国家同步辐射实验室
NATIONAL SYNCHROTRON RADIATION LABORATORY

Polychromatic Synchrotron Interferometer for HALF: Single-Shot Two-Dimensional Beam Profiling

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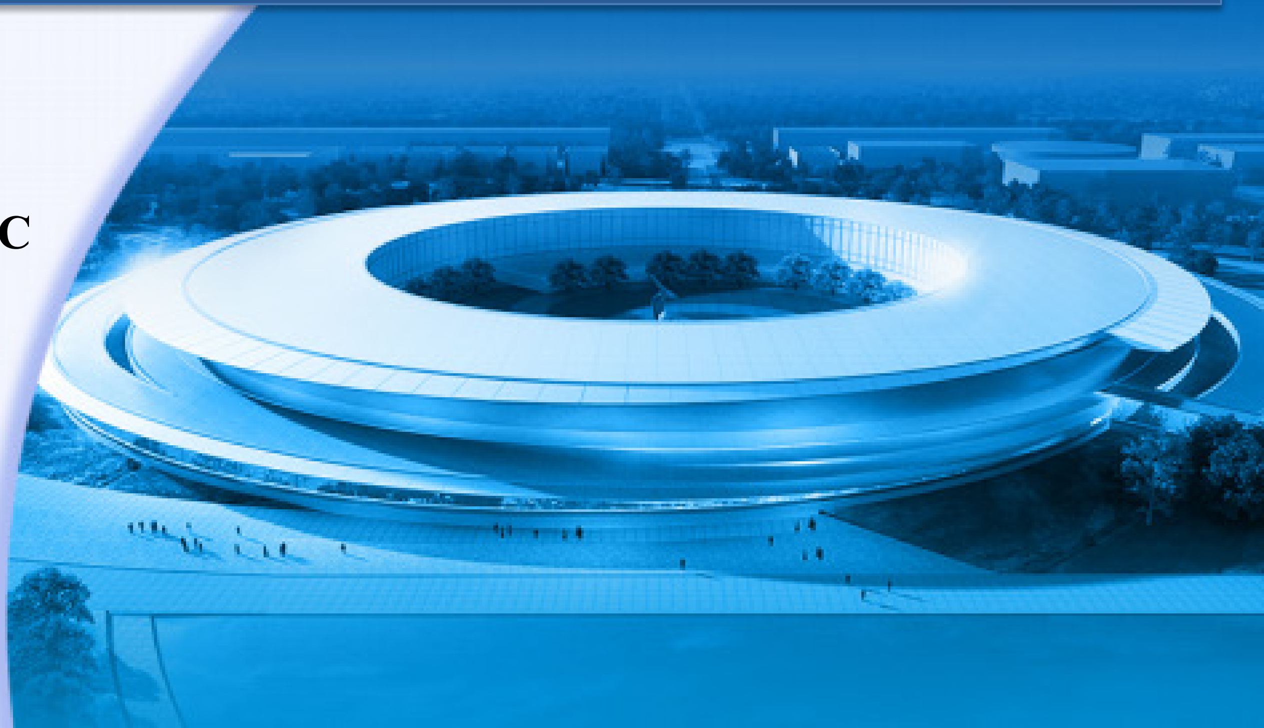
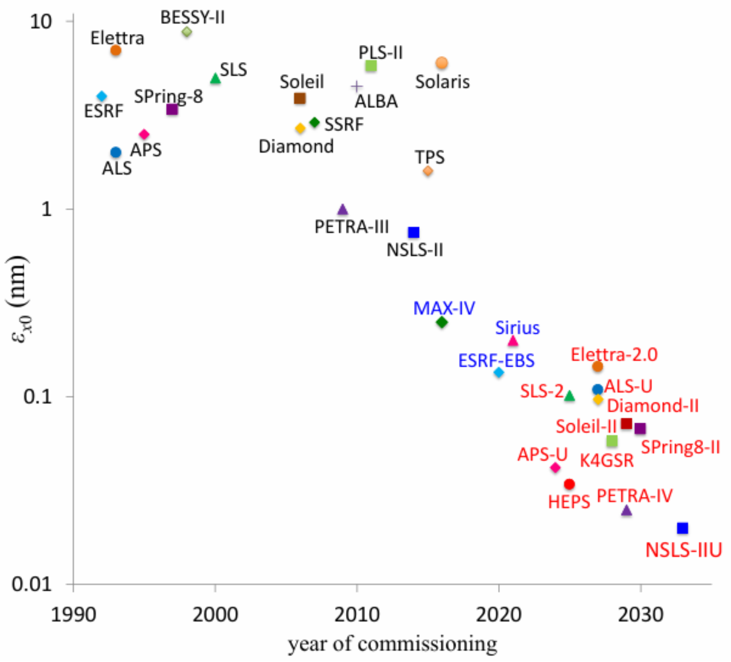


Outline

- ❑ Motivation: Diagnostics Challenges at 4th-Generation Light Sources
- ❑ Existing 2D Beam Profiling Methods
- ❑ Our Approach: Polychromatic 2D Interferometry
- ❑ Experimental Setup & Mask Design
- ❑ Results & Analysis
- ❑ Error Analysis & Systematic Effects
- ❑ Conclusion & Future Outlook

The Diagnostic Challenge for 4th-Generation Light Sources



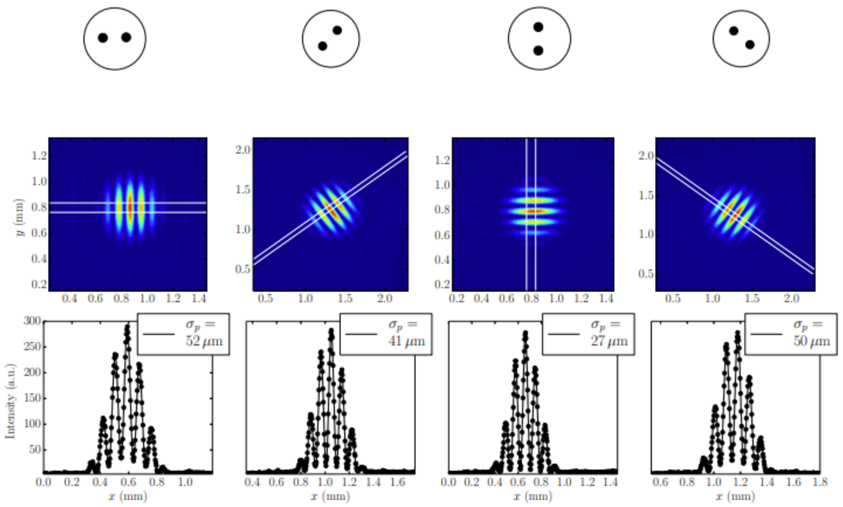
- **Emittance: < 100 pm·rad**
- **Beam Size: 5 ~ 50 μm**
- **Dynamics: Real Time**

The Imposed Demands:

- **Spatial Resolution**:
Wave-optical effects dominate; geometric imaging fails.
- **Temporal Resolution**:
Must capture fast instabilities (μs-ms timescales).
- **Dimensionality**:
Quasi-circular beam spot which requires full **2D transverse profile** characterization, not just a single projection.

Diagnostics must scale down too!

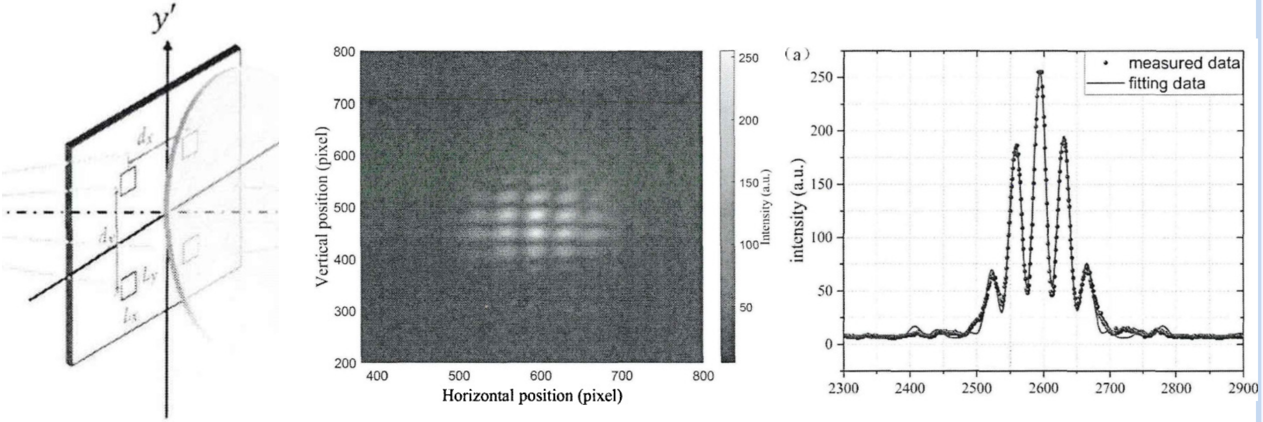
Existing 2D Beam Profiling Methods



Rotating-Mask Interferometry

- Based on a single-axis double-slit interferometer, with a precision rotation stage to change the slit orientation.

Sequential projection, NOT Single-Shot



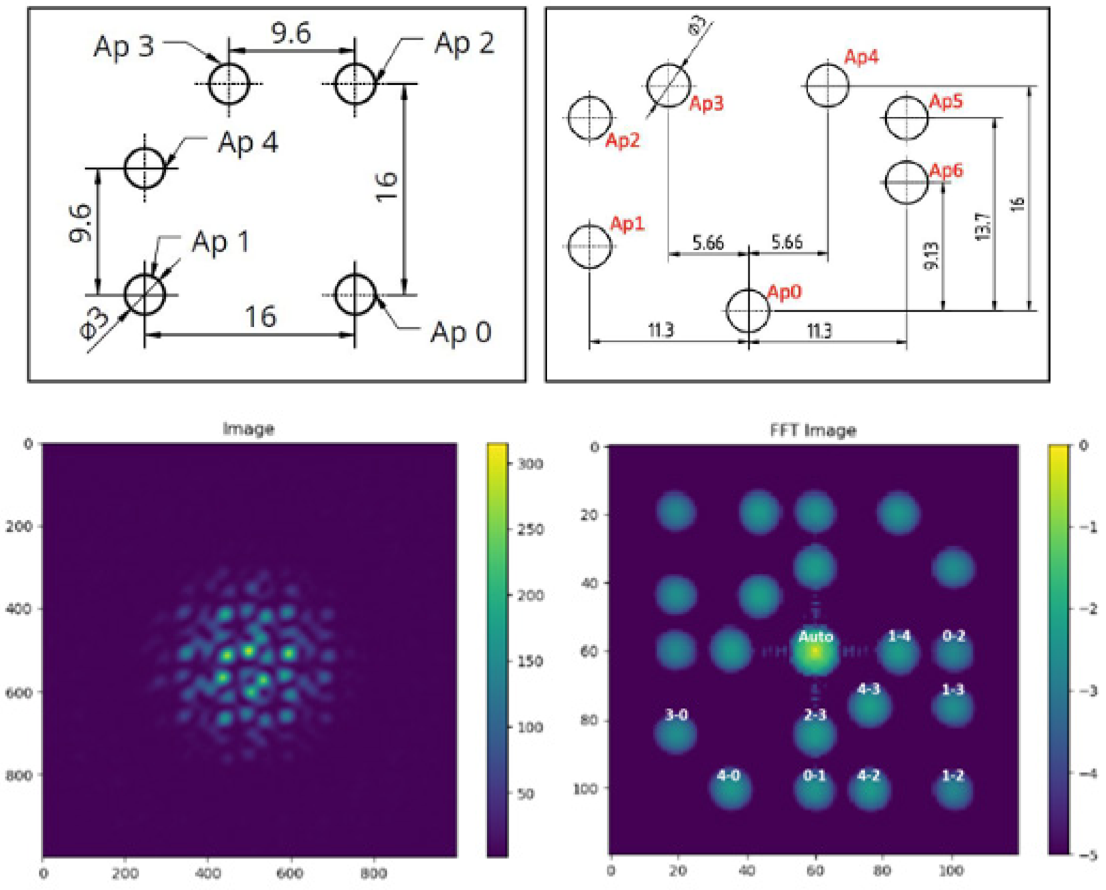
Four-Hole Aperture Interferometry

- Four apertures divide the wavefront, producing crossed 2D fringes.
- A single exposure gives both **horizontal (H)** and **vertical (V)** beam dimensions.

Only **two baselines** (H and V)

Existing 2D Beam Profiling Methods

Non-Redundant Aperture Interferometry

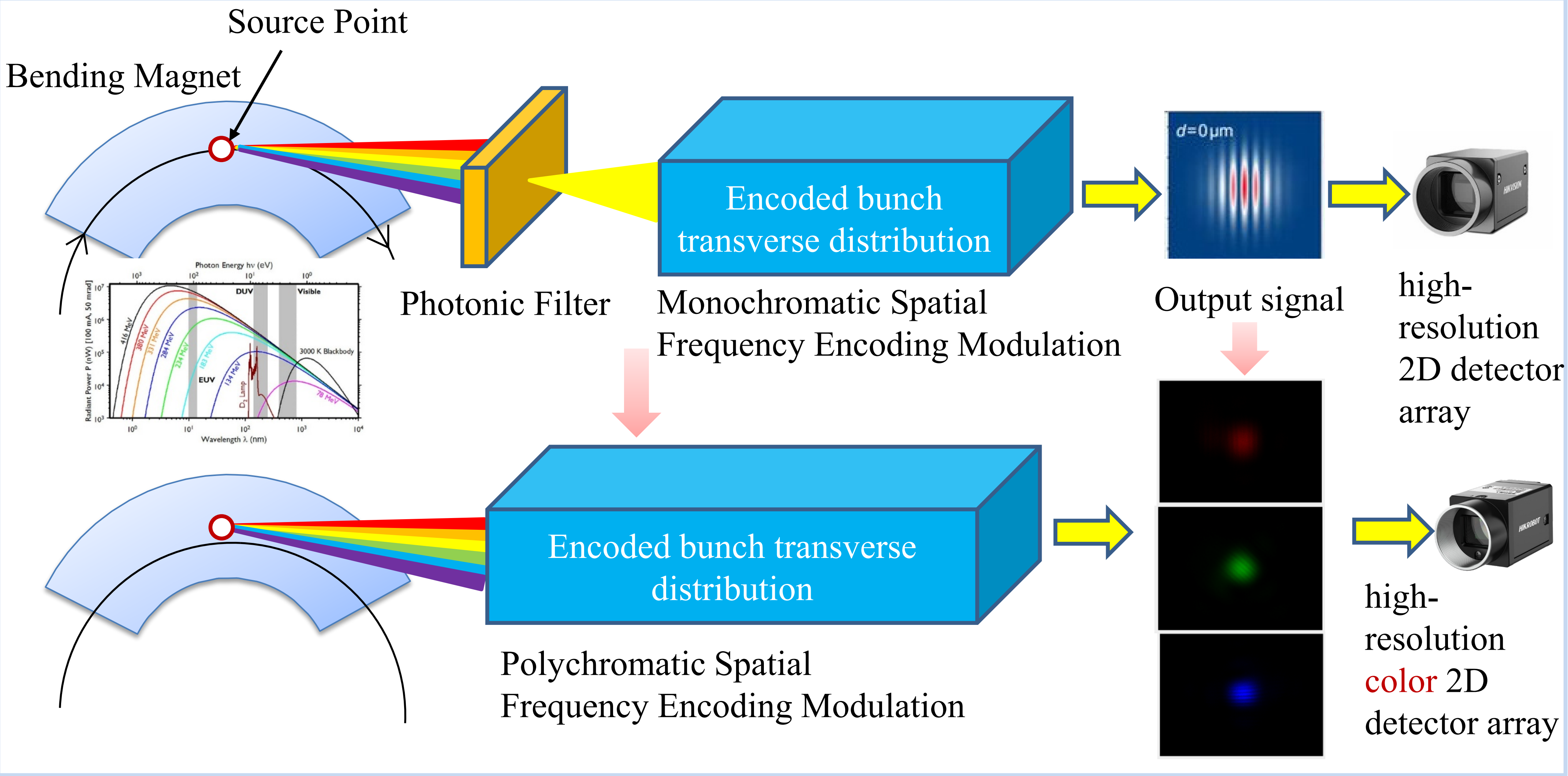


- An N-hole mask is designed such that **each baseline produces a unique spatial frequency** in the Fourier domain.
- A **single interferogram** contains all baselines simultaneously → full 2D transverse profile from one acquisition.

True Single-Shot 2D, Non-Invasive & Real-Time
Rich Spatial Frequency Coverage
High Accuracy, Robust to Phase Fluctuations

However, NRA requires complex data processing method, hole patterns demand high-precision machining to maintain baseline uniqueness.

From Monochromatic to Polychromatic Interferometry



Core Idea –Polychromatic Philosophy

Our Strategy:

- A static mask with **three dual-slit pairs**, each colour-encoded (R, G, B) to map to separate channels of a **colour CCD**.
- Simultaneously acquire **multiple angular projections** in a **single camera frame**.
- No filters or mechanical rotation – all projections are recorded **in parallel** within one exposure.

Data Processing:

- For each colour channel, apply the **standard monochromatic visibility formula** (based on the Van Cittert-Zernike theorem) to extract the transverse beam size along that specific projection angle.
- Simple data processing method – just direct visibility fitting per channel.

Achieve real-time, 2D, non-invasive profiling without complex data processing

Theoretical Foundation – Monochromatic SRI

Based on the Van Cittert-Zernike theorem, a Gaussian distribution light source, the intensity distribution is:

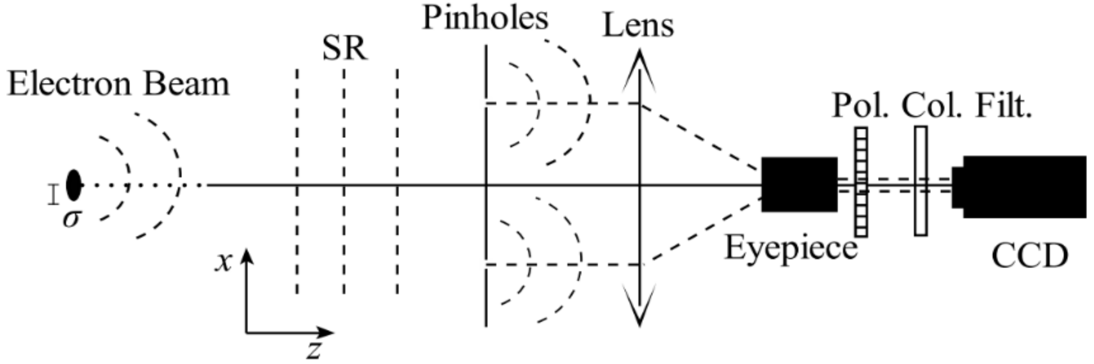
$$I(x) = I_0 exp\left(-\frac{x^2}{2\sigma^2}\right) \qquad (1)$$

The corresponding spatial coherence function:

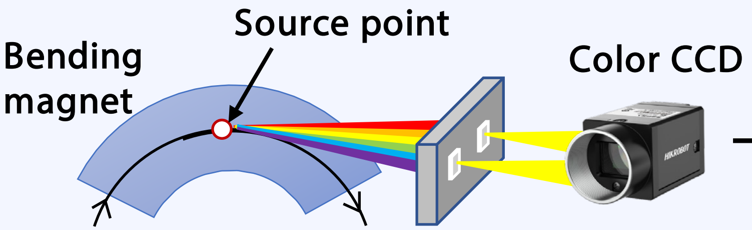
$$V = |\gamma(D)| = exp\left(-\frac{1}{2}\left(\frac{2\pi\sigma D}{\lambda R}\right)^2\right) \qquad (2)$$

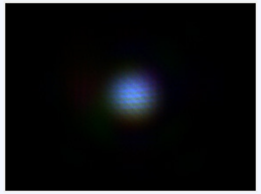
$$\sigma = \frac{\lambda R}{\pi D}\sqrt{\frac{1}{2}ln\frac{1}{V}}$$

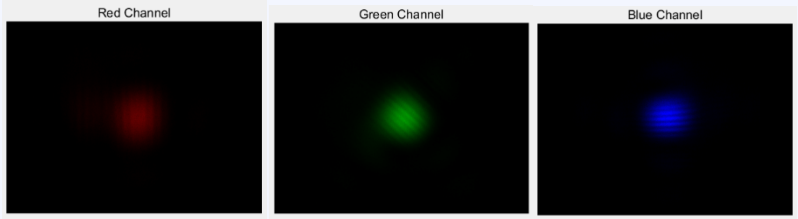
I_0: light intensity
a: slit radius
λ: synchrotron radiation wavelength
f: focal length of the optical system
D: slit separation
V: visibility
R: distance from the source point to the slit

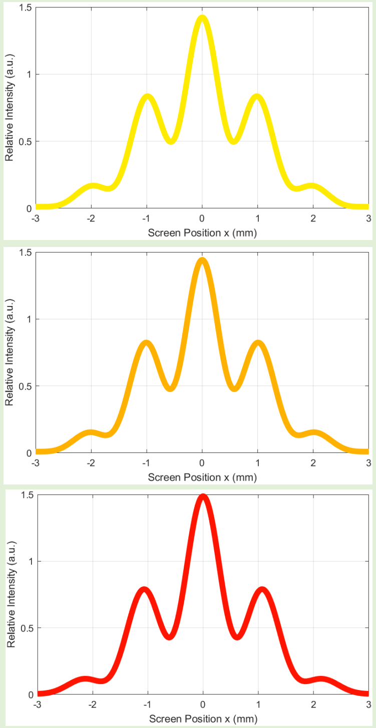


Data Processing





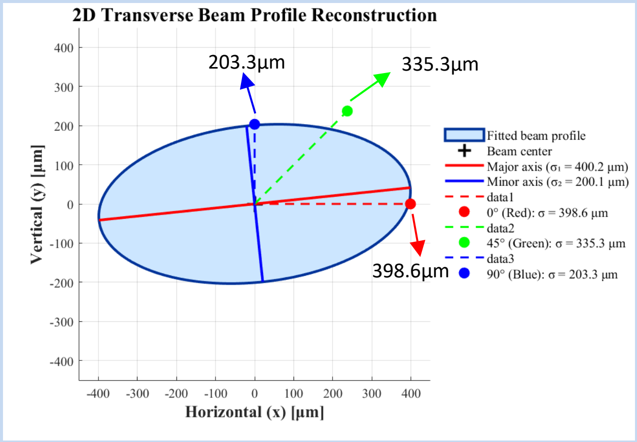




$\lambda_1 = 430\text{nm}$
$V_{\lambda_1}(\sigma_1)$

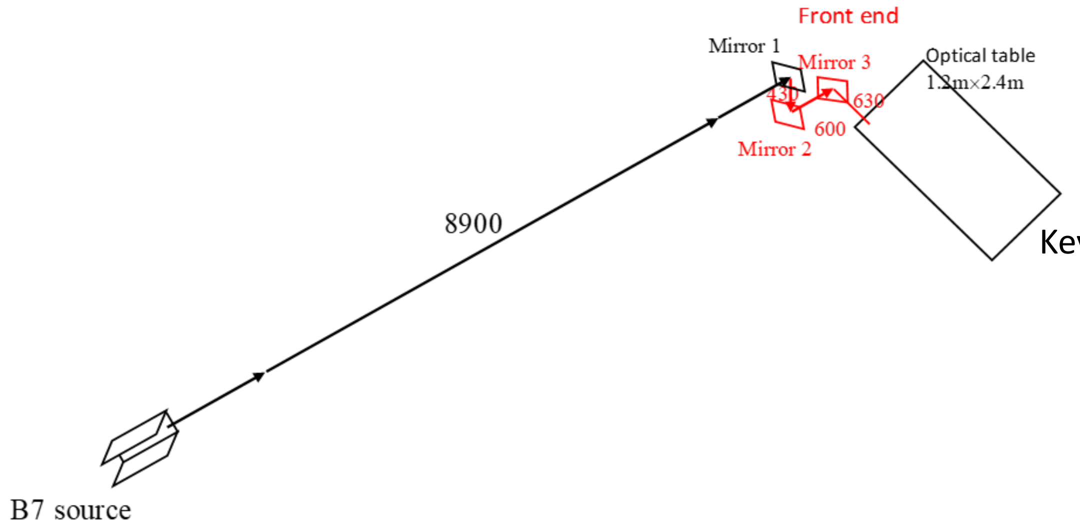
$\lambda_2 = 540\text{nm}$
$V_{\lambda_2}(\sigma_2)$

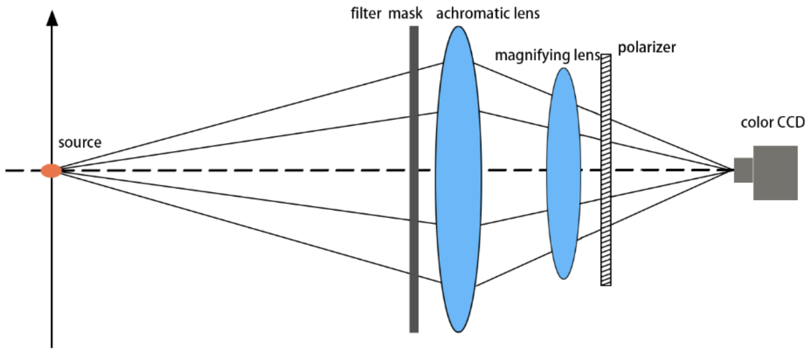
$\lambda_3 = 620\text{nm}$
$V_{\lambda_3}(\sigma_3)$



2D reconstruction within a single exposure

Experimental Setup

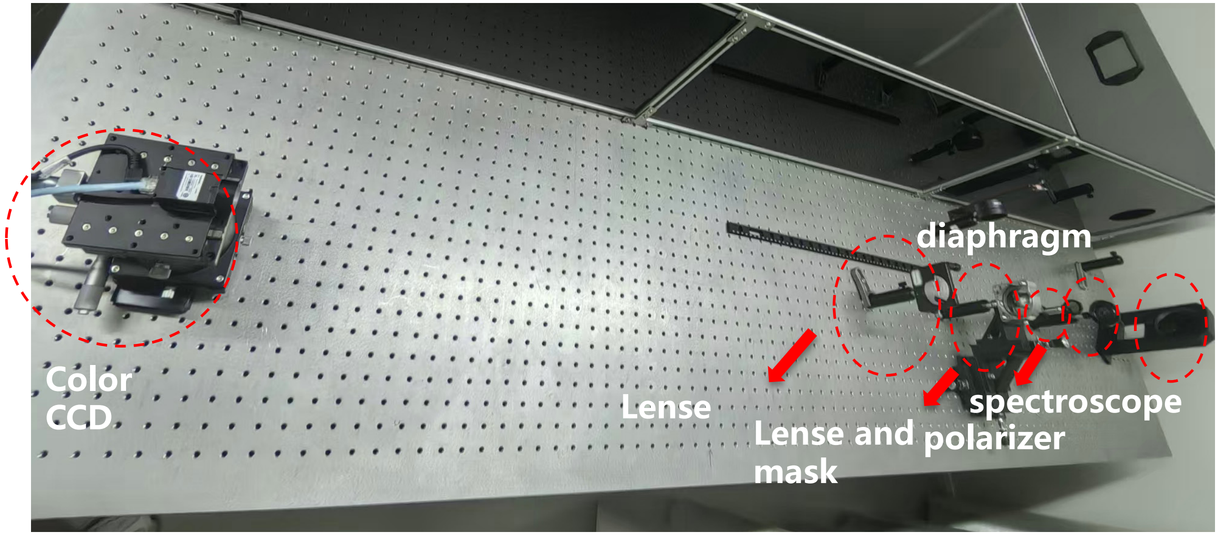




Key parameters of the HLS-II storage ring at the time of experiment

Parameter	Value	Unit
Beam energy E	0.8	GeV
RF frequency	204	MHz
Harmonic number	45	–
Radiation energy loss per turn	16.73	keV
Natural emittance ε_x (horizontal)	< 40	nm·rad
Injection current	300	mA
Natural energy spread σ_δ (rms)	0.00047	–
Beam lifetime	> 5	hours
Natural bunch length σ_z (rms)	14.8	mm ($\approx$ 50 ps)

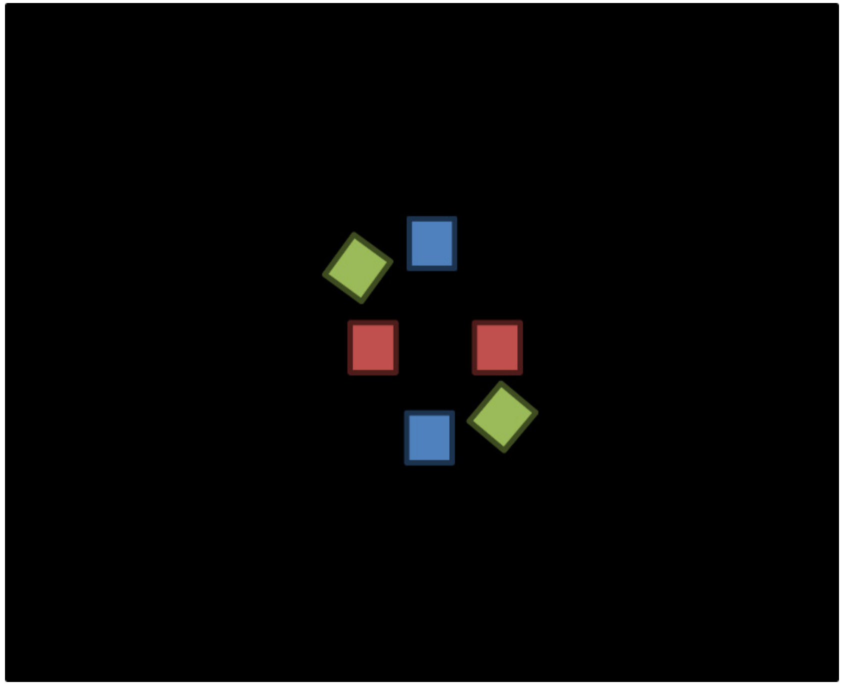
Experimental Setup



Key Optical Parameters:
- Source-to-slit distance: 11 m
- Slit width: 2 mm
- Horizontal slit spacing range: 3–6 mm
- Vertical slit spacing range: 5–8 mm
- System magnification: 8×

Hikrobot MV-CA016-10GC
Key Parameters:
•Resolution: 1440×1080 pixels
•Maximum frame rate: 78.2fps

Mask Design



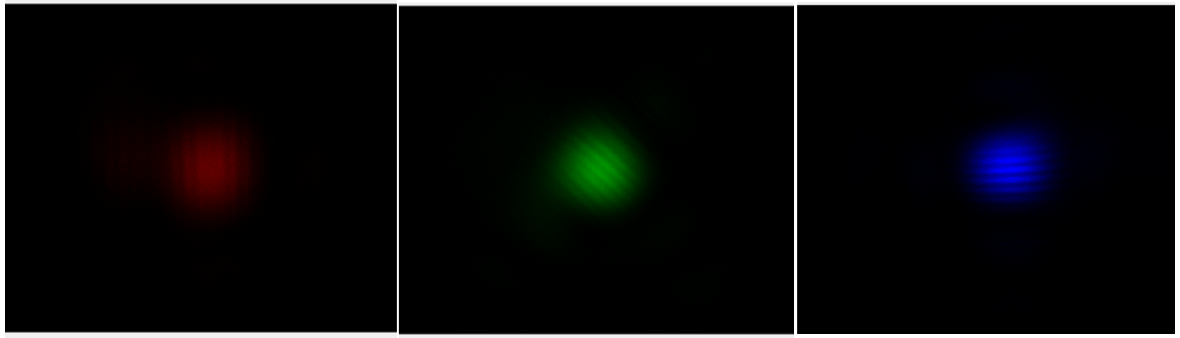
Horizontal projection :
Dual-slit oriented at 0° with a spacing of 5.0 mm
red filter

45° oblique projection :
Dual-slit oriented at 45° with a spacing of 6.0 mm,
green filter

Vertical projection :
Dual-slit oriented at 90° with a spacing of 7.0 mm,
blue filter

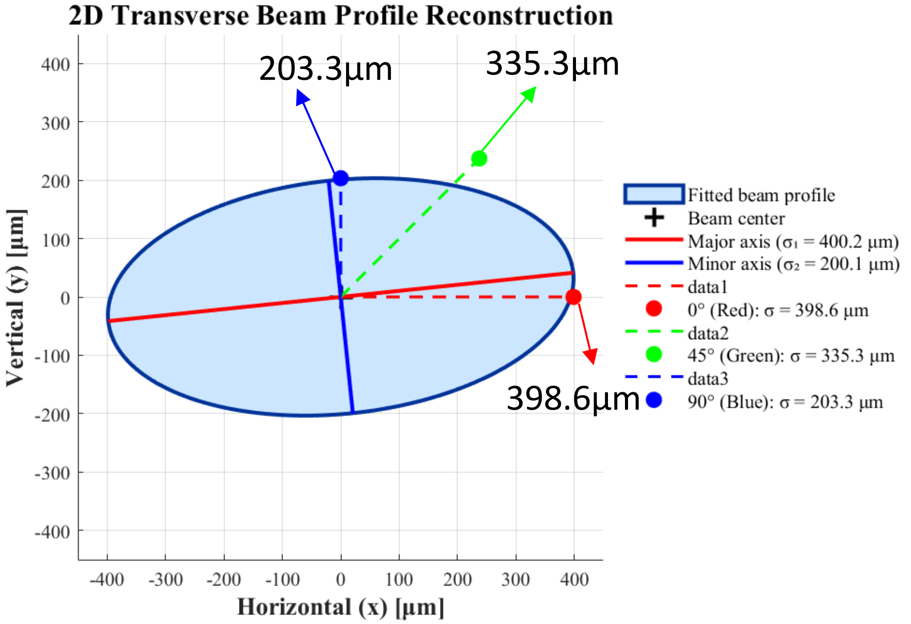
The mask design is guided by a balanced trade-off among three key factors:
(1) fringe visibility; (2) spatial frequency coverage; (3) fabrication feasibility

Results



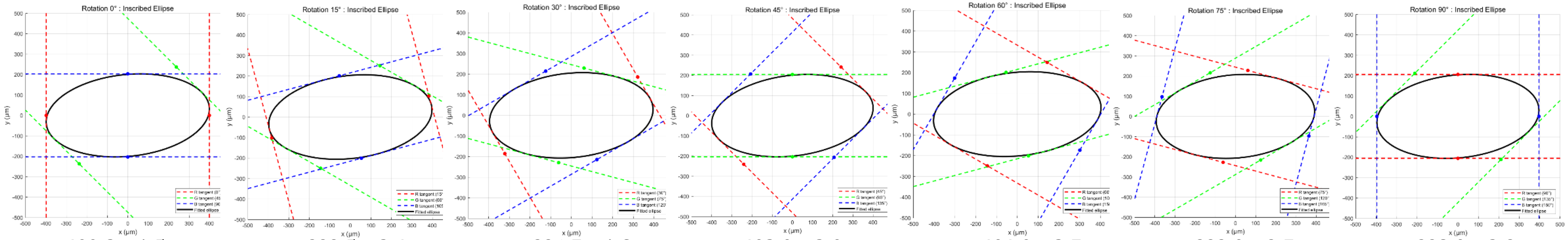
$$\sigma_x = 400.2 \pm 1.5\mu m$$
$$\sigma_y = 200.1 \pm 1.5\mu m$$
$$\theta = 6.0° \pm 0.2°$$

Channel (Filter)	Slit Spacing (mm)	Extracted σ (μm)	Projection Angle
Blue (430 nm)	7.0	203.29	90° (Vertical)
Green (540 nm)	6.0	335.34	45° (Oblique)
Red (620 nm)	5.0	398.55	0° (Horizontal)

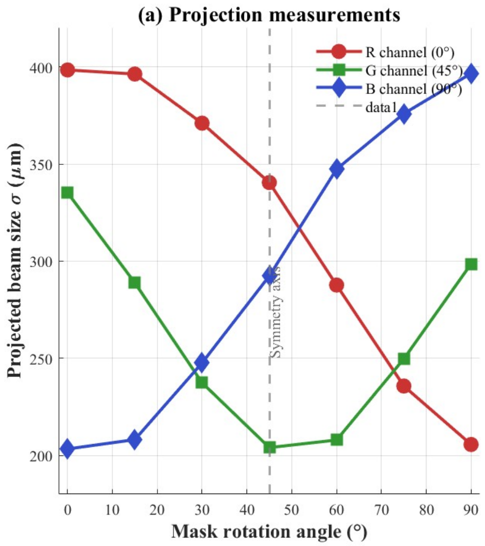


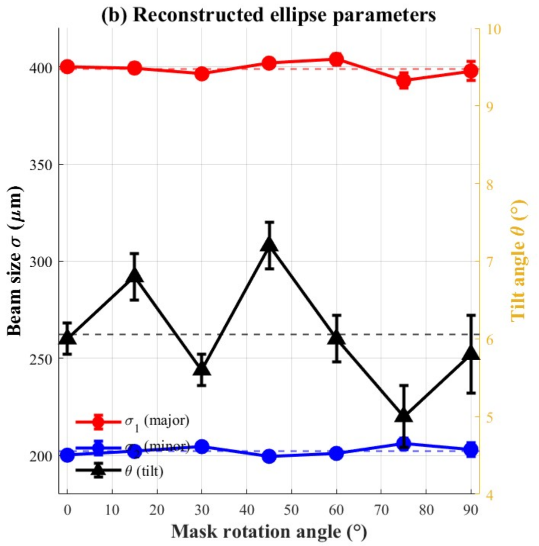
Axis	This work (μm)	Reference (μm)	Difference
Horizontal	400.2 ± 1.5	398.6	+0.4%
Vertical	200.1 ± 1.5	201.3	−0.6%

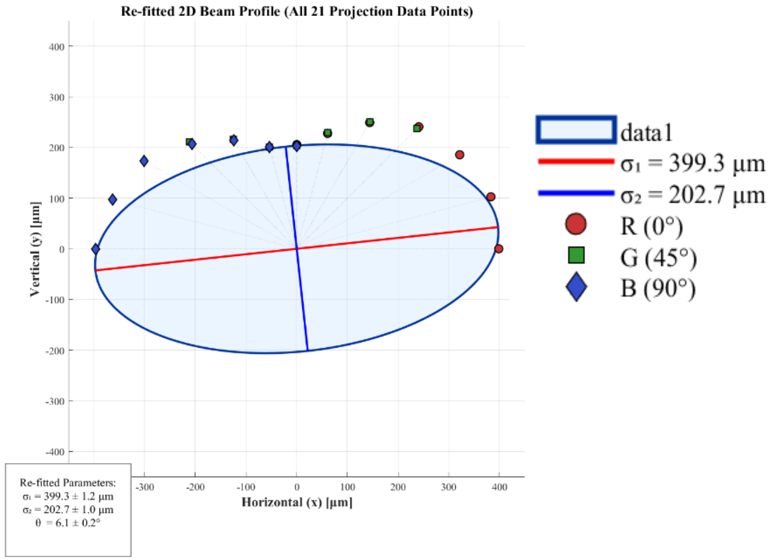
Results (Projection Angles)



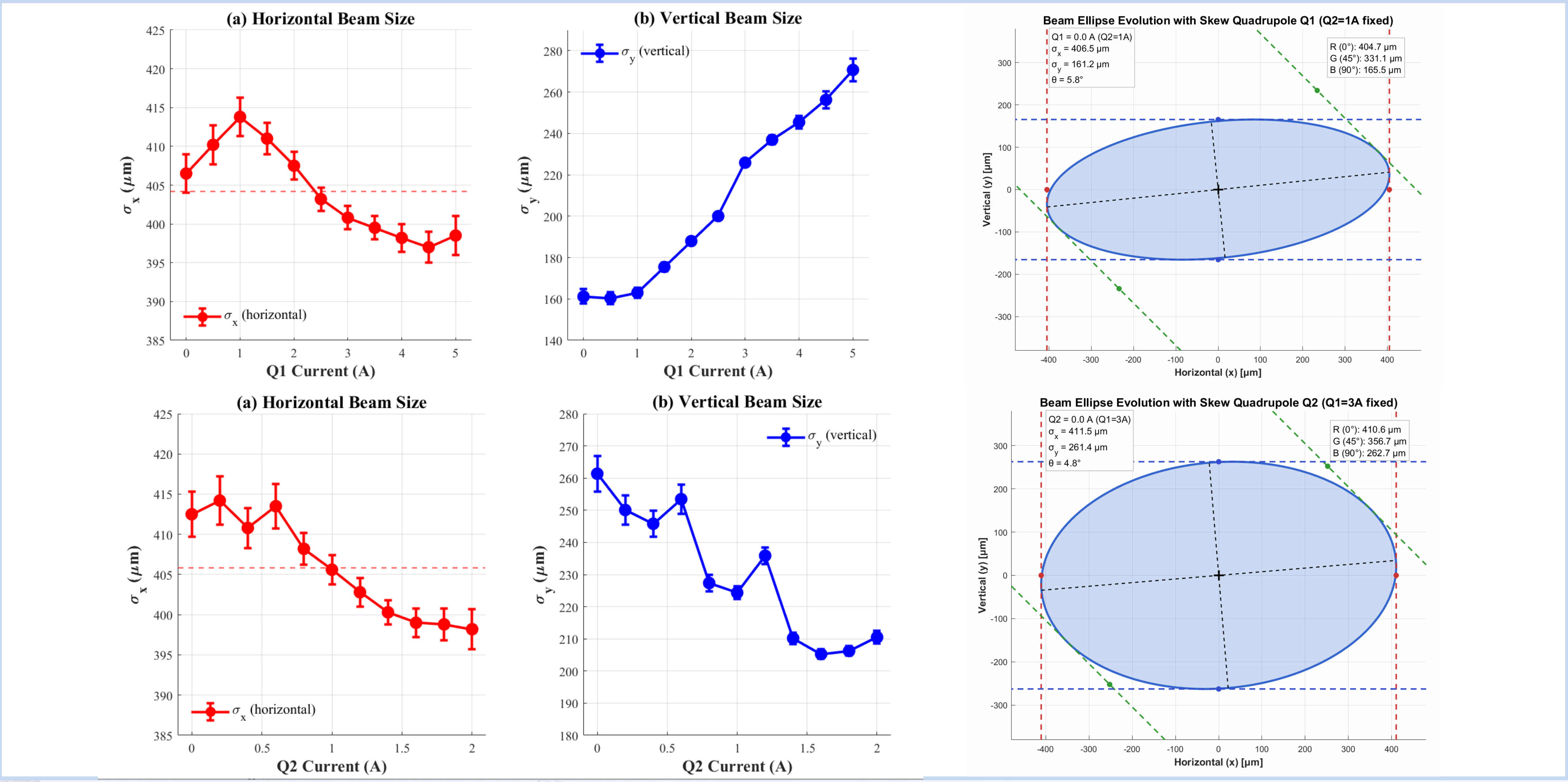
Rotation 0°	Rotation 15°	Rotation 30°	Rotation 45°	Rotation 60°	Rotation 75°	Rotation 90°
$\sigma_x = 400.2 \pm 1.5\mu m$	$\sigma_x = 399.5 \pm 2.4\mu m$	$\sigma_x = 396.7 \pm 1.8\mu m$	$\sigma_x = 402.0 \pm 2.0\mu m$	$\sigma_x = 404.0 \pm 2.7\mu m$	$\sigma_x = 393.0 \pm 3.7\mu m$	$\sigma_x = 398.0 \pm 2.3\mu m$
$\sigma_y = 200.1 \pm 1.5\mu m$	$\sigma_y = 202.0 \pm 2.1\mu m$	$\sigma_y = 204.5 \pm 1.9\mu m$	$\sigma_y = 199.5 \pm 1.8\mu m$	$\sigma_y = 201.0 \pm 2.5\mu m$	$\sigma_y = 206.0 \pm 1.9\mu m$	$\sigma_y = 203.4 \pm 1.8\mu m$
$\theta = 6.0° \pm 0.2°$	$\theta = 6.8° \pm 0.3°$	$\theta = 5.6° \pm 0.2°$	$\theta = 7.2° \pm 0.3°$	$\theta = 6.0° \pm 0.3°$	$\theta = 5.9° \pm 0.4°$	$\theta = 5.8° \pm 0.2°$







Results(Coupling)



Error Ayalysis&Systematic Effects

➢Uncertainty Sources

Statistical: CCD shot noise, fringe fitting residuals
Systematic: Chromatic aberration (lens defocus), spectral calibration errors
Optical: Slit positioning accuracy, magnification calibration

➢Systematic Effects: Identified and Mitigated

Intensity Imbalance

Slits sample slightly different regions of the source profile
Mitigation: Symmetrical slit placement; Fourier-based contrast extraction
Result: Imbalance effect is below measurement noise

Wavefront Distortion

WFE measured: 0.22λ RMS
Mitigation: Visibility extraction via envelope fitting (phase-insensitive)
Result: Phase tilt/distortion does NOT bias contrast measurement

Asymmetric Fringe Envelopes

Caused by illumination non-uniformity, dust/vignetting
Mitigation: 2D Fourier filtering + ROI averaging over many fringe periods
Result: Random residuals → no systematic bias

Conclusion

1. **Single-shot 2D profiling applies a color CCD and a static colour-encoded mask with three projections (0°, 45°, 90°).**
2. **Simple visibility fitting per channel requires no complex data processing.**
3. **45° projection adds asymmetry characterisation beyond four-hole method.**
4. **HLS-II experiments validate consistent 2D reconstruction across rotation angles.**
5. **Error analysis and systematic effects analysis ensure system robustness.**

Future Outlook

1. All-Reflective Optics

Replace refractive achromatic lenses with mirrors to eliminate chromatic defocus entirely — inherently achromatic across the full spectral range.

2. Hyperspectral Imaging

Continuous spectral information enables direct source spectrum measurement without separate calibration.

3. Advanced Algorithms

Machine learning for rapid fringe analysis, Bayesian inference for uncertainty quantification, and real-time processing for dynamic monitoring.

Acknowledgements

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Thank You

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