Advancement in plasma sources towards high repetition rate operation

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Acknowledgements

Alex Picksley, James Cowley, Chris Arran, Alexander Boetticher, Oscar Jakobsson, Jakob Jonnerby, Rob Shalloo, Roman Walczak, Simon Hooker

John Adams Institute for Accelerator Science, University of Oxford

Chris Thornton, Nic Bourgeois

Rutherford Appleton Laboratory

Harry Jones, Laura Corner

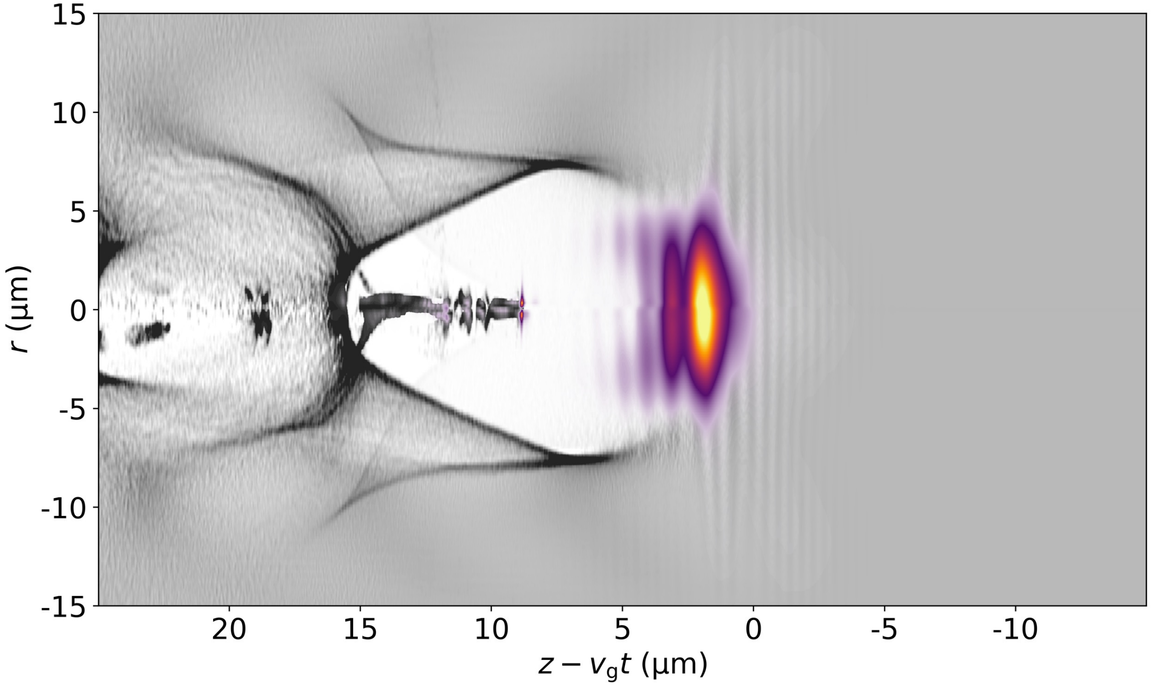
Cockcroft Institute, University of Liverpool

Laser Plasma Accelerators

→ Conventional accelerators are ubiquitous in science, medicine and industry

→ Typically, these accelerators are based on accelerator cavities, which can withstand up to $\lesssim$100 MV/m

→ Laser plasma accelerators, driven by intense laser plasmas, can support up to 100s GV/m



⇒ Reduction in size, cost and shielding needs

→ However, users of accelerators have requirements beyond the current LPA, such as **operation at kHz-rates**

Outline

- Towards a 10 GeV scale Laser Plasma Accelerator
- Guiding of intense pulses in >100mm HOFI Channels
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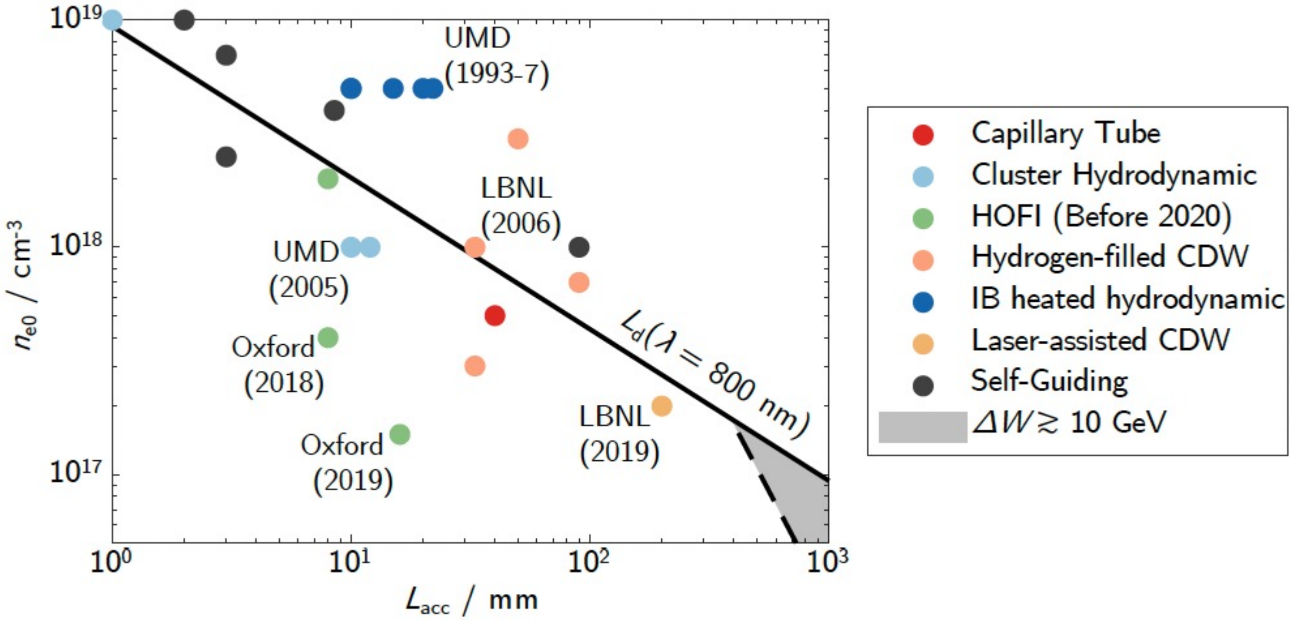
Requirements for a suitable waveguide

→ The acceleration length of a LPA can be extended by using plasma channels

→ Similar to GRIN optical fibers, propagating through a transverse electron density profile with a minimum on-axis can counteract diffraction

→ Different techniques have been studied as waveguides, including capillary discharge waveguides or self-guiding

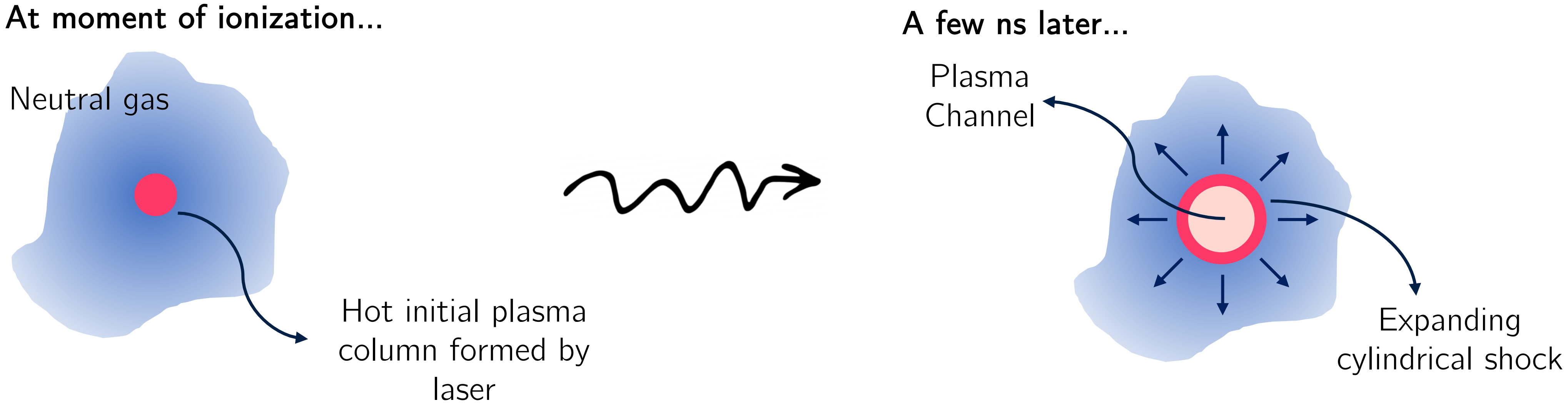


Required parameters

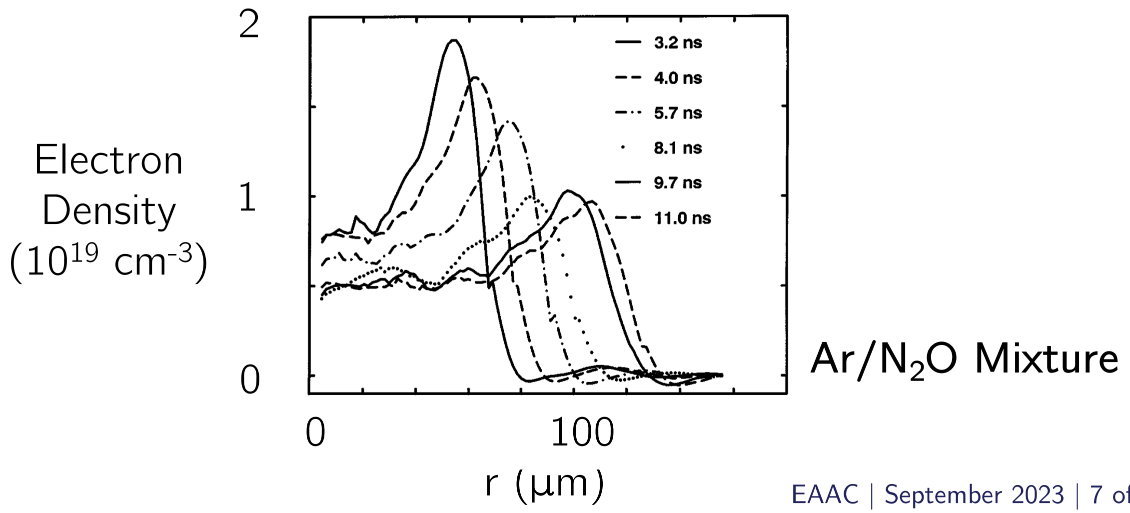
Intensity to be guided, I_{peak}	$\gtrsim 10^{18}$ W cm^{-2}
Matched spot-size, w_m	$10 - 100$ µm
Axial density, n_{e0}	$\lesssim 10^{17}$ cm^{-3}
Length, L_{acc}	$0.25 - 1$ m
Channel shape, $n_e(r)$	Tunable to match accelerator
Transmission $T(z = L_{acc})$	$\sim 100\,\%$
Gas species	Low-Z (H_2, He)
Repetition rate, f_{rep}	$\gtrsim 1$ kHz
Lifetime	$> 10^8$ shots
Stability	High
Energy cost	$\lesssim 10\,\%$ of total stage energy
Diagnostic access	Transverse and longitudinal

Waveguides from expansion of a plasma column

→ Plasma channels can be formed from the hydrodynamic expansion of a laser generated plasma column

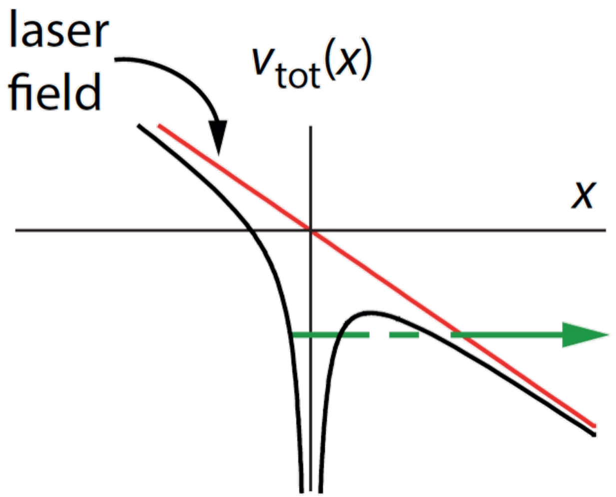


- A secondary laser pulse is used to pre-ionize the gas ($\tau \cong 100$ ps, $I \cong 10^{13}$ Wcm^{-2})
- Pioneering work based on electron heating via **inverse Bremsstrahlung** $\Rightarrow n_e \geq 10^{19}$ cm^{-3}
- Plasma channels are **free-standing** making them ideal for high repetition rate operation



[Durfee & Milchberg, PRL (1993); Durfee *et al.*, PRE (1995); Clark & Milchberg, PRL (1997)]

HOFI Channels

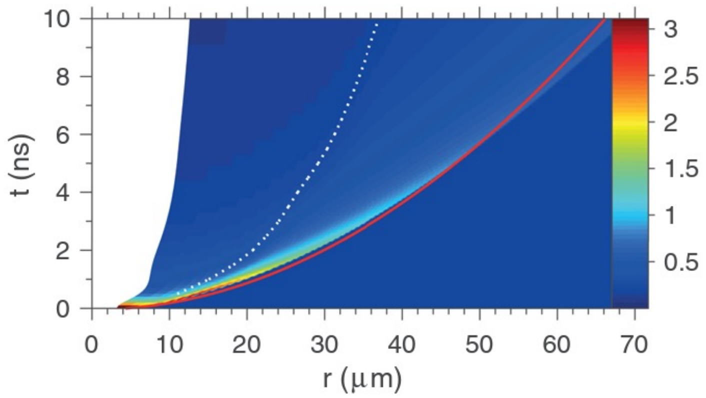


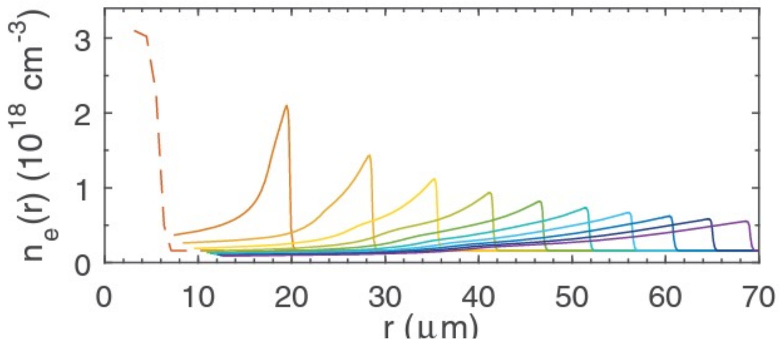
→ Hydrodynamic Optical-Field-Ionisation (HOFI) Channels are waveguides specifically suited for low density, high repetition rate operation

→ Plasma column formed and heated by **optical field ionisation** (residual energy after process of tunnelling ionisation)

→ OFI acts on the atomic level ⇒ electron heating independent of the initial density

→ Electron temperature set only by the gas species ($k_B T_e \cong 10$ eV for H)





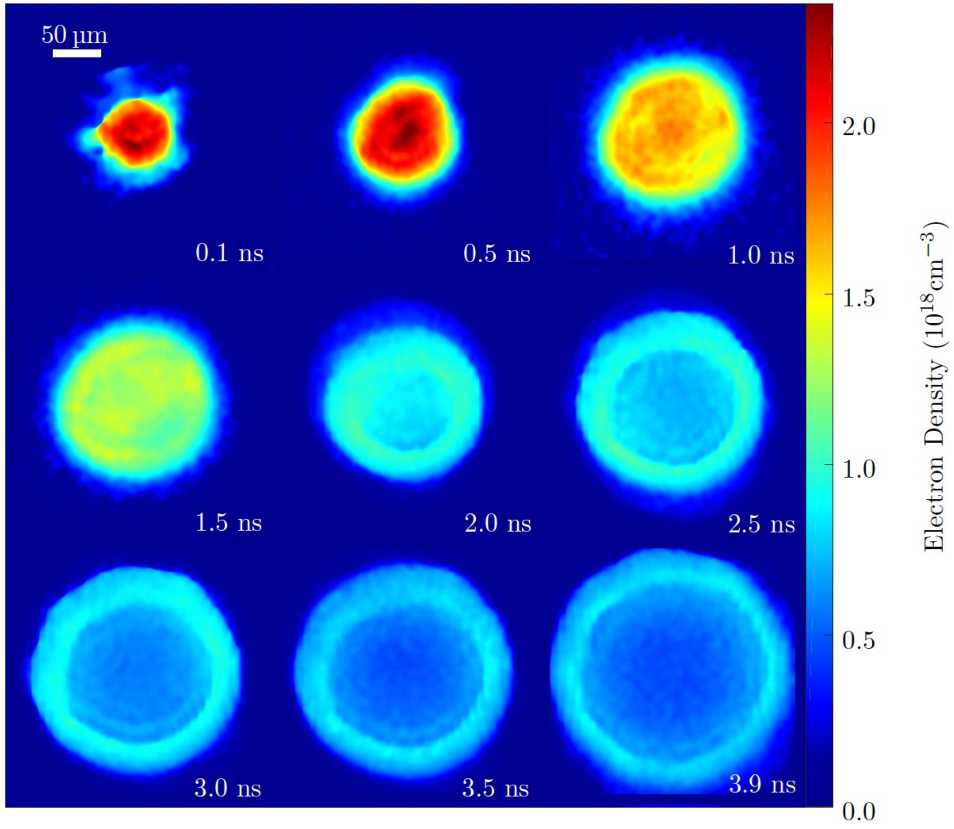
→ Formation of plasma channels shown using MHD simulations

→ Evolution expected to follow the Sedov-Taylor blast wave theory

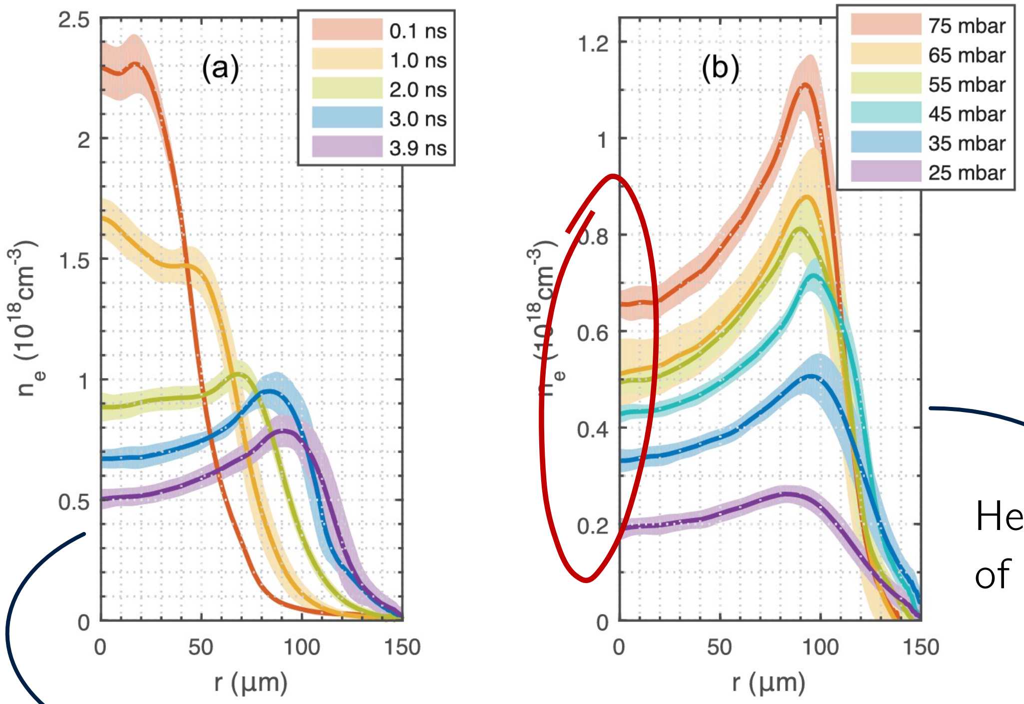
[Shalloo *et al.*, Phys. Rev. E 97 (2018); Lemos *et al.* PoP 20.6 (2013); Lemos *et al.* PoP 20.10 (2013)]

HOFI Channels. Proof-of-principle

- → Proof-of-principle experiment to demonstrate viability of HOFI channels
  - → HOFI channel generated by lens-focusing a TW laser (few mm in length)
  - → Characterized through longitudinal probing



Only a few mJ per mm of channel



Heating independent of initial density

Closely matches Sedov-Taylor blast wave theory for $k_B T_e$ = 9.2 eV

[Shalloo *et al.*, Phys. Rev. E 97 (2018)]

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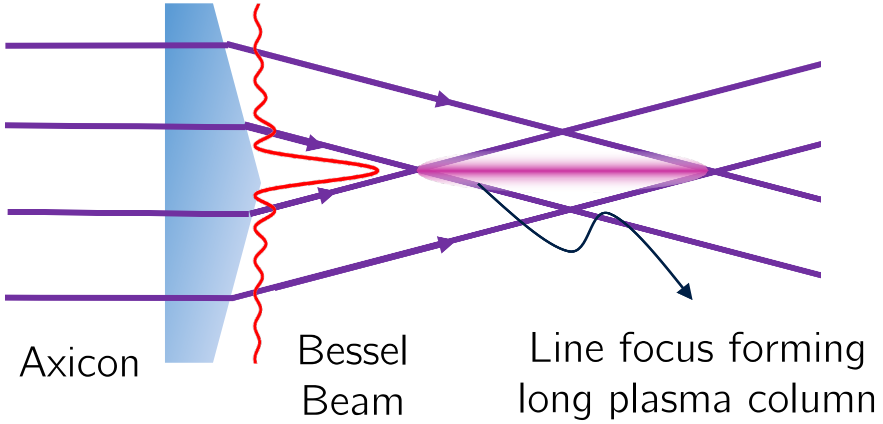
Guiding by Long, Low-density HOFI Channels

→ Experiment to demonstrate HOFI plasma channels guiding high-intensity, joule-level pulses (Gemini TA3, CLF–RAL, 2019)

→ Longer plasma columns can be produced by optics with longer focal range ⇒ **Axicons**



[A. Picksley, A. Alejo, *et al*. (2020), PRAB 23(8), 81303]

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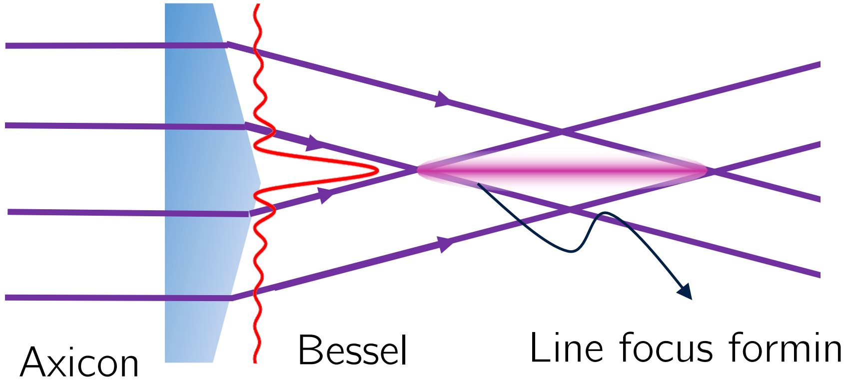
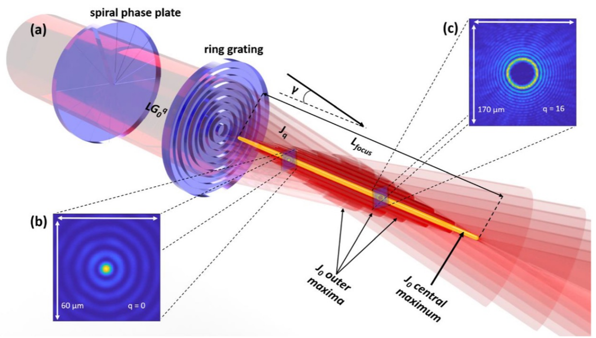
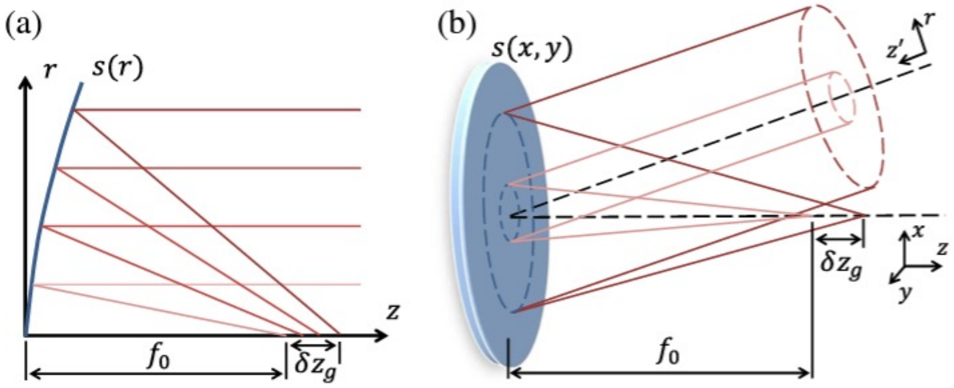


→ Previously demonstrated to generate hydrodynamic channels by Milchberg *et al.* [PRL 71(15), 1993]

→ Alternatives to axicons are begin actively studied, such as **phase plates** or **axiparabolae**



[J.E. Shrock *et al.* Phys. Plasmas 29, 073101 (2022)]



[S. Smartsev *et al.* (2019). Optics letters, 44(14), 3414]

Cedric Thaury's talk on Wednesday morning

[A. Picksley, A. Alejo, *et al.* (2020), PRAB 23(8), 81303]

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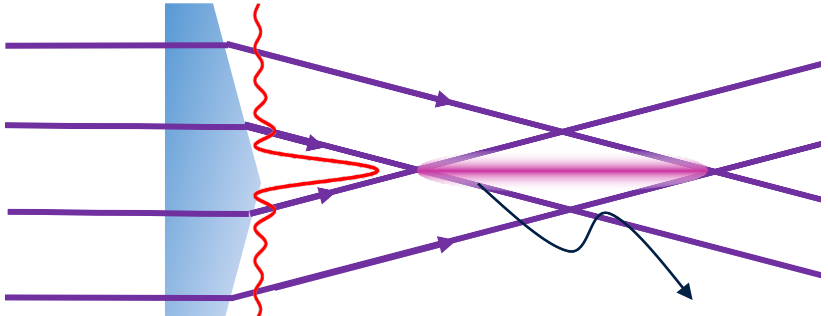
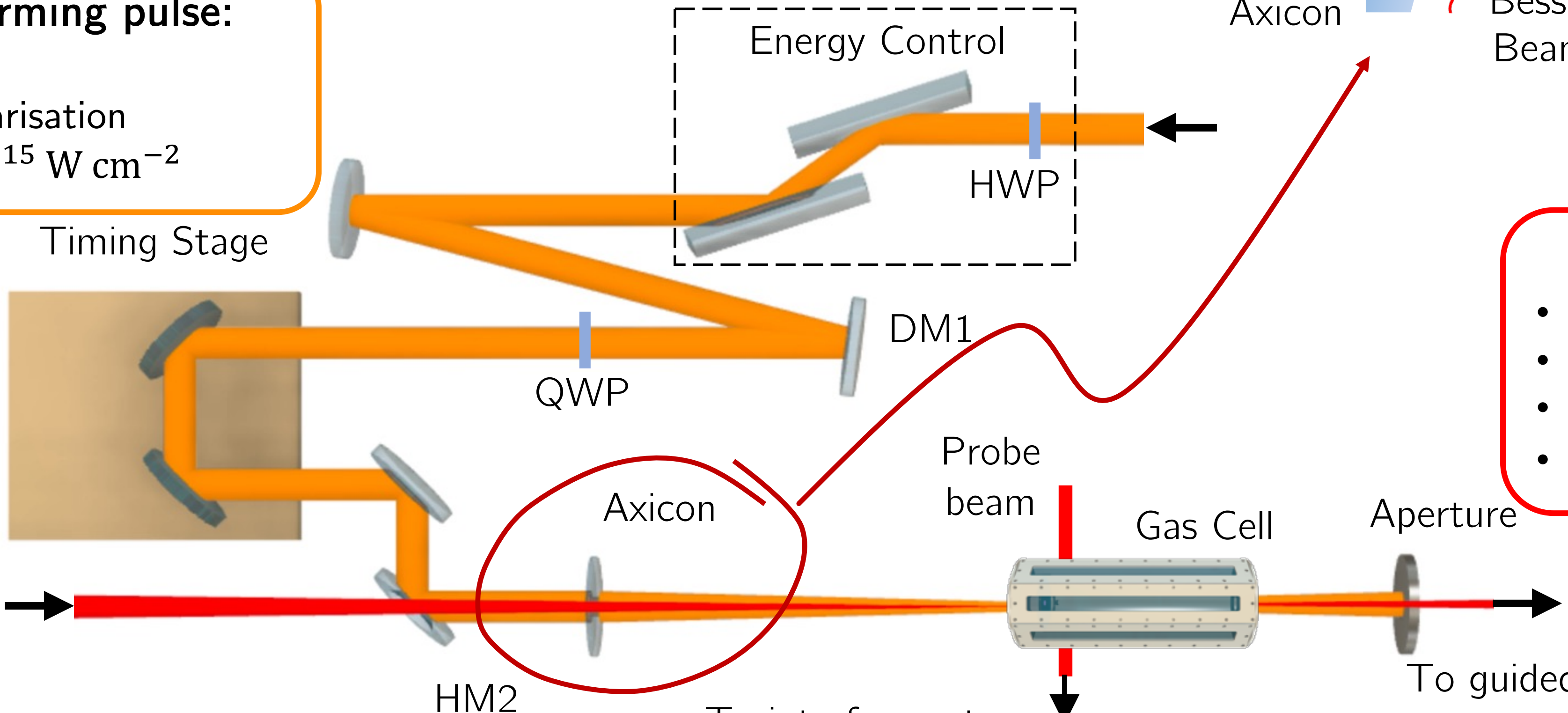


Channel-forming pulse:

- (45 ± 3) fs
- Circular Polarisation
- $I_{ax} = 5 \times 10^{15}\ \mathrm{W\,cm^{-2}}$



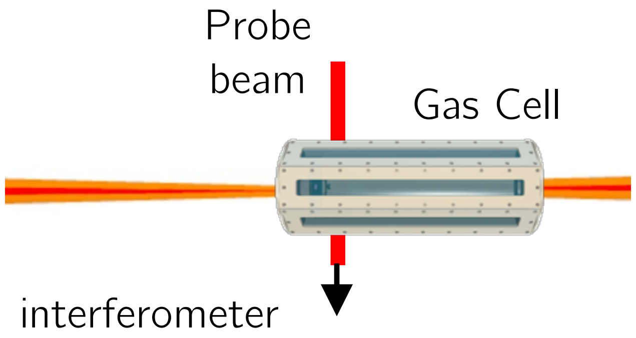
Guided Pulse

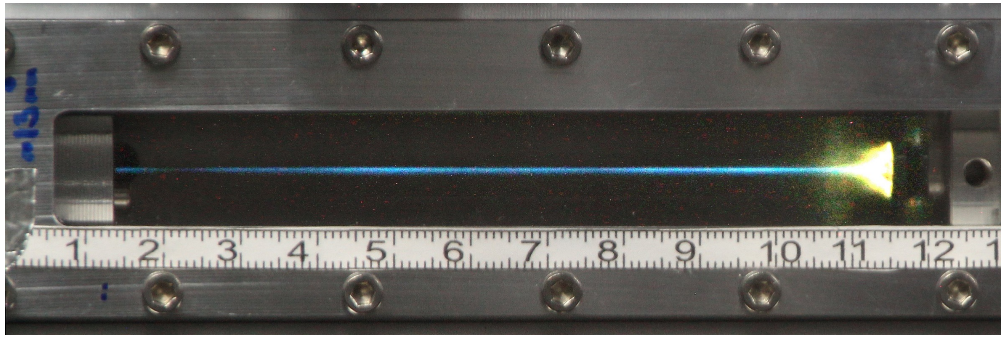
- $\mathcal{E} = 1.1$ J
- (45 ± 3) fs
- Focused by f/40
- $I_{peak} \approx 6 \times 10^{17}\ \mathrm{W\,cm^{-2}}$

[A. Picksley, A. Alejo, *et al.* (2020), PRAB 23(8), 81303]

HOFI Channels – Density profile

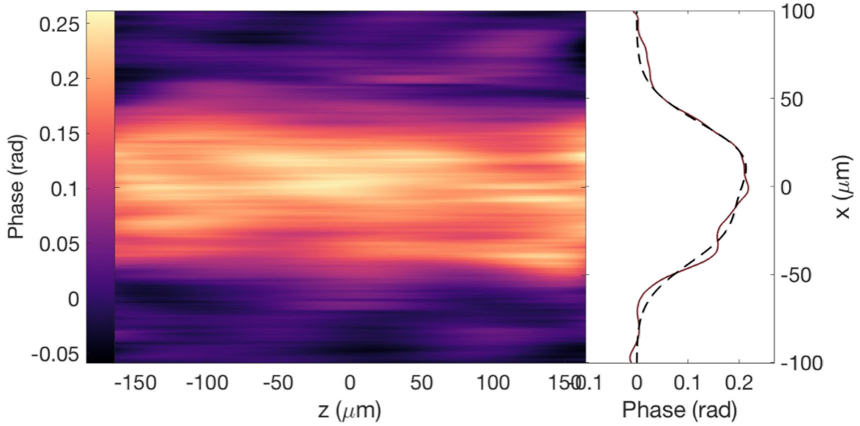
→ Plasma density was characterized using transverse optical probing





→ Analysis routine developed to allow profile retrieval

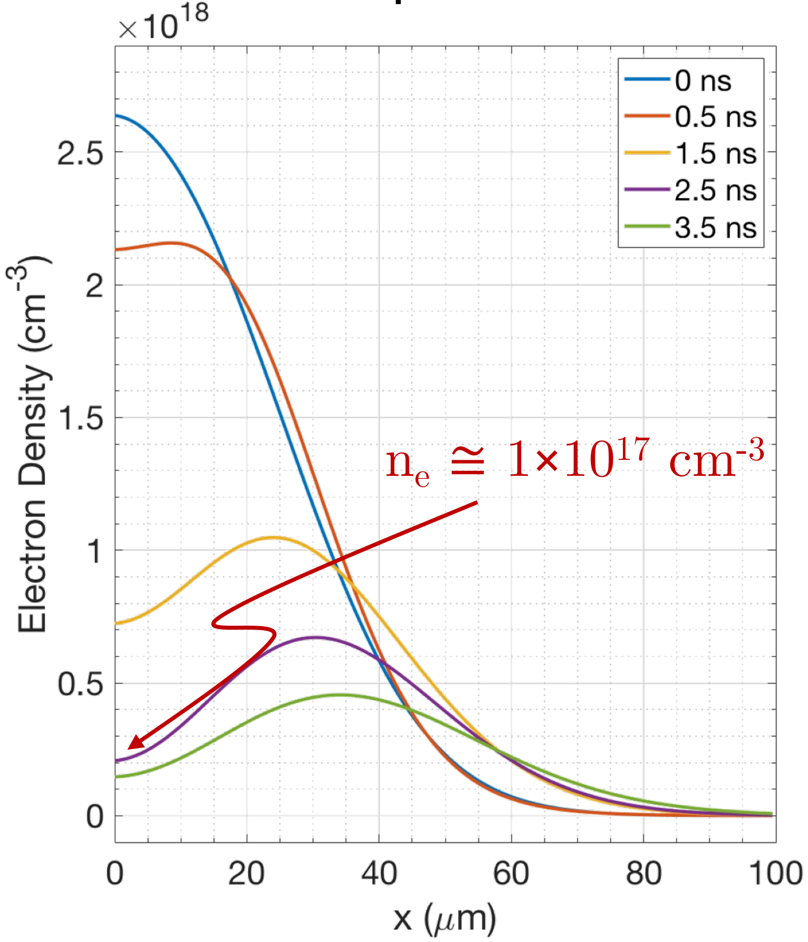
Phase Map



Low density ⇒ greater uncertainty

- Data tends to be noisier (low phase shift)
- The analysis requires a good background reference
- Abel inversion can amplify small levels of noise to yield large errors near axis

Measured evolution of an axicon-formed HOFI plasma channel



[A. Picksley, A. Alejo, *et al.* (2020), PRAB 23(8), 81303, R. Shalloo *et al.*, Phys. Rev. Accel. Beams 22 (2019)]

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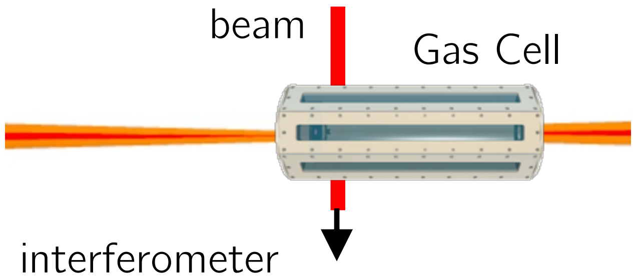

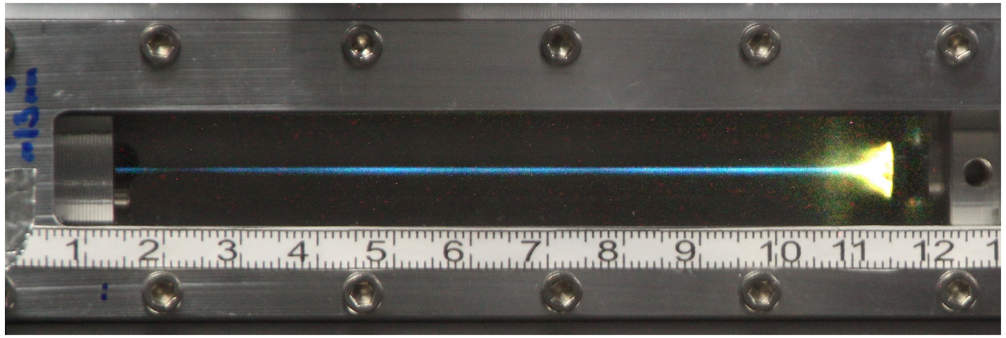

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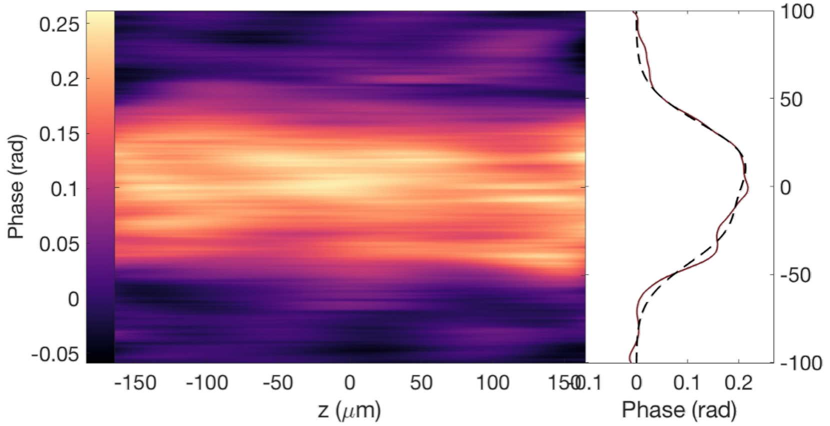

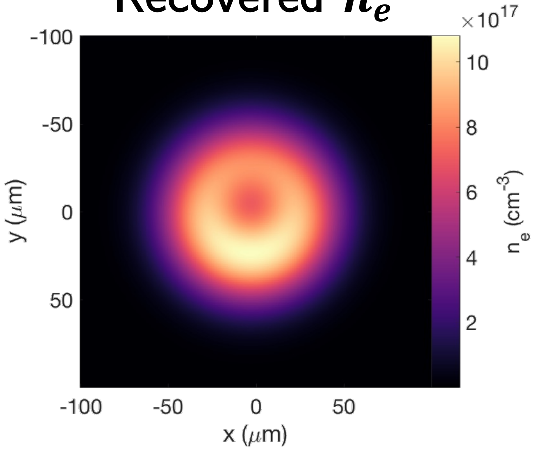

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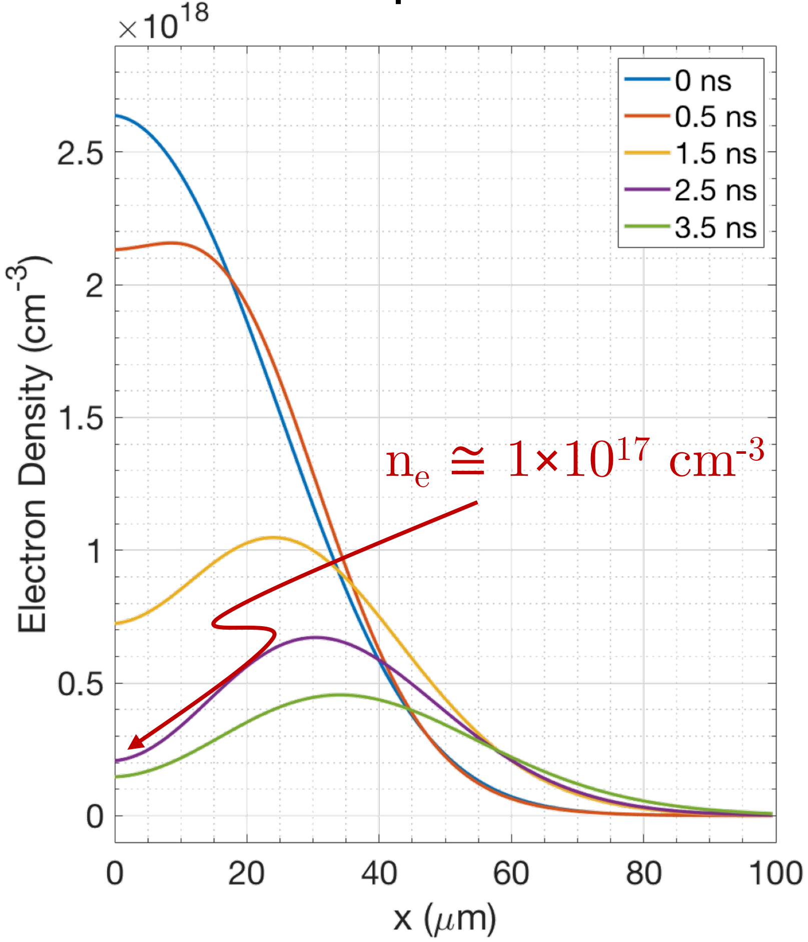

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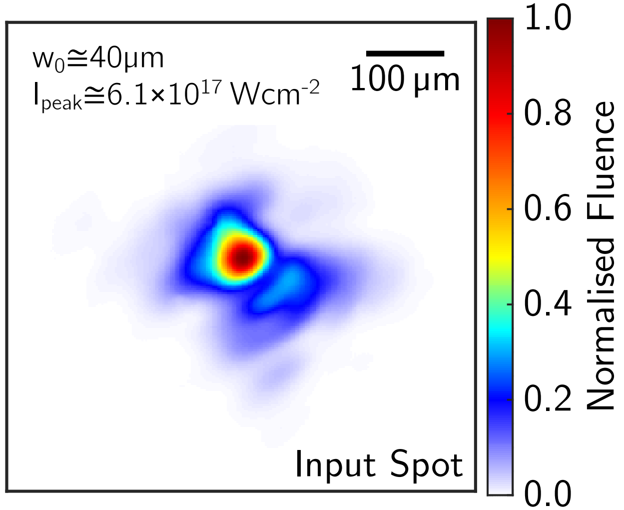
HOFI Channels – Guiding

z = 0 mm

Free propagation



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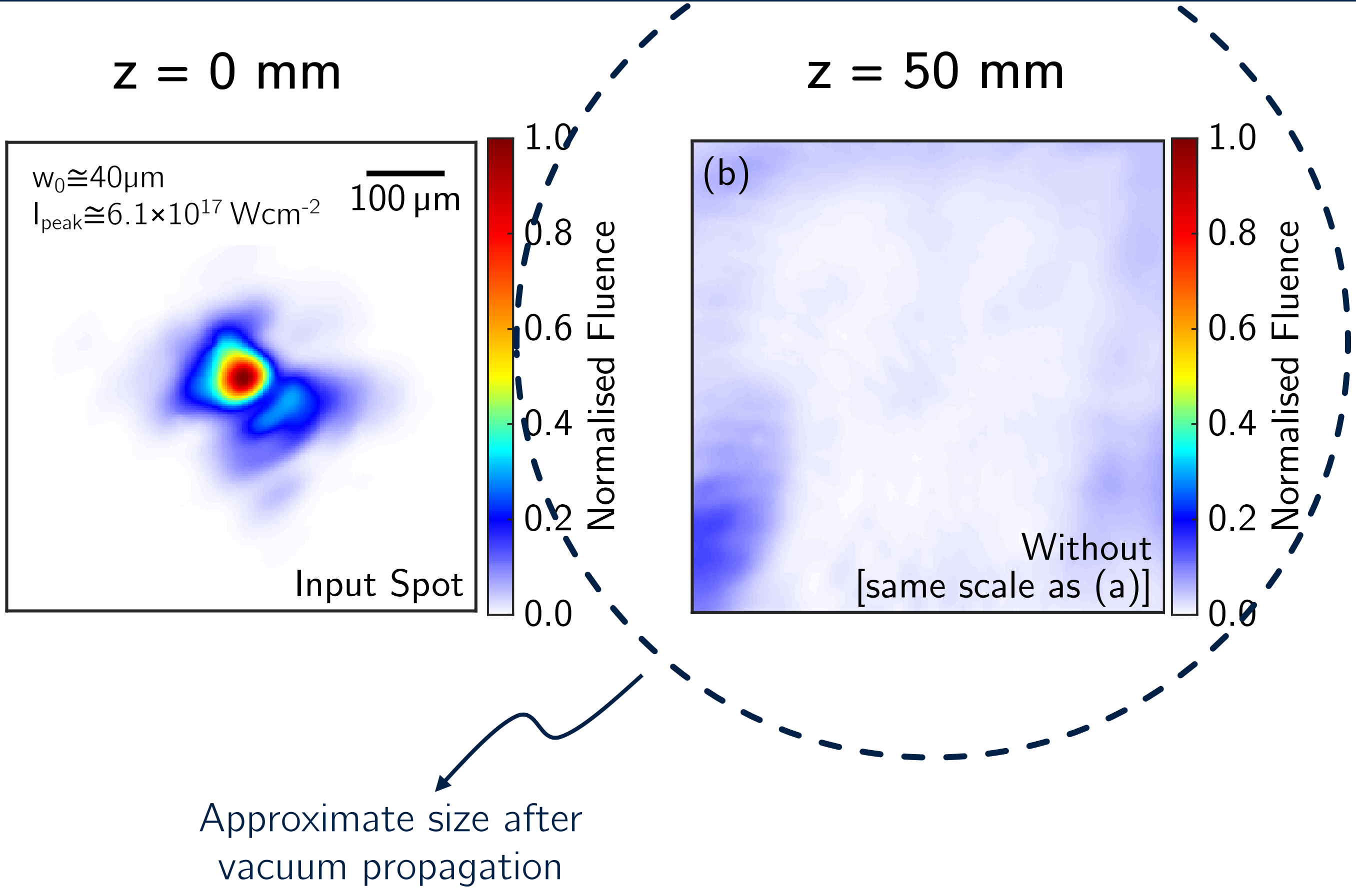

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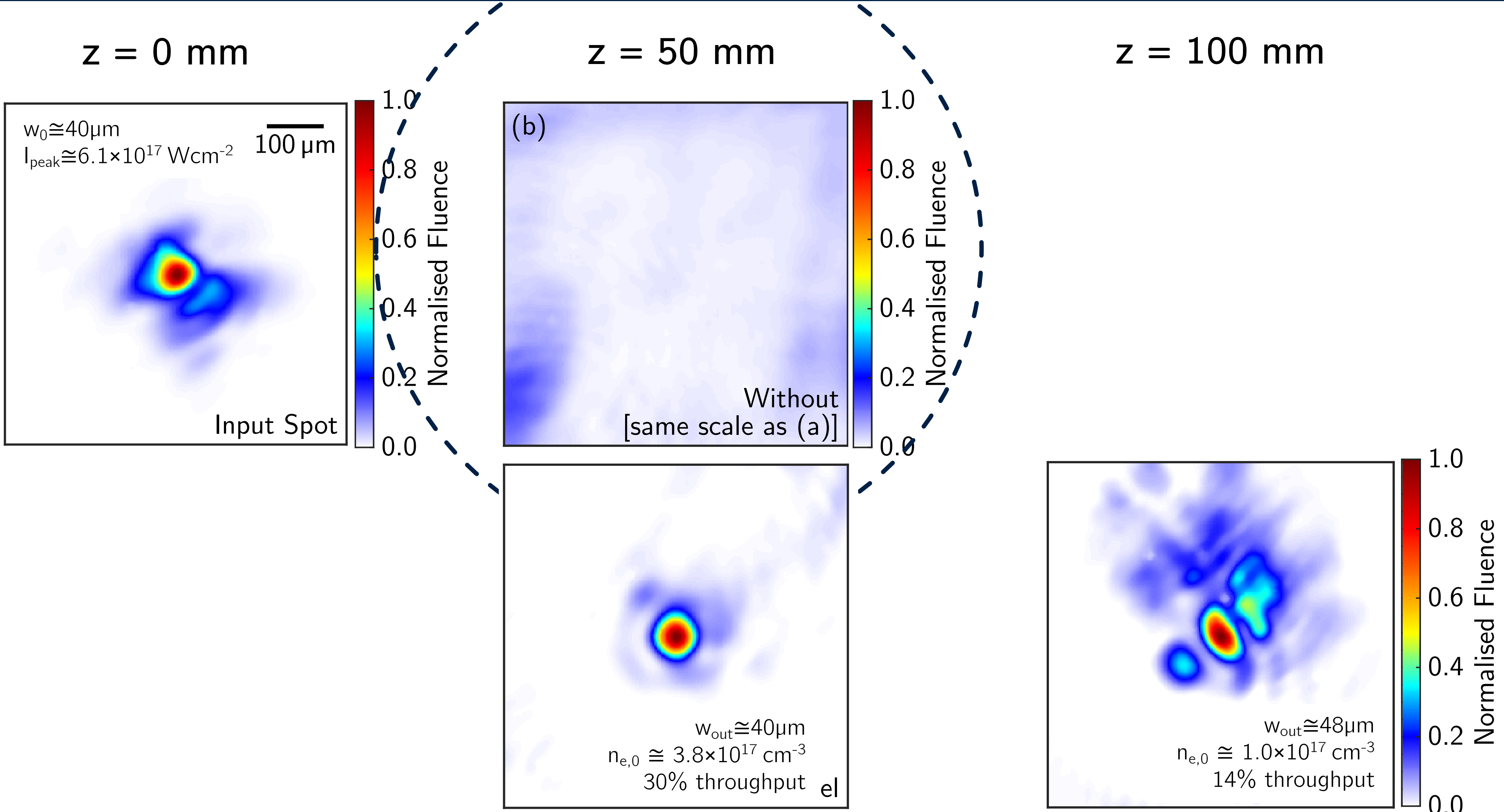

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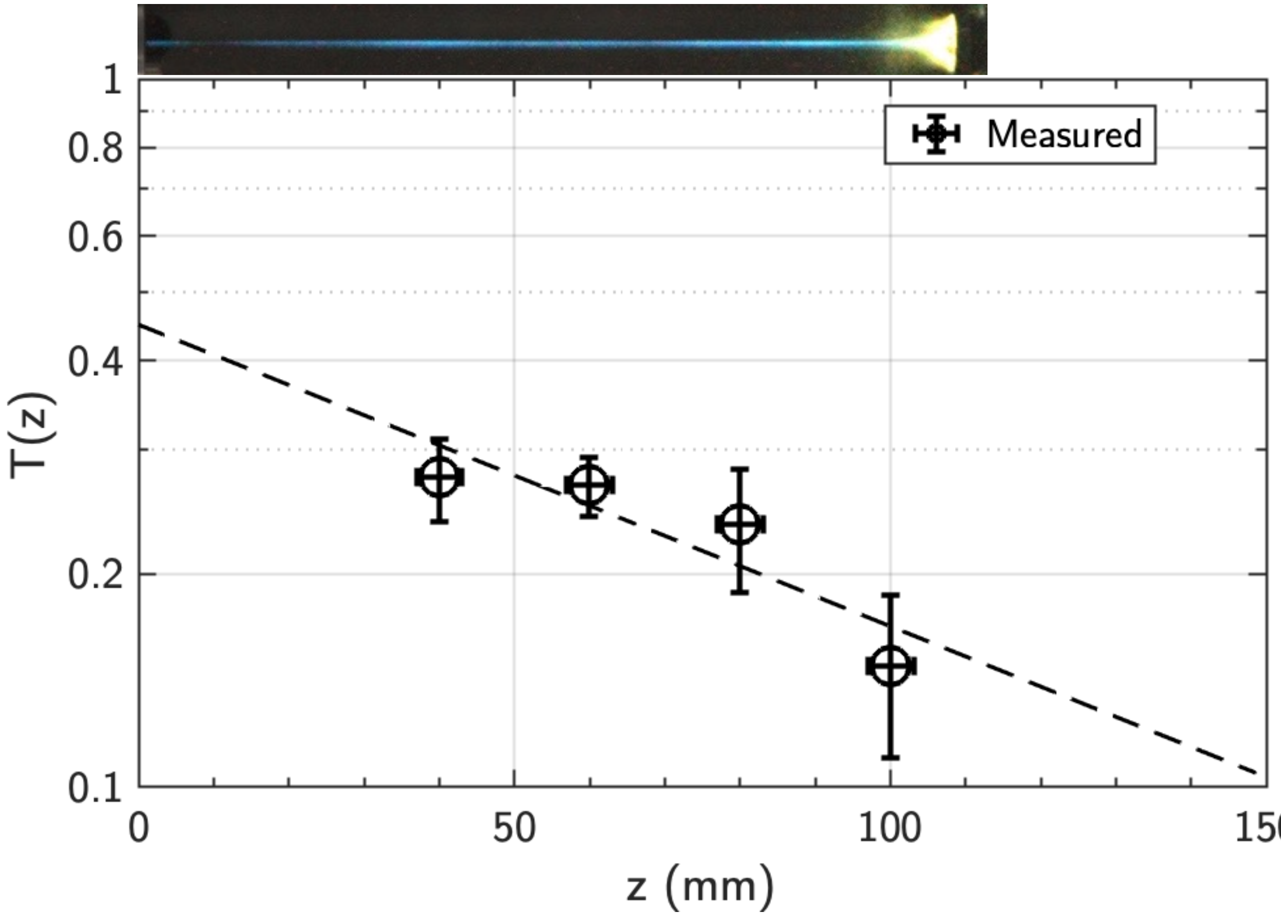
HOFI Channels – Transmission

→ In the low-intensity limit ($a_0 \ll 1$), zeroth order mode of the channel follows,

$$T(z) = T(0) \times \exp(-z/L_{att})$$

Energy coupled into 0^{th}-order mode

Intensity drop of 0^{th} order due to leakage



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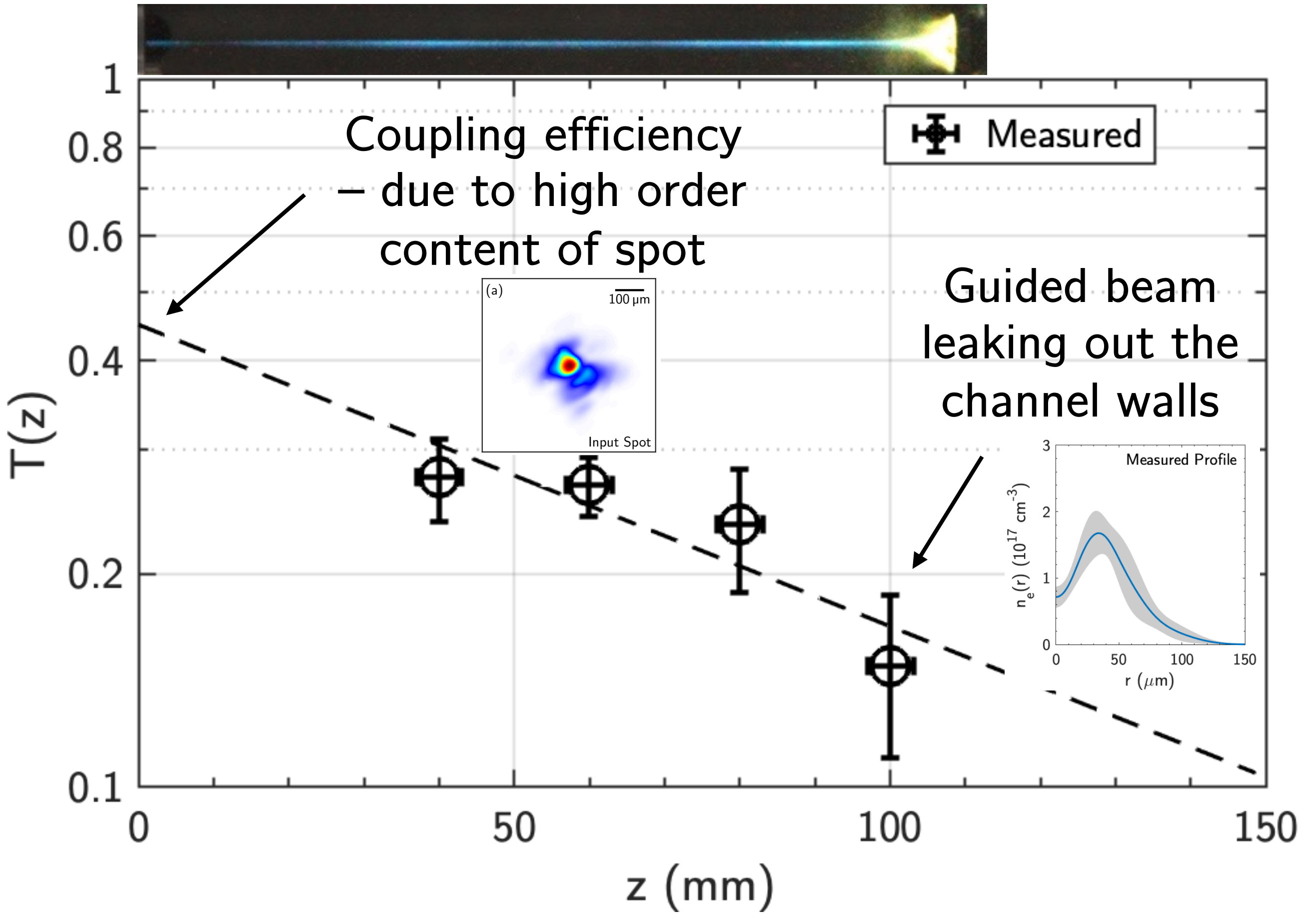

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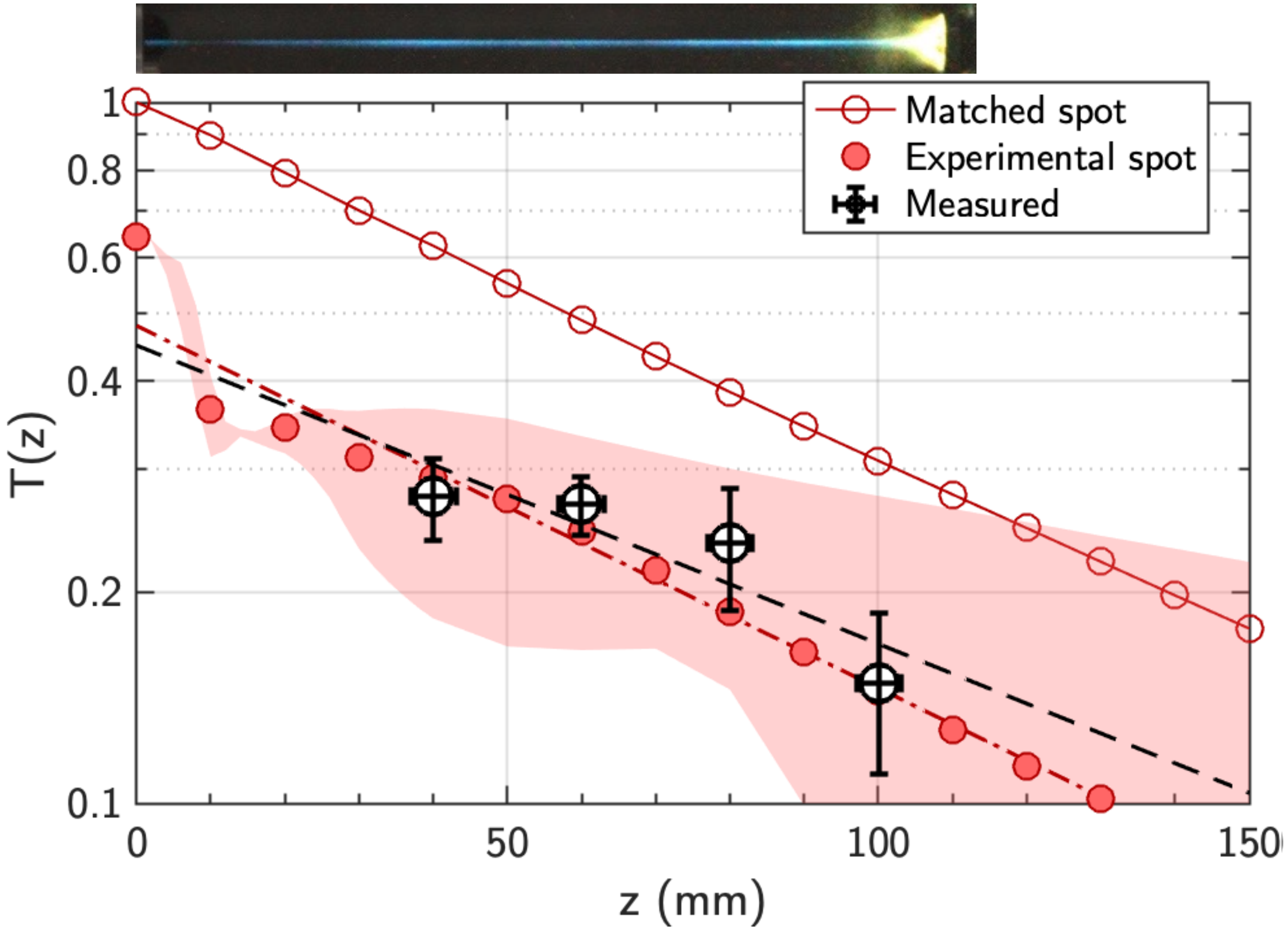

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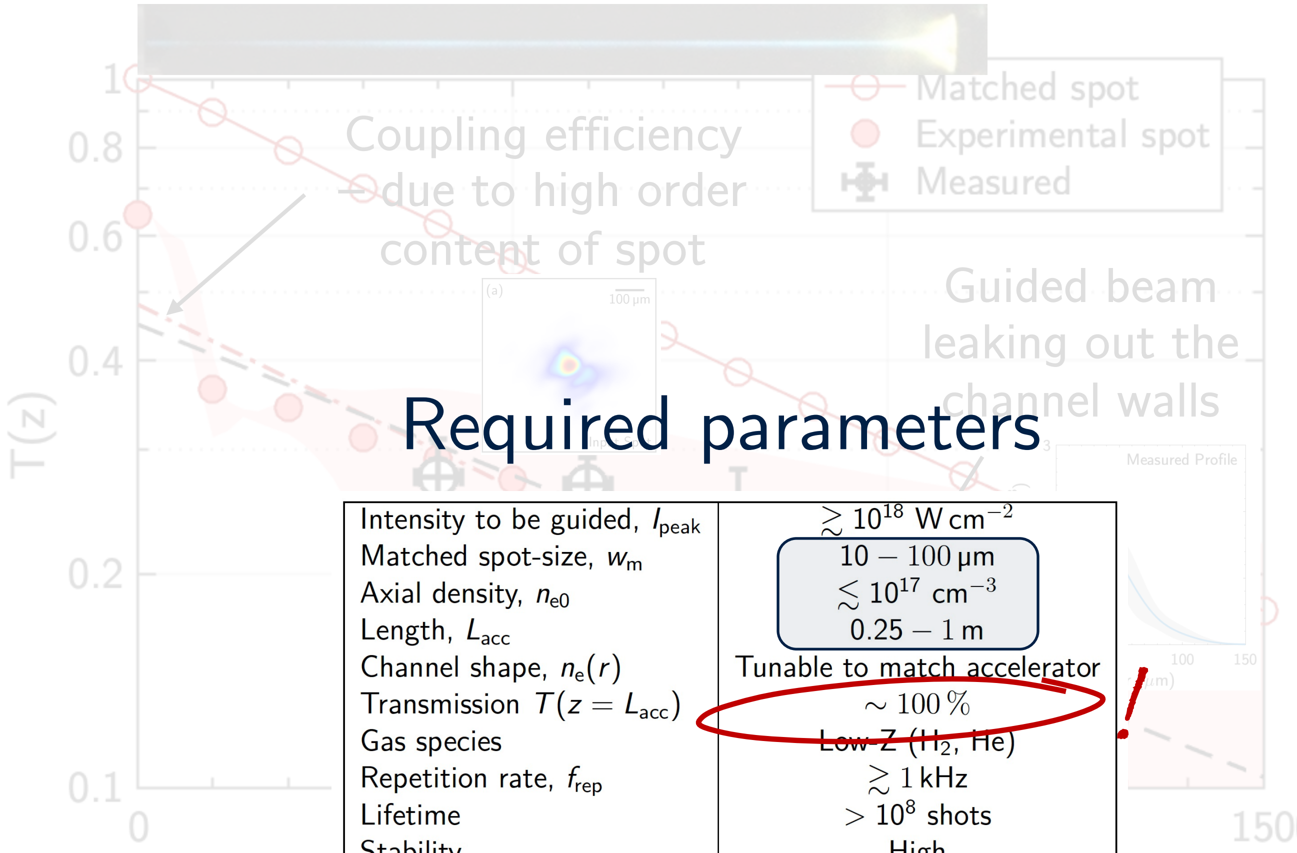

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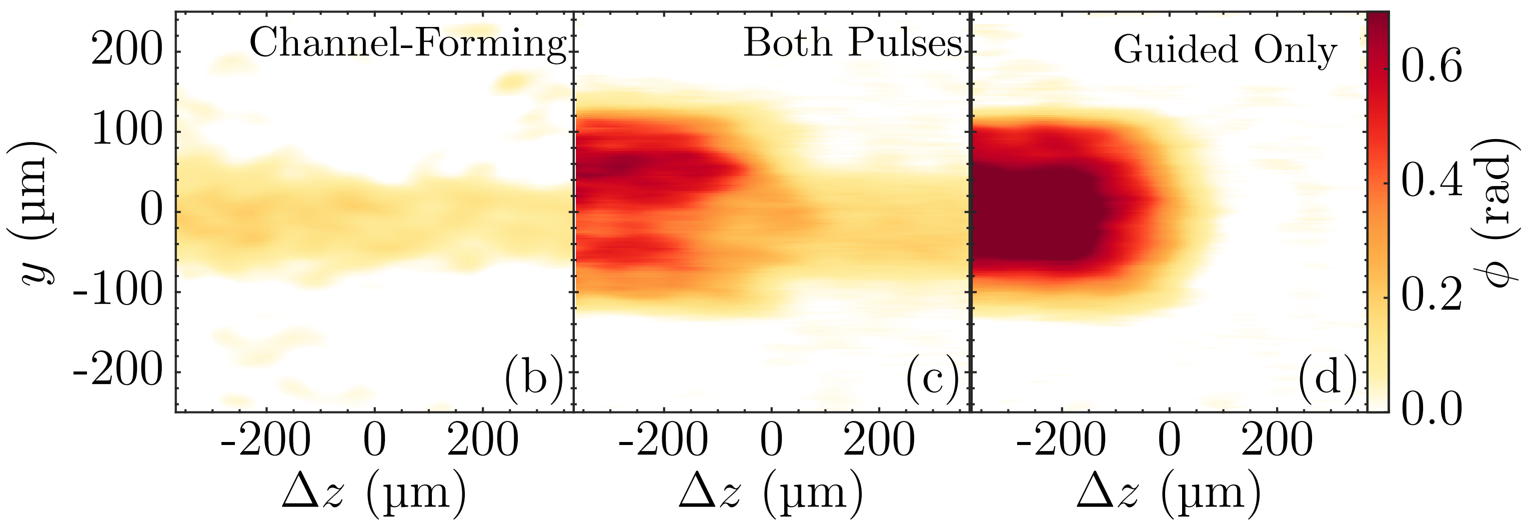
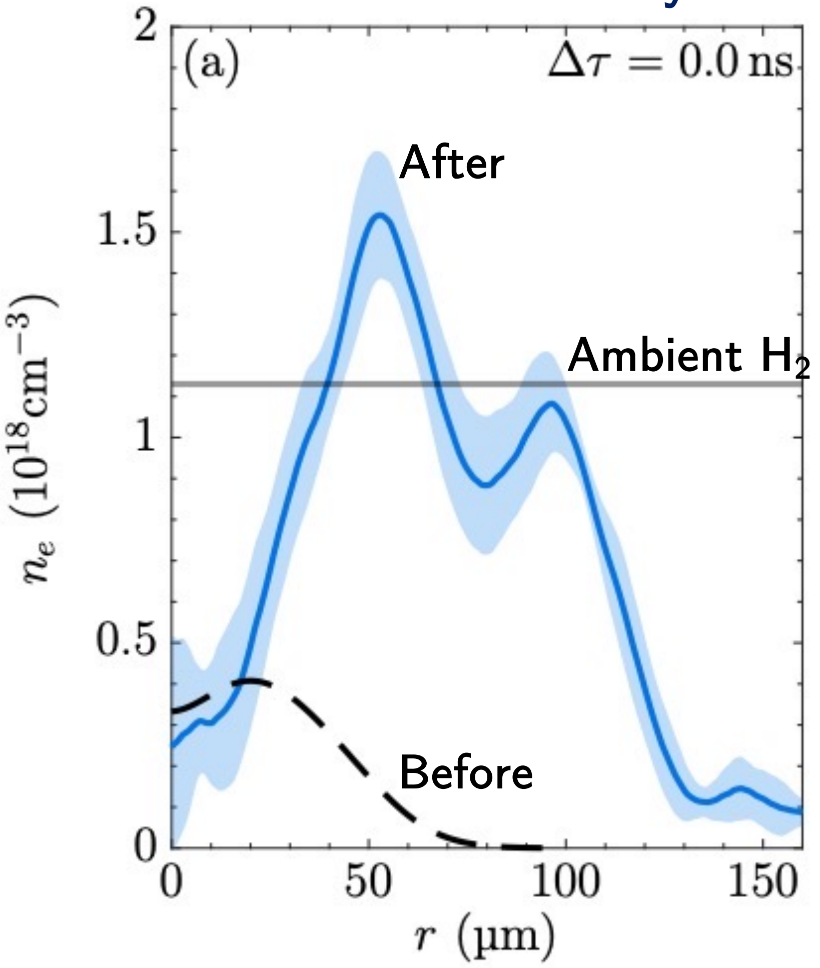
Conditioning of HOFI channels

→ Transverse interferometry reveals guided pulse **conditions** the plasma channel to increase confinement



Electron Density



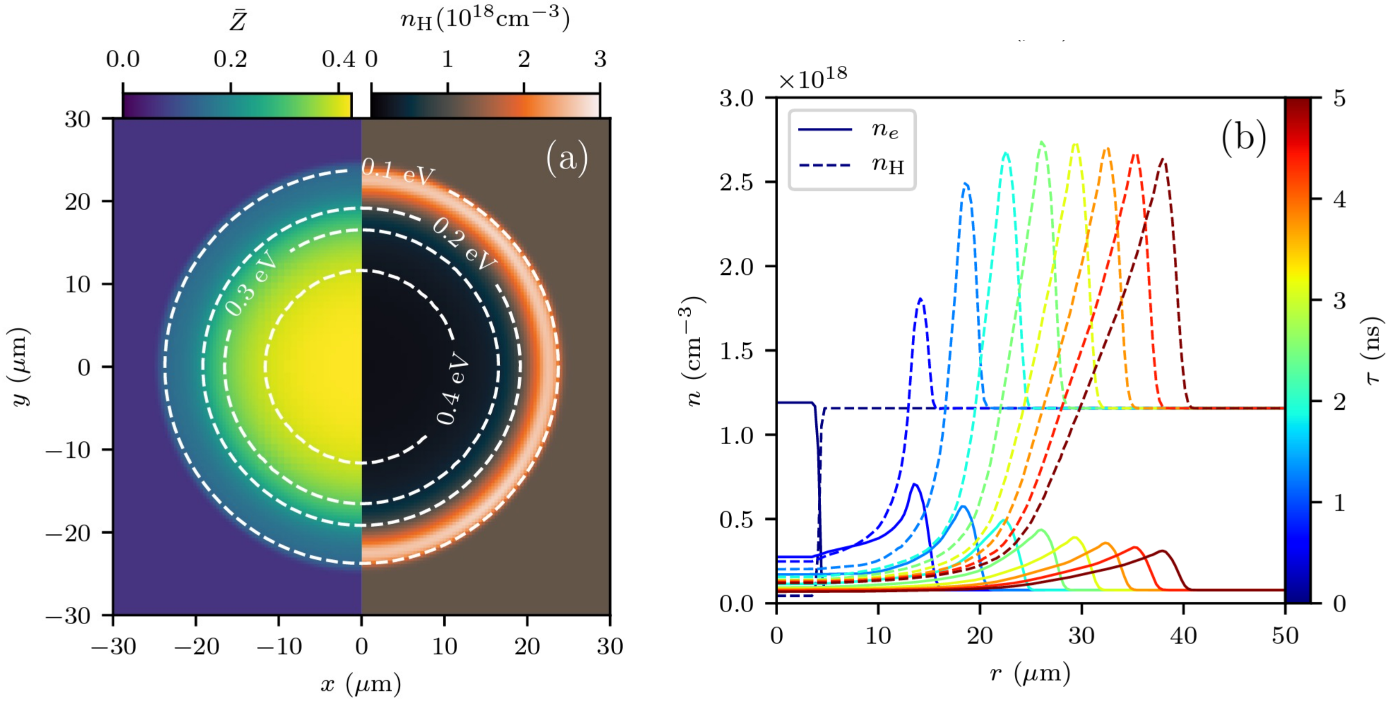
→ Plasma density profiles indicate a clear enhancement of the channel depth

[A. Picksley, A. Alejo *et al.*, Phys. Rev. E **102** (2020)]

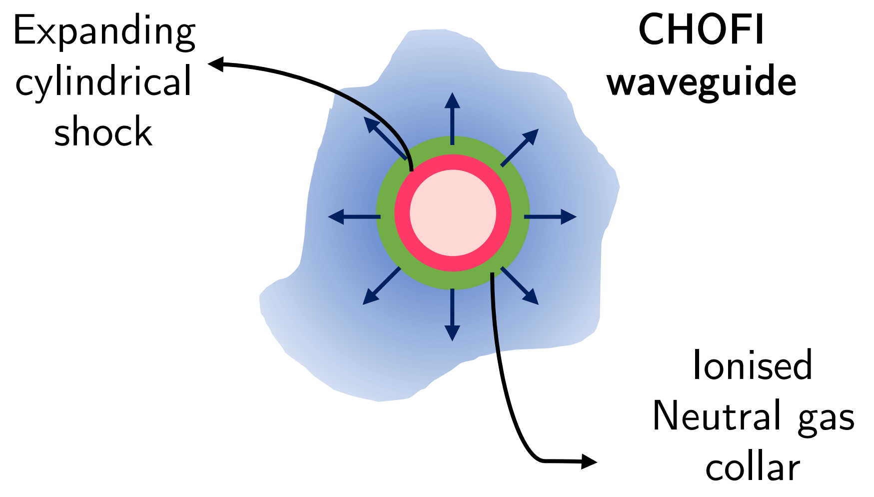
Conditioning of HOFI channels

→ *Conditioning* → The leading edge of the drive pulse ionises the surrounding neutral gas to increase the depth

→ Above-ambient densities are explained by the accumulation of neutral gas in the regions close to the shock front



[A. Picksley, A. Alejo *et al.*, Phys. Rev. E **102** (2020)]



→ 3D Flash simulations support the appearance of a collar or neutrals

→ Effect also demonstrated by Morozov *et al.* in high density short plasmas, and the Milchberg *et al.* using 2-colour interferometry

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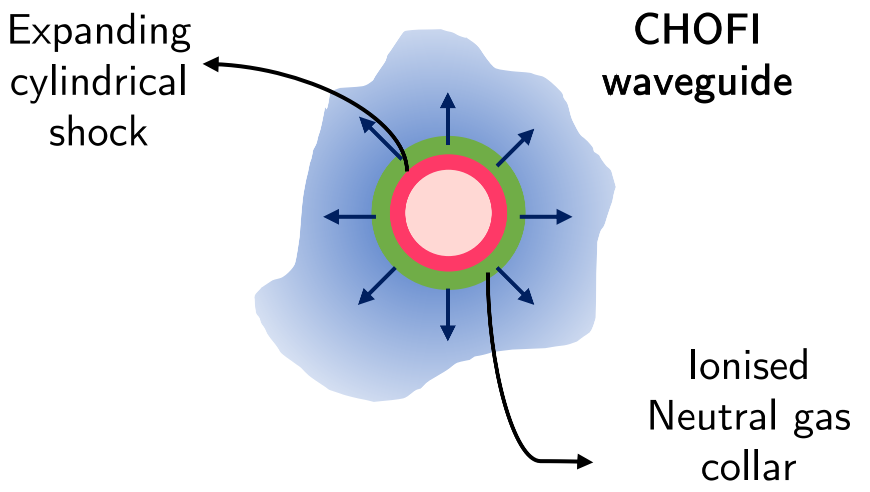
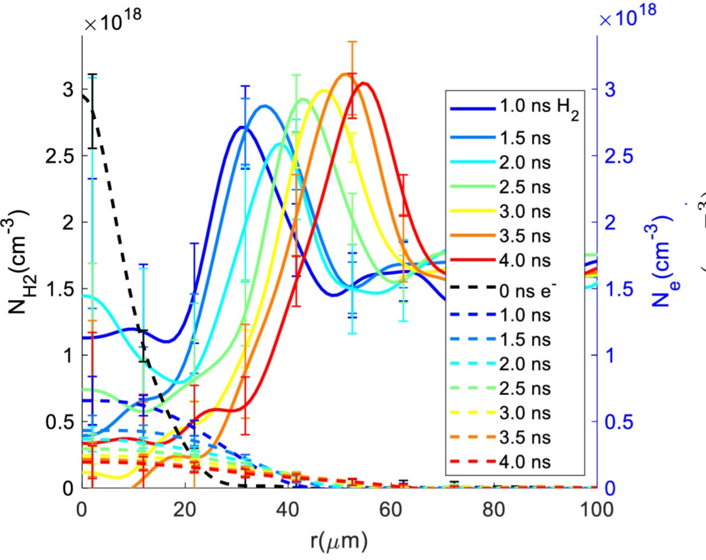
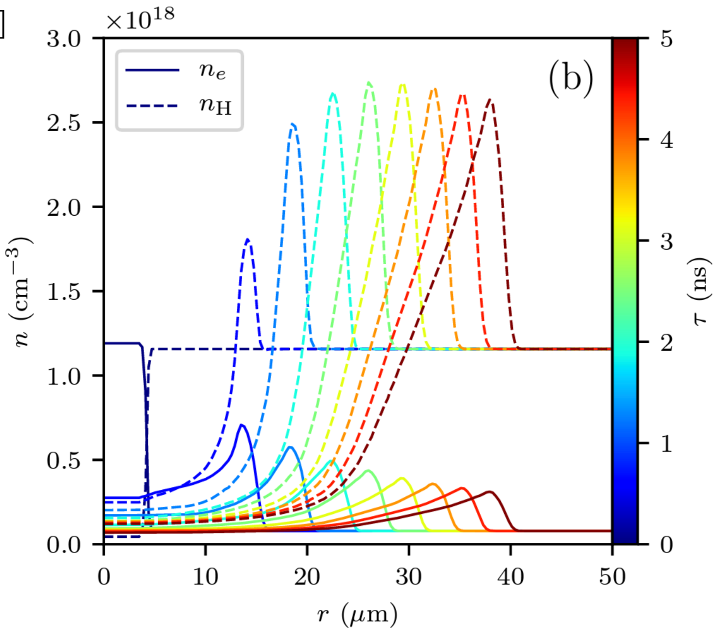


[L. Feder *et al.* (2020) Physical Review Research, 2(4)]





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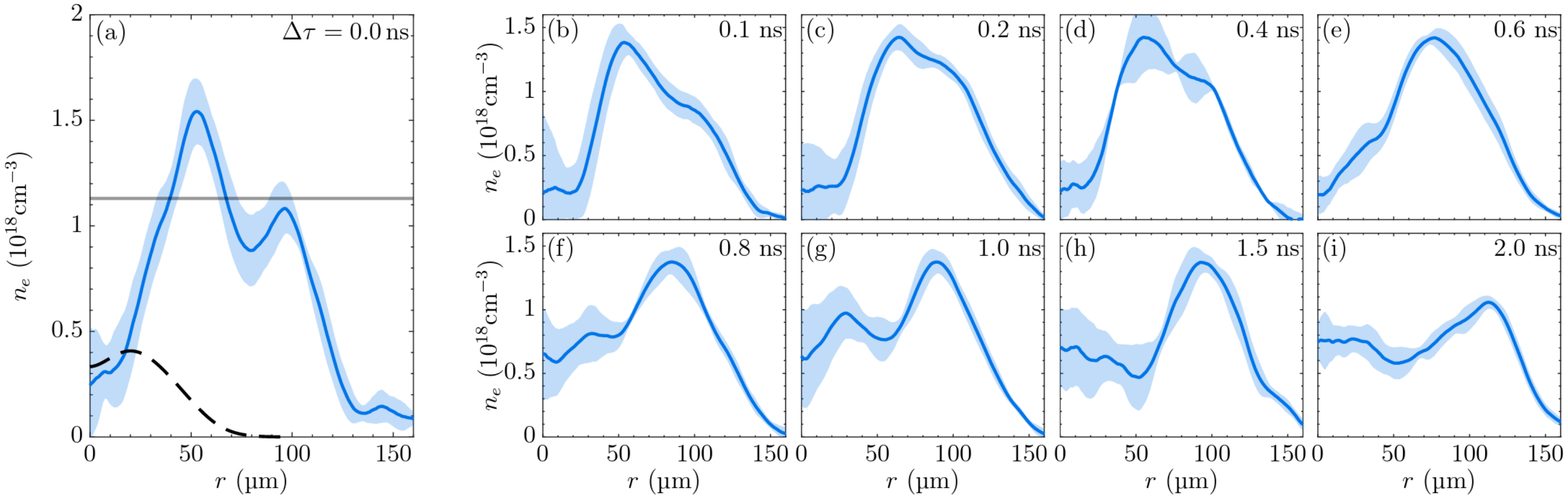
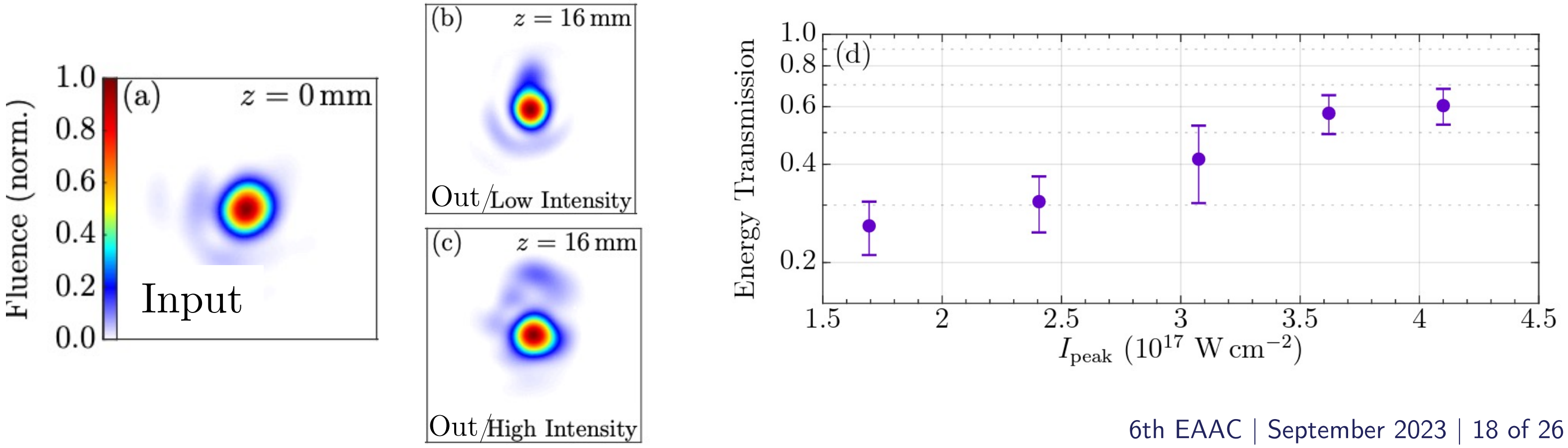
Improved channel throughput

→ Throughput of CHOFI channels improves due to deepening, **even for the conditioning pulse itself**



→ The conditioning effect relies on ionization by guided pulse ⇒ mode transmission depends on its intensity

- Varied input intensity and measured the fractional energy transmission
- Observed > 60 % transmission at highest input intensity.



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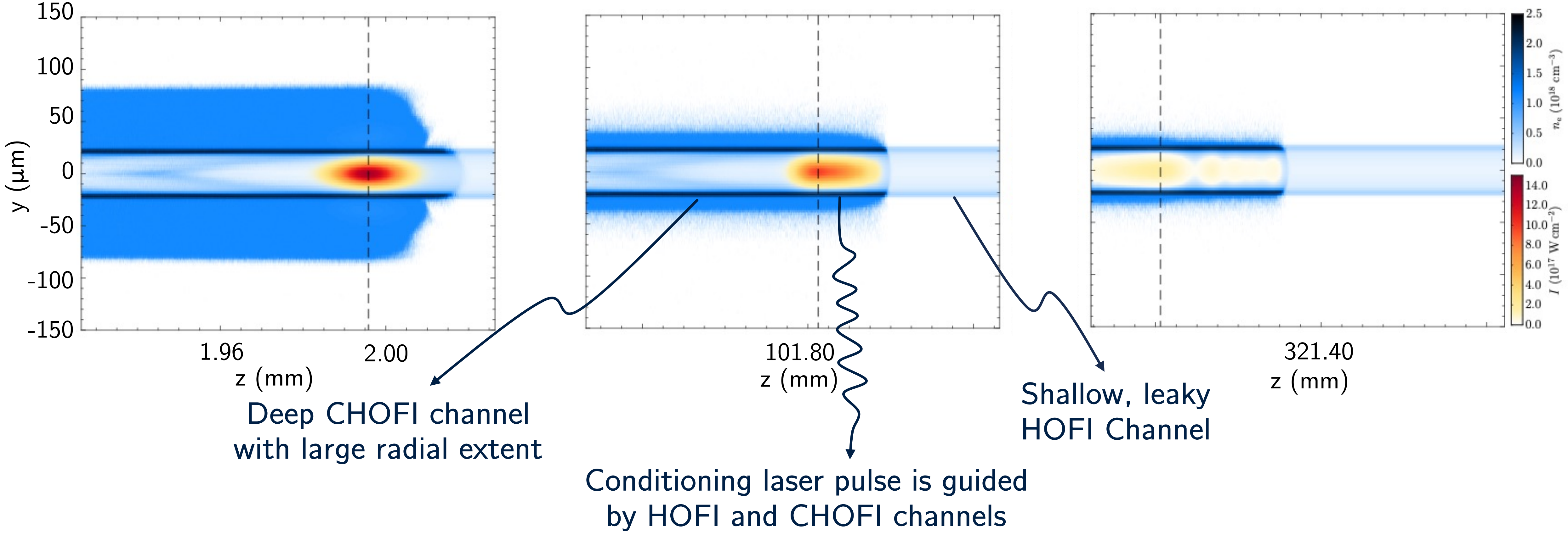
Improved channel throughput

→ PIC Simulations (FBPIC) of propagation of intense pulse through 340mm-long CHOFI waveguide



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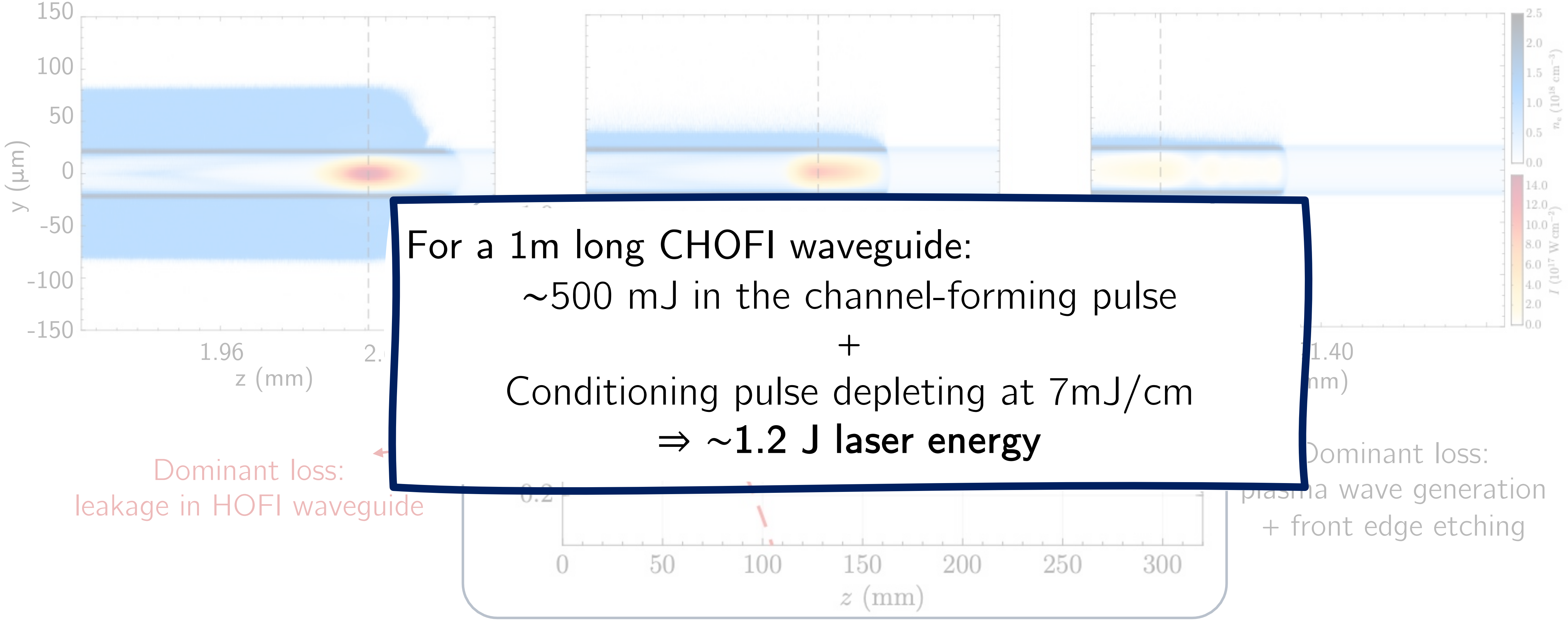

For a 1m long CHOFI waveguide:

~500 mJ in the channel-forming pulse

+

Conditioning pulse depleting at 7mJ/cm

⇒ **~1.2 J laser energy**

[A. Picksley, A. Alejo *et al.*, Phys. Rev. E **102** (2021)]

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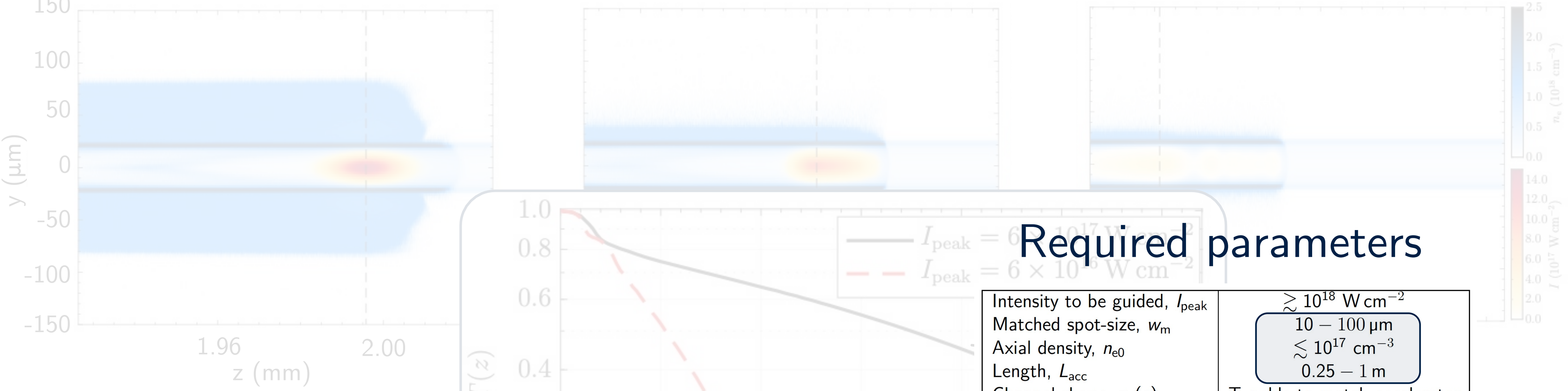

Dominant loss:
leakage in HOFI waveguide

Required parameters

Intensity to be guided, I_{peak}	$\gtrsim 10^{18}$ W cm^{-2}
Matched spot-size, w_{m}	$10 - 100\,\mu$m
Axial density, n_{e0}	$\lesssim 10^{17}$ cm^{-3}
Length, L_{acc}	$0.25 - 1$ m
Channel shape, $n_{\text{e}}(r)$	Tunable to match accelerator
Transmission $T(z = L_{\text{acc}})$	$\sim 100\,\%$
Gas species	Low-Z (H_2, He)
Repetition rate, f_{rep}	$\gtrsim 1$ kHz
Lifetime	$> 10^8$ shots
Stability	High
Energy cost	$\lesssim 10\,\%$ of total stage energy
Diagnostic access	Transverse and longitudinal

[A. Picksley, A. Alejo *et al.*, Phys. Rev. E **102** (2021)]

Outline

- Towards a 10 GeV scale Laser Plasma Accelerator
- Guiding of intense pulses in >100mm HOFI Channels
- Development of meter-scale, Conditioned Hydrodynamic Optical-Field-Ionised (CHOFI) plasma channels
- **Operation of free-standing plasma channels at high repetition rate**

Operation at high rep-rate

→ Future accelerators are envisaged to be driven by ultra-intense lasers operating at kHz rates (today limited to few Hz)

Intensity to be guided, I_{peak}	$\gtrsim 10^{18}\ \mathrm{W\,cm^{-2}}$
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→ Capillary discharges are prone to damage by laser. CD waveguides operating at kHz rates have been demonstrated, but not guiding of intense pulses at such rates [A. Gonsalves *et al.* (2016), Journal of Applied Physics, 119(3)]

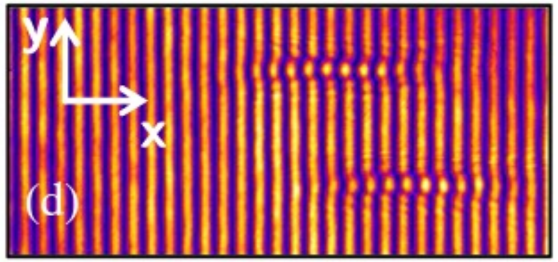
→ HOFI channels are free-standing, in principle having the potential to operate at high repetition rates for extended periods of time

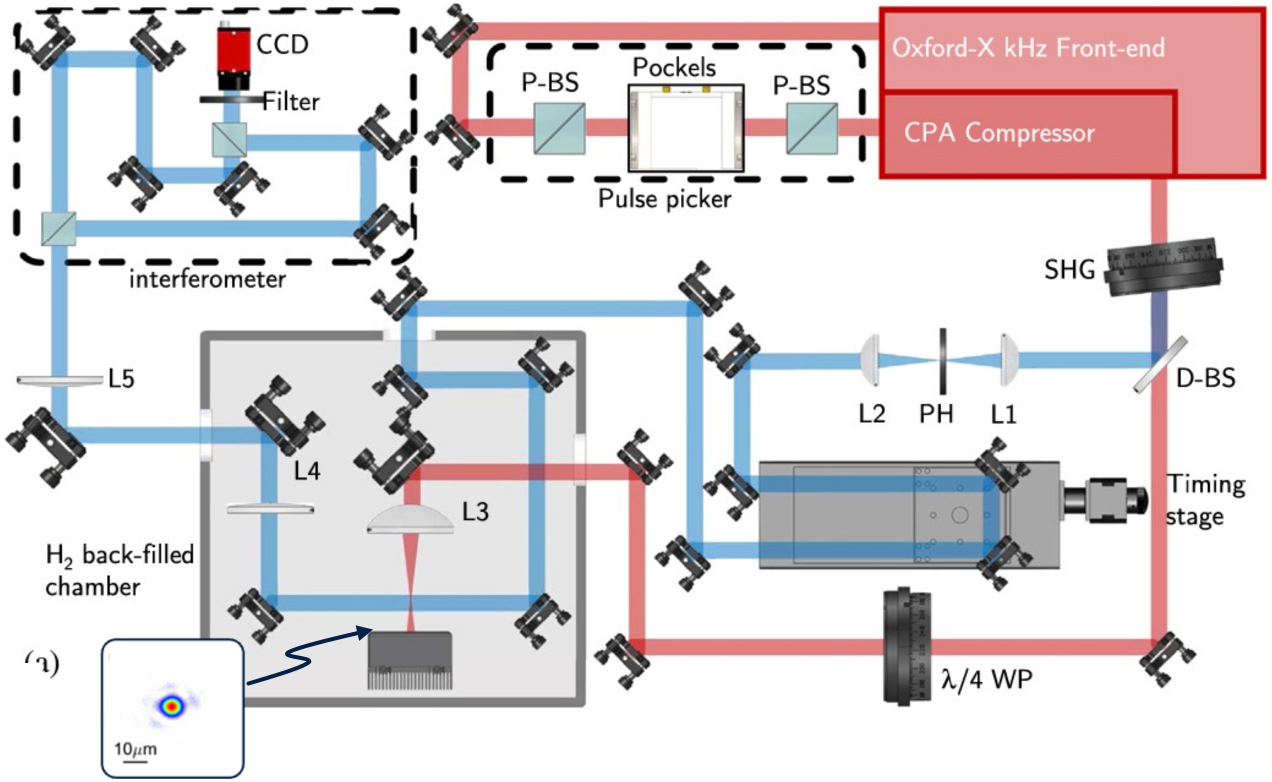
→ However, potential limitations such as gas evolution, heating, or unstable operation may limit the actual rate ⇒ Need to demonstrate this experimentally

[A. Alejo *et al.*, Phys. Rev. Accel. Beams 25 (2022)]

Operation at high rep-rate

→ Experiment carried out using the 1mJ, 1kHz front—end of the Oxford-X laser (University of Oxford)



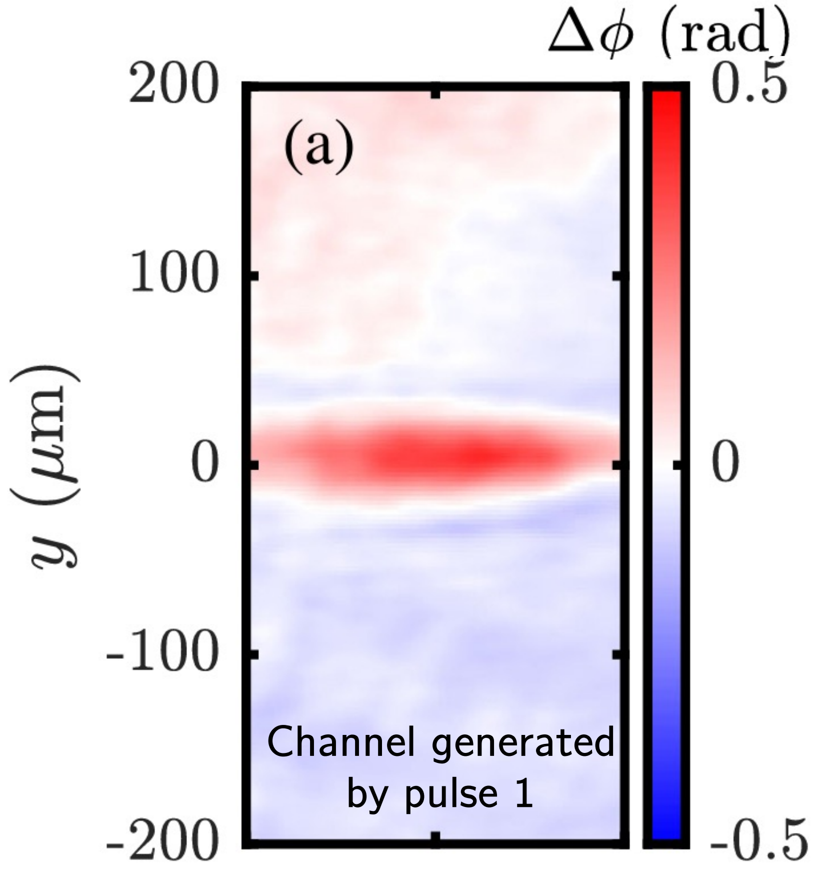


→ Pulse picker implemented in the beamline to overcome limitations of interferometry camera

[A. Alejo *et al.*, Phys. Rev. Accel. Beams 25 (2022)]

Generation of HOFI Channels at kHz rates

→ Operation at kHz rates was initially demonstrated by showing that two consecutive pulses (1ms) would generate identical channels



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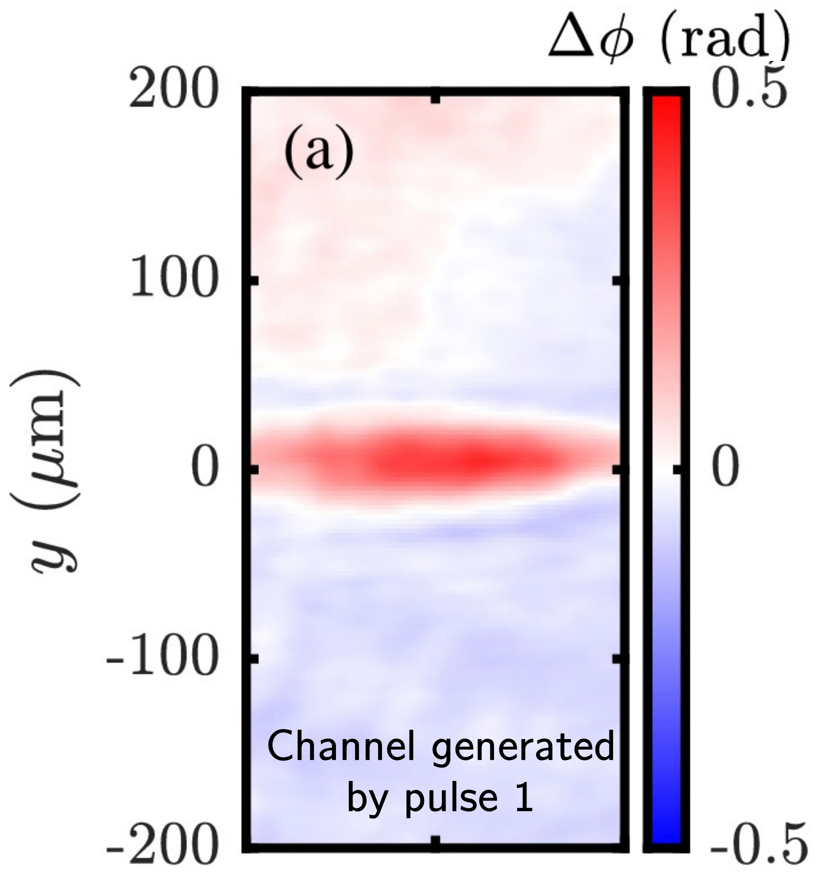

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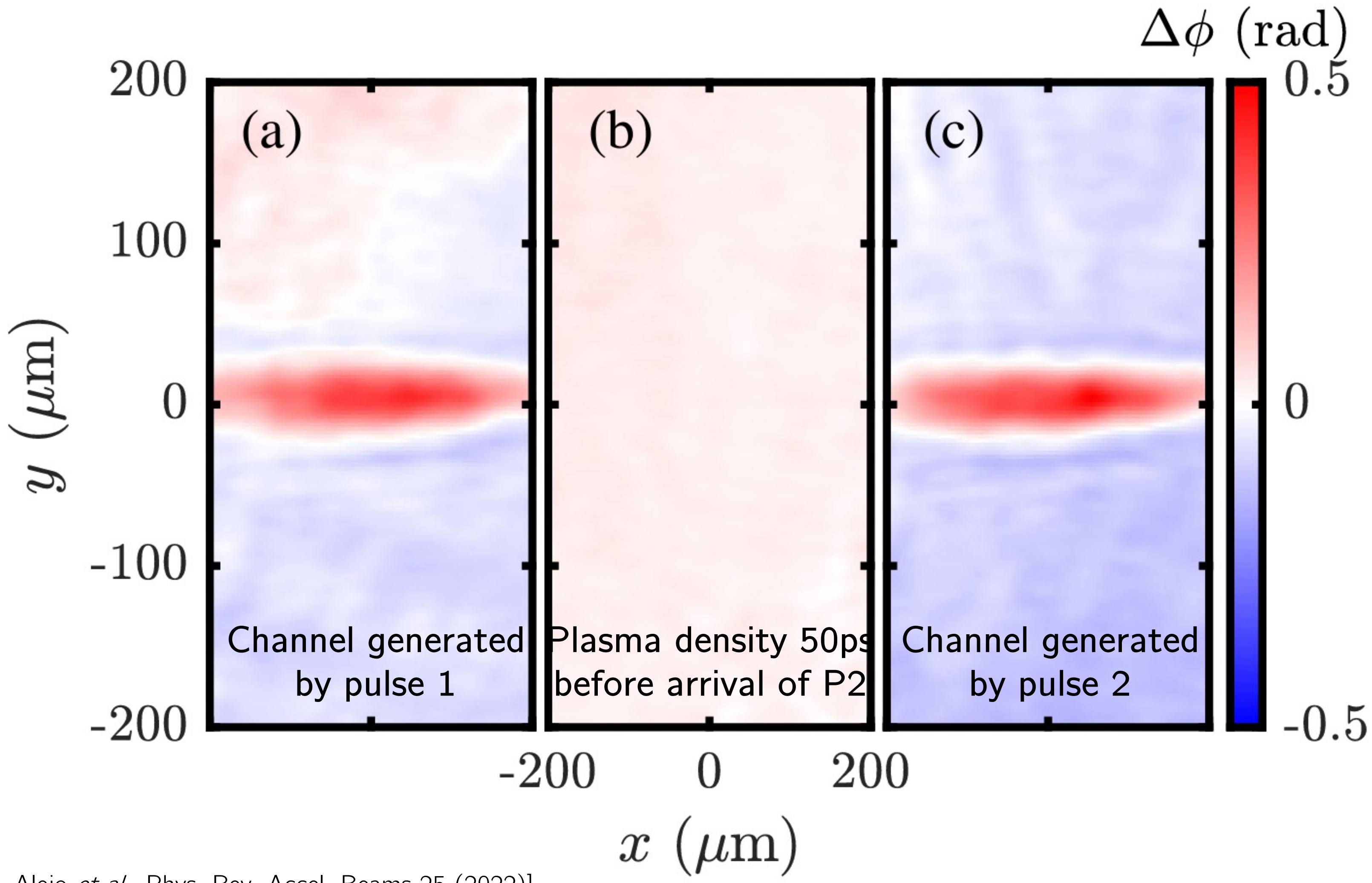

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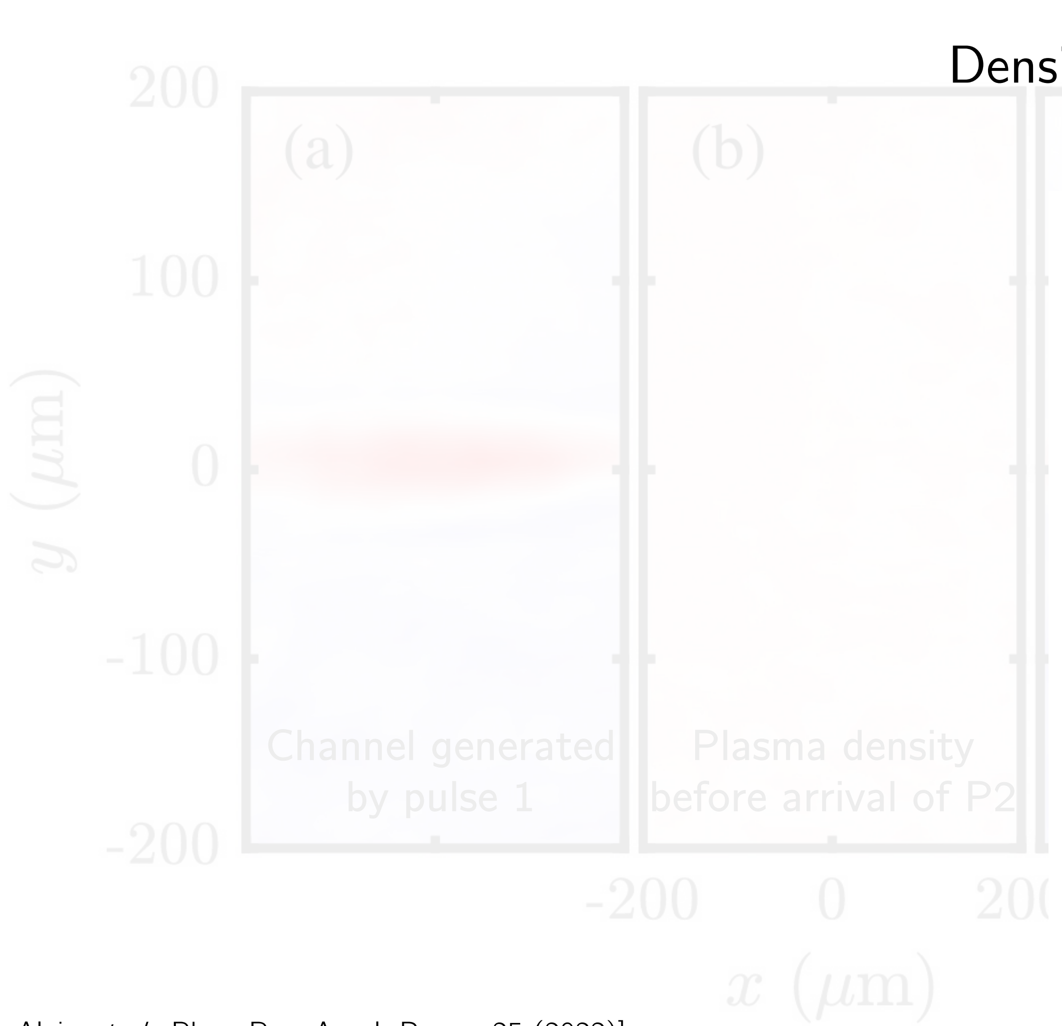
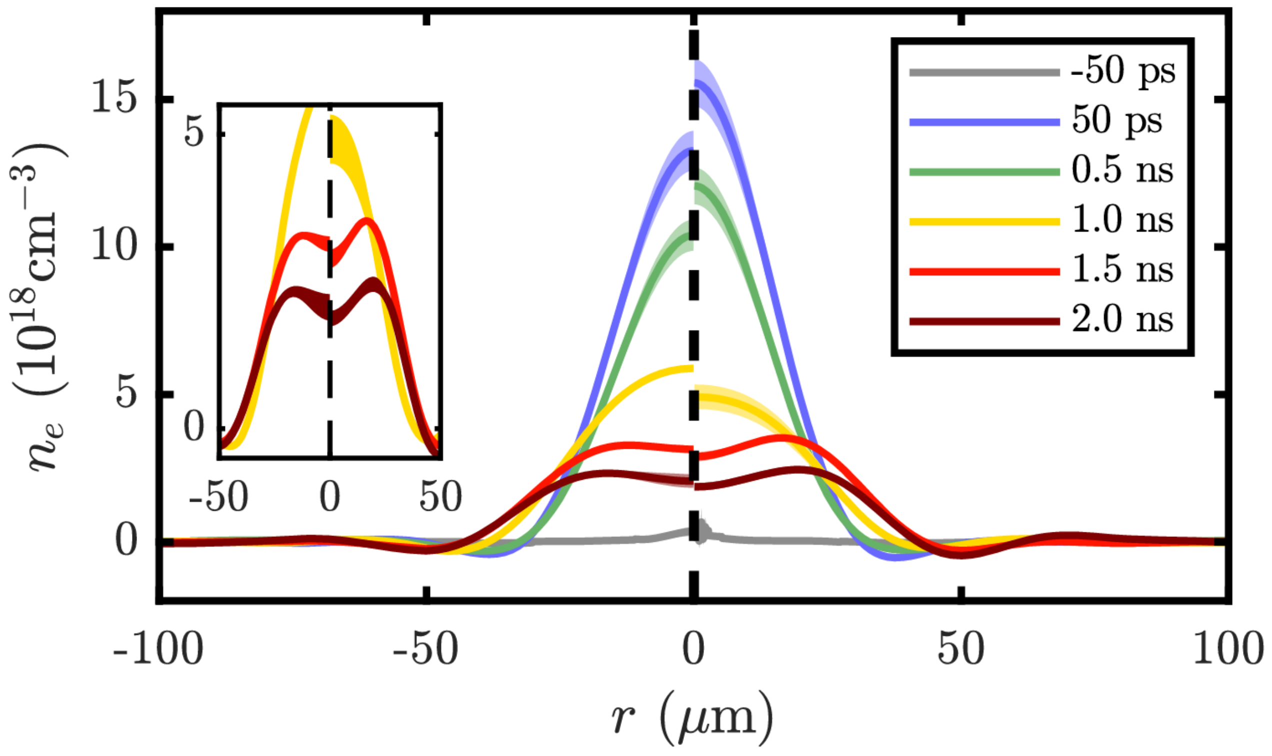


Density profiles generated by the two consecutive pulses are identical

⇒ **kHz-operation ready**



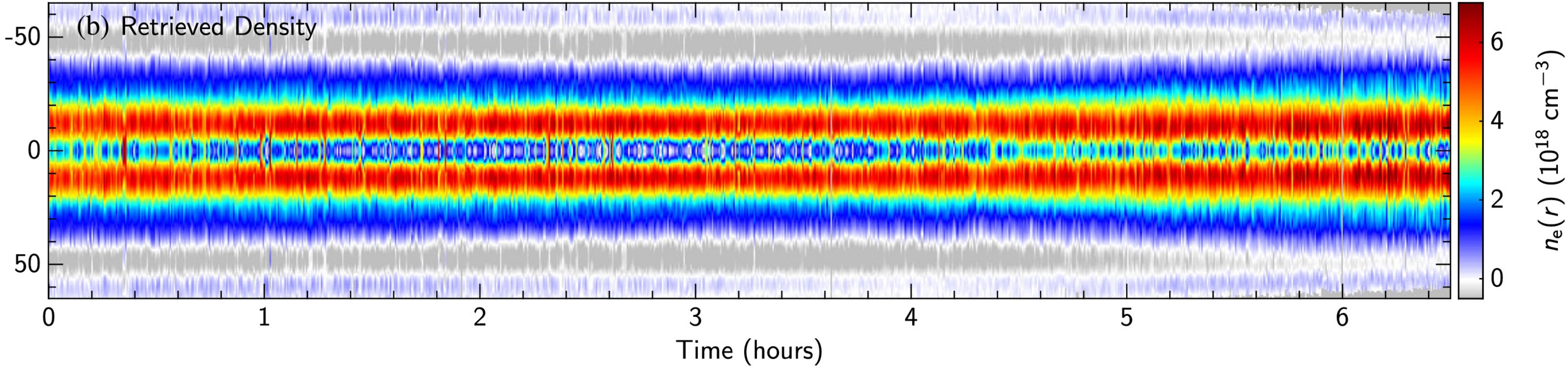
[A. Alejo *et al.*, Phys. Rev. Accel. Beams 25 (2022)]

Long-term stability of HOFI channels

→ Long-term stability of the operation of HOFI channels at HRR (0.4kHz, limited by diagnostic) was studied for a period of 6.5 hours

→ Channels measured 1.5ns after the passing of the channel-forming pulse

→ Slow heating of the gas will not have a deleterious effect on the channels for mean repetition rates at least up to 0.4kHz



[A. Alejo *et al.*, Phys. Rev. Accel. Beams 25 (2022)]

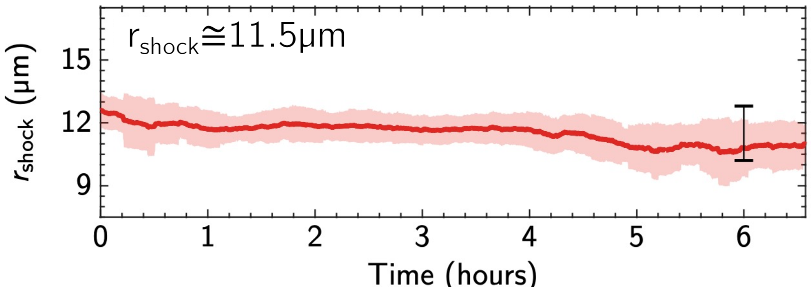
Long-term stability of HOFI channels

→ The evolution of the most relevant parameters was characterized throughout the 6.5 hour period, showing the **stability and robustness** of HOFI channels

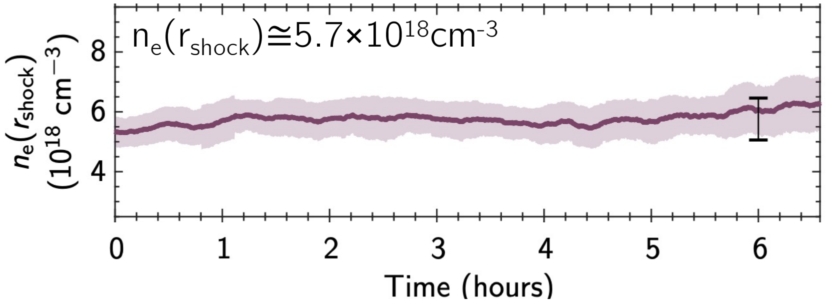
→ Showing 50-point moving average (solid line) and rms (shaded area)

→ Energy, pointing, and spatial phase of the laser were not stabilized, however HOFI is expected to be robust with respect to laser fluctuations

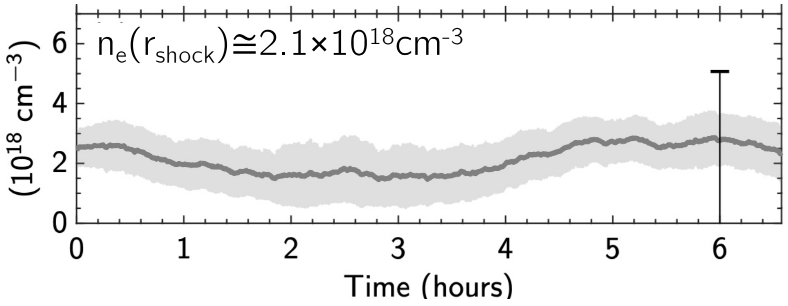
Shock radius



Density at shock front



On-axis density



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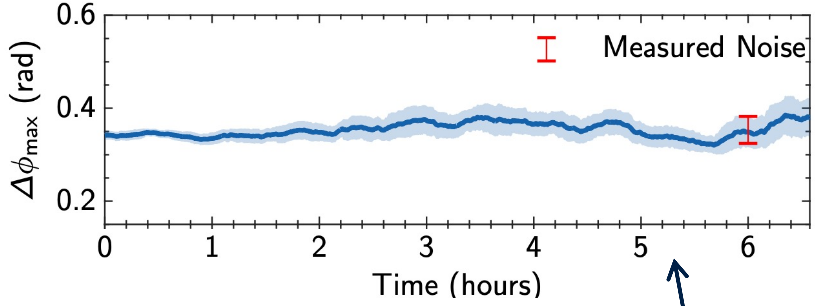
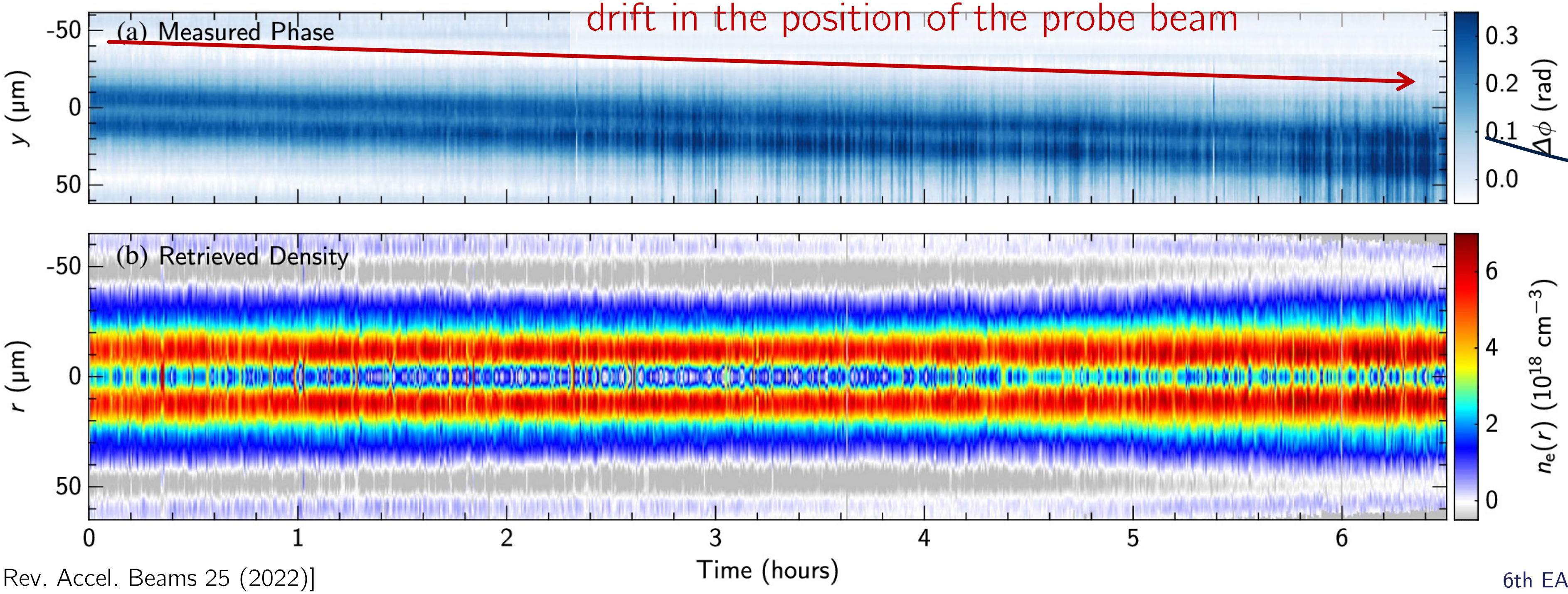


Apparent drift of channel position caused by a drift in the position of the probe beam



[A. Alejo *et al.*, Phys. Rev. Accel. Beams 25 (2022)]

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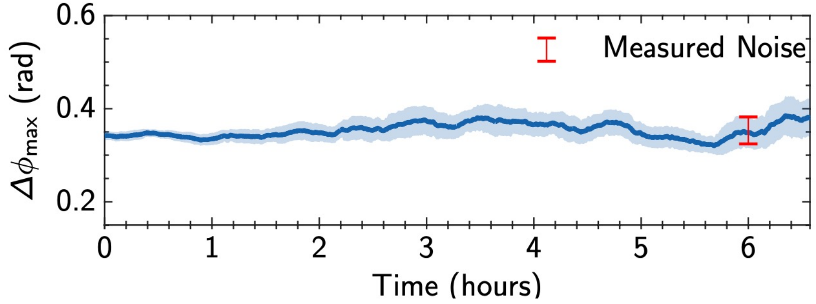
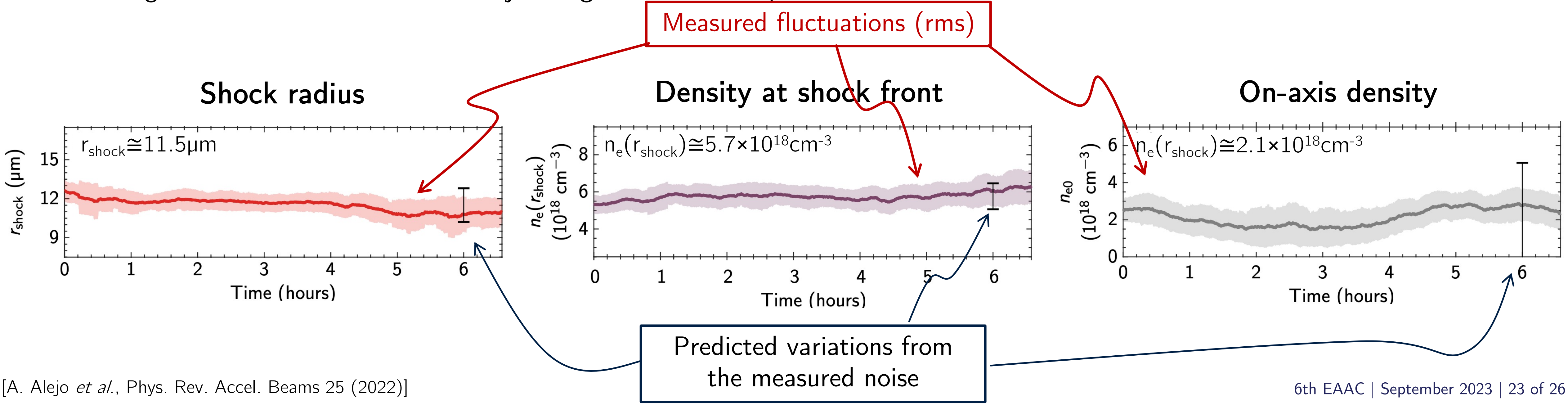


→ However, jitter is shown through Monte-Carlo modelling to be dominated by effects of noise in the measurement, rather than being an actual measurement of the jittering of the channel parameters



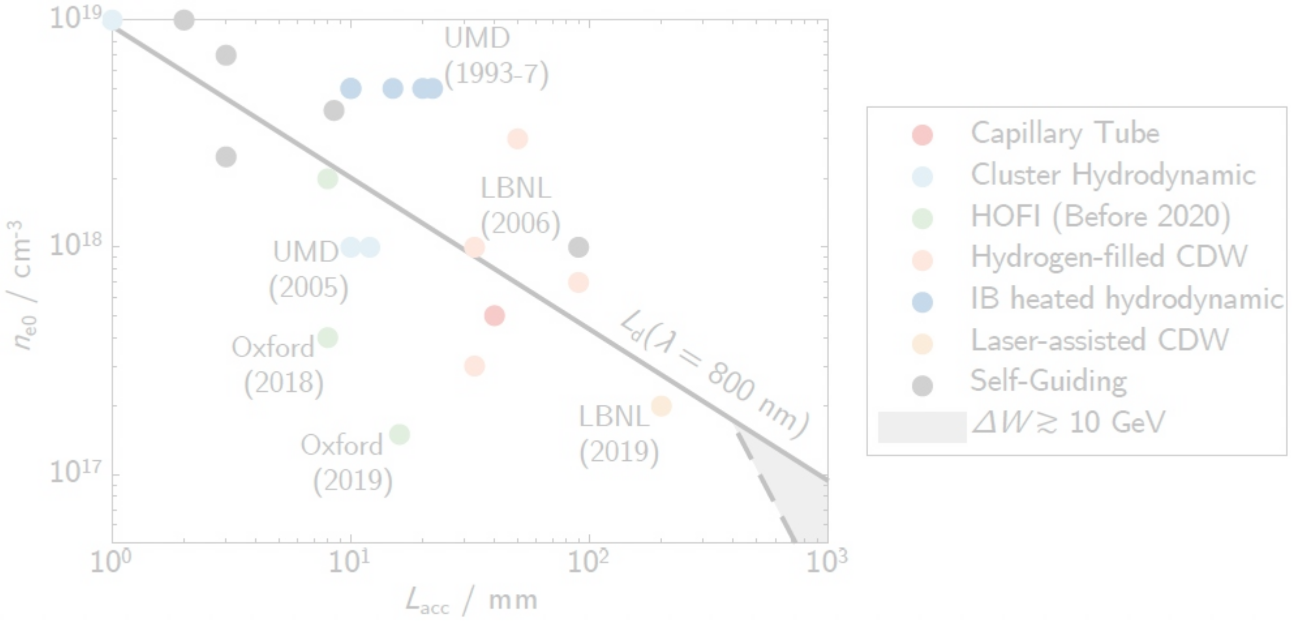
[A. Alejo *et al.*, Phys. Rev. Accel. Beams 25 (2022)]

Requirements for a suitable waveguide

→ The acceleration length of a LPA can be extended by using plasma channels

→ Similar to GRIN optical fibers, propagating through a transverse electron density profile with a minimum on-axis can counteract diffraction

→ Different techniques have been studied as waveguides, including capillary discharge waveguides or self-guiding



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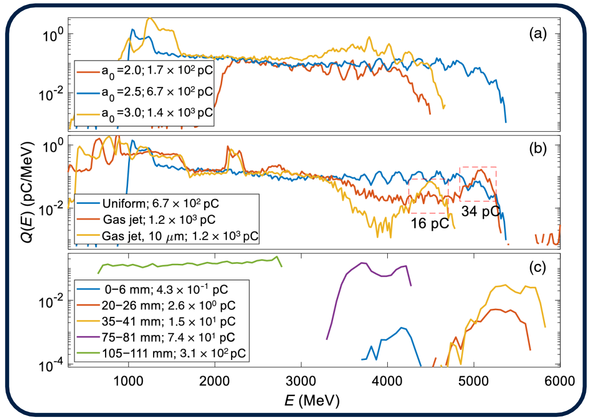
Diagnostic access	Transverse and longitudinal

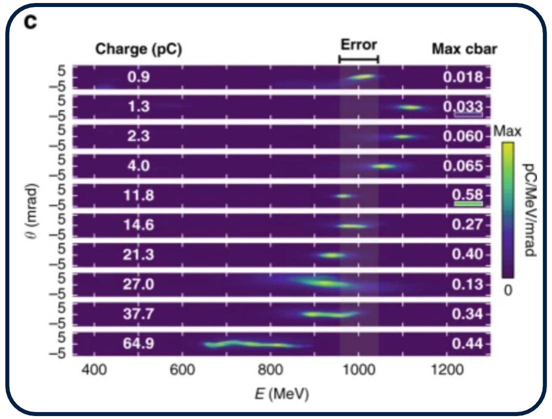
What's next?

Future perspectives

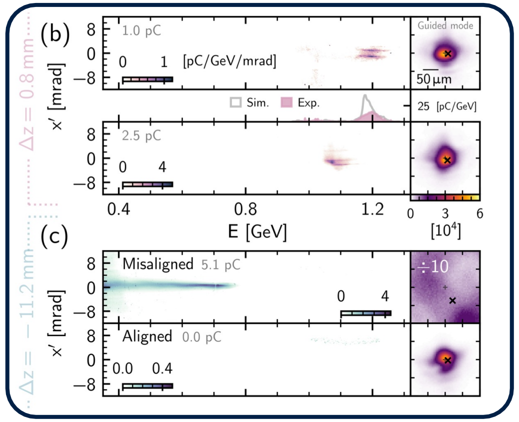
Electron acceleration in (C)HOFI channels



Narrow-band 5GeV e- beam from 200mm channel
[B. Miao *et al*. (2022) Physical Review X, 12(3), 031038.]

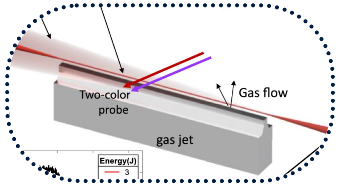


1GeV from a 50TW-class laser
[K. Oubrerie *et al*. (2022). *Light: Science & Applications*, *11*(1)]

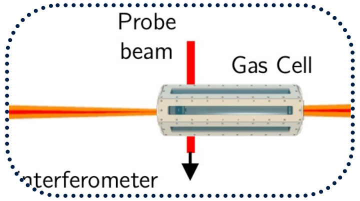


Truncated-channel injection, Narrow-band 1GeV
[A. Picksley (2023). arXiv:2307.13689]

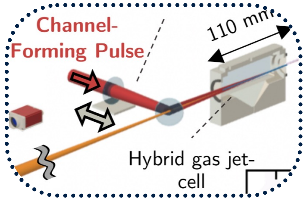
Targetry development



Gas jets
High gas load, stability

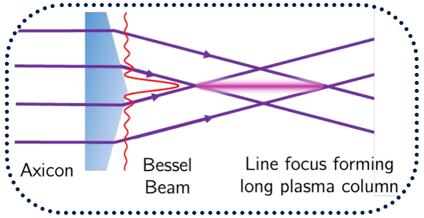


Gas cells
Coupling of channel-forming beam into cell

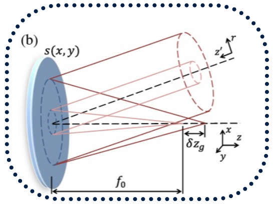


Hybrid solutions
Coupling of channel-forming beam into cell

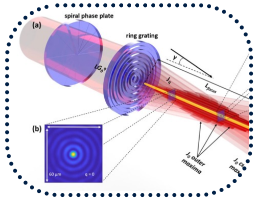
Work on optical elements



Axicons



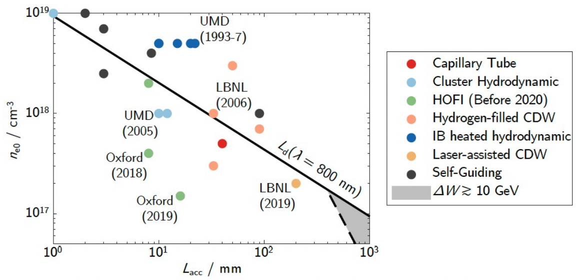
Axiparabolae



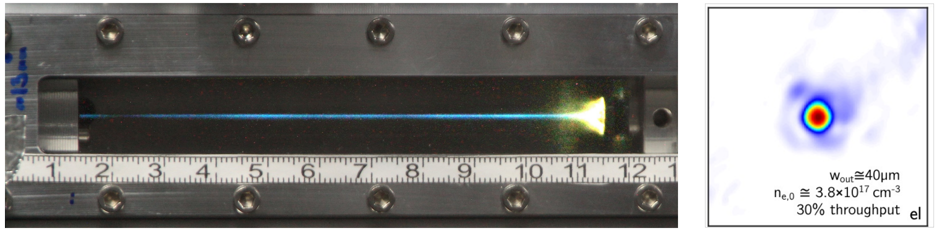
Phase plates

Summary

- A 10 GeV scale Laser Plasma Accelerator would need a suitable waveguide to operate



- Guiding of intense pulses in >100mm HOFI Channels



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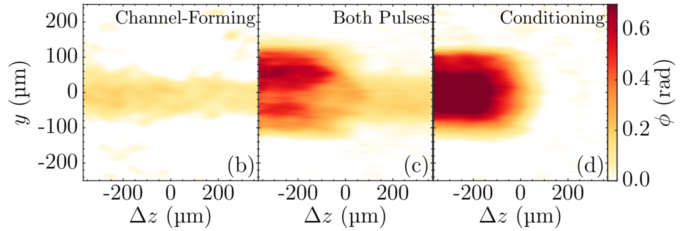

- Operation of free-standing plasma channels at high repetition rate