Resolution study of HOMBPM at FLASH

Presenter: L. Shi (U. Manchester / DESY)
Members: N. Baboi (DESY), R.M. Jones (U. Manchester), T. Wamsat (DESY),
B. Lorbeer (DESY), N. Eddy (FNAL), P. Zhang (CERN), S. Habib (WUT)

8 April 2015

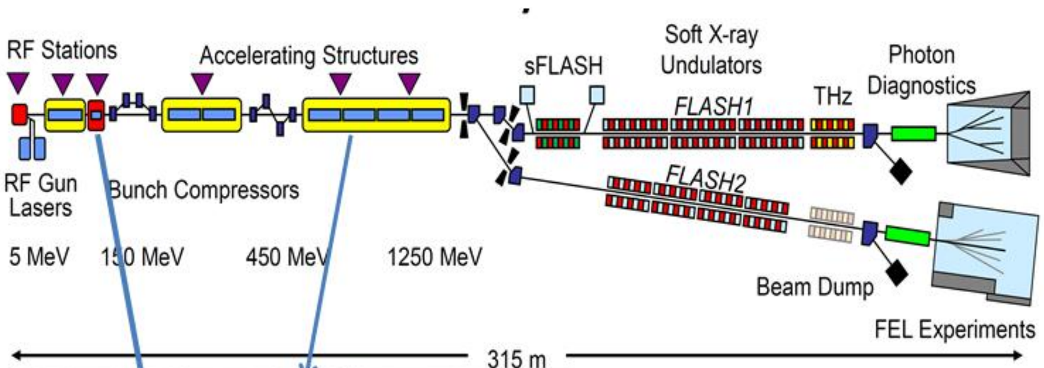
The work is supported partly by EuCARD^2 with Grant No. GA 312453

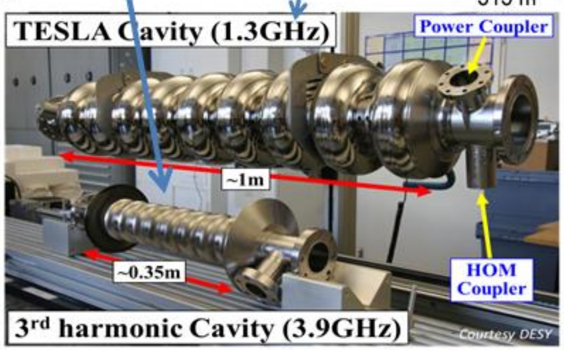
Outline

- HOMBPM system at FLASH
- HOM Data acquisition at FLASH
- Data analysis and results
  - DLR based calibration and validation
  - SVD based calibration and validation
  - NNT based calibration and validation
  - Theoretical resolution estimation
- Summary and Outlook.

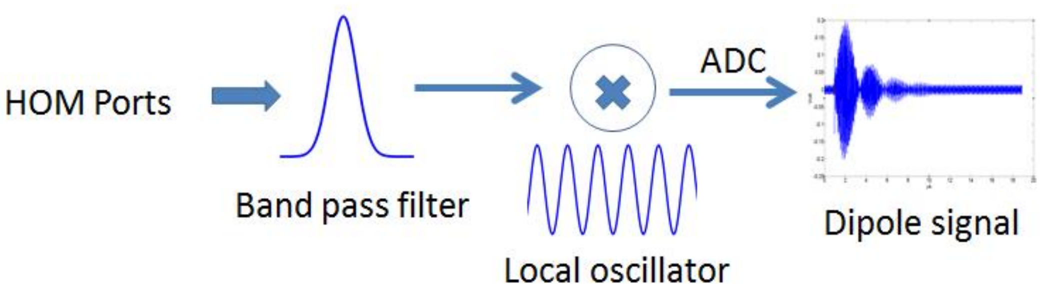
HOM: Higher Order Mode
SVD : Singular Value Decomposition
NNT: Neural Network

HOMBPM system 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



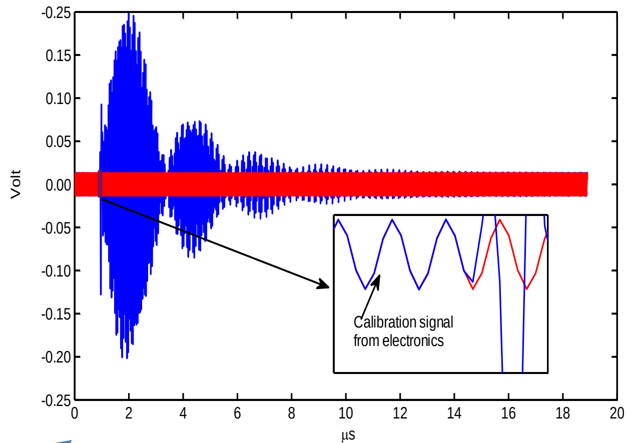
- Cavities are equipped with HOM couplers to damp the HOMs inside.
- All HOM raw data are accessible from DOOCS (control system)
- The HOMBPMs were integrated into beam orbit feedback system at FLASH. Due to instability issues of HOMBPMs, they were removed latter on.

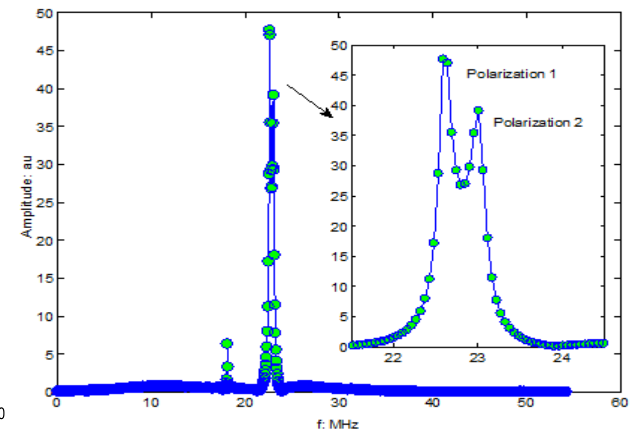
Principle of an HOMBPM

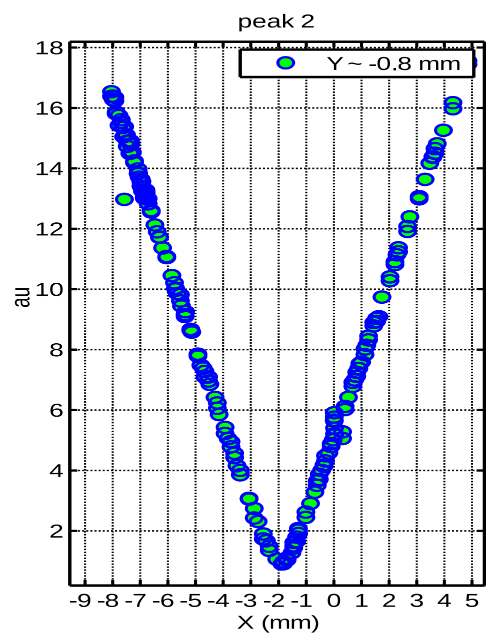
- We use accelerating cavity as a beam monitor to determine the beam position inside a cavity.
- Measured dipole voltage at HOM coupler ∝ $q \cdot (x + y) \cdot \frac{R}{Q}$, $\frac{R}{Q}$ *is a parameter to characterize beam cavity interaction*.
- To get beam position:
  - ✓ Normalize with charge *q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

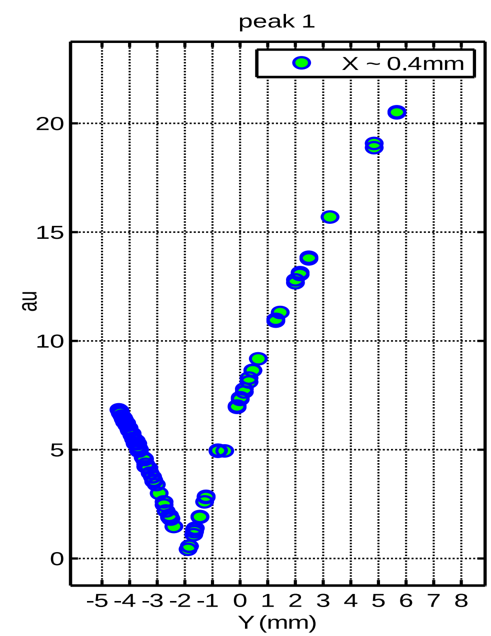
HOMBPMs at FLASH

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







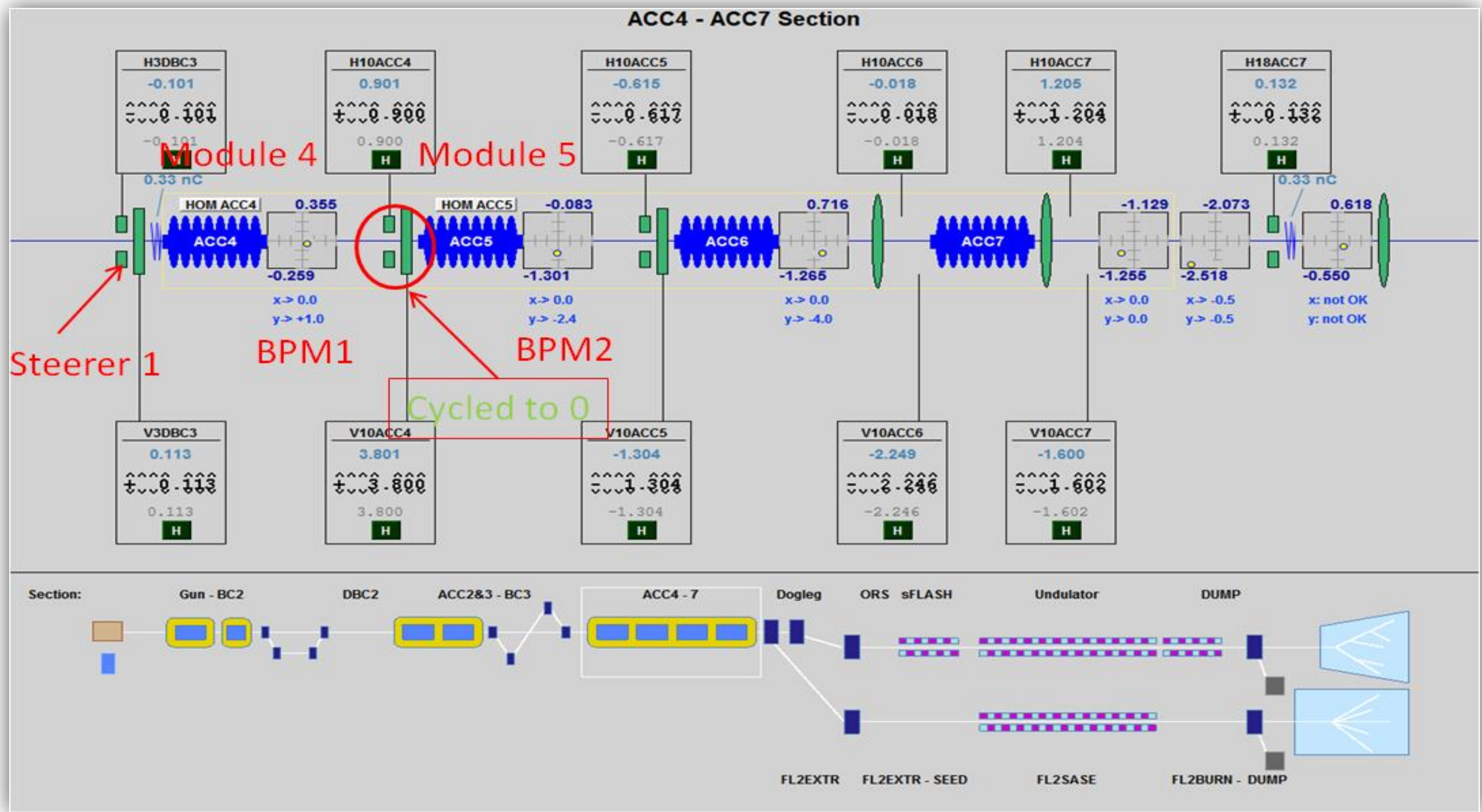


R. Wanzenberg, TESLA 2001-33, 2001

– HOMBPM system at FLASH
– HOM Data acquisition at FLASH
– Data analysis and results
– Summary and Outlook.

HOM: Higher Order Mode
SVD : Singular Value Decomposition
NNT: Neural Network

Working procedure for HOM measurements



A section of control panel for FLASH

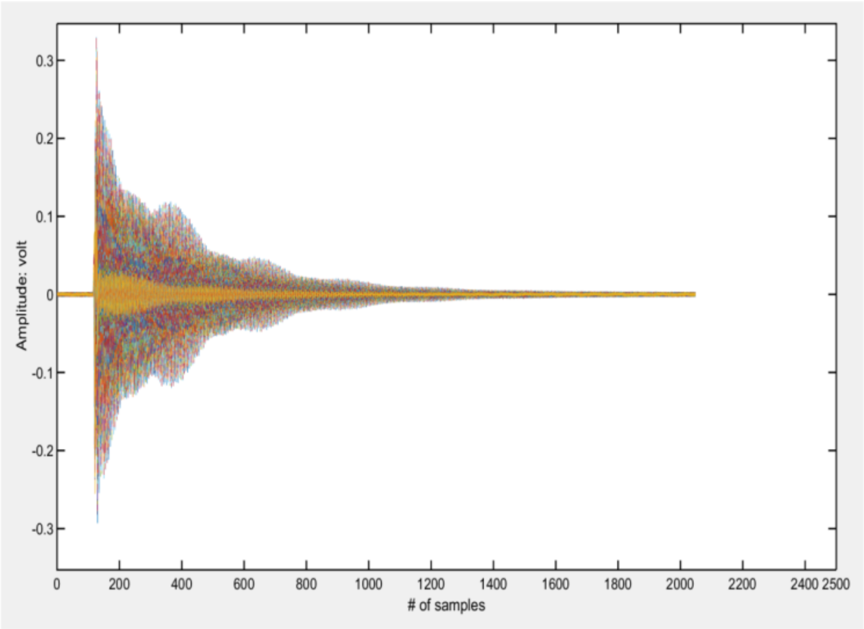
Courtesy of DESY

Working procedure for HOM measurements

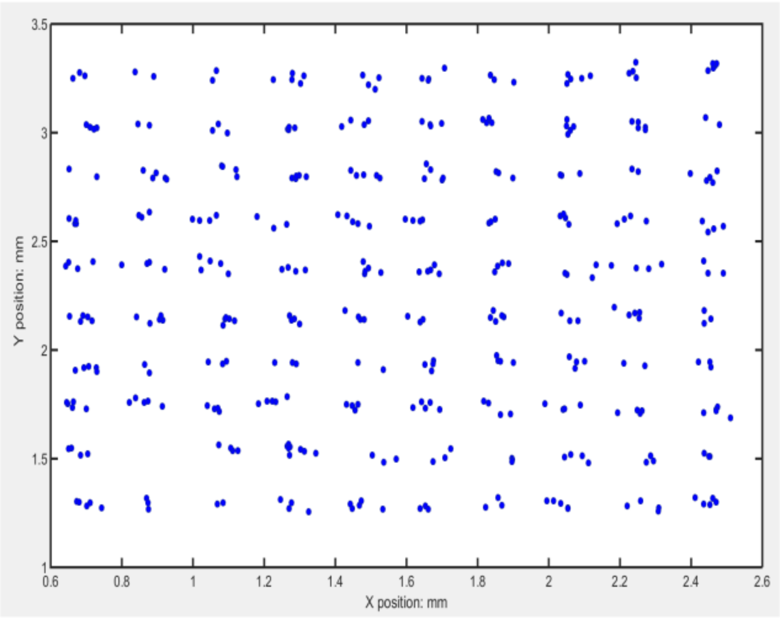
- Working condition:
  - Single bunch
  - 0.5 nC charge
  - 10 Hz repetition rate
  - RF inside the cavity off
  - Magnets in between off

- Data acquisition:
  - Dipole waveforms are gathered via DOOCS.
  - Each measurement is put in a single mat file.
  - Each file includes all necessary information for calibration

Working procedure for HOM measurements



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.

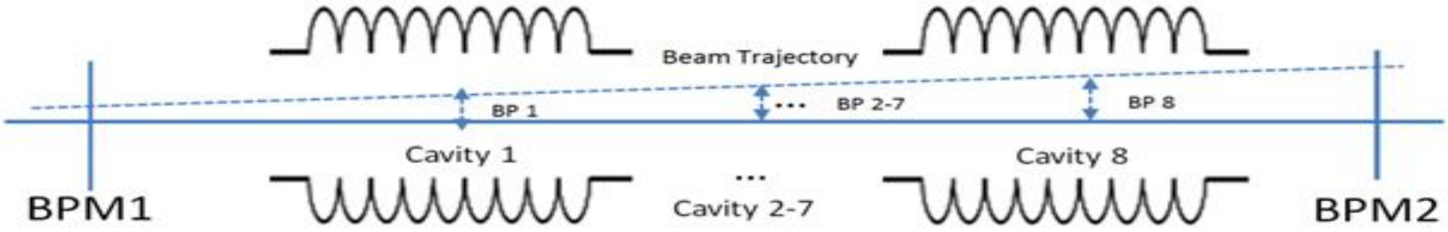
We have made measurement on Jan 23, 25 and 28 2015

- HOMBPM system at FLASH
- HOM Data acquisition at FLASH
- Data analysis and results
- Summary and Outlook.

HOM: Higher Order Mode
SVD : Singular Value Decomposition
NNT: Neural Network

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.

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

Calibration of an HOMBPM

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

Data matrix ? Position matrix

1. What can be put inside the data matrix?

Waveforms are natural selection, but the system is vulnerable to noise. So we put spectrum (FFT of waveforms) in the matrix.

2. Spectrum directly or processed?

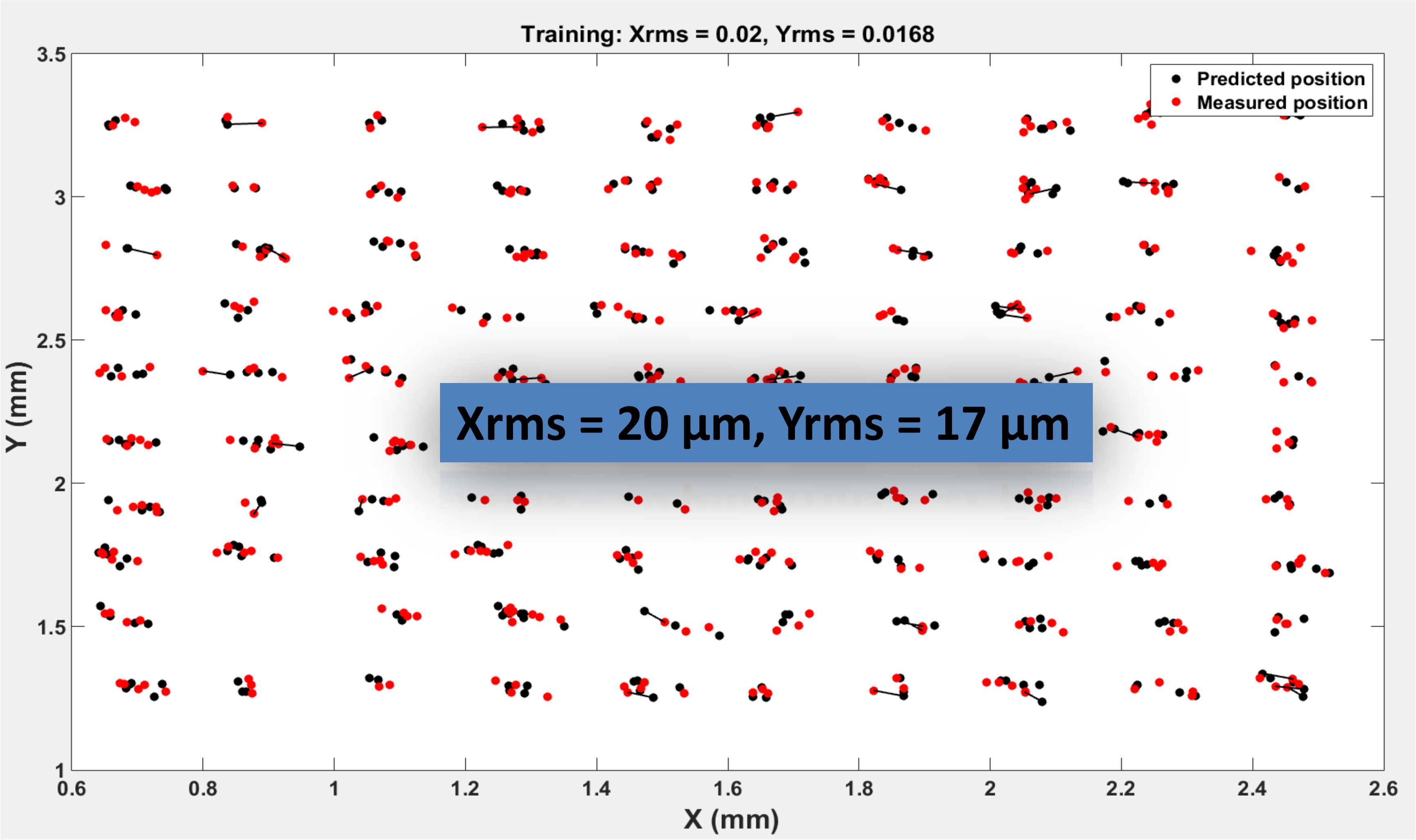
3. How to obtain the red unknown matrix?

1. Perform Linear Regression. 2. Mapping the relation from Data matrix to Position matrix

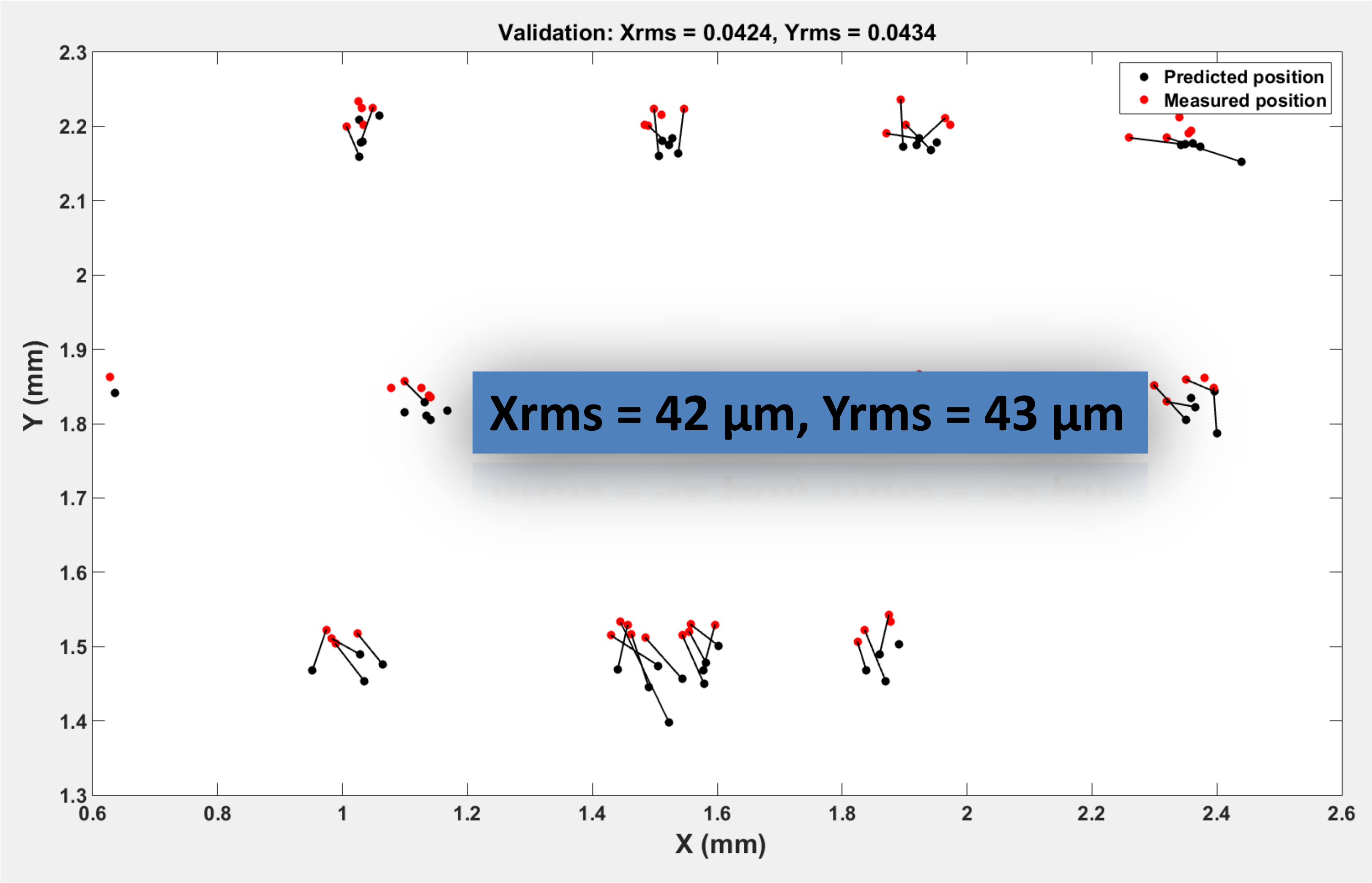
- HOMBPM system at FLASH
- HOM Data acquisition at FLASH
- Data analysis and results
  - DLR vs SVD LR
- Summary and Outlook.

HOM: Higher Order Mode
DLR: Direct Linear Regression
SVD : Singular Value Decomposition
NNT: Neural Network

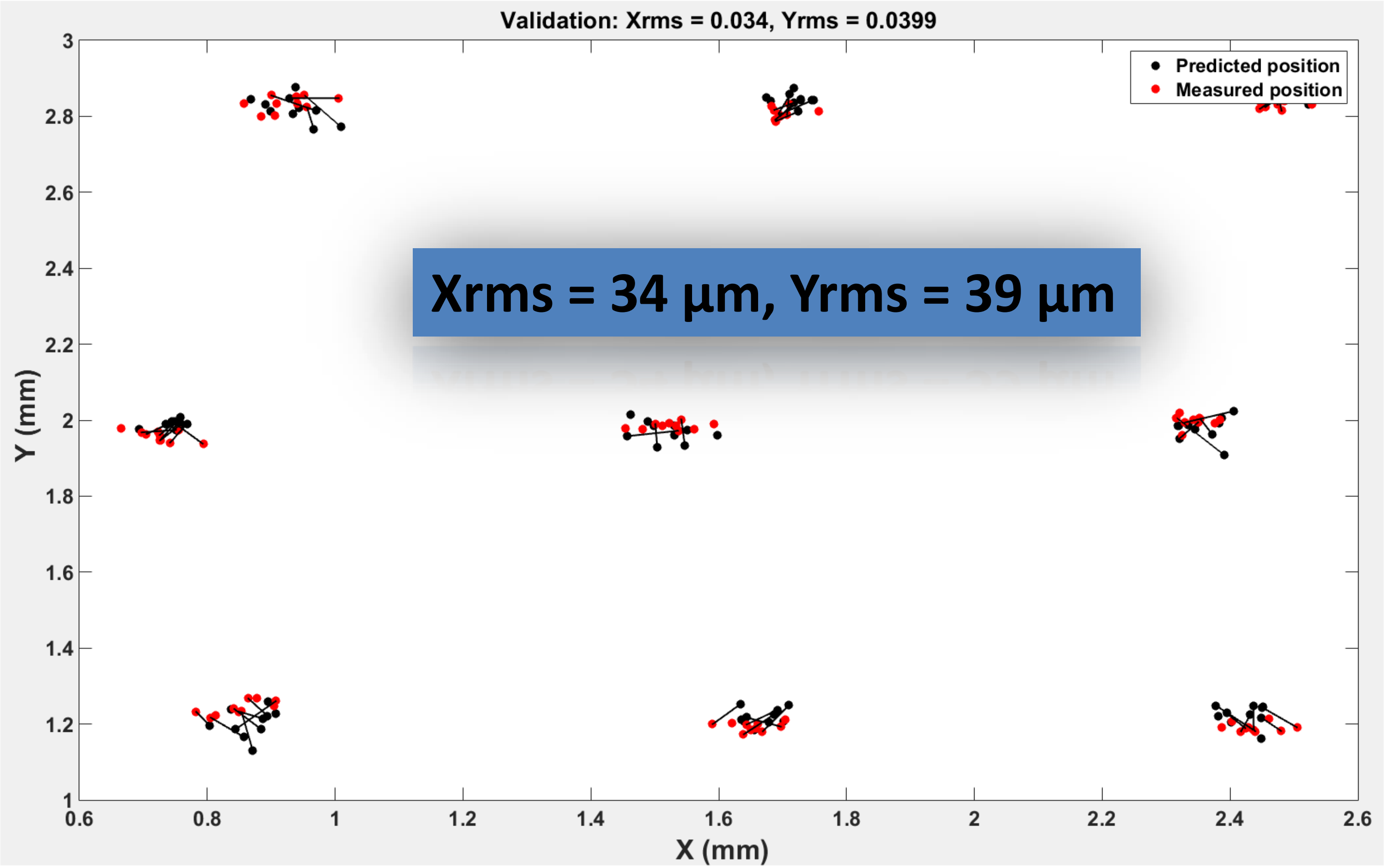
DLR- Direct Linear Regression- Jan 28



DLR- Direct Linear Regression- Jan 25

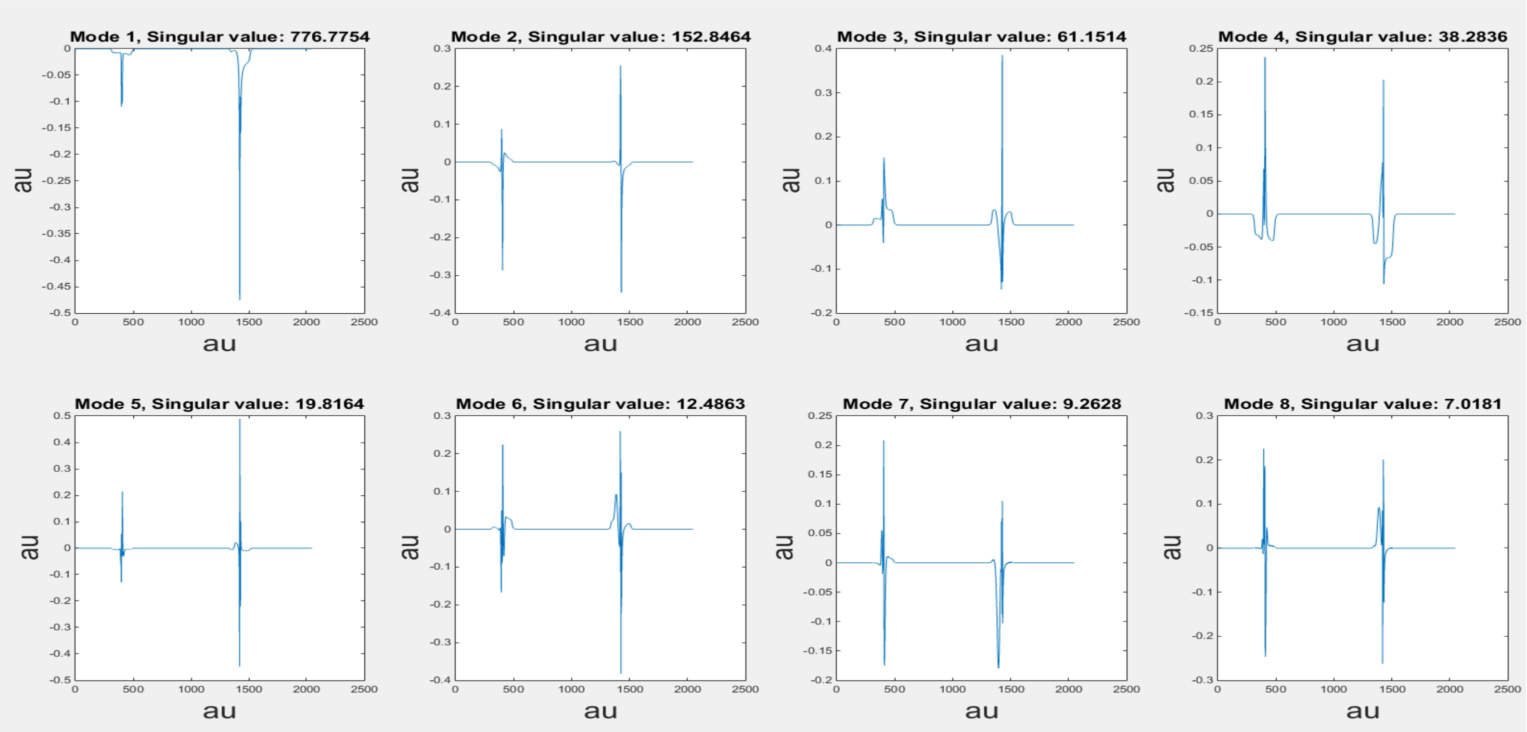


DLR- Direct Linear Regression – Jan 23



SVD based LR

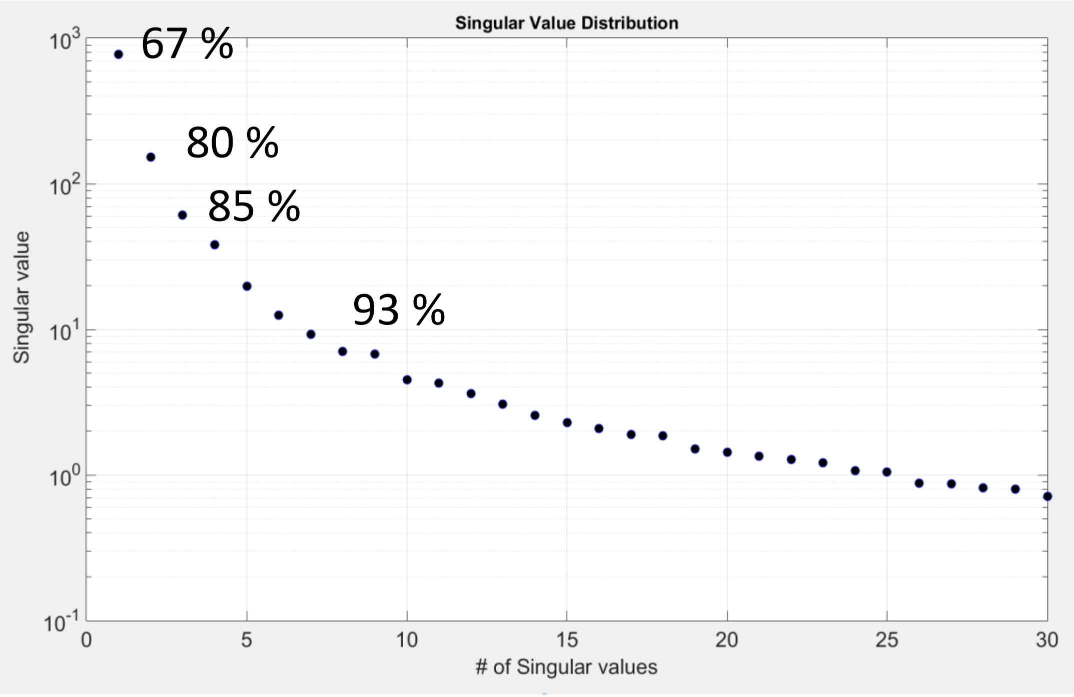
$$\begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{m1} & \cdots & d_{mn} \end{bmatrix} = U*S*V'$$



Top eight modes for dipole spectrum

SVD based LR

$$\begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{m1} & \cdots & d_{mn} \end{bmatrix} = U*S*V'$$



Top eight modes account for 93% of total variance

Amplitudes in V space are put in the data matrix

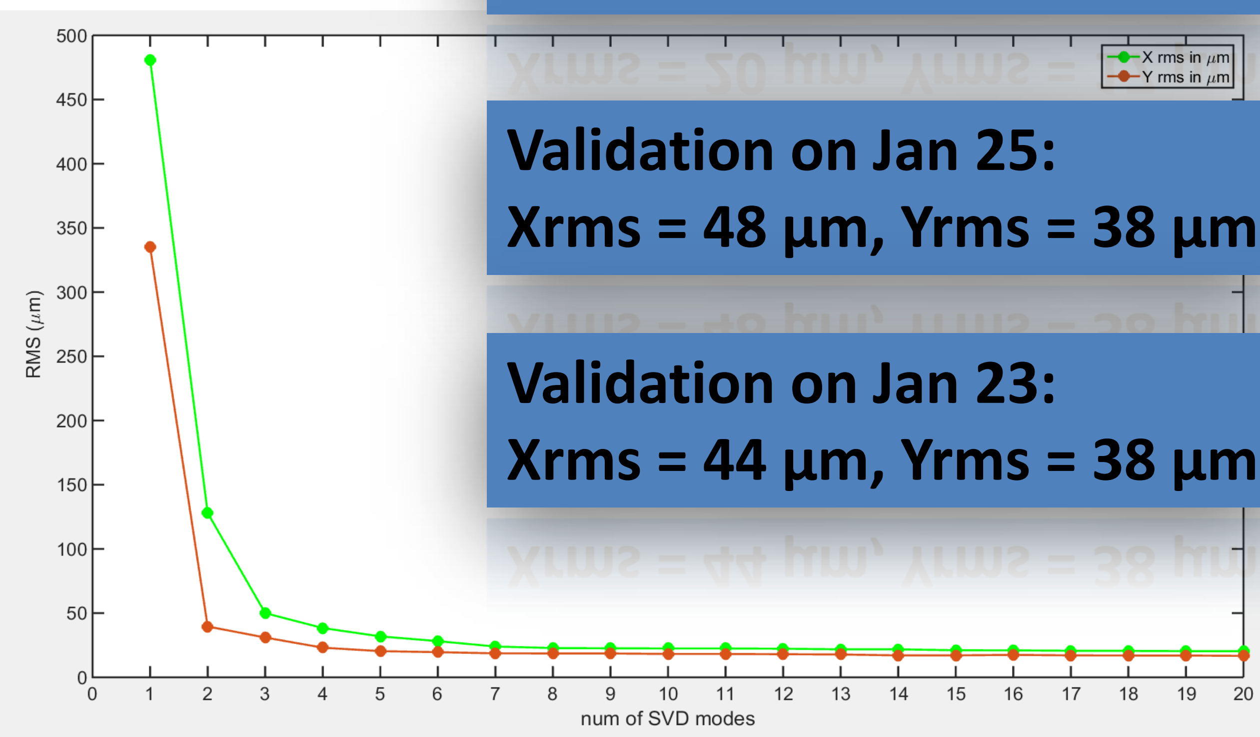
SVD based LR

$$\begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \end{bmatrix} = U*S*V'$$

Calibration on Jan 28:
Xrms = 20 µm, Yrms = 17 µm

Validation on Jan 25:
Xrms = 48 µm, Yrms = 38 µm

Validation on Jan 23:
Xrms = 44 µm, Yrms = 38 µm



1. Top eight modes were used

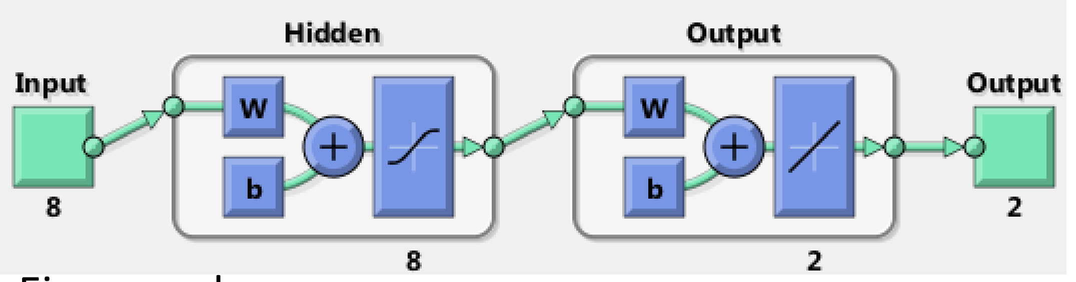
2. There is minor change in rms by taking more modes for calibration

- HOMBPM system at FLASH
- HOM Data acquisition at FLASH
- Data analysis and results
  - DLR vs SVD LR
  - NNT based calibration
- Summary and Outlook.

HOM: Higher Order Mode
DLR: Direct Linear Regression
SVD : Singular Value Decomposition
NNT: Neural Network

NNT based calibration

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

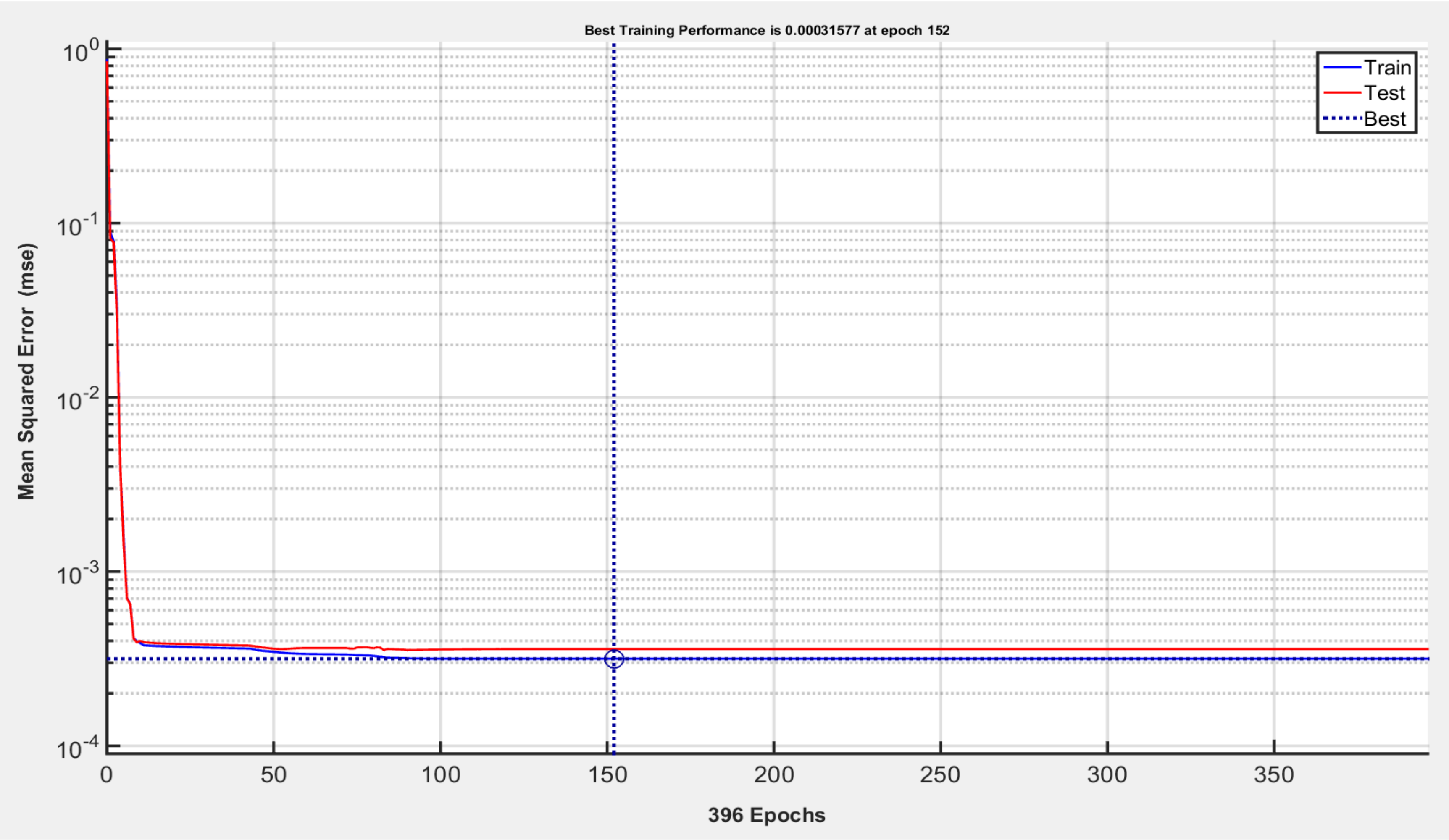


Top Eight Eigen modes

Position Outputs

Ten networks were trained, and the average was taken as the output

NNT based calibration



Best training performance was found around iteration number of 152 based on MSE

RMS summary of DLR, SVD, NNT

(X, Y)	Jan 28 (Calibration)	Jan 25 (Validation)	Jan 23 (Validation)
DLR (f domain)	(20,16 μm)	(42,43 μm)	(34,39 μm)
NNT (f domain)	(17,15 μm)	(42,44 μm)	(34,39 μm)
SVD LR (f domain)	(22,18 μm)	(48,38 μm)	(44,38 μm)
SVD NNT (f domain)	(19,16 μm)	(48,38 μm)	(44,41 μm)
SVD LR (t domain)	(62, 60 μm)	(983, 1590 μm)	(1250, 1690 μm)

Top 8 modes were used based on singular values in SVD methods

- Note: Directly using data in time domain gives unacceptable RMS degradation over time.
- RMS does not necessarily become worse over time.
- NNT gives comparable results when compared with other methods. There is no bias from algorithm side

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 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 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 (~0.1 %), 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.

Summary

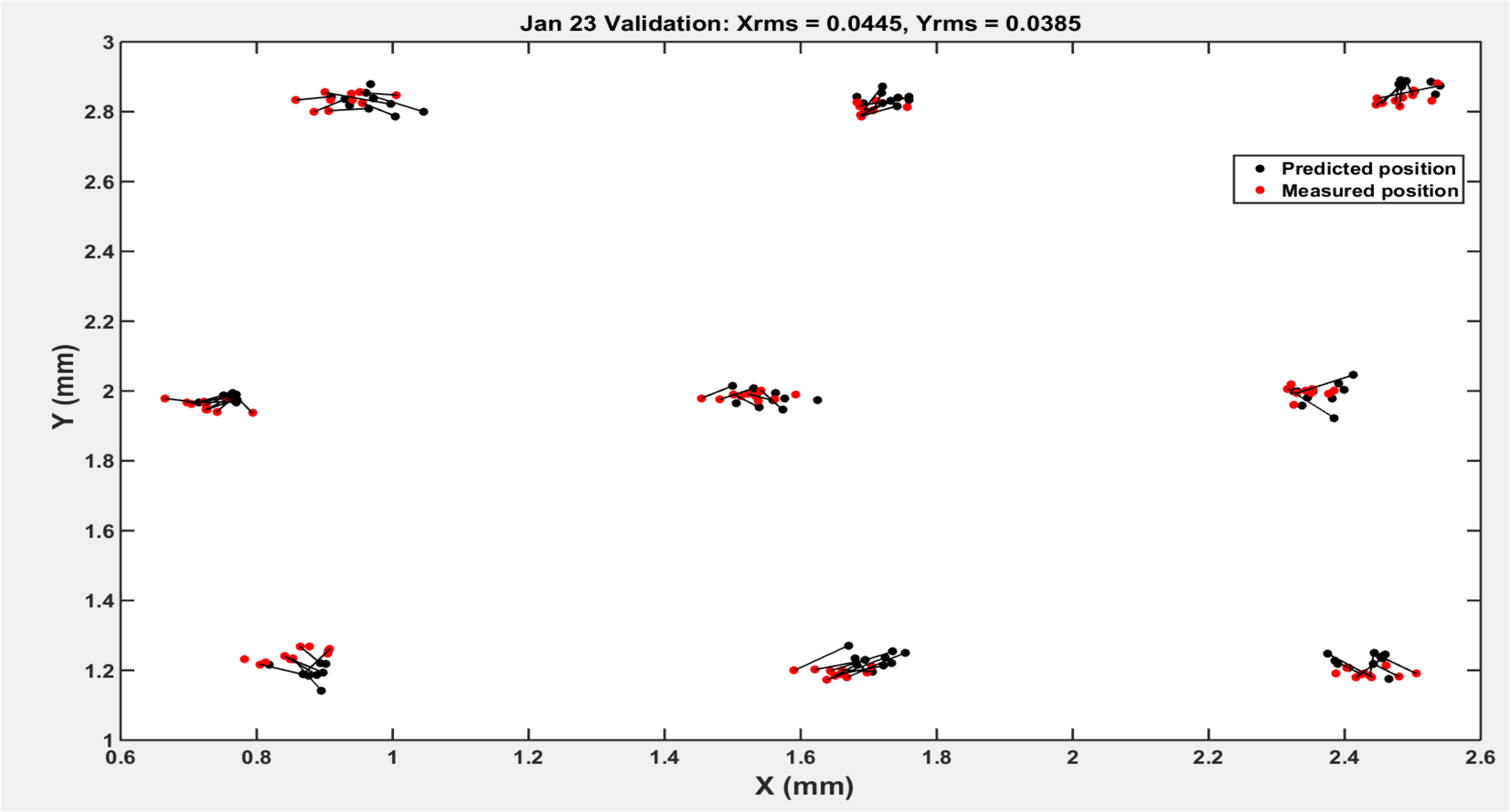
- All methods converge to below 50 µm, and the resolution did not degrade over time.
- Positive results in frequency domain tell us phase noise plays a vital part in the HOMBPM system.
- We are far from the theoretical resolution limits and current results are mainly limited by cavity BPMs used for calibration.

Outlook

- Figure out how much beam angle plays in the calibration and validation.
- More beam time data to verify the results.
- Similar study for HOMBPM for 3rd harmonic module.
- HOM based beam phase monitor measurement.

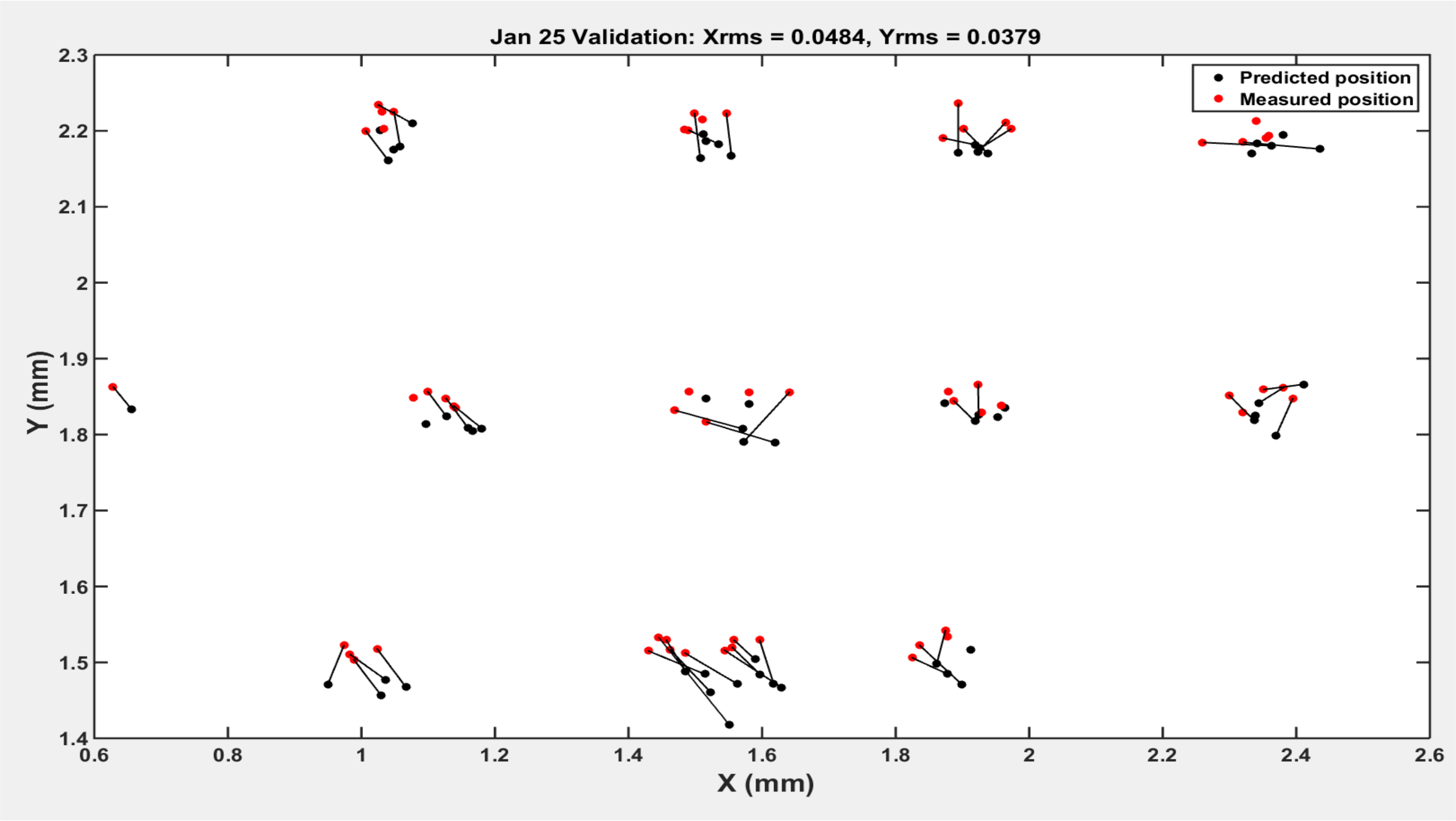
Thank you for your attention!

SVD LR



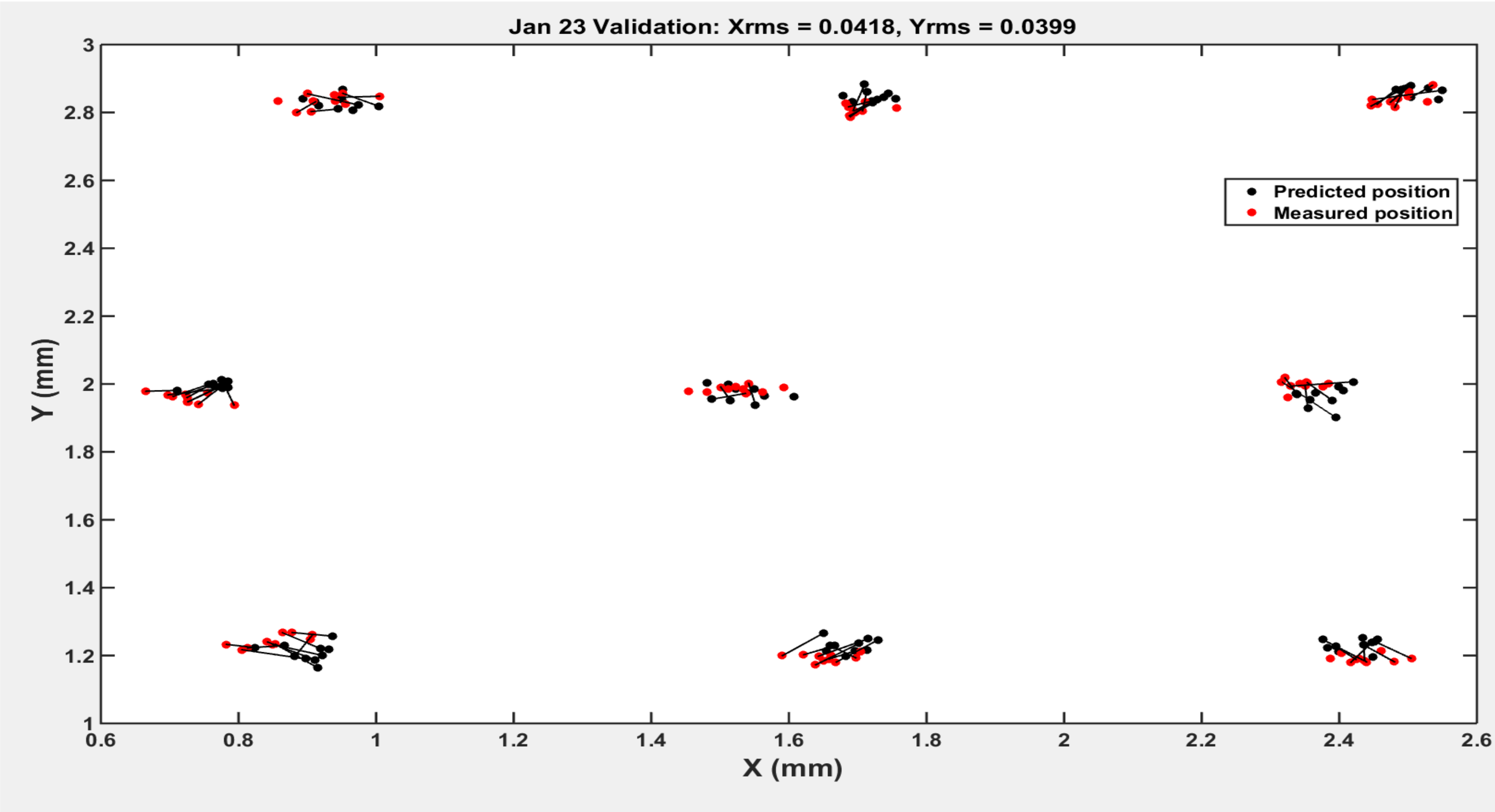
Jan 23 Validation: Xrms = 0.0445, Yrms = 0.0385
Predicted position
Measured position
Y (mm)
X (mm)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6

SVD LR



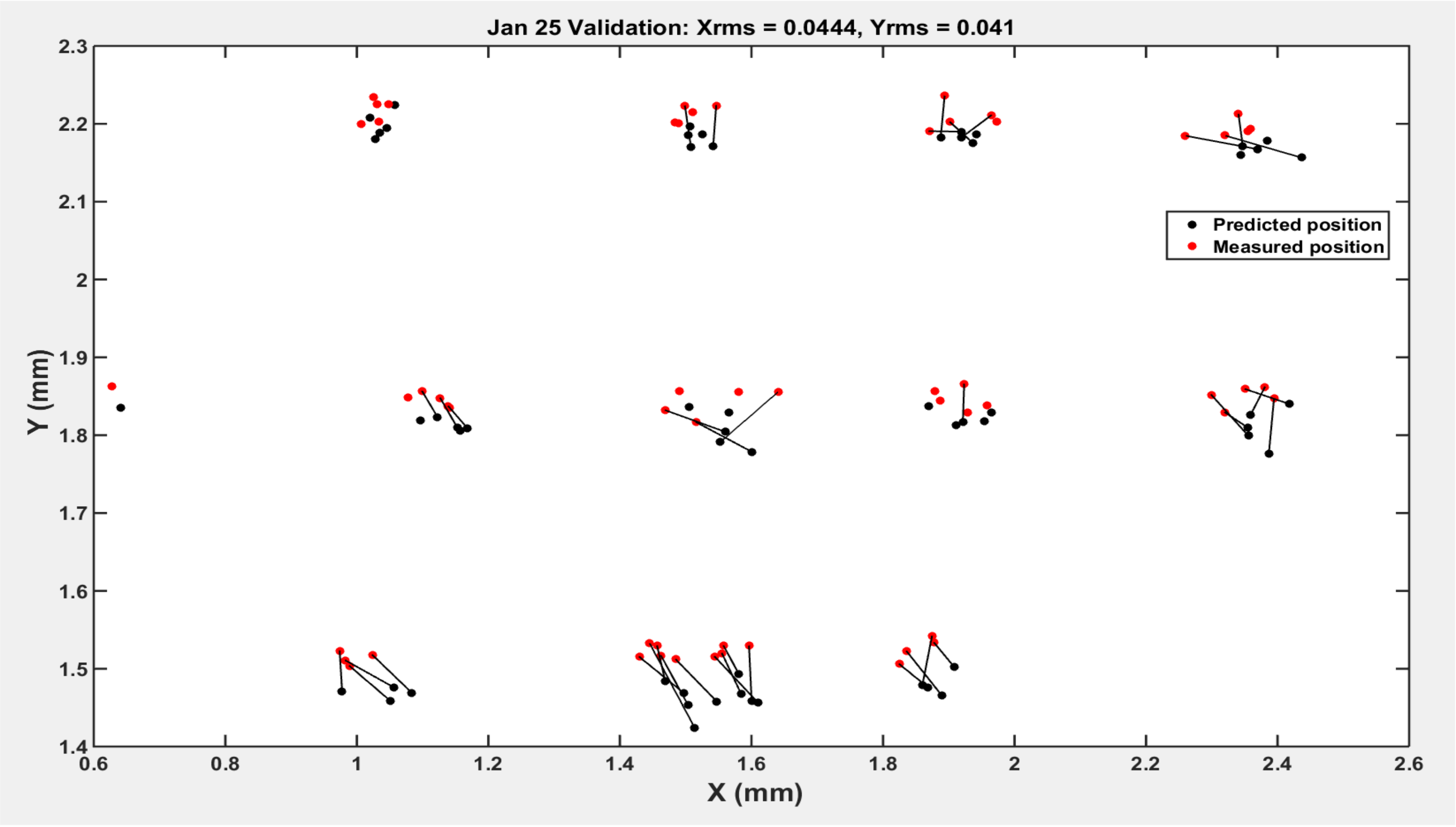
Jan 25 Validation: Xrms = 0.0484, Yrms = 0.0379
Predicted position
Measured position
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
Y (mm)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
X (mm)

NNT



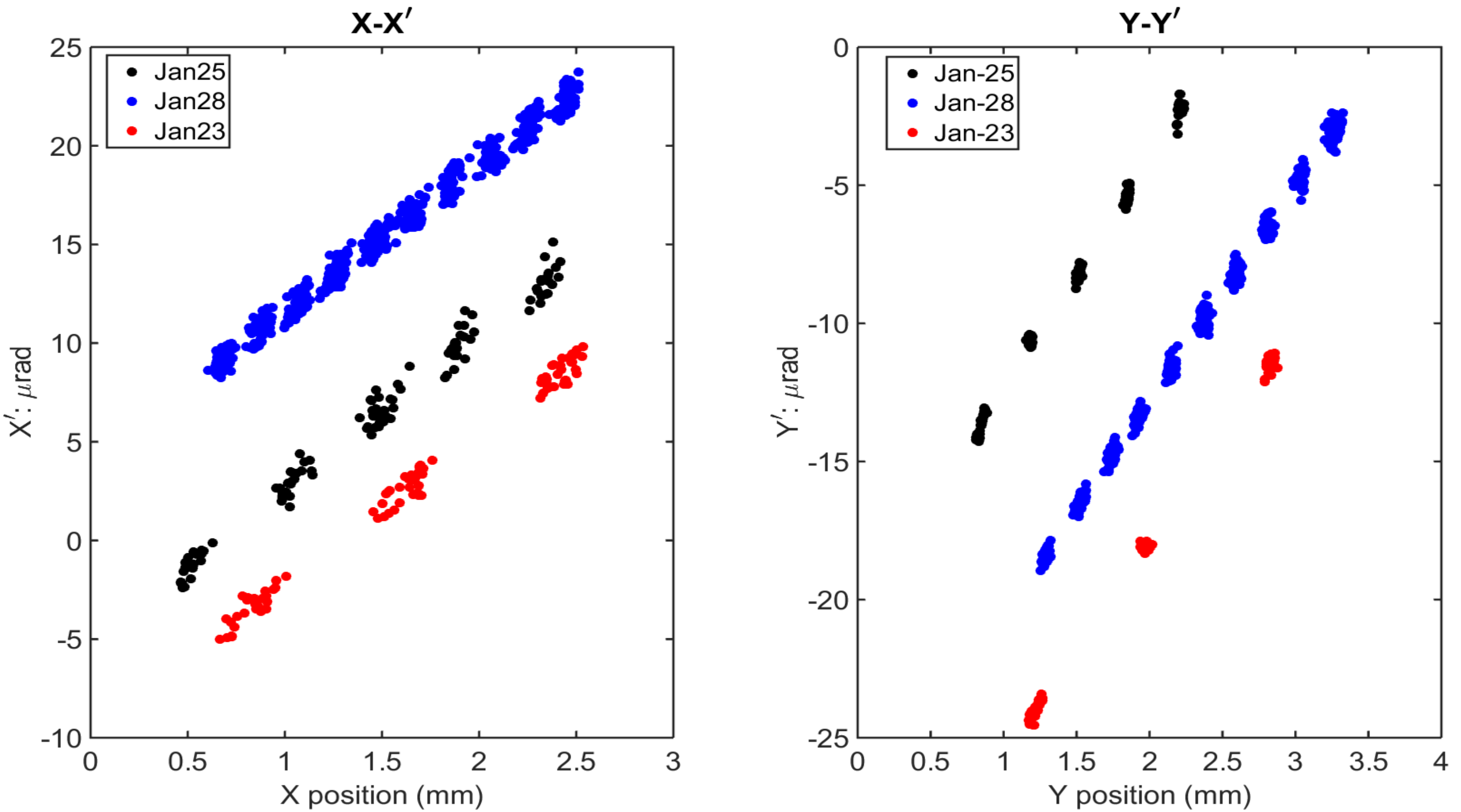
Jan 23 Validation: Xrms = 0.0418, Yrms = 0.0399
Predicted position
Measured position
Y (mm)
X (mm)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6

NNT



Jan 25 Validation: Xrms = 0.0444, Yrms = 0.041
Y (mm)
X (mm)
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
Predicted position
Measured position

Beam angle


X-X′
Jan25
Jan28
Jan23
X′: μrad
X position (mm)
Y-Y′
Jan-25
Jan-28
Jan-23
Y′: μrad
Y position (mm)