STABILITY STUDY OF BEAM POSITION MEASUREMENT BASED ON HIGHER ORDER MODE SIGNALS AT FLASH.

J. H. Wei[1,2], N. Baboi[1], L. Shi[3]

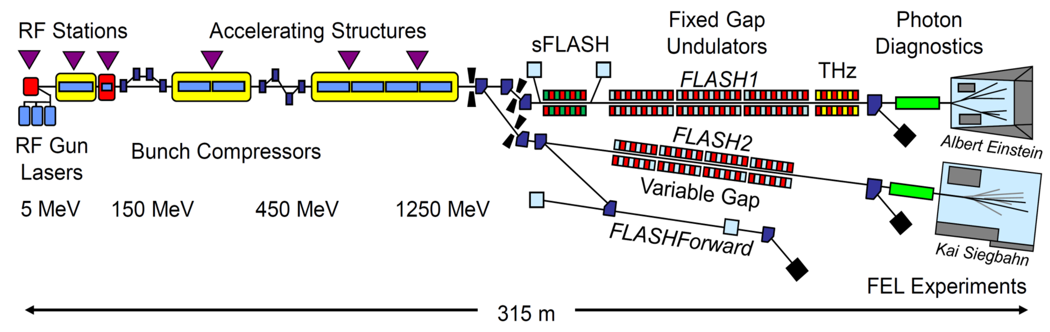
[1] Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

[2] University of Science and Technology of China (USTC), Hefei, China

[3] Paul Scherrer Institute (PSI), Villigen, Switzerland

Introduction

FLASH is a free-electron laser driven by a superconducting linac at DESY in Hamburg. It generates high-brilliance XUV and soft X-ray pulses by SASE (Self Amplified Spontaneous Emission). Many accelerating cavities are equipped with HOMBPMs (Higher Order Mode based Beam Position Monitors) to align the beam and monitor the transverse beam position. However, these lose their position prediction ability over time. In this paper, we applied an efficient measurement and signal analysis routine with various data process methods including PLS (Partial Least Square) and SVD (Singular Value Decomposition) to determine the transverse beam position. By fitting the HOM signals with a genetic algorithm, we implemented a new HOMBPM calibration procedure and obtained reliable beam prediction positions over a long time. A stable RMS error of about 0.2 mm by using the spectra of signals and 0.15 mm by using signal fitting over two months has been observed.

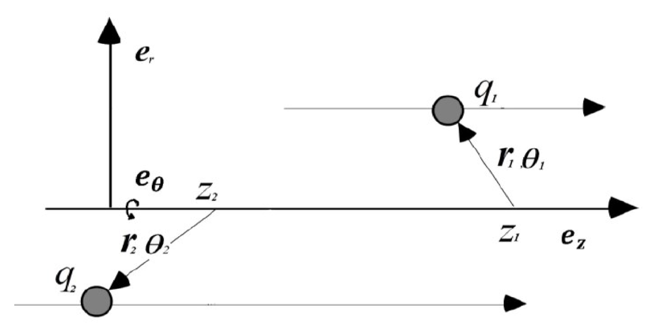


Schematic layout of FLASH facility

Reference: M. Vogt, et al., "Status of the Soft X-ray Free Electron Laser FLASH", 2017

HOMBPM Principle

Transverse wake potential

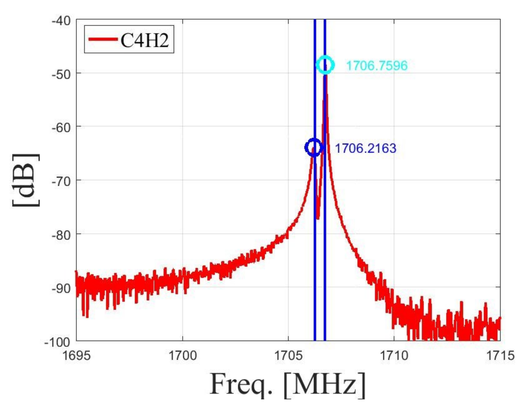


$$W_\perp \cong r_1 c \sum_n \left(\frac{R}{Q}\right)^{(1n)} \sin\left(\frac{\omega_{1n} s}{c}\right) H(s)\,[\cos(\theta_1-\theta_2)\,\boldsymbol{e_r} + \sin(\theta_1-\theta_2)\,\boldsymbol{e_\theta}].$$

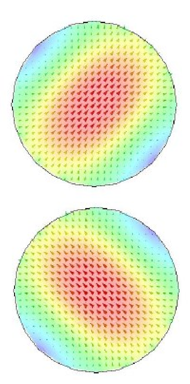
Transverse wake potential from dipole modes:
The transverse wake potential has an approximately linear dependence on the beam offset of the leading bunch.

Dipole Mode at 1.7 GHz

- TE111-6, at ca. 1.7GHz has strong coupling to beam (high R/Q) and is used for beam position monitoring.
- Two peaks corresponding to two polarizations.
- Frequency varies from cavity to cavity (± 10 MHz).
- Mode separation also varies from cavity to cavity .
- Mode polarization direction is usually not horizontal or vertical.

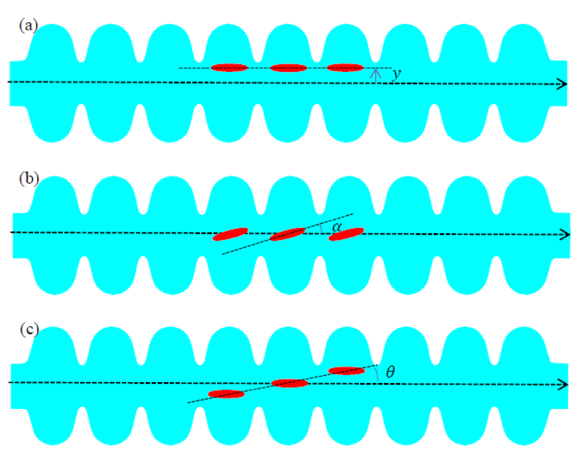


TE11



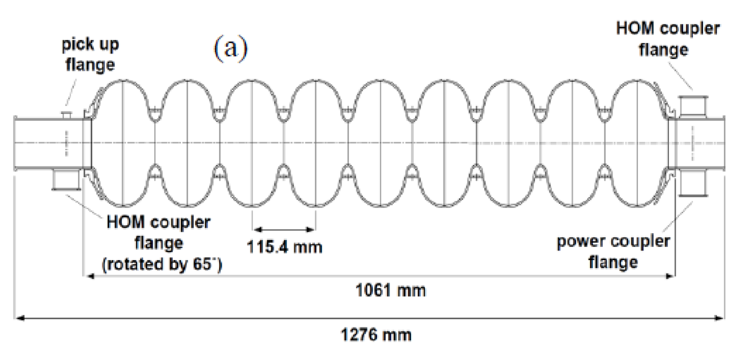
Dipole Mode Excitation

- There are three scenarios of a bunch traveling through a cavity:
  - (a) the bunch travels with an offset,
  - (b) the bunch is tilted and
  - (c) the bunch travels with an angle with respect to cavity axis.
- For short bunches, as is the case at FLASH, signals from bunch tilt (b) are vanishingly small compared with beam offset (a).
- Estimates predict that 5 mrad trajectory tilt (c) will excite the same signal amplitude as 1 mm bunch offset (a) for 1.3 GHz cavities.
- The trajectory tilt is kept very small during the beam position measurement.



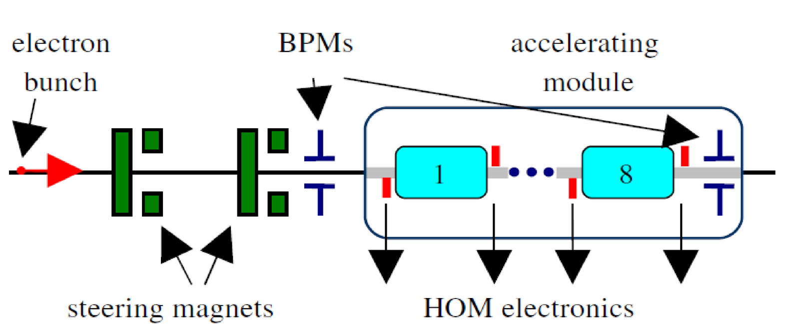
HOMBPM Measurement

TESLA Cavity



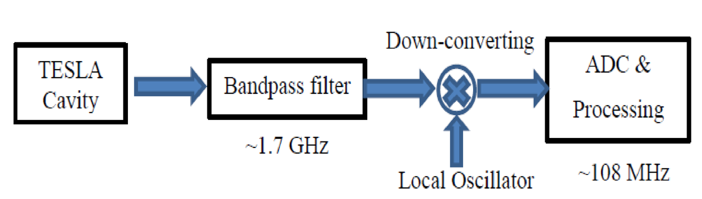
- The 9-cell TESLA cavity works at 1.3 GHz.
- Each cavity has a fundamental power coupler to input the RF power from a klystron and a field probe to detect the accelerating field for calibration and control by the LLRF system.
- Two additional couplers are installed at both sides of the cavity to damp the beam-excited HOMs.
- The two HOM couplers span an angle of 115° .

Measurement Setup



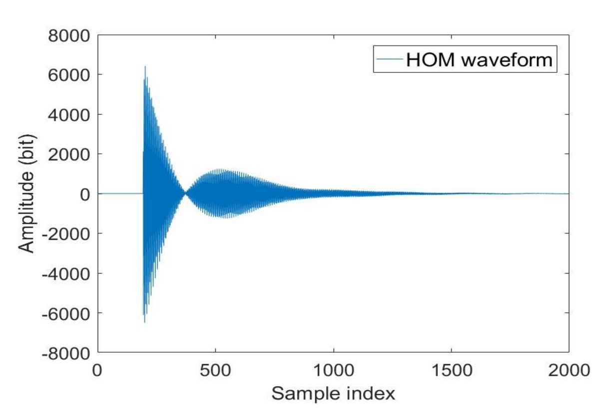
- Two pairs of steering magnets are used to move the beam. RF is switched off , the quadrupole magents are cycled to 0.
- The beam is steered over a range of approximately 10 mm x 10 mm in X and Y in cavity 4 of module 5.
- Two BPMs located upstream and downstream of the module give the interpolated beam positions in the cavity.
- A straight beam trajectory between the two BPMs is guaranteed by switching off quadrupoles, dipoles, and RF inside the module.

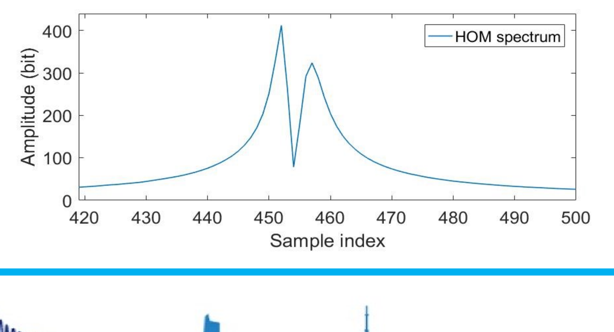
HOM Signal Processing



- The data acquisition system filters the HOM signal at 1.7 GHz with a 20 MHz narrow bandpass and down-mixes to 20 MHz IF (intermediate frequency), which is then sampled at about 108 MHz by the ADC.

Reference: J. Frisch, et al., "Electronics and Algorithms for HOM Based Beam Diagnostics", 2006



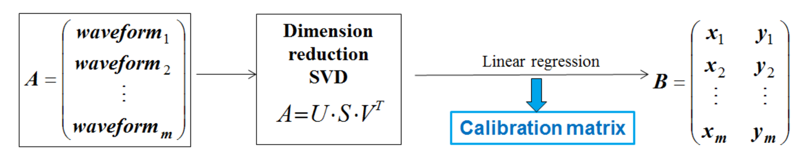


Dipole Signal Analysis

PLS and SVD

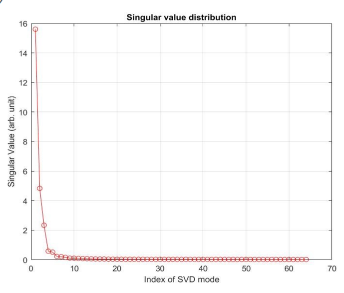
- The dipole mode signals were calibrated relative to the positions interpolated from BPMs. Therefore , a linear relationship can be written as a compact matrix formula:

$$A \cdot M = B$$



- PLS and SVD are useful methods to solve the linear regression model. They can find the latent components (8 modes were used) in the HOM data that have high correlation with the beam position to reduce the noise and matrix dimension.

Reference for PLS: R. Rosipal, et al., "Overview and Recent Advances in Partial Least Squares", 2006

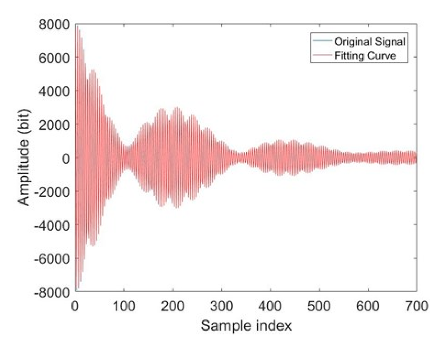


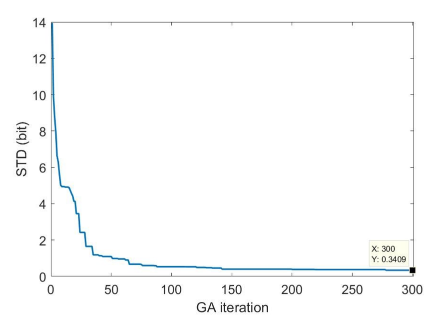
Fitting Signal

- The dipole mode signal mainly consists of two components corresponding to the two signal peaks in the frequency domain. Signal fitting can give the latent information, such as the phase, independent amplitude and decay constant of each peak.

$$\mathrm{A} = \mathrm{c} + a_1 \sin(\omega_1 t + \varphi_1)\, e^{-\frac{t}{\tau_1}} + a_2 \sin(\omega_2 t + \varphi_2)\, e^{-\frac{t}{\tau_2}}$$

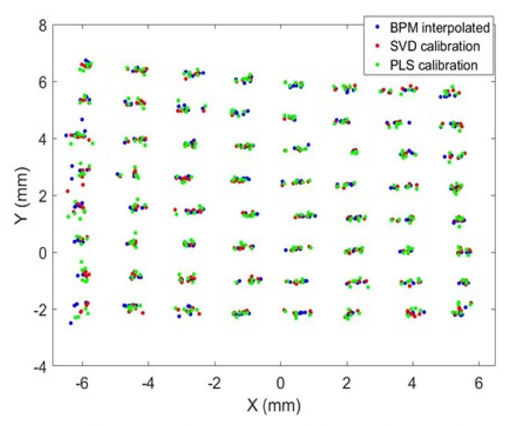
- A method based on genetic algorithm (GA) is used to fit the signal waveforms.
- The original signal waveform (blue) and the fitted signal curve (red). The red curve almost covers the original signal completely. The RMS of the signal difference is 0.34 bits while the coefficient of determination (r^2) is over 0.9990.





HOMBPM Results

Calibration Based on PLS and SVD

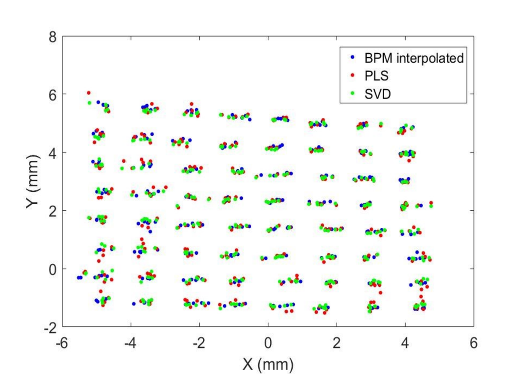


Calibrated beam positions in cavity 4

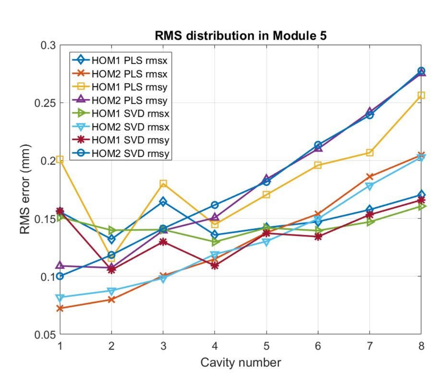
- Calibration data was measured on April 4th from module 5.
- Calibration samples of PLS and SVD are compared with interpolated beam positions by using the waveforms.
- The RMS errors of PLS and SVD from calibration in coupler 1 cavity 4 are:

RMS	X (mm)	Y (mm)
PLS	0.116	0.127
SVD	0.118	0.132

Short-term Beam Position Prediction

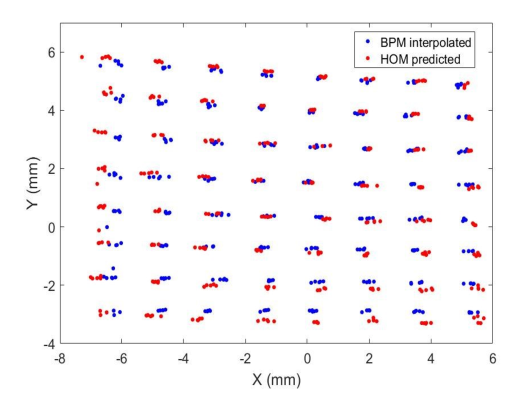


Predicted beam positions in cavity 4



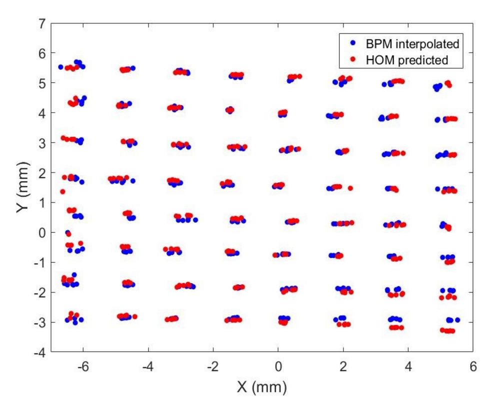
- The prediction data was also measured on April 4th from module 5.
- According to the RMS error, the SVD method has better performance.
- A resolution better than 10 μm has been achieved in cavity 5.

Long-term Beam Position Prediction



Predicted beam positions in cavity 4 with SVD method using spectra.

RMS (SVD)	X (mm)	Y (mm)
Calibration	0.176	0.165
Validation	0.228	0.173



Predicted beam positions in cavity 4 with fitting waveform method.

RMS (Fitting)	X (mm)	Y (mm)
Calibration	0.141	0.152
Validation	0.153	0.137

- For long-term validation, data was taken on Feb. 5th from module 5.
- There is a phase drift in the HOM waveforms over a long time.
- Therefore the calibration matrix based on waveforms does not work. The spectra are used instead. (left plot)
- Also, a method based on waveform fitting is implemented. (right plot)
- The new method gives better results.

Summary

- The existing HOMBPM system can be used for beam alignment in order to reduce the transverse wakefield effects. Also, it can deliver transverse beam position information, like a cavity BPM.
- The RMS error is used as a figure of merit to evaluate the HOMBPM calibration and prediction. It depends on the measurement range.
- The resolution of the system is determined for small position range, which is different from the RMS error.
- For the case of analysing dipole spectra, the RMS error of the beam position stable at about 0.2 mm over months for a beam range of about 10 mm × 10 mm.
- With a newly developed method based on signal fitting we obtained a lower RMS error of around 0.15 mm.

2018 International Beam Instrumentation Conference