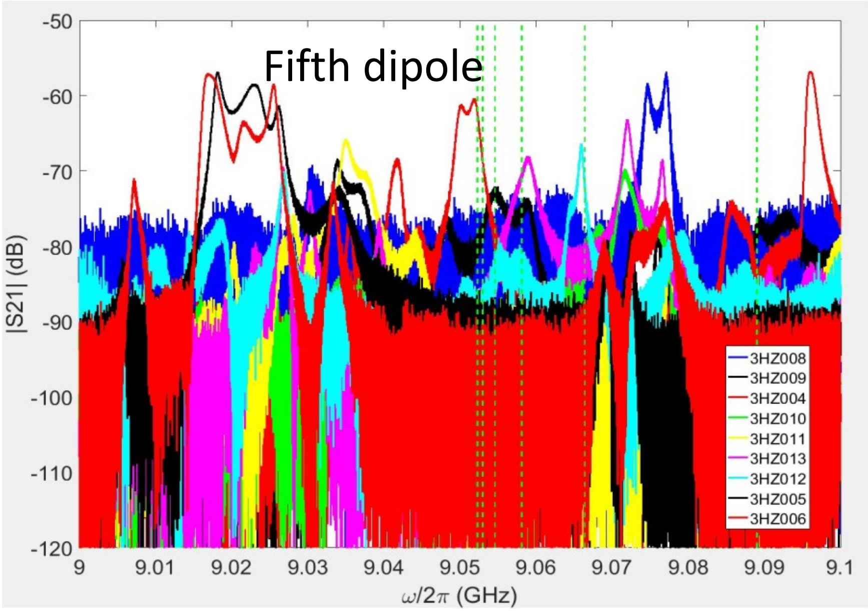


vacuum state, 273 K

1. The spectra of the first and second dipole band resemble each other.

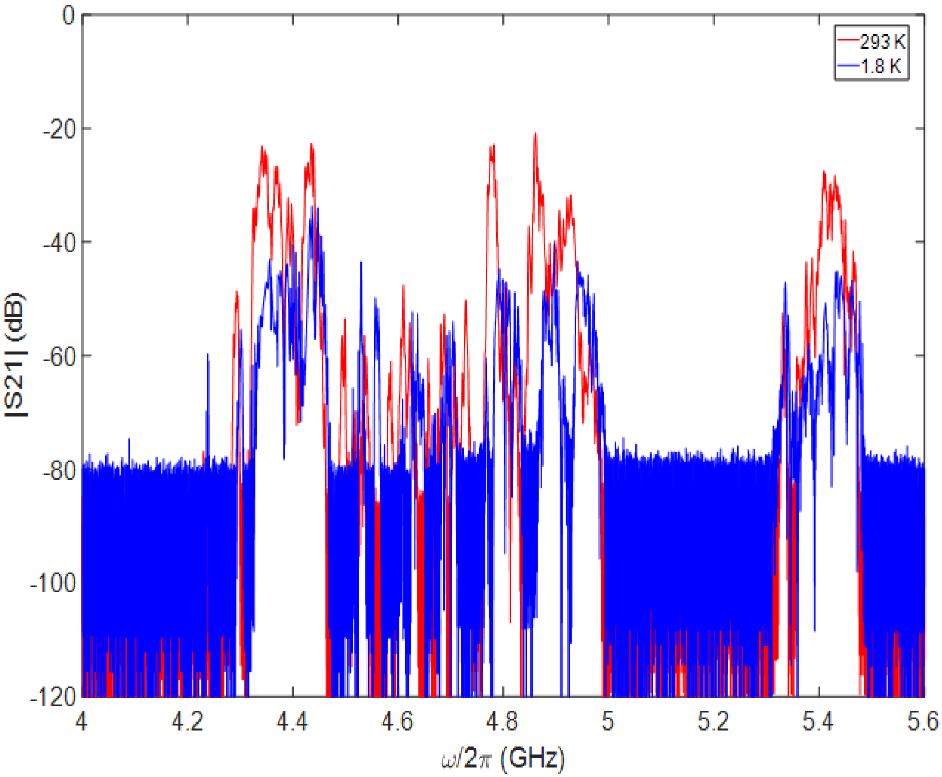
2. The spectra of the fifth dipole differ from each other.

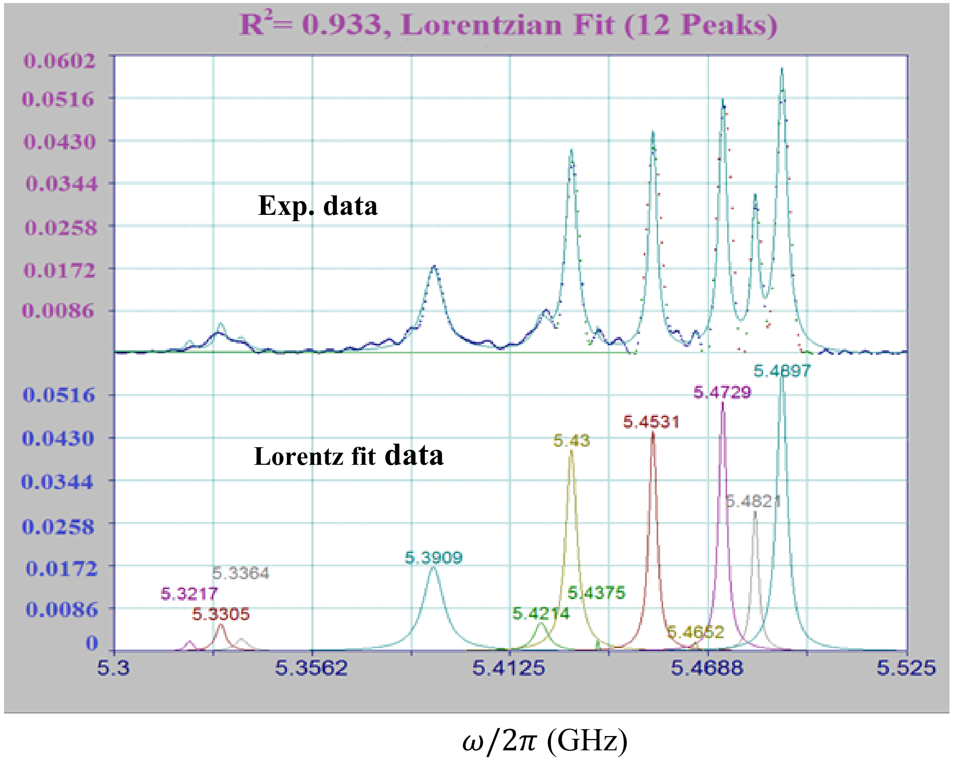




L. Shi *et al.,* DESY Report 2017, to be published

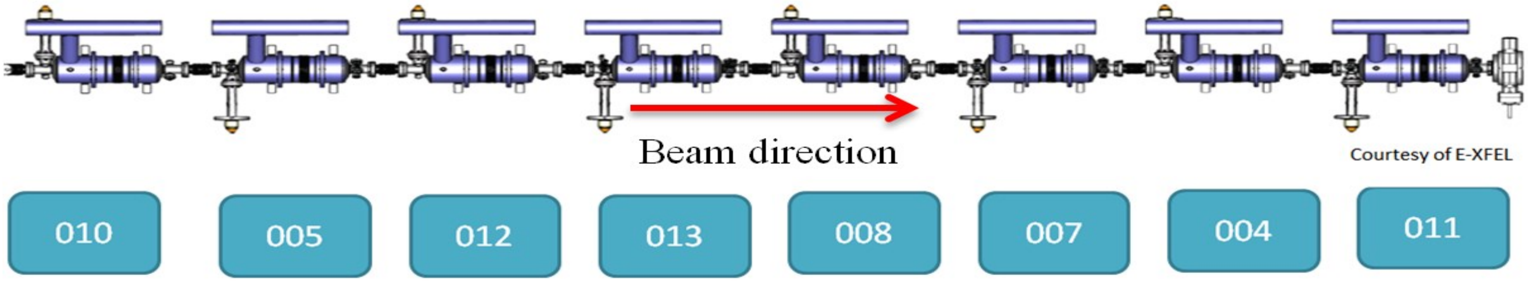
HOM spectrum characterization



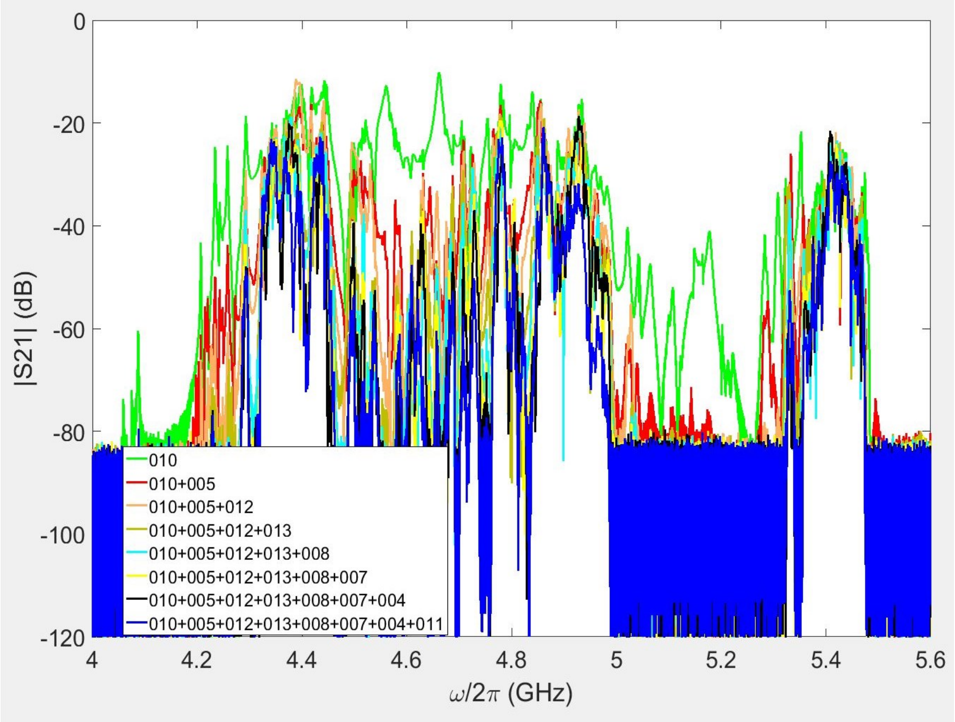


- All Q < 30,000. The modes in the 5th dipole band present higher Q values due to the fact that they are trapped inside the cavity .
- The propagating modes ~**5440 MHz** were selected to for the beam position in a module.
- The trapped modes ~ **9040 MHz** were selected for cavity beam position.

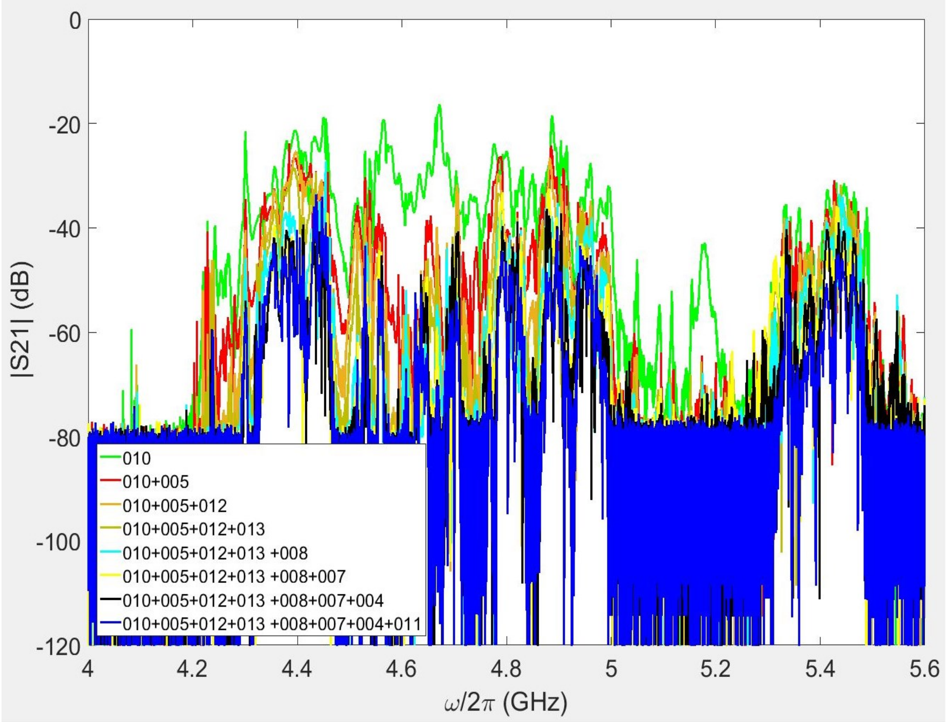
S21 measurements for coupled cavities



- Warm state (~293K, filled with Argon)
- Cold state (~2K, Vacuum)



Couplers are open



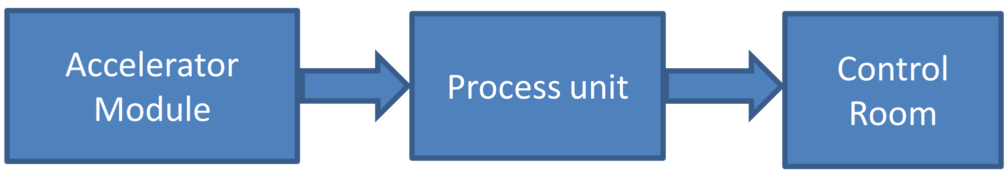
Couplers are terminated

Summary

- The resolution obtained is below 5 micron meter over months based on different data mining methods.
- The HOM measurements and characterization for the 3.9 GHz cavities are carried out for both single and coupled cavities. The higher order modes are damped below 30,000 and sliced second dipole bands are specified for the BPM application.

Possible topologies of final system

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

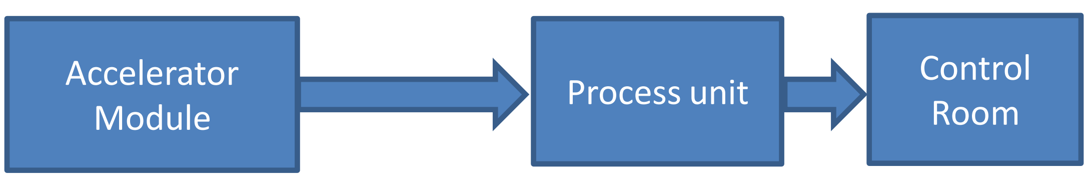


+ Less influence from the intermediate units

- Radiation protection

Vicinity of the module

- Transmit the signal over long distance and process in the middle



+ No need for radiation protection.

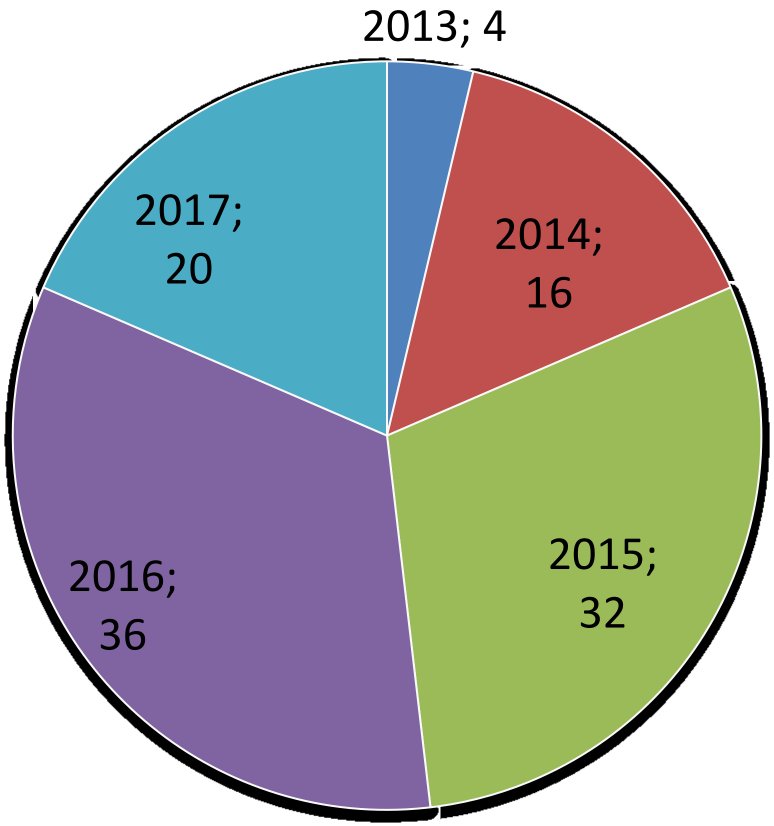
- Signal integrity issue

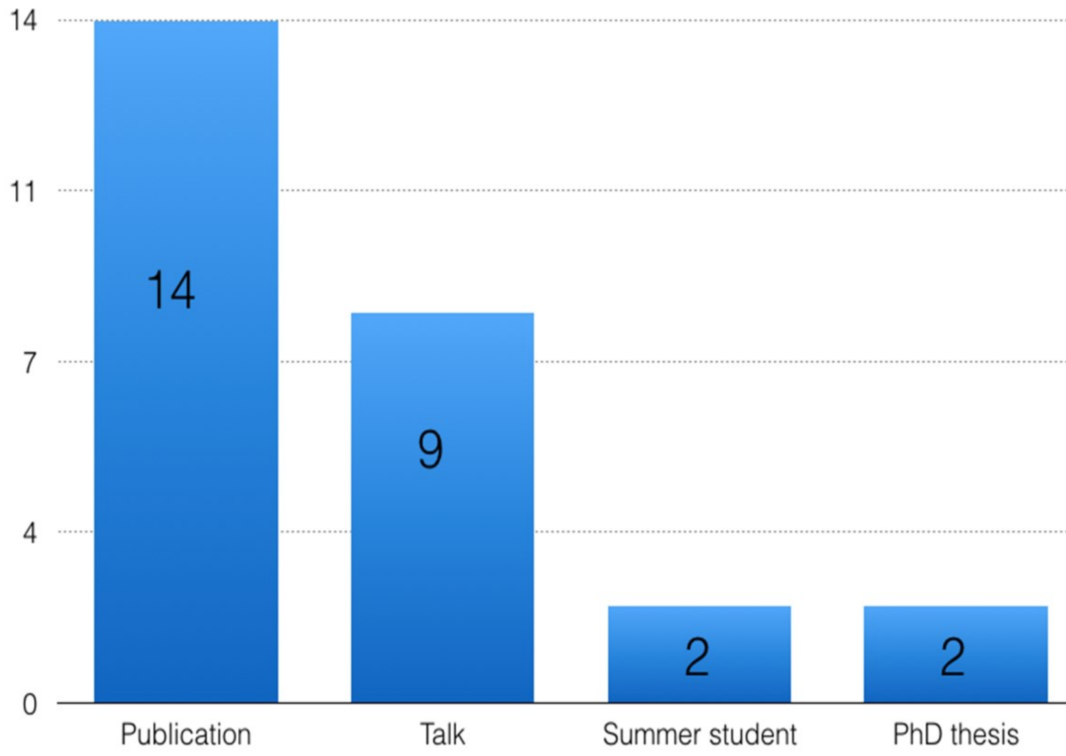
Longer cable
to different site

Summary and Outlook

- **Beam Phase Measurements**
  - I proposed the setup, developed algorithms for beam phase extraction, and made beam phase measurements.
  - Simulation has been made with coupled circuit model. At least **35 dB** SNR is required to achieve the 0.01 degree resolution.
  - Measurements are consistent with prediction from simulation and other LLRF measurements.
  - Electronics are under test in the lab.
- **Beam Position Measurements**
  - Resolution below **5 µm** has been obtained stably over **several months.**
  - HOM characterization for the 3.9 GHz cavities has been performed for single and coupled cavities.
  - Electronics are under test in the lab.

Beam time: 108 hours



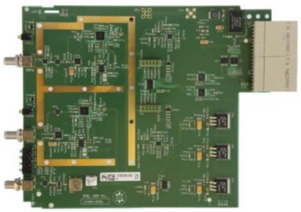


Thank you for your attention!

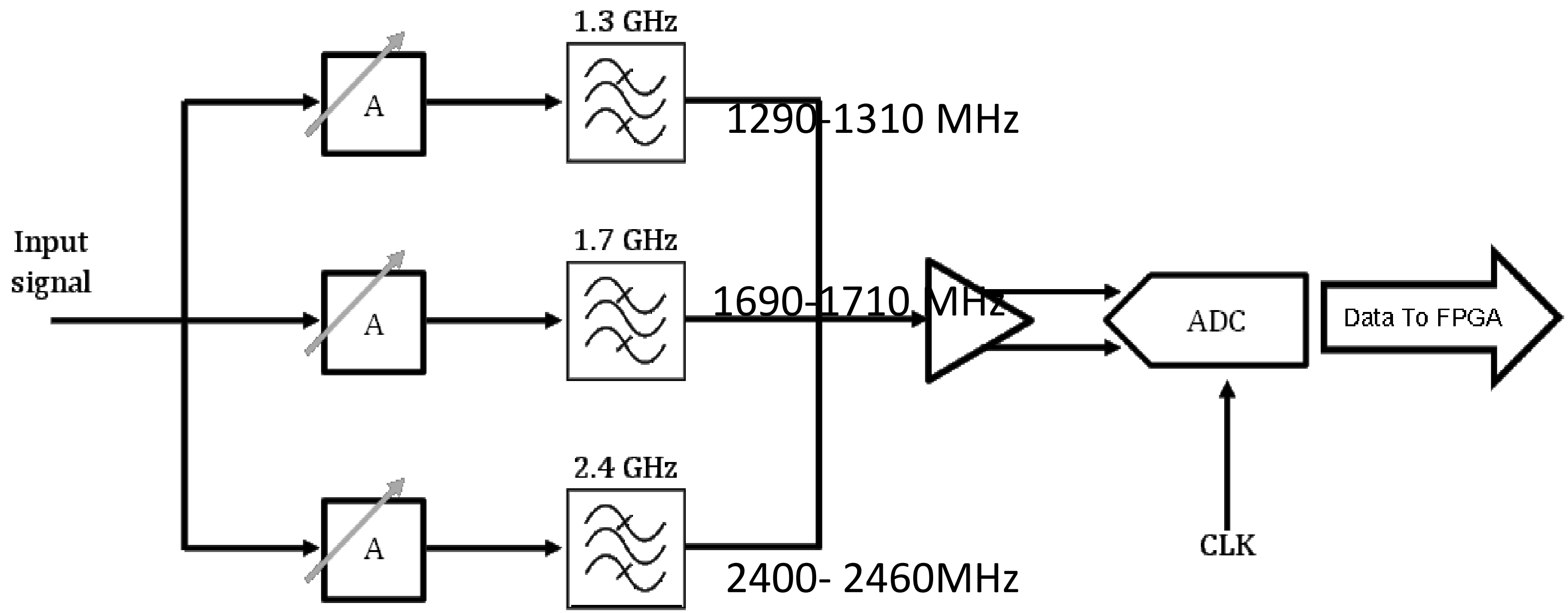
HOM-based beam diagnostics

electronics

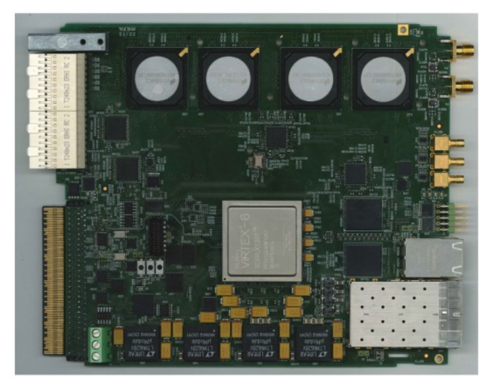





Electronics of HOM based Diagnostics- 1.3 GHz cavities



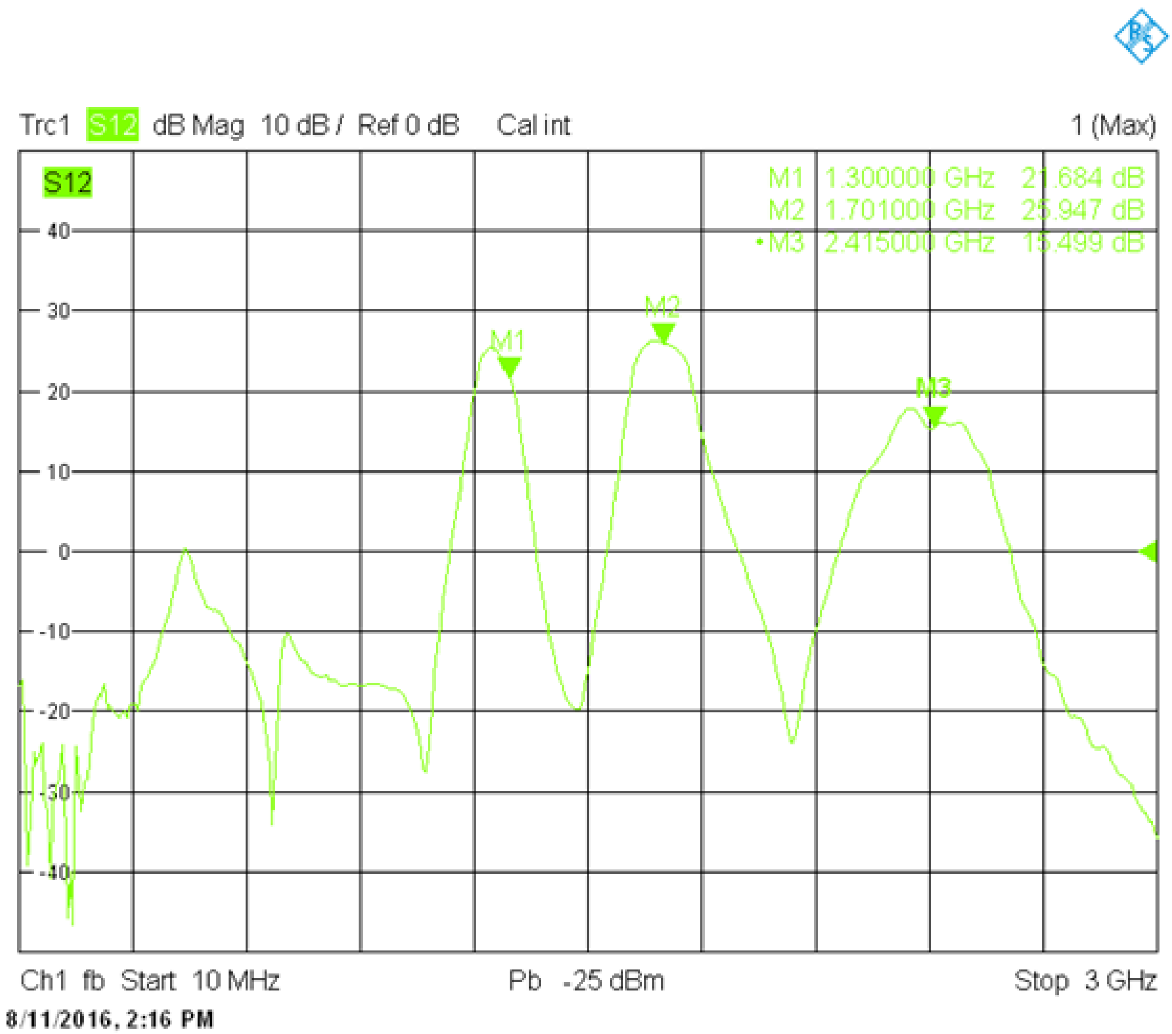
- The electronics are compact and can be used for beam phase and beam position measurements.
- It fully complies with MicroTCA.4 standard.



Fast digitizer

New Design of High Order Modes Electronics in MTCA.4 Standard for FLASH and the European XFEL, Samer, IBIC13, pp443

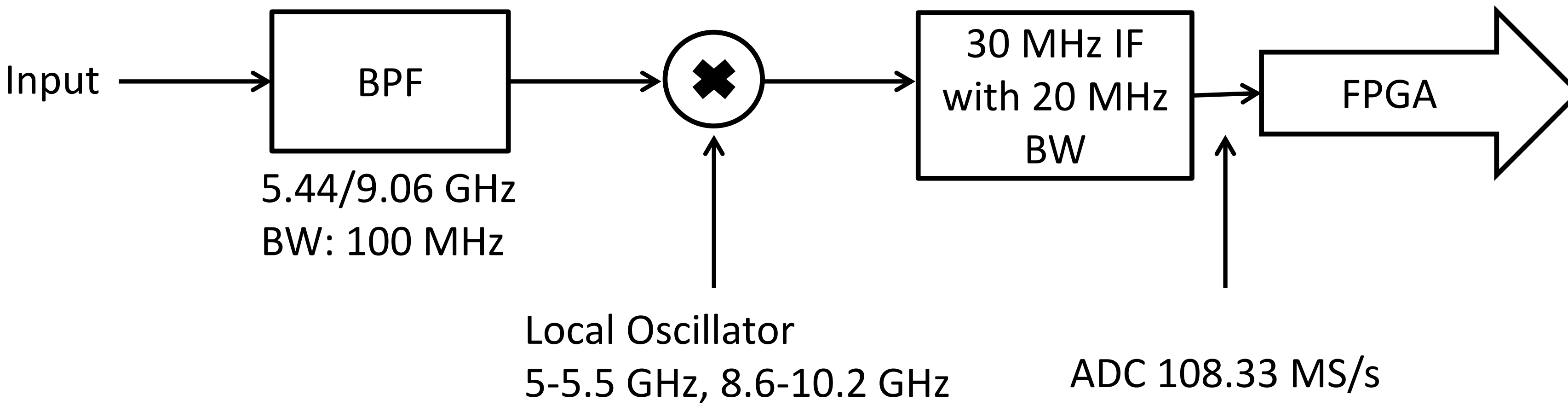
Test of Electronics in lab

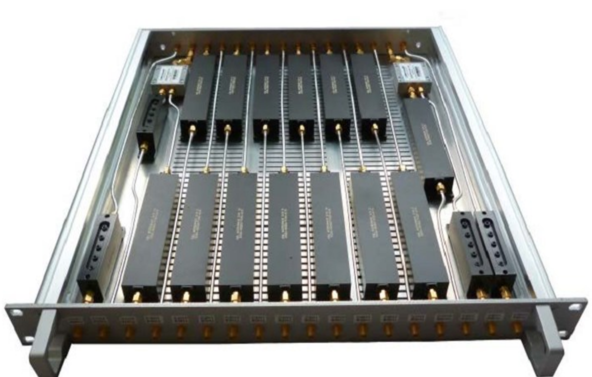


- Variation from board to board
- Optimizing parameters.
- Determine the 3dB bandwidth 100 MHz, 150 MHz, 300 MHz for 1.3 GHz, 1.7 GHz and 2.4 GHz respectively

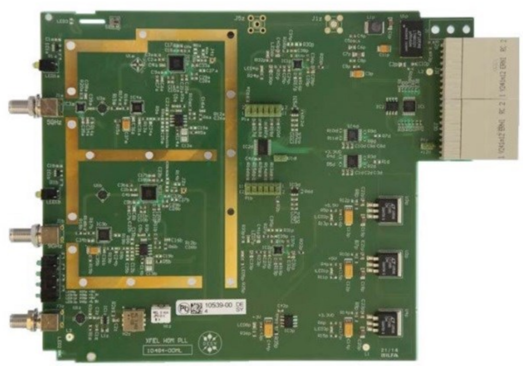
Measurements made by Uros

Electronics of HOM based Diagnostics- 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