John Adams Institute for Accelerator Science

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Experimental demonstration of kHz hydrodynamic optical-field-ionized plasma channels

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Phys. Rev. Accel. Beams **25**, 011301 (2022)

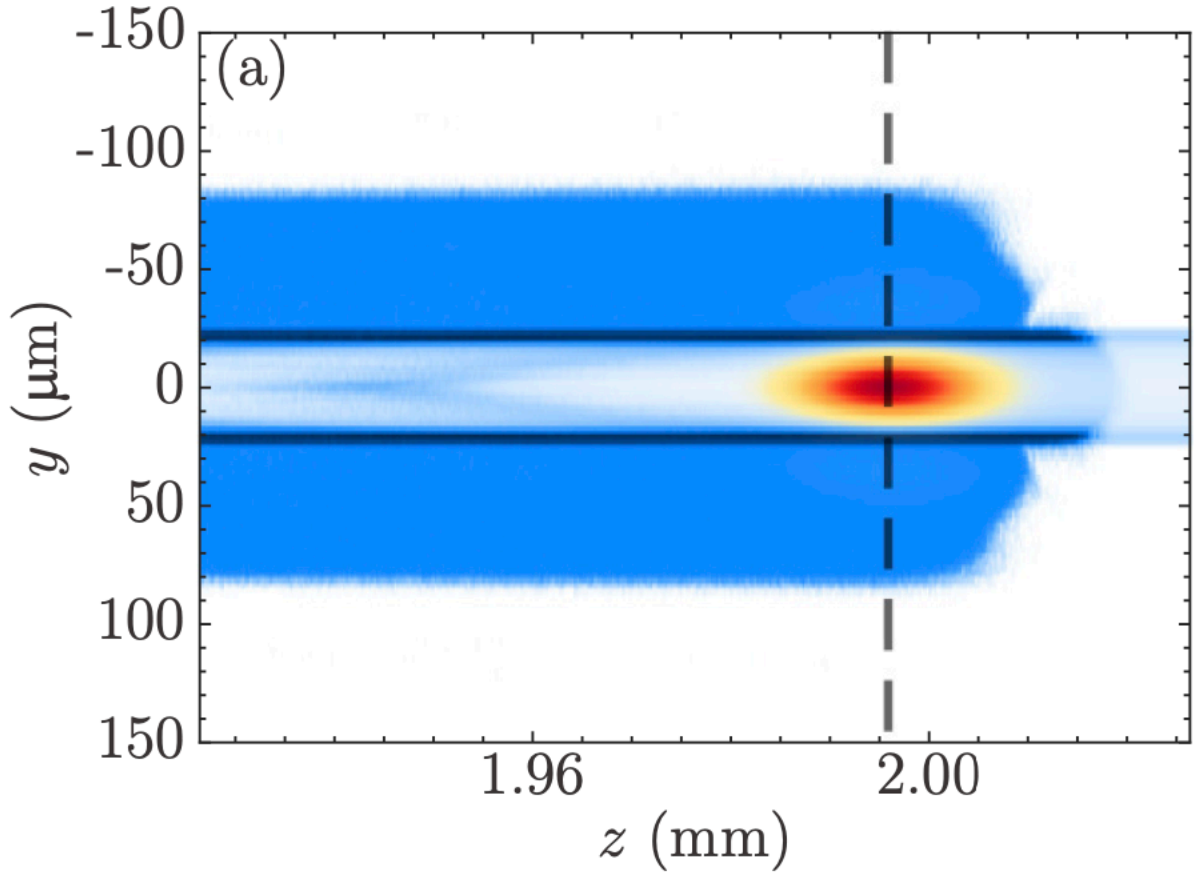
AAC 2022 - 10th November
Hyatt Regency Long Island

Motivation - kHz

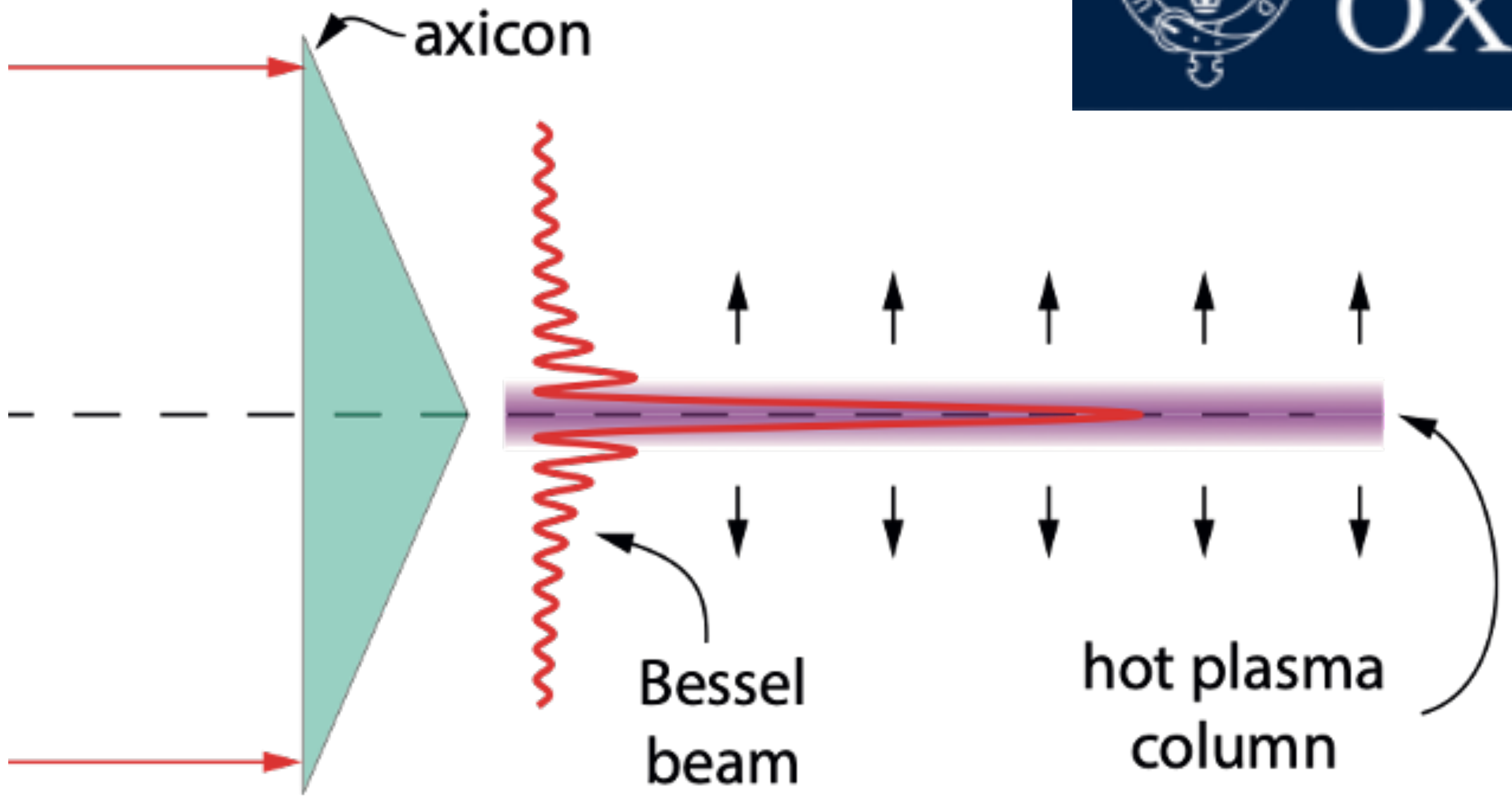
- Potential applications of plasma accelerators - compact light sources, FELs, particle colliders - require high (> kHz) pulse repetition rates
- High stability, GeV beams
- Waveguides capable of guiding high intensity lasers at this repetition rate are a major goal

- Capillary/discharge

- Plasma channels (incl. HOFI)

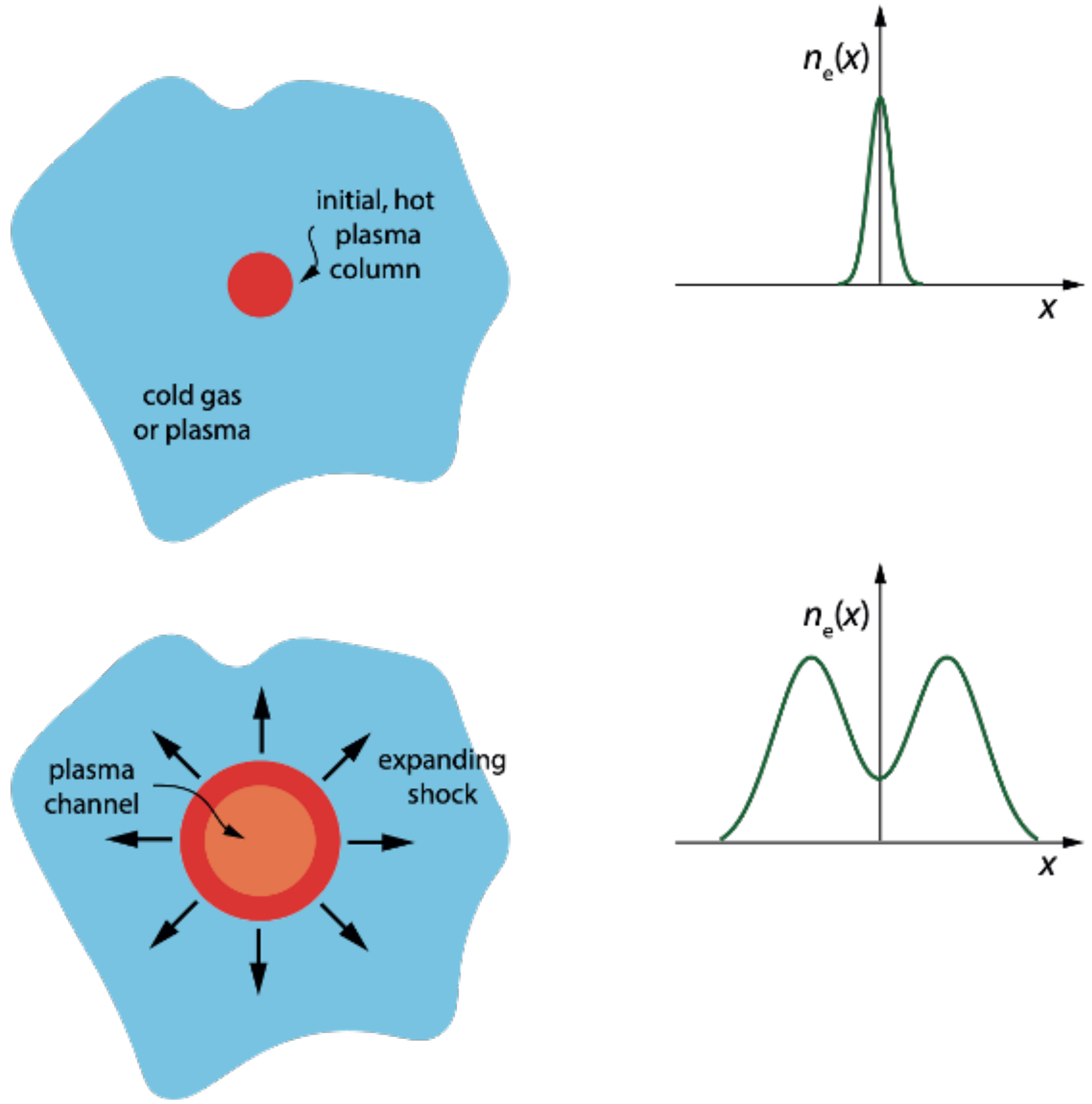


Motivation - HOFI



- Multi-GeV plasma stages require 10^{18} W cm^{-2} laser pulses to be guided over > 10 cm

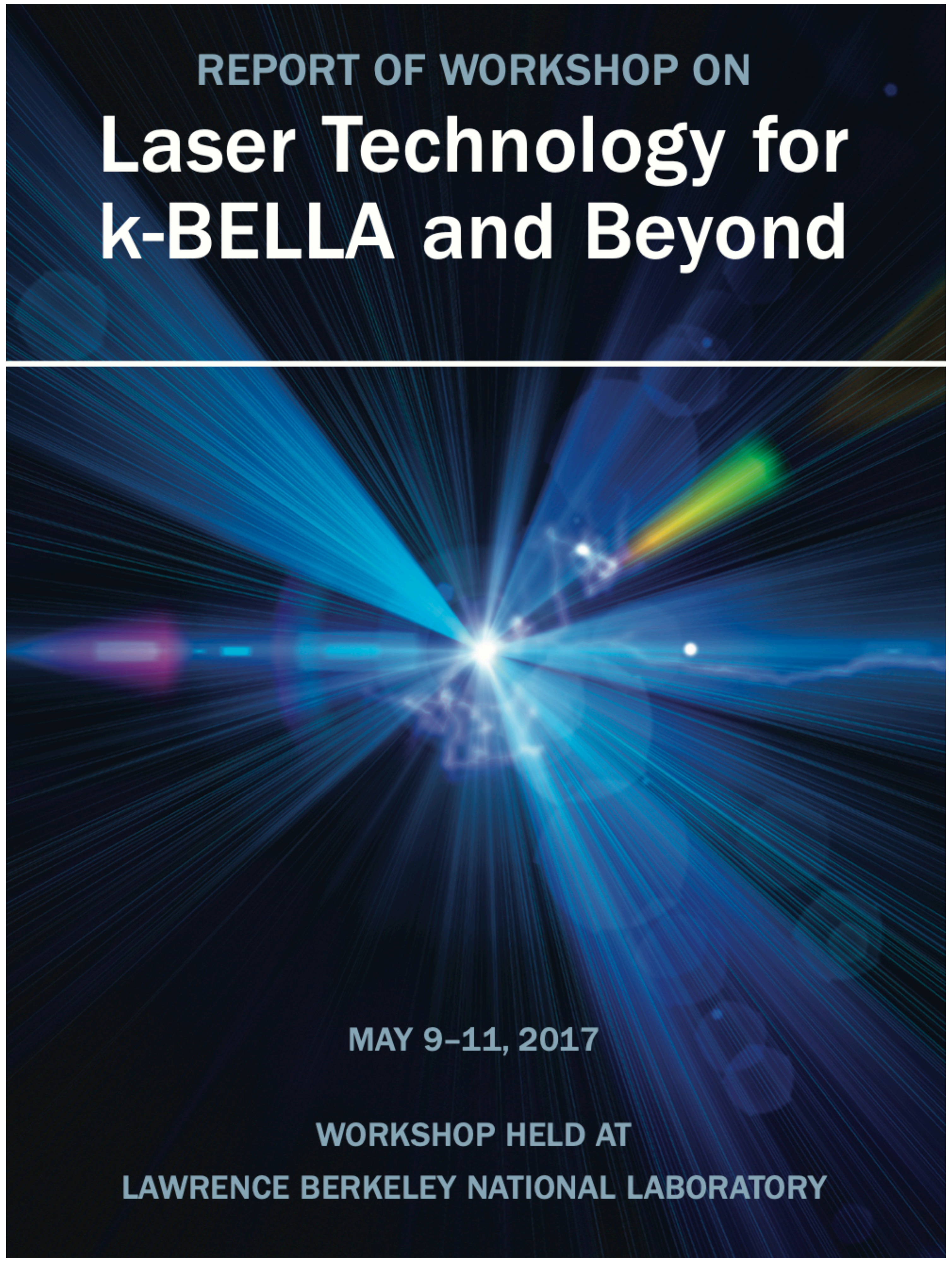
- We and others have developed optically generated, damage free waveguides



C. G. Durfee & H. M Milchberg Phys. Rev. Lett., **71** 2409 (1993)
N. Lemos *et. al.*, Nat Sci. Rep, **8** 3165 (2018)
R. J. Shalloo *et al.*, Phys. Rev. Accel. Beams **22**, 041301 (2019)
S. Smartsev *et. al.*, Opt. Lett. **44**, 14 (2019)
L. Feder *et. al.*, Phys. Rev. Research **2,** 043173 (2020)
A. Picksley *et. al.*, Phys. Rev. E **102** 053201 (2020)

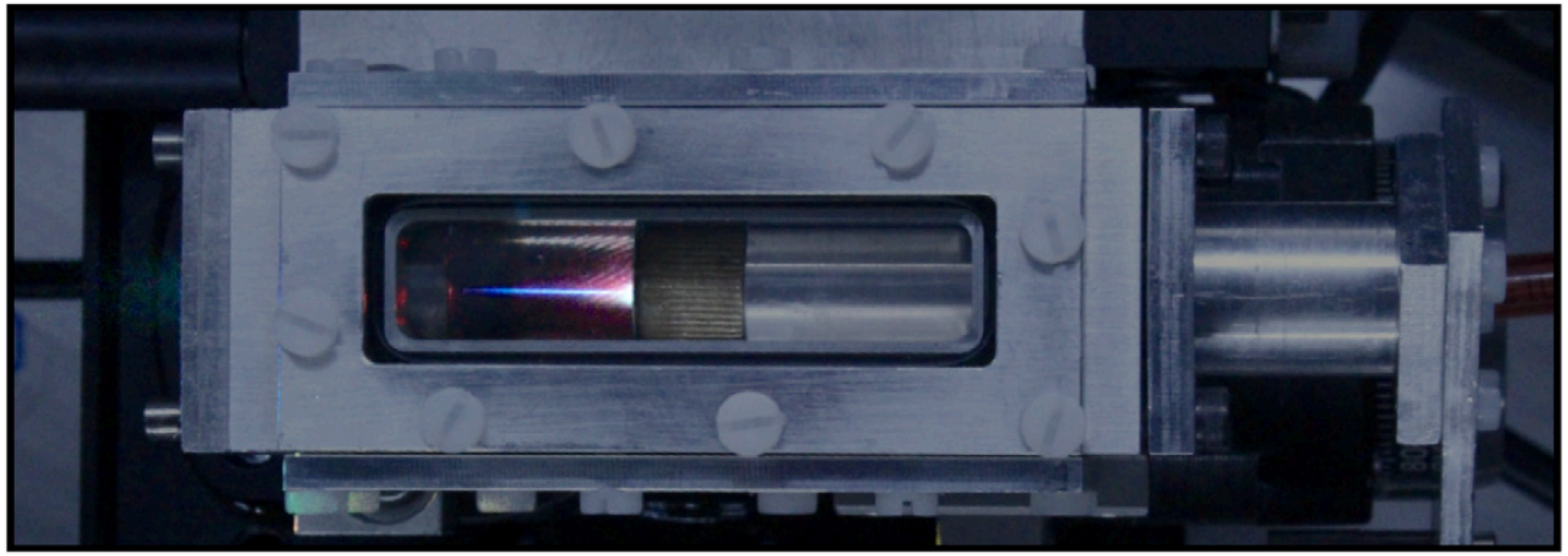
kHz plasma accelerators - on the horizon

- Emerging laser technologies mean the waveguide problem is relevant NOW
- Potentially enables use of efficient, high rep-rate laser systems to generate GeV beams
    - YLF thin disks, fibres, exotic Ti:Sa…

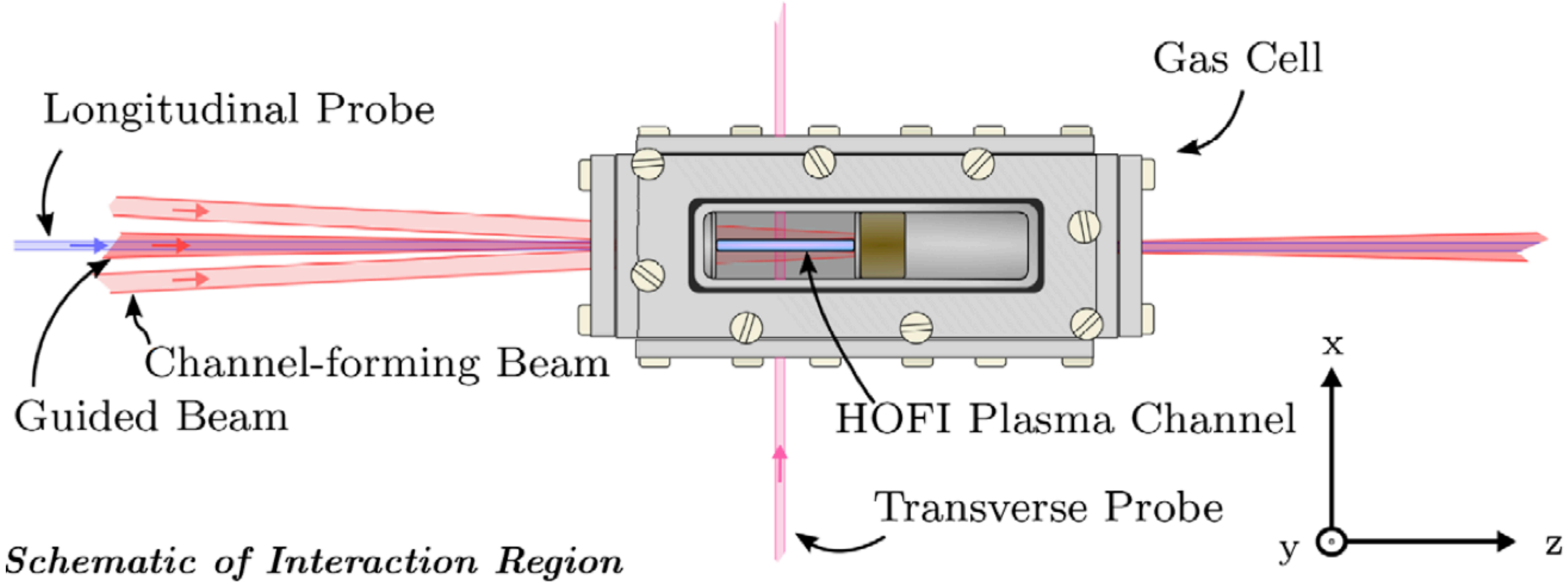


Hydrodynamic optical-field-ionized plasma channels - previous experiments

- Beam injected 1.5 ns after channel formation
- Axial densities down to 1.5×10^{17} cm^{-3}
- Axicon-generated 16 mm channel = 14 Z_R



Composite Photo of 16-mm-long HOFI Plasma Channel

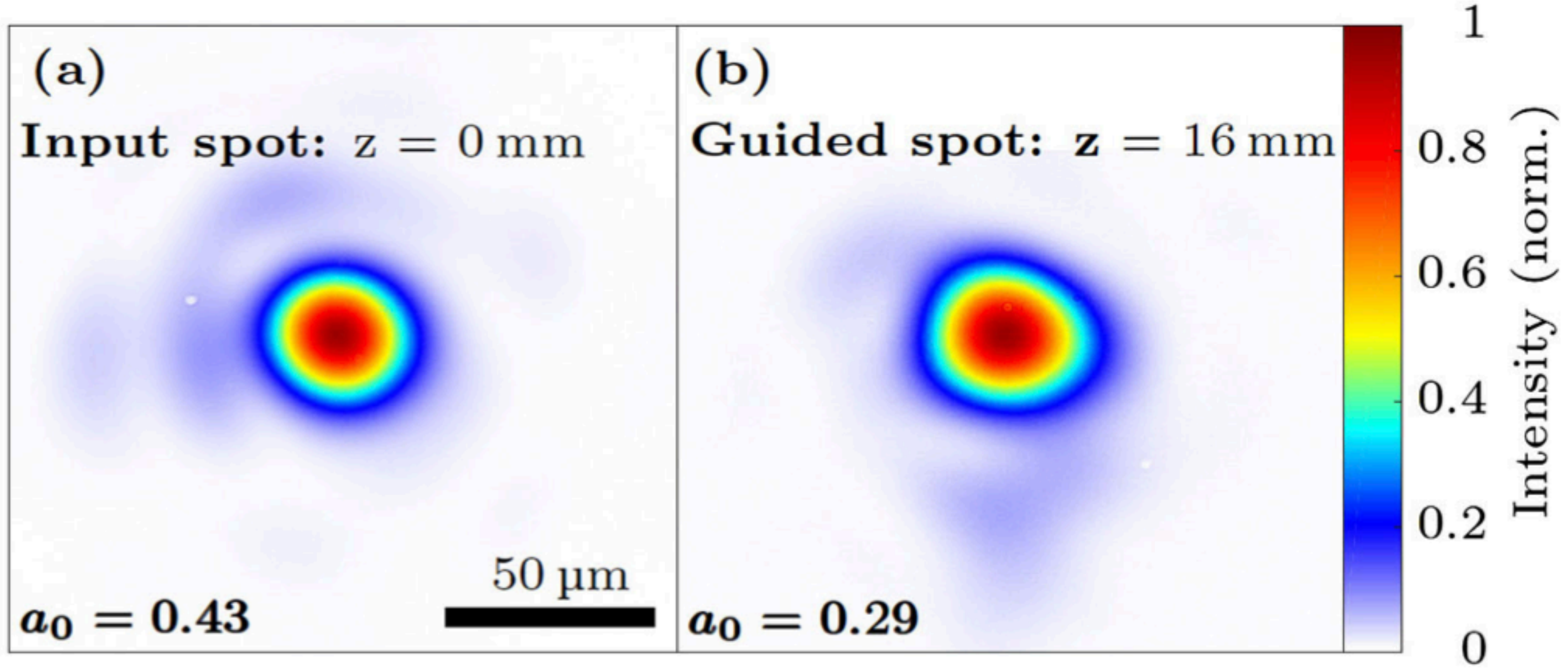


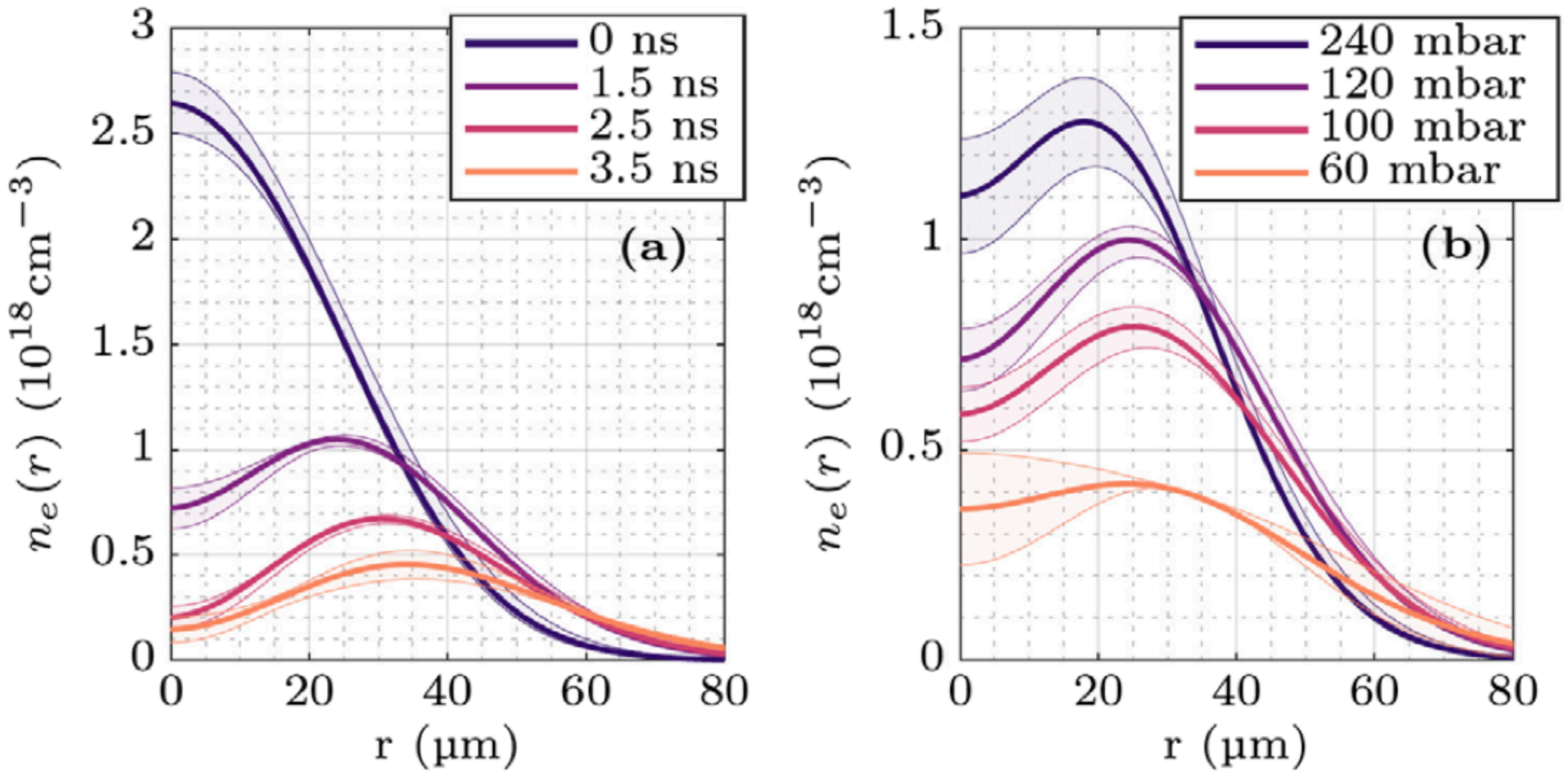
Schematic of Interaction Region

R. J. Shalloo *et al.*, Phys. Rev. Accel. Beams **22**, 041301 (2019)

Hydrodynamic optical-field-ionized plasma channels - previous experiments

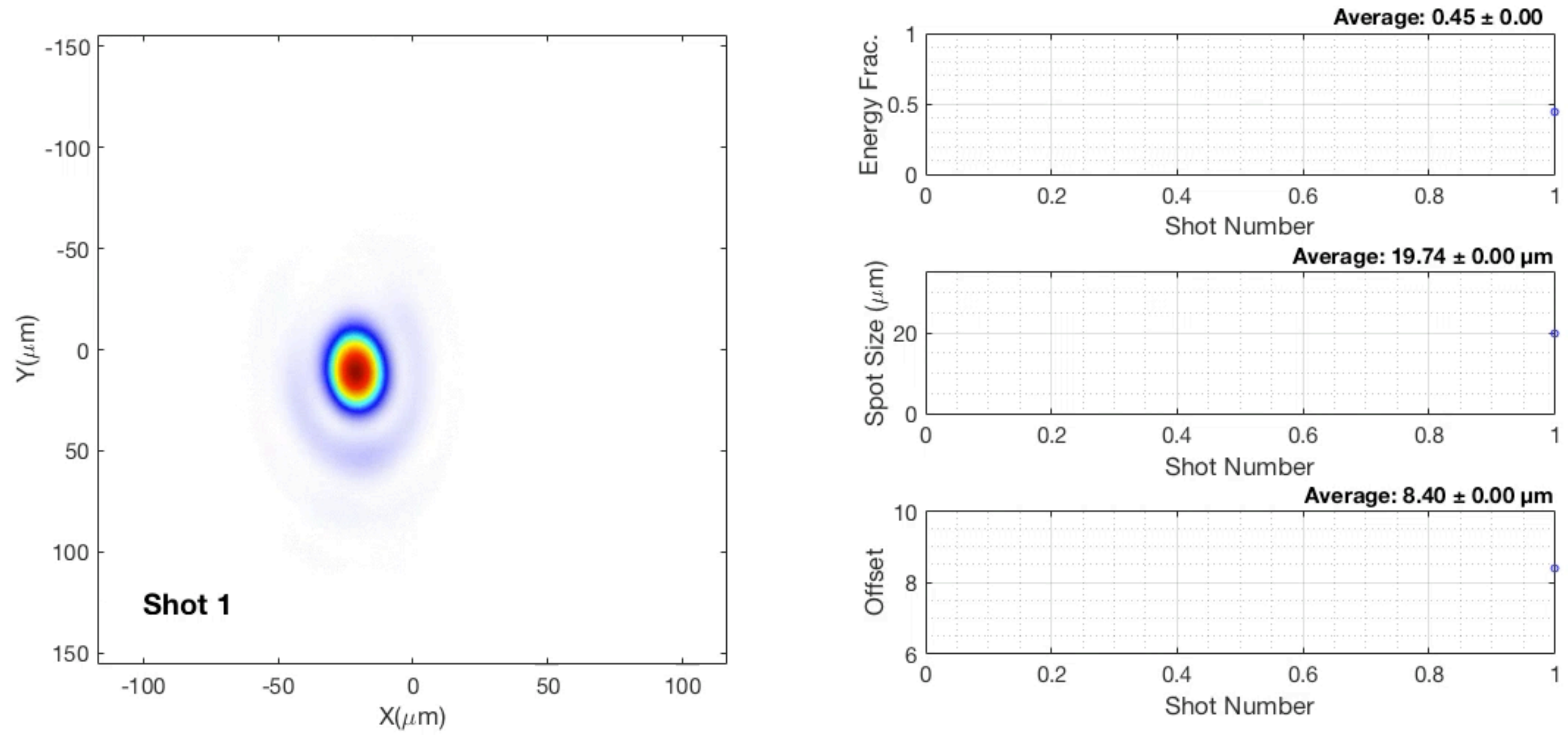
- Beam injected 1.5 ns after channel formation
- Axial densities down to 1.5 × 10^{17} cm^{-3} were generated
- Guided beam intensity ~ 4 × 10^{17} W cm^{-2}
- Total transmission 40-60%

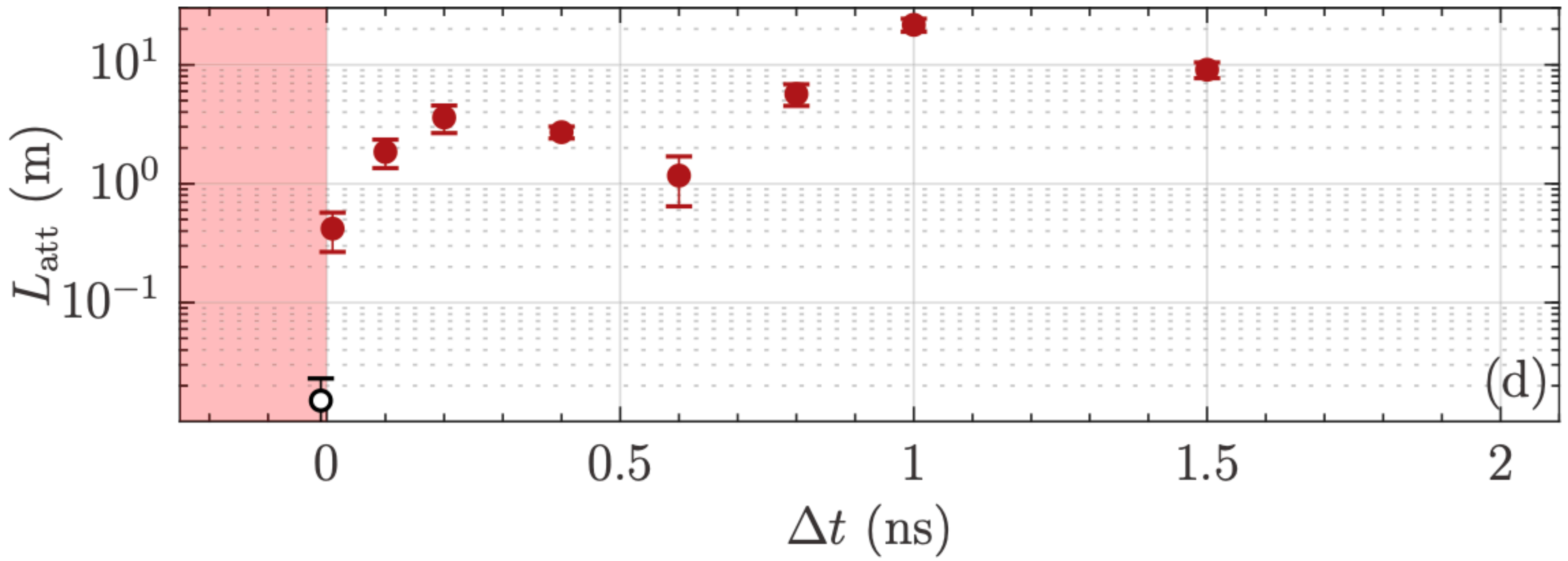




Hydrodynamic optical-field-ionized plasma channels - previous experiments

- Guiding at up to 5 Hz investigated
- Meter-scale attenuation length L_{att}
    - If neutral “cladding” is ionized - “conditioned HOFI”/“self-wave guiding”/J_{16} mode



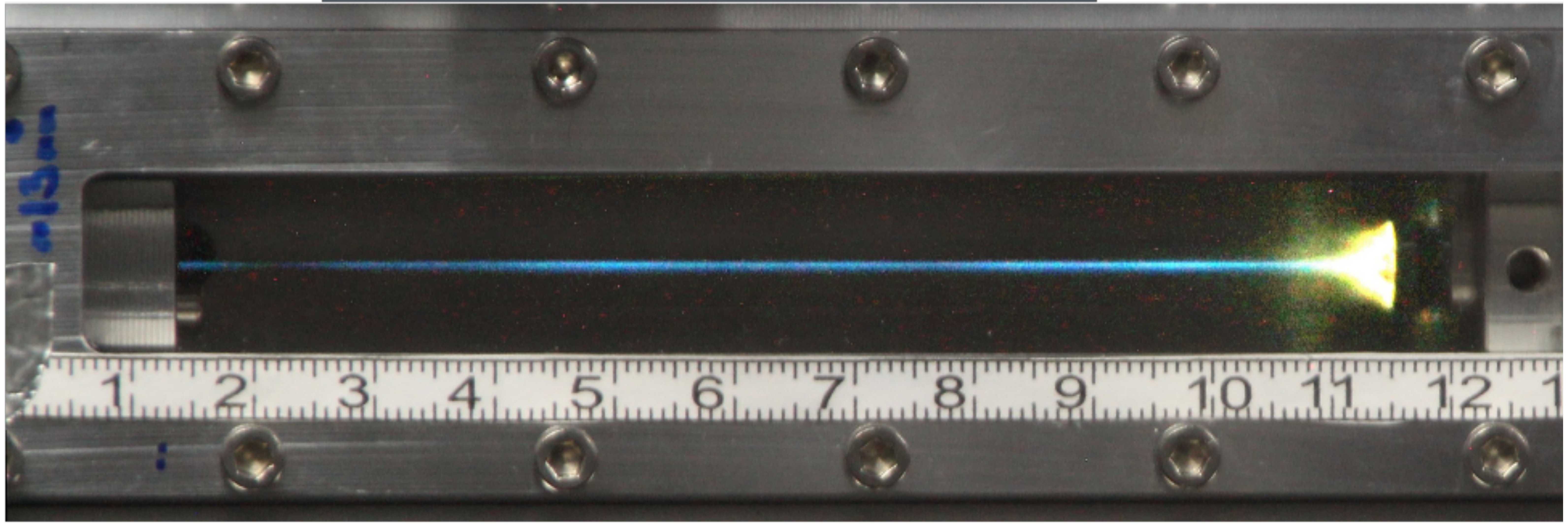


L. Feder *et. al.*, Phys. Rev. Research **2,** 043173 (2020)
A. Picksley *et. al.*, Phys. Rev. E **102** 053201 (2020)
B. Miao *et al.*, Phys. Rev. Lett. **125**, 074801 (2020)

Current achievements in HOFI channels

- 10s cm scale plasma waveguides already demonstrated
    - Gas cells or jets

100 mm long HOFI channel



See Alex Picksley's talk at 9.10

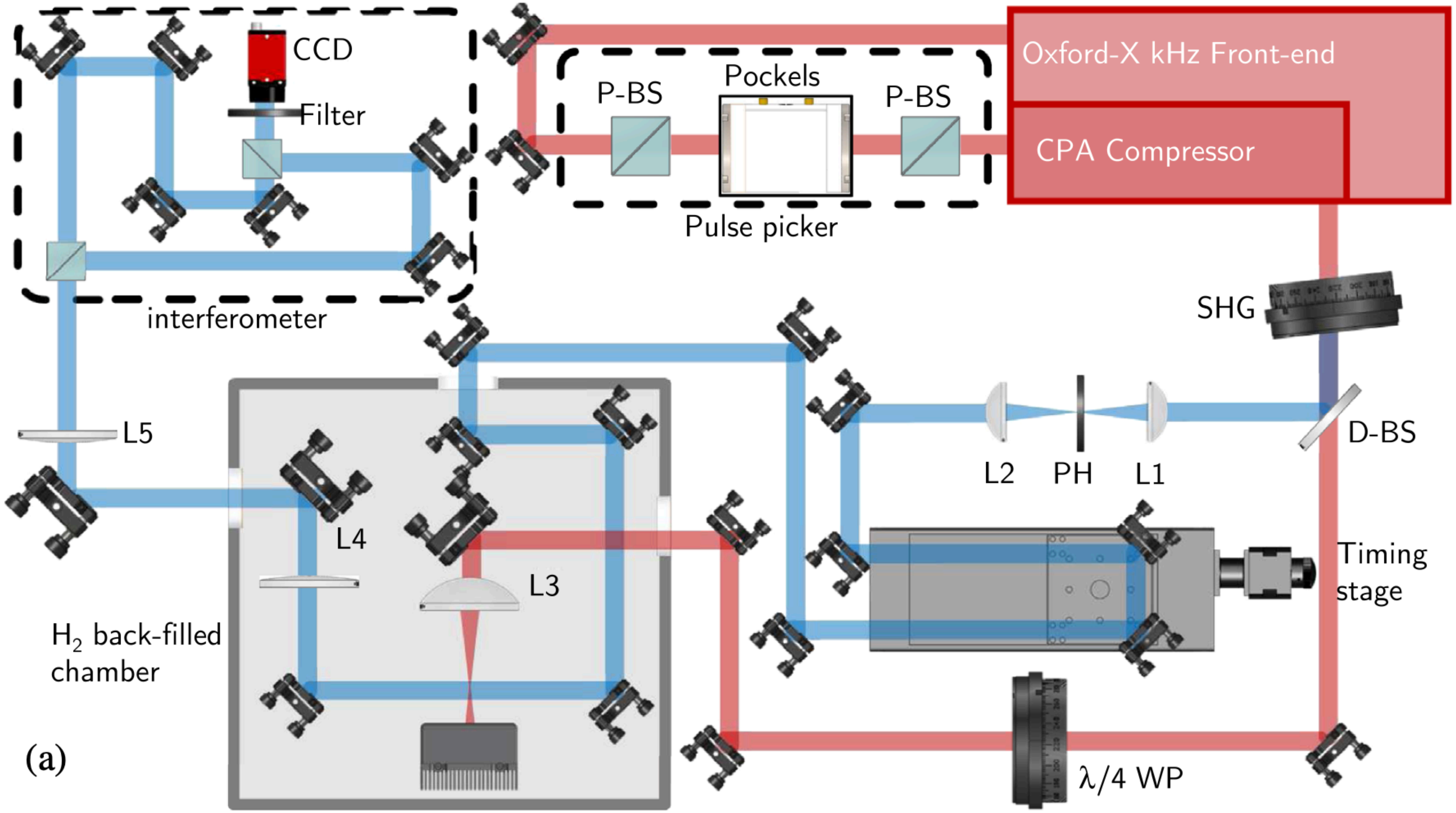
A. Picksley et al., Phys. Rev. Accel. Beams 23, 081303 (2020)
B. Miao et. al., Phys. Rev. X 12, 031038 (2022)

Already investigated

- Stable guiding of intense pulses ✓
- Long attenuation length ✓
- Low densities ✓
- Long channels 10 cm - 1 m ✓
- Maximum repetition rate ✗

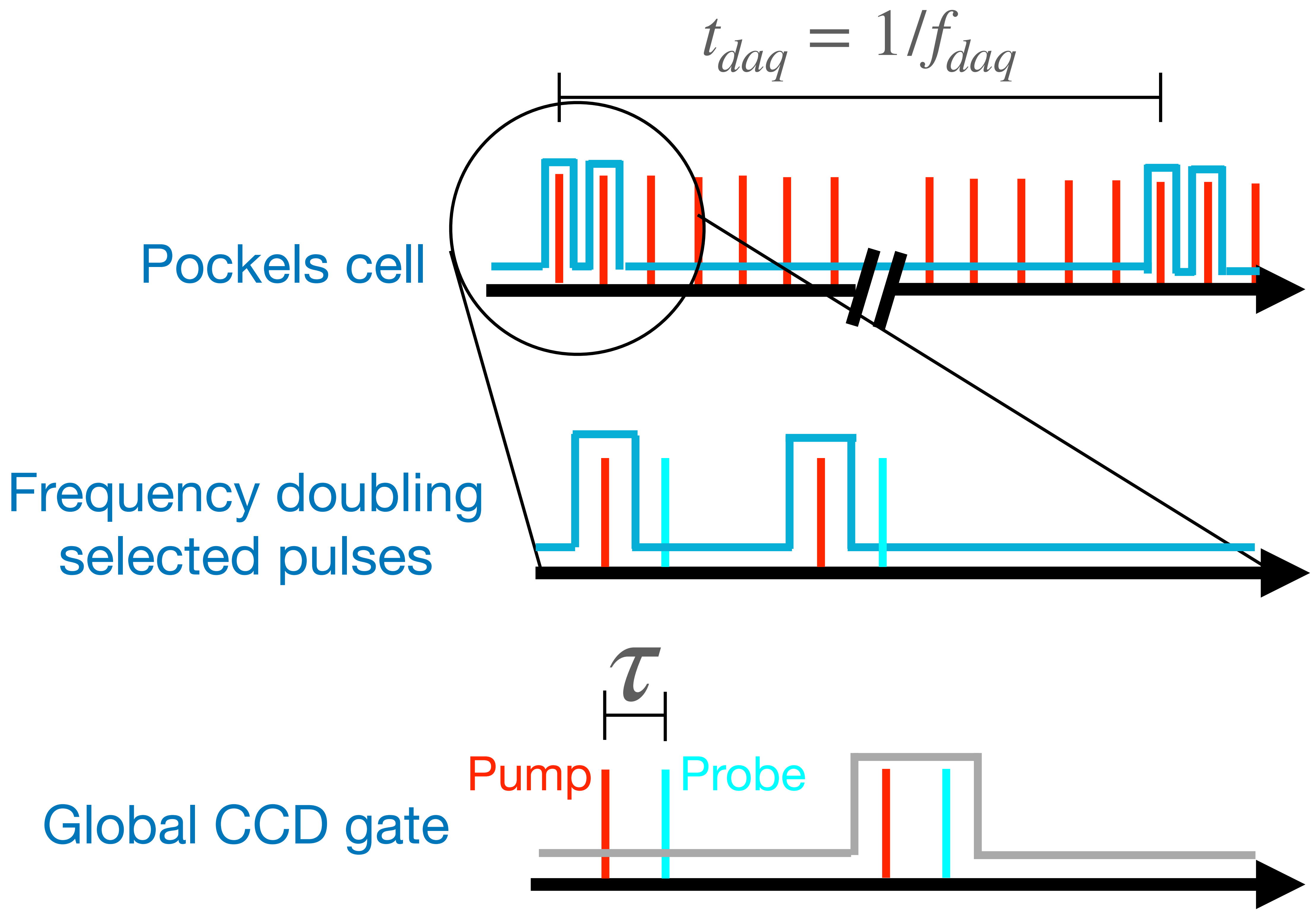
Experiment layout

- 1 kHz repetition rate, (1.05 ± 0.02) mJ, (39 ± 2) fs
- Pulse picker selects two or more pulses separated by multiples of 1 ms
- 800 nm focussed by f = 30 mm lens to 5 μm FWHM
- Chamber backfilled with H_2 at pressures 50 - 500 mbar



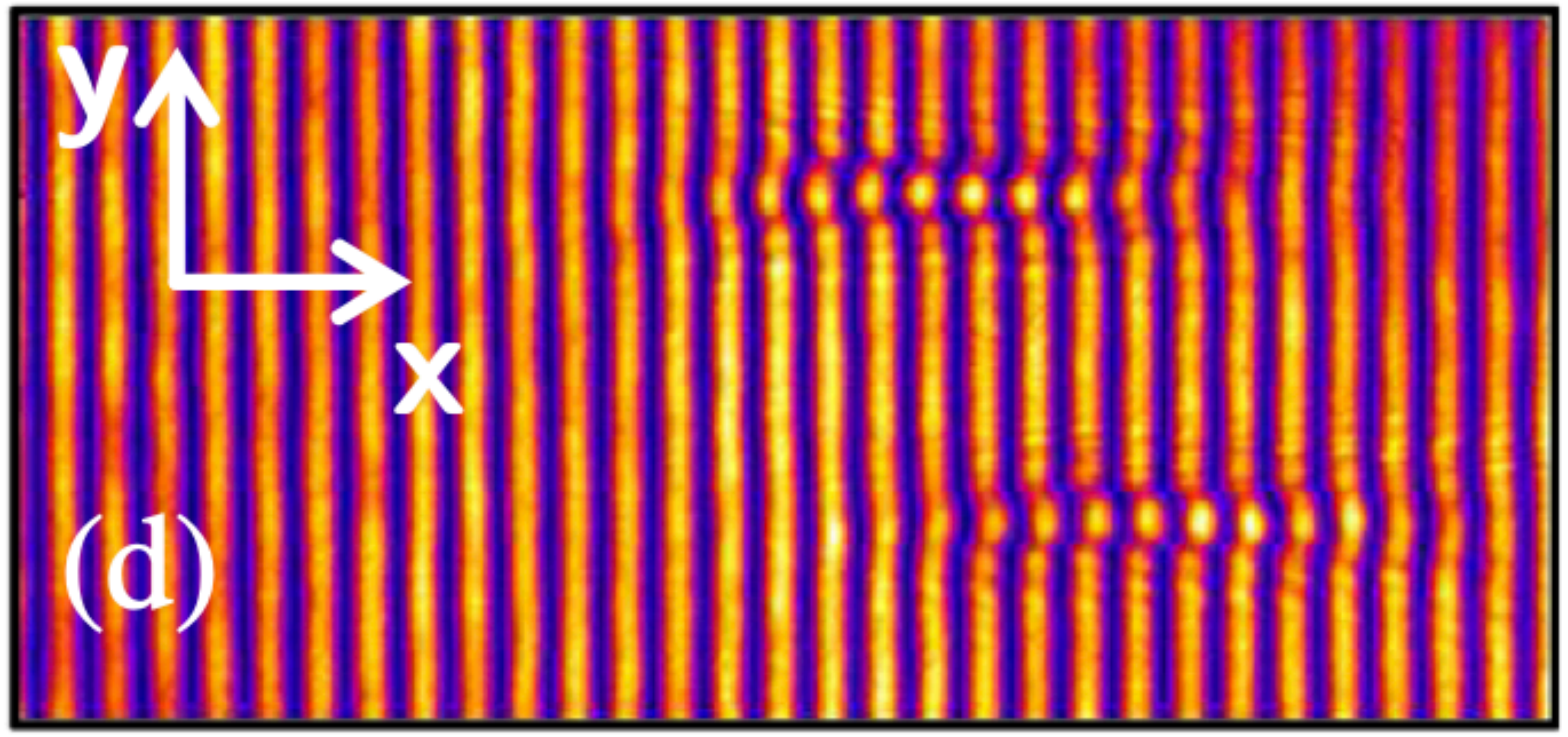
Pulse picking

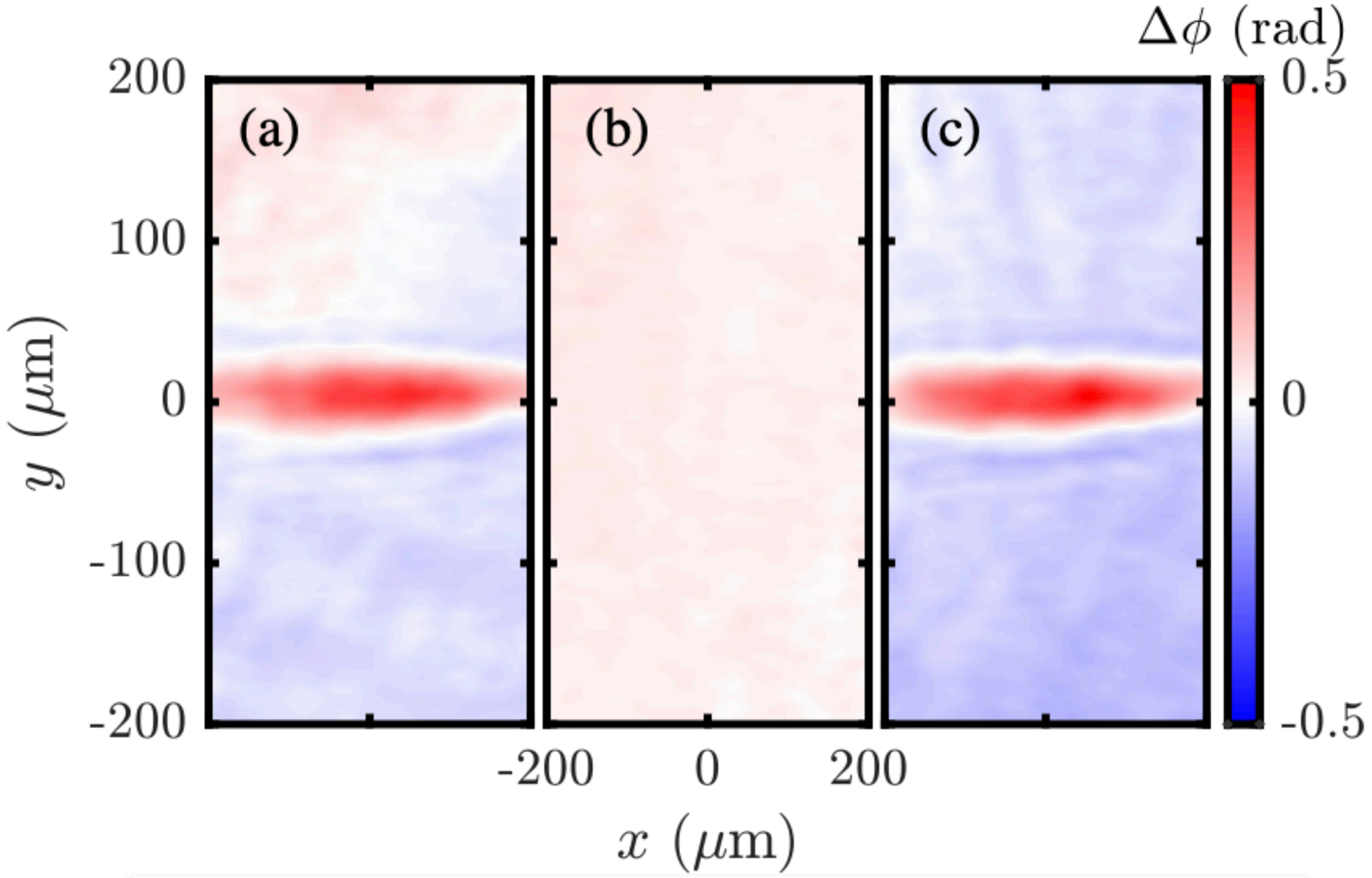
- Regenerative amplifier produced 1 kHz pulses @ 1 kHz
- Pulse pairs selected by pulse picker; part converted to 400 nm probe; spatially filtered; delayed 1 - 4 ns
  - Time between pulse pairs $t_{\mathrm{daq}} = 1/f_{\mathrm{daq}}$
- CCD triggered to record interferogram from second pulse of the pair



Diagnostics and retrieval

- Folded-wave Mach-Zehnder interferometer for transverse probing of the plasma
- Reference interferograms recorded before and after plasma generated by channel-forming beam
- Phase retrieved using Fourier transform method, polynomial background subtracted, phase maps Abel inverted





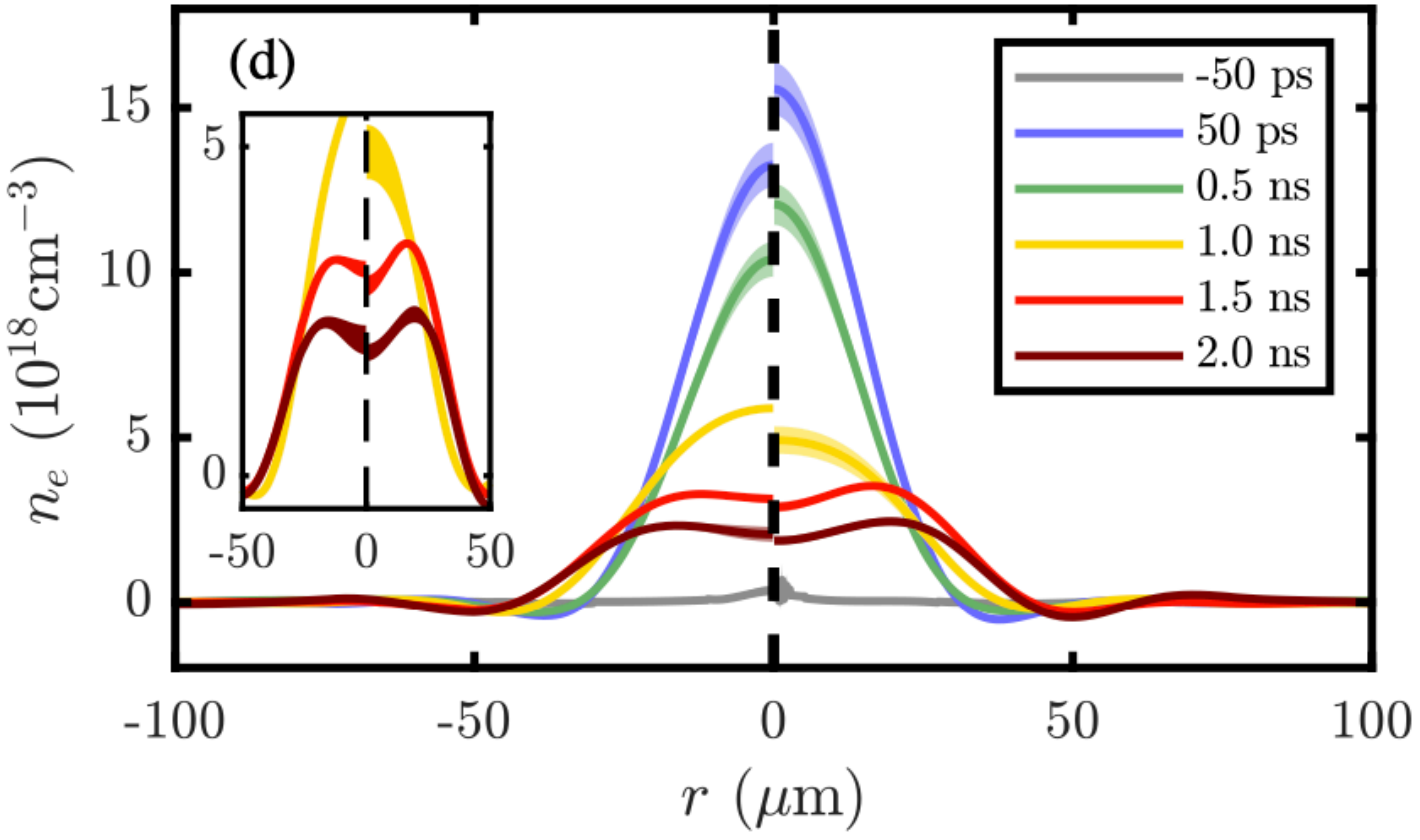
Qualitatively full recovery after 1 ms

Results - transverse interferometry

- Abel transform shows channel evolution $n_e(r)$ for fill pressure $P_b = (350 \pm 3)$ mbar
- Plasma channel exists at delay $\tau > 1$ ns
- Standard deviation over 50 shots; $f_{seq} = 10$ Hz

Single pulse

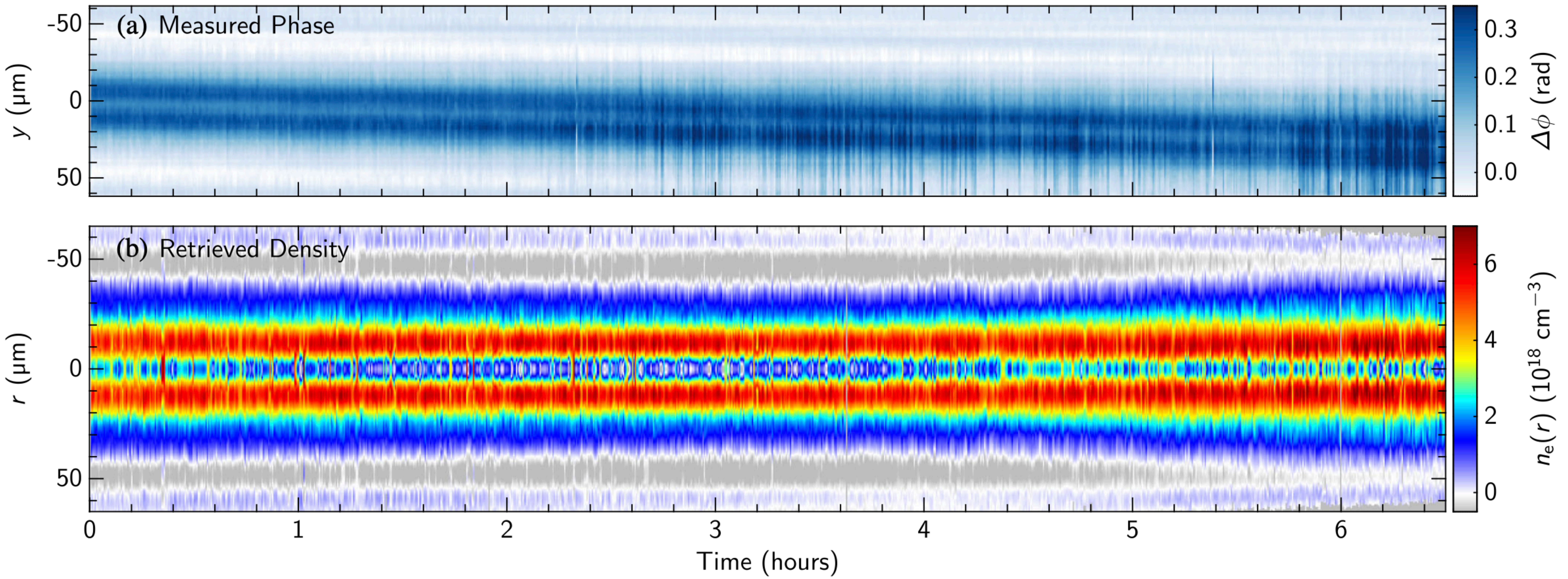
Second of two pulses (1 ms delay)



Results - long term operation

- Channel forming pulses again separated by 1 ms; pulse sequence repetition rate $f_{\mathrm{seq}} = 200$ Hz
- Mean pulse repetition rate $f_{\mathrm{rep}} = 0.4$ kHz
- Channel measured at $\tau = 1.5$ ns after second channel forming pulse
- 6.5 hour run time
- $P_{\mathrm{b}} = (350 \pm 3)$ mbar

Results - long term operation



- No significant long-term evolution of channel properties
    - Slow drift of probe beam appears to shift channel position
    - Later interferogram backgrounds less well represented by reference shots

Results - long term operation

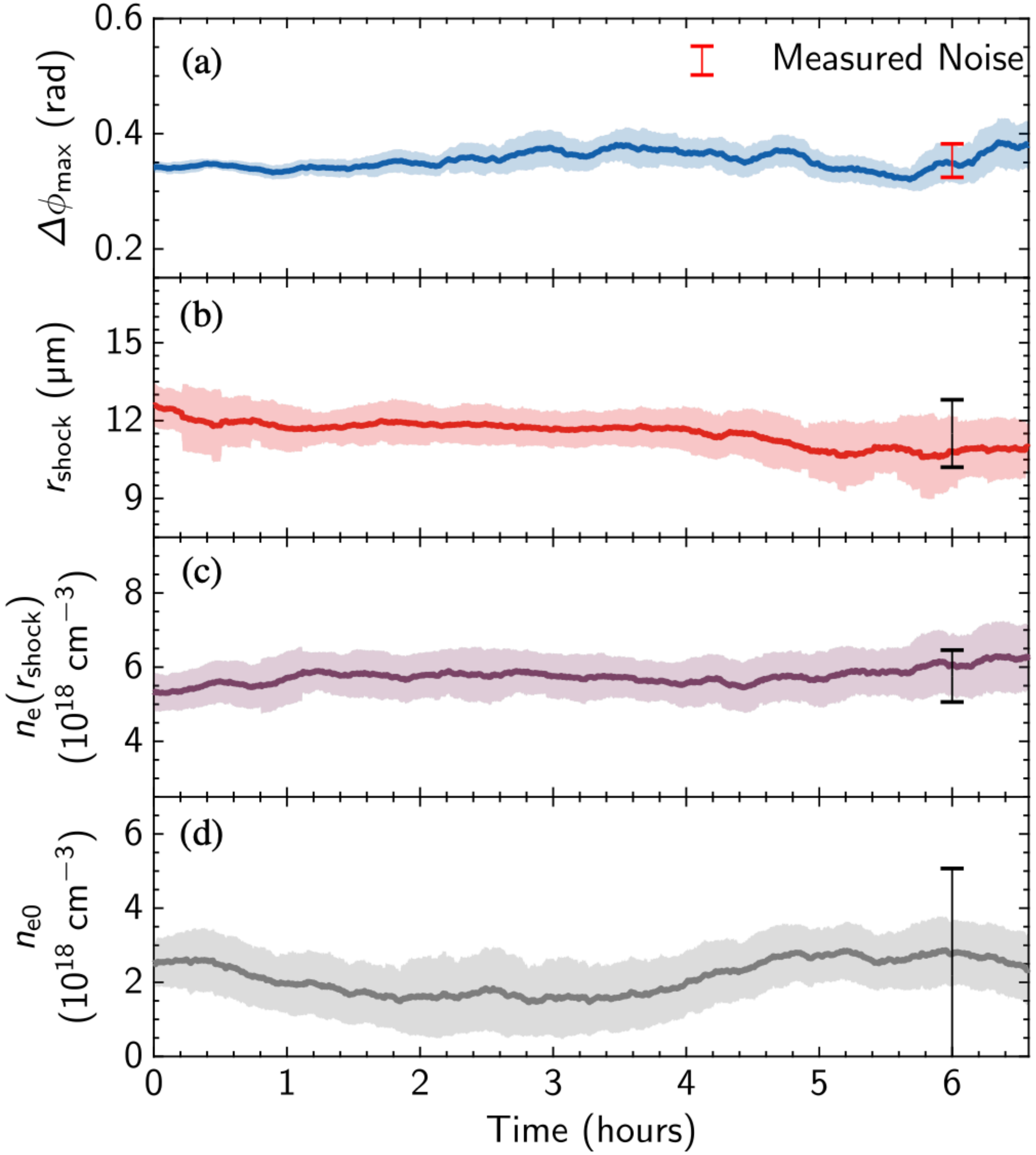
a) Maximum phase shift ~ 350 ± 40 mrad

b) Measured shock position ~ 11.5 ± 1.0 μm

c) Electron density at shock front
~ 5.7 ± 0.7 × 10^{18} cm^{-3}

d) Axial density ~ 2.10 ± 1.20 × 10^{18} cm^{-3}

- Moving average shown, with 50 shot standard deviation
- Errors largest at end of run (most noise)



Discussion

- Energy, pointing and spatial phase of the laser were not stabilized, so some fluctuations seen could be reduced
- HOFI channels are robust to variation in some laser/gas conditions
    - Increase in laser energy increases radius of ionised gas but electron energy does not change
    - Radial position of shock front varies with $E_{OFI}^{1/4}$ (energy per unit length in plasma column)
- Noise was calculated to present more significant variation in observed parameters than any real evolution

Outlook

- Operation at 1 kHz seems to be no issue for HOFI channels alone
    - But we have not investigated extra energy deposition by e.g. wakefields
- No long term heating effects of plasma seen over ~6.5 h period @ 0.4 kHz
- Upper limit of f_{rep} ~ O(MHz) if gas is flowed?
- High repetition rates achievable allow for active stabilisation

Summary slide

- Transverse interferometry showed two HOFI channels created 1 ms apart were essentially the same
- No long term heating effects seen over ~6.5 h period @ 0.4 kHz
- Beam stabilisation will improve variations in channel parameters seen due to noise
- HOFI channels are well suited to applications in future high-repetition rate multi-GeV plasma accelerators

Single pulse

Second of two pulses (1 ms delay)