Phase Space Reconstruction of Downramp-Injection LPA Electron Beam for Modeling FEL Operation

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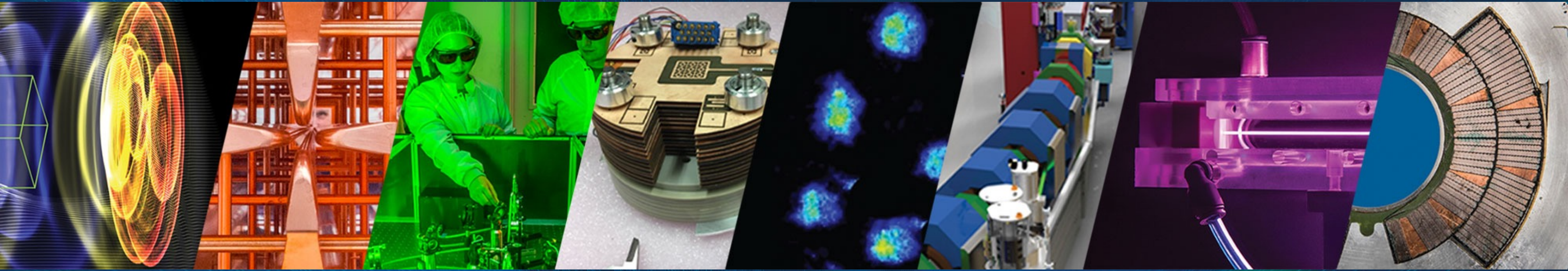
[1]BELLA Center, LBNL [2]SLAC National Accelerator Laboratory [3]University of Chicago



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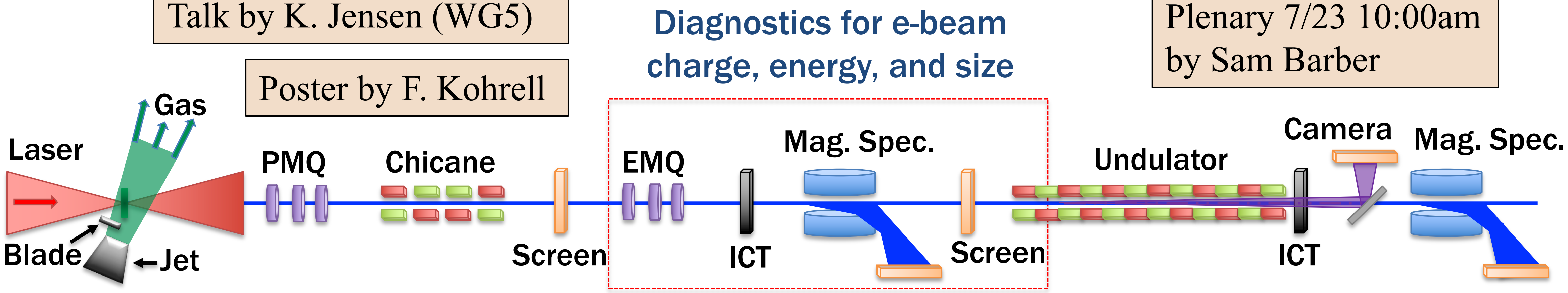
The Hundred Terawatt Undulator (HTU) experiment relies on high brightness laser-plasma accelerator (LPA) e-beams for free electron laser (FEL) development

- HTU's VISA undulator has a tight tolerance for alignment and matching
- Only a handful of diagnostics before the undulator, all except ICT are destructive
  - YAG Screens allow for e-beam images, quad scans allow for divergence info
  - Magnetic spectrometer can measure e-beam spectrum, ICTs measure the charge
- Given limited diagnostics, extracting more information from existing hardware is vital to further optimizing the undulator

Talk by K. Jensen (WG5)

Poster by F. Kohrell

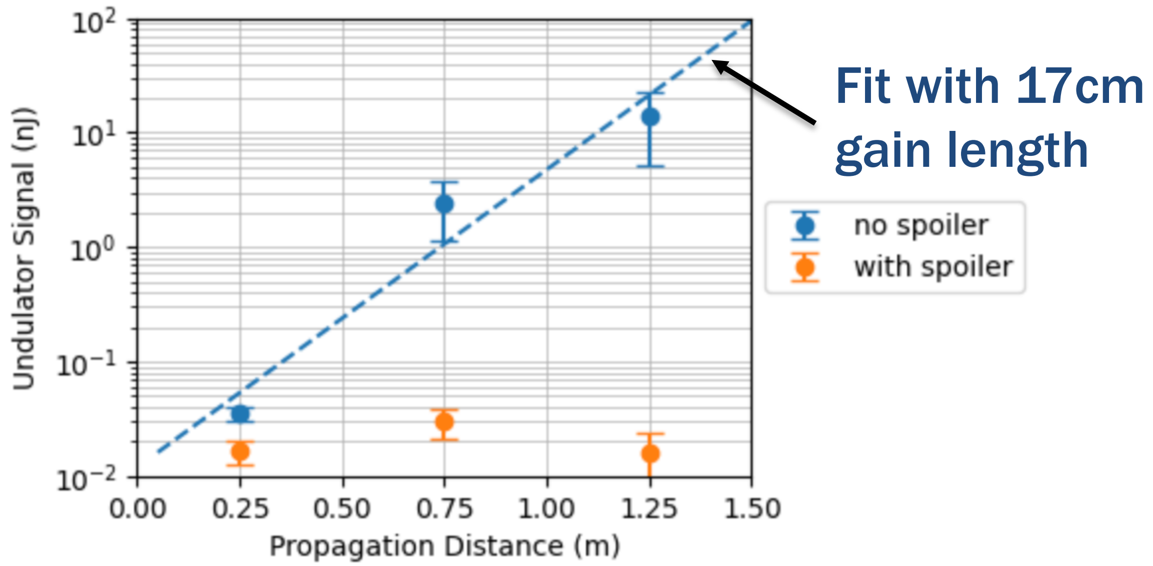
Plenary 7/23 10:00am by Sam Barber

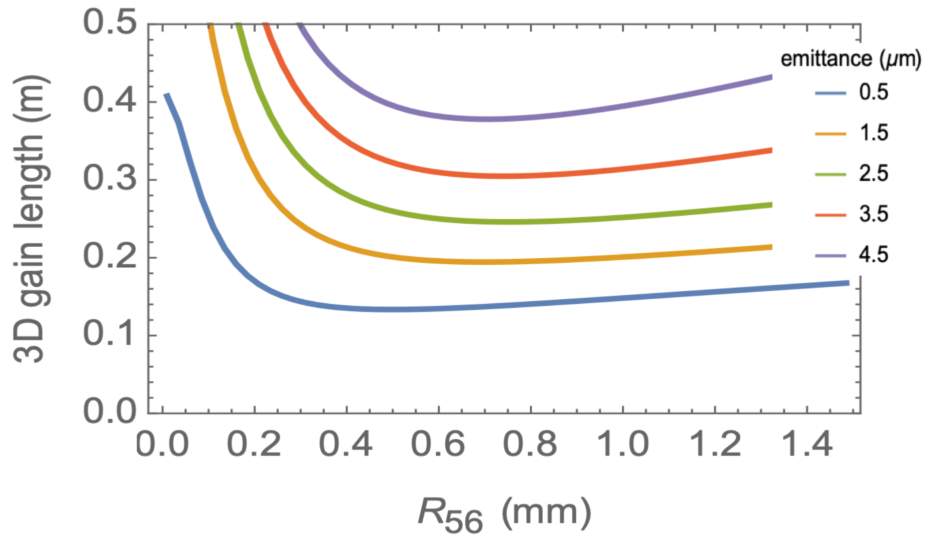


Current best emittance measurement is the undulator performance itself

- **We know from evidence of gain that the e-beam is bright and high quality**
- **From theory, lasing in the HTU VISA undulator suggests that the emittance of the electron beams is at least better than <~6 μm-rad[1]**

Recent FEL light vs Distance at HTU



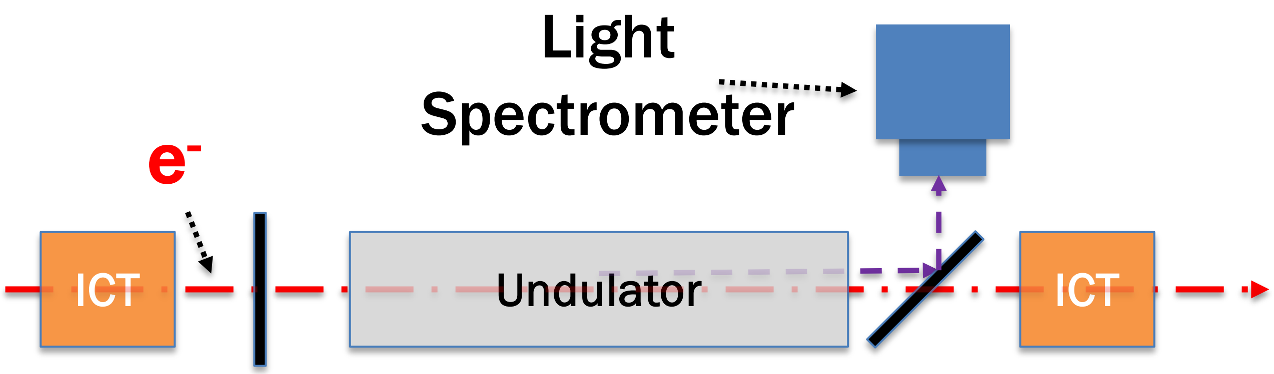


Genesis simulations with 3kA, 8pc/MeV e-beam, calculations using Ming Xie parameterizations[2]

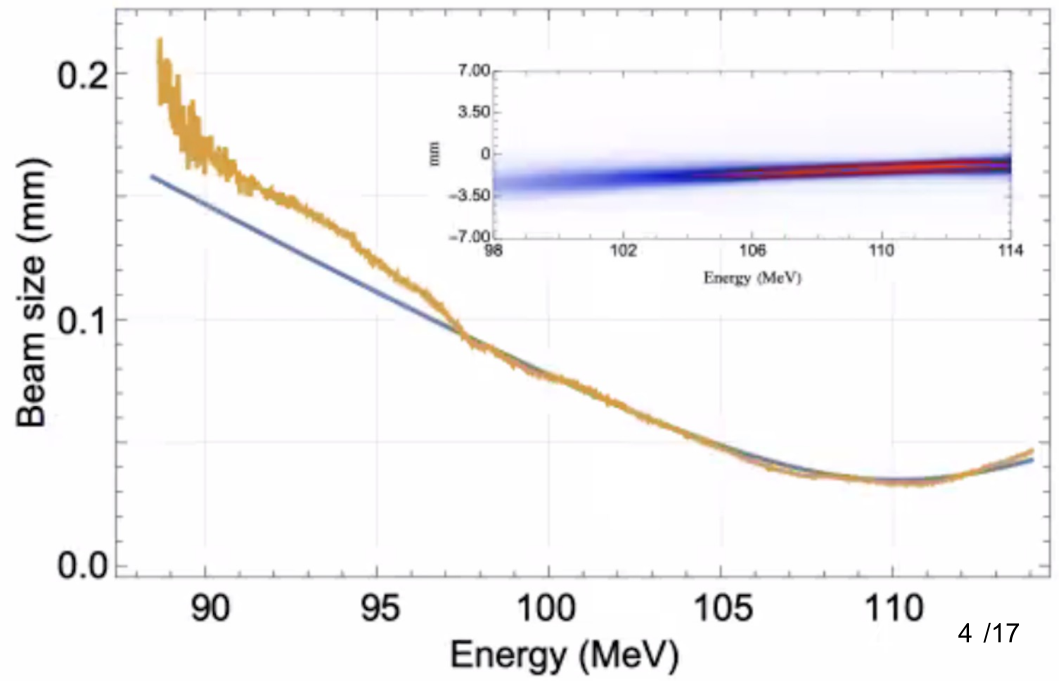
[1]Free-Electron Lasers in the Ultraviolet and X-Ray Regime (2014)
[2]M. Xie, Nucl. Instrum. Meth. A **445,** 59 (2000)

Multiple clues indicate low emittance, but want to learn more about the full transverse phase space

- We can turn on and off the coherent FEL process by inserting a 10 μm thickness pellicle upstream of the undulator to spoil the e-beam emittance[3]
- Estimated emittance growth is 10-20 μm-rad
- Incoming e-beam emittance must be at least better than 10 μm-rad



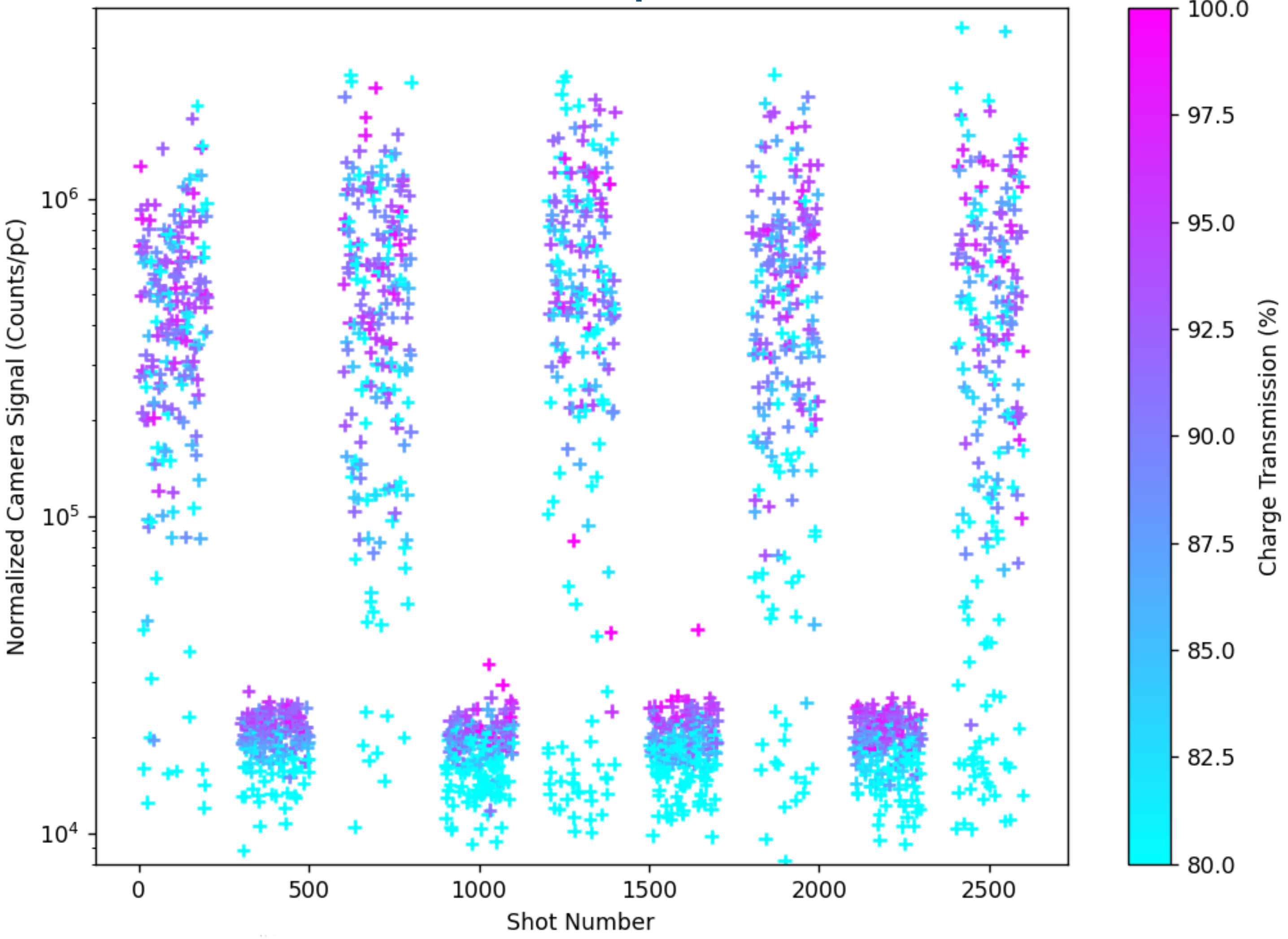
"Bowtie" ensemble emittance estimate using average of 100 shots: ~2 μm-rad



[3] M. Reid, J. Appl. Phys. **70**, 7185-7187 (1991)

Demonstrated FEL gain on HTU indicates great level of beam quality

Charge-normalized FEL light collected with and without spoiler inserted



- 100x signal increase when spoiler is removed is good, but now we want to push for another order of magnitude
- Knowledge of the phase space (quantitative and/or qualitative) enables optimization studies

Limited diagnostics make it difficult to fully measure phase space distribution

- **Simulations confirm high quality beams[4], but they are hard to measure in practice**

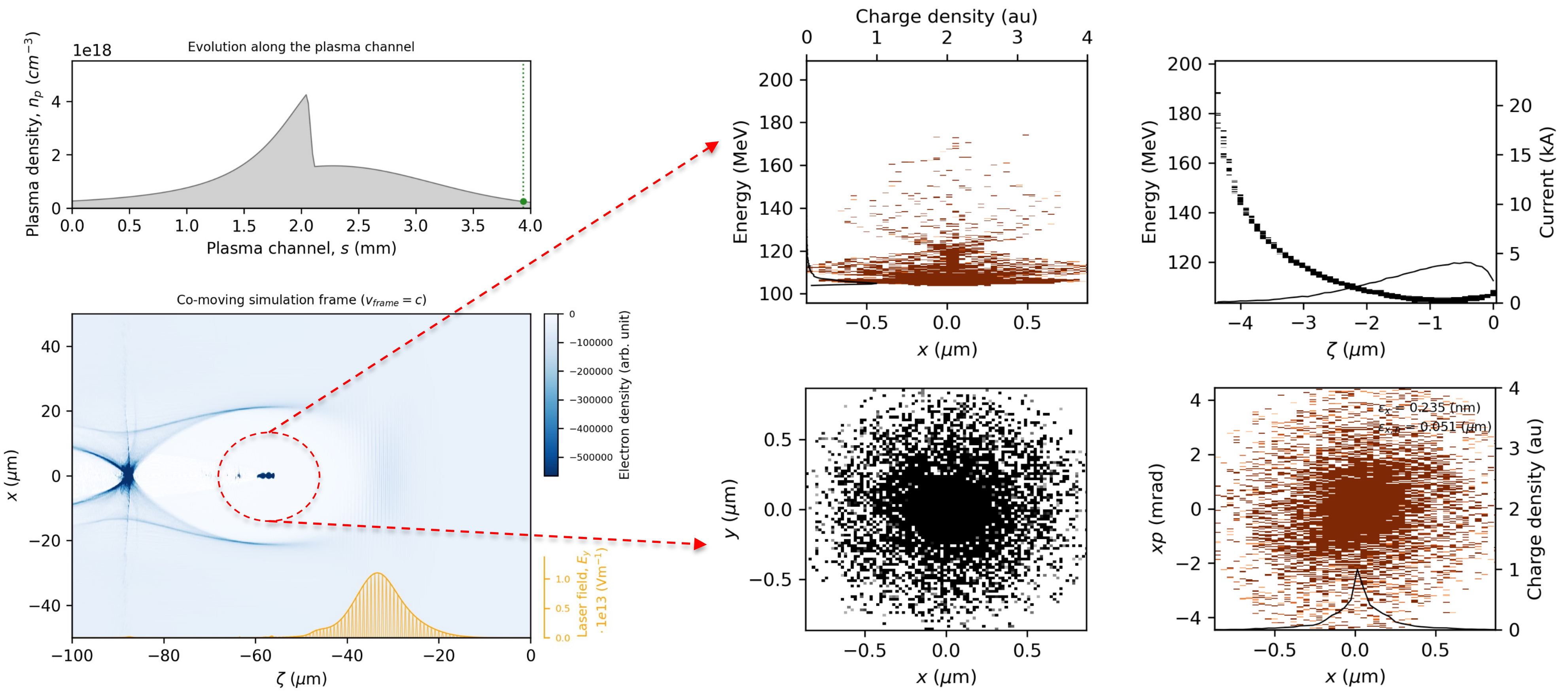
Downramp Injection:

Q > 10's pC

E ~ 100 MeV

σ_E ~ 5%

ϵ_N < 1 µm-rad



[4]S. Schröder, EAAC (2023)

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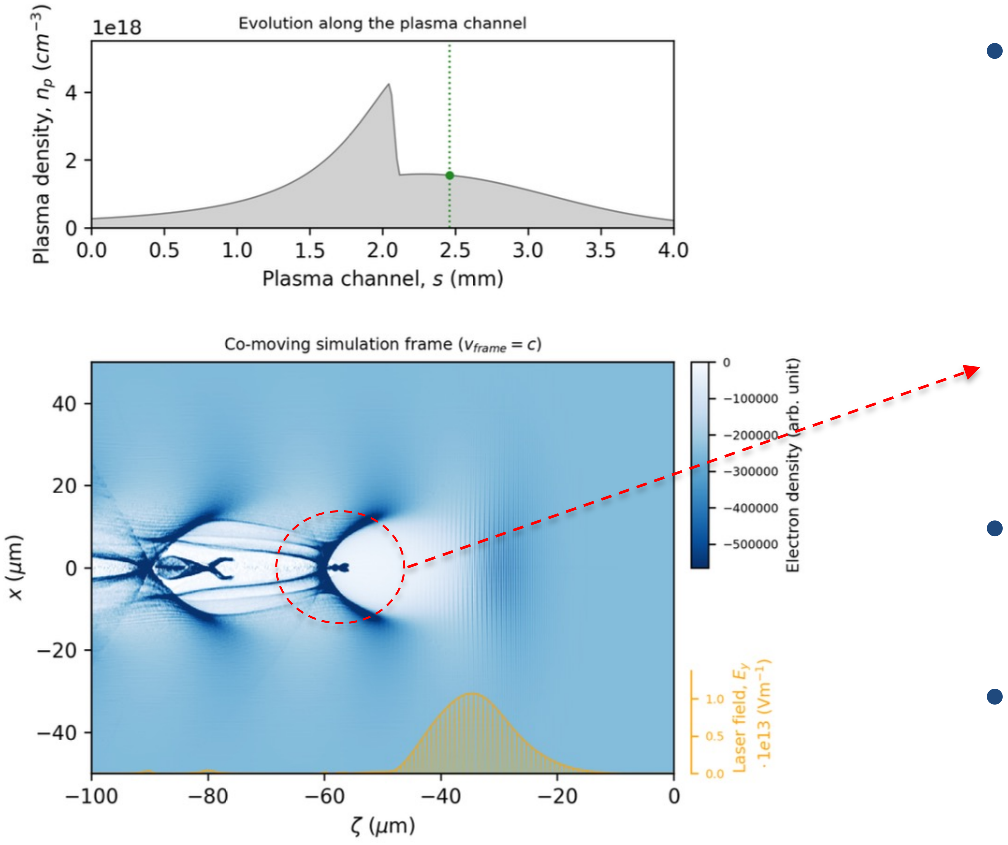
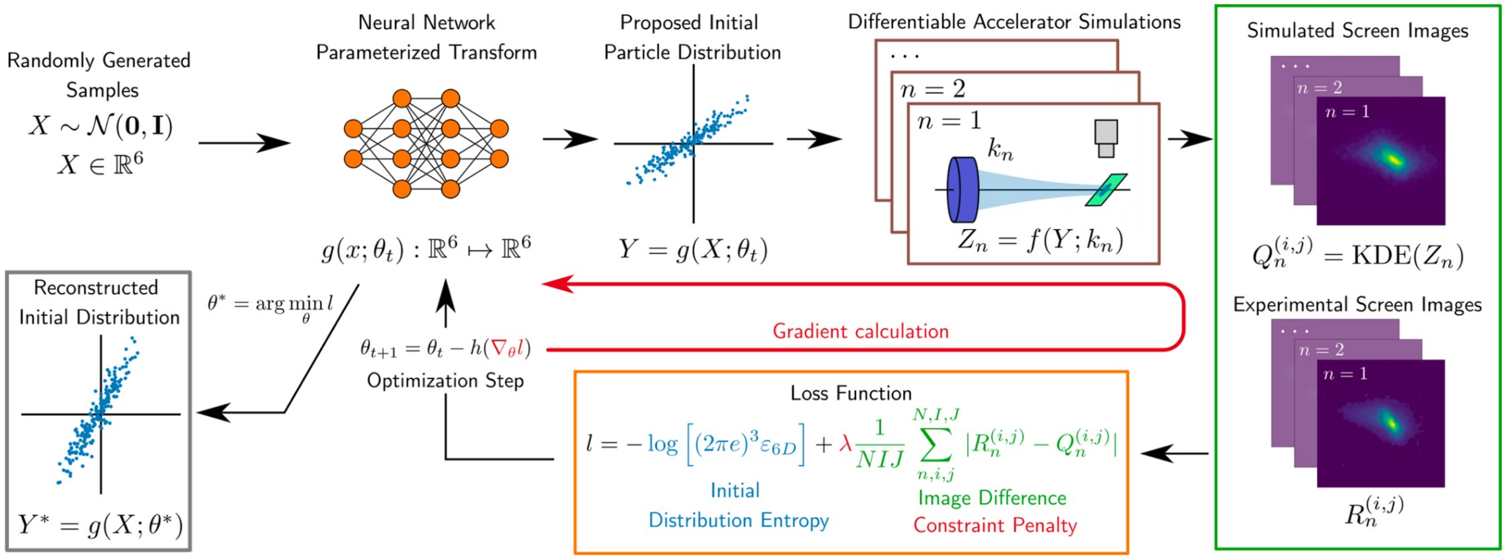


- In the accelerating phase further back in the gas jet, there are many aspects not optimized
  - Beam loading
  - Longitudinal plasma density
- Highly susceptible to jitter in experiment
- Results in beams with non-Gaussian distributions

[4]S. Schröder, EAAC (2023)

Phase space reconstruction is a promising technique to extract complex beam distributions through efficient ML algorithms

- Can be applied towards 4D reconstruction of transverse phase space using a quad scan[5] or towards a full 6D reconstruction by including a mag. spec. and a TCAV[6]
- Previously shown to be accurate with conventionally-accelerated e-beams



Talk and Poster by R. Roussel (WG5)

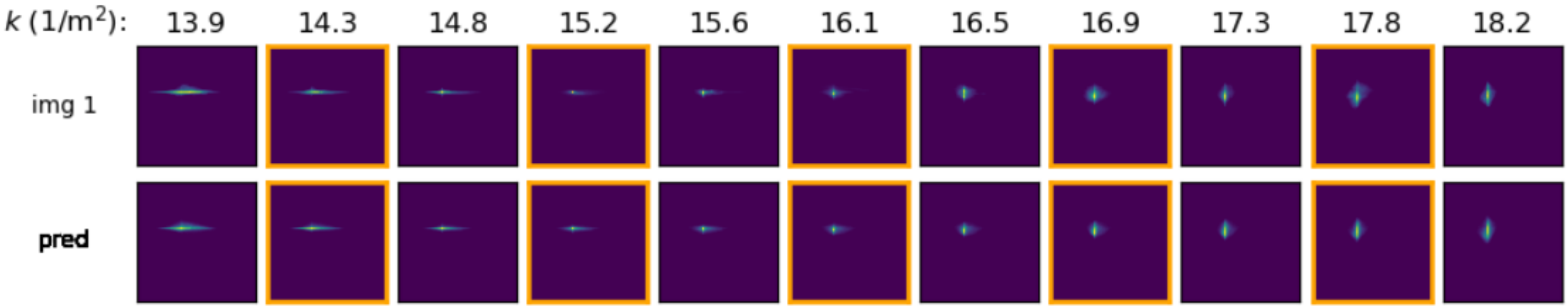
Talk and Poster by J.P. Gonzalez-Aguilera (WG5)

Here we attempt to apply phase space reconstruction towards HTU's LPA beam

[5]R. Roussel et al, PRL **130**, 145001 (2023)
[6]R. Roussel et al, arXiv:2404.10853 (2024)

Reconstructions give reasonable e-beams that qualitatively match the training and test images from a quad scan in experiment

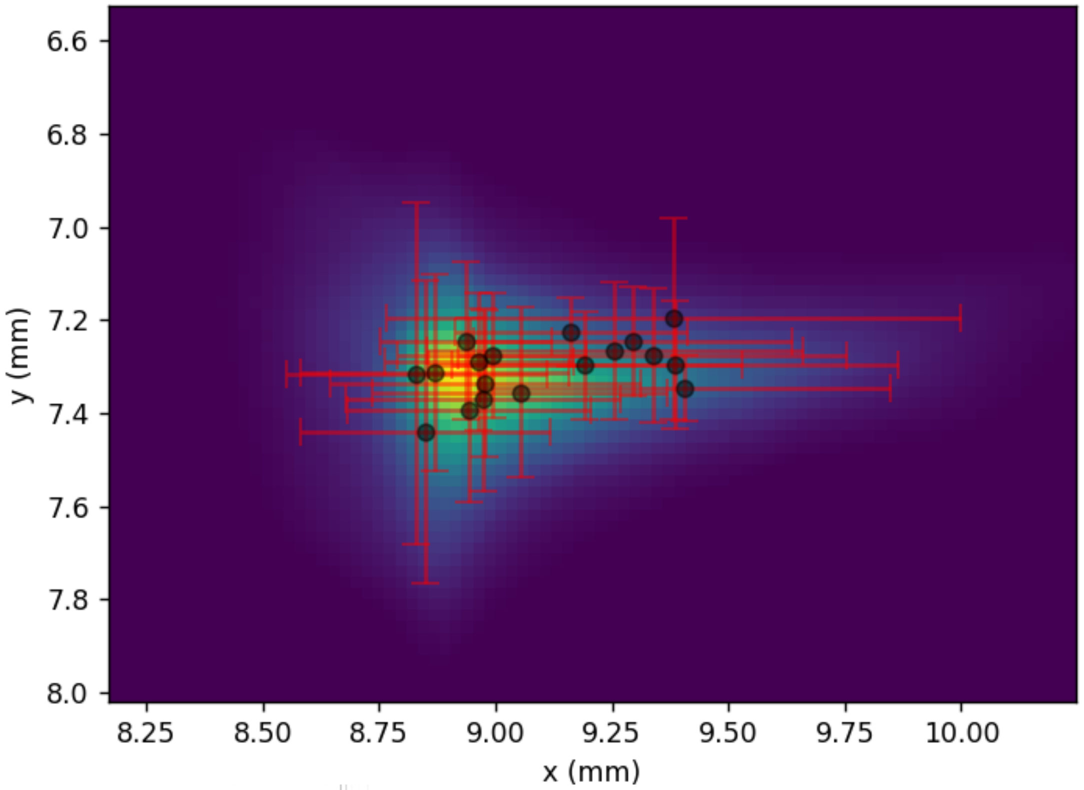
- Quad scan using the third EMQ of the triplet onto a YAG screen
- Each experimental image (top row) is the average of 20 shots for that k value

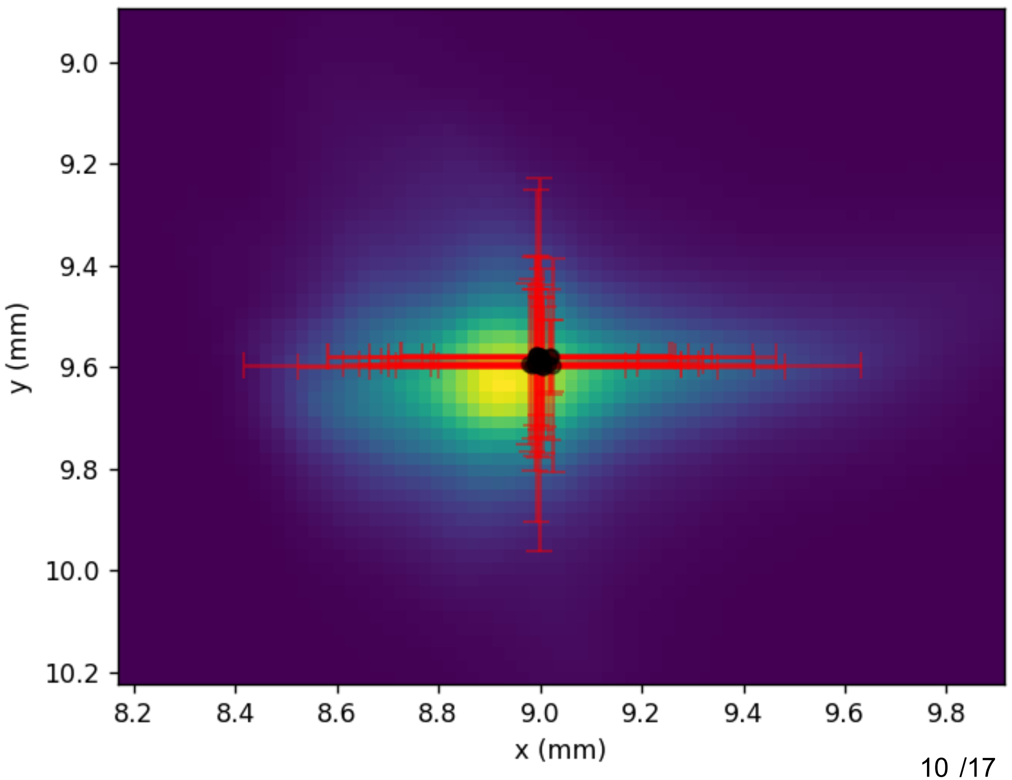


- Images with orange border are not used in the training, instead are used to test
- Algorithm iteratively builds a <u>4D</u> beam distribution to match images using a simulated beamline

Shot-to-shot variation in the e-beam energy, charge, and pointing can artificially inflate the training images

- Sample summed training image (left) overlayed with individual beam sizes
- Locking each image to the same center-of-mass (right) is one option
  - Tradeoff of 1st order information (position and angle) for better higher order representation
- In both cases, we are reconstructing an ensemble of e-beams

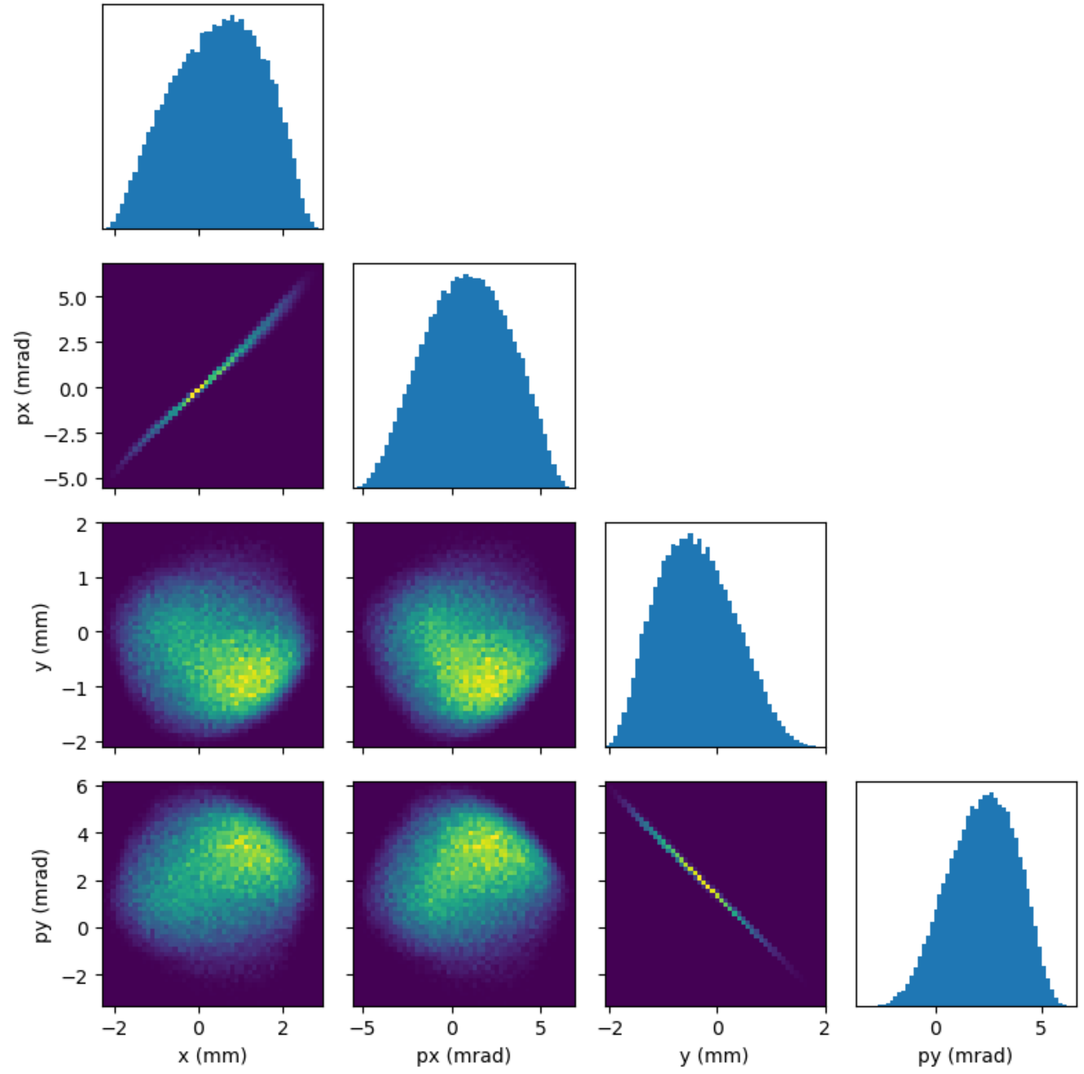




Reconstructions give e-beam ensembles with large, but qualitatively reasonable distributions

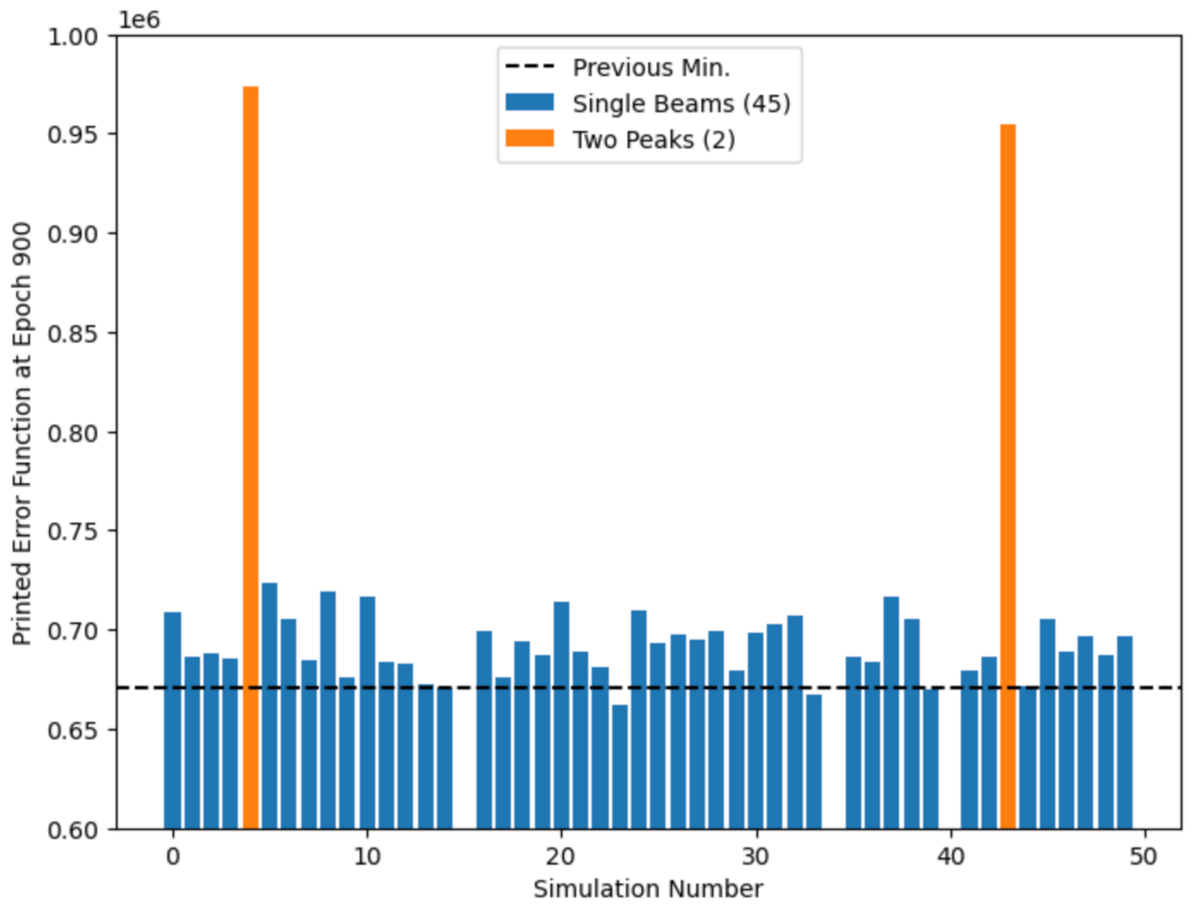
- 4D reconstructed distribution gives reasonable, but large estimates for the ensemble 4D volume at the entrance of the third EMQ magnet
  - This example quad scan ensemble reconstruction: 40 x 8.5 μm-rad
  - Much larger than known max. limit from FEL results
  - Asymmetry between x and y not in ideal sims.

- <u>Used resources: 1 GPU node on NERSC for about 2 mins</u>
  - About as long as it takes to collect data
  - Promise for eventual closed-loop implementation

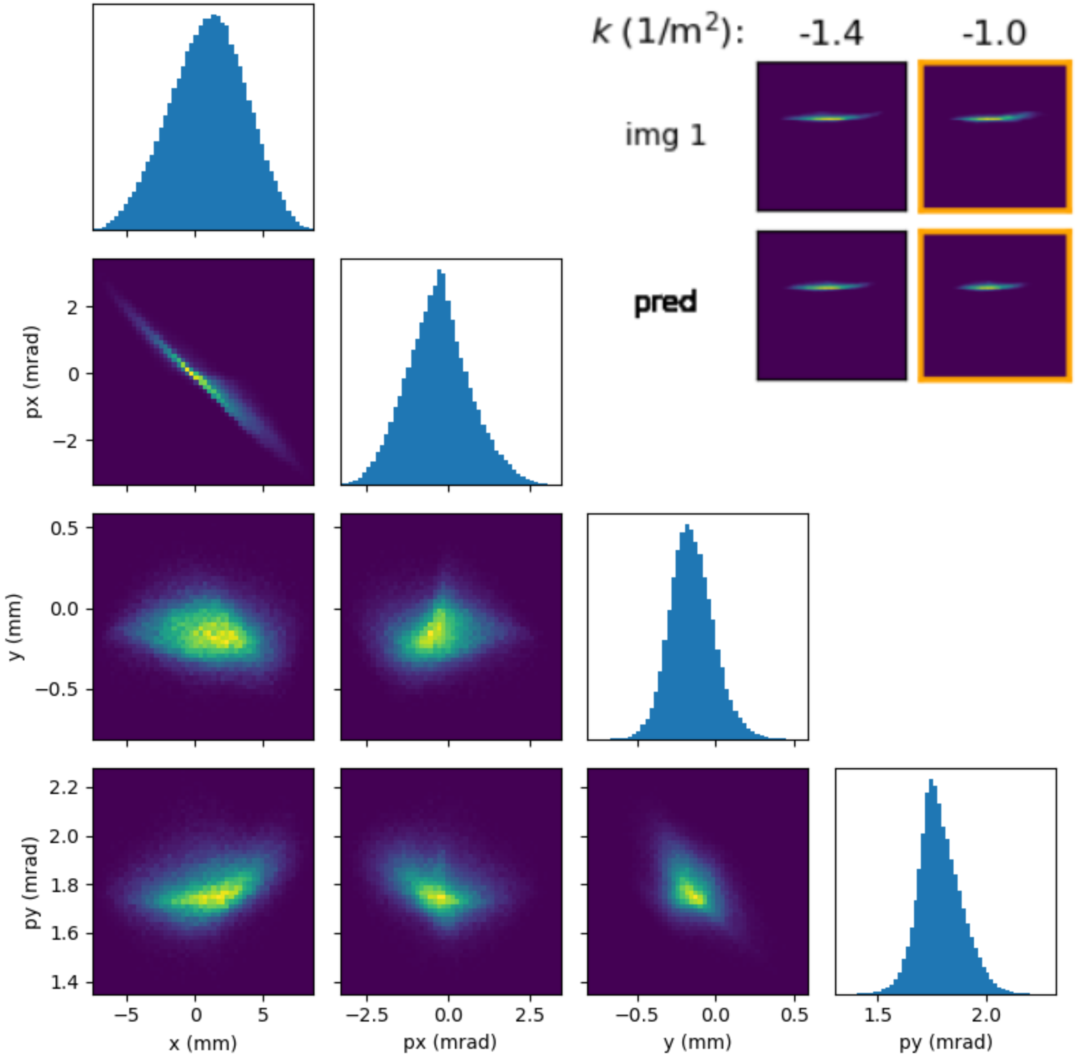


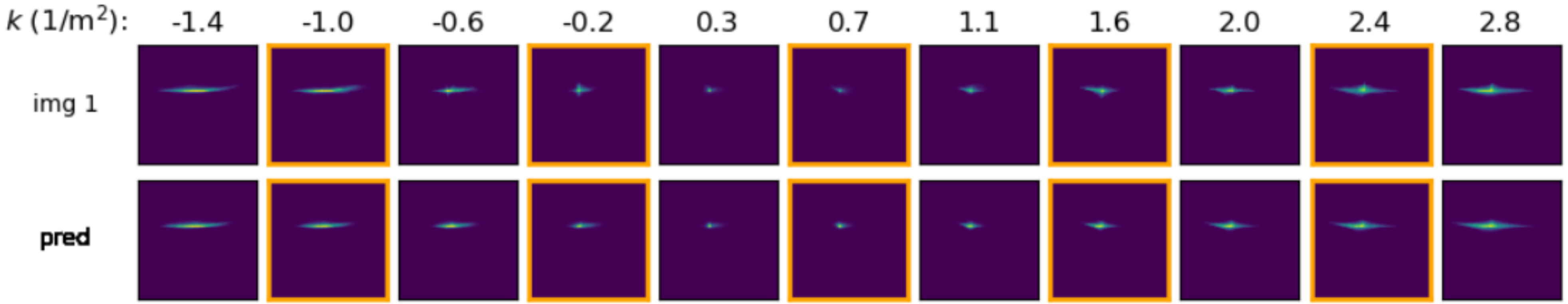
Performing the same reconstruction 50x shows repeatability of the algorithm is robust

- **The reconstruction showcased a high success rate.**
  - 90% of the time, succeeded by converging to a one-bunch beam with similar error function and beam distribution
  - 4% converged to a two-bunch beam and had a much larger error function.
  - 6% crashed, not returning an error function
- **The final error function corresponds to how well the reconstructed beam matches the data**



When the reconstruction is performed in a doublet EMQ configuration with a quad scan about Q3=0, beams appear more asymmetric





- Doublet configuration where the first two EMQ magnets are set to focus and the third varies about zero
- Strong focusing in y results in minimal variation due to Q3
- Reconstructed ensemble 4D volume: 124 x 2.4 μm-rad

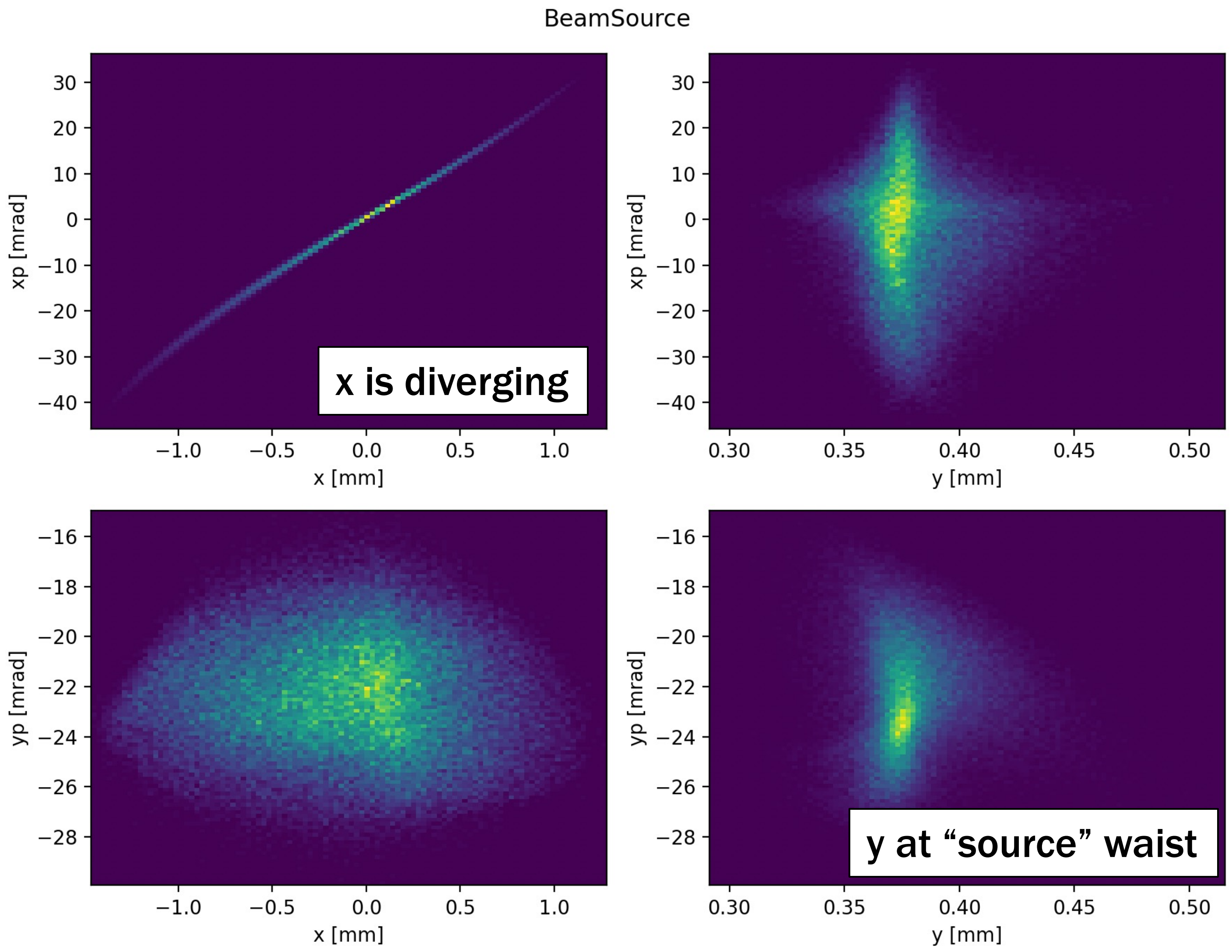
Several reconstructions performed from data taken the same day shows how results can vary depending on the reconstruction approach

EMQ Setting	Laser Stabilization	Image Averaging Process	Error Function (x10^5)	Recon. Ens. Area, X (μm-rad)	Recon. Ens. Area, Y (μm-rad)
Doublet	ON	Raw	5.0	124	2.4
Doublet	ON	CoM	4.2	153	3.5
Doublet	OFF	Raw	13.0	73	2.9
Doublet	OFF	CoM	5.0	116	3.5
Triplet	ON	Raw	6.8	40	8.5
Triplet	ON	CoM	5.2	94	11
Triplet	OFF	Raw	46.0	9.6	344
Triplet	OFF	CoM	6.7	75	6.8

- **EMQs in a doublet setting led to more asymmetric reconstructions**
- **Center-of-mass locking improves error function**
- **Laser stabilization OFF hurts reconstruction when directly using raw images**
- **Asymmetry in x and y always appears to some degree**

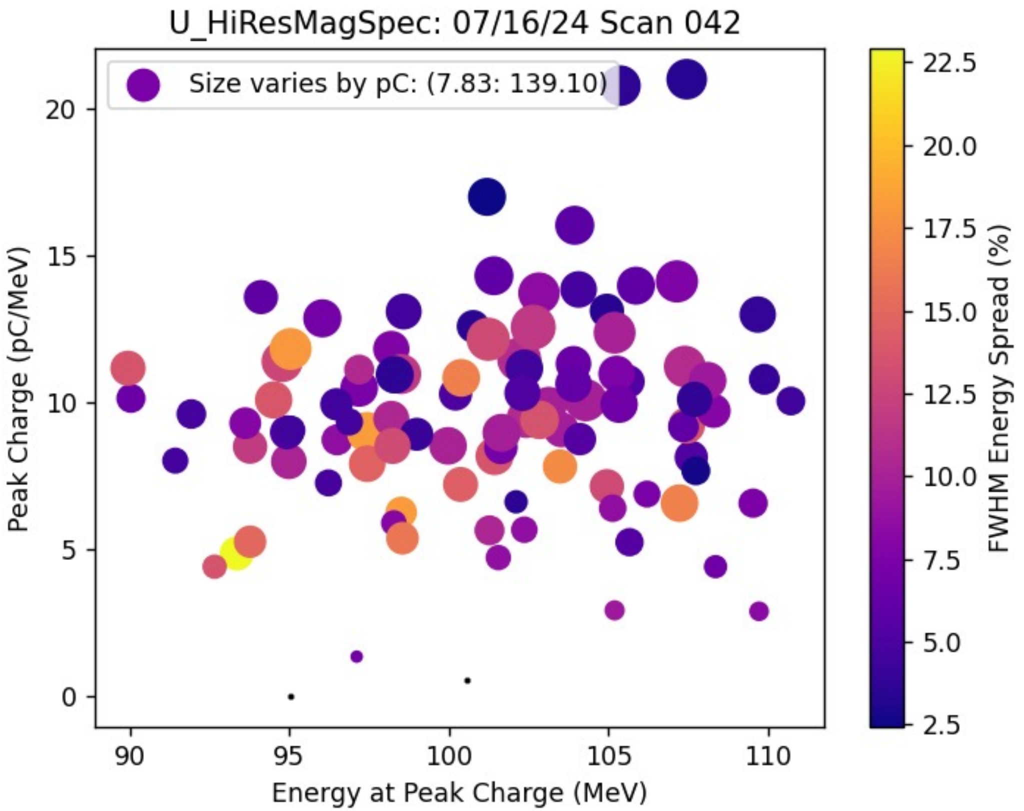
Can back-propagate reconstructed beams in Elegant to the approximate source location

- From ideal simulations, would expect to see an axisymmetric point source
- Difference of 40 mm between the reconstructed ensemble's virtual waist in x (σ = 43 μm) and y (σ = 19 μm)
- Many factors could lead to discrepancy:
    - Incorrect chromatics
    - No plasma focusing/defocusing
    - Shot-to-shot jitter
    - Virtual beamline parameters



A 5D phase space reconstruction of the e-beam will be more versatile through including spectra

- Information from just a 4D reconstruction is useful, but limited
- With the available diagnostics on HTU, the magnetic spectrometer can be used for a 5D reconstruction
- Reconstructing the beam's spectra would allow for:
  - Information on beam dispersion
  - Better back-tracking through magnetic lattice
  - More reliable Genesis simulations



Magnetic spectrometer is currently used for measuring the single-shot spectrum

Summary and Discussion

- We're using ML phase space reconstruction to attempt to reconstruct LPA electron beam ensembles
  - HTU beam is lasing so must have ~few um-rad emittance, but looking for more info on phase space
- 4D reconstructions of the transverse phase space are quick, robust, and produce reasonable electron beam ensembles
  - Exploring methods to reduce the effect of shot-to-shot jitter
- In the near future, including the energy spectrum in 5D reconstructions will enable more precise models of the electron beam
  - Including chromatics will be crucial to correctly model the LPA beam
- Ultimately, we seek to use this technique to better understand our LPA source and undulator performance

Thank You!

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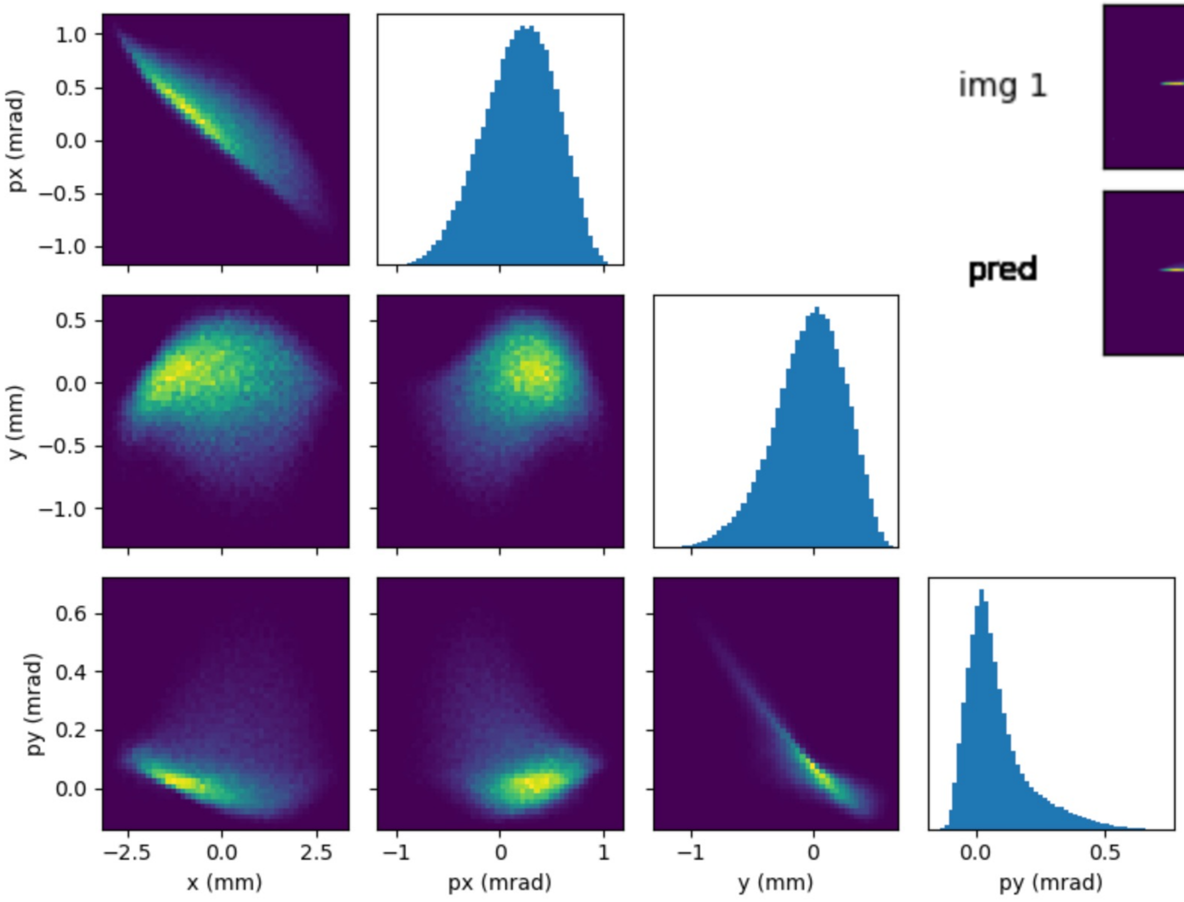
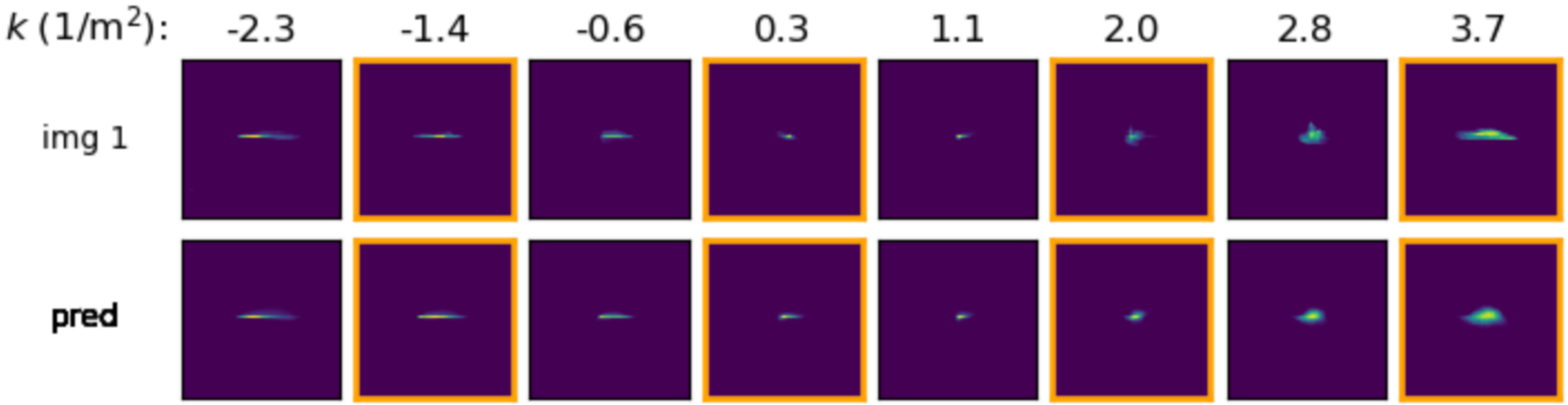
Looking into "single-shot-per-step" reconstruction, but so far no significant improvements over taking 20 shots per step





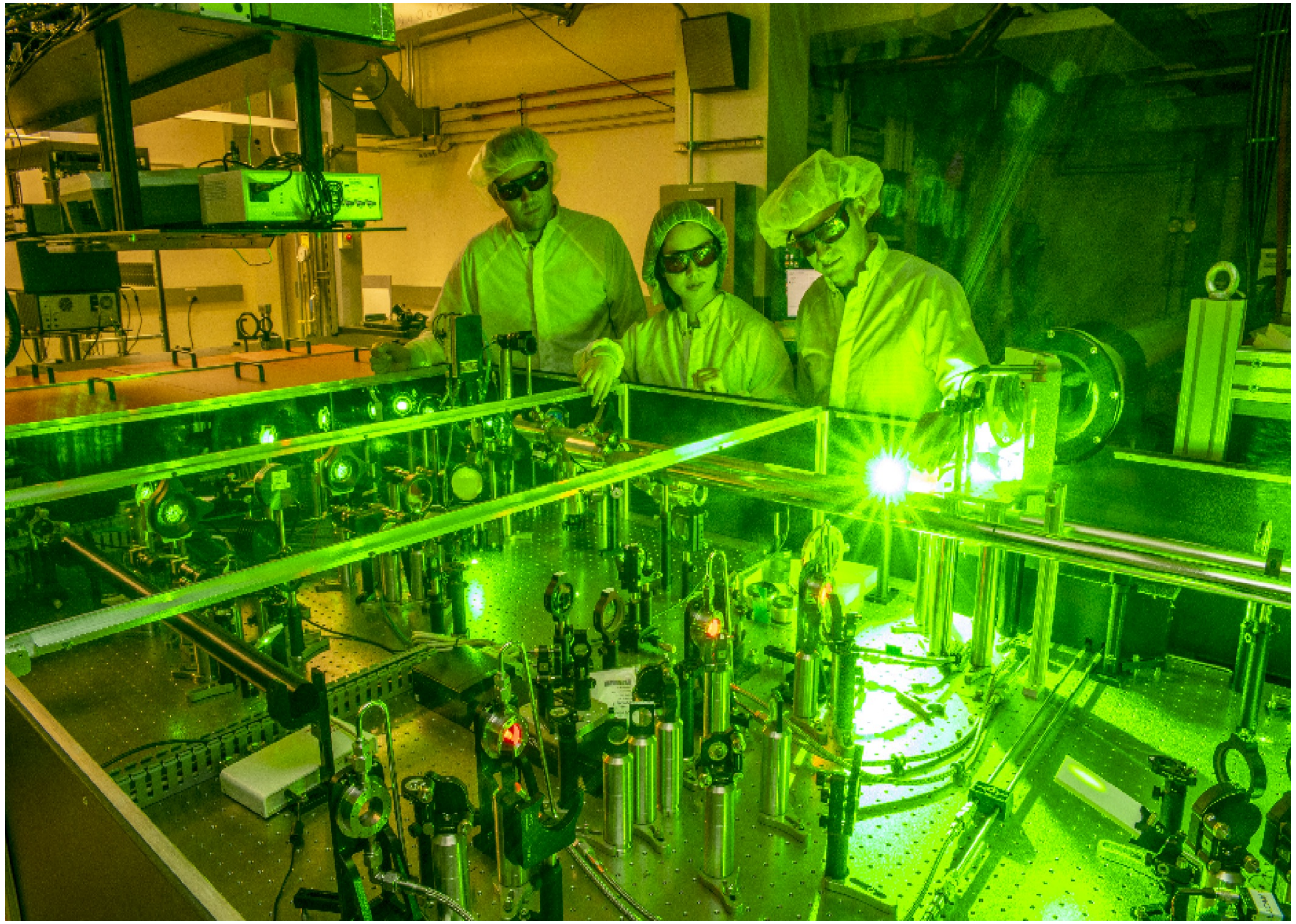
- Doublet configuration
- Lock each image's center-of-mass to same axis
- ϵ_N = 41 x 3.2 um-rad
- Further improvement: pick shots with near-equivalent charge?

Laser system provides a stable, high-intensity driver for LPA

- Ti:Sapph chirped pulse amplification
- 800nm, 2.5J, 40μm, 35fs, 1-5Hz

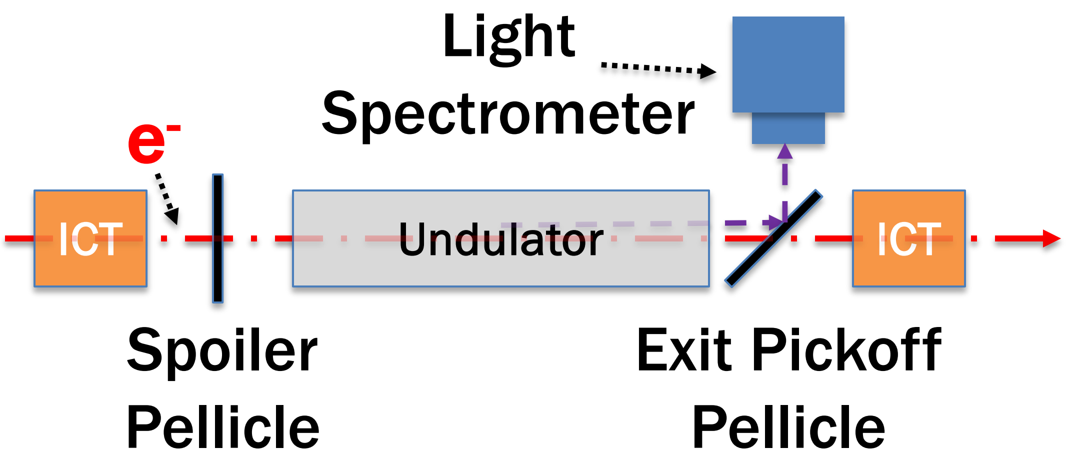
- Deformable mirror optimizes wavefront post-compression
- Laser room adjacent to accelerator cave

- OAP focuses laser to a 27μm spot at target gas jet
- Ghost beam pickoff allows us to monitor the laser focus during experiments

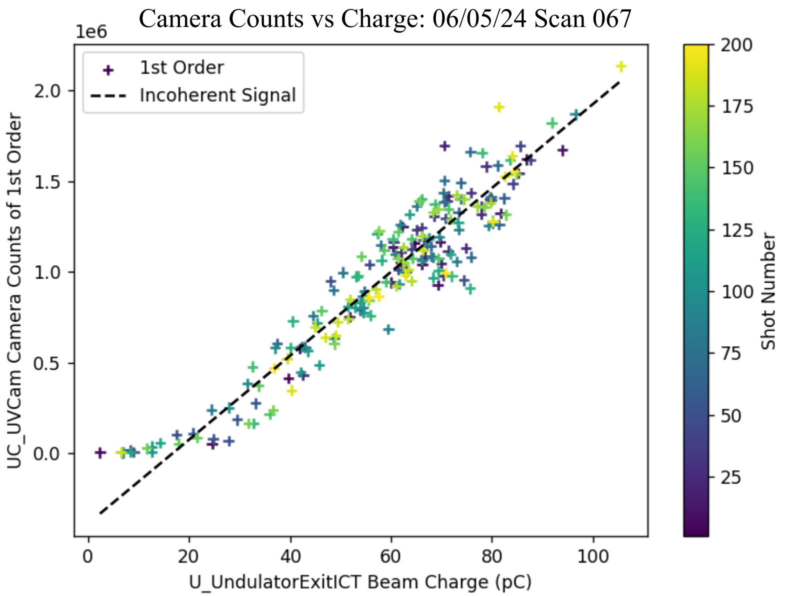


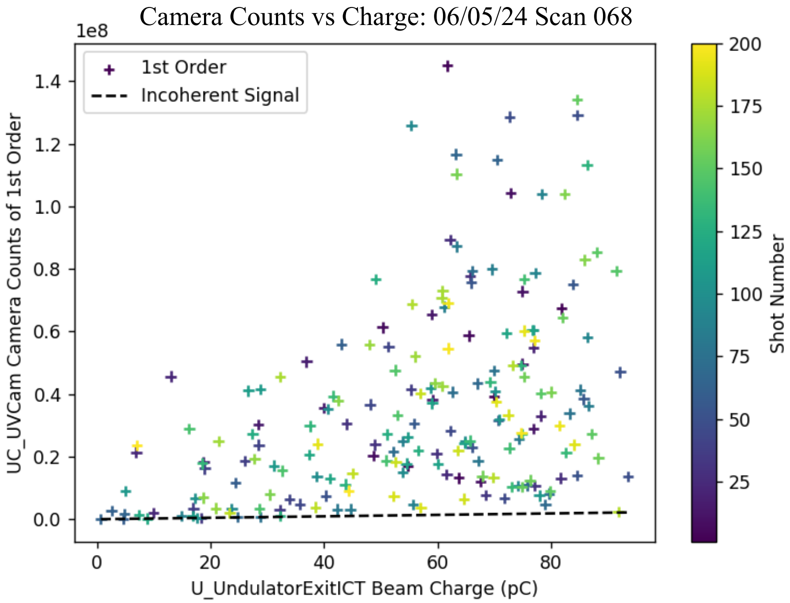
Can measure charge transmission while spoiling the beam emittance to turn on and off the FEL process

- Thin pellicles allow for charge transmission measurement while spoiling the beam emittance



- We observe 10-100x more signal with spoiler removed
- FEL vs Spontaneous Radiation





- With pellicle inserted, can fit a clear incoherent radiation signal vs beam charge
- Increase in signal is the ratio of signal with pellicle removed to the previous fit

Longitudinal Focal Stability (LFS) System

- Minimizes the low frequency jitter
- Collaboration with radiasoft