Plasma Acceleration R&D

Simon Hooker

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Outline

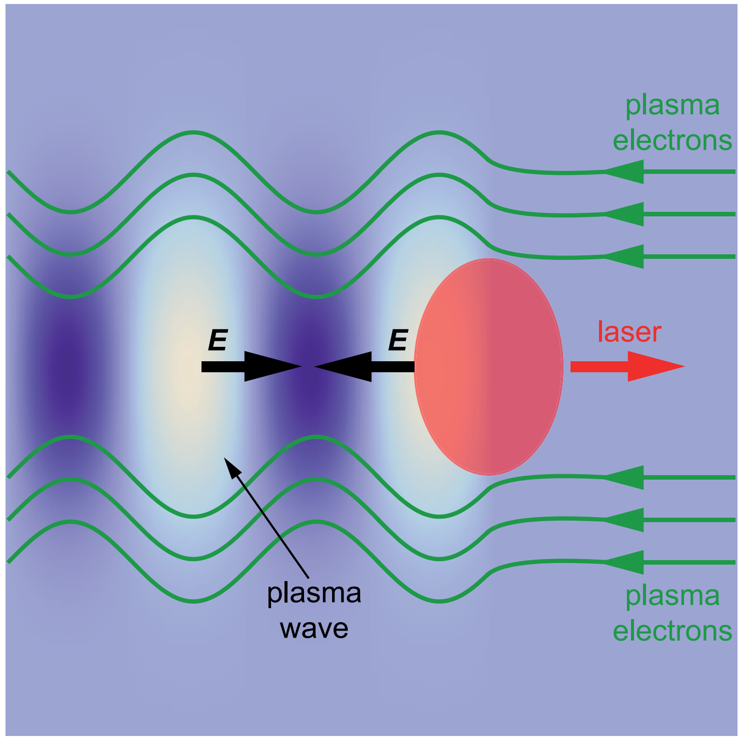
- Very brief introduction to plasma accelerators
- Overview of some recent work in JAI

Oxford-JAI team

Staff	Simon Hooker, Peter Norreys, Roman Walczak
Post-docs	Aarón Alejo, Jimmy Holloway + TBA
Students	Alexander von Boetticher, Jakob Jonnerby, Alex Picksley, Aimee Ross
Visitors	Anthony Dyson
Collaborators	Eric Adli (Oslo), Howard Milchberg (Maryland)
Recent leavers:	Laura Corner (UL @ University of Liverpool) Chris Arran (Post-doc @ University of York) Rob Shalloo (Post-doc @ Imperial College London) Chris Thornton (Rutherford Appleton Laboratory)

Laser-plasma accelerators

- Ponderomotive force of an intense laser pulse expels electrons from the region of the pulse to form a trailing plasma wakefield
- The wakefield moves at speed of laser pulse (close to speed of light)
- Electric fields within wakefield are very large (~ 100 GV / m)



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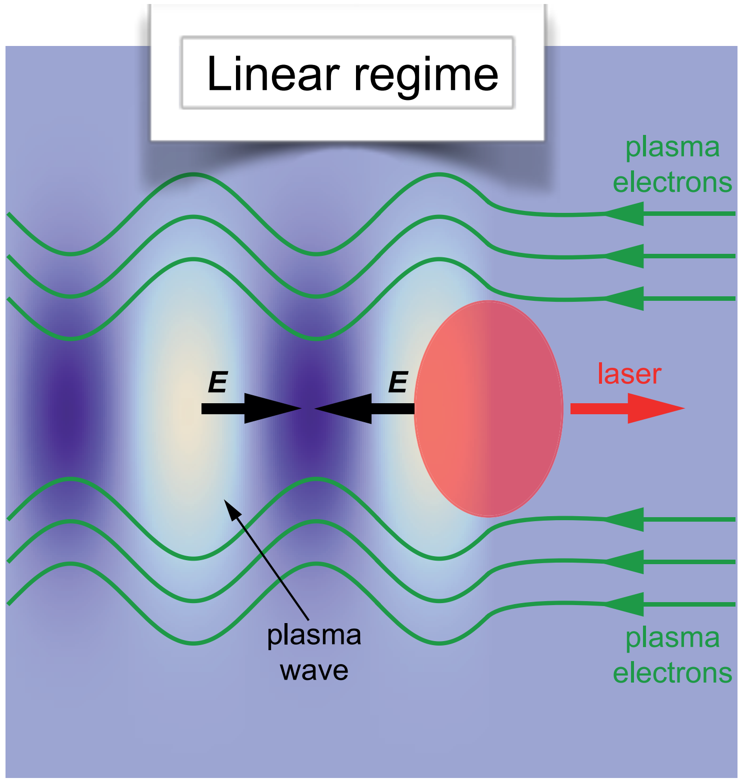
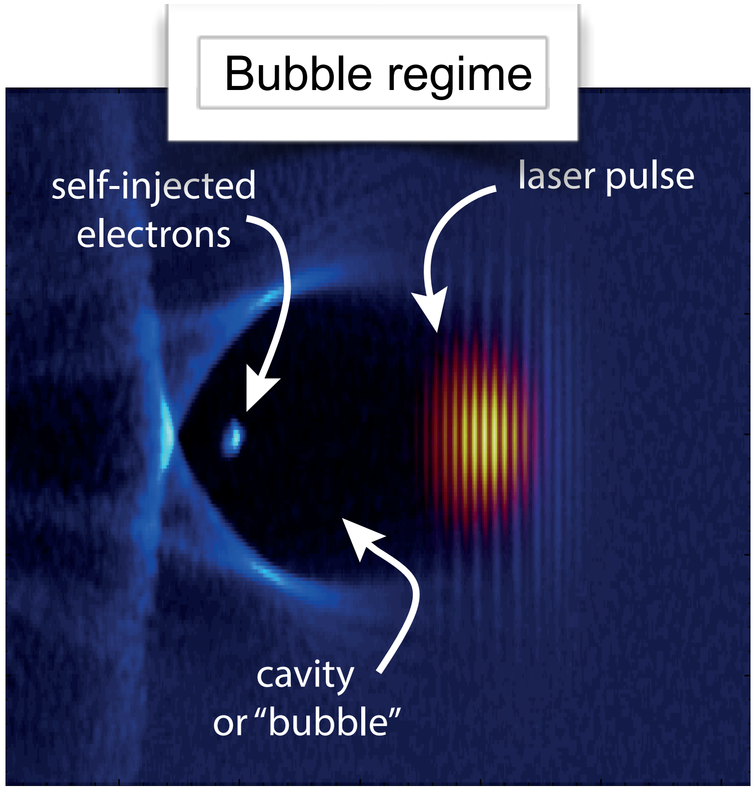


- Linear regime:
  - Driving laser pulse needs external guiding
  - Background electrons cannot be trapped
  - Requires "external" injection
- Nonlinear ("bubble") regime
  - Driving laser pulse self-guided
  - Background electrons can be trapped ("self-trapping")



Current activities

- Plasma acceleration at the energy frontier
- Plasma accelerator staging
- Development of new schemes for efficient, high-rep-rate operation
- Controlled injection
- Development of waveguides for high-intensity driving pulses
- Radiation generation from plasma-accelerated beams
- Ion acceleration
- Particle beam-driven plasma accelerators (AWAKE)
- Development of novel diagnostics
- Development of plasma lenses
- High-field physics
- Applications

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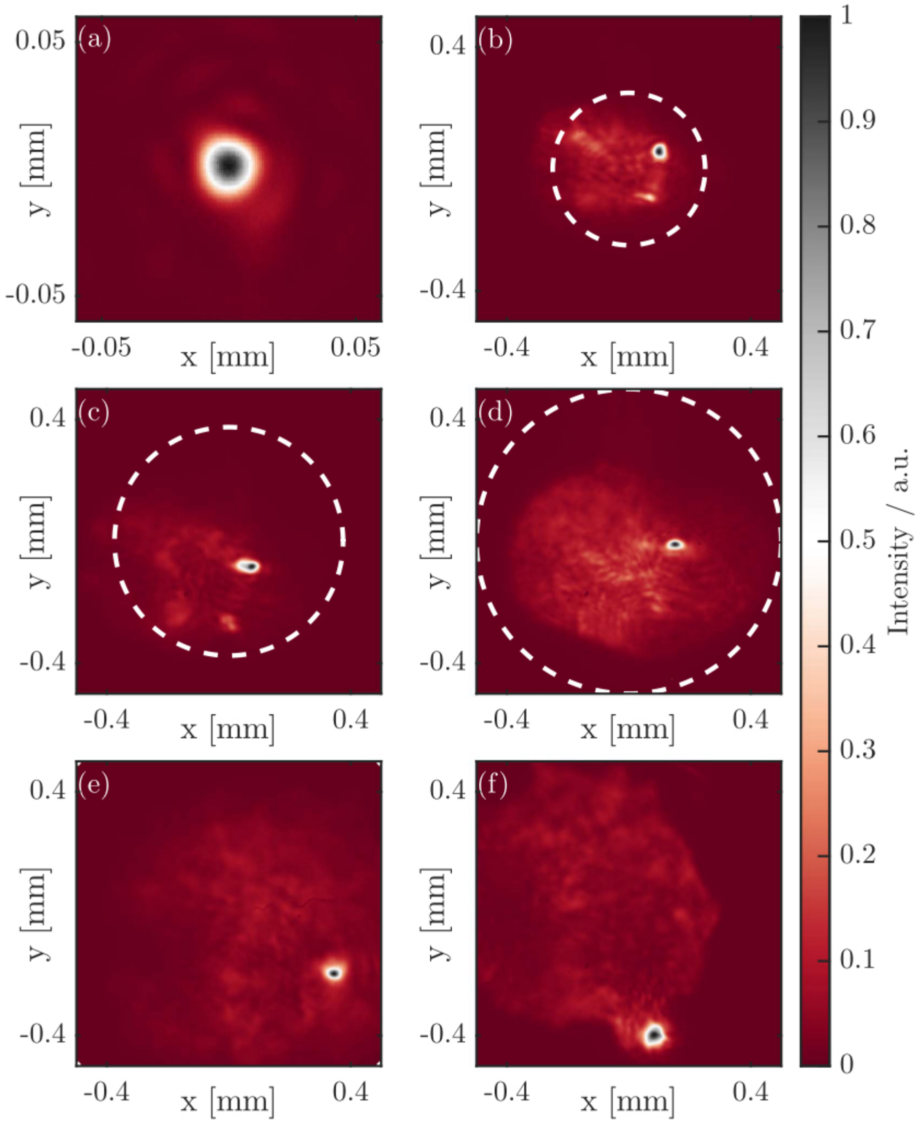
- **Applications**

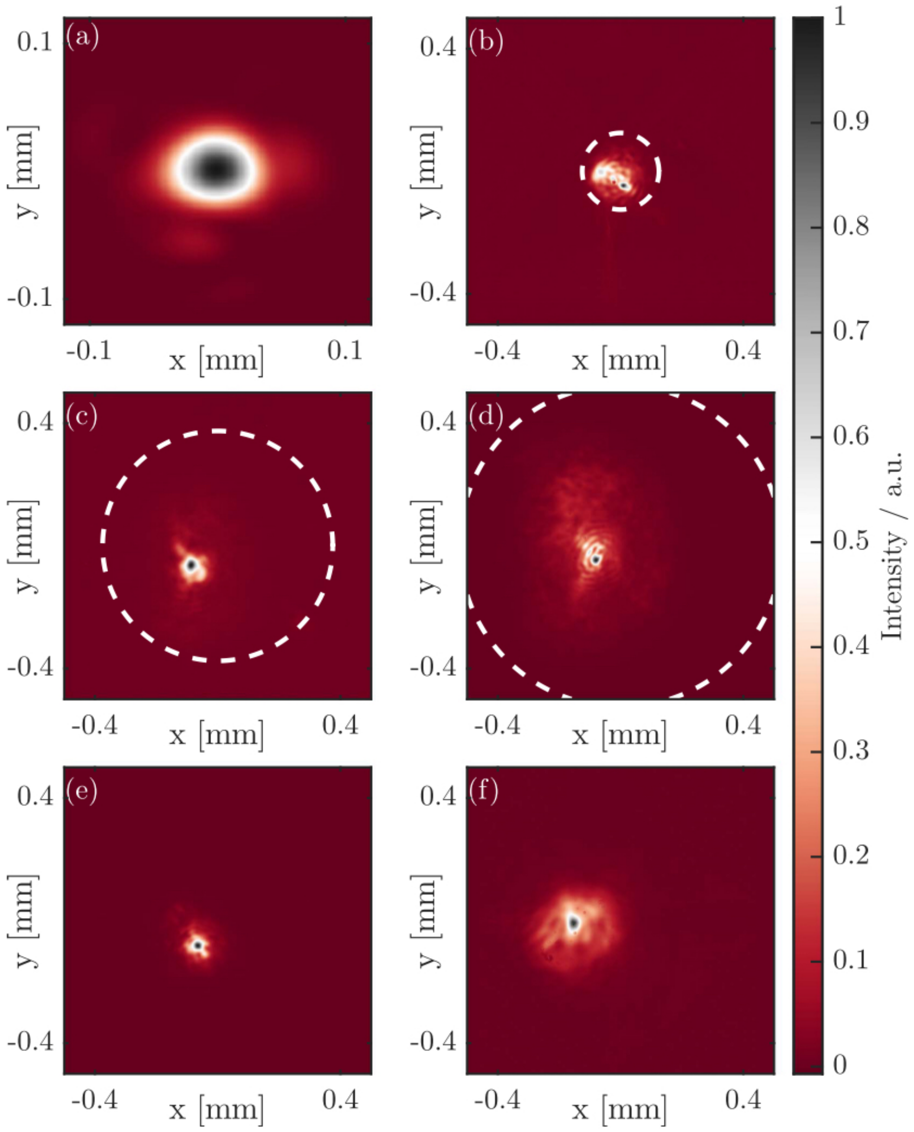
Experiments in self-guiding regime

Self-guiding of Gemini laser measured in gas cells

f/20



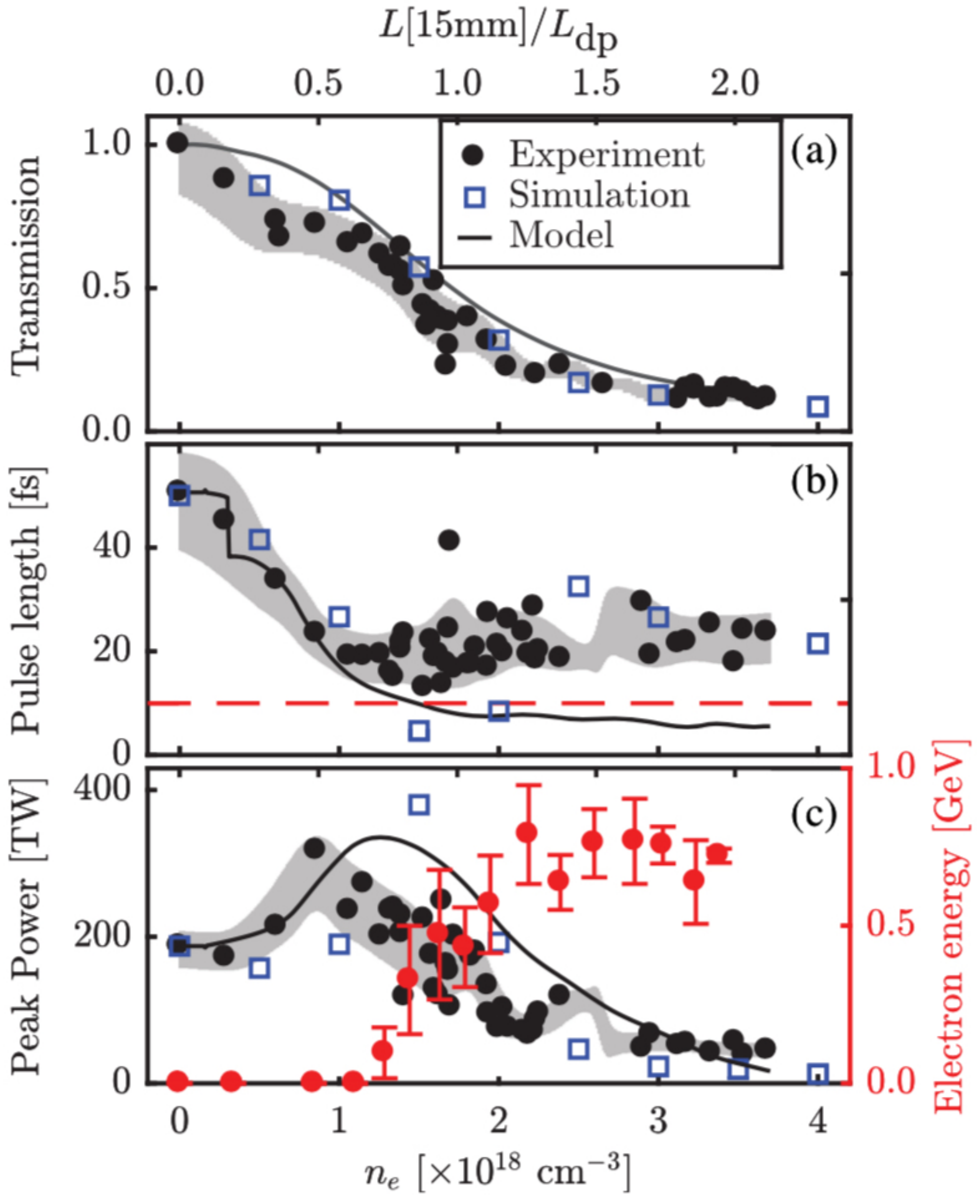
f/40

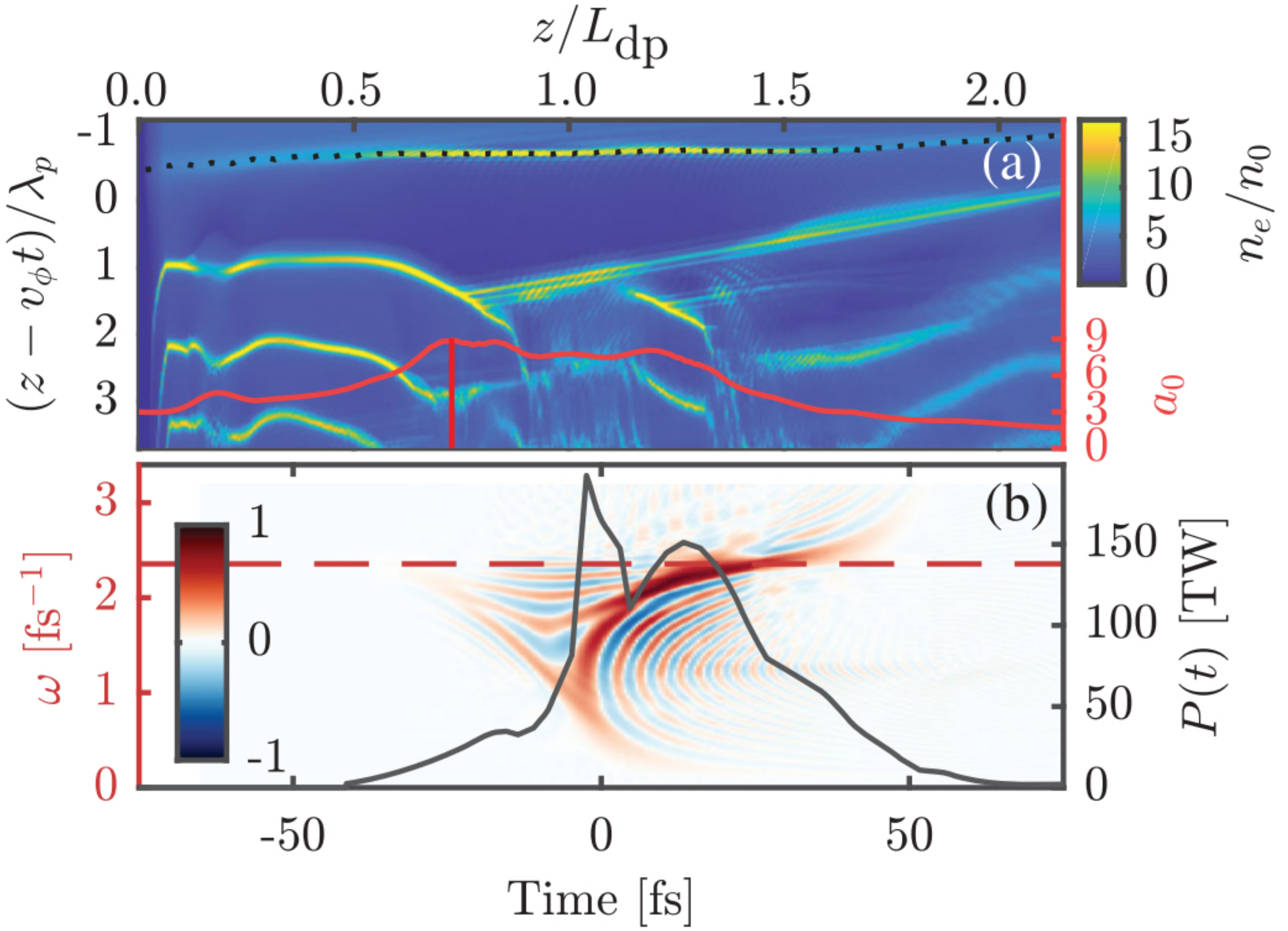


Guided mode is better directed with long (*f*/40) focussing as compared to (*f*/20). Guiding over 9 cm observed.

K. Poder, et al., Measurements of self-guiding of ultrashort laser pulses over long distances, Plasma Phys. Control. Fusion 60, (2018).

Power amplification of LWFA driver observed:



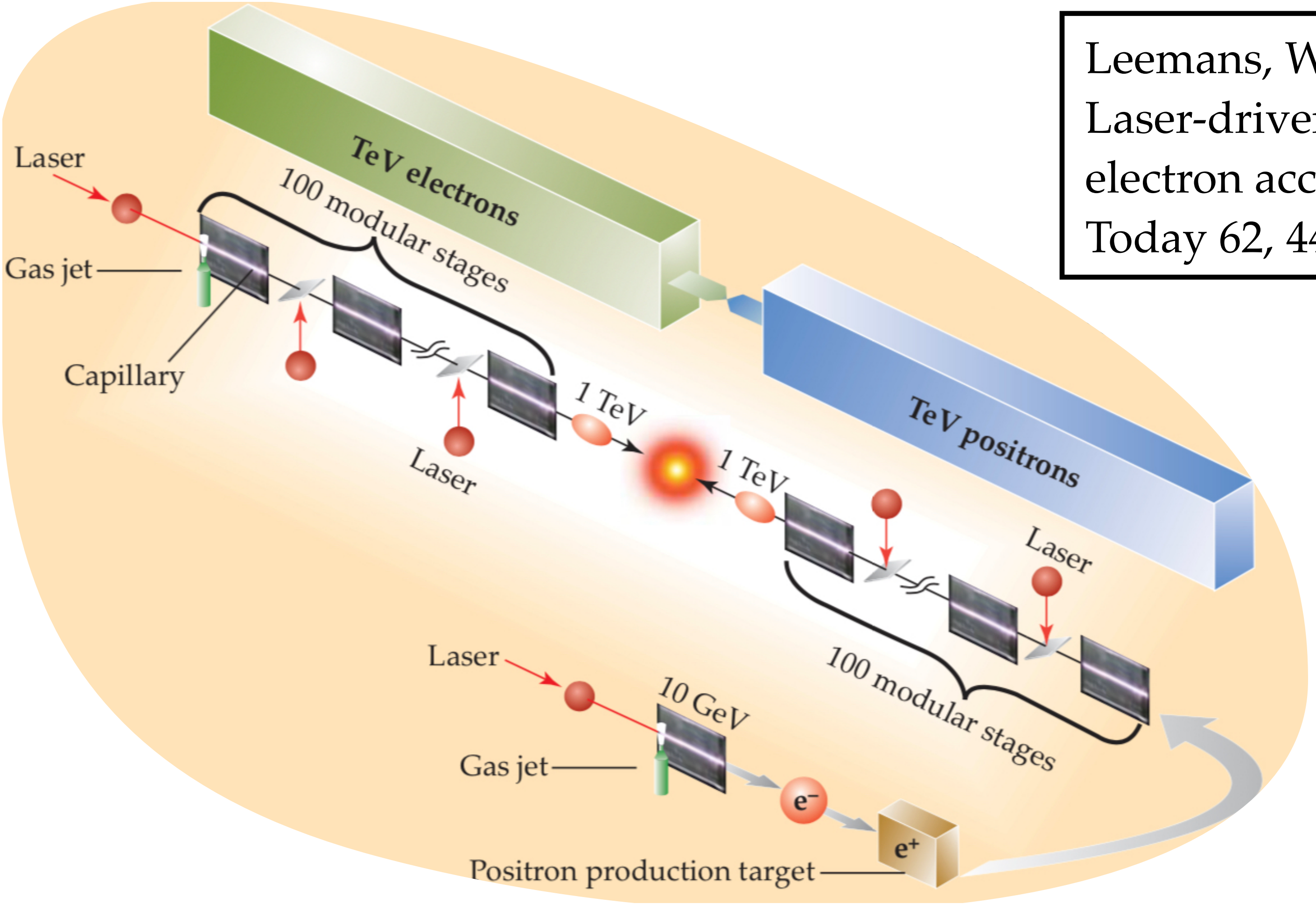


Explained by redshifting and phase slippage of driver

M. J. V. Streeter et al, Observation of Laser Power Amplification in a Self-Injecting Laser Wakefield Accelerator, Phys. Rev. Lett. 120, 254801 (2018).

Plasma accelerator staging

Staging of laser wakefield accelerators



Leemans, W. & Esarey, E. Laser-driven plasma-wave electron accelerators. Phys. Today 62, 44–49 (2009).

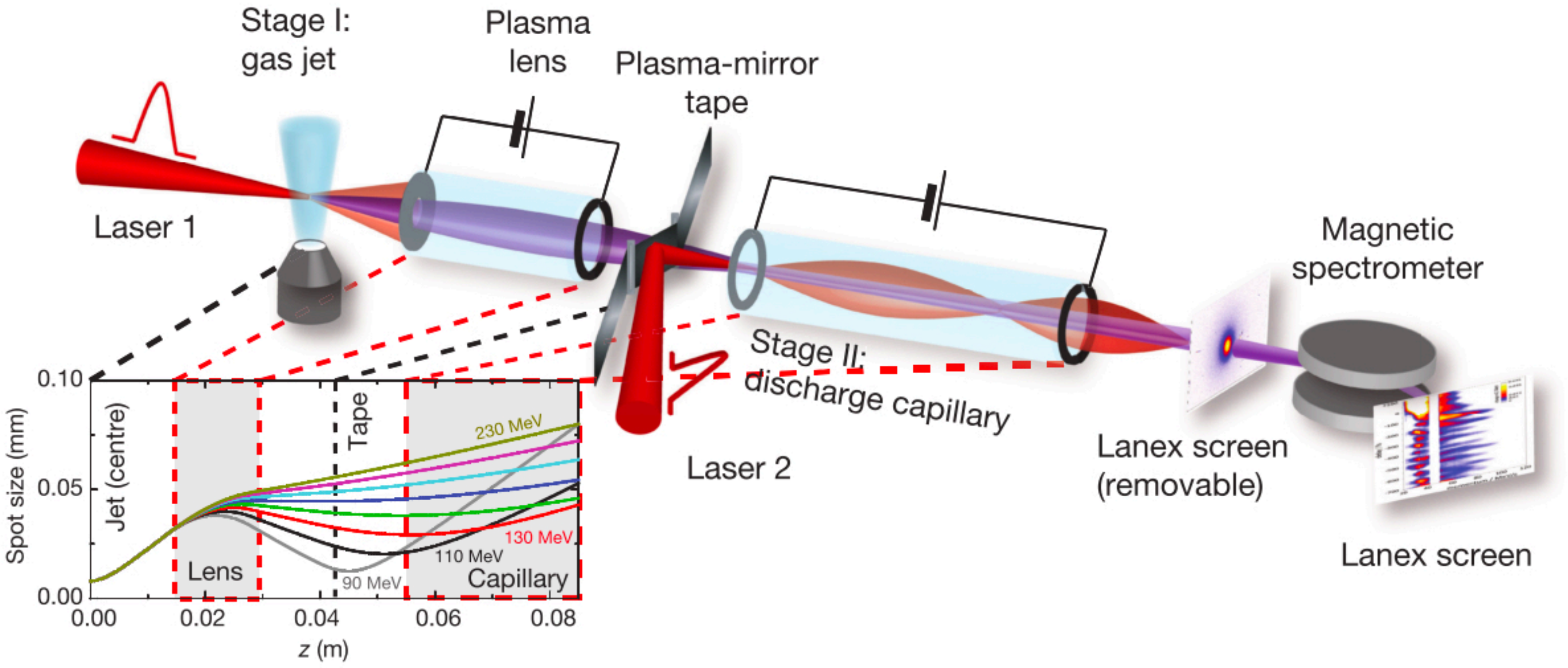
$$\Delta W \propto \frac{1}{n_e}$$

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

- Length of single stage: $L \propto \Delta W^{3/2}$
- Length of focussing optic for optimal self-guiding: $f \propto L \propto \Delta W^{3/2}$
  - e.g. 10 GeV: $L \approx 2$m, $f \approx 60$ m
  - 100 GeV: $L \approx 60$ m, $f \approx 600$ m
- Accelerator could be much more compact by using multiple stages, especially if focussing is not collinear

Staging: existing work

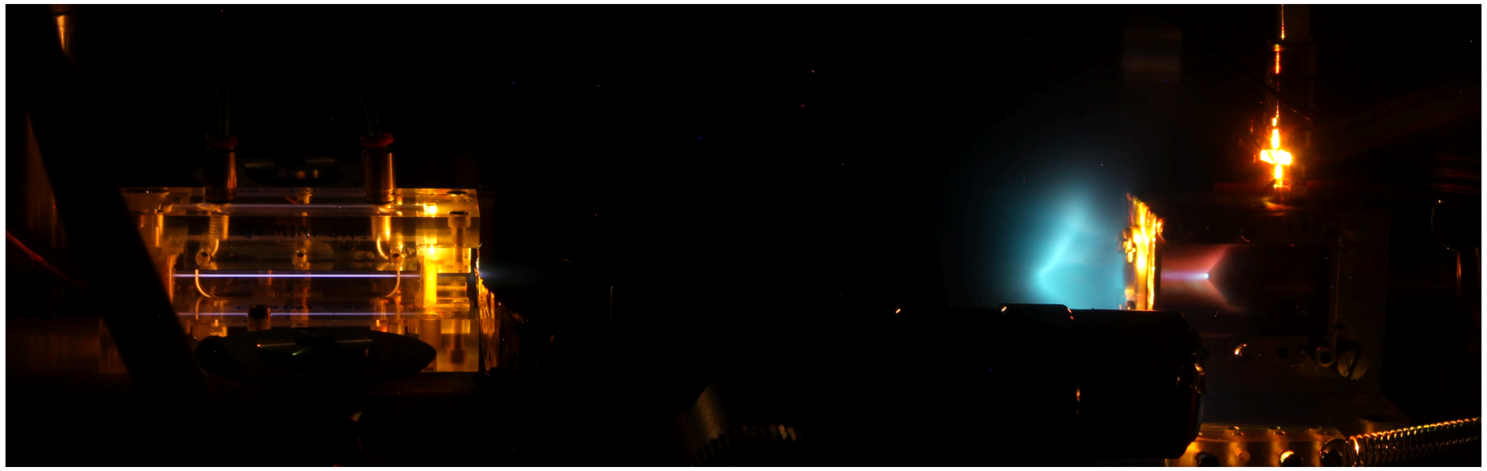
LBNL have demonstrated staging at low energies (~200 MeV increased to ~300 MeV).

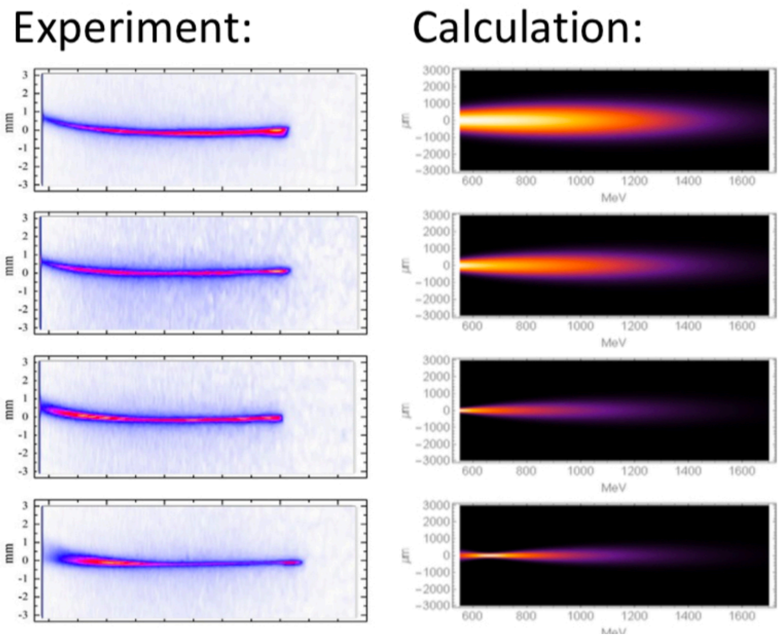


Steinke, S. et al. Multistage coupling of independent laser-plasma accelerators. Nature 530, 190–193 (2016).

Van Tilborg, J. et al. Active Plasma Lensing for Relativistic Laser-Plasma-Accelerated Electron Beams. Phys. Rev. Lett. 115, 184802 (2015).

They have pioneered the use of plasma focussing elements.

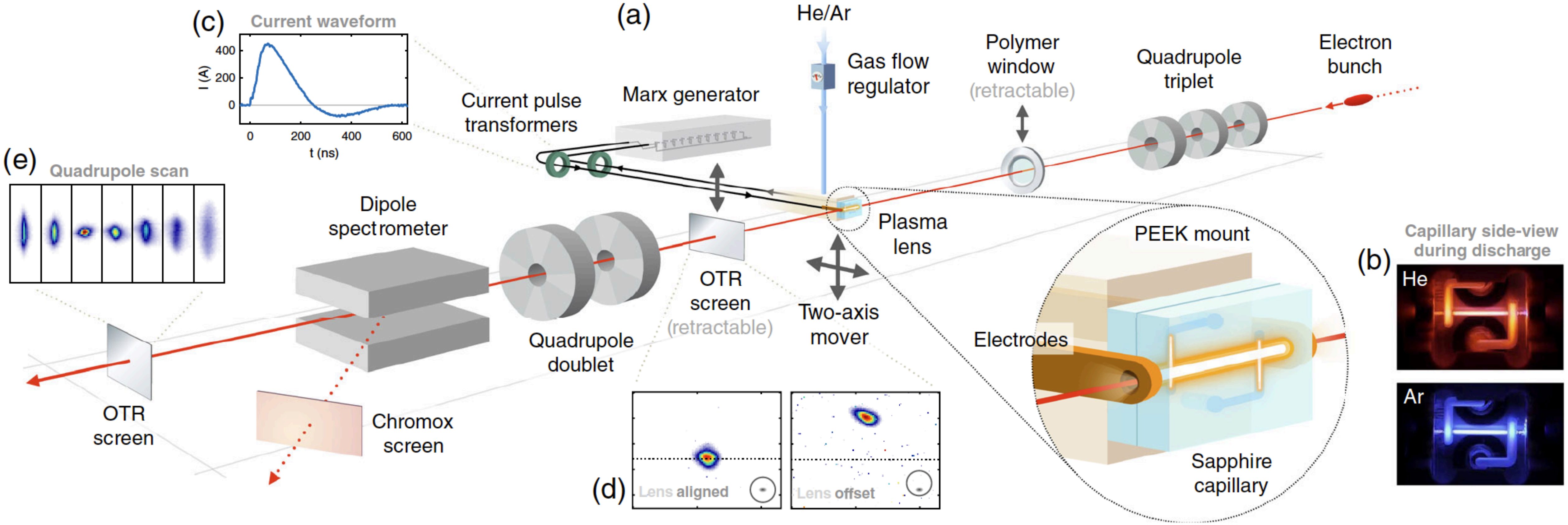




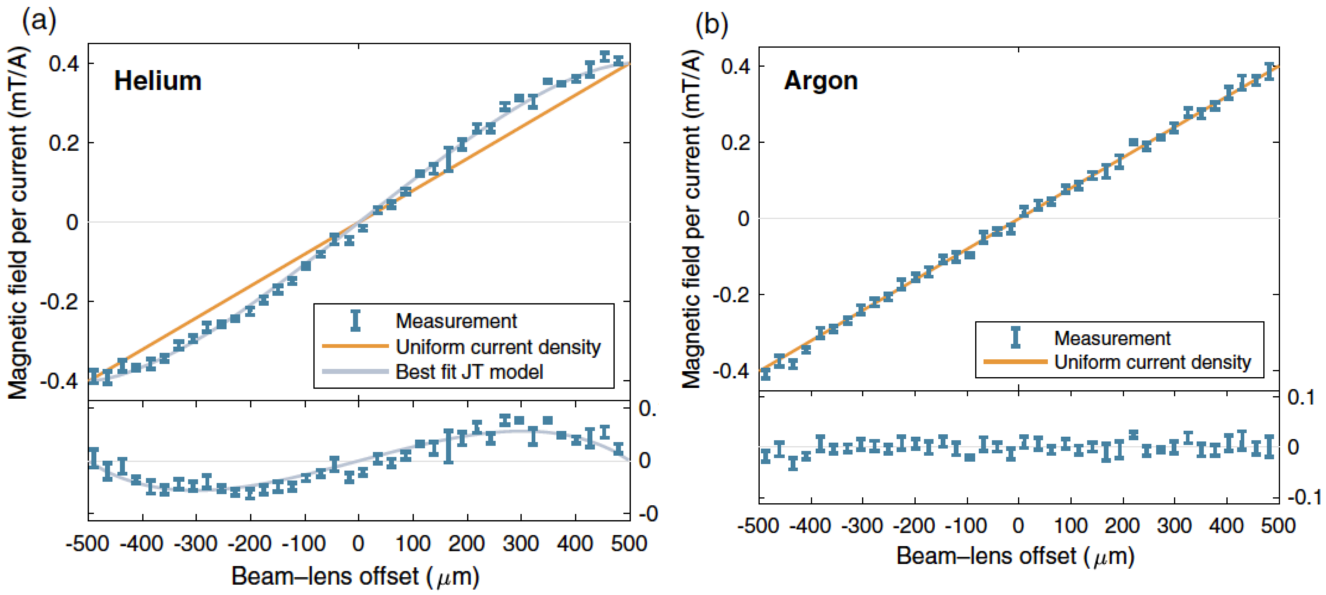
Here installed on a joint QUB / ICL / LBNL experiment on Astra Gemini (Dec 2017) focussing at up to 1 GeV

CLEAR results

C. A. Lindstrøm *et al.* *Phys Rev Lett* **121** 194801 (2018)

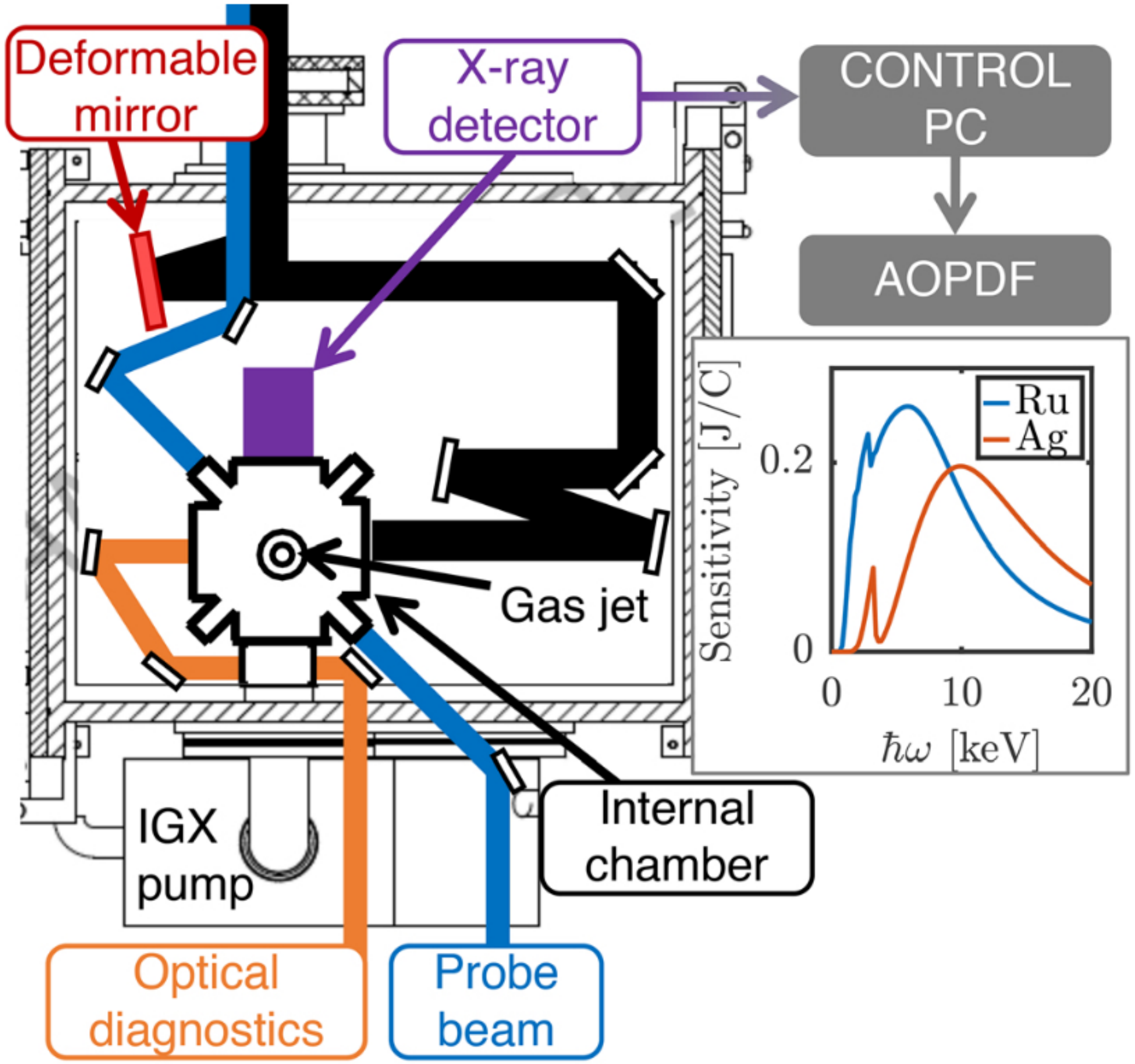


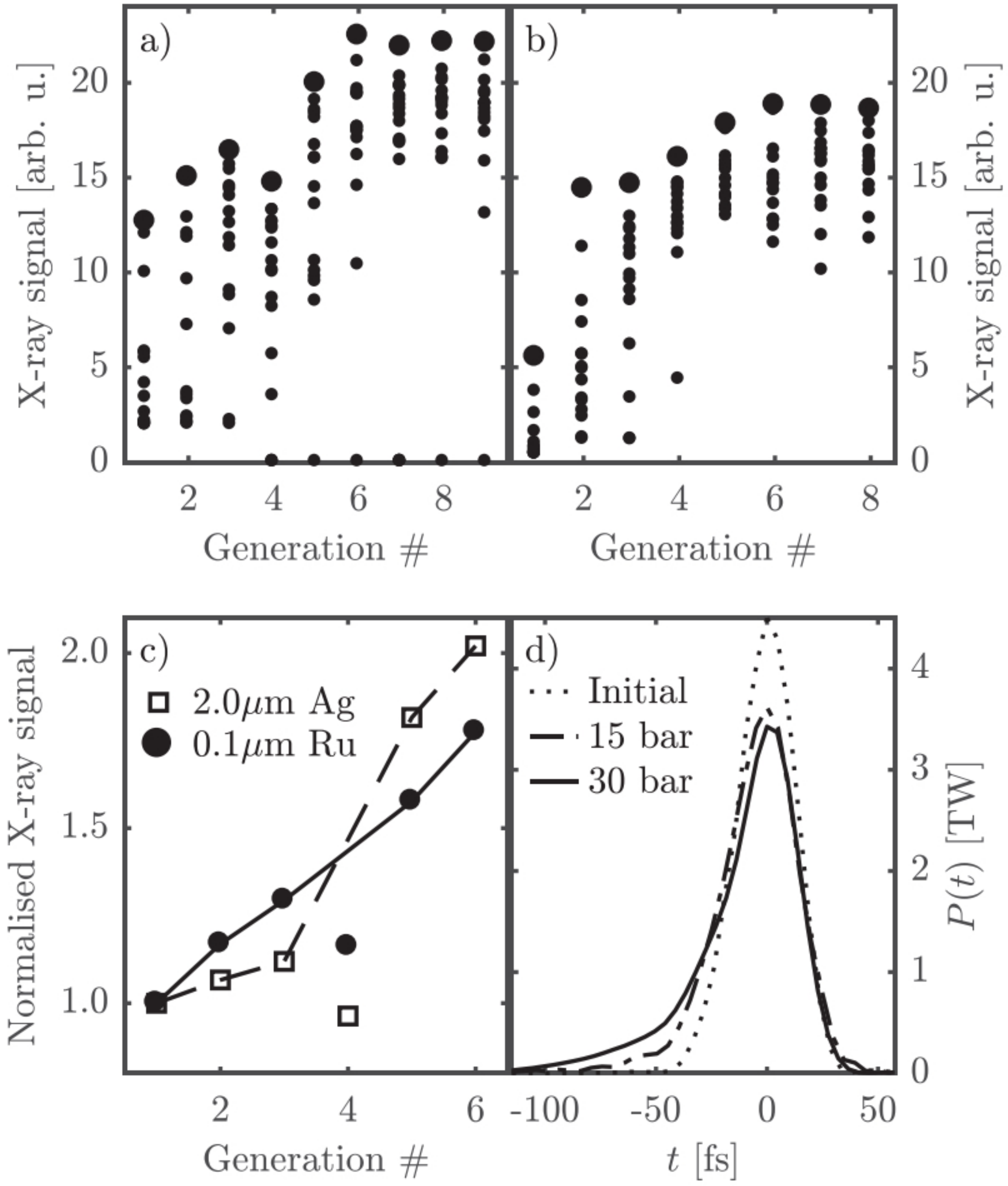
- APLs can provide kT/m focusing fields
- But, previous work shows that non-uniform temperature profile leads to aberrations
- Experiments at CLEAR facility (led by Erik Adli) demonstrated that this can be suppressed by using a heavier gas (Ar instead of He)



High-repetition rate operation

Operation of high intensity Astra TA2 facility at 5 Hz





Optimisation of x-ray emission from clusters, but also applied to LWFA

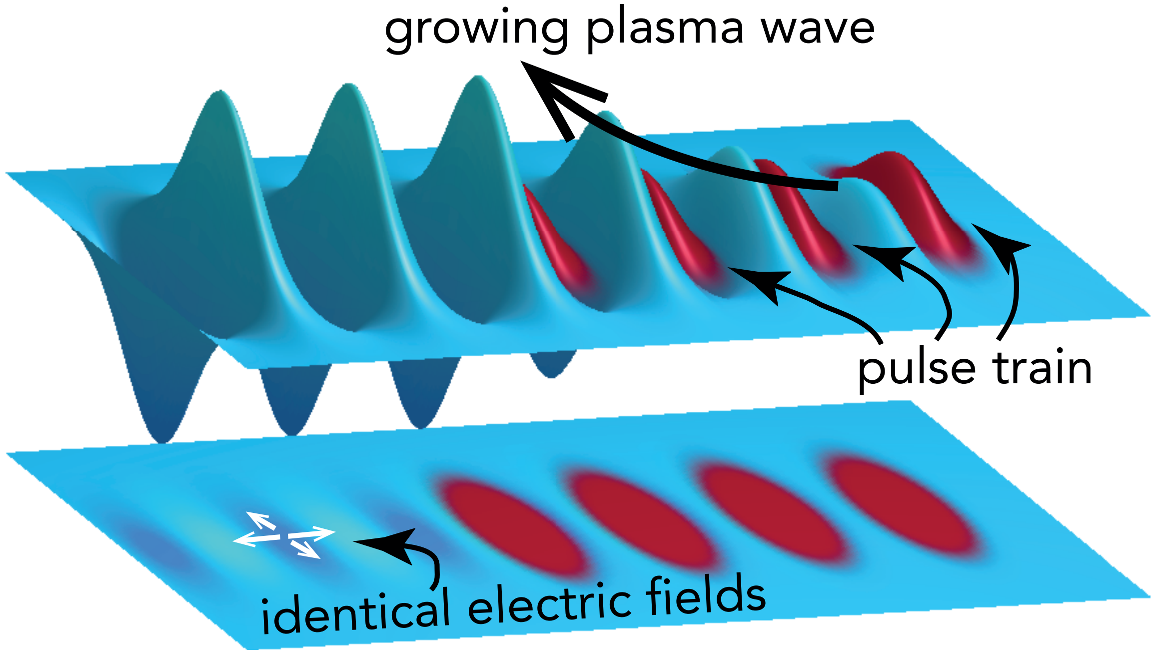
M. J. V. Streeter , et al. Temporal feedback control of high-intensity laser pulses to optimize ultrafast heating of atomic clusters, Appl. Phys. Lett. 112, 244101 (2018).

John Adams Institute for Accelerator Science

Multi-pulse laser wakefield acceleration

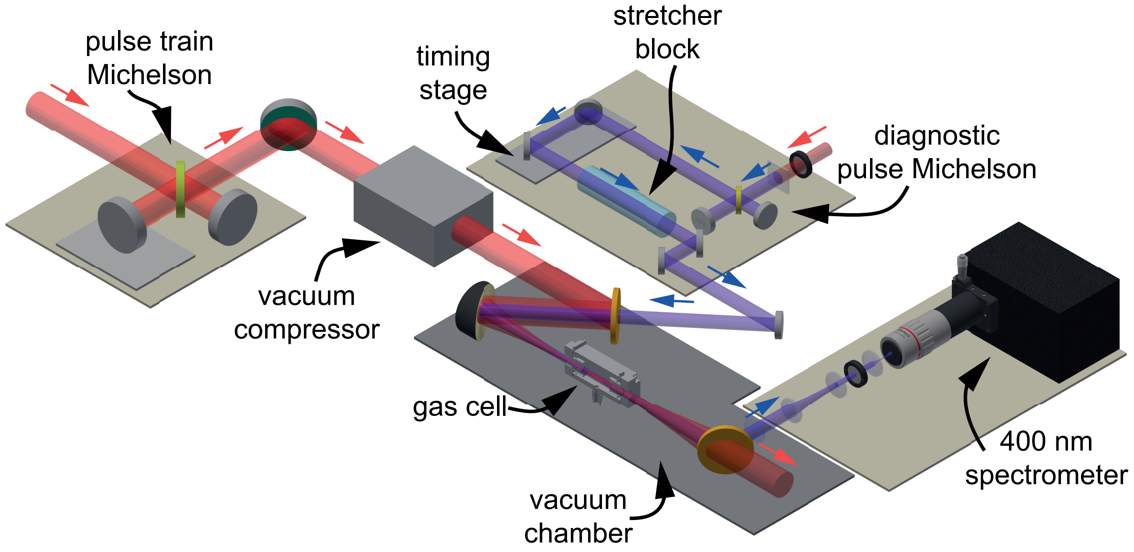
S.M. Hooker *et al.* *J. Phys. B* **47** 234003 (2013)

- Excite wakefield with train of low-energy laser pulses
- Resonant excitation if pulse spacing matched to plasma period
- Allows use of different laser technologies
  - Multi-kHz repetition rates?
  - Laser wall-plug efficiency > 10% ?
- Potential for additional control over wake excitation
- Natural architecture for “energy recovery”



Multi-pulse LWFA
Only 4 laser pulses shown. In reality would use 10 - 100!

MP-LWFA: Astra TA2 experiments

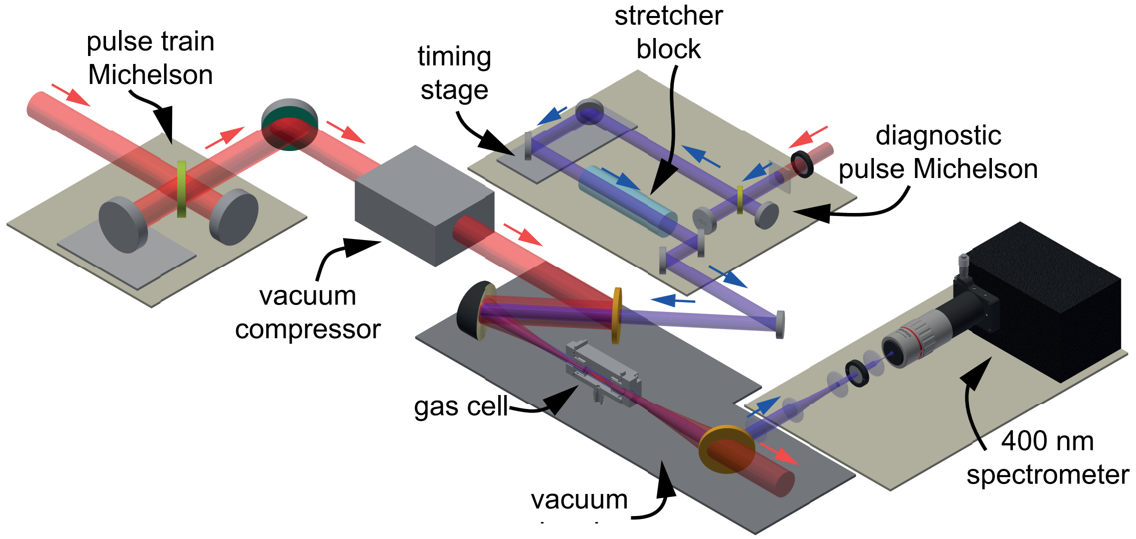


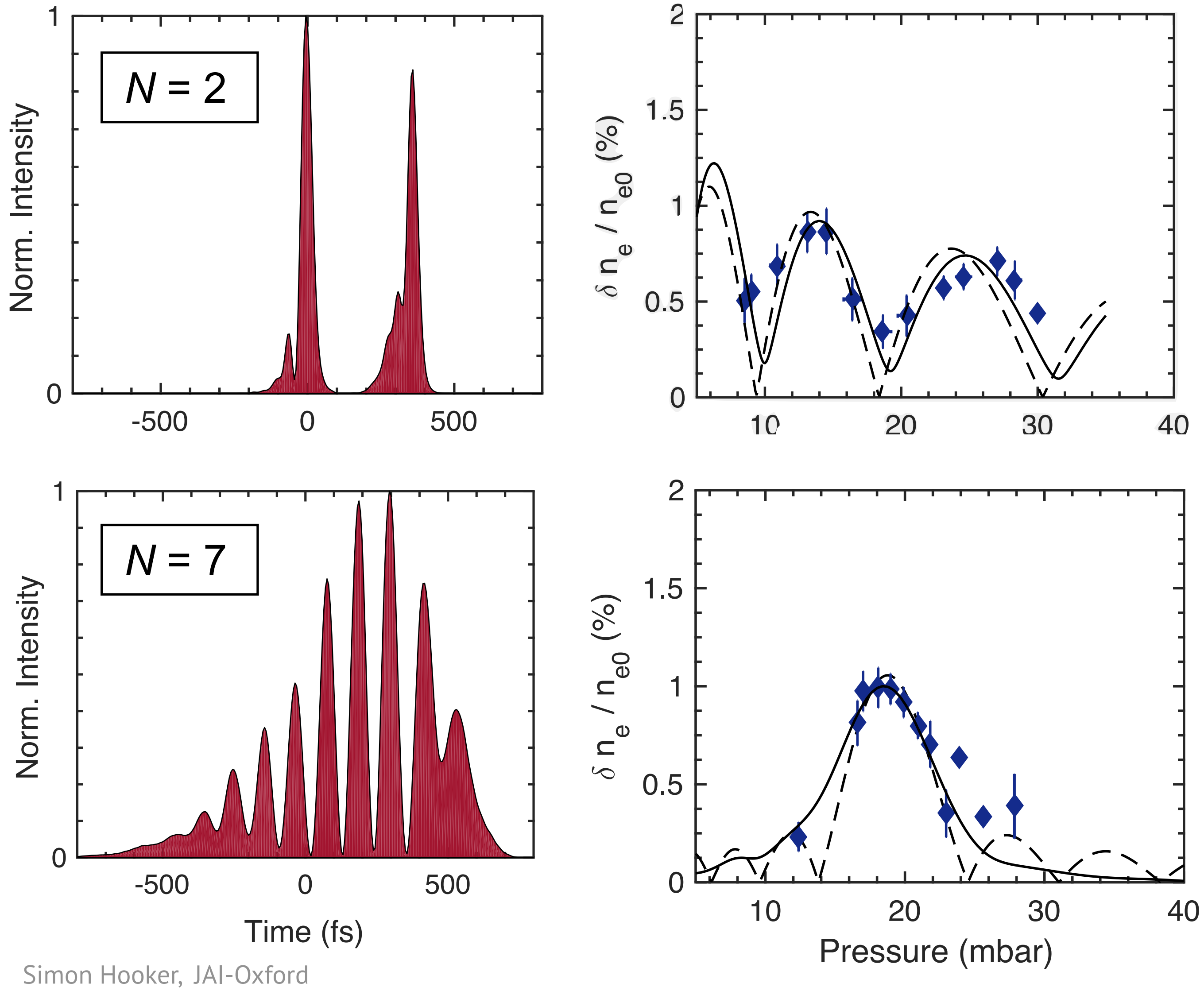
J. Cowley *et al. Phys. Rev. Lett.* **119** 044802 (2017)

- Expts with Astra-Gemini (TA2) laser at RAL
- Convert **single** 500 mJ, 40 fs Ti:sapphire pulses into train of 10 - 50 pulses
- Wakefield measured by Frequency-domain holography & TESS

MP-LWFA: Astra TA2 experiments

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





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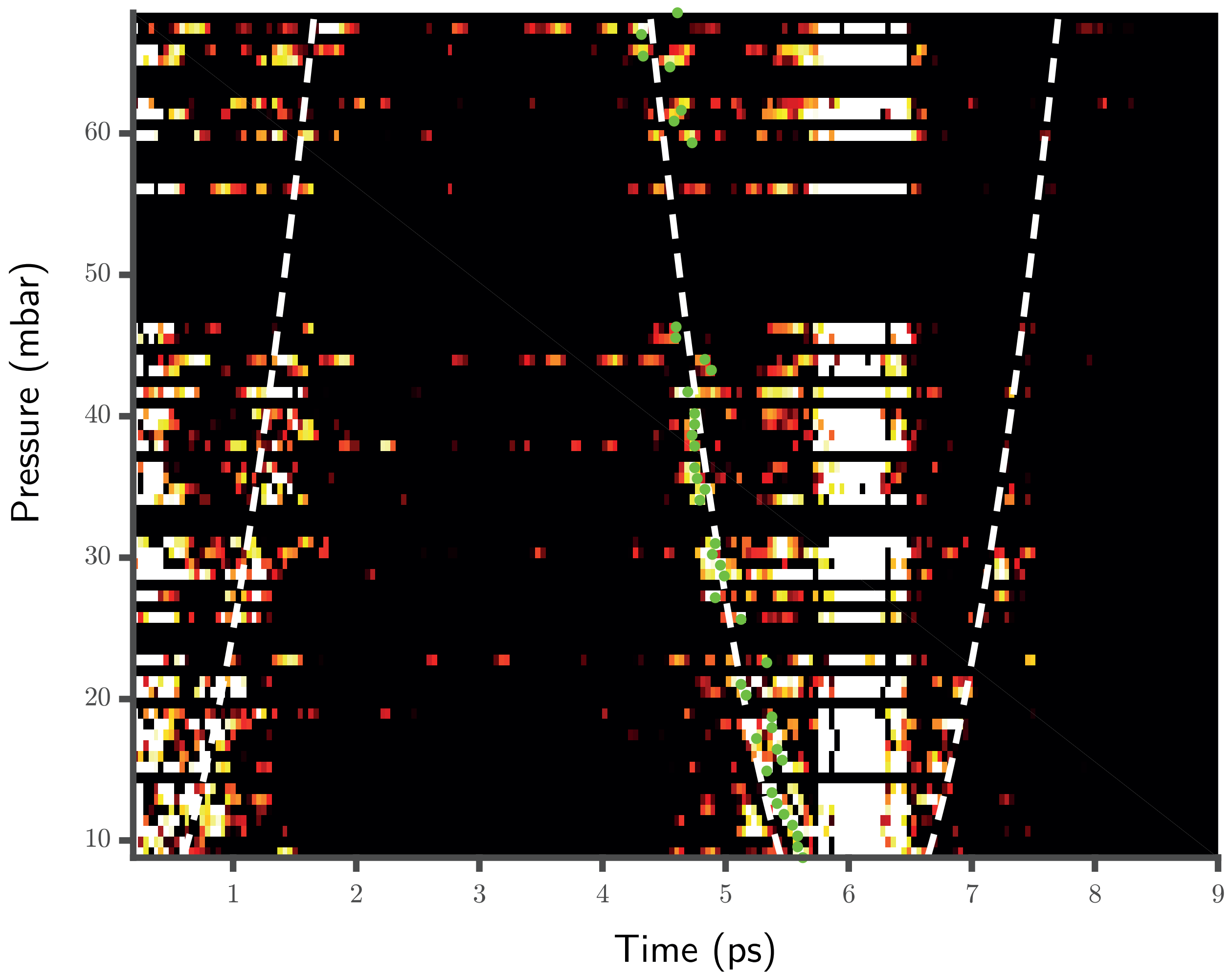
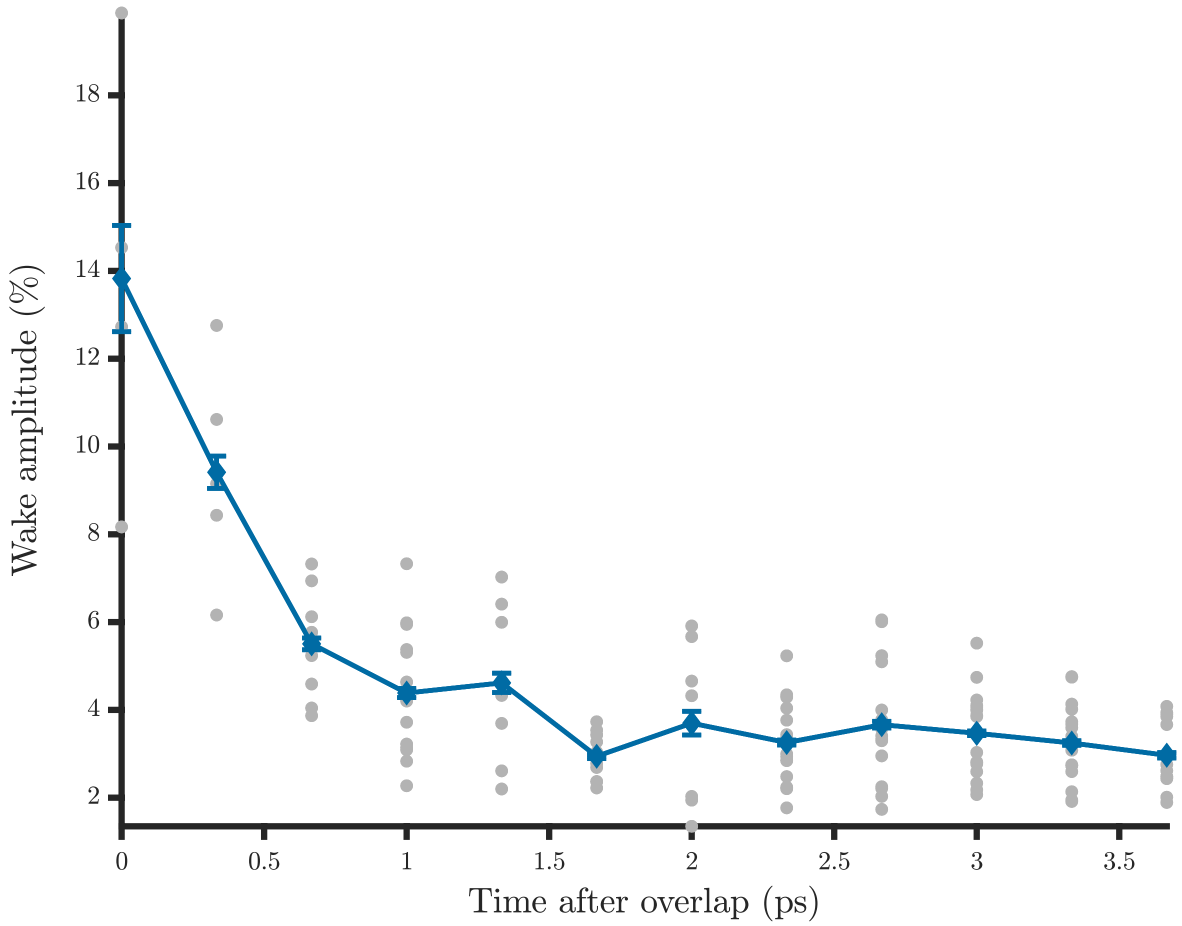
$$\frac{\delta n_e}{n_{e0}} = \left[\frac{\delta n_e}{n_{e0}}\right]_{N=1} \times \frac{\sin\left(\frac{1}{2}N\omega_{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{p0}\delta\tau\right)}$$

- Measured wakefields are in excellent agreement with analytic theory
- *N* = 2 results are first step to **energy recovery!**
- Resonant excitation clearly observed

MP-LWFA: Gemini TA3 experiments

- Experiment performed Sep 2018
- Wakefield diagnostics demonstrated with Gemini for first time …
- … but technical problems prevented most objectives from being achieved
- Tomorrow (!) will submit bid for more beam time





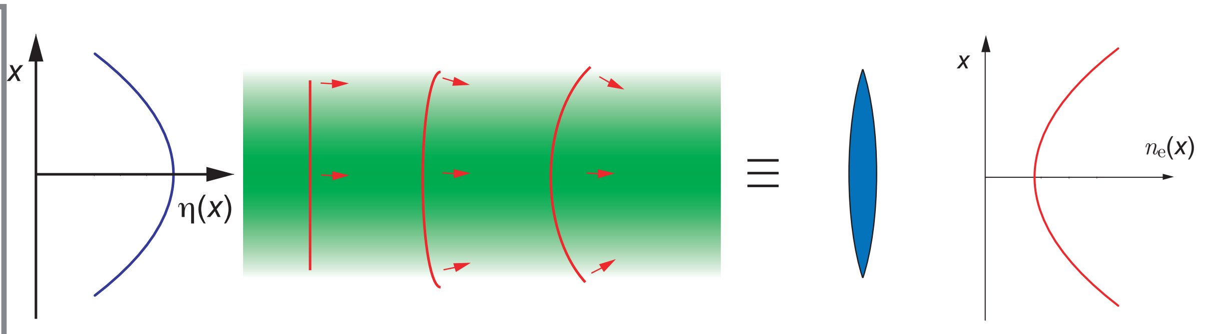
Preliminary analysis !

Development of low-density plasma waveguides

Motivation

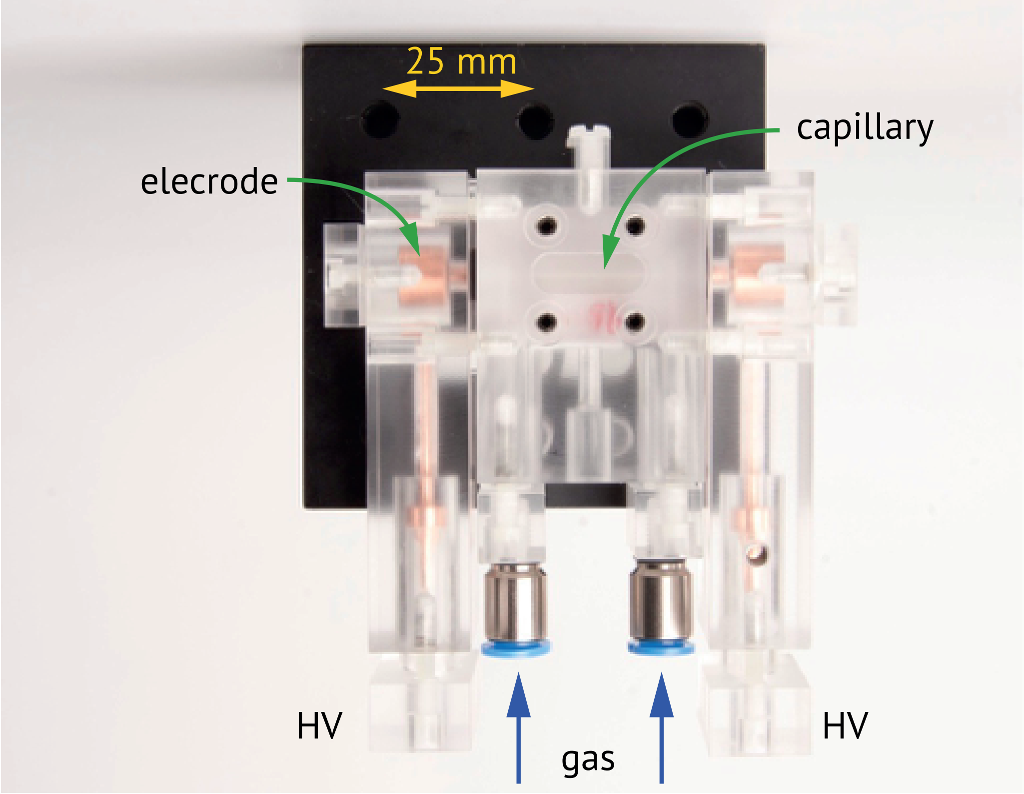
$$\Delta W \propto \frac{1}{n_e}$$

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



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

- Scaling from 1 GeV to 10 GeV requires:
  - a decrease in plasma density by factor ~ 10 ($n_e \approx 10^{18}$ cm^{-3} → $n_e \sim 10^{17}$ cm^{-3})
  - an increase in length by factor ~ 30 ($L \approx 10$ mm → $L \approx 300$ mm)
- In addition, we would like to operate:
  - At high repetition rates (kHz)
  - For extended periods without damage to waveguide
  - 8 hours @ 1 kHz = 30 million shots!

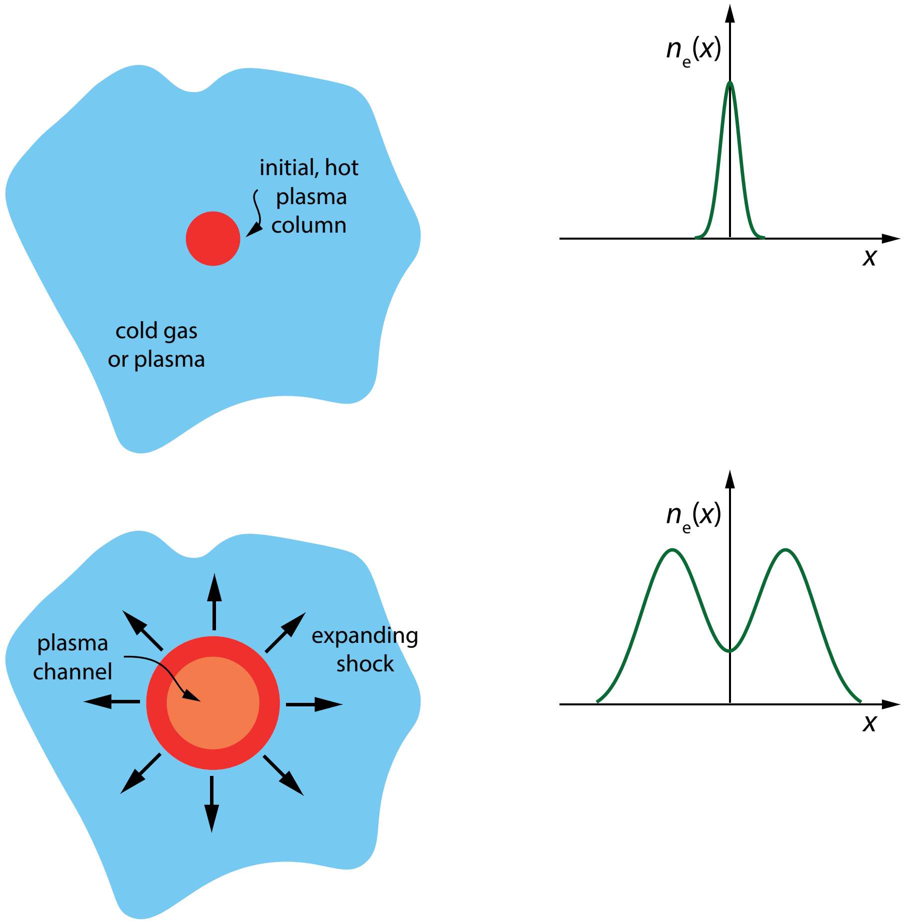


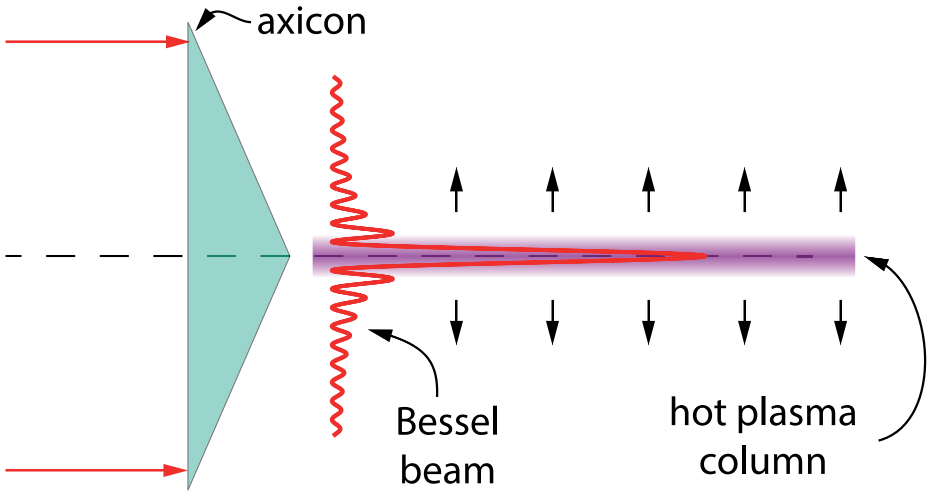
Hydrodynamic plasma waveguides

- Create & heat column of hot plasma
- Expansion into surrounding cold gas / plasma drives cylindrical blast wave
- Plasma channel formed within expanding shell

- To date, plasma column has been **heated collisionally**:
  - Durfee & Milchberg, *PRL* **71** 2409 (1993)

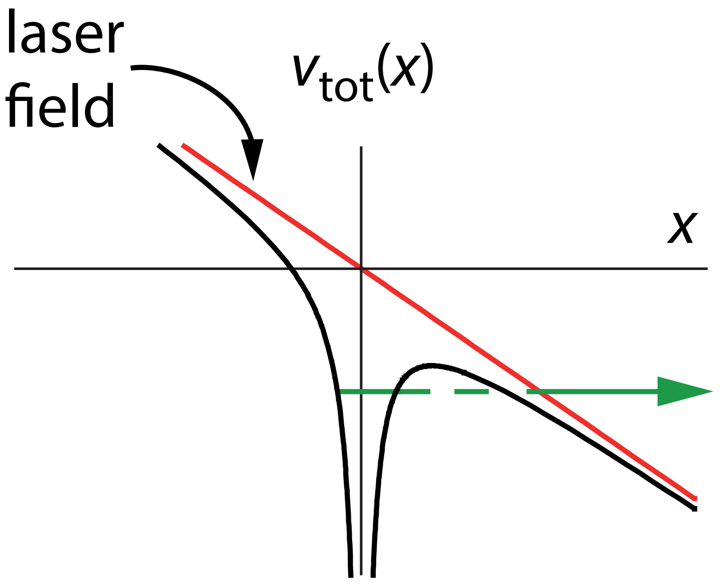
- **Requires high density** for fast heating
  - Limits axial density to ~ 10^{18} cm^{-3}

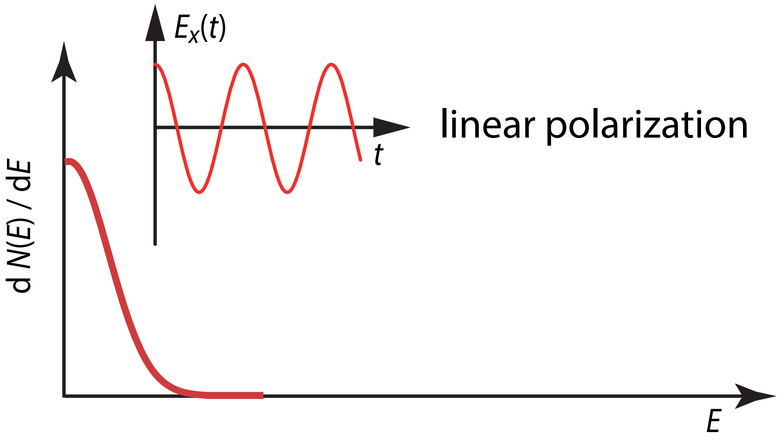


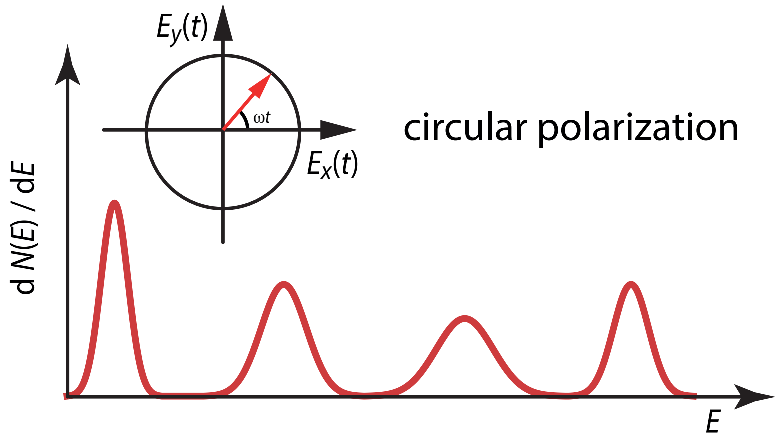


Hydrodynamic, OFI (HOFI) plasma channels

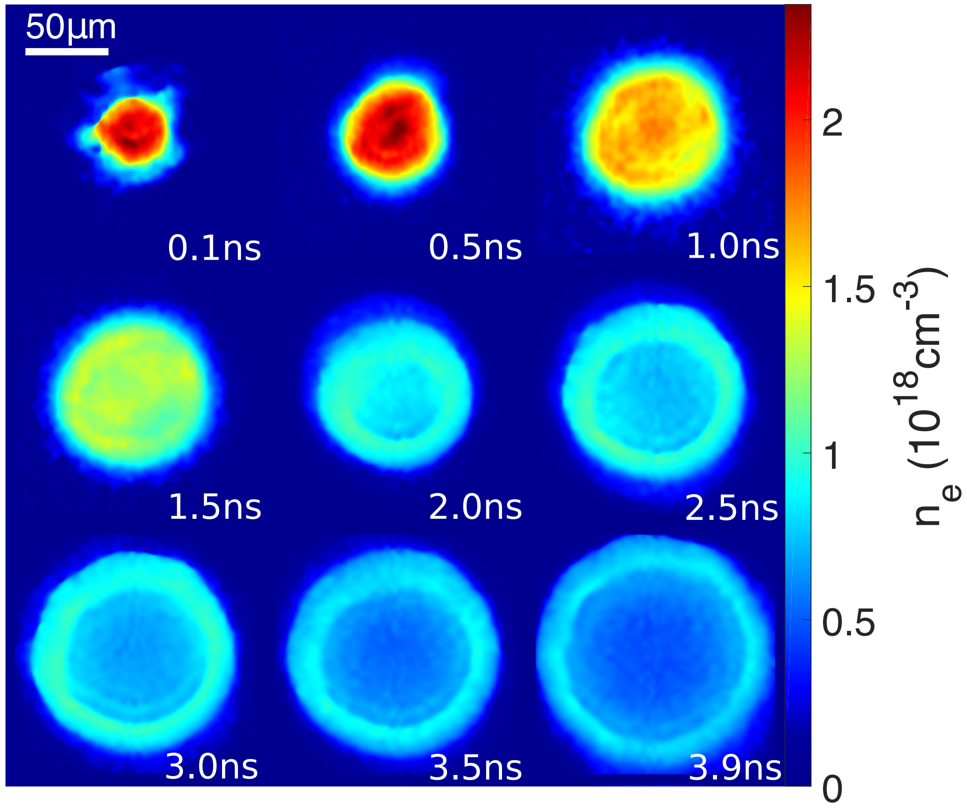
R.J. Shalloo *et al.* *Phys Rev E* **97** 053203 (2018)





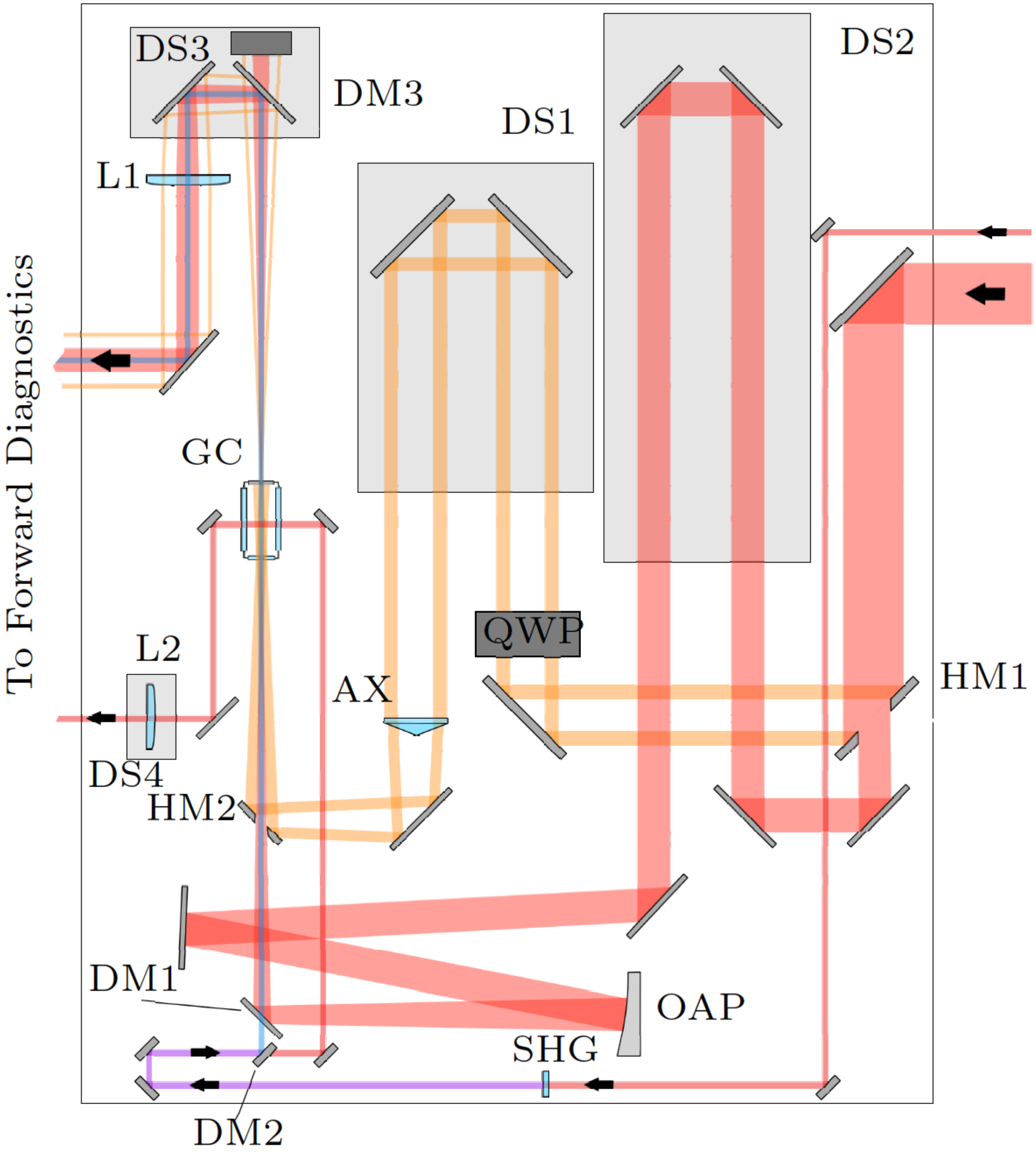


- Optical field ionization gives
  - Hot electrons & cold ions
  - Electron energy controlled by polarization
- Heating independent of density ⇒ low density channels
- Tests with spherical lens demonstrated channel formation



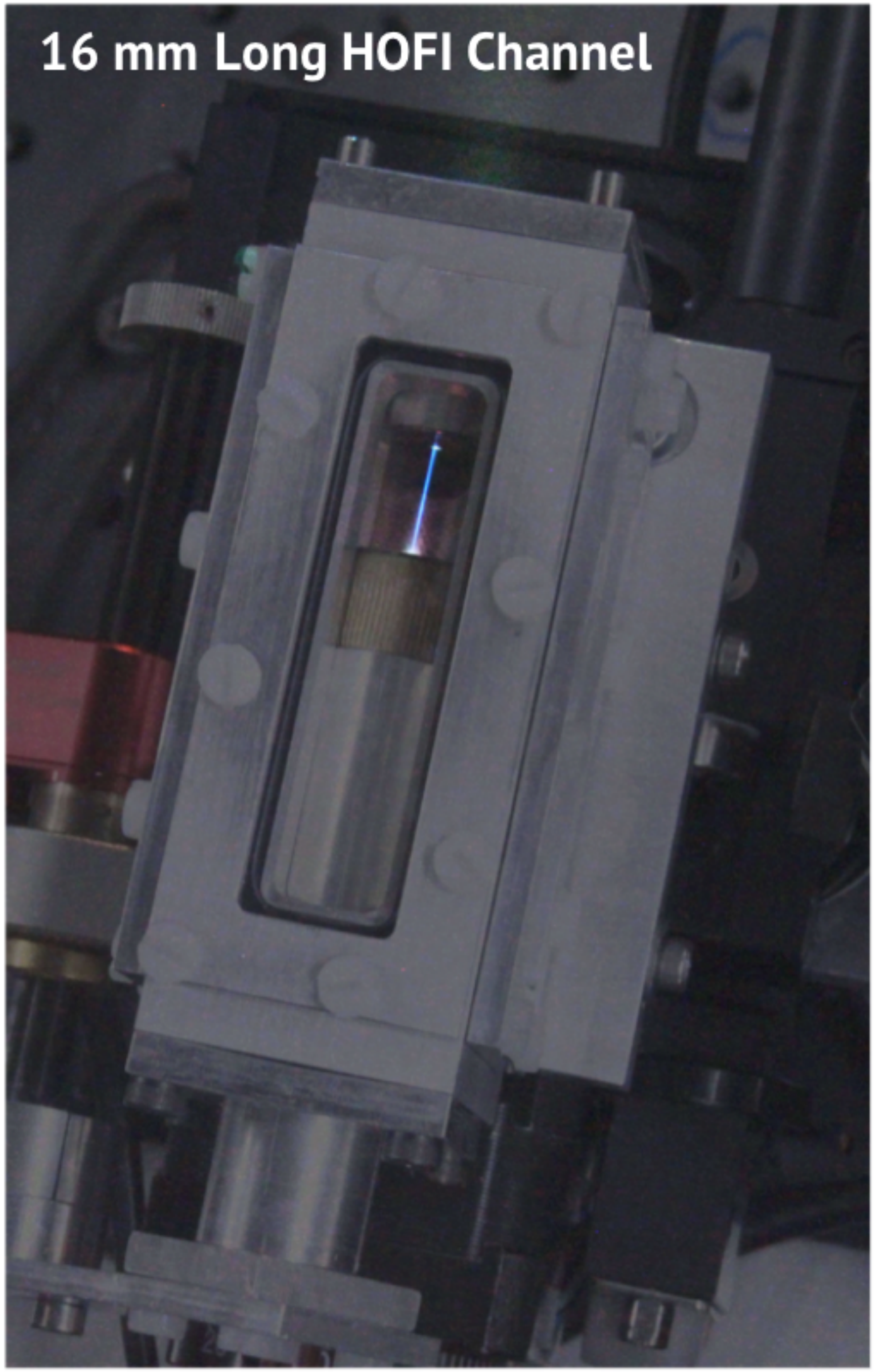
HOFI channels generated by axicon lenses

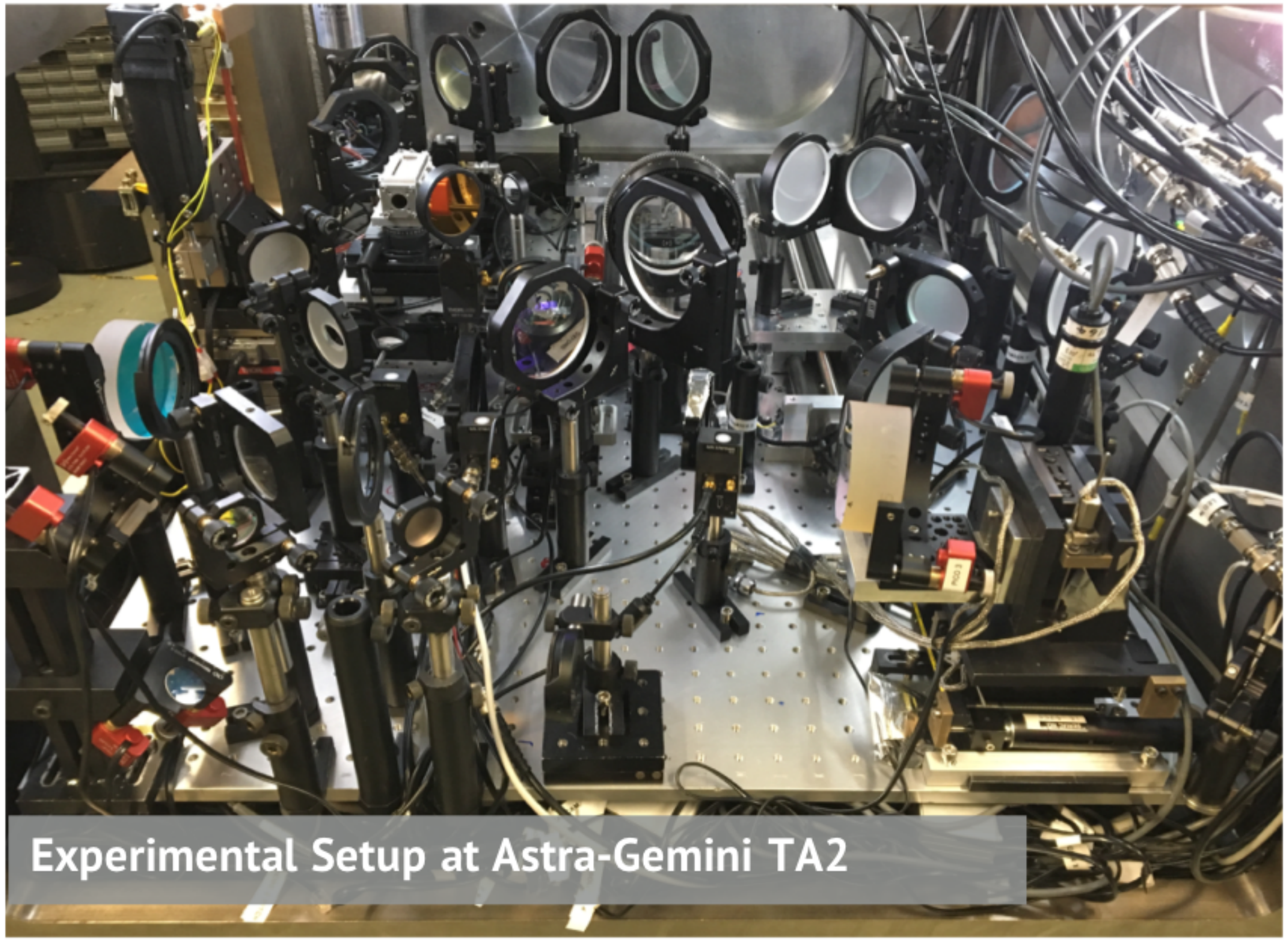
R.J. Shalloo *et al. submitted*



- Channel-forming beam focusing at 2.5 degrees with axicon
- Guided beam focusing at f/25 for an intensity of 5 x 10^{17} W cm^{-2}
- Longitudinal (400 nm) & transverse (800 nm) interferometry of channels

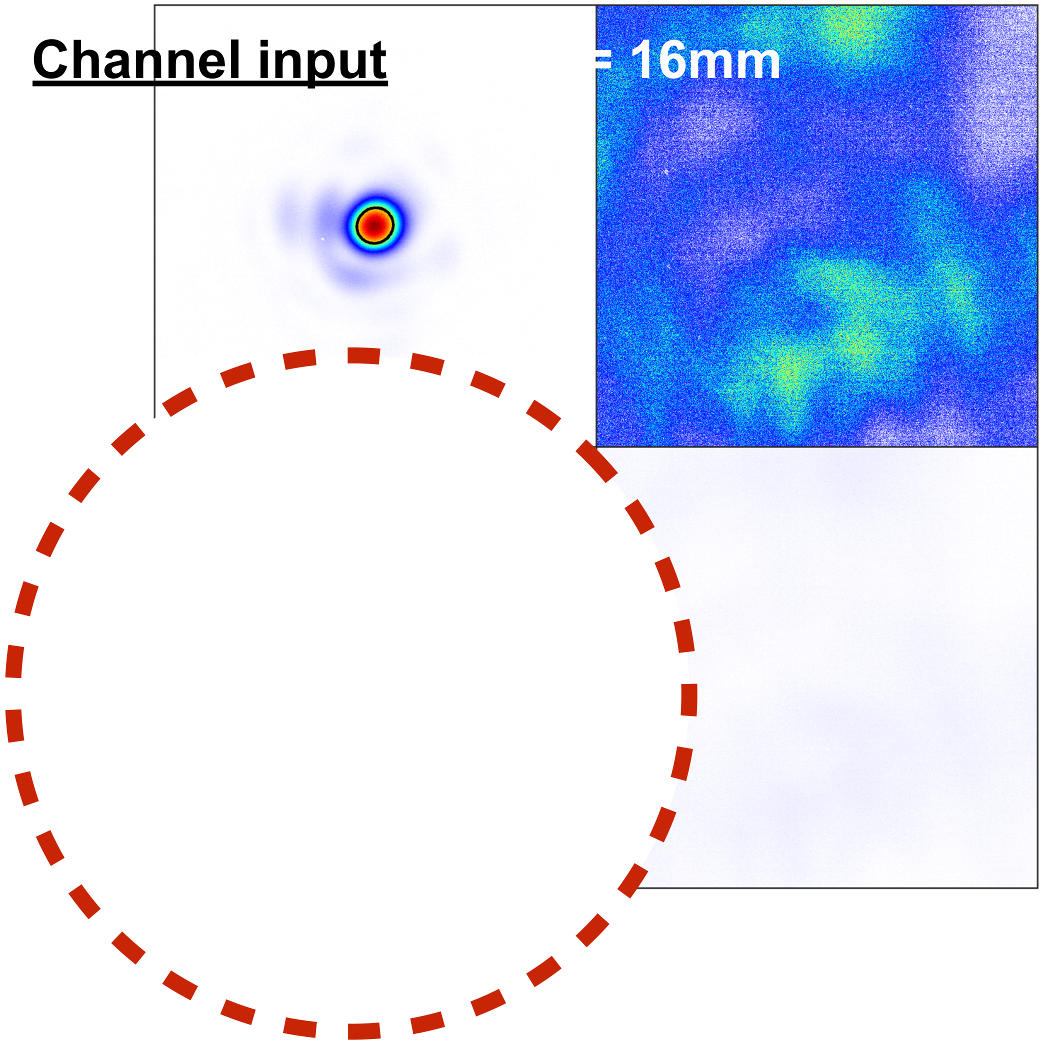
Experiment set-up

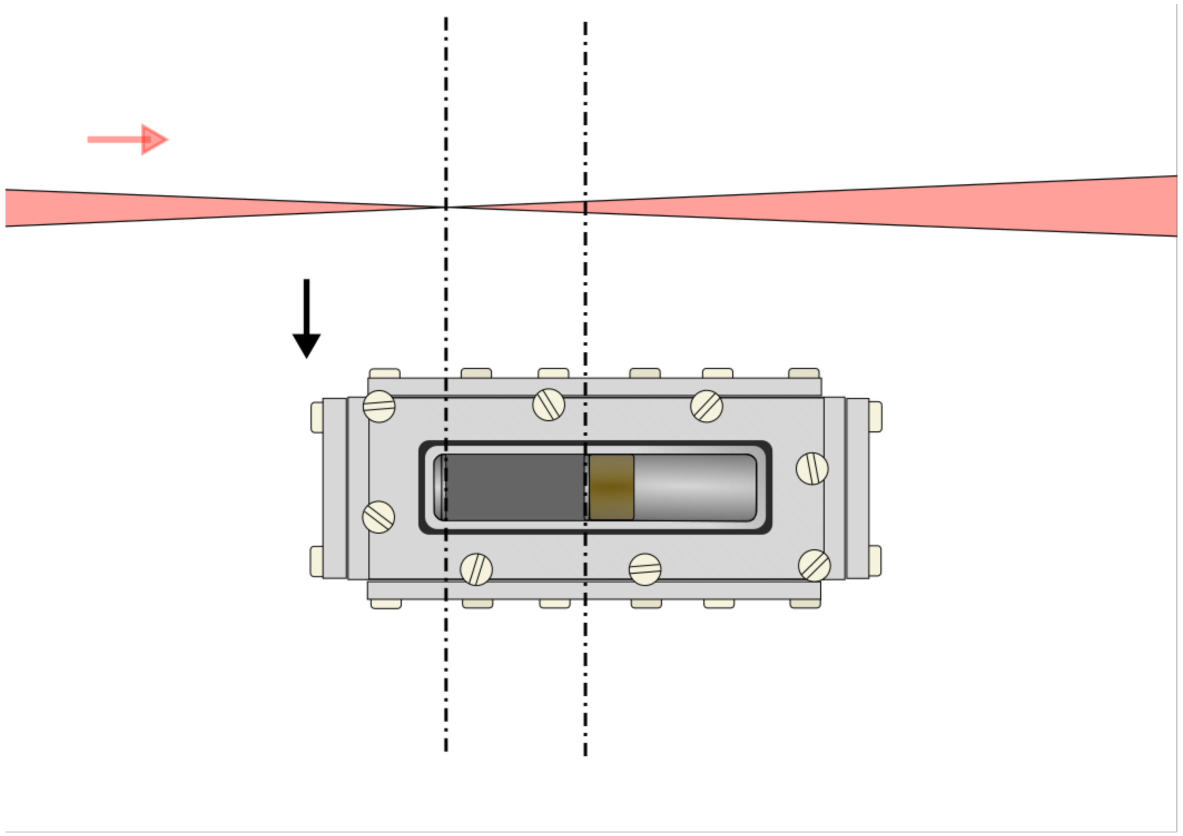

16 mm Long HOFI Channel


Experimental Setup at Astra-Gemini TA2

Axicon HOFI channels: Guiding results

- Guided beam injected into channel after 1.5 ns
- On-Axis Density ~ 6.5 x 10^{17} cm^{-3}
- Demonstration of High Intensity Guiding over 14.5 Rayleigh Ranges (16 mm)
- Guided Intensity > 10^{17} W cm^{-2}
- Consistently 40-60% energy throughput





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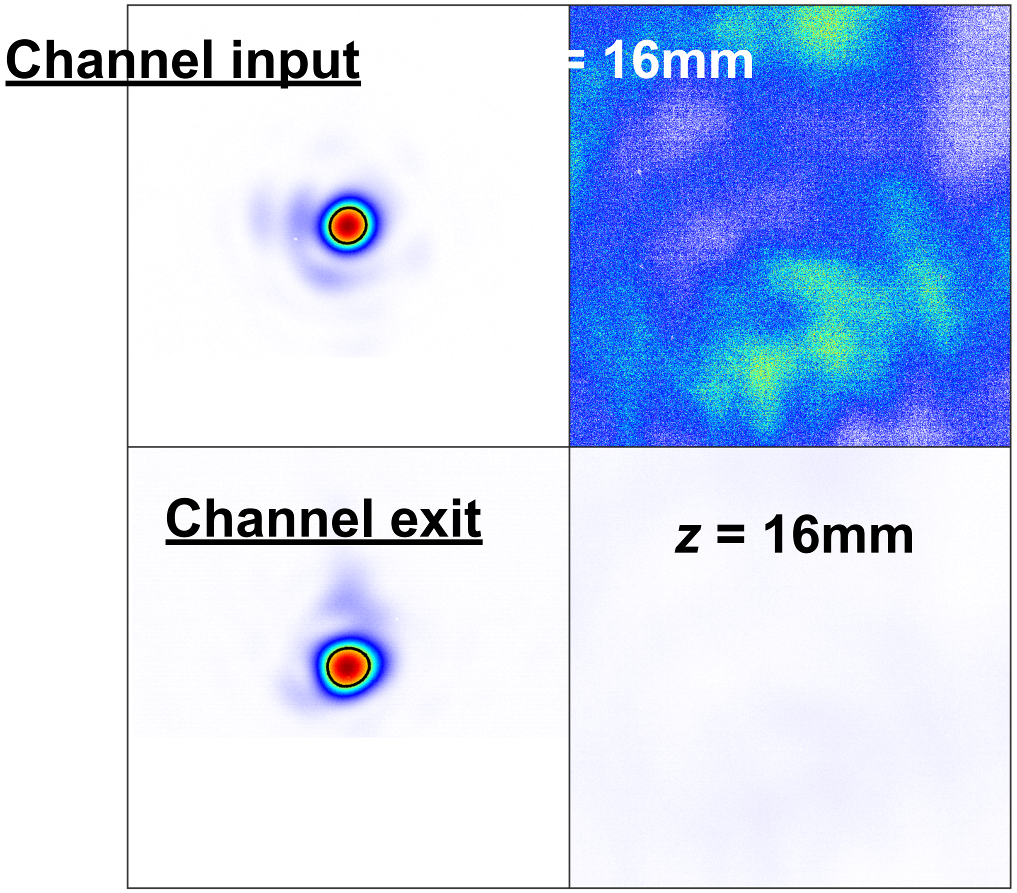

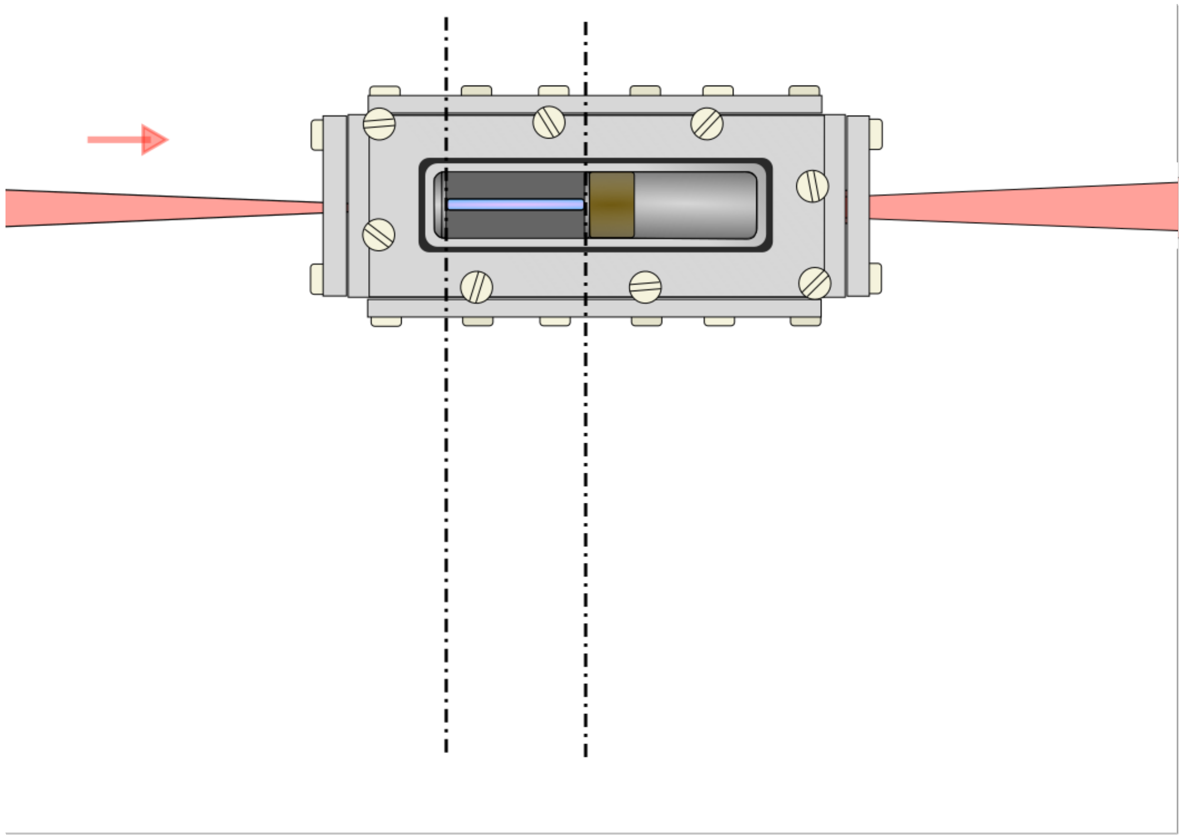

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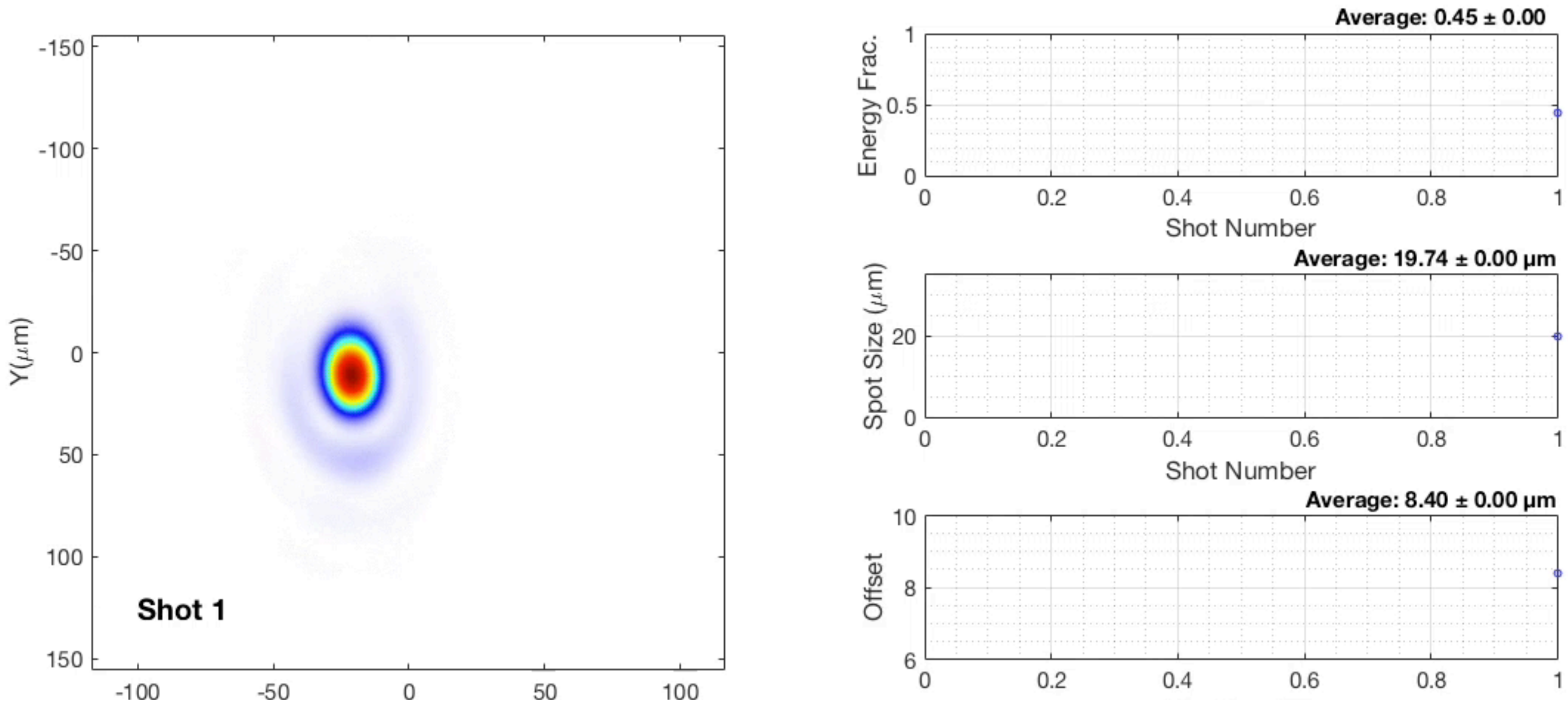
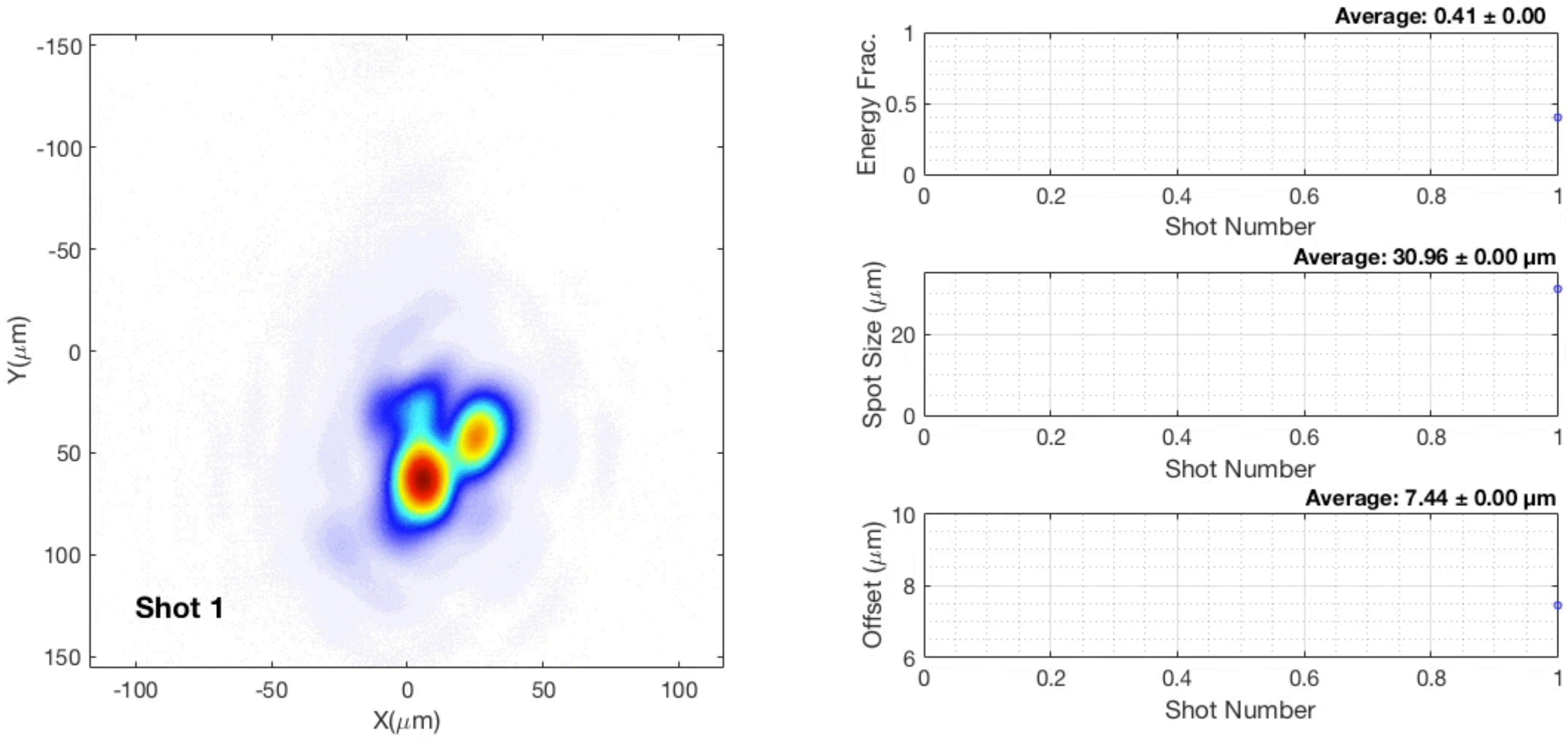
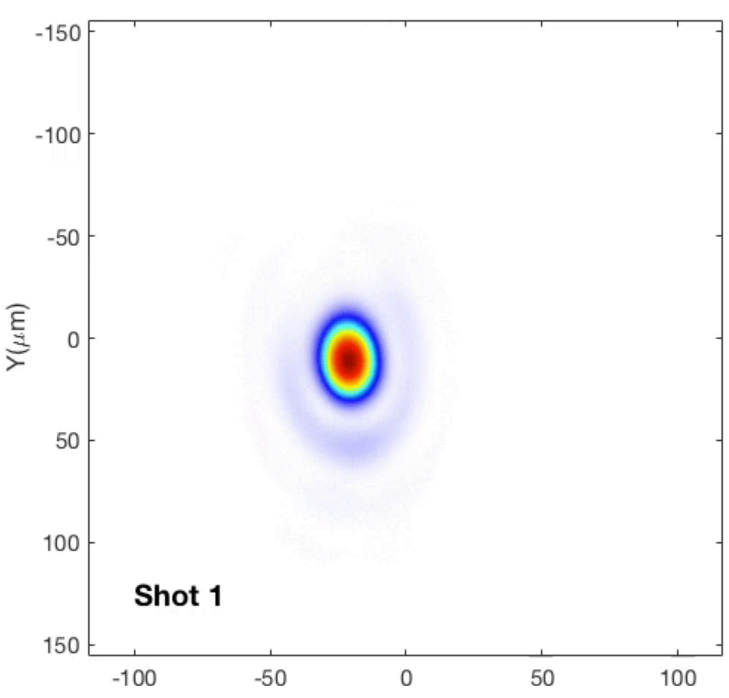


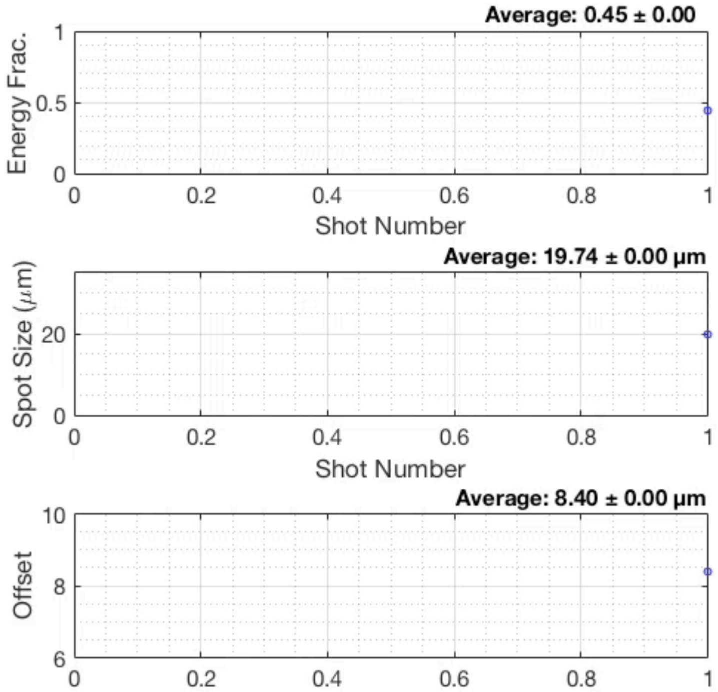
Low-power guiding (165 consecutive shots)



High-power guiding at 5 Hz (489 consecutive shots)

Axicon HOFI channels: Guiding results





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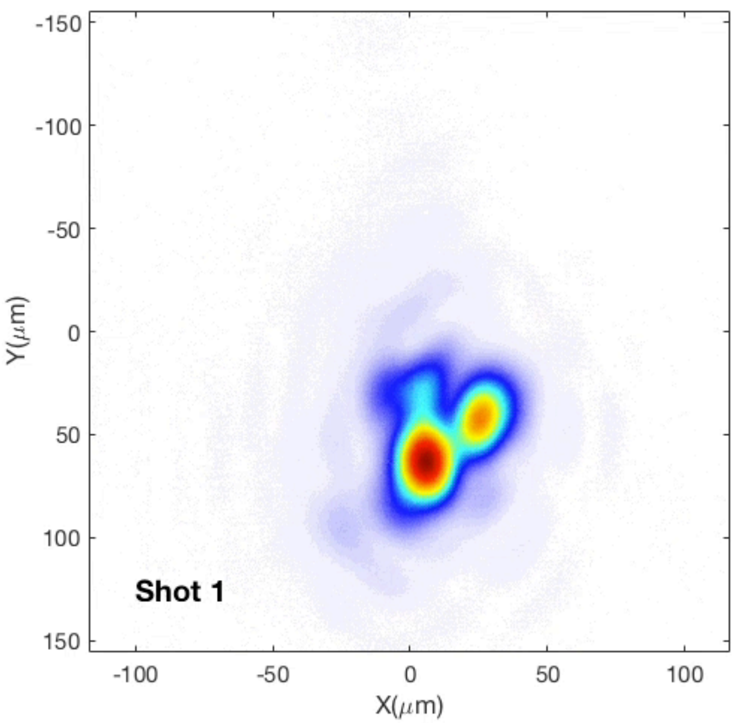

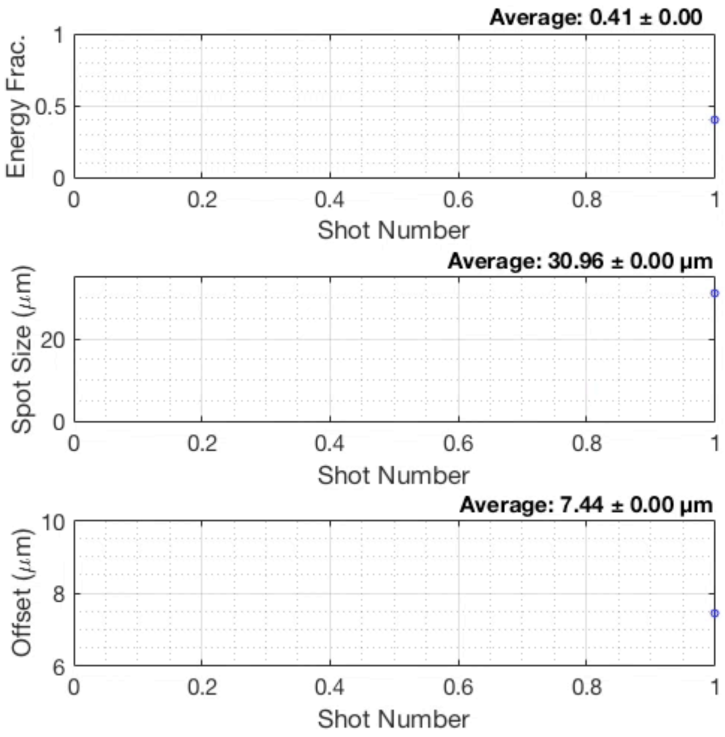

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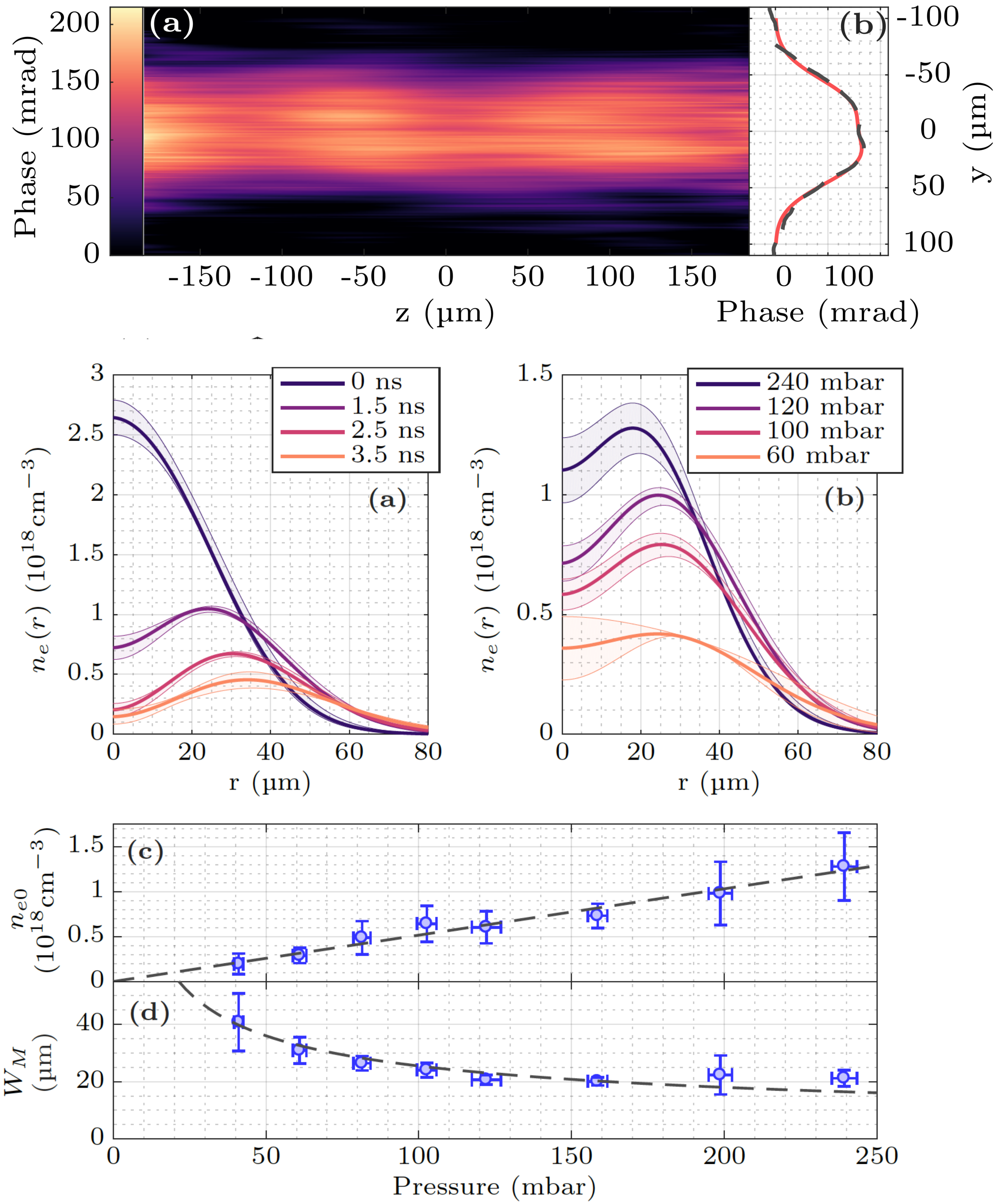
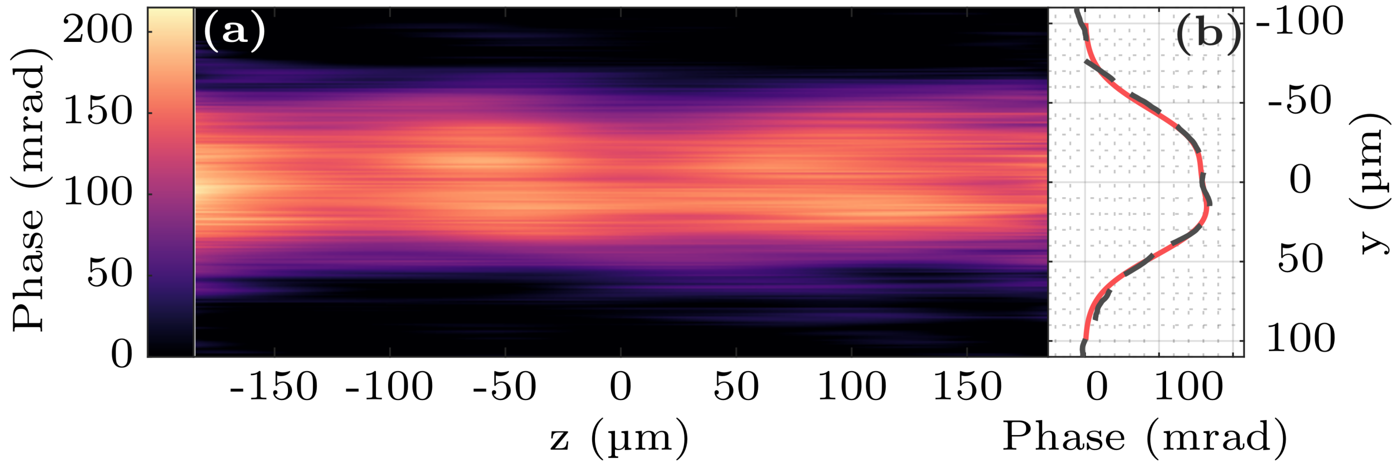
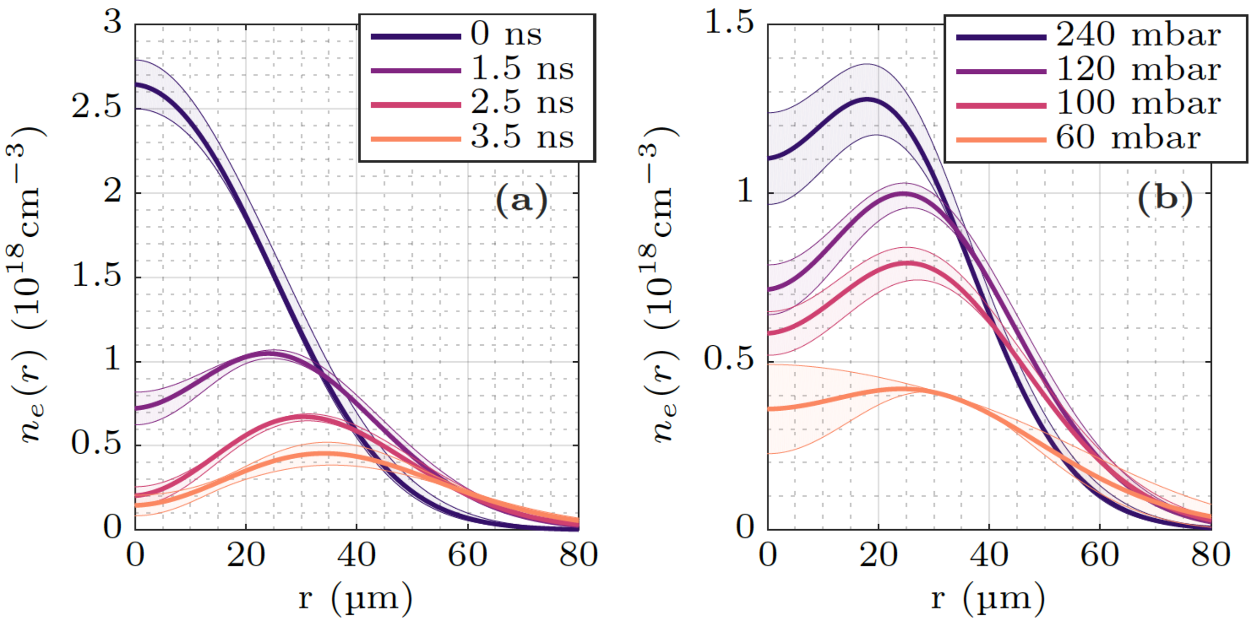
Axicon HOFI channels: Interferometry

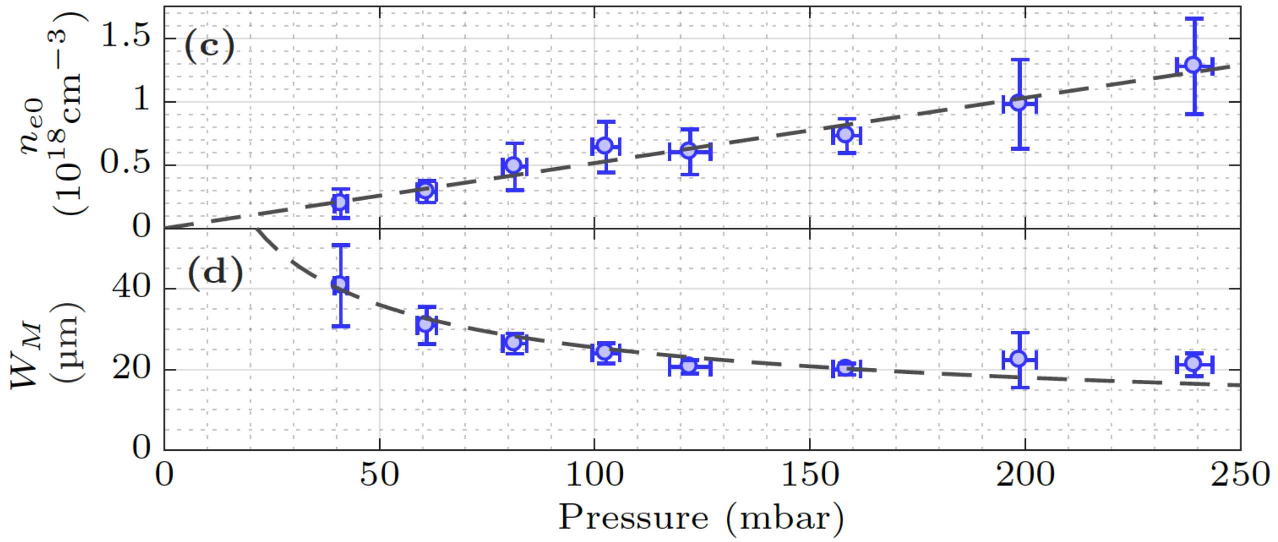


- Evolution of plasma channel over ns timescales observed
- Properties of channel can be controlled by adjusting initial pressure and delay
- Channel properties seem well suited to multi-GeV stages

Axicon HOFI channels: Interferometry







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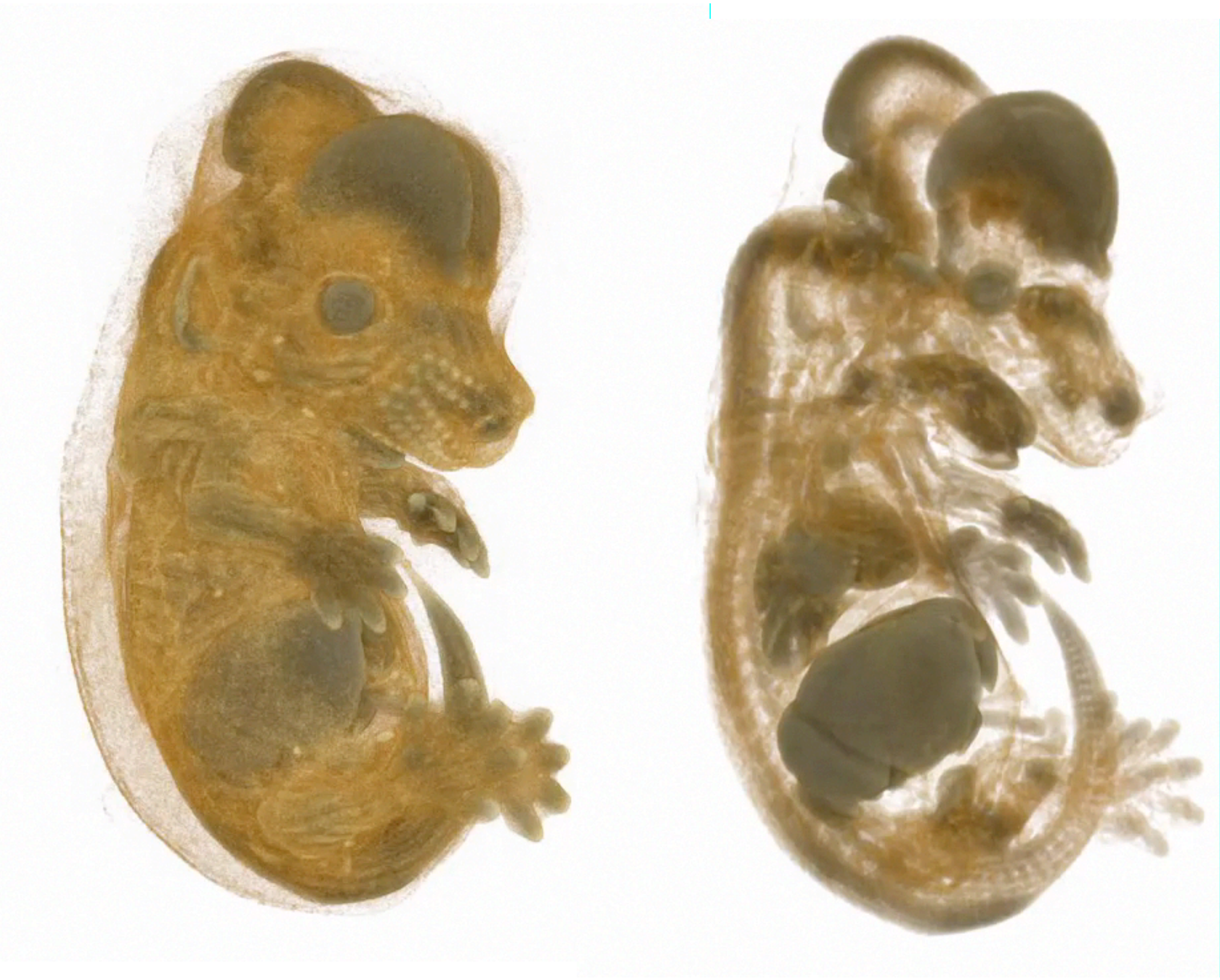
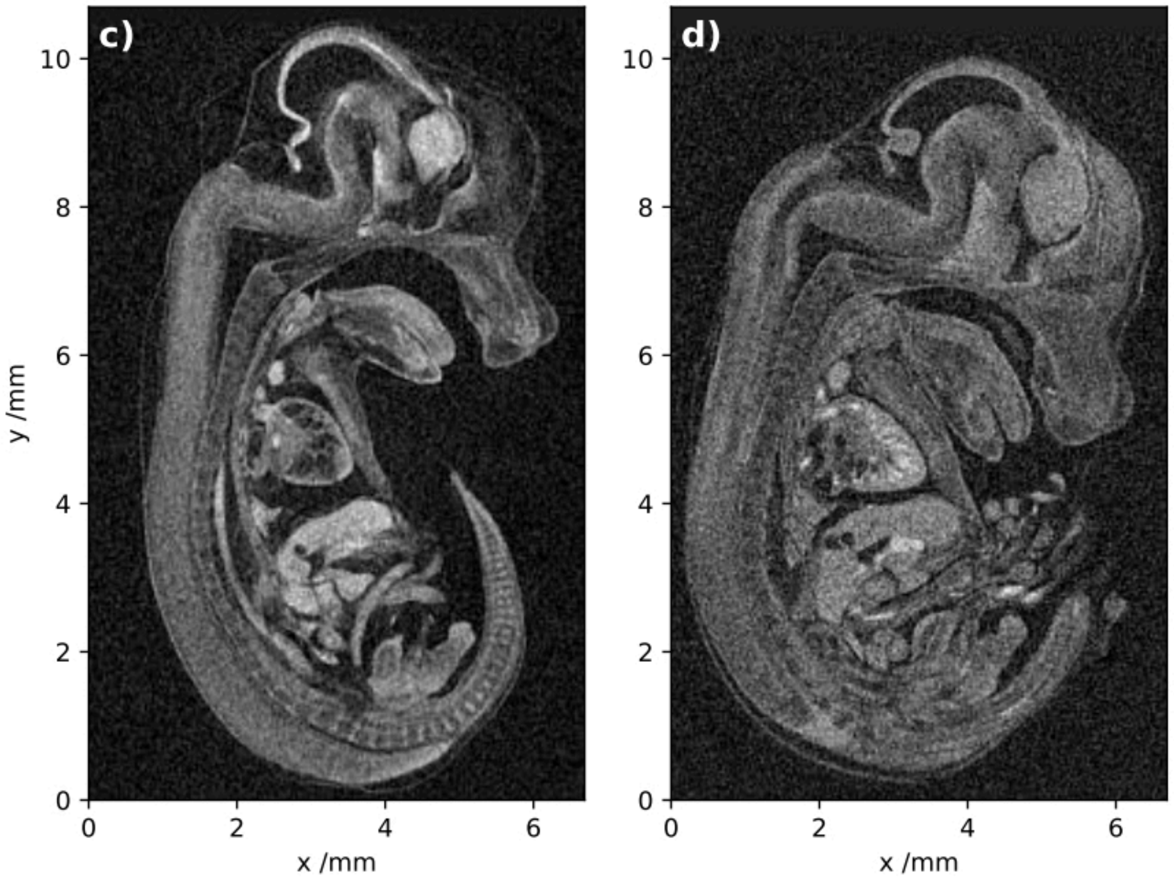
New experiments on HOFI channels in Gemini TA3 soon!

Applications

Mouse 14.5day tomography scan: 3D reconstruction allows different contours to be investigated





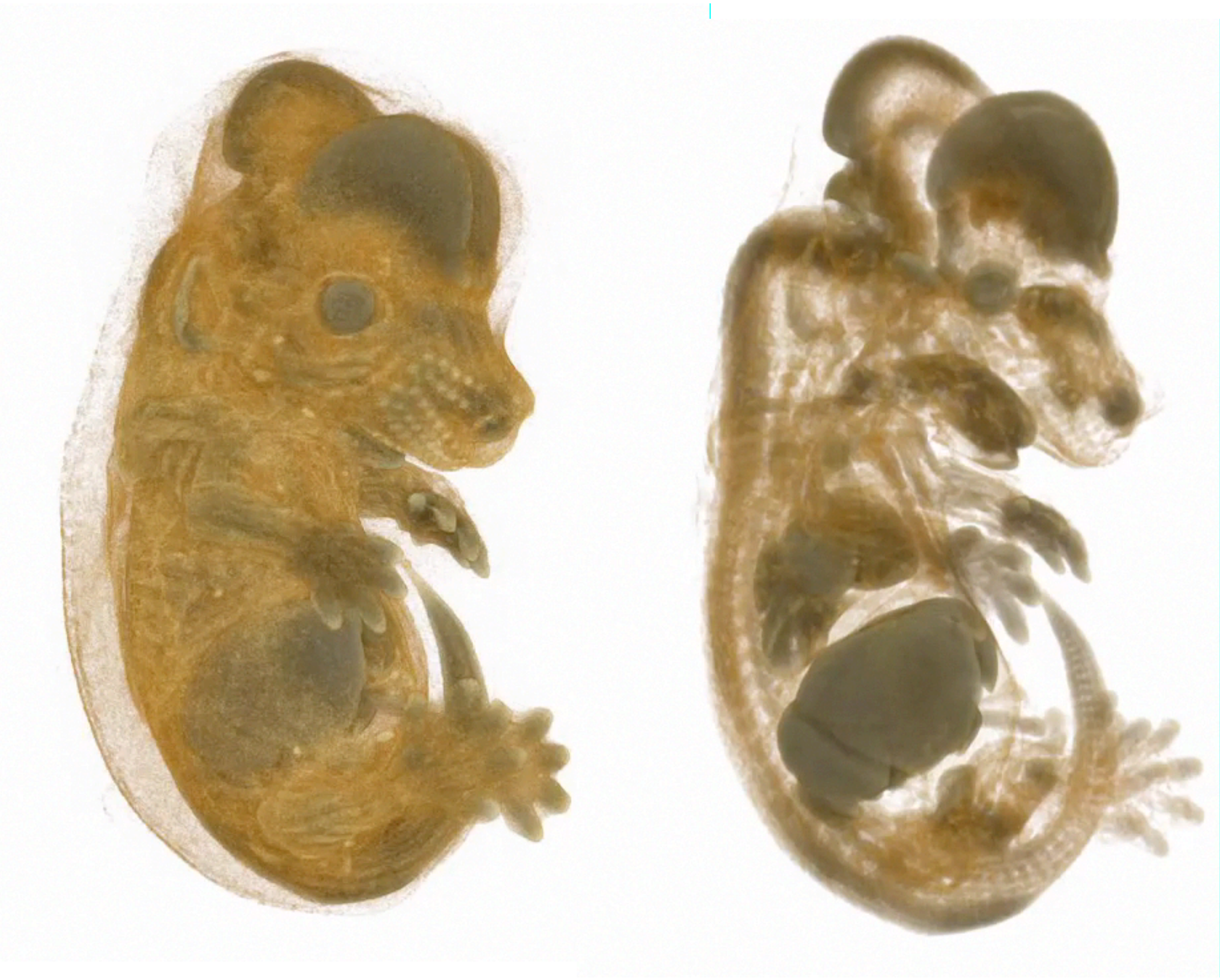
Betatron

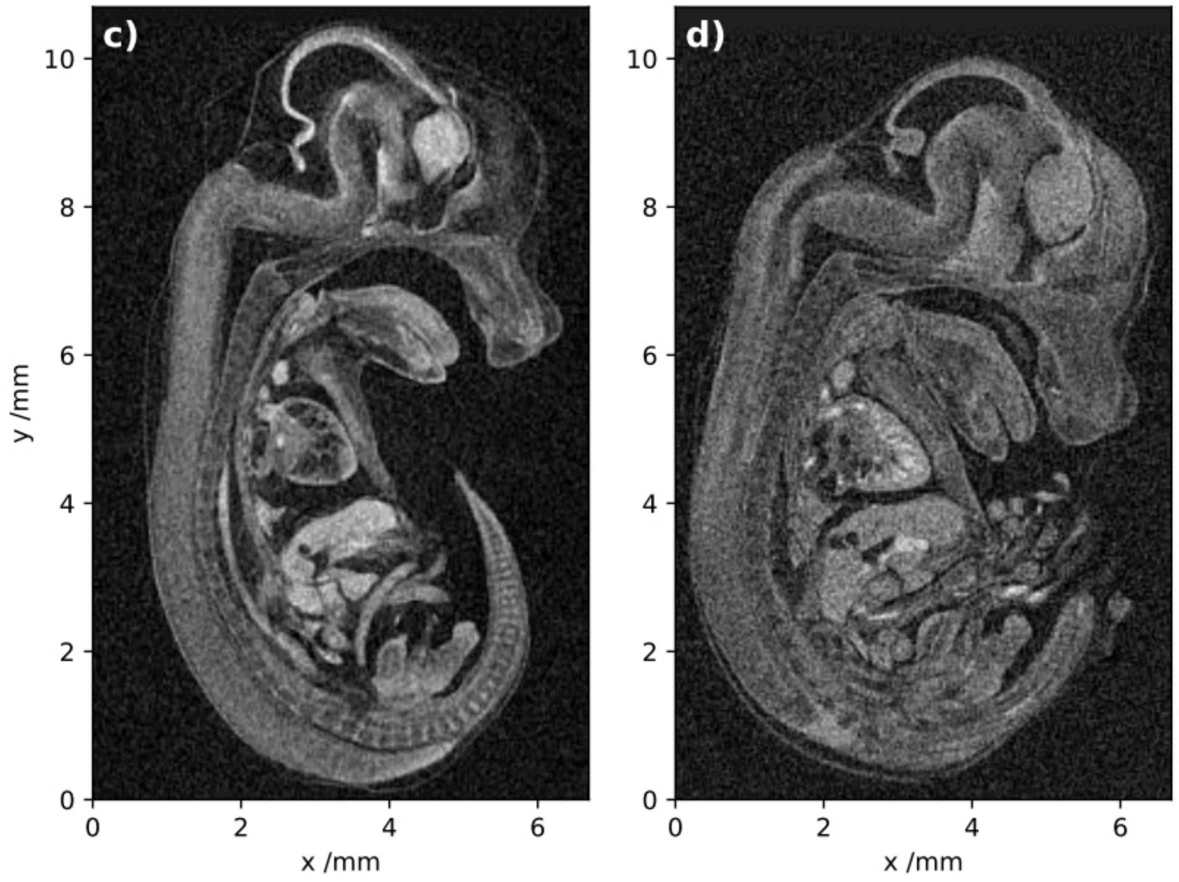
Skyscan 1172 (Bruckner)

Imaging quality at least as comparable to µCT source

J. M. Cole, et al, High-resolution µCT of a mouse embryo using a compact laser-driven X-ray betatron source, Proc. Natl. Acad. Sci. U. S. A. 115, 1802314115 (2018).

Mouse 14.5day tomography scan: 3D reconstruction allows different contours to be investigated





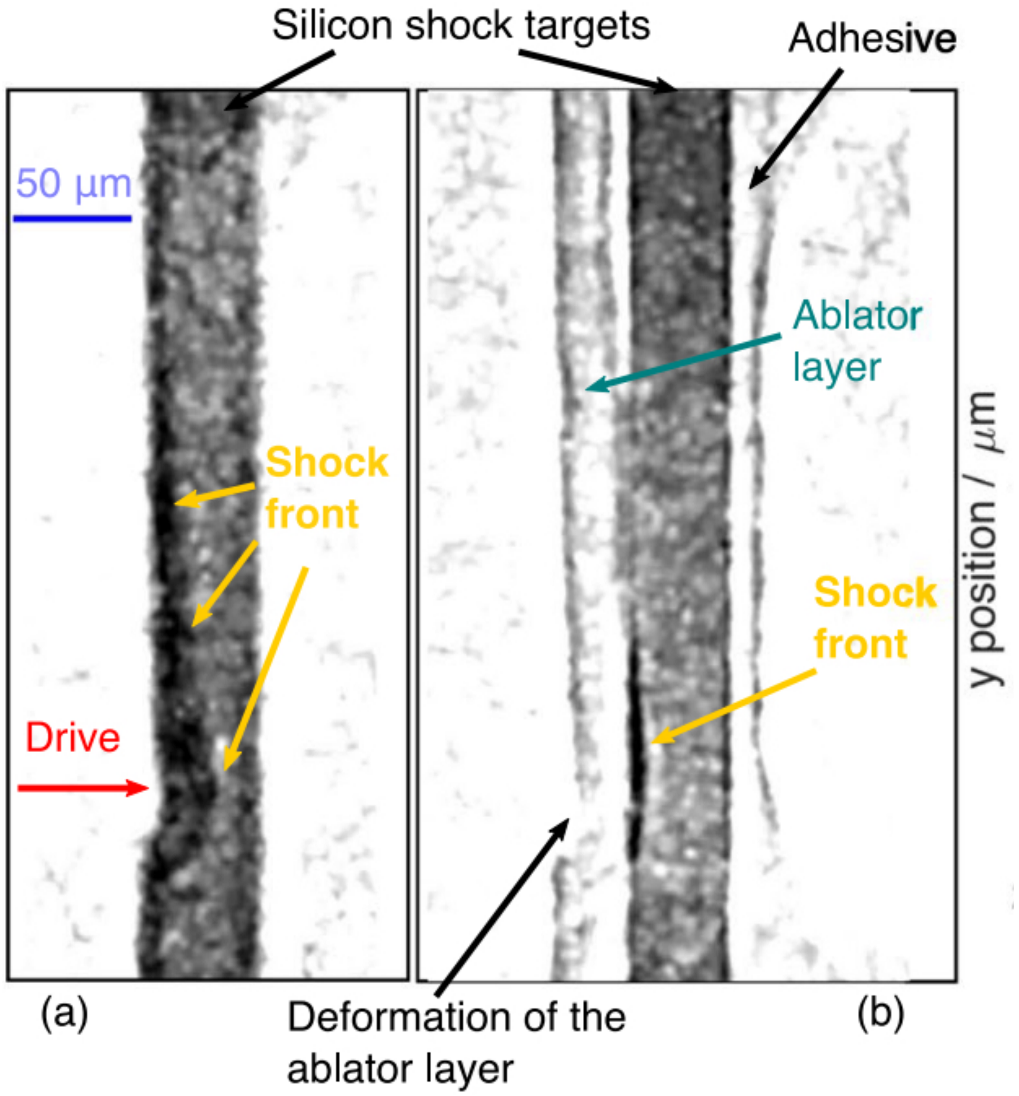
Betatron

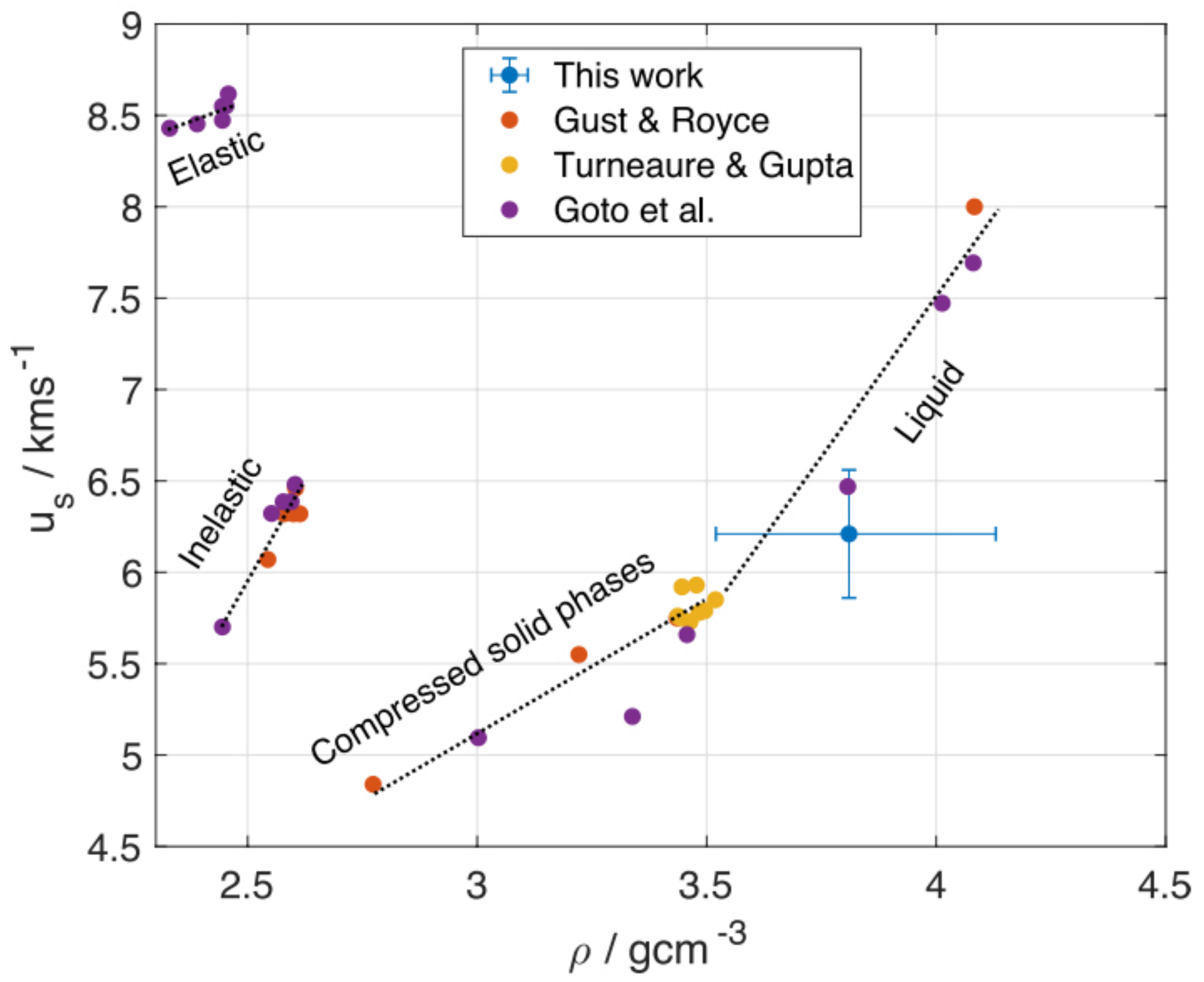
Skyscan 1172 (Bruckner)

Imaging quality at least as comparable to µCT source

J. M. Cole, et al, High-resolution µCT of a mouse embryo using a compact laser-driven X-ray betatron source, Proc. Natl. Acad. Sci. U. S. A. 115, 1802314115 (2018).

Ultrafast imaging of shocks in silicon

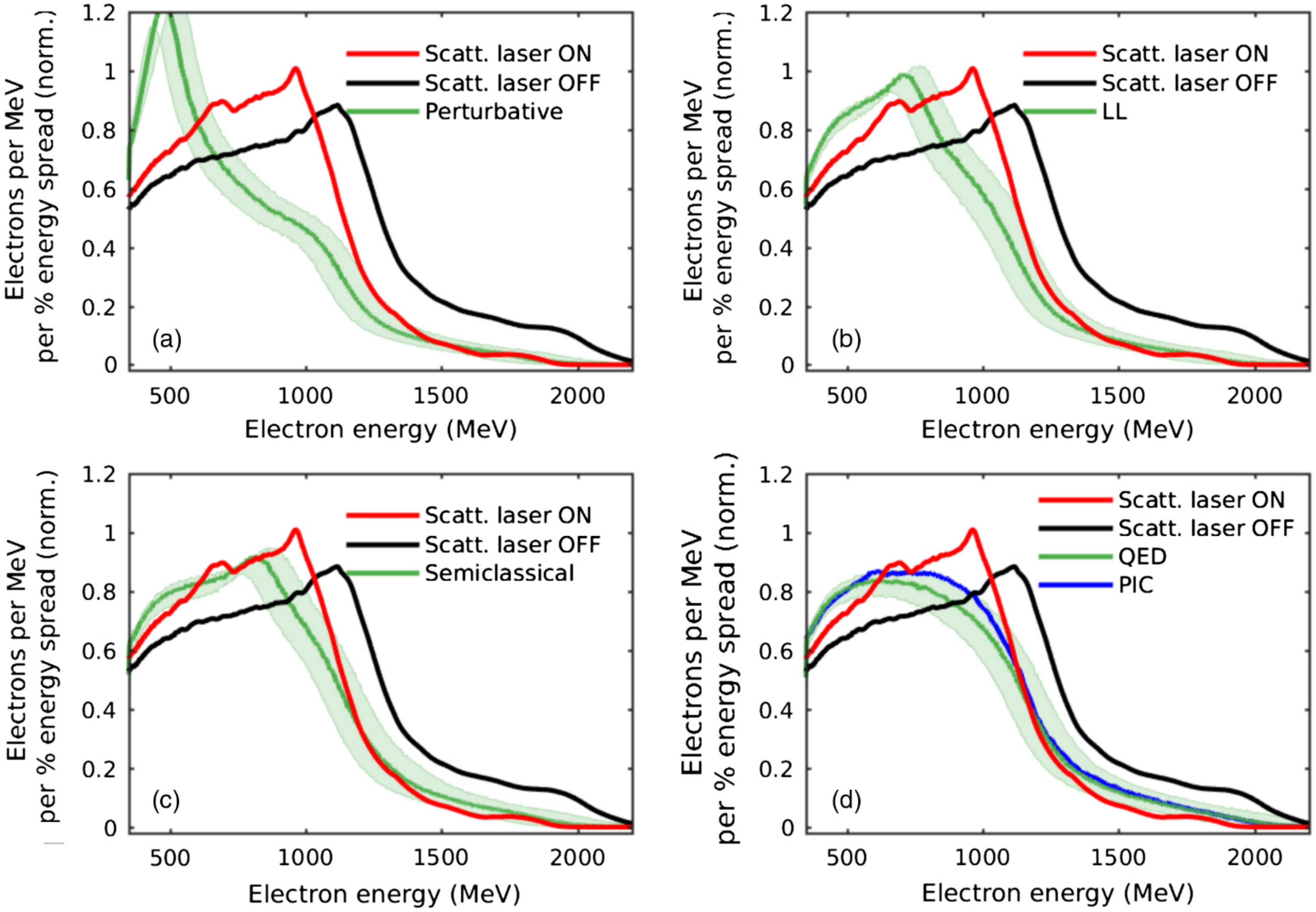




Agrees with measured data along Hugoniot

J. C. Wood, et al., Ultrafast Imaging of Laser Driven Shock Waves using Betatron X-rays from a Laser Wakefield Accelerator, Sci. Rep. 8, 11010 (2018).

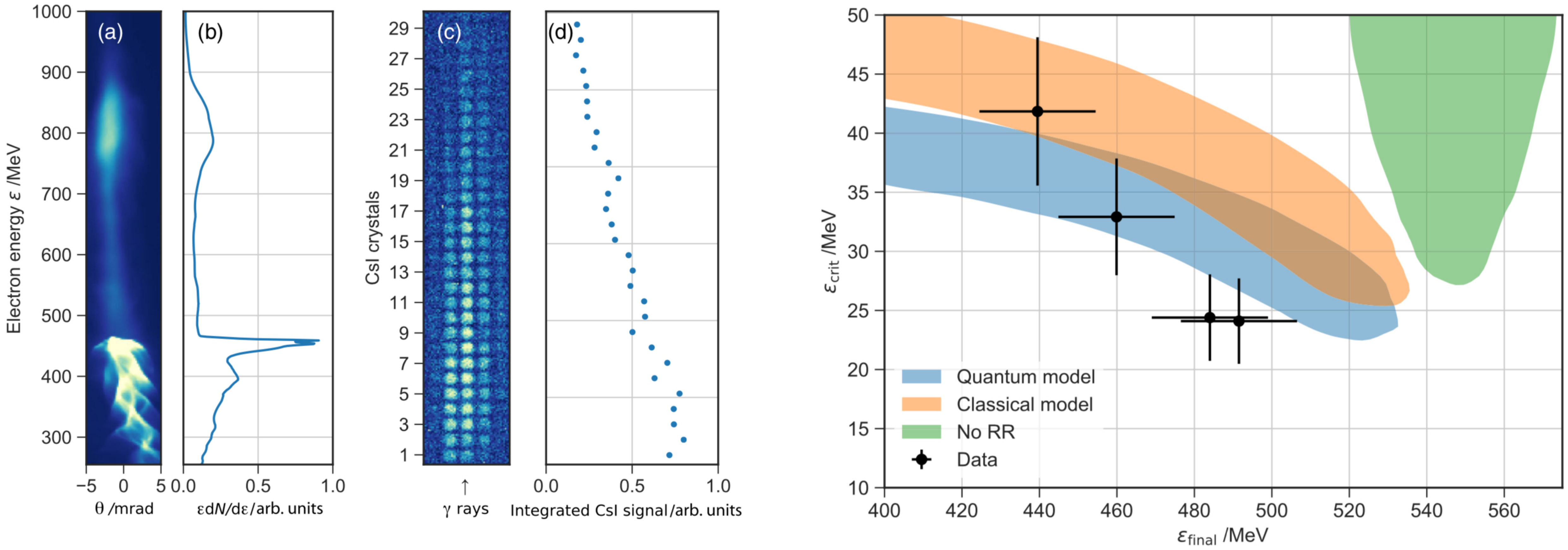
Differences in electron beam properties observed due to Compton Scattering



Modelling of experimental signatures needs better models of radiation reaction

K. Poder et al, Experimental Signatures of the Quantum Nature of Radiation Reaction in the Field of an Ultraintense Laser, Phys. Rev. X 8, 031004 (2018).

Electron energy loss coupled to properties of γ-ray beam



Data most consistent with Quantum models, more data required

J. M. Cole et al, Experimental Evidence of Radiation Reaction in the Collision of a High-Intensity Laser Pulse with a Laser-Wakefield Accelerated Electron Beam, Phys. Rev. X 8, 011020 (2018).

High-power laser labs at Oxford

Oxford high-power laser laboratory

- Have secured funding for new, joint high-power laser laboratories in basement of DWB
  - ~£400k from STFC to upgrade existing 50 mJ, 50 fs, Ti:sapphire laser to 200 mJ, 50 fs,
  - ~ £1.4M from Oxford university to construct 270m^2 shielded laboratories
  - Seeking further funds for second upgrade to 700 mJ, 50 fs
- New lab would be operated jointly with Gianluca Gregori (works on lab astro, dense plasmas, ICF)

	Possible experiments
As funded	Development of waveguides
	Pulse train generation
	Diagnostic development
	Preparation for expts at CLF & other facilities
	etc…
Further upgrade	Controlled injection experiments
	Electron acceleration tests to ~ 200 MeV
	etc…

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	Possible experiments
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	Diagnostic development
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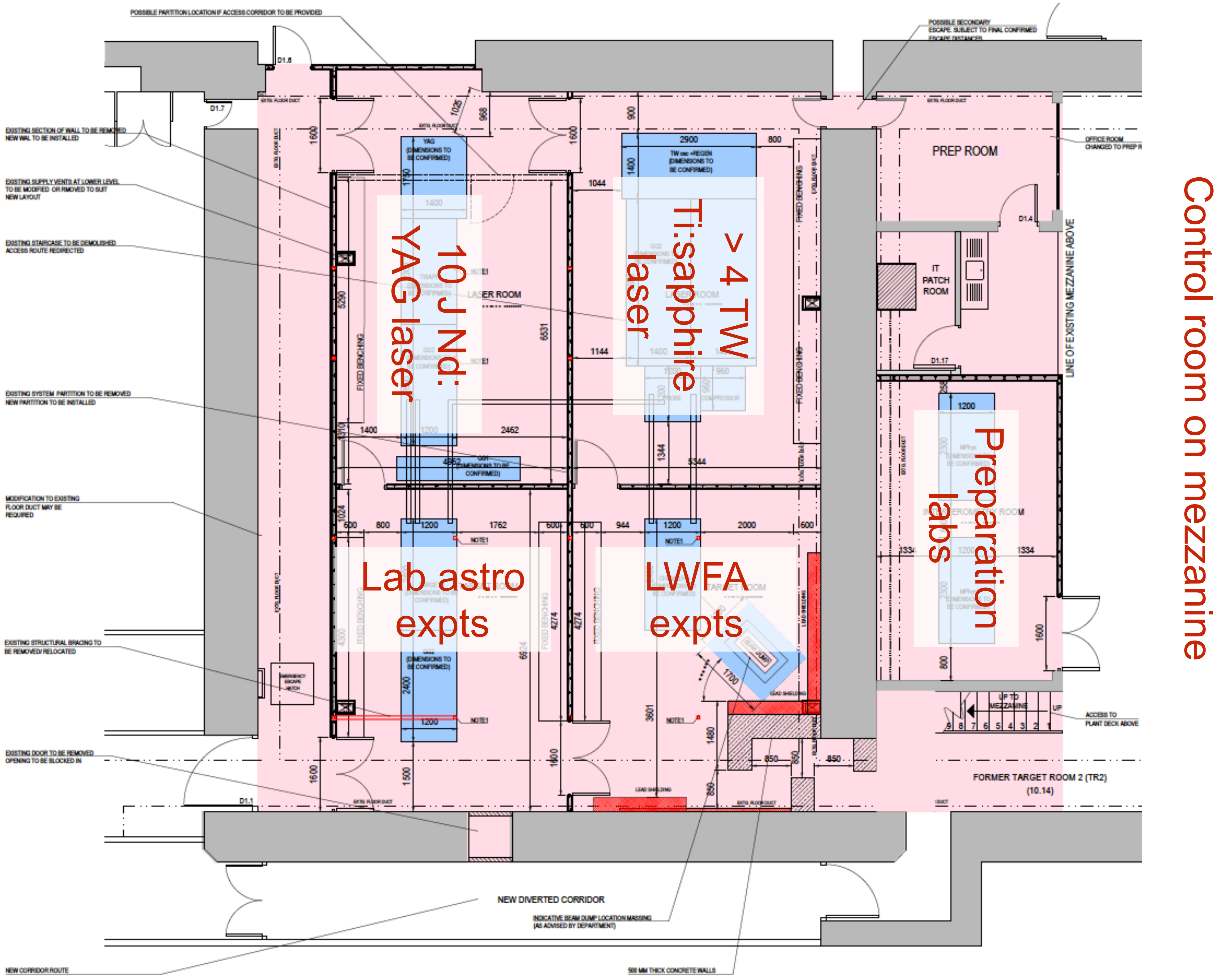
	etc…
Also now funded	Controlled injection experiments
	Electron acceleration tests to ~ 200 MeV
	etc…

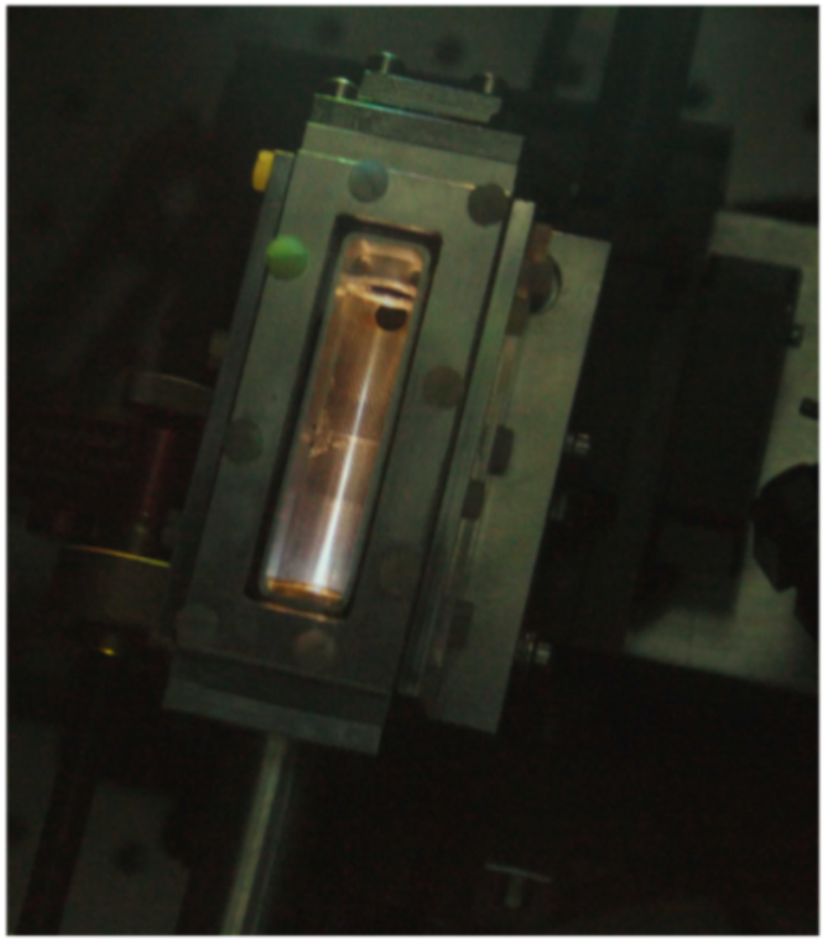
Additional funding from department and STFC secured

Oxford high-power laser laboratory



Summary

- JAI teams have obtained exciting results obtained across all aspects of plasma accelerators
  - Energy frontier experiments
  - Plasma accelerator staging
  - High-repetition rate plasma accelerators
  - Multi-pulse laser wakefield accelerators
  - Novel waveguide development
  - Plasma lens development
  - High-field physics
  - Applications

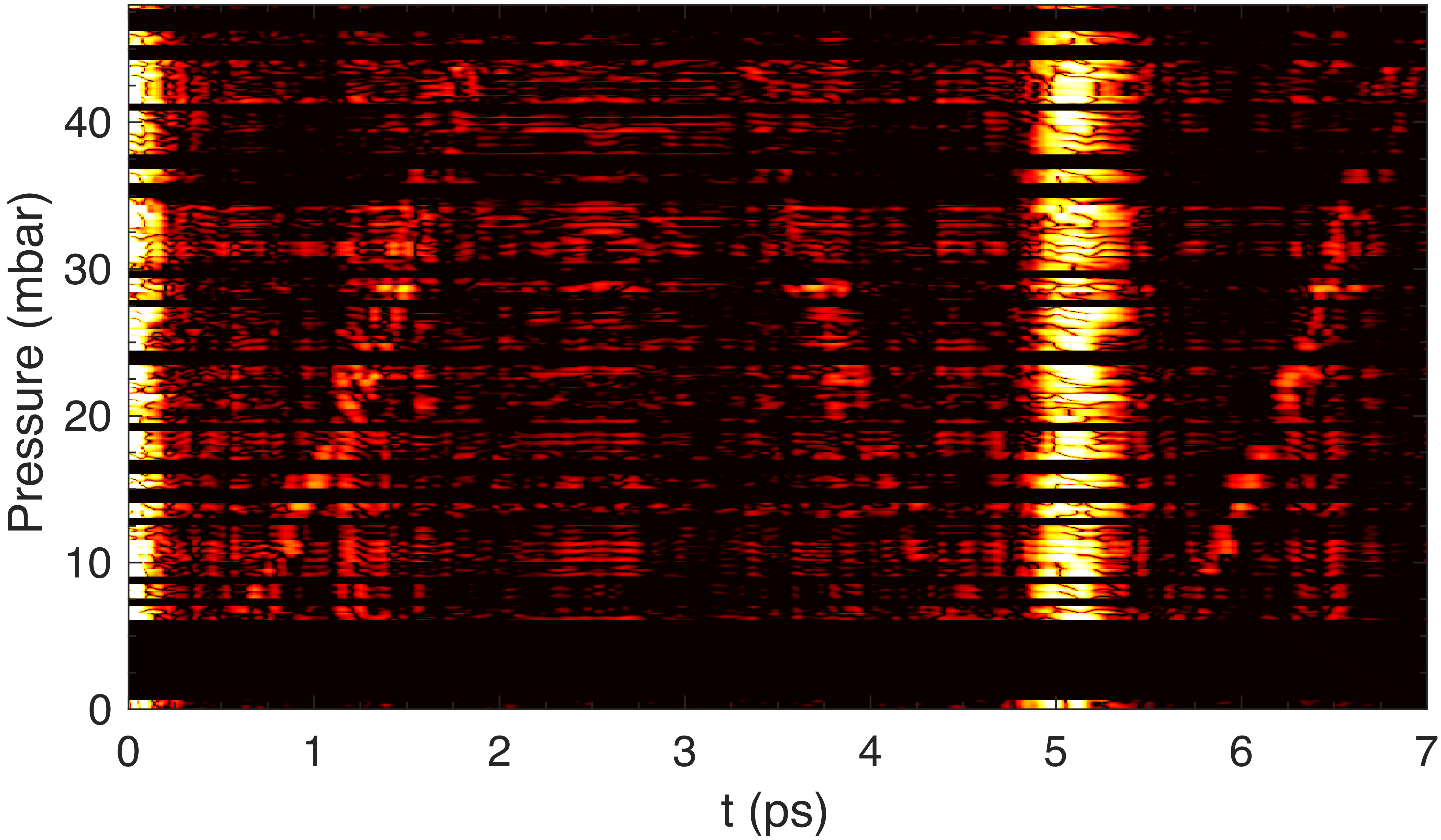


A 45 mm long axicon-generated OFI plasma

Spare slides

TESS waterfall

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



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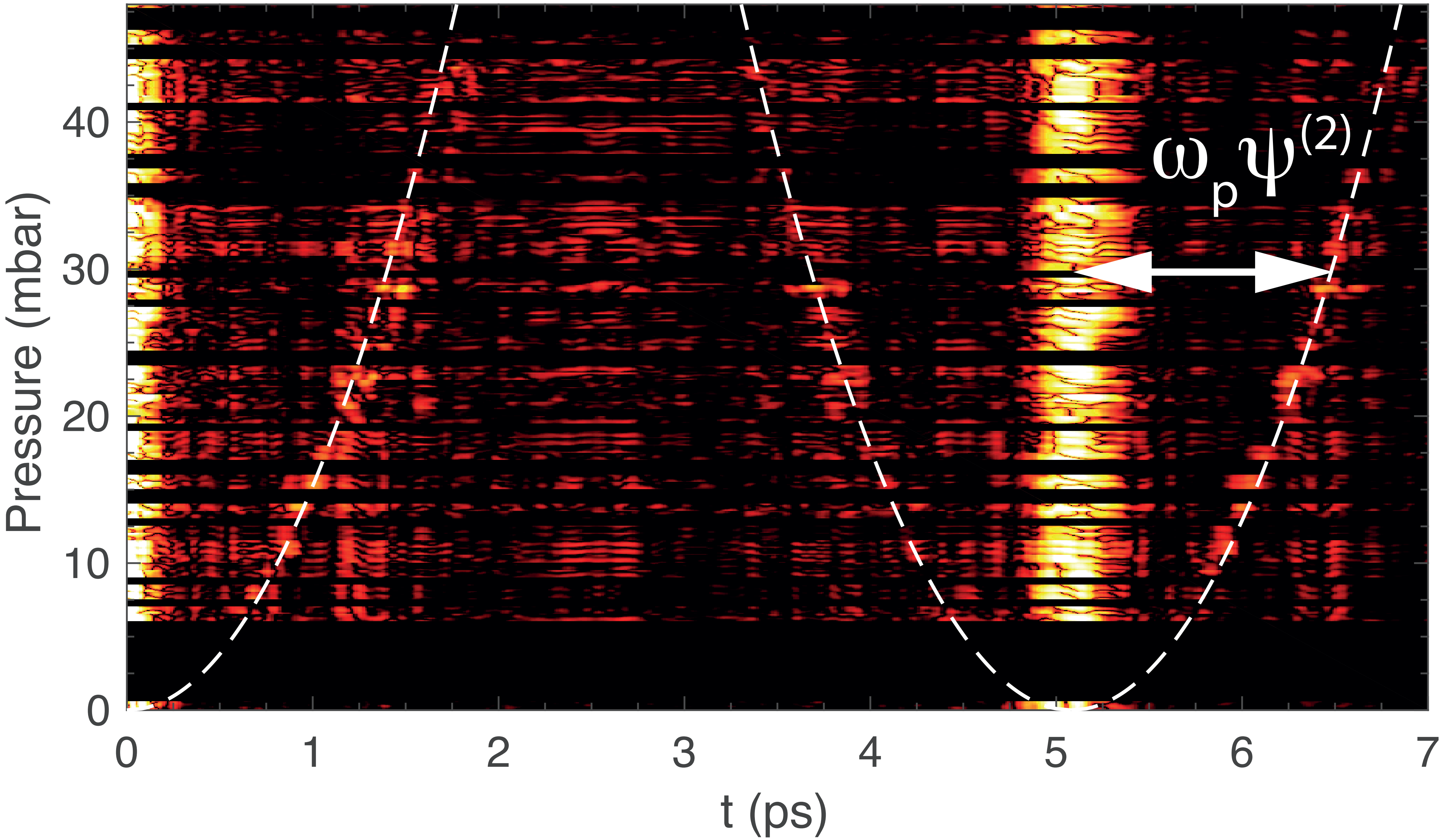
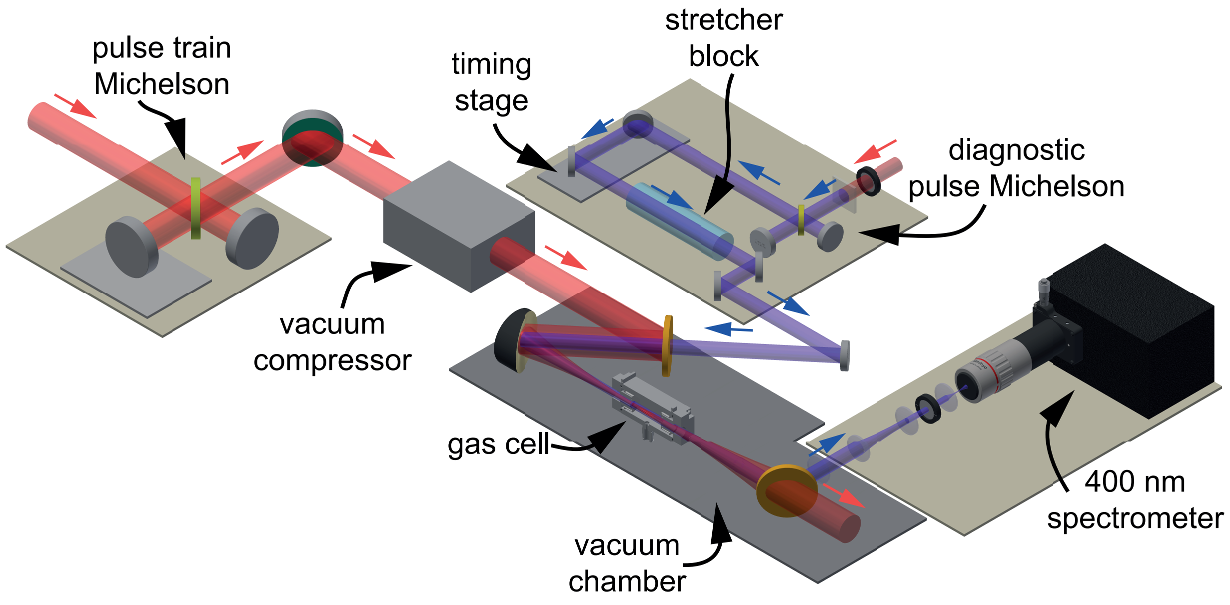
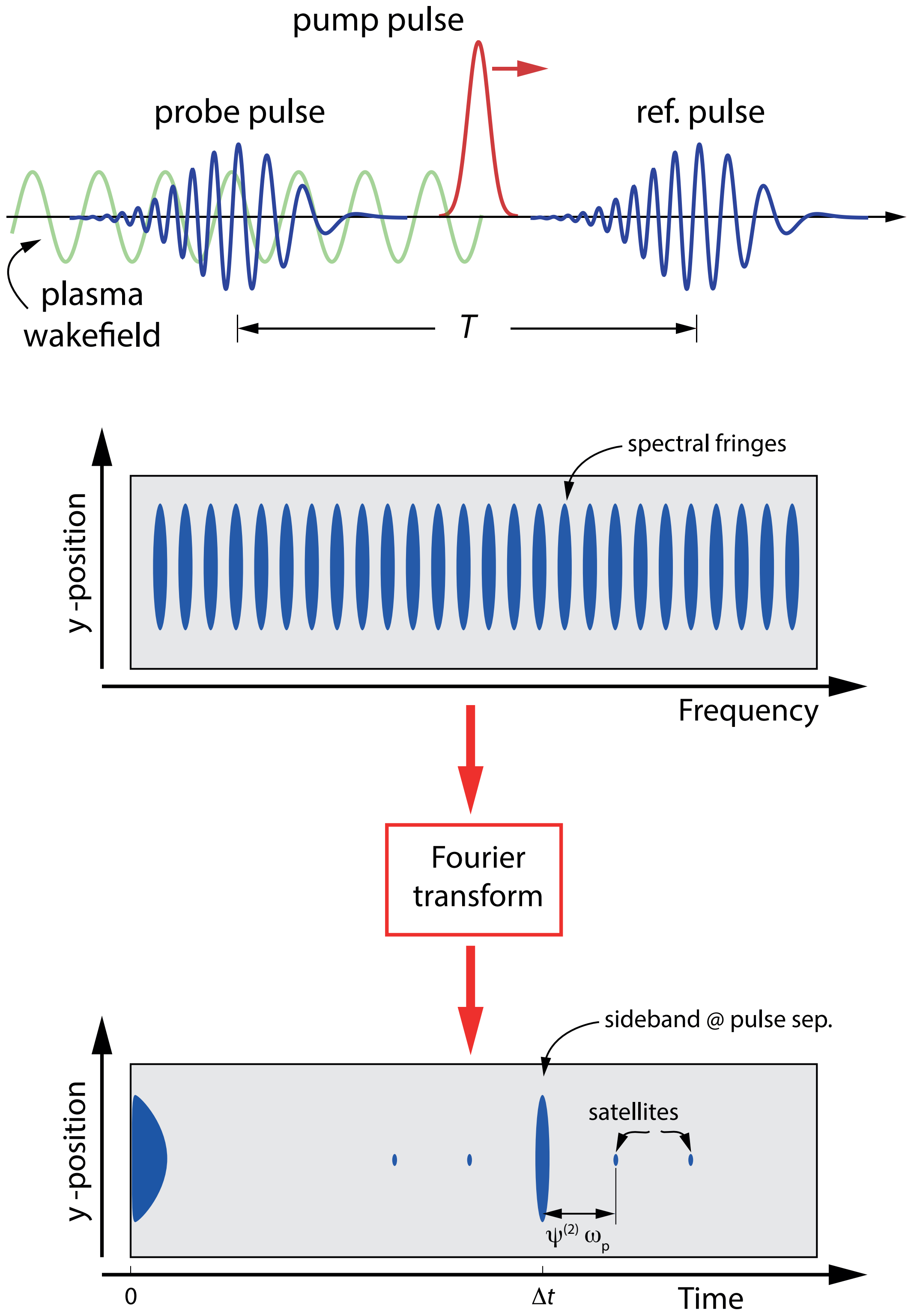


MP-LWFA: Astra TA2 experiments

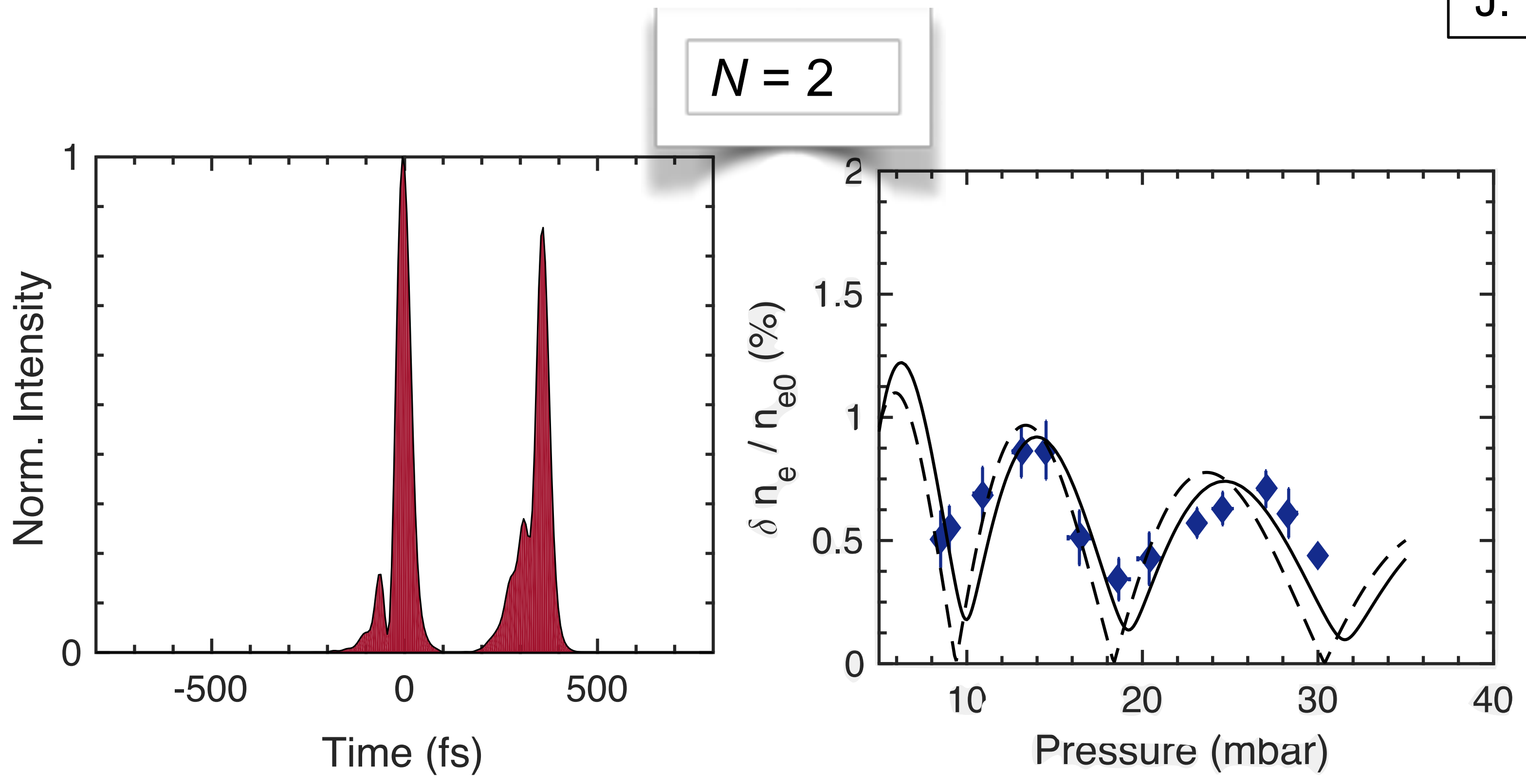


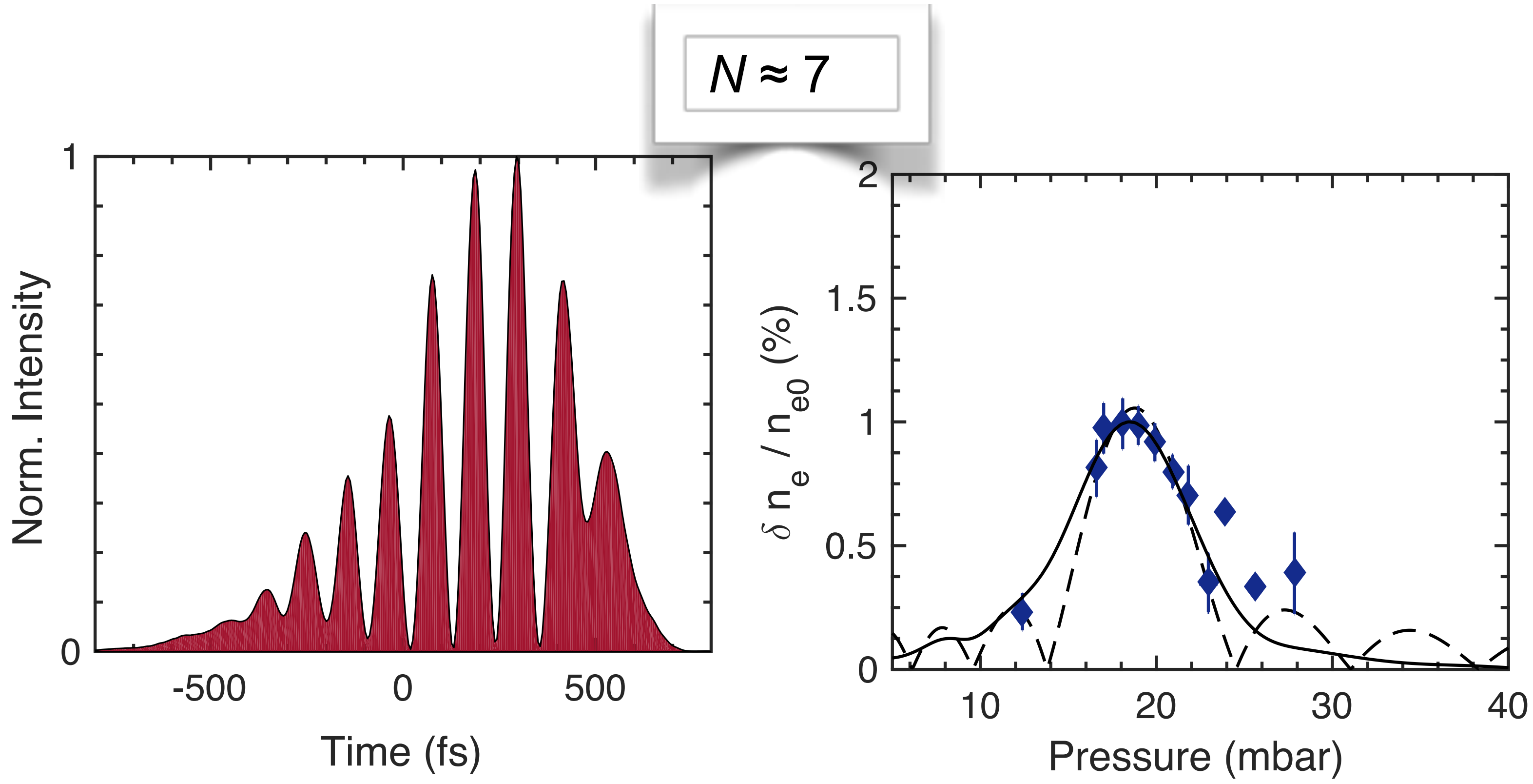


- Expts with Astra-Gemini (TA2) laser at RAL
- Astra delivers **single** 500 mJ, 40 fs Ti:sapphire pulses
- Can convert into train of 10 - 50 pulses
- Driver pulses focused into 1 - 4 mm long gas cell by f/20 OAP
- Wakefield measured by Frequency-domain holography & TESS

MP-LWFA: Astra TA2 experiments

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





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

- Measured wakefields are in excellent agreement with analytic theory
- *N* = 2 results are first step to **energy recovery!**
- Resonant excitation clearly observed