BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

# Revealing Laser and Electron Beam Evolution in 10-GeV-class Laser-Plasma Accelerators

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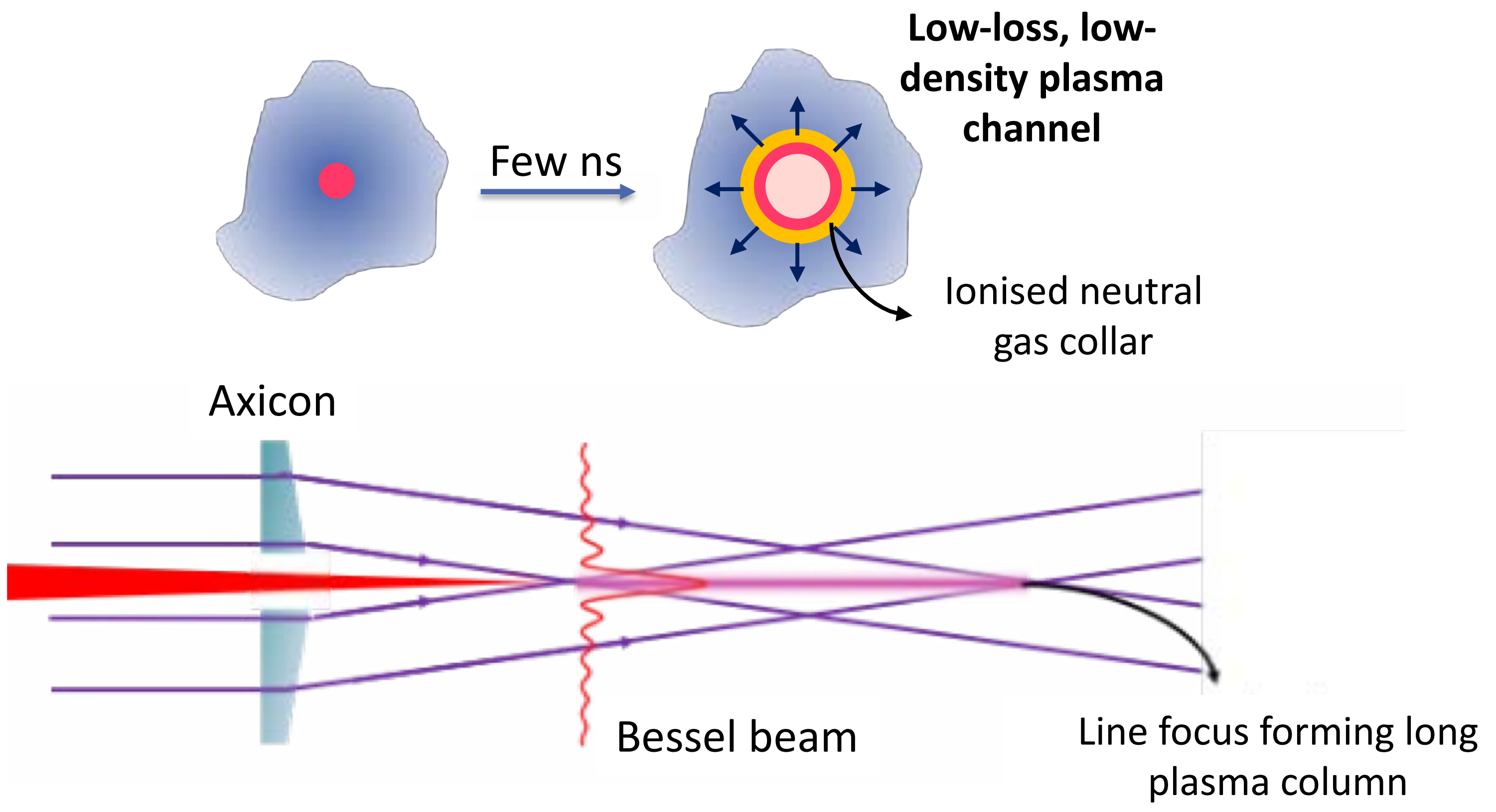
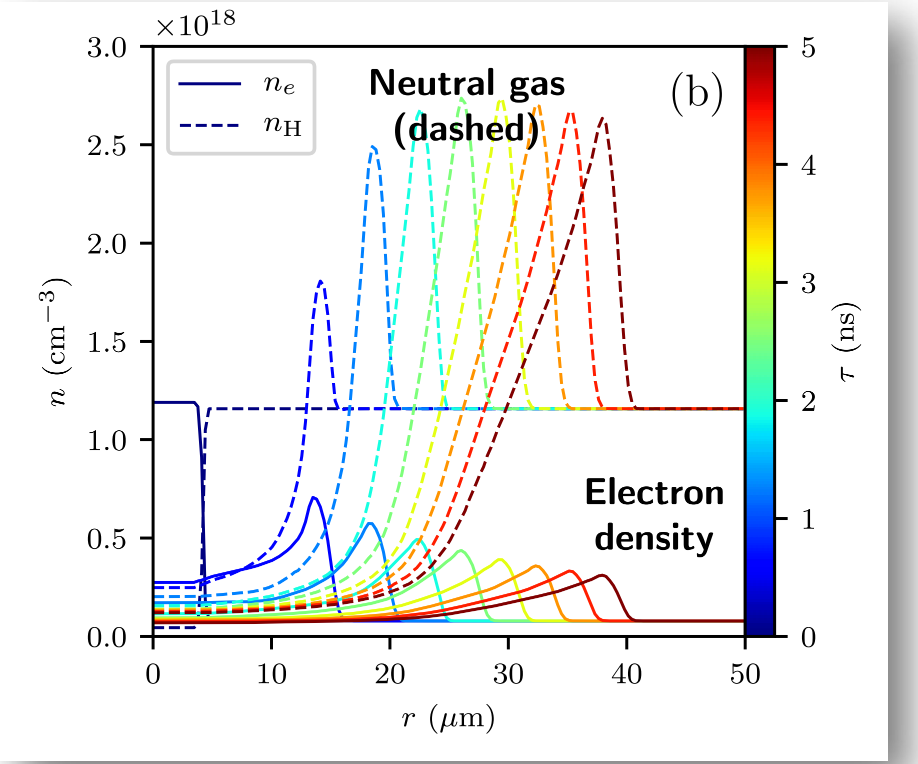
**Accelerator Technology & Applied Physics Division**

U.S. DEPARTMENT of ENERGY | Office of Science

# HOFI plasma channels can meet key requirements of 10-GeV-class LPA stages

- 10 GeV stages require laser propagation over 10's cm at densities $n_0 \sim 10^{17}\ \mathrm{cm}^{-3}$
- Channels formed by hydrodynamic expansion of optical field ionized plasma can meet these requirements



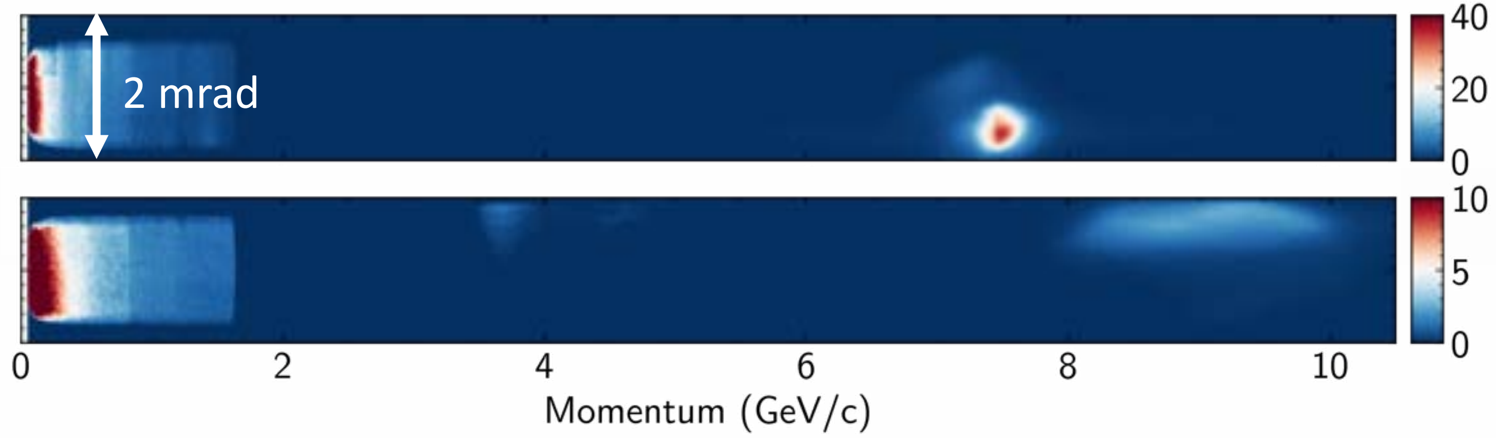




**Low density HOFI Channels**
Shalloo, R. J.,*et al.*, (2018), *PRE, 97*(5)
Shalloo, R. J.,*et al.* (2019), *PRAB, 22*(4)

**Overcome leakage by ionizing neutrals**
Morozov, A et al. (2018). *PoP, 25*(5)
Shalloo, R. J. *Thesis 2018*
Picksley, A., et al. (2020). *PRE, 102*(5)
Feder, L., et al. (2020). *PRR, 2*(4)

**10-GeV-Class LPAs in HOFI Channels**
Picksley, A., et al. *Physical Review Letters* 133.25 (2024)
Rockafellow, E, et al. *NIMA A:*1077 (2025).

# 10 GeV gain achieved in 30 cm long channels at BELLA PW




Laser Energy : 20 J

Plasma density : $n_0 \approx 1.0 \times 10^{17} \mathrm{cm}^{-3}$

Channel radius : $r_{ch} \approx 37\ \mu\mathrm{m}$



Picksley, A., et al. *Physical Review Letters* 133.25 (2024)

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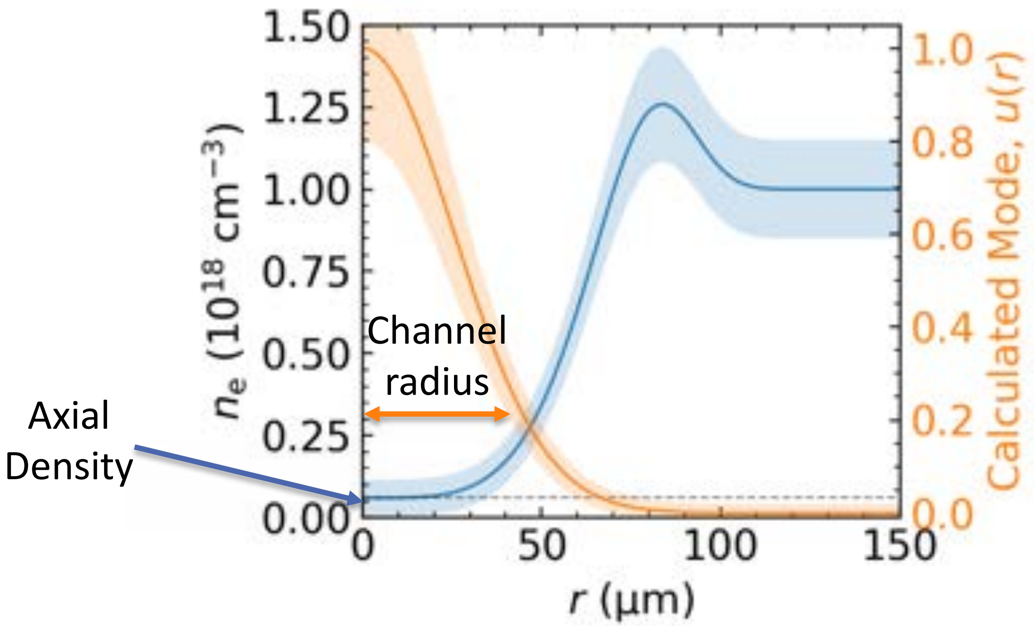
Collaboration with U. Maryland

# Physics of the LPA dictated by the channel shape, which is difficult to measure

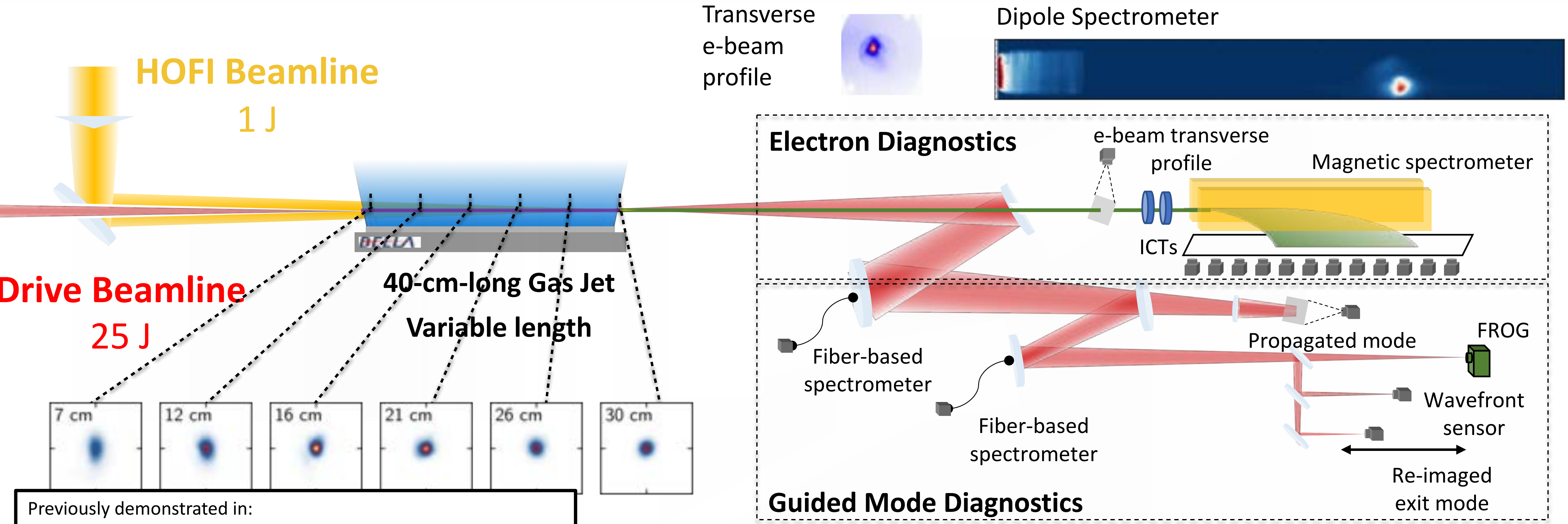
- Transverse Interferometry has low signal-to-noise (small plasma at low density) and requires perfect cylindrical symmetry
- Other uncertainties from channel-forming laser intensity, gas jet density fluctuations, etc…




**Control over the LPA requires understanding the evolution of electron beam parameters throughout the accelerator**

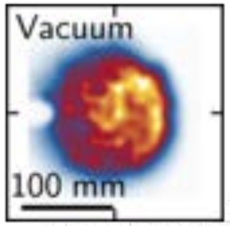
**10-GeV-Class LPAs in HOFI Channels**
Picksley, A., et al. *Physical Review Letters* 133.25 (2024)
Rockafellow, E, et al. *NIMA A:*1077 (2025).

# Aim: Use full set of tools available on BELLA PW understand what is going on inside the LPA

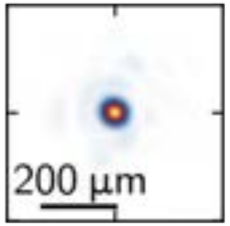



Previously demonstrated in:
Picksley, A., et al. *Physical Review Letters* 133.25 (2024)

Propagated Mode at $z \approx 10$ m:



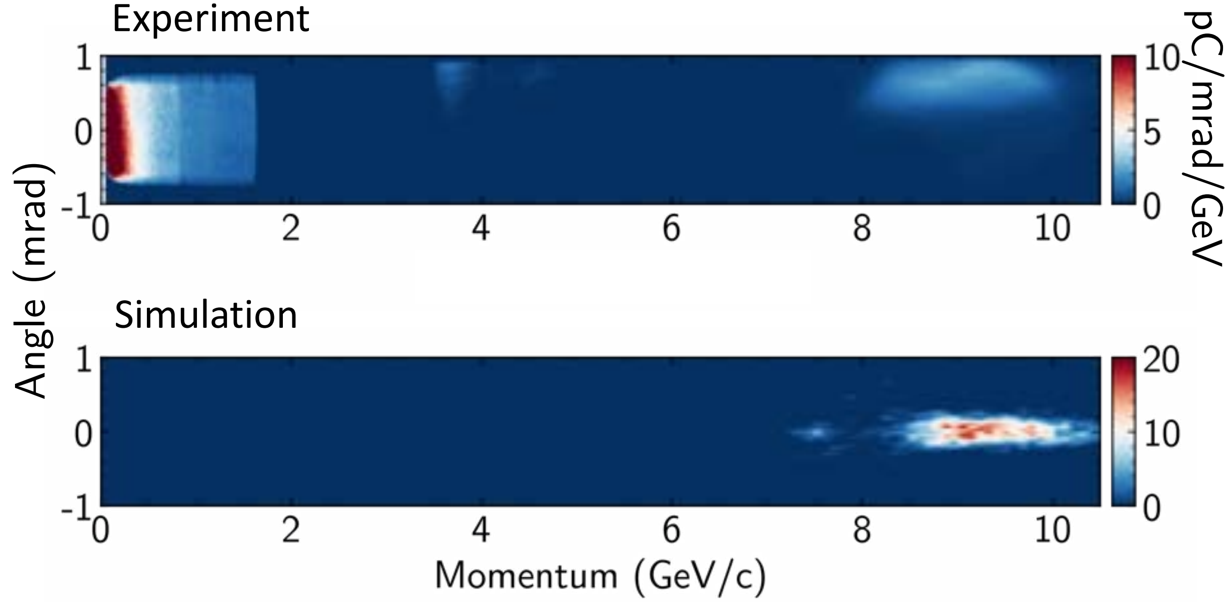

Re-imaged mode at exit:



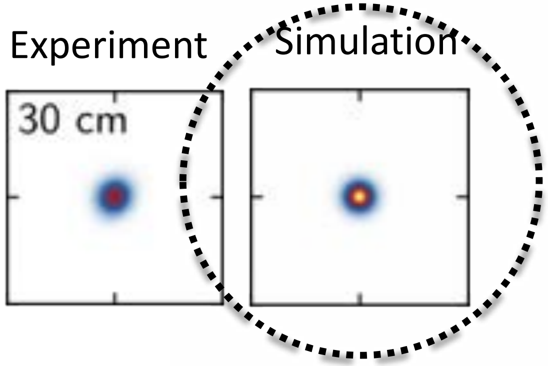
# With limited diagnostics (and terminal values only), what confidence do we have in our understanding?

- Fine tuning of parameters required to match simulations to experiment for just one diagnostic to the terminal values

**Electron Diagnostics**




**Re-imaged exit mode**



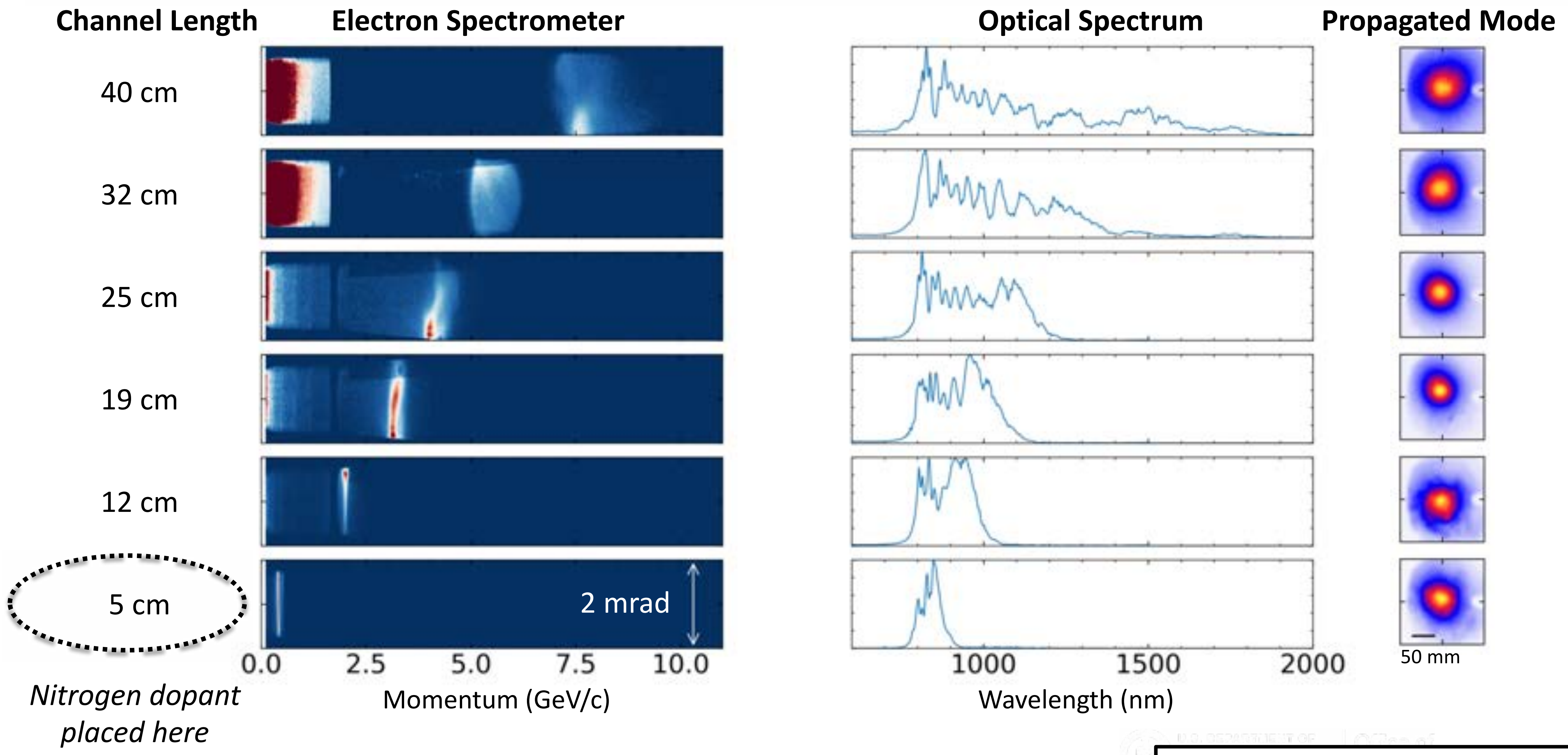

*A mystery…*



Picksley, A., et al. *Physical Review Letters* 133.25 (2024)

**Simulations using INF&RNO**
See https://blast.lbl.gov/

# We can measure the properties of the guided laser, and the electron beam at several points along the accelerator

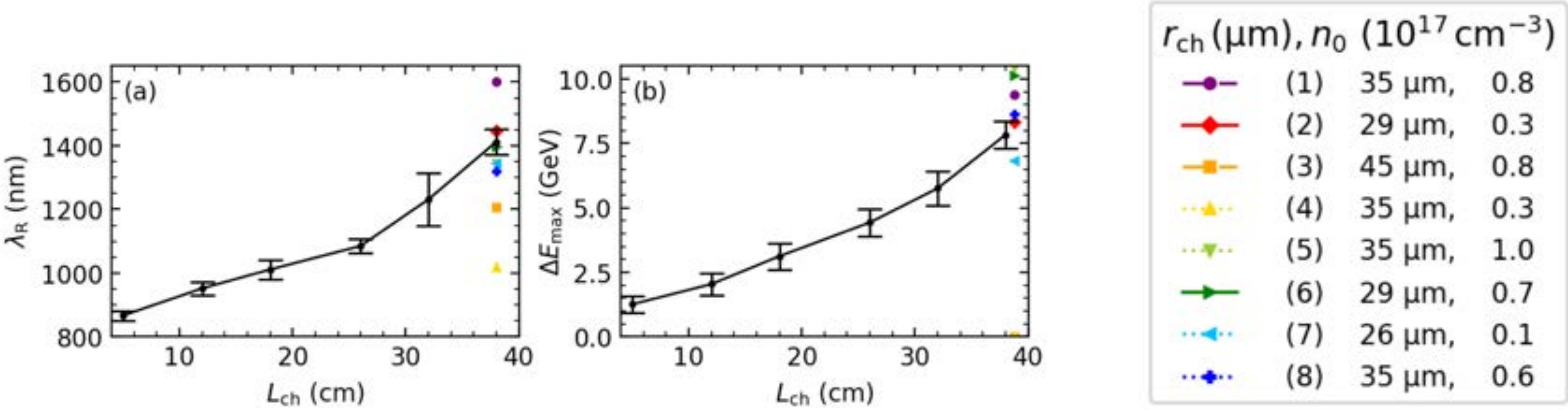



Tang, H. et al. (*Submitted*), see: arXiv [2604.25823](2604.25823)

# Using only terminal values of either the electron beam or redshifting leaves unknowns

- Shot-to-shot fluctuations of parameters, combined with little knowledge of parameter evolution means we cannot decipher the physics of the laser-plasma accelerator

- We can take simple scalar values to compare:
  - Redshifting (measure of laser depletion)
  - Max electron energy

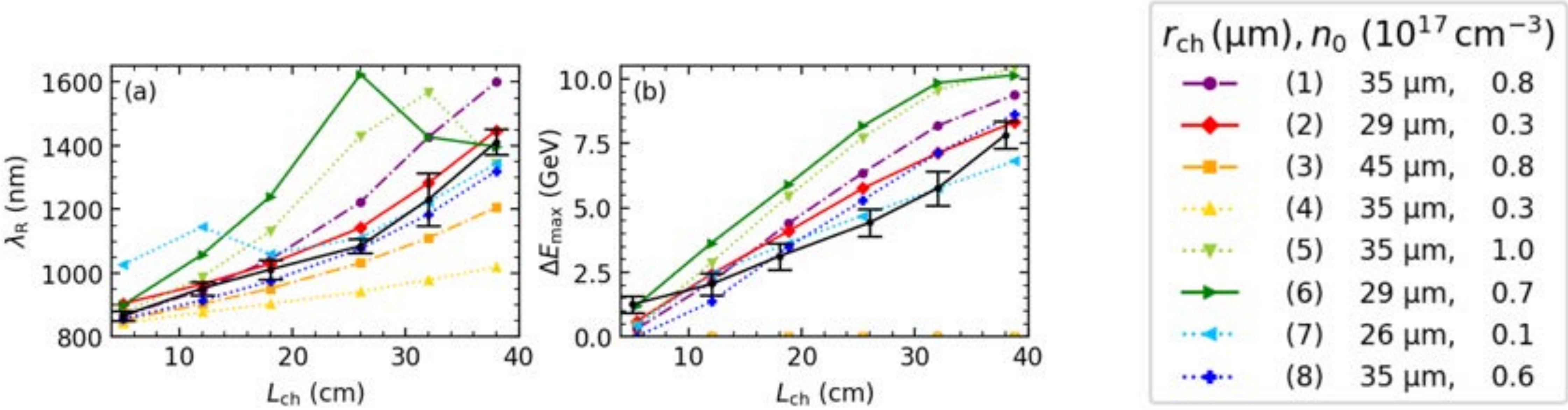



Tang, H. et al. (*Submitted*), see: arXiv 2604.25823

# The evolution of both the electron beam and redshifting is required to understand the LPA

- Using evolution values gives clearer picture of the LPA

- Some curves reproduce redshift, but not electron beams, and vice versa

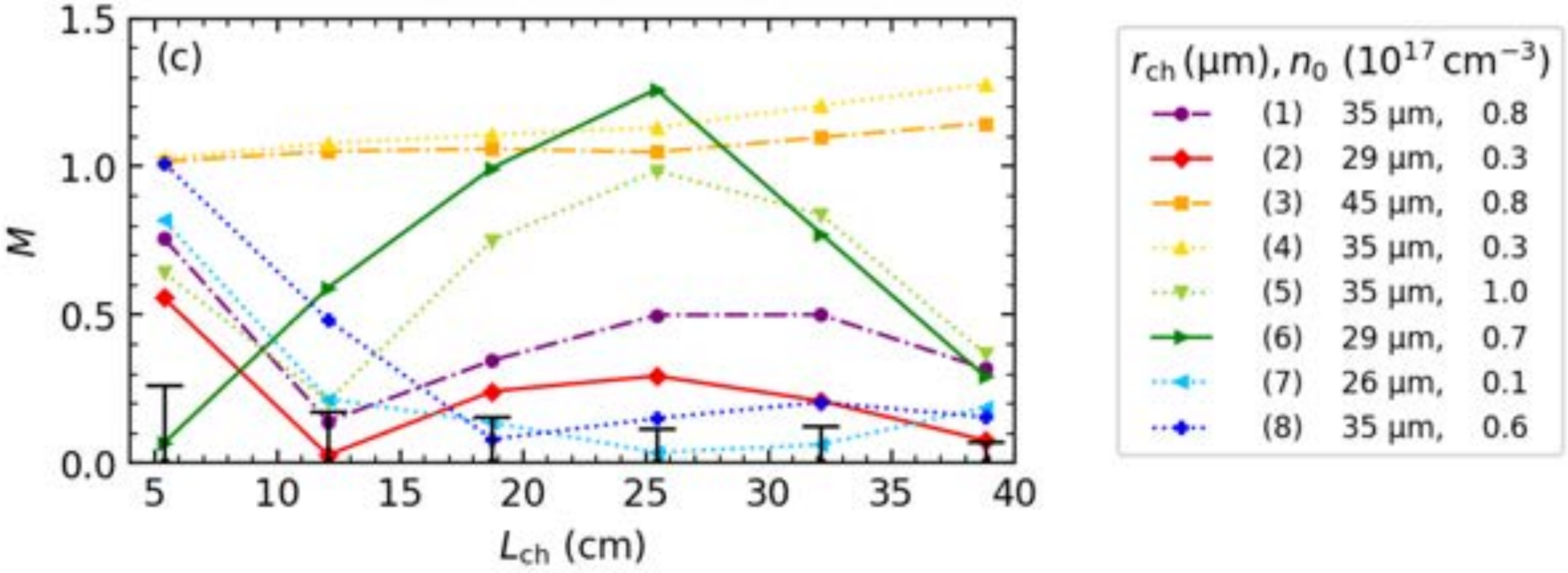


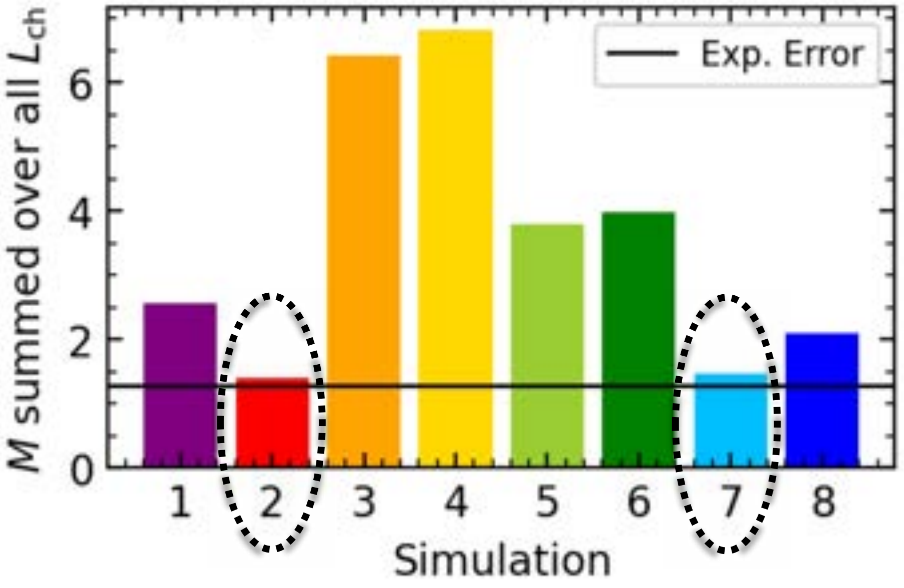

Tang, H. et al. (*Submitted*), see: arXiv 2604.25823

# Minimizing the disagreement between experiment and simulation resolves the degeneracy

- We can define a metric to minimize the disagreement of

$$M = \frac{\left|E_{\max}^{\text{sim}} - E_{\max}^{\text{exp}}\right|}{E_{\max}^{\text{exp}}} + \frac{\left|\Delta\lambda_{R}{}_{\max}^{\text{sim}} - \Delta\lambda_{R}{}_{\max}^{\text{exp}}\right|}{\Delta\lambda_{R}{}_{\max}^{\text{exp}}}$$




*Matches charge*

*< 1 pC simulated charge*

Tang, H. et al. (*Submitted*), see: arXiv 2604.25823

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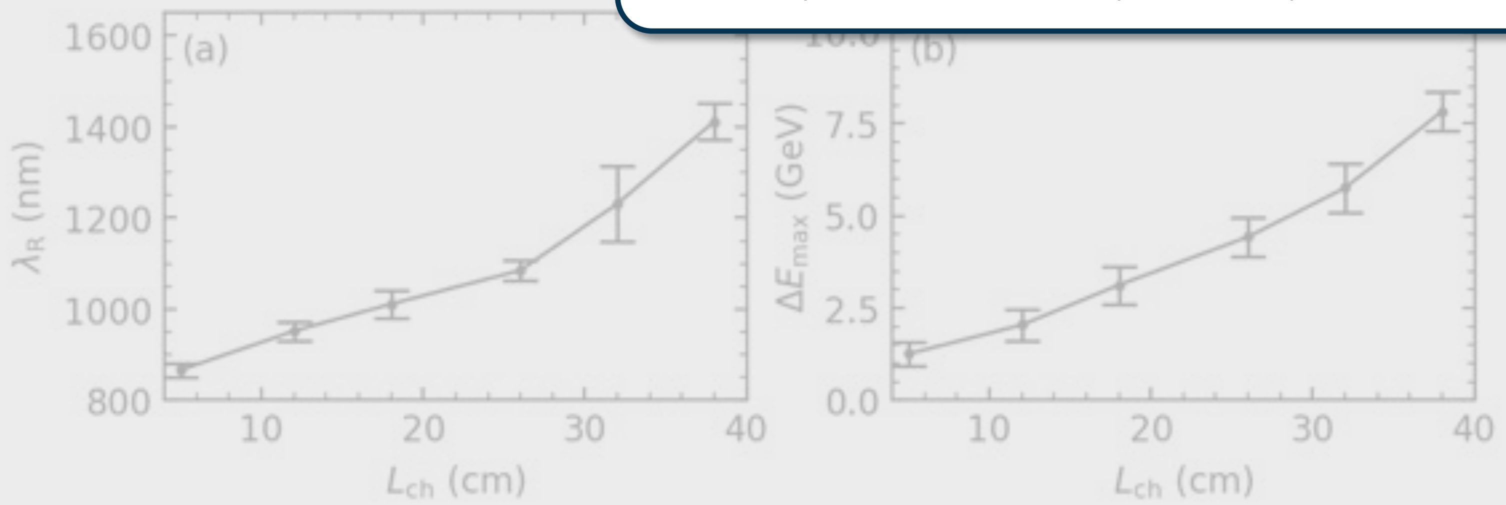
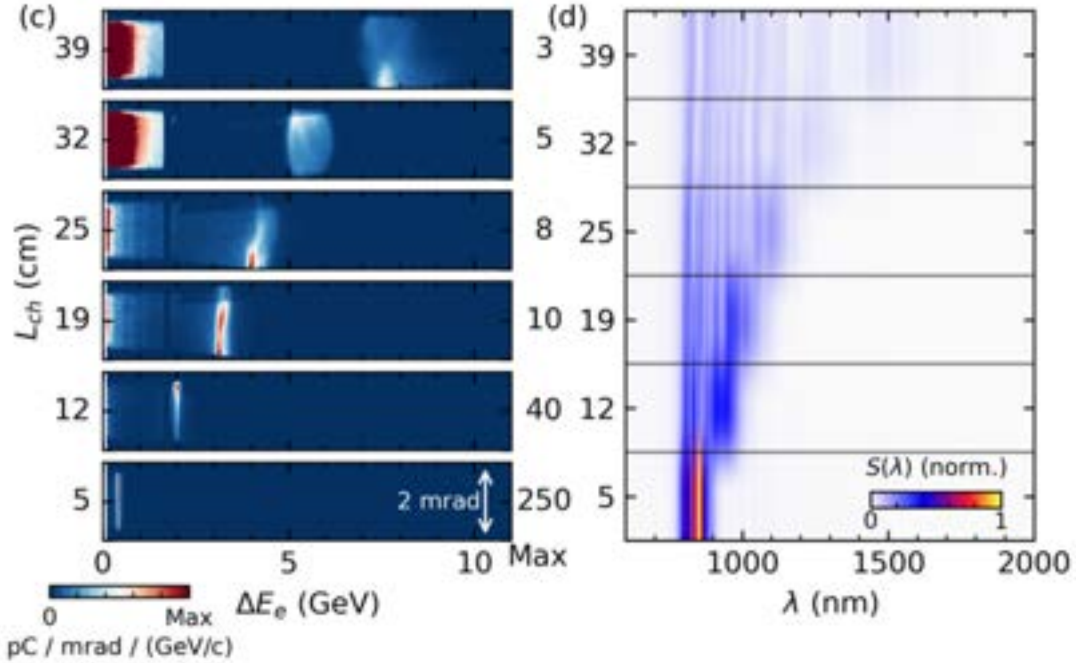
**Effects of transverse laser pointing offset in channel-guided, 10-GeV class laser plasma accelerators**
Raymond Li - Monday Student poster session



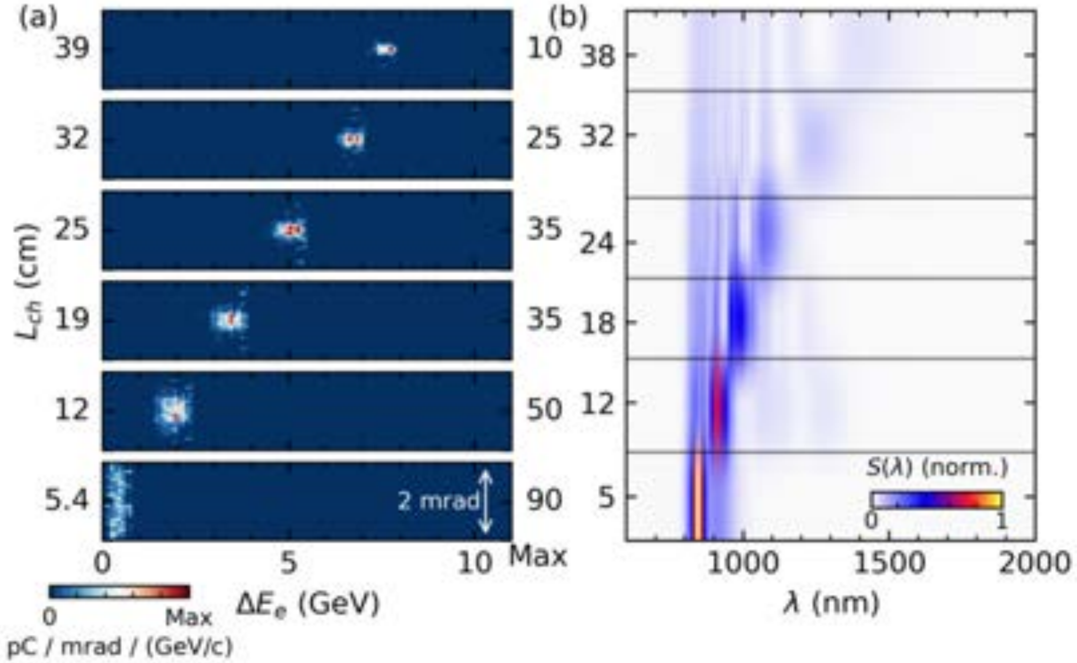

Tang, H. et al. (*Submitted*), see: arXiv 2604.25823

# Simulations of the overall behavior match up well to the best match of the scalar quantities only

**Experimental**

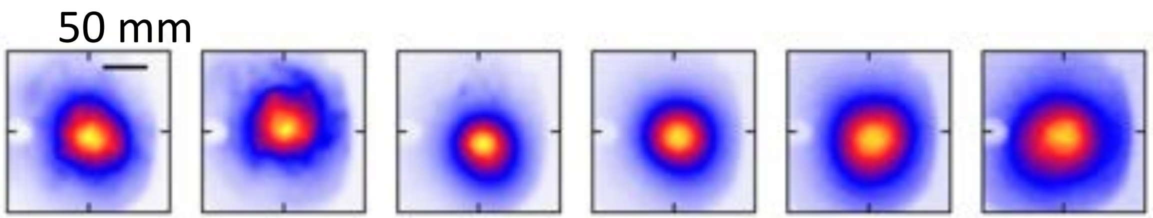


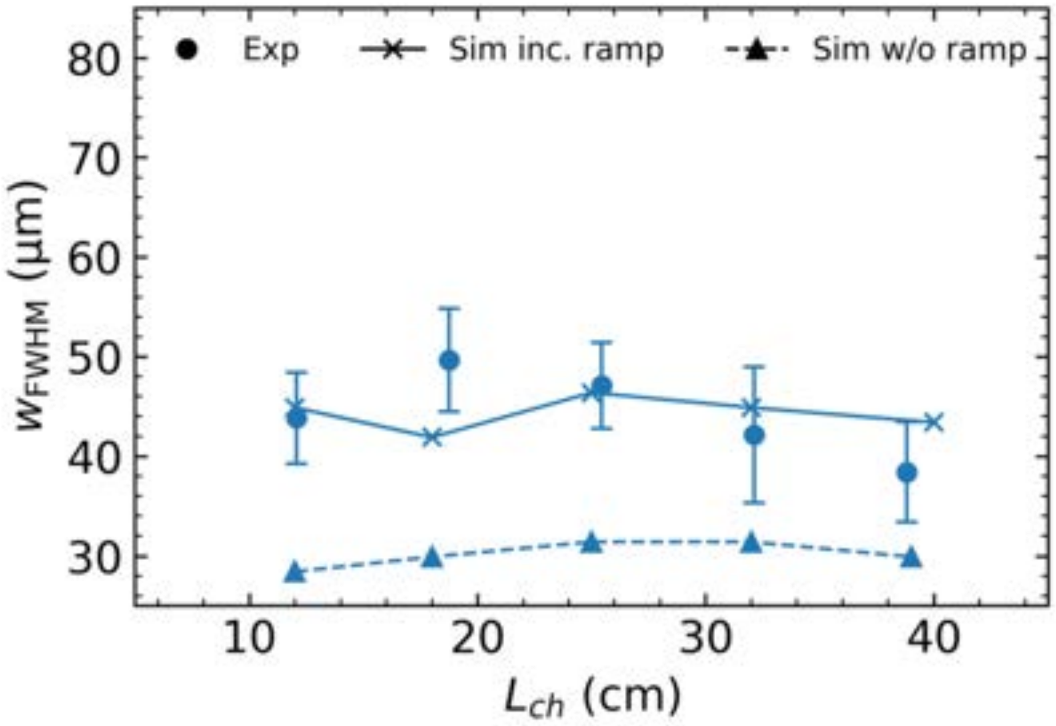

**Simulated – Best Match**




Tang, H. et al. (*Submitted*), see: arXiv 2604.25823

# Propagated mode also matches well provided that simulations include laser evolution in the downramp of the gas jet



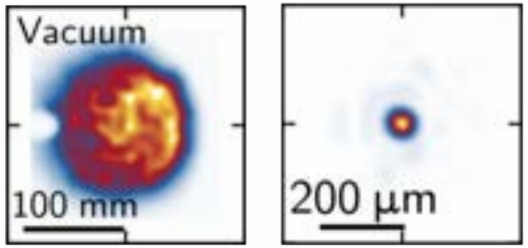




- At first look, checking the propagated mode does not match simulations, but once the downramps are accounted for, simulations match
- Adiabatic expansion of the beam in the down ramp results in a different measured size on the exit mode diagnostics
- Resolves mystery from 2024 PRL

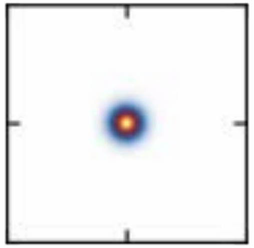
Tang, H. et al. (*Submitted*), see: arXiv 2604.25823

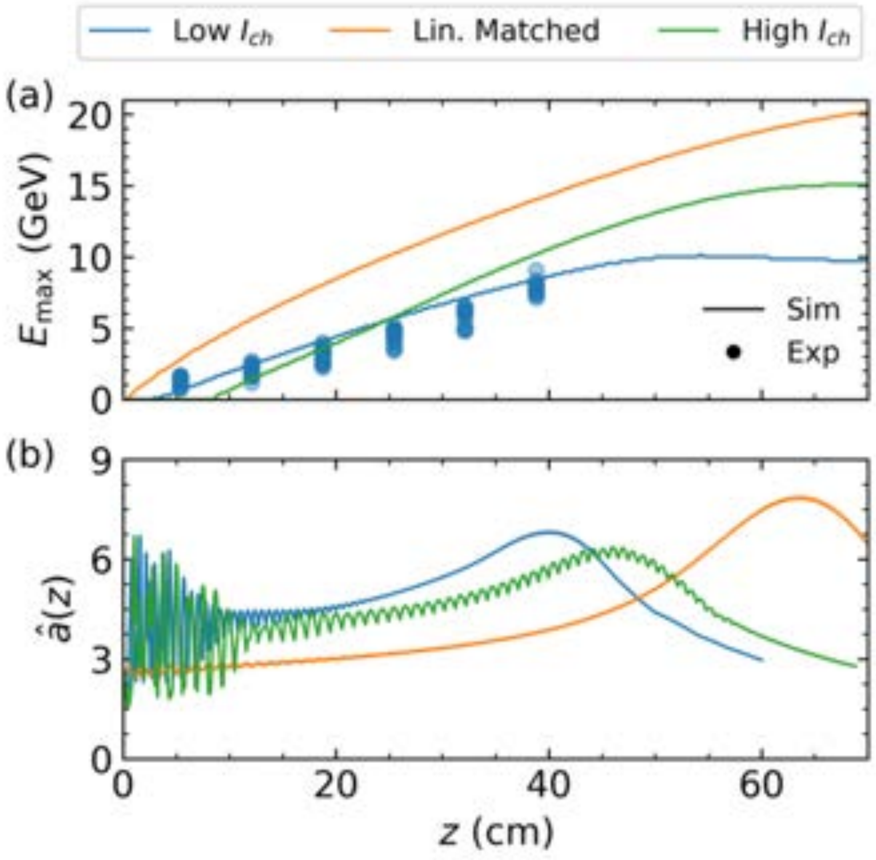
# Well benchmarked simulations can provide deeper insight and guide optimization

Experimental Mode




Linearly Matched






- Ti:Sapph laser mode (inc. imperfections of real system) cause mode beating
- Mode beating prevents injection
- Repeating simulation with mode that is matched to plasma channel shows what could be achieved
- Simulations can guide optimization. Increasing channel-forming laser intensity can increase energy to 10 GeV

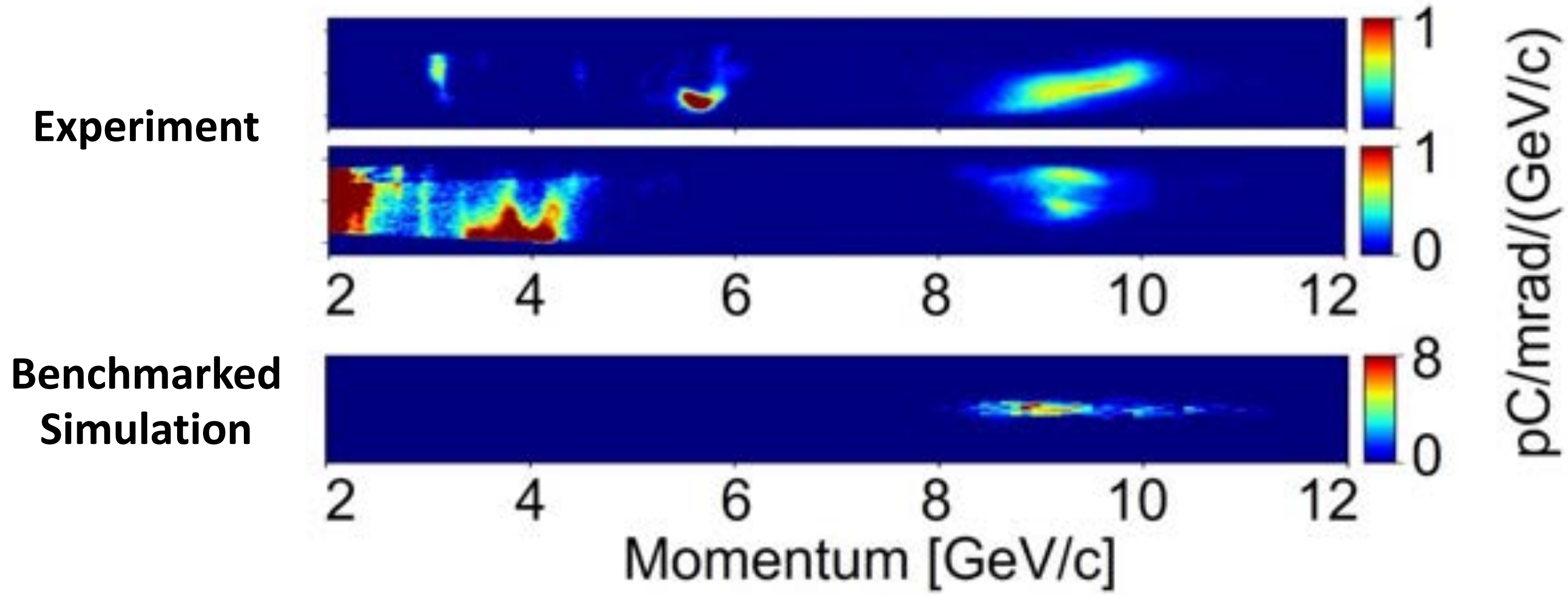

Benedetti, C., et al. *PRE* 92.2 (2015),
Benedetti, C., et al. PoP (2012)

Picksley, A., et al. *Physical Review Letters* 133.25 (2024)
Tang, H. et al. (*Submitted*), see: arXiv 2604.25823
**Mode beating** Esarey et al 1999, 2000
**Mode beating in optical channels:** Shrock, J. E., et al. *PRL (2024)*

# Well benchmarked simulations can provide deeper insight and guide optimization

Increasing gas density not possible due to pump capacity => vary channel forming laser intensity

**Channel Radius increase leads to 10 GeV Electron Beams**




Benedetti, C., et al. *PRE* 92.2 (2015),
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**Mode beating** Esarey et al 1999, 2000
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# Conclusions

- Varying the plasma channel length reveals key insight into the evolution of key parameters **inside** the laser-plasma accelerator
- Choosing simple scalar quantities enables a metric to benchmark simulations **and optimize the accelerator**
- Controlled injection into the dark current free structure led to singly peaked electron beams with max energies exceeding 10 GeV

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