Progress towards demonstration of the plasma-modulated plasma accelerator (P-MoPA)

UNIVERSITY OF OXFORD

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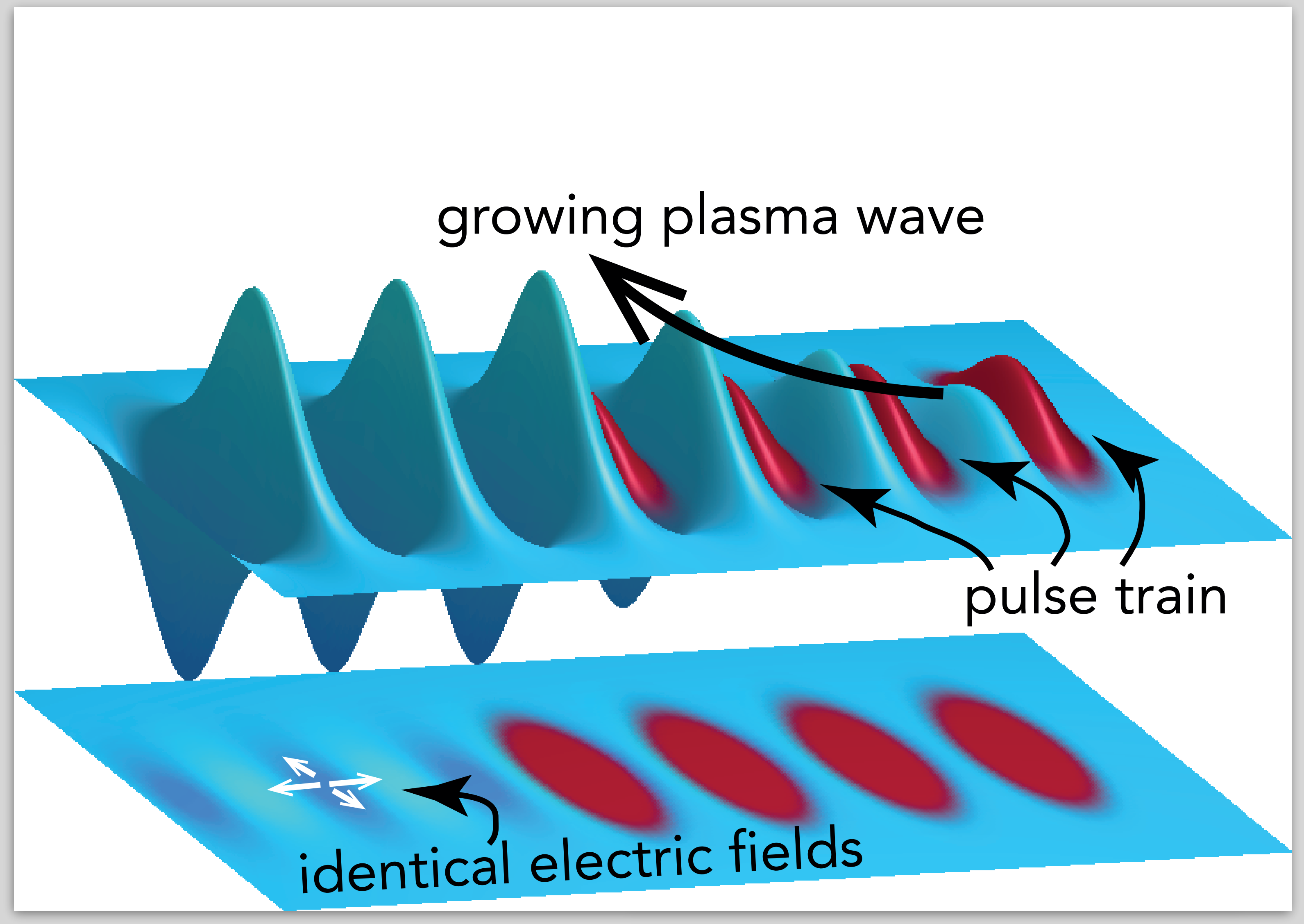
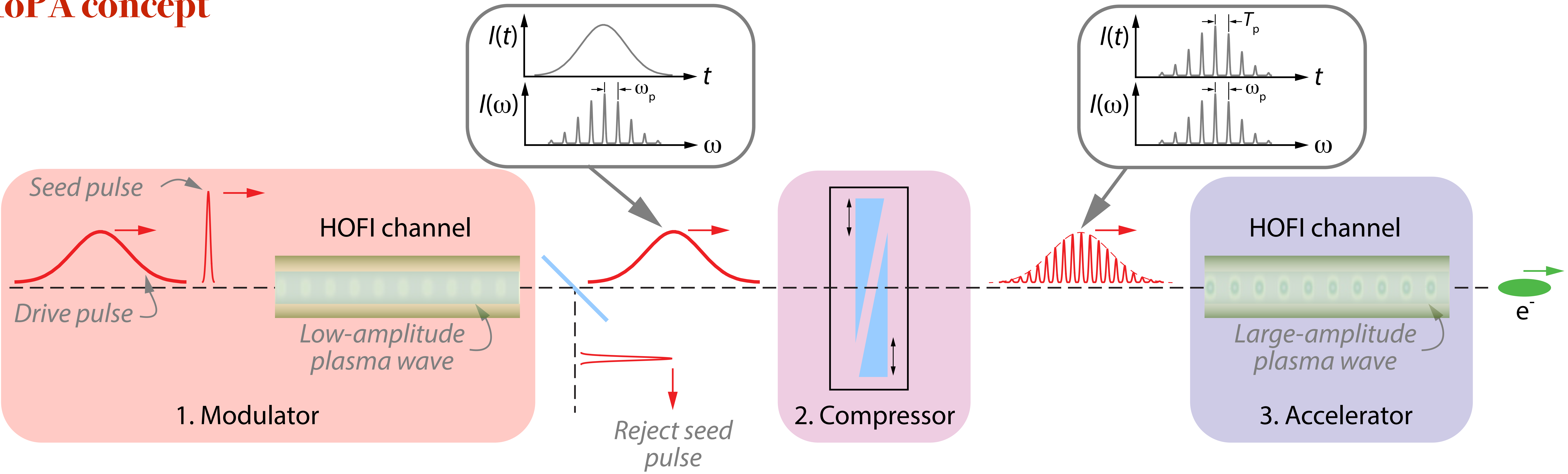
Could we drive GeV-scale, kHz accelerators with existing lasers?

- 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
- Pulses too long … but could resonantly excite wakefield if modulate pulse at plasma period
- Beat-wave ($\omega_1 - \omega_2 = \omega_p$)? Only one wavelength available (at moment)



P-MoPA: Plasma-Modulated Plasma Accelerator

The P-MoPA concept



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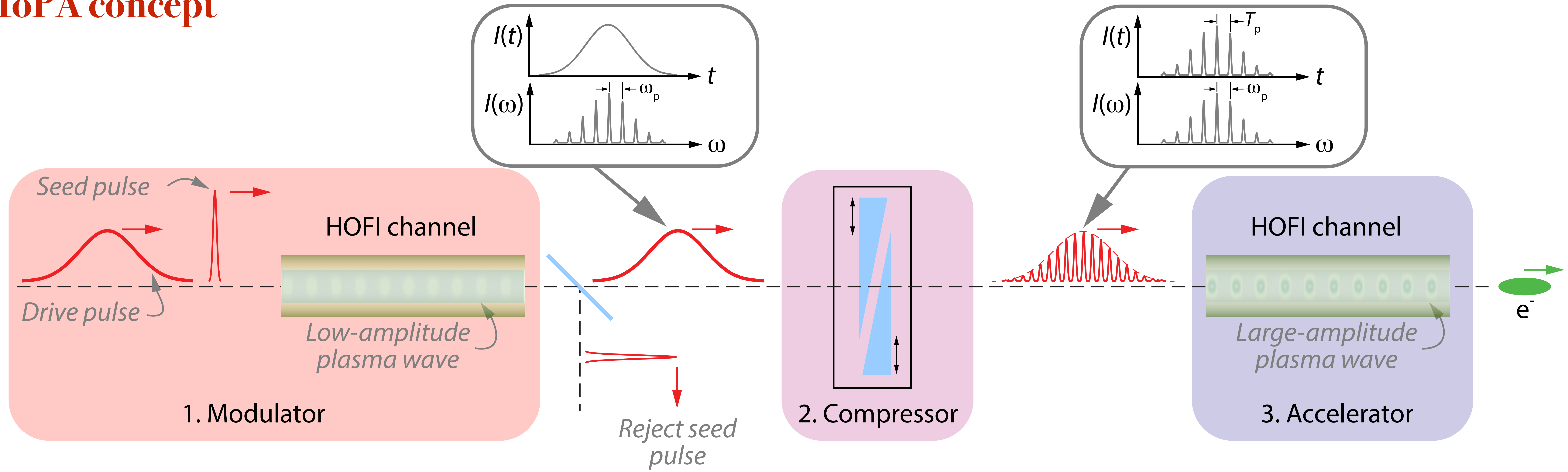

Step 1: Modulator:

- 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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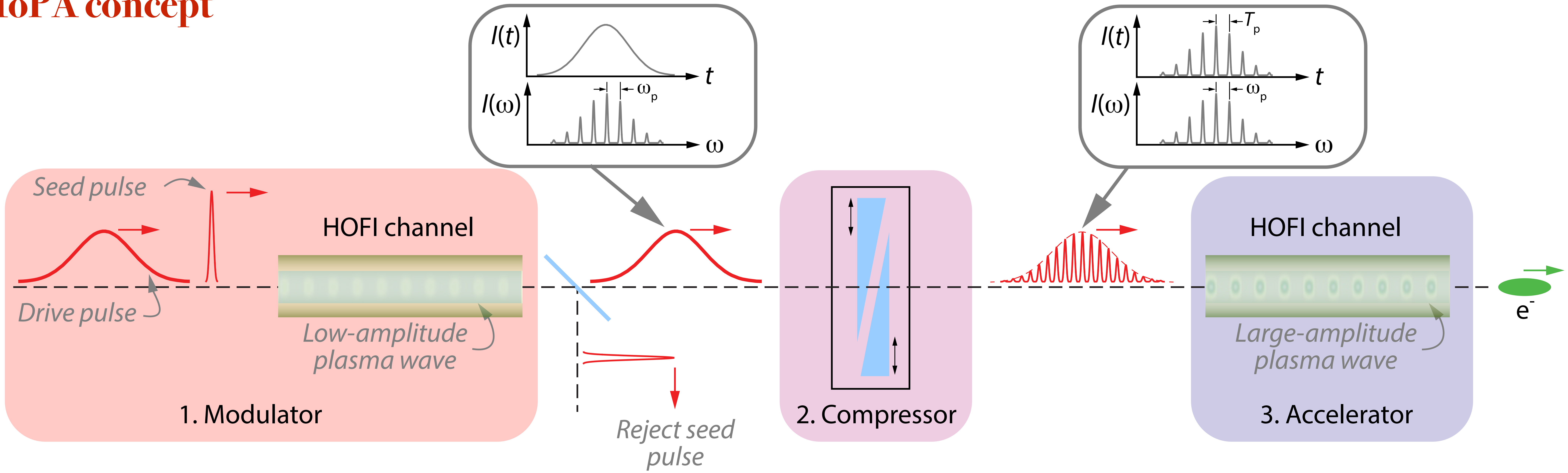
The P-MoPA concept

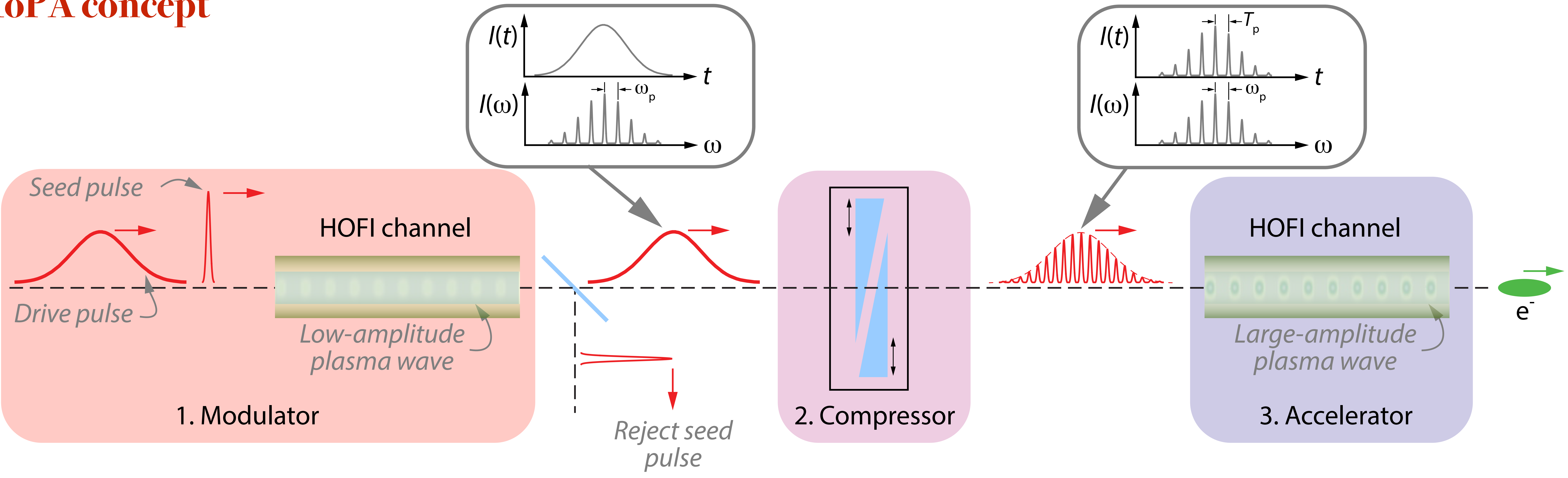


Step 2: Compressor:

- 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

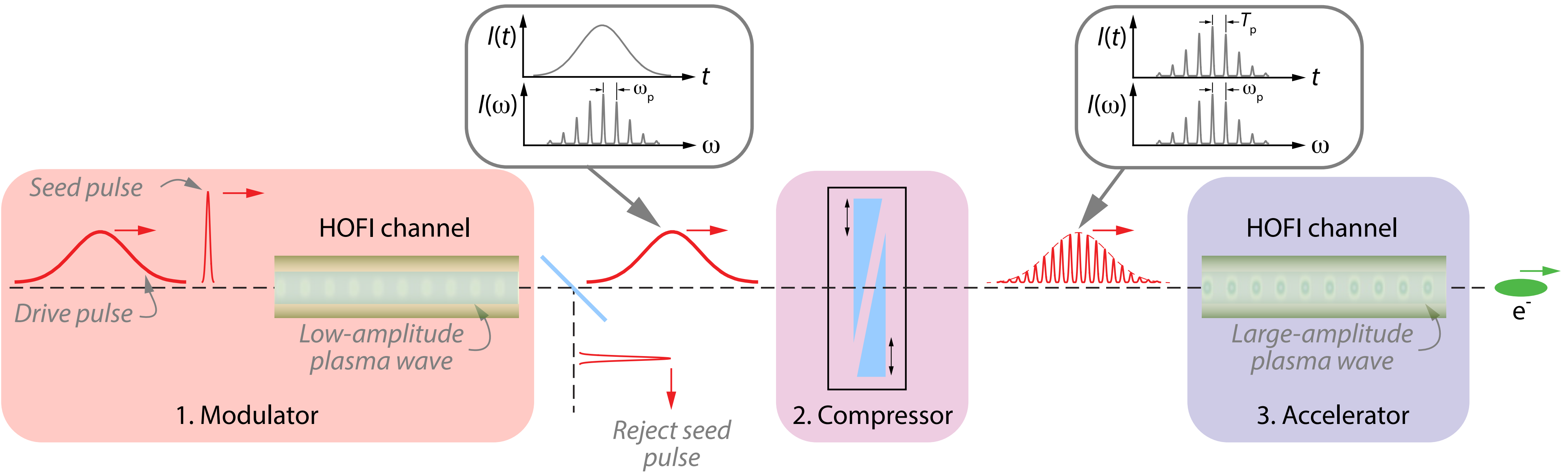


Step 3: Accelerator:

- 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 CLF

Related presentations

Mon poster	Roman Walzcak	"Potential applications of P-MoPAs"
Tue 16:20	Stefan Karsch	"Towards better electrons for applications…"
Wed poster	Sebastian Kalŏs	"Experimental progress towards the P-MoPA"
Wed 18:00 & poster	Darren Chan	"Curved HOFI waveguides"
Fri 11:40	Paolo Tomassini	"Design of high-brightness electron beams with MP-LWFA …"

Overview of analytical theory and numerical simulations of P-MoPAs

P-MoPA: Modulator

- Seed-driven wake modulates amplitude of drive to:

sidebands

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

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

modulator parameter

P-MoPA: Modulator

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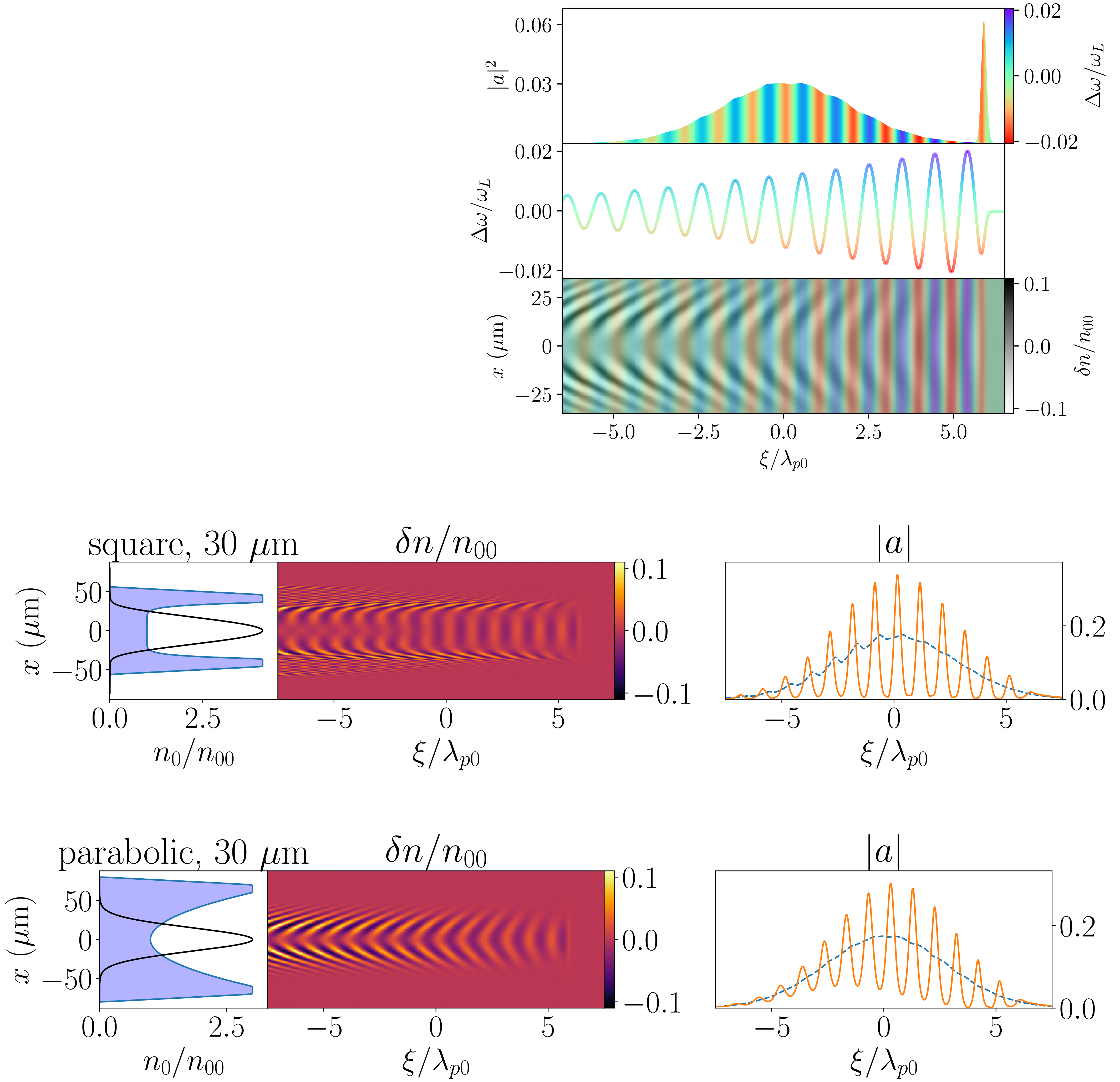
$$\beta = 2\frac{\omega_{p0}^2}{8\omega_L}\frac{\delta n_e}{n_{e0}}\frac{L_{\mathrm{mod}}}{v_{\mathrm{g,mod}}}$$ modulator parameter

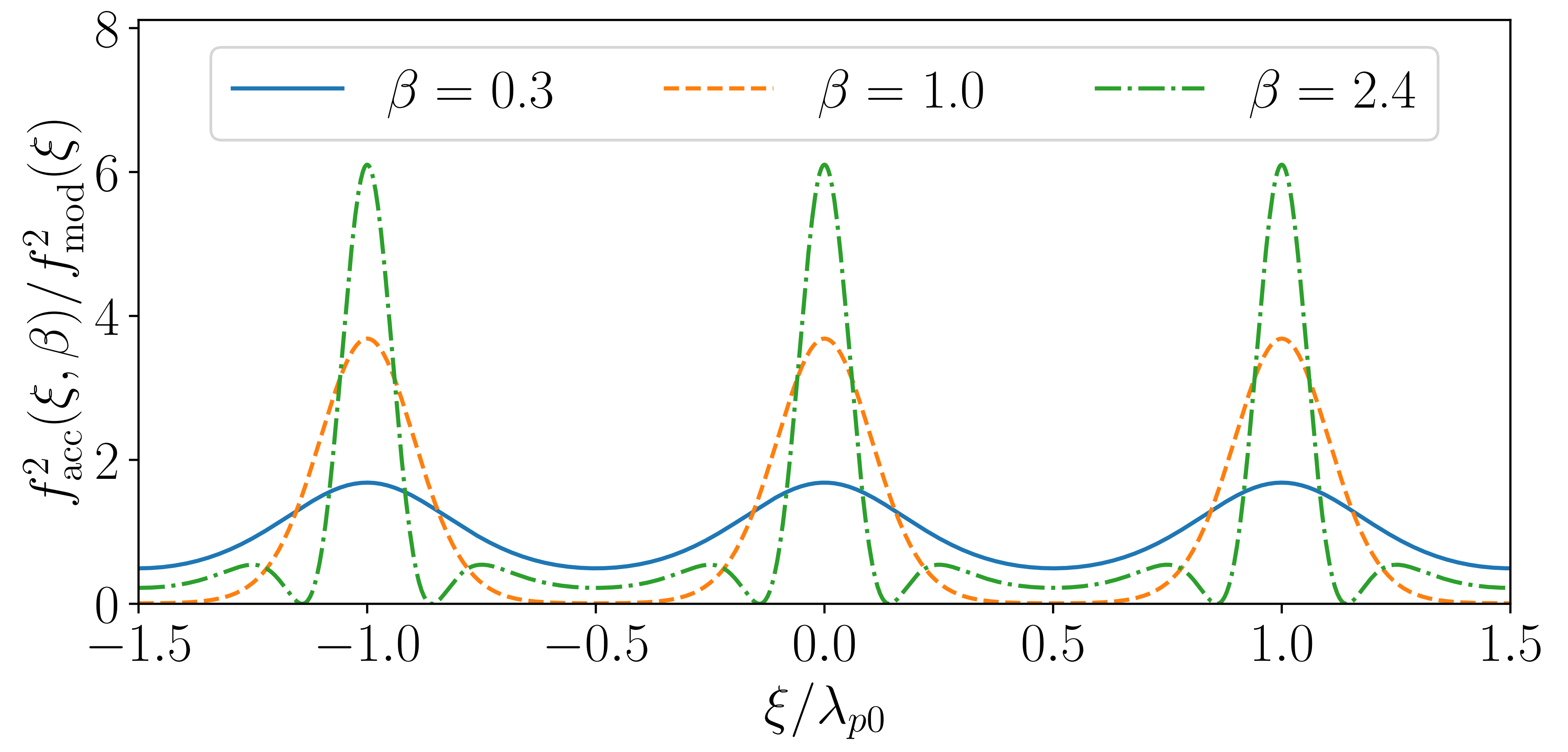
- 3D fluid theory shows:
  - Spectral modulation is a radial average ⇒ independent of radial position
  - Curvature of wake reduces modulation
  - Stable operation possible over wide range of parameters

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



P-MoPA: Accelerator

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



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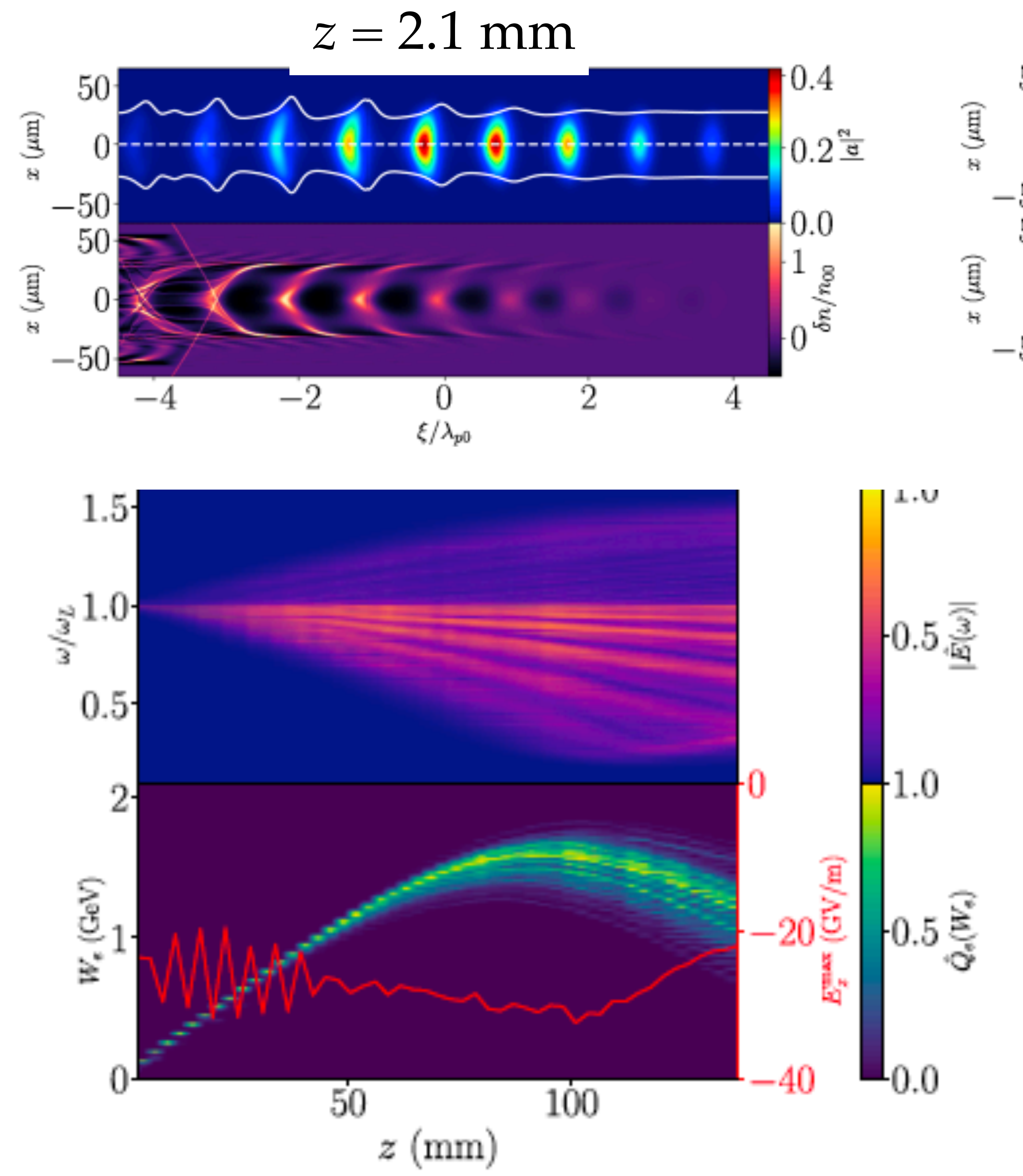
van de Wetering *et al.* *Phys. Rev. E* **109** 025206 (2024)

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



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

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

Experimental set-up

- Dummy pulse train
  - Send single, chirped Ti:sapphire pulse through Michelson interferometer
- Pulse train guided through 110 mm long HOFI channels
  - ~ 70% of input overlaps with lowest-order channel mode

Astra-Gemini Laser, RAL

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

Pulse train

$E = (2.5 \pm 0.5)$ J

$w_0 = (45.5 \pm 3.4)\,\mu$m

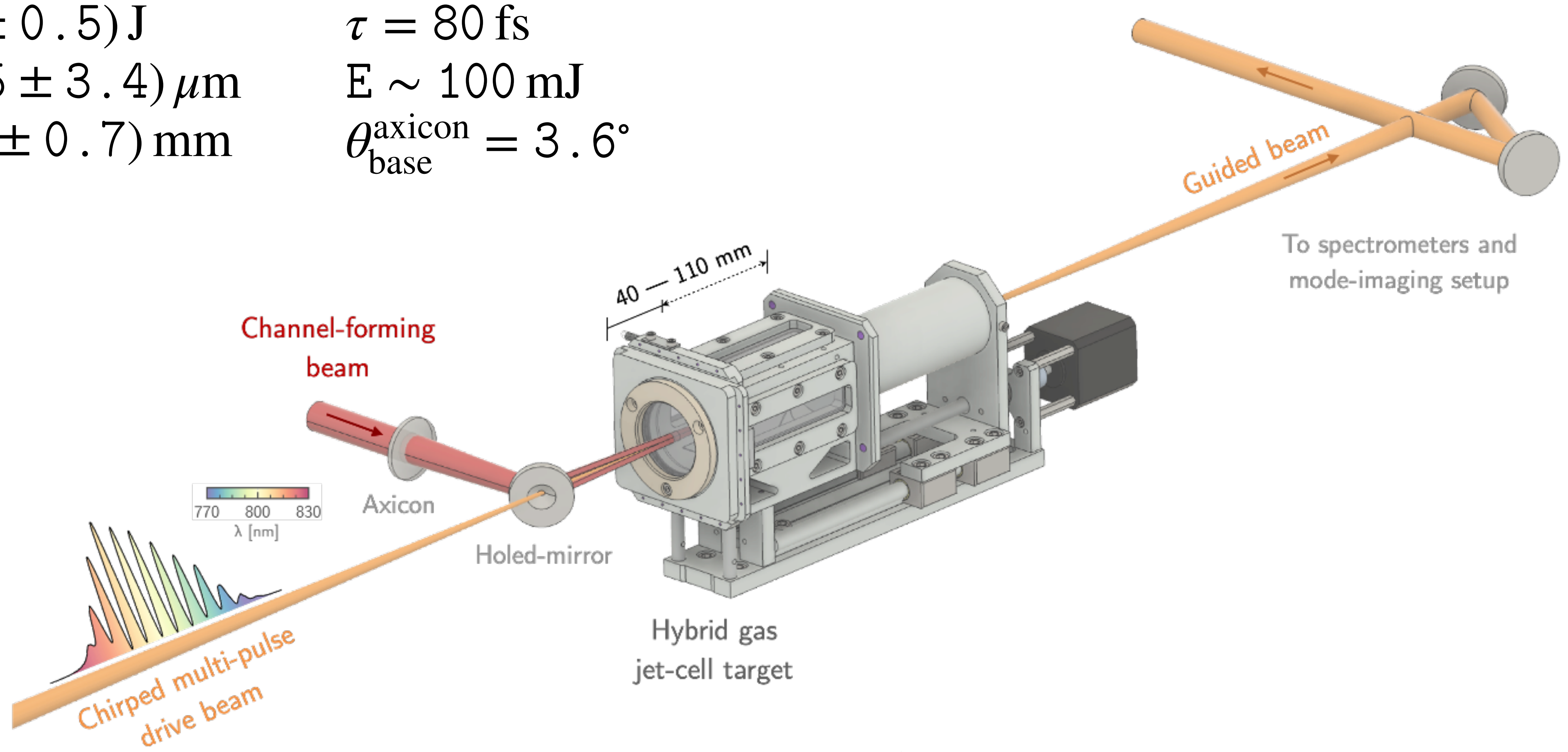
$z_R = (7.9 \pm 0.7)$ mm

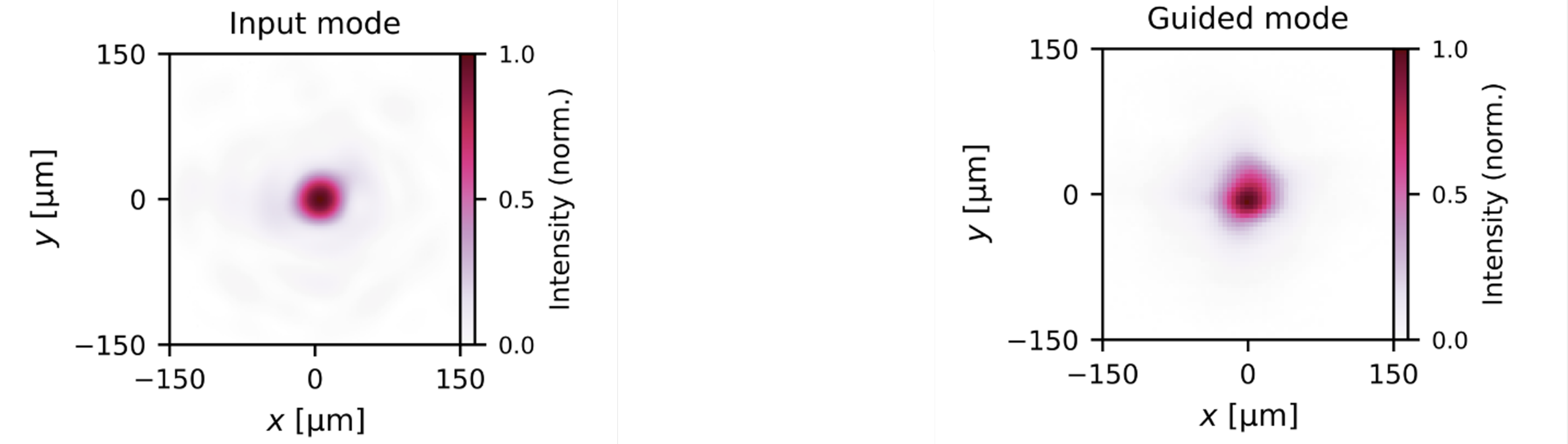
Channel-forming beam

$\tau = 80$ fs

$E \sim 100$ mJ

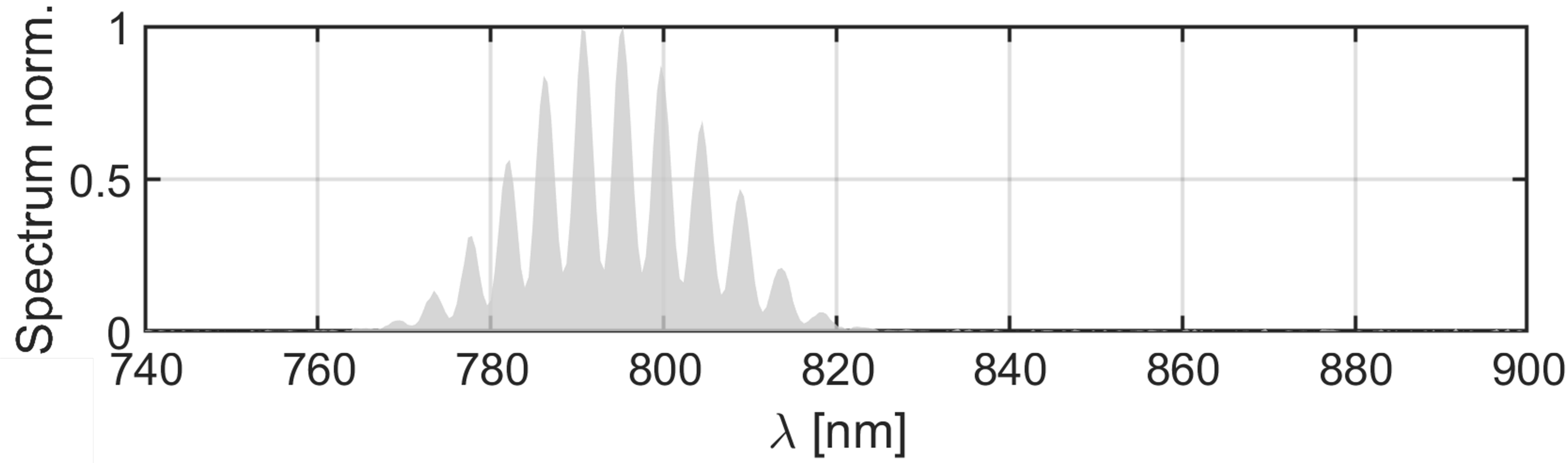
$\theta_{\mathrm{base}}^{\mathrm{axicon}} = 3.6°$





Pulse train spectra show resonant excitation

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



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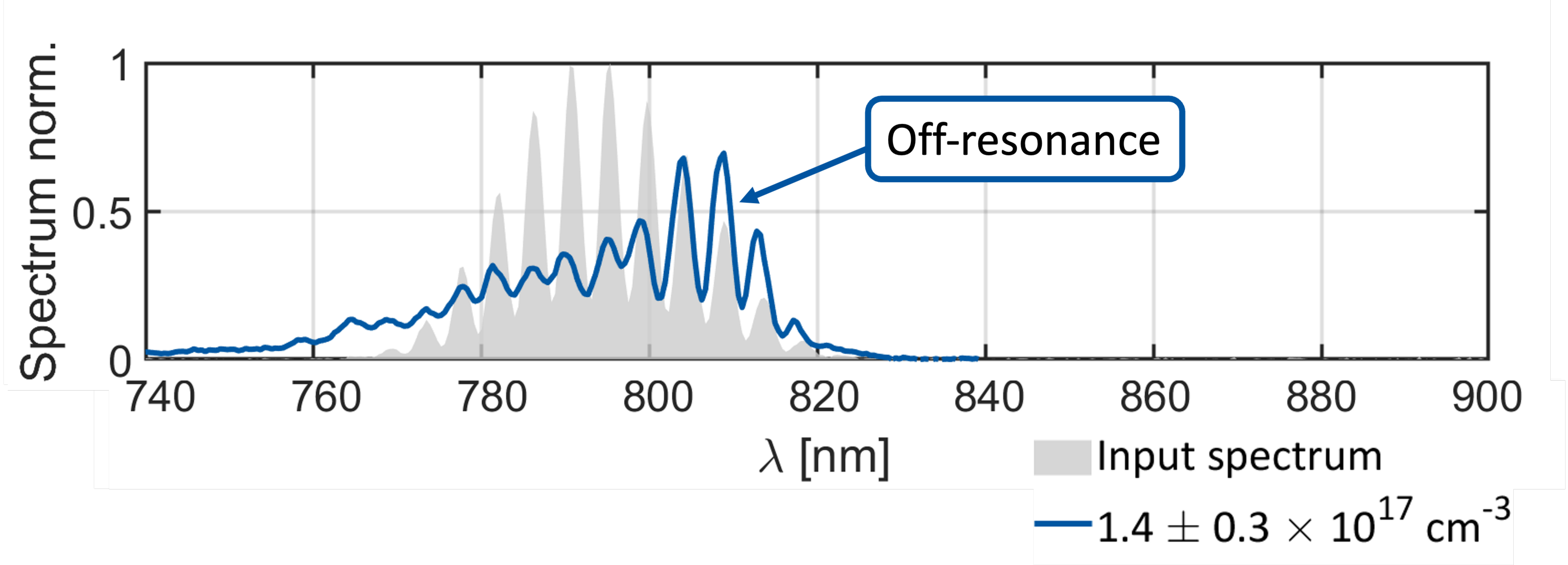

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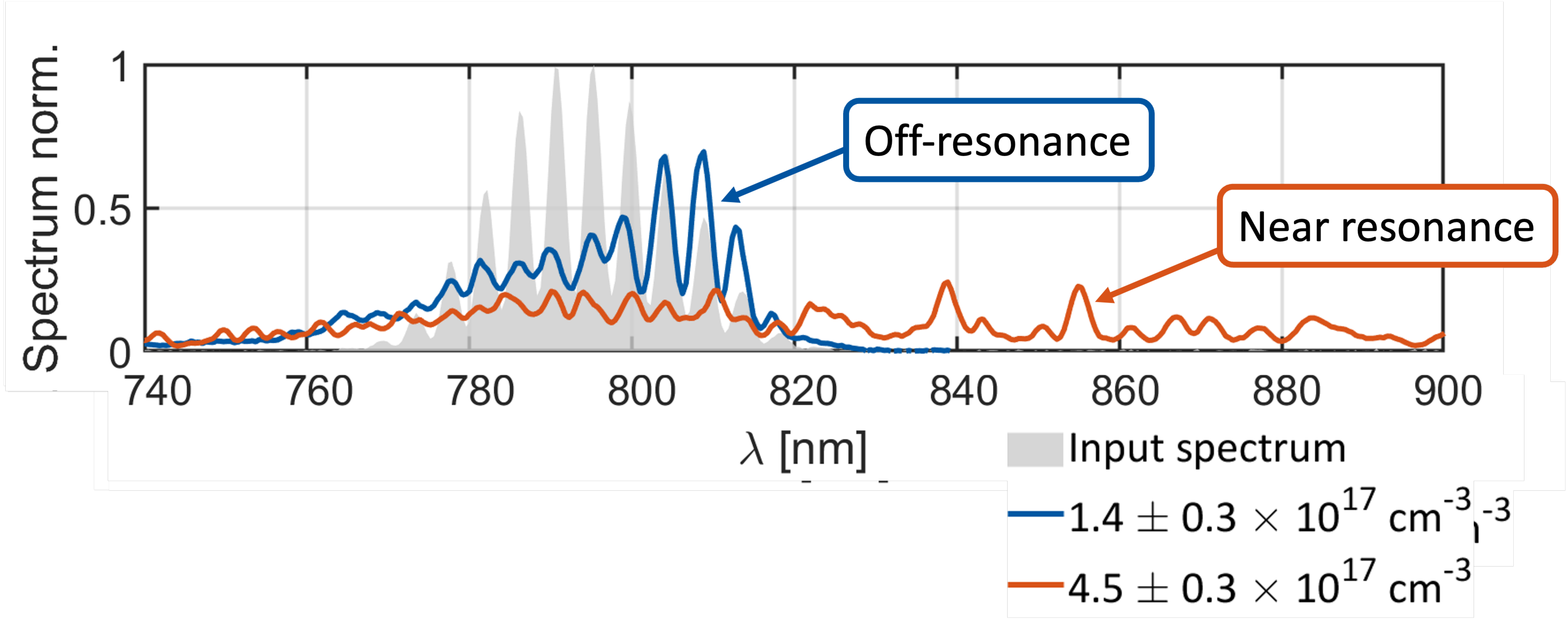
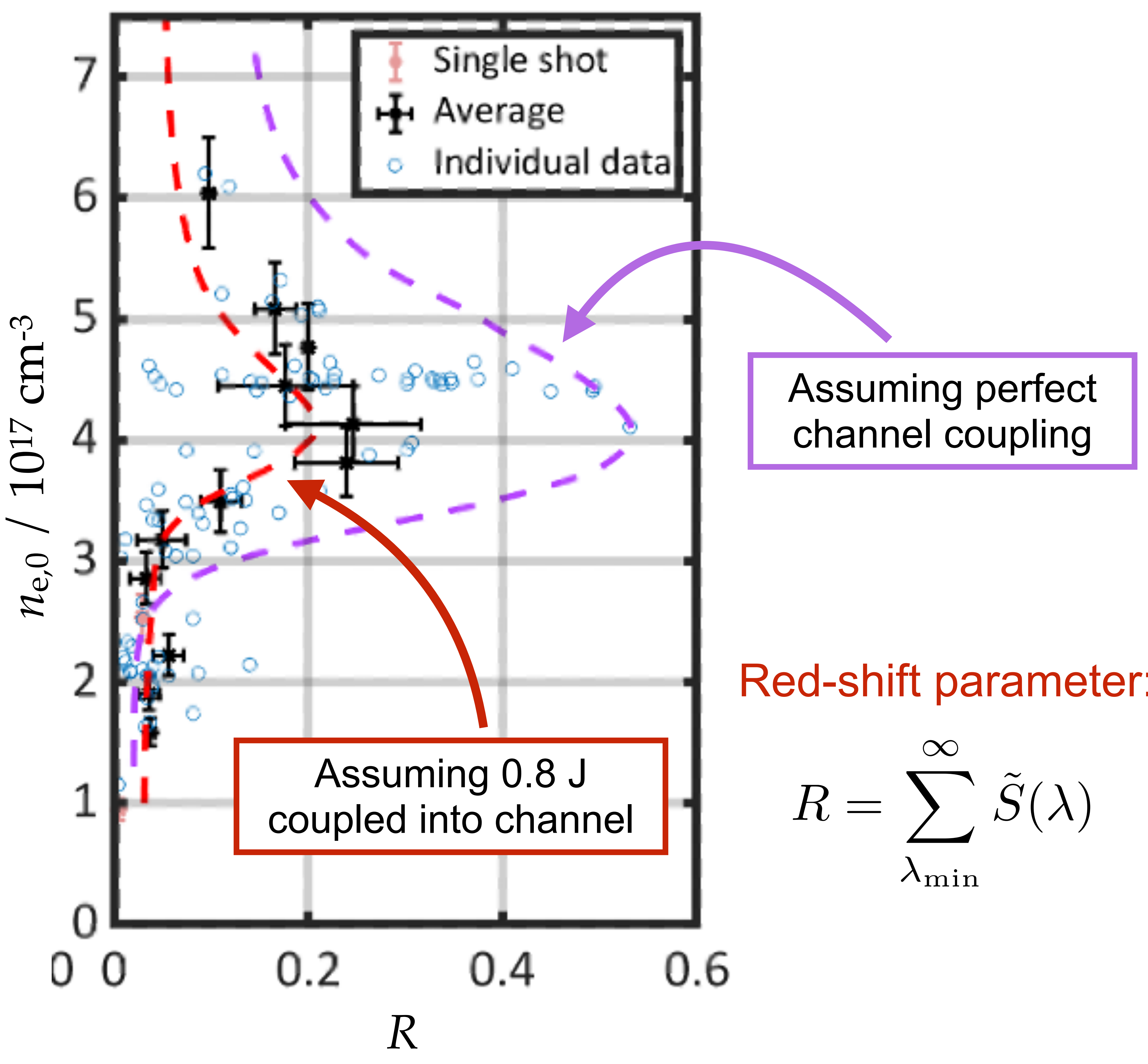


Measured red-shift agrees well with fluid simulations

- 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)

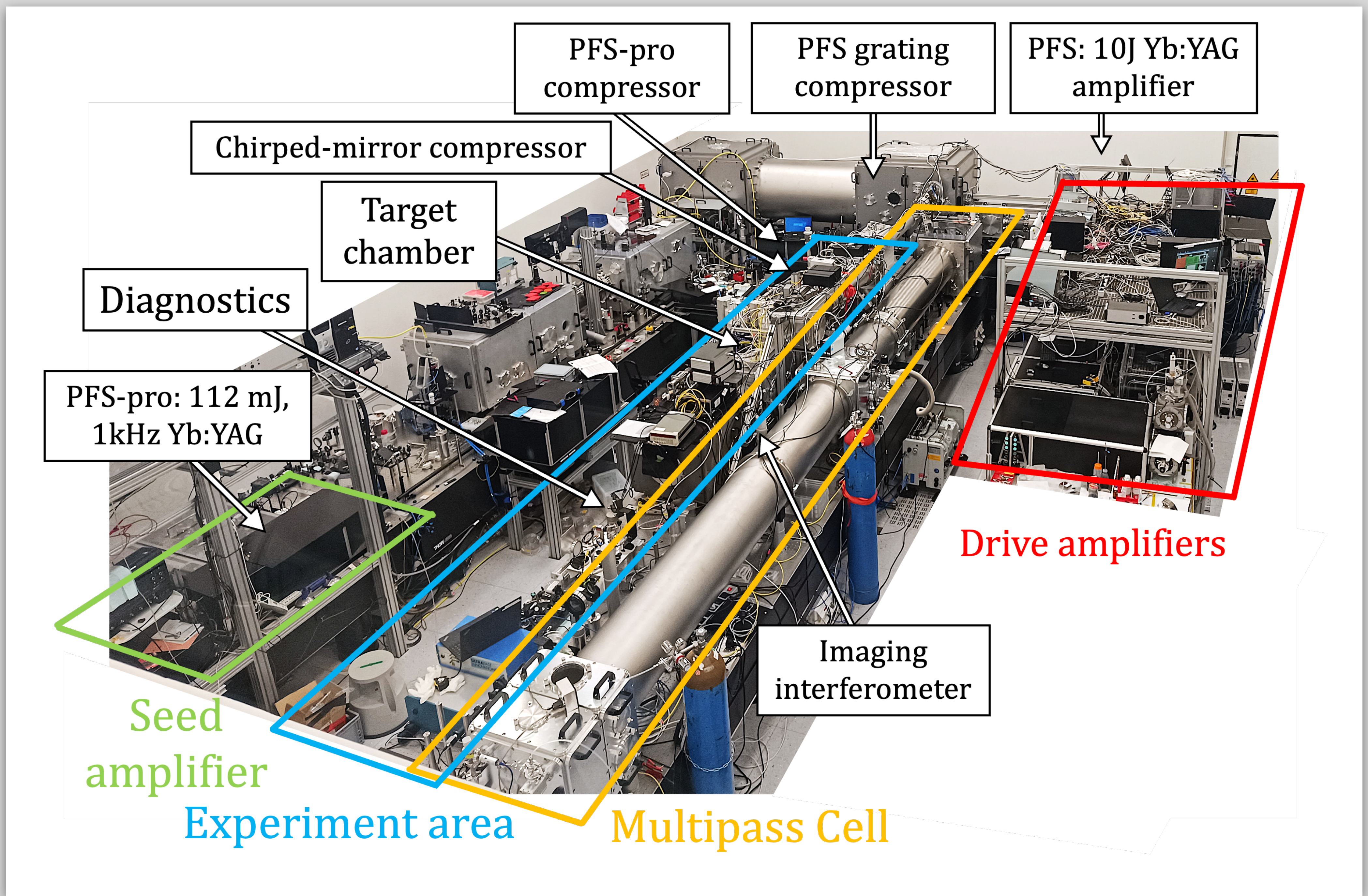


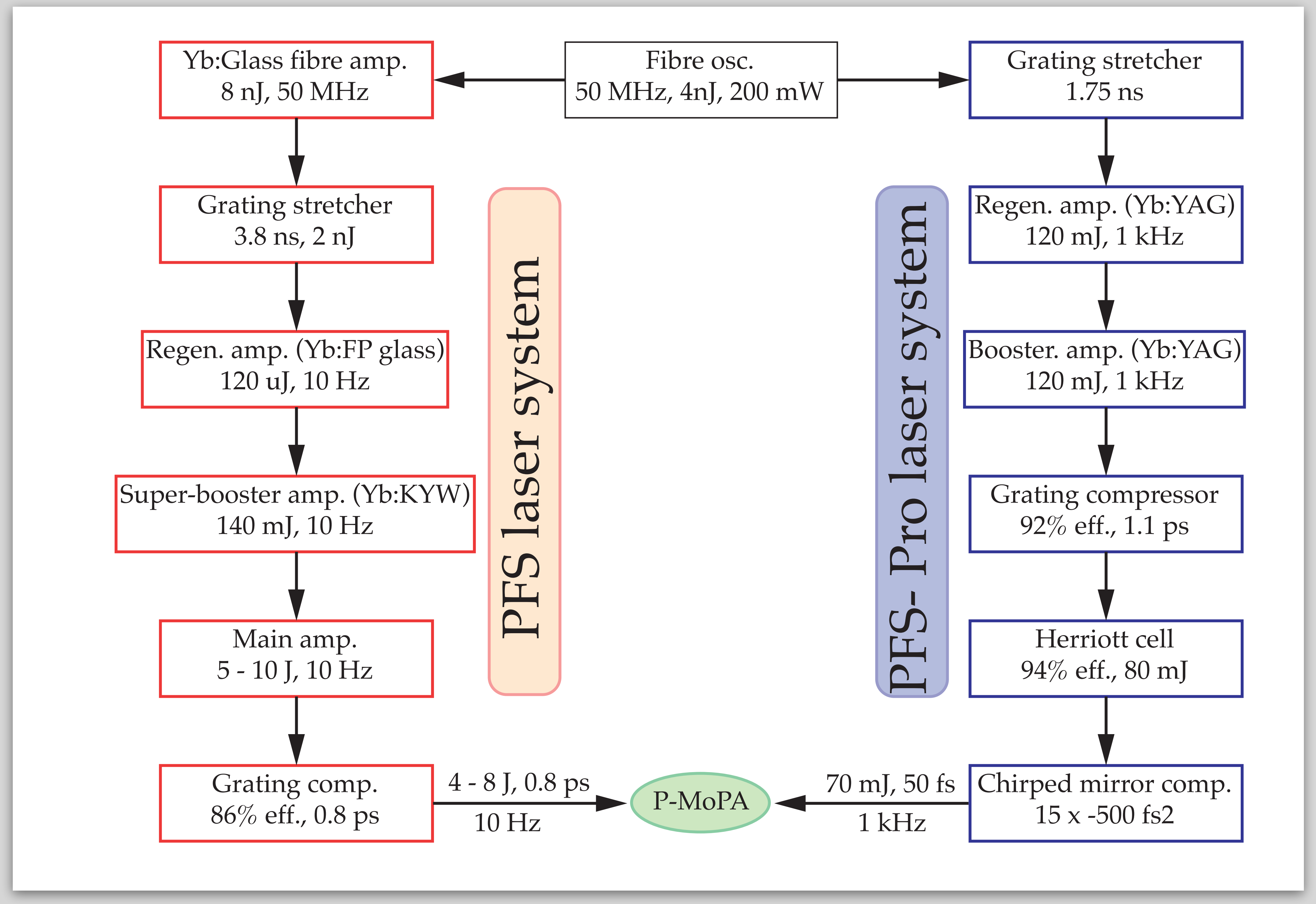
Red-shift parameter:

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

Progress towards demonstrating P-MoPA at CALA

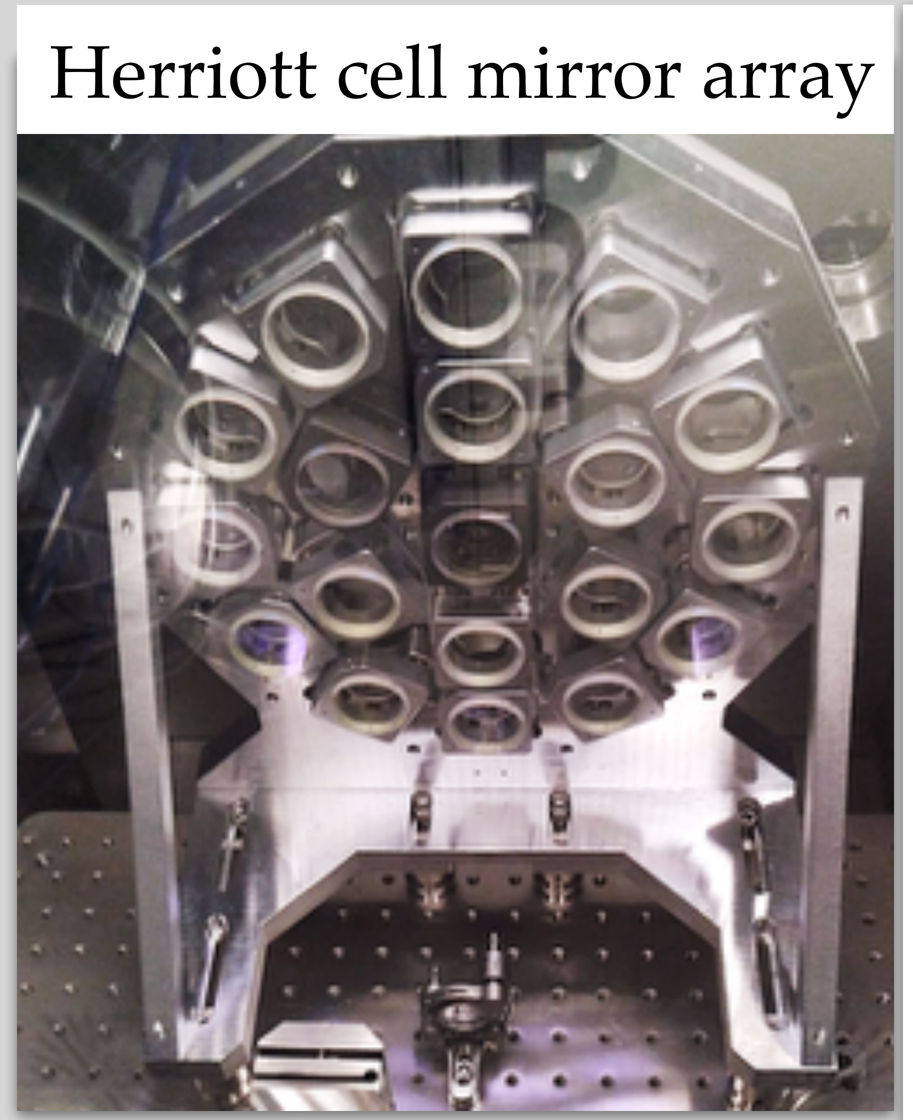
CALA TDL system

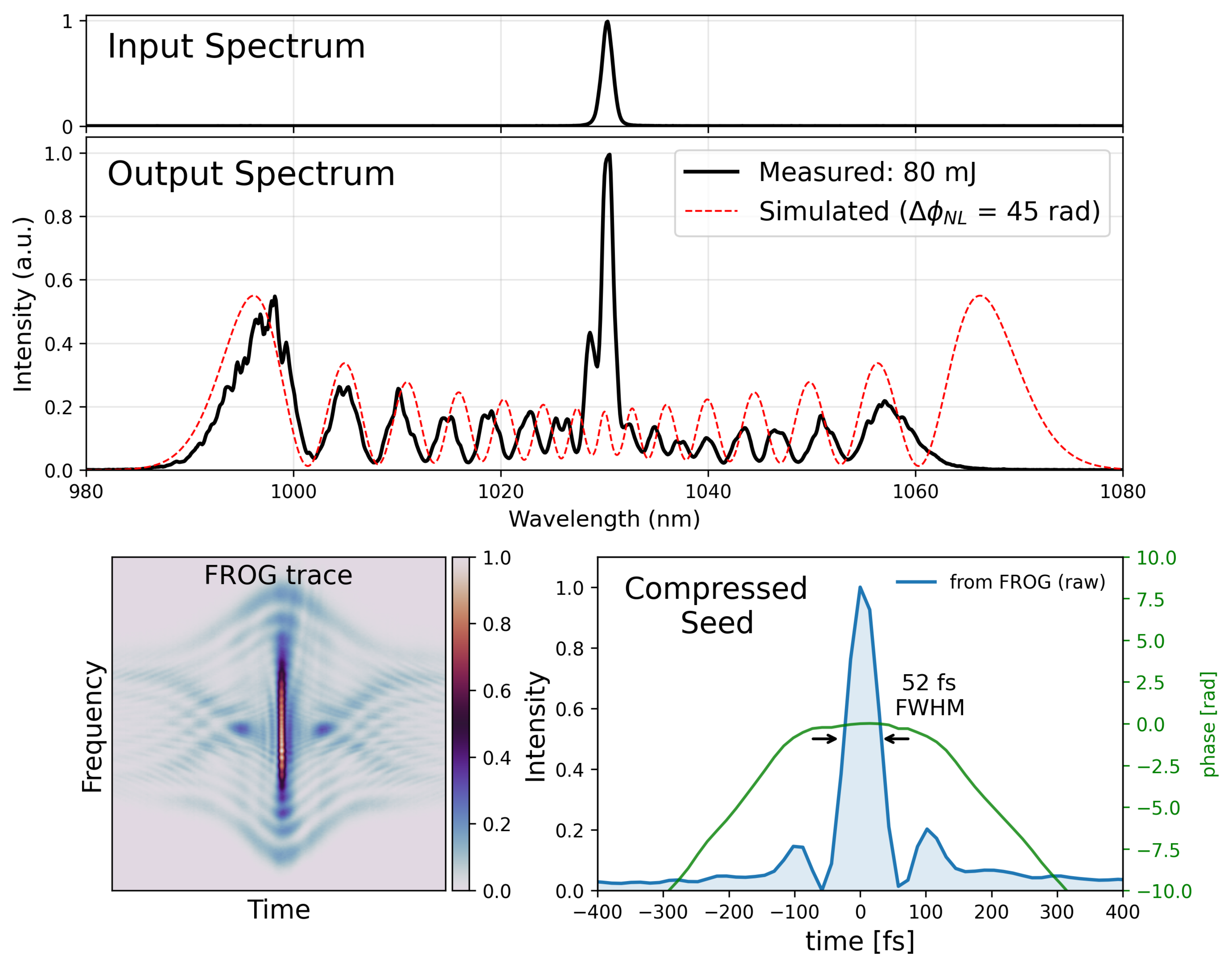




- Pulses required for P-MoPA:
  - Channel-forming pulses (x 2): $\geq$ 50 mJ, $\sim$ 50 fs … or…..?
  - Seed pulse: $\geq$ 50 mJ, $\leq$ 100 fs
  - Drive pulse: $\sim$ 1 J, $\sim$ 1 ps

Generation of seed pulse





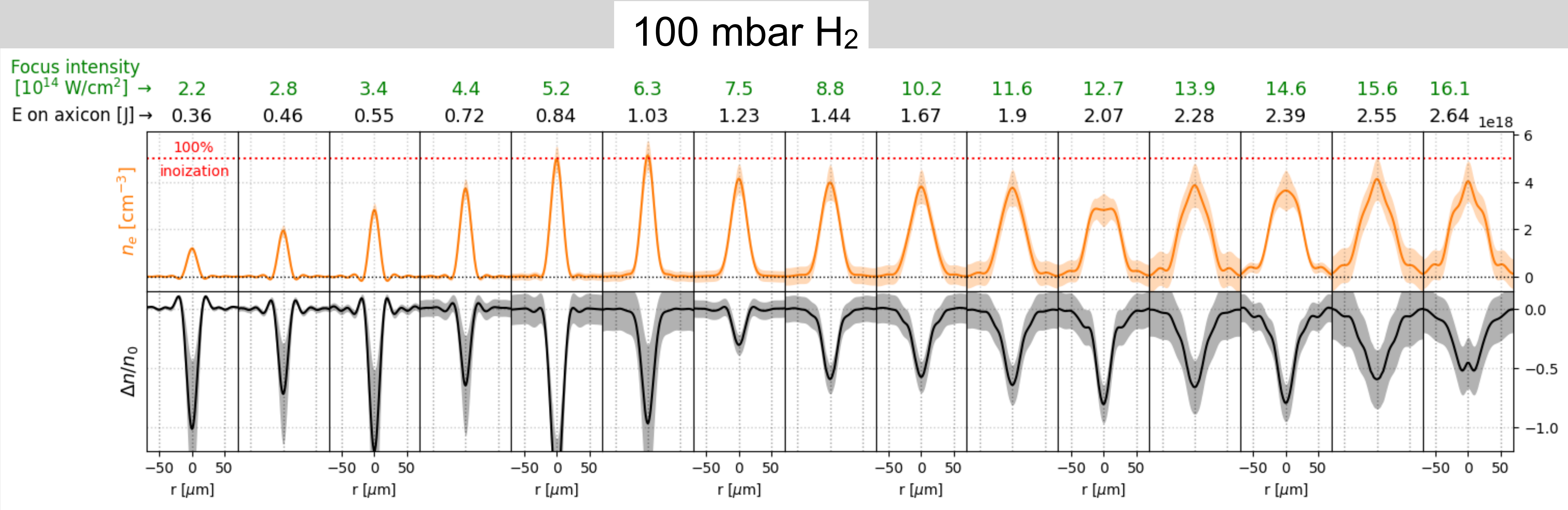
- PFS-Pro pulses spectrally broadened 36-pass, 8 m long, Ar-filled Herriott cell
- Temporal compression to $\sim$ 70 mJ, $\sim$ 50 fs by chirped mirrors

✓ Seed pulse generated!

Generation of HOFI channels

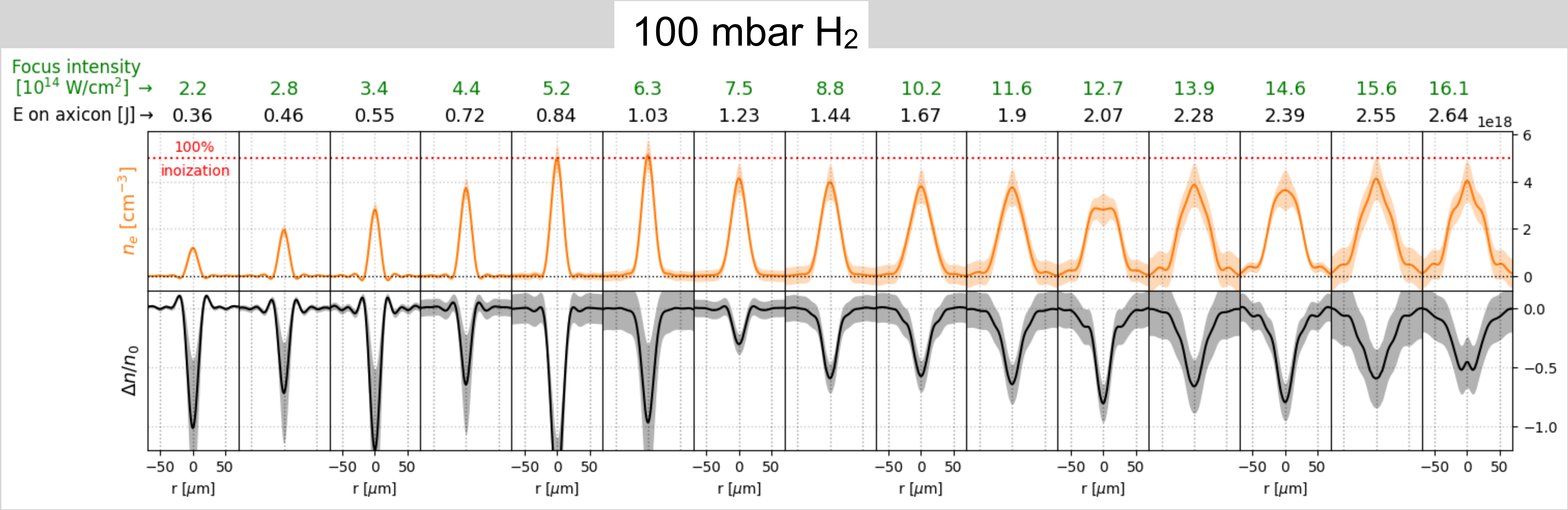
- Short-pulse energy precious. Could we generate HOFI channels with ps pulses?

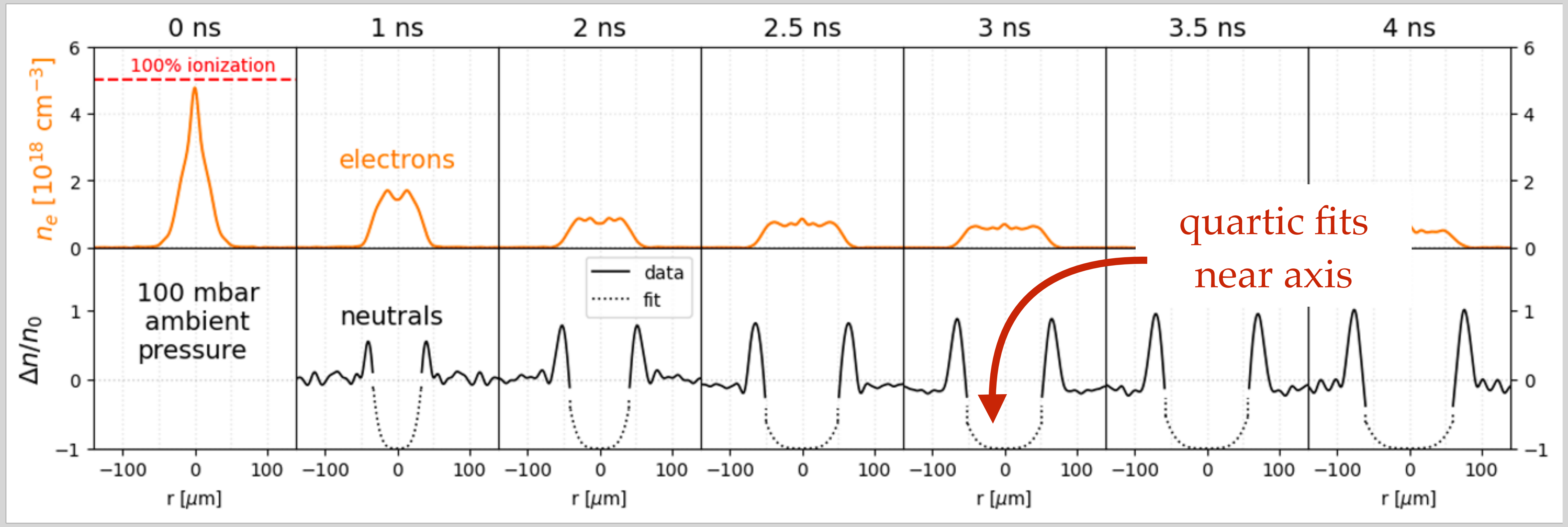
Generation of HOFI channels



- Short-pulse energy precious. Could we generate HOFI channels with ps pulses?
- Initial plasma column ~ 100% ionized for $I \sim 5 \times 10^{14}\,\mathrm{W\,cm^{-2}}$
  - Consistent with OFI

Generation of HOFI channels





- Short-pulse energy precious. Could we generate HOFI channels with ps pulses?
- Initial plasma column ~ 100% ionized for $I \sim 5 \times 10^{14}\,\mathrm{W\,cm^{-2}}$
  - Consistent with OFI
- Temporal expansion yields HOFI channels

✓ HOFI channels generated with ps-duration pulses

Guiding of drive pulse in HOFI channels

- Post-guiding interferometry shows formation of deep HOFI channel

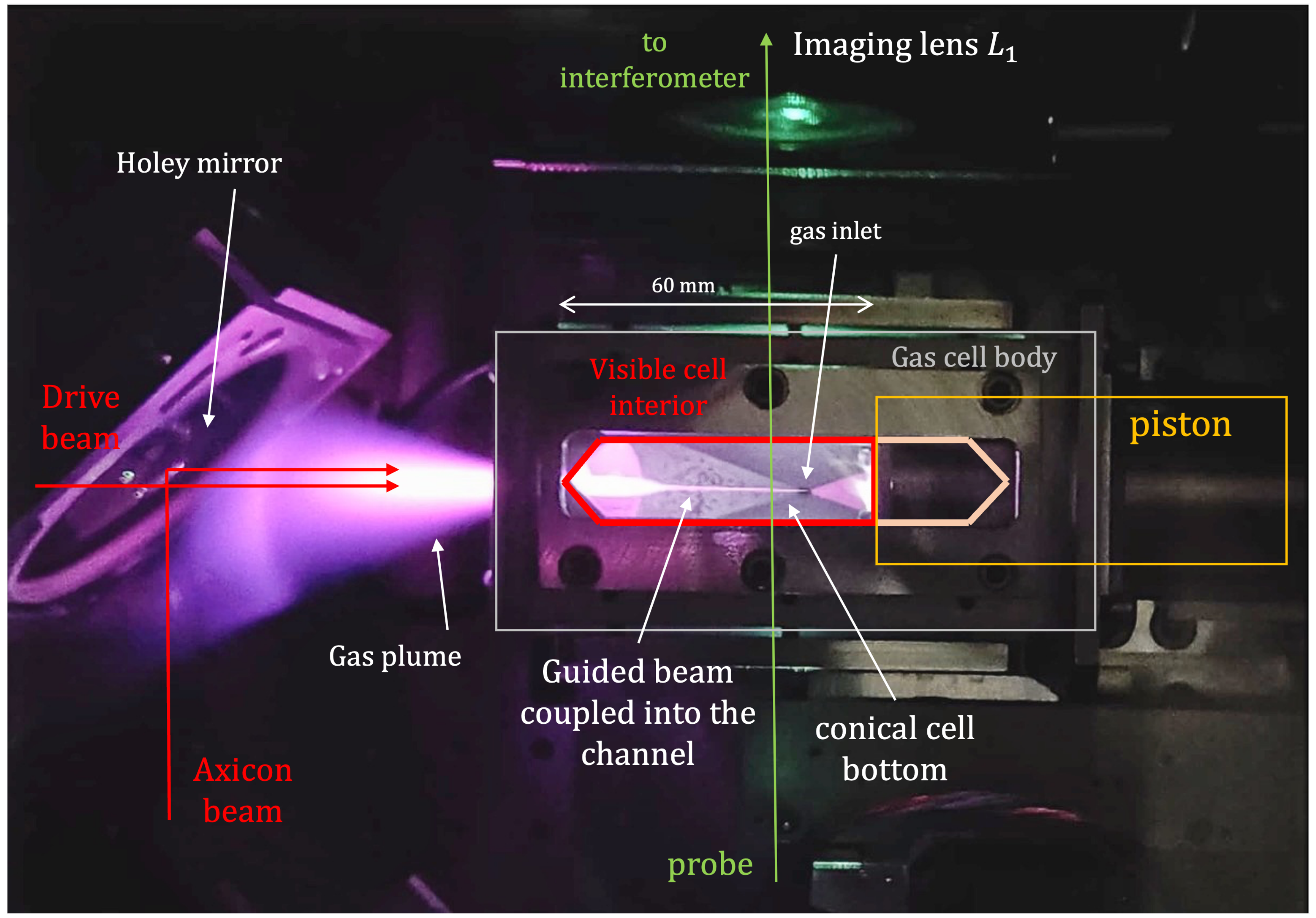
<u>Expt. parameters</u>

$E_{ch} = 1.3$ J

$E_{drive} = 1.4$ J

$\tau = 2.5$ ns

$P_{H2} = 26$ mbar



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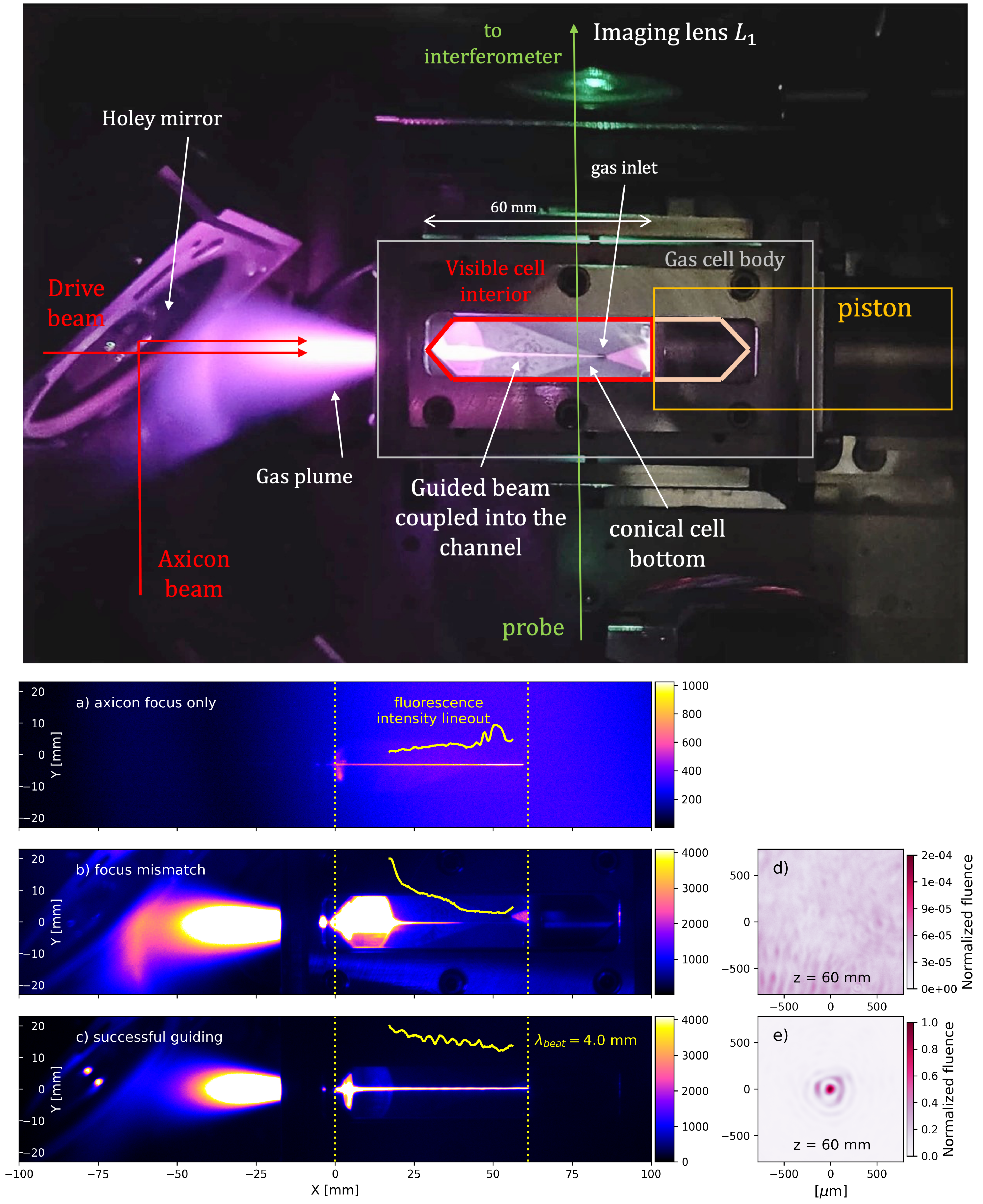

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Guiding of drive pulse in HOFI channels

- Post-guiding interferometry shows formation of deep HOFI channel

✓ Drive pulse guided in ps-generated HOFI channels

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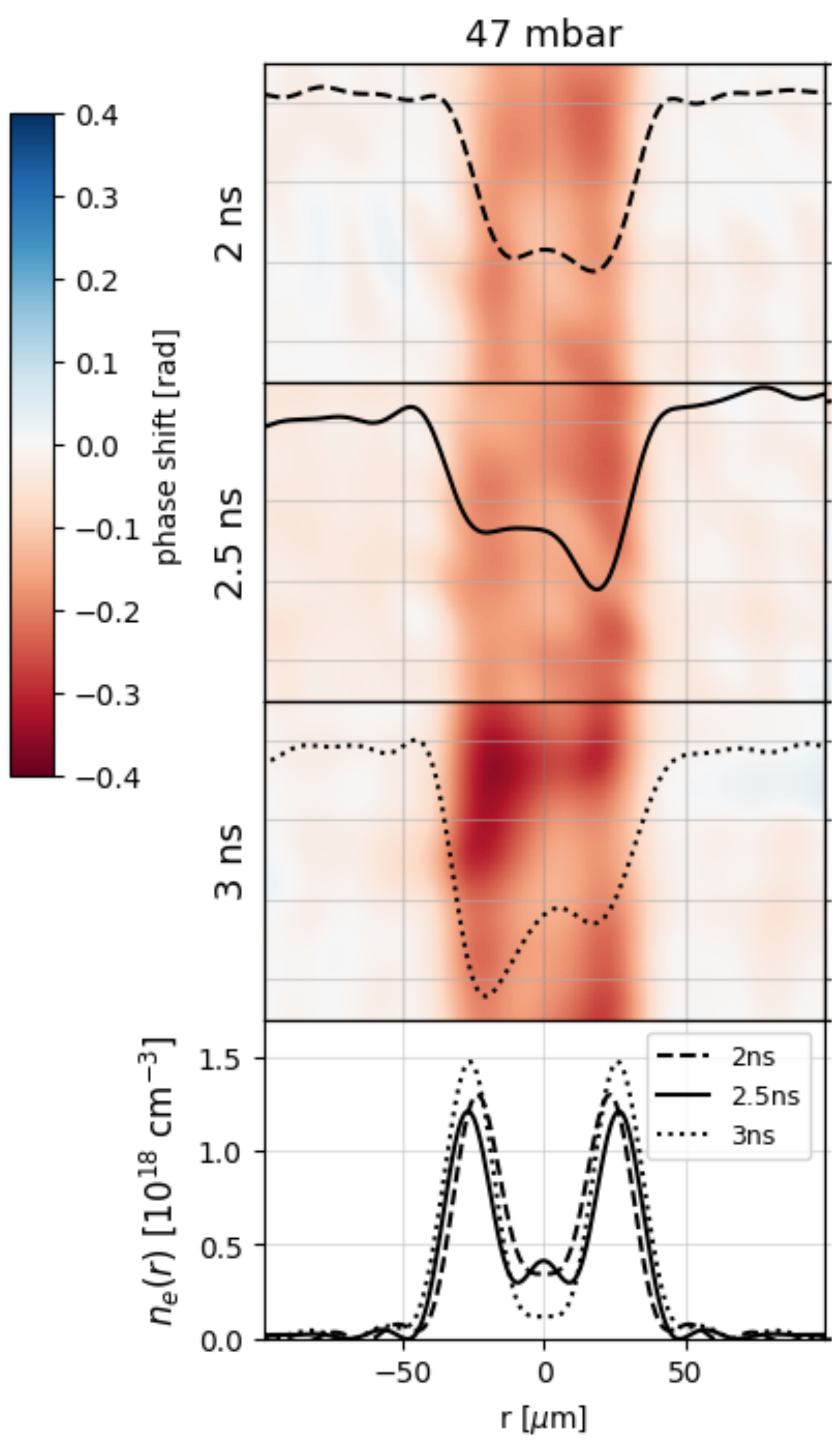
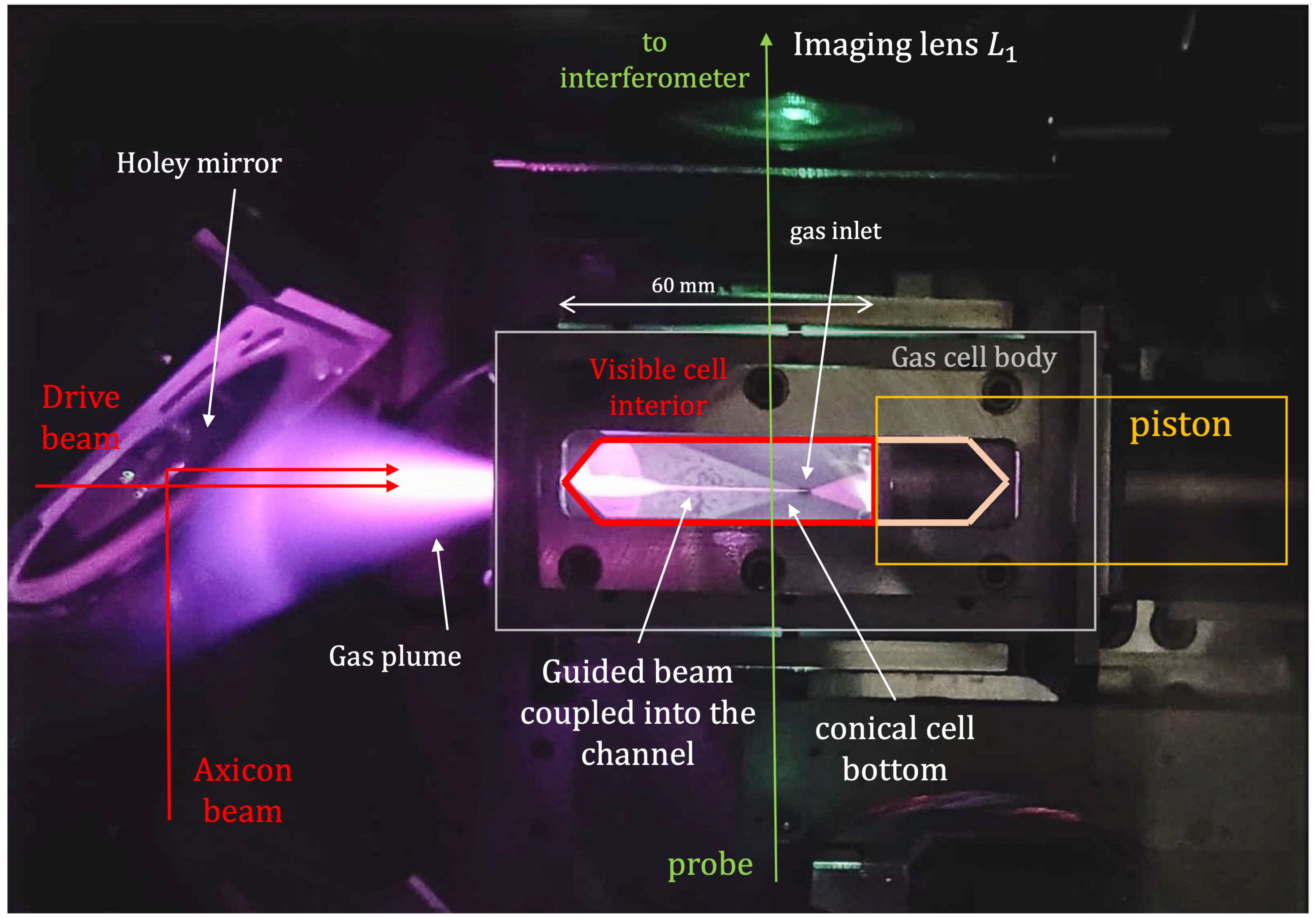
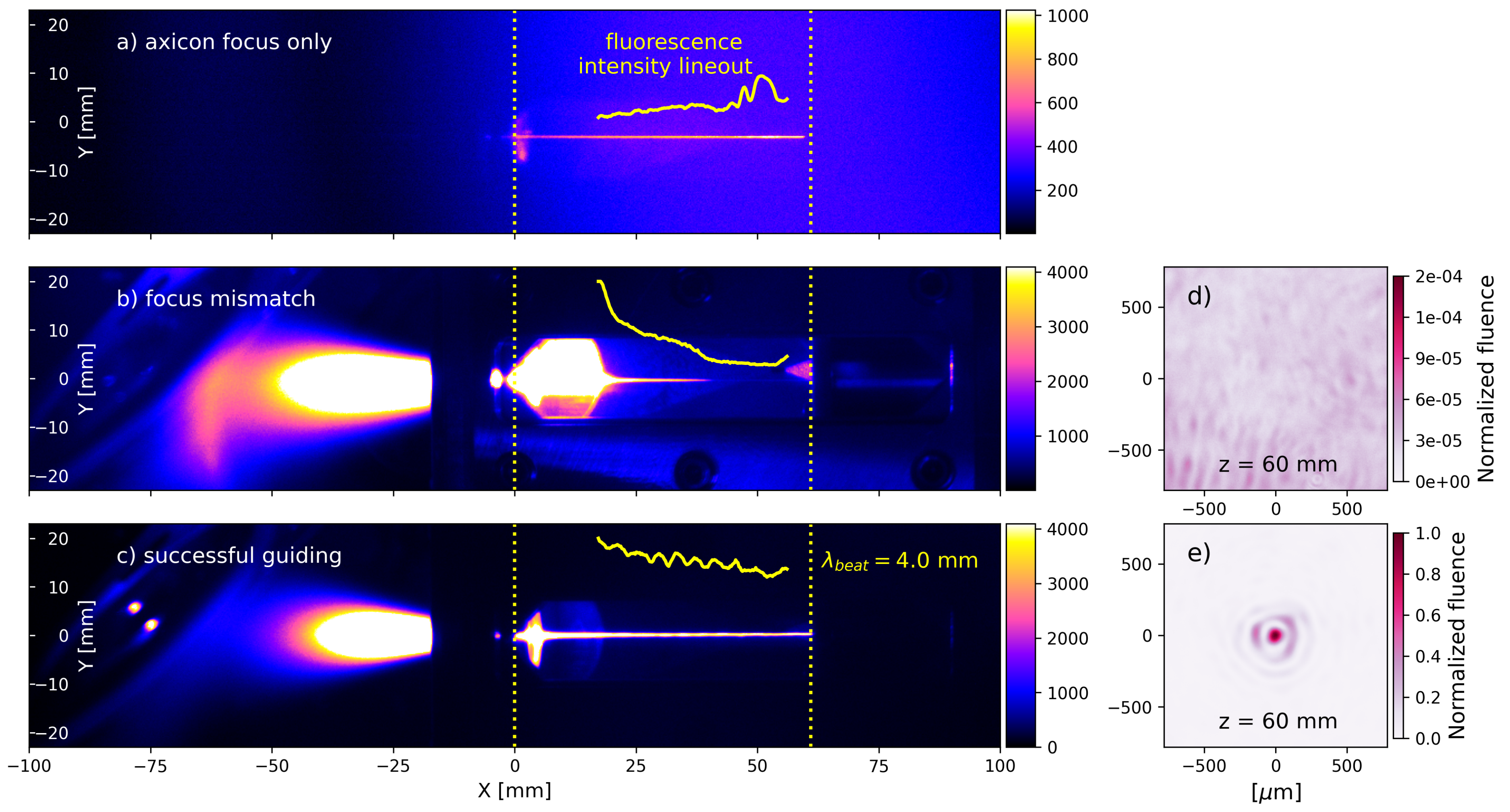
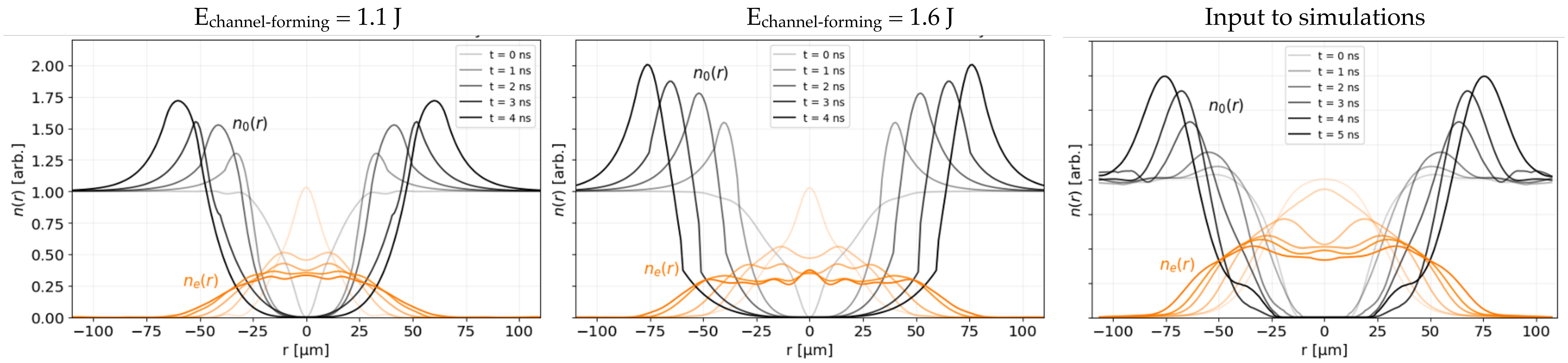






Simon Hooker
EAAC, Isola d'Elba, Italy
21 - 27 September 2025

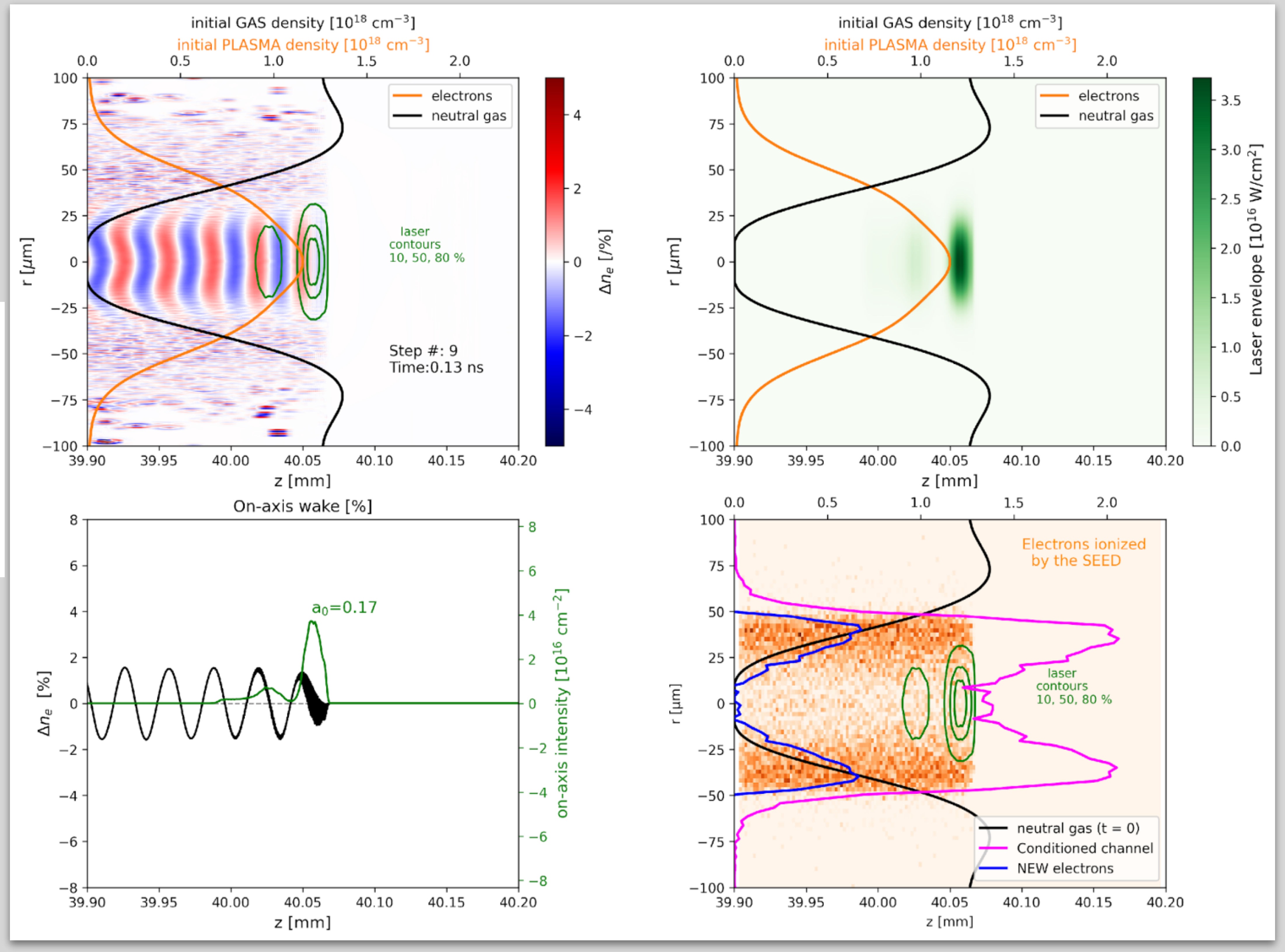
Simulations of seed pulse guiding



- Transverse electron and neutral density profiles parameterized from measured profiles

Simulations of seed pulse guiding

$z = 40$ mm



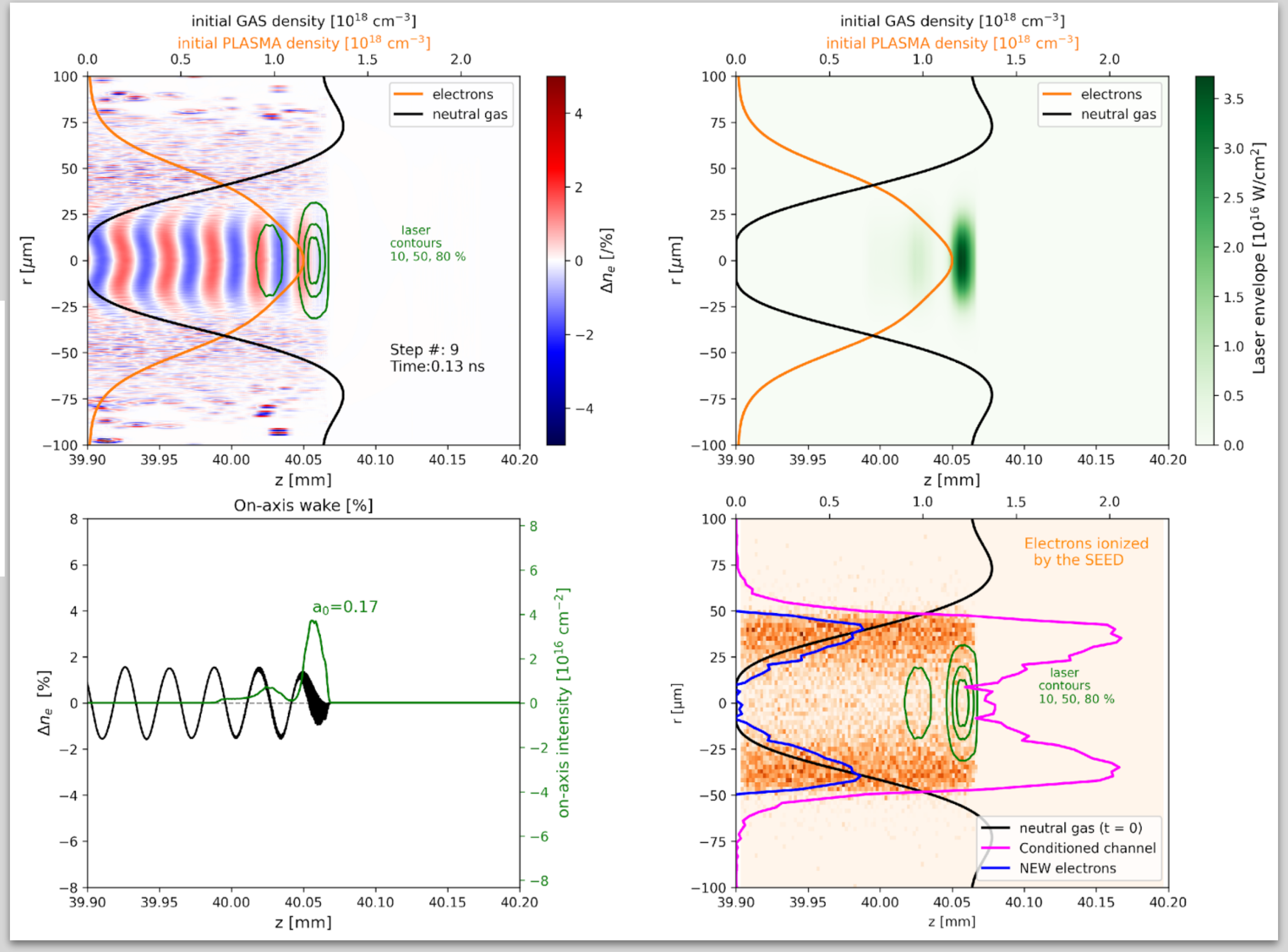
Simulation parameters

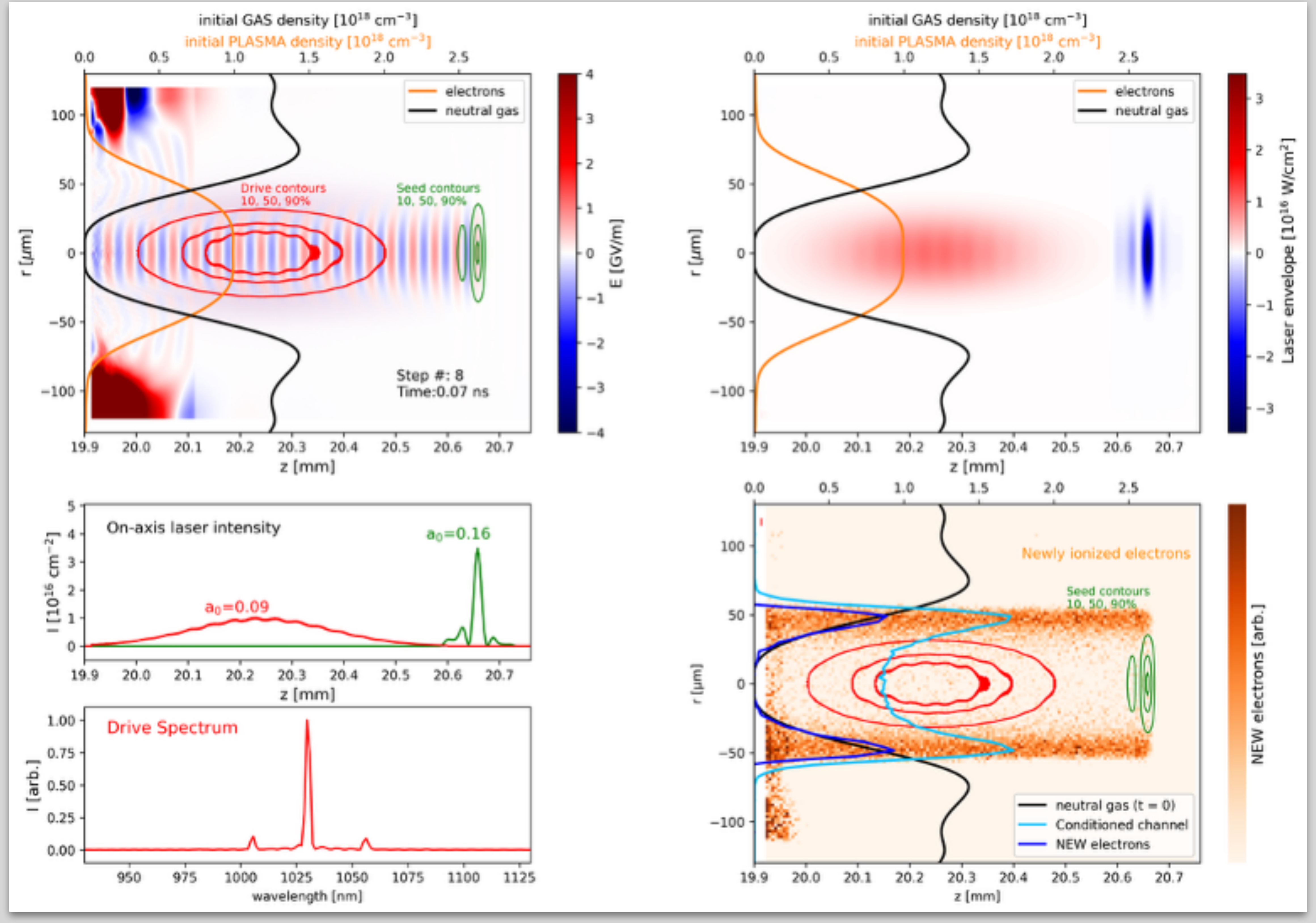
Drive pulse	Seed pulse	Channel
$E_{drive} = 0.3$ J	$E_{seed} = 70$ mJ	$P_{H2} = 25$ mbar
$w_0 = 35$ um	$w_0 = 50$ um	$n_{e0} = 1.15 \times 10^{18}\,\mathrm{cm}^{-3}$
$\tau = 0.9$ ps	$\tau = 54$ fs	$\tau_{delay} = 1.3$ ns
		$\tau = 2.5$ ns

✓ Seed pulse conditions channel & is guided over > 40 mm

Simulations of seed pulse guiding

z = 40 mm





z = 20 mm

Simulation parameters

Drive pulse	Seed pulse	Channel
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$\tau = 0.9$ ps	$\tau = 54$ fs	$\tau_{\text{delay}} = 1.3$ ns
		$\tau = 2.5$ ns

✓ Seed pulse conditions channel & is guided over > 40 mm

✓ Spectral modulation of drive pulse observed!

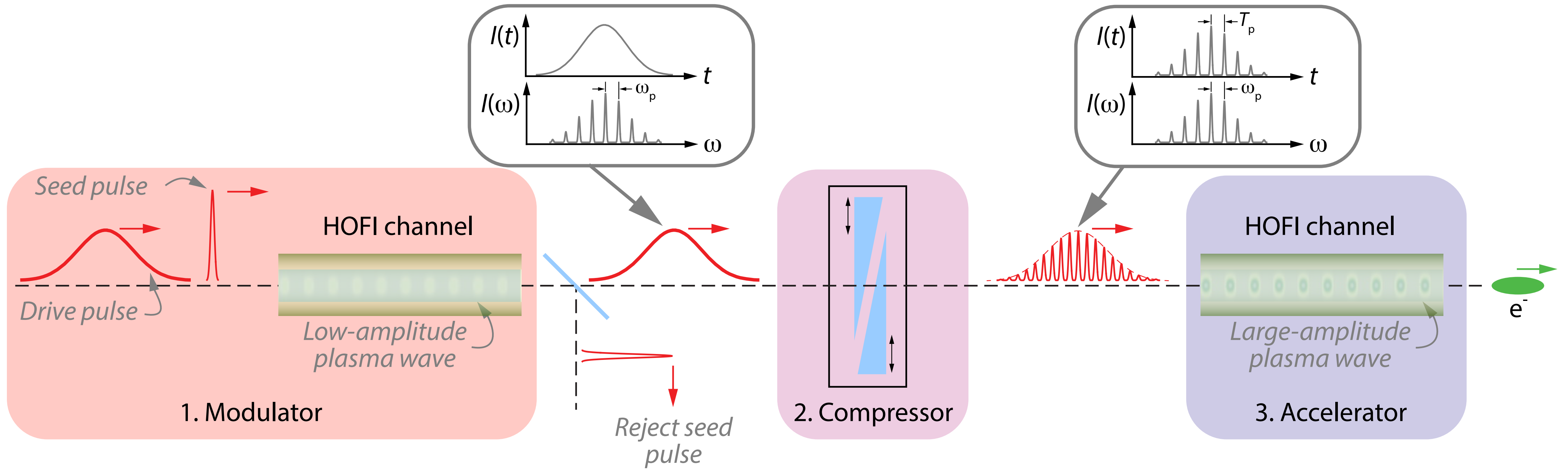
Conclusion & summary of progress

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



Step 1: Plasma modulator

- ☑ HOFI channel generated by ps TDL pulses
- ☑ Drive pulse guided in HOFI channel
- ☑ Seed pulses generated
- ☑ Seed pulses guided (in simulation!)
- ☐ Seed pulses guided (expt.)
- ☐ Spectral modulation of drive demonstrated

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

Key
- ☑ Concept demonstrated
- ☐ To be demonstrated

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