All-optical, quasi-real-time measurement of the 3- and higher-dimensional structure of microbunched electrons from a laser-driven wakefield accelerator

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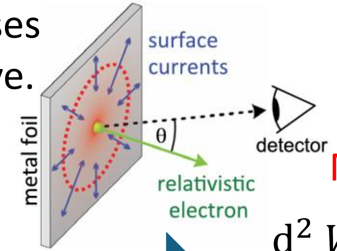
Outline

1. Introduction: coherent transition radiation & experimental setup
2. Results & analysis: quasi-real-time, all-optical, generative neural network
3. Conclusion & outlook: higher-dimensional phase space measurement

Introduction: Coherent Transition Radiation

Transition Radiation (TR) is emitted when charged particle passes from one medium into another with different index of refractive.



Single e- TR field in the far field:

$$\frac{\mathrm{d}^2 W_1}{\mathrm{d}\omega \mathrm{d}\Omega} = \frac{e^2}{4\pi^3\epsilon_0 c}\frac{\beta^2 \sin^2\theta}{(1-\beta^2\cos^2\theta)^2}$$ (Ginzburg Frank formula)

Multiple e- TR field in the far field: $F(\omega,\theta) = \int \rho(\boldsymbol{r}) e^{i\boldsymbol{kr}} \mathrm{d}\boldsymbol{r}$

$$\frac{\mathrm{d}^2 W_N}{\mathrm{d}\omega \mathrm{d}\Omega} = [N + N(N-1)\cdot |F(\omega,\theta)|^2]\cdot \frac{\mathrm{d}^2 W_1}{\mathrm{d}\omega \mathrm{d}\Omega}$$

in the near field (imaged by a lens system):

$$\boldsymbol{E}^{\boldsymbol{1}}(\boldsymbol{k},\boldsymbol{r}) = \frac{2e}{\lambda M}\int_0^{\theta_{\max}} d\theta \cdot \frac{\theta^2}{\theta^2+\gamma^{-2}} J_1(k\theta r)\,\boldsymbol{e_r}$$

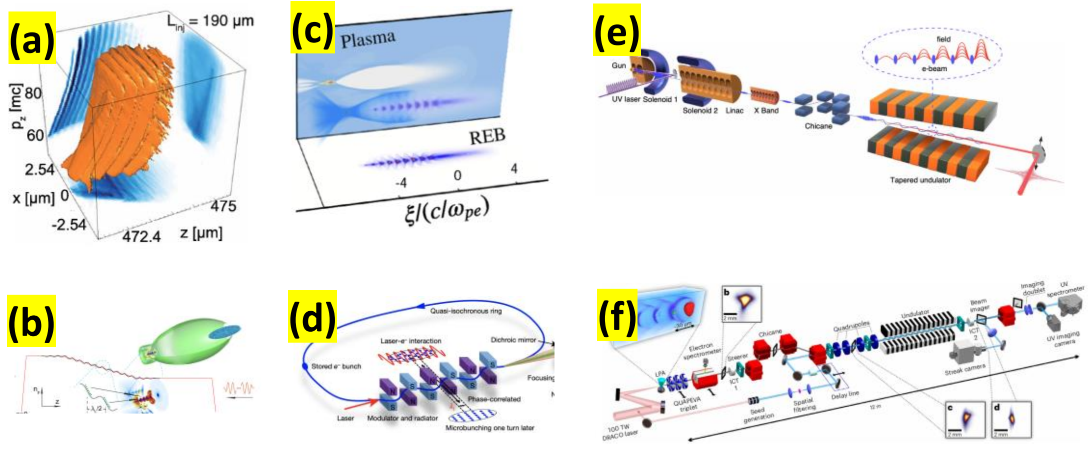
in the near field:

$$\boldsymbol{E}^{(\boldsymbol{n})}(\boldsymbol{k},\boldsymbol{r}) = \int dr'^3 \cdot Q\boldsymbol{E}(\boldsymbol{r}-\boldsymbol{r}')e^{-ikz'}\rho(\boldsymbol{r}')$$

TR becomes coherent and detectable when multiple electron radiate in phase. i.e. microbunching -> optical range

Both far-field and near-field CTR measurements contain the phase-space information of electron bunches.

(To solve the inverse problem)



μ-bunched in LWFA μ-bunched in an undulator μ-bunched in an FEL

(a) Phys. Rev. Lett. ***117****, 034801 (2016)*

(b) Nat. Commun. ***13****:3364 (2022)*

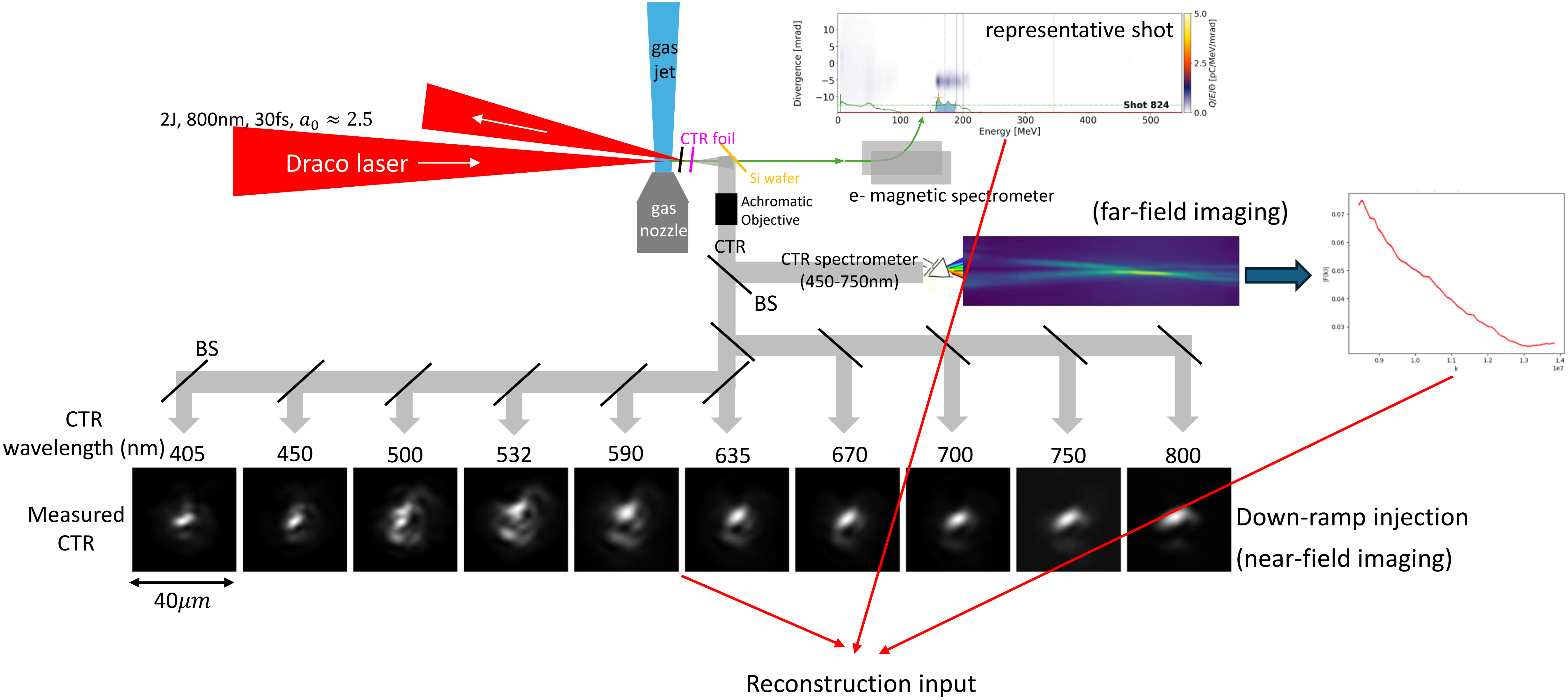
(c) MRE ***10****, 057203 (2025)*

(d) Nature ***590****, 576-579 (2021)*

(e) Light Sci. Appl. ***15****, 60 (2026)*

(f) Nat. Photon. ***17****, 150-156 (2022)*

Introduction: Experimental setup



Results & analysis: Reconstruction pipeline

electron bunch representation:

A set of macroparticles $\{p_i, i = 1,2,\ldots,n\}$. Each $p_i = (x_i, y_i, z_i, q_i, \gamma_i)$.

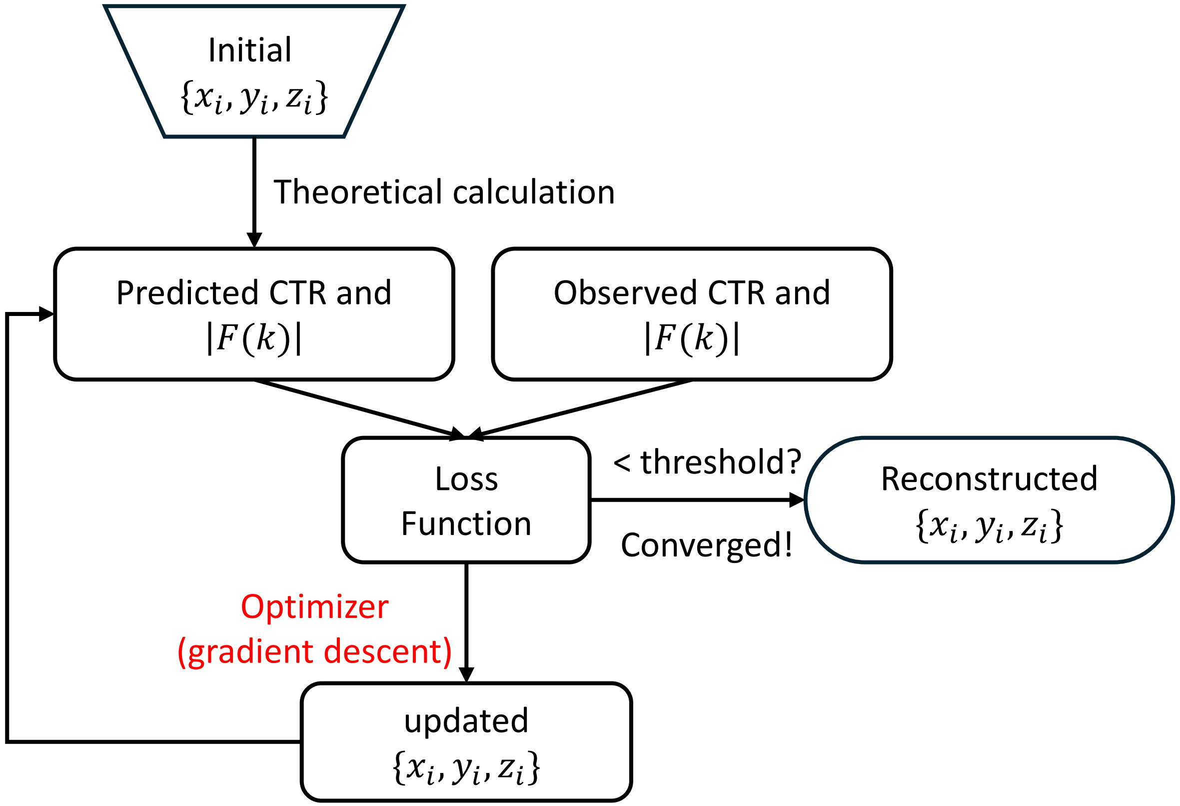
The reconstruction algorithm finds best set of (x_i, y_i, z_i), to simultaneously minimize the loss function, defined by

$$Loss = \alpha[CTR_i(k,x,y) - CTR_0(k,x,y)]^2 + \beta[|F_i(\boldsymbol{k})| - |F_0(\boldsymbol{k})|]^2$$

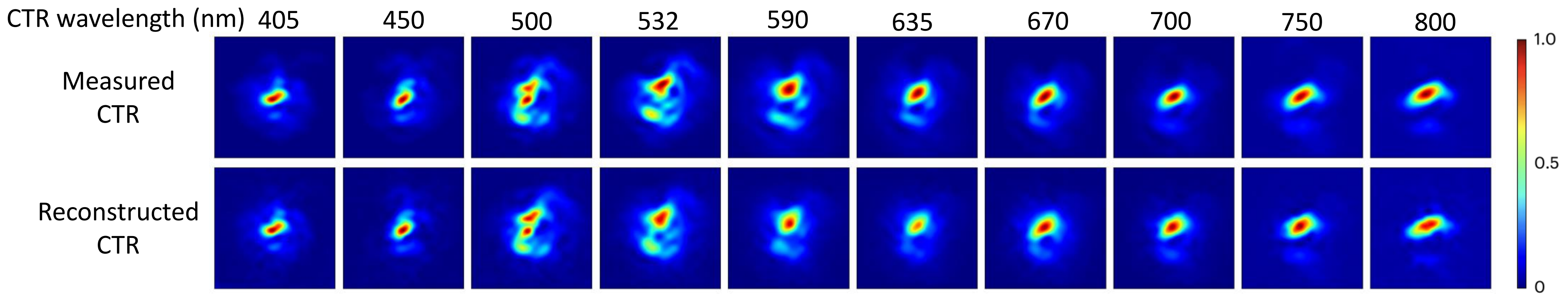
, which is the difference between **measured** and **reconstructed**

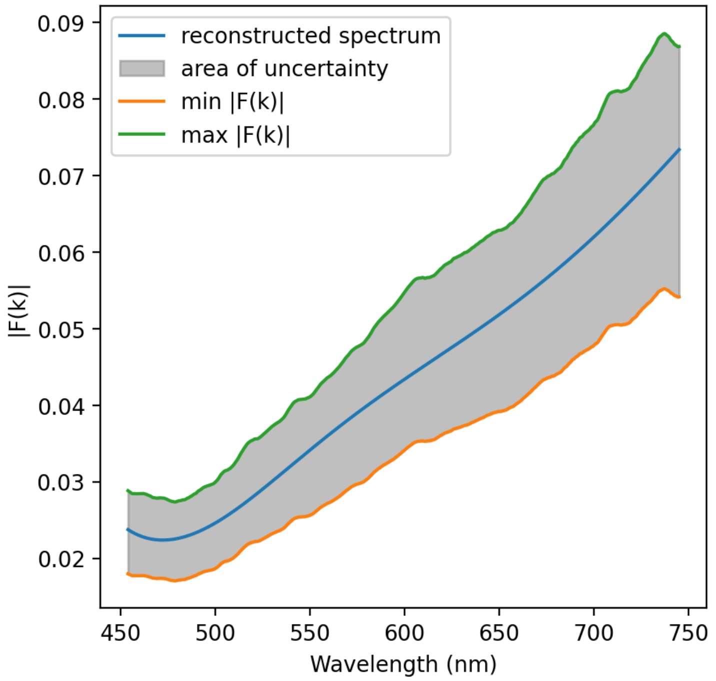
1. Multi-λ CTR images
2. form factor $|F(\boldsymbol{k})|$

Here $q_i = Q/N$, Q is total charge measured by the e- spectrometer, γ_i is the Lorentz factor, whose distribution is measured by the e- magnetic spectrometer.

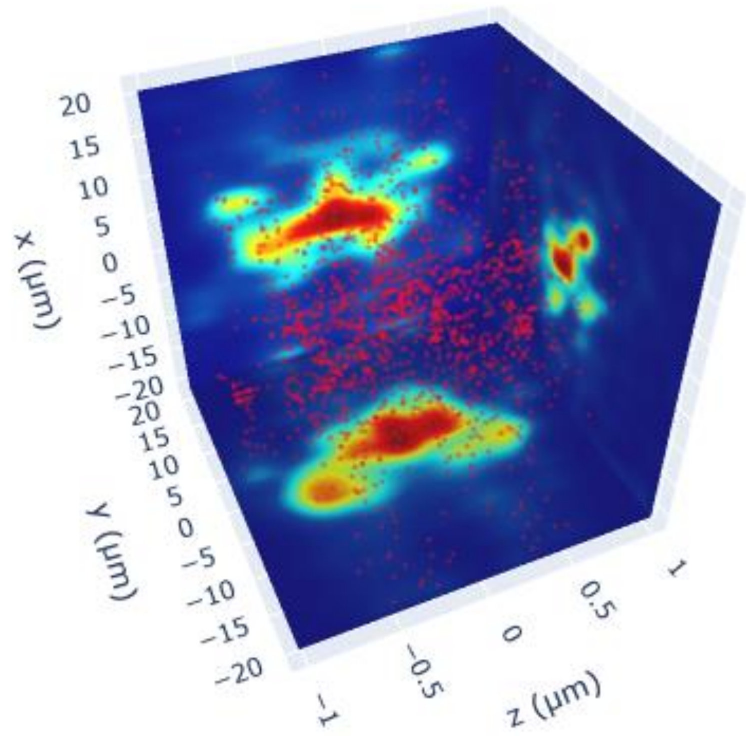


Results & analysis: Reconstruction result

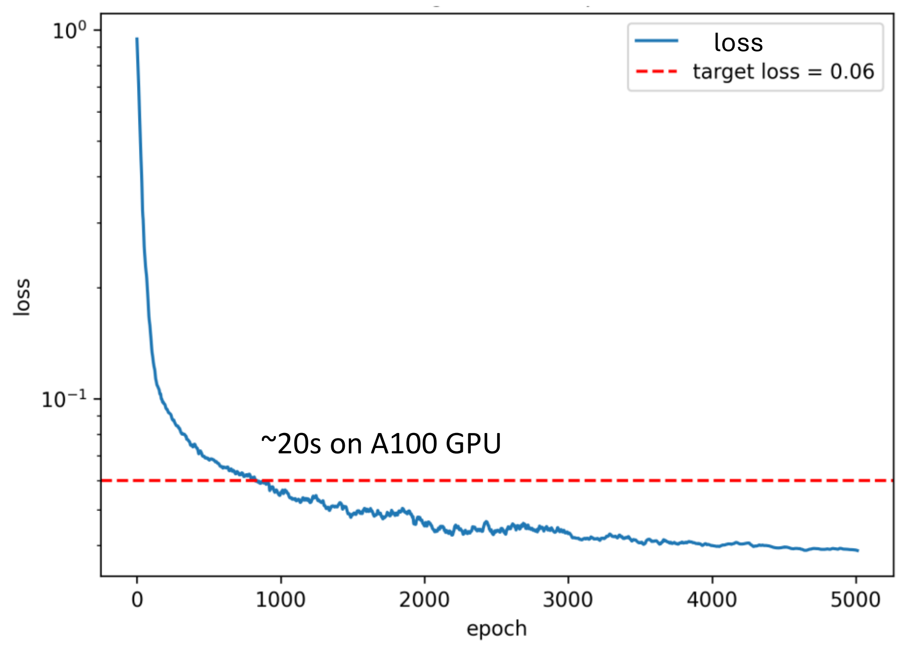




Form factor $|F(k)|$

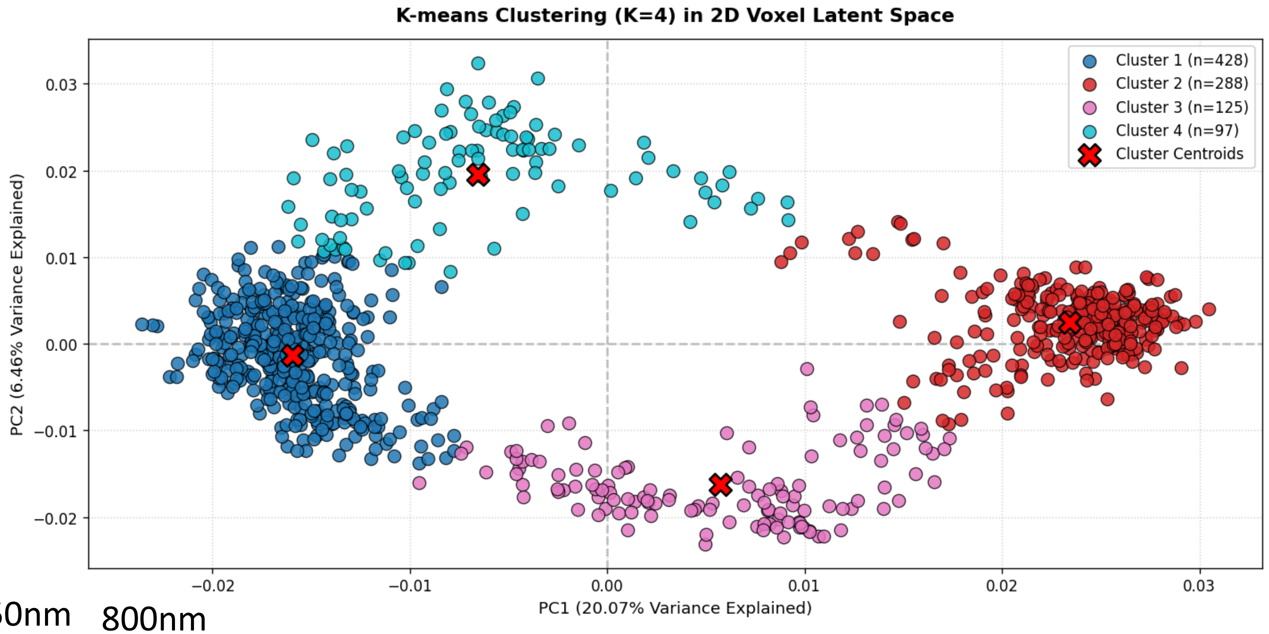


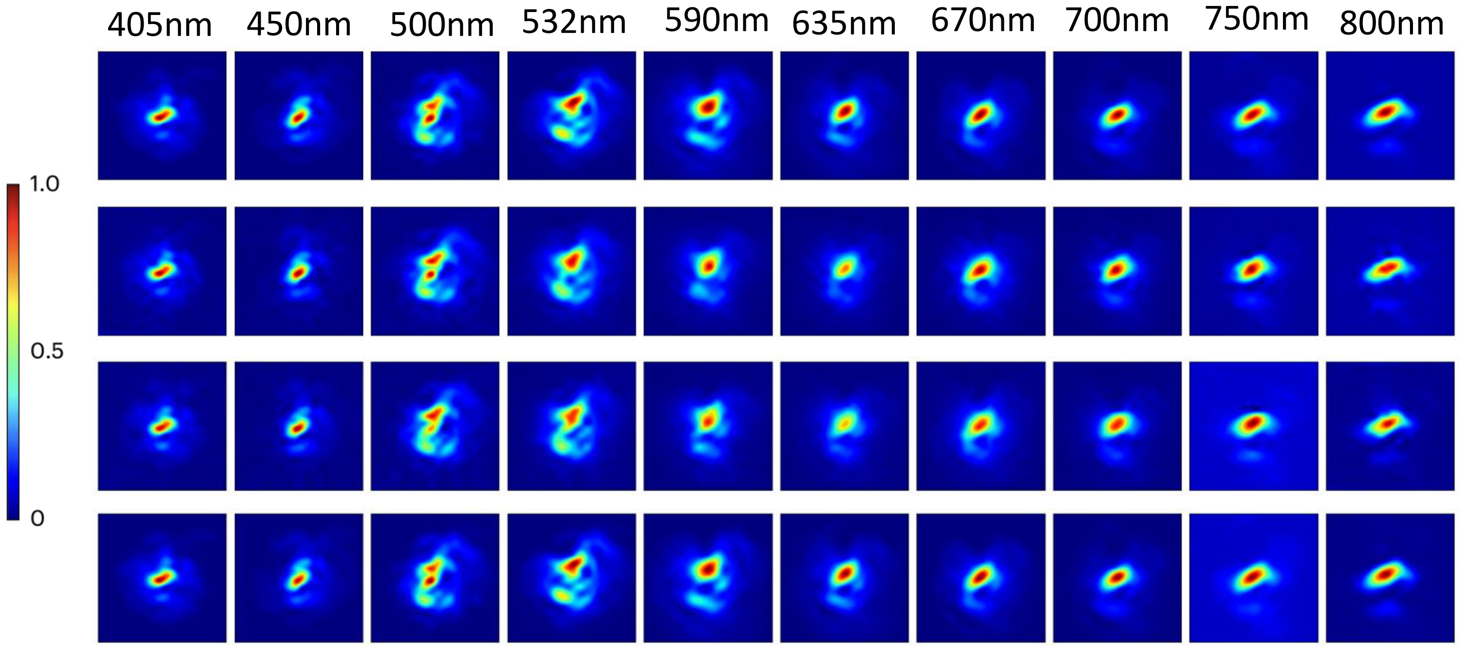
Reconstructed $\rho(x, y, z)$



Results & analysis: Uniqueness discussion

We generate ~1000 solutions, classify them into four groups using principal component analysis and K-means clustering algorithm.





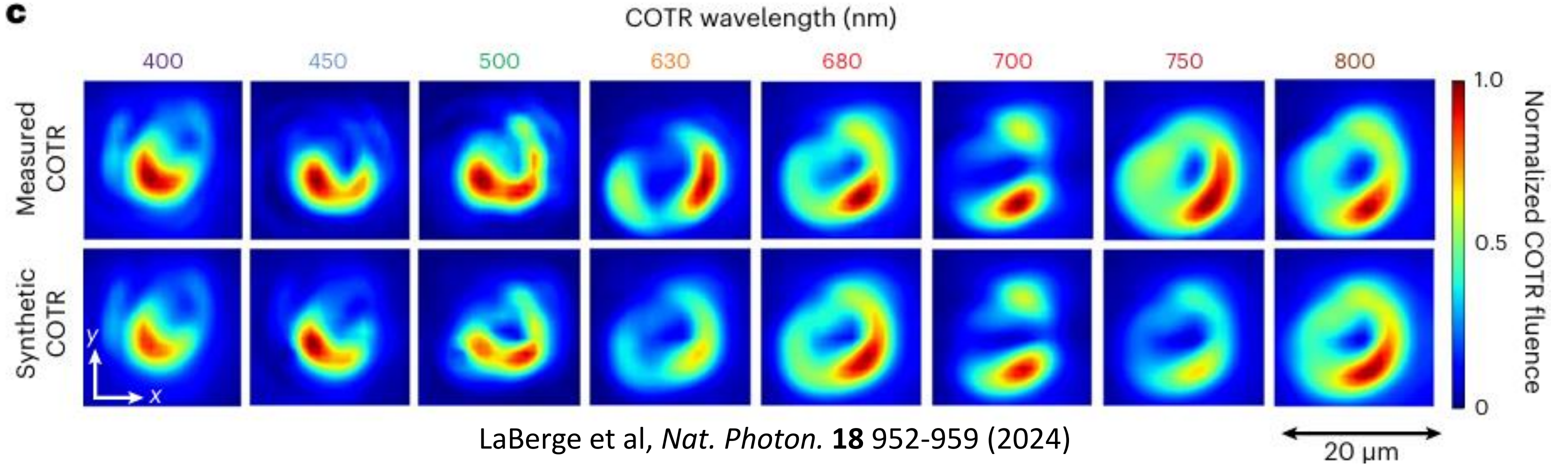
Measured CTR

Reconstructed CTR from single solution — Loss = 0.045

Reconstructed CTR from <1000-solution> e- — Loss = 0.046

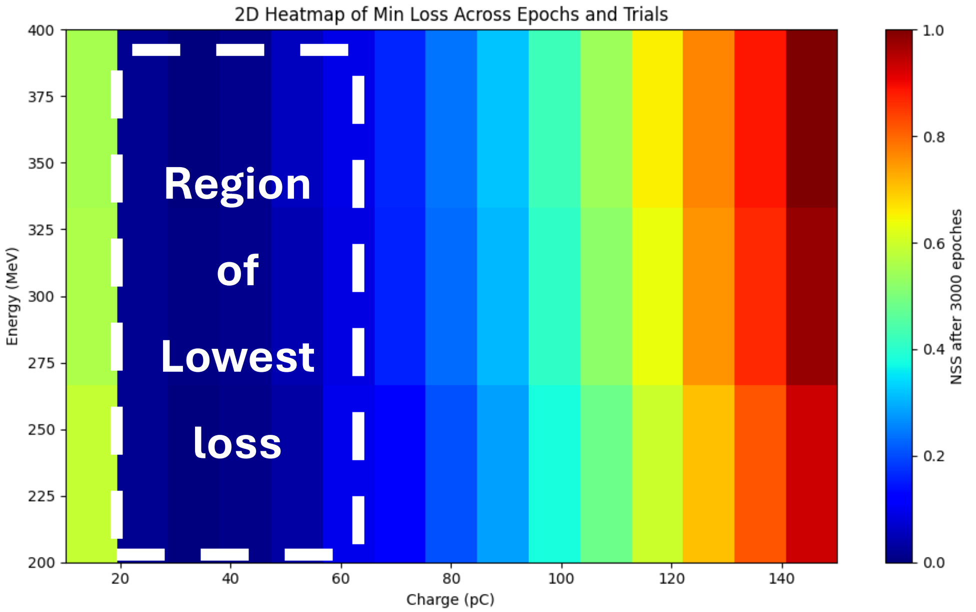
Reconstructed CTR from <cluster-1> e- — Loss = 0.044

Results & analysis: all-optical approach



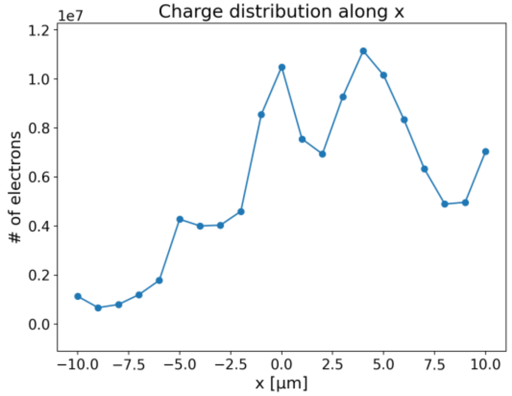
LaBerge et al, *Nat. Photon.* **18** 952-959 (2024)

For $p_i = (x_i, y_i, z_i, q_i, \gamma_i)$, (x_i, y_i, z_i) are optimized by the reconstruction algorithm, while (q_i, γ_i) are input as prior information, determined by e- magnetic spectrometer.



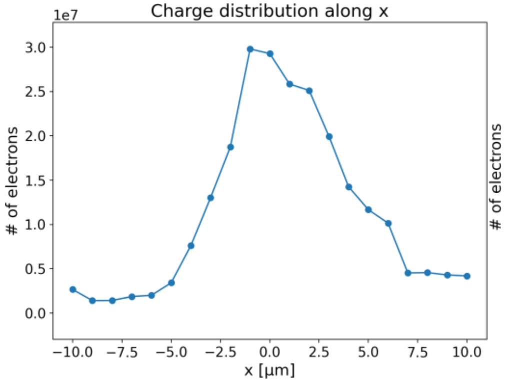
CTR is in essence γ-insensitive

40% less than nominal charge

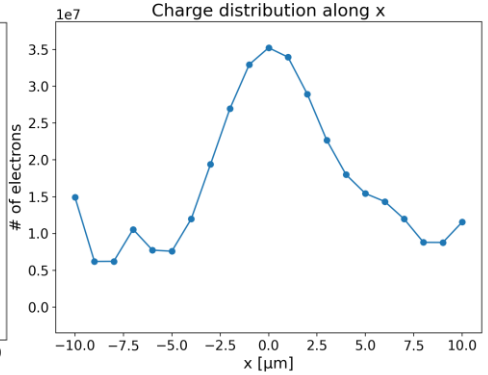


Less charge -> bad loss/convergence

nominal change = 36pC



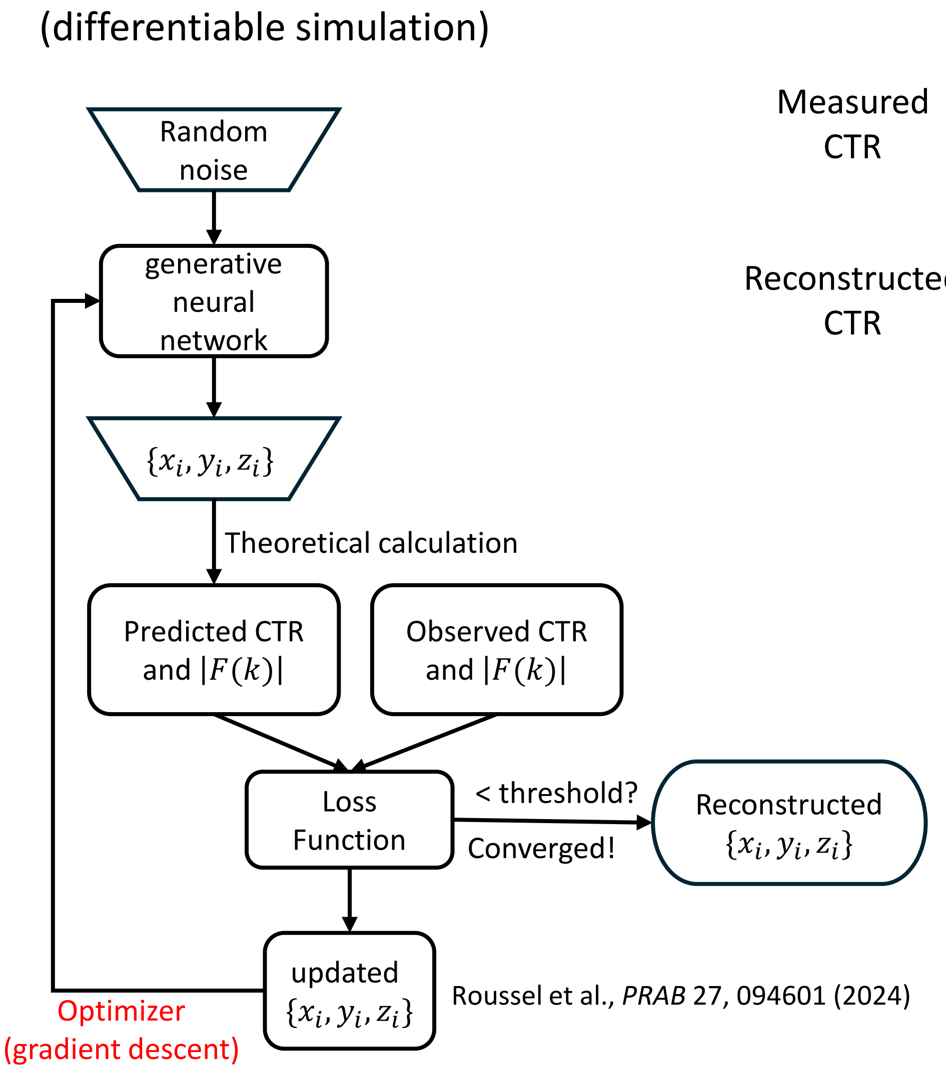
40% more than nominal charge



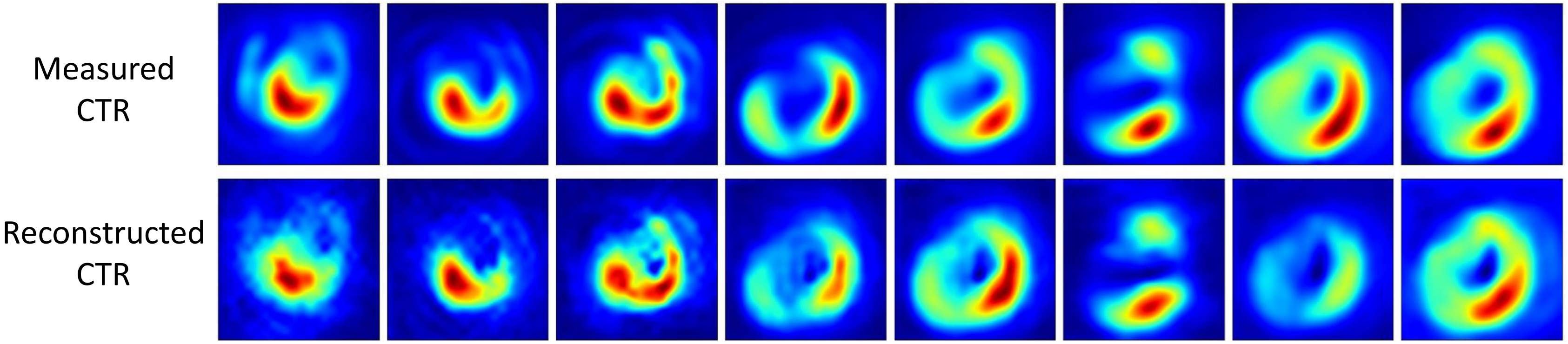
Extra charges are pushed to the edge of the simulation area

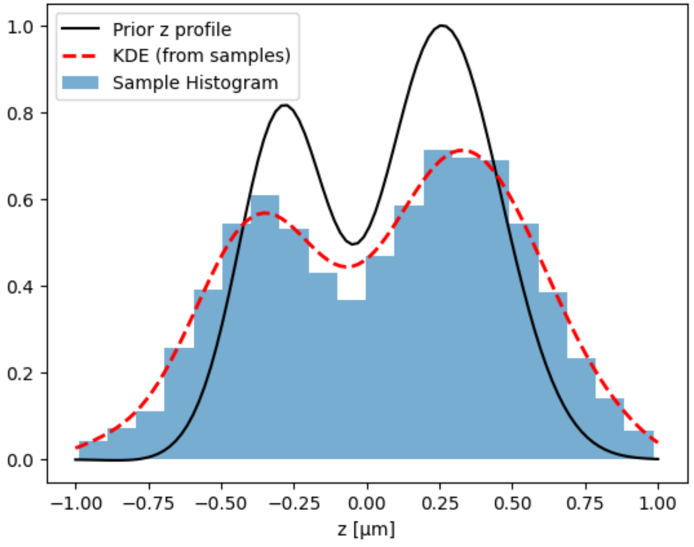
An estimation of total charge can be derived from reconstruction performance analysis.

Results & analysis: Generative Neural Network

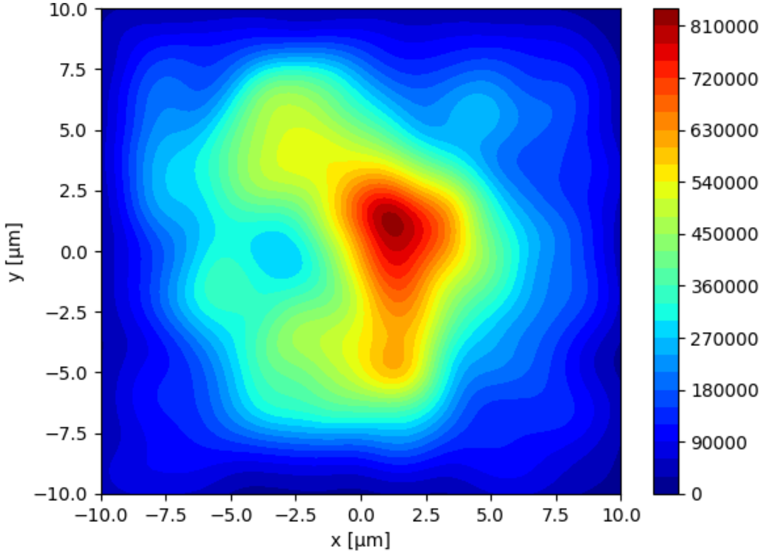


Roussel et al., *PRAB* 27, 094601 (2024)





Reconstructed $\rho(z)$



Reconstructed $\rho(x,y)$

Reduce the number of parameters to optimize

Physics-informed Neural Network (PINN)

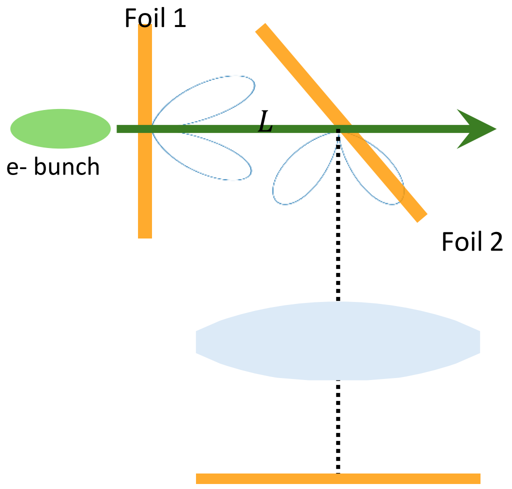
Conclusion & outlook: into higher phase space & NNs

We performed our second-generation CTR experiments:

- More λ-resolved CTR images & CTR spectrum (450-750nm)
- Quasi-real-time reconstruction
- All optical approach
- Generative neural network
- PINN

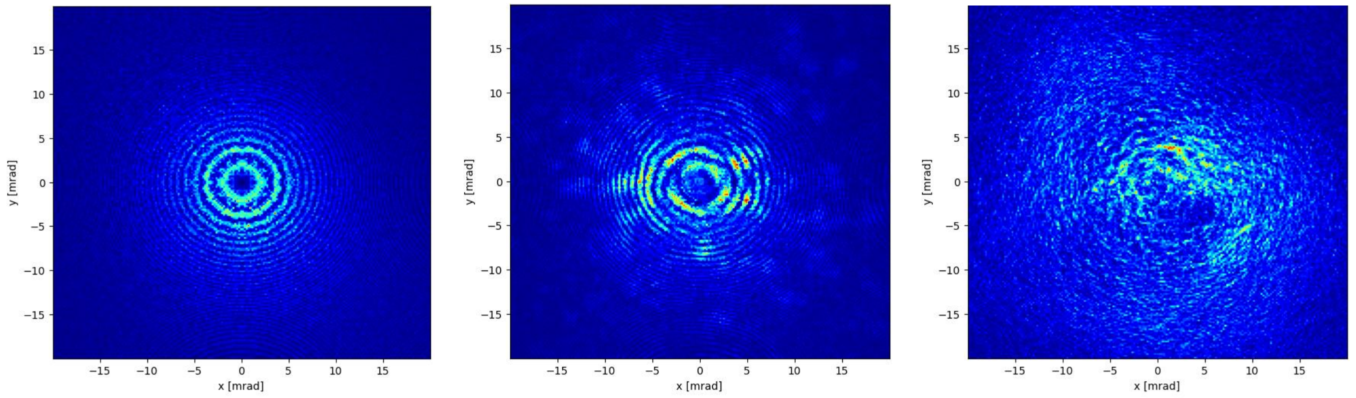
Higher-dimensional phase space

Each $p_i = (x_i, y_i, z_i, q_i, \gamma_i, p_{x_i}, p_{y_i})$



$x_s \sim N(0, 2\mu m)$
$y_s \sim N(0, 2\mu m)$
$z_s \sim N(0, 200nm)$
$\psi \sim N(0, \psi_r)$
$\varphi \sim U(0, 2\pi)$

multi-e- CTR Interferometry @600nm



ψ_r=1 μrad ψ_r=1 mrad ψ_r=10 mrad

Interferometry of two COTR sources contains the information of beam divergence.

Thanks & Questions

Collaborators:

Maxwell LaBerge,[2] Franziska Herrmann,[2,3] Patrick Ufer,[2,3] Susanne Schöbel,[2] Ritz Ann Aguilar,[2] Fong-Lin Wu,[2] Ryan Roussel,[4] Arie Irman,[2] Ulrich Schramm,[2,3] and Michael Downer[1]

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