Observation of resonant wakefield excitation by pulse trains guided in long plasma channels

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Simon Hooker, Roman Walczak, Emily Archer, James Chappell, James Cowley, Linus Feder, Oscar Jakobsson, Alex Picksley, Aimee Ross, Johannes van de Wetering, Wei-Ting Wang

John Adams Institute for Accelerator Science, University of Oxford

Science & Technology Facilities Council Central Laser Facility

Nicolas Bourgeois

Rutherford Appleton Laboratory, Harwell

The Cockcroft Institute of Accelerator Science and Technology

Laura Corner, Harry Jones, Lewis Reid

Cockcroft Institute, University of Liverpool

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Challenges of High Repetition Rate

- High repetition rate lasers not available at PW-level required for GeV electron acceleration
- Joule + lasers available at kHz repetition rate based on thin disk technology, but with ps pulse lengths
  - 1.1 J @ 4.5 ps - CSU
  - Trumpf/Cala 1 J @ $\leq$600 fs
    - Multipass broadening – 100 mJ @ 40 fs
- Solution: Convert long pulse into pulse train to resonantly drive wake at lower peak intensity

Multi-pulse Scheme - Modulator

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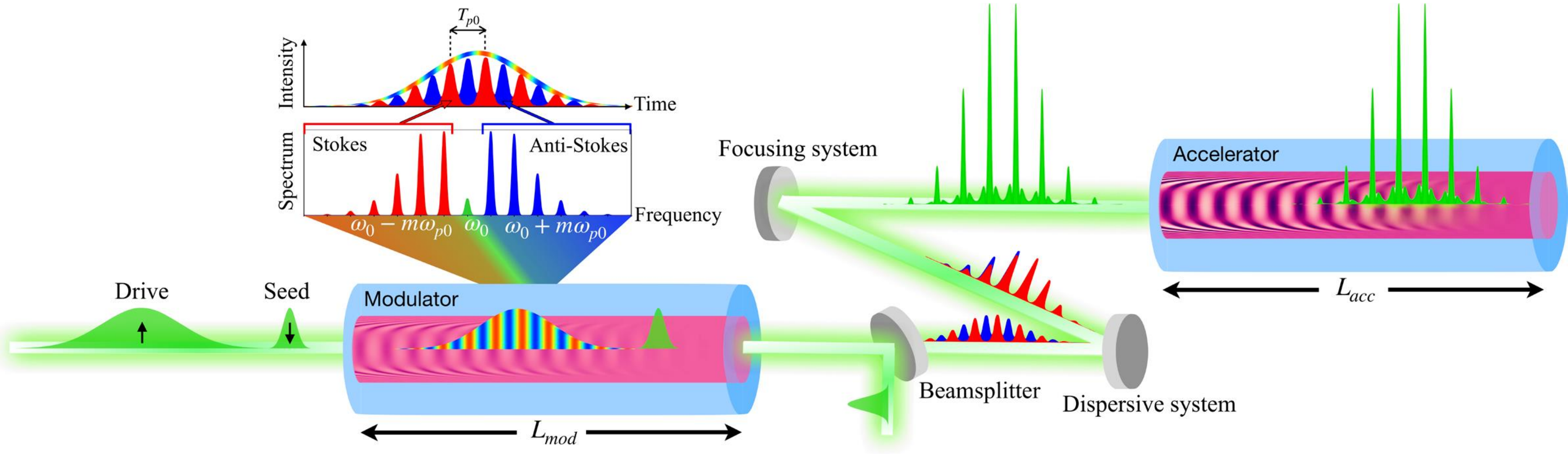
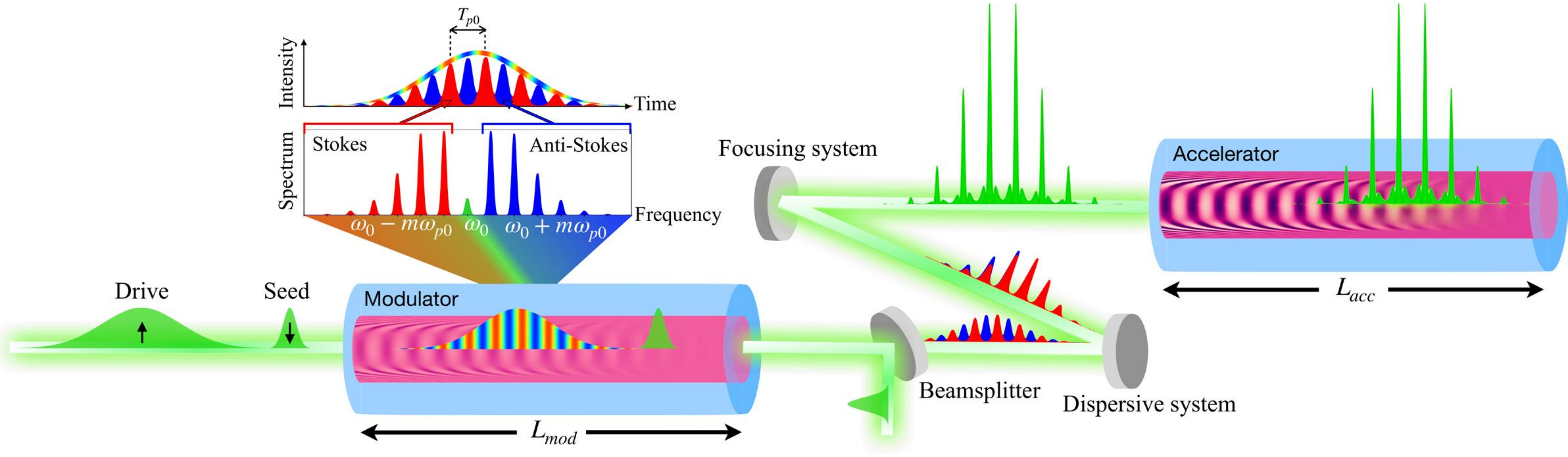
- Short (<100 fs) seed, 10s mJ seed pulse drives wake with $\delta n/n_0 \sim 1\%$
- Long ($\sim$ 1 ps) driver, 1 J + spectrally modulated by wakefield
- Interaction length $\sim 10\ cm$, confined by plasma waveguide



Multi-pulse Scheme - Compressor

- Spectrally modulated drive pulse goes through dispersive system, forming pulse train with peaks separated by plasma period T_{p0} of the modulator

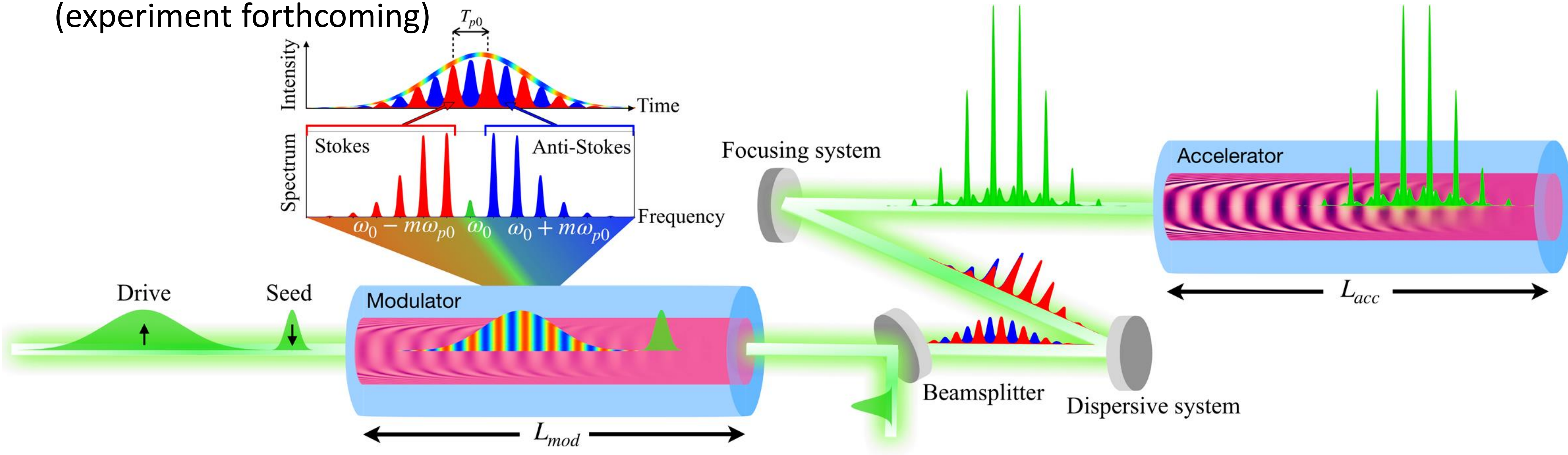


Multi-pulse Scheme – Accelerator

- Pulse train is focused into a plasma waveguide and resonantly drives a wake

$$n_{e,res} = \frac{4\pi^2 m_e \epsilon_0}{e^2}\frac{1}{\delta\tau^2}$$

- Electrons injection via external injection, resonant downramp or shock injection (experiment forthcoming)



Experimental Objectives – Gemini 2022

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1. **Guide J-scale laser pulse trains in 100 mm long plasma channels**
   - Required for modulator and accelerator

2. Demonstrate resonant wakefield excitation by channel-guided pulse trains
   - Demonstrate dependence of wake amplitude on electron density and pulse spacing

Experimental Setup

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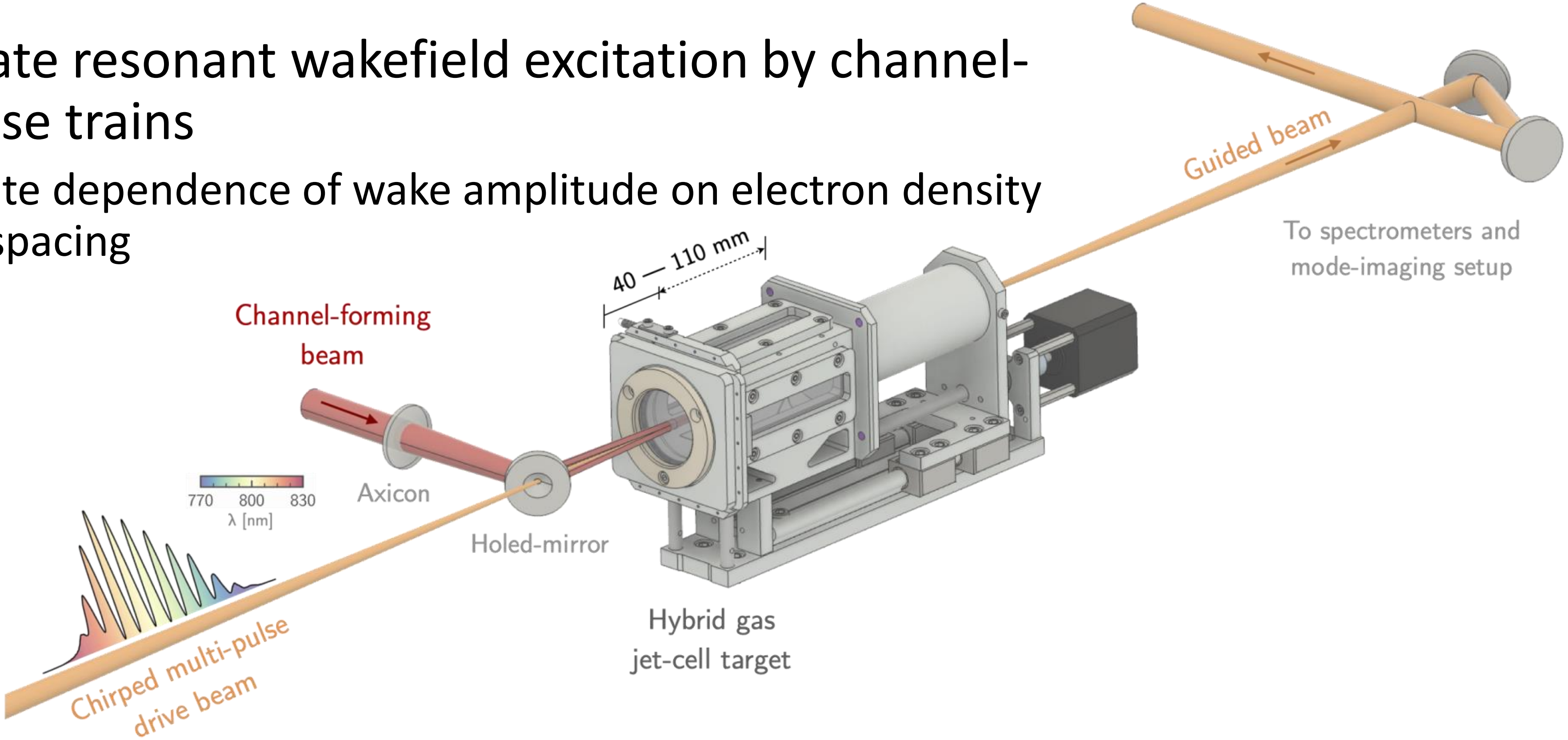
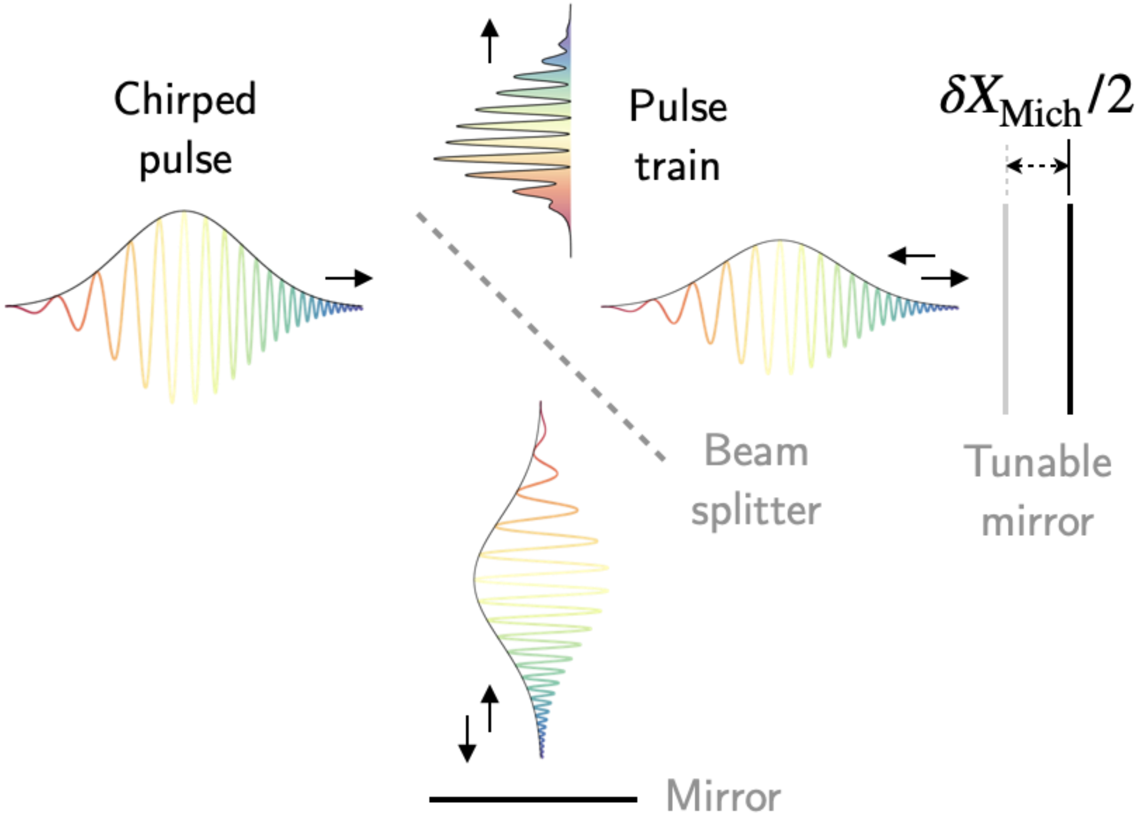


Mock-up Pulse Train

- Chirp Gemini pulse – $30\ fs \rightarrow 1\ ps$, 5 J
- Interfere two copies in Michelson interferometer, producing pulse train
- Train measured by large time window SSA



Mock-up Pulse Train

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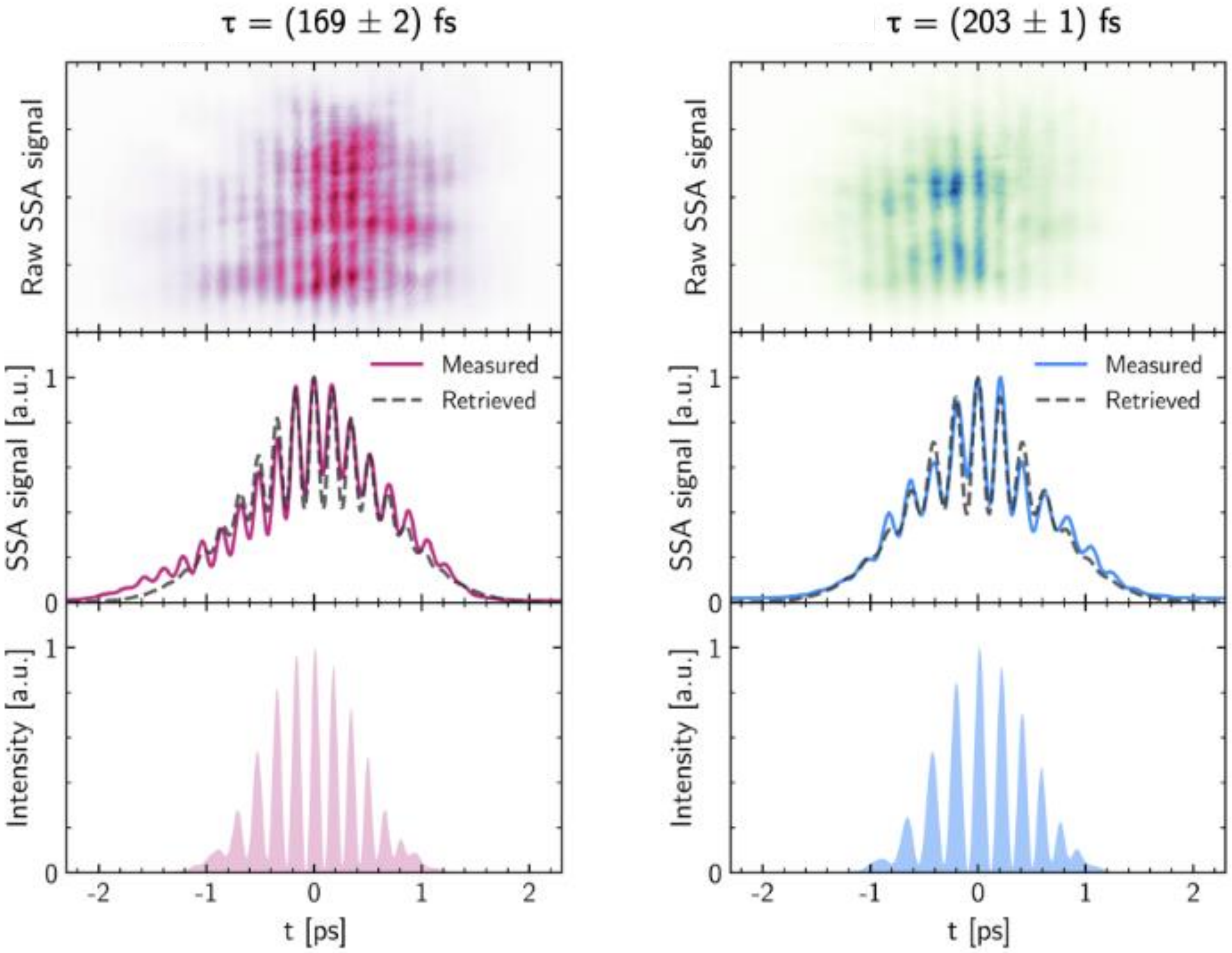
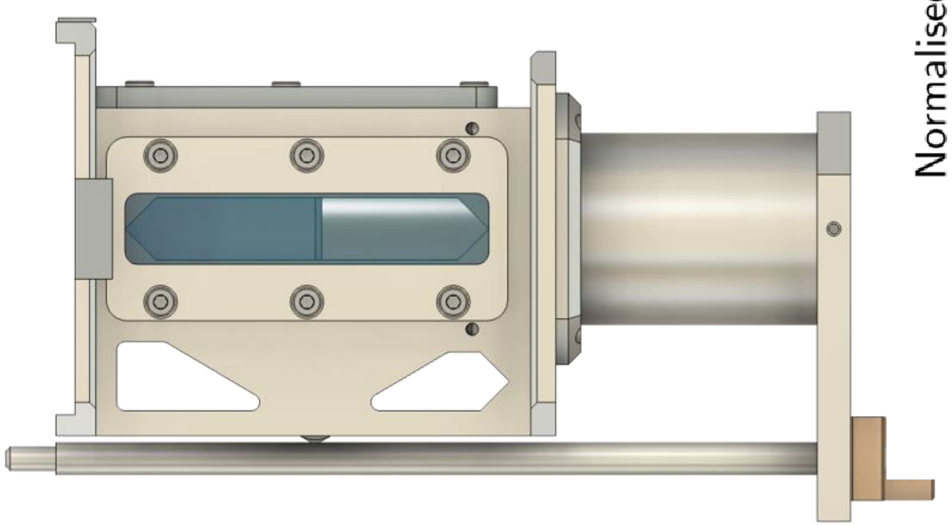
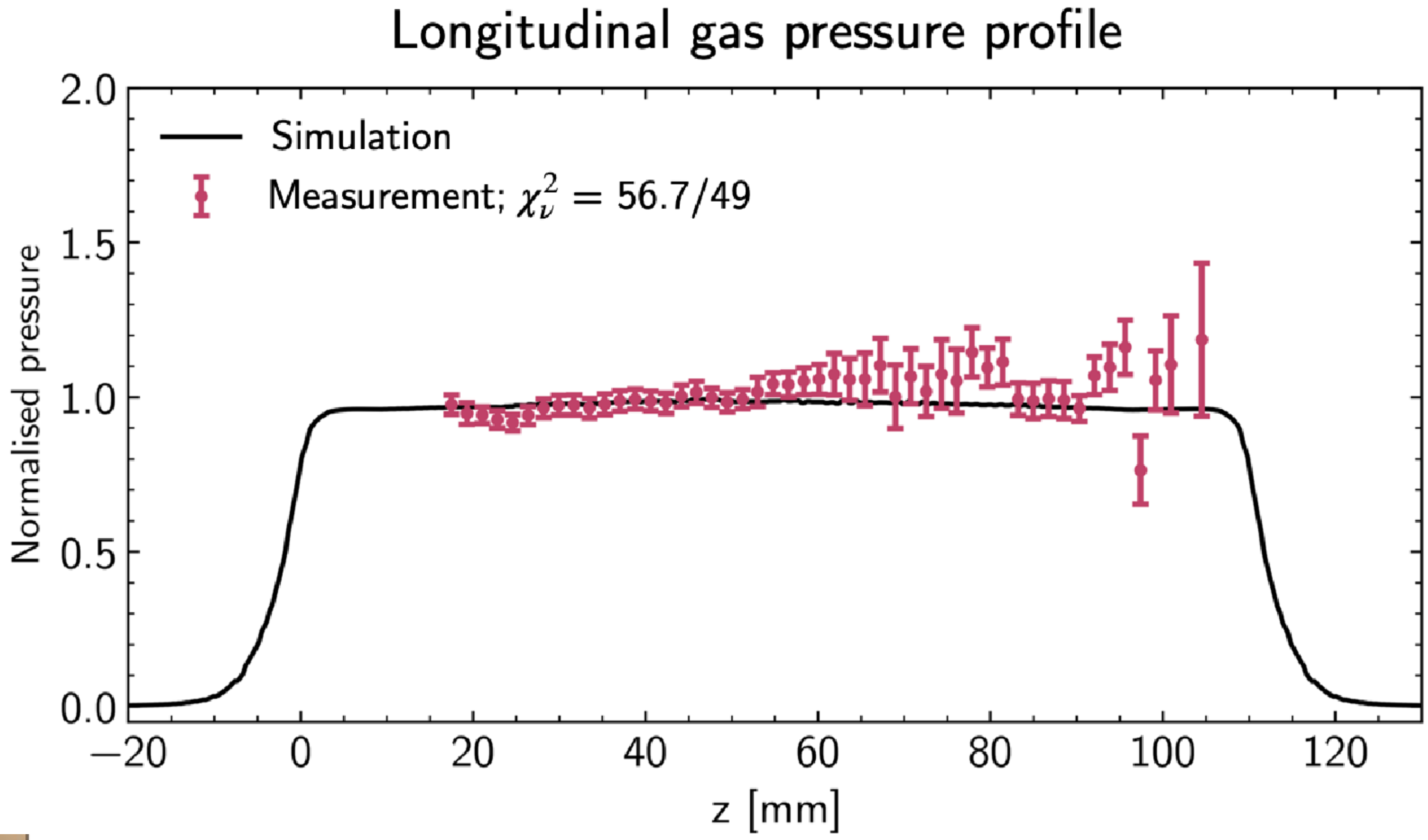
- Higher order phase smears peaks, use Dazzler to compensate
- TOD retrieved using autocorrelation using numerical optimization constrained by measured $\phi^{(2)}$ and Michelson spacing
- Uniformity of pulse train spacing ~ 0.9



Target

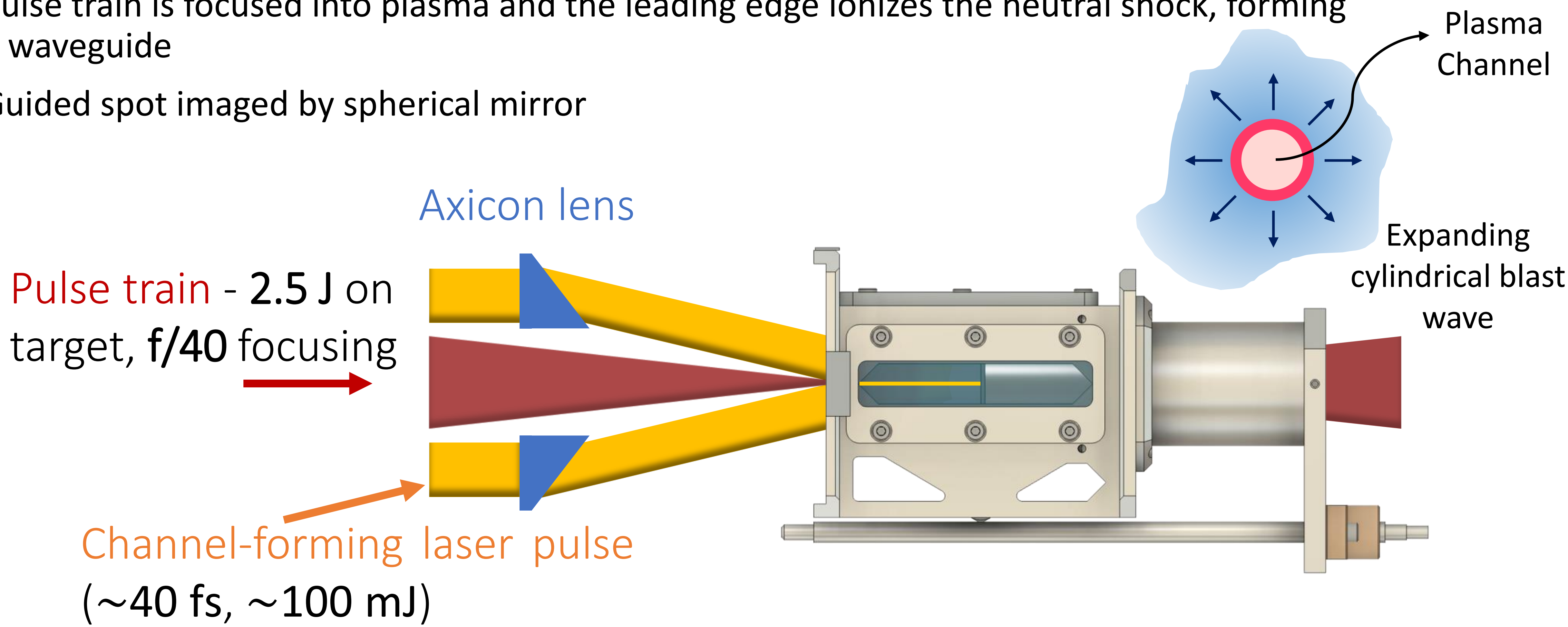
- Jet/Cell hybrid with adjustable length
- Longitudinal gas profile measured by plasma fluorescence method and confirmed by fluid simulations
- Measured on-shot with pressure transducer
- Density fluctuations >5% RMS





HOFI Plasma Waveguide

- Short channel forming pulse is focused by axicon and ionizes a plasma column
- Plasma column expands over 3 ns, driving a shock wave of plasma and neutral gas
- Pulse train is focused into plasma and the leading edge ionizes the neutral shock, forming a waveguide
- Guided spot imaged by spherical mirror



Optical guiding of pulse trains

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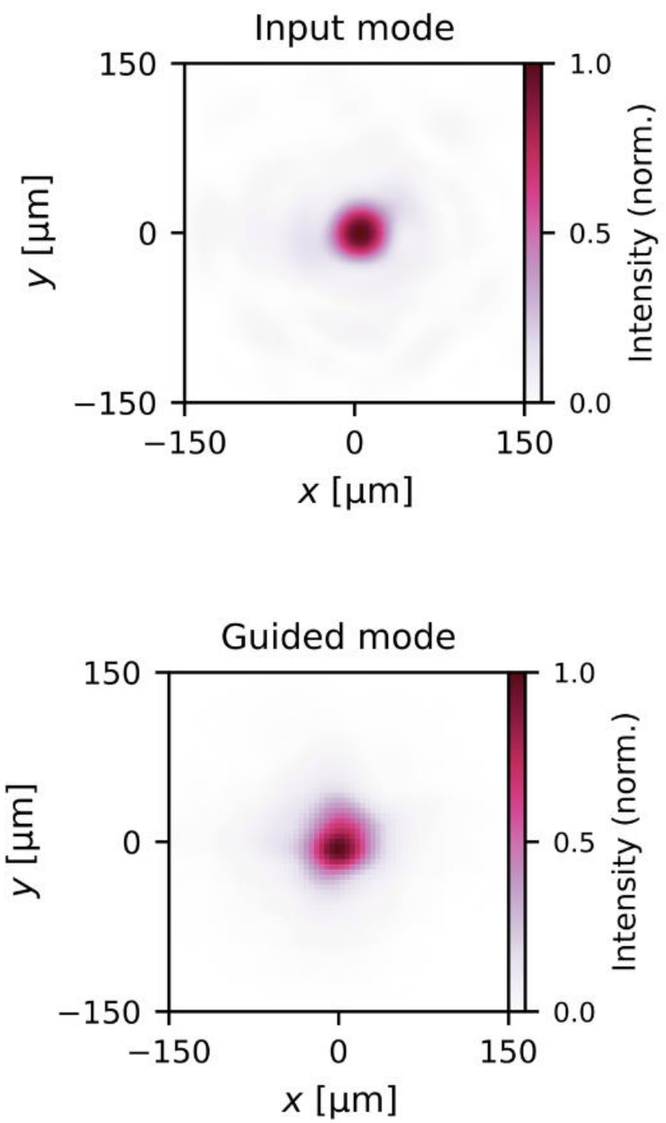
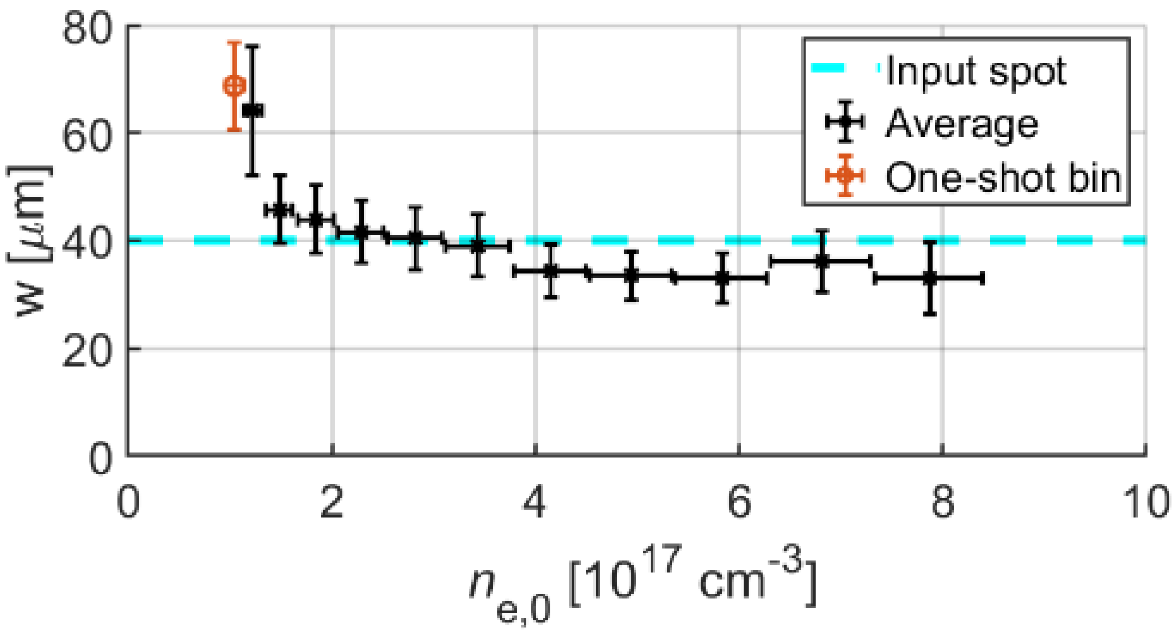


Laser parameters:

1. Pulse train: ~10 pulses, 170 fs spacing, 2.5 J on-target
2. Channel-forming: 40 fs, 100 mJ on-target

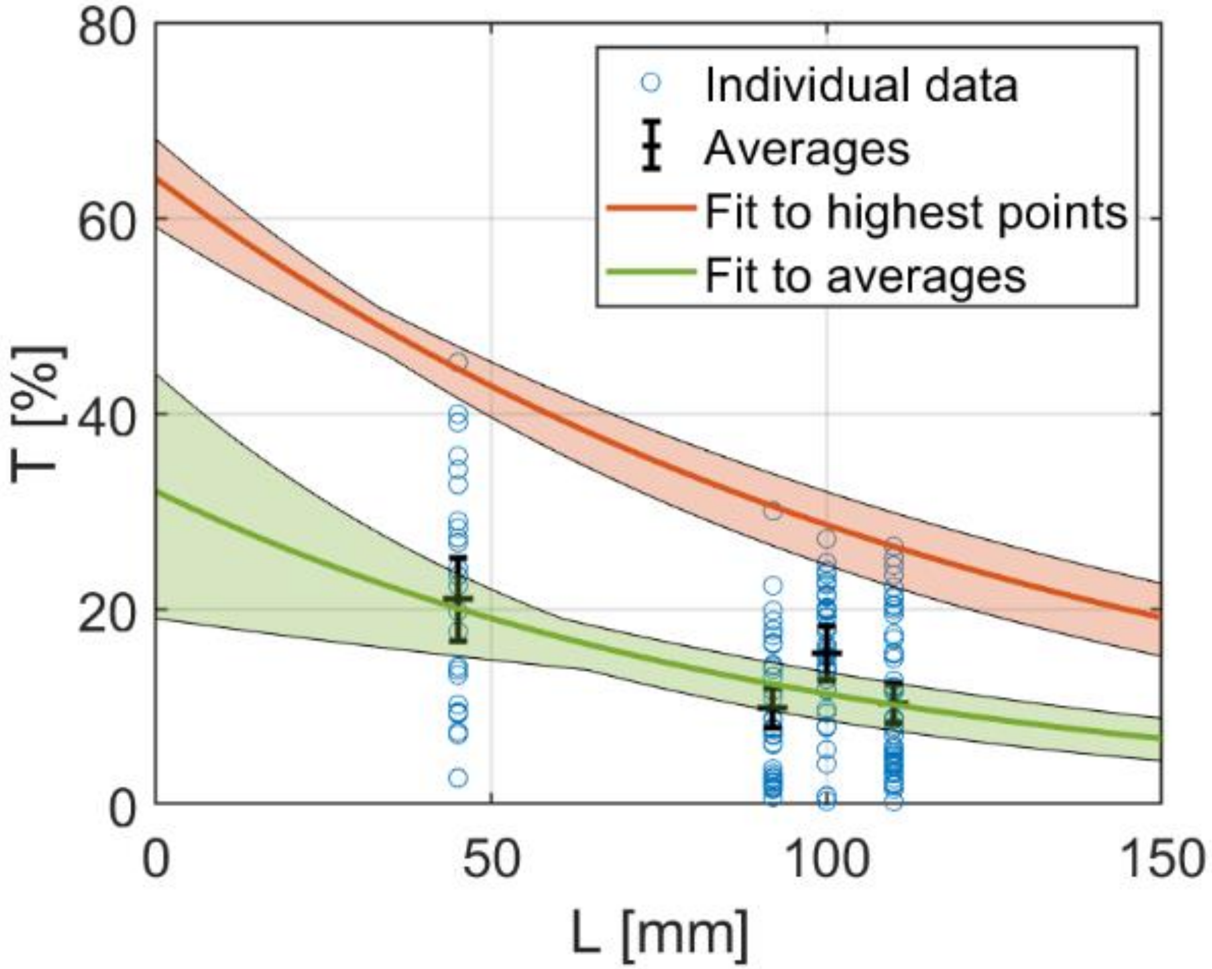
- J-scale pulses guided in 110 mm plasma channel (~17 Rayleigh ranges)
- Input spot 71 % overlap with lowest order mode of the output spot
- Matched spot size decreased at low density



Transmission

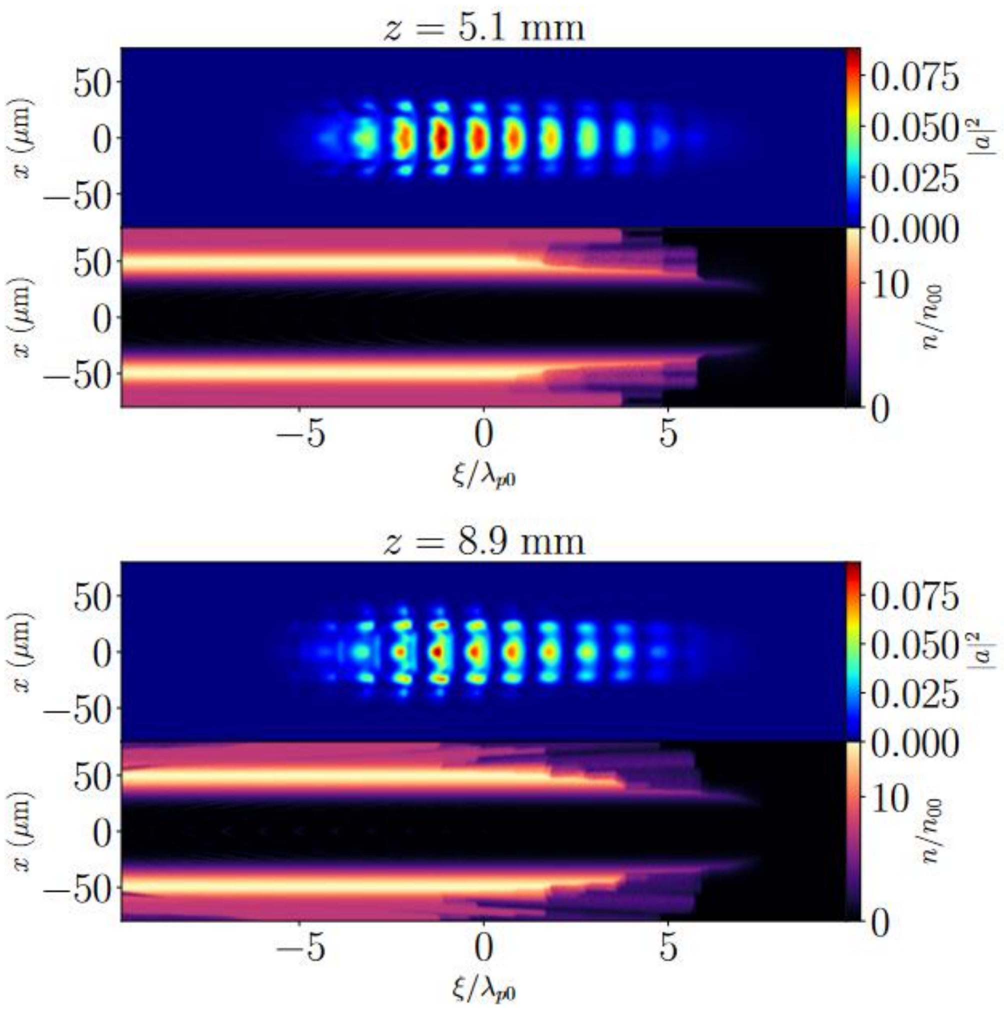
- Changing cell length separates coupling loss and attenuation
- Attenuation length $\left(T(z) = T_0 \exp\left(-\frac{z}{L_{att}}\right)\right)$ for highest points is 124 mm
- T_0~30%, with losses from mode overlap

Laser parameters:
1. Pulse train: ~10 pulses, 200 fs spacing, 2.5 J on-target
2. Channel-forming: 40 fs, 100 mJ on-target



Comparison with Smooth Pulse

- Similar transmission to earlier experiments with smooth pulse (Picksley et. Al (2020)) despite 1/8 intensity
- Pic simulations confirm conditioning by first few pulses in train, fully conditioned for most pulses



(Poster: Stability of the Plasma-Modulated Plasma Accelerator (P-MoPA), Johannes Van de Wetering
Paper: PHYSICAL REVIEW E 108, 015204 (2023))

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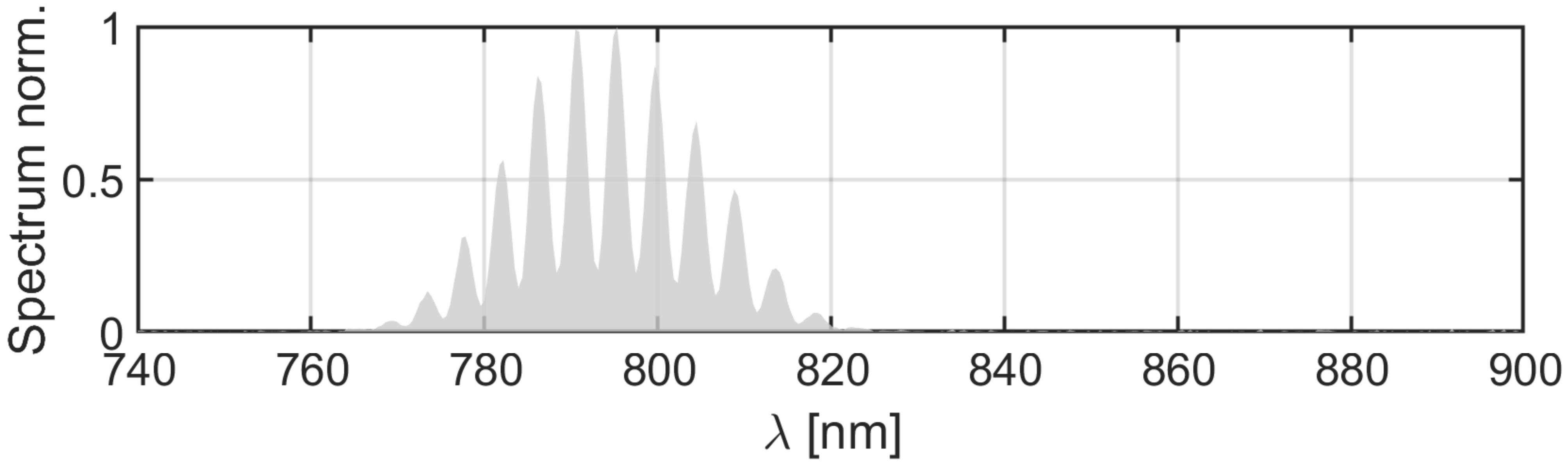
2. **Demonstrate resonant wakefield excitation by channel-guided pulse trains**
   - Wakefield excitation was measured by observing redshift of the drive beam

Redshift of Transmitted Spectra



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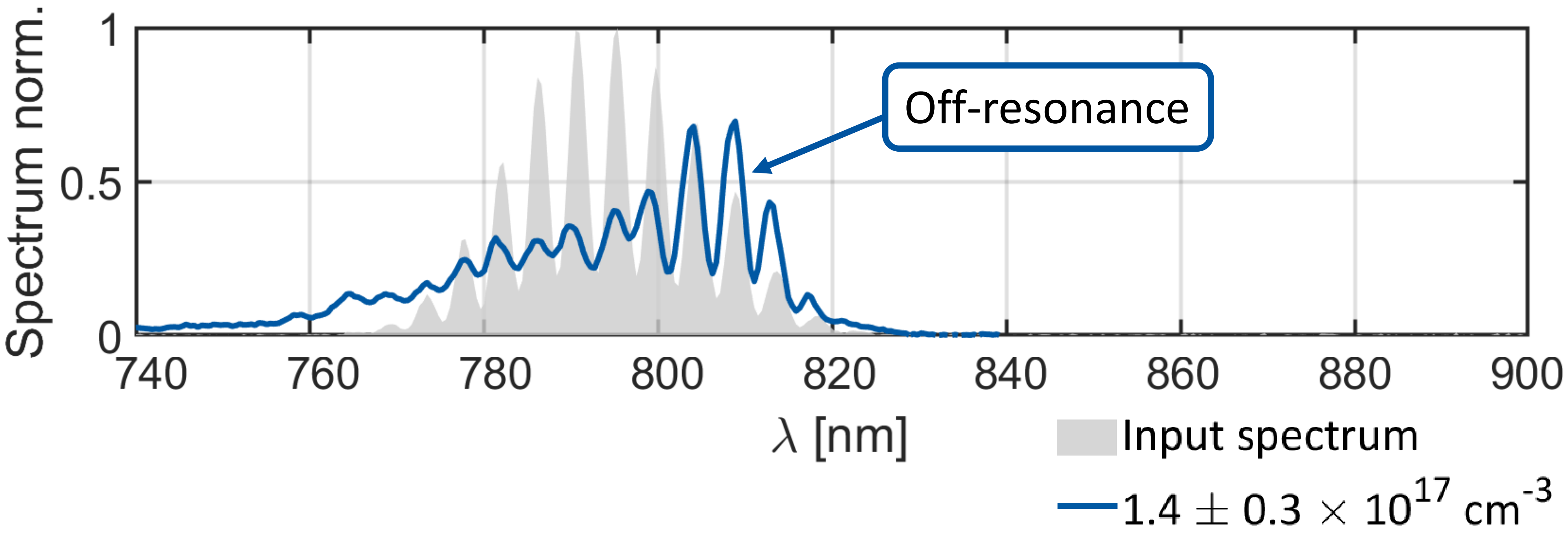
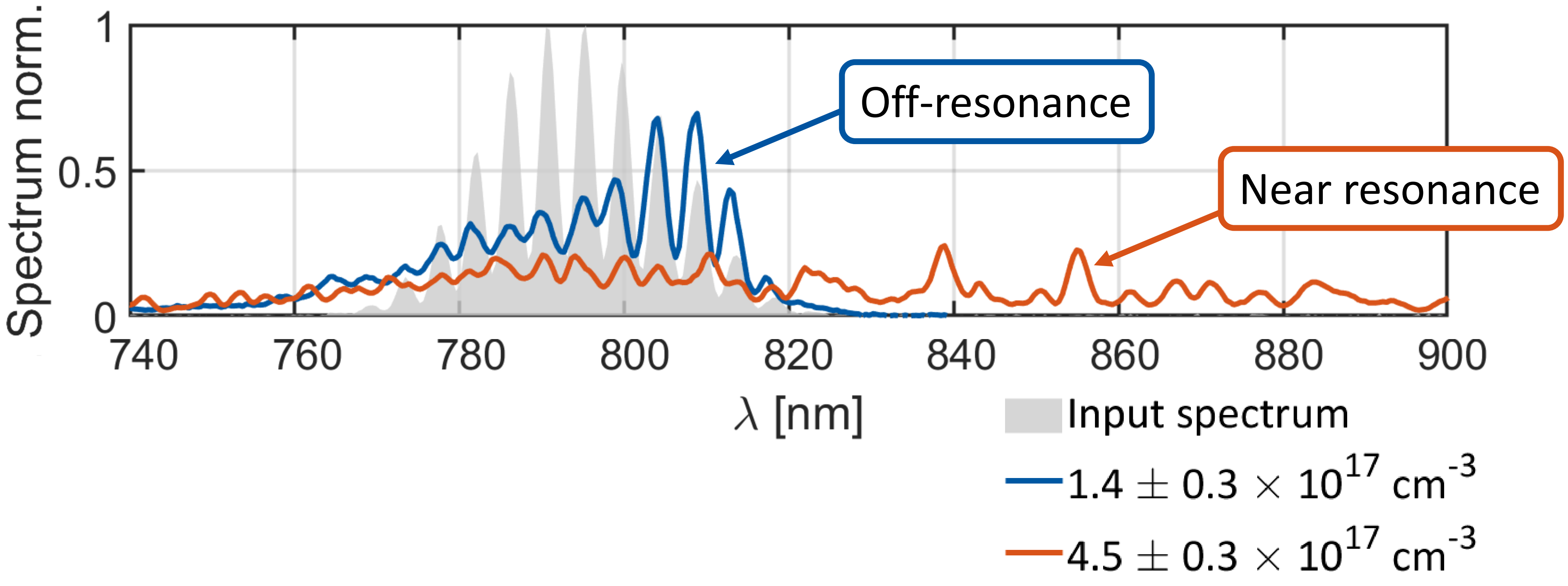


Redshift of transmitted spectra



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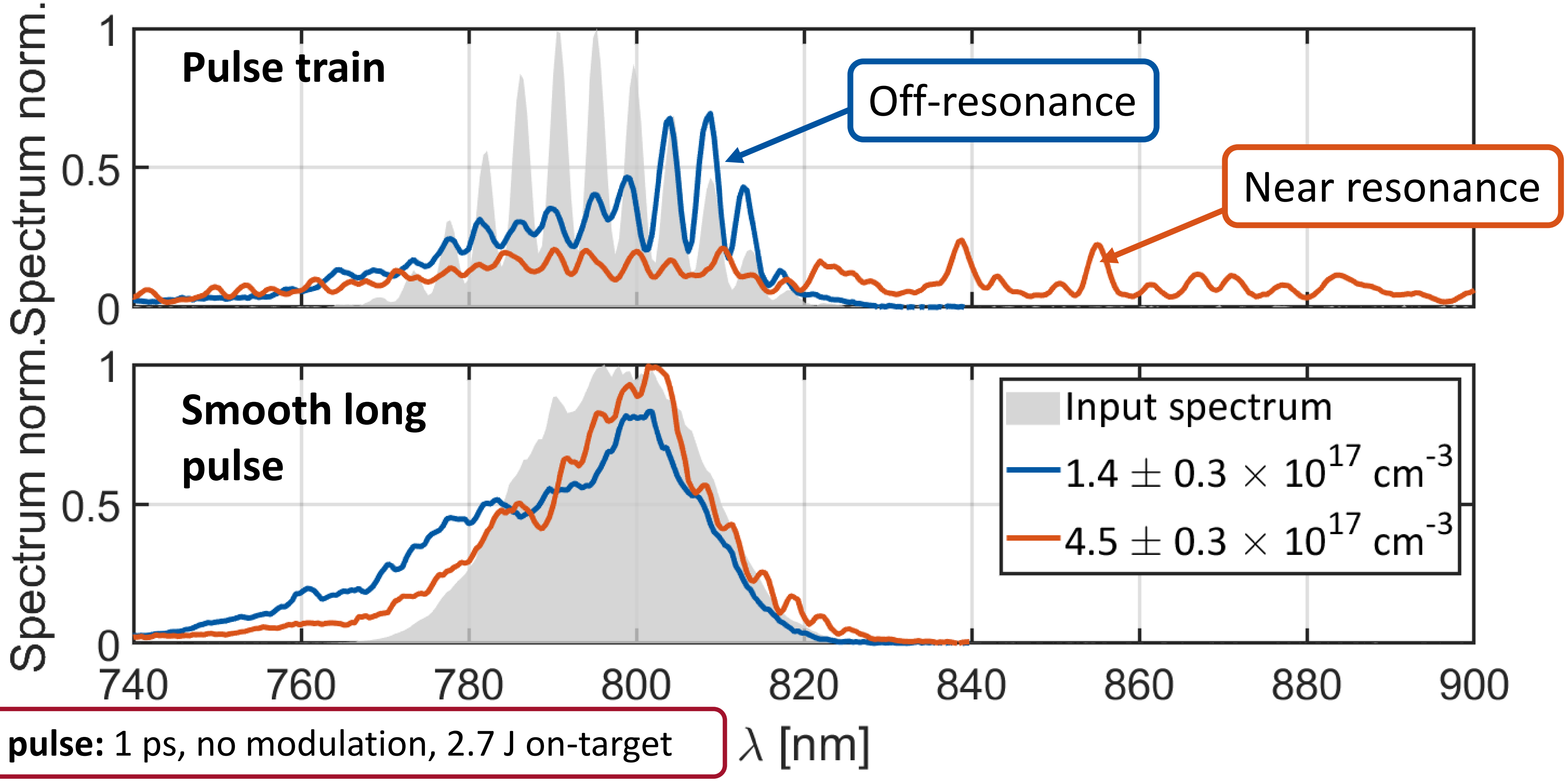
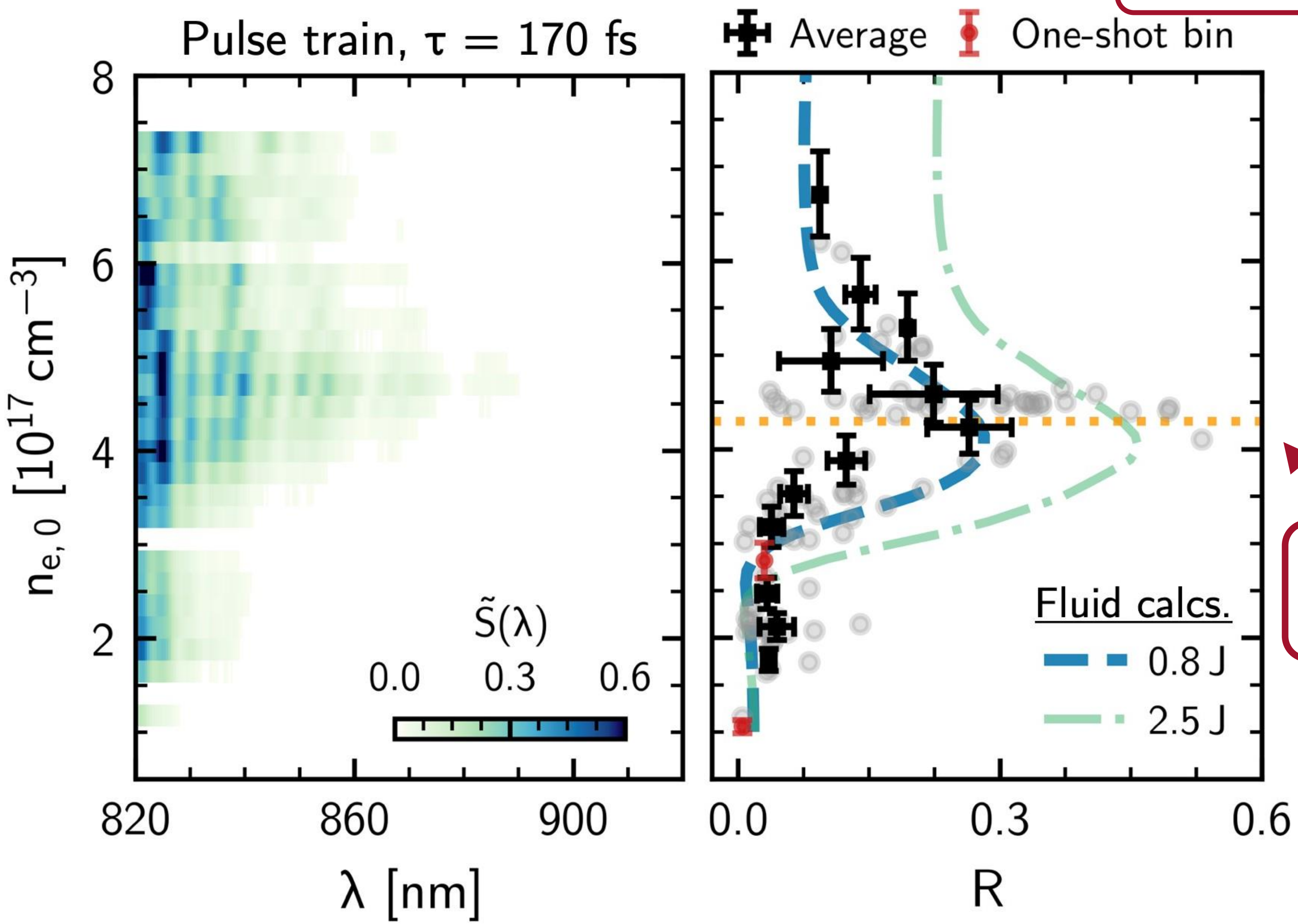
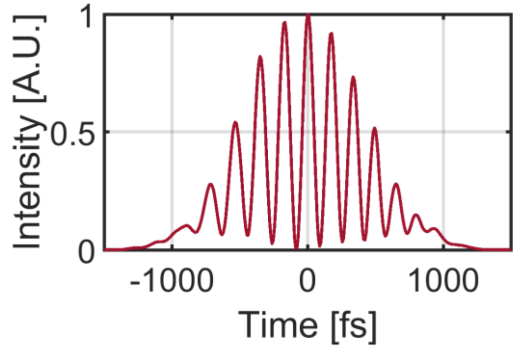


Smooth pulse: 1 ps, no modulation, 2.7 J on-target

Density Resonance of Redshift

$\delta\tau = 170$ fs ➡ $n_{e,res} = 4.3 \times 10^{17}$ cm^{-3}





Expected resonant density

$\mathbf{R} = \sum_{\lambda > \lambda_{\text{thresh}}} f(\lambda)$

Smooth pulse – No Resonance

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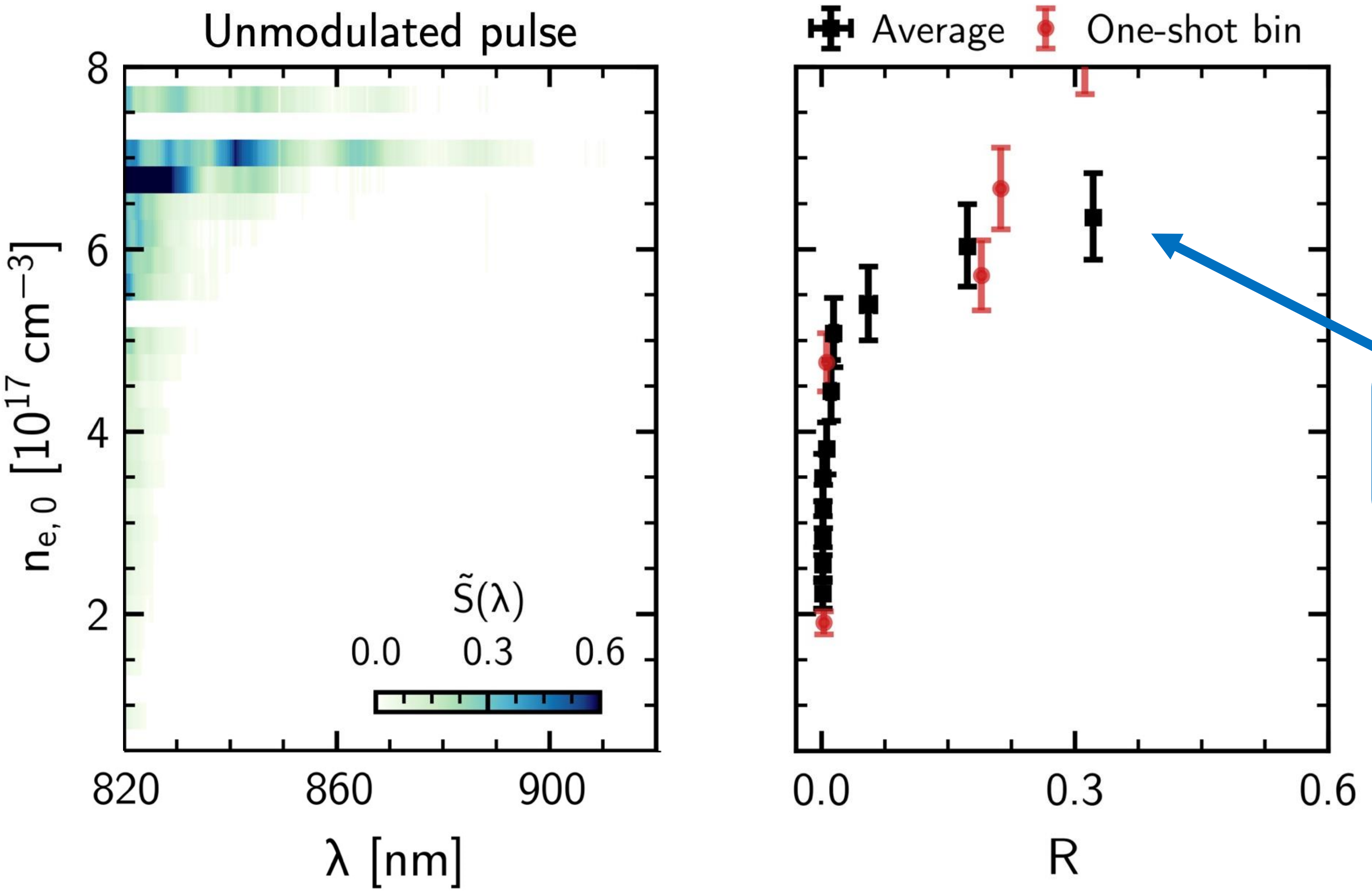
Smooth pulse: 1 ps, no modulation, 2.7 J on-target



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

Simulation Results of Density Resonance

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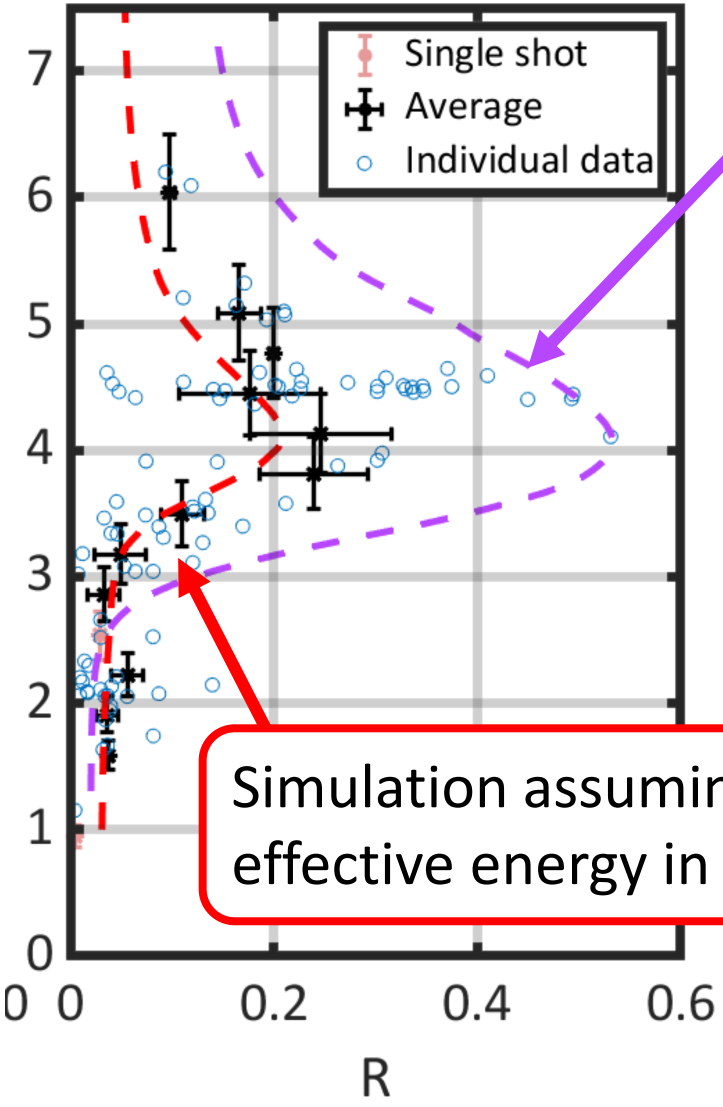
- Redshifts were compared to expected redshifts from 2D cylindrical fluid calculations, benchmarked against PIC simulations

Experimentally measured red-shift were reduced since:

- Lowest order mode overlap ~ 80%
- Spatial jitter of drive beam at channel entrance ~ 31 microns
- Density ramps at start and end of gas target



Simulation assuming perfect channel coupling

Simulation assuming 800 mJ effective energy in pulse train

Suggests wakefield amplitude = **3-10 GV/m**

Dependence of Resonance on Pulse Spacing

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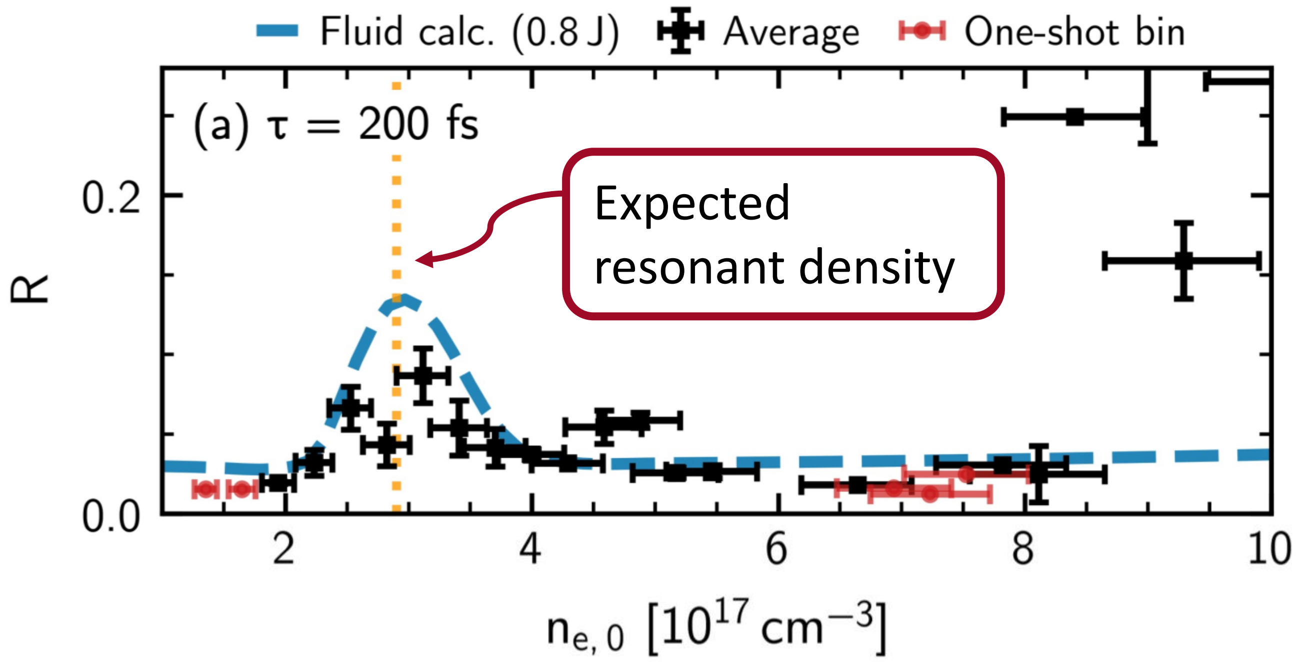
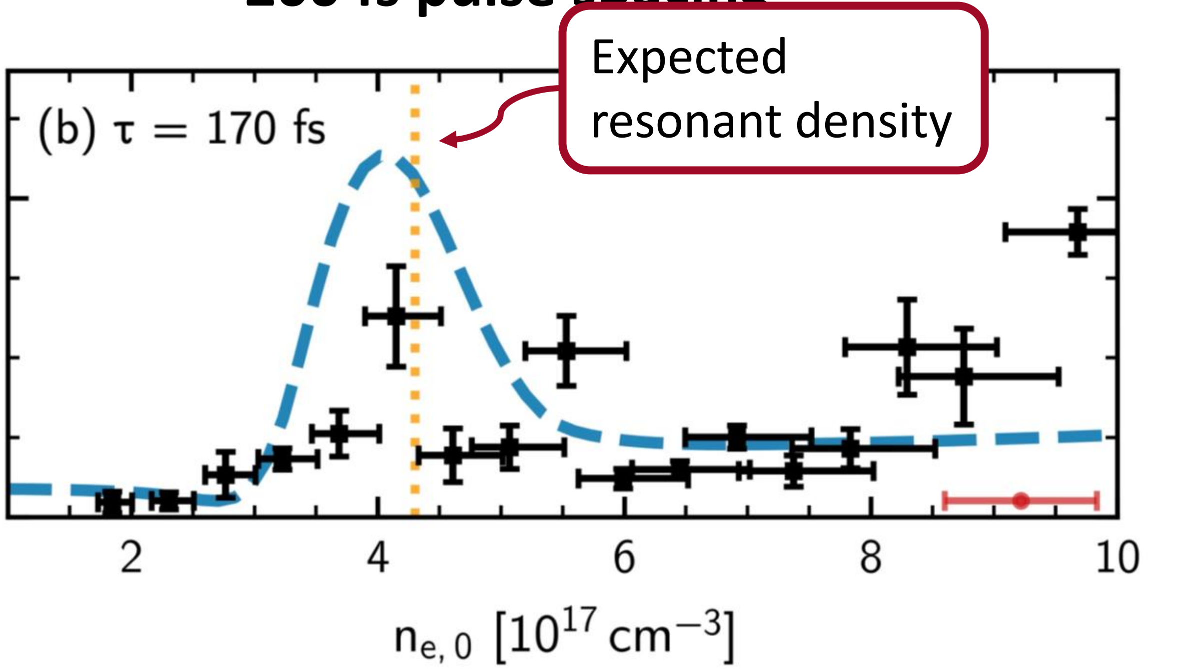
70 mm propagation

170 fs pulse spacing



200 fs pulse spacing



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2. Demonstrate resonant wakefield excitation by channel-guided pulse trains
   - Observed density-dependent redshifts in the drive spectrum, indicating wakefields were resonantly excited by channel-guided pulse trains
   - Resonance at expected density and consistent with RZ-fluid simulations
   - Simulations suggest acceleration gradient of **3-10 GeV/m**

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3. **Upcoming: Modulation experiments with true ps pulse at CALA**