Improved particle statistics for laser-plasma self-injection simulations

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Motivation

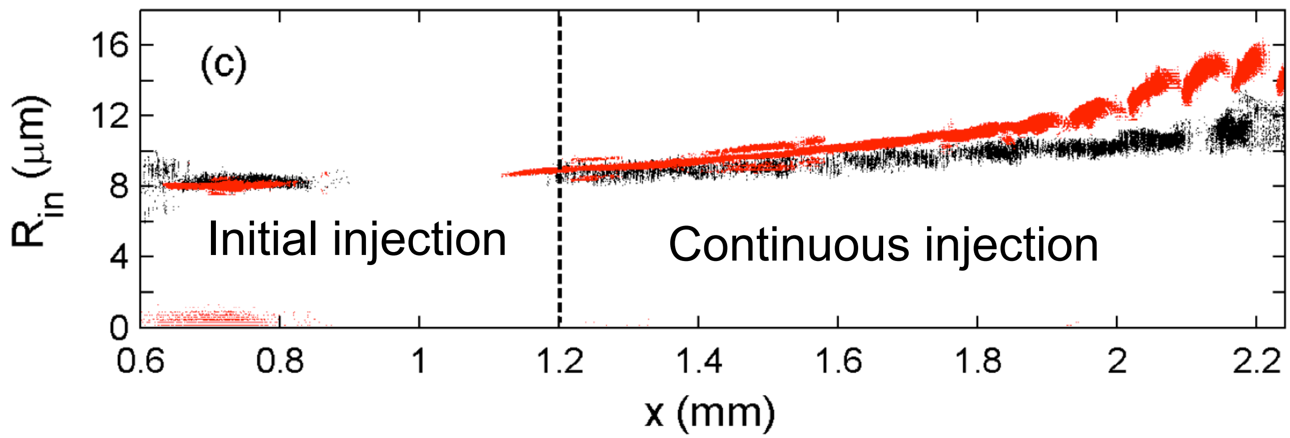
- Laser-plasma acceleration (LPA): Short, intense laser pulse drives, plasma wave, achieves orders of magnitude higher gradient than conventional accelerators
- LPA experiments have been producing quasi-monoenergetic beams for many years
- Beam energy and quality steadily improving
- New capabilities bring interest in a wide range of applications
  - Compact x-ray sources, coherent light sources, phase contrast imaging, NMD detection, colliders
  - Some of these have tight beam quality requirements
- Bubble regime injection remains attractive due to simplicity

Simulation challenges

- Need simulations with high quantitative accuracy
  - Understanding the physics
  - Designing LPA systems
- LPA injection is highly sensitive to parameters
  - What are physical vs. numerical effects?
  - Numerical artifacts can expand the phase space of the injected beam
- Particle statistics play a key role in accuracy
- Want to see convergence in key beam parameters (charge, energy, energy spread emittance) showing adequate statistics
- Outline
  - Enhanced loading
  - Blob particles
  - Controlled dispersion

Collection volumes

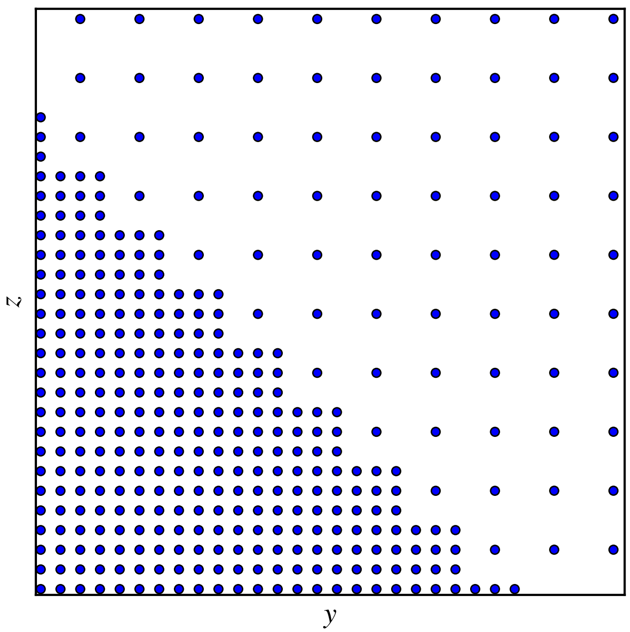
- We can enhance particle statistics with *a priori* knowledge from an initial simulation
- We use the *collection volume* — the range of initial positions of injected electrons



Collection volume of injected electrons in an LPA injection simulation. Here the plasma has a uniform density of 6.5 × 10^{24} m^{-3}, and the laser has peak intensity given by a_0 = 3.27, duration 30 fs, and spot size 13.6 μm. Good agreement is seen between Calder-Circ (black) and Vorpal (red). From B. Cowan *et al.*, "Computationally efficient methods for modelling laser wakefield acceleration in the blowout regime," J. Plasma Phys. (published online 6/13/12)

Enhanced statistics in the collection volume

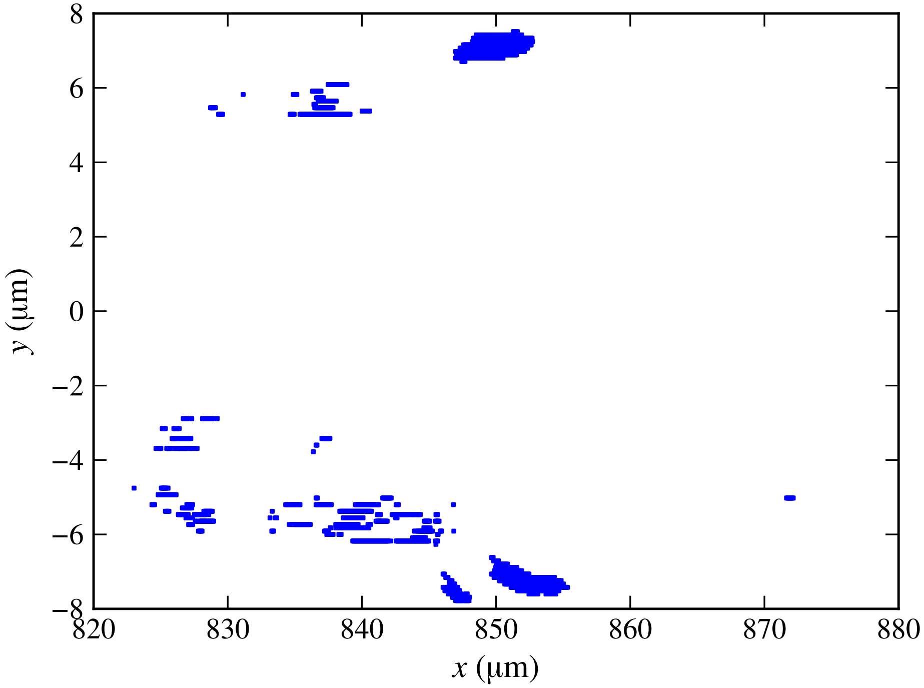
- The collection volume forms an annular region around the axis
- We load a larger number of particles per cell in that region
- With grid loading, we enhance on a cell-by-cell basis
  - Preserves quiet start
  - Loading is enhanced if the cell center is in the collection volume
  - Load on a uniform grid within each cell



Transition between unenhanced and enhanced regions

Tests in 2D

- We use 2D (slab) simulations to test effects of enhanced loading, perform convergence studies
- 2D simulation parameters: Plasma has 800 μm upramp, 400 μm uniform region at 8×10^{24} m^{-3} density, and 800 μm downramp; laser has $a_0 = 3.2$ and a 13.6 μm spot size
- Injection observed in second bucket

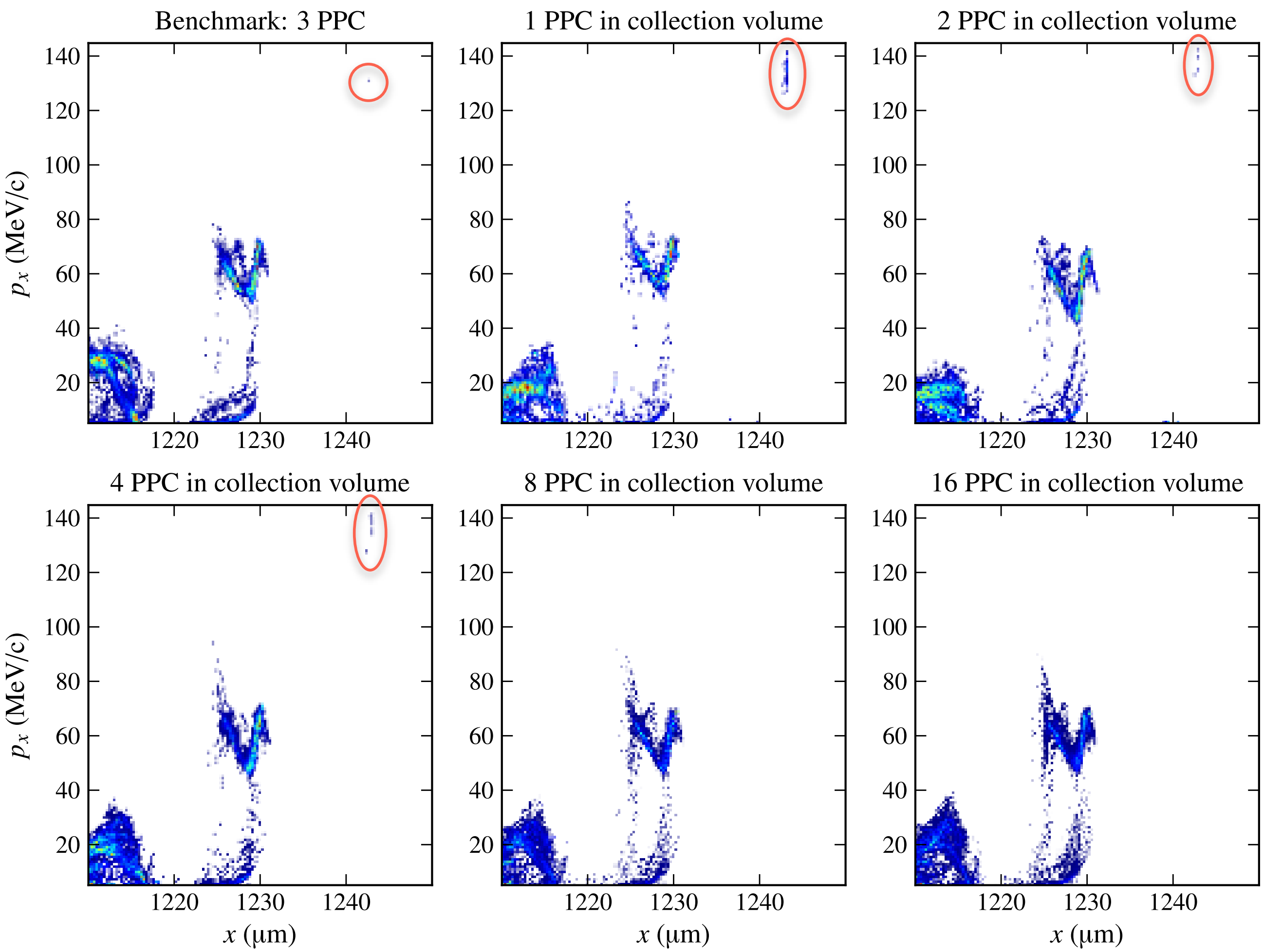


Collection volume for 2D run

- Annular region not as narrow as 3D case
- Consider it to be 2–8 μm

2D results: Longitudinal phase space

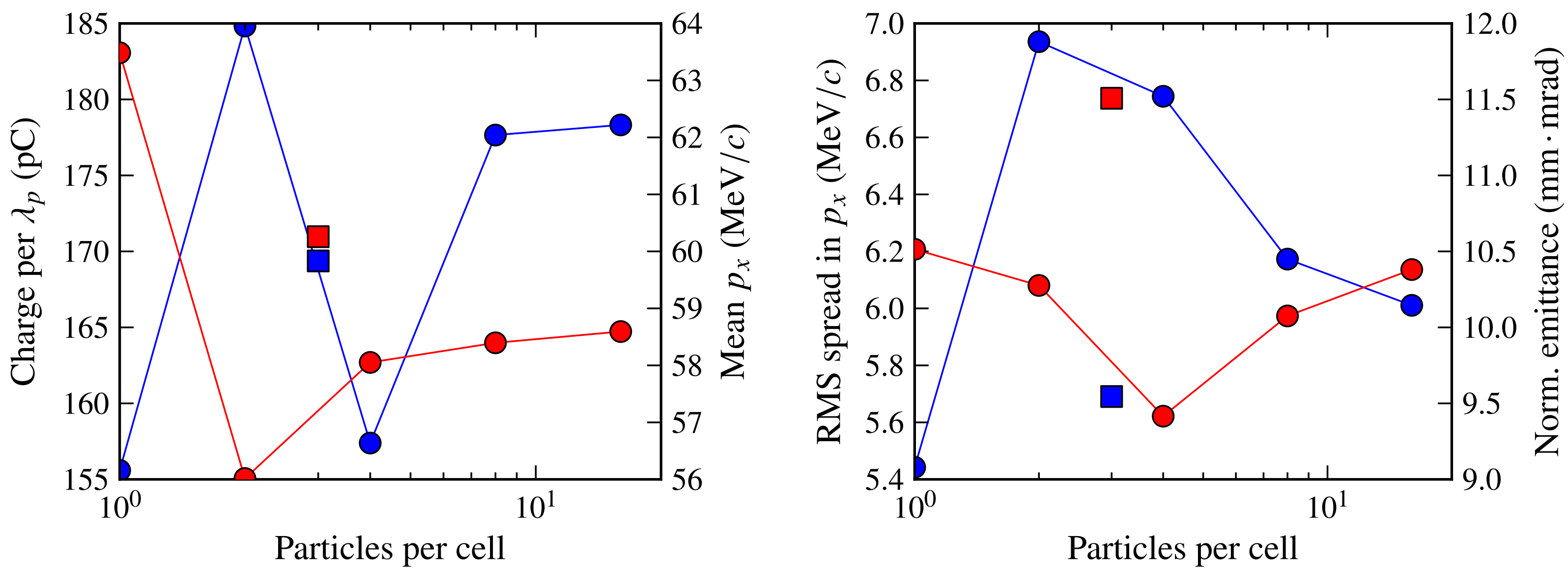
- Ran tests with 1, 2, 4, 8, and 16 PPC in collection volume and 1 PPC outside, as well as benchmark with 3 PPC everywhere



- Observed at point of minimal energy spread
- Up to 4 PPC (including benchmark) shows small injection in first bucket
- Conclusion: Injection in first bucket due to statistical noise, and more than 4 PPC required to eliminate it

2D results: Figures of merit

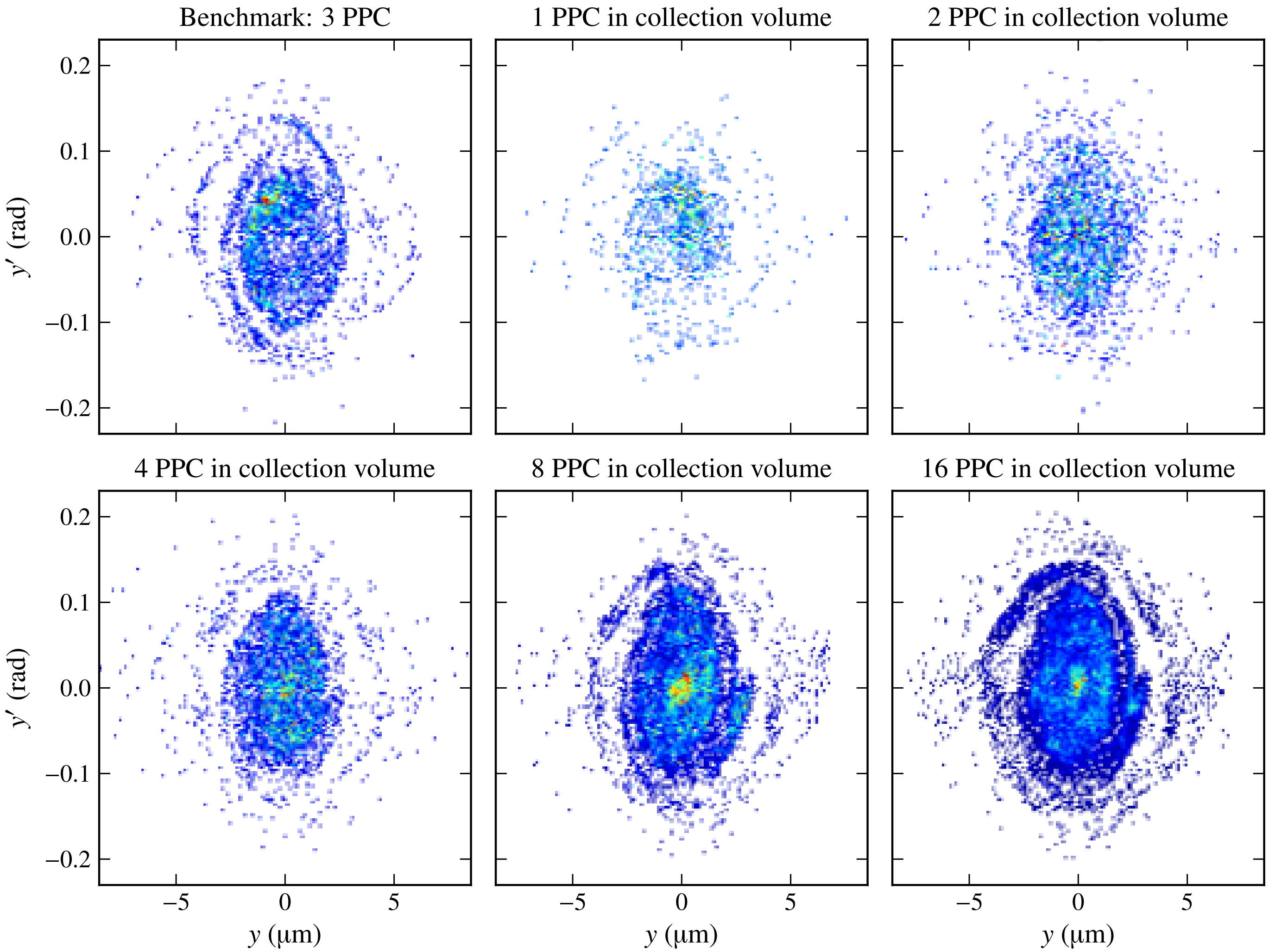
- Computed bunch charge, mean longitudinal momentum, longitudinal momentum spread, and transverse emittance



- Excellent agreement
  - Charge and mean p_x for 8 and 16 PPC within 0.4%
  - For p_x spread and emittance within 3%
  - Benchmark values not within difference ⇒ enhanced loading in collection volume helps; outside not so much

2D results: Transverse phase space

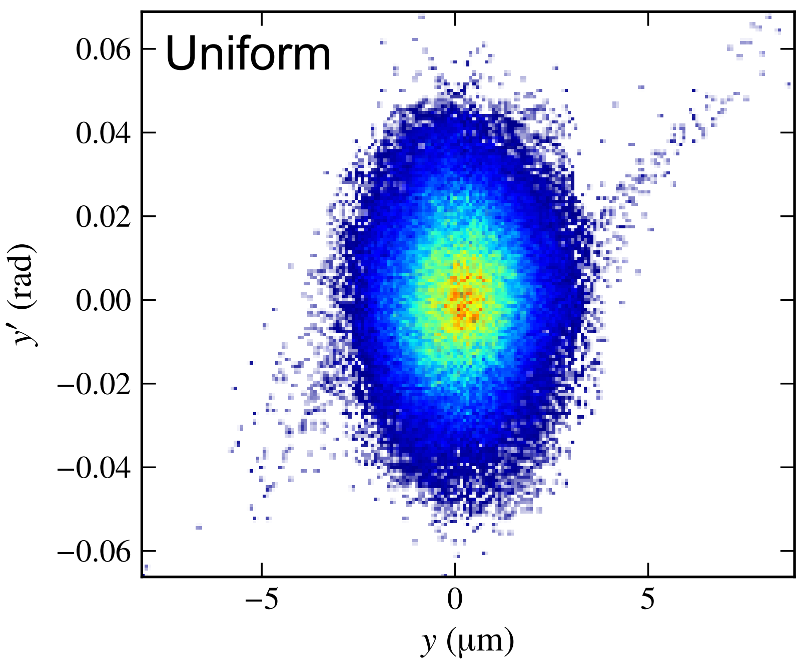
- Enhanced loading reveals, clarifies features

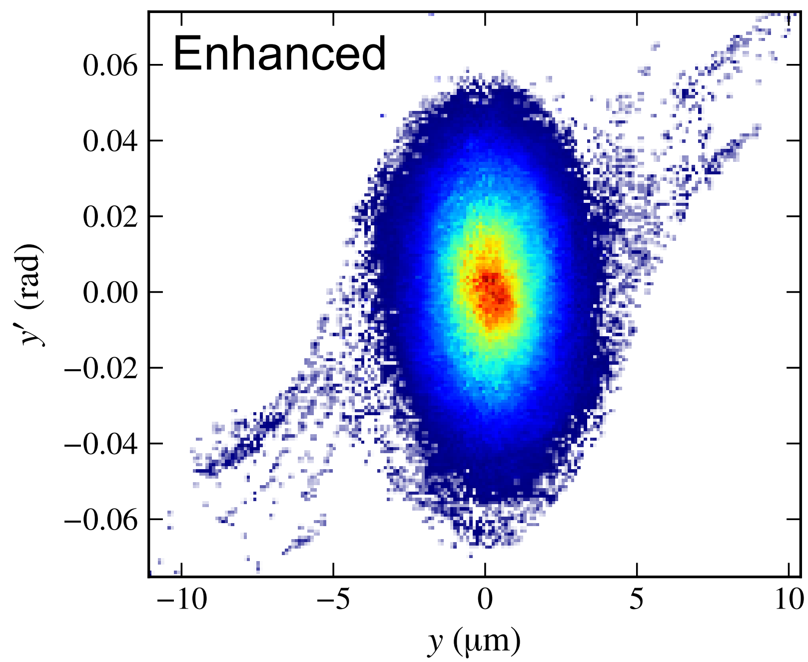


- Halo around core of beam phase space more clearly defined with enhanced loading
- Spiral pattern reveals nonlinear effects
- At 16 PPC, additional spiral pattern visible even within core

3D comparison

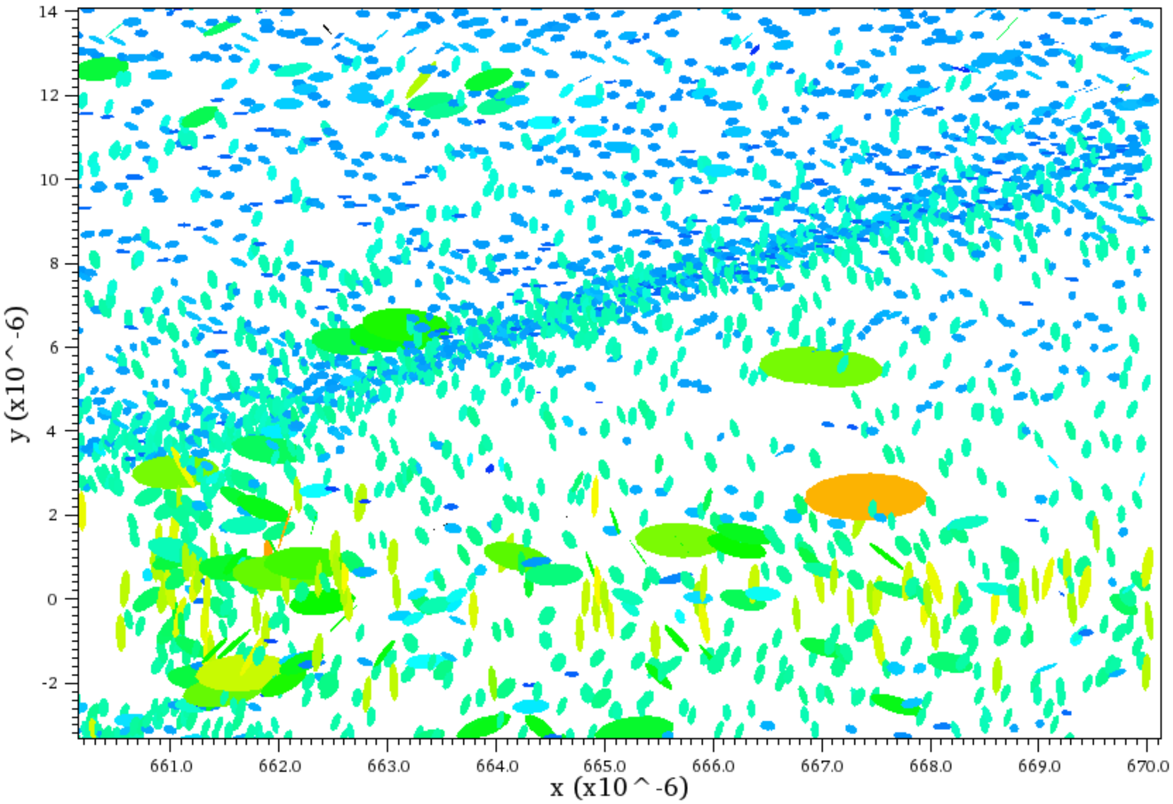
- For uniform loading, used 4 PPC everywhere
- For enhanced loading, used 16 PPC ($1 \times 4 \times 4$) inside collection volume (radius 7–10 μm), 1 PPC outside
- Compared transverse phase space
  - Better definition of halo for enhanced loading
  - Cleaner resolution of Gaussian core





Blob particles

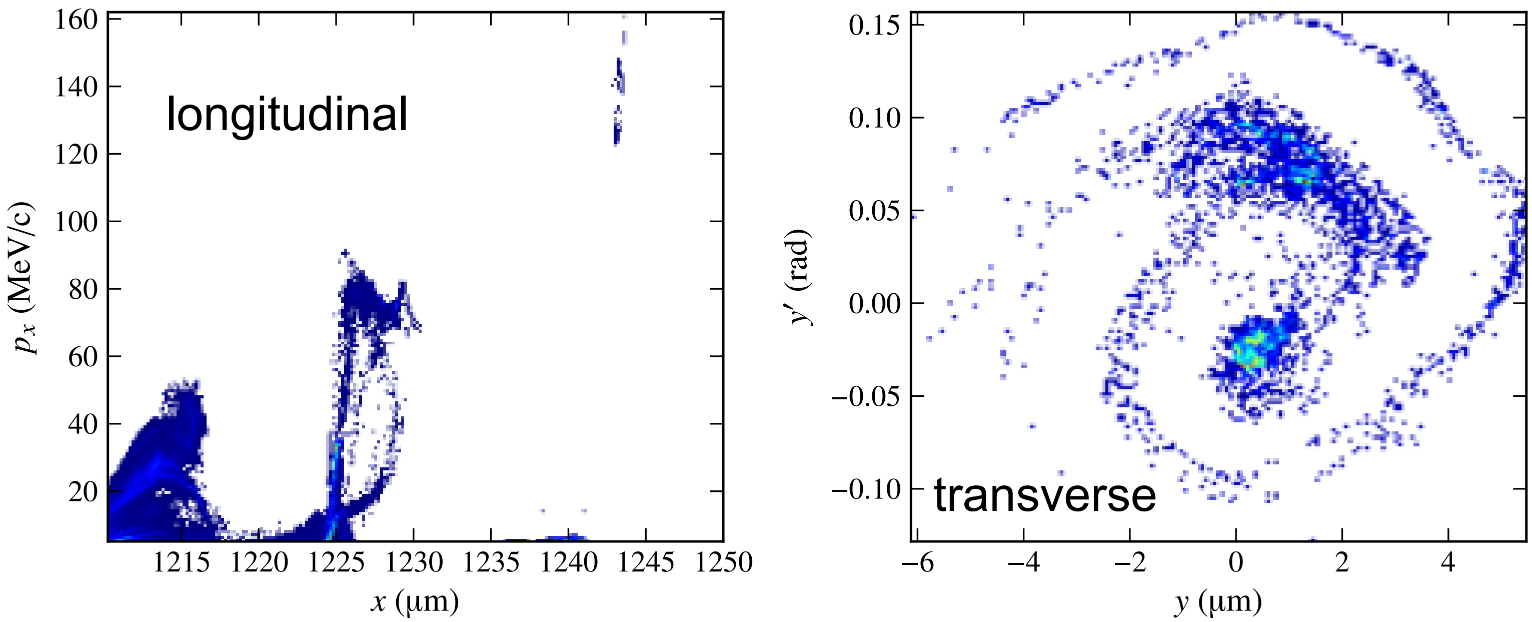
- Idea: Let particles choose their own statistics
- Particles deform according to tidal forces on them
- When they expand by a given amount in any direction, they split



Deformed particles around bubble sheath

Blob beam comparison

- Quantitative results don’t match enhanced loading values, but phase space shows interesting aspects



- Quantitative mismatch: 6× less charge, ~30% higher mean p_x, ~50% lower p_x spread, ~25% higher emittance
- Noise issues due to splitting; first bucket not suppressed
- But *occupied* transverse phase space volume much lower

Performance issues

- Enhanced loading can actually be faster
  - For 3D test, enhanced loading used 68% fewer particles than uniform loading
  - Simulation ran faster without any optimization effort
- Blob particles slow
  - Lots of linear algebra
  - But optimization could improve performance significantly

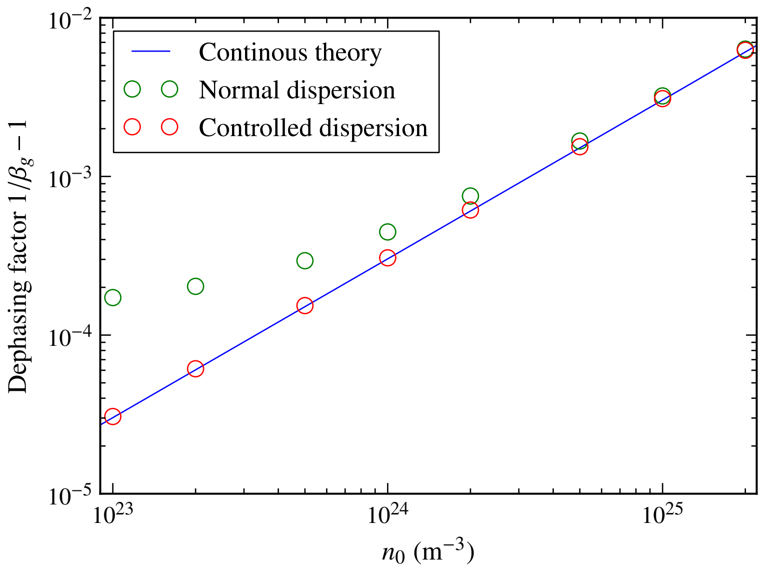
Controlled dispersion

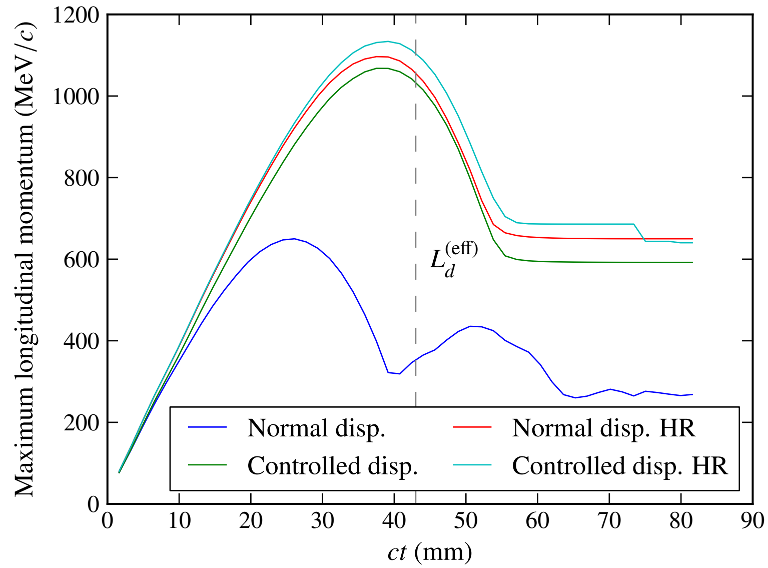
- Accuracy in LPA simulations requires correct group velocity of laser pulse
- Standard FDTD update known to exhibit numerical dispersion for waves propagating along an axis
- Use generalized method to achieve much more accurate dispersion for on-axis waves
  - Following [1] and [2]; generalized to arbitrary aspect ratios and benchmarked [3]
  - Fields are smoothed for computation of curl, in directions transverse to the derivative

[1] A. J. Pukhov, J. Plasma Phys. **61**, 425–433 (1999)
[2] M. Kärkkäinen *et al.*, Proc. ICAP 2006, 35–40 (2006)
[3] B. Cowan *et al.*, submitted to PRST-AB (2012)

Controlled dispersion benchmarking

- Shown to nearly eliminate dispersion error in linear channel propagation tests
- Shown to produce more physical, better converged results in quasilinear stage tests

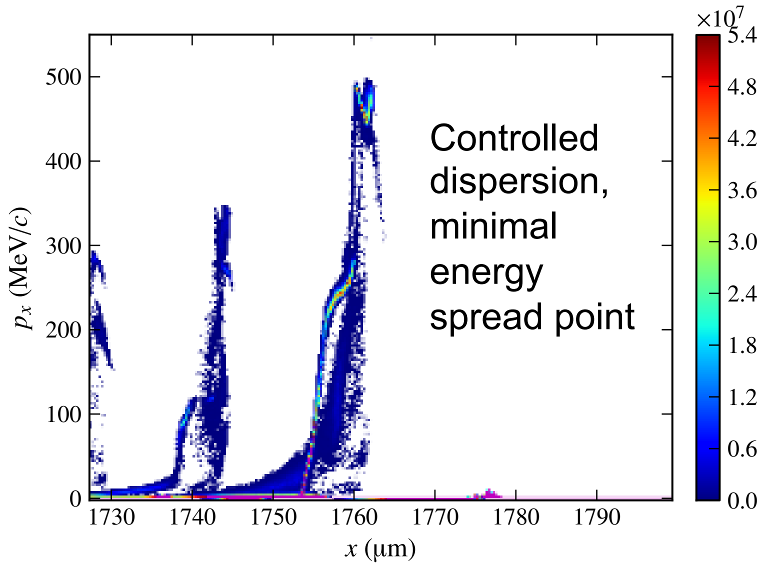


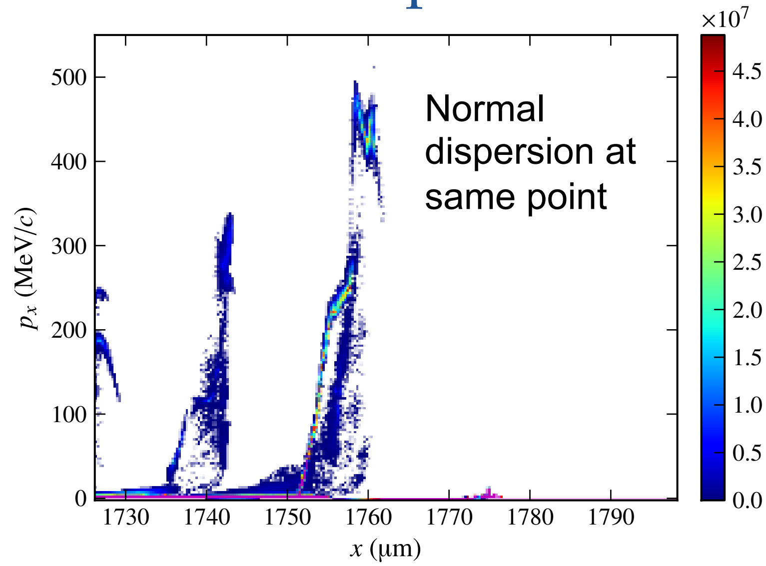


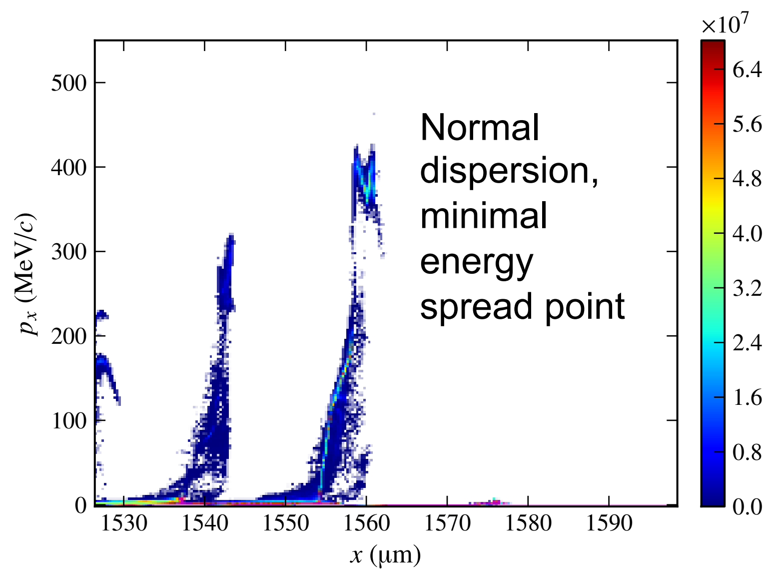
- Algorithm development, benchmarking done in collaboration with C. G. R. Geddes *et al.*, LBNL

Implications for self-injection simulations

- With controlled dispersion, injected beam dephases more slowly, gains more energy







B. Cowan *et al.*, J. Plasma Phys (2012)

Conclusions and outlook

- Enhanced loading provides access to details unavailable from conventional technique
  - Enables particle statistics needed for adequate resolution of particle beam; demonstrated convergence
  - Allows high statistics in collection volume that would be intractable if used uniformly (i.e. 16 PPC)
- Blob particle benefits uncertain, but interesting questions remain
  - How is it that it results in lower occupied phase space volume, even with noise issues?
- Controlled dispersion improves accuracy
- Next steps
  - Improve performance via load balancing, cell ordering
  - Convergence w/statistics demonstrated; what about resolution?
  - Continue investigation of blob particles