Low-Density Waveguides for multi-GeV LPAs

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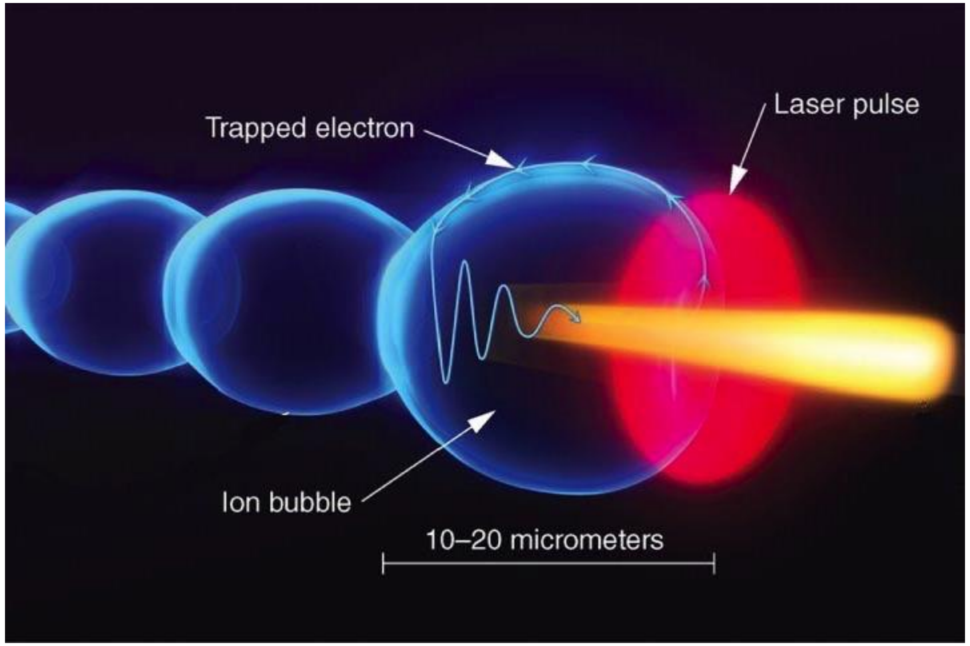
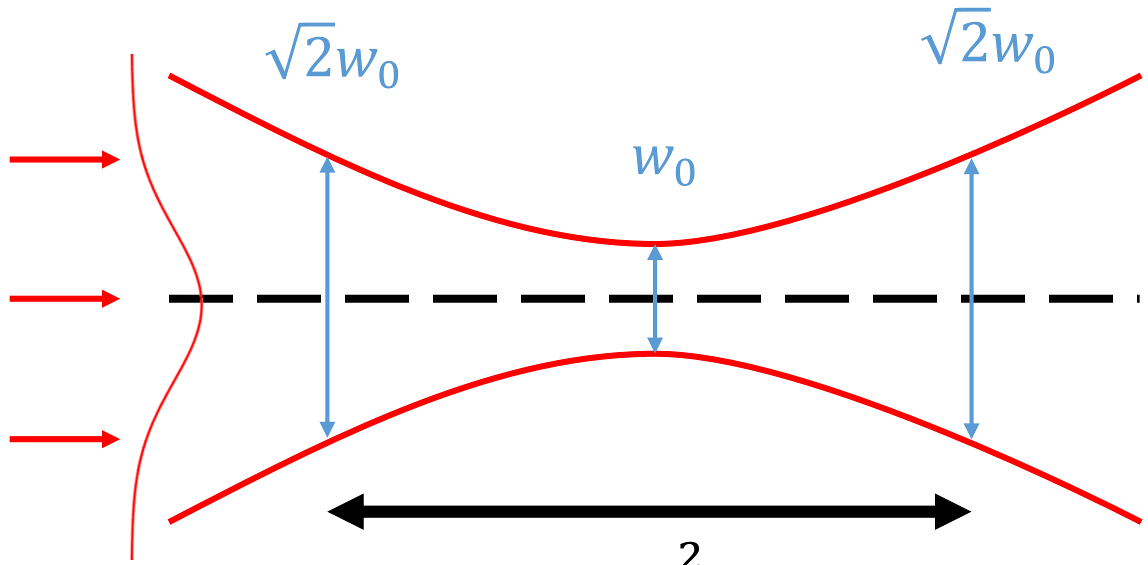
Laser Plasma Accelerators

- LPAs can achieve **high accelerating gradients** without breakdown
- Multi-GeV electron acceleration possible in stages just **a few cm** long
- Move towards kHz operation for applications



Multi-GeV LPAs

- Electron energy gain is limited by **dephasing** but pulse **diffracts** faster



$$z_R = \frac{\pi w_0^2}{\lambda} \sim 1 \text{ cm}$$

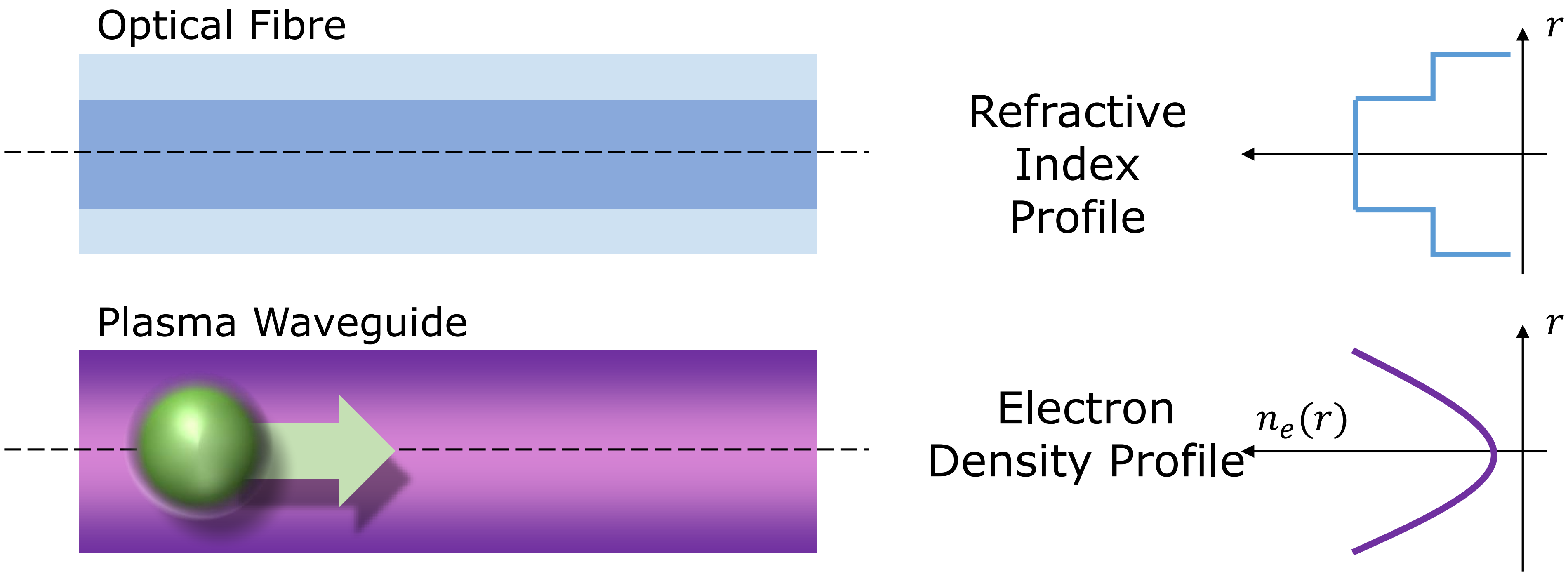
Diffraction

Maximum energy gain $\propto \frac{1}{n_e}$

$$L_{dephasing} \propto \frac{1}{n_e^{3/2}} \sim 10 \text{ cm}$$

Dephasing

What is a Plasma Waveguide?



- A Gaussian pulse with spot size $w_0 = w_m$ will be guided in a parabolic plasma channel:

$$n_e(r) = n_e(0) + \frac{r^2}{\pi r_e w_m^4}$$

Multi-GeV LPAs

Ideal waveguide:

- Low density on-axis $\sim 1 \times 10^{17}\ \mathrm{cm}^{-3}$
- 10's of cm long
- Capable of multi-kHz operation
- **Indestructible**

EUPRAXIA 5 GeV Stage[1]

$L \sim 10\ \mathrm{cm}$

$n_e(0) \sim 2 \times 10^{17}\ \mathrm{cm}^{-3}$

BELLA 10 GeV Stage[2]

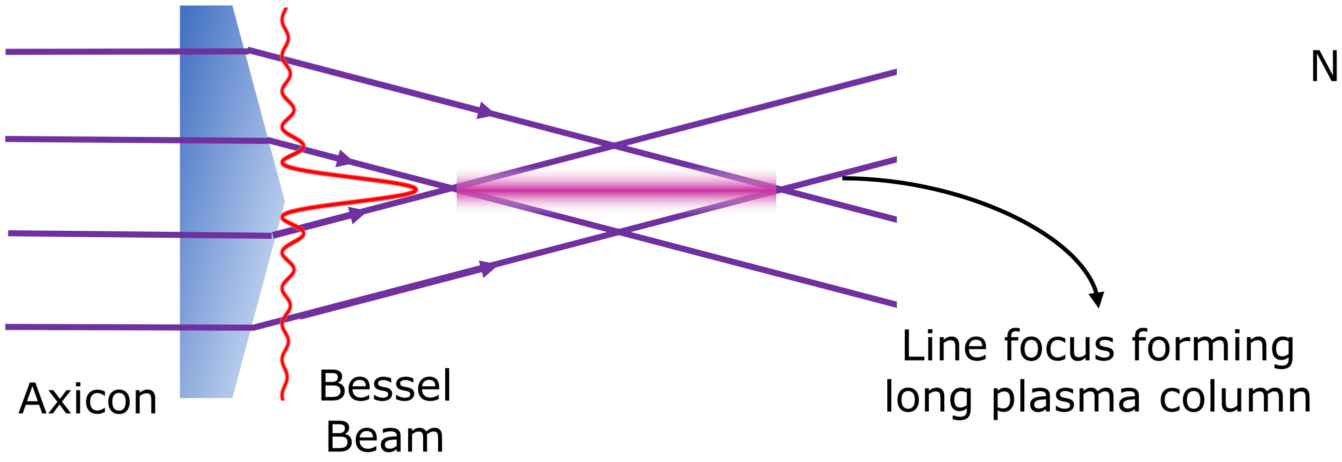
$L \sim 60\ \mathrm{cm}$

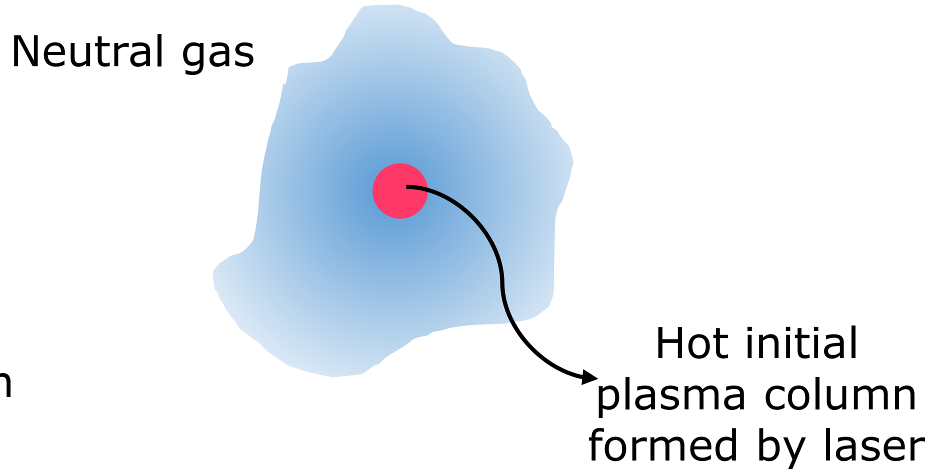
$n_e(0) \sim 1 \times 10^{17}\ \mathrm{cm}^{-3}$

[1] T. Audet *et al*., EuPraxia Milestone Report M3.1 (2017)
[2] W. P. Leemans *et al*., Proc. PAC 2011, **1416** 5 (2011)

HOFI Plasma Channels

- Use a low energy laser pulse to create a long column of hot plasma.





Hydrodynamic Plasma Channels:
Durfee and Milchberg (1993)

HOFI Plasma Channels

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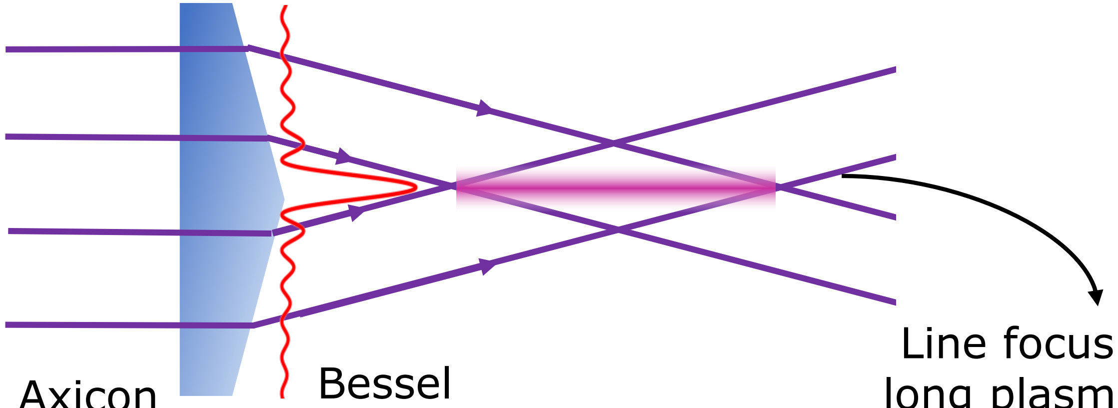
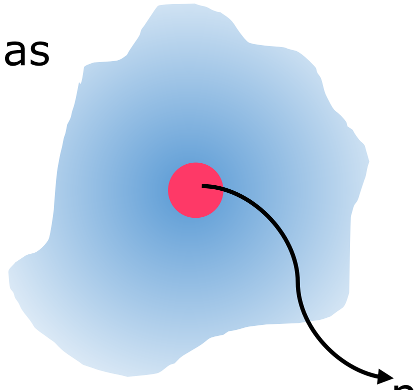
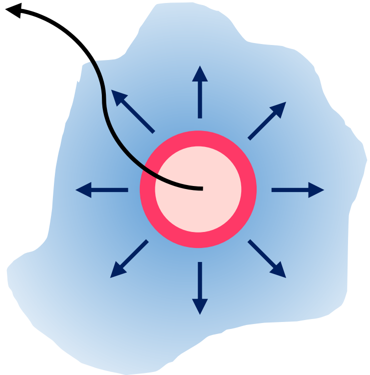




- Electrons on-axis are heated through **optical-field-ionisation** (OFI)

- Hot electrons expand outwards into neutral gas, forming shock front of high n_e, leaving low n_e on-axis



Hydrodynamic Plasma Channels:
Durfee and Milchberg (1993)

Short, high-density OFI channels:
N. Lemos *et al.* (2013), N. Lemos *et al.* (2013), N. Lemos *et al.* (2018)

Why do we need new waveguides?

Capillary Discharge

20 cm demonstrated

Used to demonstrate 8 GeV electron acceleration

Not-indestructible – Sapphire damages

Spence and S. M. Hooker (2000)
A. Butler *et al*. (2002)

Hydrodynamic Expansion in Gases

Self-healing

Guiding possible over a few cm

Relies on collisional ionization - Restricted to **high-density**

Durfee & Milchberg (1993)
Volfbeyn *et al*. (1999)

Self-Guiding

> 2 GeV electron energies demonstrated

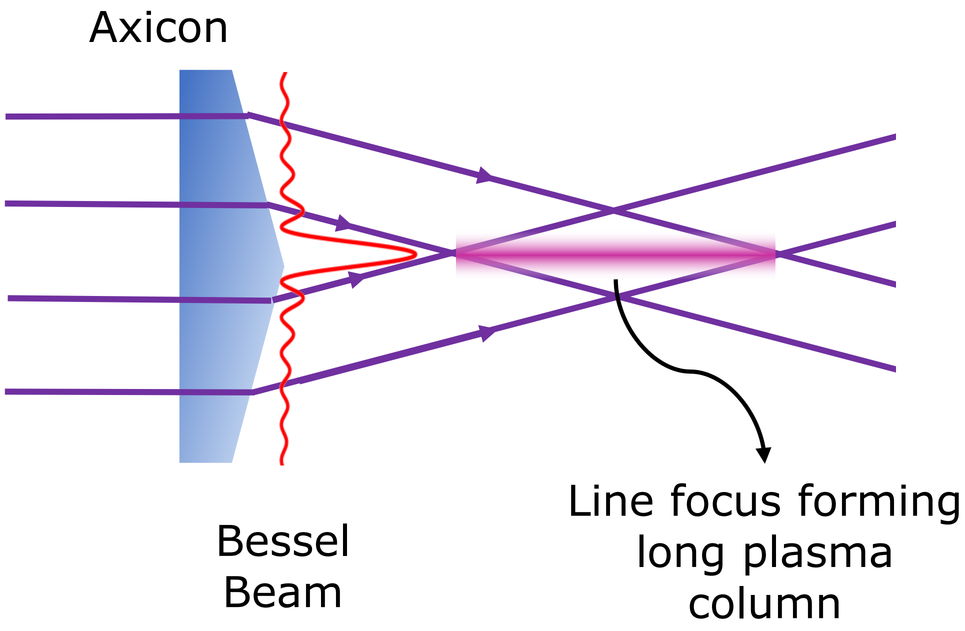
Higher laser power required

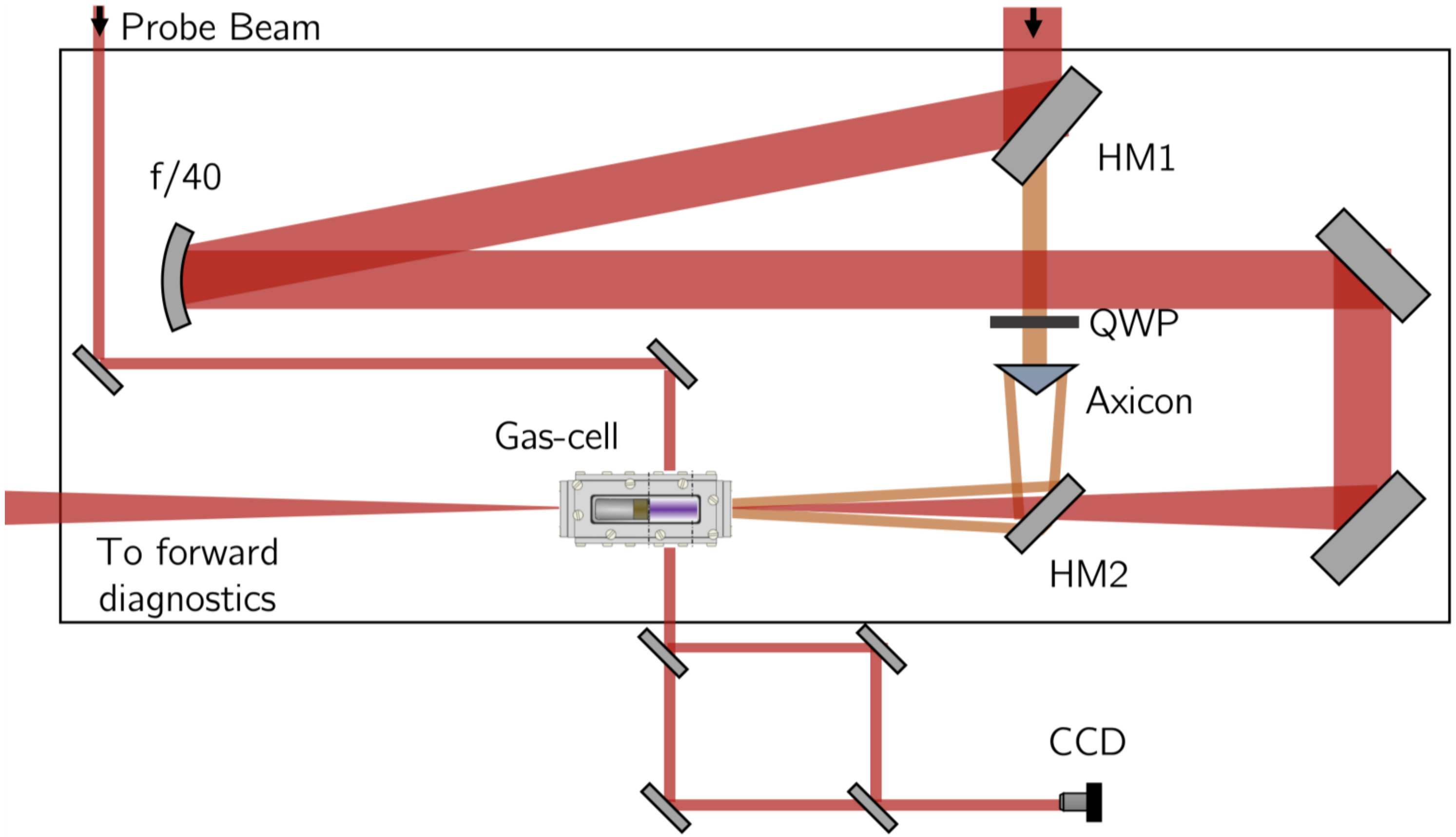
Relies on non-linear processes

Mangles *et al.* (2012)

Experimental Setup

- **Axicon** generates line focus, and long column of hot plasma
- Probe plasma channel with **transverse interferometry**
- Quarter wave plate to switch the polarisation





Experimental Setup

- **Axicon** gene
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- Quarter wave

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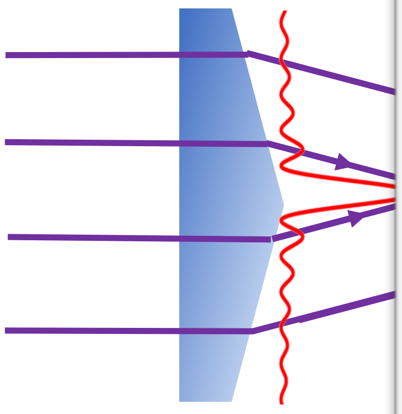
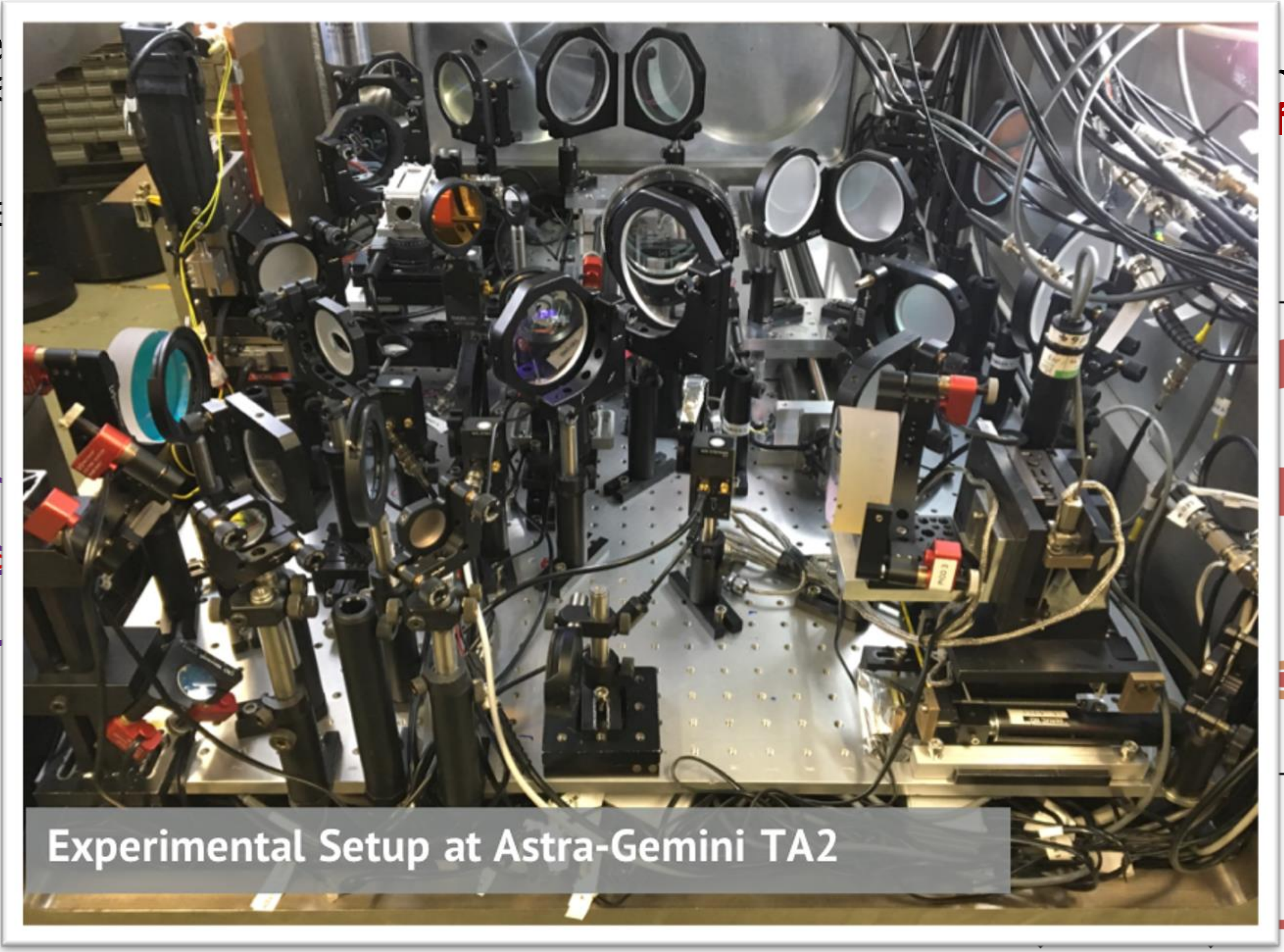
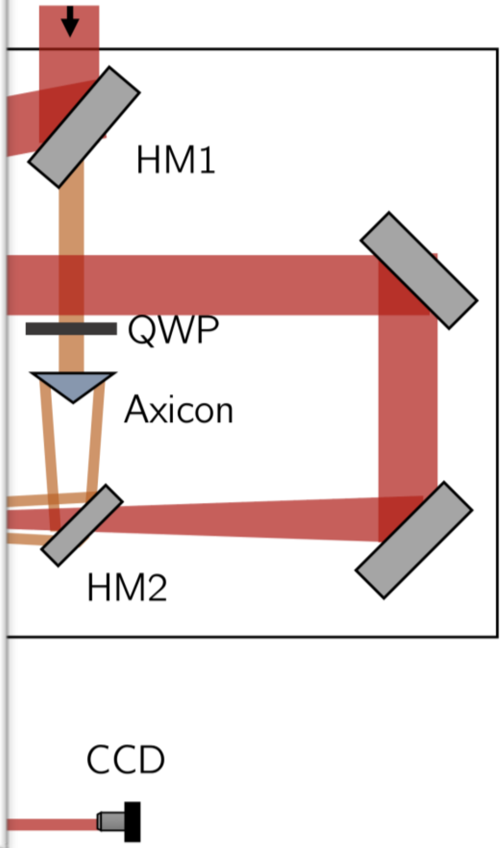
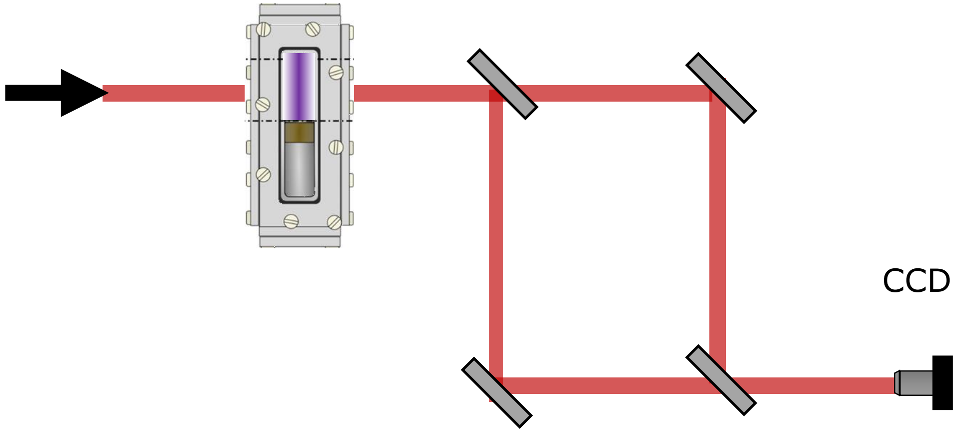


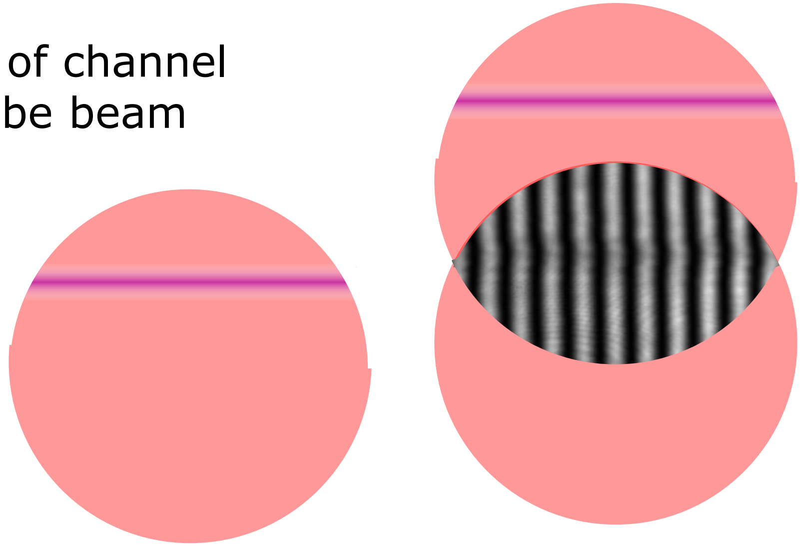




Measuring the Plasma Channel



Shadow of channel
on probe beam

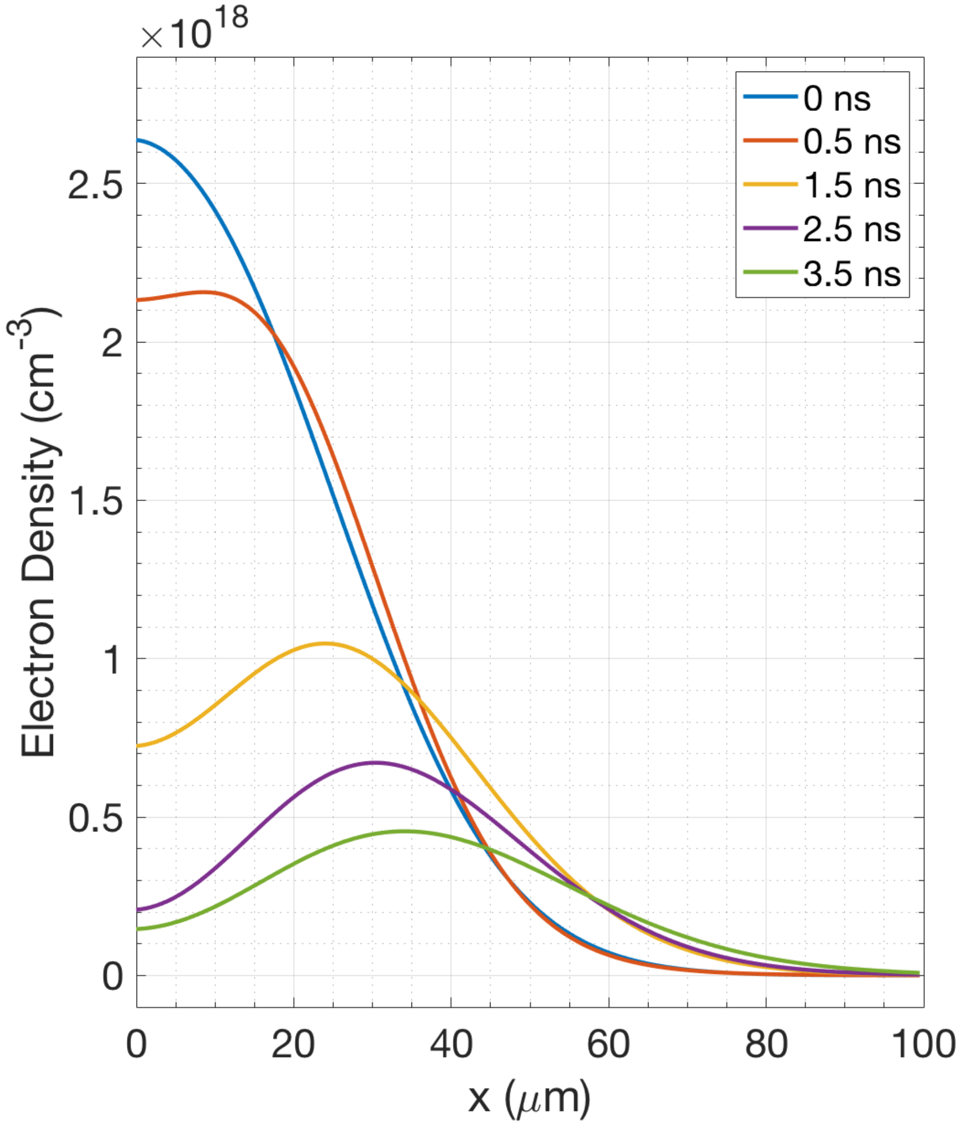


Interference
Region

- HOFI plasma channels were:
  - Small in size
  - **Low phase shift**
  - Somewhat **asymmetric**
- Abel inversion was impractical
- Developed new method to retrieve density from transverse projections

R. Shalloo *et al.* (2019)

Evolution of the Plasma Channel

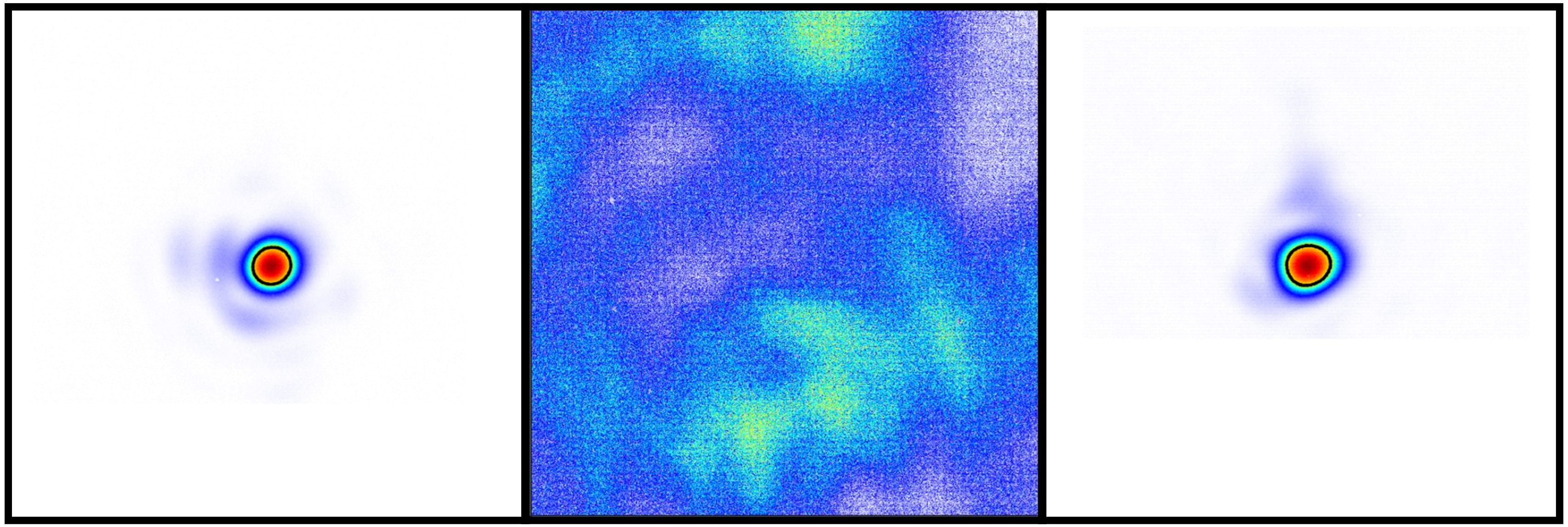


- Used a forward fitting technique
- Represented the electron density profile as a superposition of basis functions
- Able to recover the density profile and see **shock evolution**
- Enabled us to measure the **guiding properties**

R. Shalloo *et al.* (2019)

Short Channel Formation

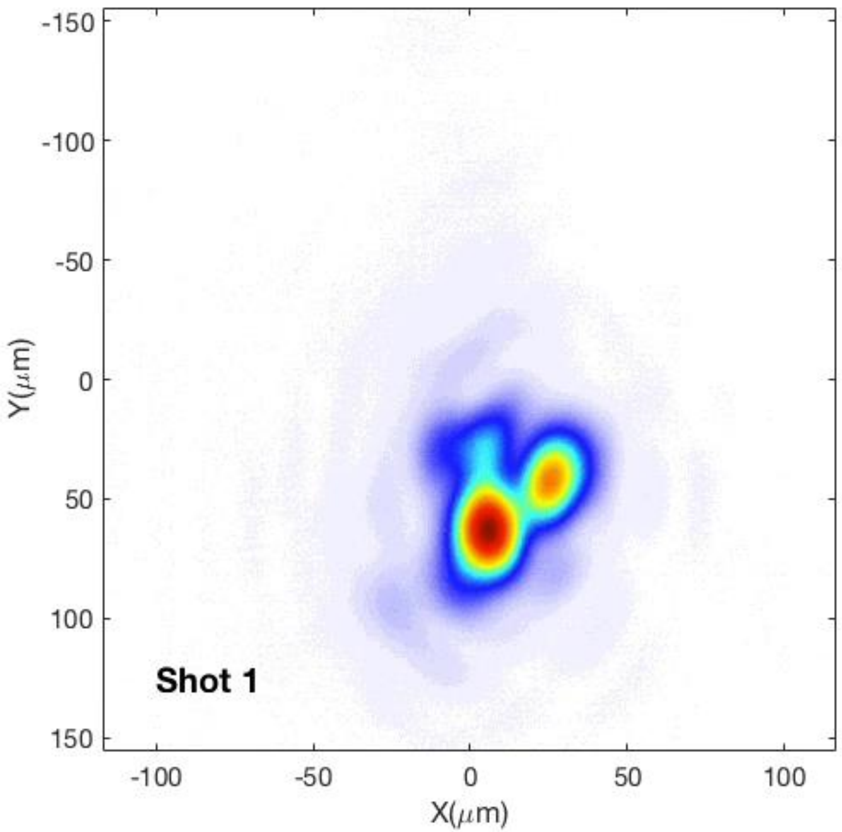
- Experiments performed with Astra-Gemini TA2 laser
- Guided beam focused with *f*/25 OAP
- Evidence of guiding of high intensity pulse through HOFI channel. Output spot closely resembles input



Input spot, $z = 0$ mm | **Unguided spot,** $z = 16$ mm | **Guided spot,** $z = 16$ mm

R. Shalloo *et al.* (2019)

Short Channel Formation



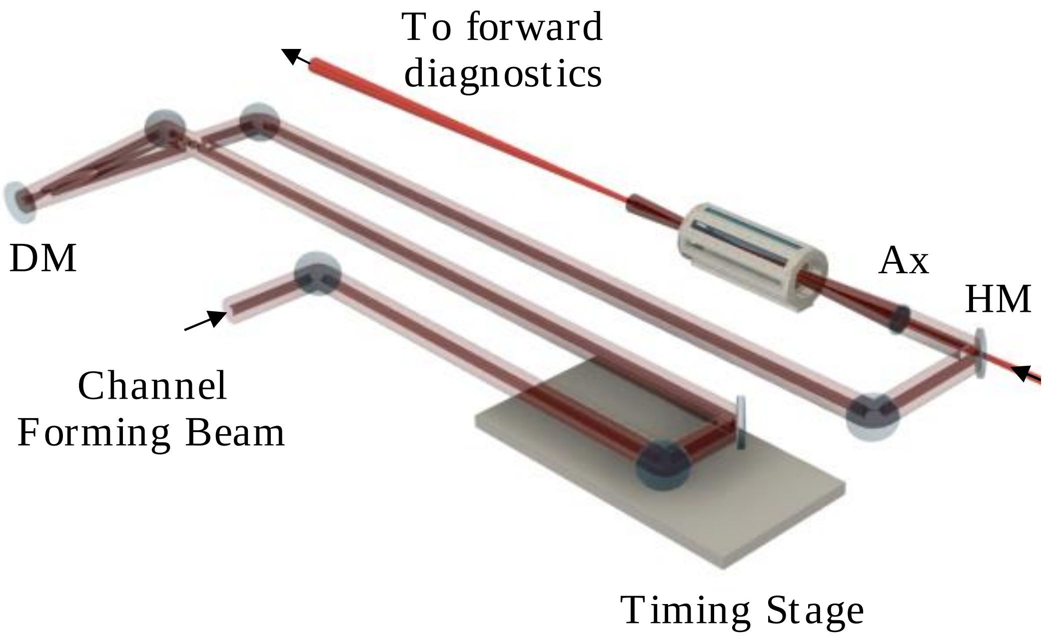
Animation courtesy of Robert Shalloo

High-power guiding at 5 Hz

N: 489 consecutive shots
I_0: 4×10^{17} W cm^{-2}
5 Hz: 12 shots every 45 s

R. Shalloo *et al.* (2019)

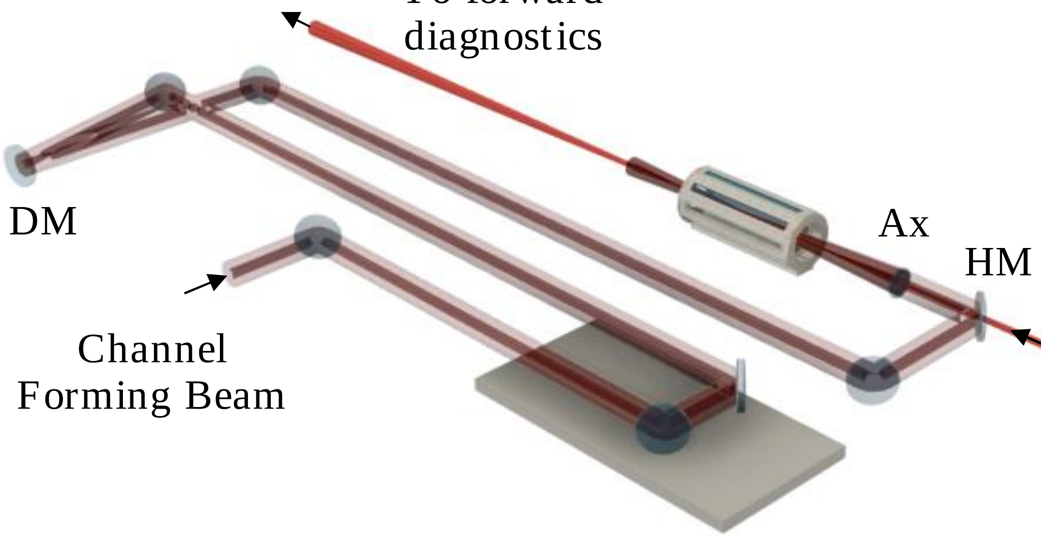
10 cm Channel Formation

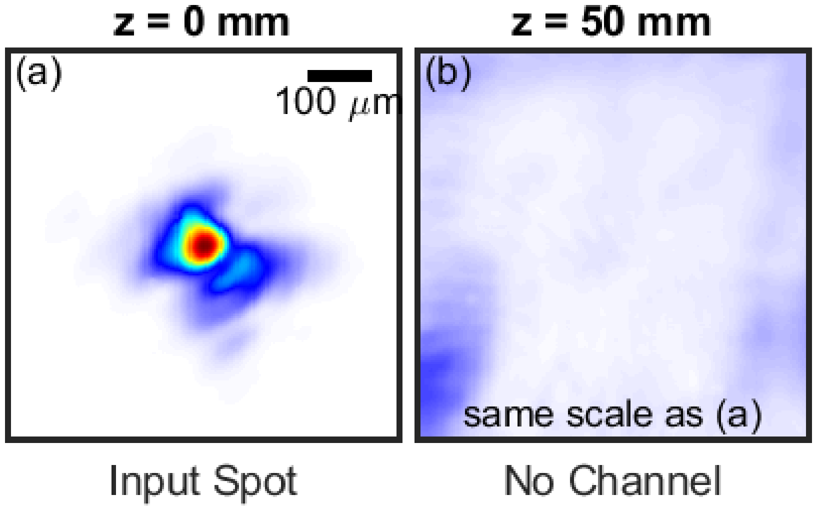


- Second experiment at Gemini TA3 facility
- Accelerator driver beam:
  - $I = 6.1 \times 10^{17}\ \mathrm{W\,cm^{-2}}$
  - $38\ \mu\mathrm{m}$ spot
  - $a_0 = 0.54$ - linear wakefield
- Went to **100 mm long** channels
- On-axis densities $\leq 1 \times 10^{17}\ \mathrm{cm^{-3}}$

A. Picksley *et al.* (in prep)

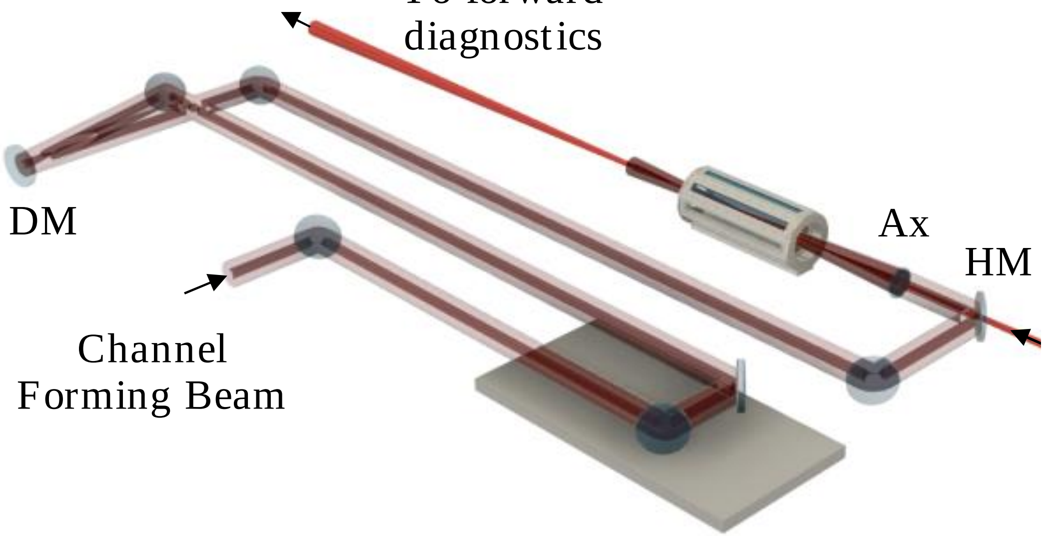
10 cm Channel Formation

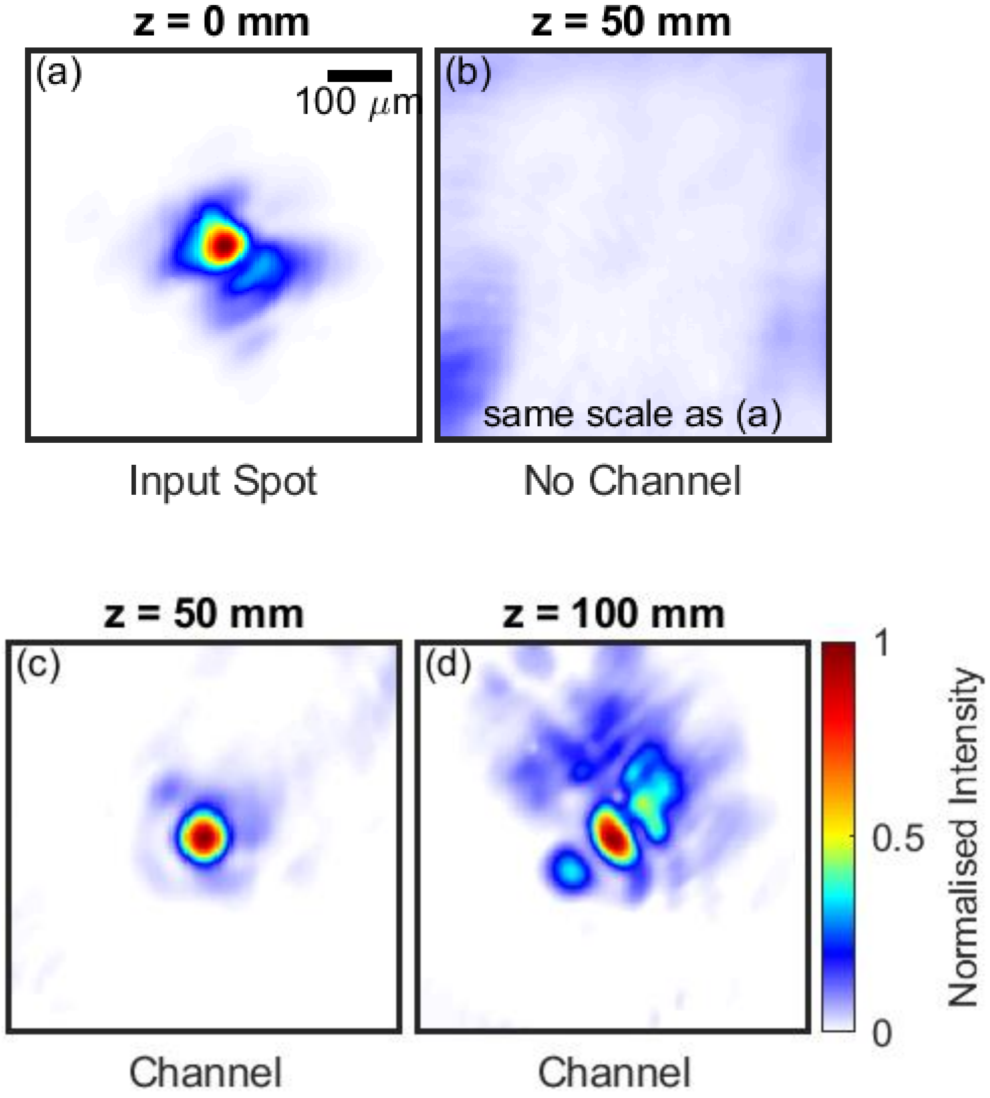




A. Picksley *et al.* (in prep)

10 cm Channel Formation

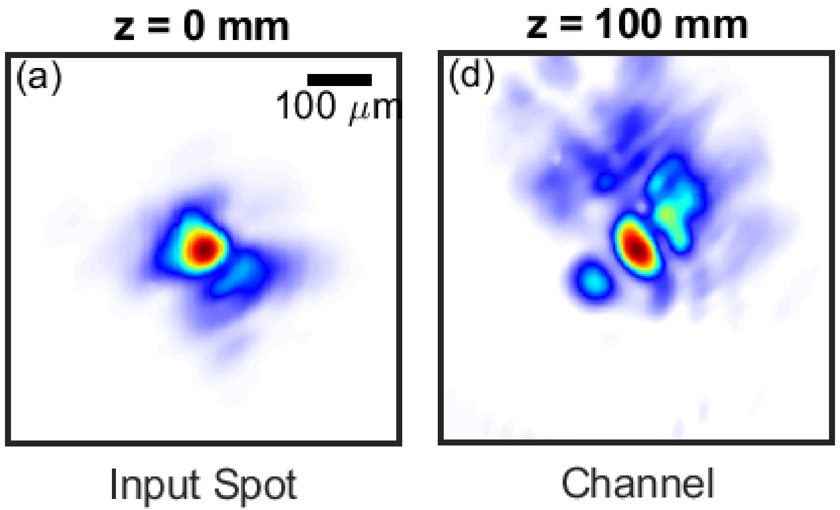




A. Picksley *et al.* (in prep)

Summary

- Developed a technique to produce better guiding structures in LWFA's
- Channels are kHz ready and suitable for multi-GeV LPA stages
- Demonstrated generation of HOFI channels:
  - Low density, $\sim 1 \times 10^{17}\ \mathrm{cm}^{-3}$
  - 10 cm long
  - Capable of kHz operation



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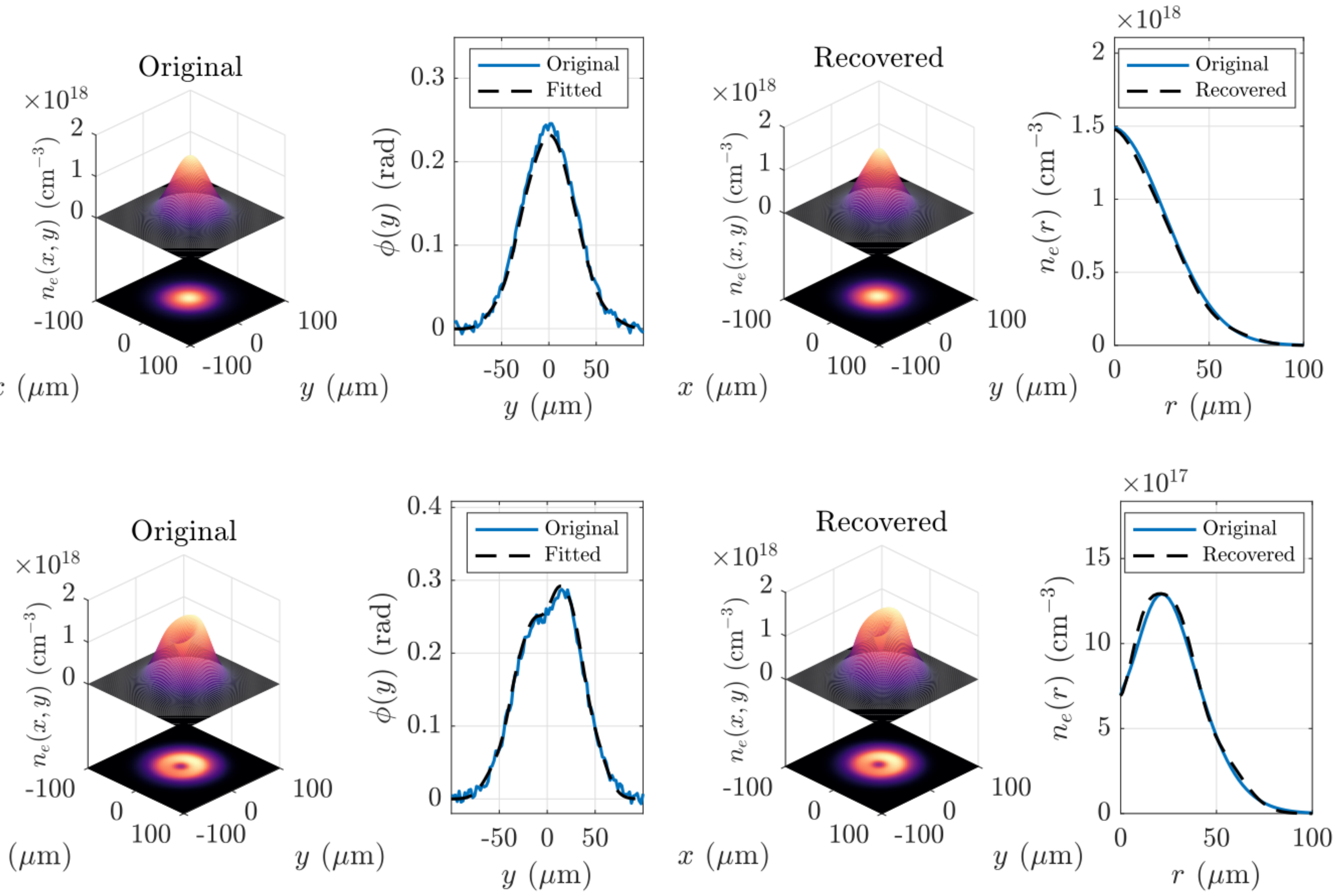
Spare Slides

Recovering Asymmetric Profiles



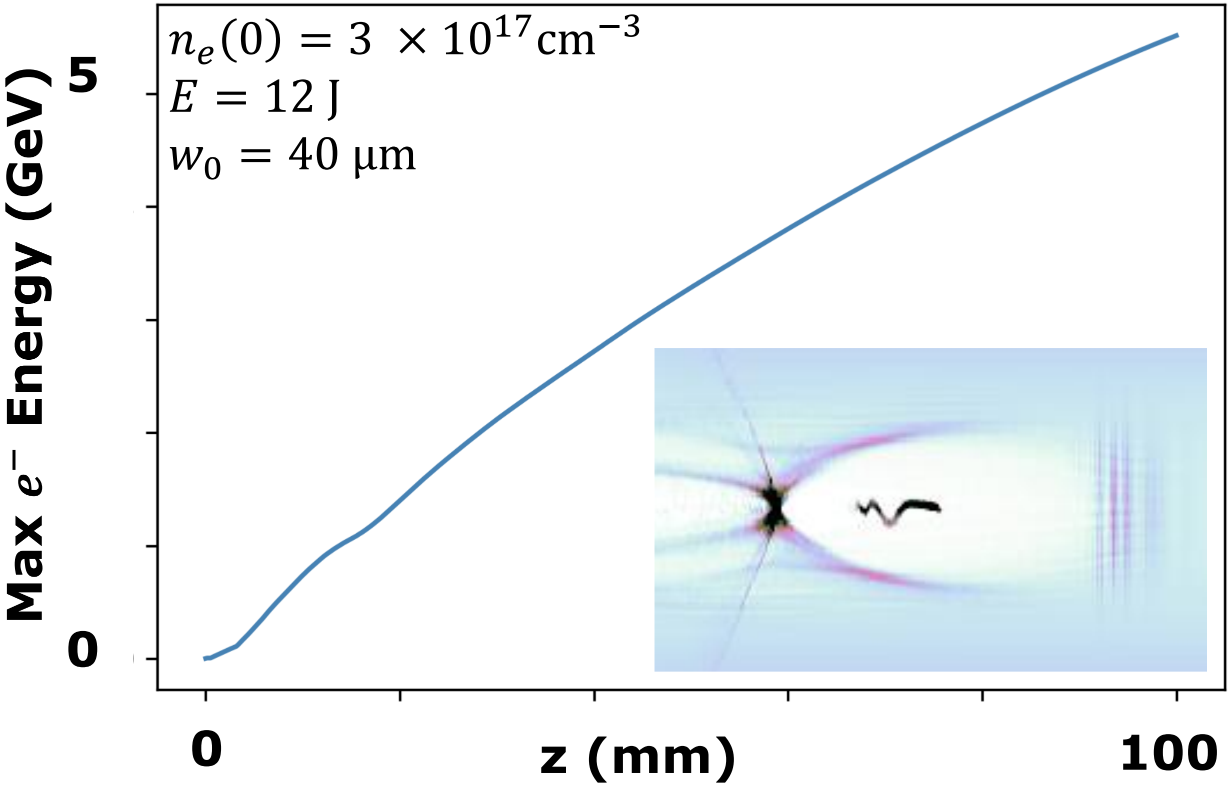
- Assume $n_e(x,y)$ can be written as superposition of basis functions
- Generate projection from trial superposition
- Fit using NL least squares
- Allow asymmetry using aLG modes

R. Shalloo *et al.* (2019), A. Picksley *et al.* (in prep)

Kovalev et al. PRA 93 063858 (2016)

Simulating a multi-GeV Stage

- Gemini Parameters

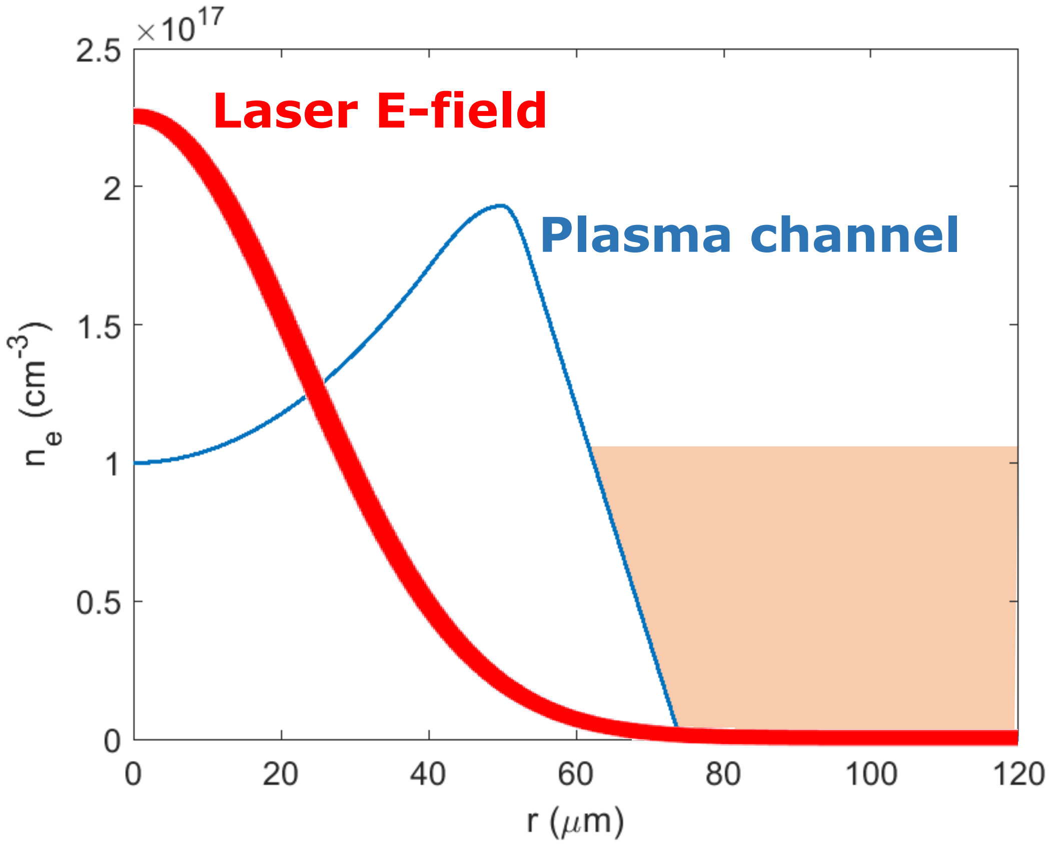


Simulations courtesy of James Cowley

Why Parabolic?

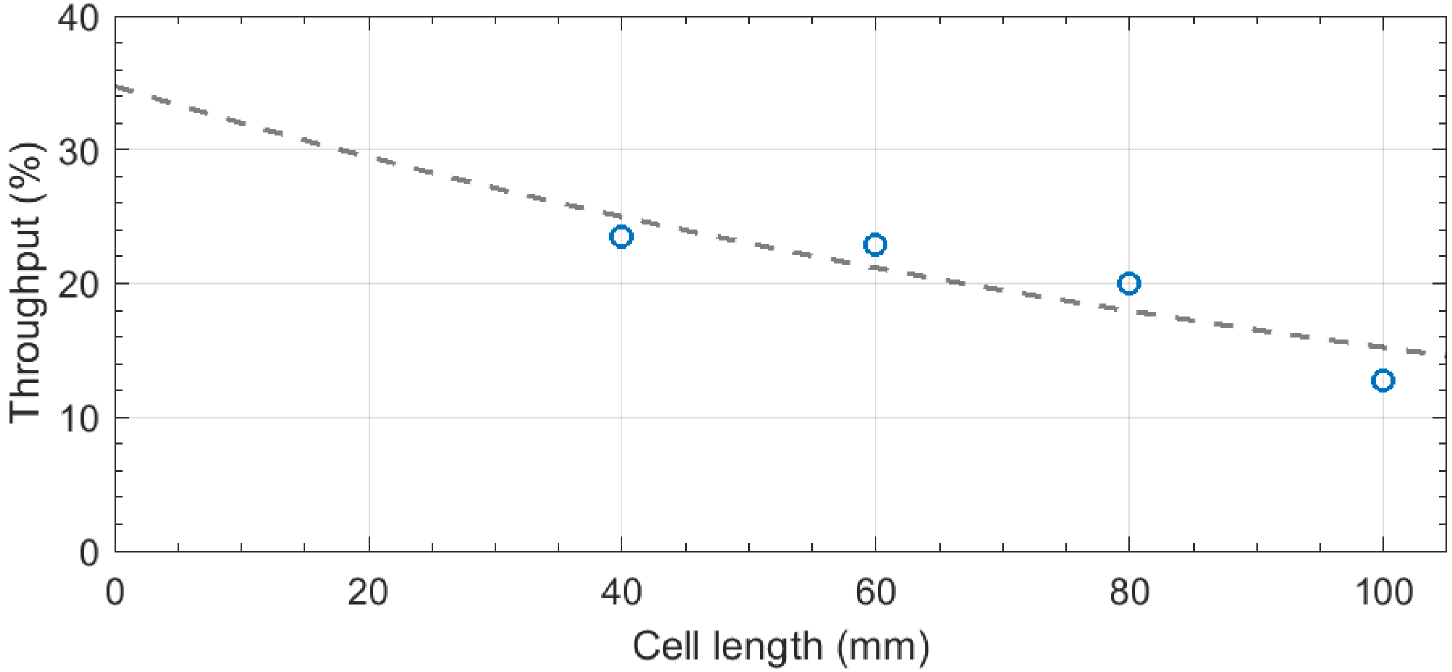
Guiding Properties

- Unlike capillary discharges, field can tunnel past the shock wall
- Like fibres – coupling losses and attenuation losses

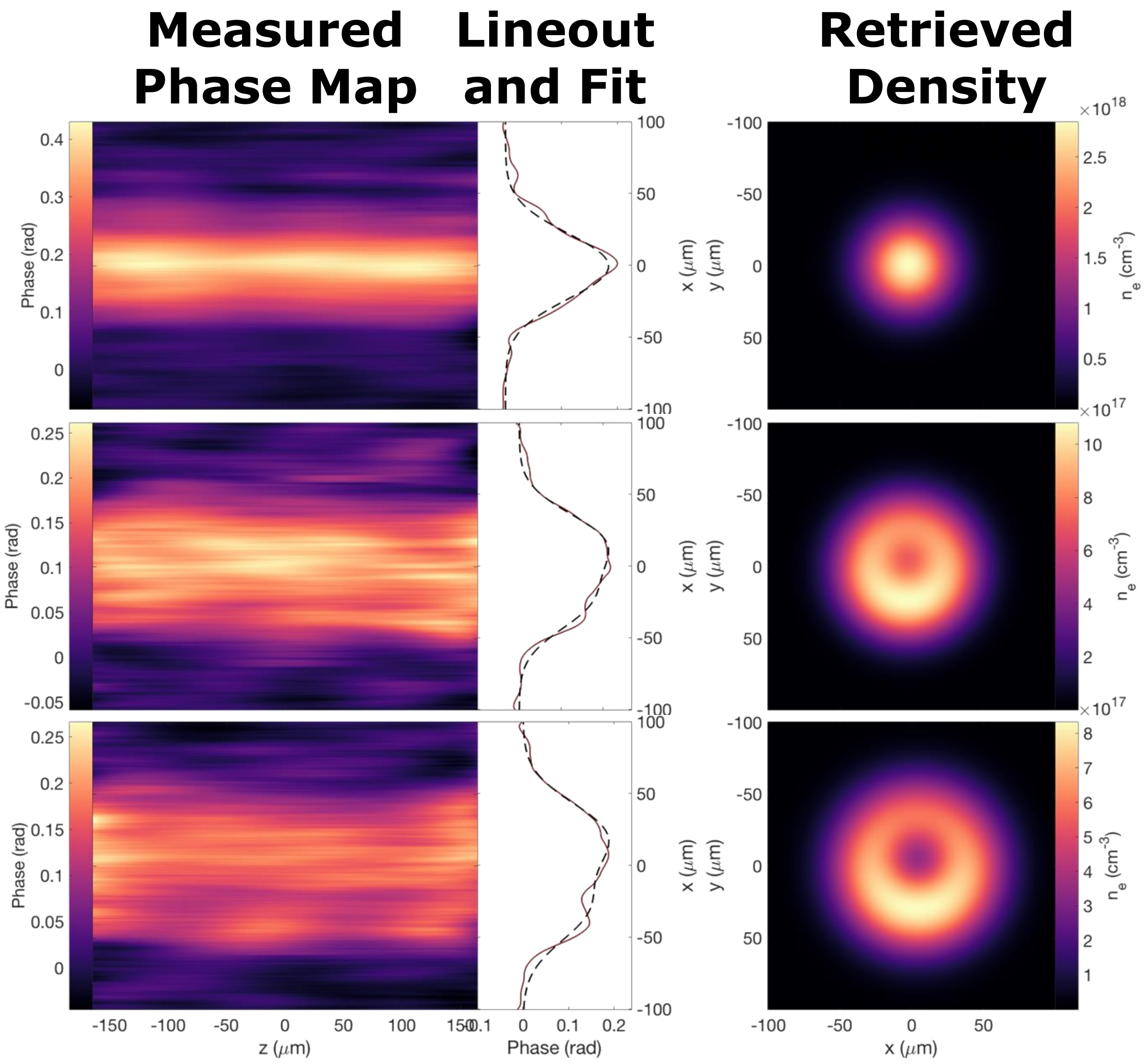


Attenuation length:
$L_{att} = 100\text{ mm}$

Dephasing length:
$L_{dephasing} \sim 200\text{ mm}$



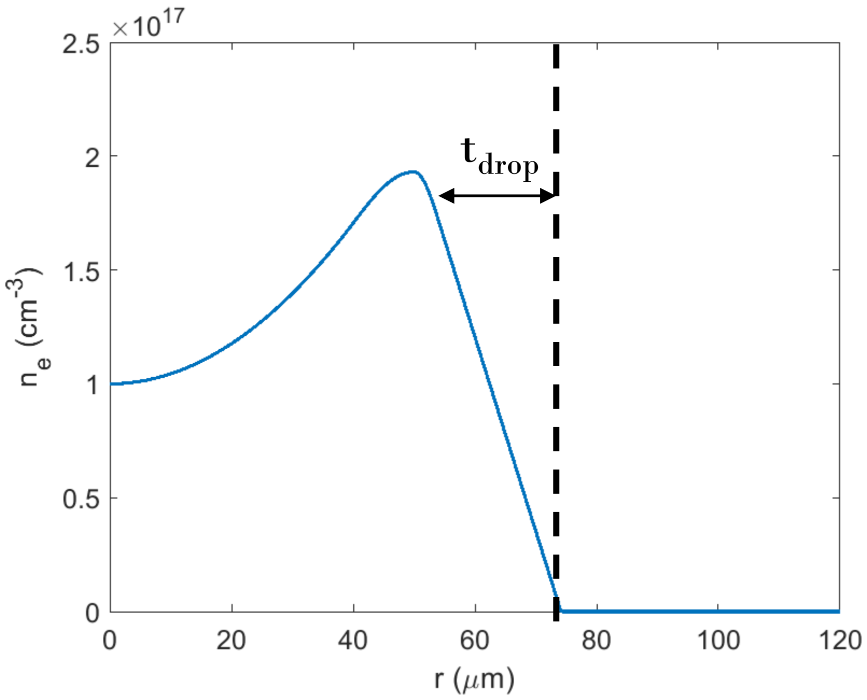
Forward Fitting Algorithm



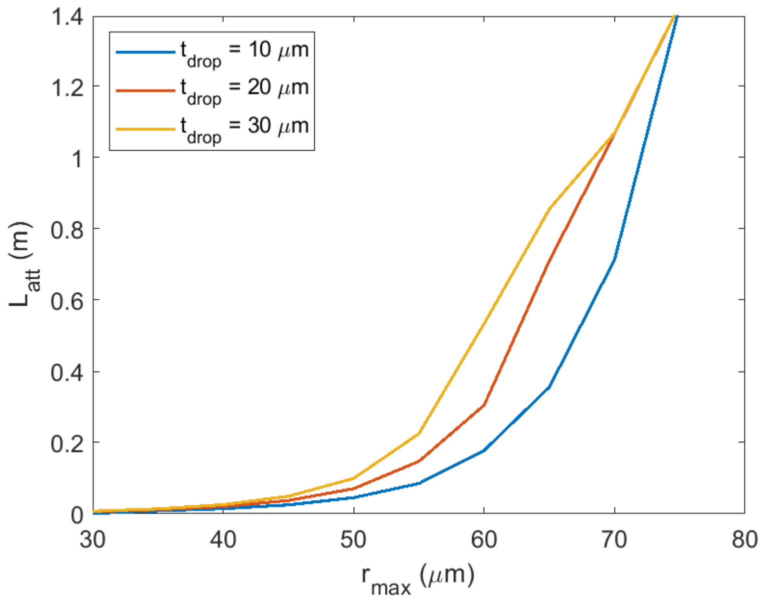
R. Shalloo *et al.* (2019)

Leaky Modes Code

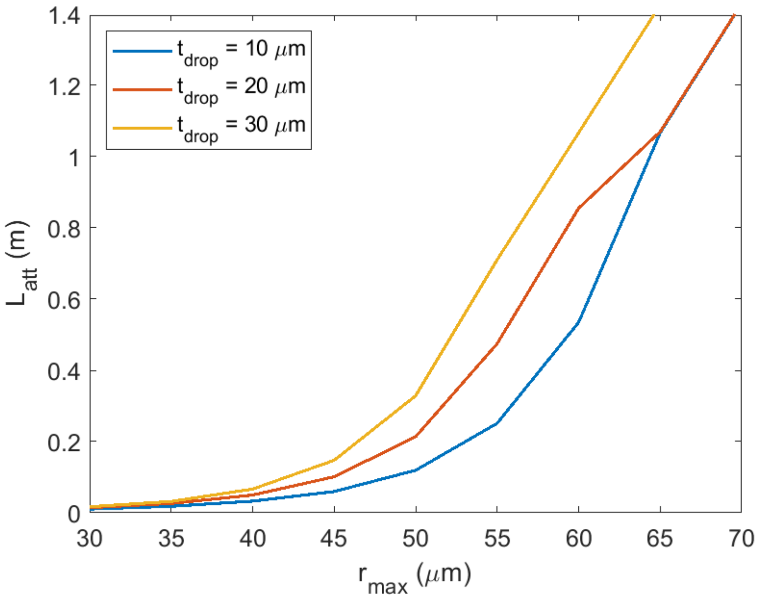
Matched $n(r)$ and $\frac{dn}{dr}$ at boundaries



Wall Thickness = 15 μm



Wall Thickness = 30 μm



Next Step: FBPIC simulation

GRIN Fibres

- **What happens to a guided pulse when it is misaligned at the channel entrance?**

Optical and Quantum Electronics **16** (1984) 9–18

Variation of the speckle contrast in a graded-index fibre by misalignment of the incident beam

T. TSUJI, T. ASAKURA, H. FUJII
Research Institute of Applied Electricity, Hokkaido University, Sapporo, Hokkaido 060, Japan

Received 21 March 1983

The speckle pattern observed at the output end of a multimode fibre is closely related to the modal noise. In this paper, the average contrast of the speckle pattern is studied as a function of the radial position in the output end plane for three kinds of misalignment of the incident beam, i.e. defocusing, axial misalignment and angular misalignment. It is found that a variation of the speckle contrast is very sensitive to all kinds of misalignment of the incident beam and that its varying form strongly depends on the kind of misalignment of the incident beam. The speckle contrast at the centre of the output end plane is also examined as a function of the magnitude of misalignment. It is found that the contrast increases from a minimum value in the correct alignment to a certain saturated value with an increase of misalignment.

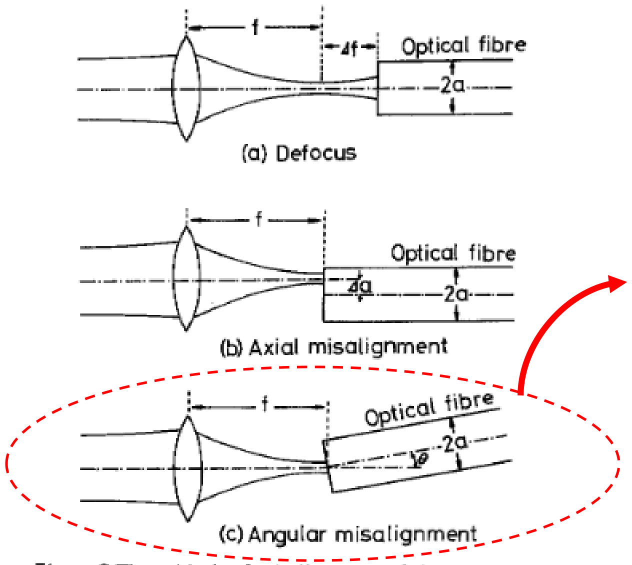
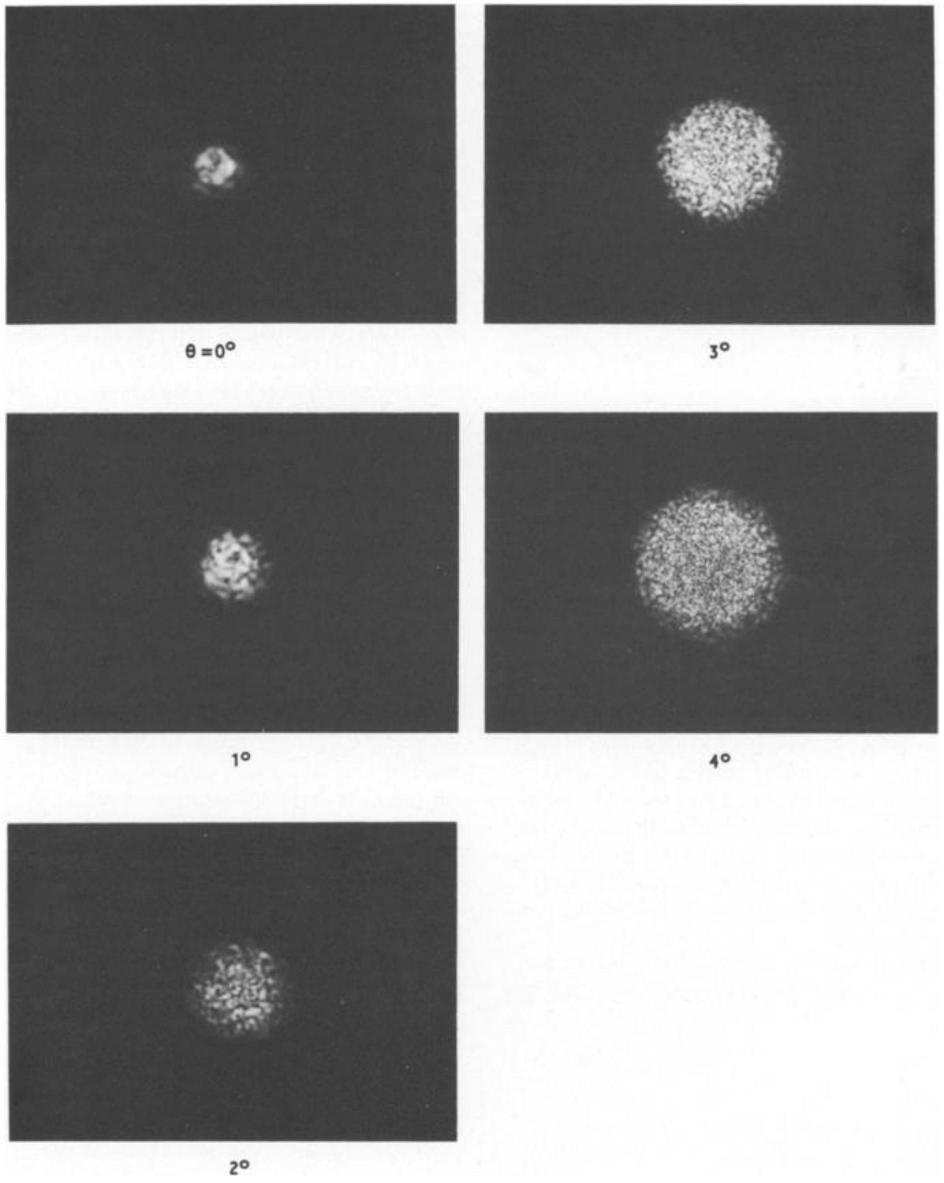


Figure 2 Three kinds of misalignment of the incident beam into a fibre: (a) defocusing, (b) axial misalignment, and (c) angular misalignment.



HOM's excited, 'speckle' observed, exit mode beam size increases