

Development of Experimental Control System for Ptychography at HEPS-HXCS

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Beamline Control System, HEPS

September 16, 2026

2026 MicroTCA/ATCA Workshop for Large Scientific Facility Control, Beijing, China

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HXCS Beamline

- High Energy Photon Source (HEPS)

- beam energy: up to 6 GeV
- Natural emittance reached: 34.8 pm•rad
- Brilliance: $(1.04 \pm 0.02) \times 10^{22}$ photons/s/mm²/mrad²/0.1% BW

- HXCS: Dedicated nm-class coherence beamline in Phase I

- Hard X-Ray Coherent Scattering beamline
- Energy Range: 7~25 keV
- Beam-size range: ~100nm to 20 μ m
- Coherent flux: $>10^{12}$ photons/s
- Main techniques:
 - ◆ Opened : ptychography-tomo, SAXS XPCS, WAXS XPCS
 - ◆ To be opened: Ptychography&XRF, Ptychography&Mapping, BCDI etc.



Ptychography Sample System

- Design specifications

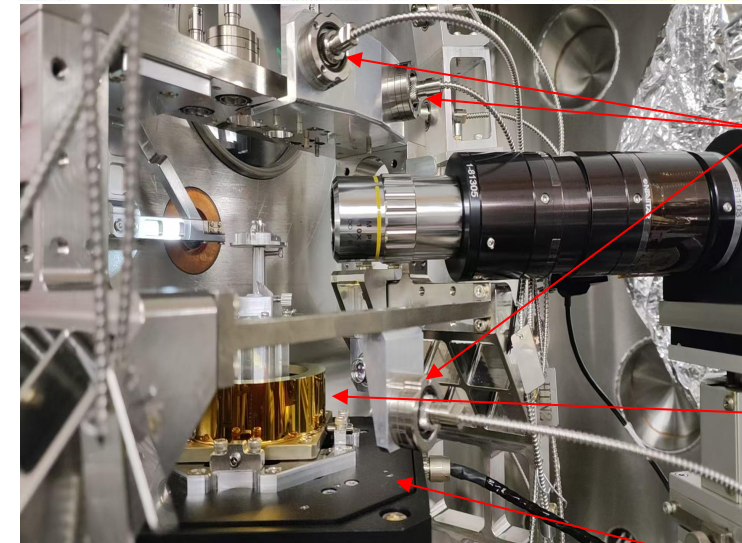
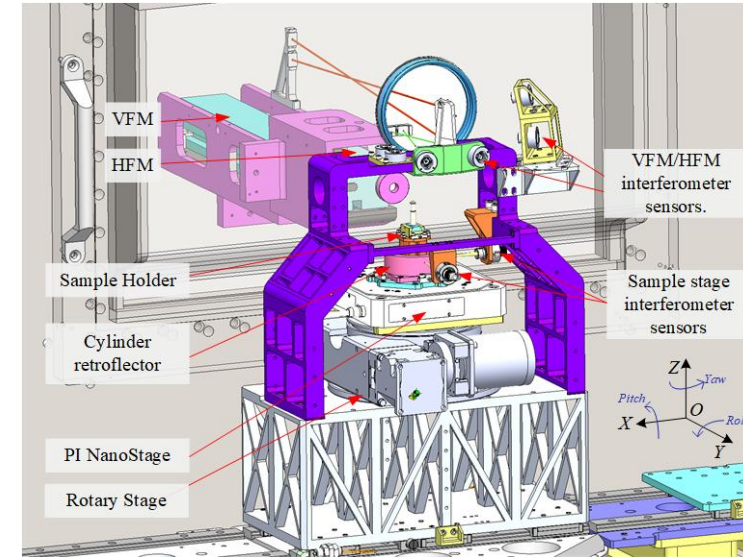
- Beam size: 100nm-5 μ m;
- resolution: 5-50 nm;
- field of view: 1-100 μ m;
- sampling frequency: 10-10000 Hz

- Key Units

- PI P-563 3-axis nano stage;
- IDS3010 interferometers;
- Huber 410 rotation stage(0.0005°/360°);
- 3-axis granite air-bearing stage for coarse positioning

- Required Function of the Control system

- Fly & Step scan;
- Various scanning trajectories
- Nm-precision motion control based on capacitive and interferometer sensors;



8 IDS3010 sensors

Cylinder retroreflector

3-axis PI NanoStage

The metrology & real structure of the ptychography sample System

Hardware Structure of the Control System

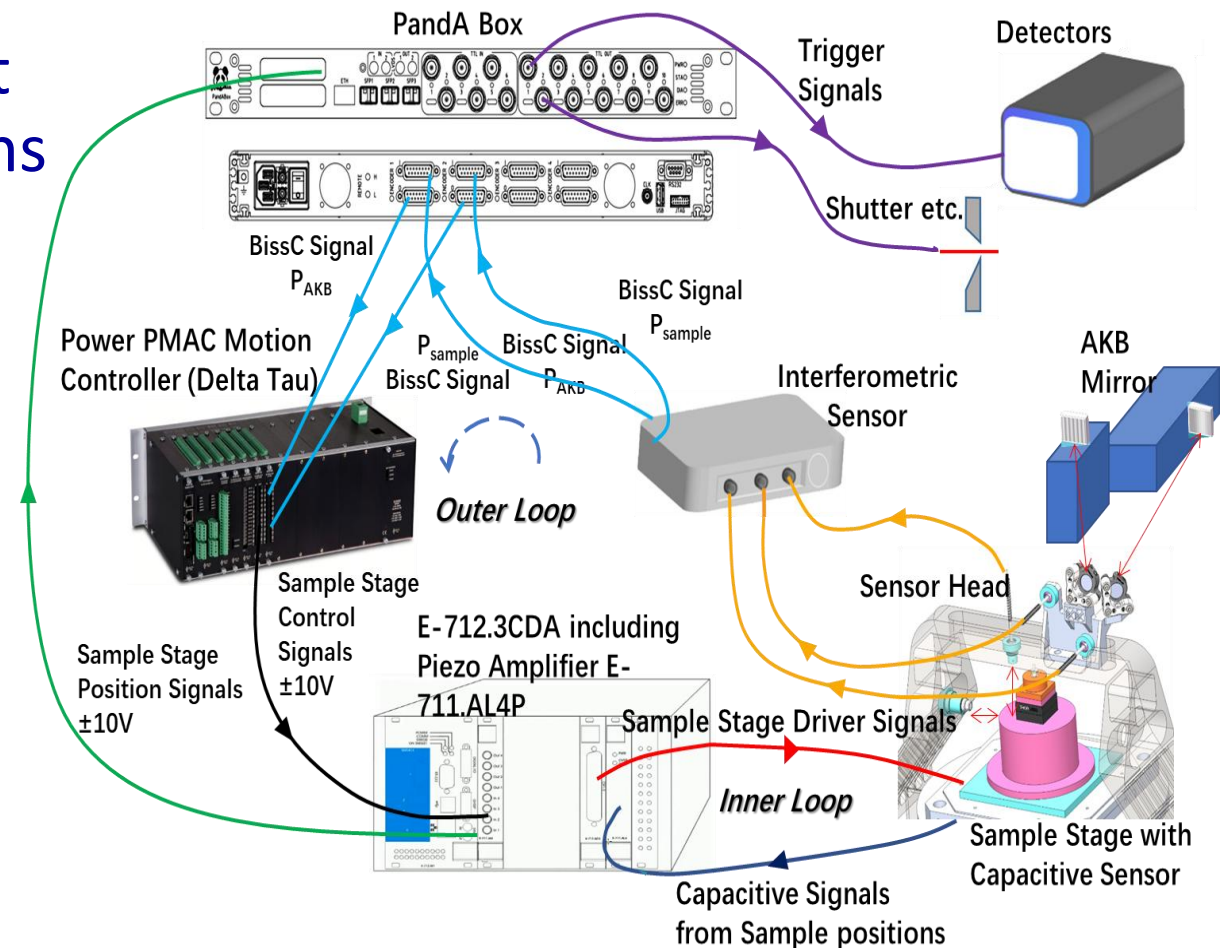
- One of the two nm-Class Fly Scan Beamlines at HEPS

- A combination of fly scan requirement and nm spatial resolution specifications

- Sufficient flexibility for commissioning and operation

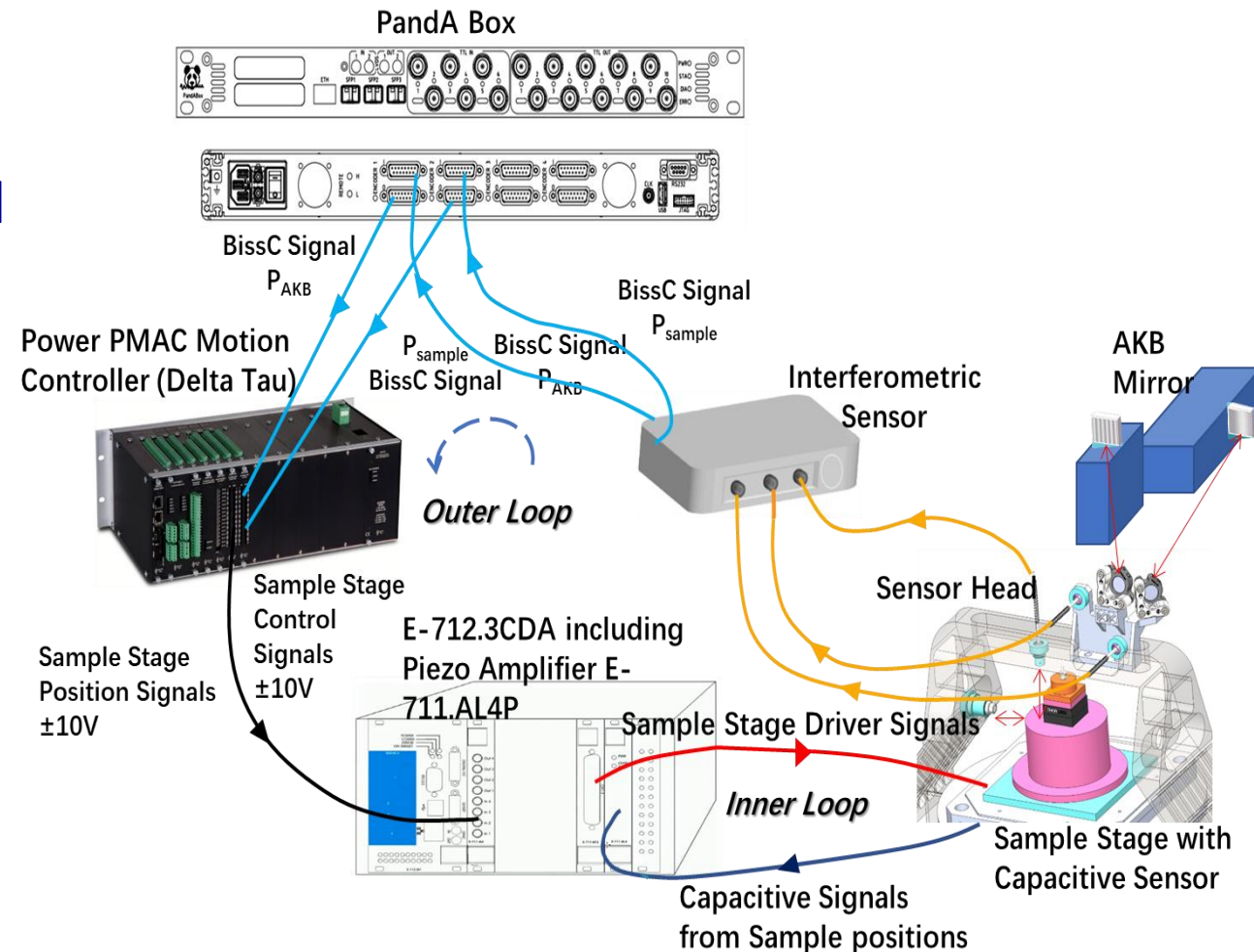
- Core Unit

- Experiment Logic Controller
 - ◆ PandA Box;
- Dual-loop motion control:
 - ◆ PMAC ~ interferometers
 - ◆ E-712 ~ capacitive sensors
- Complement each other



Nano-Stage Motion Control

- Nano-stage is controlled in Outer and inner loops
- Interferometric and Capacitive position sensors are used separated in outer and inner loops;
- XZ plane differential data measured by interferometer are calculated from 8-axis interferometers sensors
- The calculated positions data are used in servo loop in PMAC
- Control voltage from PMAC is performed by E-712 to conduct the closed-loop feedback control of the nano sample stage



Interferometers Metrology Algorithm

$$\begin{bmatrix} Z_e \\ X_e \end{bmatrix} = \begin{bmatrix} Z_S \\ X_S \end{bmatrix} - \begin{bmatrix} Z_{KB} \\ X_{KB} \end{bmatrix}$$

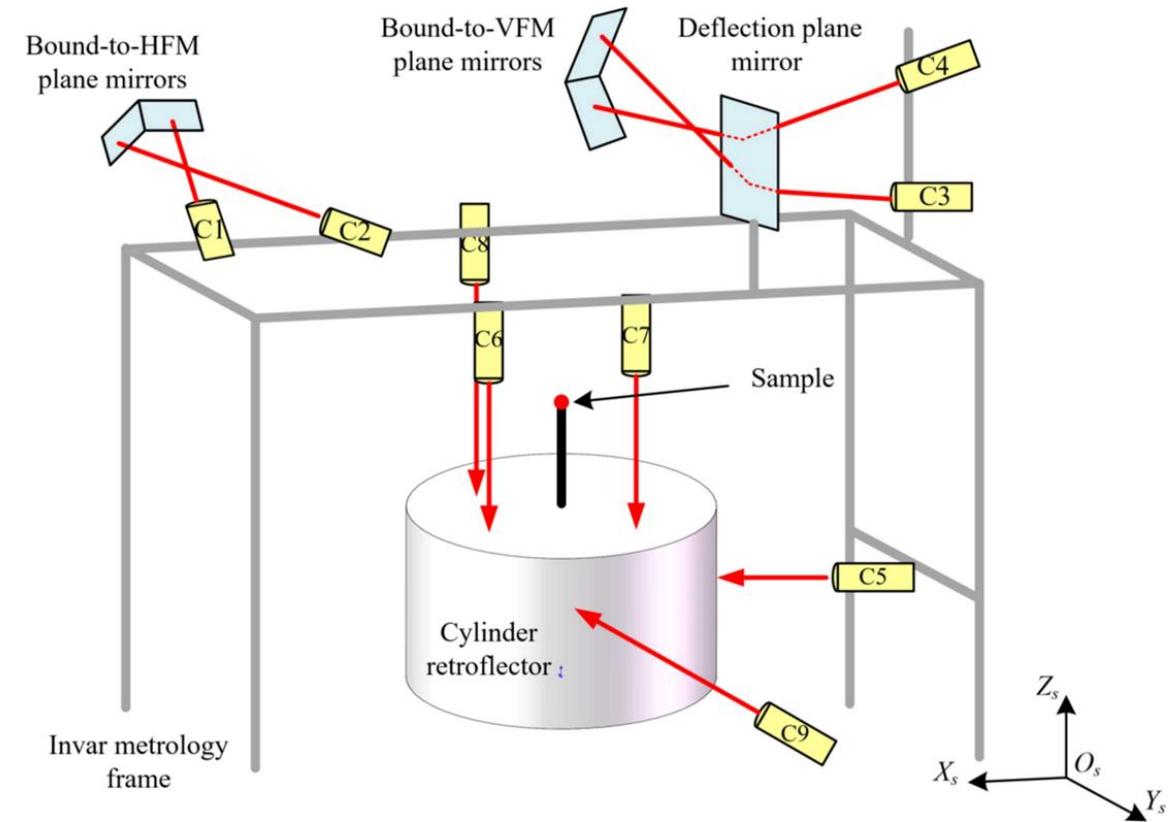
$$= \mathbf{K}_S \begin{bmatrix} (C_8 + C_6)/2 \\ C_5 \\ C_6 - C_7 \end{bmatrix} - \mathbf{K}_{KB} \begin{bmatrix} C_3 - C_4 \\ C_1 - C_2 \end{bmatrix}$$

Interferometers metrology formula

$\mathbf{K}_S$ are linear calibration coefficient between nano-stage axis and interferometer sensors.

$\mathbf{K}_{KB}$ are linear calibration coefficient between KB mirror and interferometer sensors

- The metrology conversion formulas are processed in servo loop in Power PMAC
- It is one key reason for PMAC selected.

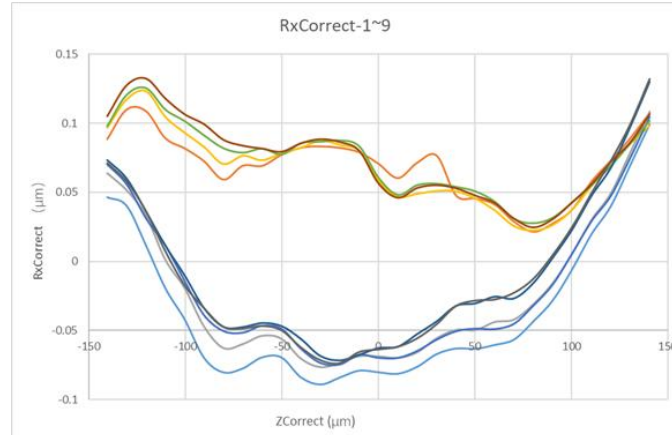


Metrology schematic diagram

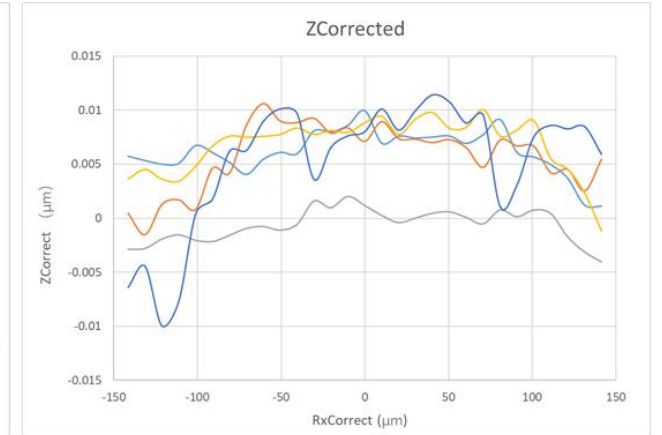
*A beam-direction cross-vessel metrology method and error analysis for the ptychography setup at HEPS ID09, JOURNAL OF SYNCHROTRON RADIATION(2026) 33:1289–1302

Interferometer-based Closed-loop Control

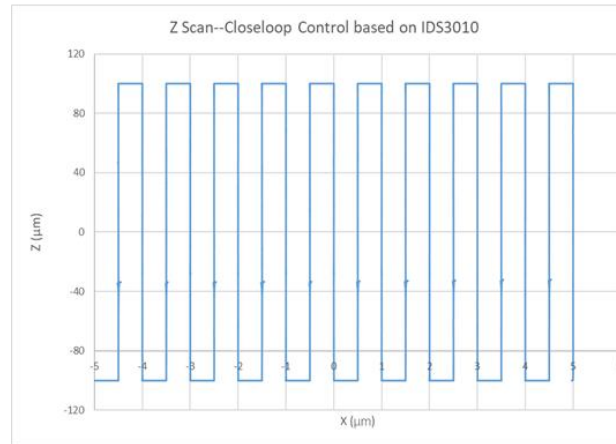
- Interferometer: Monitor VS Closed-loop feedback control
- For nm-scale scanning experiments at HXCS, the following cannot be ignored:
 - The random error at the >20nm scale
 - ◆ Caused by cross-talk, environmental low-frequency noise and motion control, etc.
 - ◆ Real-time performance of the position sensors
 - Random errors fluctuate
- For Ptychography at HEPS-HXCS, interferometer-based closed-loop motion control is needed



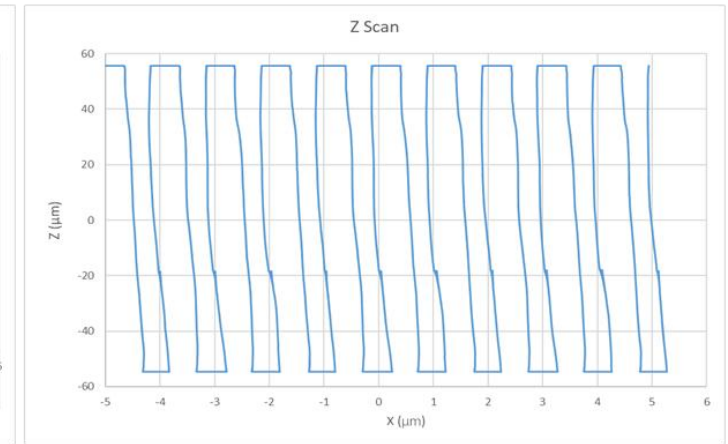
The X-axis position fluctuates during Z-axis scanning



The Z-axis position fluctuates during X-axis scanning



Interferometer-based closed-loop Z-axis scanning



Z-axis Scanning with Interferometer Monitoring

*Data in above figure are all from IDS3010 interferometer



HEPS

HIGH ENERGY
PHOTON SOURCE

Software Structure of Control System

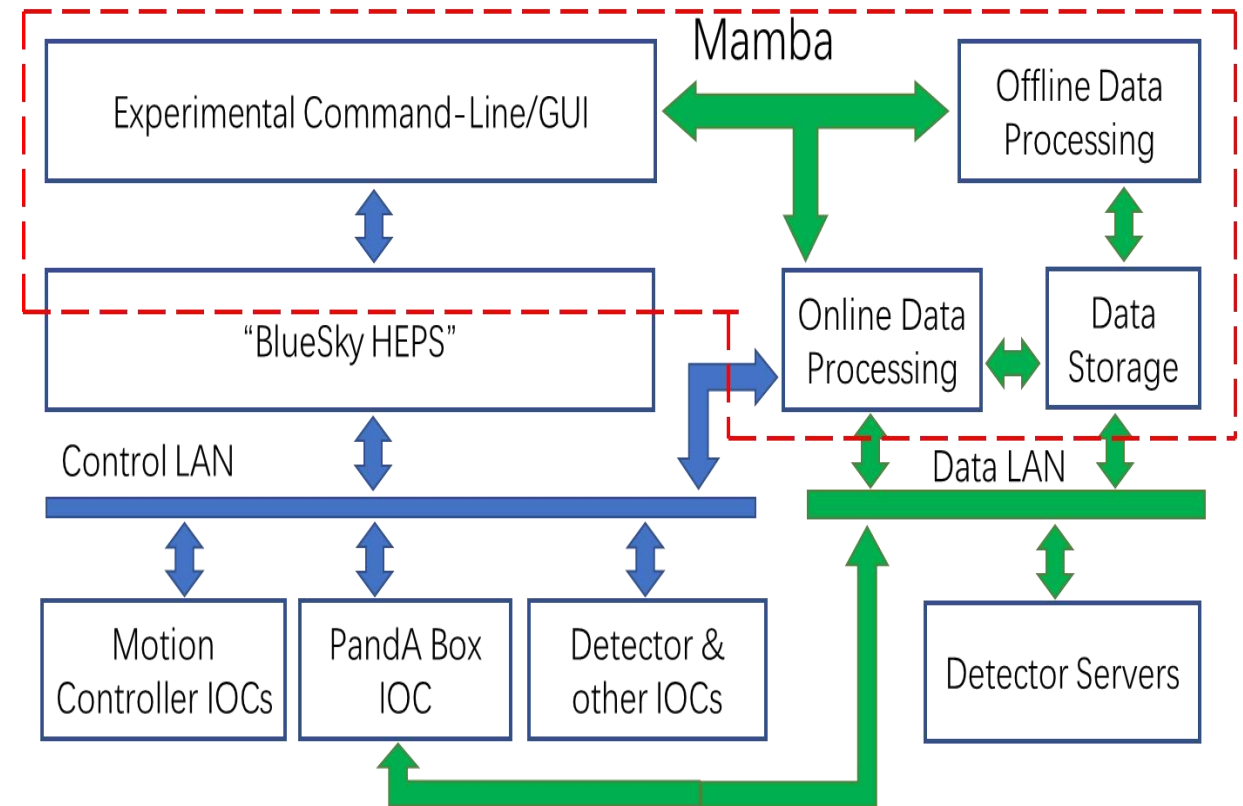
- Data Stream: Control & High-Throughput Stream
- “BlueSky HEPS”: Control Stream

- Self-customized for HEPS
- Widely employed at HEPS
- Customized Ophyd for Panda
- Produce Scan trajectory data
- & Experiment logic sequence
 - ◆ Acquire “Position” data
 - ◆ Trigger Detectors
 - ◆ Control beam shutters

- High-throughput stream

- MDW* in Mamba

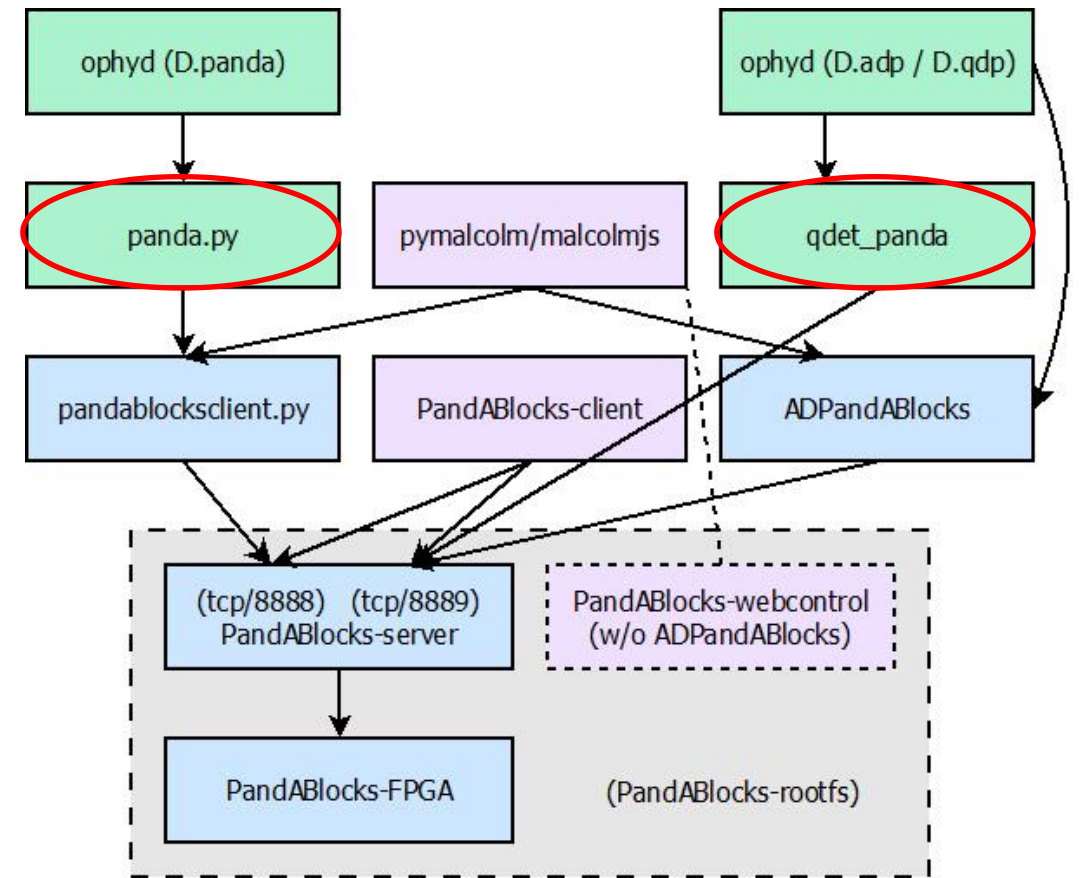
*Mamba: Experimental software at HEPS



Software Structure of Control System

• Customized Ophyd for Panda

- Control command stream and captured data stream are assigned to 8888/8889 ports respectively
- Control commands is communicated with PandABlocks-server by self-developed panda.py based on Diamond's pandablocksclient.py
- Captured data were transferred by ADPandABlocks and self-developed Python IOC qdet_panda for frame rates > a few kHz
- PandABlocks-webcontrol is kept which is trimmed-down pymalcolm



PandABox's software communication flow

*PandA(Box) flies on Bluesky: maintainable and user-friendly fly scans with Mamba at HEPs, Radiation Detection Technology and Methods (2023) 7:493–501

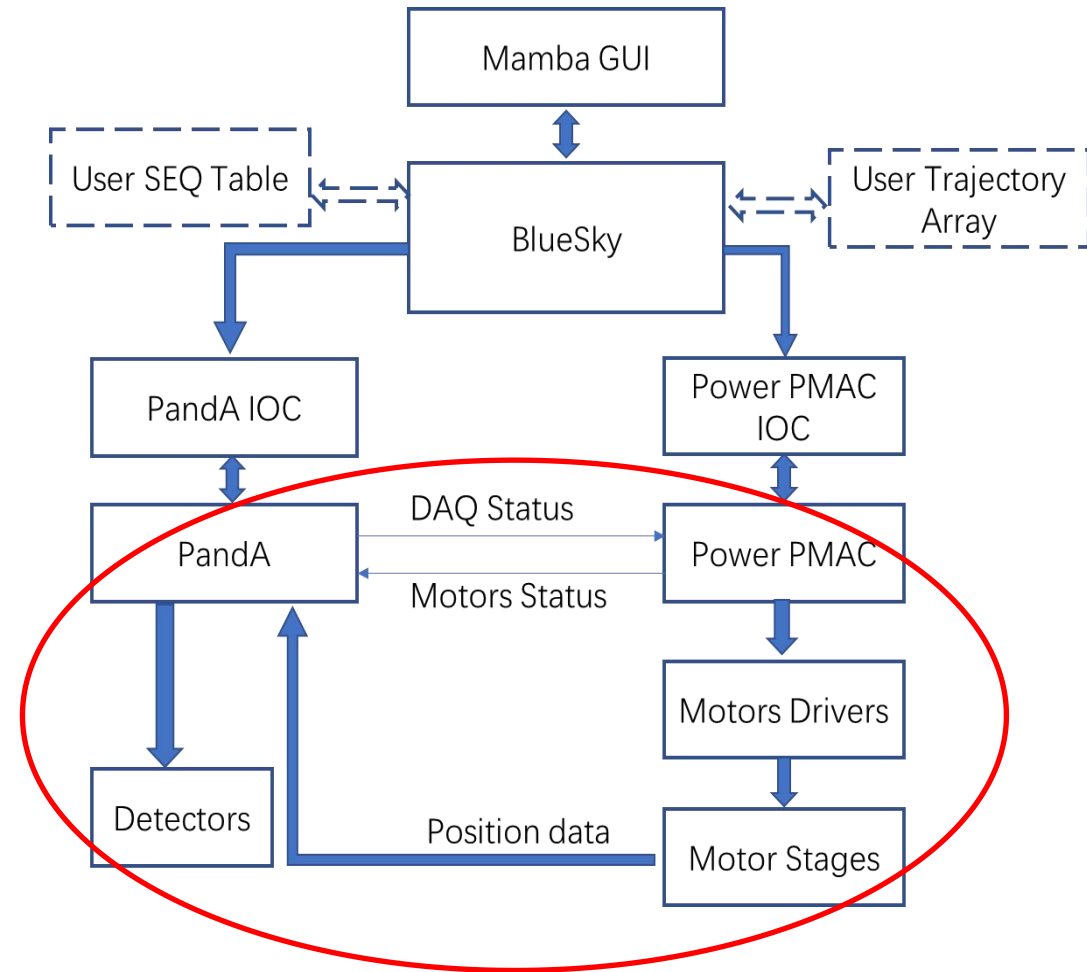
Experiment Scan technologies provided

● Fly scan(Continuous scan)

- Fully utilize the features of HXCS , high coherent flux, small beam-size, etc.
- Improve experimental efficiency and reduce radiation damage
- Reduce the impact of vibration on the experiment

● Step Scan

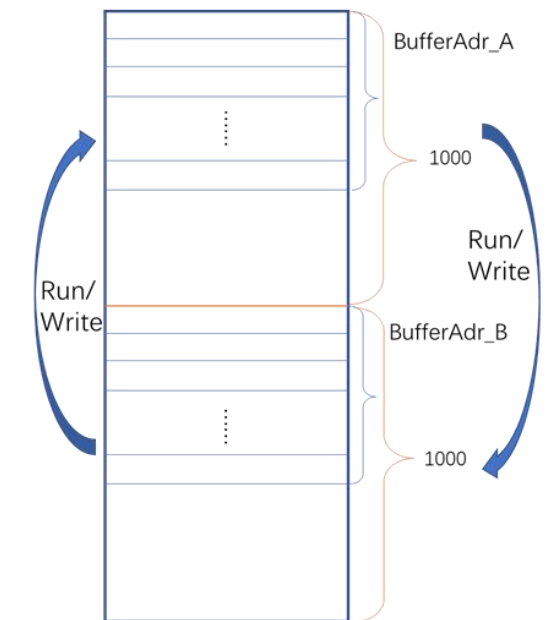
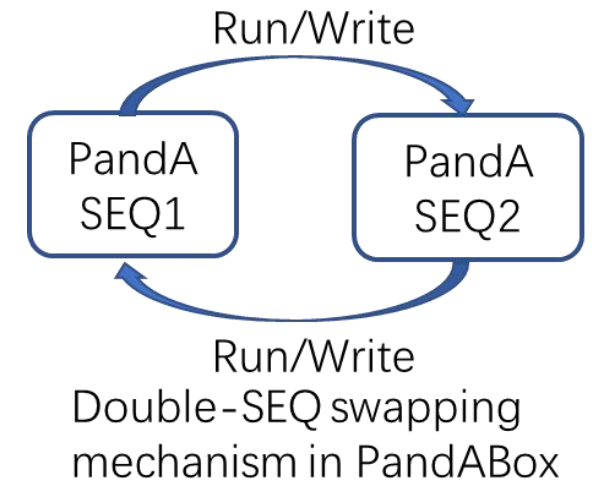
- Necessary for correction, low SNR experiments, etc.
- Conventional step scan
- Pseudo-Step scan based trajectory
- Step scan based IO (To be deployed)



Experimental scan logic structure

Fly Scan in Details

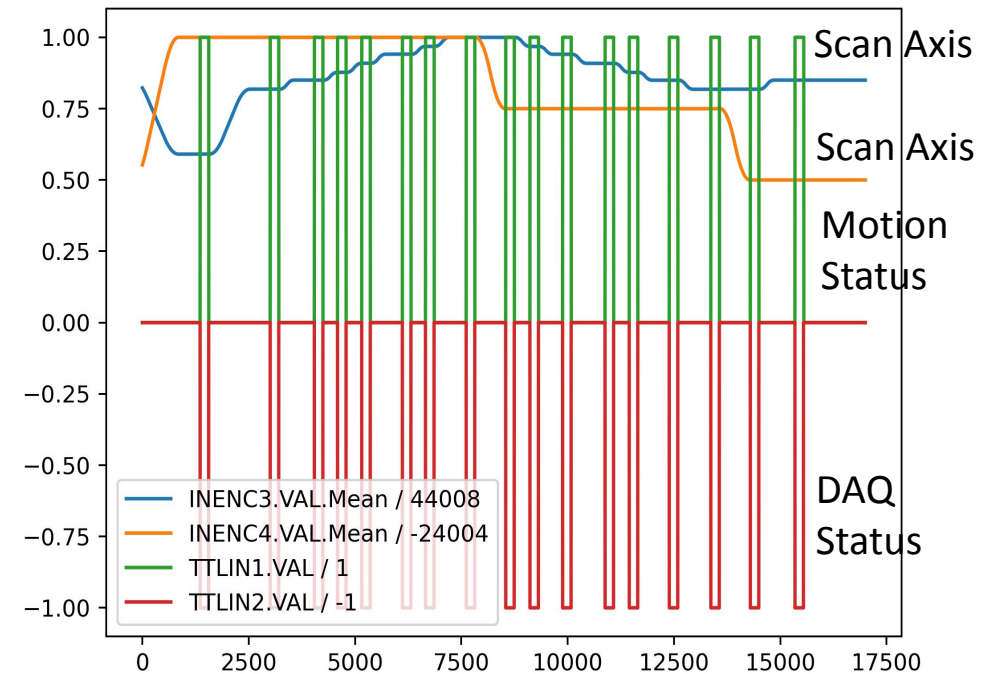
- In terms of reliability and schedule, mature commercial products are selected
- From the perspective of technical implementation, two factors affecting fly scan efficiency are considered
 - Data acquisition frequency is usually a key metric
 - ◆ Limited hardware resources and massive data points are contradictory
 - Swapping scheme is developed and deployed separately in Panda IOC and PMAC IOC
 - ✓ Time costed in writing data to PMAC < 0.2s
 - ✓ Time costed in writing data to Panda < 0.24s
 - some detailed configuration parameters are derived therefrom. Trajectory/trigger descriptions detail, motion velocity, etc.
 - Data acquisition & storage
 - ◆ External trigger
 - ◆ MDW* in Mamba
- Have been deployed for more than 2 years



Double-buffer swapping mechanism in Power PMAC

Step Scan in Details

- Step scan is necessary for linear calibration coefficient of metrology algorithm, experiment function verification, etc.
- Three approaches
 - Conventional step scan
 - ◆ the easiest and minimal dependency one
 - ◆ Minimal equipment required and maximum equipment flexibility
 - Pseudo-Step scan based trajectory
 - ◆ only modify fly trajectories to step trajectories
 - ◆ Higher efficiency than convention ones
 - ◆ Experiment data quality is worse
 - IO based Step scan (To be deployed)
 - ◆ Experiment process is closer to conventional step scan
 - ◆ Efficiency is equal to pseudo-step scan
 - ◆ Hardware structure is slightly more complex



Experimental Results from Fly Scan

- Sample: Siemens star

- A well-established test target to evaluate the spatial resolution in the field of ptychography

- After performance optimization

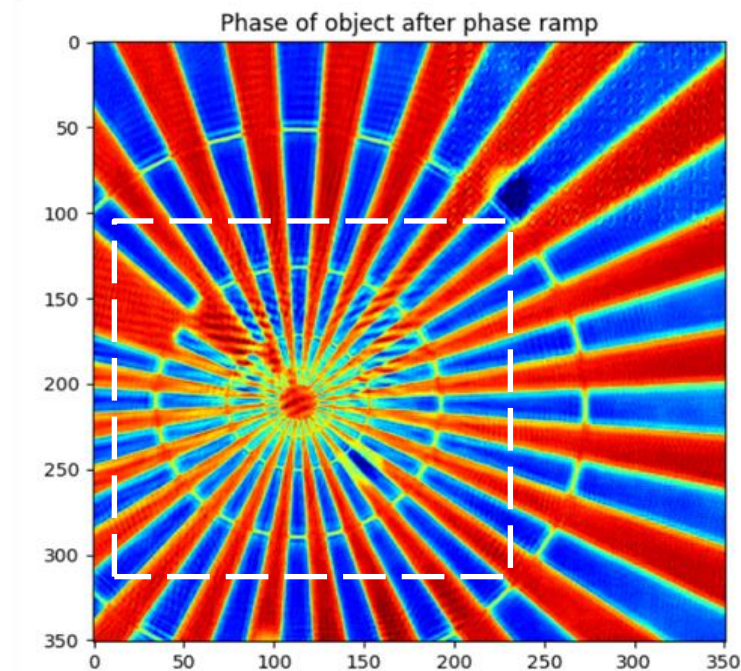
- Artifact has been eliminated
- the finest features (30nm) are clearly resolved

- Aspect

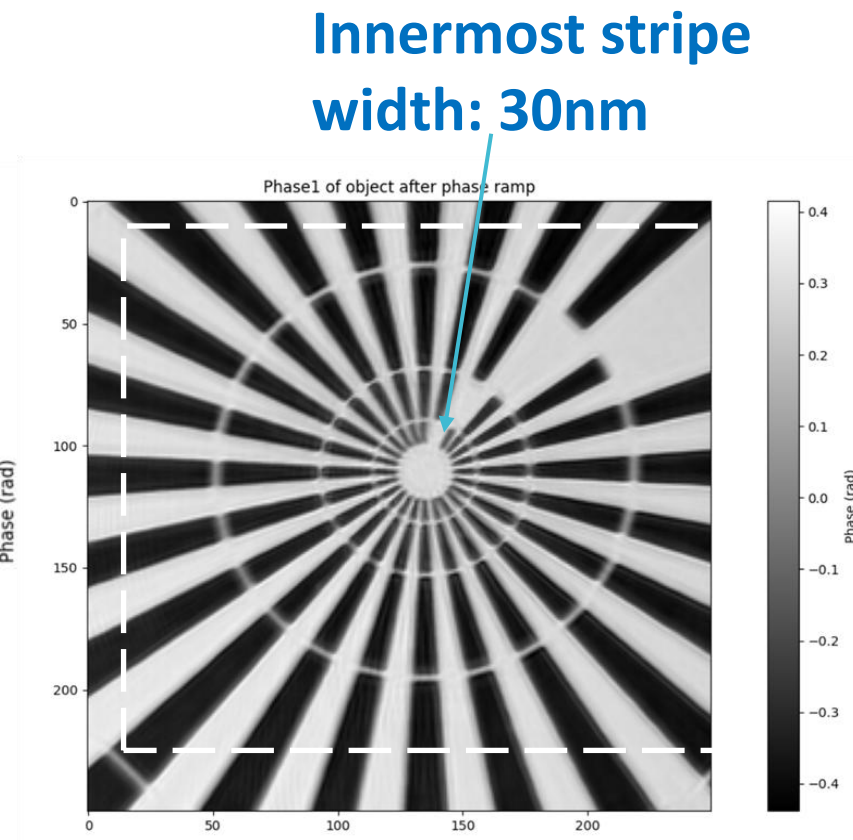
- Reduce Noise

- Optimize

- ◆ Servo algorithm
- ◆ Scan parameters
- ◆ Reconstruction algorithm, etc.



Reconstruction of **first** fly scan
Ptychography experiment



Reconstruction of fly scan
Ptychography experiment after
performance optimization

Experiment Results from Step Scan

• Sample: Siemens star

Conventional Step Scan⁽¹⁾ : 2Hz Freq, 0.1s Acquisition Time

◆ Reconstruction Pixel Size is 6.9nm

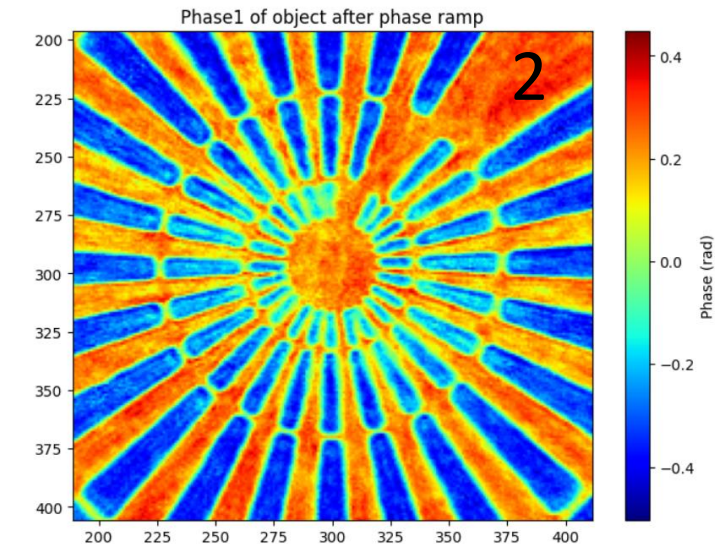
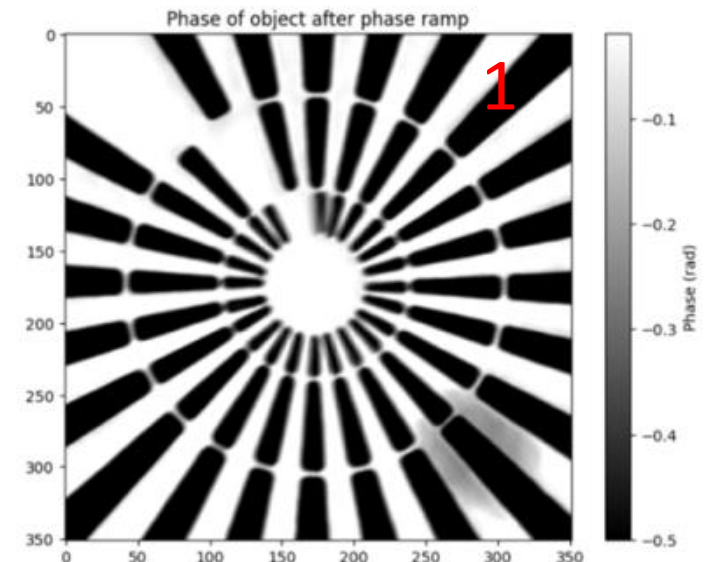
➢ acceptance metrics: 10nm; design metrics: 5nm

■ Pseudo-Step Scan⁽²⁾ : 5Hz, 100ms Acquisition Time

• SNR of Pseudo-step scan reconstruction is worse, and the next should be done

■ Optimize trajectory

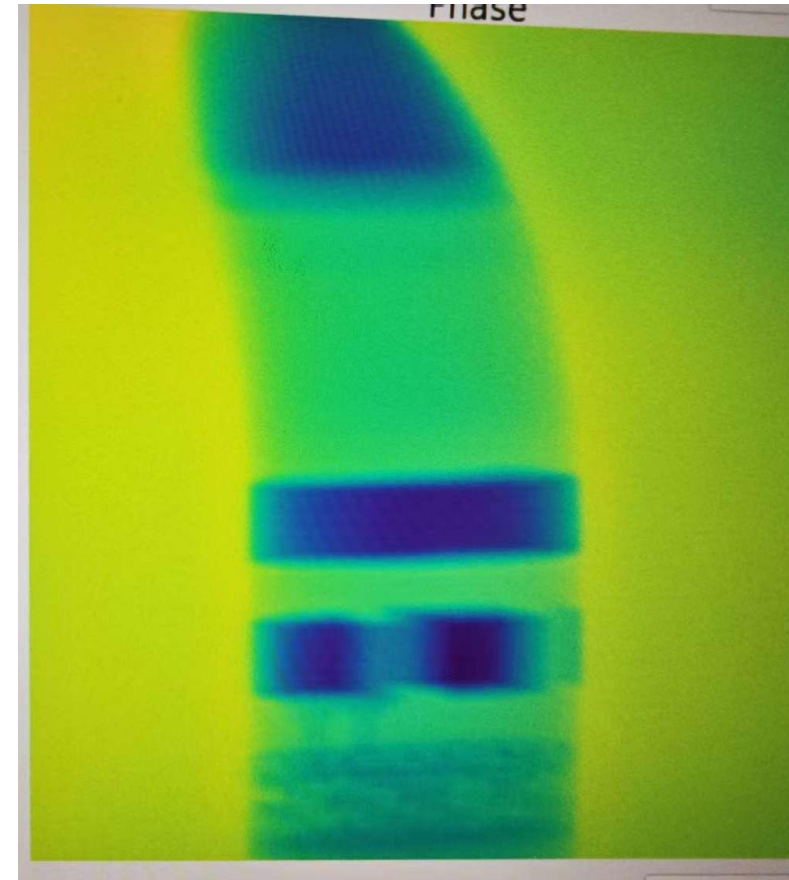
■ IO based step scan



Reconstruction of conventional step⁽¹⁾ and Pseudo-step⁽²⁾ scans
Ptychography experiments **15**

Summary

- The experimental control system for Ptychography at HXCS has been deployed for more than 1 year. Design specifications have achieved.
- 2D fly scan has successfully completed and the experimental functions are verified.
- The similar system structure has been deployed at HEPS-NAMI (Hard X-ray Nanoprobe Multimodal Imaging Beamline) and the first fly scan experiment has been done
 - it works correctly
 - the optimizations is still ongoing



Reconstruction result of **first** fly scan Ptychography experiment at NAMI beamline

The Next Steps

- 3D scanning experiment test will be performed in this round of experimental cycle at HXCS
- The following issue will be considered
 - Involving structure
 - ◆ The signal-to-background intensity is too low, resulting in unsatisfactory reconstruction quality when fly scan frequency is greater than 50Hz.
 - ◆ The measurement laser beam of interferometer malfunctions when sample stage rotates a full 360°.
 - ◆ Bandwidth issue in the closed-loop feedback control based on interferometer
 - Involving user-friendliness and convenience
 - ◆ automatic optimization of scan parameters
 - ◆ application of automatic combination of fly and step scan
 - ◆ Adaptive scans based on processing of the scan data that have already been produced, etc.

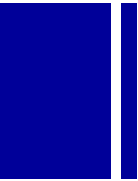
Contributions

- Beamline Control: Gang LI, Yu LIU, Xiaobao DENG;
- HXCS: Liang ZHOU, Xuan WANG, Zhongzhu ZHU, Han XU;
- Fine Mechanics: Shanzhi TANG, Ruiying LIAO, Zina OU;
- Software: Yi ZHANG, Chenglong ZHANG, Pengcheng LI, Xiaoxue BI;



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Thanks for your attention



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