Progress towards high-repetition-rate plasma accelerators

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Outline

- Multi-pulse laser wakefield acceleration
- Controlled injection
- Novel plasma channels

Funding acknowledgements

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- Science and Technology Facilities Council [Grant Nos ST/M50371X/1, ST/N504233/1, ST/P002048/1, ST/R505006/1]
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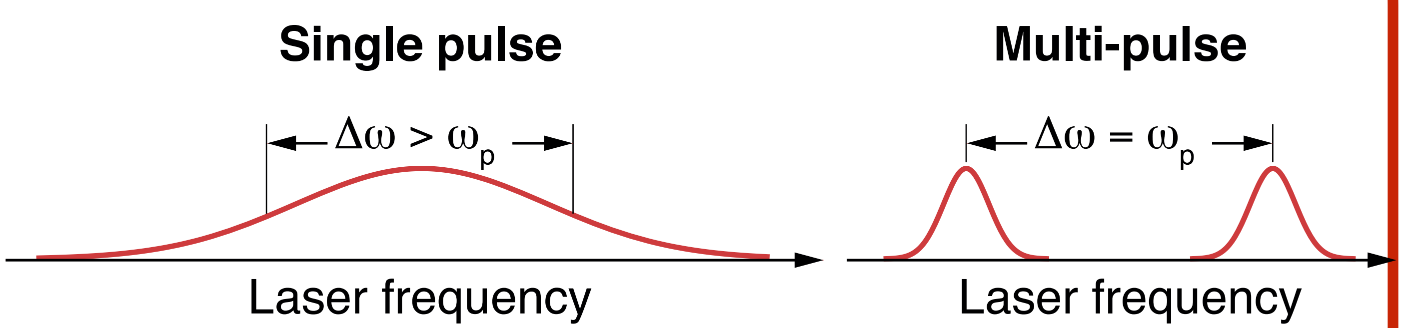
Multi-pulse laser wakefield acceleration

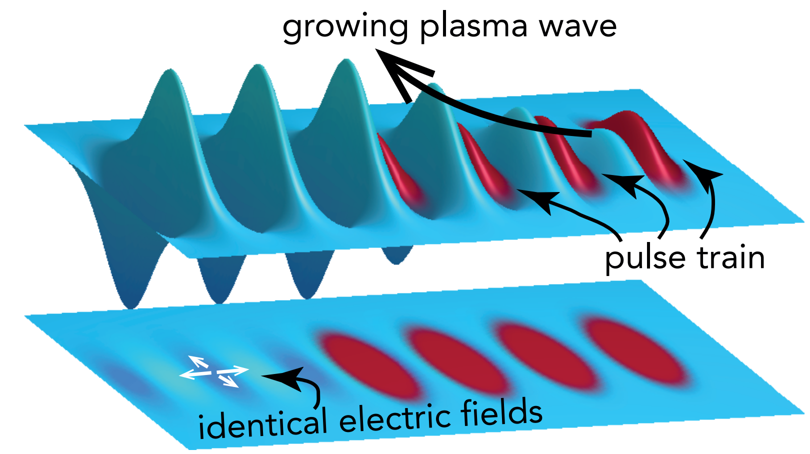
Multi-pulse laser wakefield acceleration

S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

MP-LWFA advantages



- Do not need large laser bandwidth,
- Allows different laser technologies
  - Fibre lasers: 5.7 mJ, 200 fs @ 40 kHz
  - Thin-disk: 0.2 - 1 J, 1 ps at 5 kHz commercially available
- Route to multi-kHz repetition rates with high wall-plug efficiency?
- Natural architecture for "energy recovery"
- Reduced driver E-field helps ionization-based controlled injection schemes

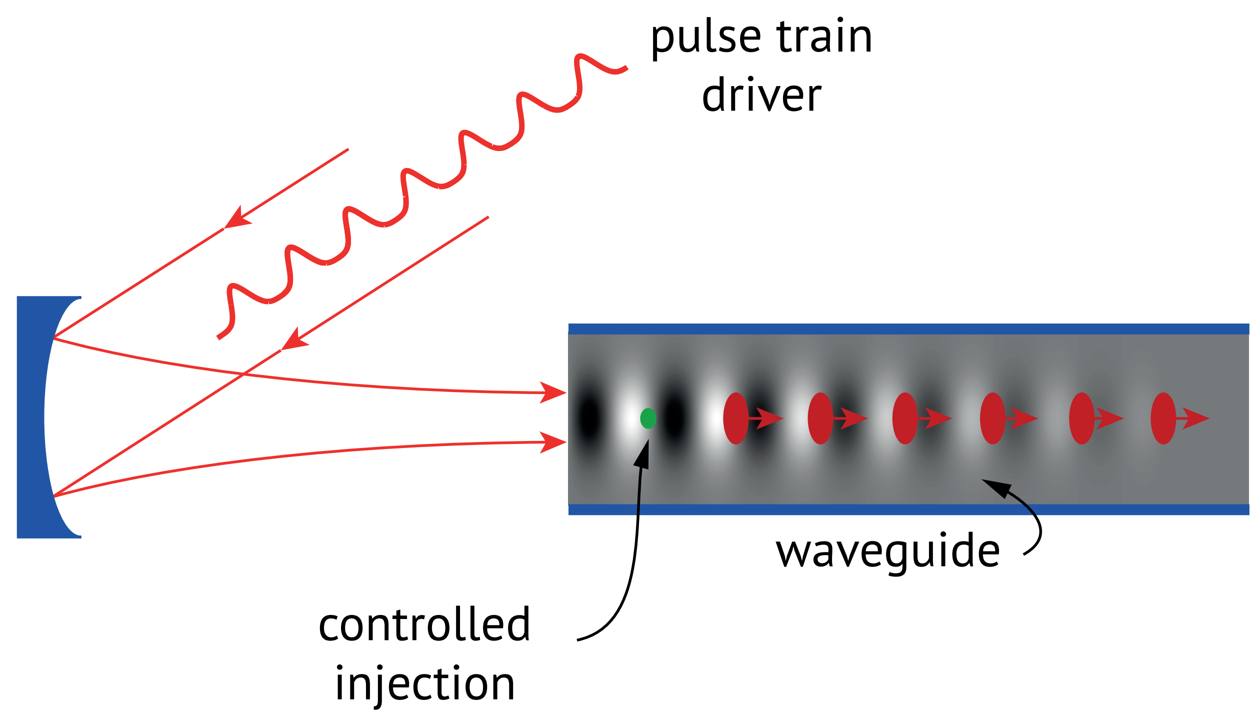


- Drive wakefield with train of low-energy laser pulses
- Resonant excitation if pulse spacing matched to plasma period
- Not a new idea
  - Many theory papers published in 1990s
  - Related work for PWFAs

MP-LWFAs: Key features

Key features

- Quasi-linear regime
- No self-injection
  - Need controlled injection scheme
- No self-focusing
  - Need a waveguide



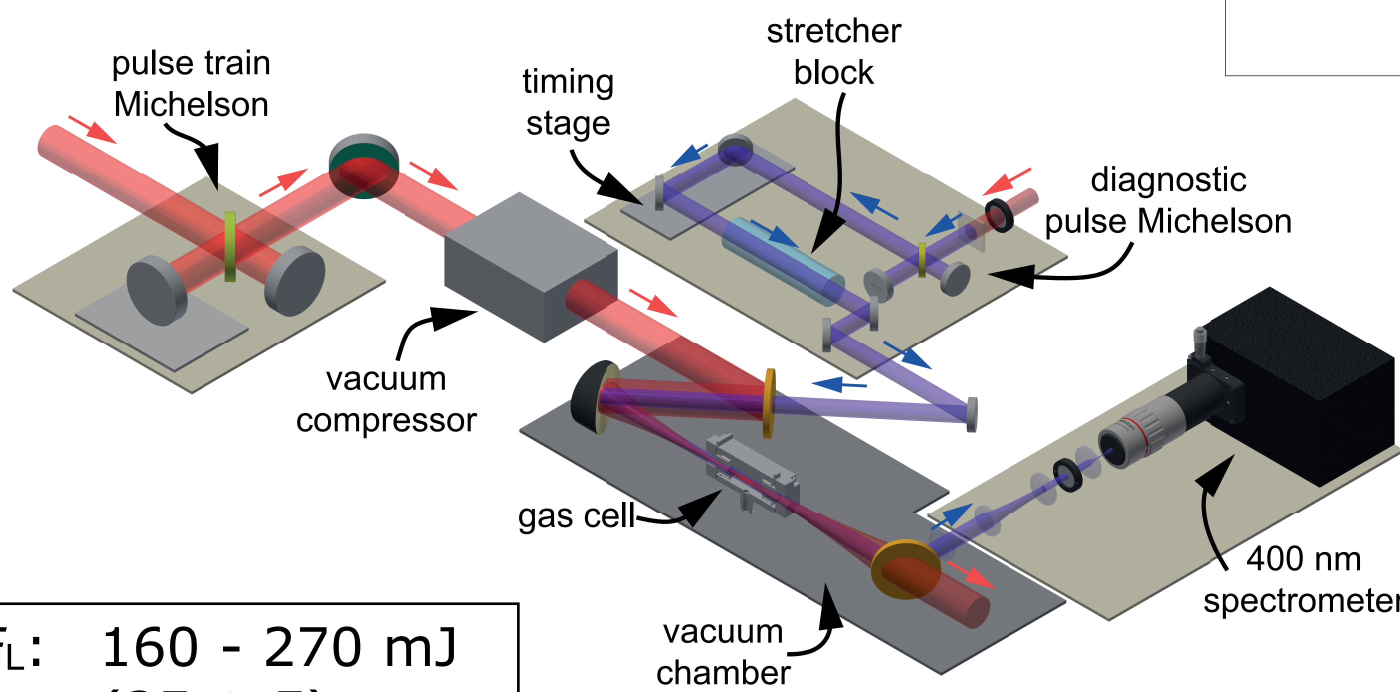
- Physics of MP-LWFAs
  - Jakob Jonnerby: WG5 Thurs 18:20

- Controlled injection
  - Jimmy Holloway: Mon poster session

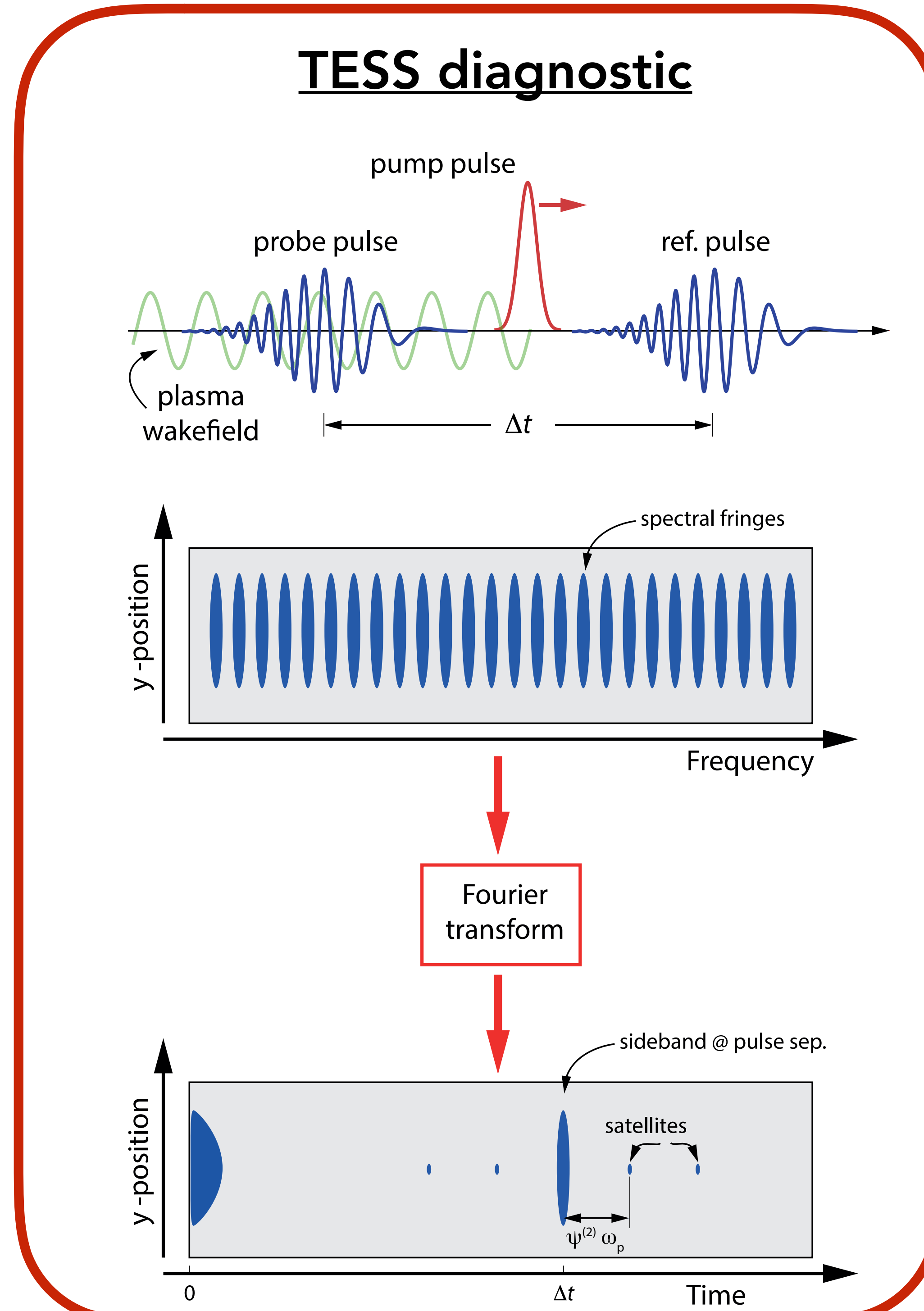
- Novel waveguides
  - Alex Picksley: Mon poster session
  - Alex Picksley & Aimee Ross: Wed poster session

Proof-of-principle demonstration

J. Cowley *et al. Phys. Rev. Lett.* **119** 044802 (2017)
N.H. Matlis *et al. Opt Lett* ***41*** *5503 (2016)*
C. Arran *et al. PRAB* **21** 103501 (2018)



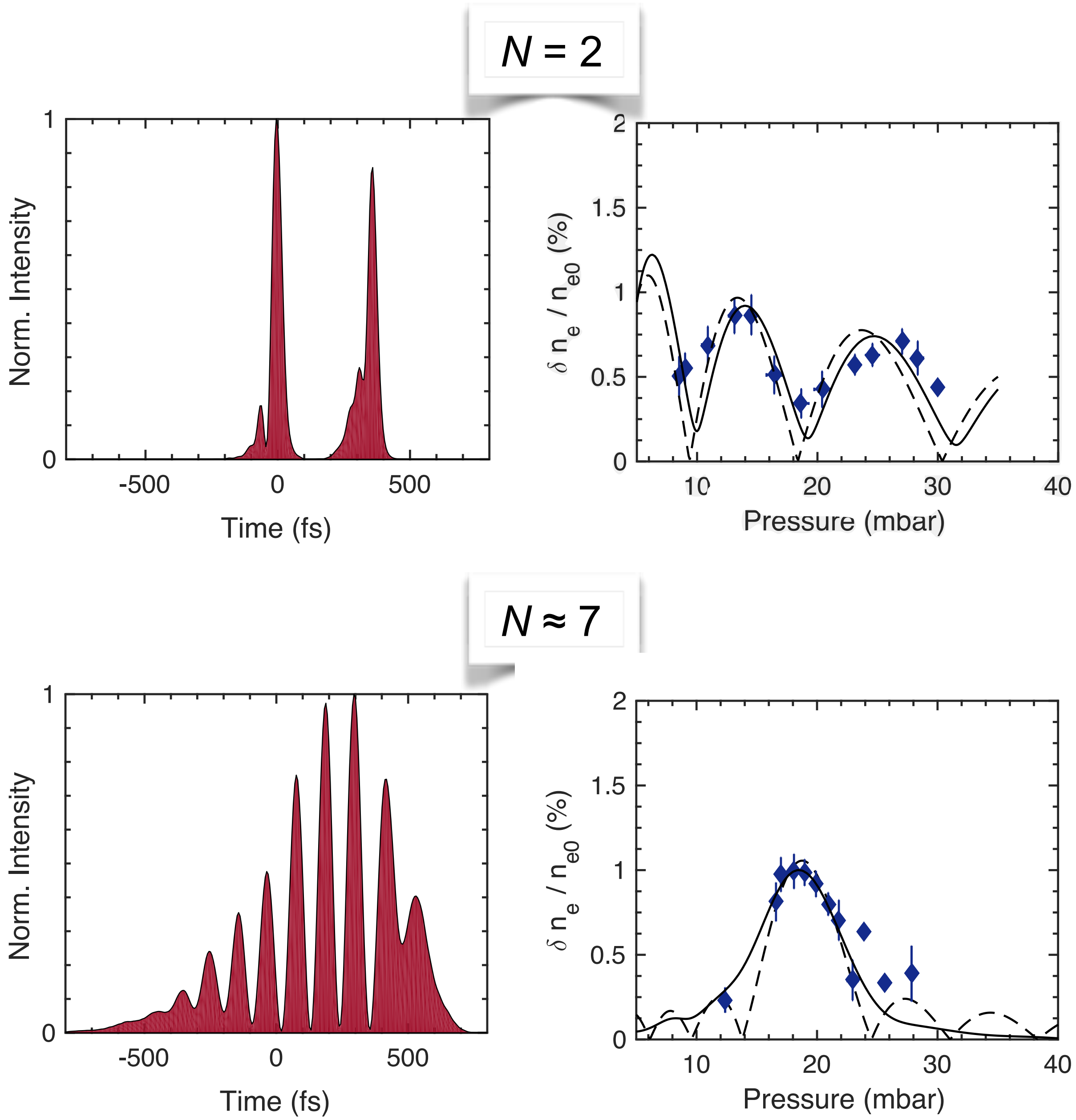
E_L: 160 - 270 mJ
w_0: (35 ± 5) μm
L_{cell}: 3 mm



- Expts with Astra-Gemini TA2 laser at RAL
- Astra delivers single 500 mJ, 40 fs Ti:sapphire pulses
- Converted single pulses into train of N = 1 - 7 pulses
- Wakefield measured by frequency-domain holography & TESS

Observation of wakefields driven by pulse trains

J. Cowley *et al. Phys. Rev. Lett.* **119** 044802 (2017)



$$\left[\frac{\delta n_{\rm e}}{n_{\rm e0}}\right]_N = \left[\frac{\delta n_{\rm e}}{n_{\rm e0}}\right]_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_{\rm p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{\rm p0}\delta\tau\right)}\right|$$

- Measurements in excellent with linear theory
- First step towards energy recovery!
  - Wake amplitude reduced by (44 ± 8)%
- Resonant excitation for *N* ≈ 7 pulses clearly observed

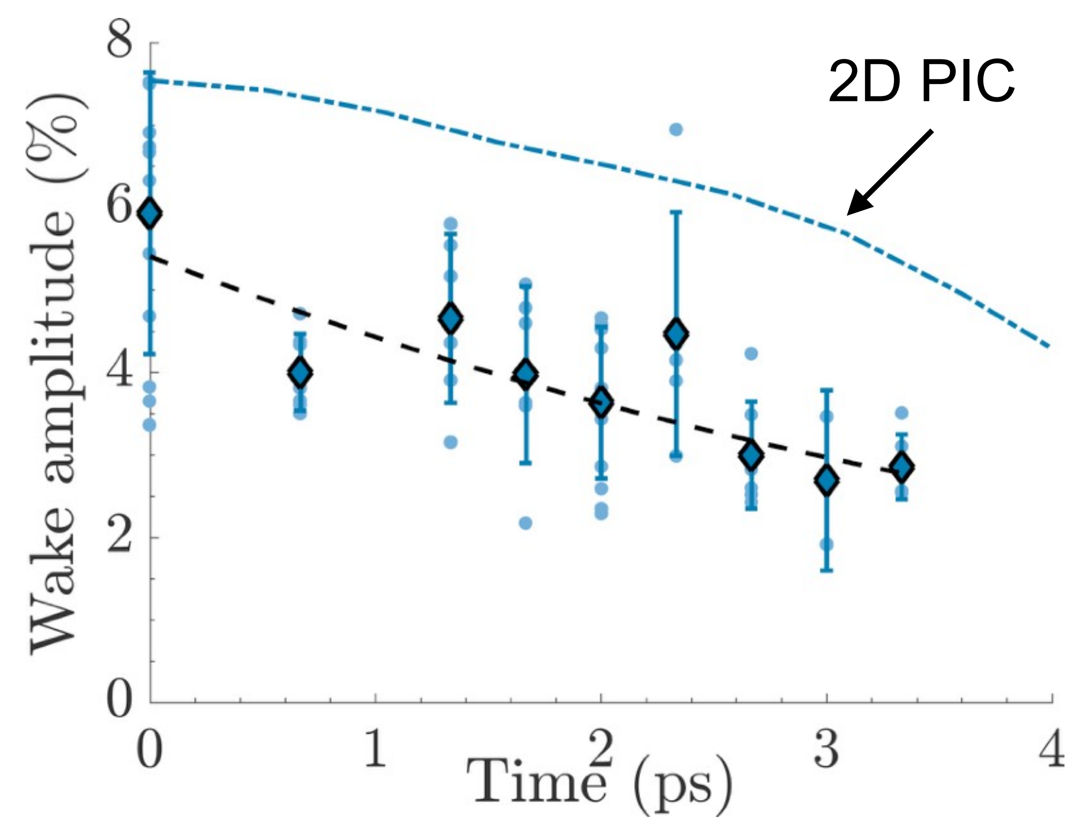
Measurements of plasma wave decay

Hydrogen
P: 20 mbar
τ_{pe}: 110 fs
τ_{pi}: 4.7 ps

- If wake decay dominated by ion motion then max no. useful pulses approx.

$$\frac{\tau_{pi}}{\tau_{pe}} = \frac{\omega_{pe}}{\omega_{pi}} = \sqrt{\frac{1}{Z}\frac{M_i}{m_e}}$$

- Recent experiments with Astra-Gemini TA3 laser at CLF show:
  - Timescale for wake decay consistent with ion plasma freq
  - $\Rightarrow N_{max} \approx 50 - 100$



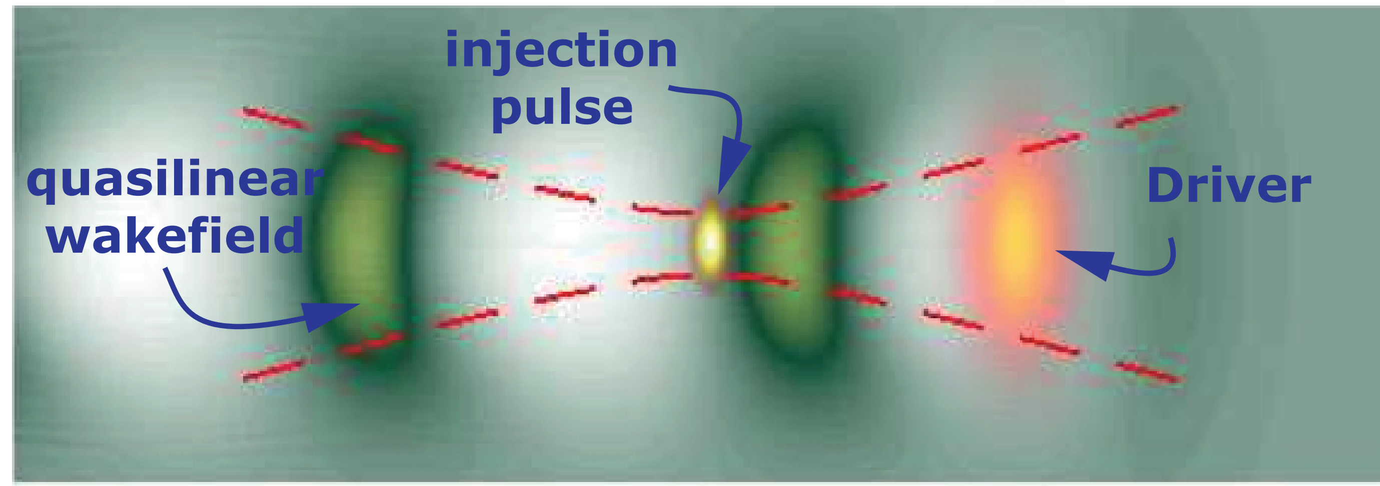
Preliminary results!

See Jakob Jonnerby's talk
WG5, Thurs 18:20

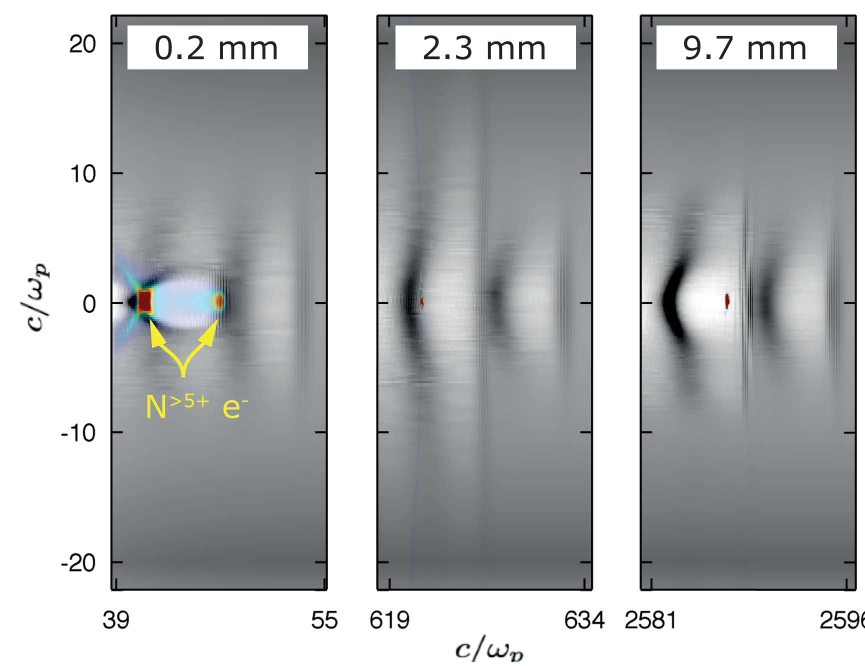
Controlled injection

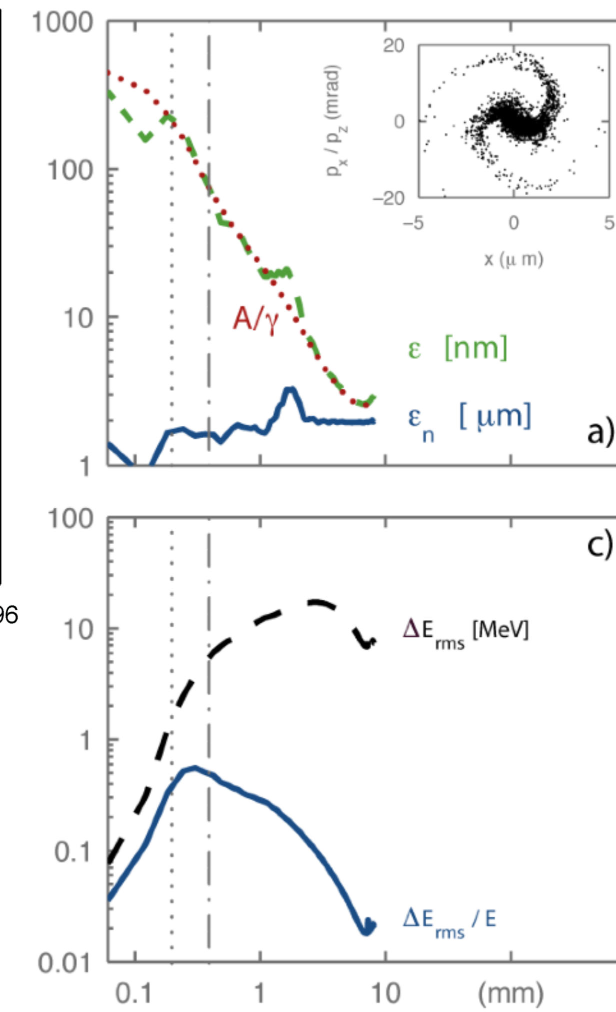
Two-pulse ionization (2PII)

N. Bourgeois *et al. Phys. Rev. Lett.* **111** 155004 (2013)

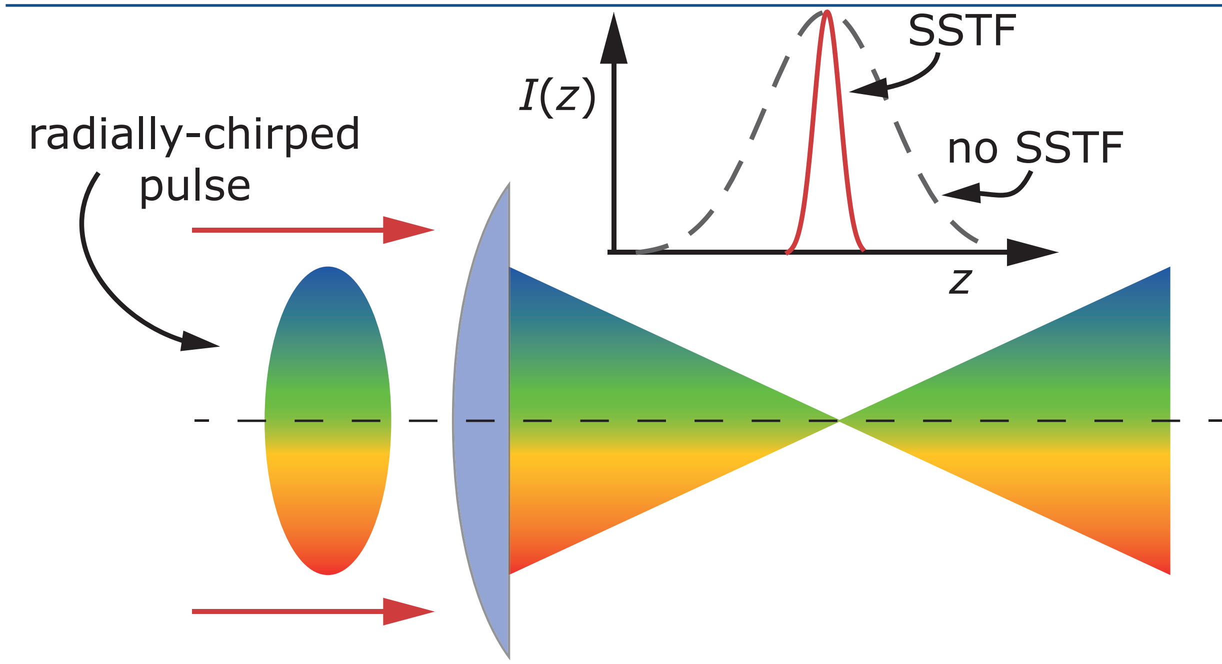


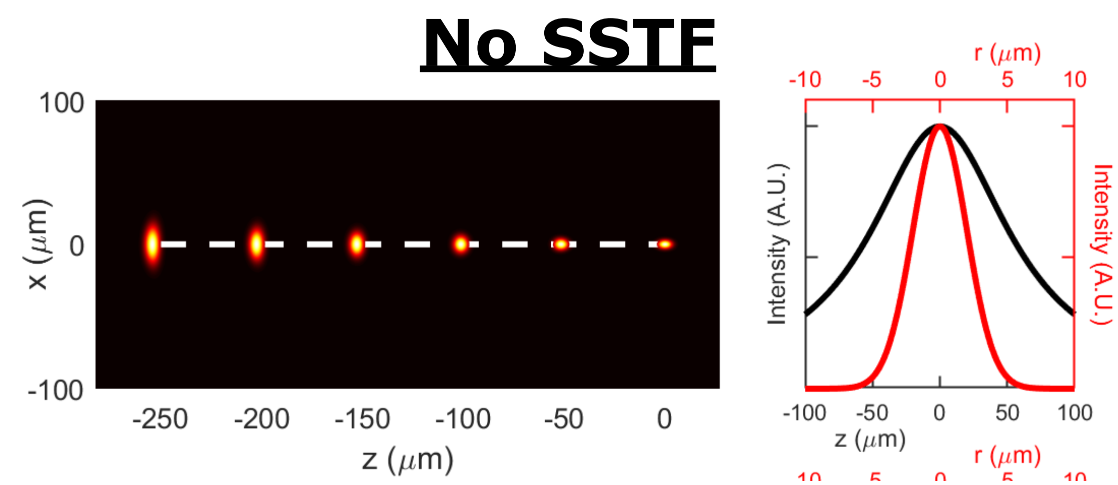
- Based on plasma photocathode concept
  - Hidding et al. PRL **108** 035001 (2012)
- $a_0 \sim 1$ driver excites quasilinear wakefield
- Tightly-focused injector
  - ionizes dopant
  - enhances wakefield
  - diffracts rapidly
- PIC simulations show injected bunch with:
  - E ≈ 370 MeV
  - *ΔE / E ≈ 2%*
  - $\varepsilon_{n,rms}$ ≈ 2.0 μm
- In 2013 paper we suggested **SSTF could reduce *ΔE / E* and $\varepsilon_{n,rms}$**

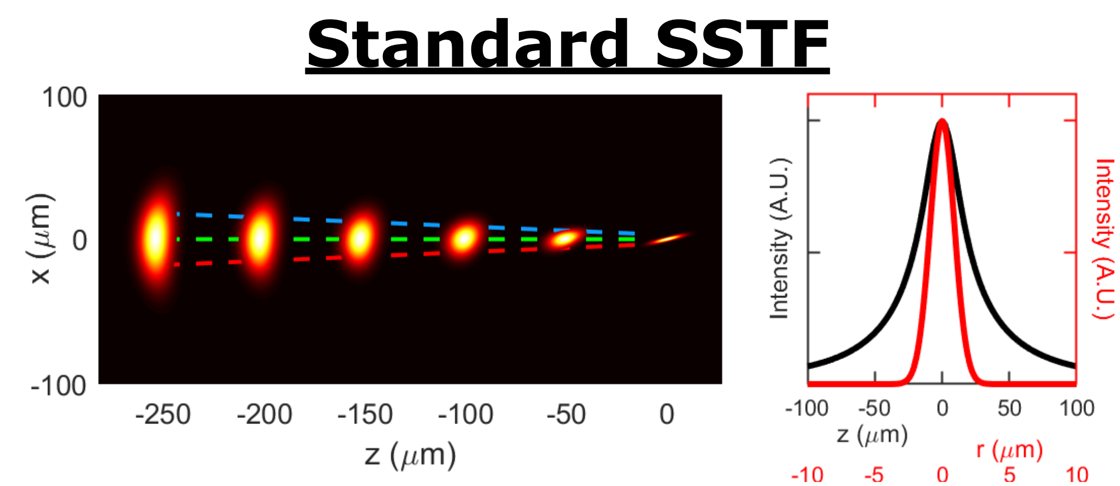




Annular, Radially-Chirped Ionization Injection

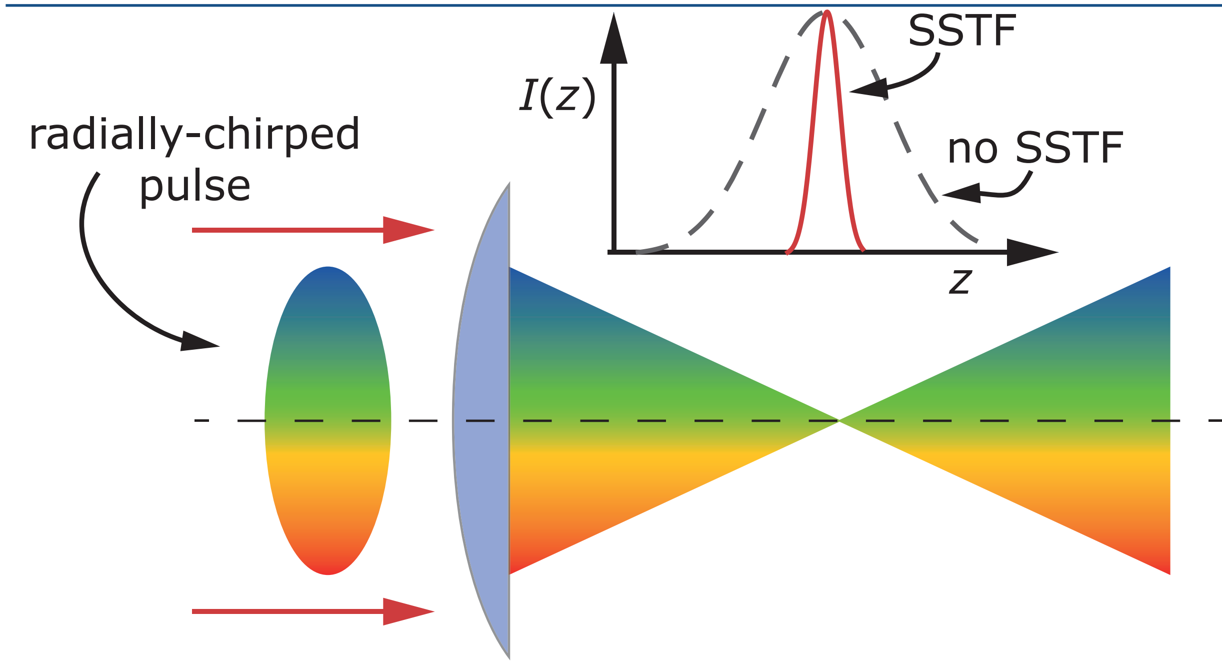




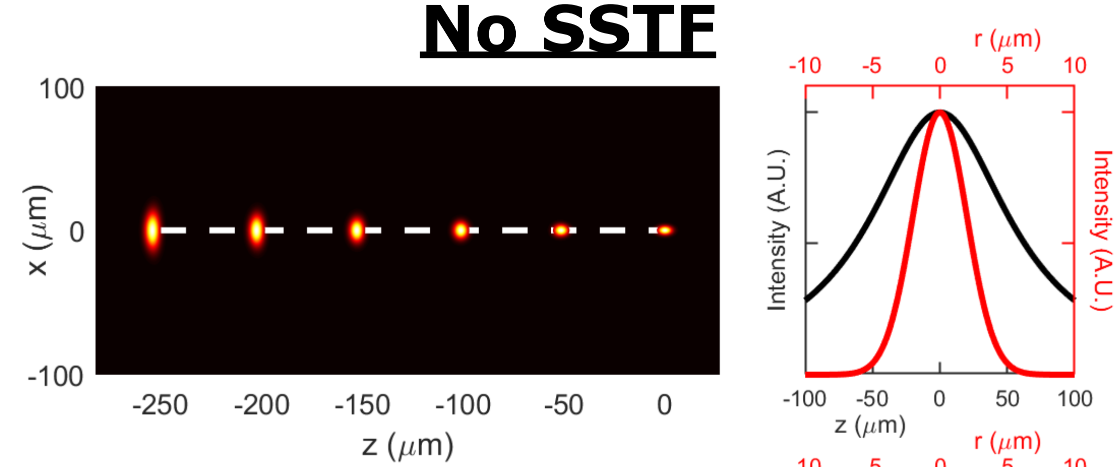


- Standard SSTF:
  - Transversely-chirped pulse reduces local bandwidth
  - Reduces effective z_R by factor ~ 10
  - Suffers from PFT

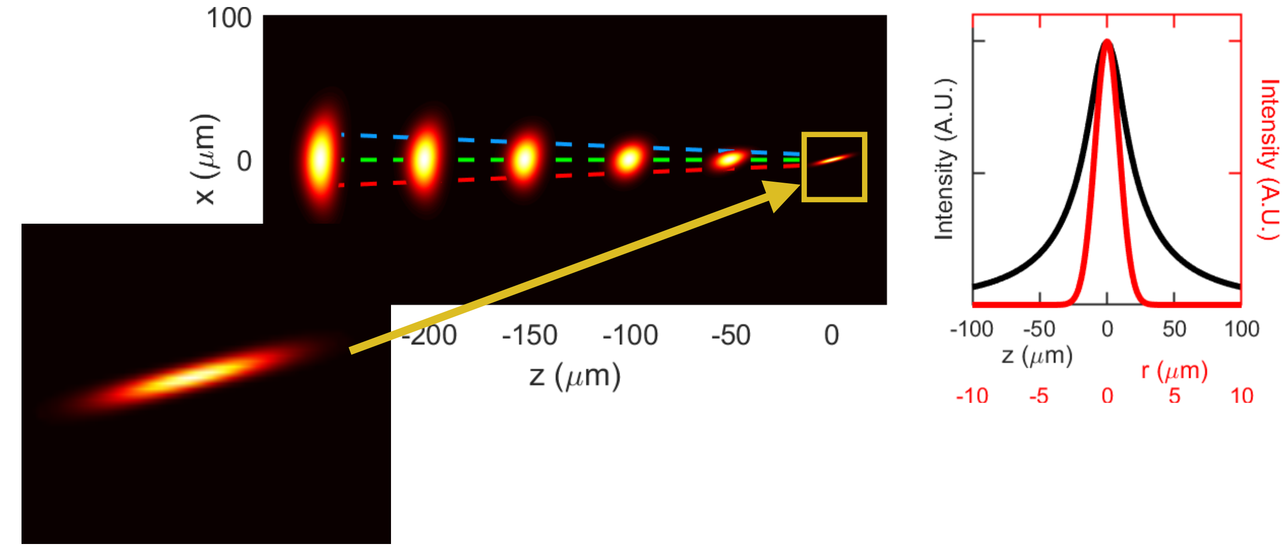
Annular, Radially-Chirped Ionization Injection



No SSTF



Standard SSTF



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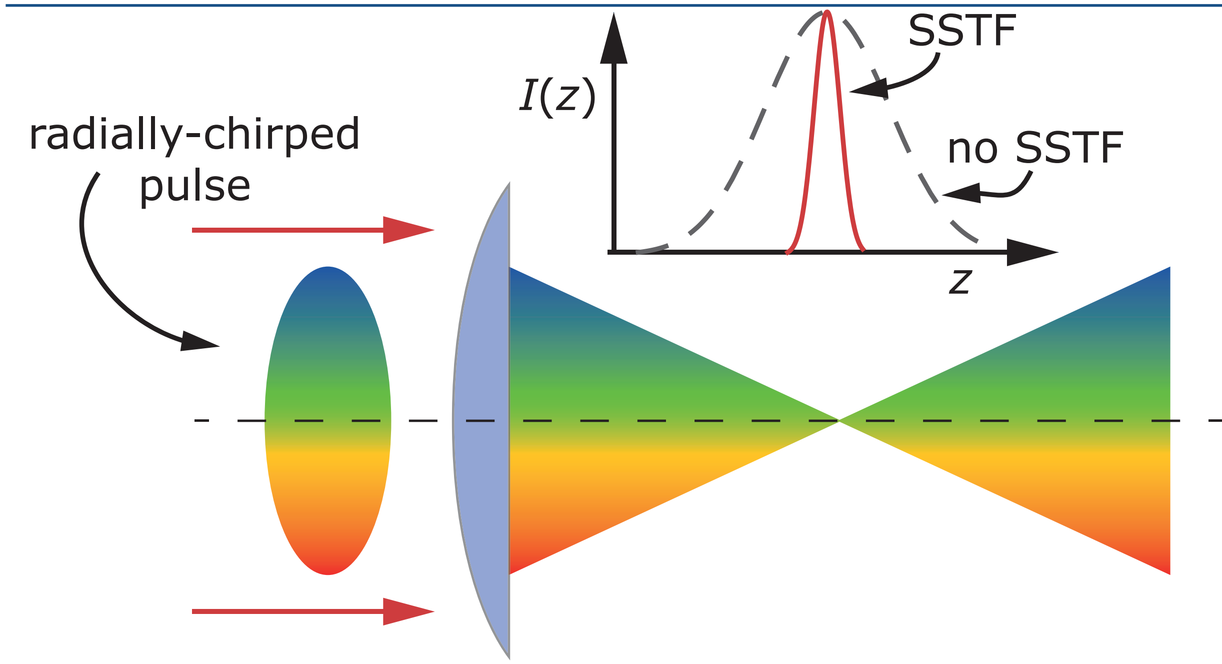
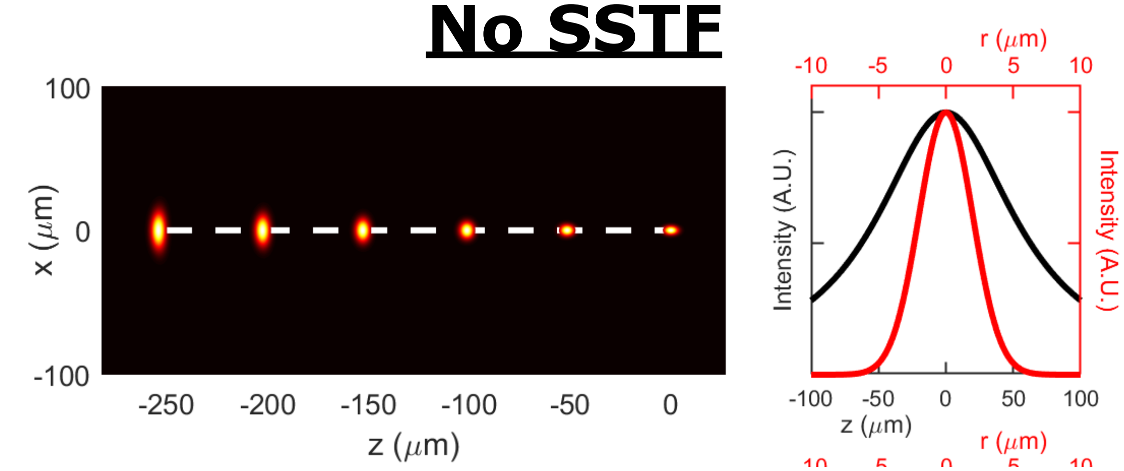
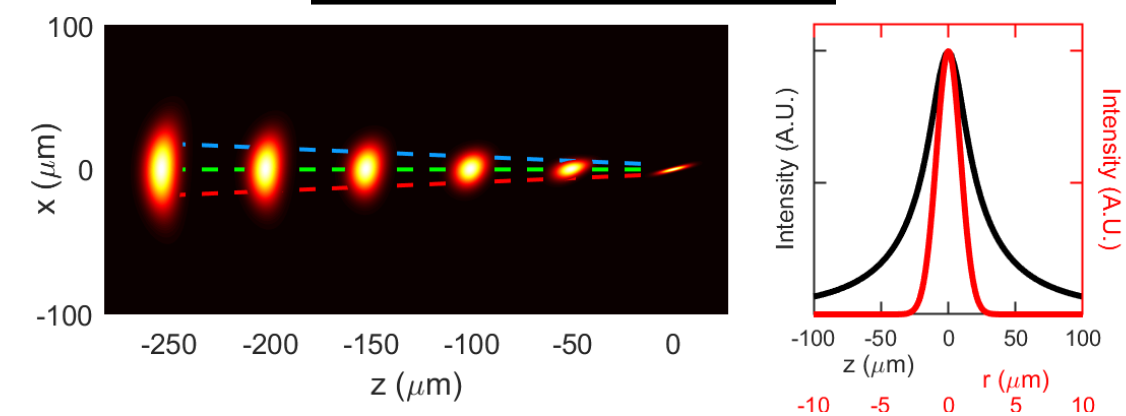


- Standard SSTF:
  - Transversely-chirped pulse reduces local bandwidth
  - Reduces effective z_R by factor ~ 10
  - Suffers from PFT
- We use an **annular beam** & a **radial chirp**
  - Avoids PFT
  - Rapid injector diffraction, gets injector out of way
  - Control of injector v_g ⇒ control injection of electrons into phase space

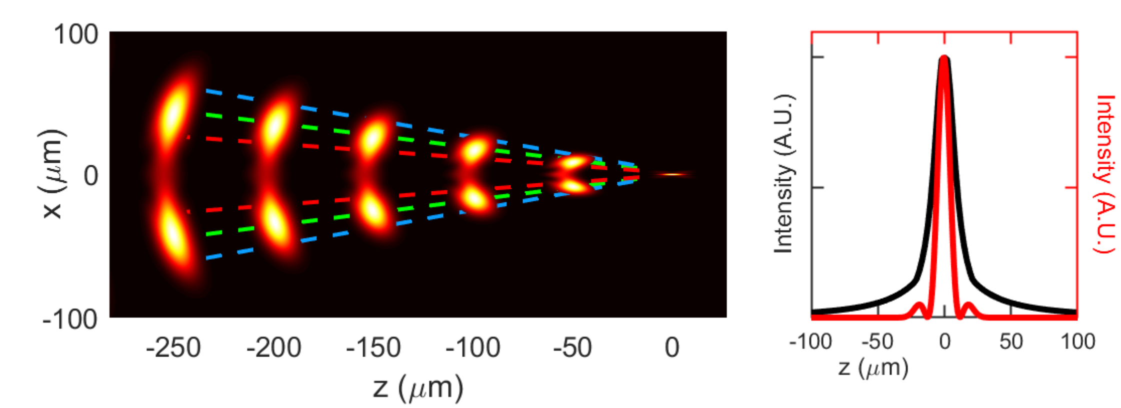
No SSTF



Standard SSTF



Radial SSTF

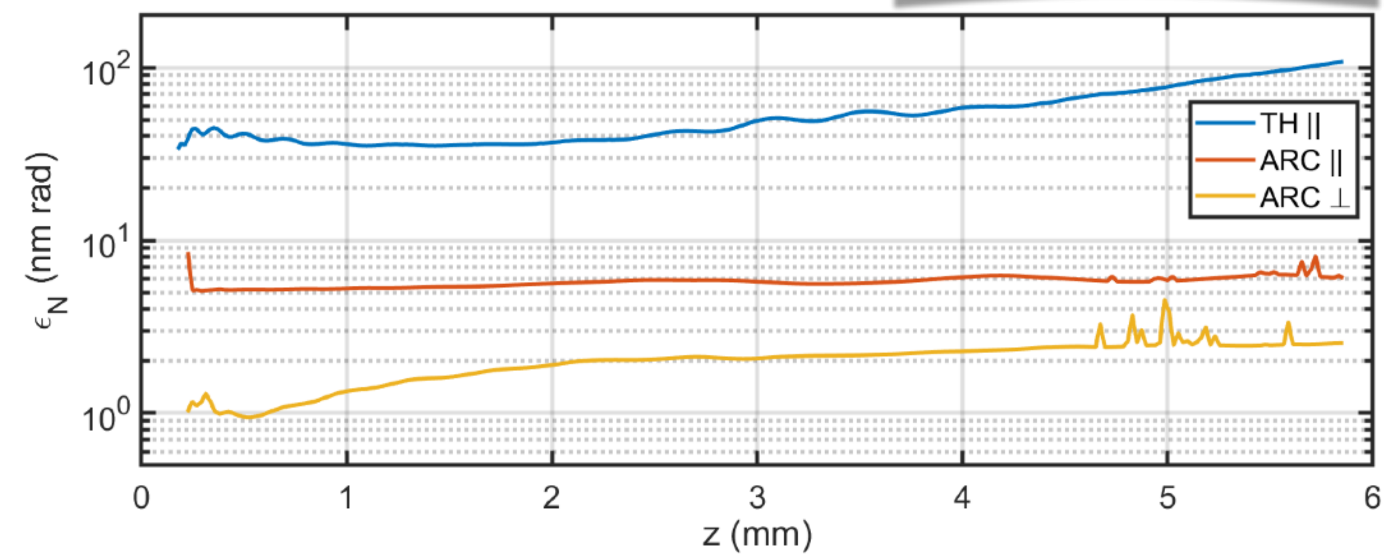


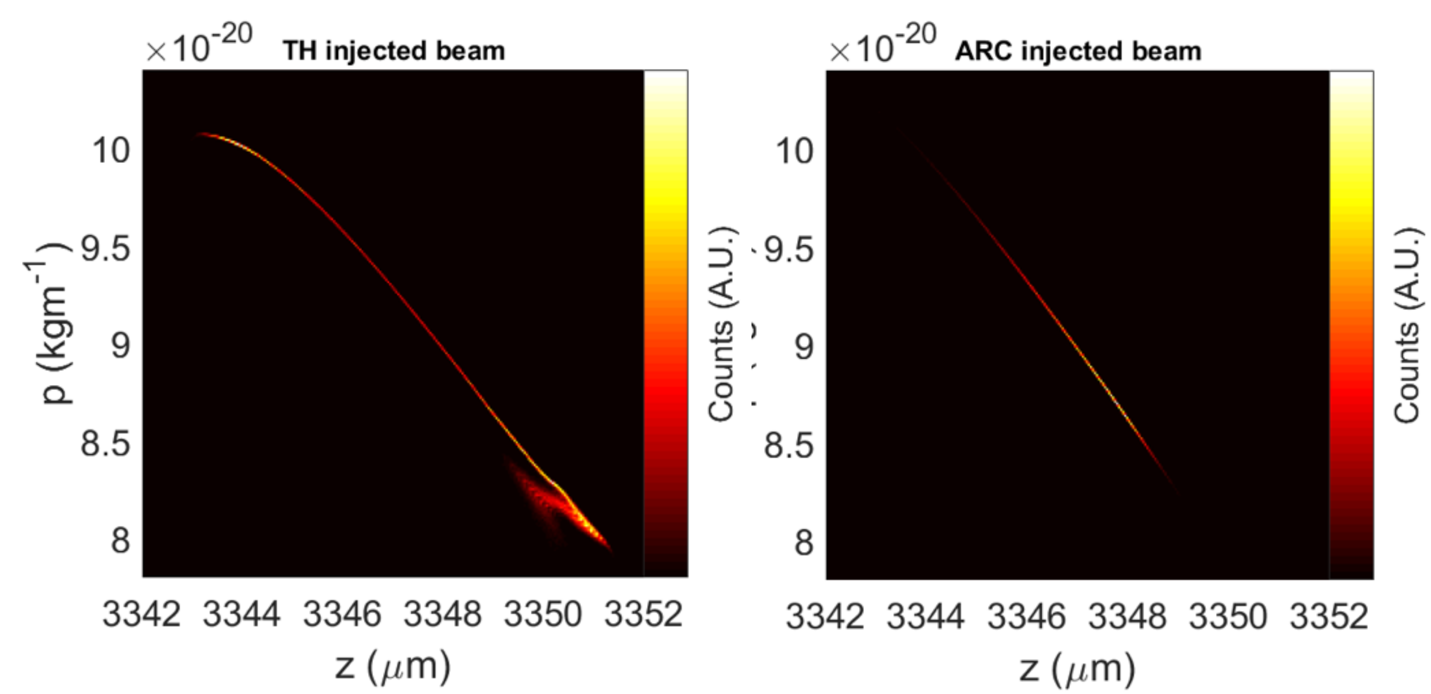
Annular, Radially-Chirped Ionization Injection

- Preliminary PIC simulations for **particle driver** show factor ~ 10 reduction in emittance:
  - TH: $\varepsilon_{n,rms} \approx 40$ nm
  - ARC: $\varepsilon_{n,rms} \approx 5$ nm
- Very linear energy chirp
  - Slice energy spread as low as 0.02%
  - Could be de-chirped?
- Could be adapted to other ionization injection schemes
  - ReMPI scheme
  - Two-colo(u)r injection
  - etc…

Preliminary results!

See Jimmy Holloway's poster (No. 175) Mon





HOFI plasma channels

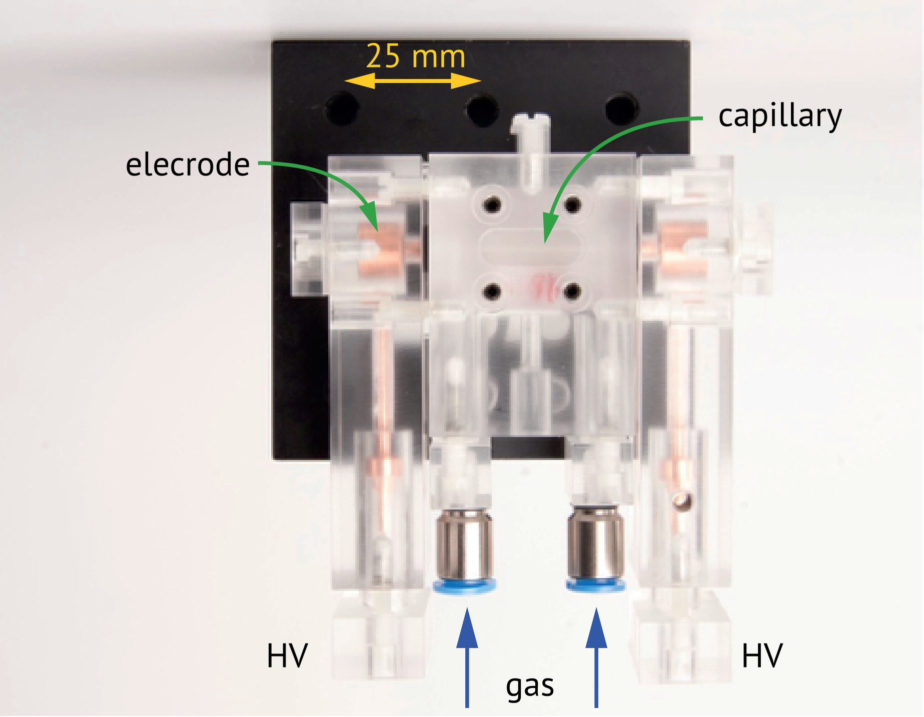
Why are new waveguides needed?

- Lower plasma density
  - 10 GeV stages require $n_e \approx 10^{18}$ cm^{-3} → ≈ 10^{17} cm^{-3}
- Higher pulse repetition rate
  - Roadmaps require f_{rep} → kHz range
- Capillary discharge waveguides:
  - Operated down to $n_e \approx 10^{17}$ cm^{-3} …
  - … at f_{rep} = 1 kHz

    A. J. Gonsalves *et al. J. Appl. Phys*. **119** 033302 (2016)
  - Use of additional laser heater gives deeper channels

    N. A. Bobrova et al. PoP **20** 020703 (2013)

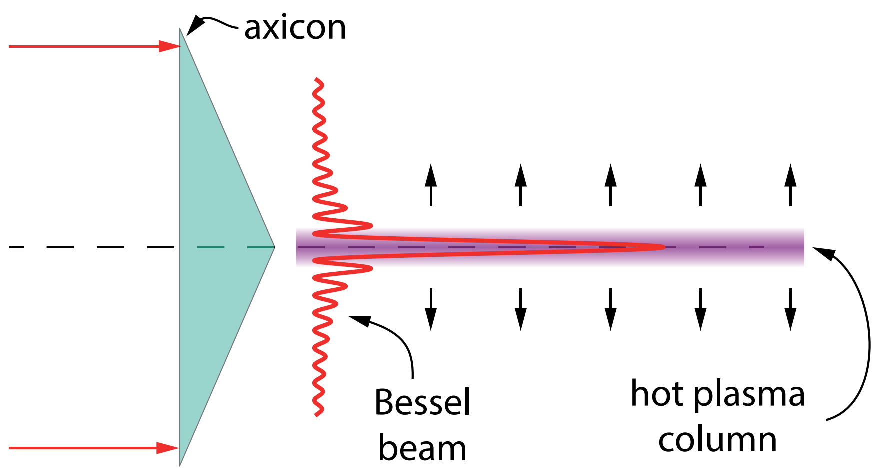
    A. J. Gonsalves et al. PRL **122** 084801 (2019)

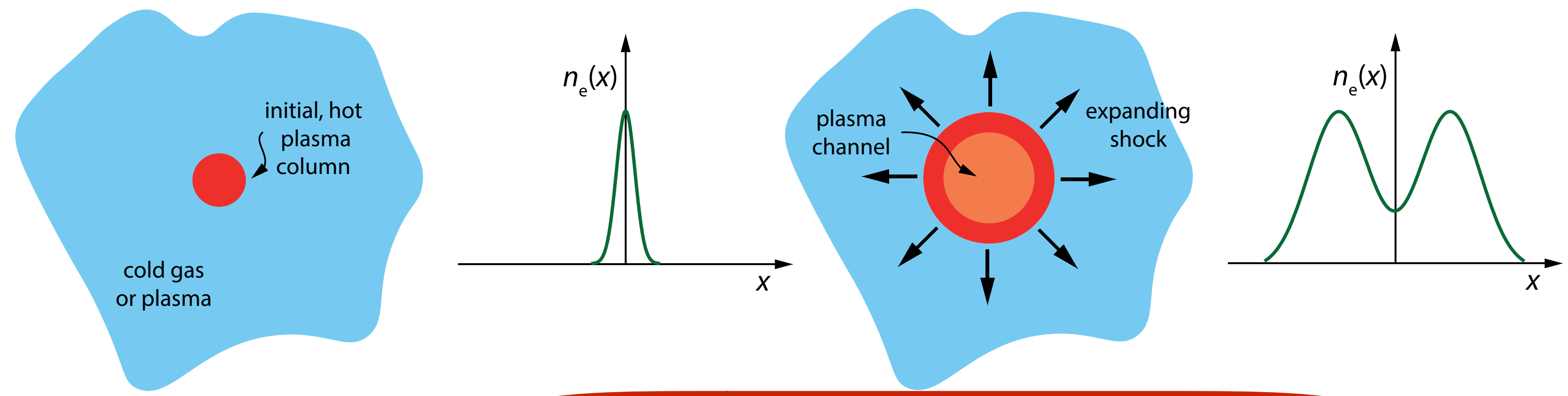


D. Spence and S. Hooker, *Phys Rev E* **63** 015401 (2000)
A. Butler *et al.*, *Phys Rev Lett* **89** 185003 (2002)

- … but, long-term operation at kHz repetition rates when guiding multi-joule laser pulses will be challenging!

Hydrodynamic plasma channels





- Attractive for high repetition rates since free-standing and "indestructible"
- Traditionally plasma column is **heated collisionally**:
  - Durfee & Milchberg, *PRL* **71** 2409 (1993)
  - Volfbeyn *et al*. *POP* **6** 2269 (1999)
- Collisional heating requires high density for fast heating
  - **Limits axial density to ~ 10^{18} cm^{-3}**

HOFI plasma channels

- Optical field ionization gives:
  - Hot electrons (10 - 1000 eV)
  - Electron energy controlled by polarization
- Heating independent of density ⇒ **low density channels**
- IST & Strathclyde groups have demonstrated generation of short channels by a spherical lens:

  N. Lemos *et al. Phys Plasm.* **20** 063102 (2013)

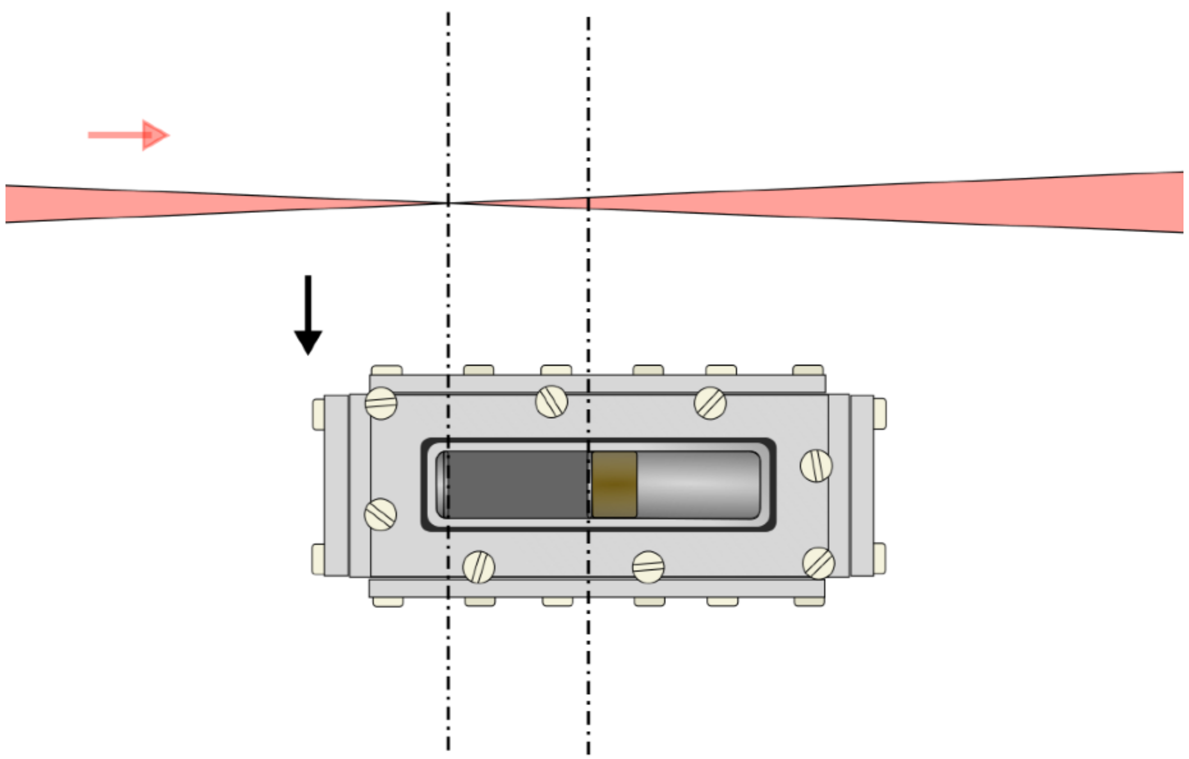
  N. Lemos *et al. Phys Plasm.* **20** 103109 (2013)

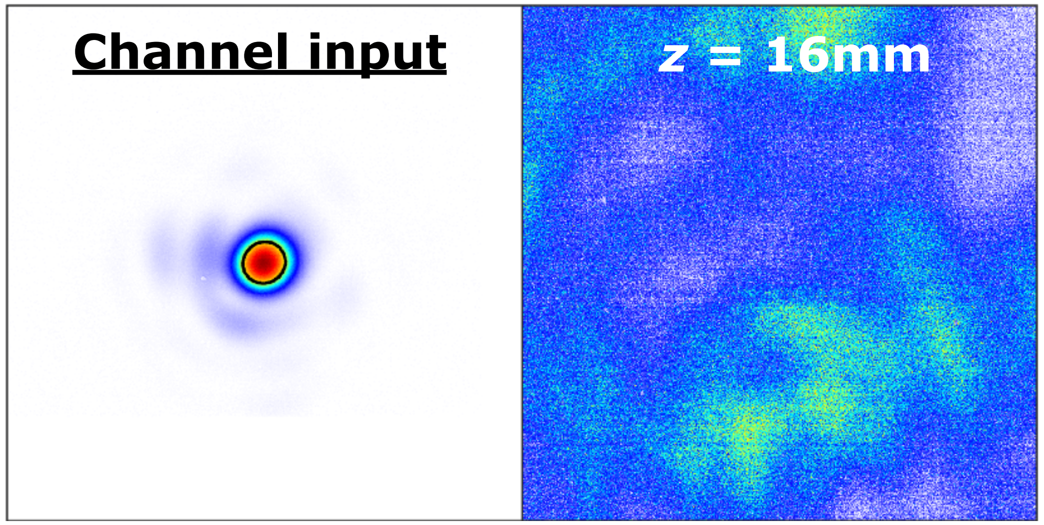
  N. Lemos *et al. Nat. Sci. Rep.* **8** 3165 (2018)

16 mm long HOFI channels: Guiding

R.J. Shalloo *et al. PRAB*, **22** 041302 (2019)

- Experiments formed with Astra-Gemini TA2 laser
- Guided beam injected into channel after delay $\tau = 1.5$ ns
- $P_{cell} = 60$ mbar
- On-axis density $n_e(0) \approx 6.5 \times 10^{17}$ cm^{-3}
- Guiding over 14.5 z_R (16 mm)





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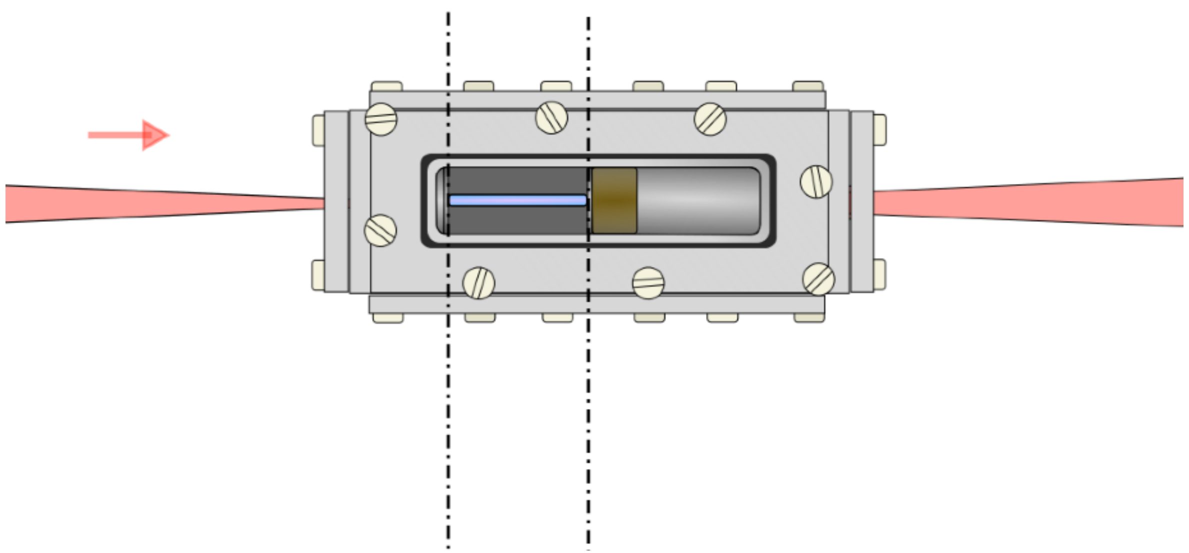

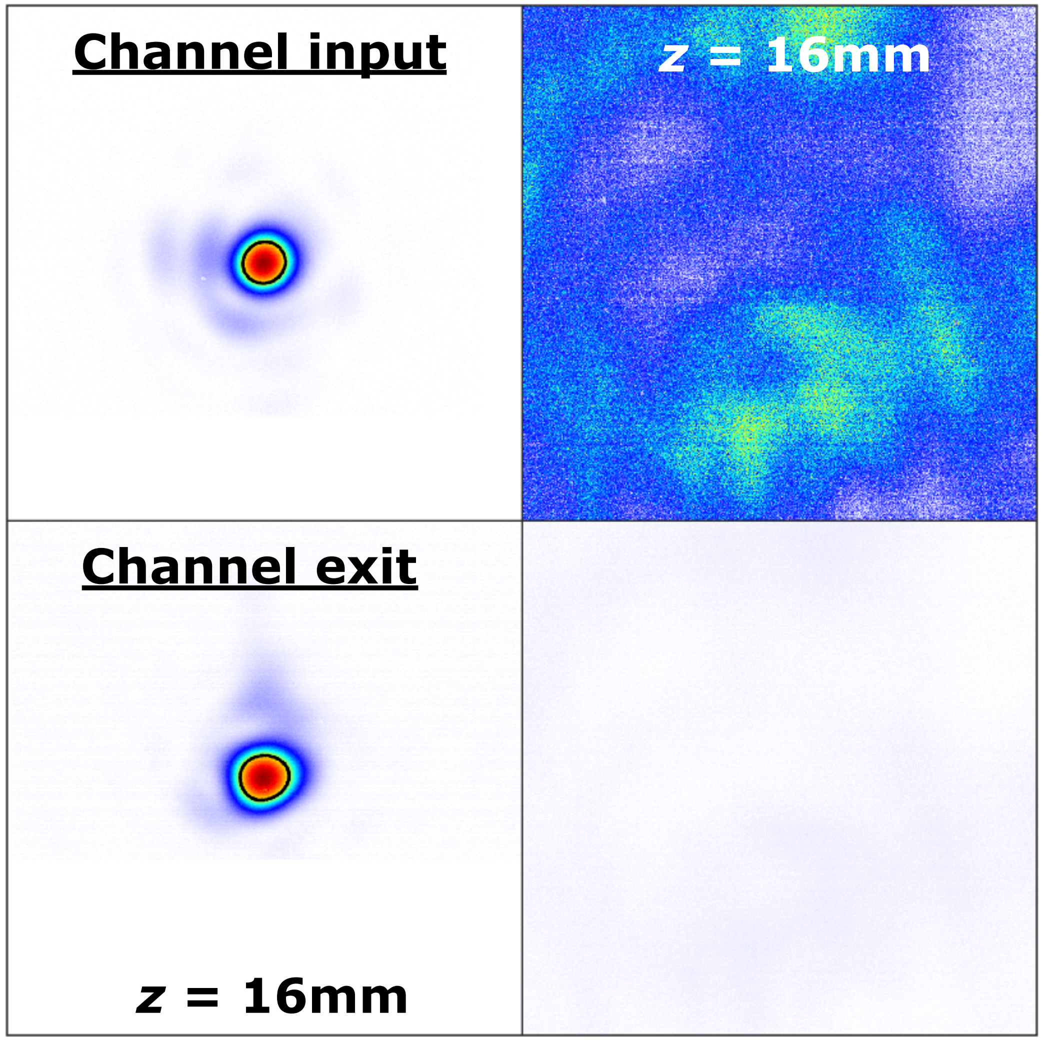

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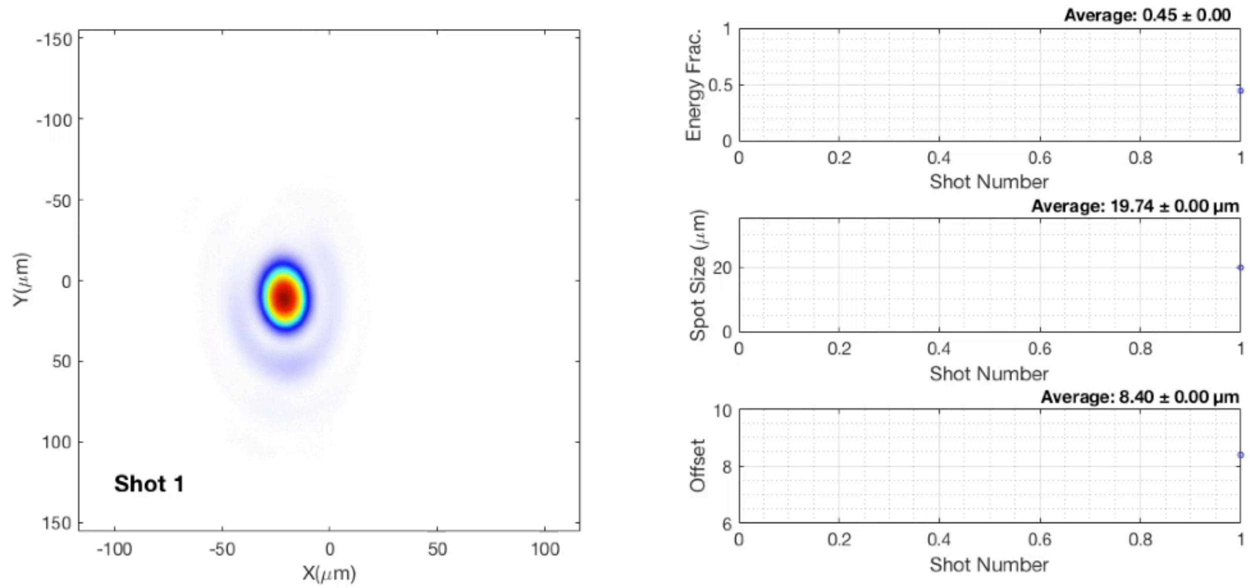
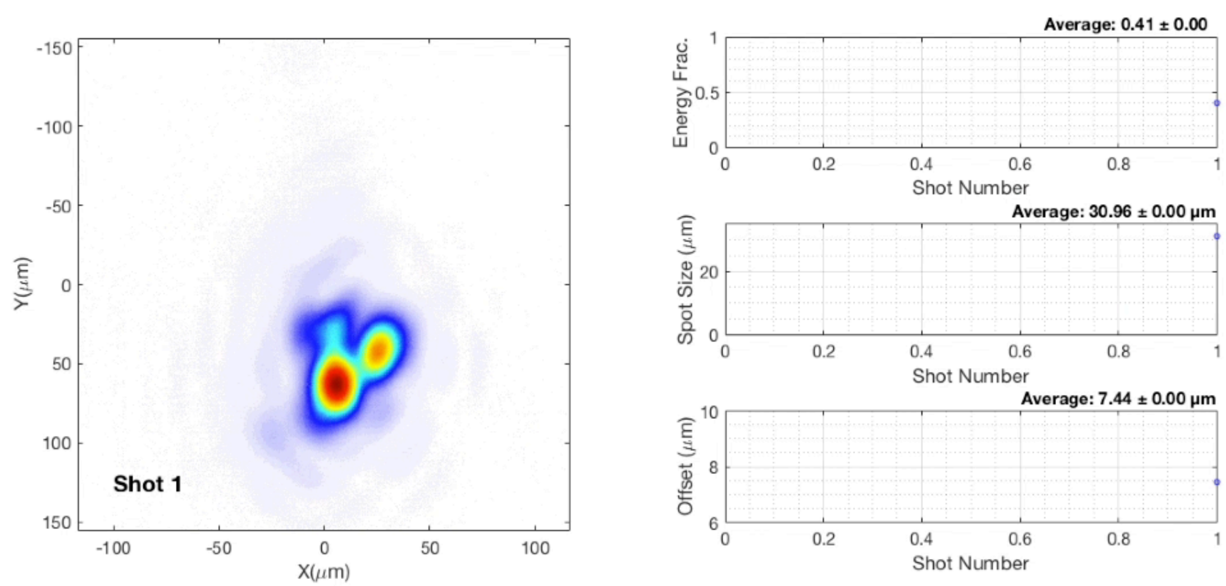
R.J. Shalloo *et al.* *PRAB*, **22** 041302 (2019)



Low-power guiding

N: 165 consecutive shots



High-power guiding at 5 Hz

N: 489 consecutive shots

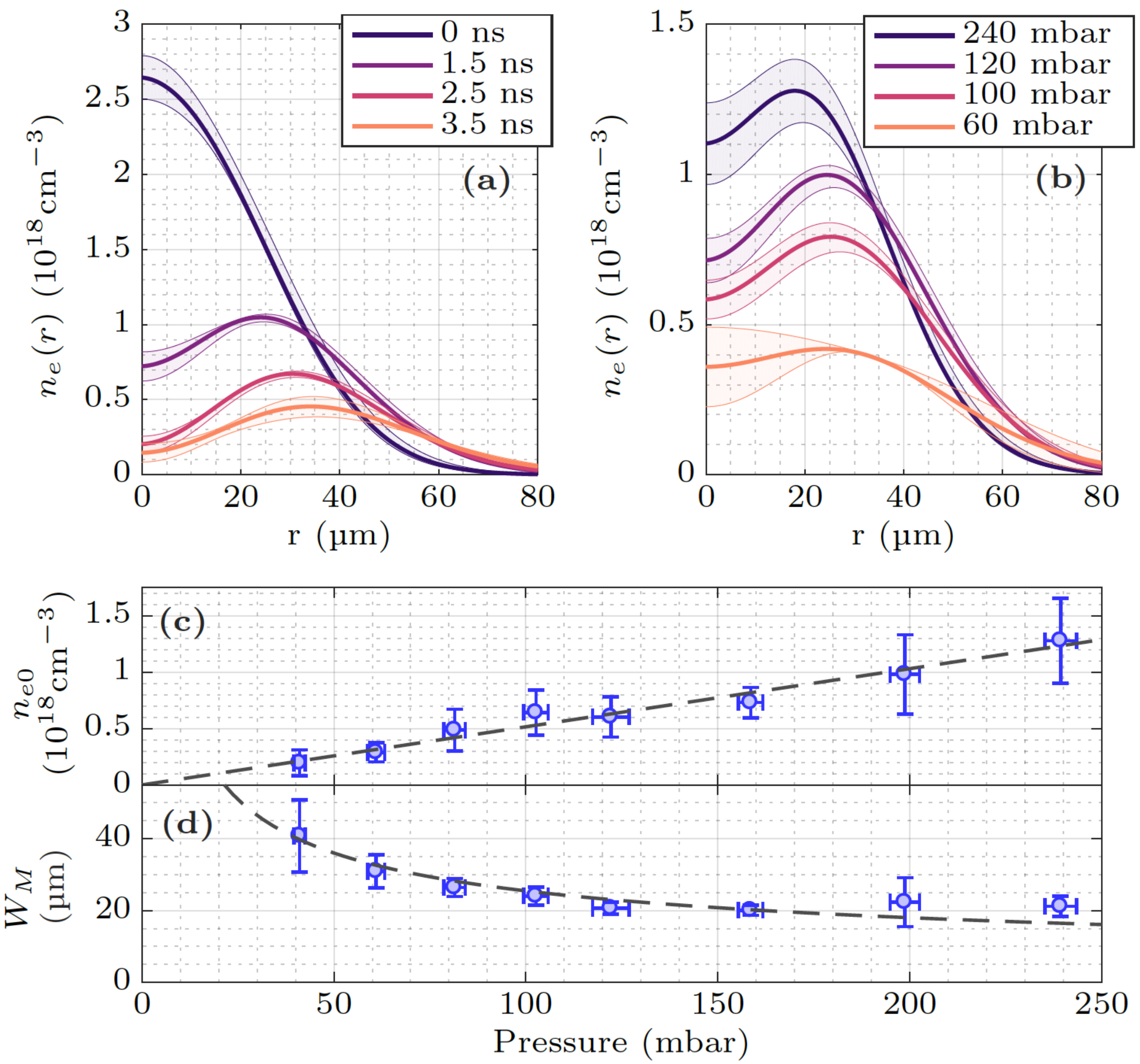
I_0: 4×10^{17} W cm^{-2}

5 Hz: 12 shots every 45 s

16 mm long HOFI channels: Interferometry

P = 120 mbar | **τ = 1.5 ns**

R.J. Shalloo *et al.* *PRAB*, **22** 041302 (2019)

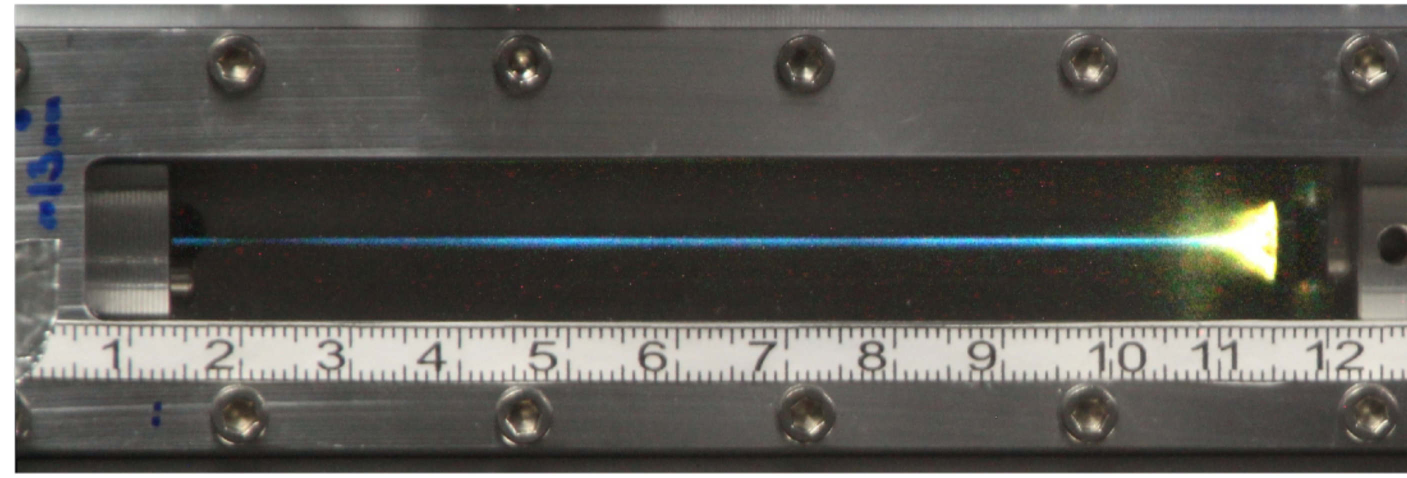


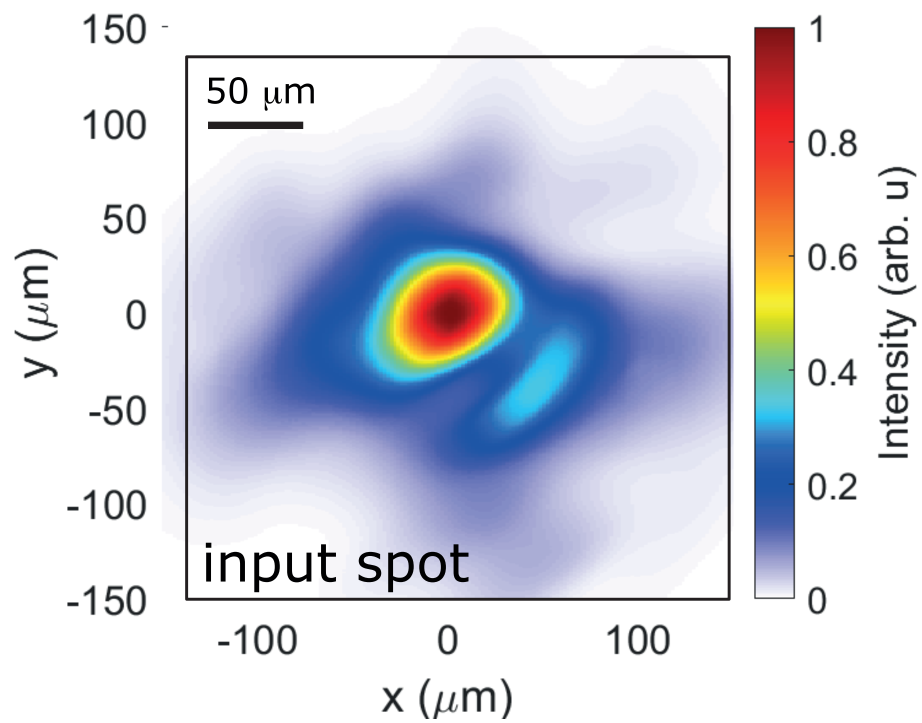
- Interferometry shows channel formation over few ns with:
  - $n_e(0)$ as low as 1×10^{17} cm^{-3}
  - 20 μm WM < 40 μm

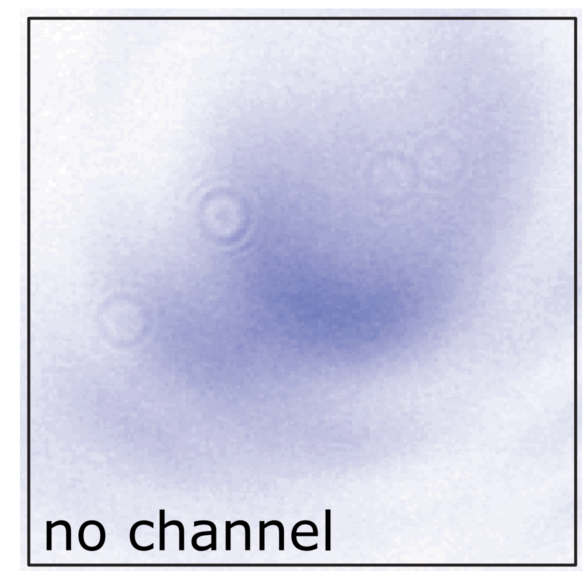
See Alex Picksley's poster
Mon poster 201

100 mm long, low-density HOFI channels

- Experiments performed with Astra-Gemini TA3 laser





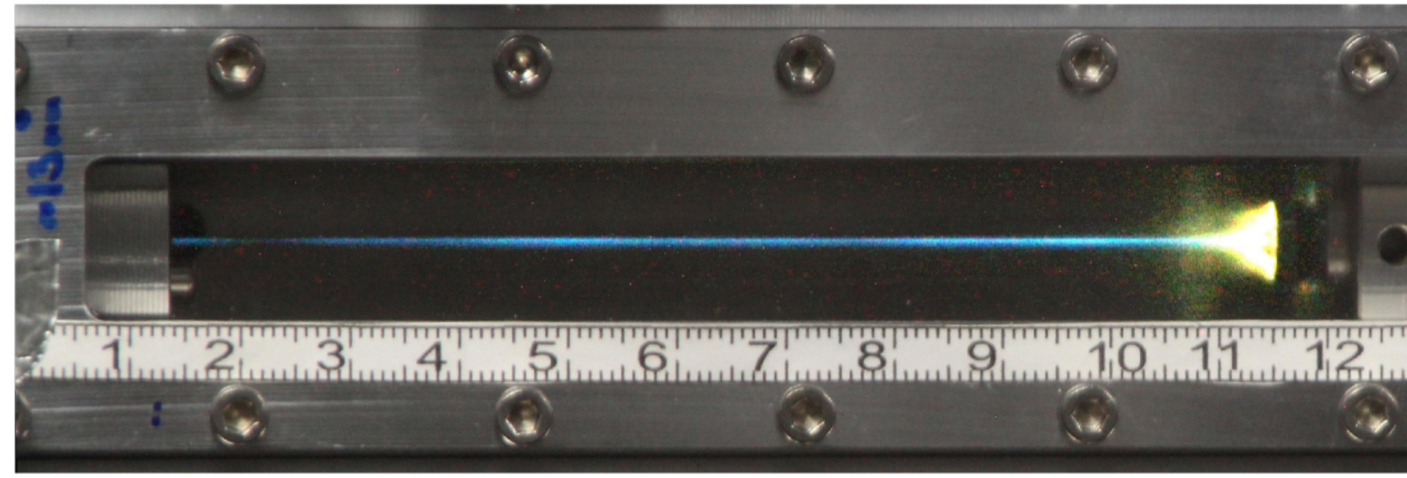


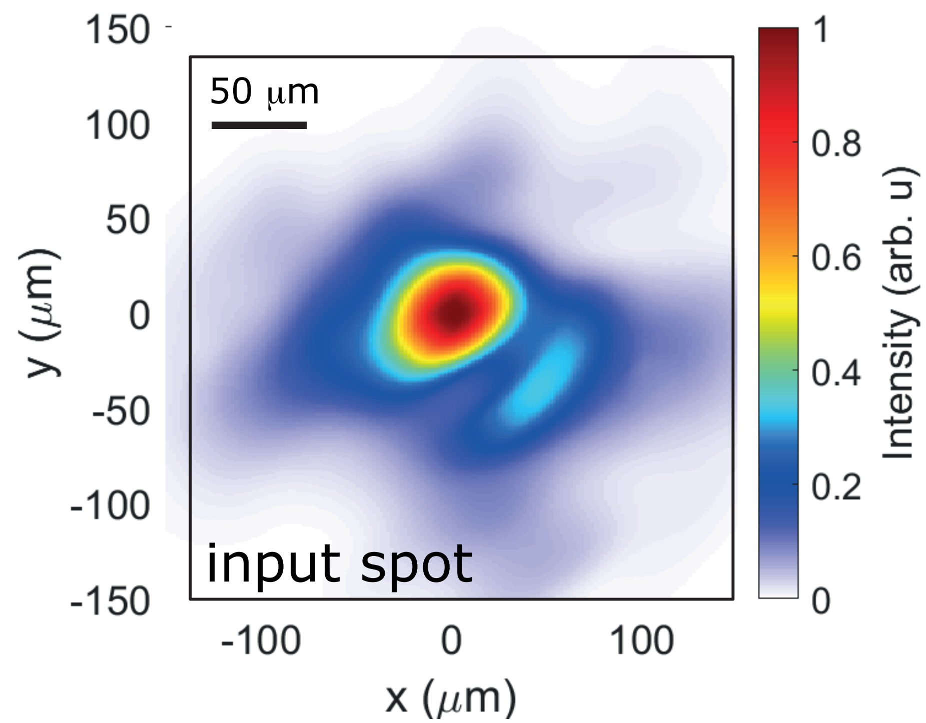
I_0: 8×10^{17} Wcm-2
P_{cell}: 30 mbar
τ: 2.5 ns

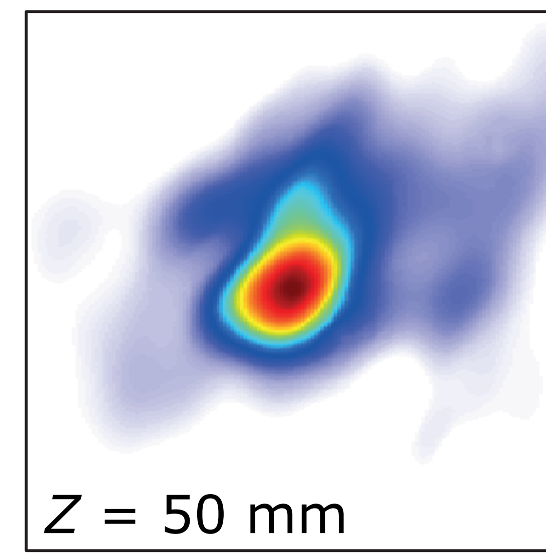
Preliminary results!

100 mm long, low-density HOFI channels

- Experiments performed with Astra-Gemini TA3 laser







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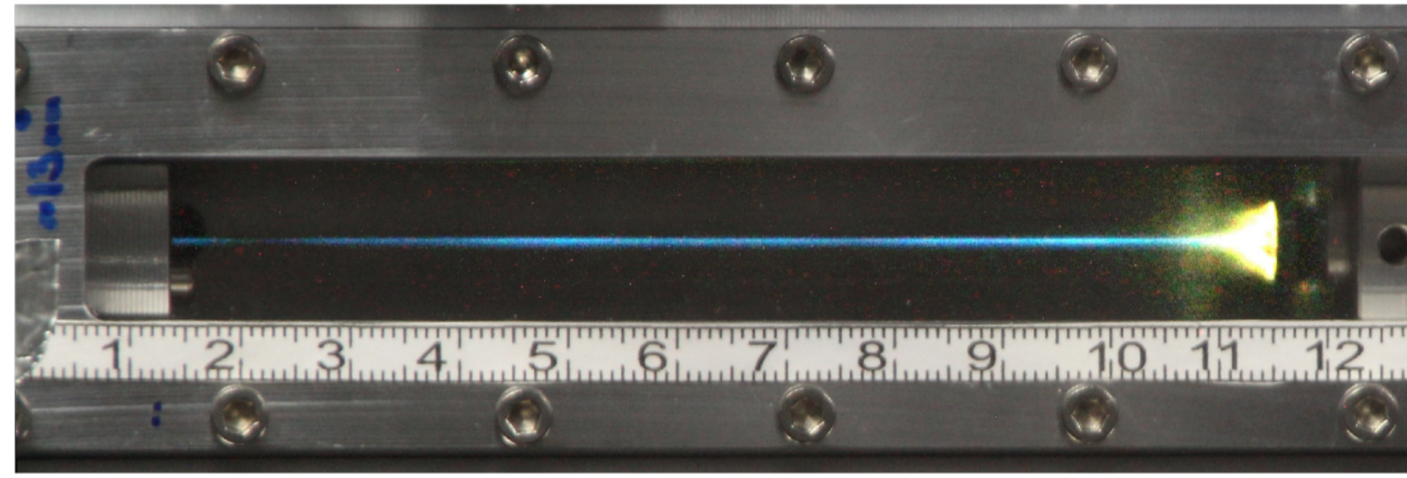
Preliminary results!

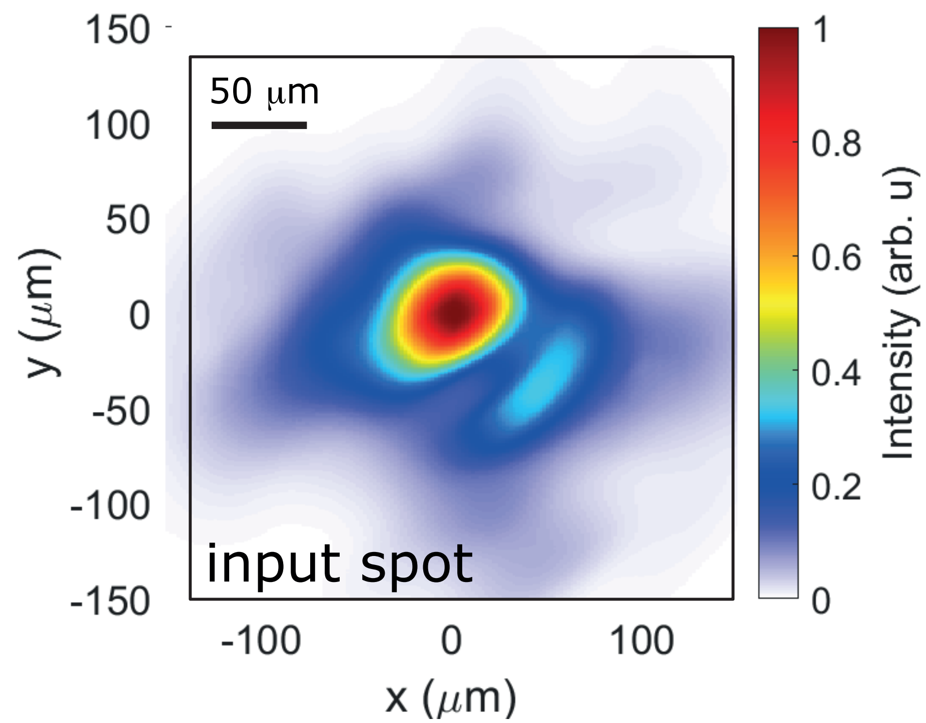
100 mm long, low-density HOFI channels

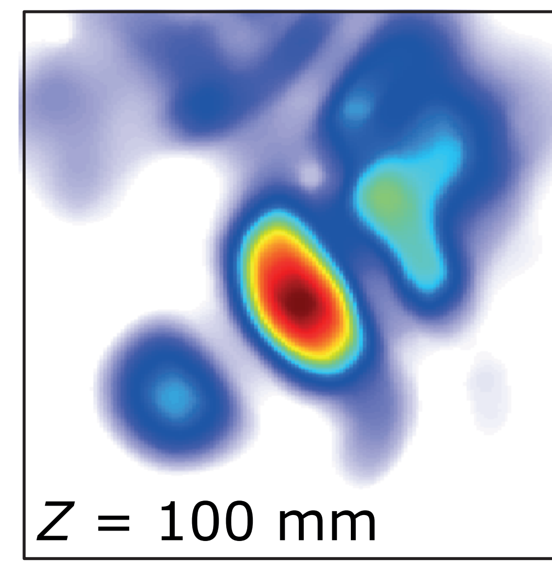
- Experiments performed with Astra-Gemini TA3 laser
- Guiding over 100mm observed
- Interferometry shows $n_e(0) \approx 1 \times 10^{17}$ cm^{-3}
- Power attenuation length $L_{att} \approx 100$ mm



See Alex Picksley's poster
Wed poster 199

See Aimee Ross's poster
Wed poster 189





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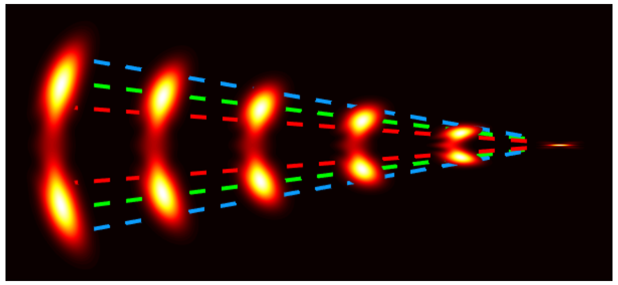
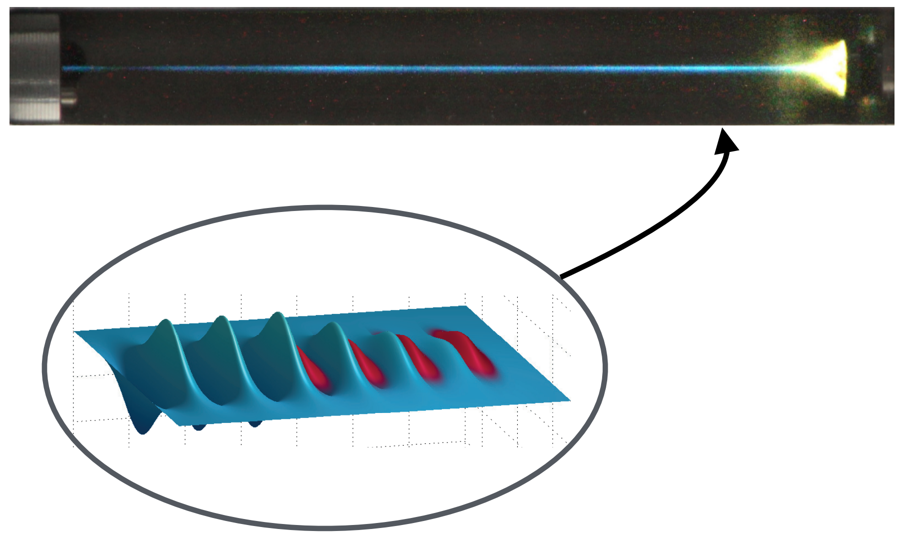
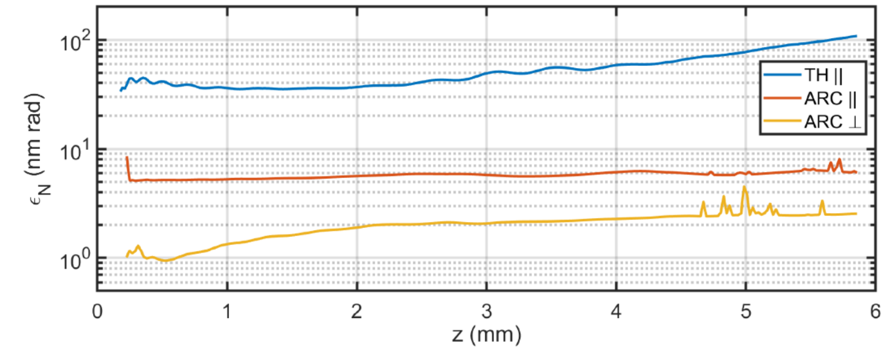
Preliminary results!

Summary







- MP-LWFA:
  - Could be route to high efficiency and high rep-rate
  - Proof-of-principle experiments in good agreement with theory
  - First steps to energy recovery demonstrated
- ARC ionization injection
  - Could allow controlled injection of bunches with sub-10nm emittance & sub 0.1% slice energy spread
- HOFI channels could provide "indestructible" kHz-ready plasma channels with:
  - Lengths of 100s mm
  - $n_e(0) \approx 1 \times 10^{17}$ cm^{-3} & $W_M \approx 10 - 40$ μm