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, Alexander Harrison, Oscar Jakobsson*, Sebastian Kalos, David McMahon, Alex Picksley*, Aimee Ross*, James Thistlewood, 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, & Alexander Podhrazsky

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
    - Wang *et al. Opt. Lett.* **45** 6615 (2020): 1.1 J, 4.5 ps, 1 kHz
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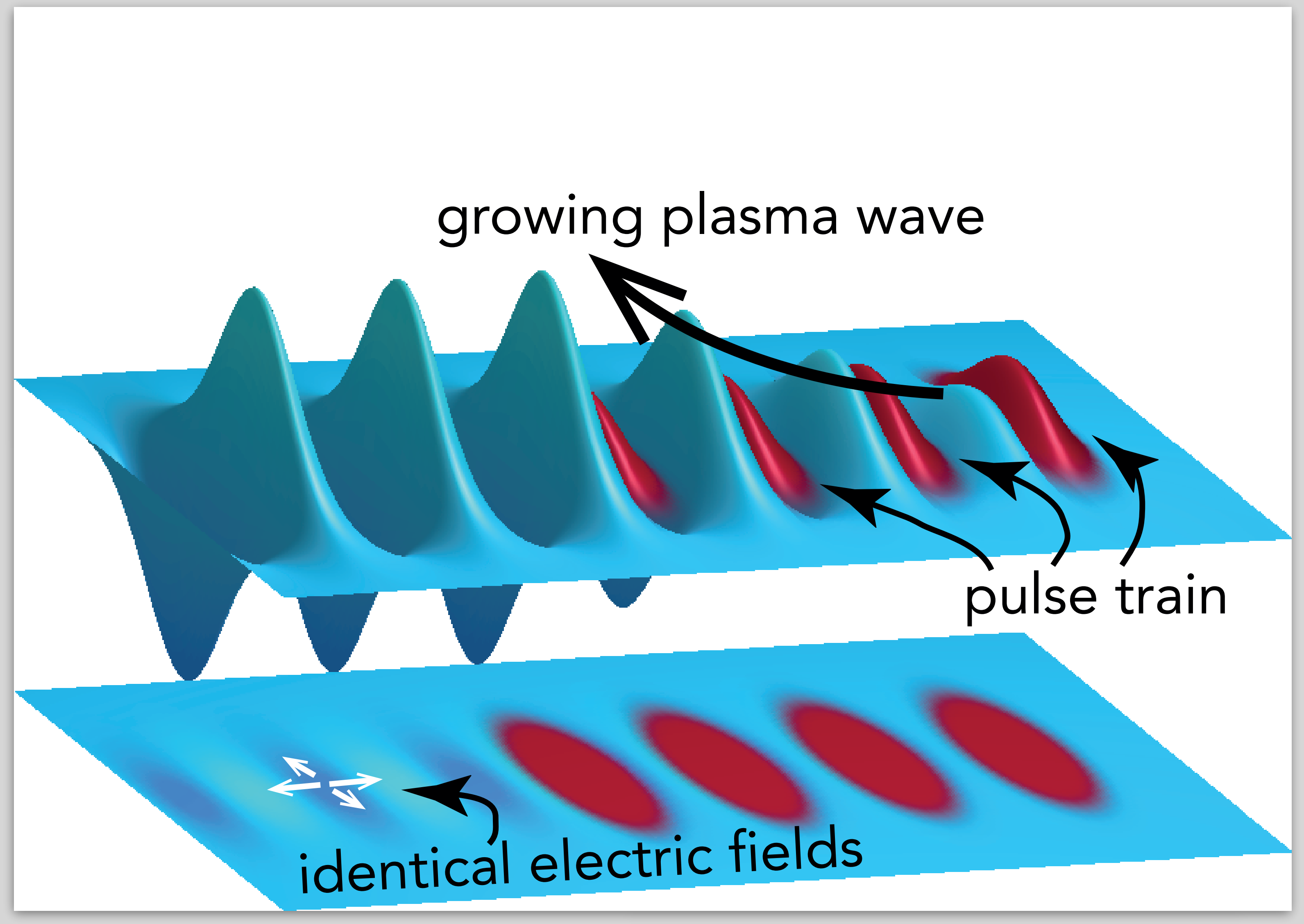
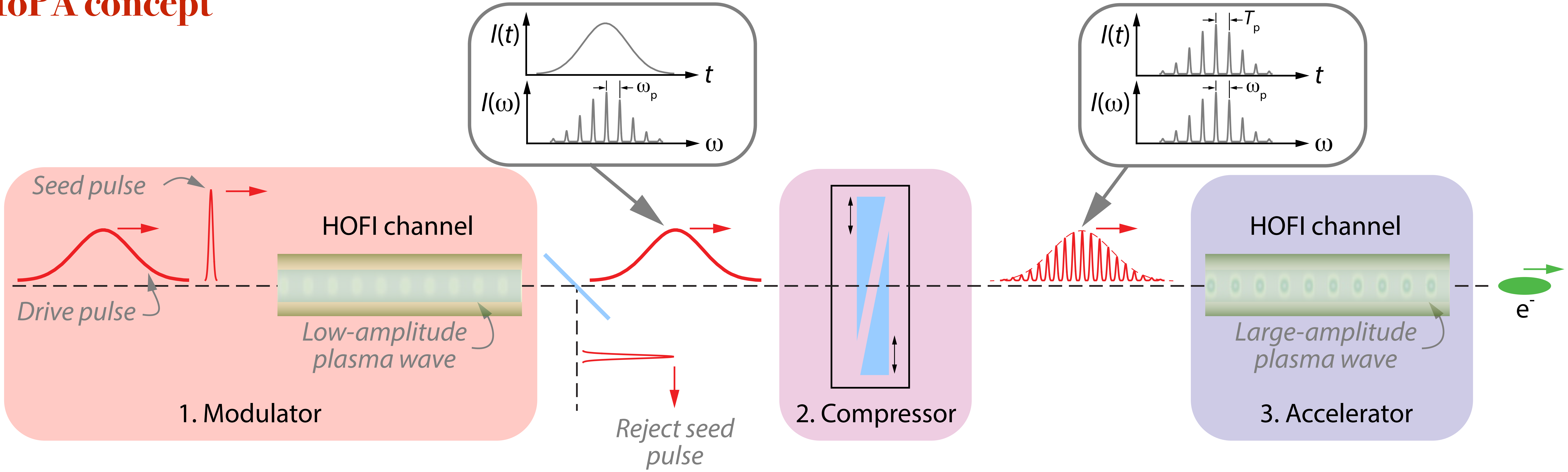


- Pulses too long to drive wake directly, but could resonantly excite wakefield if modulate pulse at plasma period
  - Many theory papers on multi-pulse published in 1990s
  - Strongly-related to plasma beat-wave accelerator (PBWA): beat two frequencies together s.t. $\omega_1 - \omega_2 = \omega_p$

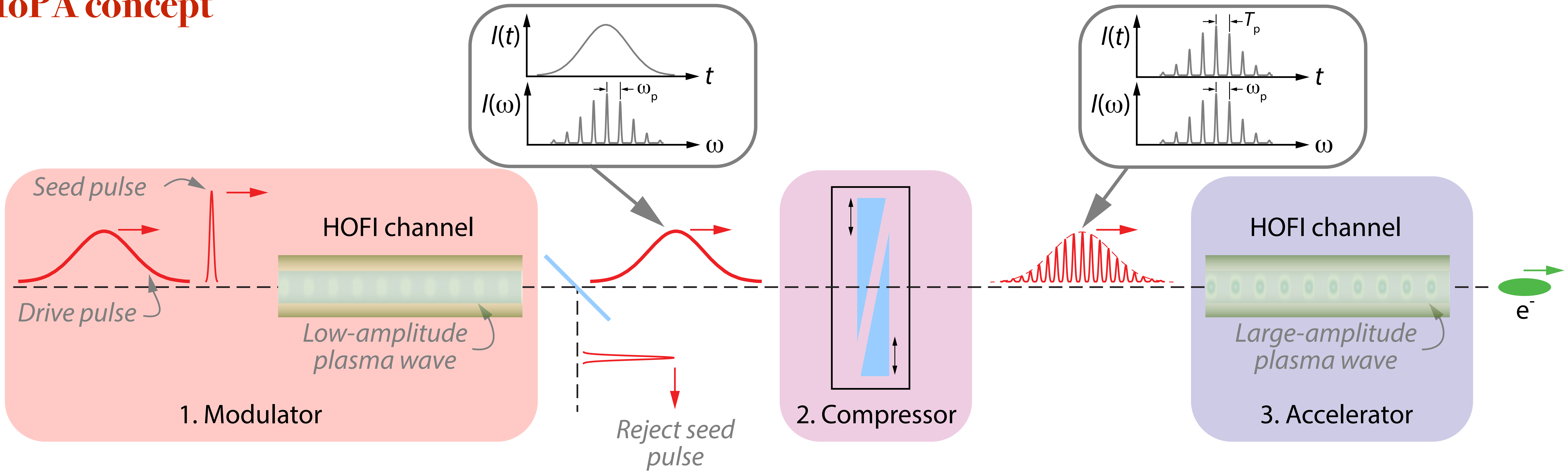
P-MoPA: Plasma-Modulated Plasma Accelerator

The P-MoPA concept



P-MoPA: Plasma-Modulated Plasma Accelerator

The P-MoPA concept



Step 1: Modulator:

- Co-propagate long (1 ps), high-energy "drive" pulse with low-amplitude wake driven by short (< 100 fs), low-energy "seed" pulse
- Drive develops sidebands at $\omega = \omega_0 \pm m\omega_p$

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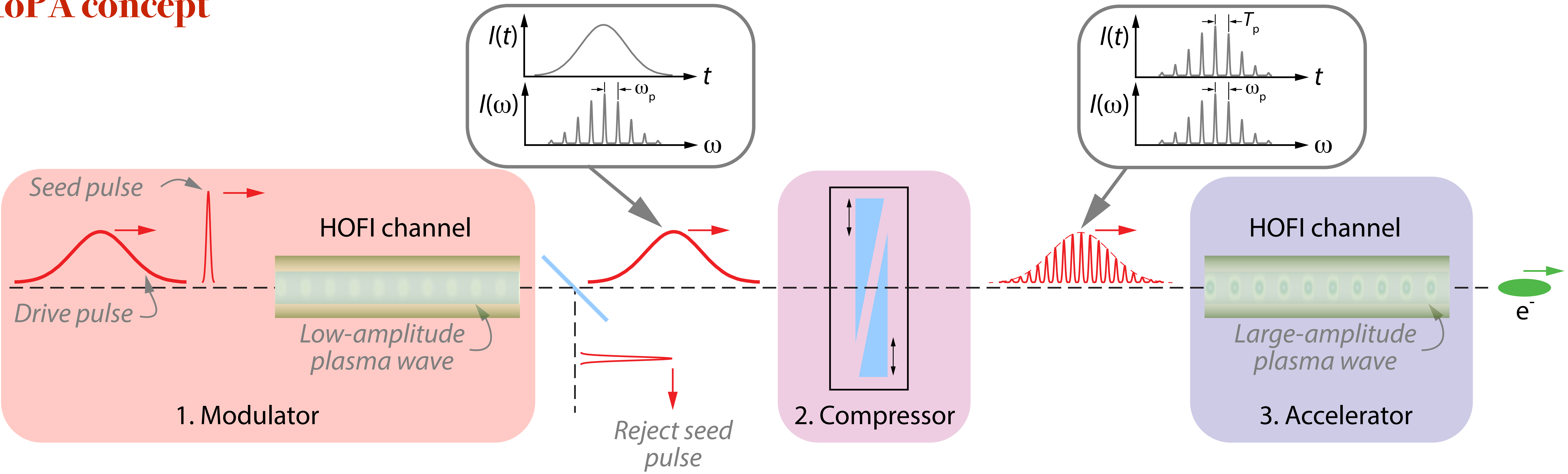
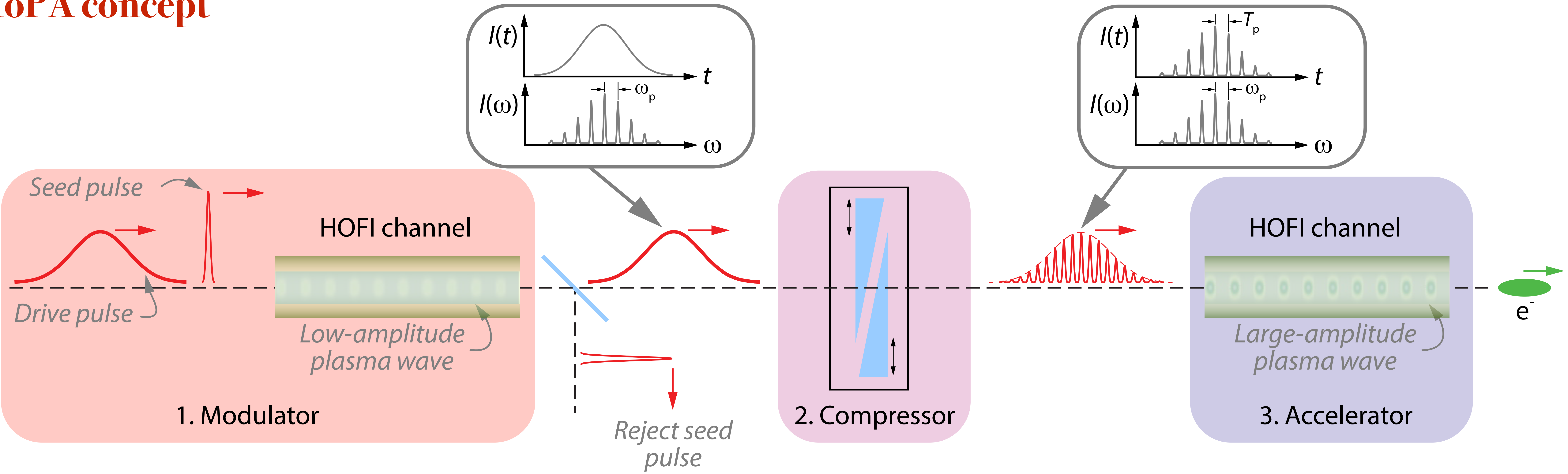


Step 2: Compressor:

- Remove spectral phase of spectrally-modulated drive
- Forms a train of short pulses spaced by $\Delta t = 2\pi/\omega_p$

P-MoPA: Plasma-Modulated Plasma Accelerator

The P-MoPA concept

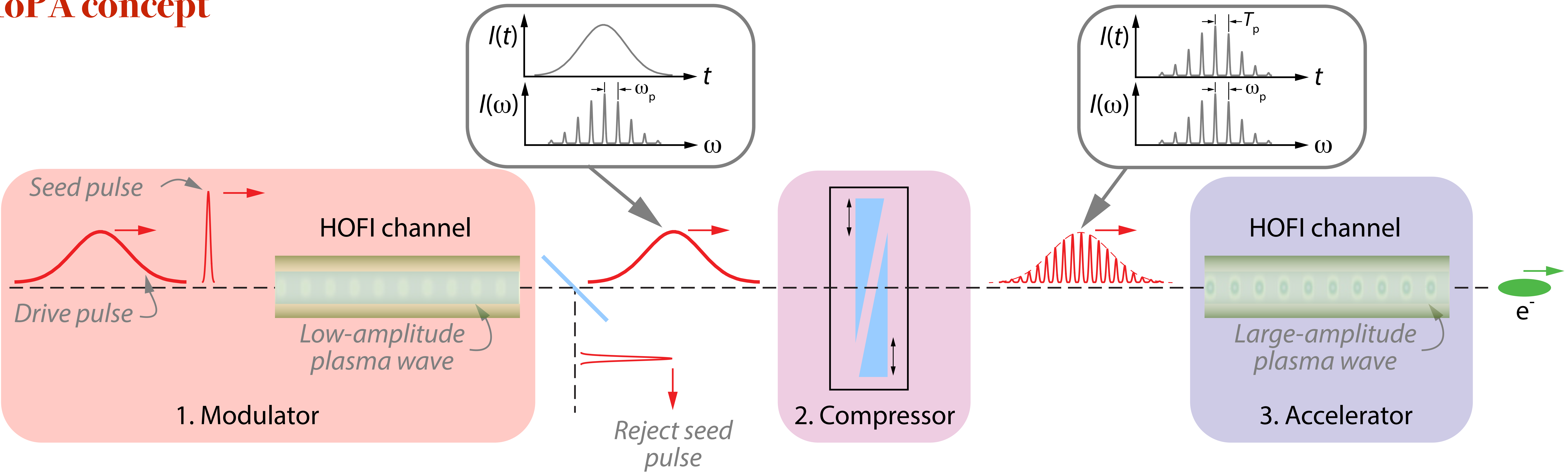


Step 3: Accelerator:

- Train resonantly excites a large-amplitude wakefield

P-MoPA: Plasma-Modulated Plasma Accelerator

The P-MoPA concept



kPAC

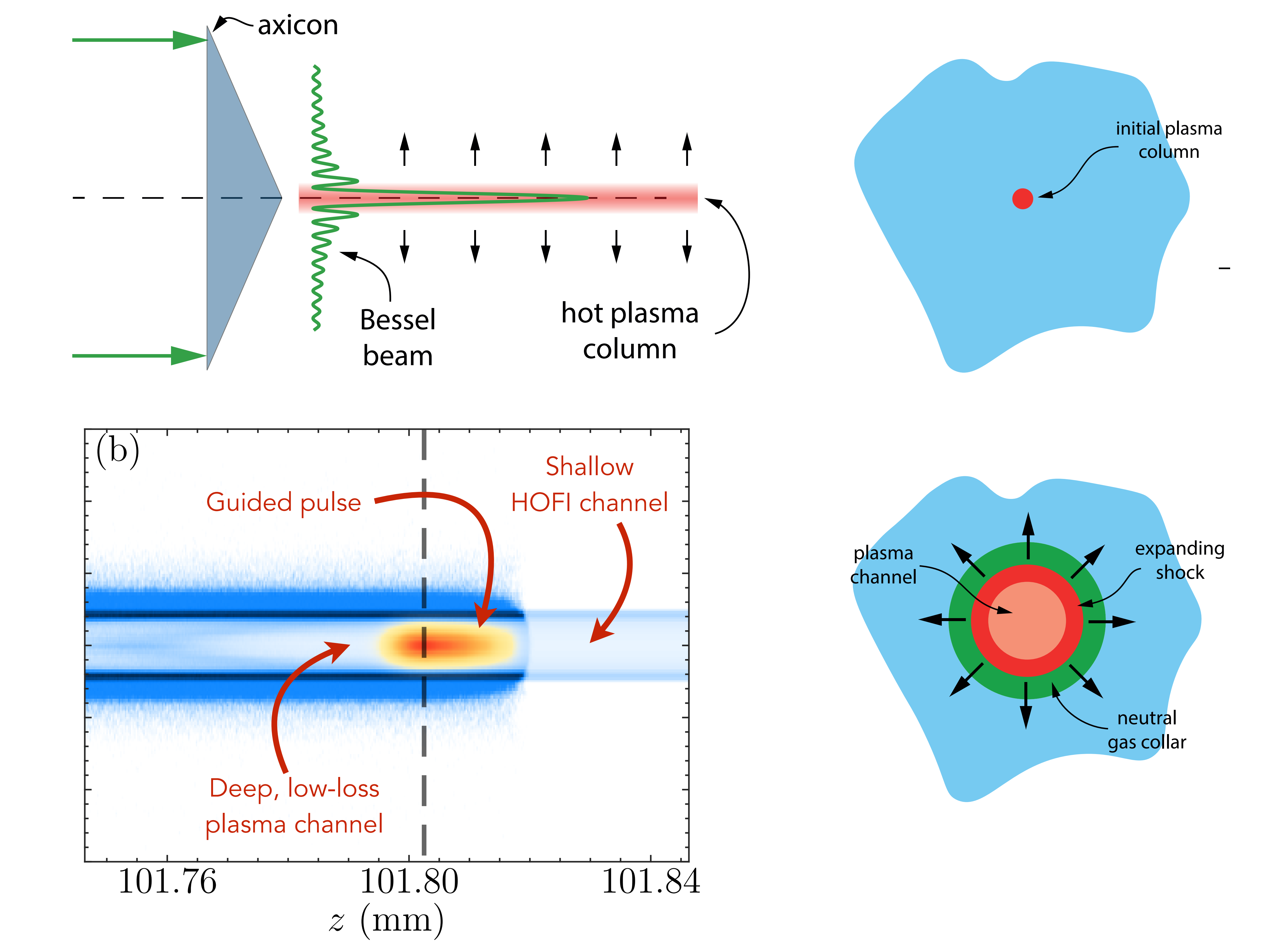
kHz Plasma Accelerator Collaboration

UNIVERSITY OF OXFORD · LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN · TRUMPF · central laser facility

HOFI plasma channels

Hydrodynamic optical-field-ionized (HOFI) plasma channels

- Channels formed by hydrodynamic expansion of collisionally-heated plasma column pioneered by Milchberg et al.
  - Free-standing & "indestructible"
  - Requires high density ($\gtrsim 10^{18}\,\mathrm{cm}^{-3}$) for efficient heating
- Optical field ionization can create lower density channels ($\lesssim 10^{17}\,\mathrm{cm}^{-3}$)
  - Expansion → weak channel
  - Ionization of gas collar → deep, low loss ($L_{\mathrm{attn}} \gg 1$ m) channels



Durfee & Milchberg, *Phys. Rev. Lett.* **71** 2409 (1993)
Volbeyn *et al.* *Phys. of Plas.* **6** 2269 (1999)
Lemos *et al.*, *Phys. of Plas.* **20** 063102 (2013)
Lemos *et al.*, *Phys. of Plas.* **20** 103109 (2013)
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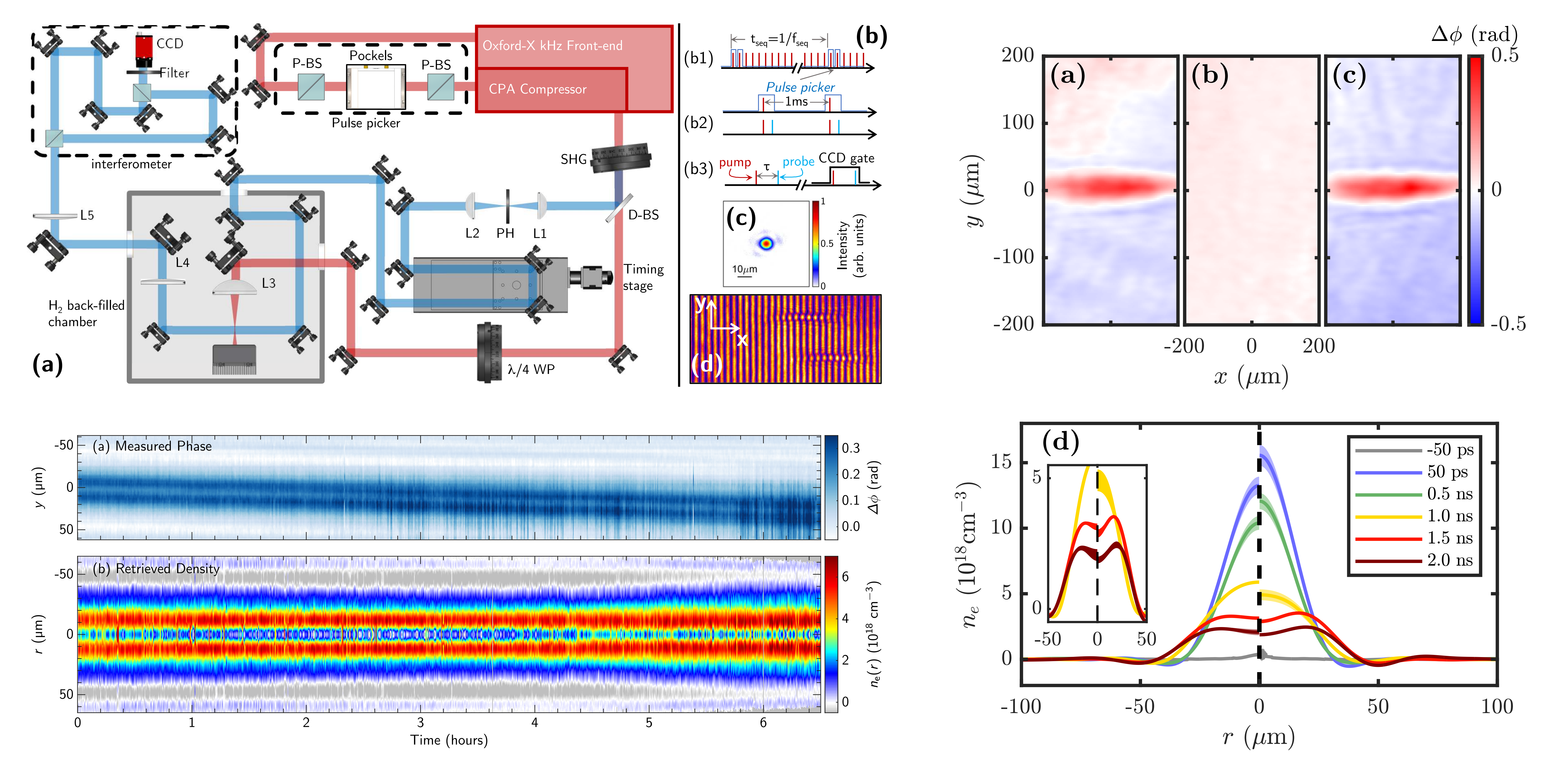
Shalloo *et al.* *Phys. Rev. E* **97** 053203 (2018)
Shalloo *et al.* *Phys. Rev. Accel. Beam* **22** 41302 (2019)
Picksley *et al.* *Phys. Rev. E* **102** 053201 (2020)
Feder *et al.* *Phys. Rev. Res.* **2** 043173 (2020)
Maio *et al.* *Phys. Rev. Lett.* **125** 074801 (2020)
Alejo *et al.* *Phys. Rev. Acc. Beams* **25** 011301 (2022)
Shrock *et al.* *Phys. Rev. Lett.* **133** 045002 (2024)
Miao *et al.* *Phys. Rev. Accel. Beams* **27** 081302 (2024)
Picksley *et al.* *Phys. Rev. Lett.* **133** 255001 (2024)

HOFI channels are capable of kHz repetition rates



Alejo *et al.* *Phys. Rev. Acc. Beams* **25** 011301 (2022)

- 2 HOFI channels generated 1 ms apart have same properties
- (short) HOFI channels generated at 0.4 kHz for 6.5 hours

Simulations of P-MoPAs

P-MoPA: Modulator

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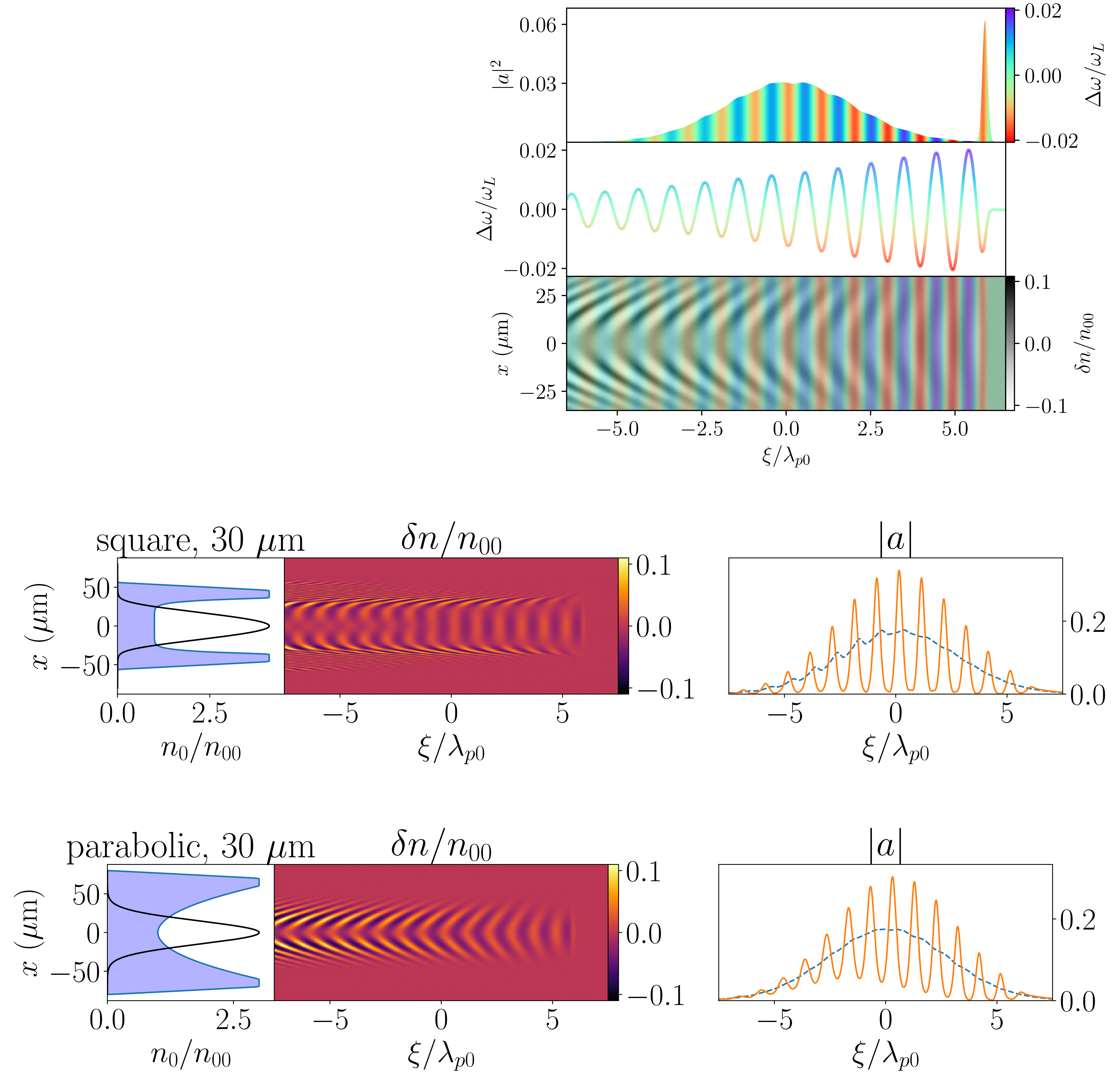
$$\beta = 2\frac{\omega_{p0}^2}{8\omega_L}\frac{\delta n_e}{n_{e0}}\frac{L_{\text{mod}}}{v_{\text{g,mod}}}$$ modulator parameter

- 3D fluid theory shows:
  - Spectral modulation is a radial average ⇒ independent of radial position
  - Curvature of wake reduces modulation
  - Stable operation possible over wide range of parameters

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



P-MoPA: Compressor

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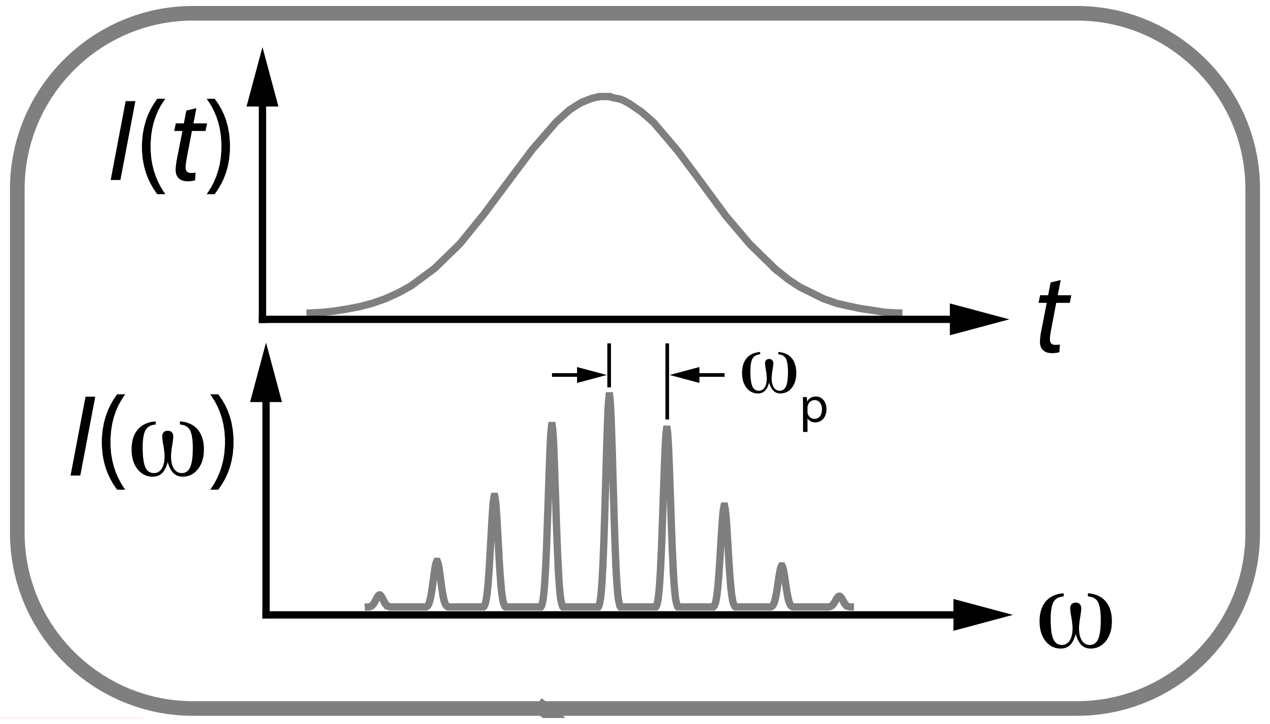
sidebands

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

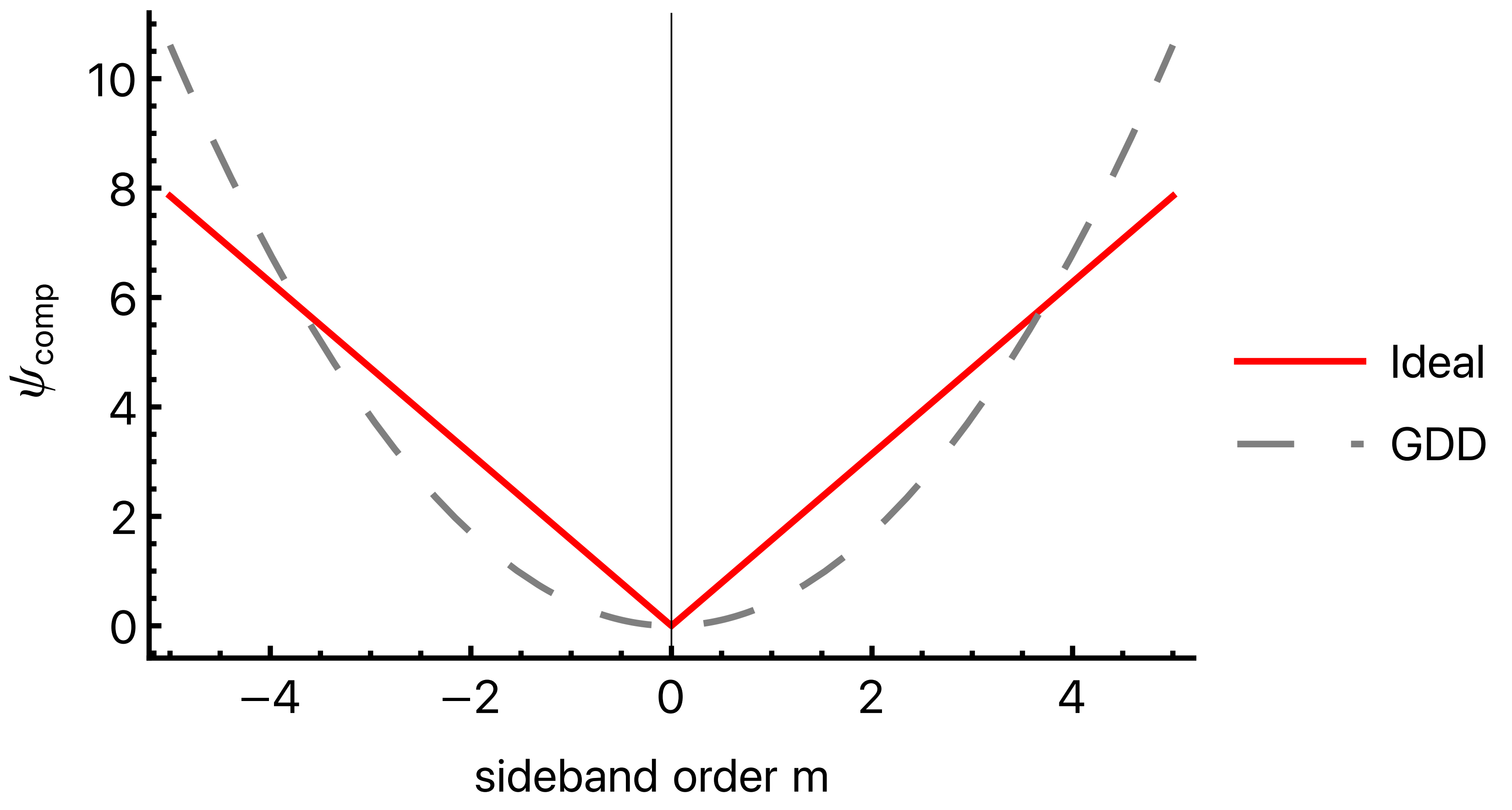
$$\text{Spectralphase}: \quad \psi_m \approx -|m|\frac{\pi}{2}$$

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

Temporal domain

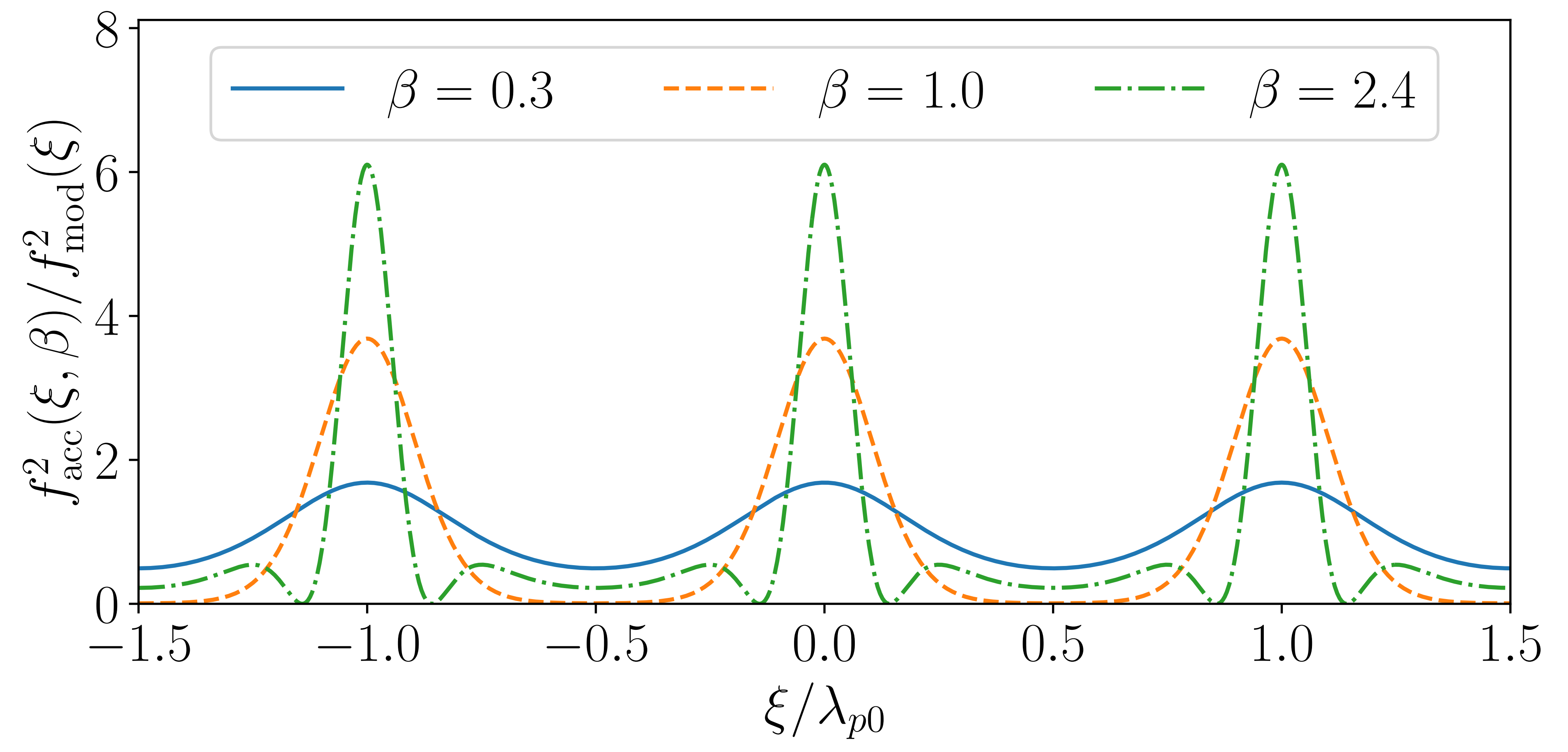


Spectral domain



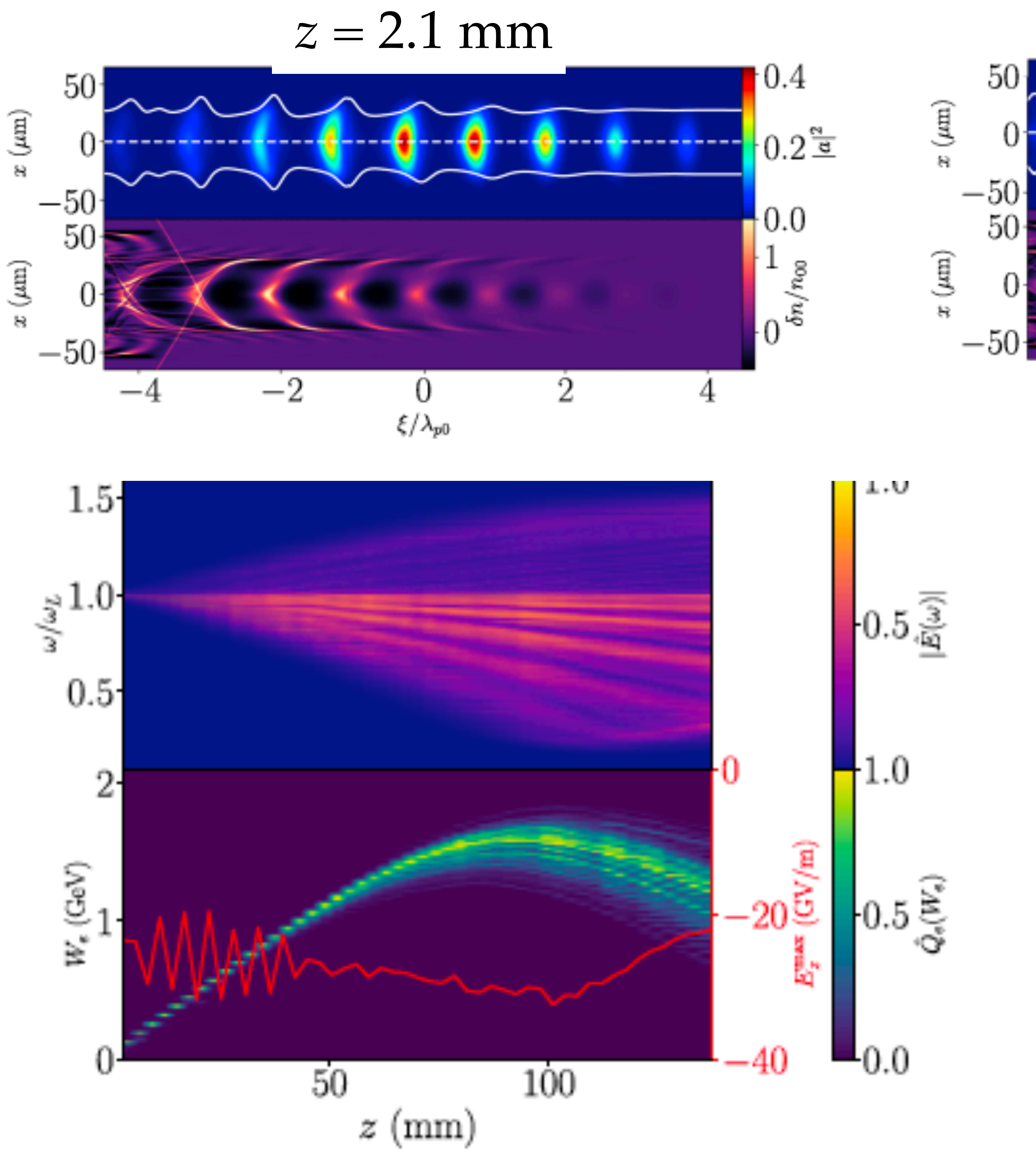
P-MoPA: Accelerator

- Modulator parameter β controls temporal profile of pulse train
  - For $\beta_{opt} \approx 1.43$, wake 72% larger than PBWA with same pulse energy
  - Can drive wakes with ~ 50% E_{wb}



Jakobsson *et al. Phys. Rev. Lett.* **127** 184801 (2021)
van de Wetering *et al. Phys. Rev. E* **108** 015204 (2023)
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
$n_{e0} = 2.5 \times 10^{17}\ \text{cm}^{-3}$

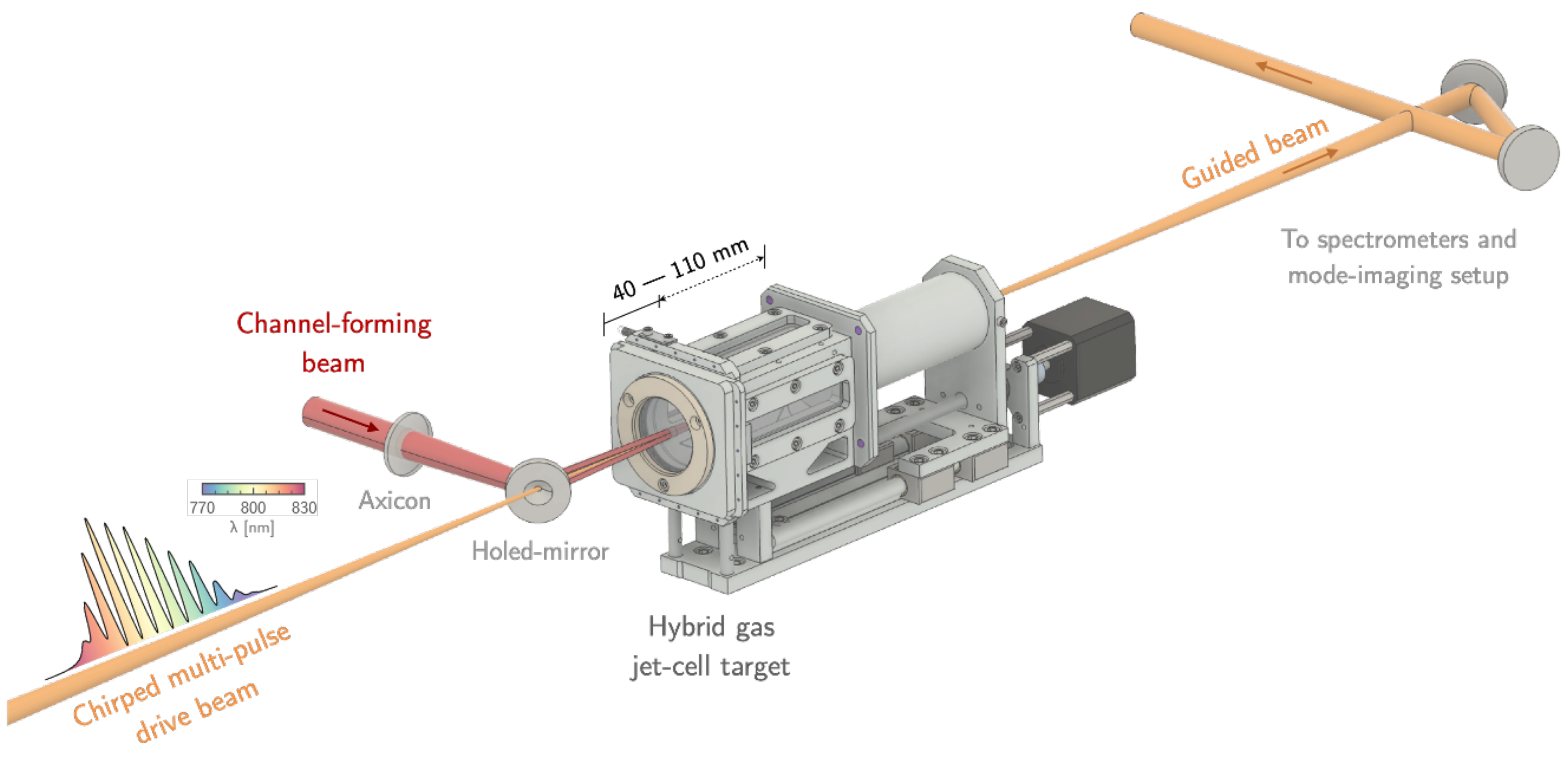
Demonstration of Step 3 :
Resonant wakefield excitation in a plasma channel

Experimental set-up

- Objectives
  - Demonstrate guiding of joule-scale pulse trains in ~ 100 mm long HOFI channels
  - Demonstrate resonant excitation of wakefield

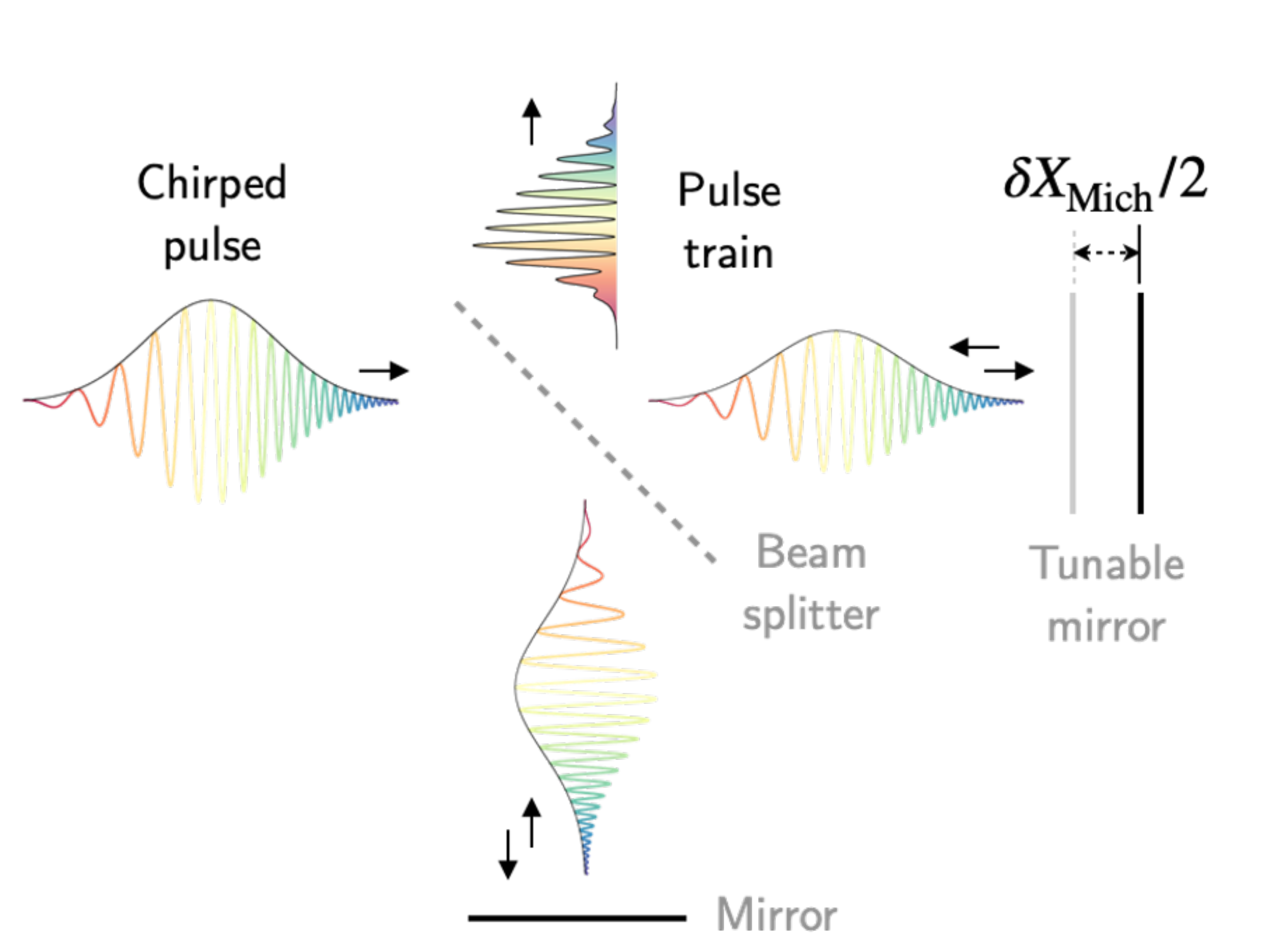
Astra-Gemini Laser, RAL

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



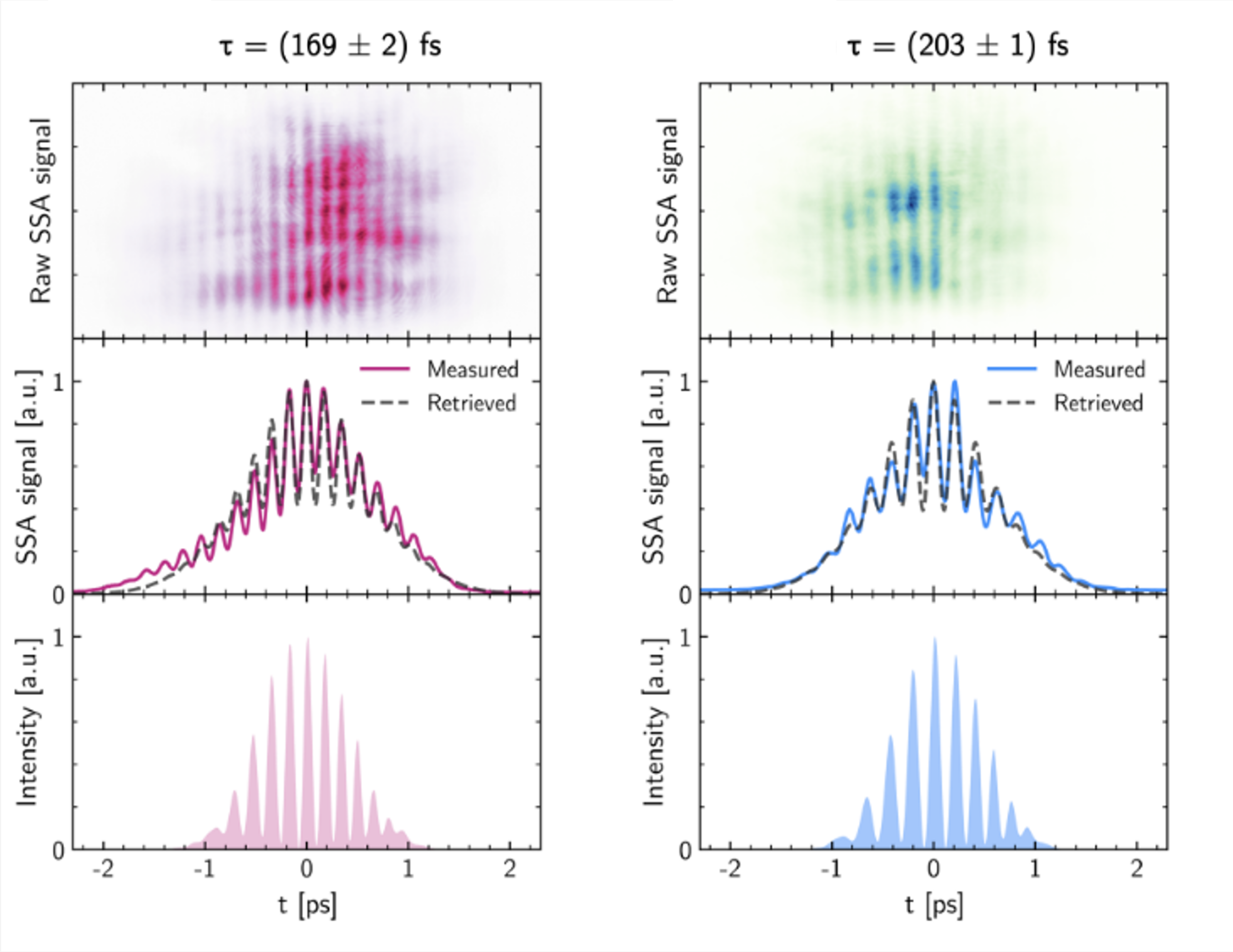
Pulse train	Channel-forming beam
$E = (2.5 \pm 0.5)$ J	$\tau = 80$ fs
$w_0 = (45.5 \pm 3.4)\,\mu$m	$E \sim 100$ mJ
$z_R = (7.9 \pm 0.7)$ mm	$\theta_{base}^{axicon} = 3.6°$

Generation of "dummy" pulse trains



- 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

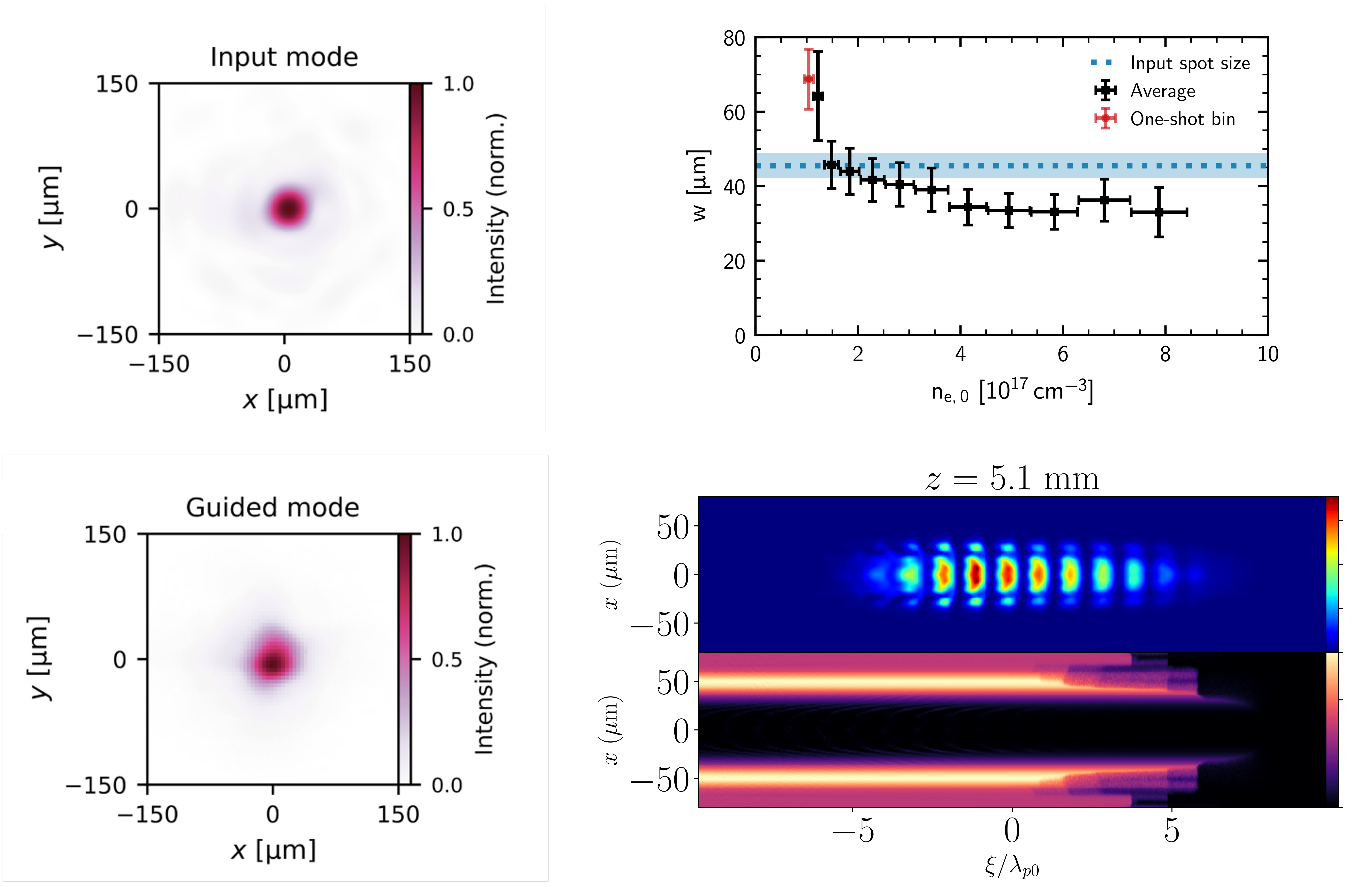
Ross *et al. Phys. Rev. Res.* **6** L022001 (2024)



Joule-scale pulse trains can be guided in a HOFI channel

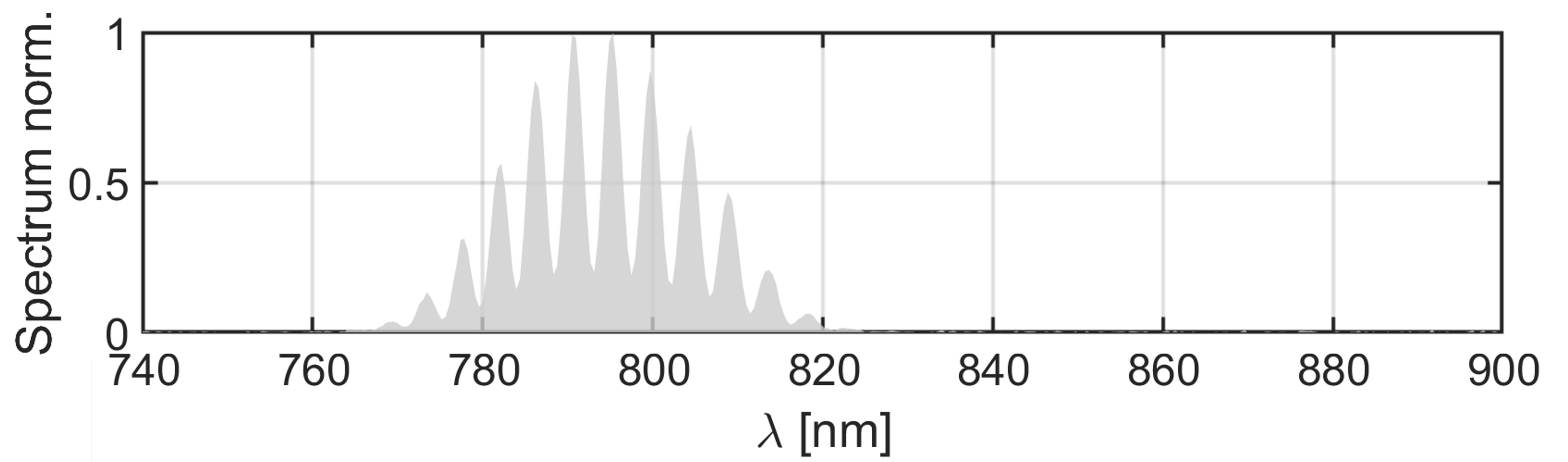
- Joule-scale pulse trains guided over 110 mm ($\sim 17\, z_R$)
- Input spot ~70% overlap with lowest-order mode
- PIC simulations confirm that first few pulses condition the HOFI channel

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



Pulse train spectra show resonant excitation …

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



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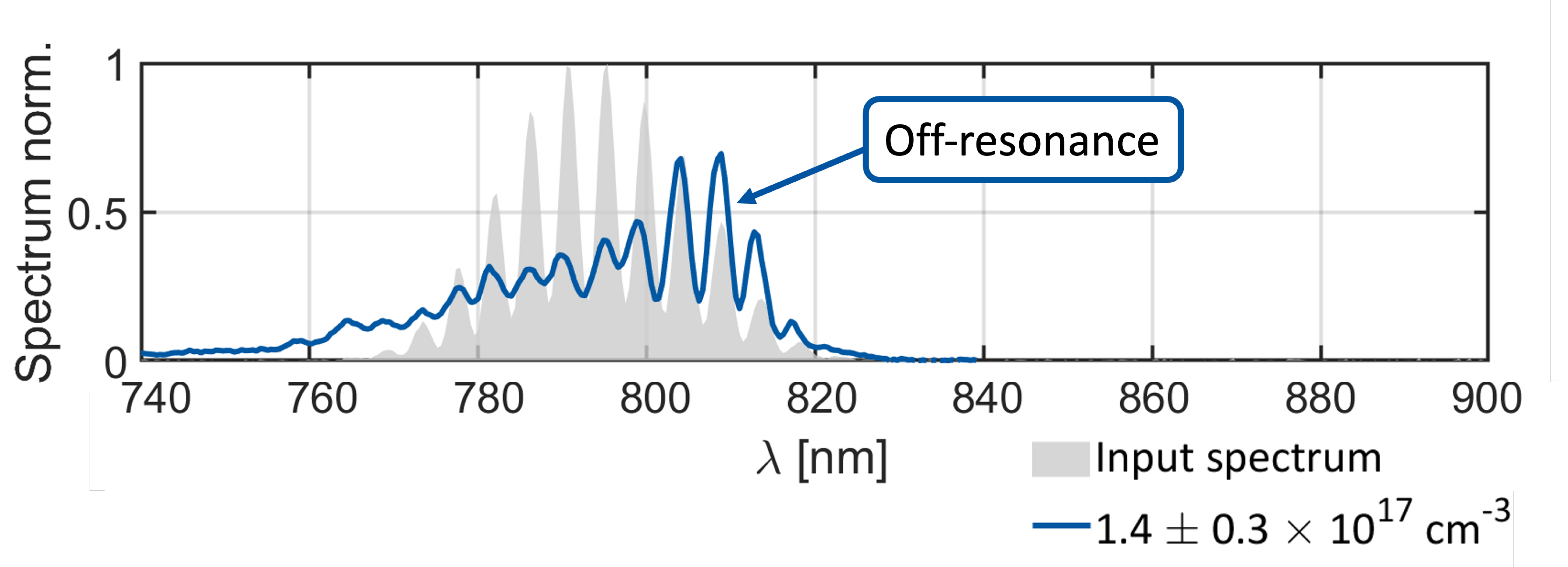
Ross *et al.* *Phys. Rev. Res.* **6** L022001 (2024)



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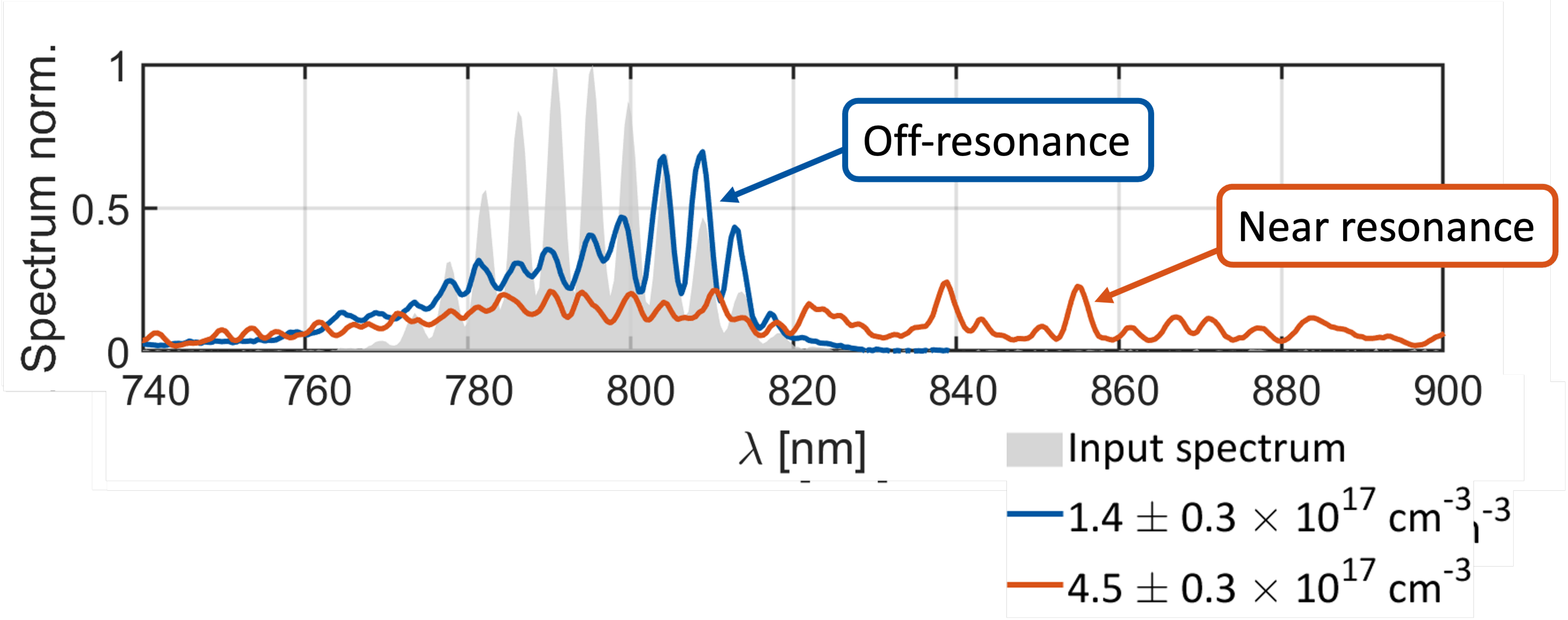
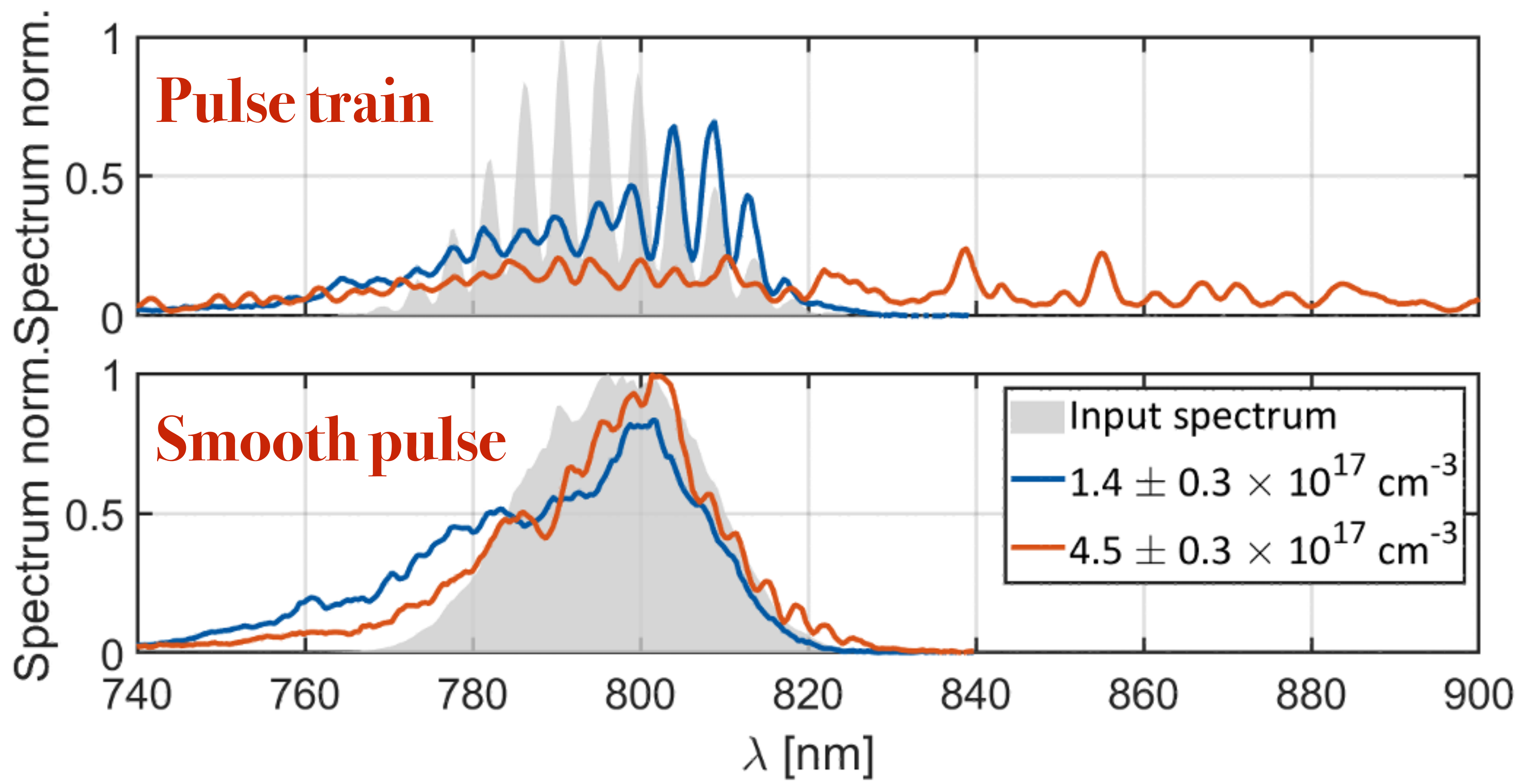


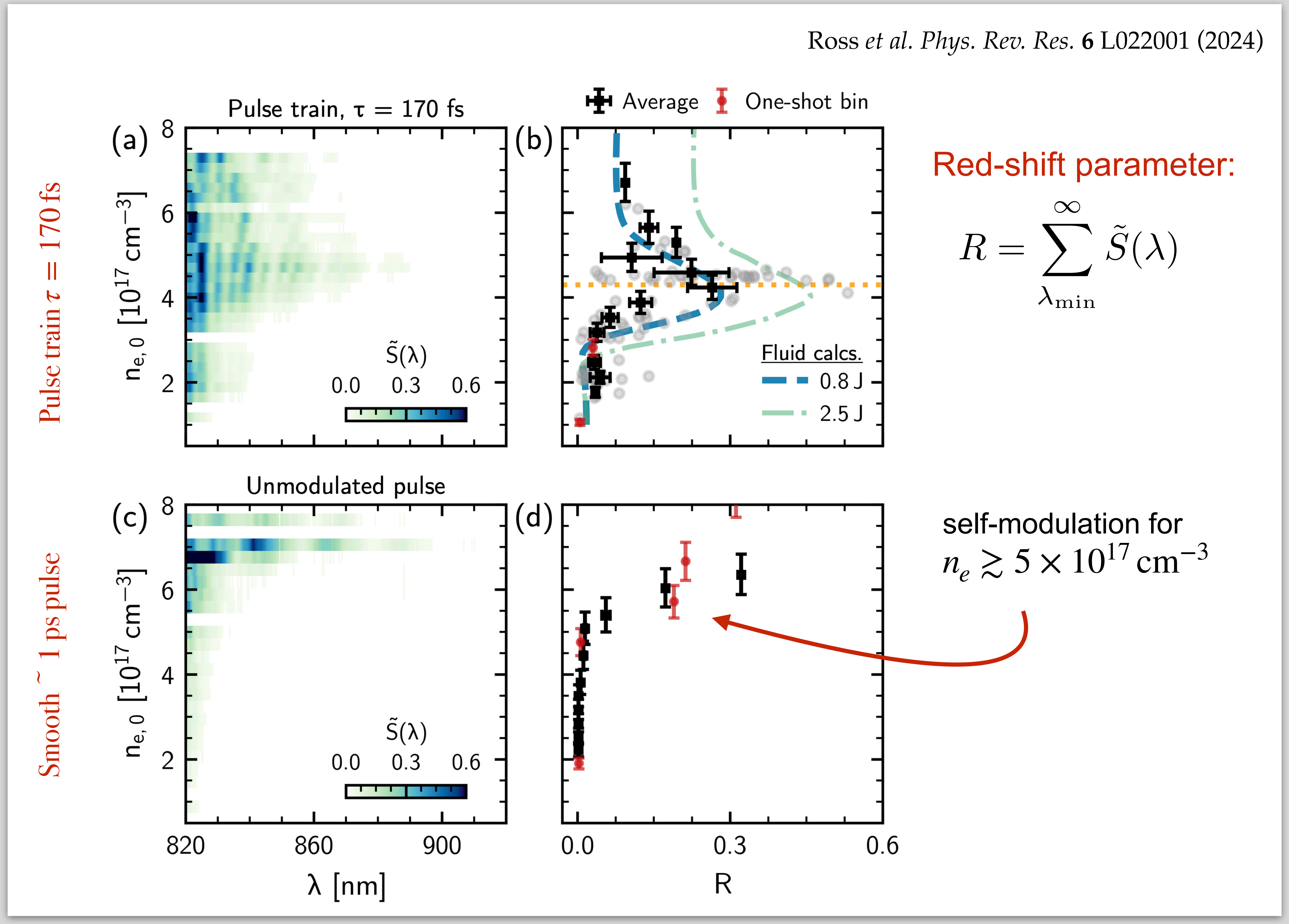
… but smooth pulse does not

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, but not for smooth pulses



Red-shift parameter:

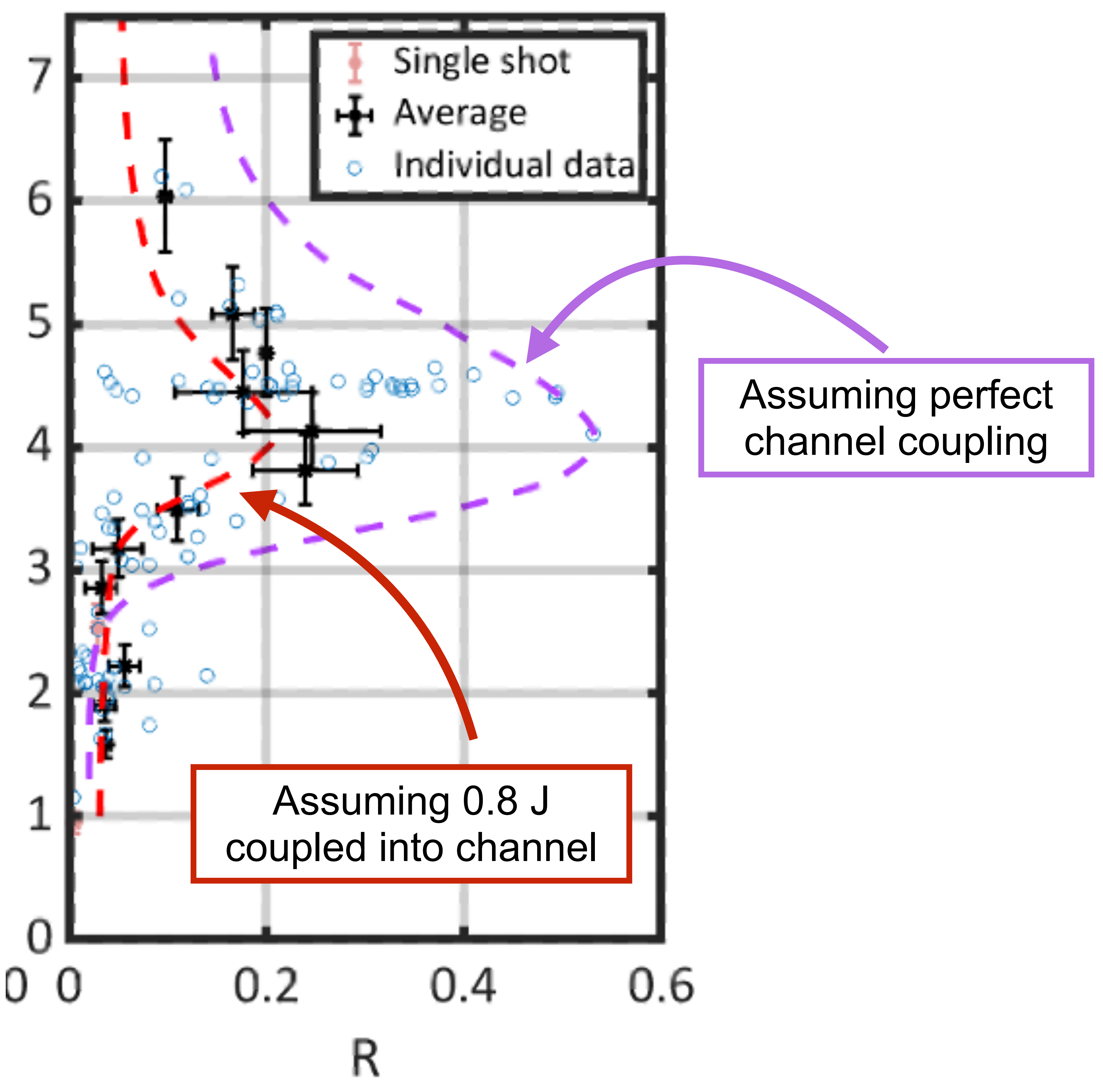
$$R = \sum_{\lambda_{\min}}^{\infty} \tilde{S}(\lambda)$$

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

Comparison with simulations

- 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
  - [i.e. (0.3 - 1) GeV over the stage]

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



Summary of progress

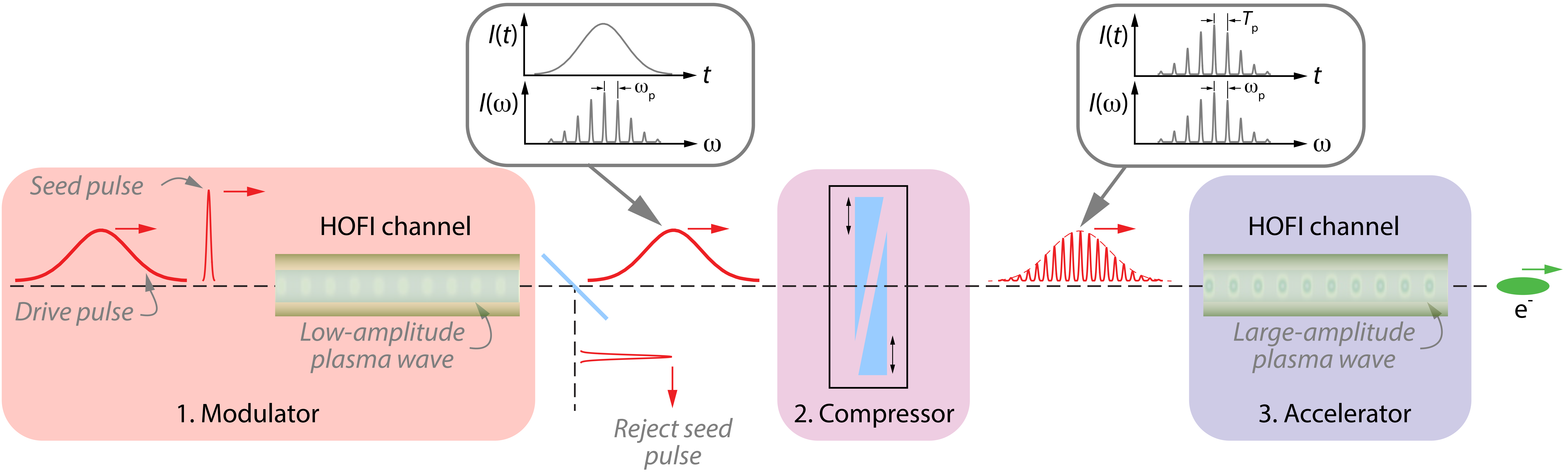
Technologies

Drive laser
- ✓ Industrial-class
- ✓ Multi-joule
- ✓ Multi kilohertz
- ✓ Optical efficiency ~ 40%

Seed laser
- ✓ Industrial-class
- ✓ ~ 100 mJ
- ✓ Multi kilohertz

HOFI plasma channel
- ✓ Low loss
- ✓ > 100 mm guiding
- ✓ kHz rep. rate

Key
- ☑ Concept demonstrated
- ☐ To be demonstrated

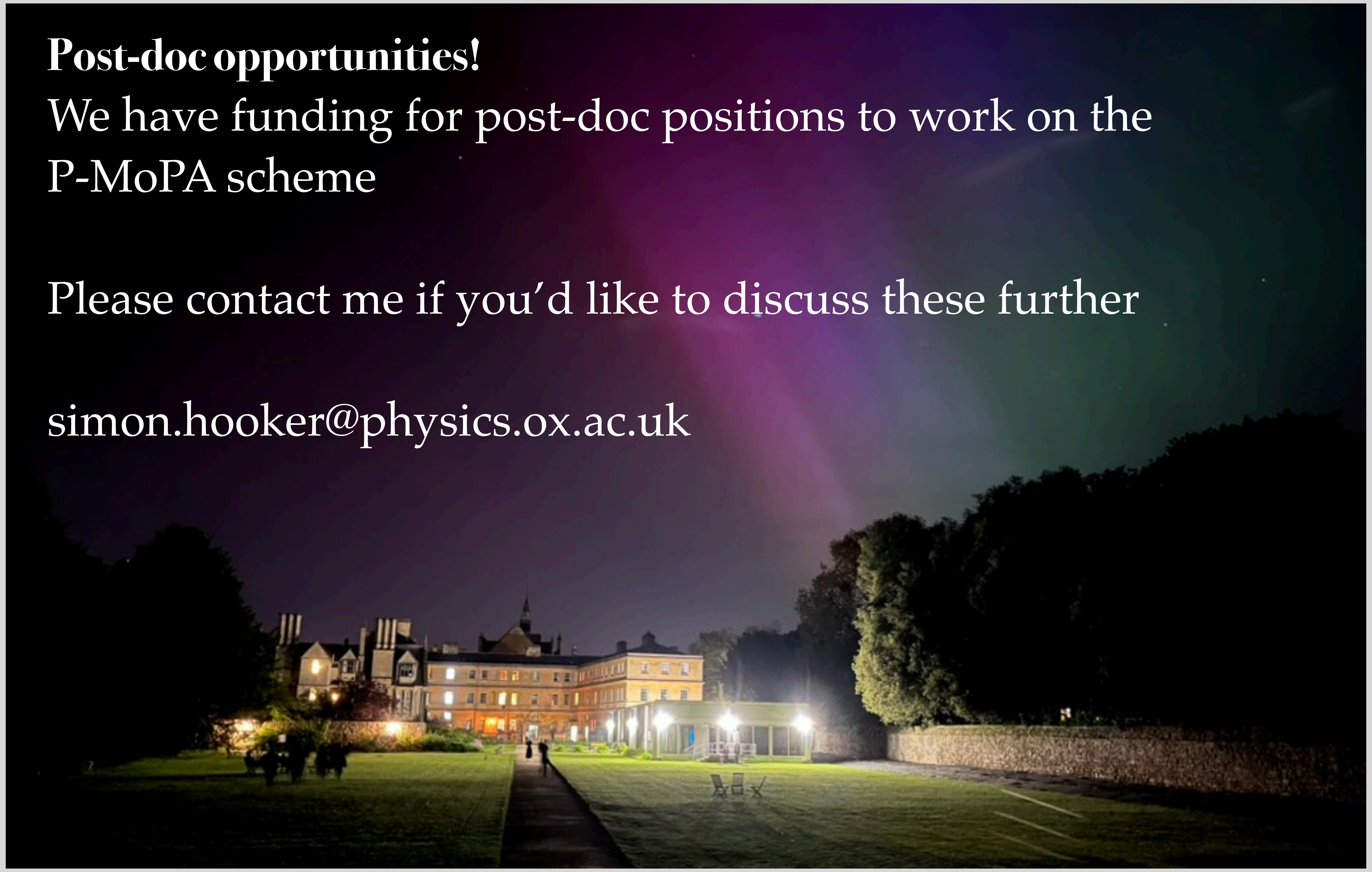


Step 1: Plasma modulator
- ☑ Drive & seed pulses guided in HOFI channel
- ☐ Spectrum of drive pulse modulated by wake driven by seed pulse

Step 2: Train generation
- ☐ Spectrally-modulated drive pulse converted to pulse train by dispersive system

Step 3: Accelerator
- ☑ Resonant wake excitation by pulse train guided in HOFI channel
- ☐ Acceleration of injected electrons to multi-GeV energies @ kHz rep. rate

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)

This work was supported by:
- EPSRC [grant numbers EP/V006797/1, EP/R513295/1];
- STFC [grant numbers ST/P002048/1, ST/R505006/1, ST/S505833/1, ST/V001655/1, ST/V001612/1];
- UKRI [ARCHER2 Pioneer Projects];
- InnovateUK (Grant No. 10059294);
- the UK Central Laser Facility;
- the Ken and Veronica Tregidgo Scholarship in Atomic and Laser Physics (Wolfson College, Oxford);
- John Fell Oxford University Press Research Fund;
- This material is based upon work supported by the Air Force Office of Scientific Research under award numbers FA9550-18-1-7005 & number FA8655-24-1-7030.
- This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 653782.
- Computing resources provided by STFC Scientific Computing Department's SCARF cluster; the plasma HEC Consortium [EPSRC Grant No. EP/R029149/1], and the ARCHER and ARCHER2 [ARCHER2 PR17125] UK National Supercomputing Service
- This research used the open-source particle-in-cell code WARPX, primarily funded by the U.S. DOE Exascale Computing Project. We acknowledge all WARPX contributors.