Single-shot, transverse self-wakefield reconstruction from screen images

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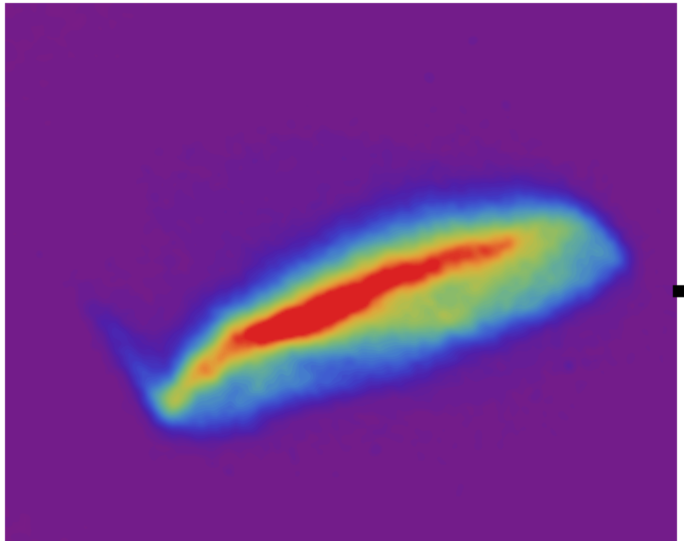
Motivation

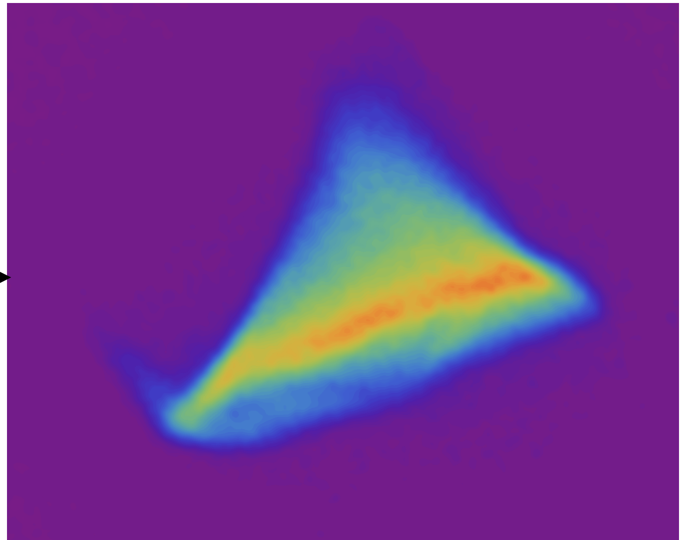
- Goal is to understand the transverse self-wakefields
  - Can be both beneficial (streakers) or problematic (BBU)
  - See Walter Lynn's talk "Observation of Skewed Electromagnetic Wakefields in an Asymmetric Structure Driven by Flat Electron Bunches"
- Complements simulation
- May pair with longitudinal diagnostics for greater insight
- May play well with multileaf collimators; giving very granular, real-time control over wakes

Initial beam



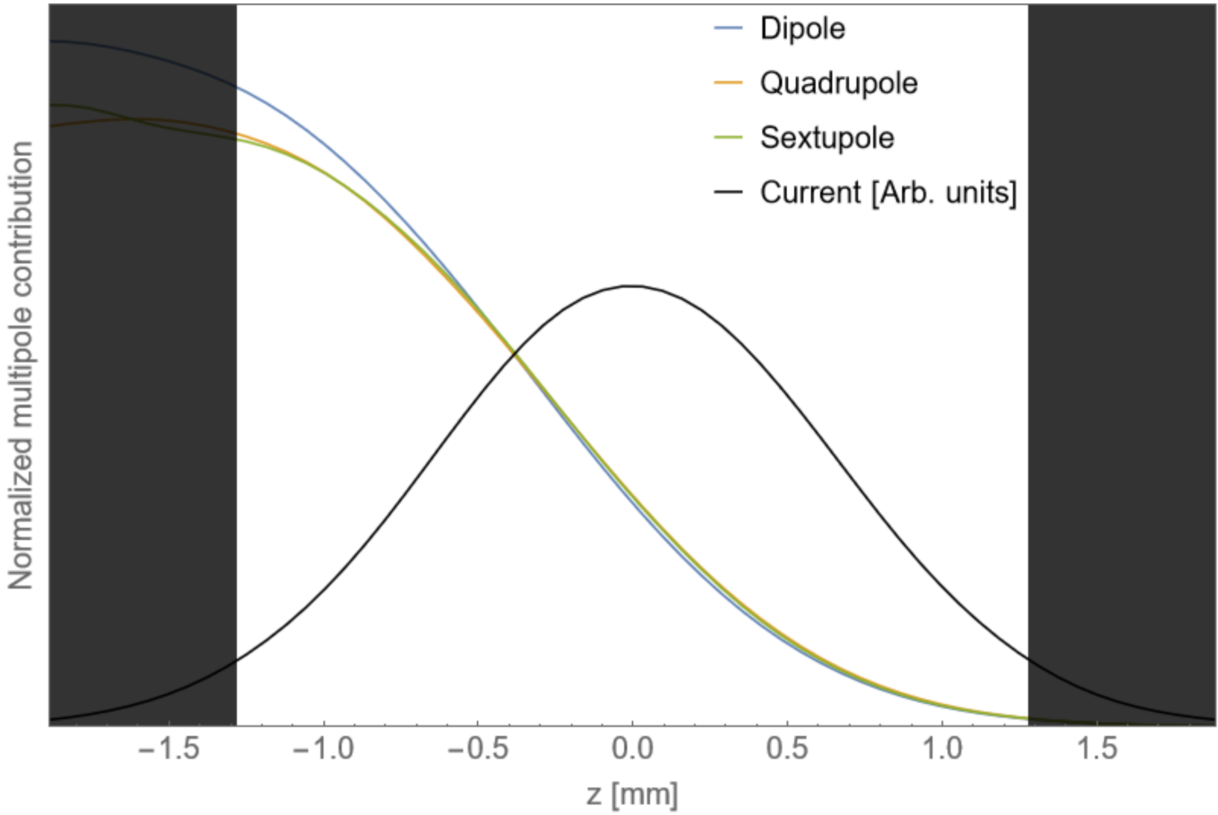
Unknown wakefields

Final beam

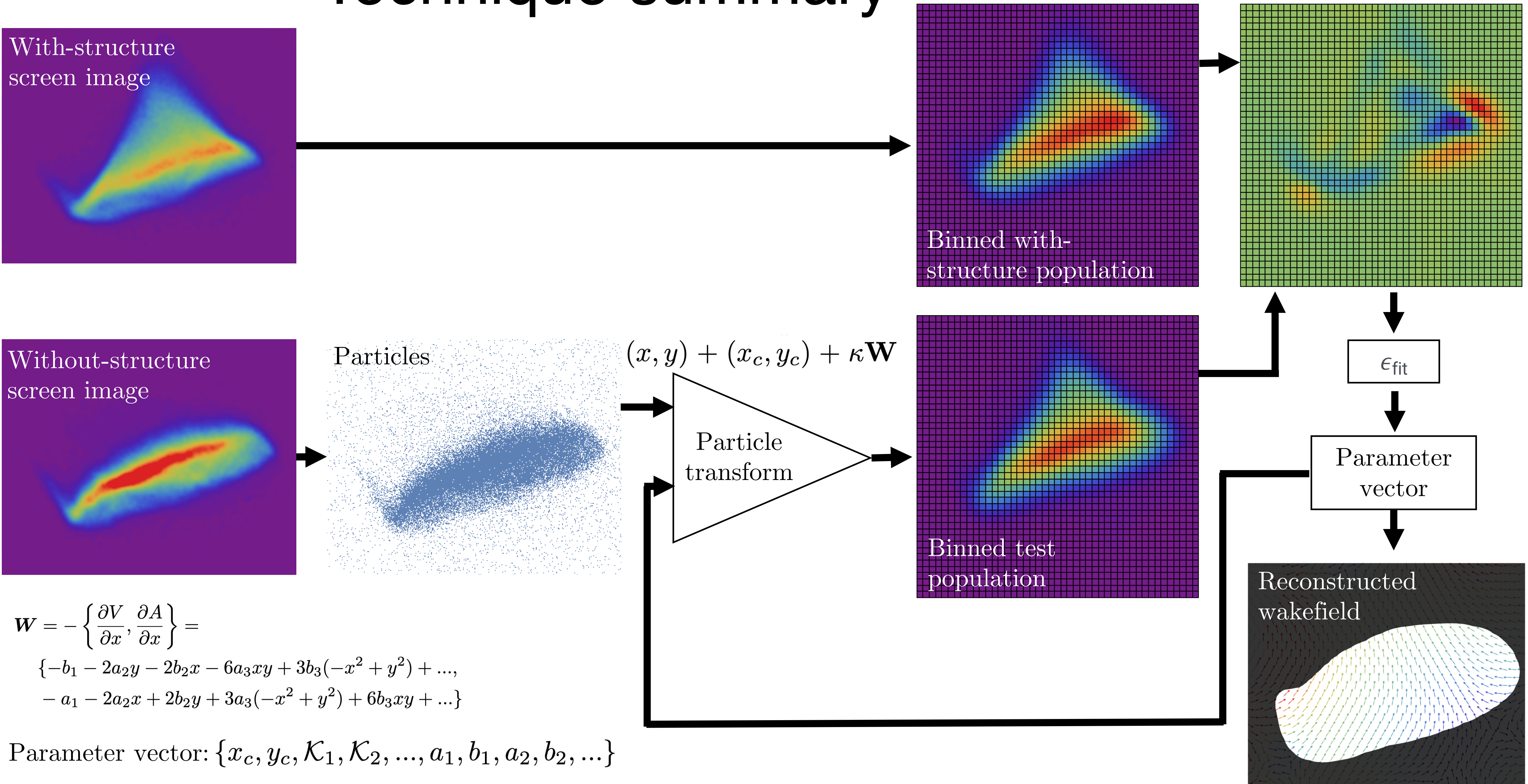


Assumptions

- Thin lens approximation
  - Beam spatial distribution does not appreciably change over interaction
  - Each particle only "feels" one part of the wakefield
- Wakefield is the same, up to multiplicative constant, along ζ
  - Satisfied if beam is short relative to the wavelength of all relevant modes
    - Each mode's wake response approximated by linear function with different slopes; ratio constant
- Wakefield is well approximated by low order multipoles



Technique summary



$$\boldsymbol{W} = -\left\{\frac{\partial V}{\partial x}, \frac{\partial A}{\partial x}\right\} =$$

$$\{-b_1 - 2a_2y - 2b_2x - 6a_3xy + 3b_3(-x^2 + y^2) + ...,$$
$$- a_1 - 2a_2x + 2b_2y + 3a_3(-x^2 + y^2) + 6b_3xy + ...\}$$

Parameter vector: $\{x_c, y_c, \mathcal{K}_1, \mathcal{K}_2, ..., a_1, b_1, a_2, b_2, ...\}$

Benchmarking to simulation: setup

Extract exact 3D wakefields, W_{sim}

↓

Get slicewise multipole coefficients

$$\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_{\text{slice}}) - \boldsymbol{W}_{\text{guess}}(x_k, y_k)|\rangle_{95\%}$$

→ **Quantify with $\epsilon_{\text{slicewise}}$**

$$\epsilon_{\text{slicewise}} = \frac{\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_k) - \boldsymbol{W}_{\text{slicewise}}(x_k, y_k, z_k)|\rangle_{95\%}}{\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_k)|\rangle_{95\%}}$$

↓

Generate aggregate field

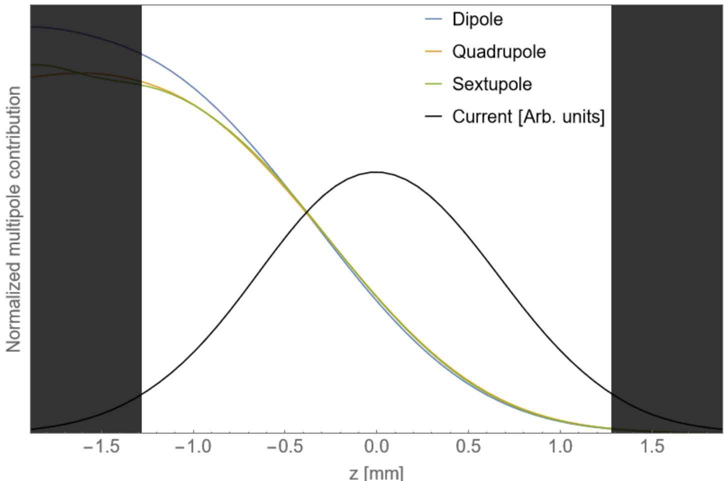
$$\boldsymbol{c}_{\text{agg}} = \sum_{\text{slices}} I(z_{\text{slice}})\boldsymbol{c}_{\text{slice}} \Big/ \sum_{\text{slices}} I(z_{\text{slice}})$$

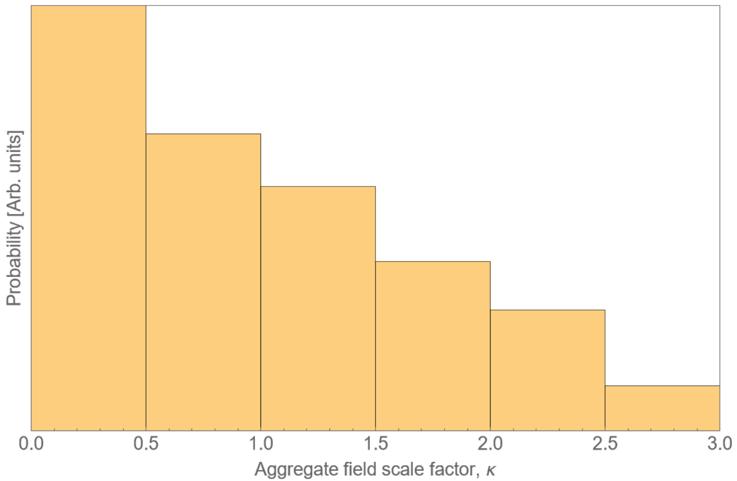
→ **Quantify with ϵ_{agg}**

$$\epsilon_{\text{agg}} = \frac{\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_k) - \kappa(z_k)\boldsymbol{W}_{\text{agg}}(x_k, y_k)|\rangle_{95\%}}{\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_k)|\rangle_{95\%}}$$

↓

Get κ(z) and kick PDF →





Benchmarking to simulation: example

500 MeV, 2 nC, 2.2° tilt, 7.7:1 spot size, run past 15 cm long dielectric slab

Extract exact 3D wakefields, W_{sim}

Fit to n=6

Get slicewise multipole coefficients

$$\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_{\text{slice}}) - \boldsymbol{W}_{\text{guess}}(x_k, y_k)|\rangle_{95\%}$$

Generate aggregate field

$$\boldsymbol{c}_{\text{agg}} = \sum_{\text{slices}} I(z_{\text{slice}})\boldsymbol{c}_{\text{slice}} \Big/ \sum_{\text{slices}} I(z_{\text{slice}})$$

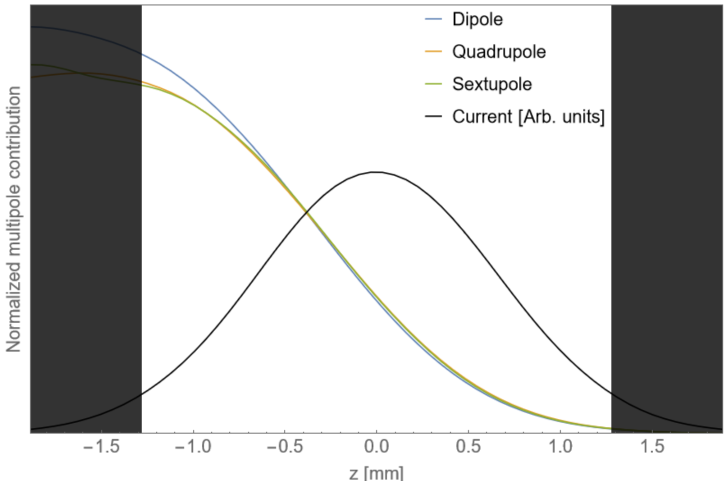
Get κ(z) and kick PDF

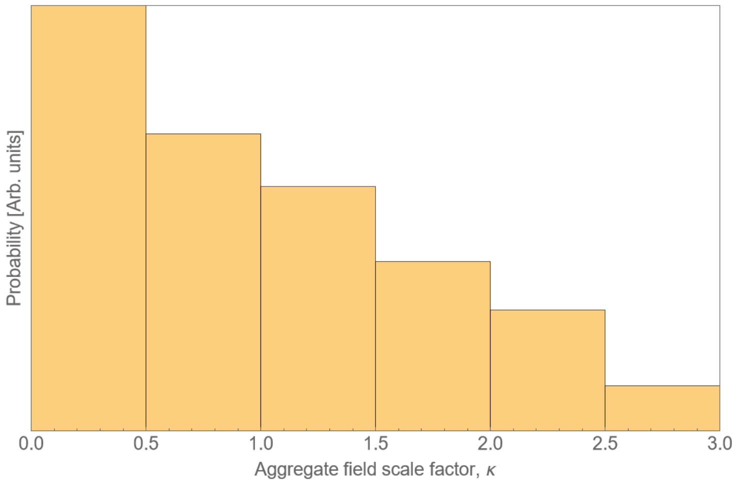
Quantify with $\epsilon_{\text{slicewise}}$ 1.5%

$$\epsilon_{\text{slicewise}} = \frac{\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_k) - \boldsymbol{W}_{\text{slicewise}}(x_k, y_k, z_k)|\rangle_{95\%}}{\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_k)|\rangle_{95\%}}$$

Quantify with ϵ_{agg} 2.3%

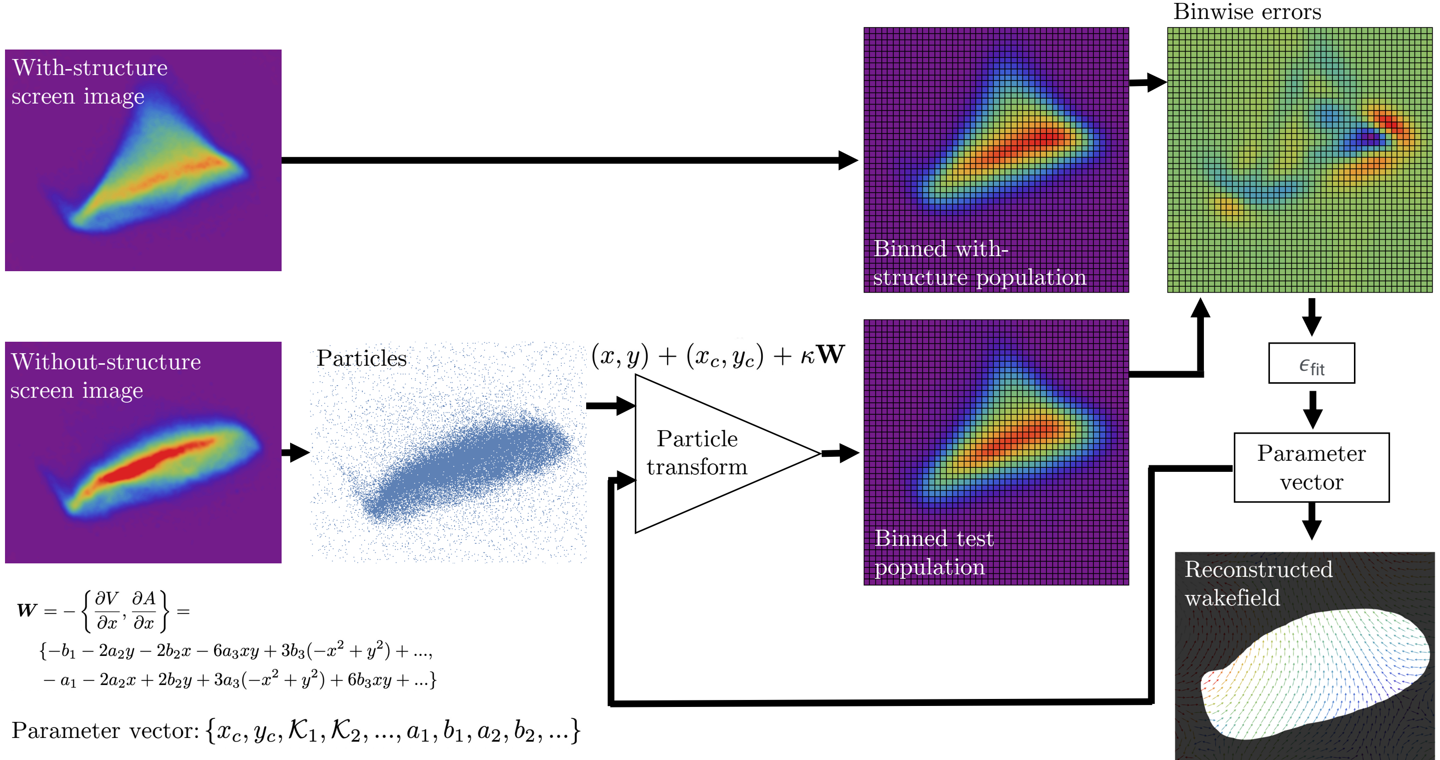
$$\epsilon_{\text{agg}} = \frac{\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_k) - \kappa(z_k)\boldsymbol{W}_{\text{agg}}(x_k, y_k)|\rangle_{95\%}}{\langle|\boldsymbol{W}_{\text{sim}}(x_k, y_k, z_k)|\rangle_{95\%}}$$

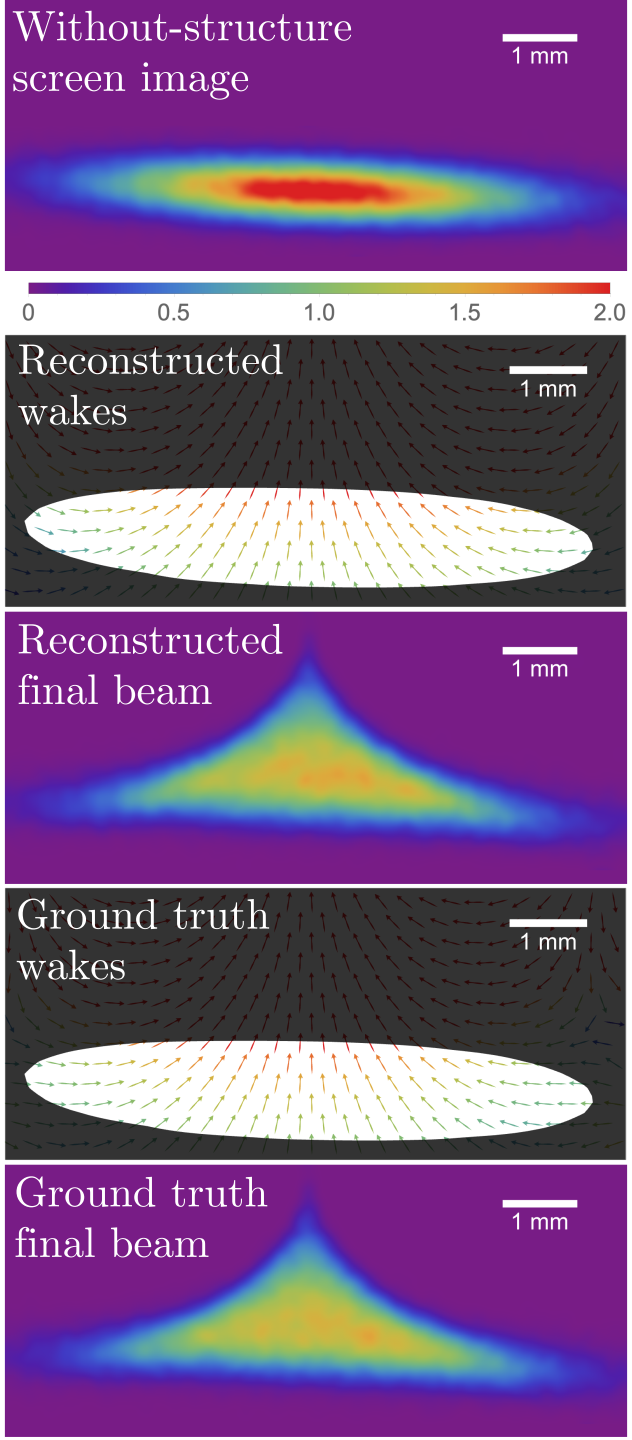




Benchmarking to simulation: reconstruction

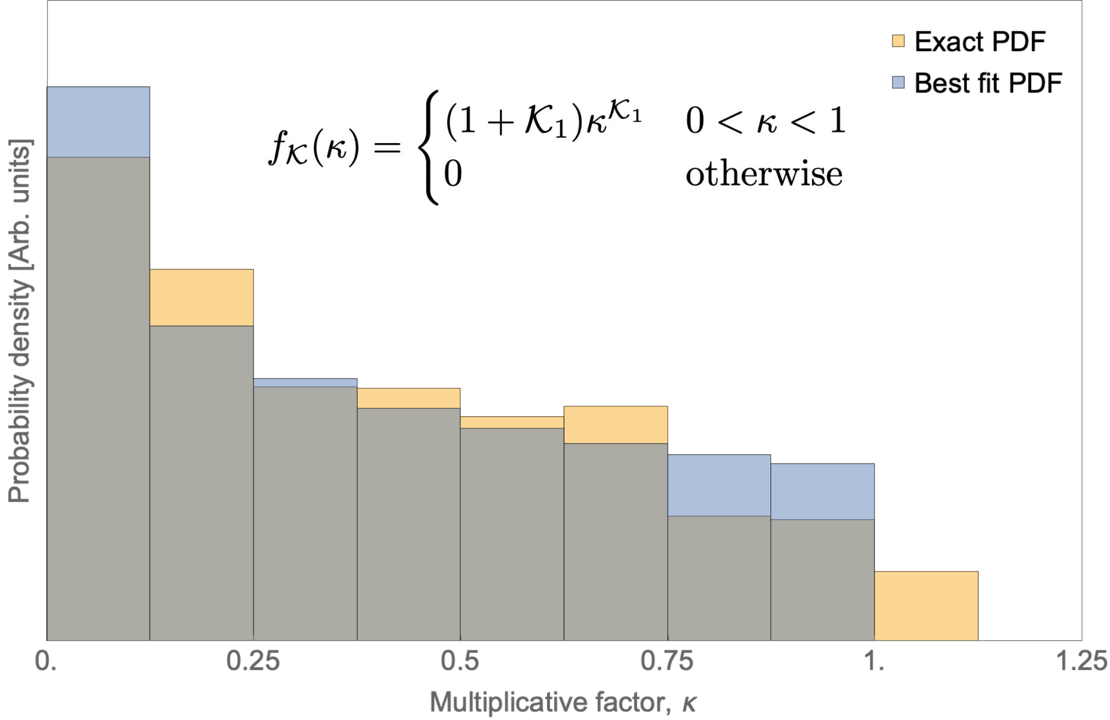
- Create virtual screen images
- Reconstruct to n = 6, using known κ PDF
  - 12 free parameters
- Optimizer figure of merit: ϵ_{fit} = 1.3%
- Compare reconstructed fields to ground truth: ϵ_{recons} = 2.6%

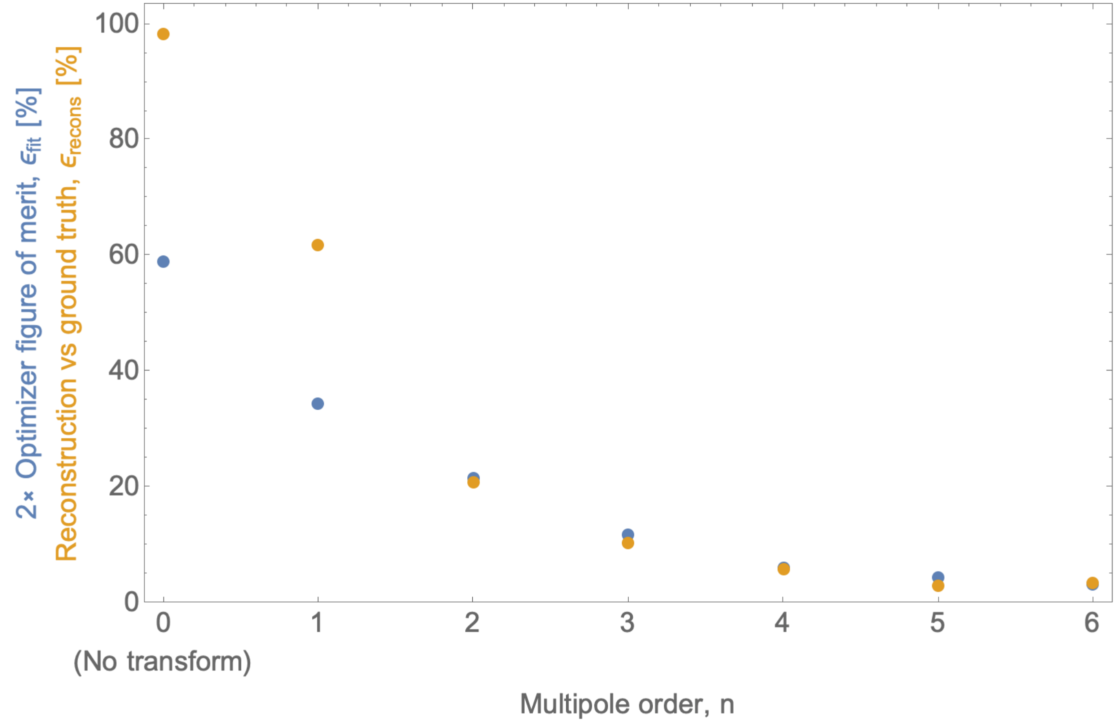




Moving closer to experiment

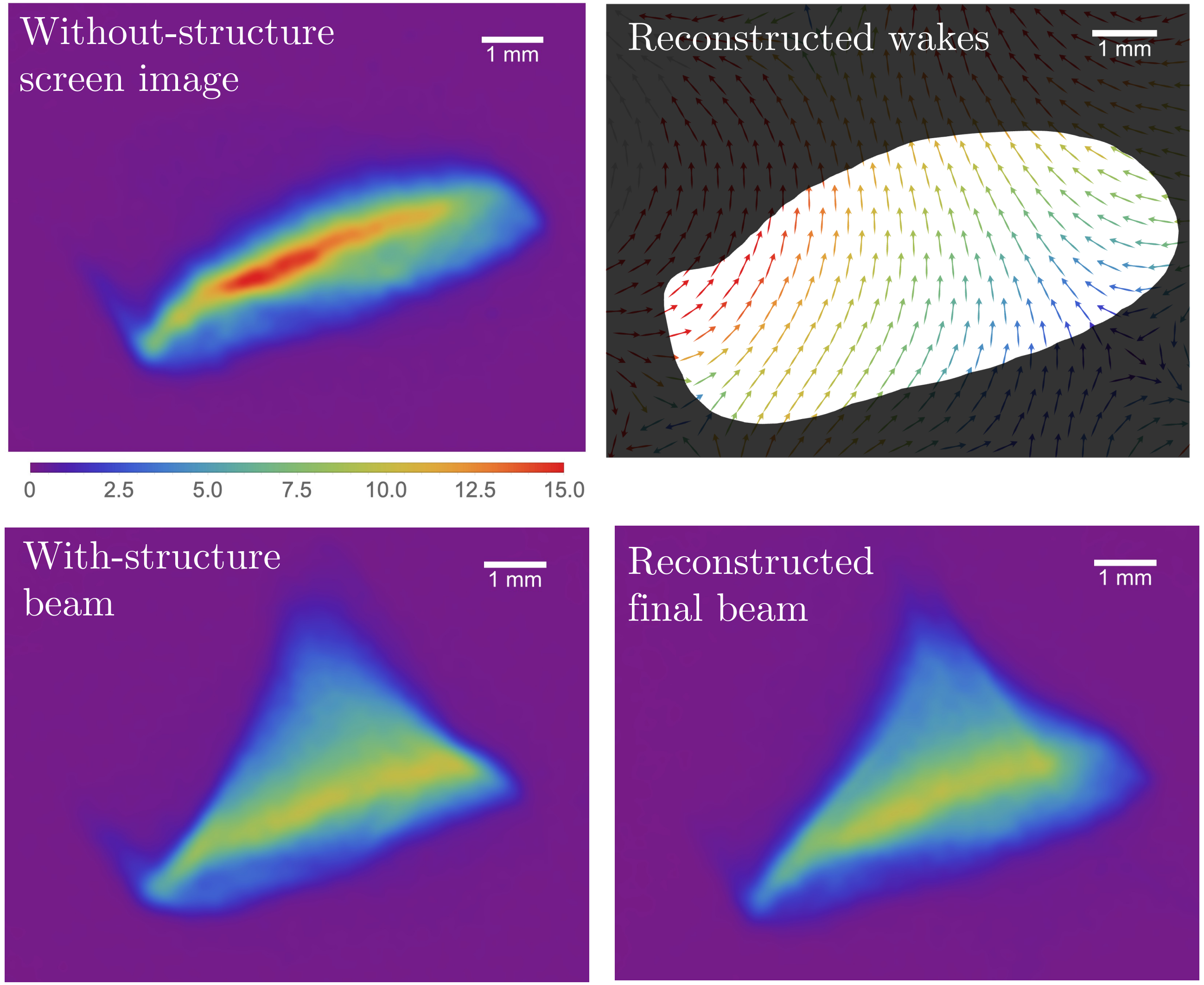
- Drop known κ PDF, use parameterized distribution
  - Simple but powerful, single parameter
  - ϵ_{fit} from 1.3% to 1.8%, ϵ_{recons} from 2.6% to 3.1%
- Vary n to see how ϵ_{fit} and ϵ_{recons} respond
  - We knew n=6 was sufficient, wouldn't know that in experiment before reconstructing





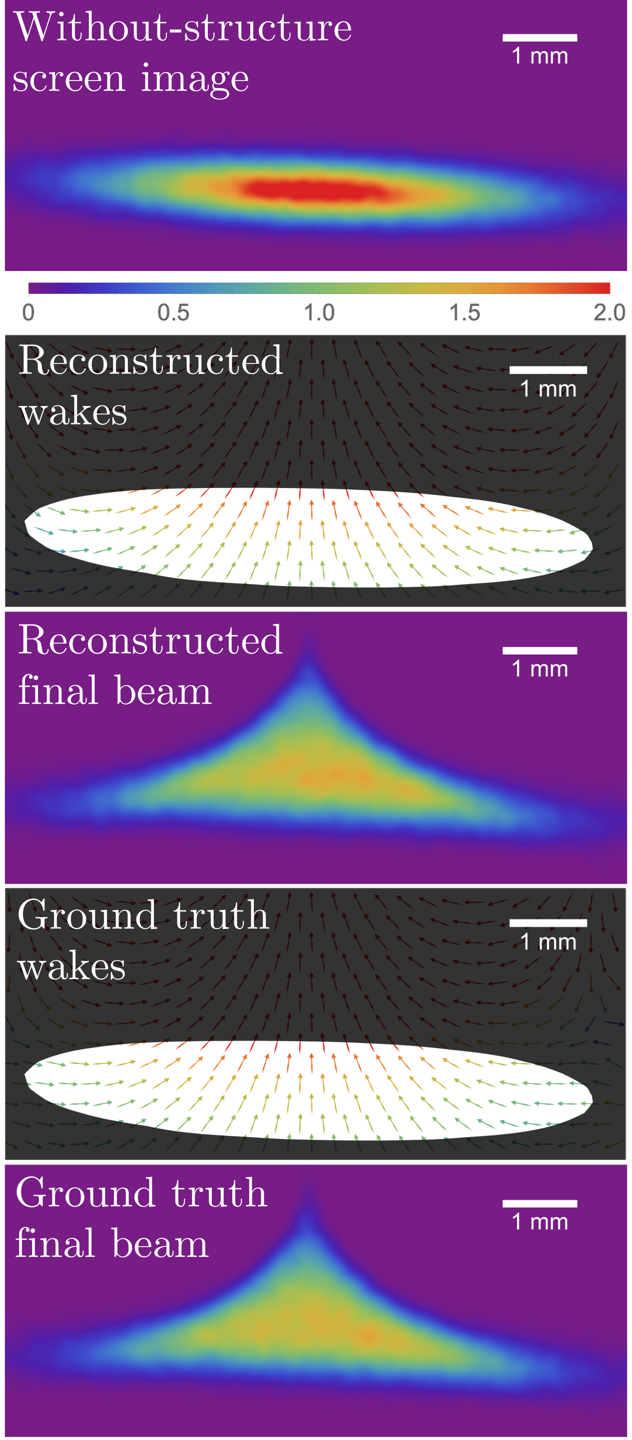
Experimental data reconstruction

- AWA flat beam skew wake data
  - 43 MeV
- Parameterized κ PDF, n = 6, x_c and y_c active
  - 15 free parameters
- $\epsilon_{\text{fit}} = 6.0\%$



Conclusion

- Transverse wakefields are important to understand but hard to measure
- Introduced a technique to reconstruct the self-wakefields without additional hardware; a single screen is sufficient
- Relies on assumptions which can be defended
- Benchmarked against simulation data
- Applied to experimental data
- Room to grow



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