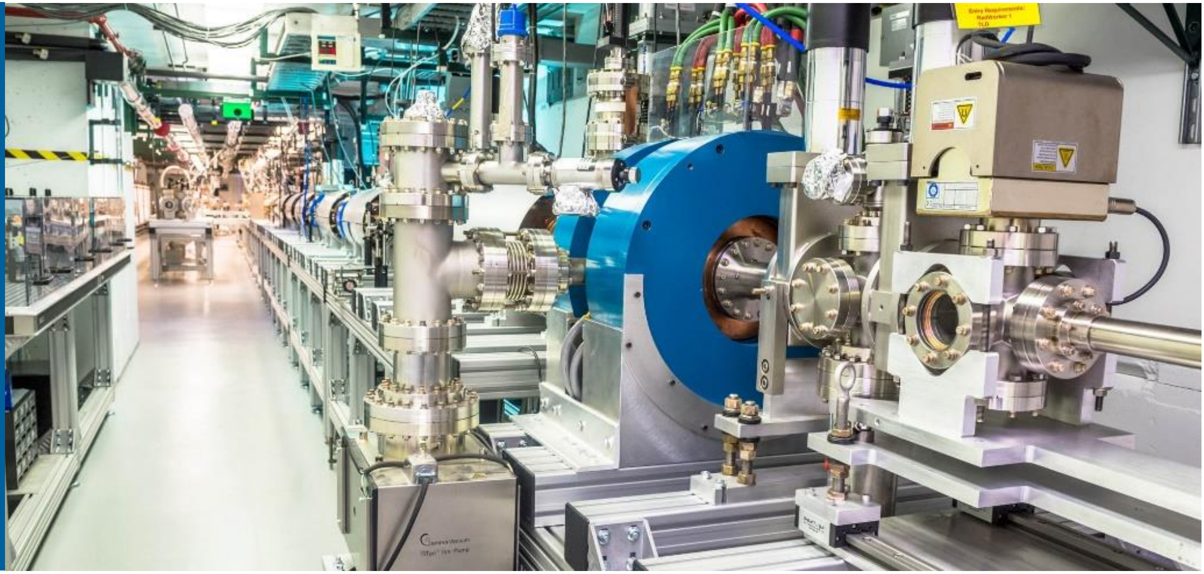
AUGUST 11, 2023

EXPERIMENTAL DEMONSTRATION OF ROUND-TO-FLAT AND FLAT-TO-ROUND BEAM TRANSFORMATION



SEONGYEOL KIM
On behalf of Argonne Wakefield Accelerator Group

Work supported by DOE SBIR Grant DE-SC0021733 and by the U.S. Department of Energy (DOE), Office of Science, under contract No. DE-AC02-06CH11357 with Argonne National Laboratory (ANL).

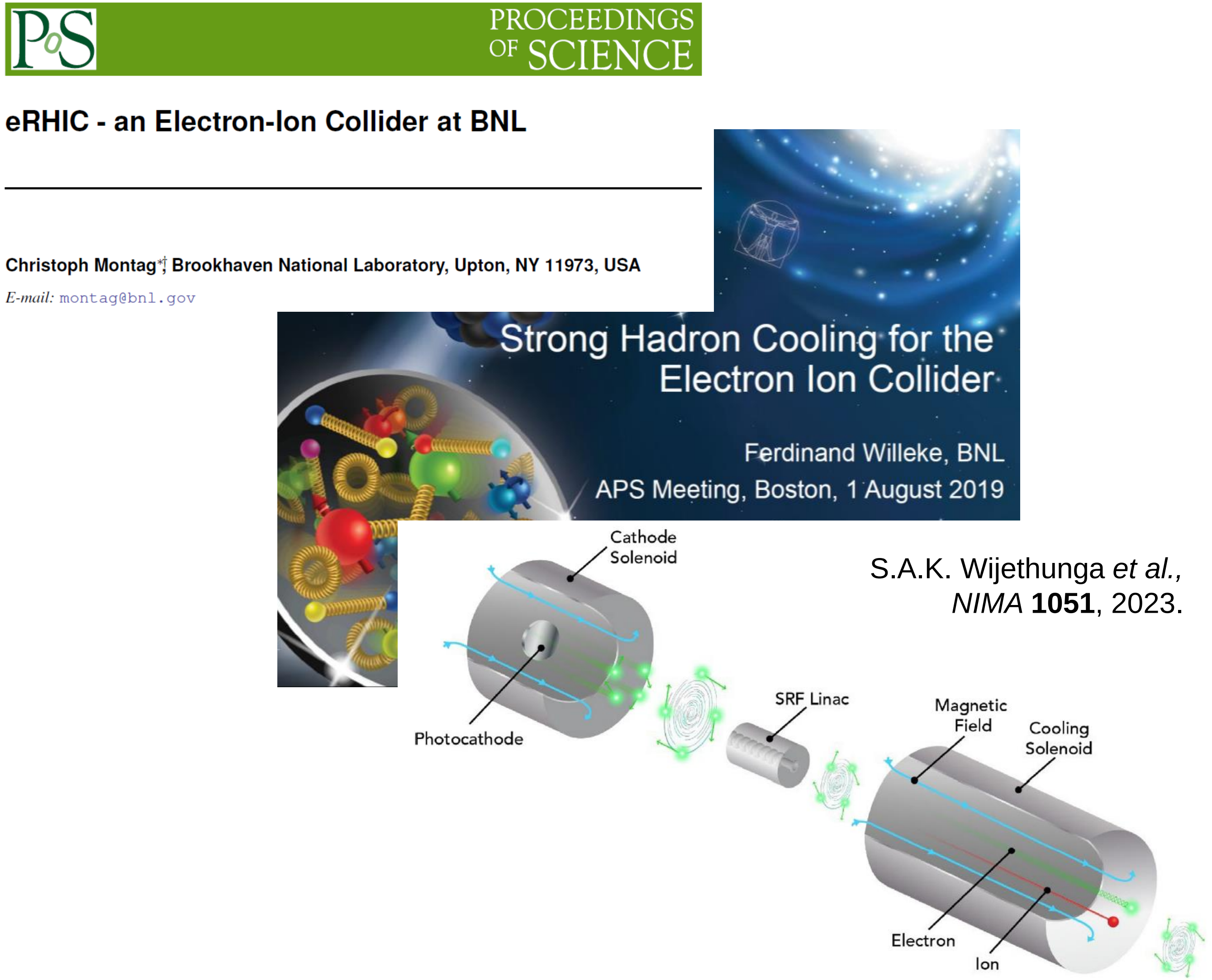
Contents

Introduction and motivation

*EIC: Electron-Ion Collider @ BNL
G. Budker, Soviet Atomic Energy **22, 1967.
***Y. Derbenev, arXiv:1703.09735, 2017.

Cooling of hadron beam for EIC*
(reduce 6D emittance to increase luminosity against intra-beam scattering)

→ **magnetized,
bunched electron beam**



PROCEEDINGS OF SCIENCE

eRHIC - an Electron-Ion Collider at BNL

Christoph Montag[*][†] **Brookhaven National Laboratory, Upton, NY 11973, USA**
E-mail: `montag@bnl.gov`

Strong Hadron Cooling for the Electron Ion Collider

Ferdinand Willeke, BNL
APS Meeting, Boston, 1 August 2019

S.A.K. Wijethunga *et al.*,
NIMA **1051**, 2023.

*EIC: Electron-Ion Collider @ BNL
G. Budker, Soviet Atomic Energy **22, 1967.
***Y. Derbenev, arXiv:1703.09735, 2017.

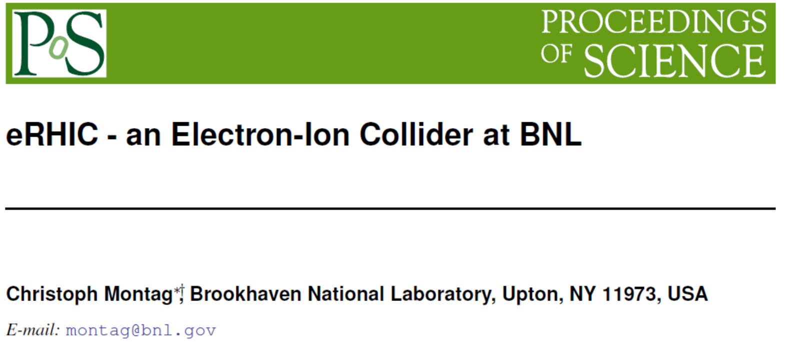
Introduction and motivation

Cooling of hadron beam for EIC*

(reduce 6D emittance to increase luminosity against intra-beam scattering)

➡ **magnetized, bunched electron beam**

- Hadron beam cooling using magnetized electron beam** for higher cooling effieicncy: proposed by Derbenev*** (increasing Coulomb interaction time with helical path)
- For EIC @ BNL, maximum proton beam energy is about 255 GeV >> higher beam energy ranging from 20-150 MeV is needed to match the beam temperature (velocity)
- However, magnetized beam focus/propagation is hard using normal solenoid/quadrupole

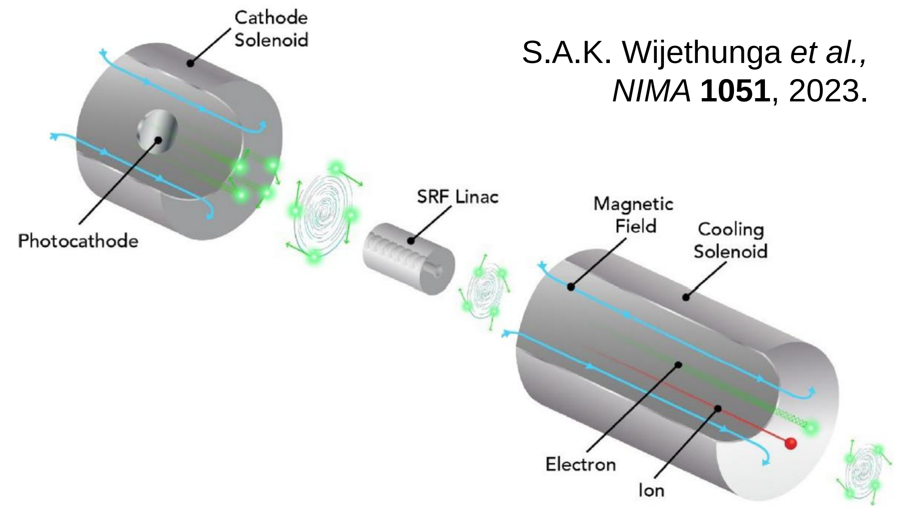

PoS PROCEEDINGS OF SCIENCE

eRHIC - an Electron-Ion Collider at BNL

Christoph Montag*† Brookhaven National Laboratory, Upton, NY 11973, USA
E-mail: montag@bnl.gov


Strong Hadron Cooling for the Electron Ion Collider

Ferdinand Willeke, BNL
APS Meeting, Boston, 1 August 2019



S.A.K. Wijethunga *et al.*, *NIMA* **1051**, 2023.

Introduction and motivation

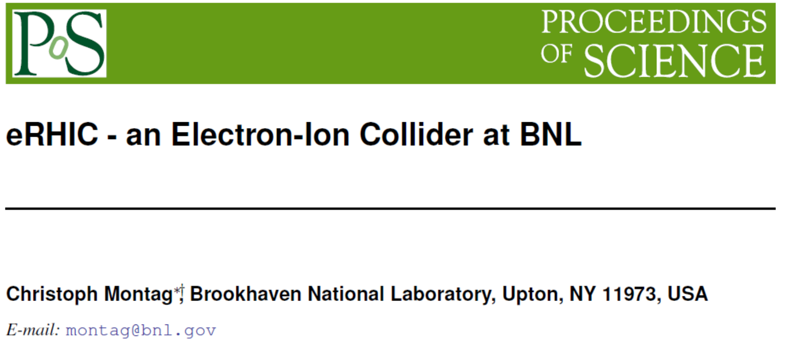
*EIC: Electron-Ion Collider @ BNL
G. Budker, Soviet Atomic Energy **22, 1967.
***Y. Derbenev, arXiv:1703.09735, 2017.

Cooling of hadron beam for EIC*

(reduce 6D emittance to increase luminosity against intra-beam scattering)

→ **magnetized, bunched electron beam**

- Hadron beam cooling using magnetized electron beam** for higher cooling effieicncy: proposed by Derbenev*** (increasing Coulomb interaction time with helical path)
- For EIC @ BNL, maximum proton beam energy is about 255 GeV >> higher beam energy ranging from 20-150 MeV is needed to match the beam temperature (velocity)
- However, magnetized beam focus/propagation is hard using normal solenoid/quadrupole



PoS PROCEEDINGS OF SCIENCE

eRHIC - an Electron-Ion Collider at BNL

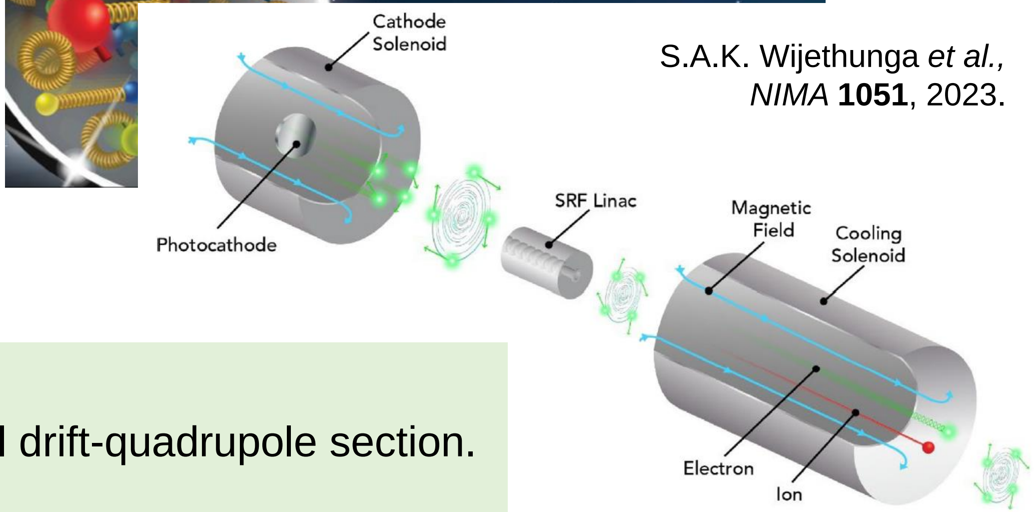
Christoph Montag*† Brookhaven National Laboratory, Upton, NY 11973, USA

E-mail: `montag@bnl.gov`

Strong Hadron Cooling for the Electron Ion Collider

Ferdinand Willeke, BNL

APS Meeting, Boston, 1 August 2019



S.A.K. Wijethunga *et al.*, *NIMA* **1051**, 2023.

Proposed solution:

- Decouple the beam (flat-beam) and propagate it along normal drift-quadrupole section. Then transform it back to coupled beam for actual application

Magnetization and eigenemittance

Averaged angular momentum

Non-zero Bfield at the cathode

$$\mathcal{L} = \frac{\langle L \rangle}{2m_e c} = \frac{eB_c\sigma_c^2}{2m_e c}$$

RMS UV size at the cathode

Magnetization

Initial, magnetized beam

$$\Sigma_0 = \begin{bmatrix} \epsilon_{eff}T_0 & \mathcal{L}J \\ -\mathcal{L}J & \epsilon_{eff}T_0 \end{bmatrix}$$

After transformation using coupled matrix (with skew quads),

$$\Sigma_1 = M\Sigma_0 M^{\intercal}$$

Decoupled Flat beam

$$\Sigma_1 = \begin{bmatrix} \epsilon_+T_+ & 0 \\ 0 & \epsilon_-T_- \end{bmatrix}$$

where $T_0 = \begin{bmatrix} \beta & -\alpha \\ \alpha & \gamma \end{bmatrix}$ $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ $\epsilon_{4D} = \epsilon_{th}^2 = \epsilon_{eff}^2 - \mathcal{L}^2$

Thermal emittance at the cathode

Magnetization and eigenemittance

Averaged angular momentum

Non-zero Bfield at the cathode

$$\mathcal{L} = \frac{\langle L \rangle}{2m_e c} = \frac{eB_c\sigma_c^2}{2m_e c}$$

RMS UV size at the cathode

Magnetization

For round-to-flat beam transformation,

if $\mathcal{L} \gg \epsilon_{th}, \quad \epsilon_{\pm} = \sqrt{\epsilon_{th}^2 + \mathcal{L}^2} \pm \mathcal{L}$

$$\epsilon_+ \approx 2\mathcal{L} \quad \epsilon_- \approx \frac{\epsilon_{th}^2}{2\mathcal{L}}$$

Eigenemittance

(Invariance of 4D emittance: $\epsilon_{th} = \sqrt{\epsilon_+\epsilon_-}$)

Flat beam: has large emittance ratio

Initial, magnetized beam

After transformation using coupled matrix (with skew quads),

Decoupled Flat beam

$$\Sigma_0 = \begin{bmatrix} \epsilon_{eff}T_0 & \mathcal{L}J \\ -\mathcal{L}J & \epsilon_{eff}T_0 \end{bmatrix} \xrightarrow{\Sigma_1 = M\Sigma_0 M^{\intercal}} \Sigma_1 = \begin{bmatrix} \epsilon_+ T_+ & 0 \\ 0 & \epsilon_- T_- \end{bmatrix}$$

where $T_0 = \begin{bmatrix} \beta & -\alpha \\ \alpha & \gamma \end{bmatrix}$ $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ $\epsilon_{4D} = \epsilon_{th}^2 = \epsilon_{eff}^2 - \mathcal{L}^2$

Thermal emittance at the cathode

Magnetization and eigenemittance

Averaged angular momentum

Non-zero Bfield at the cathode

$$\mathcal{L} = \frac{\langle L \rangle}{2m_e c} = \frac{eB_c\sigma_c^2}{2m_e c}$$

RMS UV size at the cathode

Magnetization

For round-to-flat beam transformation,

if $\mathcal{L} \gg \epsilon_{th}, \quad \epsilon_{\pm} = \sqrt{\epsilon_{th}^2 + \mathcal{L}^2} \pm \mathcal{L}$

$$\epsilon_+ \approx 2\mathcal{L} \quad \epsilon_- \approx \frac{\epsilon_{th}^2}{2\mathcal{L}}$$

Eigenemittance

(Invariance of 4D emittance: $\epsilon_{th} = \sqrt{\epsilon_+ \epsilon_-}$)

Flat beam: has large emittance ratio

Initial, magnetized beam

$$\Sigma_0 = \begin{bmatrix} \epsilon_{eff} T_0 & \mathcal{L}J \\ -\mathcal{L}J & \epsilon_{eff} T_0 \end{bmatrix}$$

After transformation using coupled matrix (with skew quads),

$$\Sigma_1 = M \Sigma_0 M^{\intercal}$$

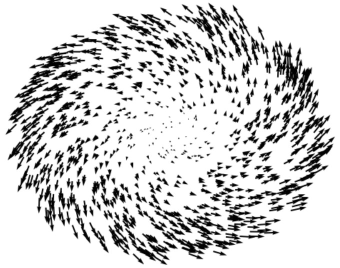
Decoupled Flat beam

$$\Sigma_1 = \begin{bmatrix} \epsilon_+ T_+ & 0 \\ 0 & \epsilon_- T_- \end{bmatrix}$$

where $T_0 = \begin{bmatrix} \beta & -\alpha \\ \alpha & \gamma \end{bmatrix}$ $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ $\epsilon_{4D} = \epsilon_{th}^2 = \epsilon_{eff}^2 - \mathcal{L}^2$

Thermal emittance at the cathode

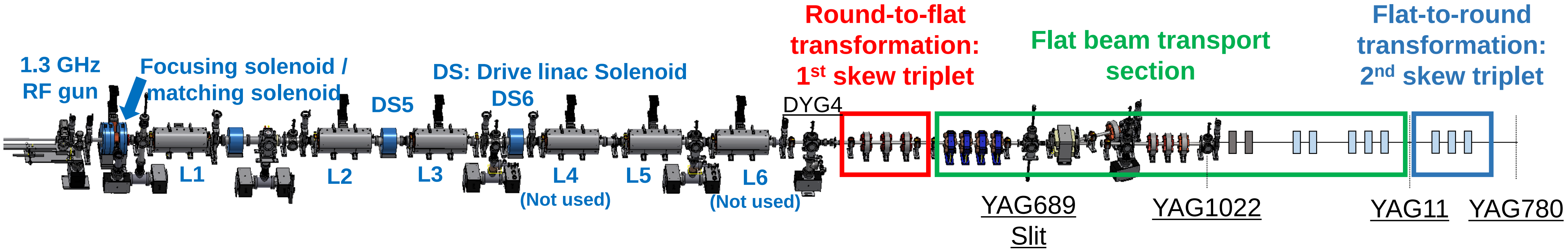
Flat beam (Transversely uncoupled)



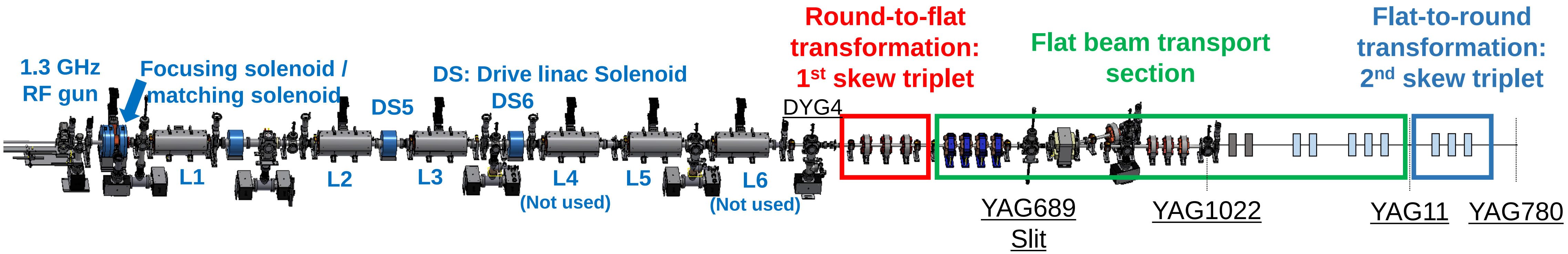
Magnetized beam (Transversely coupled)

Start-to-end OPAL simulation results

AWA beamline for demonstration



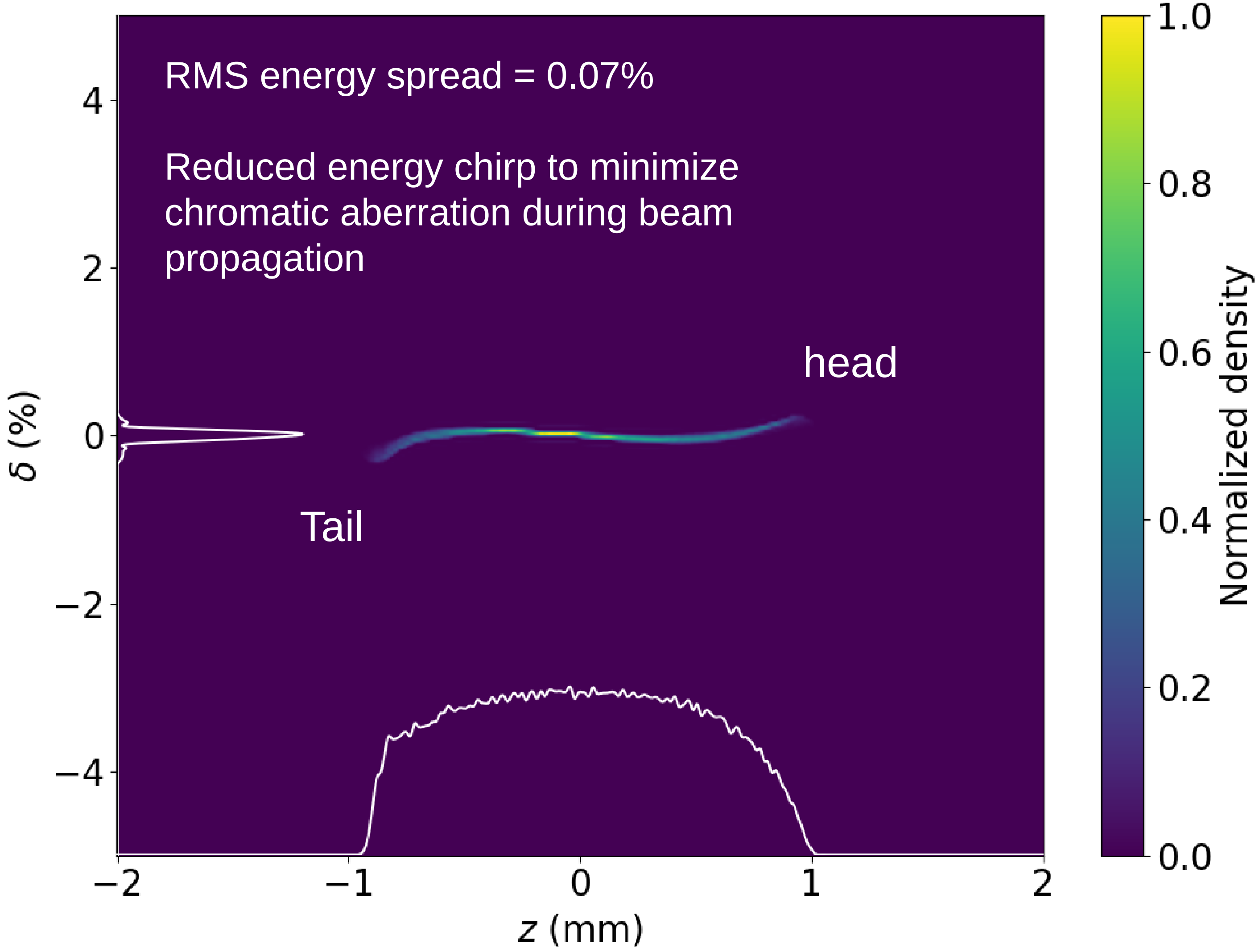
AWA beamline for demonstration



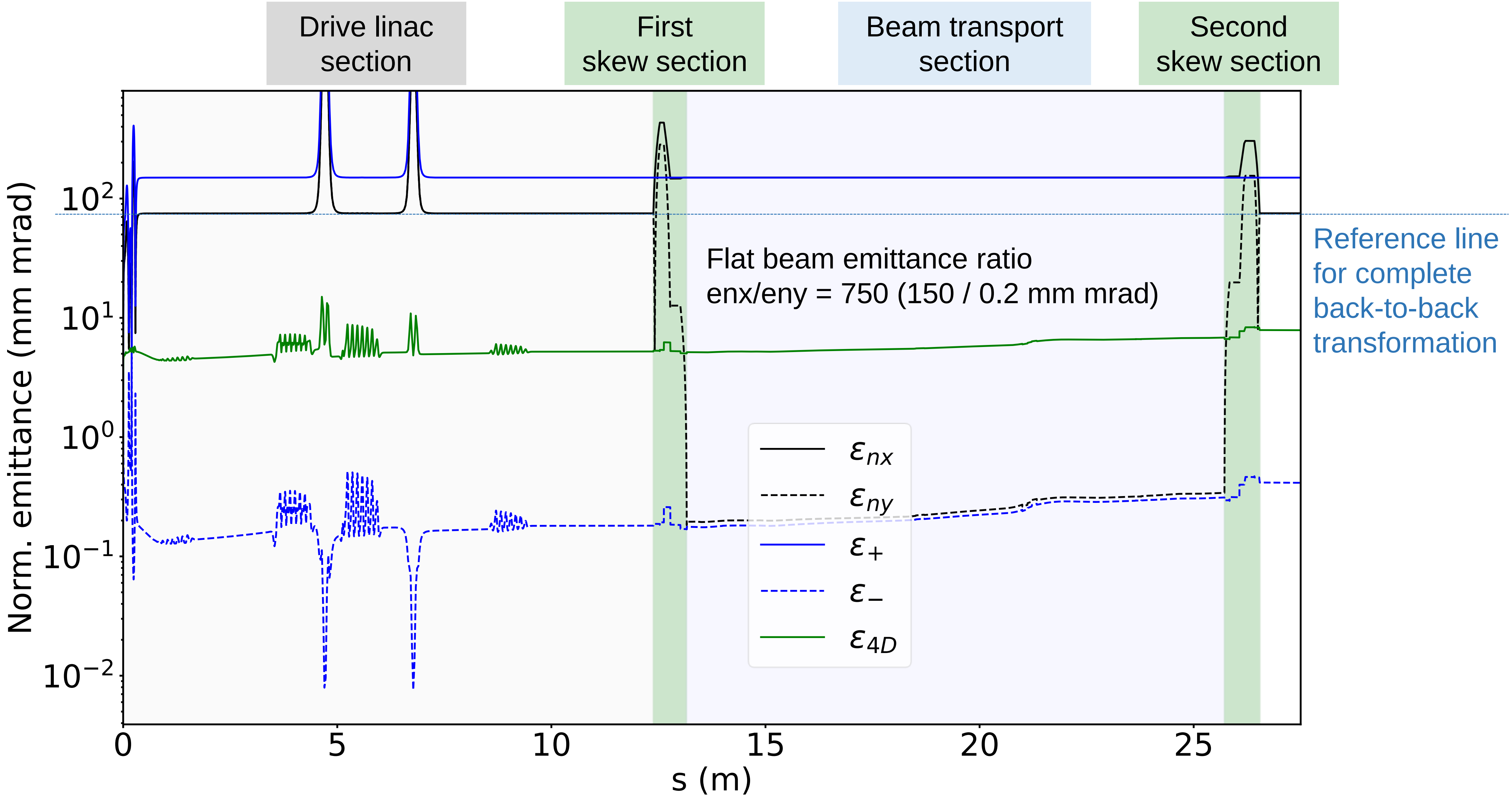
Parameters	Value
Initial UV radius	2.7 mm (1sigma = 1.35 mm)
UV pulse	3.0 ps FWHM (in exp, 4 BBO crystals used)
Charge	1.0 nC
Gun phase^1 Linac phase^2	^{1} -25 degree from 50 degree ^{2} -12 / -12 / -25 / -25 degree from on-crest (L1, 2, 3, 5)
Beam energy	40 MeV
B/F solenoid magnet	550 A >> 0.14 T

Start-to-end OPAL simulation results

- Longitudinal phase space (LPS) after drive linac



Start-to-end OPAL simulation results

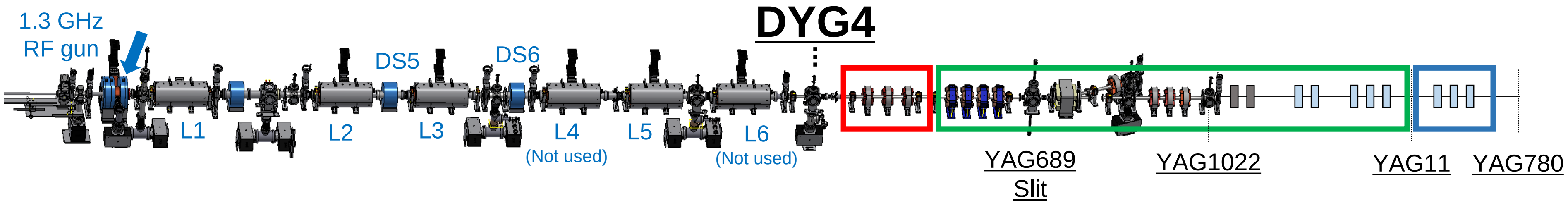


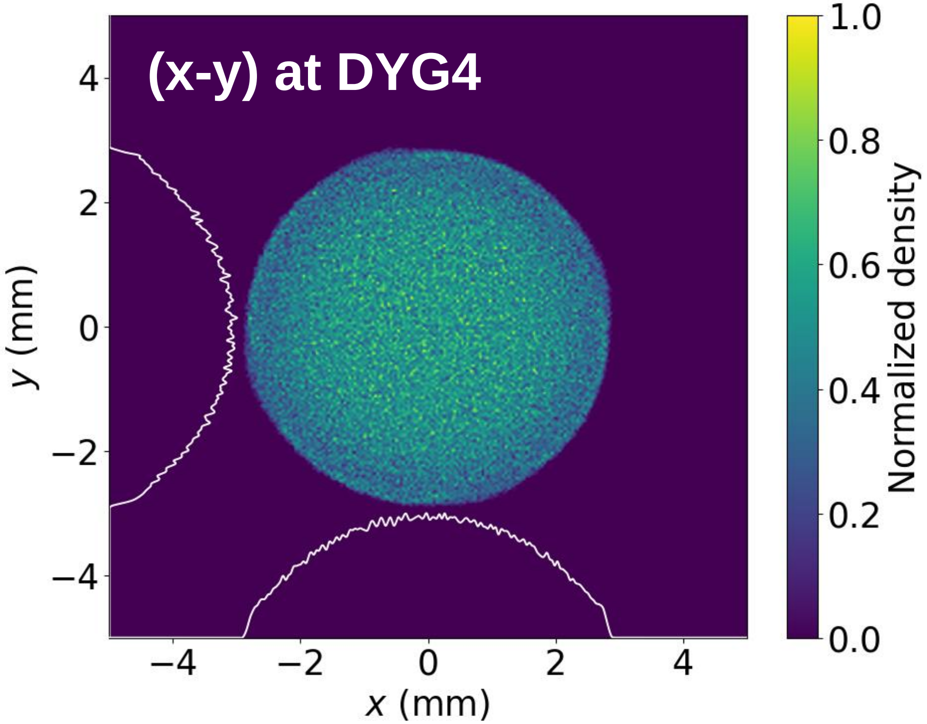
Flat beam emittance ratio
enx/eny = 750 (150 / 0.2 mm mrad)

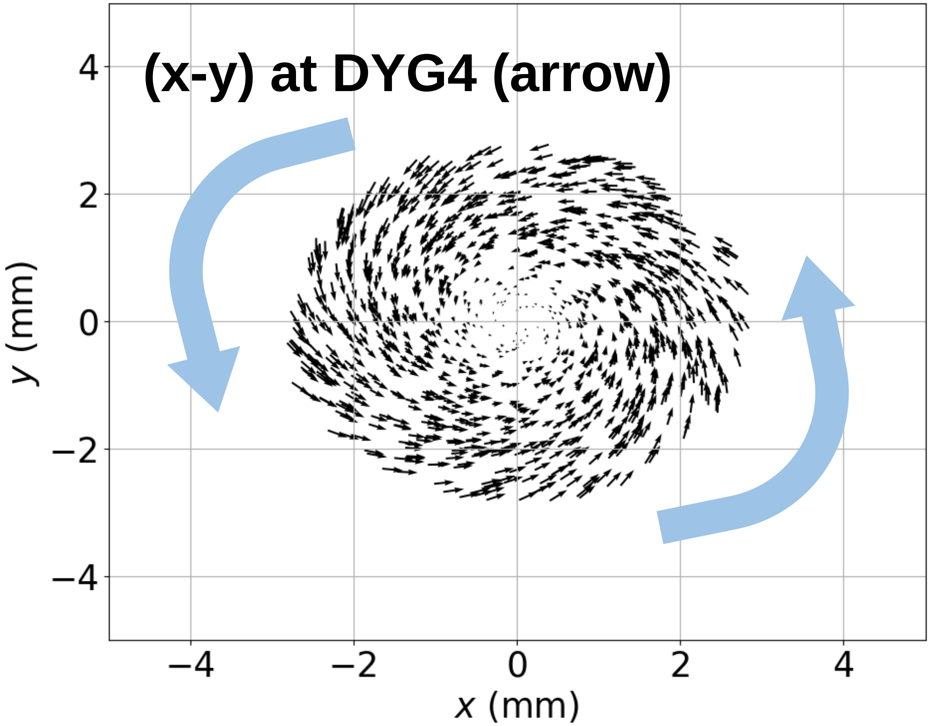
Reference line for complete back-to-back transformation

Start-to-end OPAL simulation results

- **Position a): Round, magnetized beam: at DYG4 position**

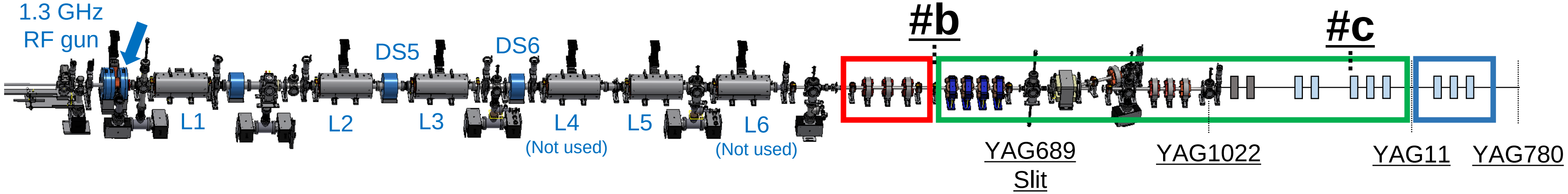


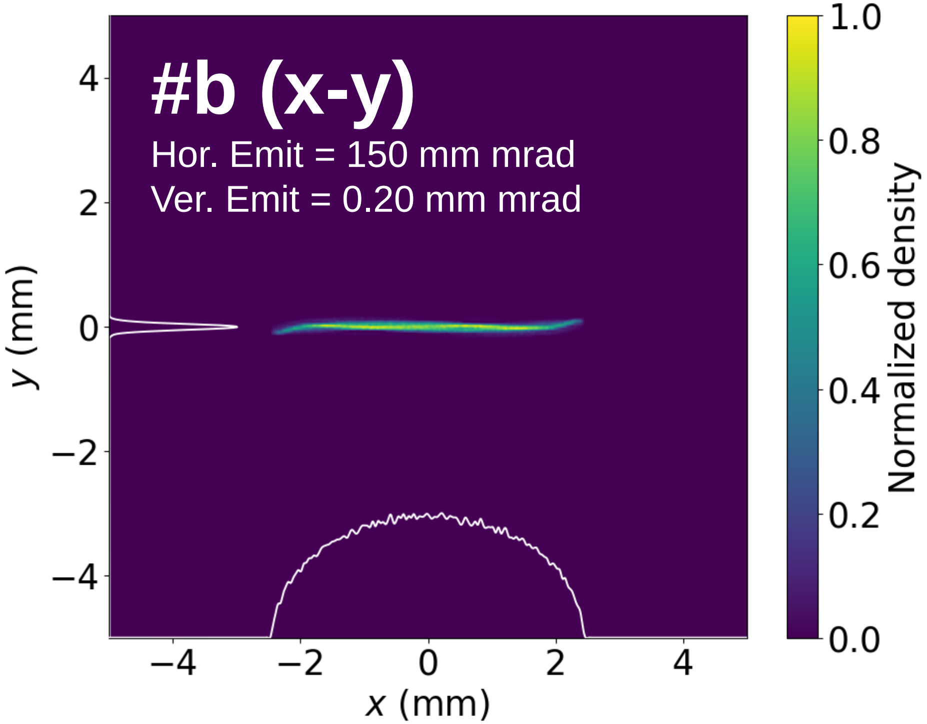


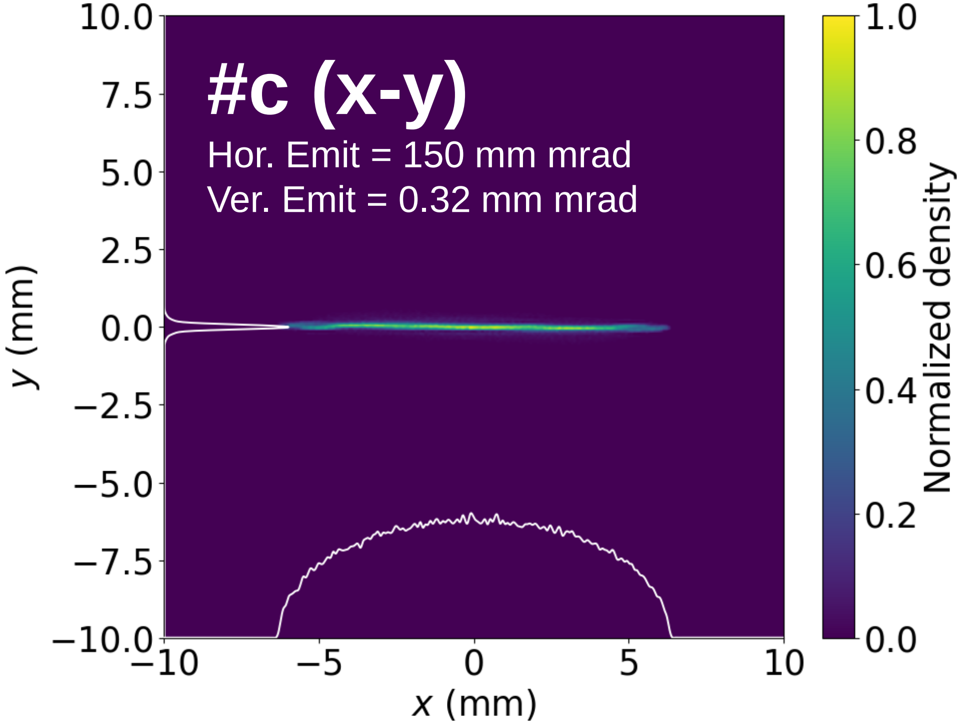


Start-to-end OPAL simulation results

- **Position b) and c): Right after 1st, and before 2nd skew triplets**

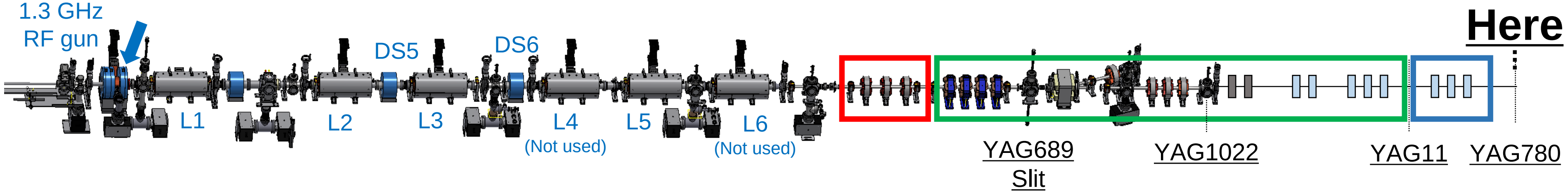


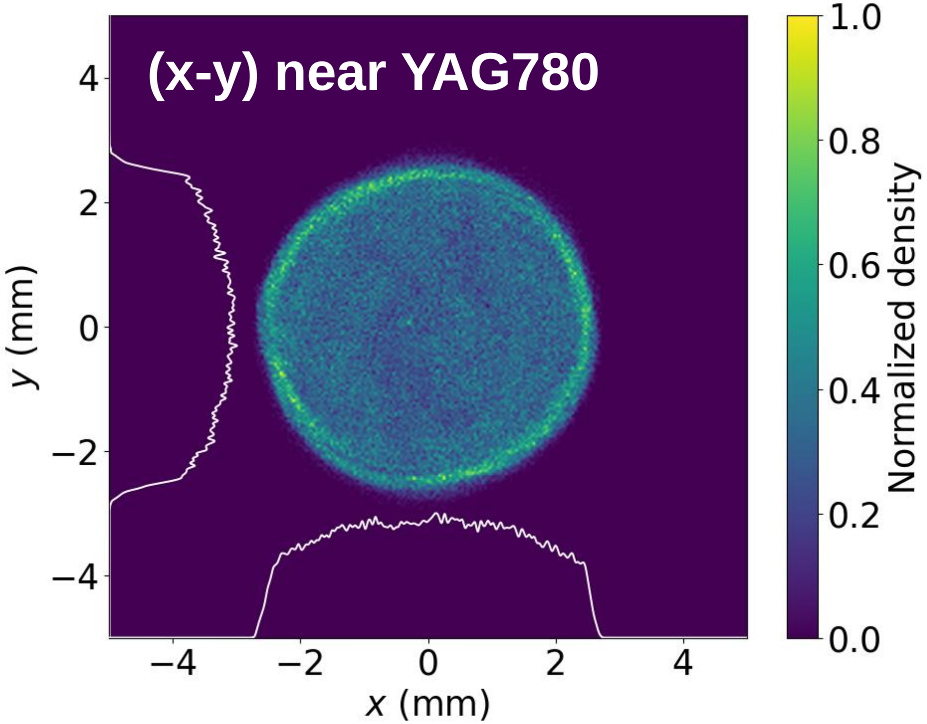


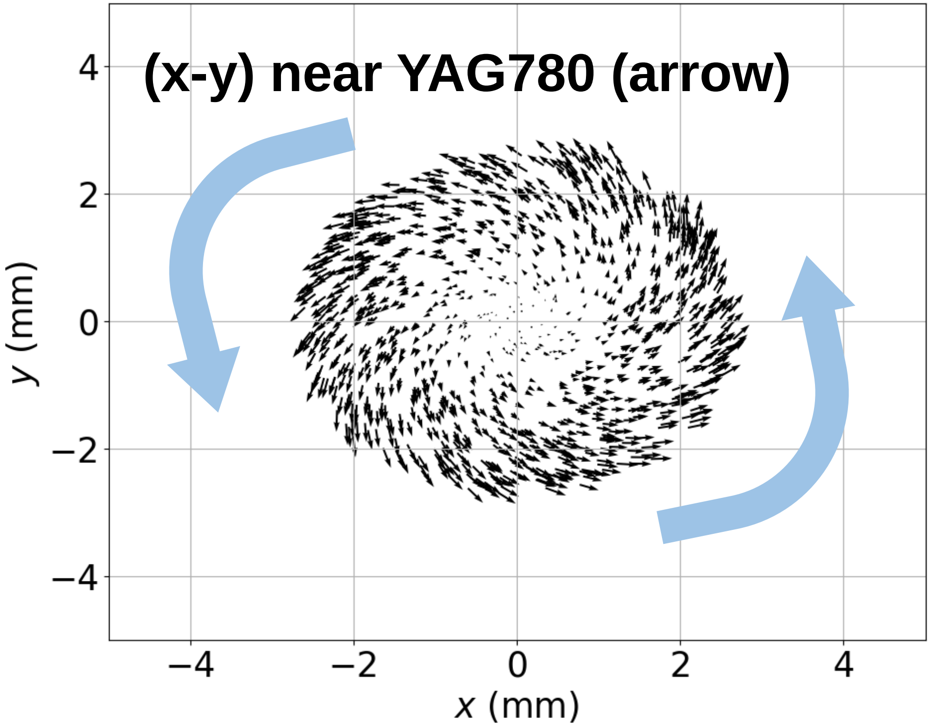


Start-to-end OPAL simulation results

- **Position d: After 2nd skew triplet**

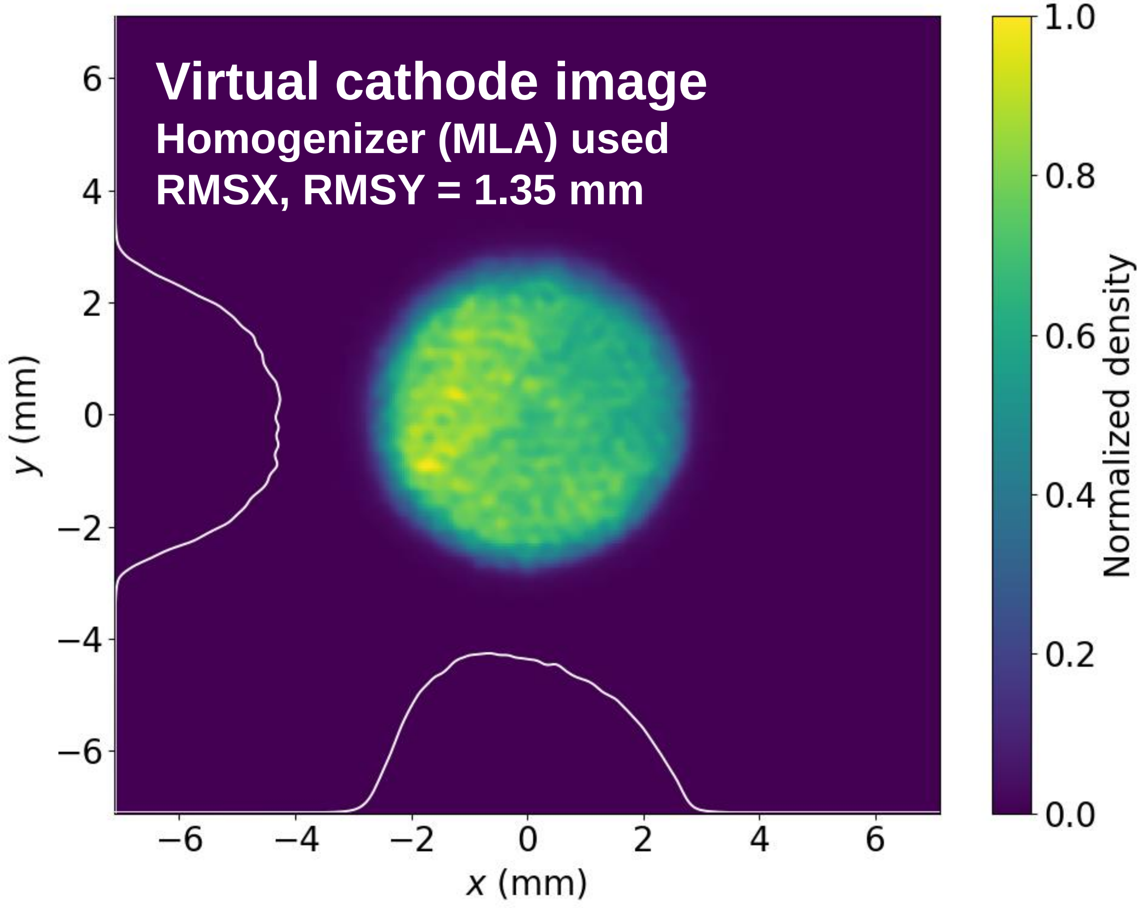


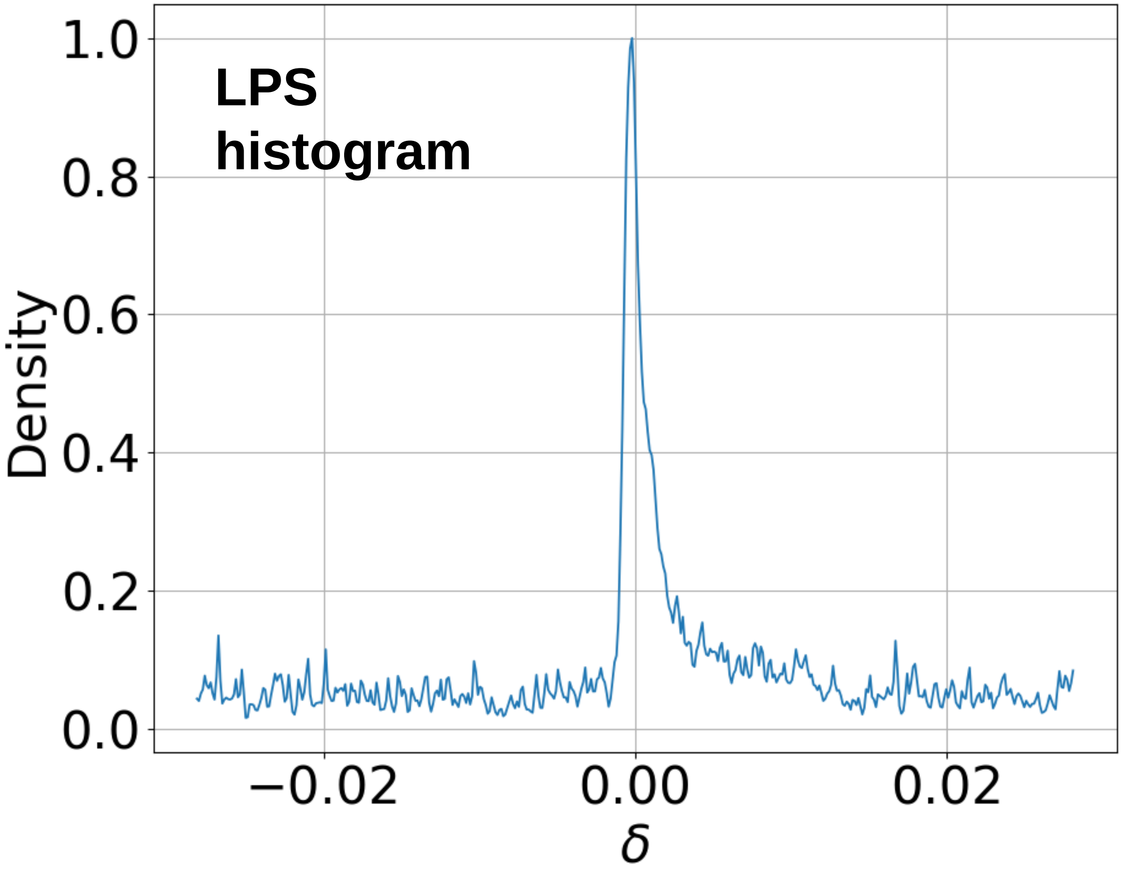




Experimental demonstration at the AWA

Virtual cathode and LPS measurement



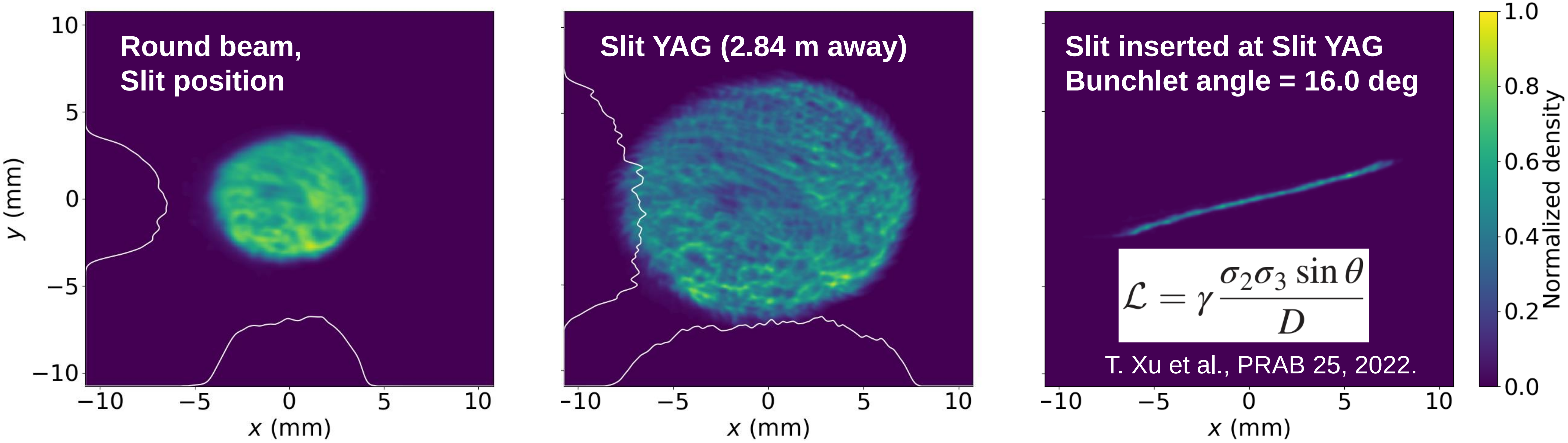


*Systematic error not included
**Including 10% error of virtual cathode measurement

Round beam Magnetization measurement

- **550 A Focusing solenoid current (~0.14 T)**

Beam energy = 43.36 MeV

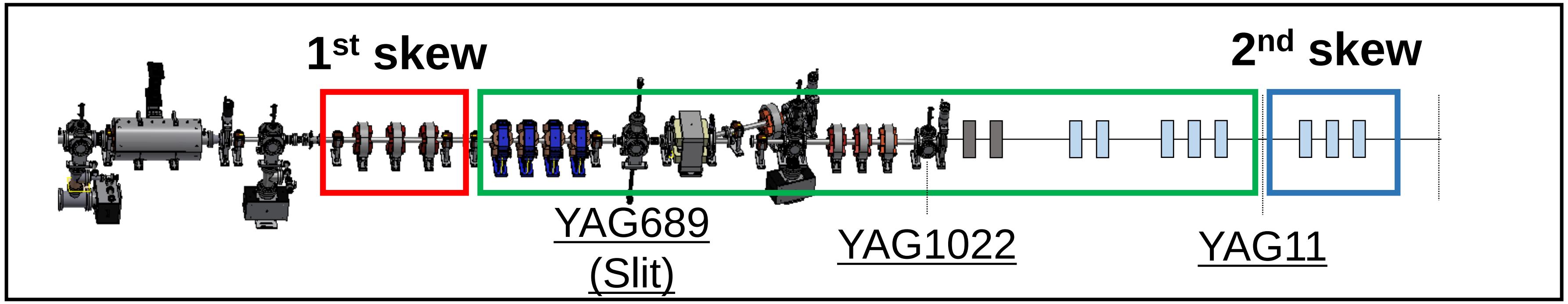


$$\mathcal{L} = \gamma \frac{\sigma_2 \sigma_3 \sin\theta}{D}$$

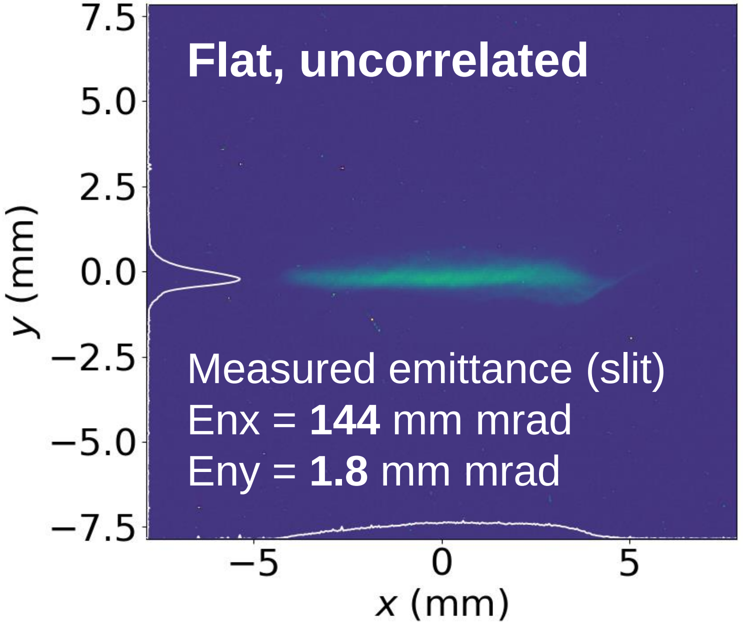
T. Xu et al., PRAB 25, 2022.

Magnetization L = 63.1±0.7 um*
(Theoretically, 74.7±15.7 um **)

Flat beam measurement



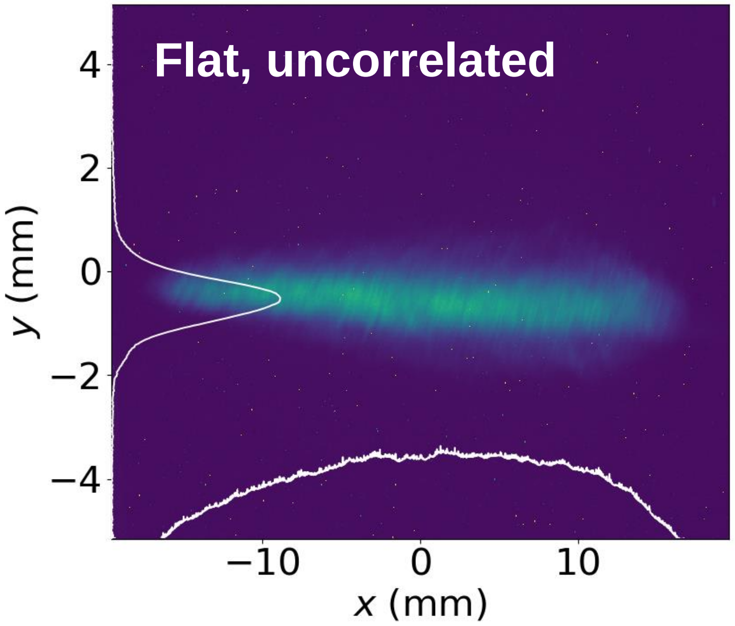
YAG689 (after 1st skew)



Flat, uncorrelated

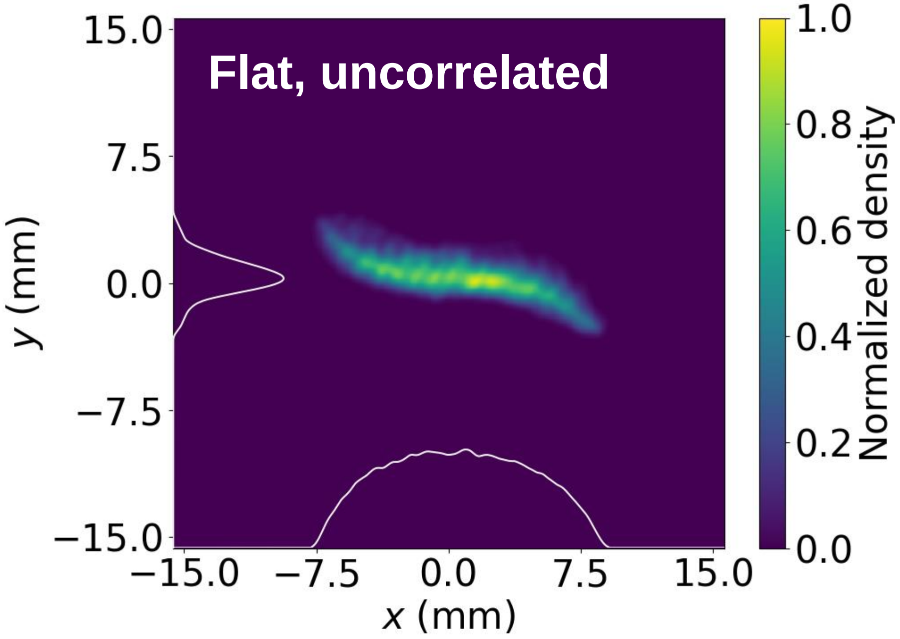
Measured emittance (slit)
Enx = **144** mm mrad
Eny = **1.8** mm mrad

YAG1022 (2.84 away from YAG689)



Flat, uncorrelated

YAG11 (right before 2nd skew triplet)

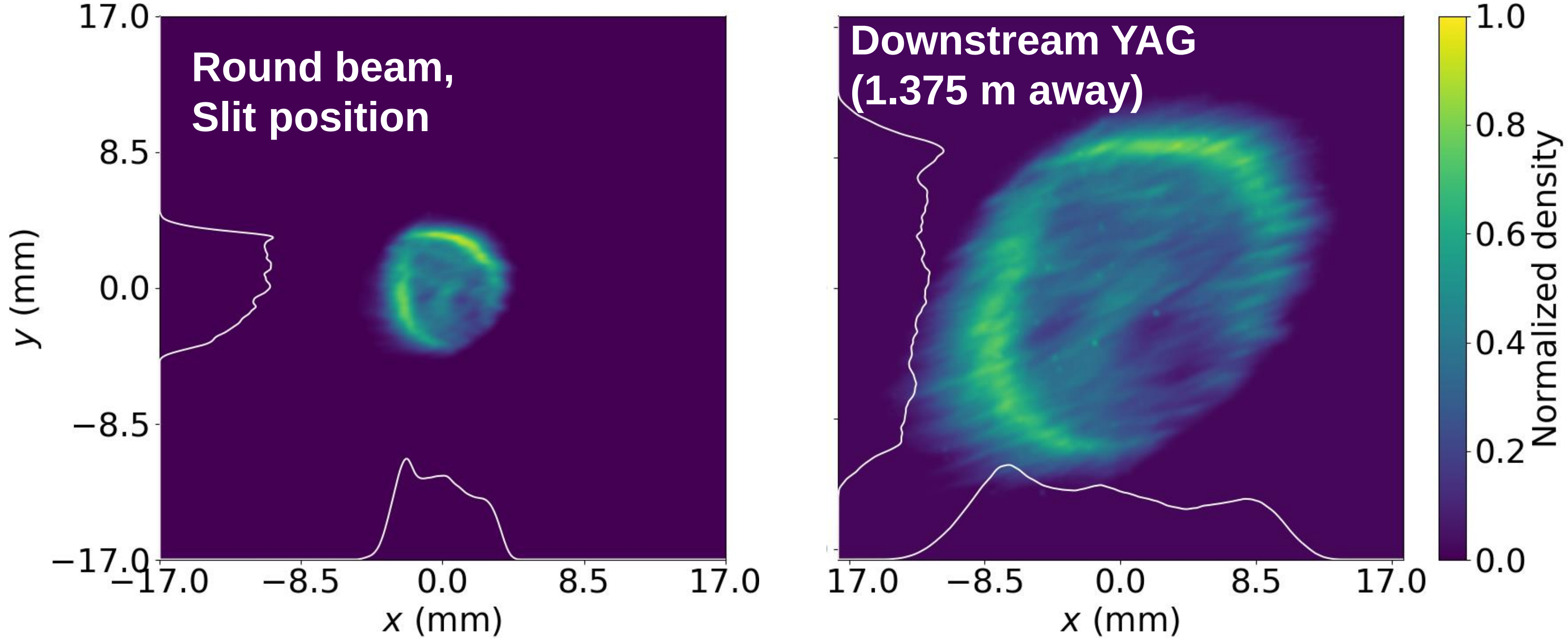


Flat, uncorrelated

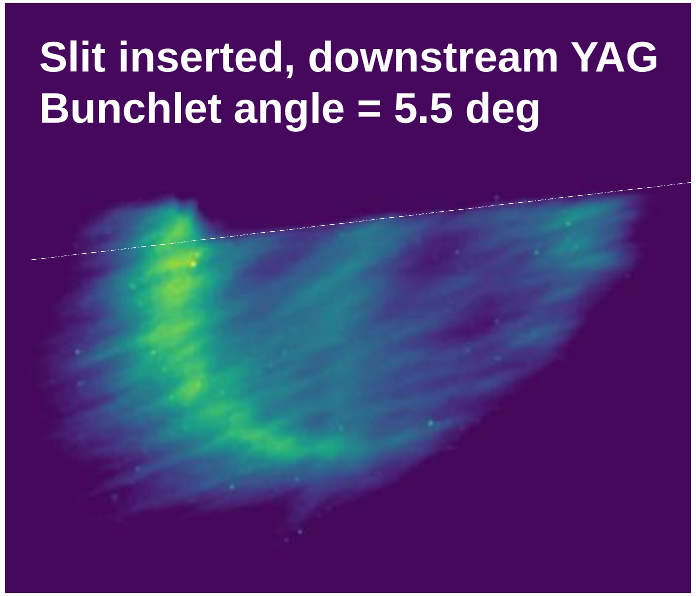
*Systematic error not included

Magnetization measurement: Zone 5

- **After second skew triplet**



Beam energy = 43.36 MeV



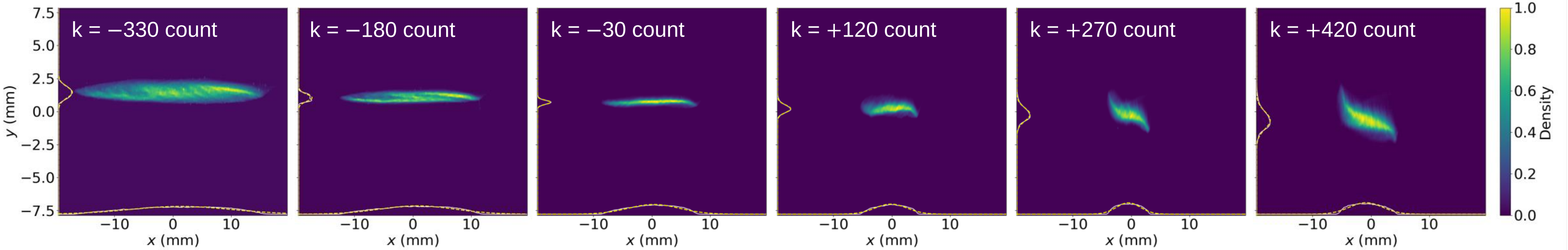
Magnetization L = 87.6±2.5 um*

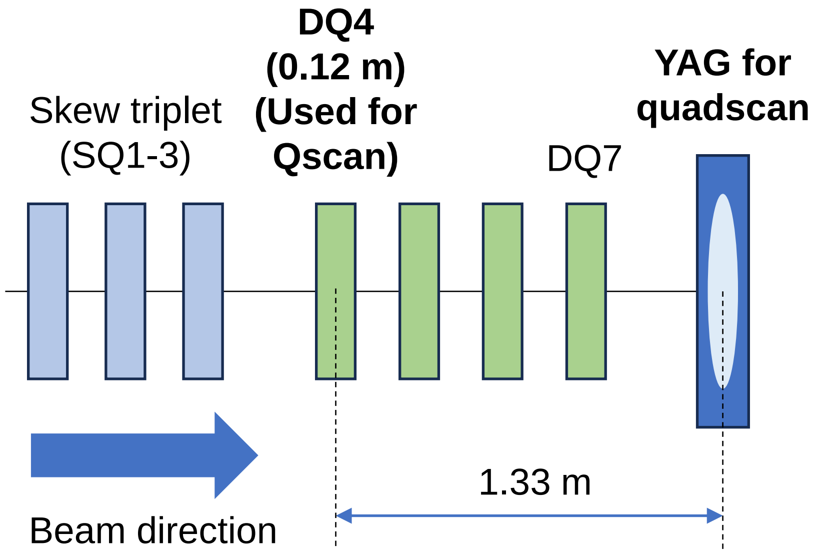
(Further data analysis and discussion are underway)

Beam characterization using phase space reconstruction*

- * Phase space reconstruction using differentiable simulation and neural networks, R. Roussel *et al.*, *Phys. Rev. Lett.* **130**, 145001, 2023.

Experimental data: Flat-beam quadscan





Skew triplet (SQ1-3)

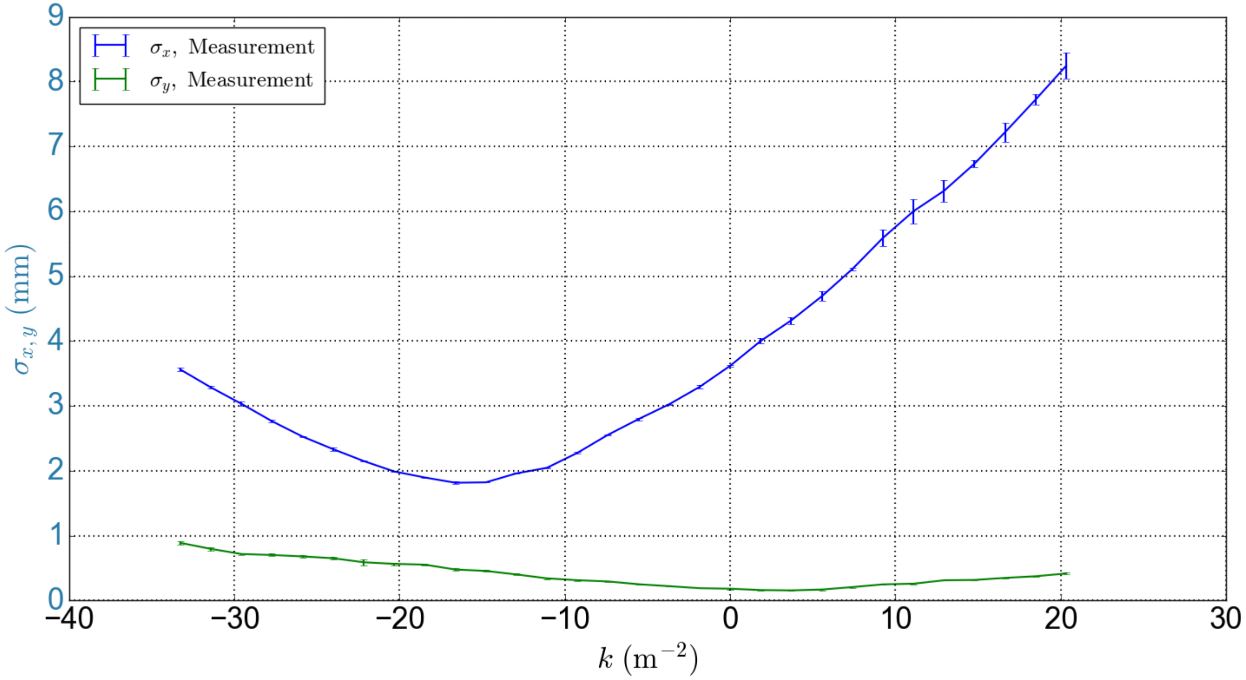
DQ4 (0.12 m) (Used for Qscan)

DQ7

YAG for quadscan

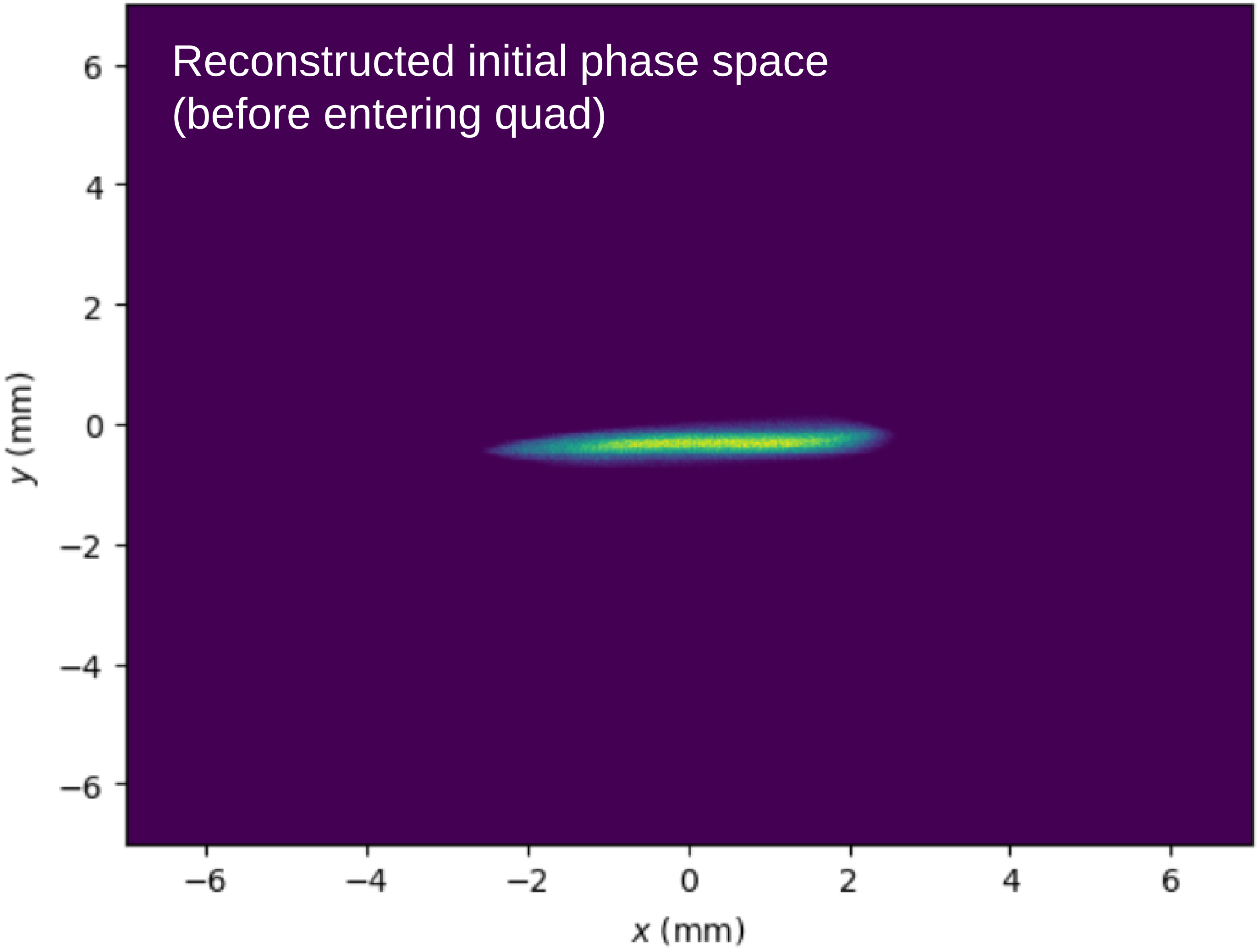
1.33 m

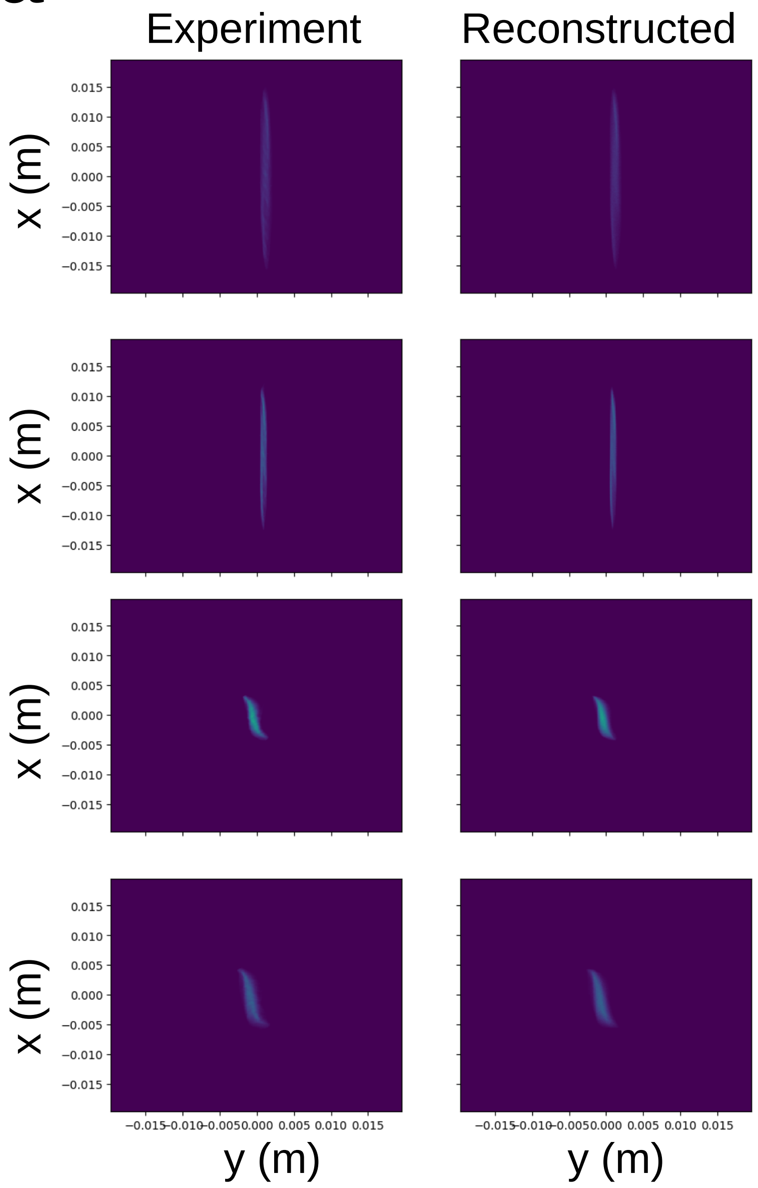
Beam direction



PS reconstruction using quadscan data

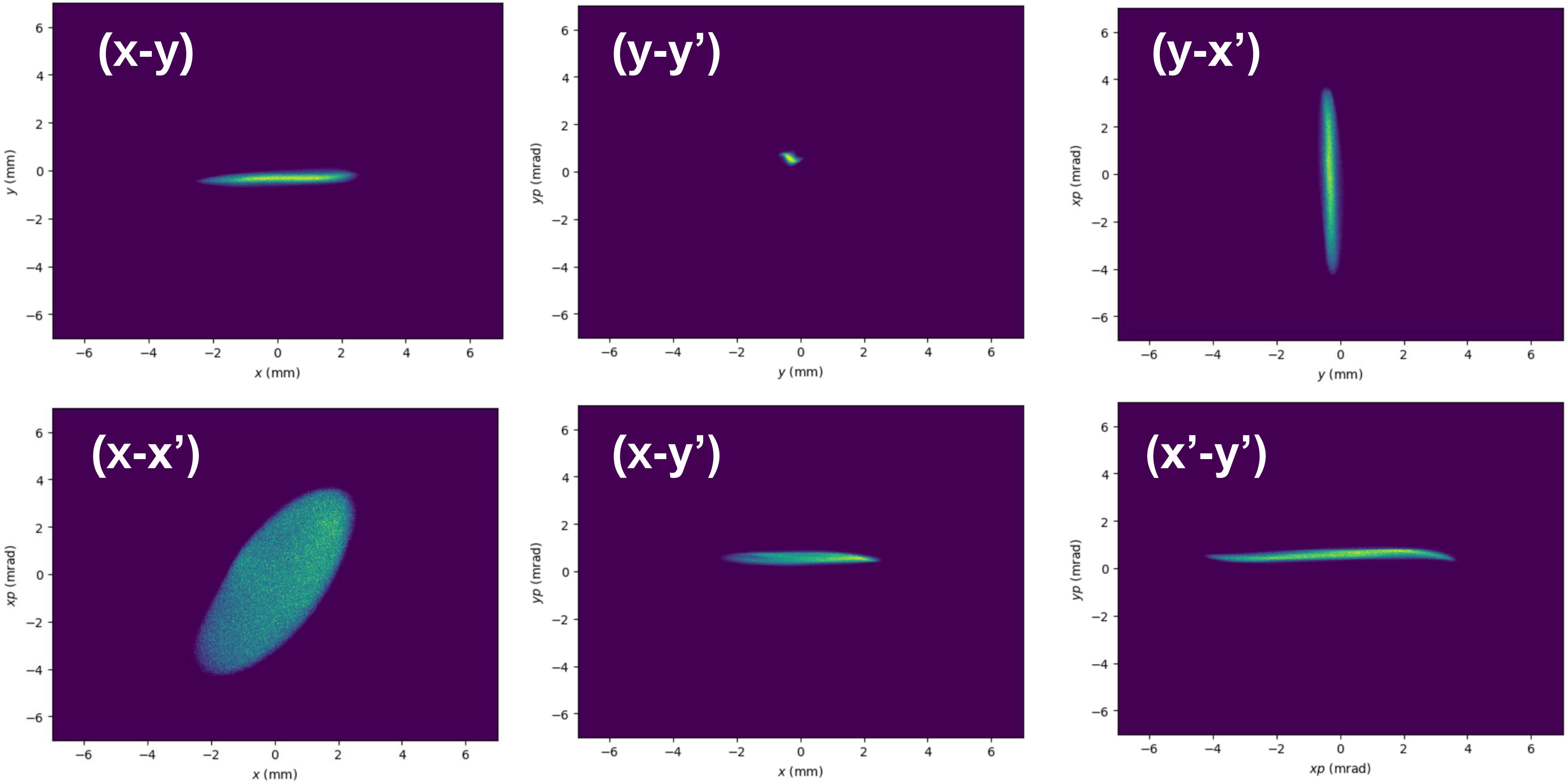
- 100k particle, 2000 Epoch, 1E11 loss function parameter





PS reconstruction: Initial phase space of flat-beam

- ➢ No significant transverse correlations observed



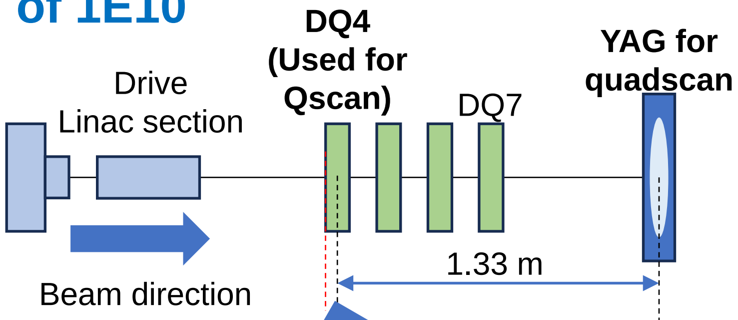
Comparison of beam parameters

Horizontal	Quadscan	PS-Reconstruction	Slitscan
Twiss beta (m)	0.92	0.84	Measured position is different
Twiss alpha (rad)	–1.02	–0.94	
Emit_nx (mm mrad)	144.6	133.0 (within 10%)	144.0

Vertical	Quadscan	PS-Reconstruction	Slitscan
Twiss beta (m)	1.42	1.11	Measured position is different
Twiss alpha (rad)	1.61	0.42	
Emit_ny (mm mrad)	1.5	1.4	1.8

PS reconstruction results

- **50k particle for NN, 21 dataset (quad strengths), 2000 epoch, loss function of 1E10**



Drive Linac section

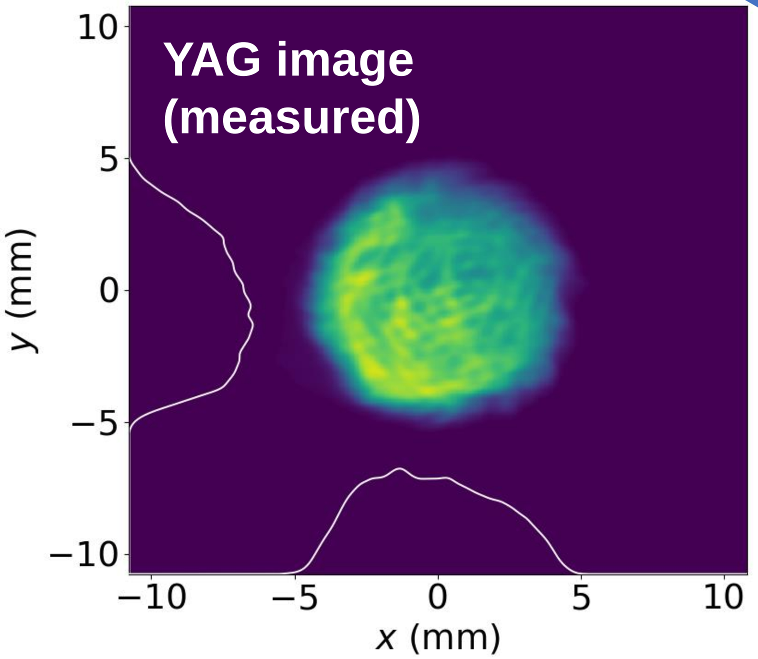
DQ4 (Used for Qscan)

DQ7

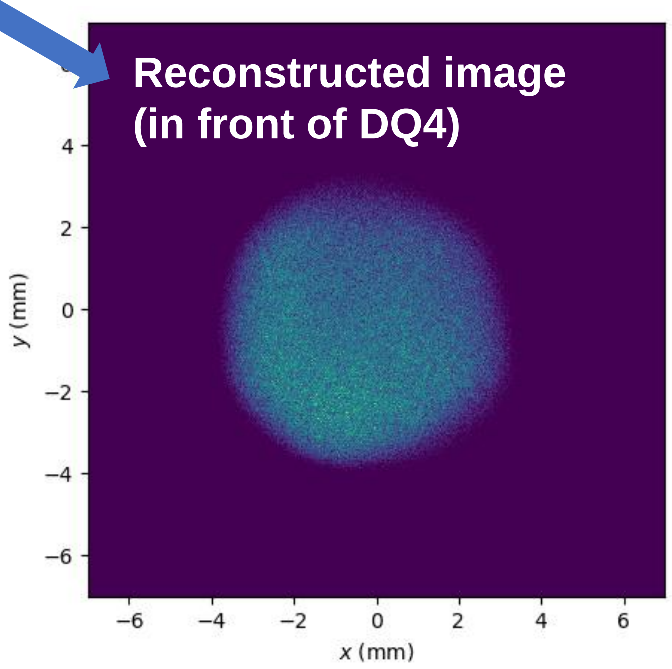
YAG for quadscan

1.33 m

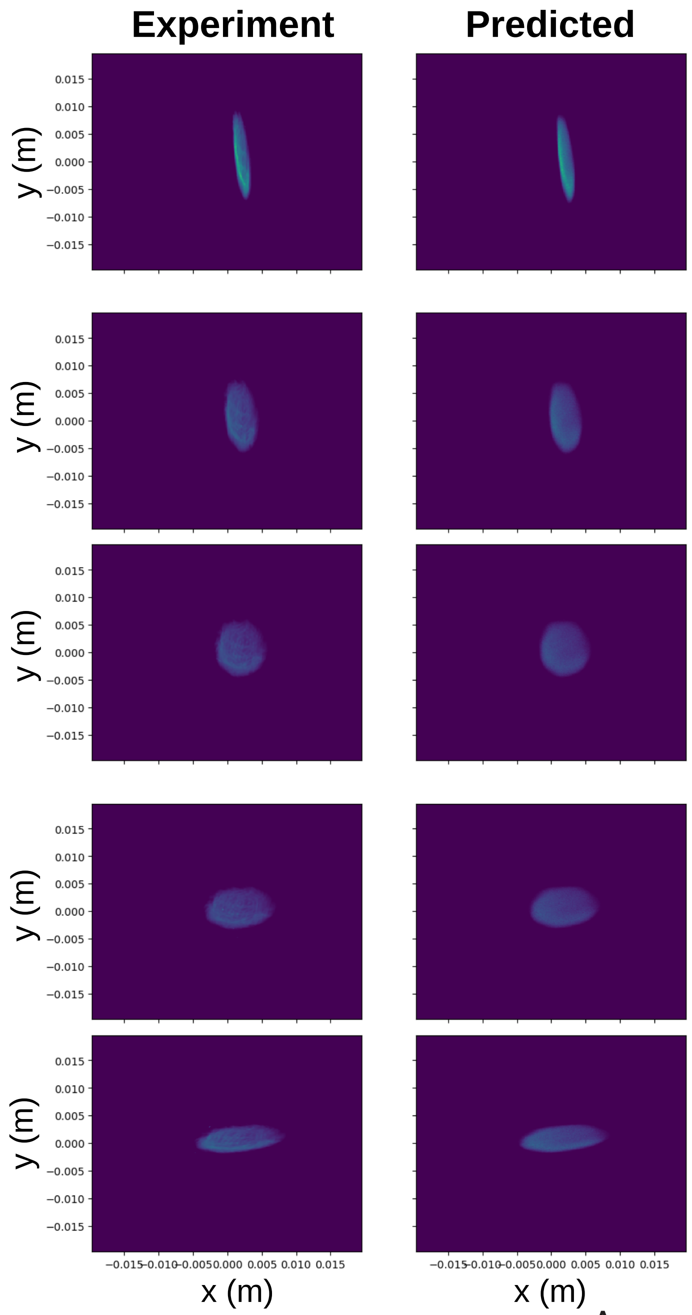
Beam direction



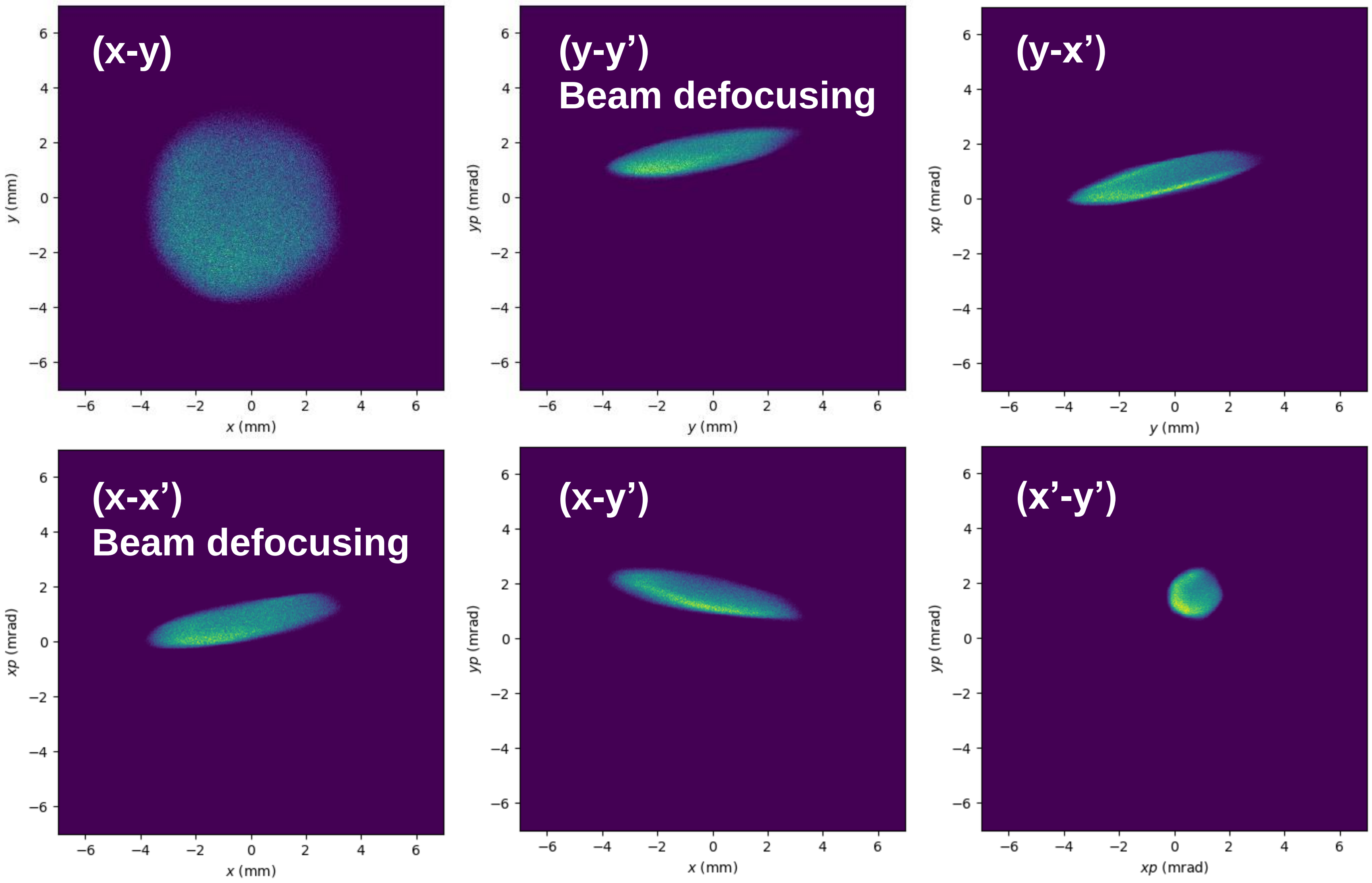
YAG image (measured)



Reconstructed image (in front of DQ4)



PS reconstruction results



(y-y') Beam defocusing

(x-x') Beam defocusing

Summary

- **Experimental demonstration of back-to-back was completed**
  - We successfully generated flat beam, and **transformed it back to round**
  - We are **currently investigating** the reason of emittance growth of the flat beam before second skew triplet, and the **increase of the magnetization**

- **Phase space reconstruction for flat and magnetized beams**
  - We found that the **reconstruction algorithm reconstructs the initial 4D phase space** (including coupling) for both flat beam and magnetized beam
  - For flat-beam: Through the reconstruction, we found that **the experimentally measured vertical emittance is larger than 1 mm mrad**
  - For round beam: we successfully reconstruct transversely coupled beam phase space
  - Further data analysis is on-going: magnetization measurement using slit+reconstructed 4D phase space compared to the experimental data

- **Future plans**
  - **We are working on two papers:** one for experimental demonstration, and the other for beam characterization using phase space reconstruction method

Acknowledgements

- **Argonne National Laboratory**

John Power, Gongxiaohui Chen
Scott Doran, Wanming Liu
Eric Wisniewski, Charles Whiteford

- **Northern Illinois University**

Philippe Piot (Principal Investigator)
Tianzhe Xu (Now at SLAC)

- **SLAC**

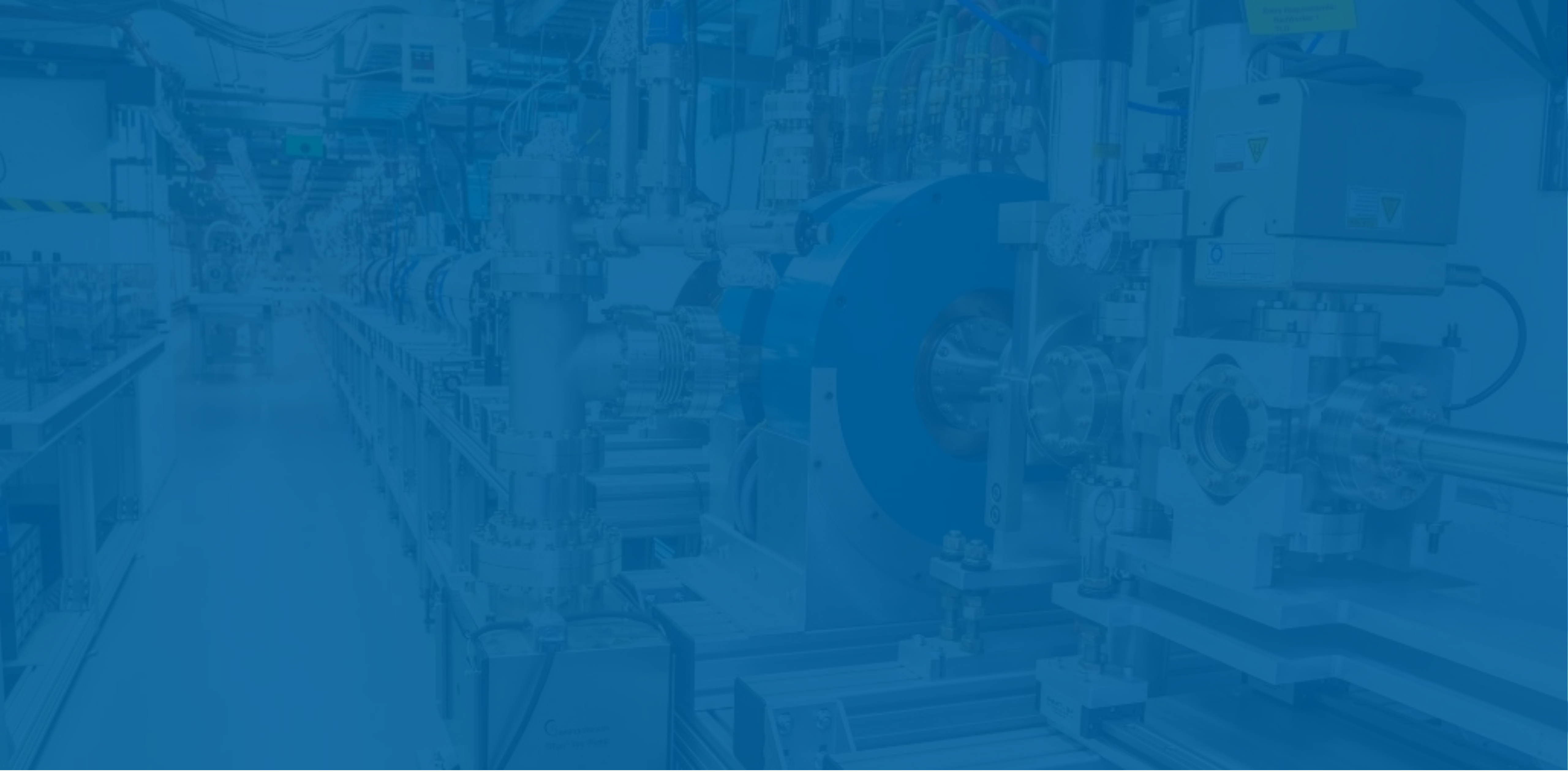
Auralee Edelen, Ryan Roussel

- **University of Chicago**

Juan Pablo Gonzalez-Aguilera

- **PSI, Switzerland**

Andreas Adelmann



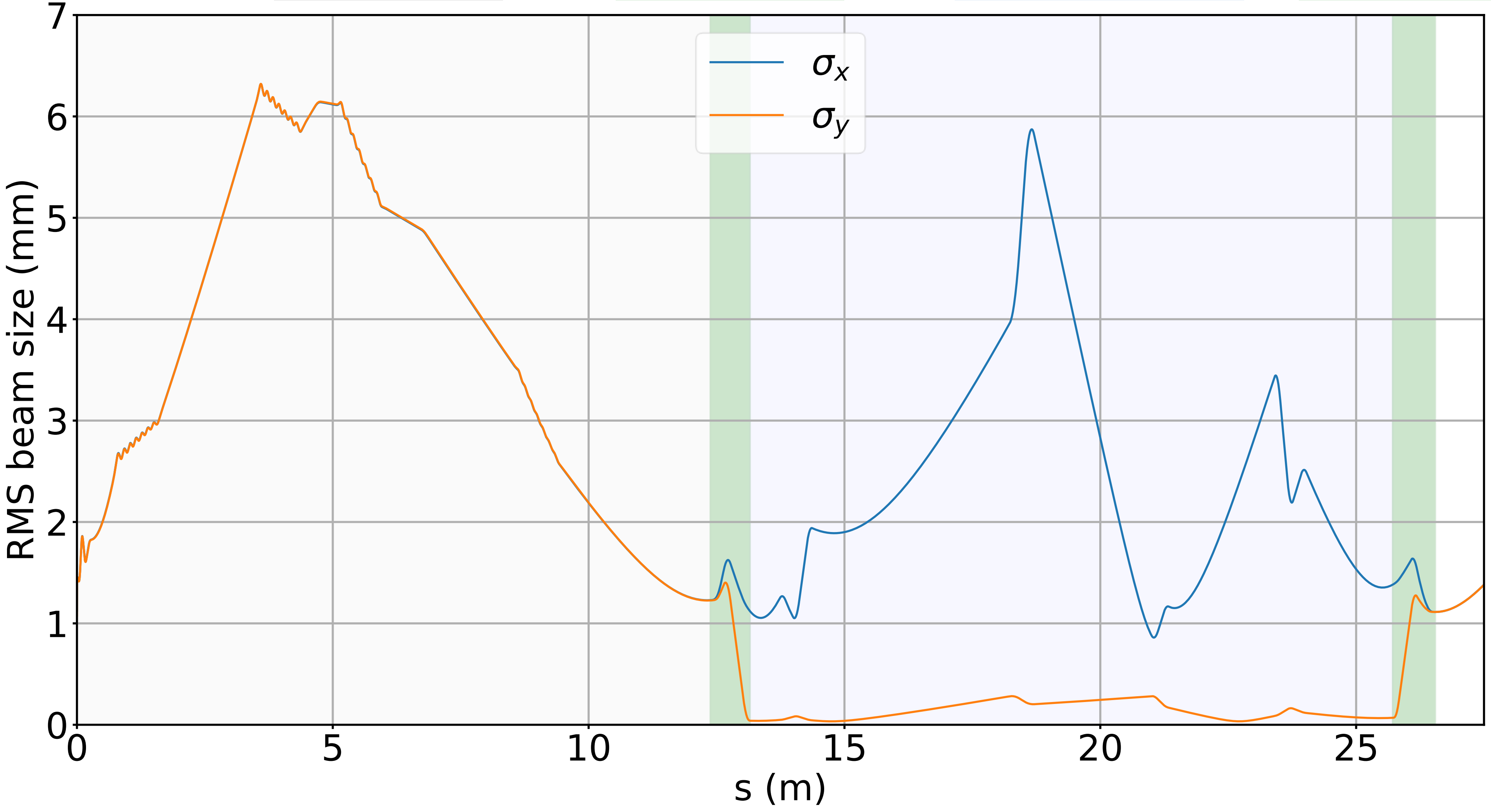
Start-to-end OPAL simulation results

Drive linac section

First skew section

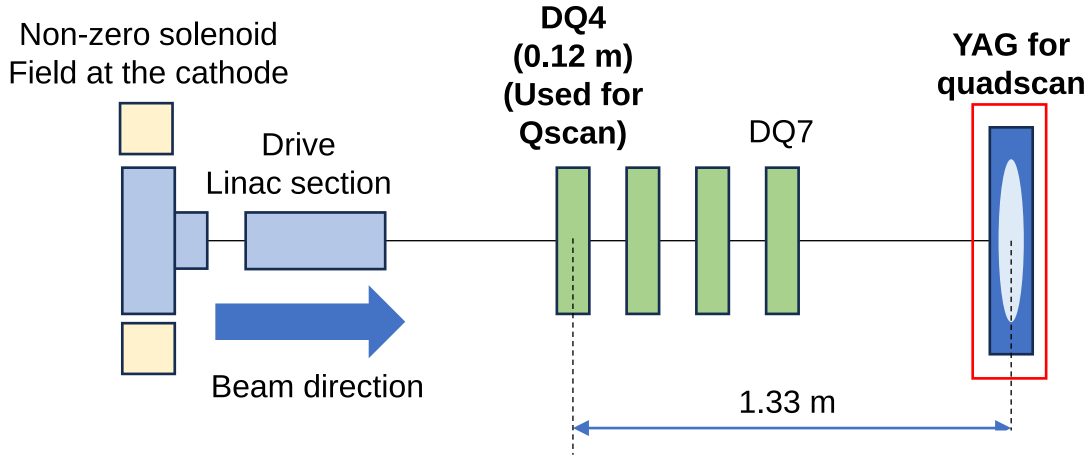
Beam transport section

Second skew section



Magnetized beam phase space reconstruction

- ➢ **393 A Focusing solenoid current (~0.10 T)**



Non-zero solenoid
Field at the cathode

Drive
Linac section

Beam direction

DQ4
(0.12 m)
(Used for
Qscan)

DQ7

YAG for
quadscan

1.33 m