Progress towards high-repetition-rate GeV-scale plasma-modulated plasma accelerators

UNIVERSITY OF OXFORD

Simon Hooker, Emily Archer, Darren Chan, James Chappell, James Cowley, Linus Feder, Oscar Jakobsson, Sebastian Kalos, David McMahon, Alex Picksley*, Aimee Ross*, Johannes van de Wetering, Roman Walczak & Wei-Ting Wang

UKRI Science and Technology Facilities Council

Nicolas Bourgeois, David Emerson, Xiaojun Gu

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Stefan Karsch, Mathias Krüger & Andreas Muenzer

UNIVERSITY OF LIVERPOOL

Laura Corner, Harry Jones*, Lewis Reid,

* Former member of group

Could we drive GeV-scale, kHz accelerators with existing lasers?

- Difficult to drive multi-GeV, multi-kHz LWFAs with Ti:sapphire owing to their low wall-plug efficiency
- Commercially-available Yb:YAG thin-disk lasers can generate ~ 1 J, ~ 1 ps, 1 kHz pulses:
  - Herkommer *et al. Opt. Exp.* **28** 30164 (2020): 0.72 J, 0.9 ps, 1 kHz
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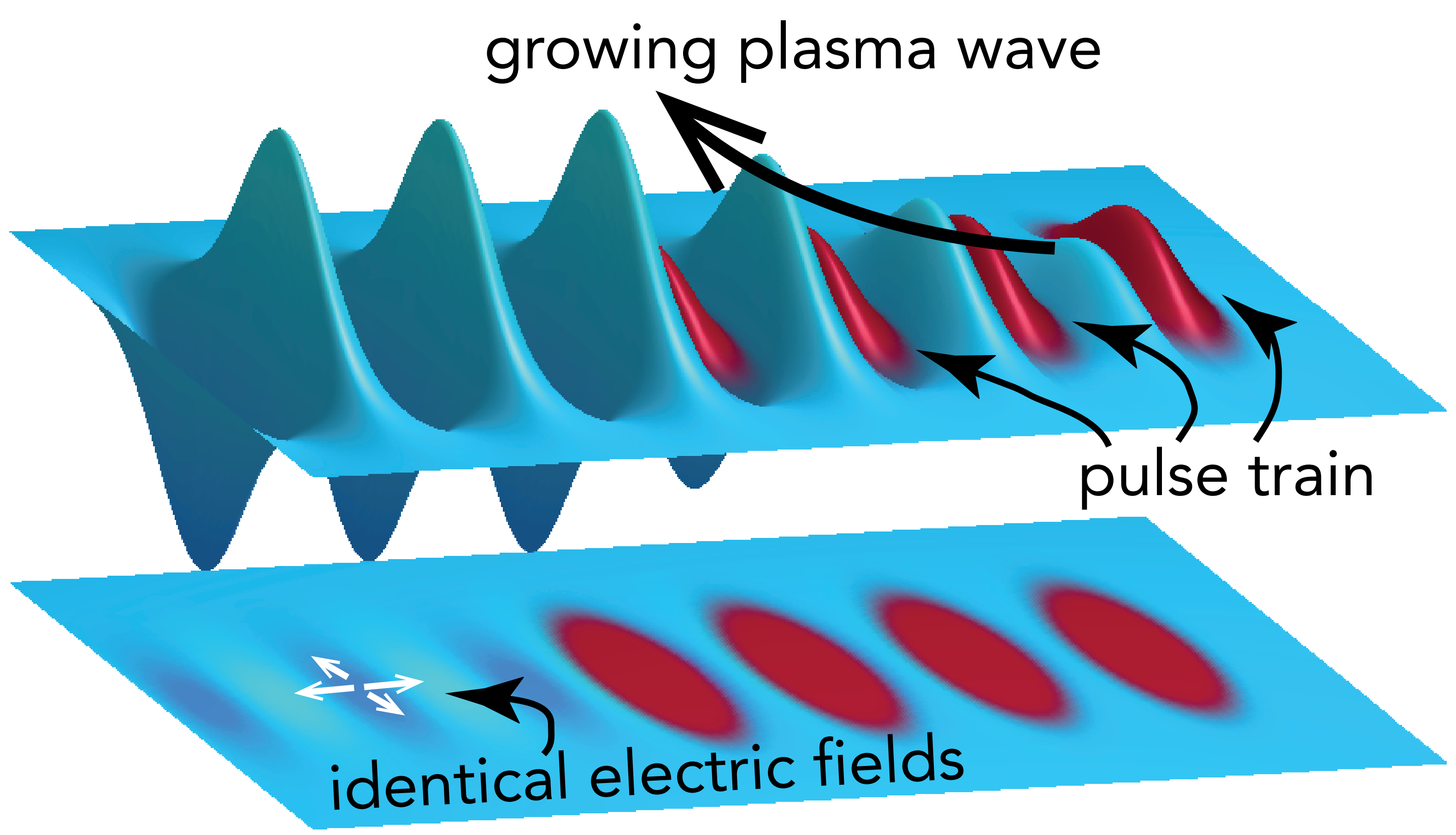
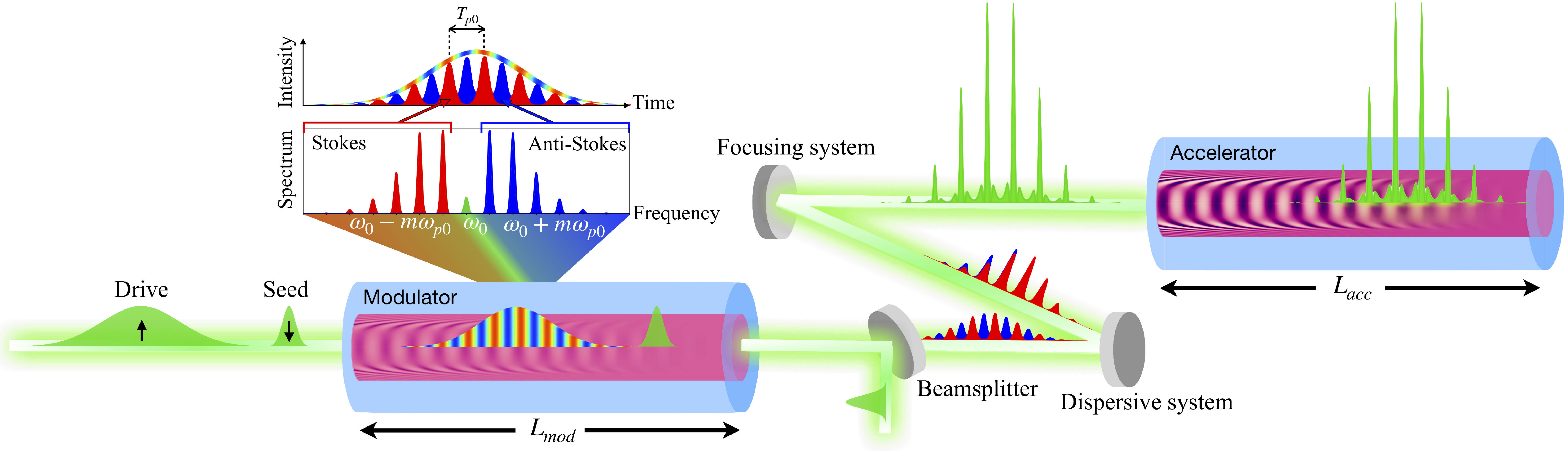


- Pulses too long to drive wake directly, but could resonantly excite wakefield if modulate pulse at plasma period
  - Many theory papers on multi-pulse published in 1990s
  - Strongly-related to plasma beat-wave accelerator (PBWA): beat two frequencies together s.t. $\omega_1 - \omega_2 = \omega_p$

P-MoPA: Plasma-Modulated Plasma Accelerator



P-MoPA: Plasma-Modulated Plasma Accelerator

John Adams Institute for Accelerator Science

Step 1: Plasma modulator

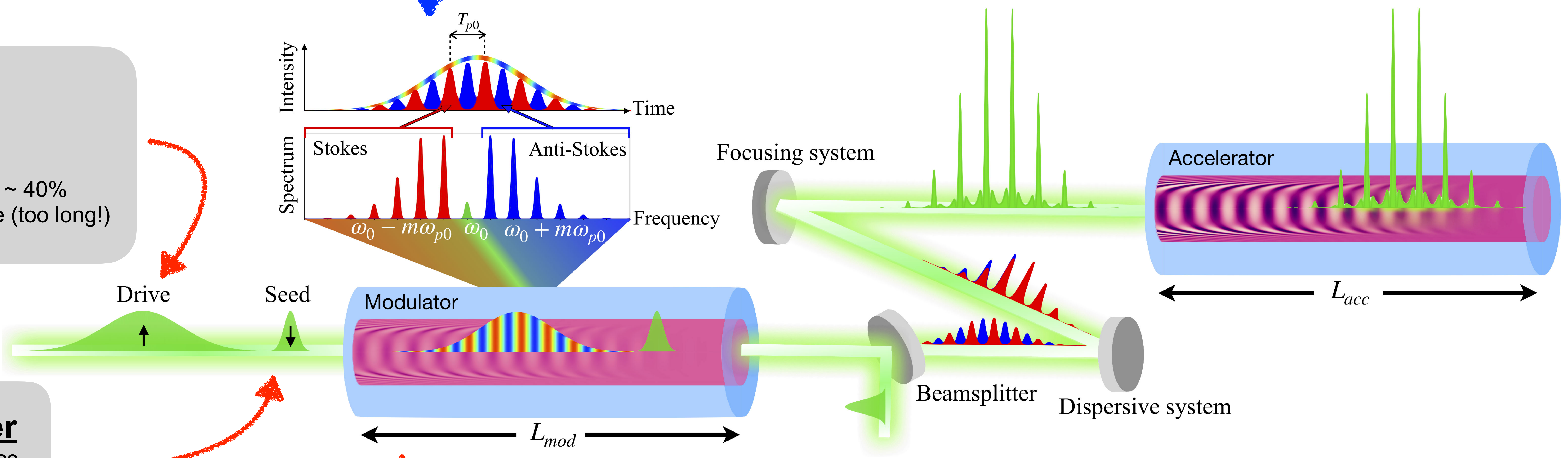
- ☐ Drive & seed pulses guided in HOFI channel
- ☐ Spectrum of drive pulse modulated by wake driven by seed pulse

Drive laser

✓ Industrial-class
✓ Multi-joule
✓ Multi kilohertz
✓ Optical efficiency ~ 40%
✗ Picosecond pulse (too long!)

Seed laser

✓ Industrial-class
✓ ~ 100 mJ
✓ Multi kilohertz



HOFI plasma channel

✓ Low loss
✓ > 100 mm guiding
✓ kHz rep. rate

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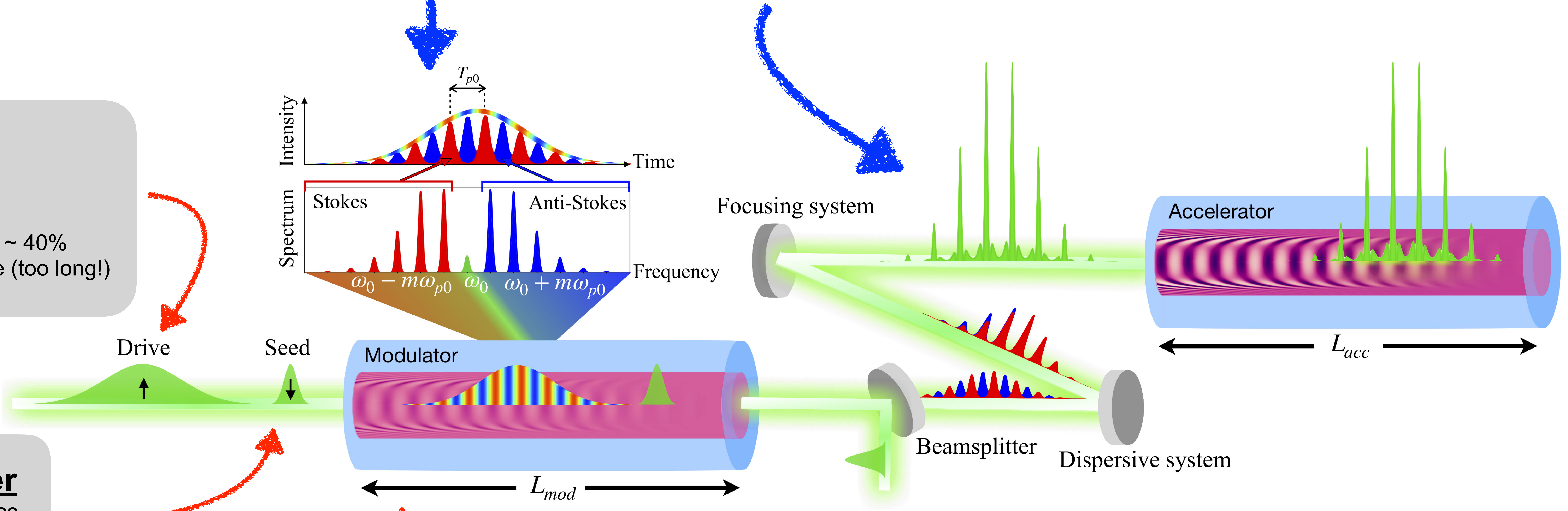

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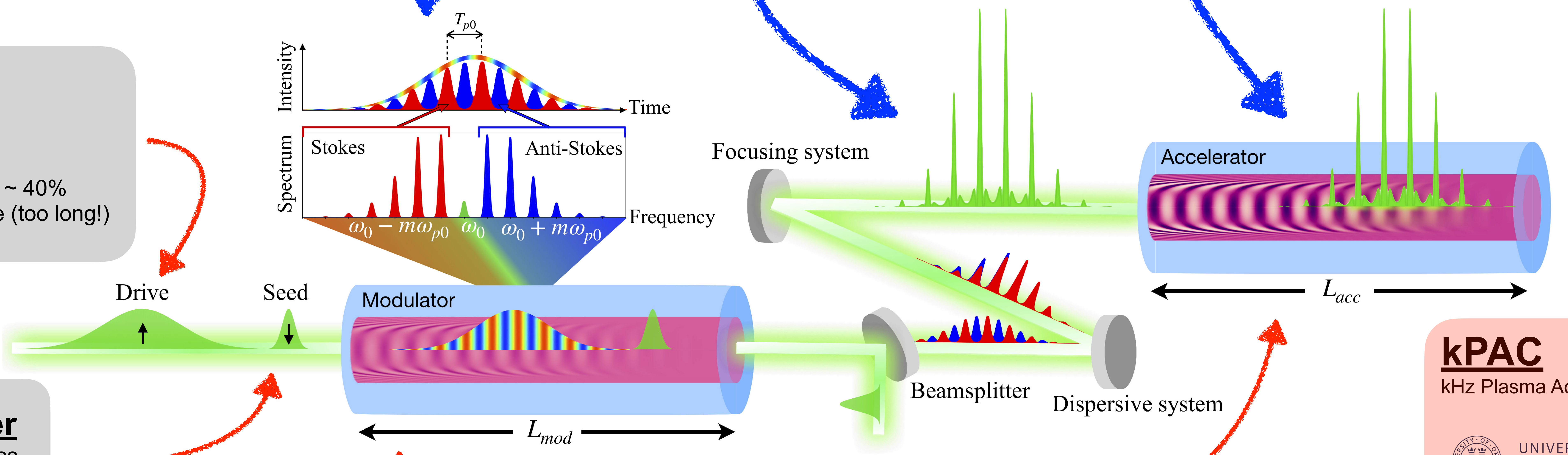

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kPAC
kHz Plasma Accelerator Collaboration

UNIVERSITY OF OXFORD · central laser facility · LMU Ludwig-Maximilians-Universität München · TRUMPF

Simulations of P-MoPAs

P-MoPA: Modulator

Jakobsson *et al. Phys. Rev. Lett.* **127** 184801 (2021)
van de Wetering *et al. Phys. Rev. E* **108** 015204 (2023)

- Seed-driven wake modulates amplitude of drive to:

sidebands

$$b(\zeta, \tau) \approx |b(\zeta, 0)| \sum_{m=-\infty}^{\infty} i^m J_m(-\beta) \exp[im(\omega_{p0}\tau + \Delta\phi')]$$

$$\beta = 2 \frac{\omega_{p0}^2}{8\omega_L} \frac{\delta n_e}{n_{e0}} \frac{L_{\text{mod}}}{v_{\text{g,mod}}}$$

modulator parameter

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modulator parameter

- 3D fluid theory shows:
  - Spectral modulation is a radial average ⇒ independent of radial position
  - Curvature of wake reduces modulation
  - Drive energy limited by transverse mode instability, but stable operation still possible over wide range of parameters

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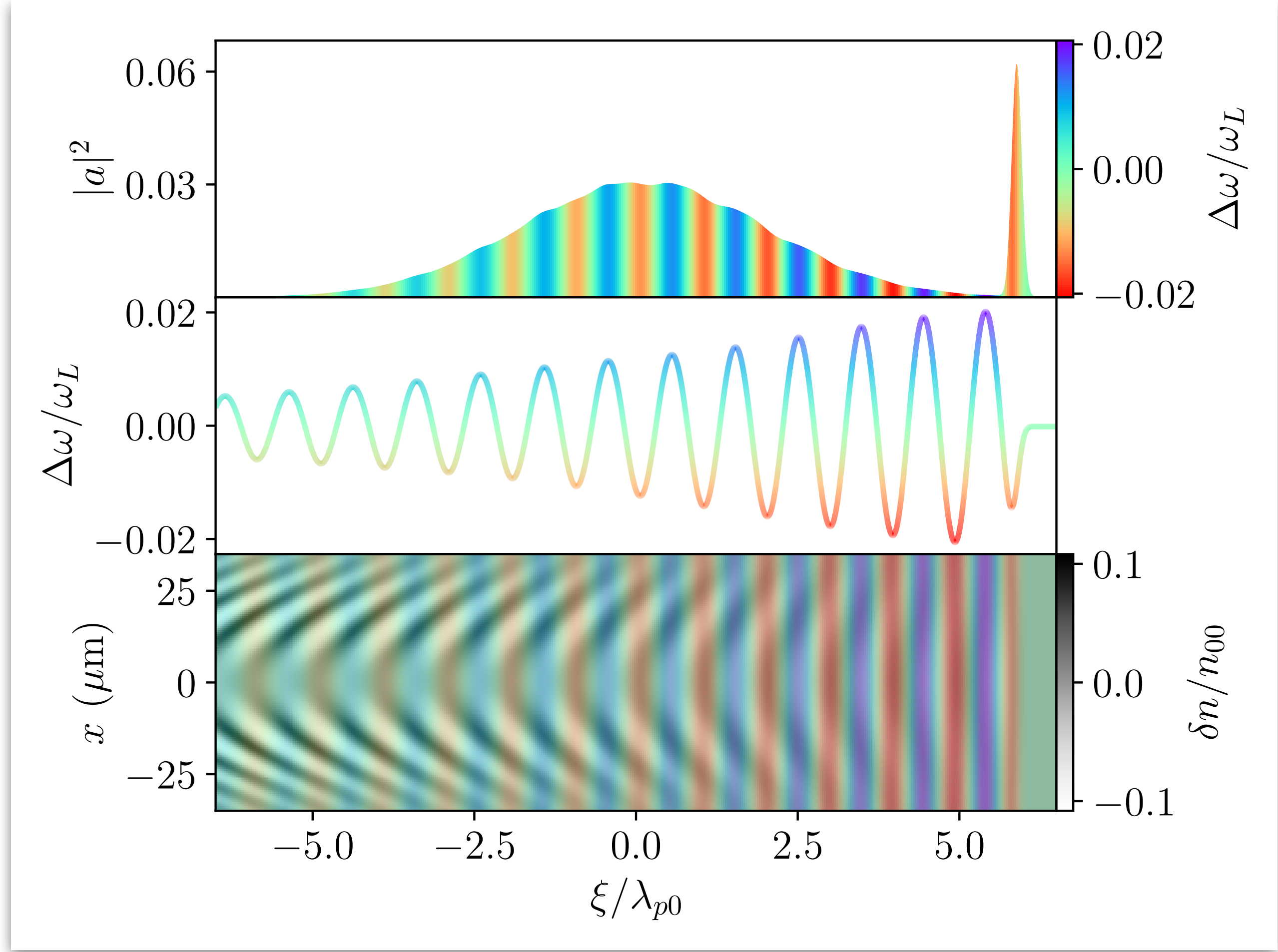

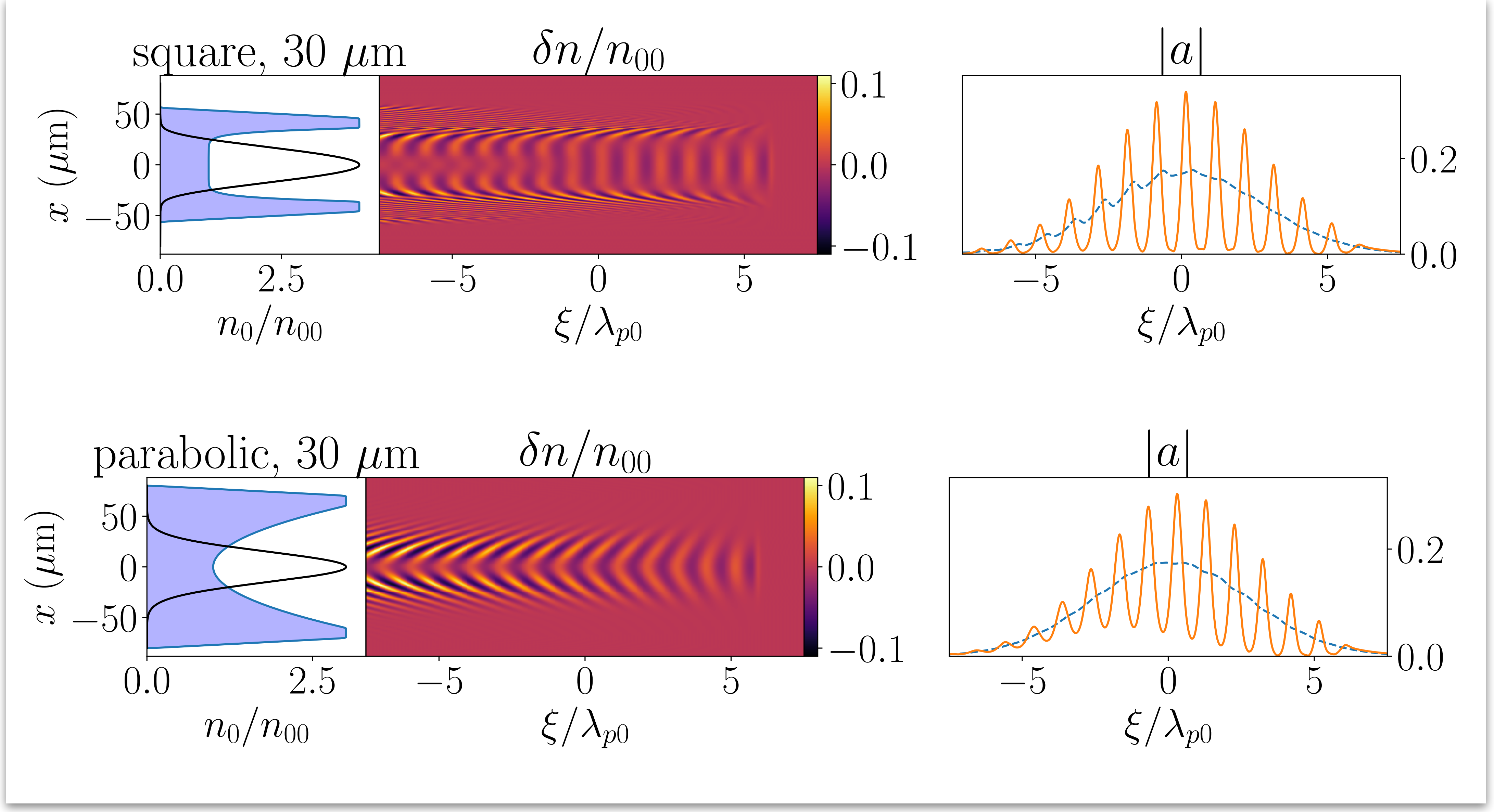

P-MoPA: Compressor

- Seed-driven wake modulates amplitude of drive to:

sidebands

$$b(\zeta,\tau) \approx |b(\zeta,0)| \sum_{m=-\infty}^{\infty} i^m J_m(-\beta) \exp[im(\omega_{p0}\tau + \Delta\phi')]$$

$$\text{Spectralphase}: \quad \psi_m \approx -|m|\frac{\pi}{2}$$

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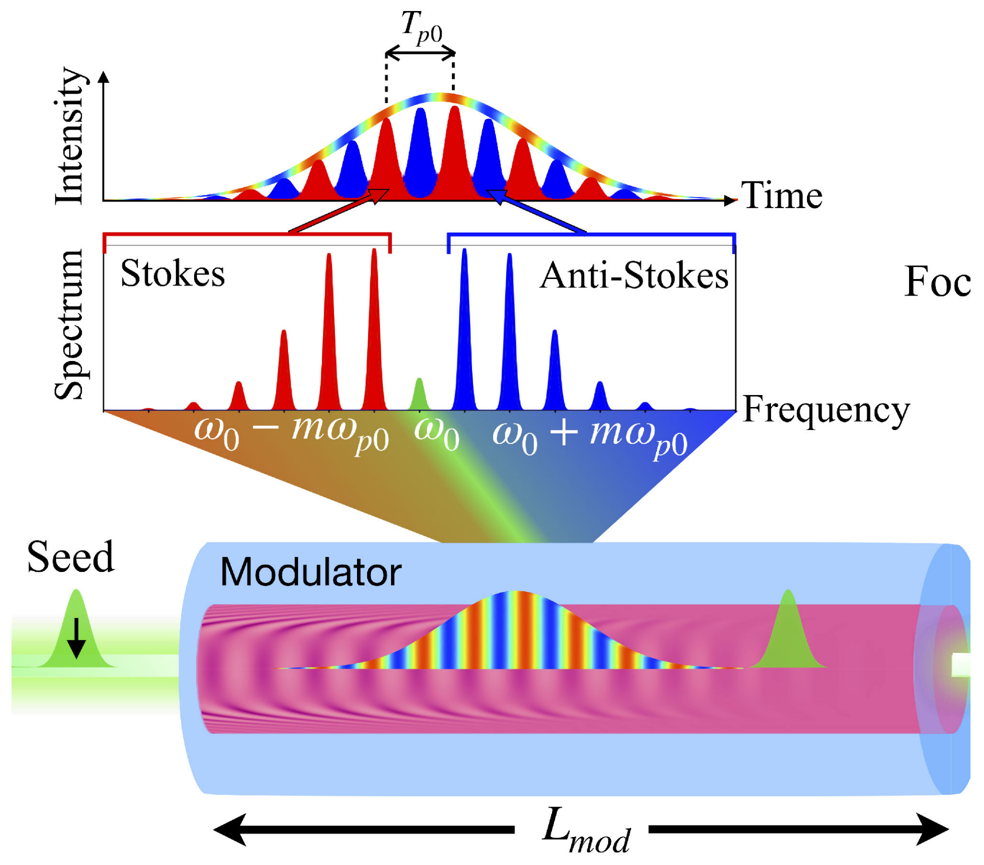
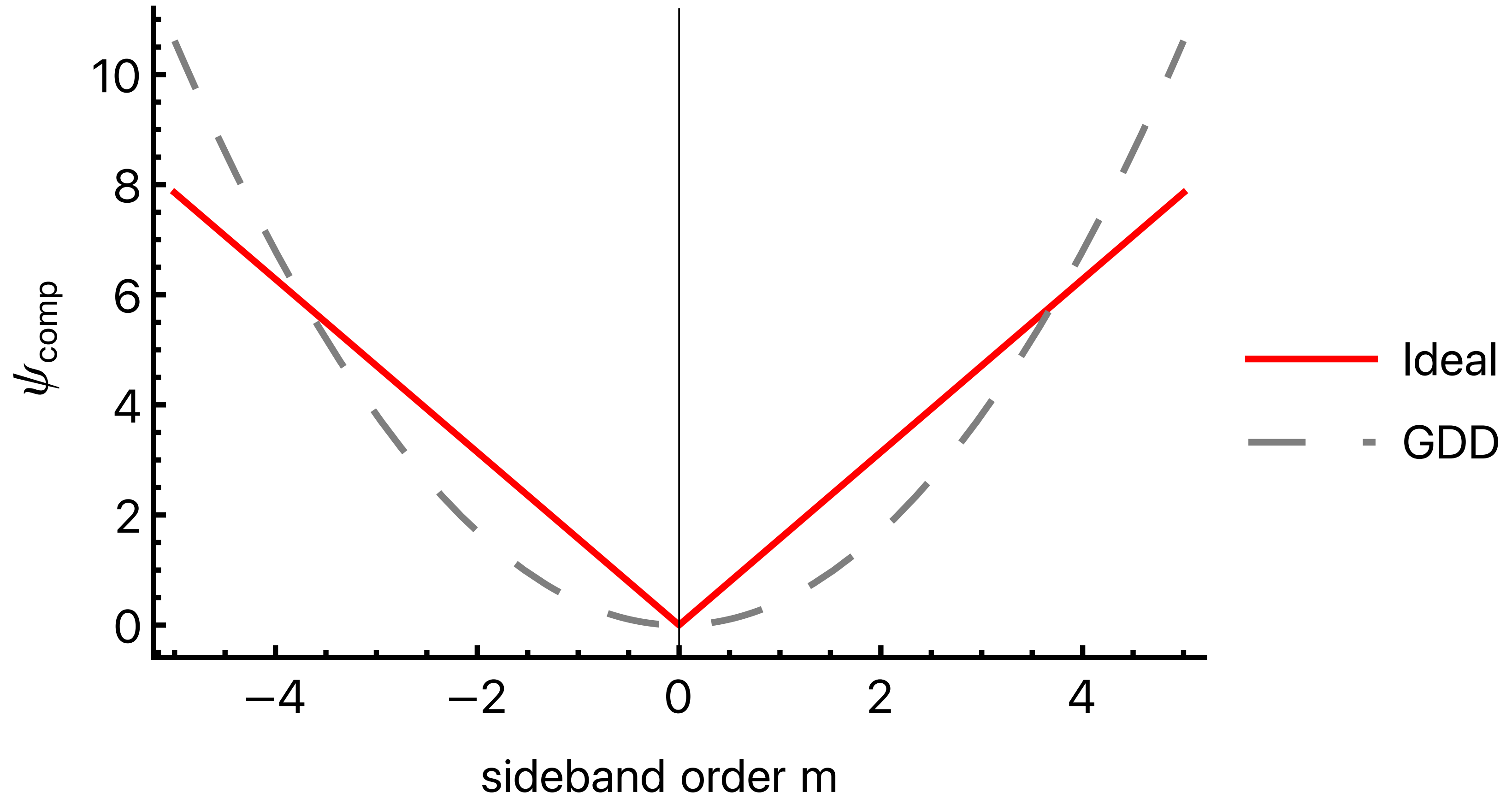
Temporal domain

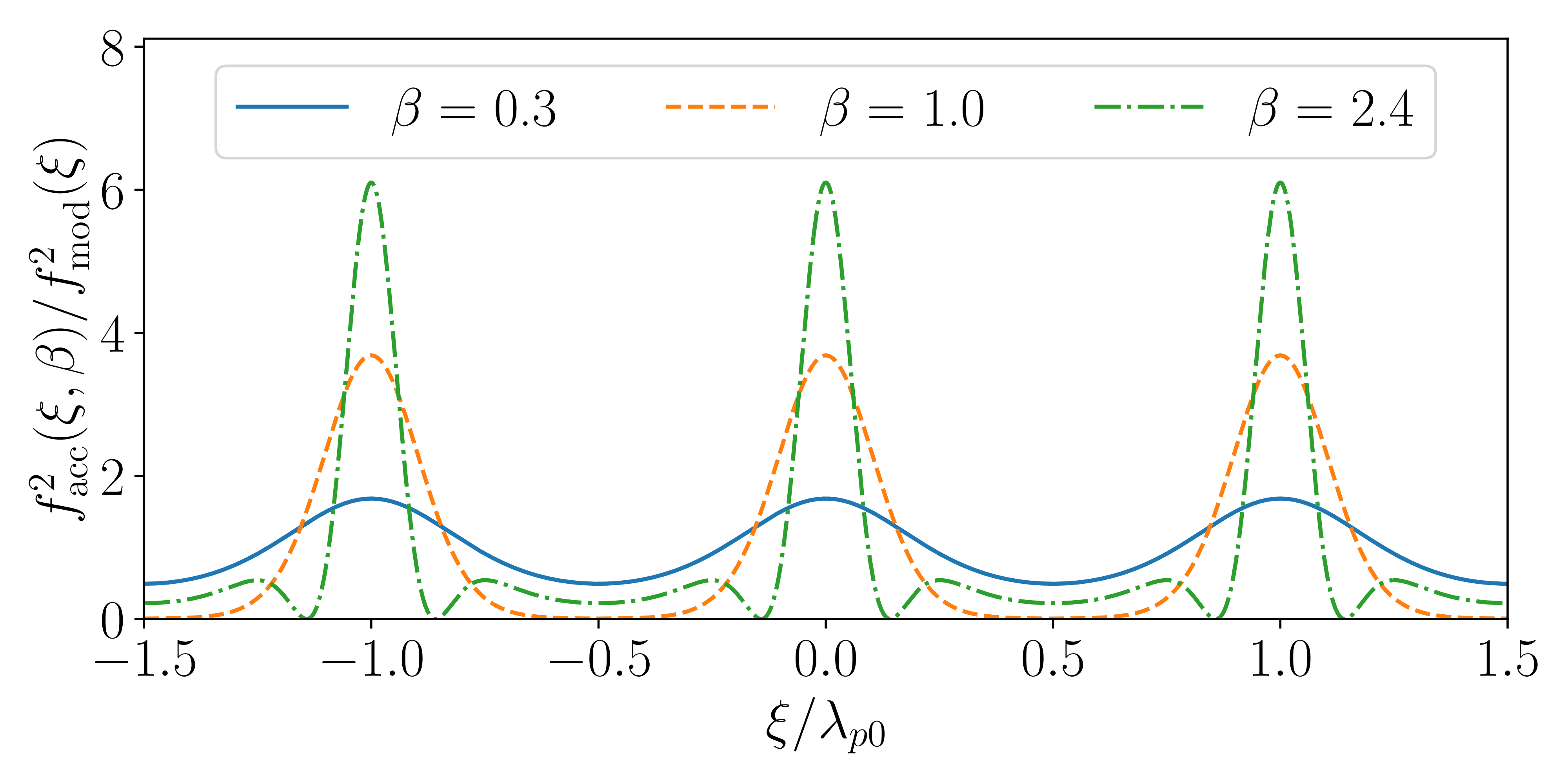


Spectral domain



P-MoPA: Accelerator

- Modulator parameter controls temporal profile of pulse train
  - For optimum , wake 72% larger than PBWA with same pulse energy
  - Can drive wakes with ~ 50% E_{wb}



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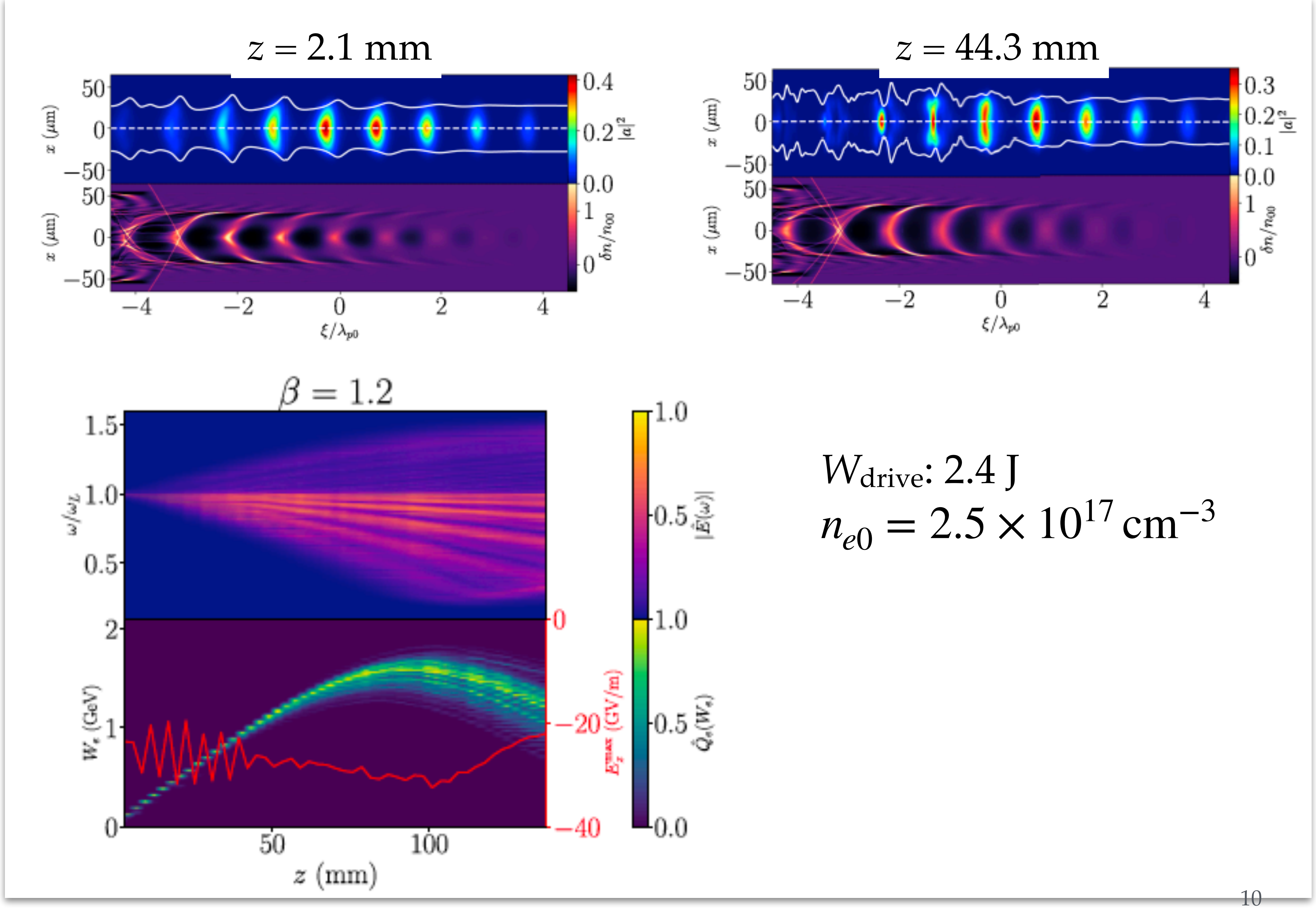
van de Wetering *et al. Phys. Rev. E* **109** 025206 (2024)

- 2D PIC simulations show wake excitation over ~ 100 mm
  - Stage energy gain ~ 1.5 GeV
  - $E_{max}/E_{wb} \approx 0.5$



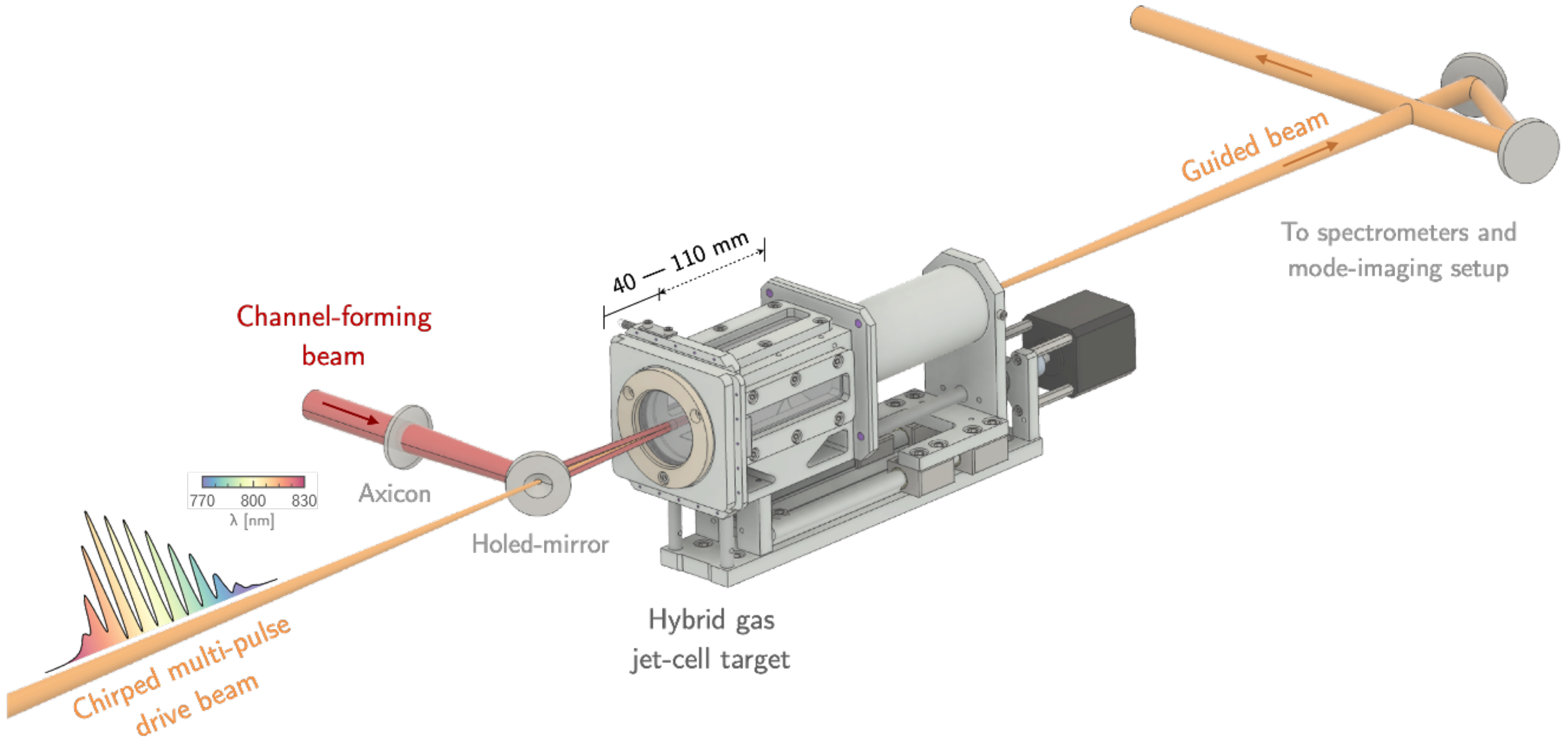
W_{drive}: 2.4 J
$n_{e0} = 2.5 \times 10^{17}\,\mathrm{cm}^{-3}$

Resonant wakefield excitation in a plasma channel

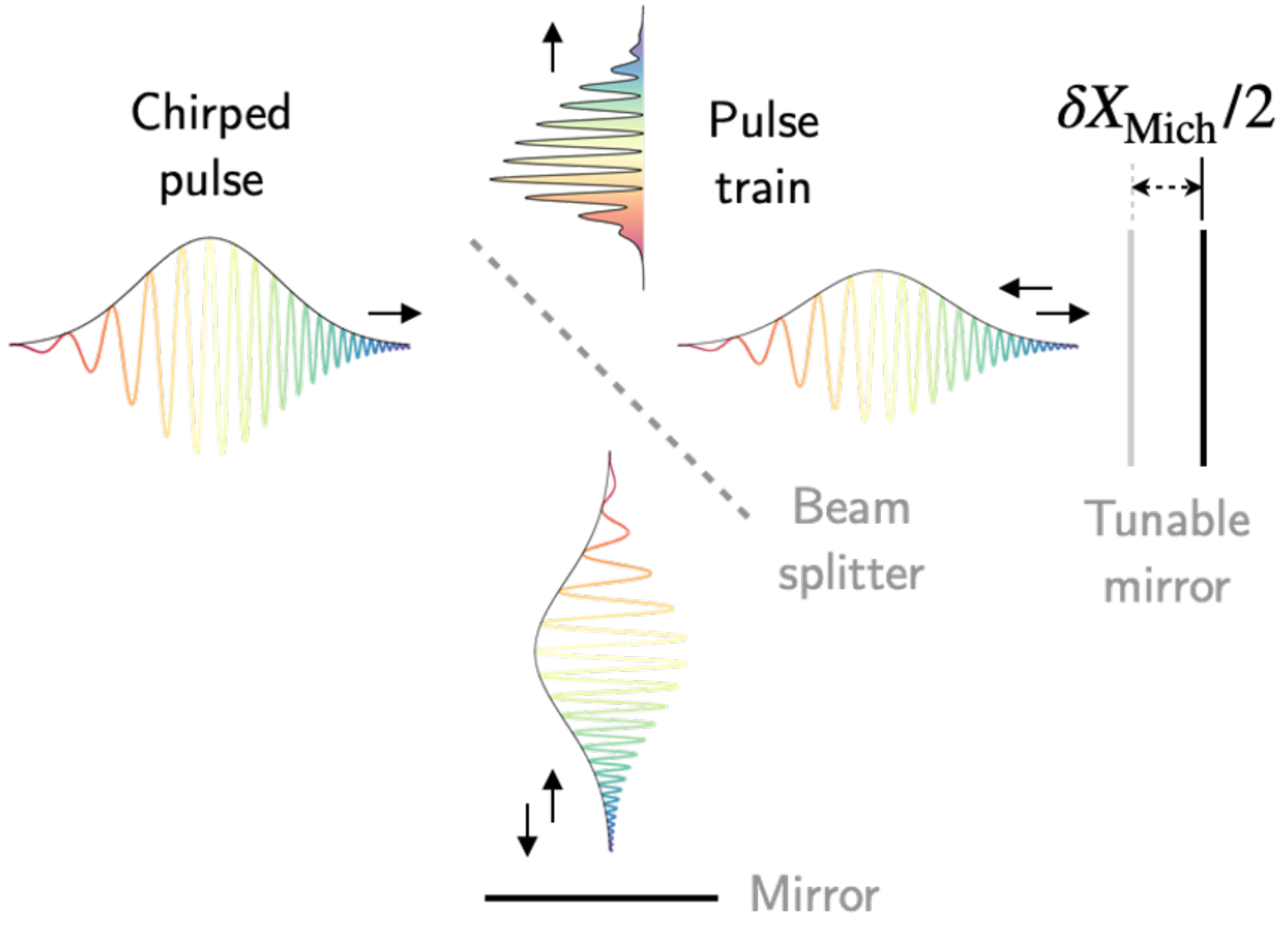
Experimental set-up

Ross *et al.* *Phys. Rev. Res.* **6** L022001 (2024)

- Objectives
  - Demonstrate guiding of joule-scale pulse trains in ~ 100 mm long HOFI channels
  - Demonstrate resonant excitation of wakefield
- Astra-Gemini laser
  - Pulse train: 2.5 J on target; f/40 focusing
  - Channel-forming pulse: ~ 100 mJ, 40 fs



Generation of "dummy" pulse trains



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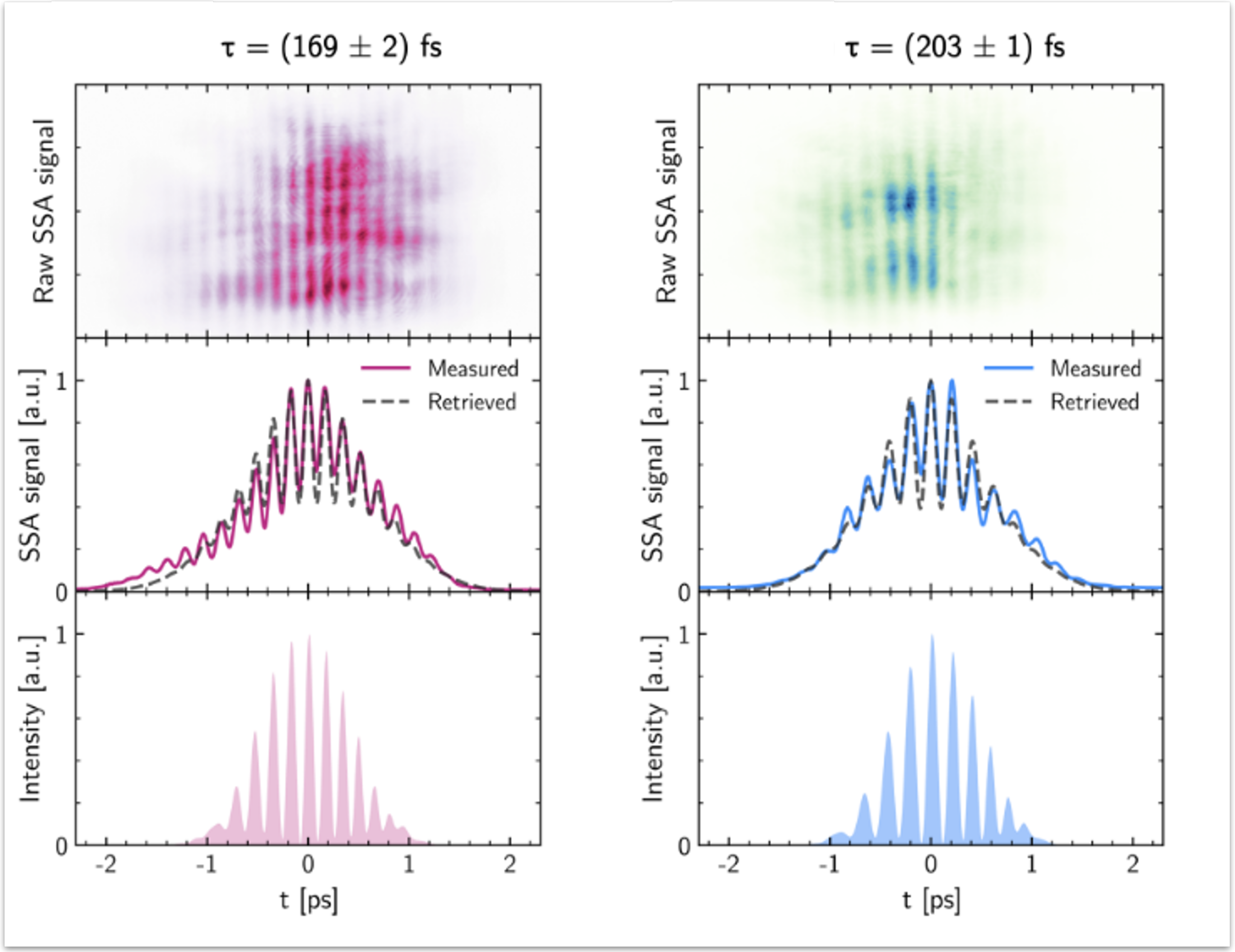
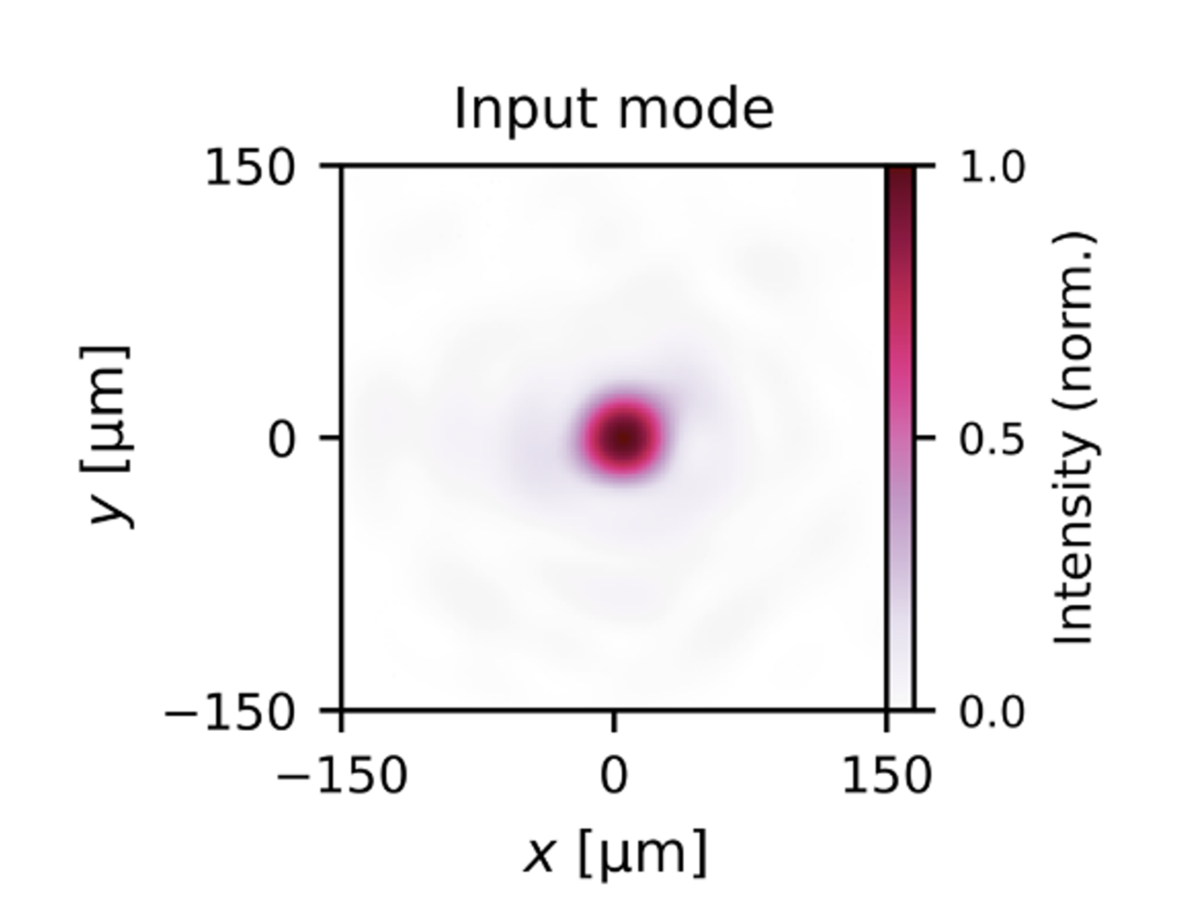


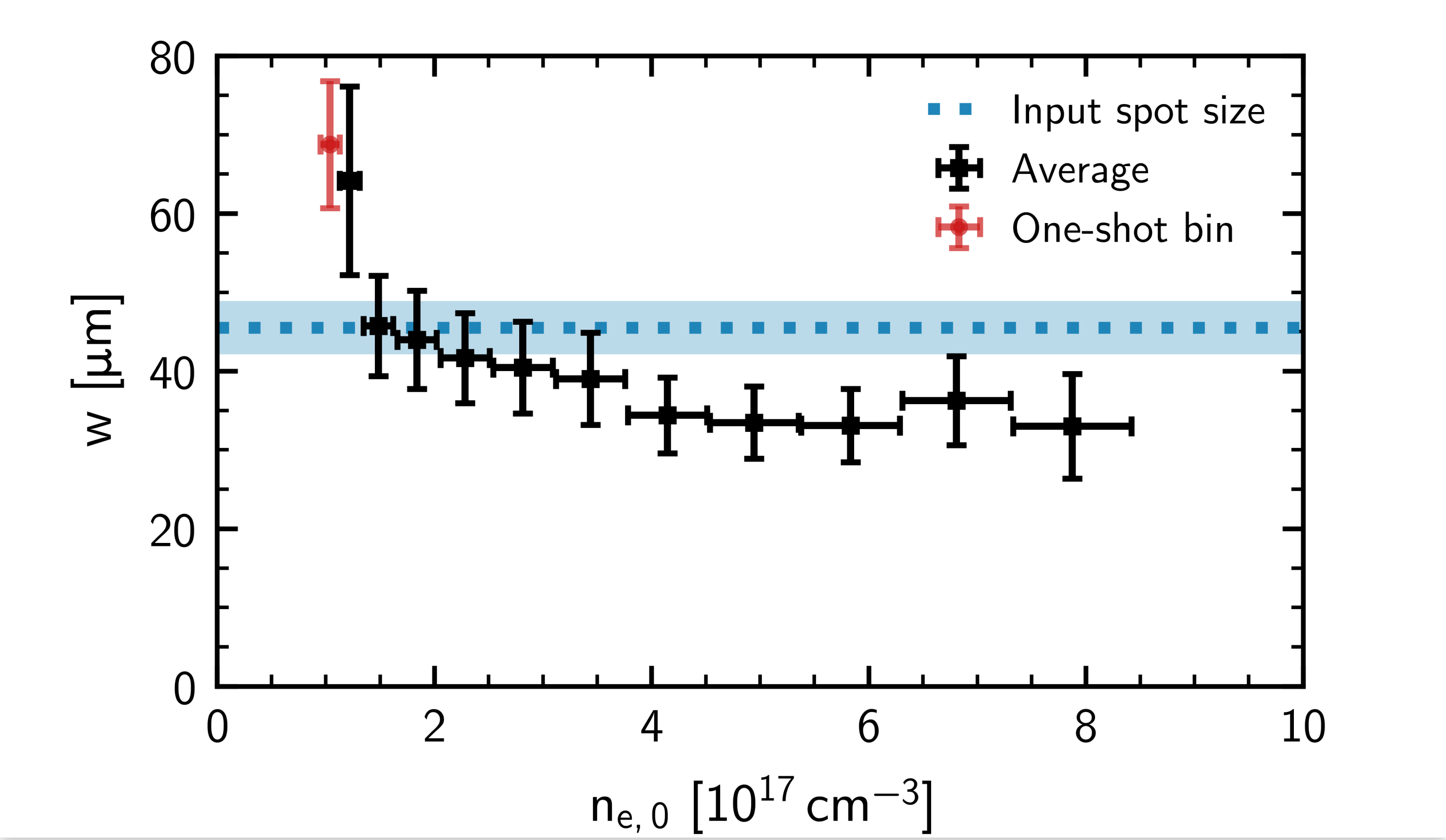
- Pulse train generated by:
  - Chirping Gemini pulse to ~ 1 ps
  - Filtering chirped pulse with Michelson interferometer
- Trains characterized by;
  - Measuring spectrum
  - SSA
  - Use Dazzler to compensate for TOD

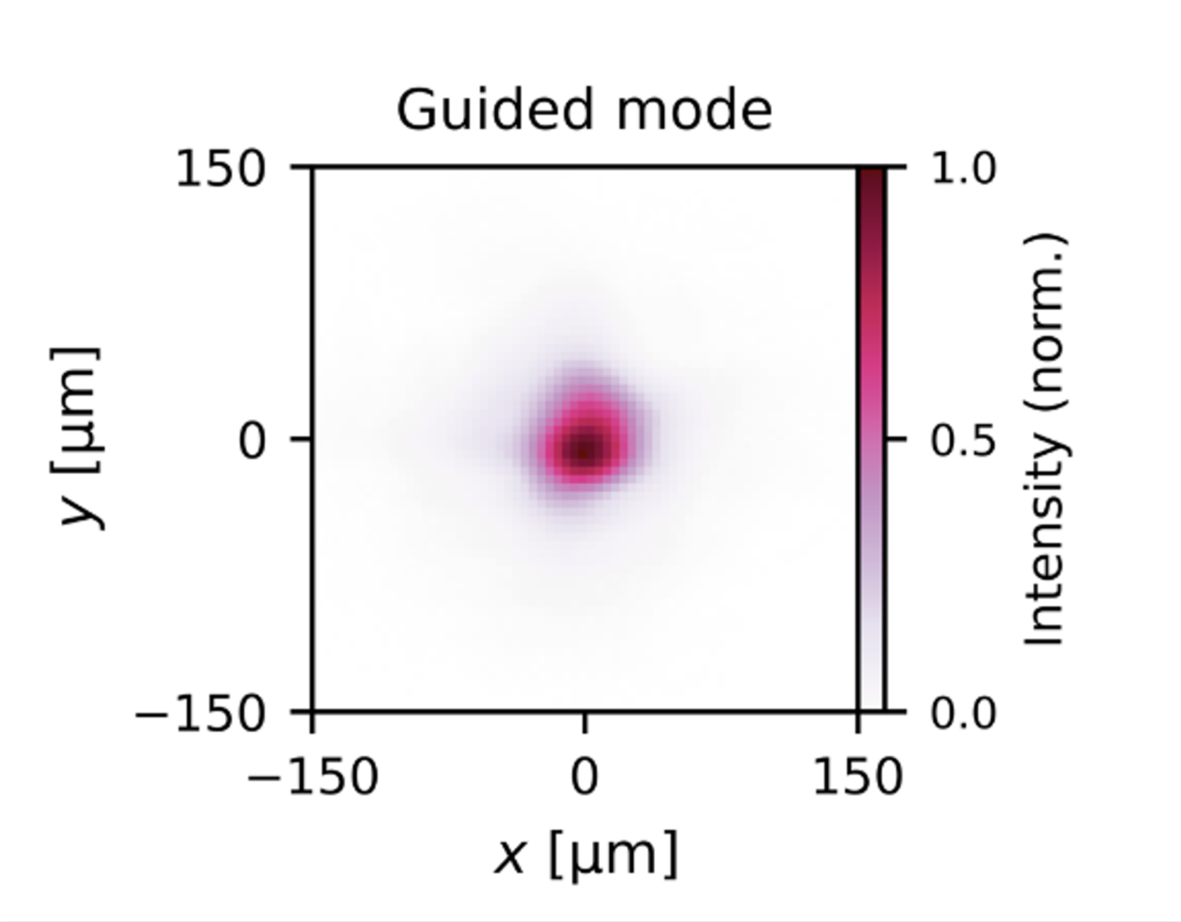
Guiding joule-scale pulse trains

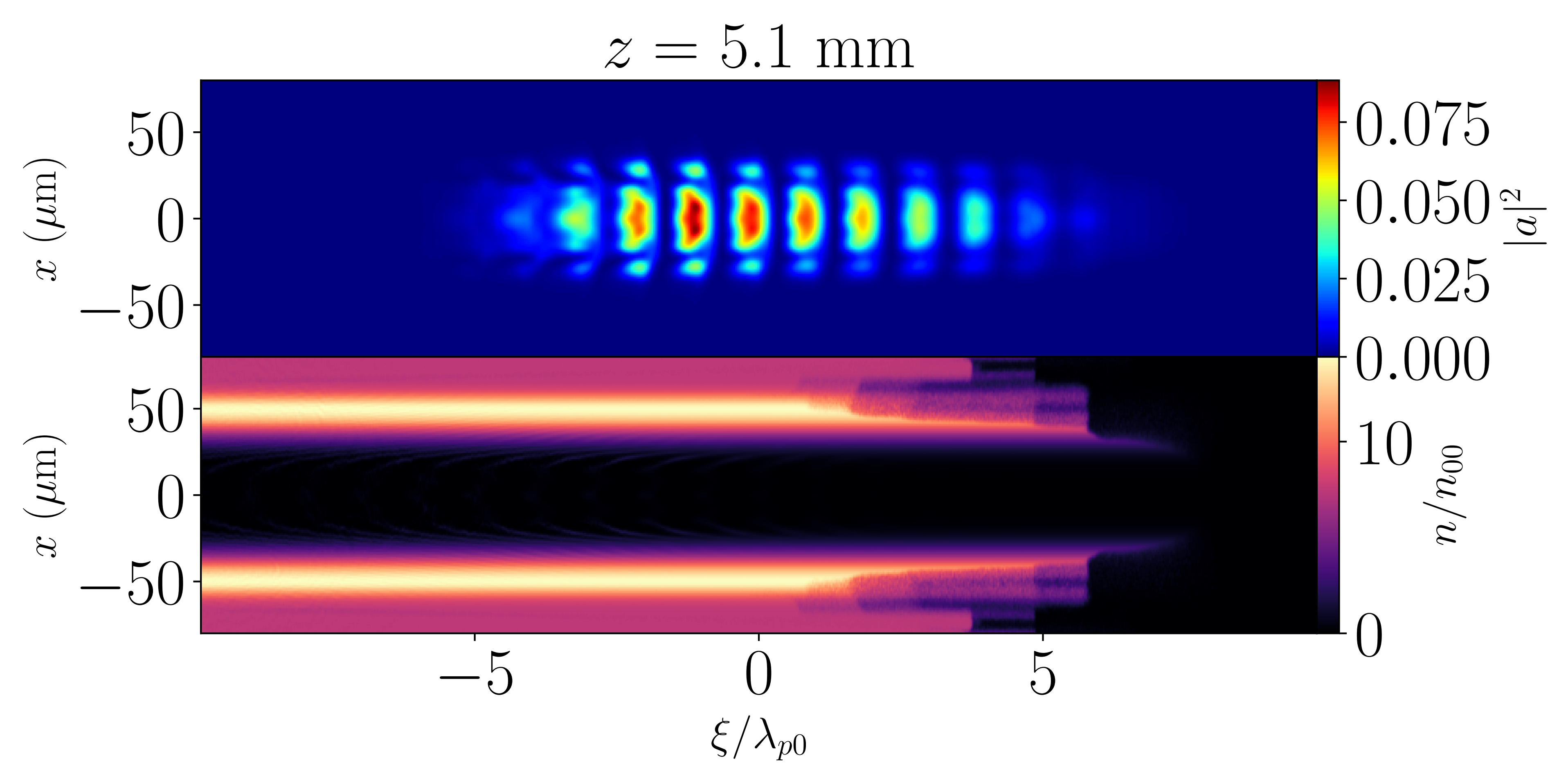
Ross *et al*. *Phys. Rev. Res.* **6** L022001 (2024)

- Joule-scale pulse trains guided over 110 mm ($\sim 17\, z_R$)
- Input spot ~70% overlap with lowest-order mode
- PIC simulations confirm that first few pulses condition the HOFI channel



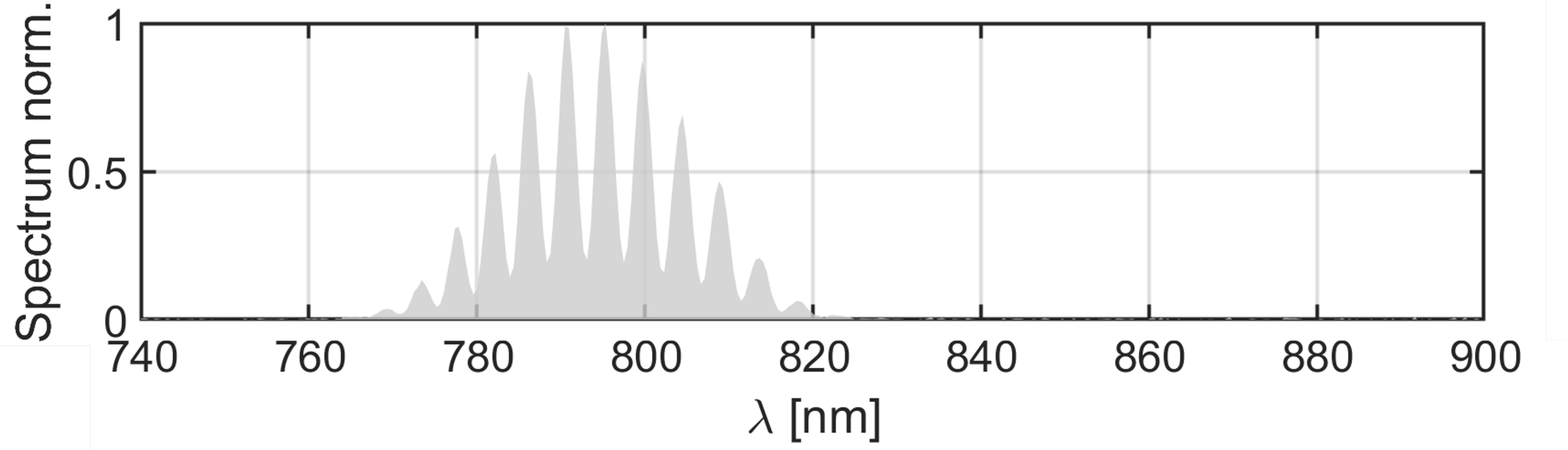






Pulse train spectra show resonant excitation …

Ross *et al*. *Phys. Rev. Res.* **6** L022001 (2024)



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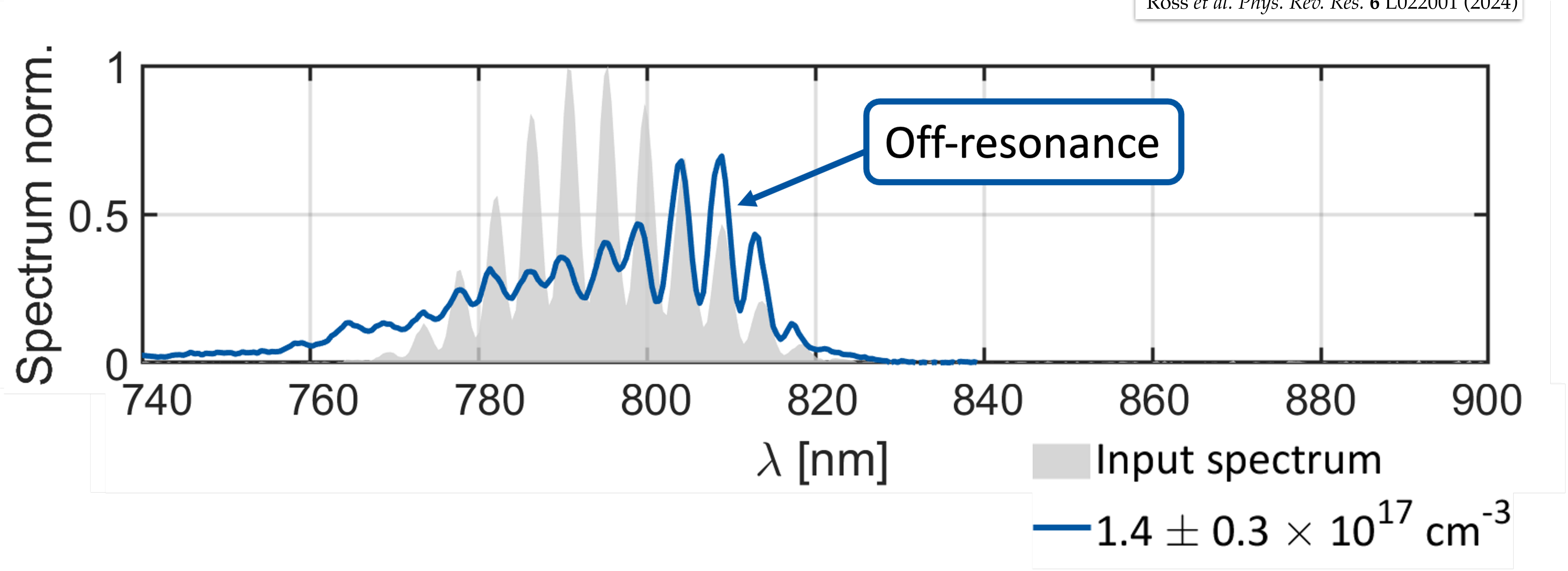

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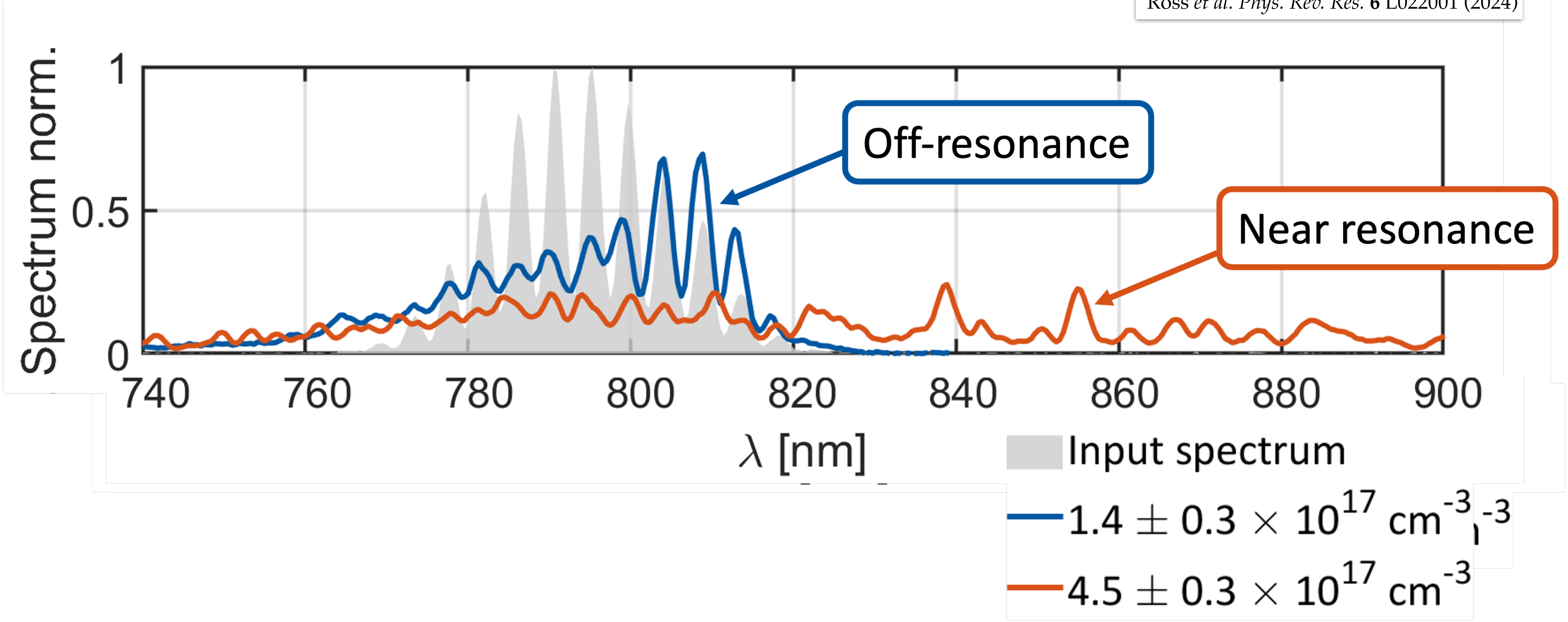
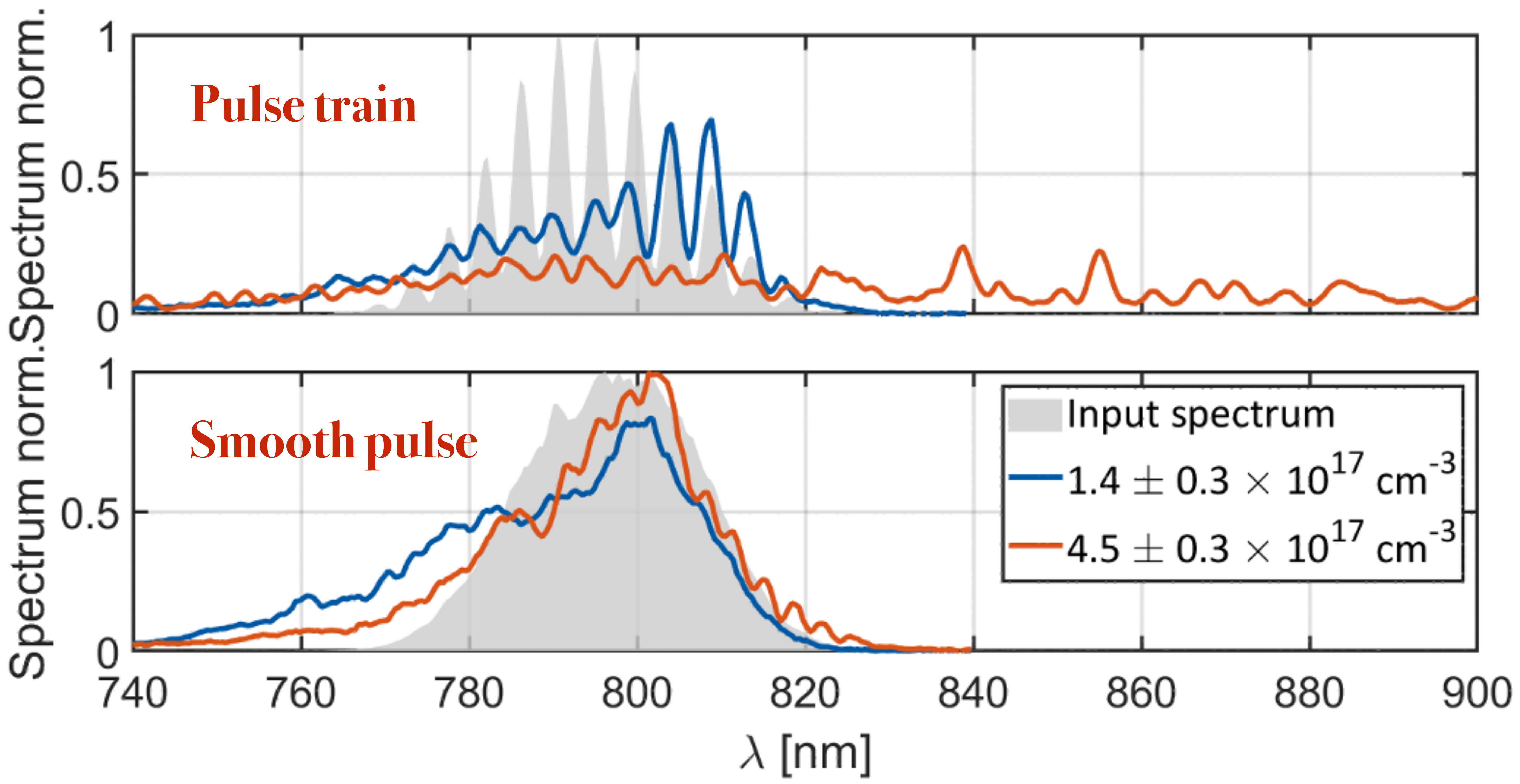


… but smooth pulse does not

Ross *et al.* *Phys. Rev. Res.* **6** L022001 (2024)



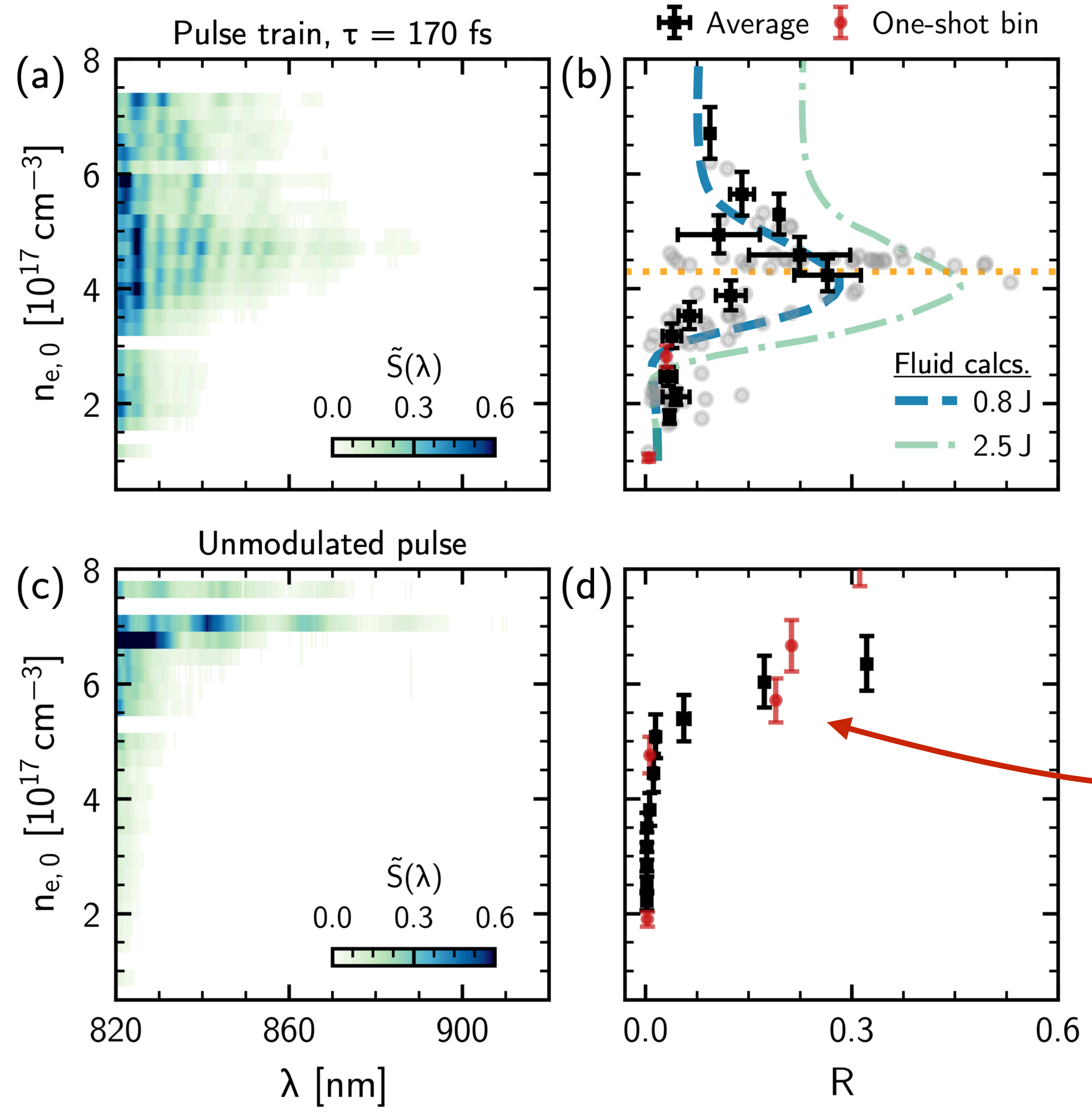
- Block one-arm of Michelson
  - Smooth ~ 1 ps pulse
  - 2.7 J on target
- No red-shifting observed!

Clear resonance observed for pulse trains

Ross *et al.* *Phys. Rev. Res.* **6** L022001 (2024)

Pulse train τ = 170 fs

Smooth ~ 1 ps pulse



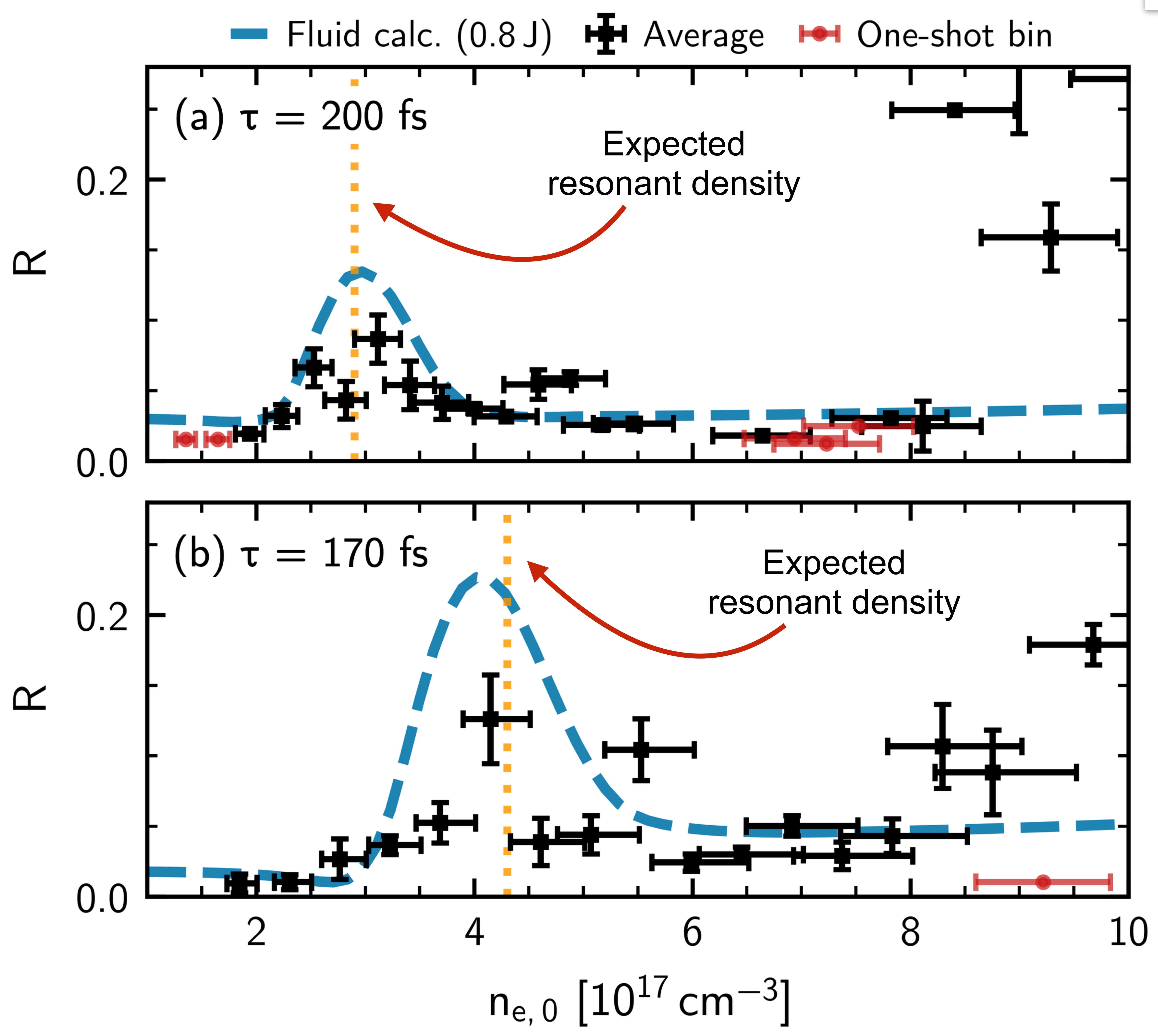
Red-shift parameter:

$$R = \sum_{\lambda_{min}}^{\infty} \tilde{(S)}(\lambda)$$

self-modulation for $n_e \gtrsim 5 \times 10^{17}\,\mathrm{cm}^{-3}$

Observed resonance shifts with density

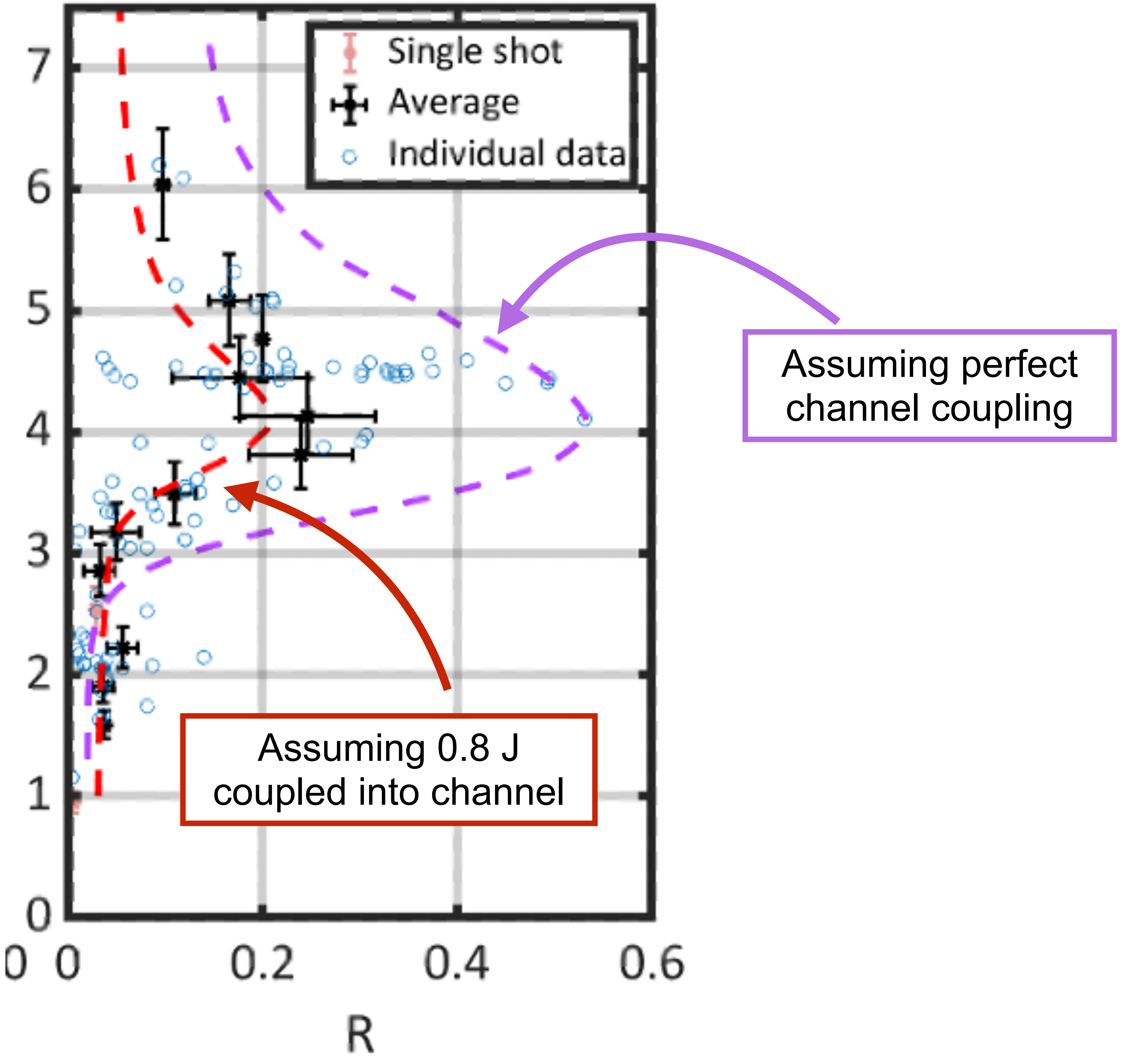
Ross *et al.* *Phys. Rev. Res.* **6** L022001 (2024)



Comparison with simulations

Ross *et al.* *Phys. Rev. Res.* **6** L022001 (2024)

- Experimental realities
  - Lowest-order mode overlap ~ 80%
  - Pointing jitter of pulse train at channel entrance ~ 31 μm
- Simulations
  - 2D cylindrical fluid benchmarked against PIC
  - Largest shifts agree well with calcn for perfect coupling
  - Average shifts consistent with ~ 0.8 J coupled into channel
  - Accel. gradient 3 - 10 GeV / m



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Summary of progress

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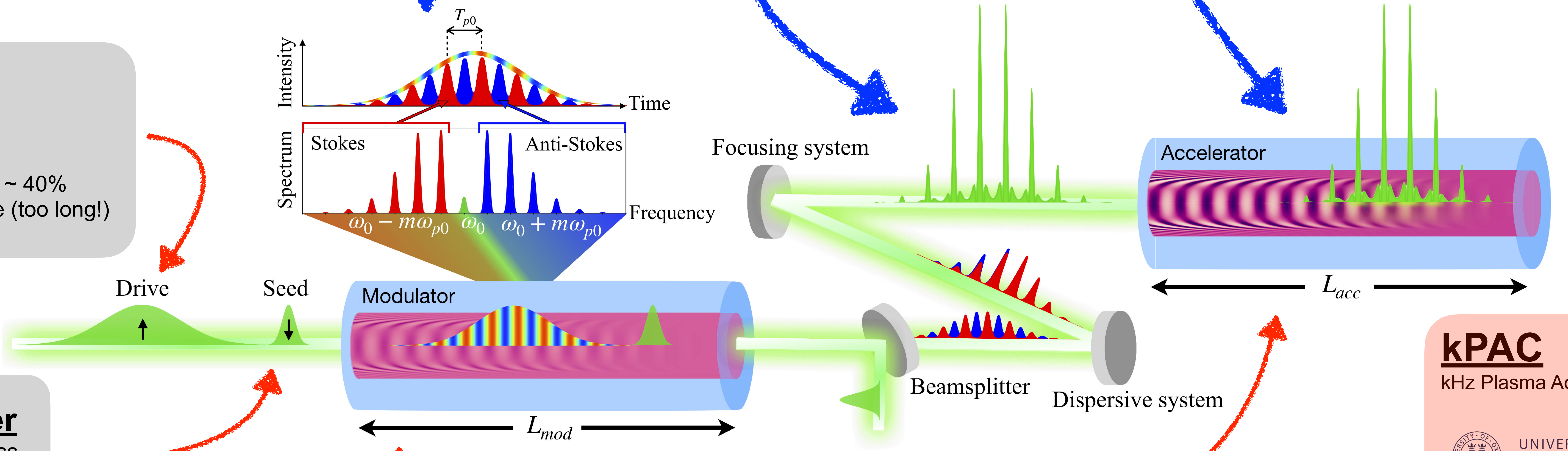

Seed laser
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kPAC
kHz Plasma Accelerator Collaboration

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central laser facility
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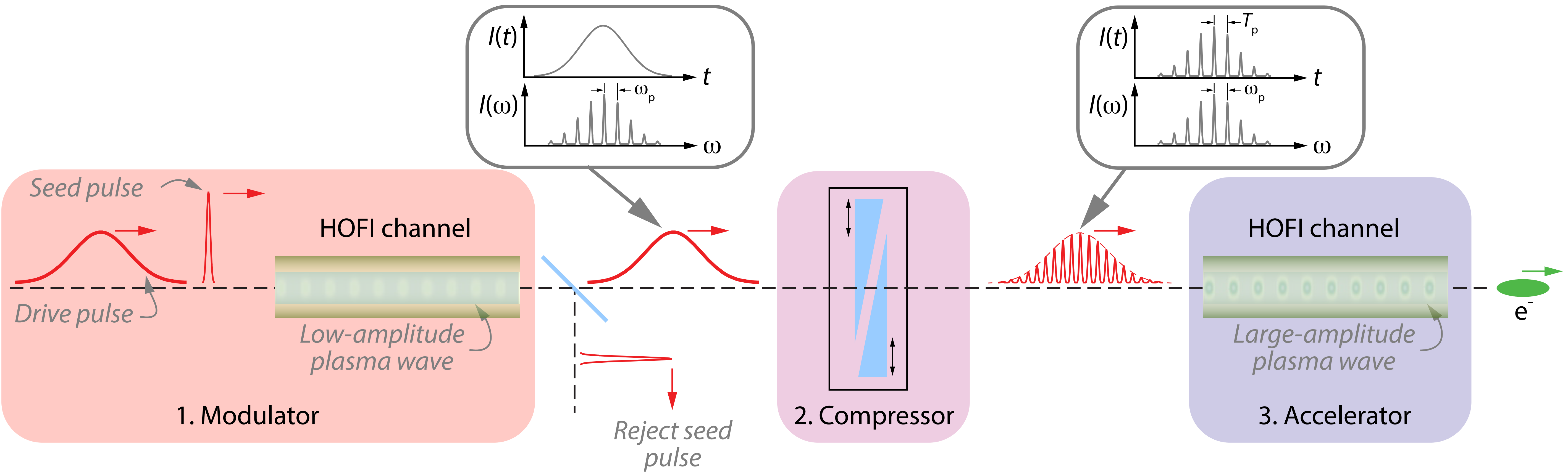
Key
- ☑ Concept demonstrated
- ☐ To be demonstrated

20

Summary



- The P-MoPA scheme offers a possible route to kHz, GeV-scale plasma accelerators driven by industrial-class lasers
- HOFI channels can meet requirements of modulator & accelerator stages
  - Operate at kHz rep. rate for extended period
  - Guide joule-scale pulse trains over ~ 100 mm
- Successful proof-of-principle demonstration of accelerator stage
  - Joule-scale pulse trains guided in ~ 100 mm HOFI channel
  - Resonant wakefield excitation in plasma channel observed
  - Acceleration gradient 3 - 10 GeV / m (~ 1 GeV stage energy gain)

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