Guiding of high intensity laser pulses in 100 mm-long all-optical plasma channels

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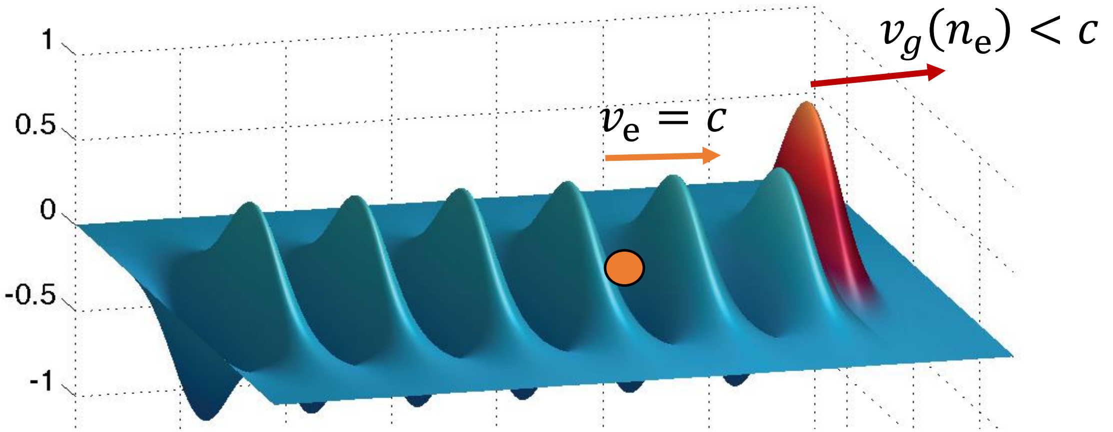
Outline

- Introduction to plasma channels
  - Motivation for $100\ \mathrm{mm}$ plasma channels for laser wakefield acceleration
  - Physics of our plasma channels
- Experiments with the Astra-Gemini TA3 laser
  - Experimental setup
  - Demonstration of guiding over $100\ \mathrm{mm}$
  - Increasing the attenuation length

Picksley, A, *et al.*, *PRAB* (2020), *23*(8), 81303.
Picksley, A, *et al.*, *PRE* (2020), *102*(9), 53201.

Laser Wakefield Acceleration

- Laser wakefield cavities
  $\mathrm{E} \sim 100\ \mathrm{GV/m}$
- Towards multi-GeV electron beams, at kHz repetition rates
- Inherent limits on accelerator length include:
  - diffraction – small laser spot size has short Rayleigh range, $z_R \sim w_0^2$
  - dephasing – electrons catch up with laser, $L_\phi \sim 1/n_\mathrm{e}$



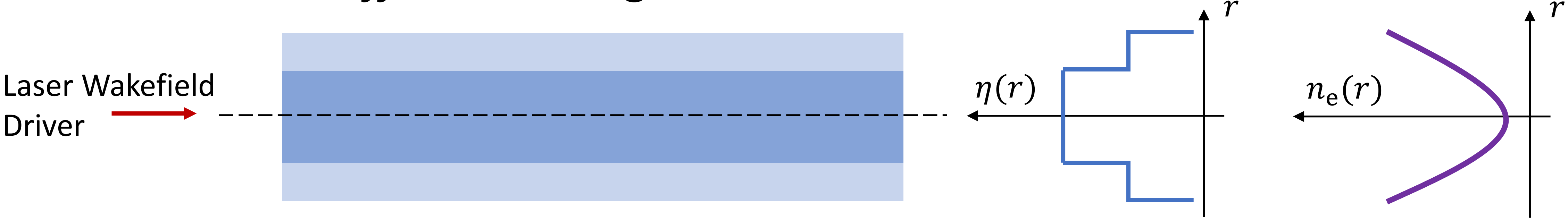
EuPRAXIA design:

- $n_\mathrm{e} \sim 2 \times 10^{17}\mathrm{cm}^{-3}$
- $L_\phi \sim 120\ \mathrm{mm}$
  - ➢ 5 GeV beams

T. Audet *et al.*, EuPRAXIA Milestone Report M3.1 (2017)

HOFI plasma channels as laser waveguide

- Hydrodynamic Optical-Field-Ionised (HOFI) plasma channels overcome *diffraction* length limitation



- HOFI channels can be:
  - All-optical, free-standing
  - Low density = $10^{17}\mathrm{cm}^{-3}$ and lower
  - Long = $100\ \mathrm{mm}$ +
  - Efficient

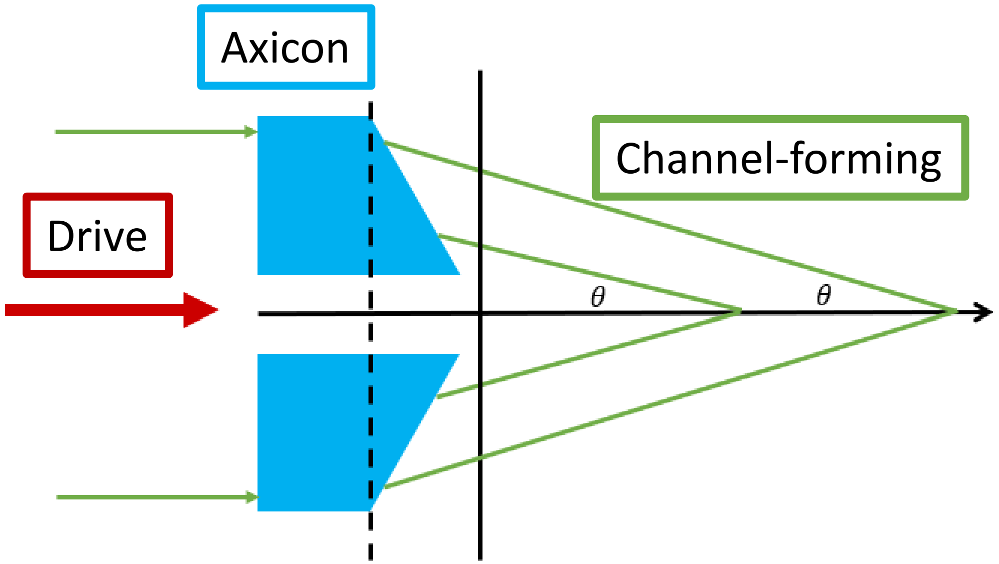
EuPRAXIA design:

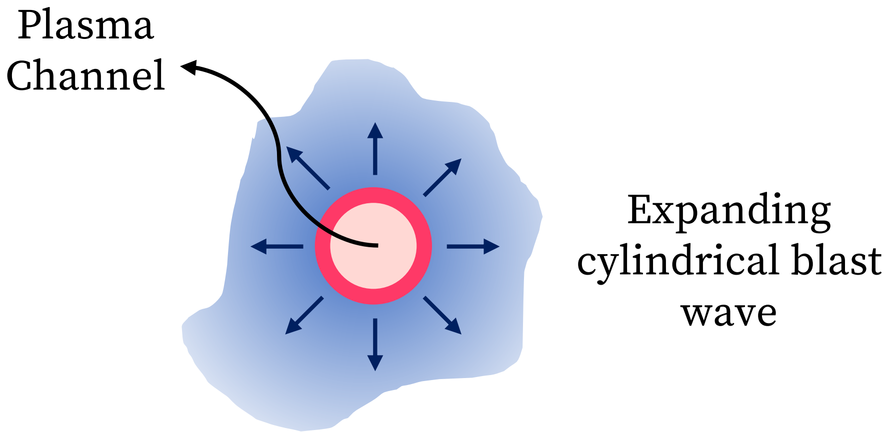
- $n_e \sim 2 \times 10^{17}\mathrm{cm}^{-3}$
- $L_\phi \sim 120\ \mathrm{mm}$
  - ➢ 5 GeV beams

Durfee & Milchberg (1993), *PRL*, 71(15), 2409–2412.
Durfree, Lynch and Milchberg (1995). *PRE*, *51*(3), 2368–2387.

Physics of HOFI channels

- Axicon focuses a channel-forming beam to a line longitudinally
- Optical field ionisation liberates and instantaneously heats electrons
- Rapid radial expansion leads to plasma channel with low on-axis density and high density walls
- Electron density corresponds to refractive index variation



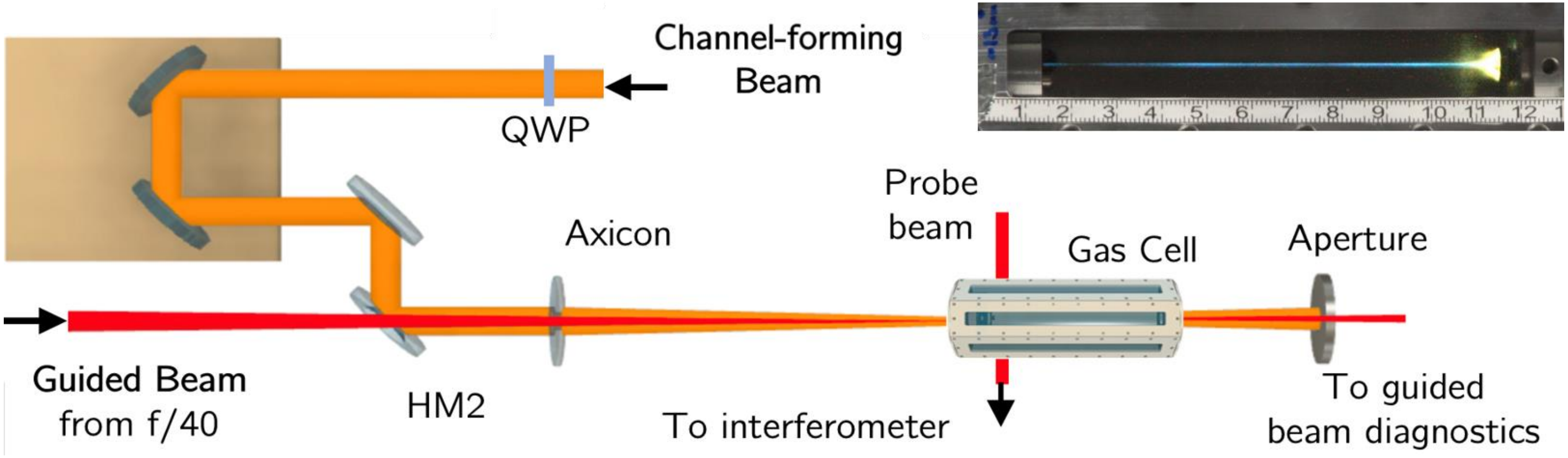


Shalloo *et al.*, (2018), *PRE, 97*(5), 1–8
Lemos, N., et al. (2013). *Physics of Plasmas, 20*(6).
Lemos, N., et al. (2013). *Physics of Plasmas, 20*(10).

Experimental demonstration of 100 mm guiding

Experimental setup

- Experiments performed on the Astra-Gemini TA3 laser at the Rutherford Appleton Laboratory in 2019
- Objective: demonstrate $100\ \mathrm{mm}$ guiding of high intensity laser pulses using a HOFI plasma channel



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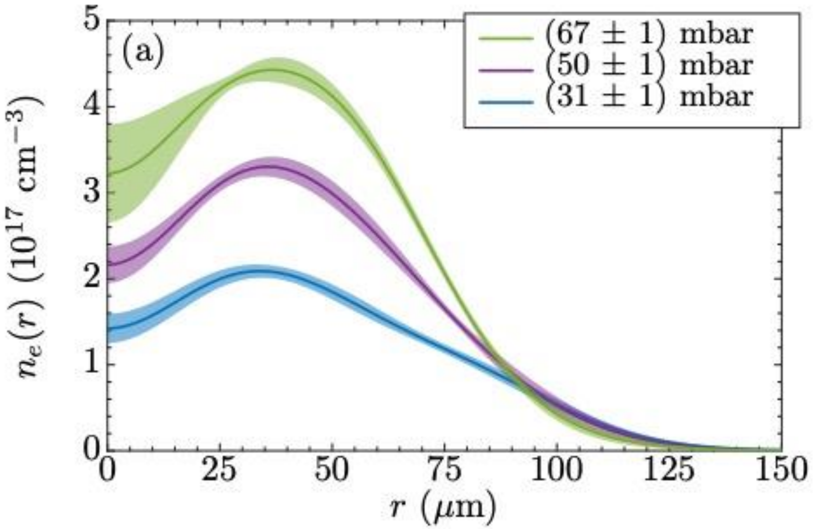
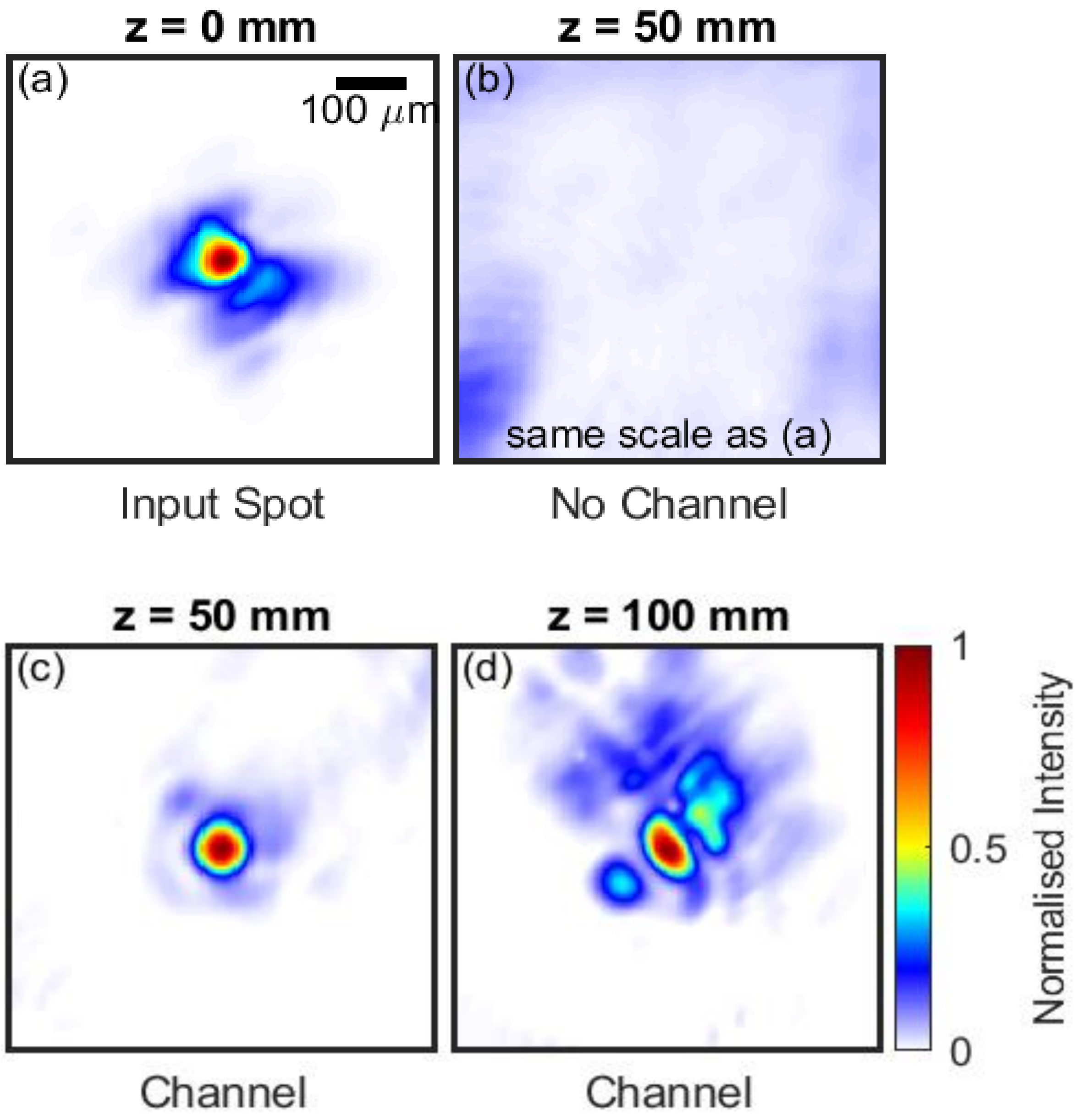
Guiding results

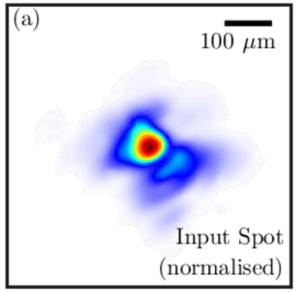


- 100 mm ~ 20 Rayleigh ranges
- Parameters for 100 mm guide:
  - $n_{e,0} = 1 \times 10^{17}\ \mathrm{cm}^{-3}$
  - $I_0 = 6 \times 10^{17}\ \mathrm{W\ cm}^{-2}$

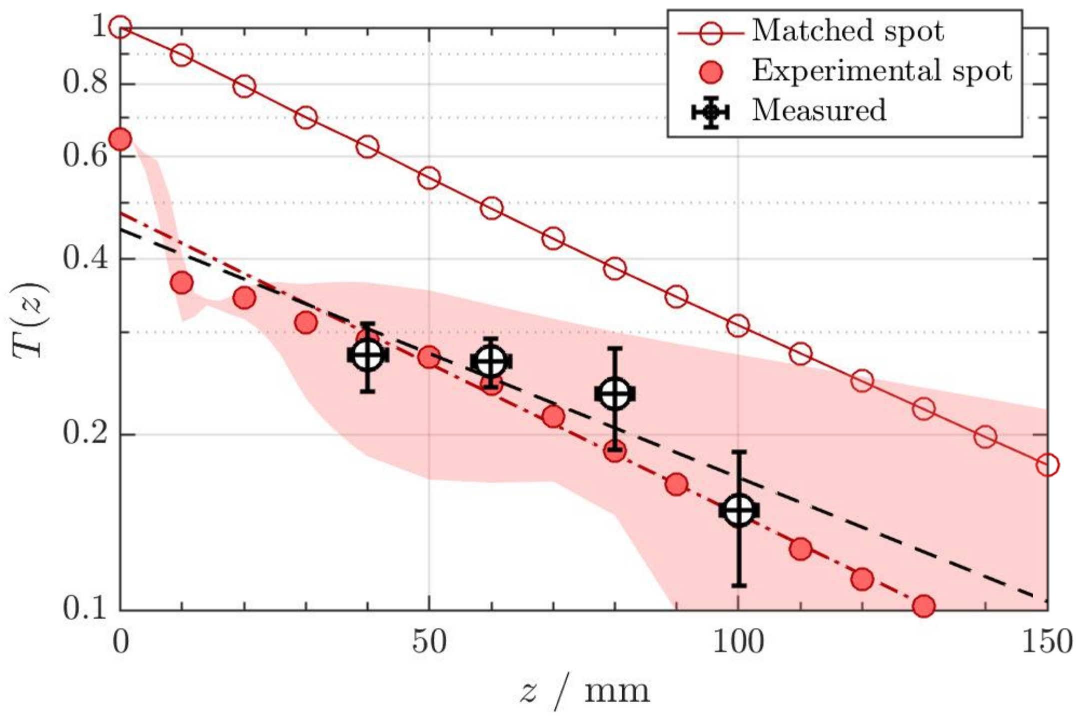


Picksley, A, *et al.*, *PRAB* (2020), *23*(8), 81303.

Guiding efficiency



Transmission fraction as function of longitudinal position down channel



- Black dashed line is fit of measured data to
  $$T_{\text{theory}}(z) = T(0)\exp(-z/L_{att})$$
- Red points calculated from Helmholtz mode solver
  - Hollow for ideal Gaussian input laser spot
  - Filled for the real, imperfect laser spot on experiment

$$T(0) = 48\ \%, L_{att} = 84\ \text{mm}$$

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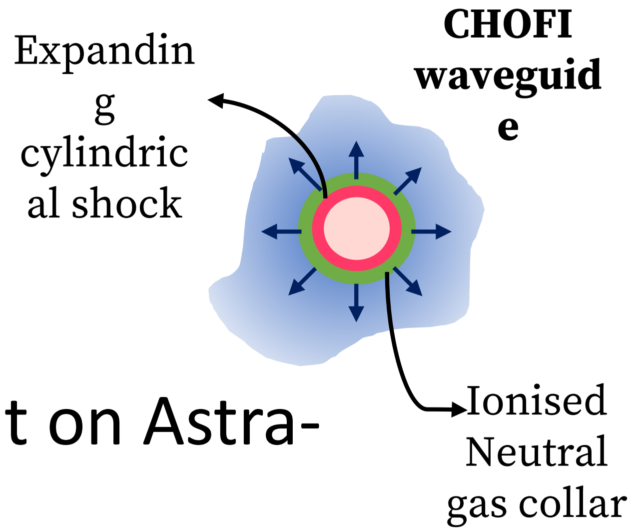
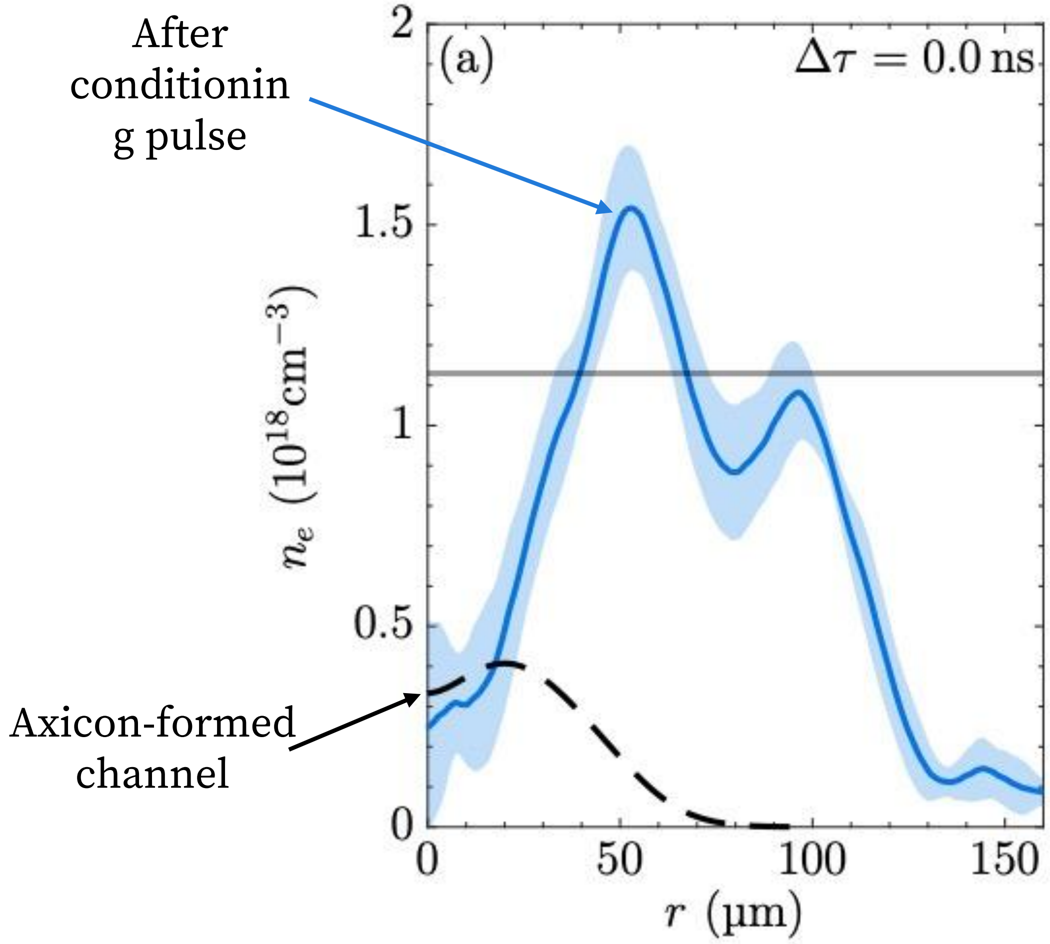
Increasing the attenuation length

Conditioned HOFI plasma channels





- Data from experiment on Astra-Gemini TA2 in 2018
- Guided pulse itself causes further ionisation beyond axicon-formed channel wall
- Resulting channel is a highly efficient waveguide

$$L_{att} \gtrsim 1\ \mathrm{m}$$

Picksley, A, *et al.*, *PRE* (2020), *102*(9), 53201.

Summary

- HOFI plasma channels offer a route towards all-optical, free-standing, low density waveguides
- We have demonstrated guiding of high intensity laser pulses over 100 mm with $n_\text{e} \sim 10^{17}\text{cm}^{-3}$
- Conditioned HOFI plasma channels allow attenuation lengths to be extended to the metre-scale

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New Oxford Laser-Plasma Accelerator Lab