Long Plasma Channels for LWFA

Simon Hooker, Aarón Alejo, Chris Arran*, Alexander von Boetticher, James Holloway, Jakob Jonnerby, Alex Picksley, Rob Shalloo**, Roman Walczak

John Adams Institute for Accelerator Science & Department of Physics, University of Oxford

Laura Corner

Cockcroft Institute, University of Liverpool

Chris Thornton

Rutherford Appleton Laboratory

George Hine & Howard Milchberg

University of Maryland

* Now at University of York

** Now at Imperial College London

Acknowledgements

This work was supported by:

- Science and Technology Facilities Council (STFC UK) [grant numbers ST/J002011/1, ST/P002048/1, ST/M50371X/1, ST/N504233/1, ST/R505006/1]
- Engineering and Physical Sciences Research Council [Studentship No. EP/N509711/1]
- Helmholtz Association of German Research Centres [Grant number VH- VI-503]
- This material is based upon work supported by the Air Force Office of Scientific Research under award numbers FA8655-13-1-2141 and FA9550-18-1-7005.
- This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 653782.
- GH and HMM were supported by US Dept. of Energy (Grant No. DESC0015516), Dept. of Homeland Security (Grant No. 2016DN077ARI104), National Science Foundation (Grant No. PHY1619582), AFOSR (Grants No. FA9550-16- 10121 and FA9550-16-10284)
- The plasma HEC Consortium EPSRC grant number EP/L000237/1,
- CLF and the Scientific Computing Department at RAL for the use of SCARF-LEXICON computer cluster
- ARCHER UK National Supercomputing Service

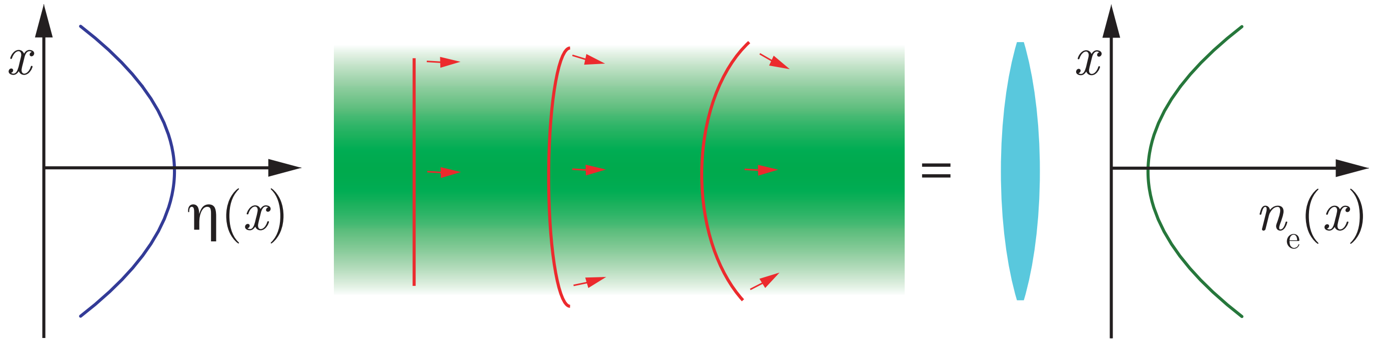
Outline

- Motivation: what do we need for ALIC?
- HOFI plasma channels
- Summary

Motivation

$$\Delta W \propto \frac{1}{n_e}$$

$$L_d \approx \frac{\lambda_p^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}}$$



$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

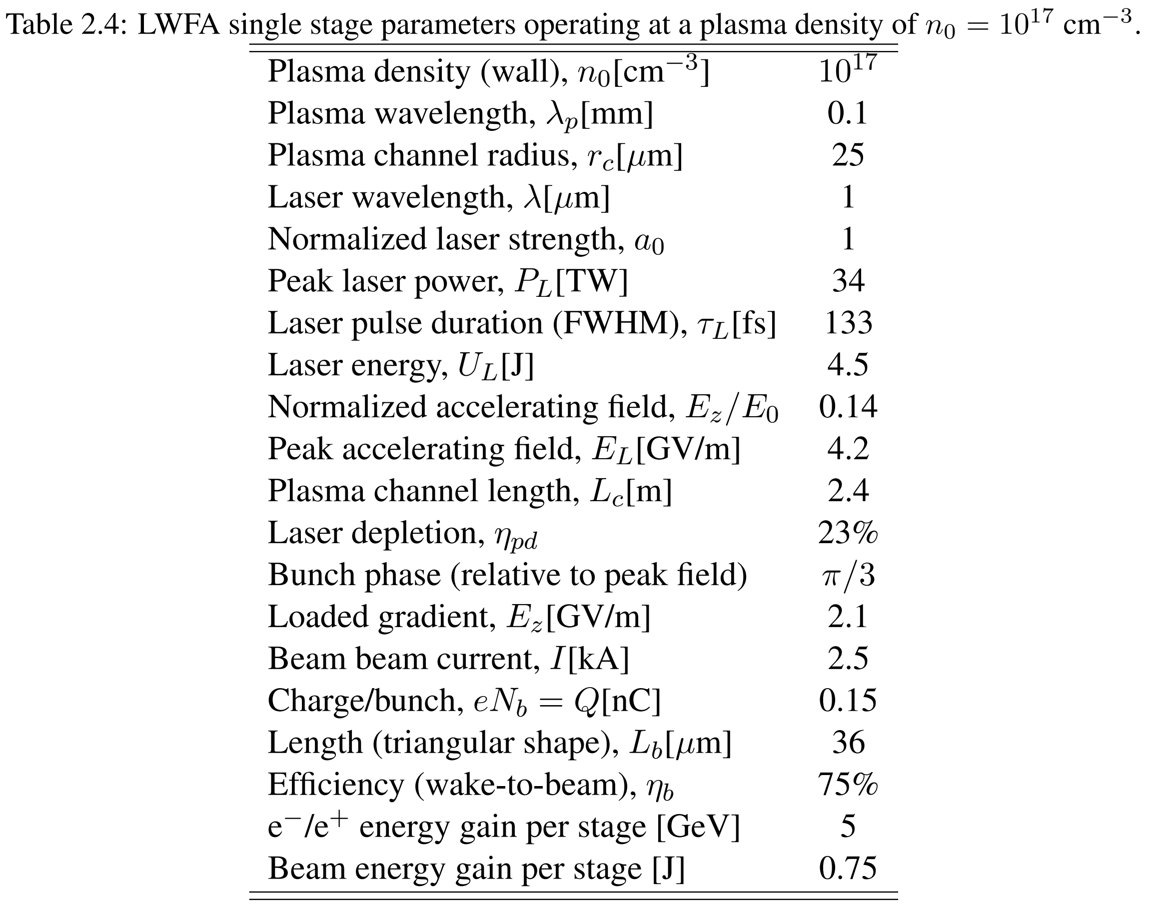


Table 2.4: LWFA single stage parameters operating at a plasma density of $n_0 = 10^{17}$ cm^{-3}.

Plasma density (wall), n_0[cm^{-3}]	10^{17}
Plasma wavelength, λ_p[mm]	0.1
Plasma channel radius, r_c[μm]	25
Laser wavelength, λ[μm]	1
Normalized laser strength, a_0	1
Peak laser power, P_L[TW]	34
Laser pulse duration (FWHM), τ_L[fs]	133
Laser energy, U_L[J]	4.5
Normalized accelerating field, E_z/E_0	0.14
Peak accelerating field, E_L[GV/m]	4.2
Plasma channel length, L_c[m]	2.4
Laser depletion, η_{pd}	23%
Bunch phase (relative to peak field)	$\pi/3$
Loaded gradient, E_z[GV/m]	2.1
Beam beam current, I[kA]	2.5
Charge/bunch, $eN_b = Q$[nC]	0.15
Length (triangular shape), L_b[μm]	36
Efficiency (wake-to-beam), η_b	75%
e$^-$/e$^+$ energy gain per stage [GeV]	5
Beam energy gain per stage [J]	0.75

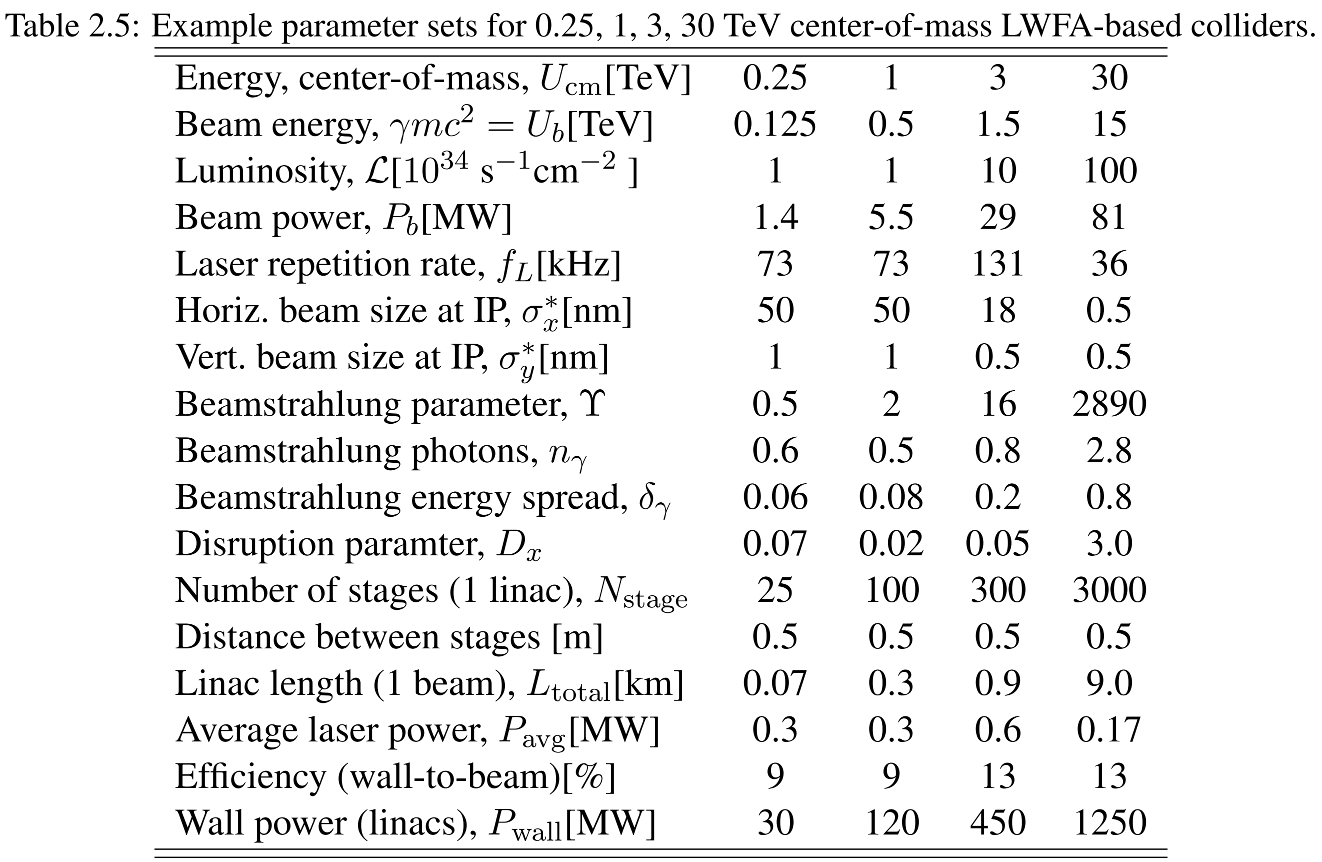


Table 2.5: Example parameter sets for 0.25, 1, 3, 30 TeV center-of-mass LWFA-based colliders.

Energy, center-of-mass, $U_{\rm cm}$[TeV]	0.25	1	3	30
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.125	0.5	1.5	15
Luminosity, $\mathcal{L}[10^{34}$ s^{-1}cm^{-2}]	1	1	10	100
Beam power, P_b[MW]	1.4	5.5	29	81
Laser repetition rate, f_L[kHz]	73	73	131	36
Horiz. beam size at IP, σ_x^*[nm]	50	50	18	0.5
Vert. beam size at IP, σ_y^*[nm]	1	1	0.5	0.5
Beamstrahlung parameter, Υ	0.5	2	16	2890
Beamstrahlung photons, n_γ	0.6	0.5	0.8	2.8
Beamstrahlung energy spread, δ_γ	0.06	0.08	0.2	0.8
Disruption paramter, D_x	0.07	0.02	0.05	3.0
Number of stages (1 linac), $N_{\rm stage}$	25	100	300	3000
Distance between stages [m]	0.5	0.5	0.5	0.5
Linac length (1 beam), $L_{\rm total}$[km]	0.07	0.3	0.9	9.0
Average laser power, $P_{\rm avg}$[MW]	0.3	0.3	0.6	0.17
Efficiency (wall-to-beam)[%]	9	9	13	13
Wall power (linacs), $P_{\rm wall}$[MW]	30	120	450	1250

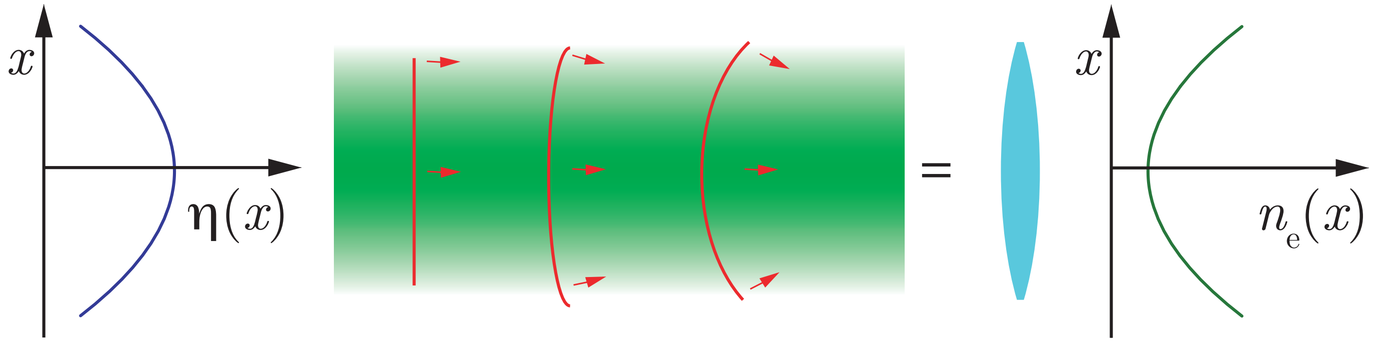
Towards an Advanced Linear International Collider
ALEGRO collaboration *arXiv:1901.10370v2*

- One proposed set of parameters for ALIC
  - Nb: channel considered here is hollow

Motivation

$$\Delta W \propto \frac{1}{n_e}$$

$$L_d \approx \frac{\lambda_p^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}}$$



$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

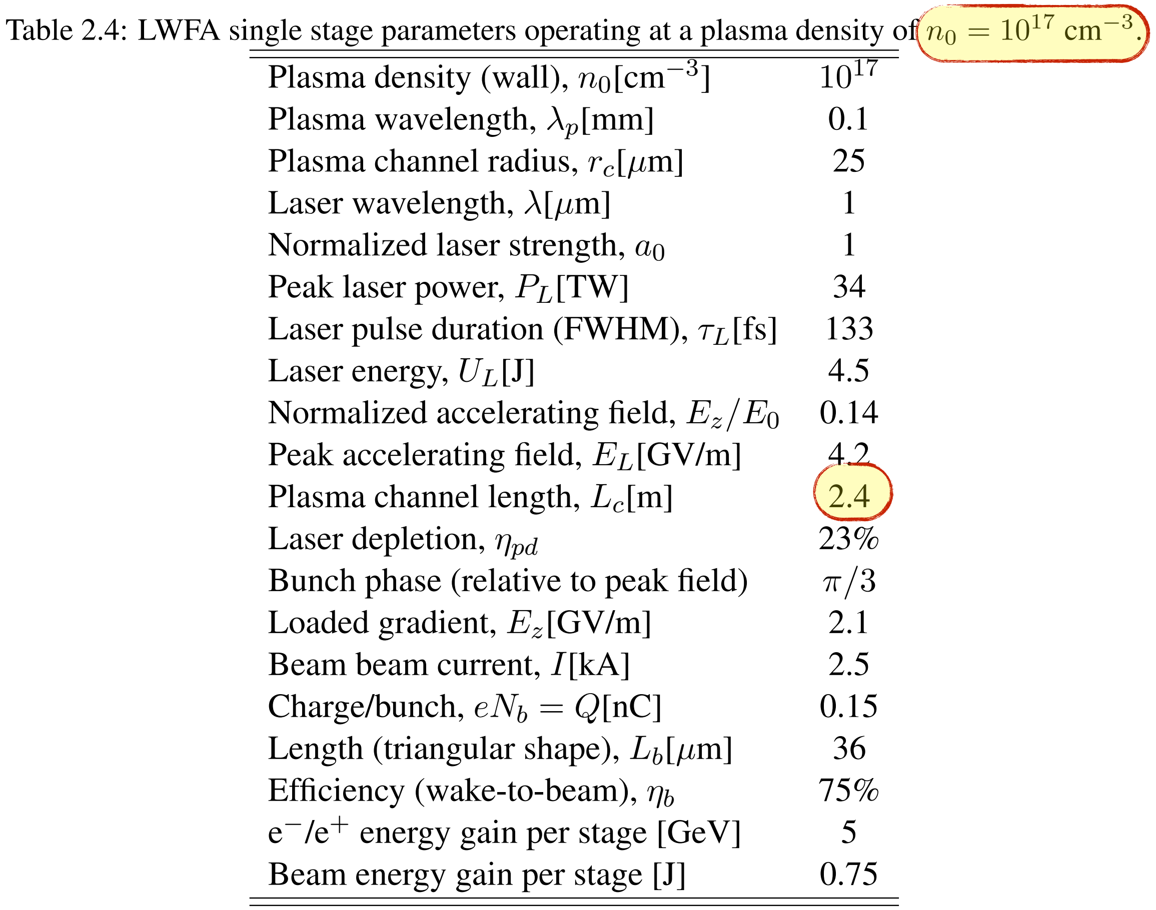


Table 2.4: LWFA single stage parameters operating at a plasma density of $n_0 = 10^{17}$ cm^{-3}.

Plasma density (wall), n_0[cm^{-3}]	10^{17}
Plasma wavelength, λ_p[mm]	0.1
Plasma channel radius, r_c[μm]	25
Laser wavelength, λ[μm]	1
Normalized laser strength, a_0	1
Peak laser power, P_L[TW]	34
Laser pulse duration (FWHM), τ_L[fs]	133
Laser energy, U_L[J]	4.5
Normalized accelerating field, E_z/E_0	0.14
Peak accelerating field, E_L[GV/m]	4.2
Plasma channel length, L_c[m]	2.4
Laser depletion, η_{pd}	23%
Bunch phase (relative to peak field)	$\pi/3$
Loaded gradient, E_z[GV/m]	2.1
Beam beam current, I[kA]	2.5
Charge/bunch, $eN_b = Q$[nC]	0.15
Length (triangular shape), L_b[μm]	36
Efficiency (wake-to-beam), η_b	75%
e$^-$/e$^+$ energy gain per stage [GeV]	5
Beam energy gain per stage [J]	0.75

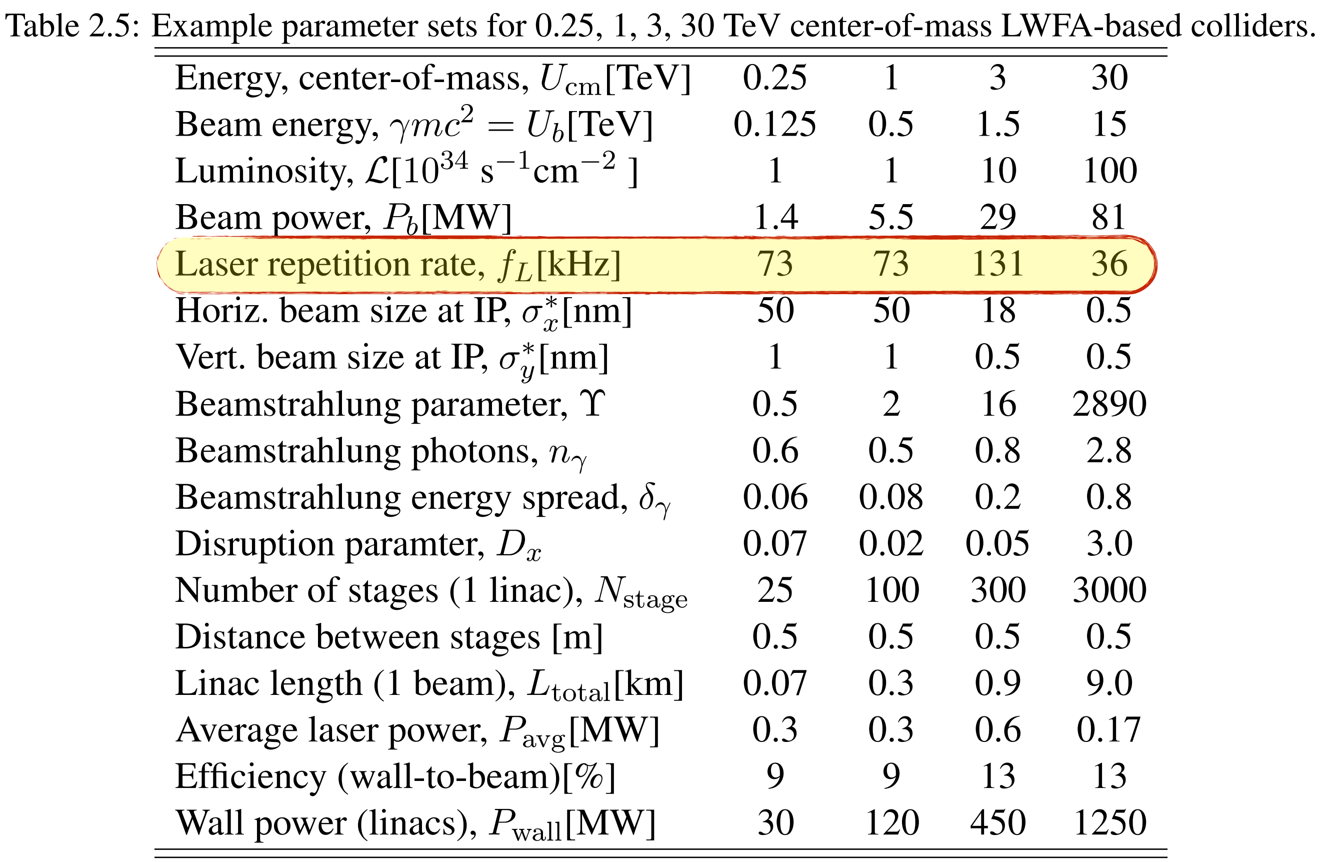


Table 2.5: Example parameter sets for 0.25, 1, 3, 30 TeV center-of-mass LWFA-based colliders.

Energy, center-of-mass, $U_{\rm cm}$[TeV]	0.25	1	3	30
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.125	0.5	1.5	15
Luminosity, $\mathcal{L}[10^{34}$ s^{-1}cm^{-2}]	1	1	10	100
Beam power, P_b[MW]	1.4	5.5	29	81
Laser repetition rate, f_L[kHz]	73	73	131	36
Horiz. beam size at IP, σ_x^*[nm]	50	50	18	0.5
Vert. beam size at IP, σ_y^*[nm]	1	1	0.5	0.5
Beamstrahlung parameter, Υ	0.5	2	16	2890
Beamstrahlung photons, n_γ	0.6	0.5	0.8	2.8
Beamstrahlung energy spread, δ_γ	0.06	0.08	0.2	0.8
Disruption paramter, D_x	0.07	0.02	0.05	3.0
Number of stages (1 linac), $N_{\rm stage}$	25	100	300	3000
Distance between stages [m]	0.5	0.5	0.5	0.5
Linac length (1 beam), $L_{\rm total}$[km]	0.07	0.3	0.9	9.0
Average laser power, $P_{\rm avg}$[MW]	0.3	0.3	0.6	0.17
Efficiency (wall-to-beam)[%]	9	9	13	13
Wall power (linacs), $P_{\rm wall}$[MW]	30	120	450	1250

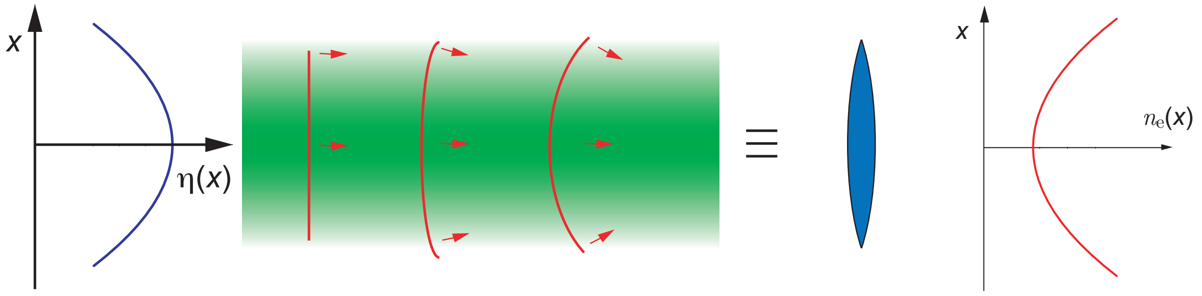
Towards an Advanced Linear International Collider
ALEGRO collaboration *arXiv:1901.10370v2*

- One proposed set of parameters for ALIC
  - Nb: channel considered here is hollow

Motivation

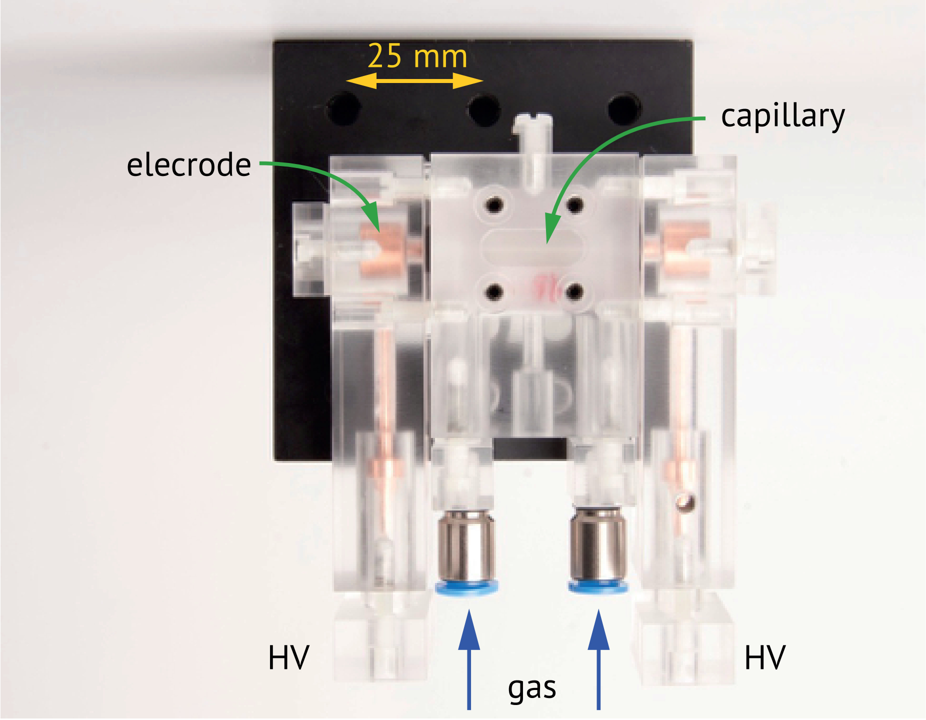
$$\Delta W \propto \frac{1}{n_e}$$

$$L_d \approx \frac{\lambda_p^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}}$$



$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

- Multi-GeV stages require decrease in plasma density from $n_e \approx 10^{18}$ cm^{-3} to **$n_e \approx 10^{17}$ cm^{-3}**
- ALIC requires increase in repetition rate to **kHz range**
- Capillary discharges:
  - Successfully operated at $n_e \approx 10^{17}$ cm-3
  - f_{rep} = 1 kHz demonstrated [A. J. Gonsalves *et al. J. Appl. Phys.* **119** 033302 (2016)]
  - Use of additional laser heater gives deeper channels [A. J. Gonsalves *et al. PRL* **122** 084801 (2019)]

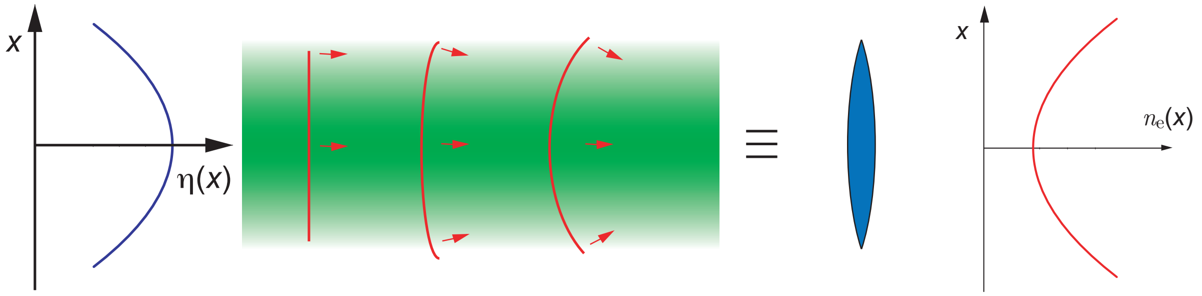


D. Spence and S. Hooker, *Phys Rev E* **63** 015401 (2000)
A. Butler *et al.*, *Phys Rev Lett* **89** 185003 (2002)

Motivation

$$\Delta W \propto \frac{1}{n_e}$$

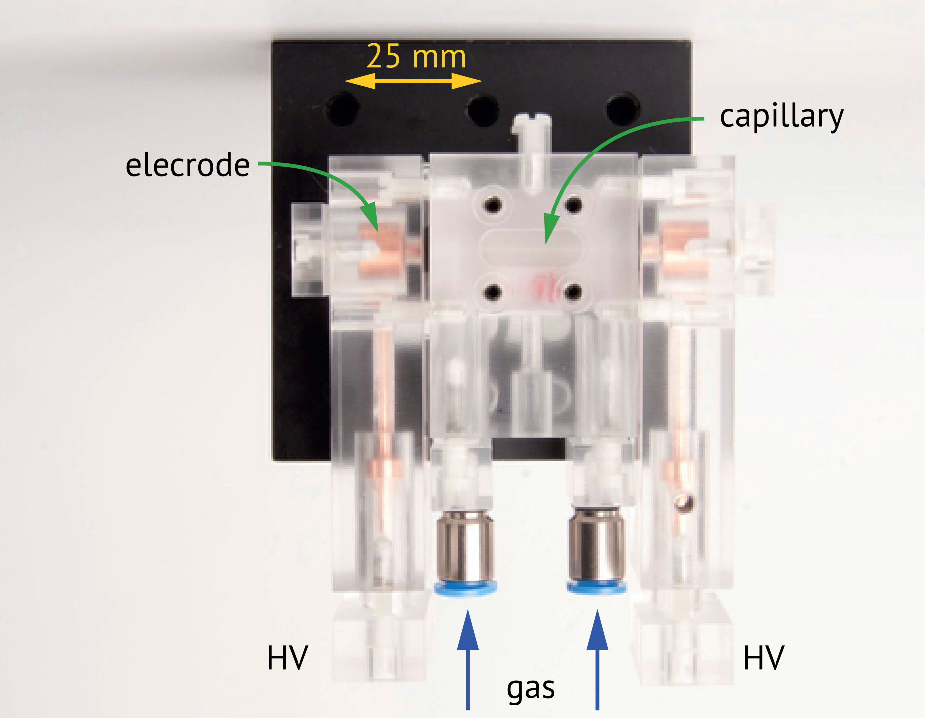
$$L_d \approx \frac{\lambda_p^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}}$$



$$\eta = \sqrt{1-\left(\frac{\omega_p}{\omega}\right)^2}$$

$$\approx 1-\frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

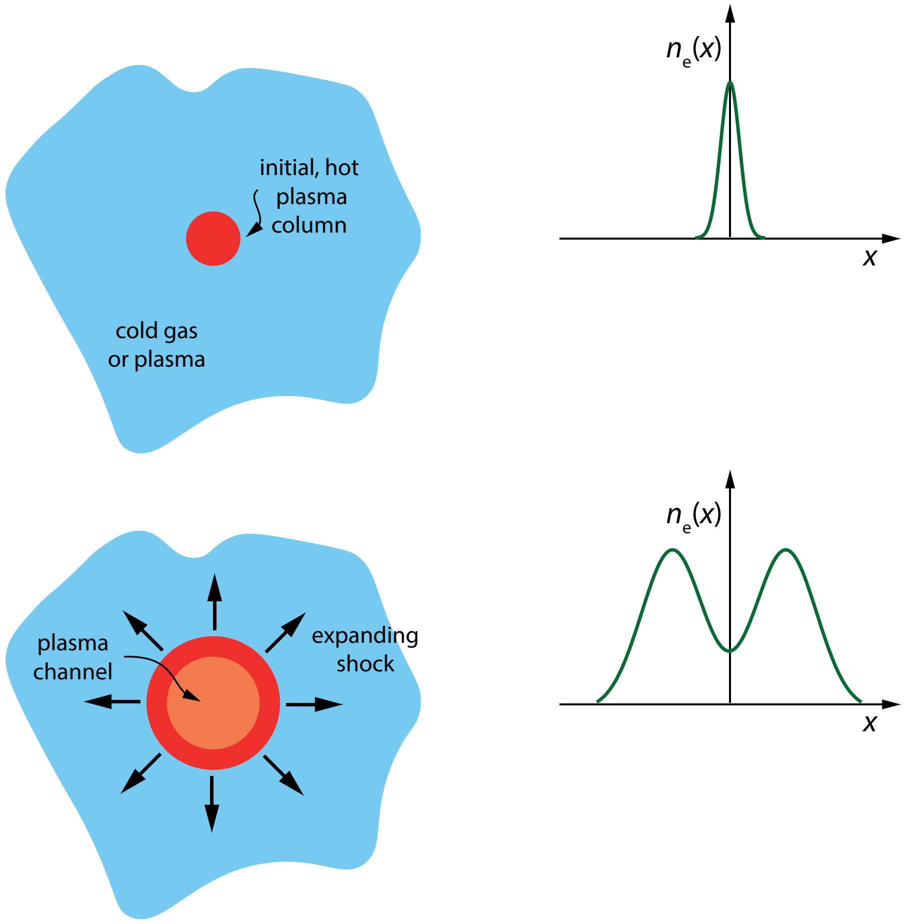
- Multi-GeV stages require decrease in plasma density from $n_e \approx 10^{18}$ cm^{-3} to **$n_e \approx 10^{17}$ cm^{-3}**
- ALIC requires increase in repetition rate to **kHz range**
- Capillary discharges:
  - Successfully operated at $n_e \approx 10^{17}$ cm-3
  - f_{rep} = 1 kHz demonstrated [A. J. Gonsalves *et al. J. Appl. Phys.* **119** 033302 (2016)]
  - Use of additional laser heater gives deeper channels [A. J. Gonsalves *et al. PRL* **122** 084801 (2019)]
- However, long-term guiding of multi-joule laser pulses at kHz rep. rates will clearly still be challenging!



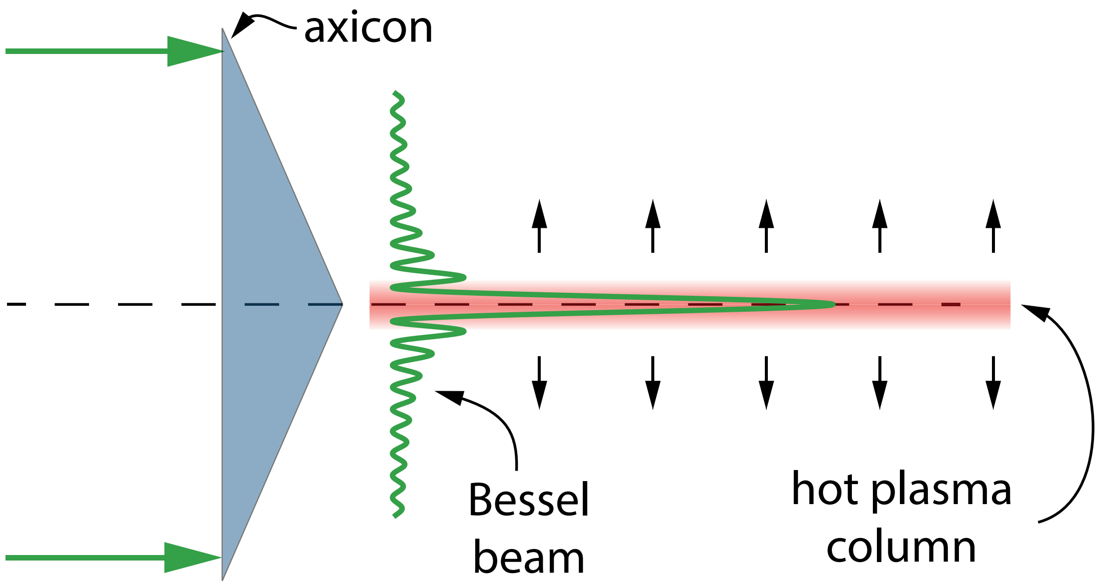
D. Spence and S. Hooker, *Phys Rev E* **63** 015401 (2000)
A. Butler *et al.*, *Phys Rev Lett* **89** 185003 (2002)

Hydrodynamic plasma waveguides

- Create & heat column of hot plasma
  - ~ 100 ps laser pulse creates and heats plasma
  - Expansion into surrounding cold gas / plasma drives cylindrical blast wave
  - Plasma channel formed within expanding shell
- **Attractive for high rep rate since free-standing and "indestructible"**



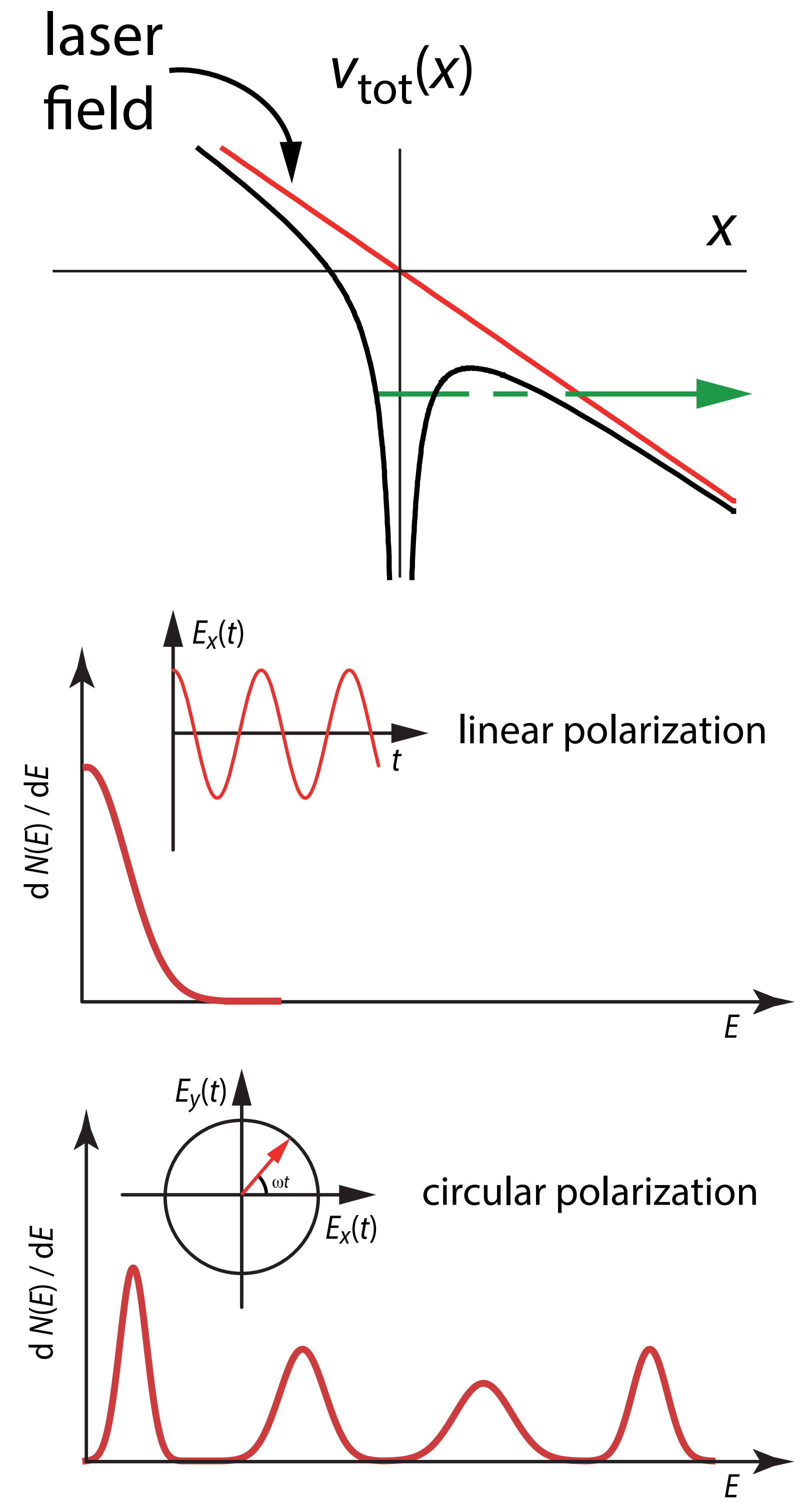
- To date, plasma column has been **heated collisionally**:
  - Durfee & Milchberg, *PRL* **71** 2409 (1993)
  - Volbeyn *et al.* *POP* **6** 2269 (1999)



- **Requires high density** for fast heating
  - Limits axial density to ~ 10^{18} cm^{-3}

Hydrodynamic OFI (HOFI) plasma channels

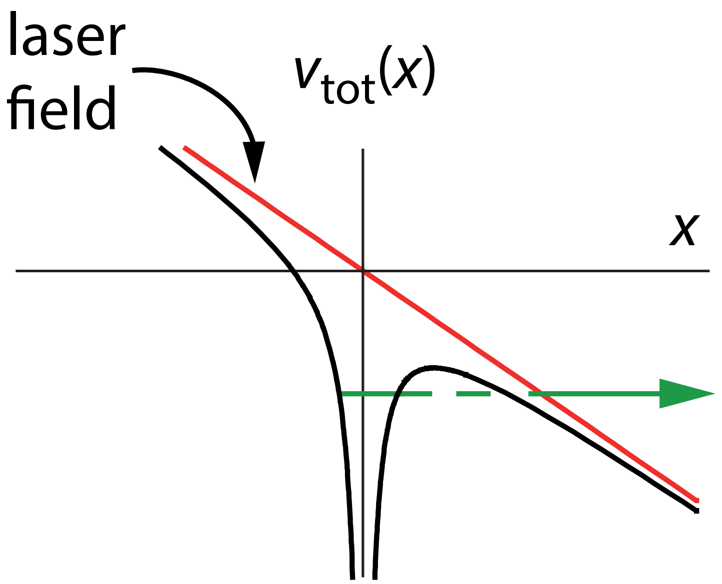
R.J. Shalloo *et al. Phys Rev E* **97** 053203 (2018)

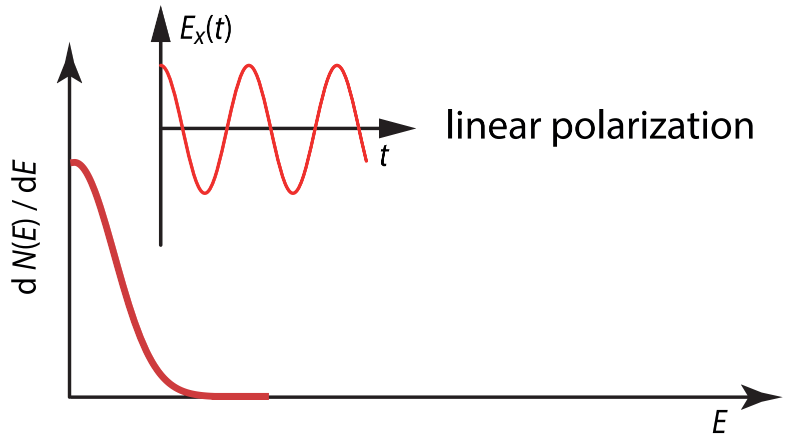


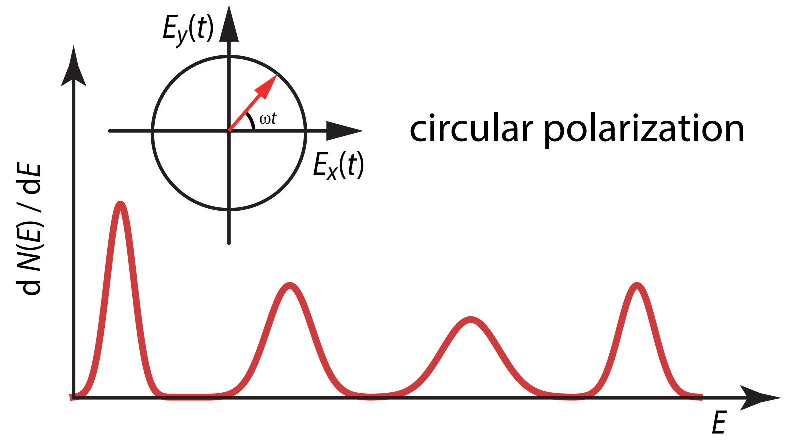
- Optical field ionization gives
  - Hot electrons & cold ions
  - Electron energy controlled by polarization
- **Heating independent of density ⇒ low density channels**

Hydrodynamic OFI (HOFI) plasma channels

R.J. Shalloo *et al. Phys Rev E* **97** 053203 (2018)





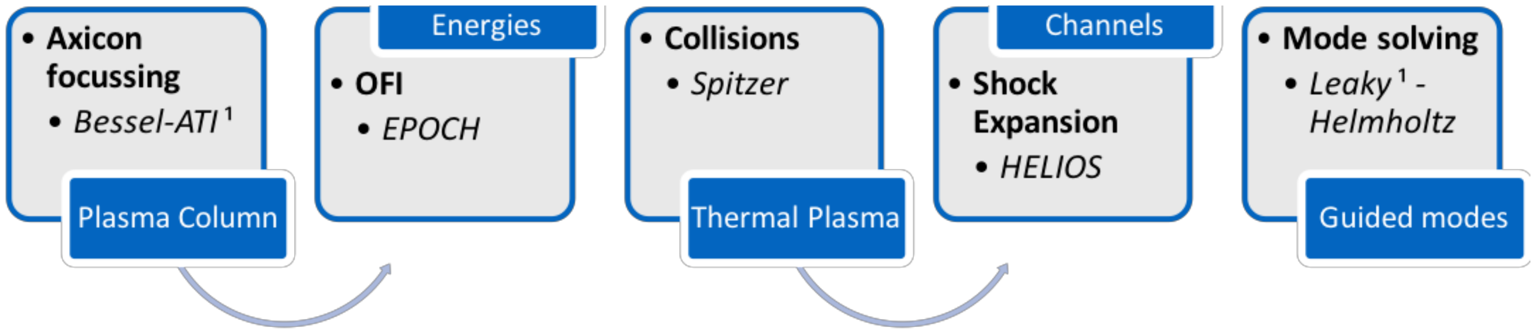


- Optical field ionization gives
  - Hot electrons & cold ions
  - Electron energy controlled by polarization
- **Heating independent of density ⇒ low density channels**

- IST & Strathclyde groups have generated short high-density channels with a spherical lens
  - Channels with $n_e(0) \approx 1 \times 10^{18}$ cm^{-3} [*POP* **20** 063102 (2013) & *POP* **20** 103109 (2013)]
  - Low-intensity guiding over ~ $4Z_R$ [*Nat. Sci. Rep.* **8** 3165 (2018)]
  - Do not seem to have considered using this as a route to generating low density channels…

Simulations of HOFI channels

R.J. Shalloo *et al. et al. PRE **97** 053203 (2018)*



- **Axicon focussing**
  - *Bessel-ATI* [1]

Plasma Column

Energies

- **OFI**
  - *EPOCH*

- **Collisions**
  - *Spitzer*

Thermal Plasma

Channels

- **Shock Expansion**
  - *HELIOS*

- **Mode solving**
  - *Leaky* [1] *- Helmholtz*

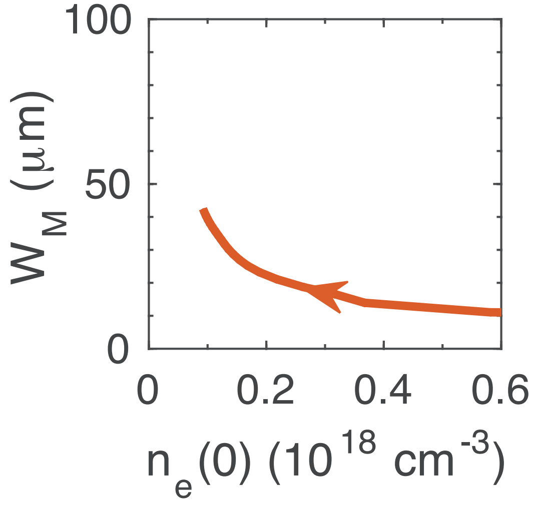
Guided modes

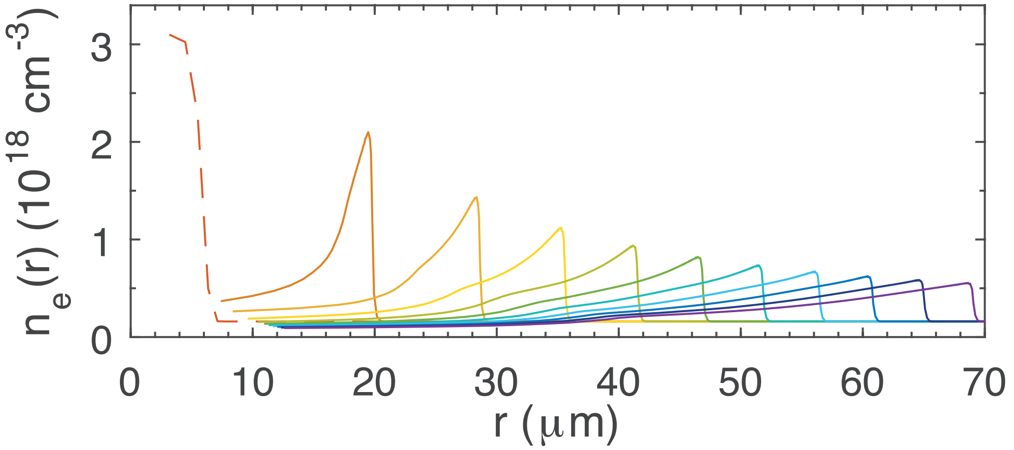
Laser: 22 mJ, circular poln

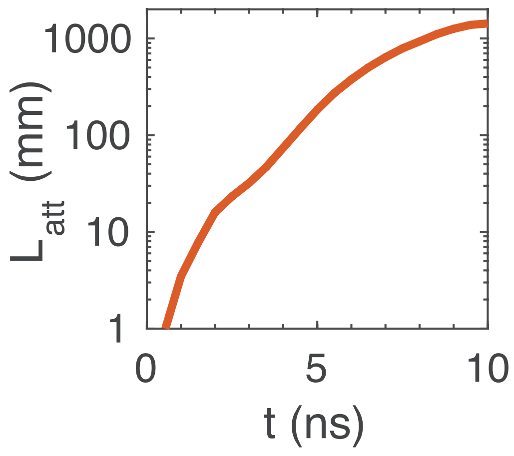
Axicon: 2.5°

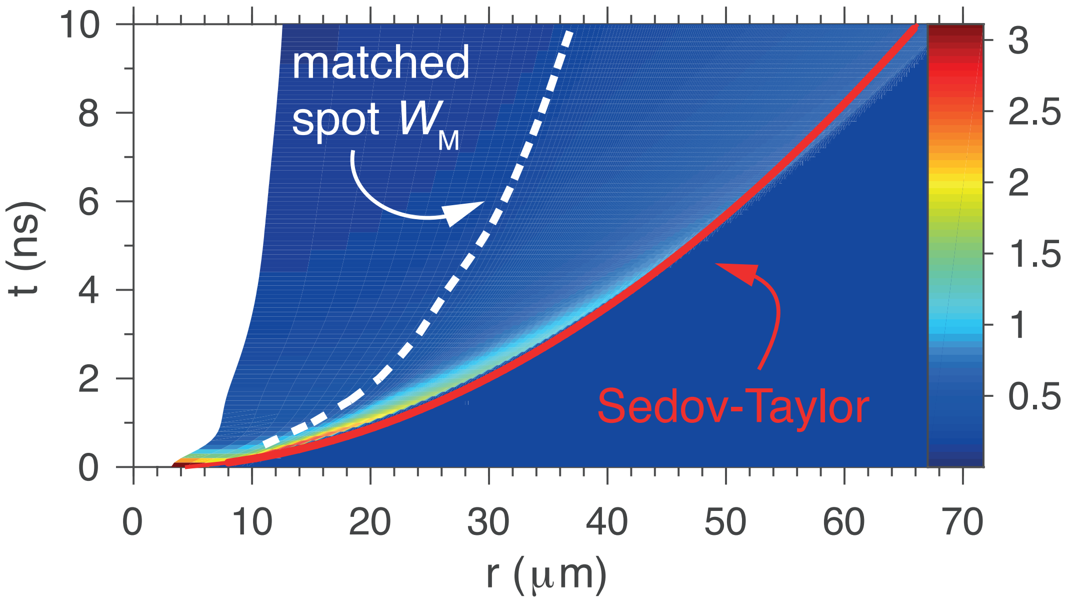
P_{H2}: 60 mbar

- Simulations show:
  - On-axis density:
  - 4 × 10^{17} cm-3 (1 ns)
  - 0.9 × 10^{17} cm-3 (10 ns)
- Matched spot:
  - WM ≈ 10 - 40 µm (1 - 10 ns)
  - *L*$_{\text{attn}}$ 100s mm (1/e power)
- **Only ~1 mJ of laser energy required per cm of channel!**



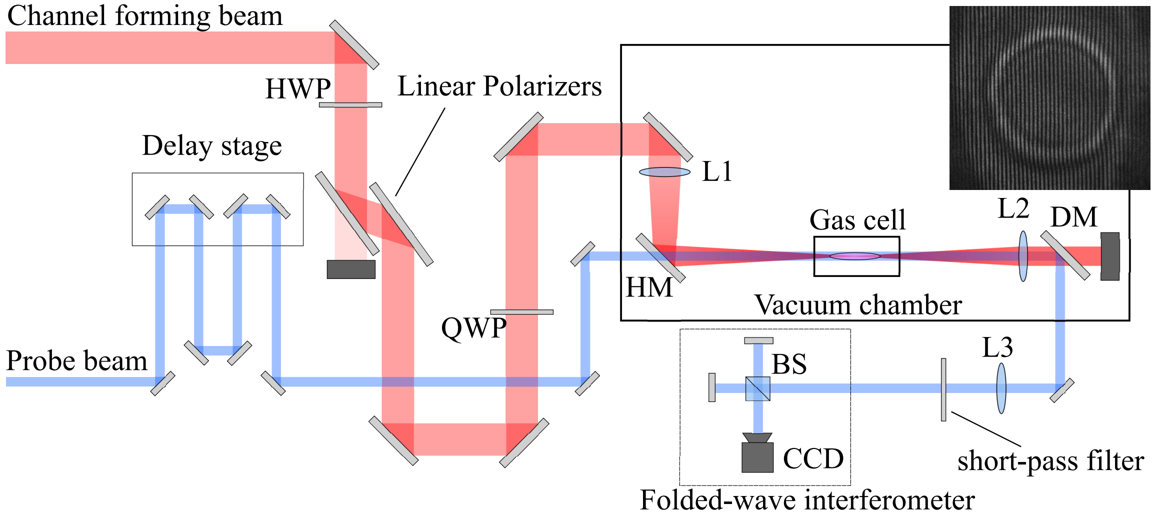






HOFI channels generated by a spherical lens

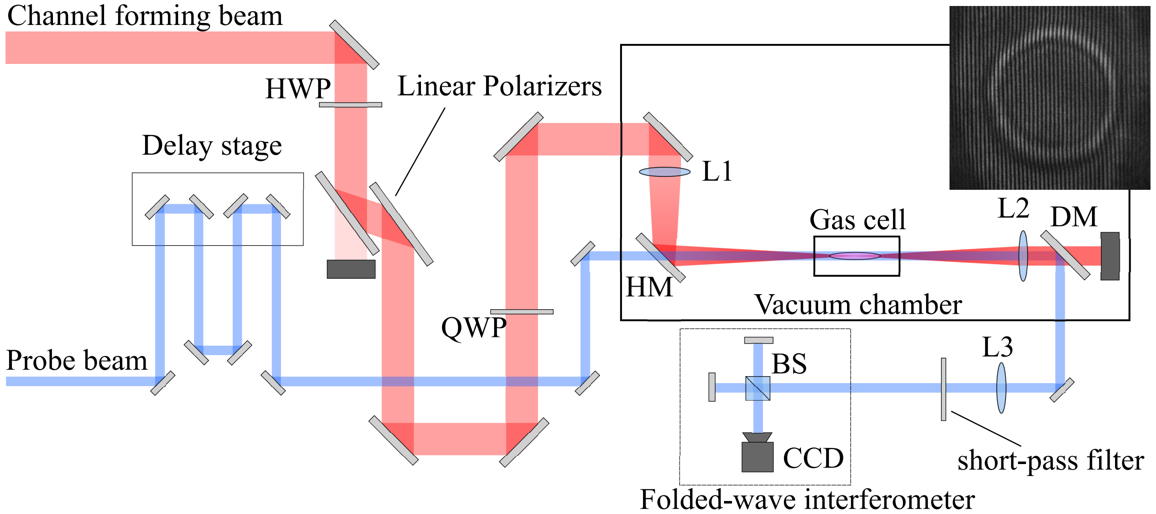
R.J. Shalloo *et al.* *et al. PRE* ***97*** *053203 (2018)*



E_L:	27 mJ
τ:	50 fs
Poln:	Circular

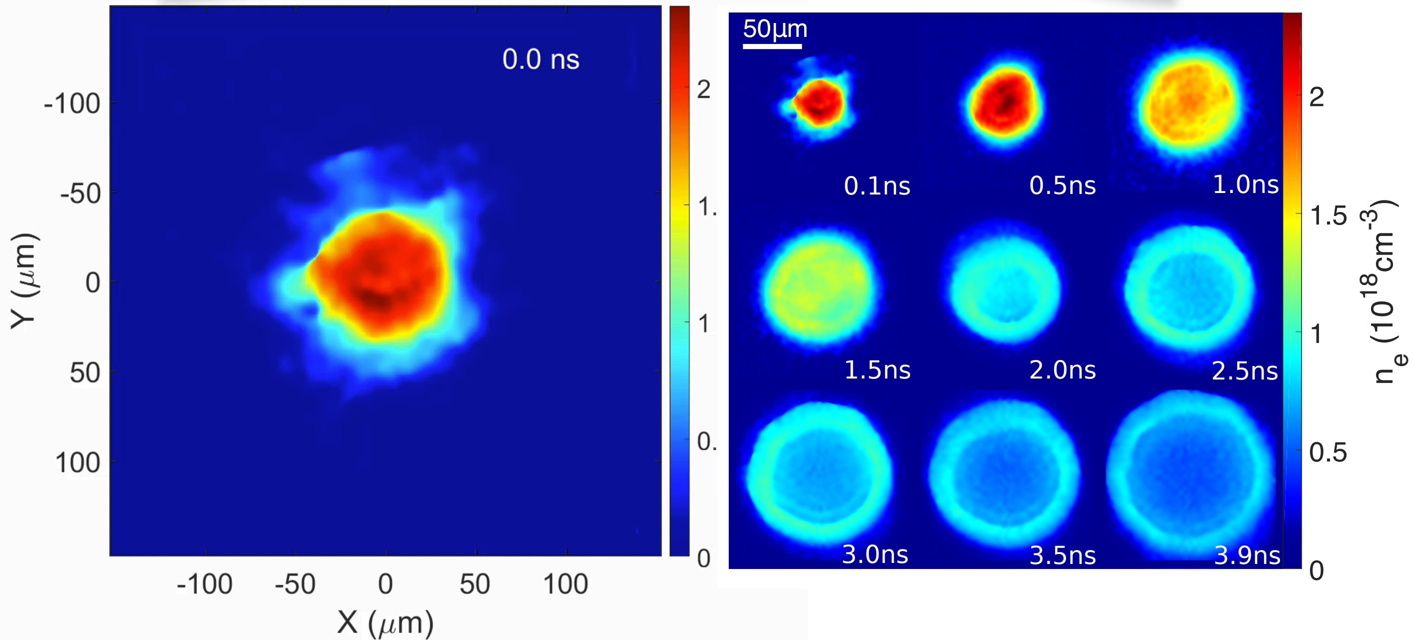
HOFI channels generated by a spherical lens

R.J. Shalloo *et al. et al. PRE* ***97*** *053203 (2018)*



E_L: 27 mJ
τ: 50 fs
Poln: Circular

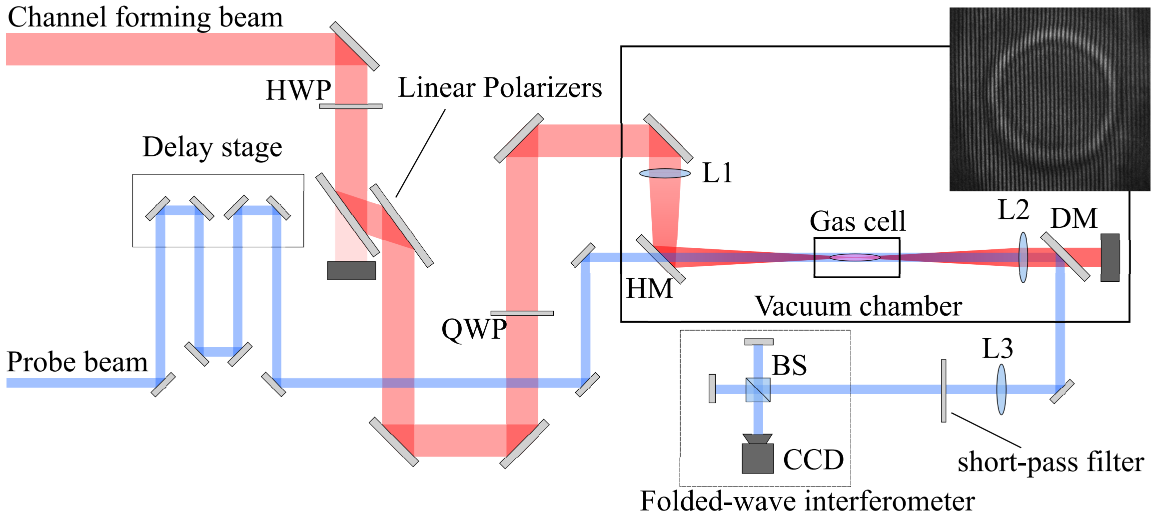
Measured channel evolution



John Adams Institute for Accelerator Science

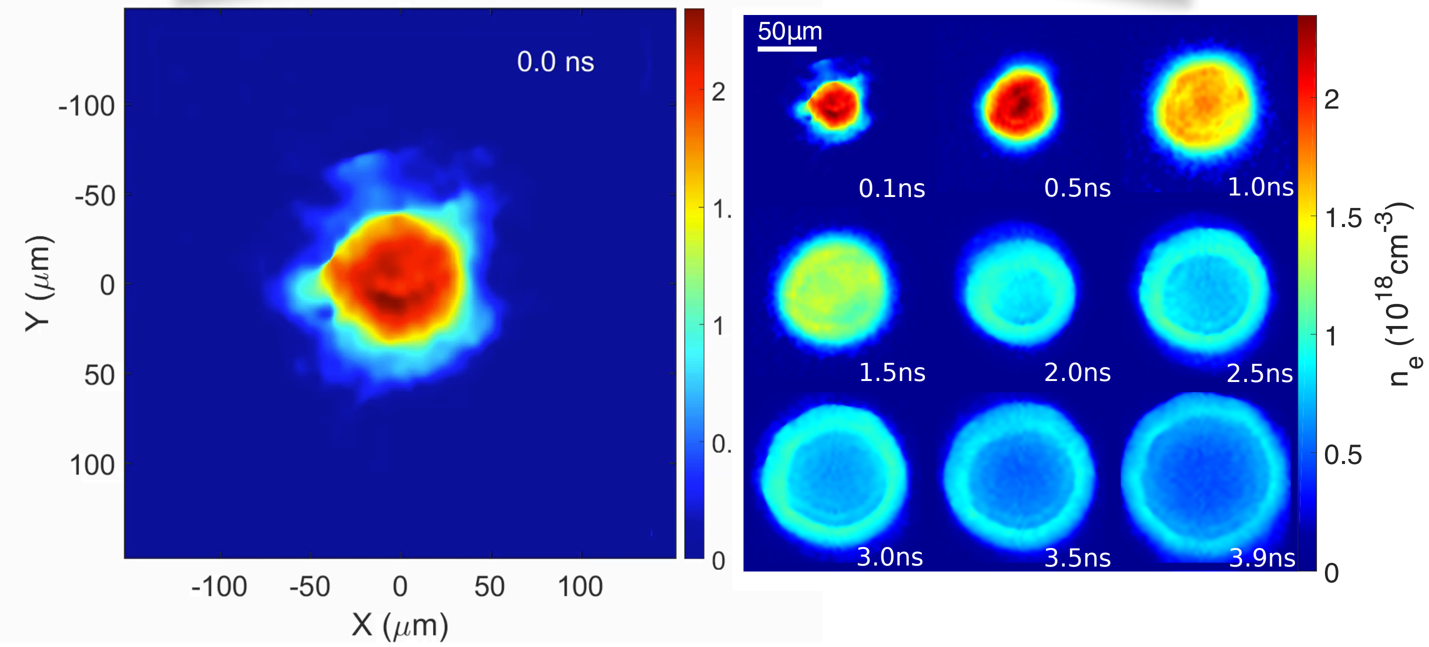
HOFI channels generated by a spherical lens

R.J. Shalloo *et al. et al. PRE* ***97*** *053203 (2018)*

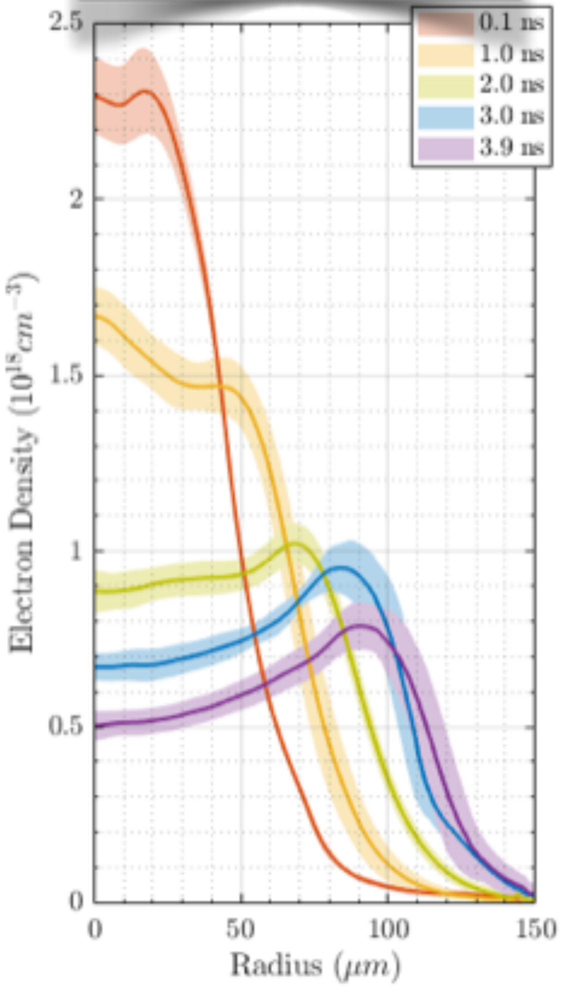


E_L: 27 mJ
τ: 50 fs
Poln: Circular

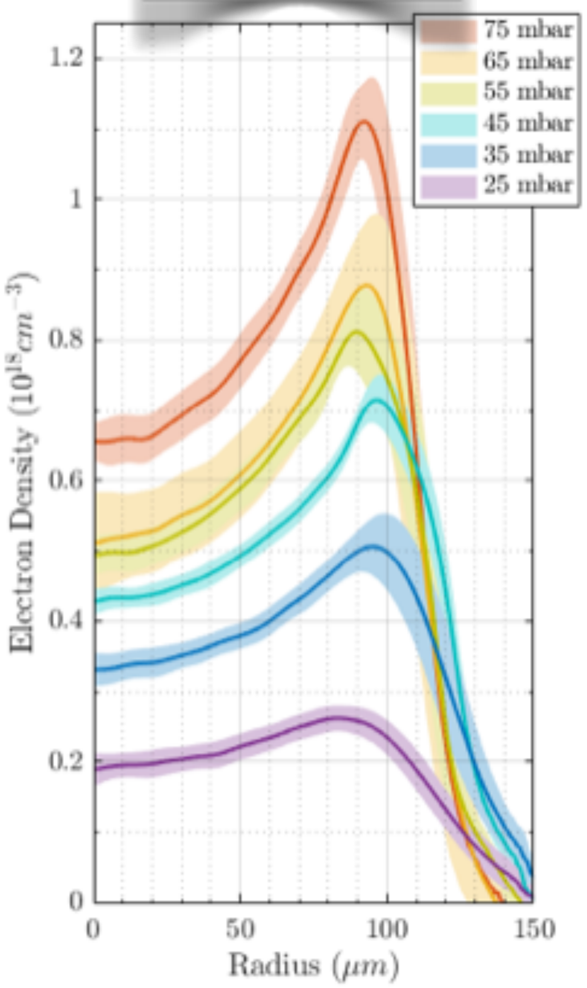
Measured channel evolution



P_{H2} = 50 mbar



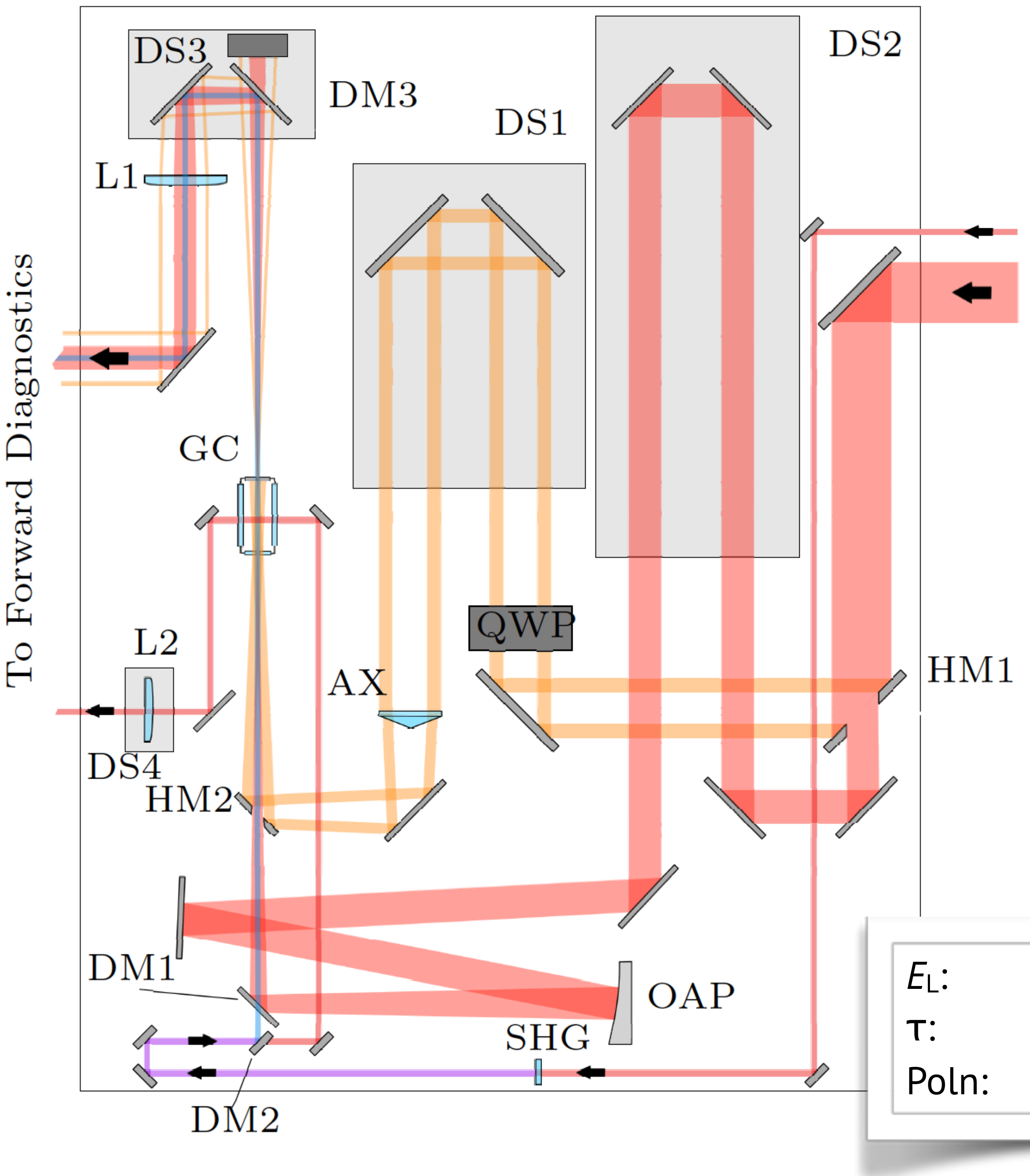
τ = 3.9 ns



UNIVERSITY OF OXFORD

HOFI channels generated by an axicon lenses

R.J. Shalloo *et al. arXiv:1902.05596*

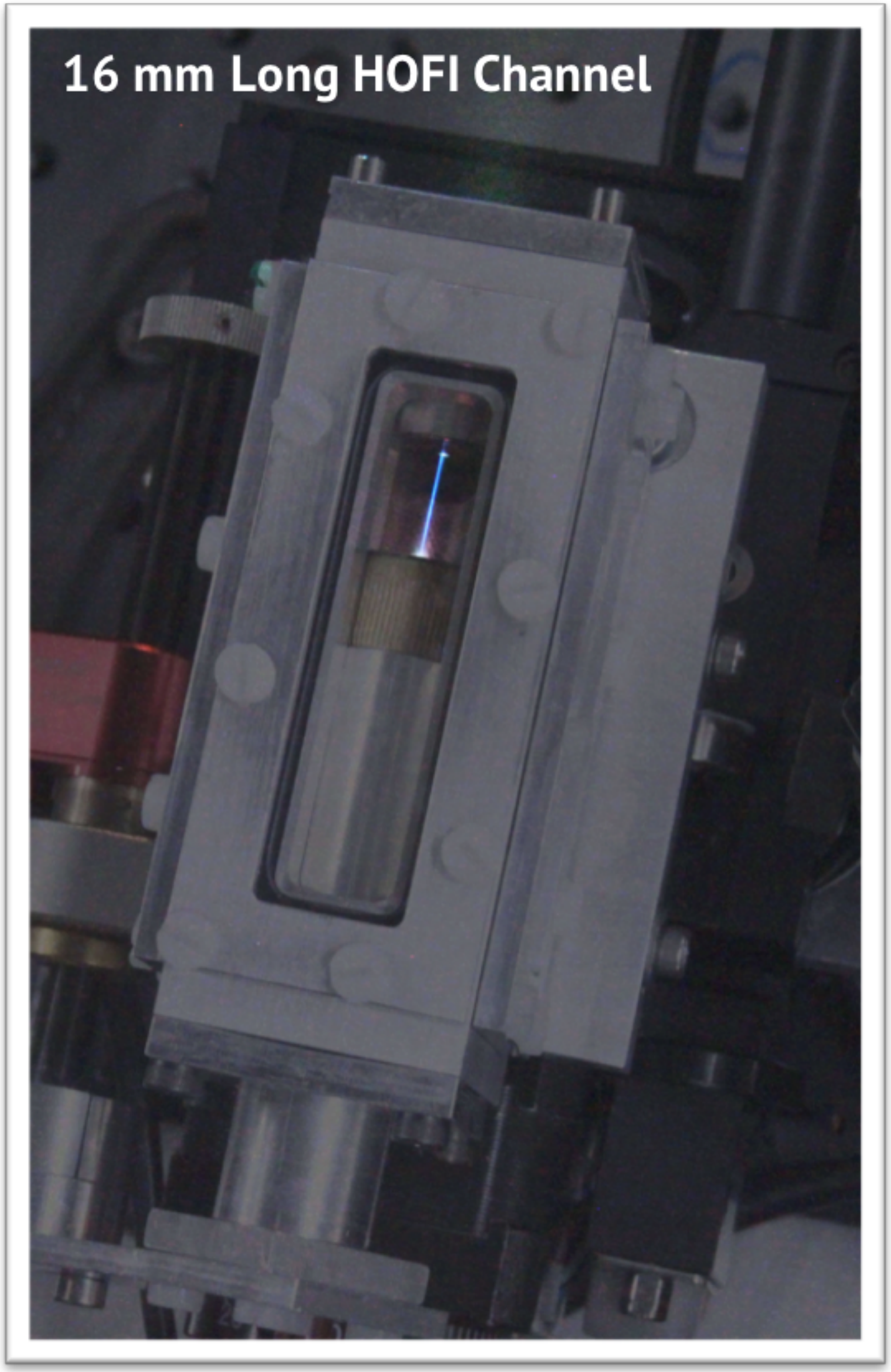


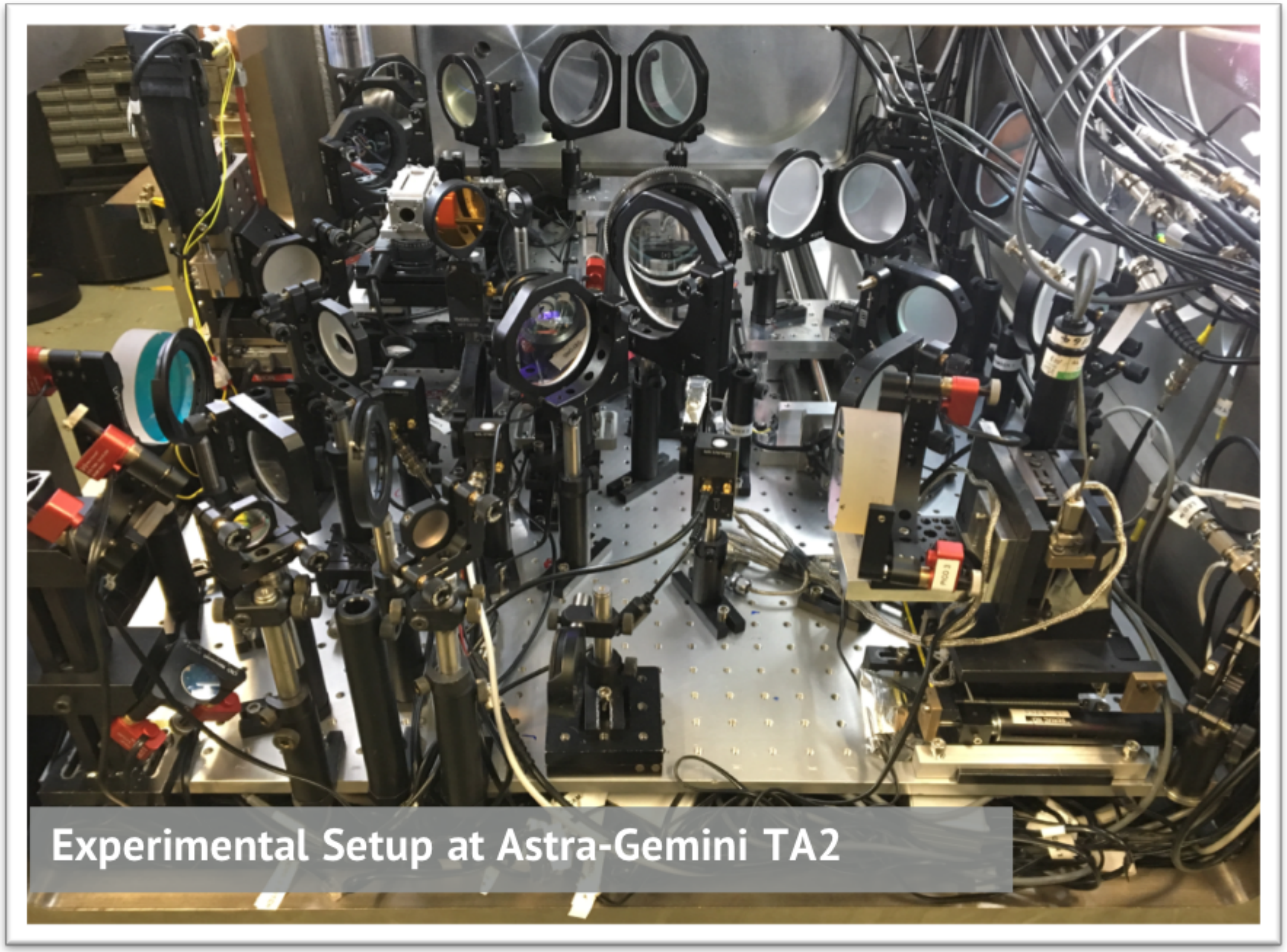
- Channel-forming beam focusing with axicon (2.5 degree approach angle)
- Guided beam focused with *f*/25 OAP
- Longitudinal (400 nm) & transverse (800 nm) interferometry of channels

E_L:	430 mJ (total)
τ:	45 fs
Poln:	Linear → Circular

Experiment set-up

R.J. Shalloo *et al. arXiv:1902.05596*

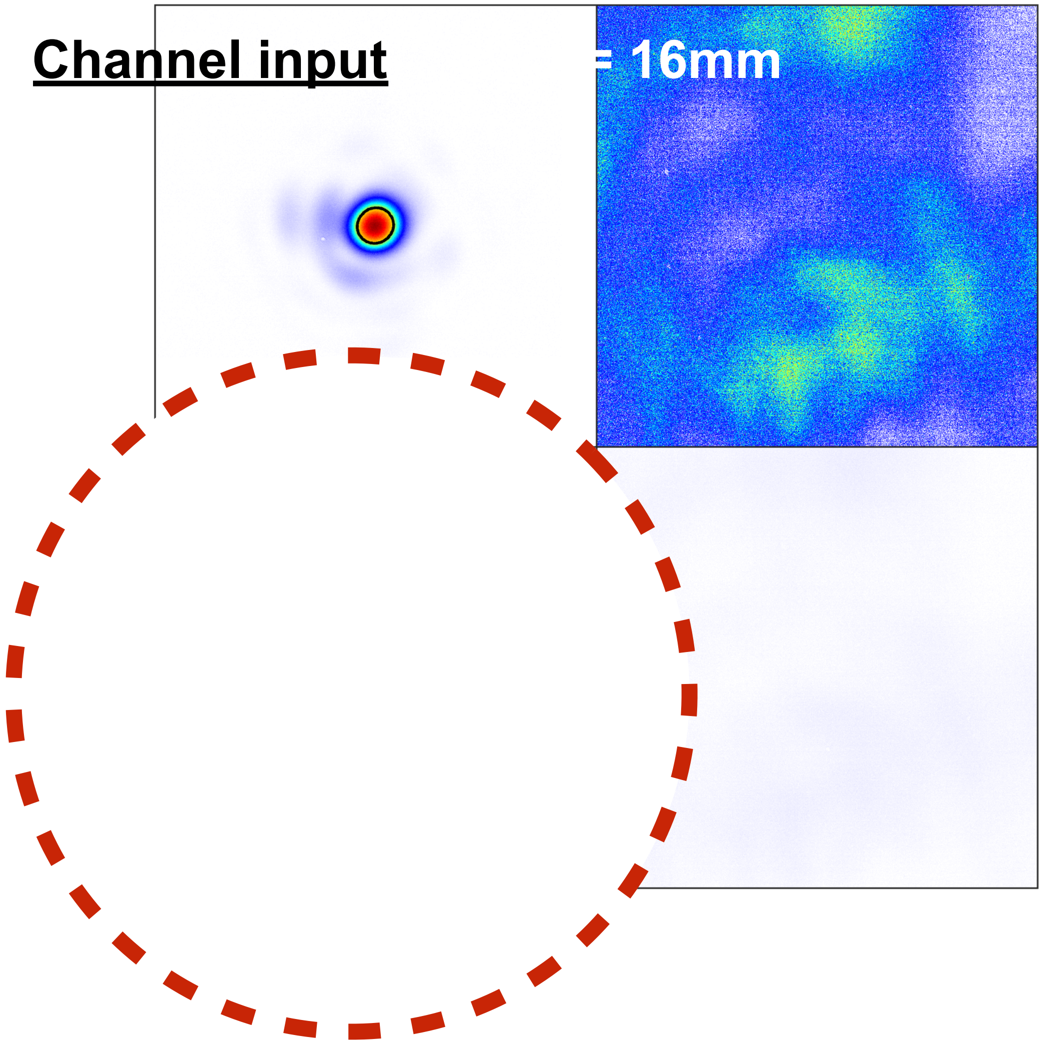


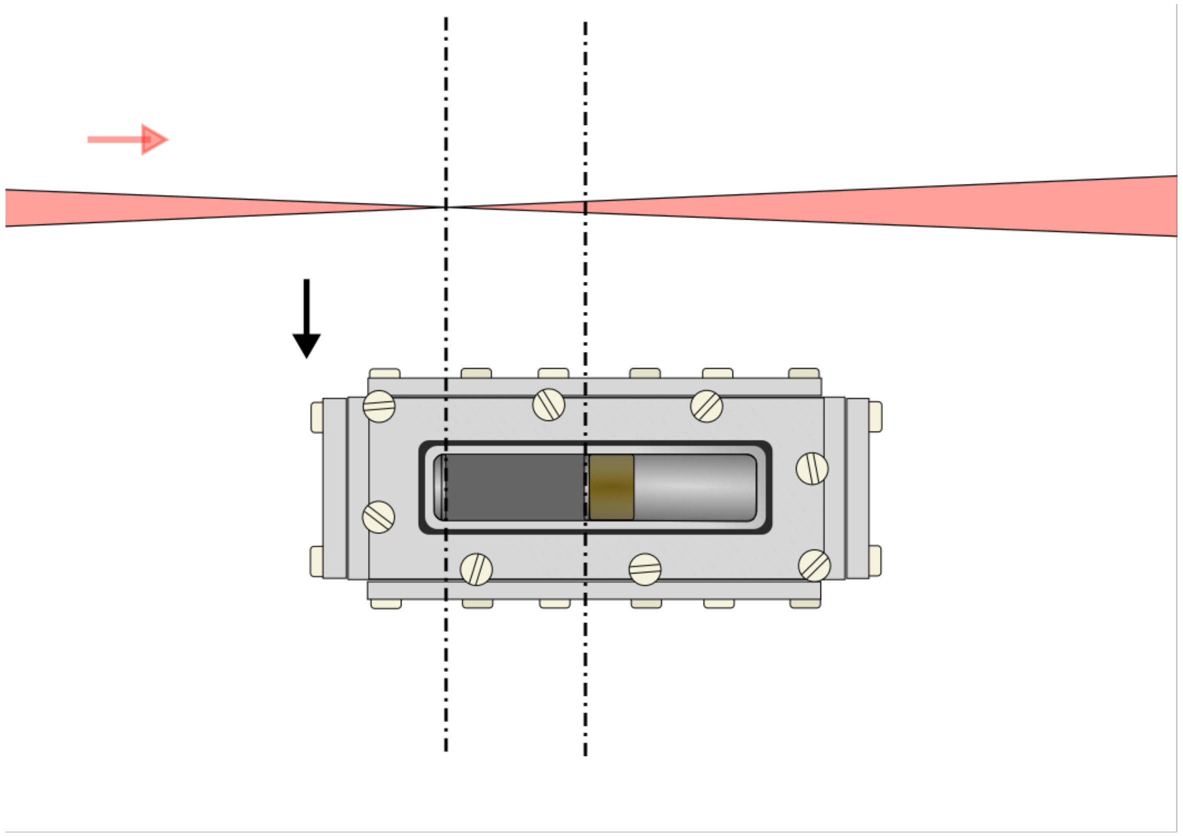


Axicon HOFI channels: Guiding results

R.J. Shalloo *et al. arXiv:1902.05596*

- Guided beam injected into channel after delay $\tau = 1.5$ ns
- $P = 60$ mbar
- On-axis density $n_e(0) \approx 6.5 \times 10^{17}$ cm^{-3}
- Guiding over 14.5 Rayleigh ranges (16 mm)
- Energy throughput 40-60%

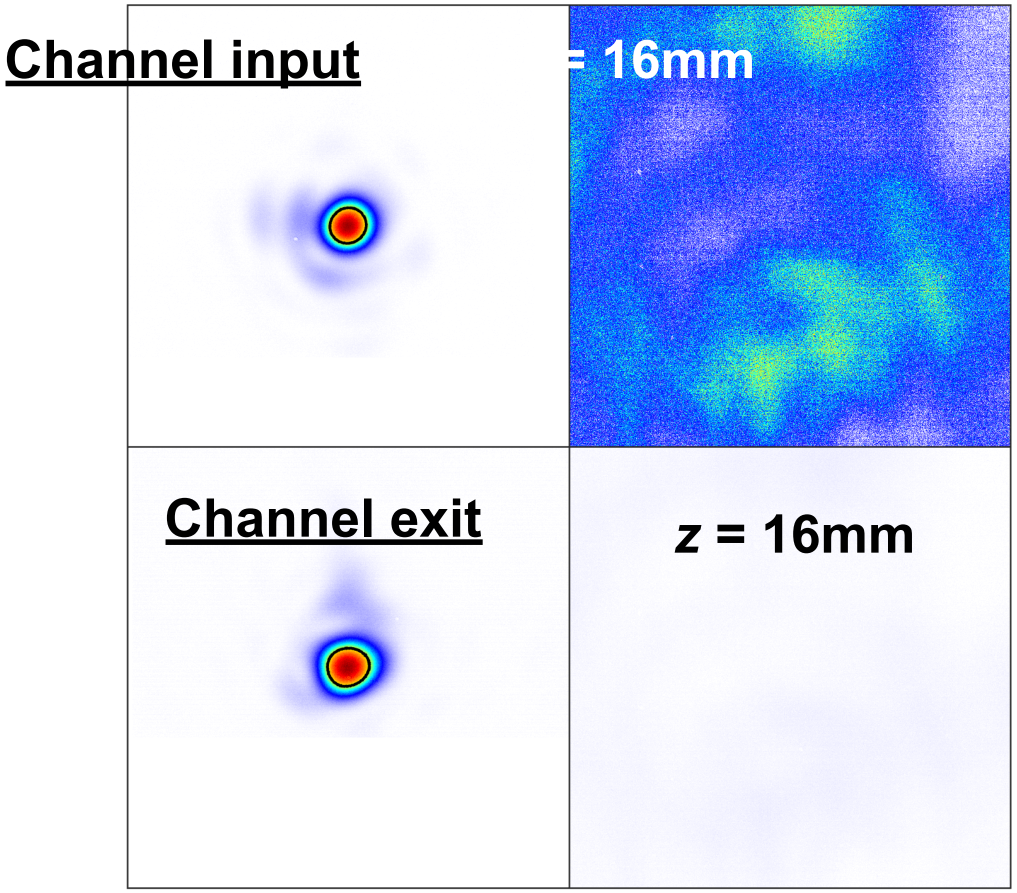


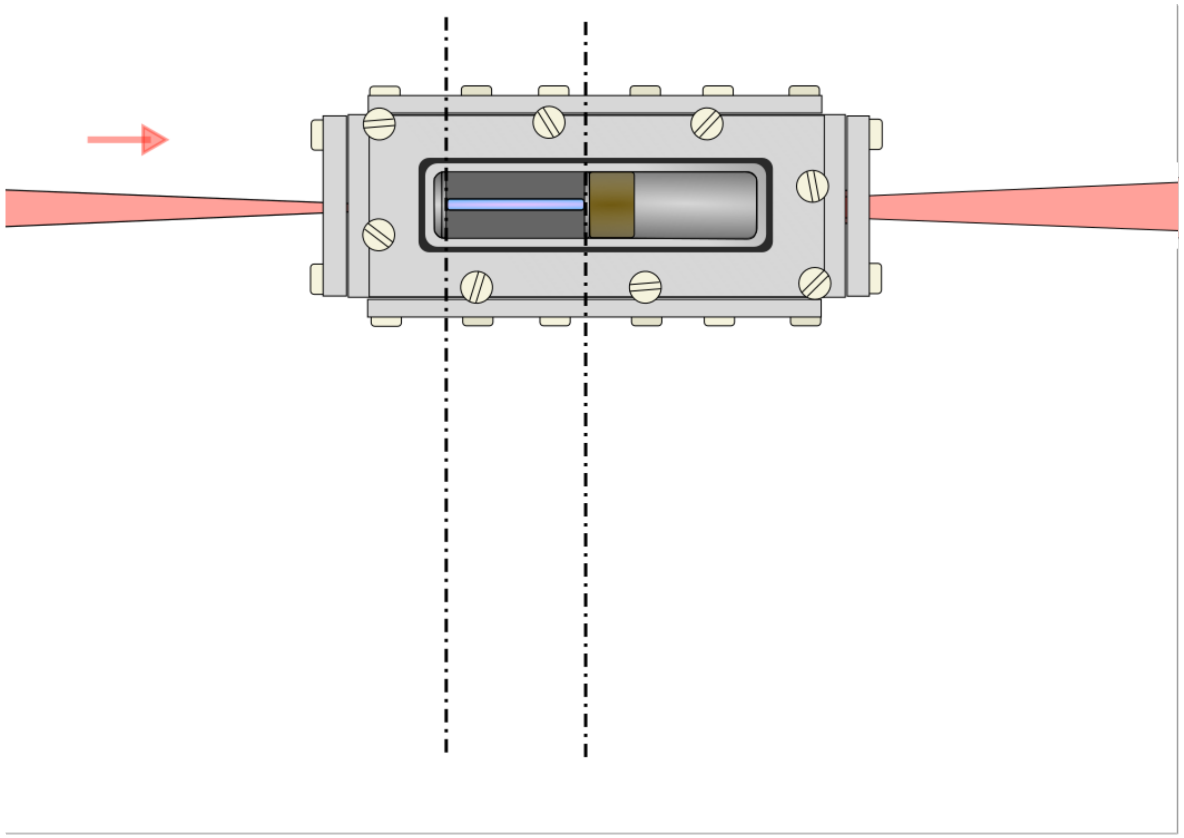


Axicon HOFI channels: Guiding results

R.J. Shalloo *et al. arXiv:1902.05596*

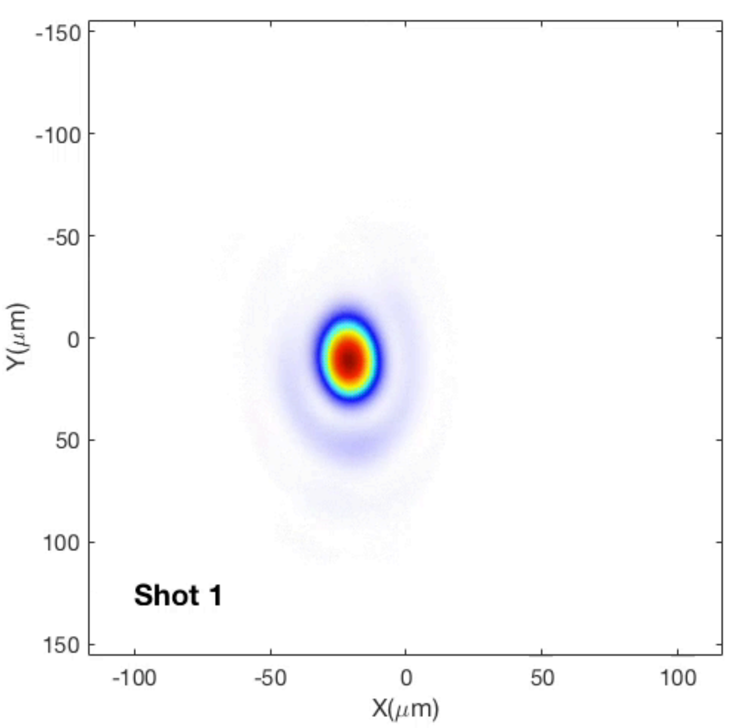
- Guided beam injected into channel after delay τ = 1.5 ns
- P = 60 mbar
- On-axis density $n_e(0) \approx 6.5 \times 10^{17}$ cm^{-3}
- Guiding over 14.5 Rayleigh ranges (16 mm)
- Energy throughput 40-60%

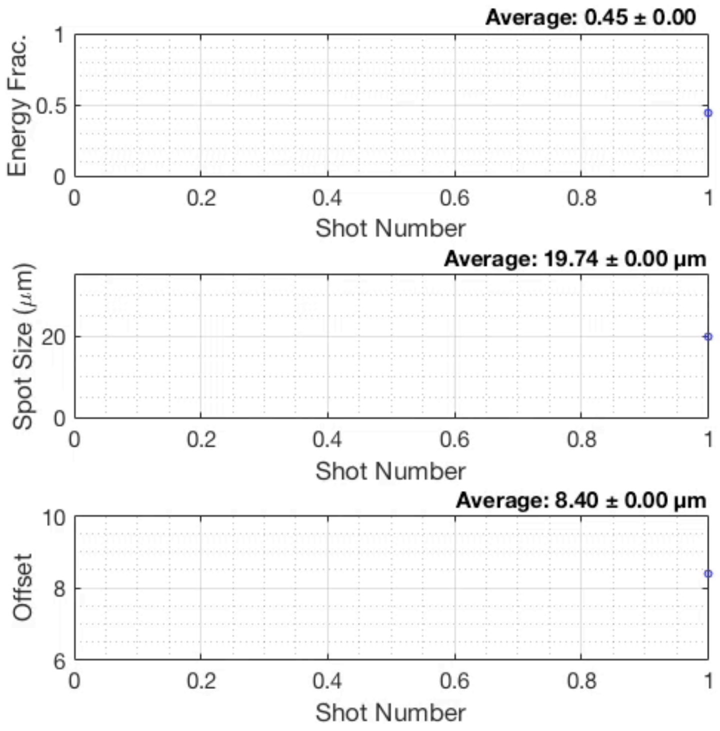




Axicon HOFI channels: Guiding results

R.J. Shalloo *et al. arXiv:1902.05596*



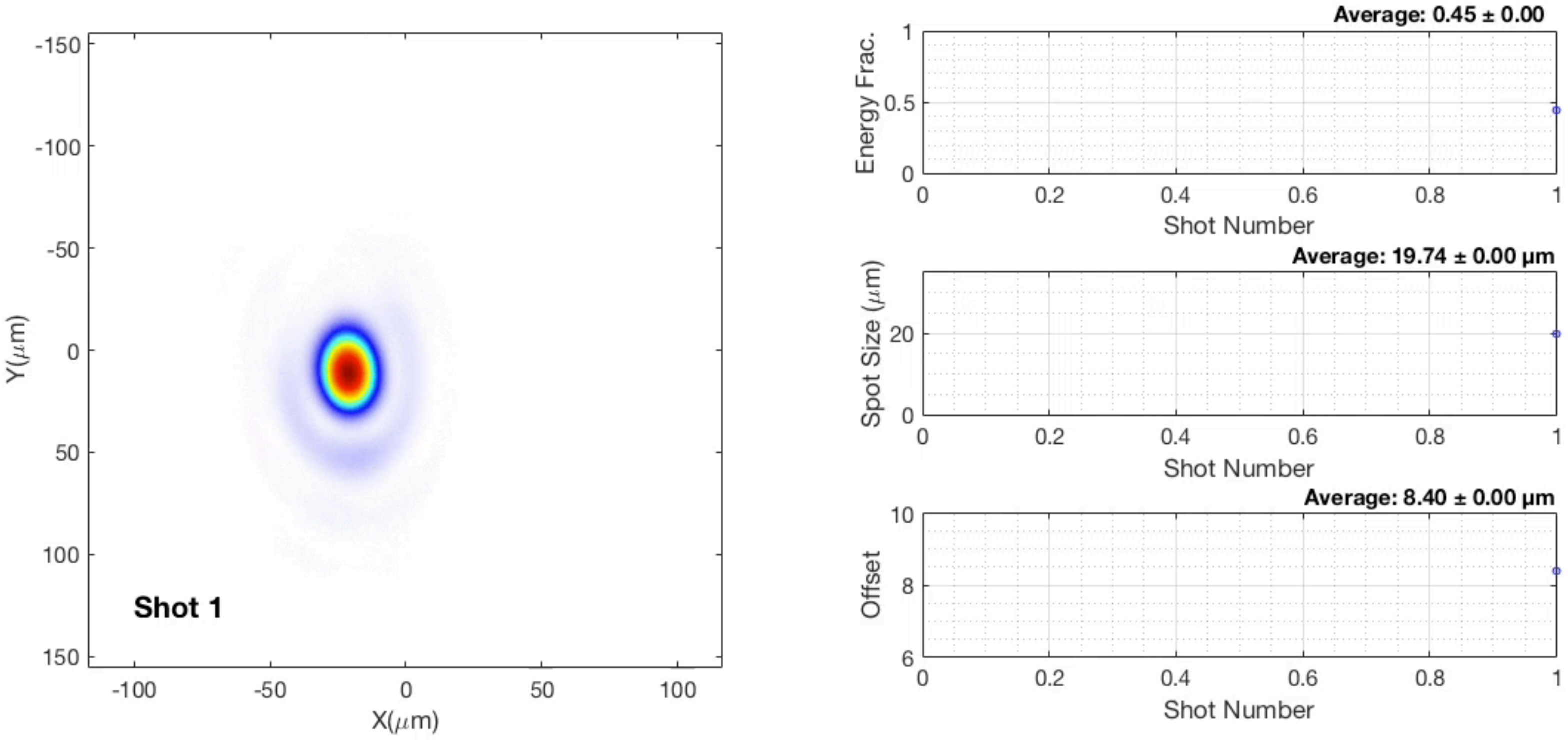


Low-power guiding at 5 Hz

N: 165 consecutive shots

Axicon HOFI channels: Guiding results

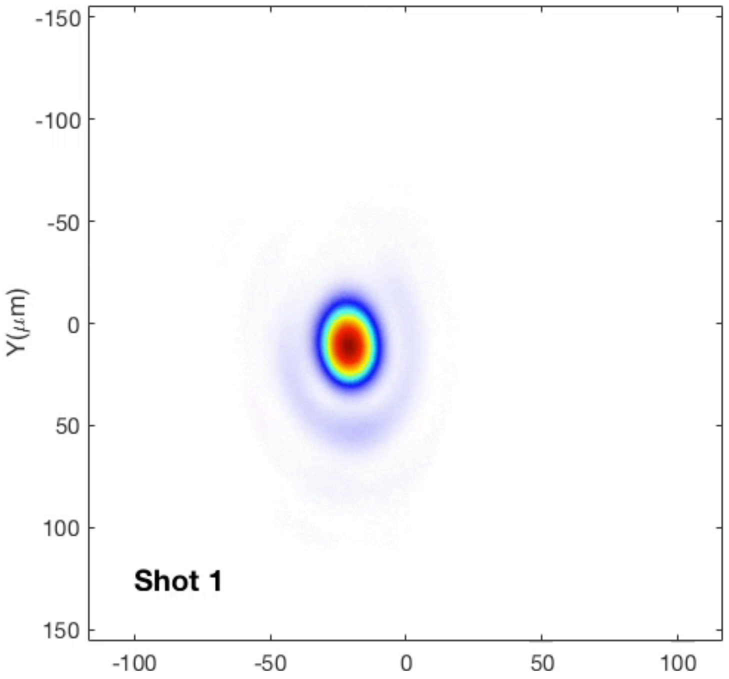
R.J. Shalloo *et al. arXiv:1902.05596*

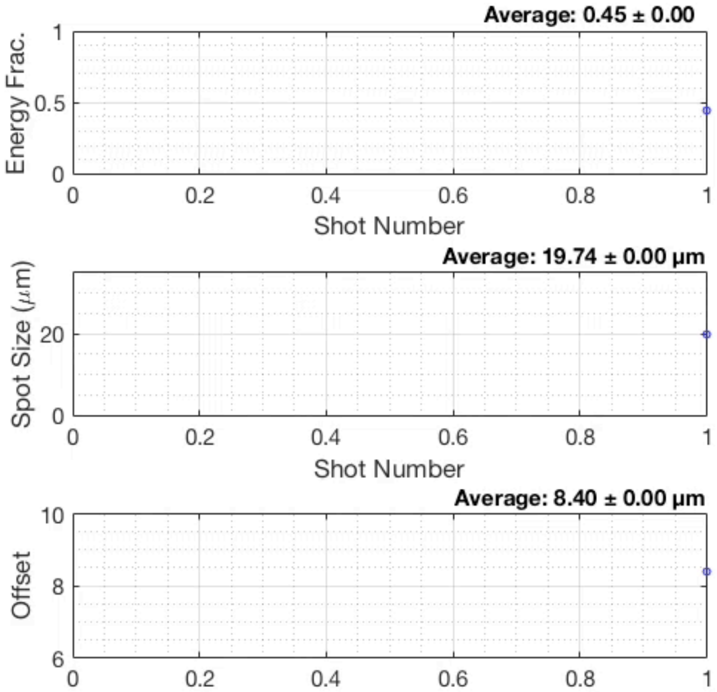


Low-power guiding at 5 Hz
N: 165 consecutive shots

Axicon HOFI channels: Guiding results

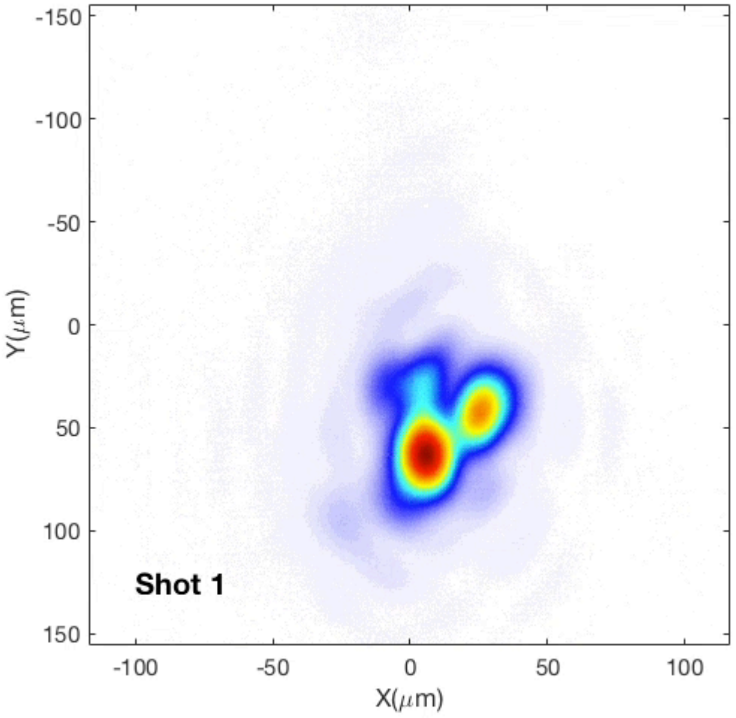
R.J. Shalloo *et al. arXiv:1902.05596*

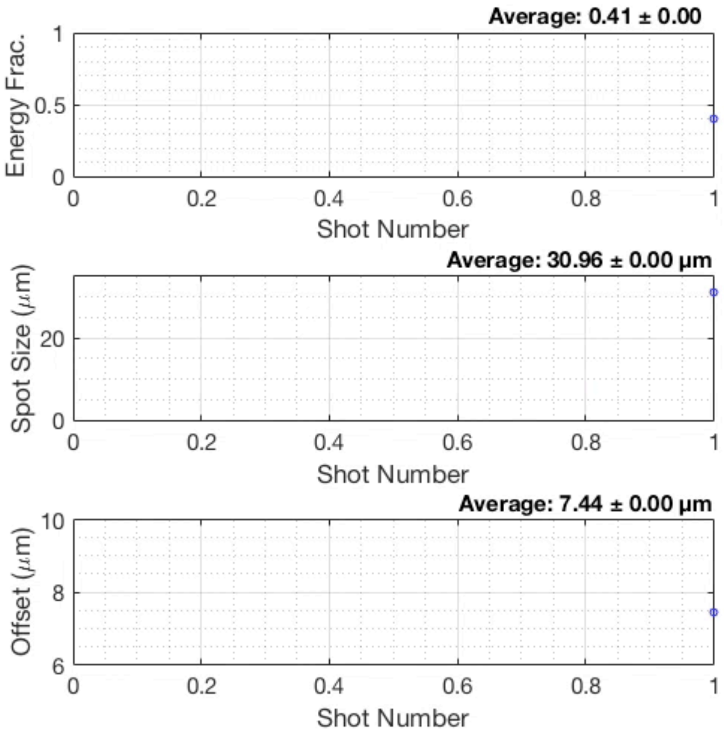




Low-power guiding at 5 Hz

N: 165 consecutive shots





High-power guiding at 5 Hz

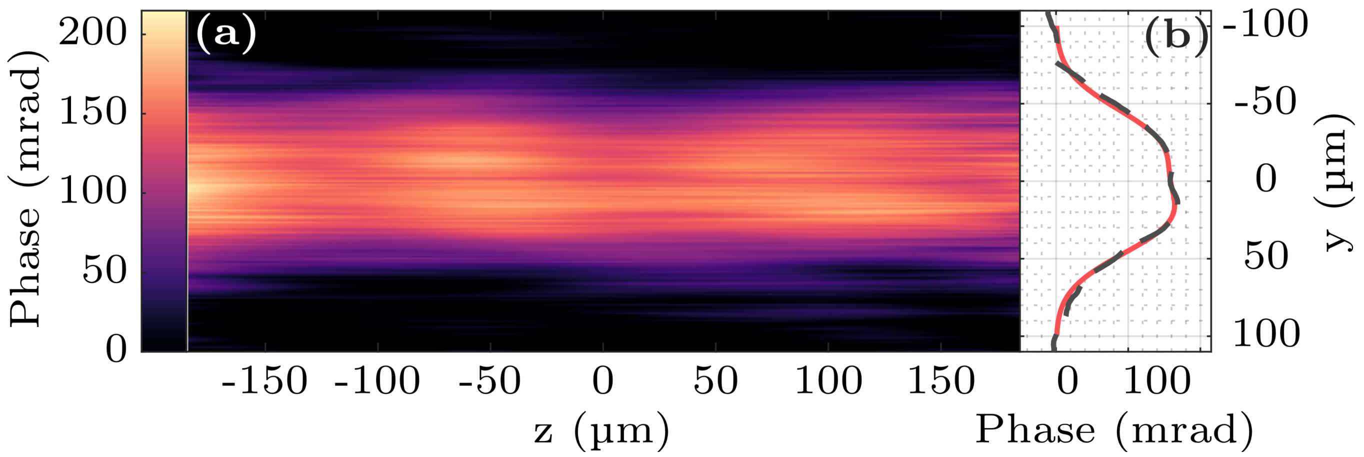
N: 489 consecutive shots

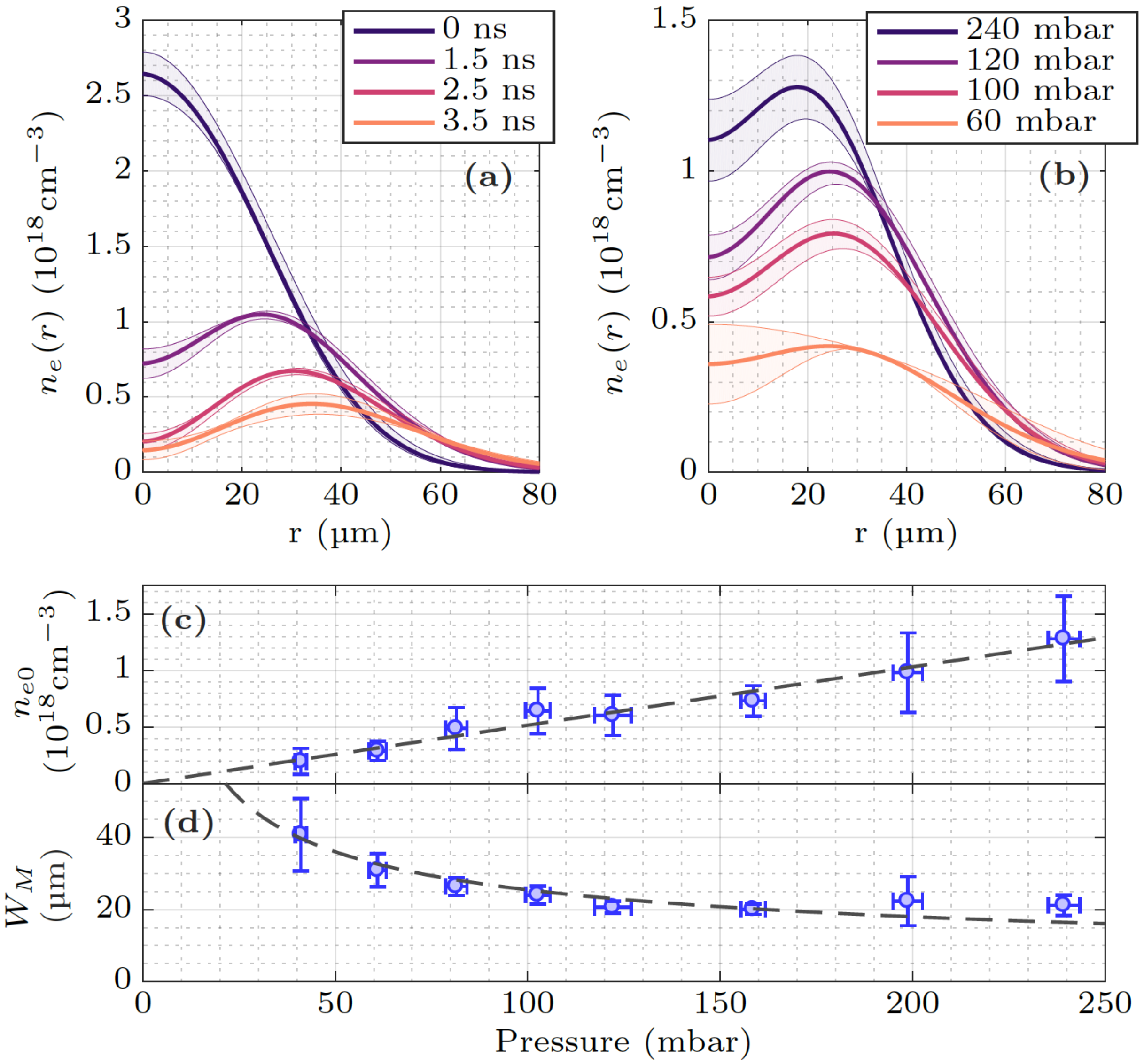
I_0: 4×10^{17} W cm^{-2}

5 Hz: 12 shots every 45 s

Axicon HOFI channels: Interferometry

R.J. Shalloo *et al. arXiv:1902.05596*

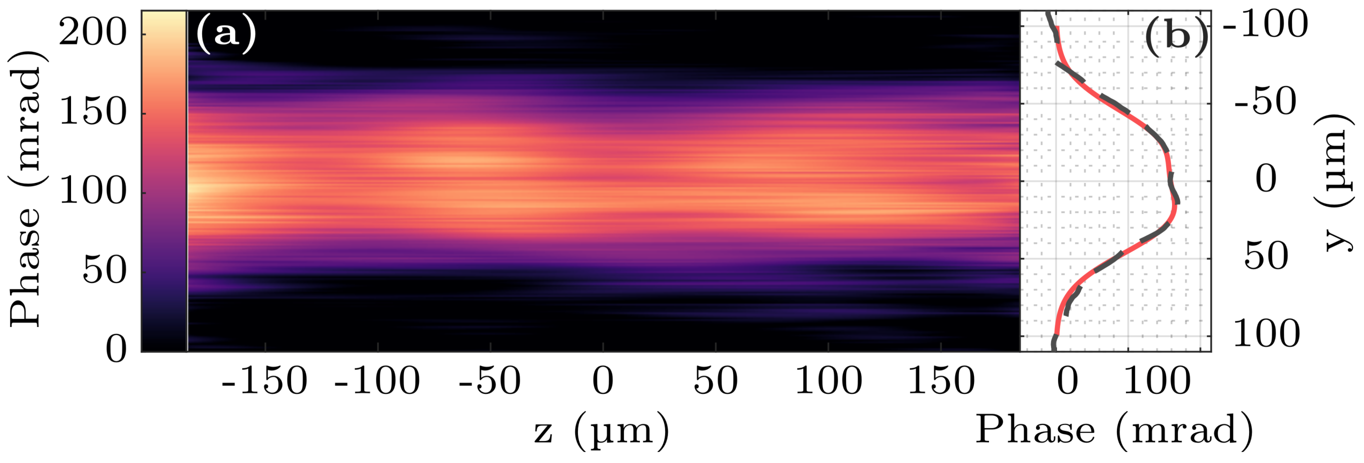


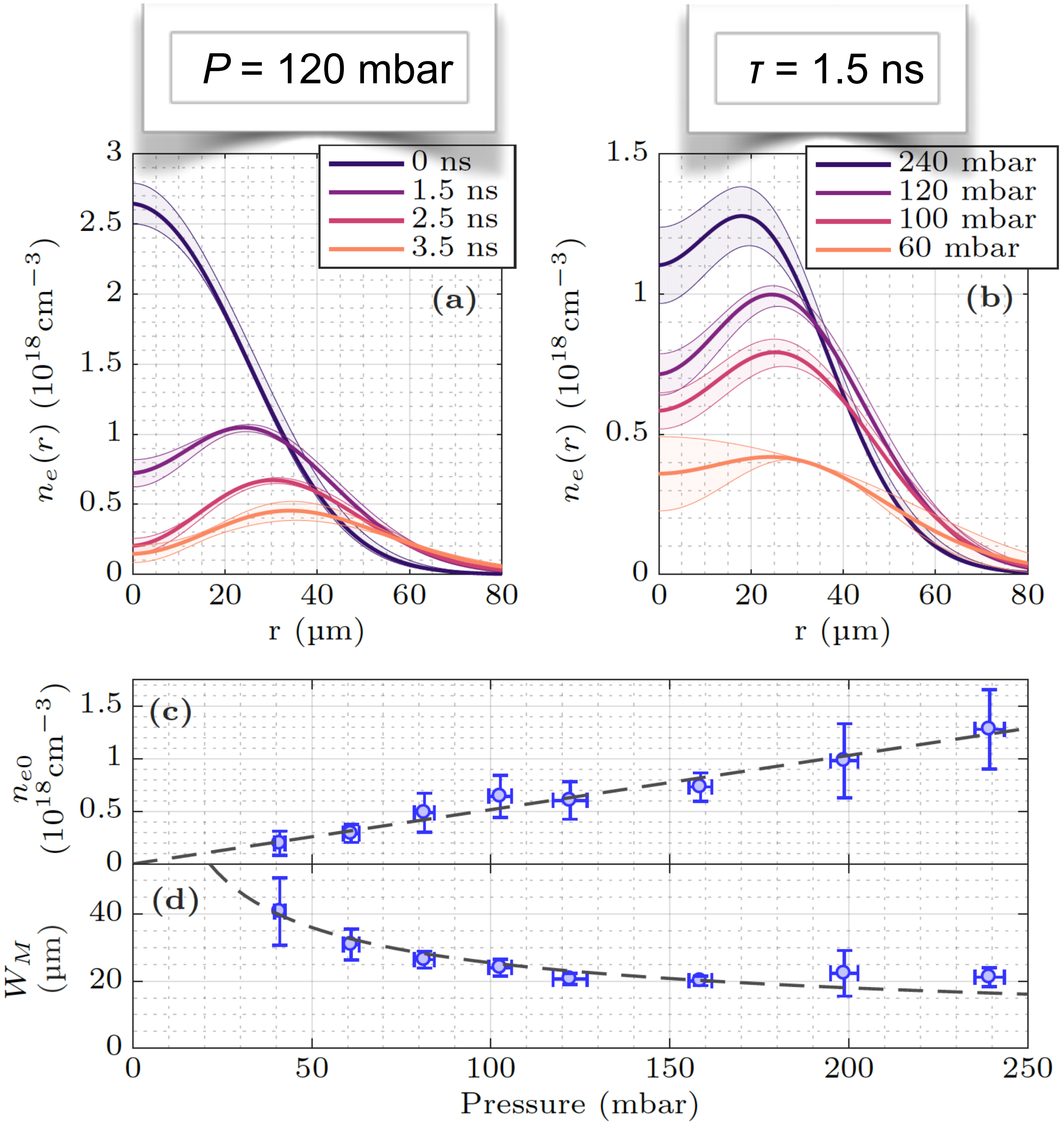


- Evolution of plasma channel over ns timescales observed
- Properties of channel can be controlled by adjusting initial pressure and delay
- Channel properties seem well suited to multi-GeV stages

Axicon HOFI channels: Interferometry

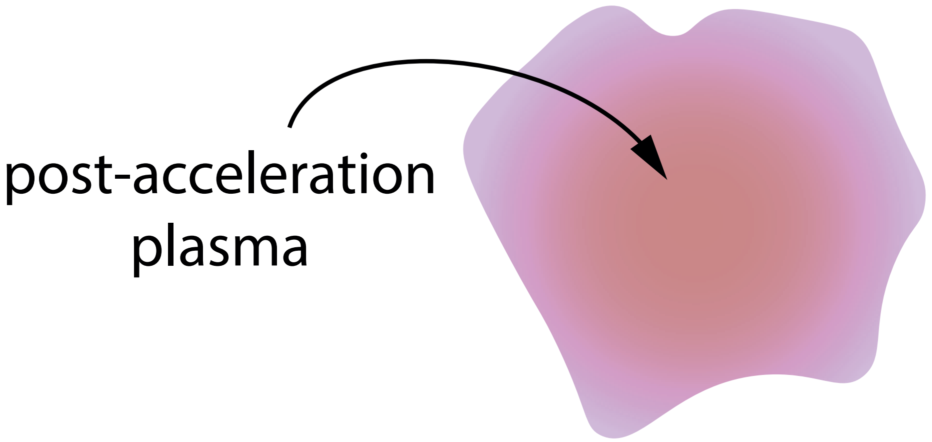
R.J. Shalloo *et al. arXiv:1902.05596*





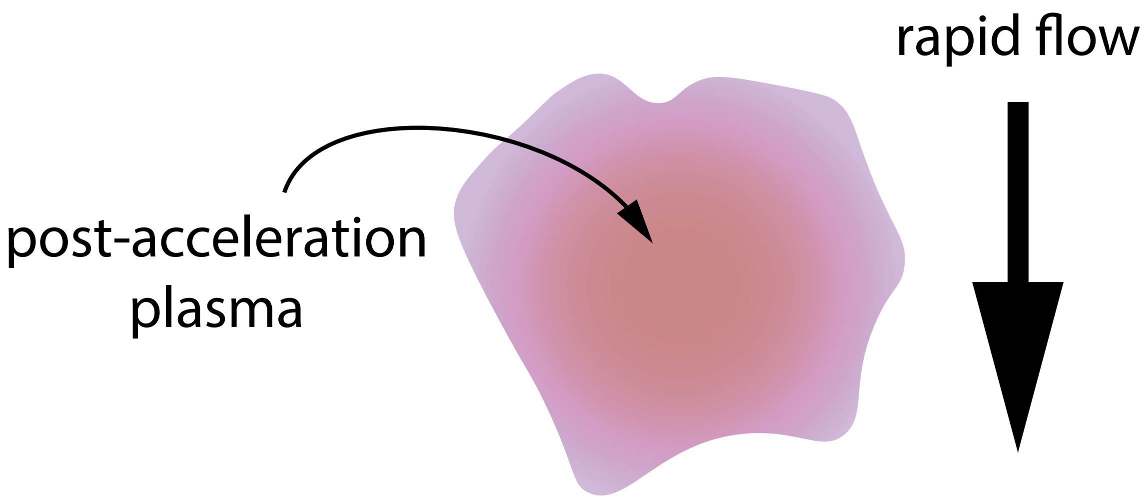
- Evolution of plasma channel over ns timescales observed
- Properties of channel can be controlled by adjusting initial pressure and delay
- Channel properties seem well suited to multi-GeV stages

What determines repetition rate (in principle)?



- In a static cell the plasma needs to:
  - Recombine
  - Redistribute to uniform density
  - Cool?

What determines repetition rate (in principle)?



$$c_s = \sqrt{\frac{\kappa}{\rho}} = \sqrt{\gamma RT} \quad \text{(ideal gas)}$$

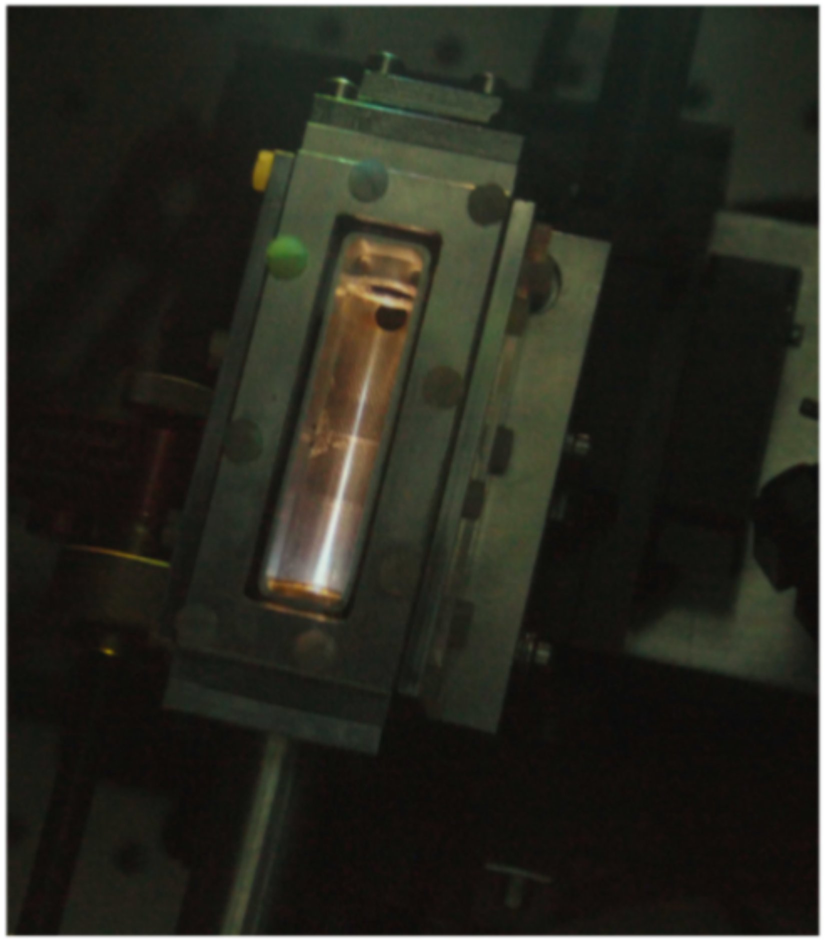
For H2: $\gamma = 1.41$

$$\Rightarrow c_s = 348 \text{ m/s}$$

- In a static cell the plasma needs to:
  - Recombine
  - Redistribute to uniform density
  - Cool?
- In worst case scenario would have to remove all gas & plasma before next shot
  - Suppose heated & "damaged" region extended for 1000 μm
  - C_s = 348 m/s for H_2 at T = 300 K
  - Flow gas at 100 m/s (i.e. sub-sonic)
  - Time between shots is 10 μs → **100 kHz rep. rate!**

HOFI channels: Future work

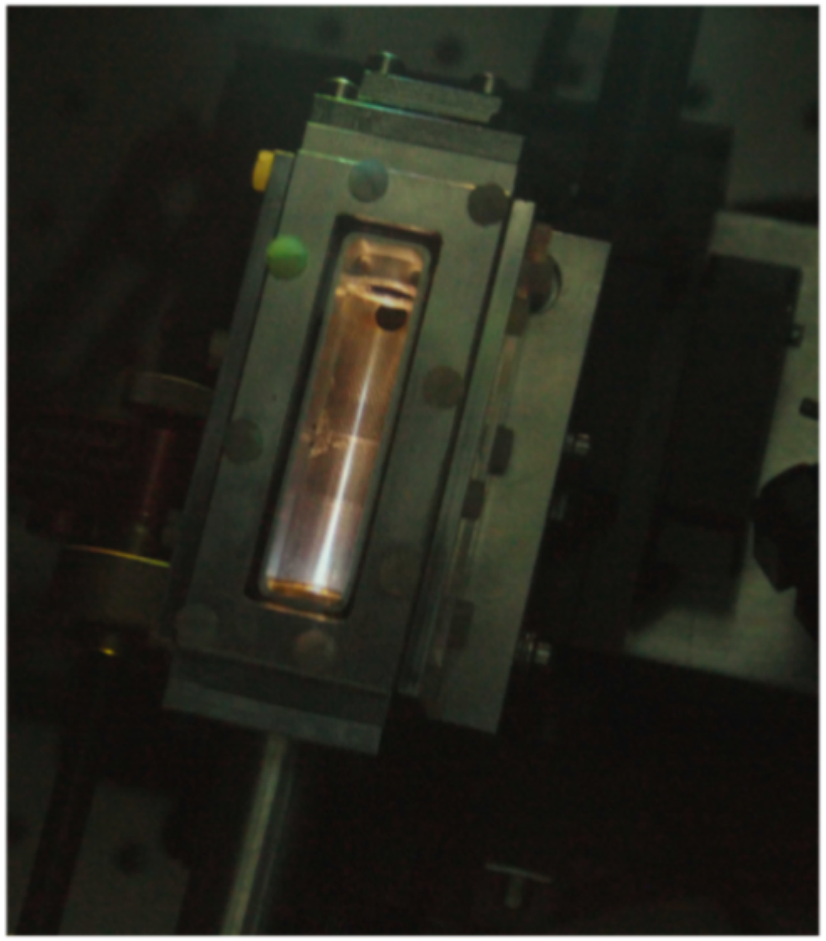
- Generation of longer channels
  - In principle the axicon used could generate 570 mm long channel
  - However, coupling channel-forming and driver beams non-trivial
  - Experimenting with "reflexicons" & other optical arrangements
- Coupling and transmission losses
- Demonstration of higher rep. rate operation
- Demonstration of electron acceleration



A 45 mm long axicon-generated OFI plasma

Summary

- HOFI plasma channels appear to be promising candidates for **multi-GeV stages** operating at **multi-kHz** rep rates
- In recent work we have generated plasma channels with:
  - $n_e(0) \approx 1.5 \times 10^{17}$ cm^{-3}
  - 20 μm $\lesssim W_M \lesssim$ 40 μm
  - Length of 16 mm (14 z_R)
  - 1 mJ / mm of channel (simulations suggest 1 mJ / **cm**)
- We have demonstrated high-quality guiding:
  - $I_{peak} = 4 \times 10^{17}$ W cm^{-2}
  - @ 5 Hz



A 45 mm long axicon-generated OFI plasma