Higher Order Mode Based Beam Phase Measurements: Simulations and Results

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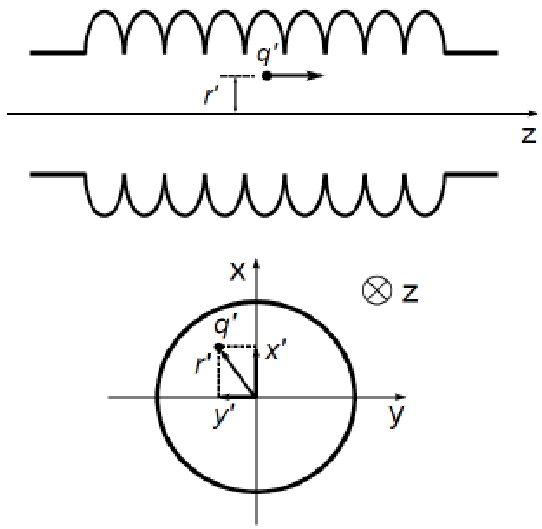
Outline

- A brief introduction to higher order modes
- Principle of beam phase determination
- Simulation with circuit model
- Measurements with a broadband setup
- Summary and Outlook

Introduction to Higher Order Modes (HOMs)

When beam transverses a cavity, wakefields are excited. These fields are classified into monopole, dipole, quadrupole modes etc.

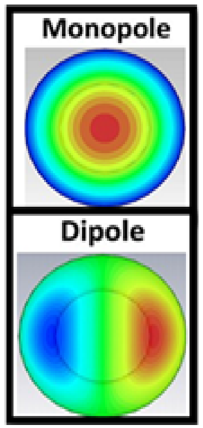


- Monopole modes dominate the longitudinal wakefield:

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

- 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 $\propto q \cdot \frac{R}{Q}$

Bunch charge

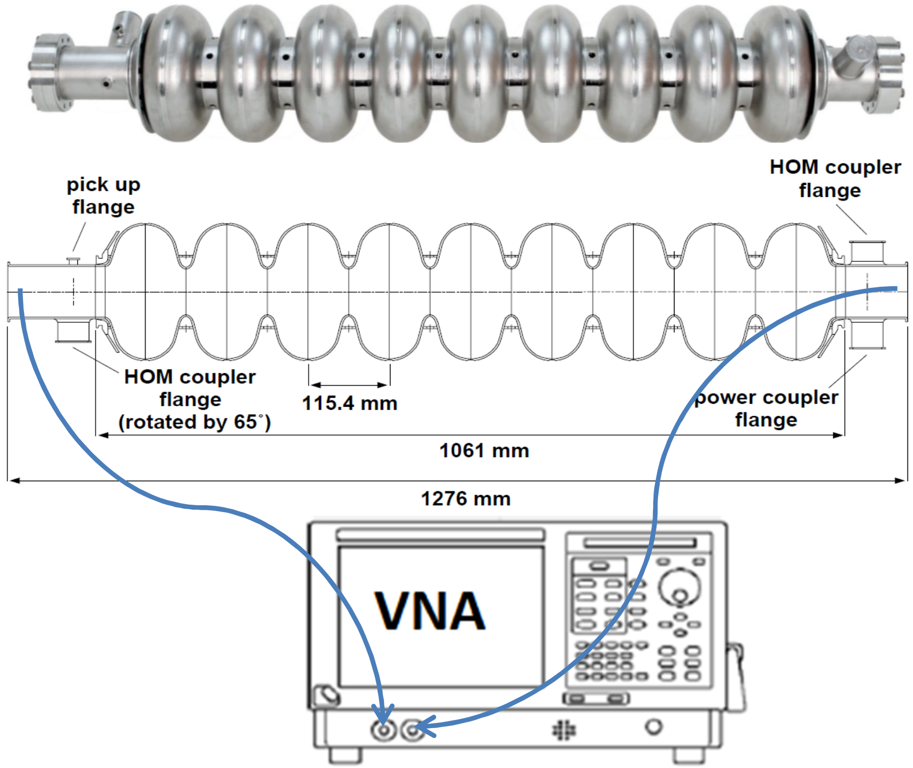
Measured Quantity $\propto q \cdot r' \cdot \frac{R}{Q}$

Bunch offset

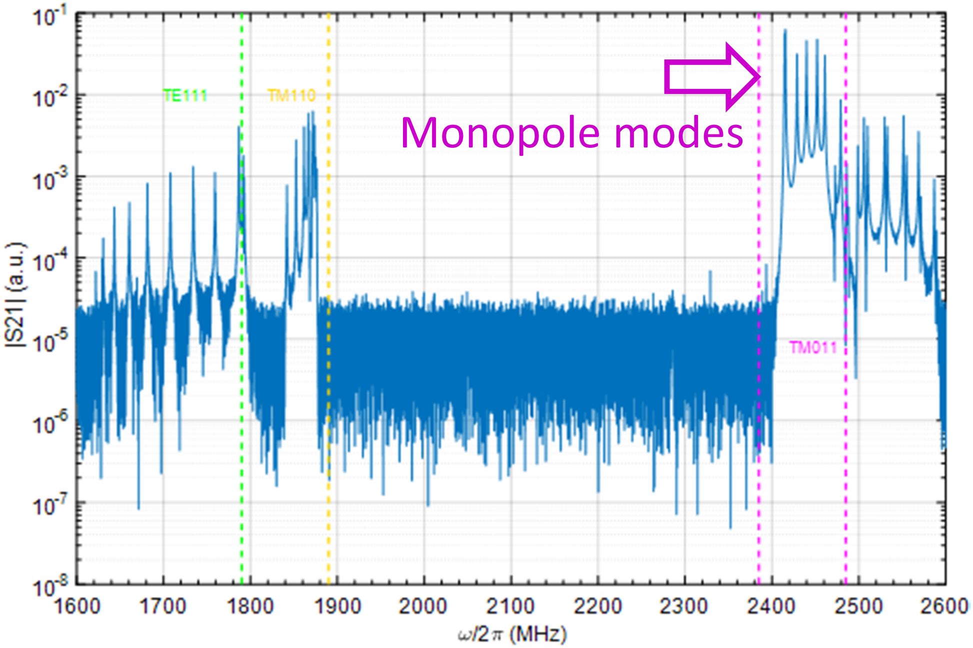
R. Wanzenberg, TESLA 2001-33, 2001.

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

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

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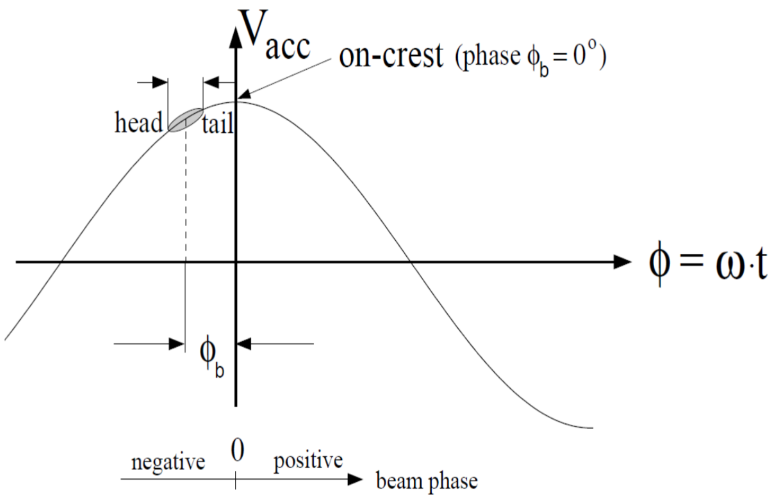
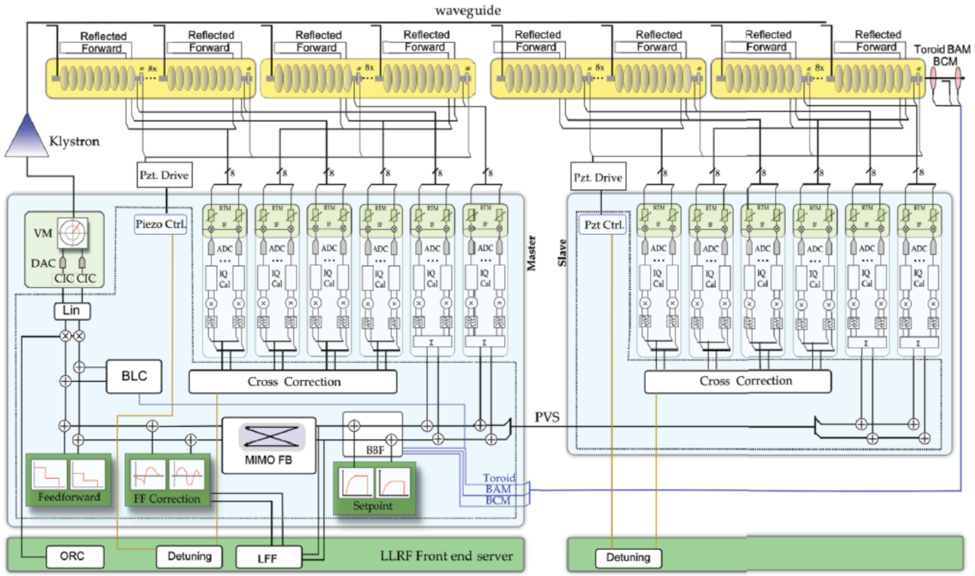
Field Control inside cavity

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



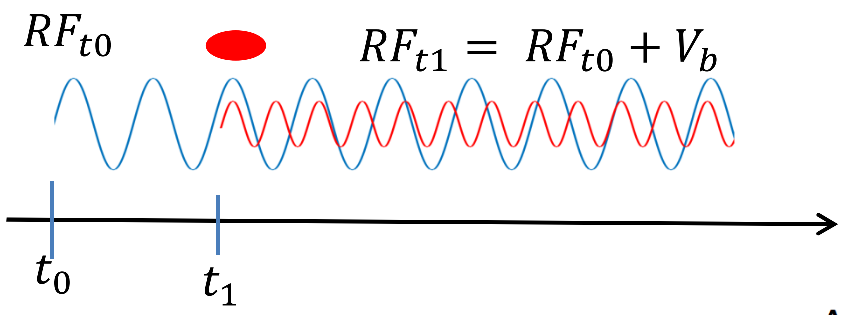
Phase 0 is defined as on crest.



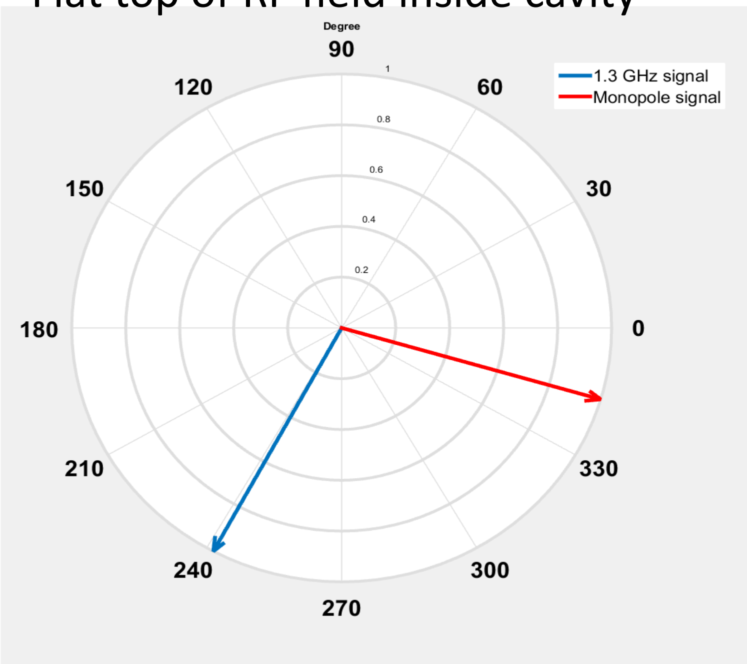
	Amp	Phase
FLASH	0.01%	0.01 degree
E-XFEL	0.01%	0.01 degree

C. Schmidt, IPAC 2013, WEPME009

How to determine the beam phase



Flat top of RF field inside cavity

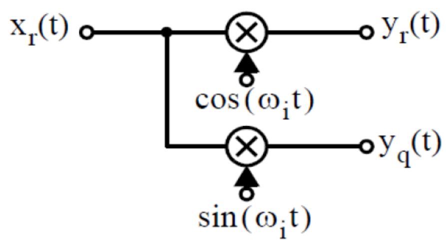


RF_{t0}: $1.3\ GHz\ signal$

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

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

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



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

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

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

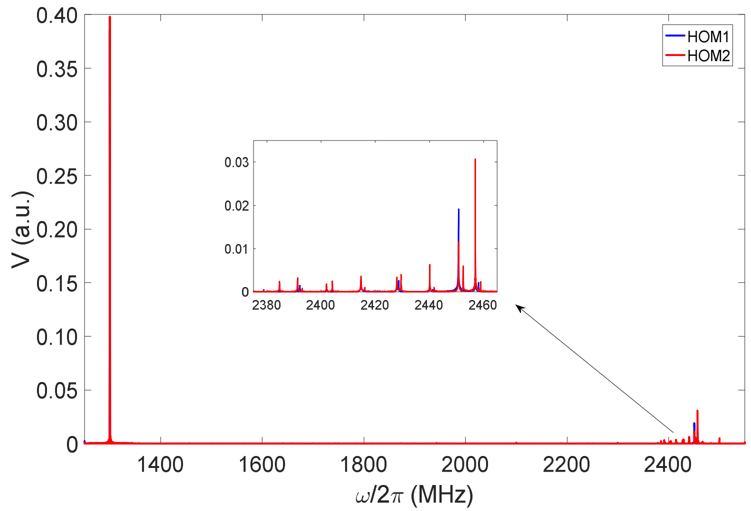
$\varphi_i s$ from HOMs can be used to define beam arrival time t_1 and the phase relative to this time for 1.3 GHz can be calculated.

Signal strength estimation

- Assume the gradient is 20 MV/m and 0.5 nC bunch charge
  - Beam induced fundamental mode: 2*0.5nC*2.08V/pC = 2080 V;
  - Beam induced high order monopole mode 2*0.5nC*0.6V/pC = 600 V;
  - Direct measurement of the fundamental mode (induced from klystron and beam) needs quite a large dynamic range.
  - The fundamental mode signals from HOM couplers are comparable to that of damped higher order modes.

Simulation

Mode	Loss factor
Pi (1.3 GHz)	2.08 V/pc
TM011 (2.4499GHz)	0.08 V/pc
TM011 (2.4419GHz)	0.60 V/pc
TM011 (2.4539GHz)	0.57 V/pc



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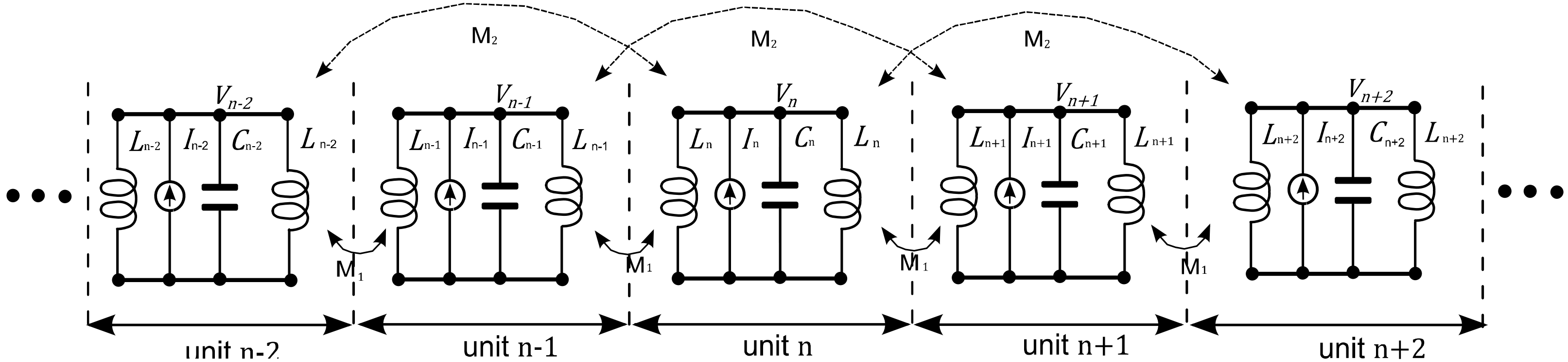
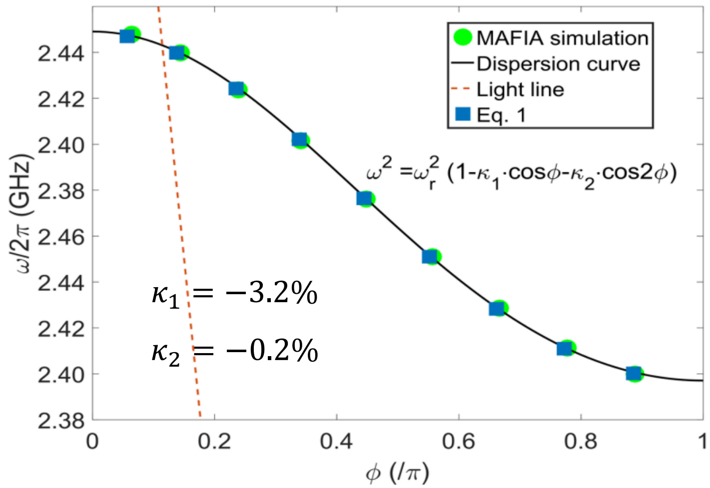
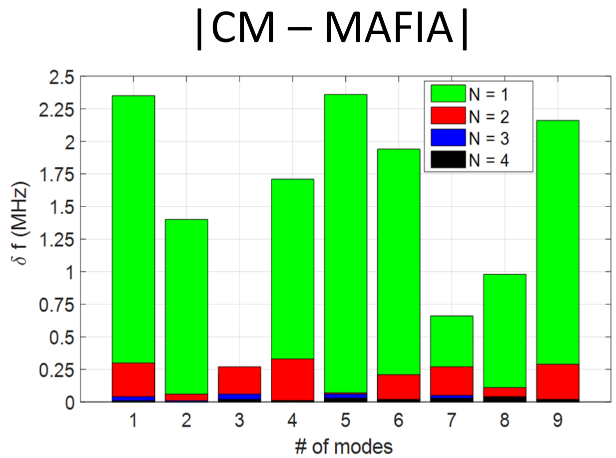
Beam Phase Monitor for 1.3 GHz cavities – Circuit model

- Single chain of coupled parallel LC circuit was used to facilitate the beam phase monitor development.



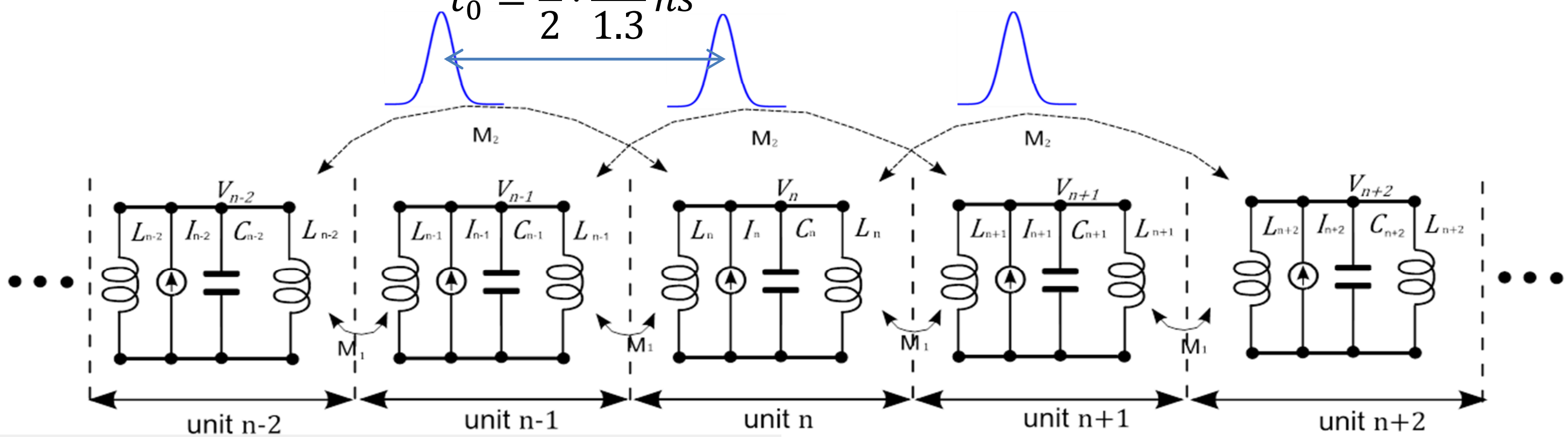
- 

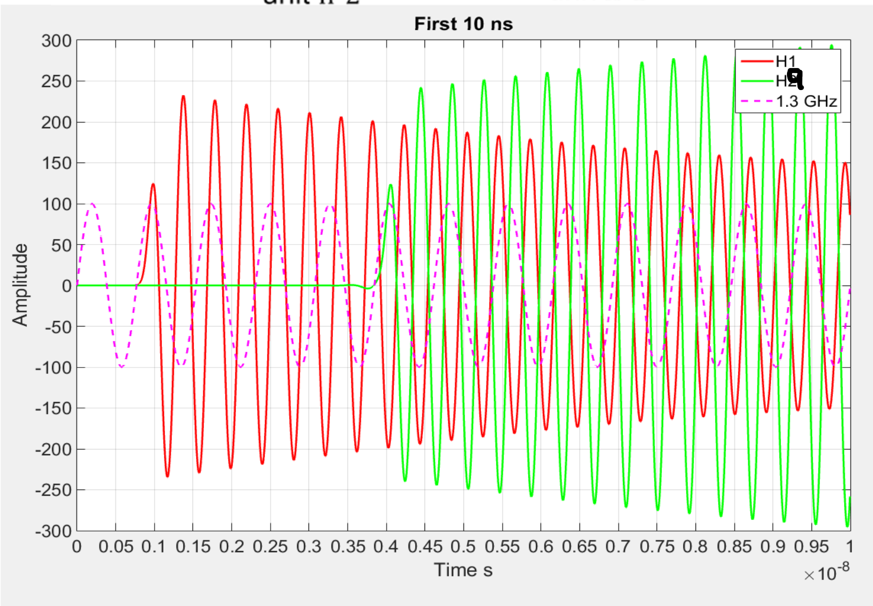


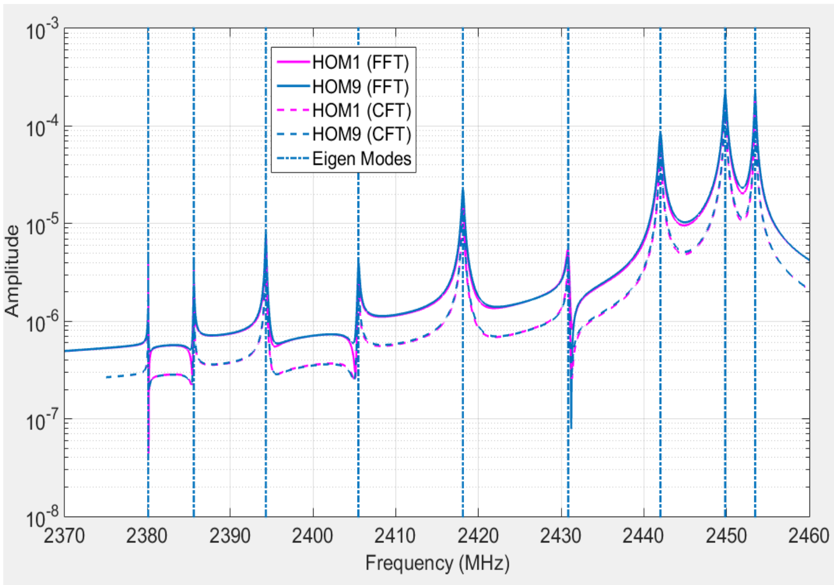
T. Shintake, C96-09-09.3, p435-454

Voltage Waveforms at cell 1 and 9

$$t_0 = \frac{1}{2} \cdot \frac{1}{1.3} ns$$

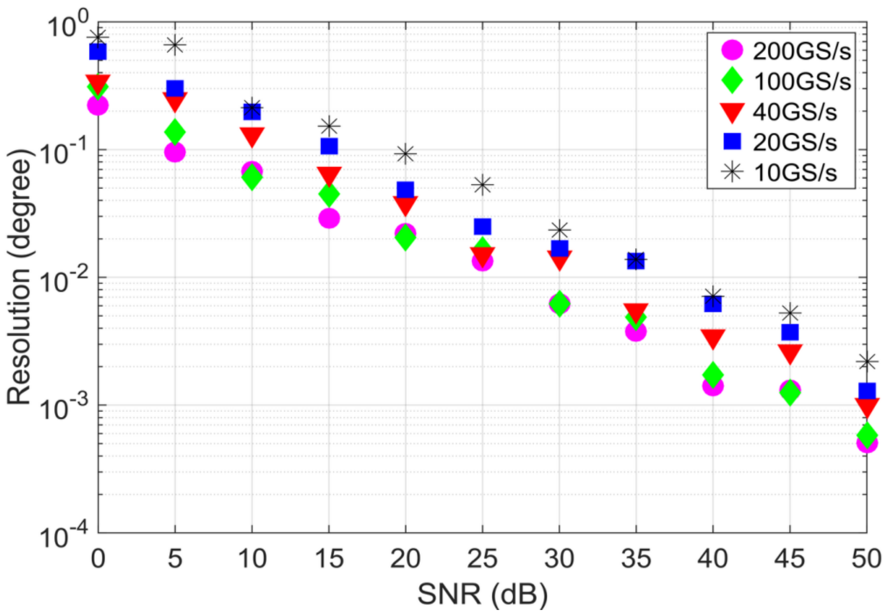






Beam Phase Determination - Circuit model

1. Vary the sampling frequency, while keep others constant
2. Variable white gauss noise is added to the simulation signal
3. By comparing phases calculated from two independent channel, resolution can be estimated.



1. The resolution clearly depends on the noise present in the system.
2. The resolution also depends on the sampling frequency.

Note: SNR is varied by keeping signal power fixed and varying noise power. Alternative way exists!

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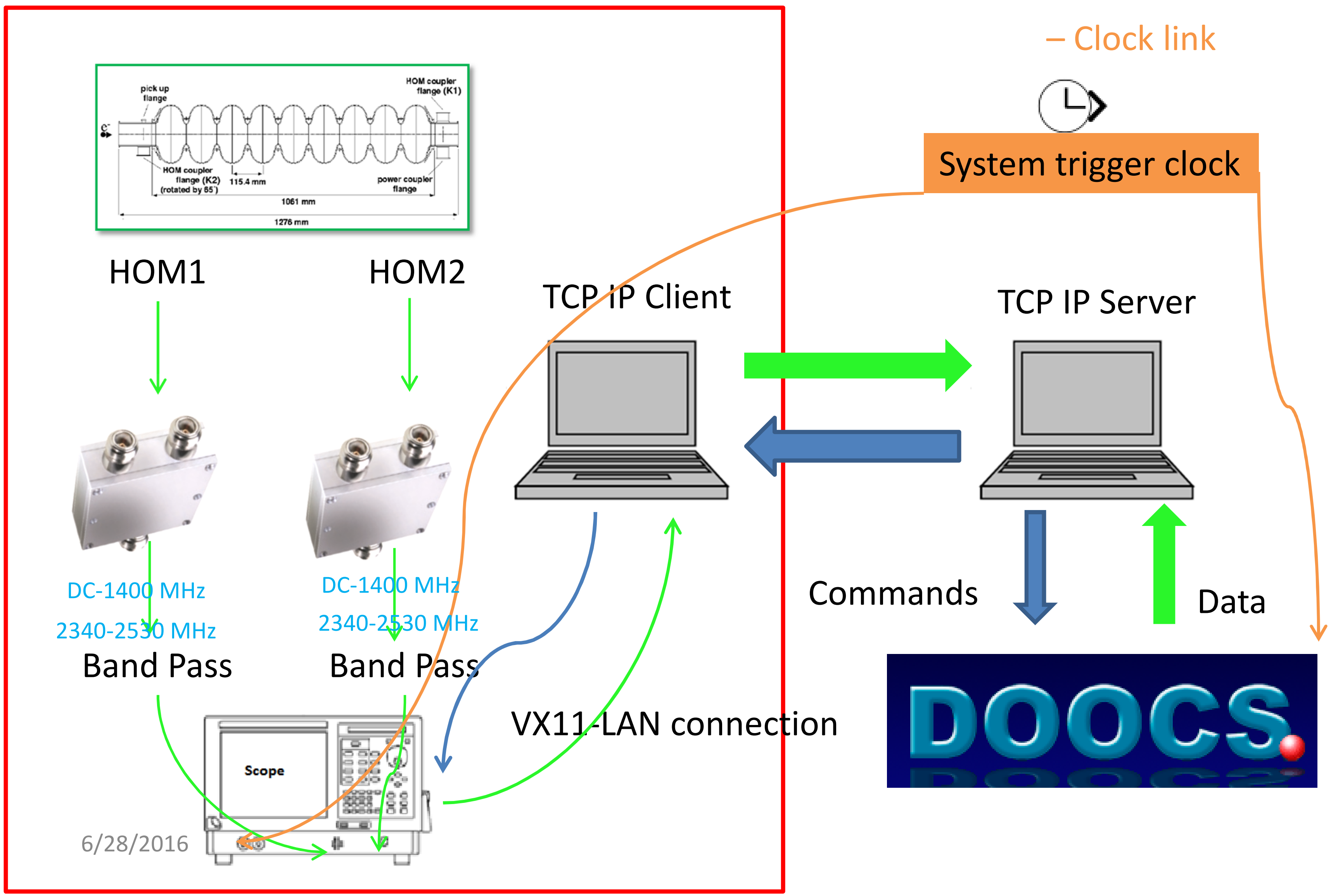
Setup for the beam phase measurements

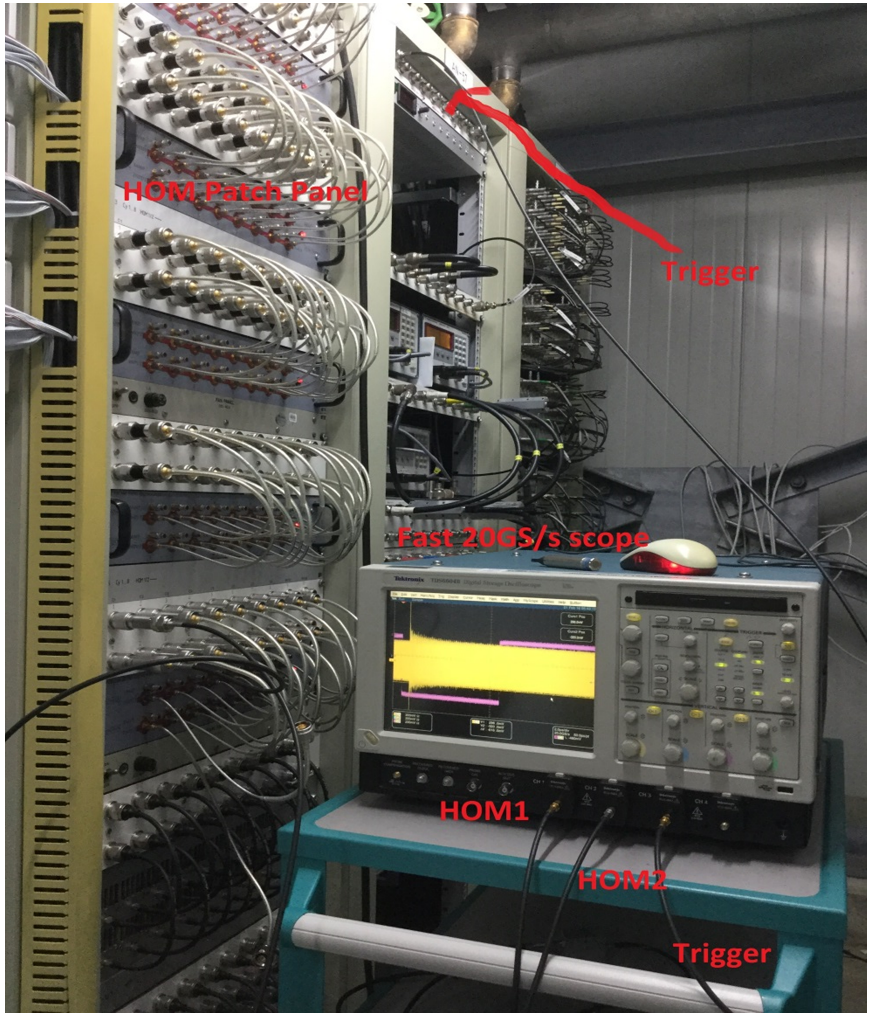
– Data link
– Command link
– Clock link



Setup for the beam phase measurements

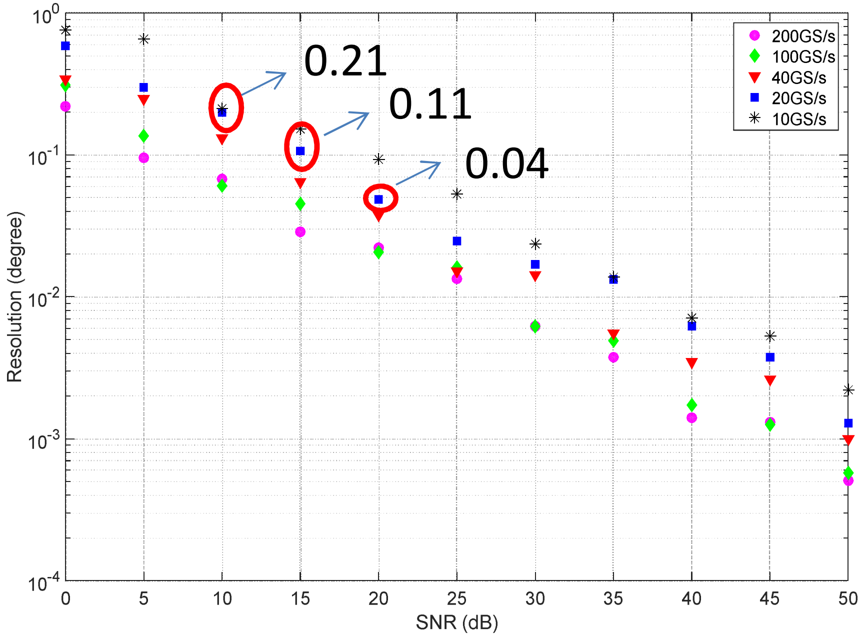
- Setup at FLASH hall

  - ❑ 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 and one channel for clock.
  - ❑ A 10 Hz external clock is used to synchronize the measurement.



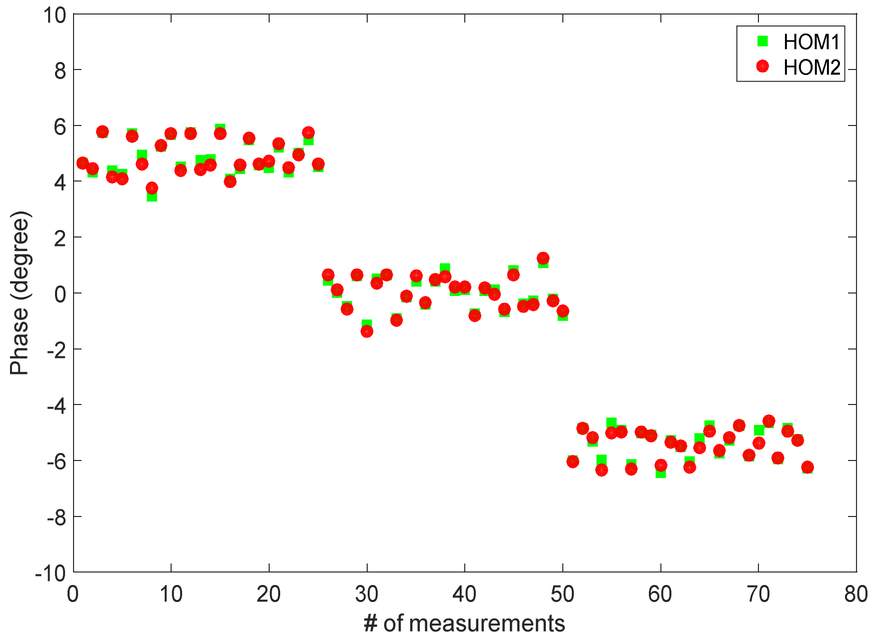
Beam Phase Monitor for 1.3 GHz cavities - Results

- Simulation (200, 100, 40, 20 , 10 GS/s)



Estimation of SNR from scope shows it is between 10 and 20 dB.

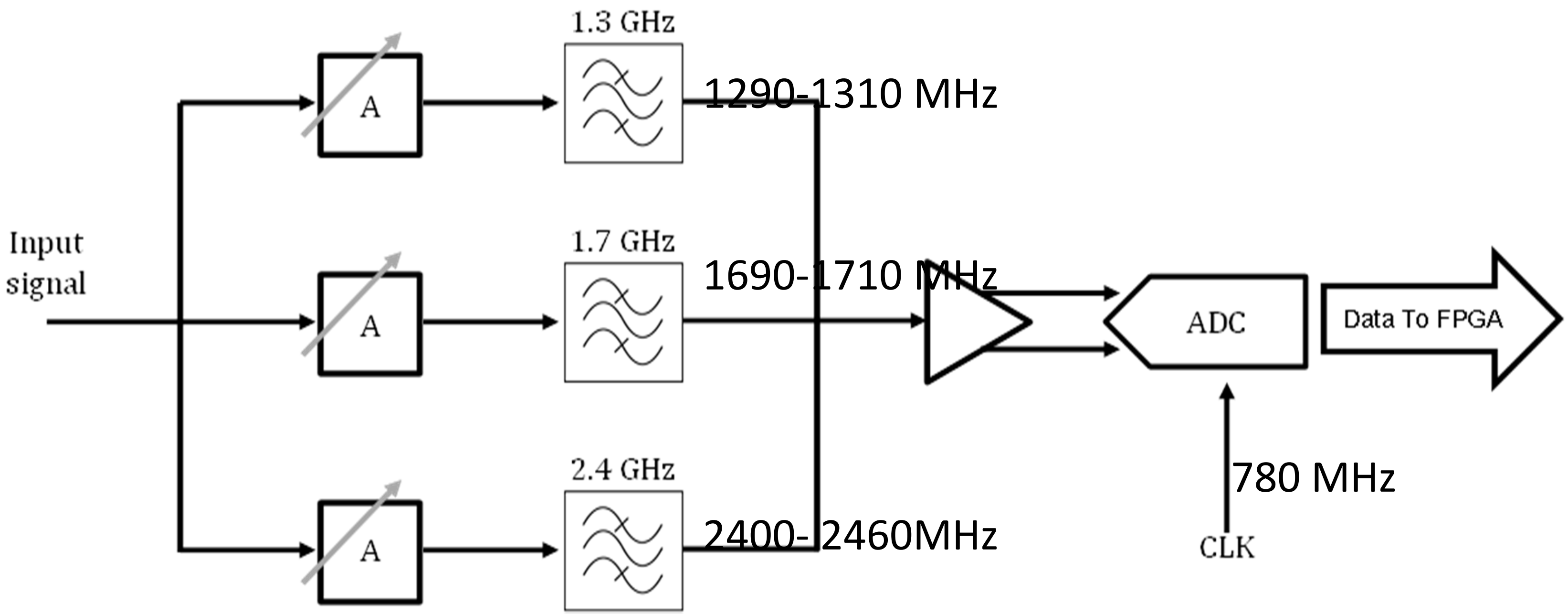
- Experiment（20 GS/s）@18MV/m, 0.3 nC



Phase was set to 5 , 0, -5 degree. Resolution is about 0.1 degree.

Thermal noise: $U_{th} = \frac{1}{2}k_bT = 0.0129\ eV\ @\ 300K; Energy\ in\ mode: kq^2 = 3.375 \cdot 10^{11}eV; SNR > 100dB$

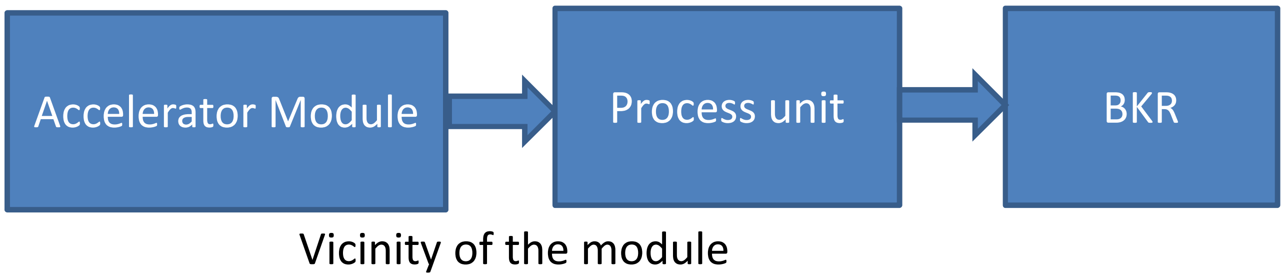
Electronics of HOM based beam Phase measurements



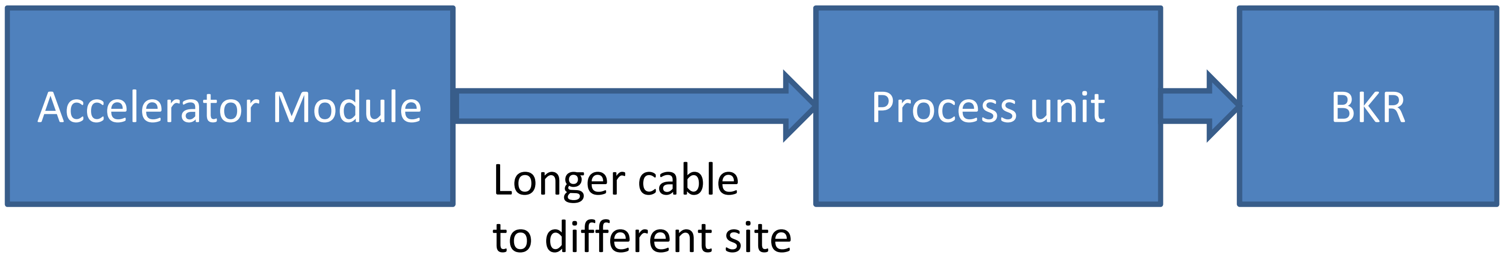
Signal can be aliased to 250-270 MHz (fundamental Monopole), 130-150 MHz (Dipole), 60-120 MHz(2nd monopole band) respectively.
The final electronics will be based on different sampling frequency .

Possible topologies of final system

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



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



Thermal expansion of RF cable

- Simply speaking, the length of RF cable will change according to the temperature variation.
- Different material's thermal expansion coefficient is different.

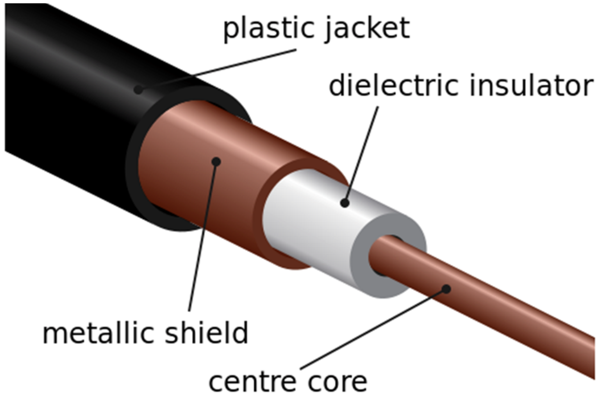


Table 1: Coefficients of Thermal Expansion

Material	Value	Units
Copper	16.5	µm/ (m·K)
PTFE	135.0	µm/ (m·K)
Aluminum	23.1	µm/ (m·K)

	Temperature	L (20m)	Phase (Degree)
1.3 GHz	0.1 K	33 um	~0.05
2.4 GHz	0.1 K	33 um	~0.095

Summary and Outlook

- Circuit model aided the development of beam phase monitor.
- Signal, noise power level and the sampling frequency need to be optimized to gain higher resolution.

- The study on the resolution dependence on other parameters is ongoing, eg. bunch charge, accelerating gradient etc.
- Cavity detuning and beam loading effects on the beam phase.
- Long term monitoring is needed to reveal any drifts.
- The hardware development for the beam phase monitor.

Thank you for your attention!