HOM based beam diagnostics study at FLASH

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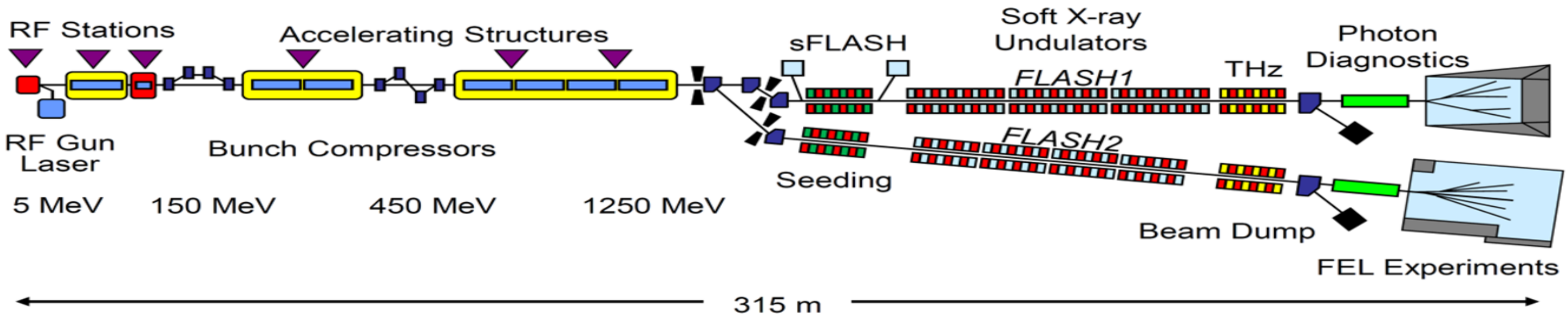
Outline

- Overview of HOM based beam diagnostics.
  1. Wakefield and HOMs
  2. Basic principle of an HOMBPM.
- Measurements at FLASH.
  1. HOMBPM measurements for 1.3 GHz cavities
  2. HOMBPM measurements for 3.9 GHz cavities
- HOM based beam phase monitor -HOMBPhM.
- Summary and Outlook.

HOM: Higher Order Mode
HOMBPM: HOM based BPM
HOMBPhM: HOM based Beam Phase Monitor

Accelerator complex at DESY

FLASH -> E-XFEL



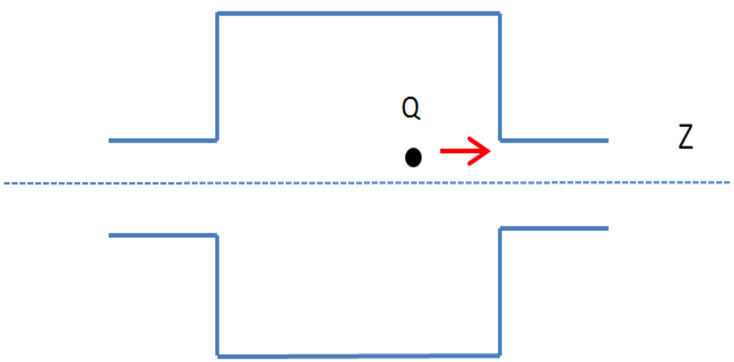
	European XFEL	FLASH	
Abbreviation for	European X-ray Free-Electron Laser	Free-Electron Laser in Hamburg	
Start of commissioning	2016	2004	
Length of the accelerator	1.7 kilometres	0.15 kilometres	× 11
Length of the facility	3.4 kilometres	0.3 kilometres	× 11
Number of accelerator modules	100	7	× 14
Maximum electron energy	17.5 billion electron volts (17.5 GeV)	1 billion electron volts (1 GeV)	17.5
Minimum wavelength of the laser light	0.05 nanometre (of the order of an atom)	4.1 nanometres (of the order of a molecule)	× 1/82
Number of undulators (magnet structures for light generation)	3, upgradeable to 5	1	
Number of experiment stations	6, upgradeable to 10	5	× 2
Location	Hamburg and Schenefeld	Hamburg	
Operator	European XFEL GmbH	DESY	

Both facilities are based on TESLA cavities and 3rd harmonic cavities .

The x-ray (0.05 nm wavelength and fs duration)produced at E-XFEL can be used for detailed atomic structure study, film the chemical reaction etc. All basic researches will benefit from this new laser source.

HOM based beam diagnostics Wakefield and HOMs

- Wakefield

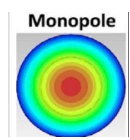


When beam traverses a cavity, it will excite electromagnetic fields inside. The excited fields generally are called wakefield.

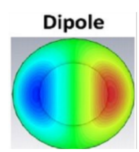
- Higher Order Modes

✓ The wakefield can be decomposed into different modes (resonant frequencies). Higher Order Modes or HOMs refer to modes which have higher frequencies than the fundamental mode (1.3 GHz or 3.9 GHz in our case).

✓ Monopole and dipole wake potential can be written as:



$$\boldsymbol{W}_{\parallel}^{\mathbf{0}} = \sum_{n=1}^{\infty} \omega_n \left(\frac{R}{Q}\right)_n cos\left(\frac{\omega_n s}{c}\right),$$
$$s > 0$$



$$\boldsymbol{W}_{\perp}^{\mathbf{1}} = (\boldsymbol{x}+\boldsymbol{y})c\sum_{n=1}^{\infty}\left(\frac{R}{Q}\right)_n sin\left(\frac{\omega_n s}{c}\right),$$
$$s > 0$$

R. Wanzenberg, TESLA 2001-33, 2001

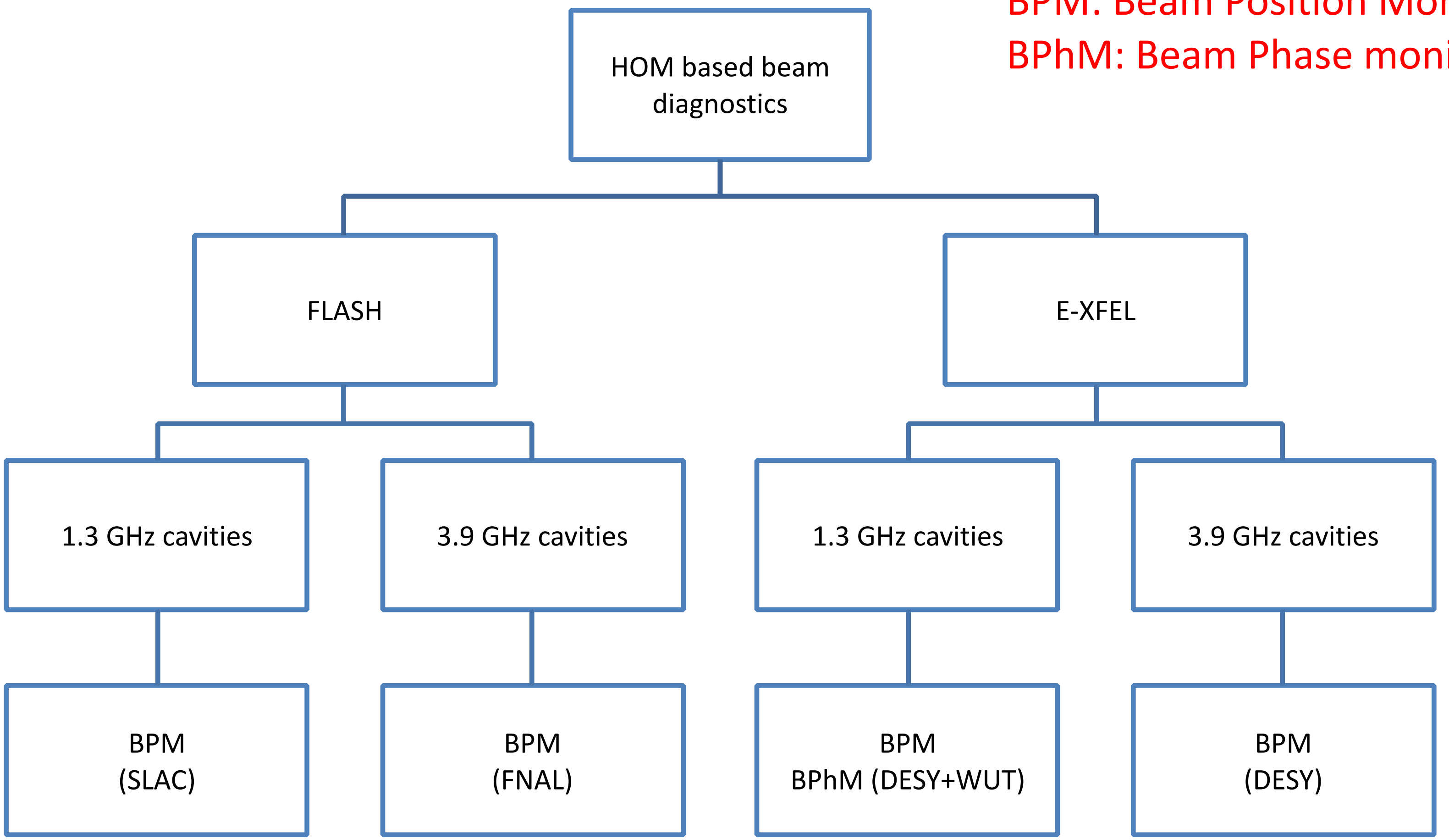
- Overview of HOM based beam diagnostics.
- Measurements at FLASH.
- HOM based beam phase monitor -HOMBPhM.
- Summary and Outlook.

Overview of HOM based beam diagnostics

1. HOM carries much information about beam (position, phase, charge etc.) and cavity (imperfection, axis etc.)
2. At FLASH, we try to determine the beam position, beam phase and perform beam alignment based on HOM signals.

HOM based Beam Diagnostics – FLASH and E-XFEL

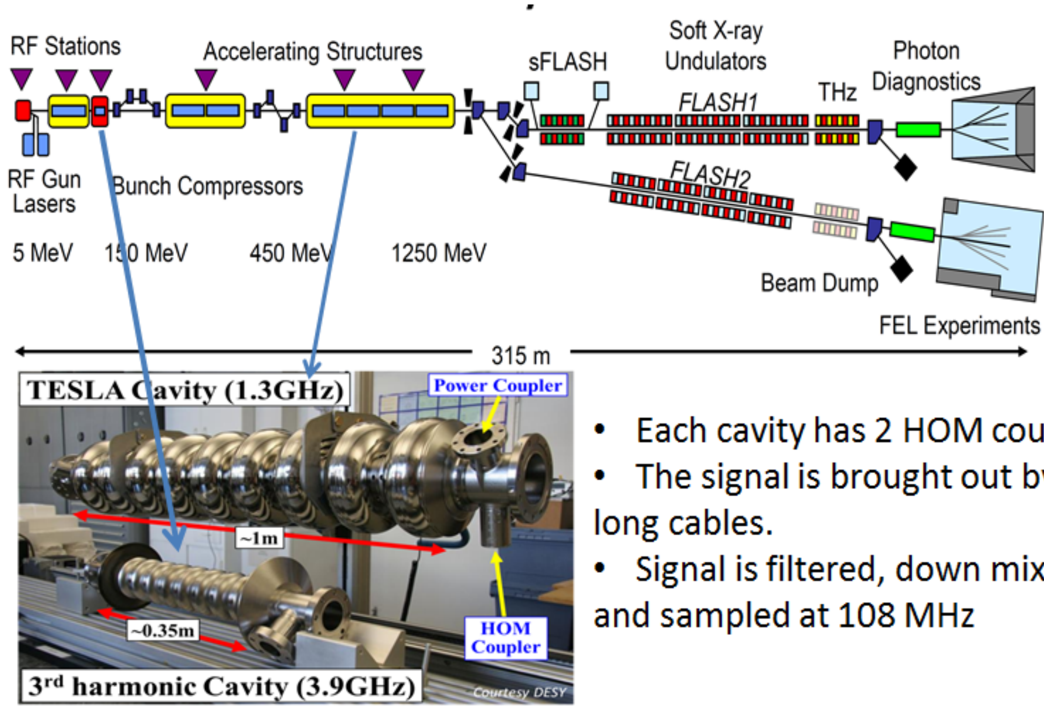
BPM: Beam Position Monitor
BPhM: Beam Phase monitor



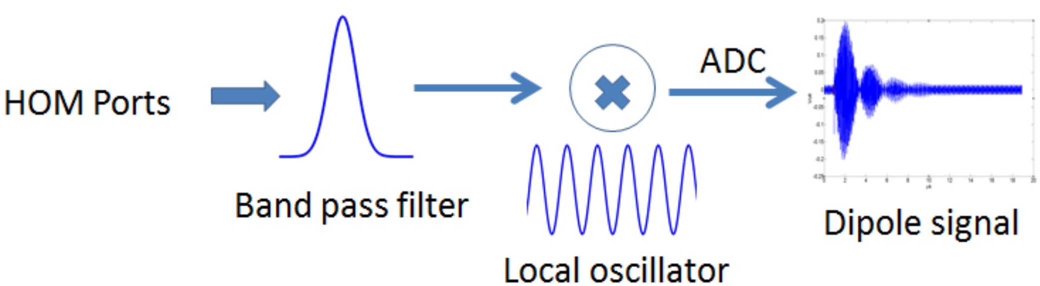
Principle of an HOMBPM

- We use accelerating cavity as a beam monitor to determine the beam position inside a cavity.
- Measured dipole voltage at HOM coupler ∝ $q \cdot (x + y) \cdot \frac{R}{Q}$, $\frac{R}{Q}$ *is a parameter to characterize beam cavity interaction*.
- To get beam position:
  - ✓ Normalize with charge *q (available from Toroid)*
  - ✓ Select the dipole mode with higher *R/Q (from simulations)*

HOMBPMs at FLASH



- Each cavity has 2 HOM couplers
- The signal is brought out by long cables.
- Signal is filtered, down mixed and sampled at 108 MHz



- Cavities are equipped with HOM couplers to damp the HOMs inside.
- All HOM raw data are accessible from DOOCS (control system)
- The HOMBPMs were integrated into beam orbit feedback system at FLASH. Due to instability issues of HOMBPMs, they were removed latter on.

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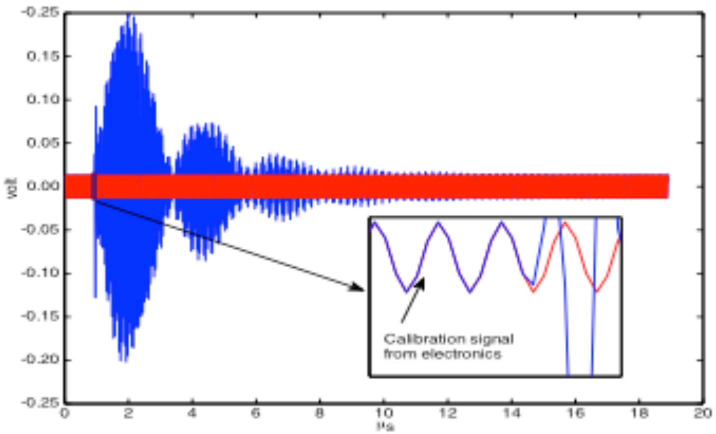
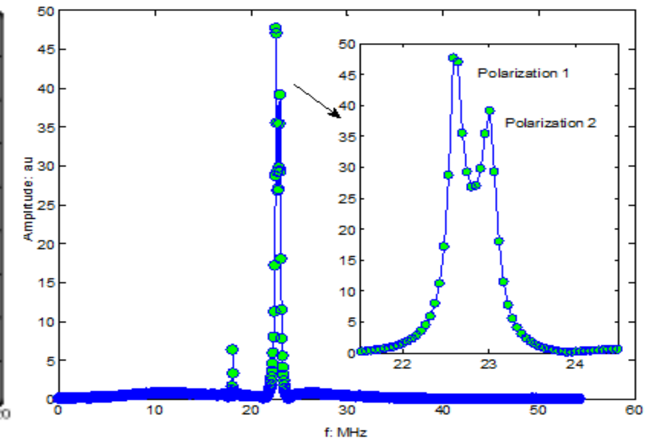
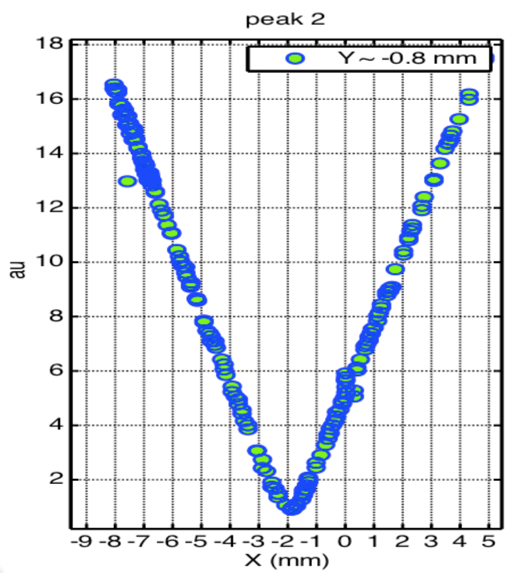
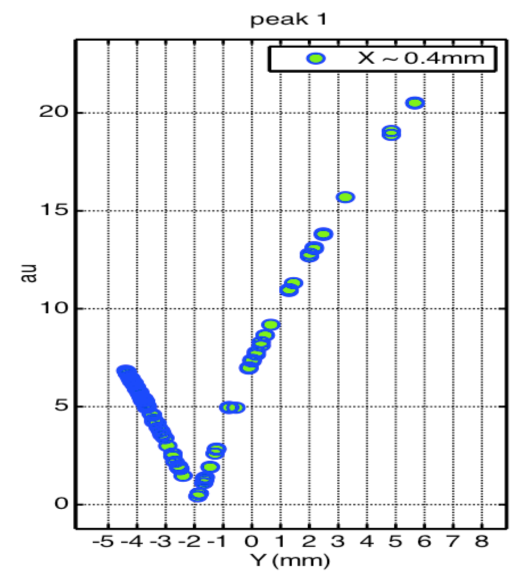
HOMBPMs at FLASH

Mode	*f* (GHz)	*R/Q* (Ω/cm²)
EE-1	1.6291	0.0014
EE-2	1.6369	0.0636
EE-3	1.6497	0.0014
EE-4	1.6671	0.3767
EE-5	1.6885	0.0689
EE-6	1.7129	5.5392
EE-7	1.7392	7.7817
EE-8	1.7656	1.0453
EE-9	1.7912	0.8059
EE-10	1.8005	0.3536





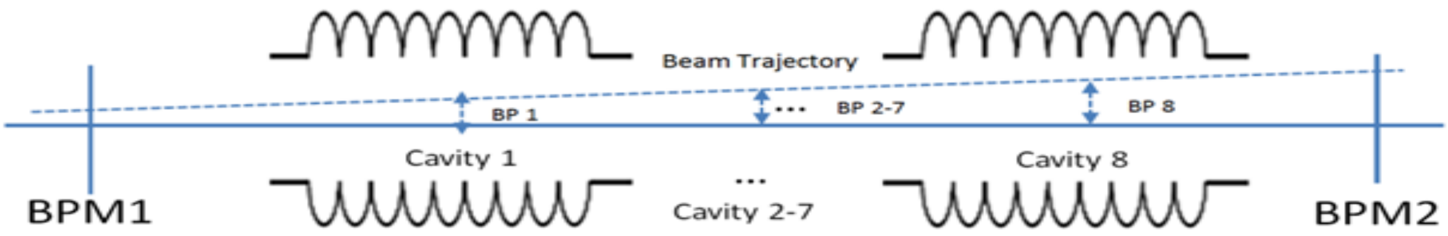




R. Wanzenberg, TESLA 2001-33, 2001

Calibration of an HOMBPM

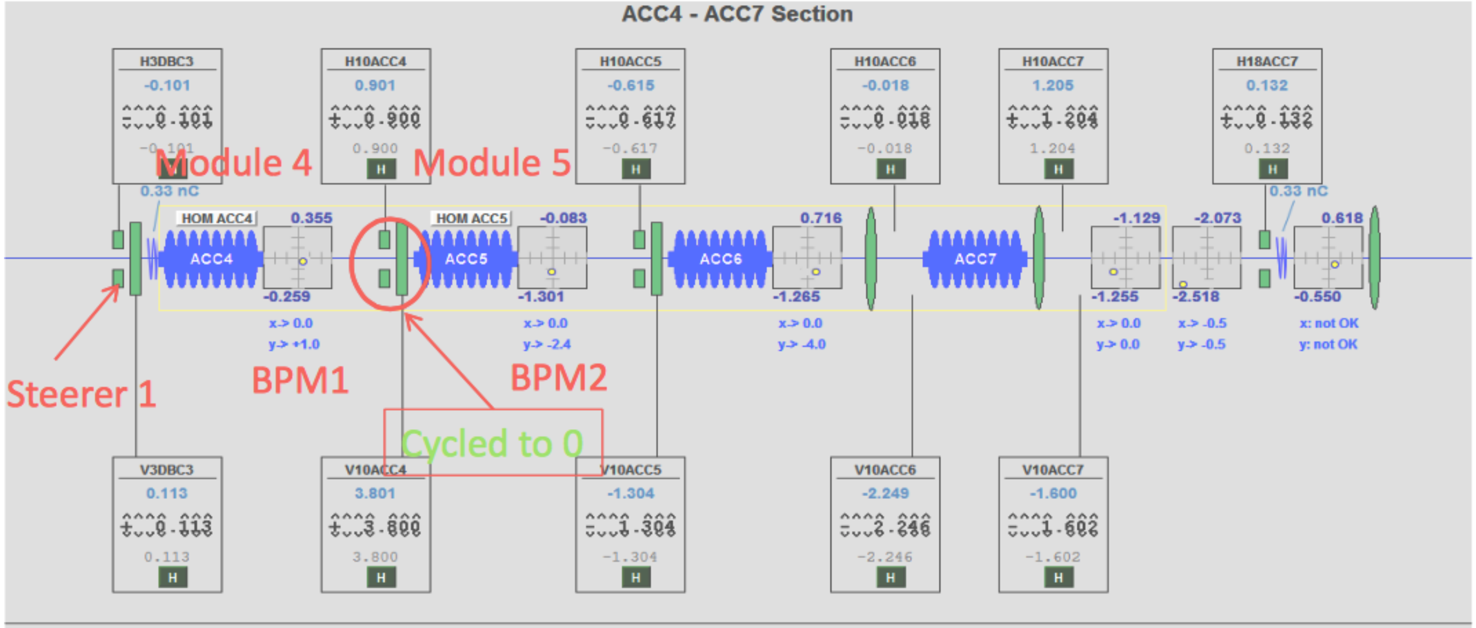
- Calibration of an HOMBPM



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.

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

SVD: Singular Value Decomposition



Workflow of HOMBPM calibration

Title

I.shi

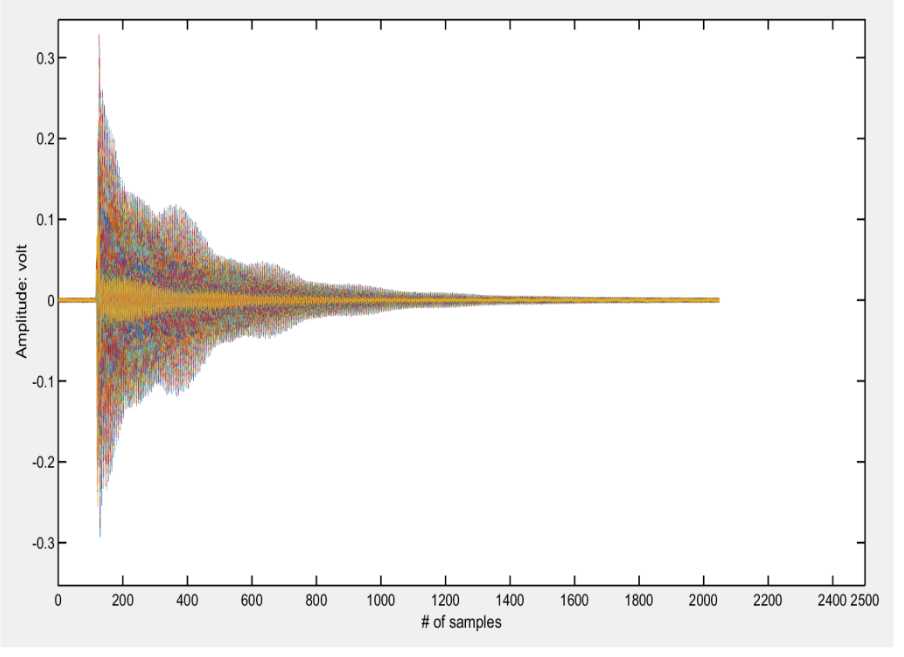
Author

1. *Turn off magnets right before the module*
2. *Turn off RF field inside the cavity*
3. *Steer the beam to several locations*
4. *Record the Dipole spectrum, record the charge from nearby Toroid, record the beam position from other BPMs.*

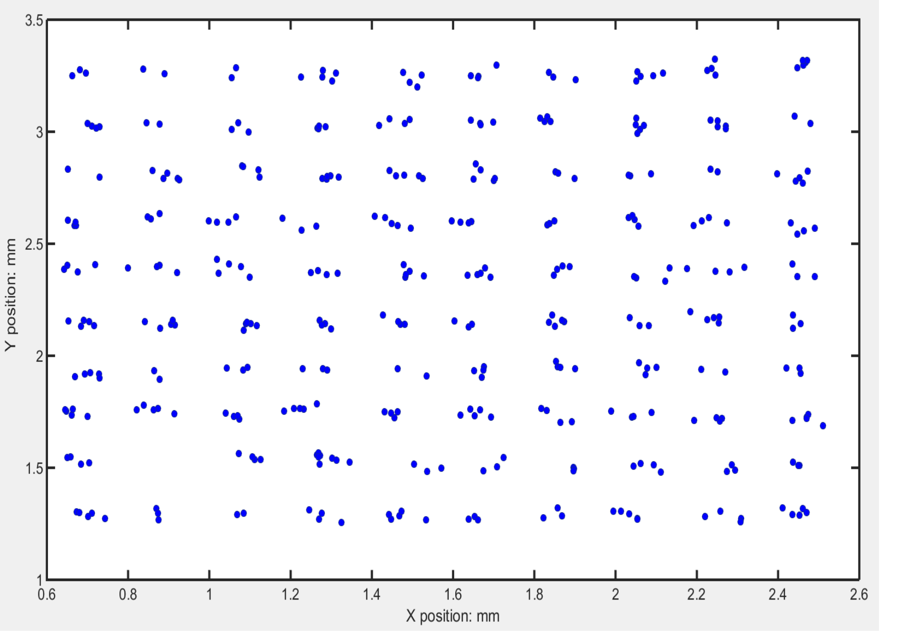
Working condition: single bunch, 10 Hz repetition rate, 0.5 nC charge

Courtesy of DESY

HOMBPMs at FLASH
Data preparation

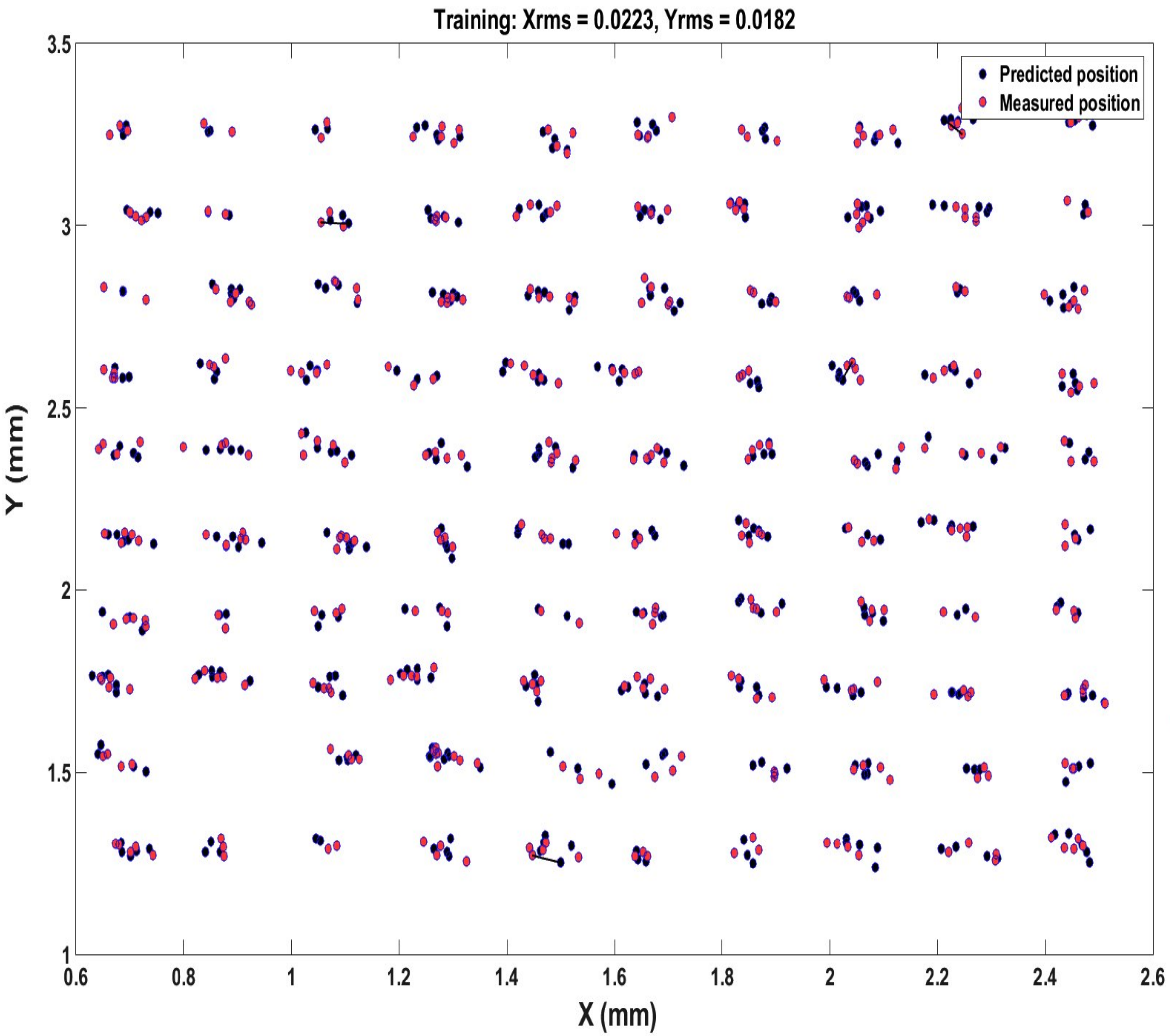


Recorded waveforms used for obtaining the spectrum at module 5 cavity 1. There are 386 records in total.



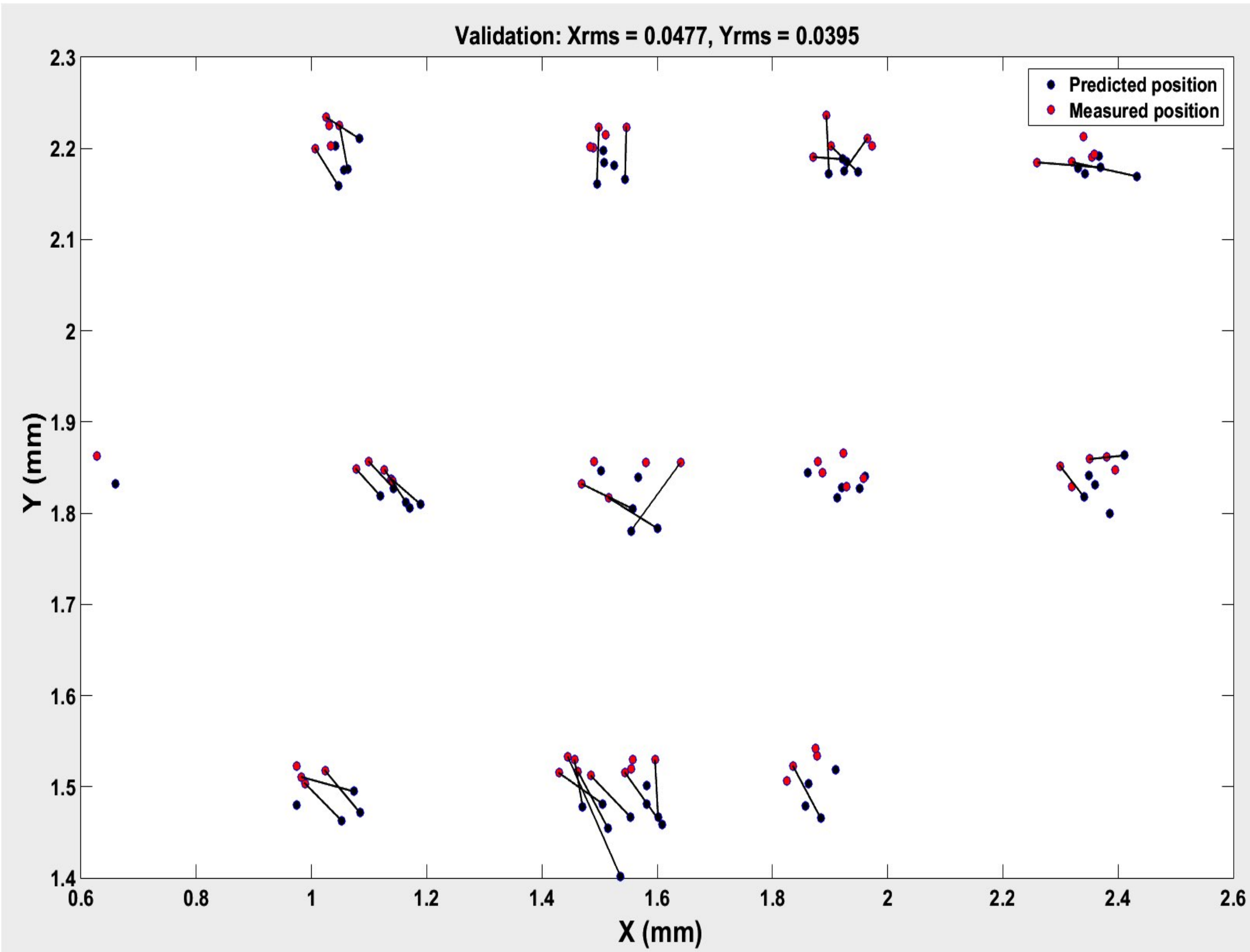
Interpolated beam position at module 5 cavity 1. Accordingly, there are 386 beam position records.

HOMBPM calibration results



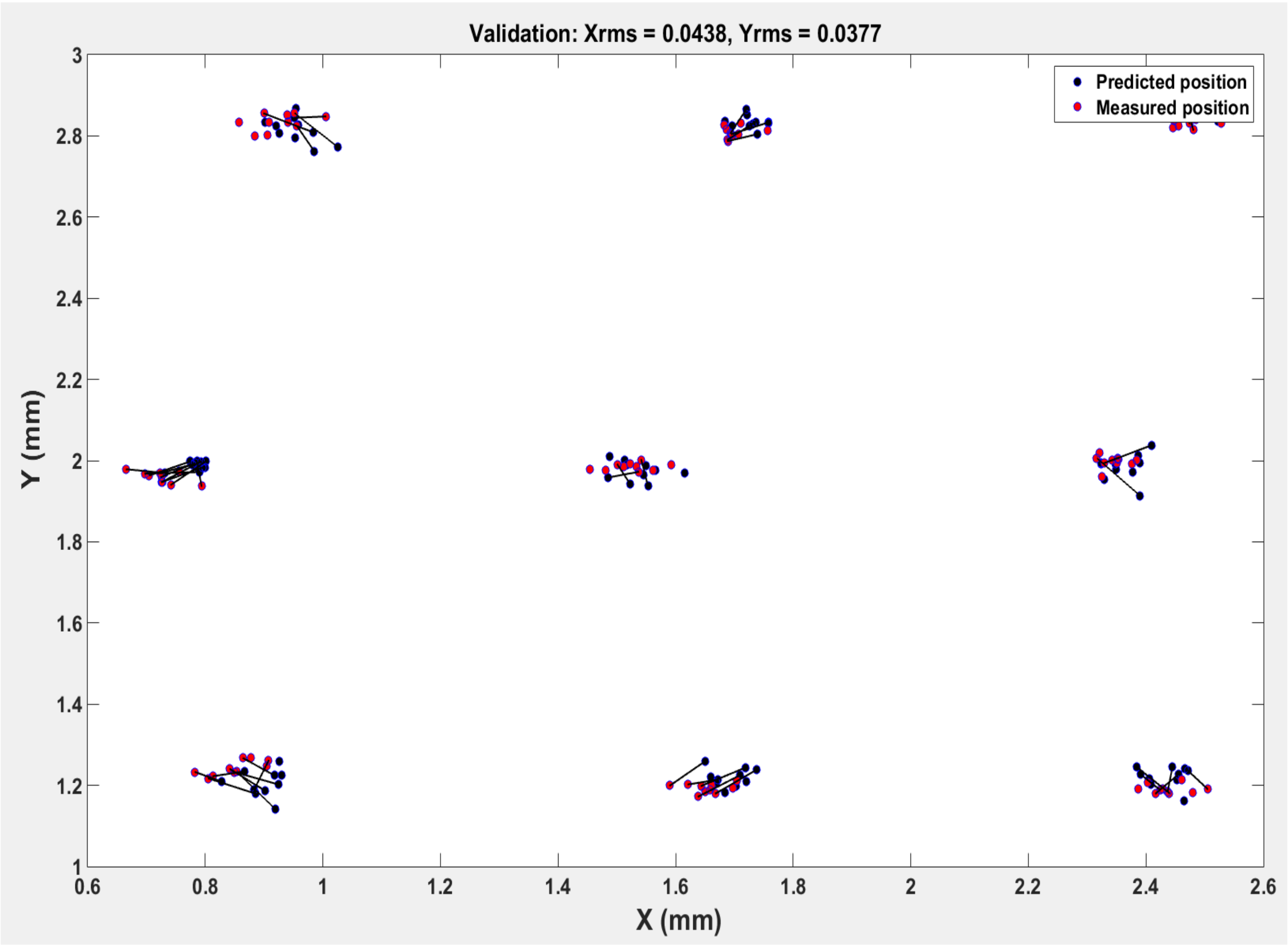
- The training RMS is 22.3, 18.2 µm in X,Y direction respectively.
- The goodness of calibration is in least square sense.

HOMBPM validation results
3 days interval



- The validation RMS is 44.7, 39.5 µm in X,Y direction respectively.
- The resolution is almost twice worse than the calibrated resolution.
- Systematic pattern in the left plot might account for the degradation.

HOMBPM validation results
5 days interval



- The validation RMS is 43.8, 37.7 µm in X,Y direction respectively.
- The validation RMS does not necessarily degrade over time.
- The systematic pattern is not as clear as in previous slide.

Resolution limits of HOMBPM

- Fundamental one: thermal noise

$$\frac{\Delta E}{E} = \frac{\frac{1}{2}k_b T}{\frac{1}{2}\cdot\frac{2\pi f}{2}(\frac{R}{Q})q^2} = 56.4\ \mathrm{nm}^2$$, correspond to 7.5 nm resolution at 0.5 nC charge

where k_b is Boltzmann constant, T = 300 K, f = 1.7 GHz, $\frac{R}{Q} = 5.53\ \Omega/cm^2$,

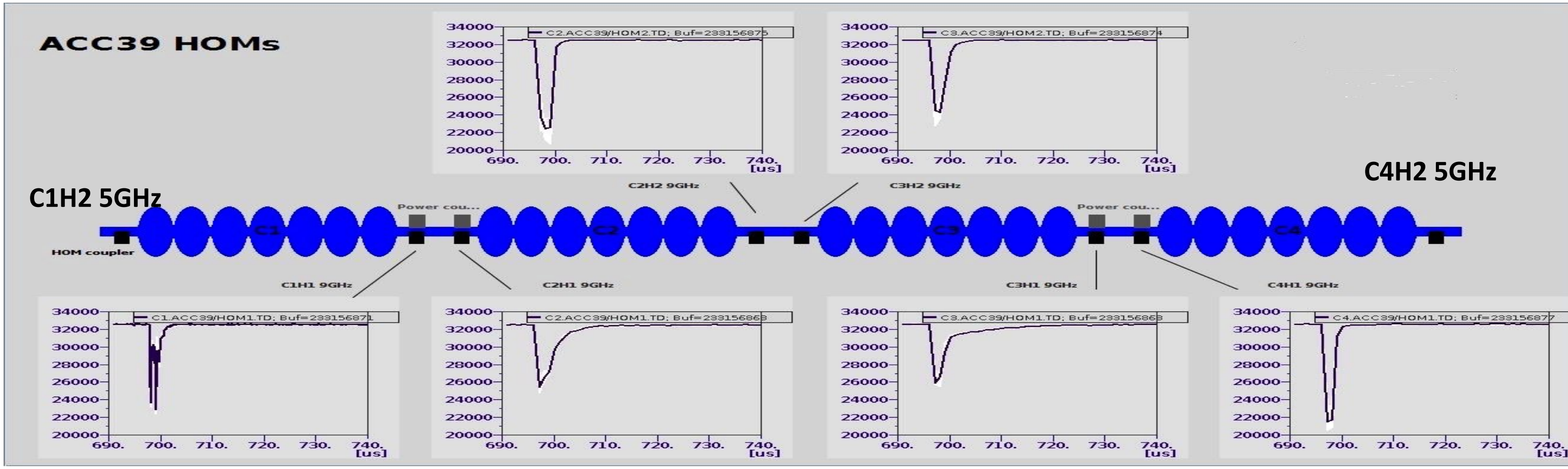
q = 0.5 nC

- Component used in the system: cables, electronics etc.

10dB from cable, 16.5 dB from electronics, they correspond to 158.5 nm resolution at 0.5 nC charge.

- Beam angle effects, bunch length effects.
- Methods and components used: beam charge measurements, least square sense, imperfection of cavity BPMs (~20 µm resolution) used for calibration.
- Last but not the least, normally we do not evaluate standard BPM in this way.

HOMBPMs for 3.9 GHz cavities

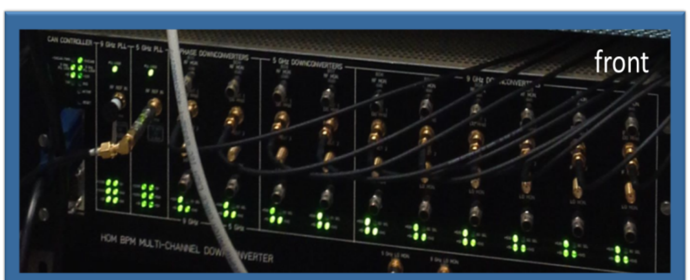


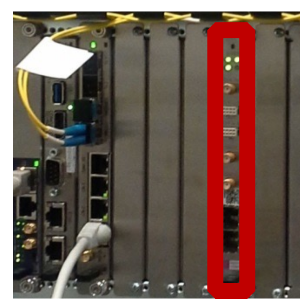
Band pass Filter
~5.43 GHz or 9.06 GHz
100 MHz BW

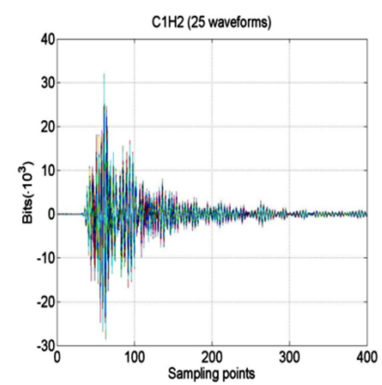
Mixer

30 MHz IF

µTCA Digitizer SIS8300 (108MS/sec)



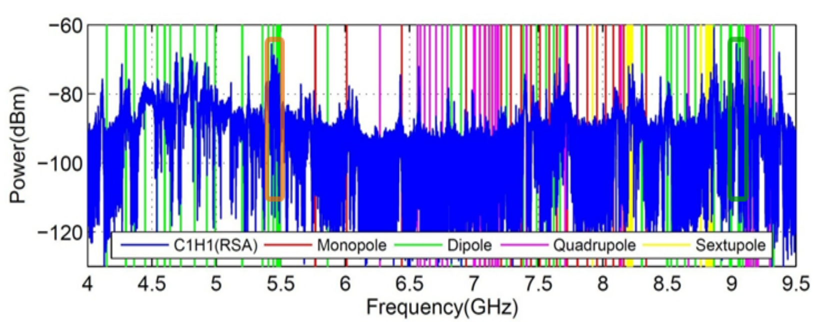




N. Baboi et al, TUPF06, IBIC14

Spectrum comparison between 3.9 and 1.3 GHz cavities

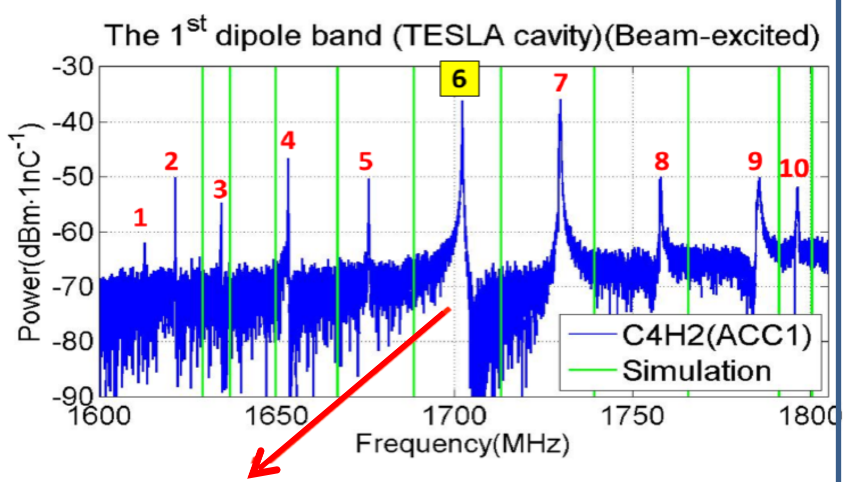
Mode type	Freq./BW (MHz)	Advantages	Disadvantages
1st & 2nd band	5465 / 30	High R/Q	Not localized
5th band	9058 / 30	Localized Cavity-based	Low R/Q



It is difficult to identify single dipole mode, a band of dipoles are used for beam position monitor.

Spectrum for 3.9 GHz cavity

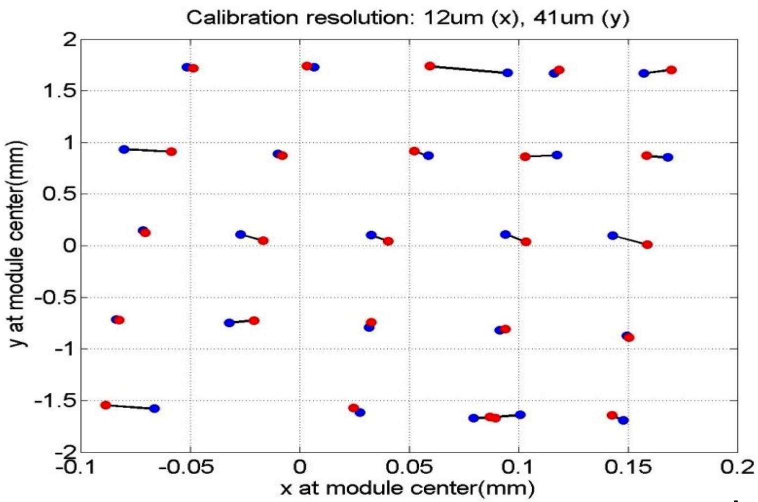
Mode type	Freq./ BW(MHz)	Advantages
TE111-6	***1721/20***	***High R/Q; Localized***

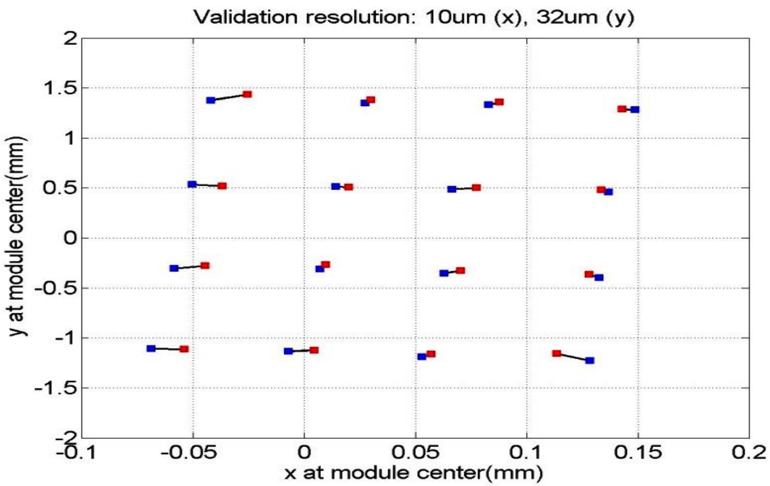


Dipole used for HOMBPM

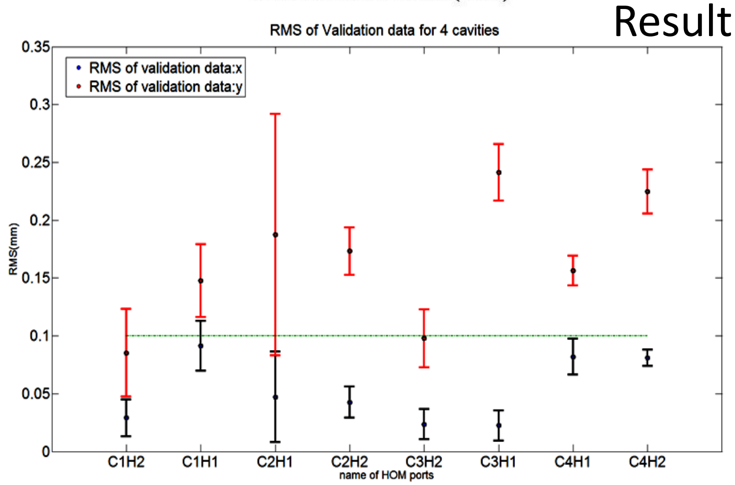
Spectrum for 1.3 GHz cavity

HOMBPM for 3.9 GHz cavities





Result from August 2014



Result from May 2014

- In general good results for 5 GHz channels and 9 GHz/x
- High RMS error for 9GHz/y: Possibly instability of signals in electronics

Summary of HOMBPM at FLASH

- First time, we get stable beam position prediction over 5 days for HOMBPM of 1.3 GHz cavities.
- RMS resolution is evaluated in a global sense (wide beam movement). Therefore, better resolution is expected when using beam jitter data within reasonable movement range.
- The resolution limit on cavity BPMs used for calibration limits our results to a large extent.
- Since the cavity and couplers are not designed for beam position purpose, the beam position determination based on standard I/Q processing is not trivial.

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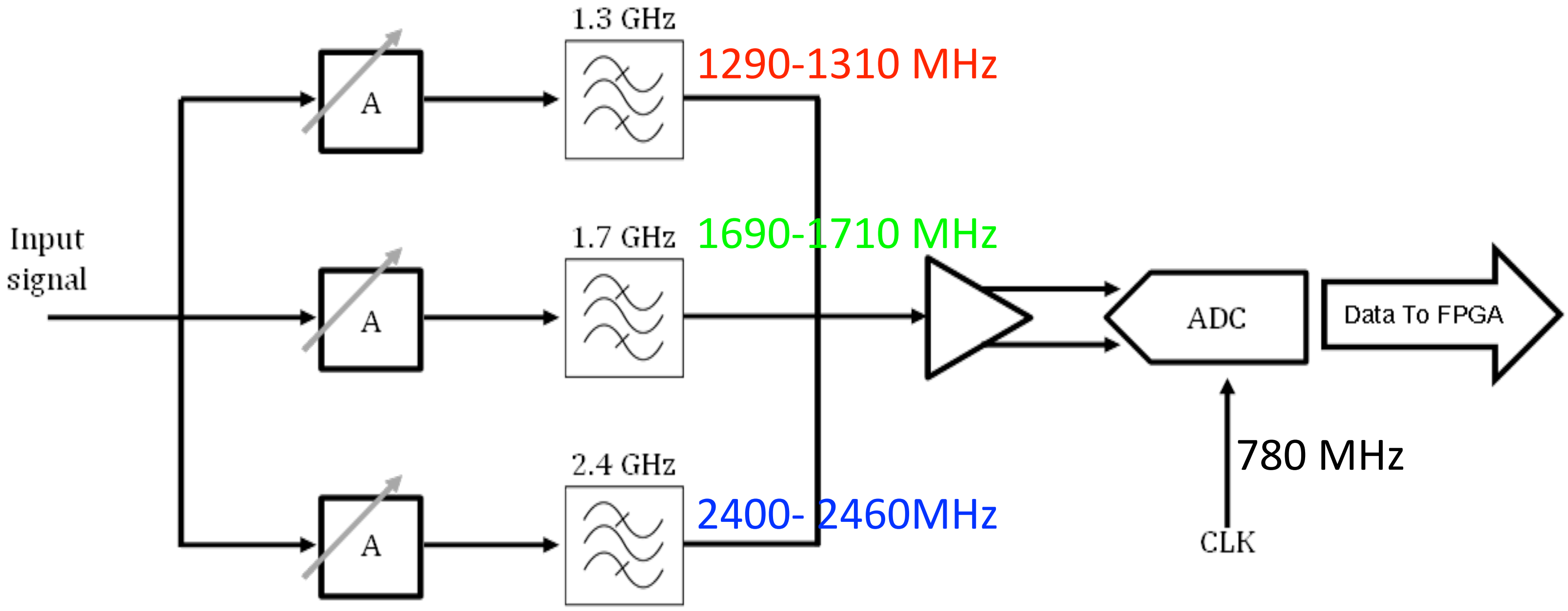
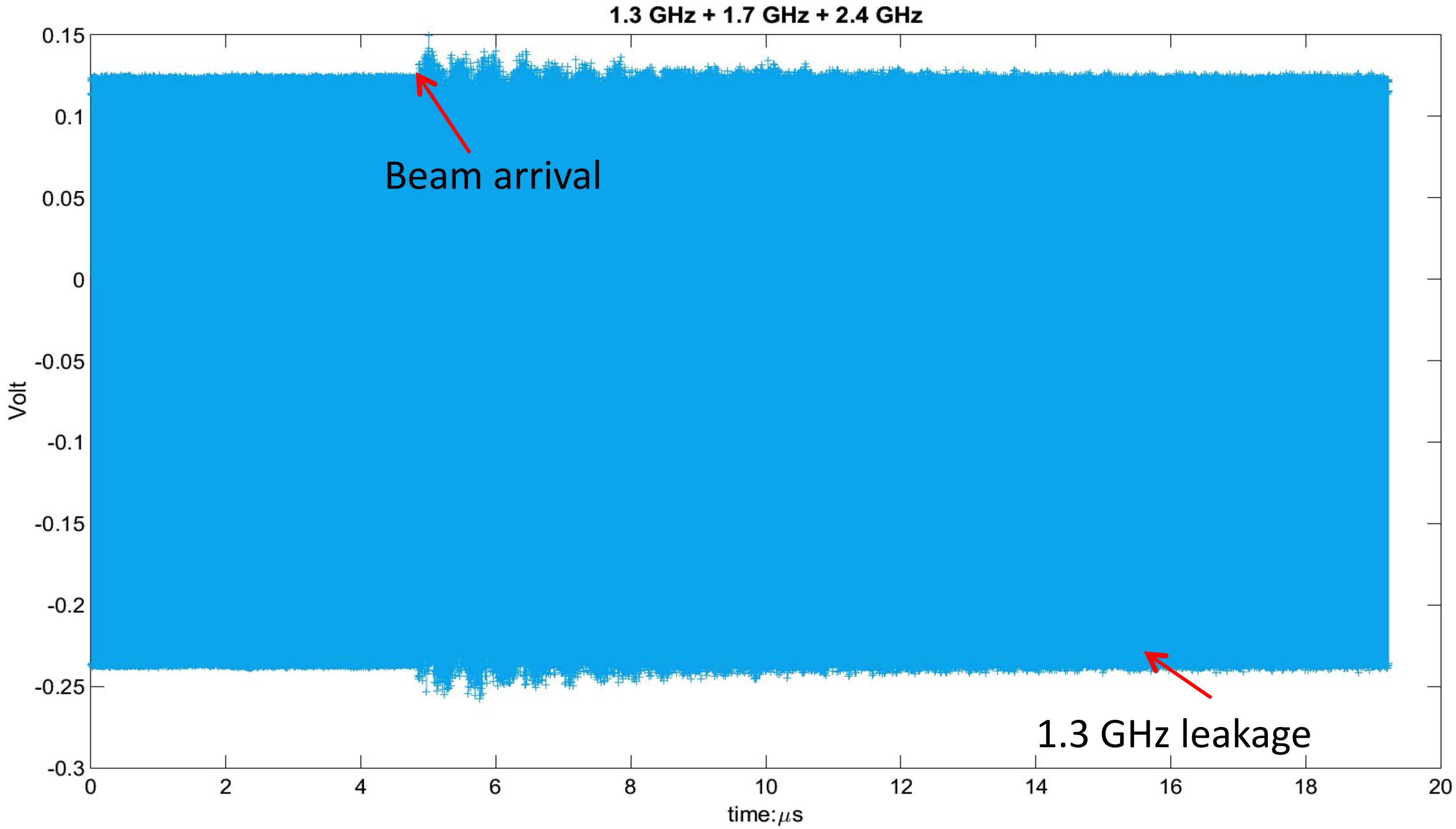
Overview of HOM based beam Phase measurements



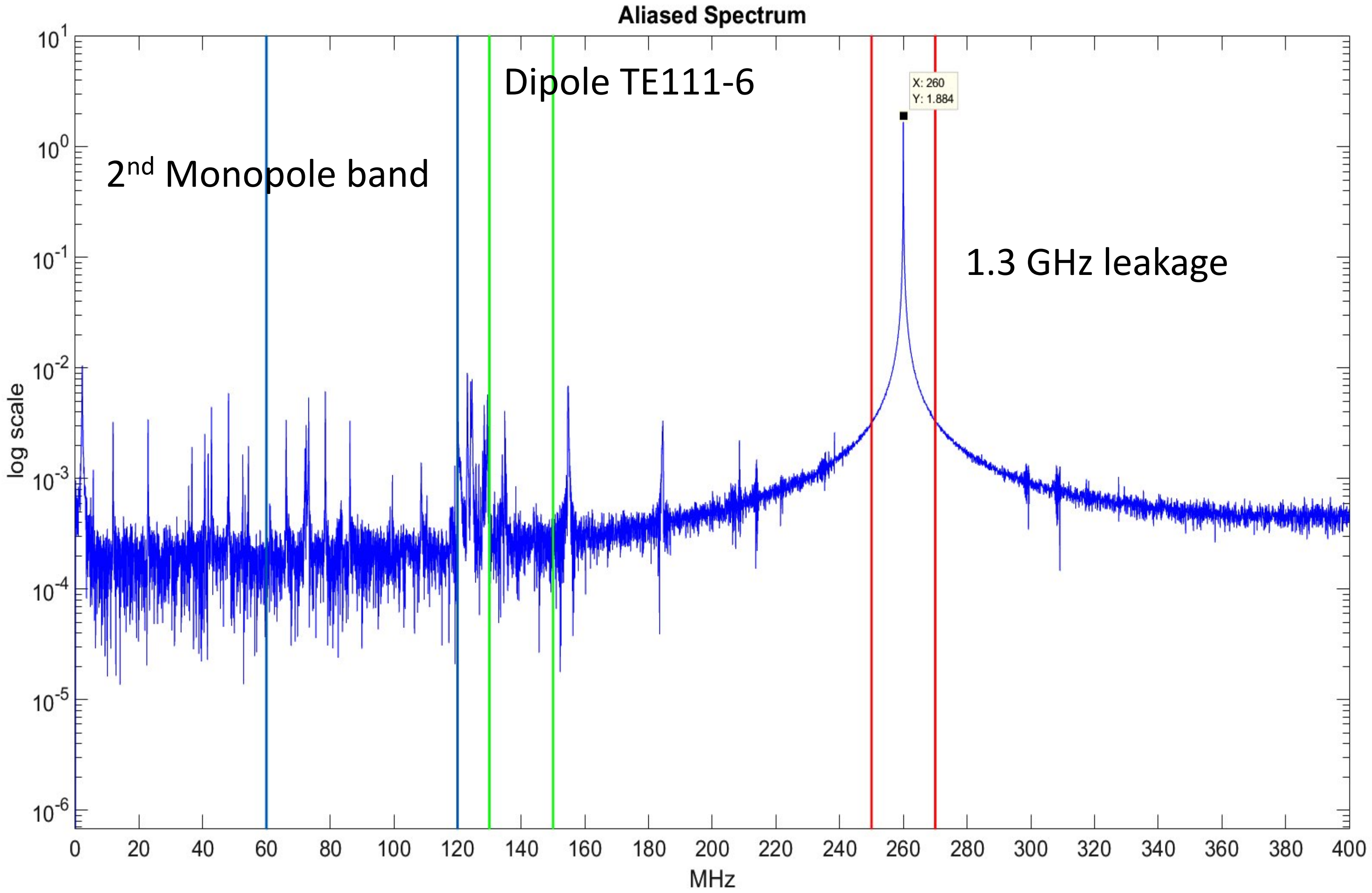
Block diagram of HOMBPhM hardware

Signal can be aliased to 250-270 MHz (fundamental Monopole), 130-150 MHz (Dipole), 60-120 MHz (2nd monopole band) respectively.

Example of single bunch

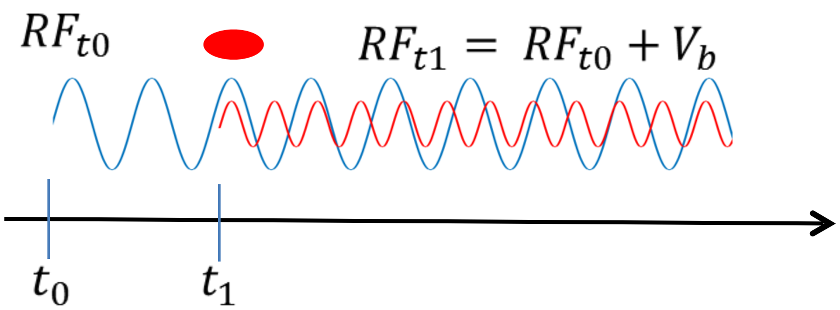


Clearly, attenuation or amplification for each channel needs to match each other.

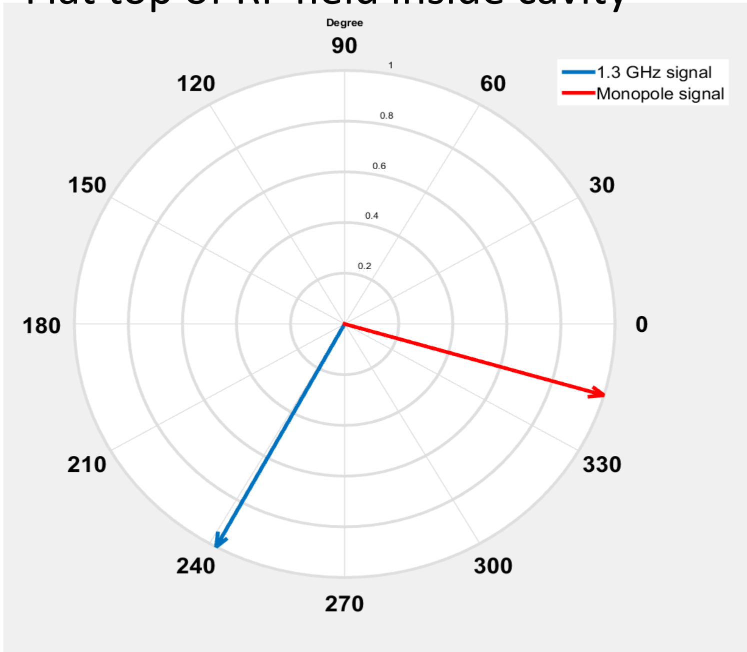


Clearly, attenuation or amplification for each channel needs to be matched with each other.

How to determine beam phase?



Flat top of RF field inside cavity



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

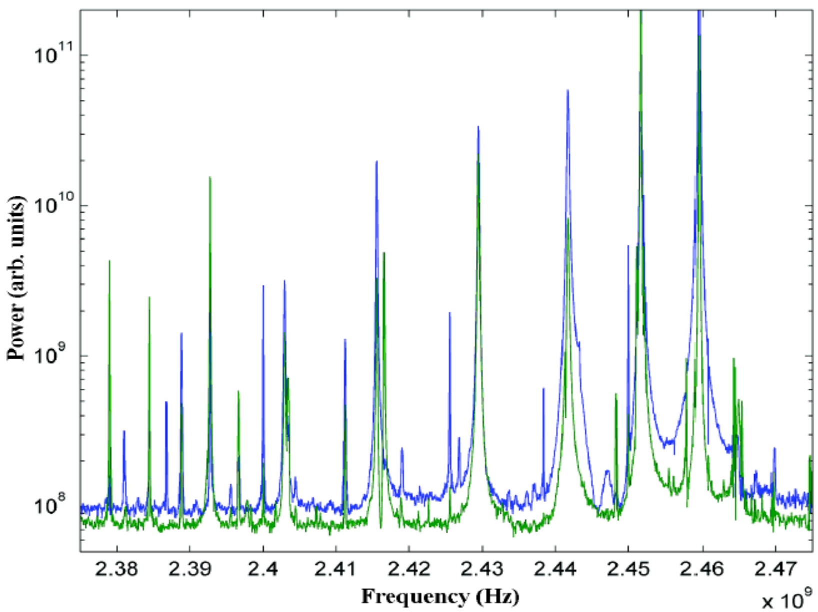
V_b: $\sim 2.4\ GHz\ beam\ induced\ signal$

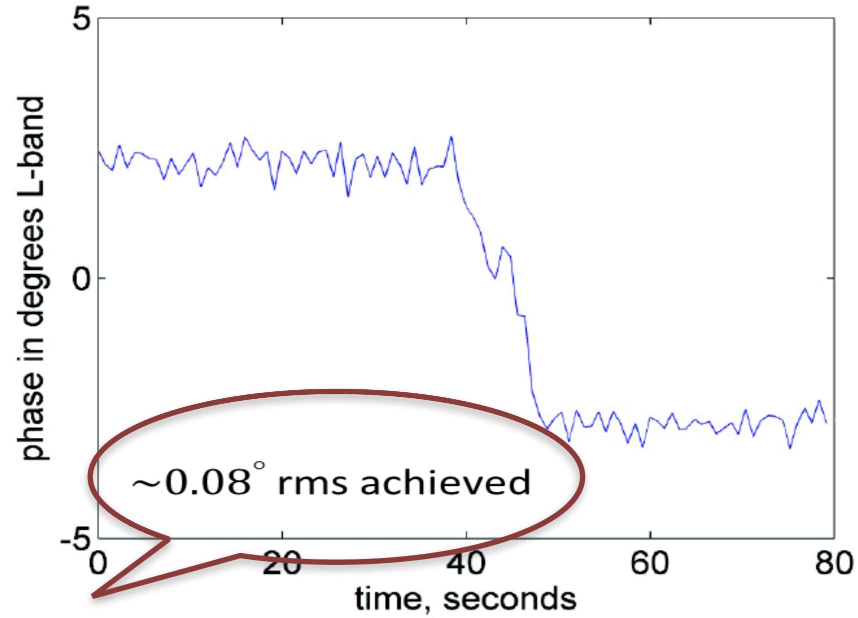
RF_{t1}: $1.3 + 2.4 GHz\ signal$

- The absolute angle spanned by RF_{t0} and V_b is not so important.
- When we change the beam phase, both phasors will rotate, the beam phase can be measured through this way relatively.

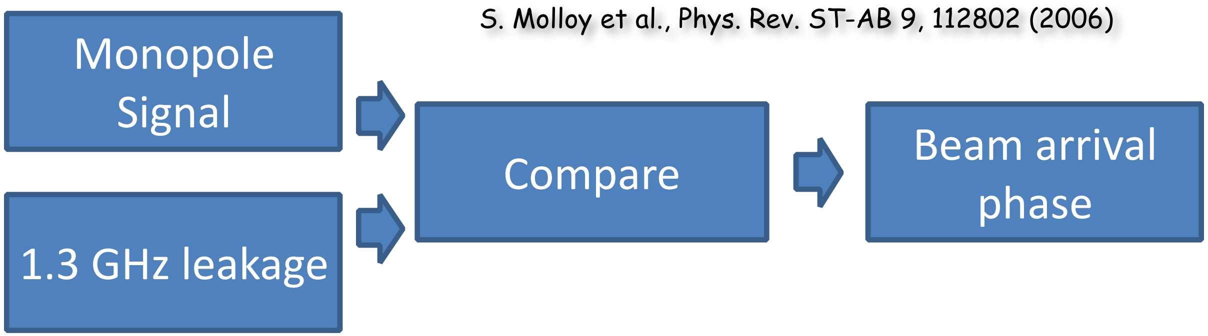
HOM based Beam Phase measurement

2nd monopole band from TESLA cavity





S. Molloy et al., Phys. Rev. ST-AB 9, 112802 (2006)



Advantages:

- Both signal are from the same cable.
- Monopole is always available

Pros and Cons of HOM Based Beam Diagnostics

\+ Accelerating cavities can be used as beam monitors.

\+ When there is no space for standard beam diagnostics instruments.

\+ It is cheaper when compared with standard BPMs.

\+ ……

\- Cavities are not designed for diagnostic purpose, therefore need efforts to get relevant information.

\- ……

Summary and Outlook

- HOMBPM works stably with beam data over a week. Compared with several hours stability in the past, this is promising for using accelerating cavity as a HOMBPM.
- There is still large room for improvements to the theoretical resolution limit.
- We tested the electronics for BPhM and found there are issues with power mismatch among channels.
- We plan to test the HOMBPM with dedicated beam time to confirm the stability.
- HOMBPhM prototype electronics will be produced soon and will be tested at FLASH.
- We are actively developing algorithms to extract beam position and beam phase information.

Thank you for your attention!