Demonstration of the Excitation and Control of Plasma Wakefields by Multiple Laser Pulses

Simon Hooker, C. Arran, L. Corner, J. Cowley, G. Cheung, J. Holloway, R.J. Shalloo, C. Thornton, R. Walczak
John Adams Institute for Accelerator Science & Department of Physics, University of Oxford

C. Gregory and D.R. Symes
Rutherford Appleton Laboratory

N.H. Matlis
Centre for Free-Electron Laser Science, DESY, Hamburg

S.P.D. Mangles
John Adams Institute for Accelerator Science & Imperial College, London

Demonstration of the Excitation and Control of Plasma Wakefields by Multiple Laser Pulses

Simon Hooker, C. Arran, L. Corner, J. Cowley, G. Cheung, J. Holloway, R.J. Shalloo, C. Thornton, R. Walczak

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

C. Gregory and D.R. Symes

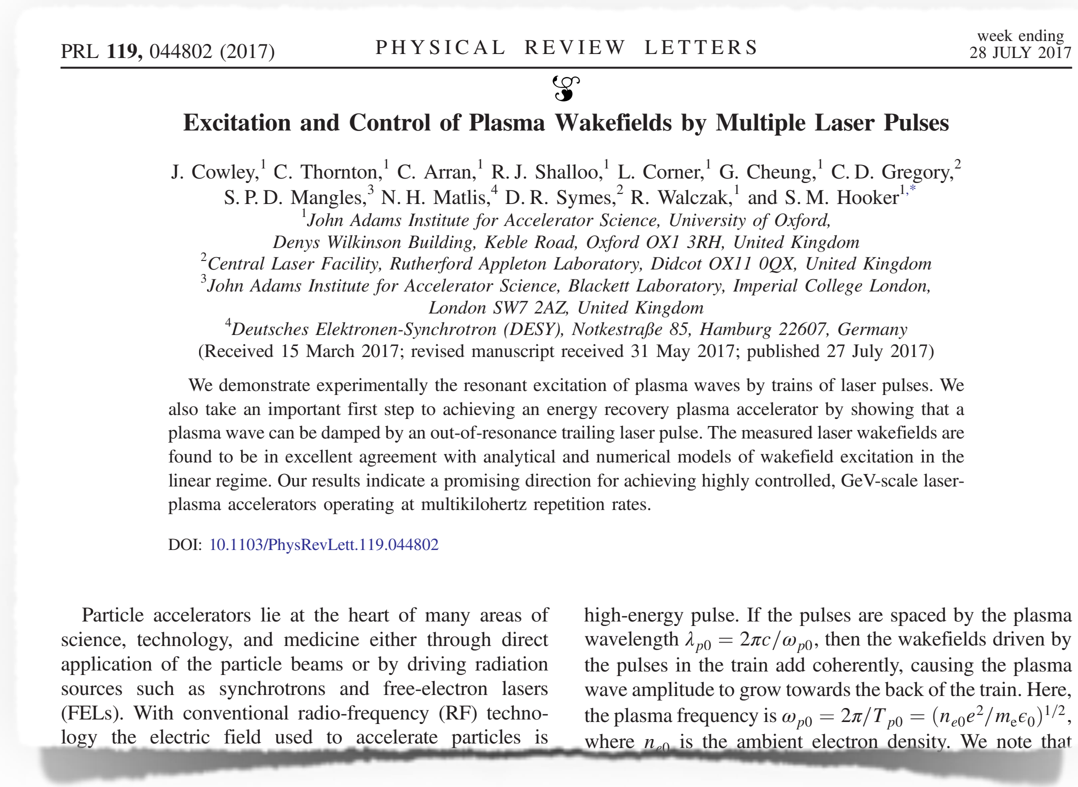
Rutherford Appleton Laboratory

N.H. Matlis

Centre for Free-Electron Laser Science, DESY, Hamburg

S.P.D. Mangles

John Adams Institute for Accelerator Science & Imperial College, London


PRL 119, 044802 (2017) PHYSICAL REVIEW LETTERS week ending 28 JULY 2017

Excitation and Control of Plasma Wakefields by Multiple Laser Pulses

J. Cowley,[1] C. Thornton,[1] C. Arran,[1] R. J. Shalloo,[1] L. Corner,[1] G. Cheung,[1] C. D. Gregory,[2] S. P. D. Mangles,[3] N. H. Matlis,[4] D. R. Symes,[2] R. Walczak,[1] and S. M. Hooker[1,*]

[1]*John Adams Institute for Accelerator Science, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom*

[2]*Central Laser Facility, Rutherford Appleton Laboratory, Didcot OX11 0QX, United Kingdom*

[3]*John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom*

[4]*Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, Hamburg 22607, Germany*

(Received 15 March 2017; revised manuscript received 31 May 2017; published 27 July 2017)

We demonstrate experimentally the resonant excitation of plasma waves by trains of laser pulses. We also take an important first step to achieving an energy recovery plasma accelerator by showing that a plasma wave can be damped by an out-of-resonance trailing laser pulse. The measured laser wakefields are found to be in excellent agreement with analytical and numerical models of wakefield excitation in the linear regime. Our results indicate a promising direction for achieving highly controlled, GeV-scale laser-plasma accelerators operating at multikilohertz repetition rates.

DOI: 10.1103/PhysRevLett.119.044802

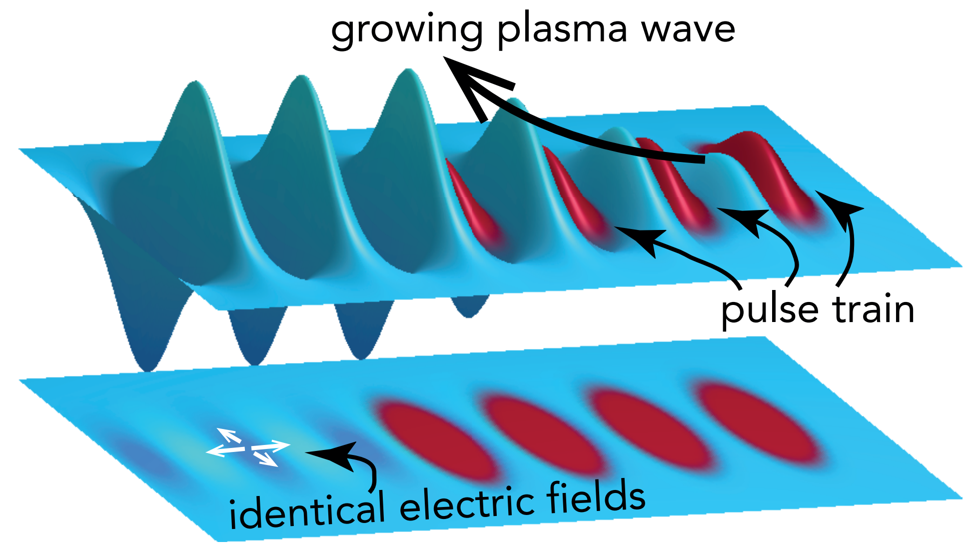
Particle accelerators lie at the heart of many areas of science, technology, and medicine either through direct application of the particle beams or by driving radiation sources such as synchrotrons and free-electron lasers (FELs). With conventional radio-frequency (RF) technology the electric field used to accelerate particles is

high-energy pulse. If the pulses are spaced by the plasma wavelength $\lambda_{p0} = 2\pi c/\omega_{p0}$, then the wakefields driven by the pulses in the train add coherently, causing the plasma wave amplitude to grow towards the back of the train. Here, the plasma frequency is $\omega_{p0} = 2\pi/T_{p0} = (n_{e0}e^2/m_e\epsilon_0)^{1/2}$, where n_{e0} is the ambient electron density. We note that

Multi-pulse laser wakefield acceleration

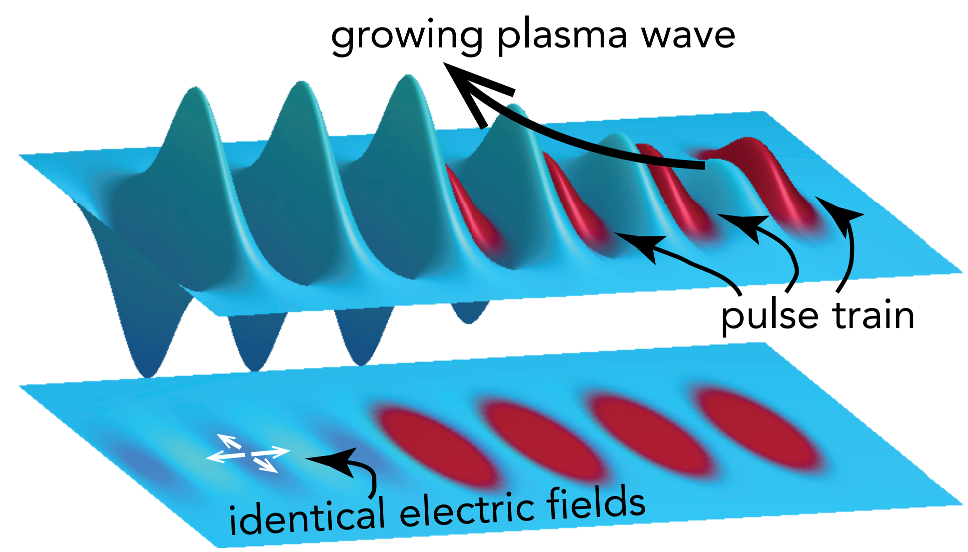
S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

- 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
  - Similar efforts underway for PWFAs
- Allows use of different laser technologies
  - Fibre lasers: 5.7 mJ, 200 fs @ 40 kHz [Klenke et al. Opt. Lett. **39** 6875 (2014)
  - Thin-disk Nd:YAG: 0.2 - 1 J, 1 ps at 5 kHz commercially available
- Could be route to multi-kHz repetition rates with high wall-plug efficiency
- 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!

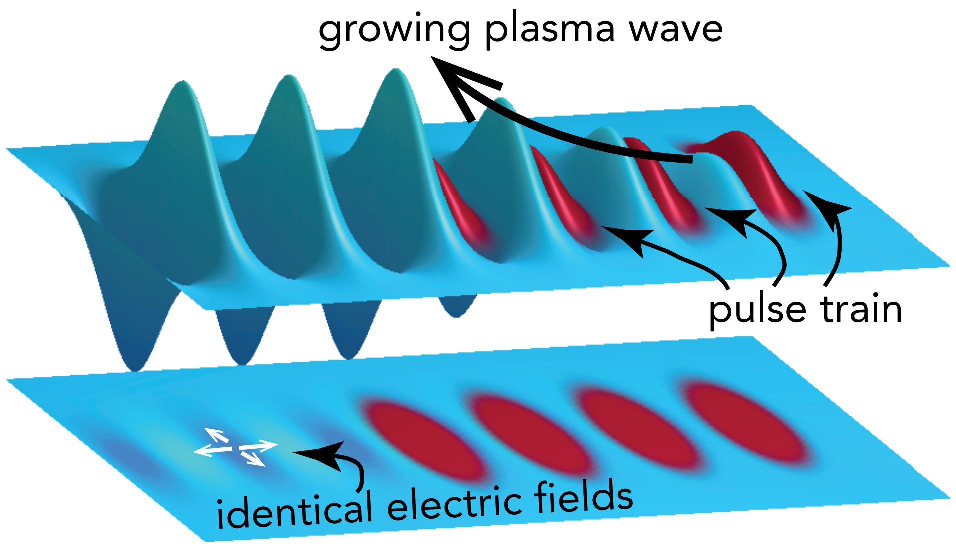
Isn’t that just beat-wave?



Isn't that just beat-wave?

Yes

- Takes advantage of resonant excitation
- One way to generate train would be to interfere two, long pulses s.t. $\omega_2 - \omega_1 = \omega_p$



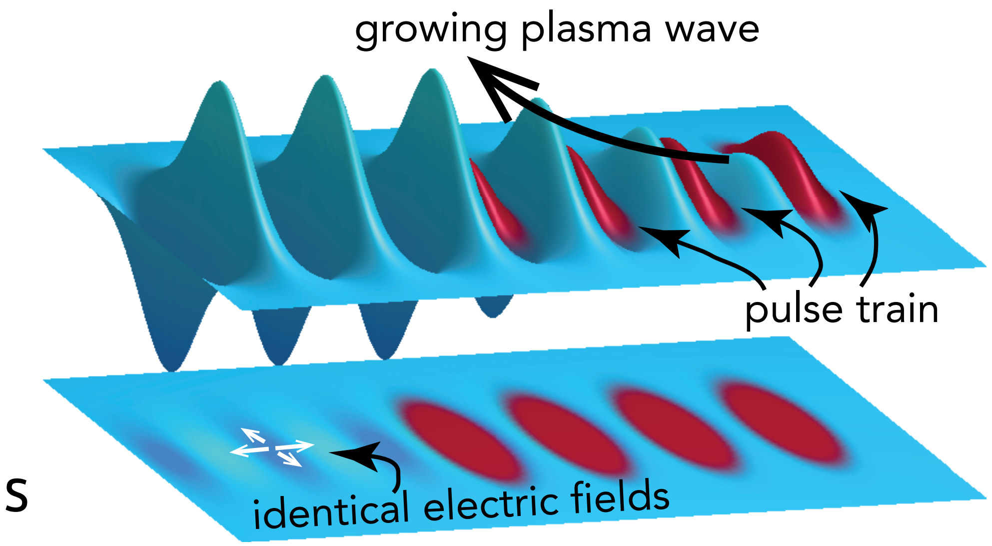
Isn't that just beat-wave?

Yes

- Takes advantage of resonant excitation
- <u>One</u> way to generate train would be to interfere two, long pulses s.t. $\omega_2 - \omega_1 = \omega_p$

No

- Much easier to find and lock to resonance
  - Total duration of pulse train **much shorter**: 1 - 30ps (i.e. N = 10 - 100), compared to 100ps - 1 ns in earlier work..
  - Relative error in density ~ $1/N$
  - Repetition rate of lasers at least **1000× higher**
- Not limited by relativistic detuning (Rosenbluth-Liu)
  - Pulse / modulation spacing **does not have to be fixed**
  - Deutsch *et al. Phys. Fluids* **B** 3 1773 - 1780 (1991)



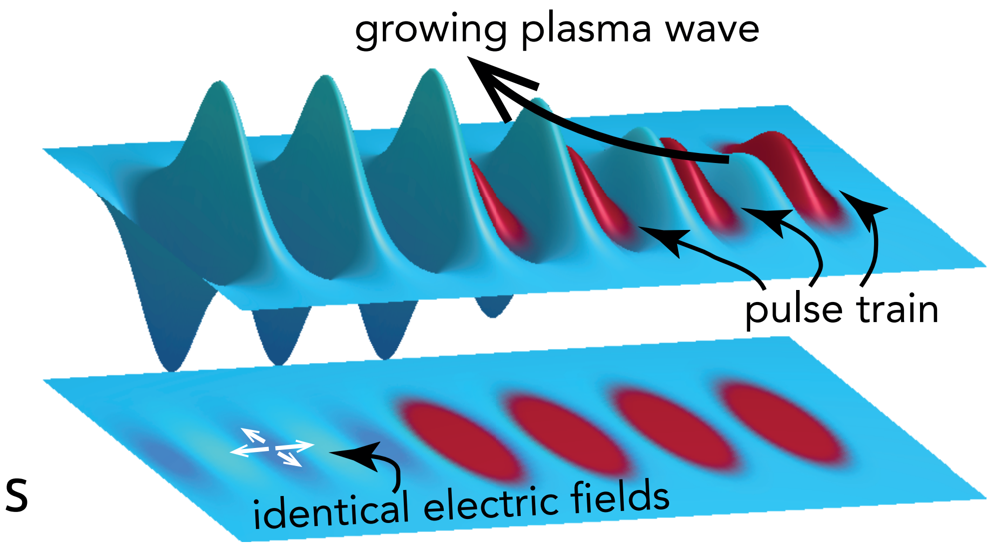
Isn't that just beat-wave?

Yes

- Takes advantage of resonant excitation
- One way to generate train would be to interfere two, long pulses s.t. $\omega_2 - \omega_1 = \omega_p$

No

- Much easier to find and lock to resonance
  - Total duration of pulse train **much shorter**: 1 - 30ps (i.e. N = 10 - 100), compared to 100ps - 1 ns in earlier work..
  - Relative error in density ~ $1/N$
  - Repetition rate of lasers at least **1000× higher**
- Not limited by relativistic detuning (Rosenbluth-Liu)
  - Pulse / modulation spacing **does not have to be fixed**
  - Deutsch *et al. Phys. Fluids* **B** 3 1773 - 1780 (1991)

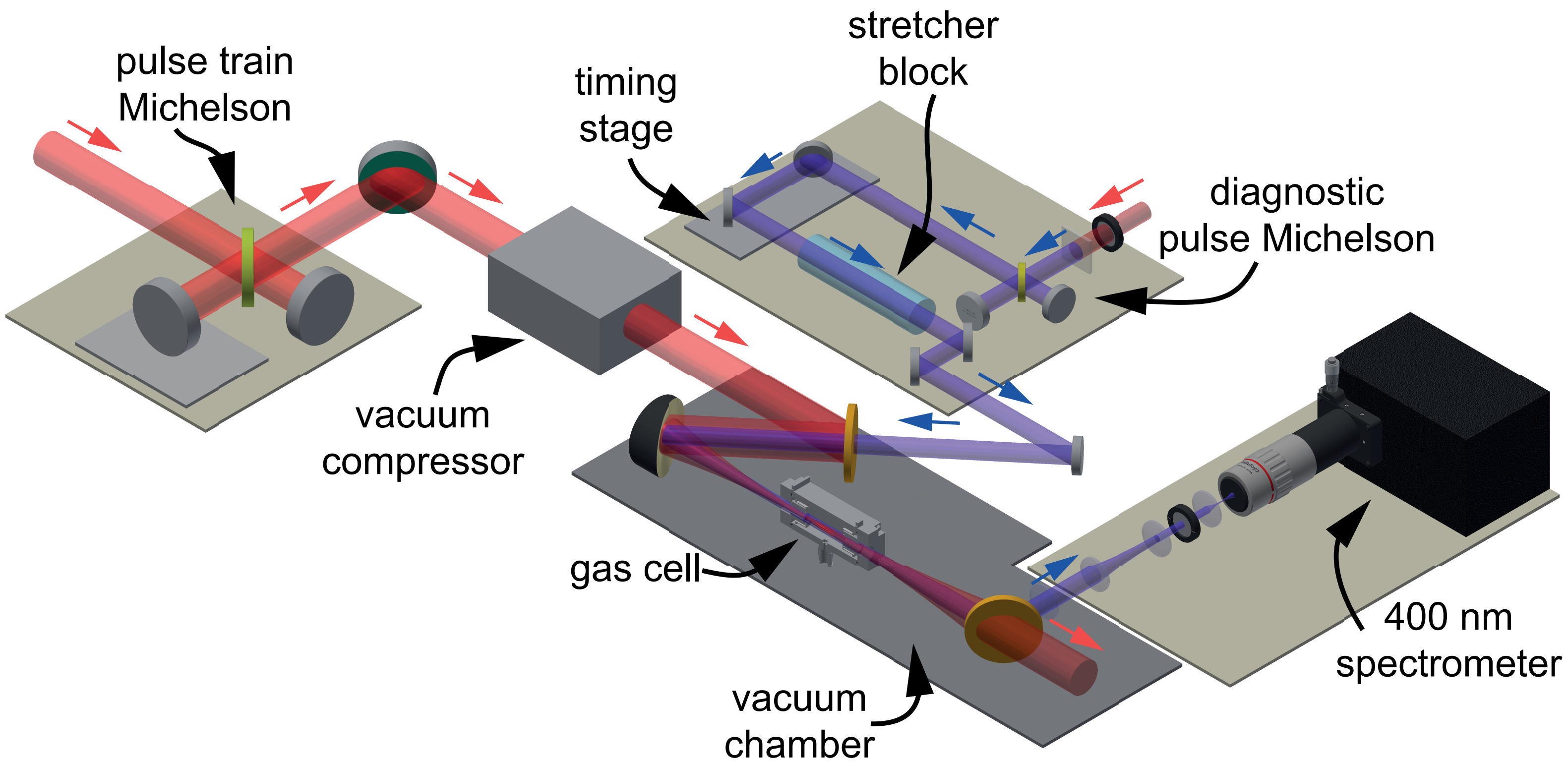


See Roman Walczak's talk WG5 Tue 18:40

Proof-of-principle demonstration

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

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



- Expts with Astra 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

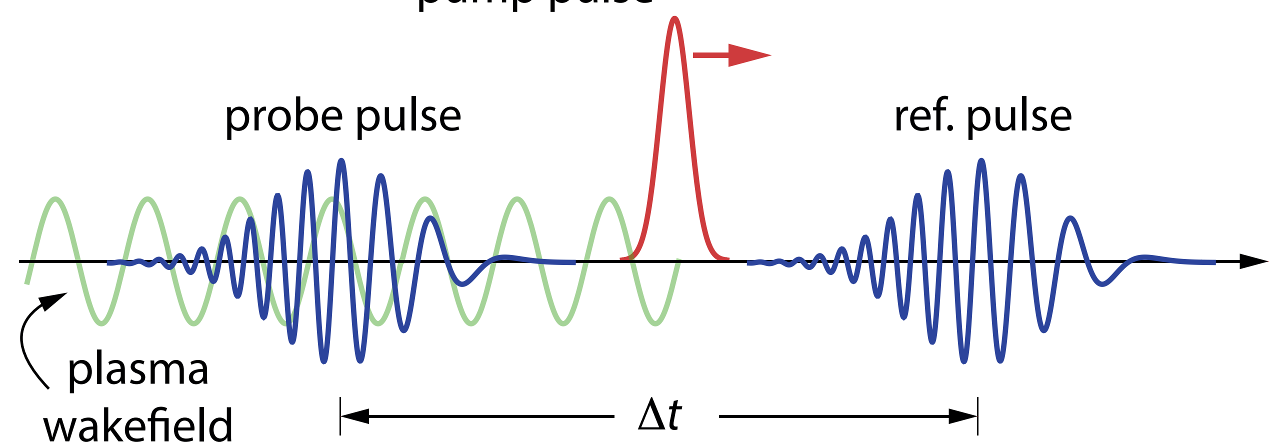
Gas cell target

Frequency-domain holography

N.H. Matlis *et al. Nat. Phys* **2** 749 (2006)

- Probe accumulates phase with propagation

$$\Delta\phi_{\mathrm{p}} \approx \frac{\omega_{\mathrm{p0}}^2}{2\omega_{\mathrm{probe}}c}\int \frac{n_{\mathrm{e}}(\zeta, z)}{n_{\mathrm{e0}}}dz$$



- Frequency maps to position ζ relative to pulse(s)
- Spectral interference with (identical) reference pulse allows phase shift to be determined

FDH signal

$$\left|\tilde{E}(\omega)\right|^2 = \left|\tilde{E}_{\mathrm{probe}}(\omega)\right|^2 + \left|\tilde{E}_{\mathrm{ref}}(\omega)\right|^2 + 2\left|\tilde{E}_{\mathrm{probe}}(\omega)\right|\left|\tilde{E}_{\mathrm{ref}}(\omega)\right|\cos\left(\omega\Delta t + \Delta\phi\right)$$

- Knowing the probe & ref spectra, and Δ*t*, allows Δφ to be extracted

TESS

N. H. Matlis *et al.* *Opt. Lett.* **41** 5503 (2016)

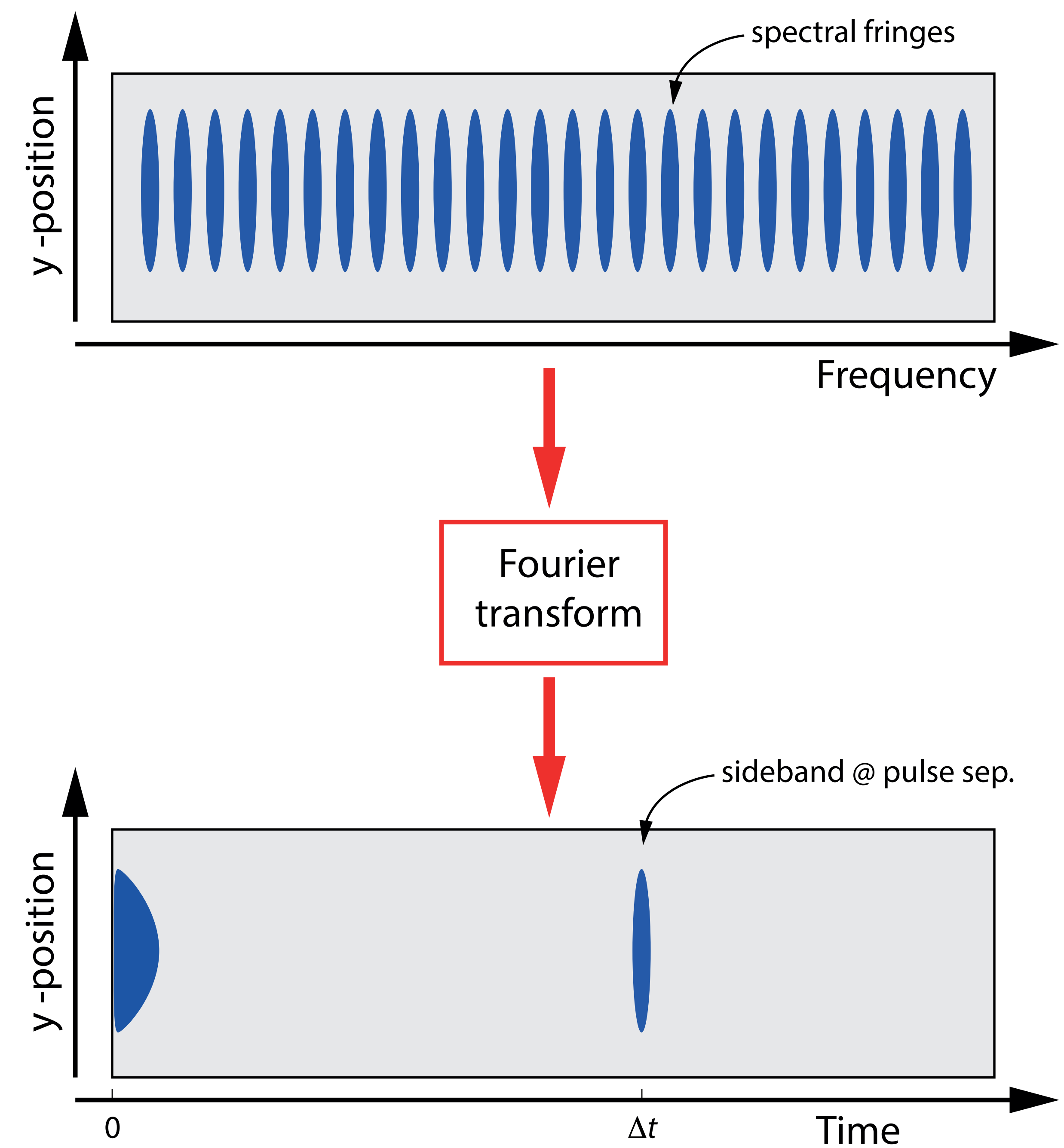
- Temporally-encoded spectral shifting (TESS)
- Assume plasma wave is sinusoidal

$$\Delta\phi_{\mathrm{p}} \approx \frac{\omega_{\mathrm{p0}}^2}{2\omega_{\mathrm{probe}}} \frac{\ell}{c} \frac{\delta n_{\mathrm{e}}}{n_{\mathrm{e0}}} \sin\left(\omega_{\mathrm{p0}}\zeta + \theta\right)$$

- Probe contains terms of form,

$$\begin{aligned} \exp\left(i\Delta\phi_{\mathrm{p}}\right) &= \exp\left[i\beta \sin\left(\omega_{\mathrm{p0}}\zeta + \theta\right)\right] \\ &= \sum_{m=-\infty}^{\infty} J_m(\beta) \exp\left[im\left(\omega_{\mathrm{p0}}\zeta + \theta\right)\right] \end{aligned}$$

- Fourier transform of interferogram:
  - Sideband at probe-ref pulse spacing: $t = T$
  - Satellites at $t = T \pm m\,\omega_{\mathrm{p}} \times \psi^{(2)}$ **give plasma period**
  - Ratio of satellite(s) to sideband **gives wake amplitude**



TESS

N. H. Matlis *et al. Opt. Lett.* **41** 5503 (2016)

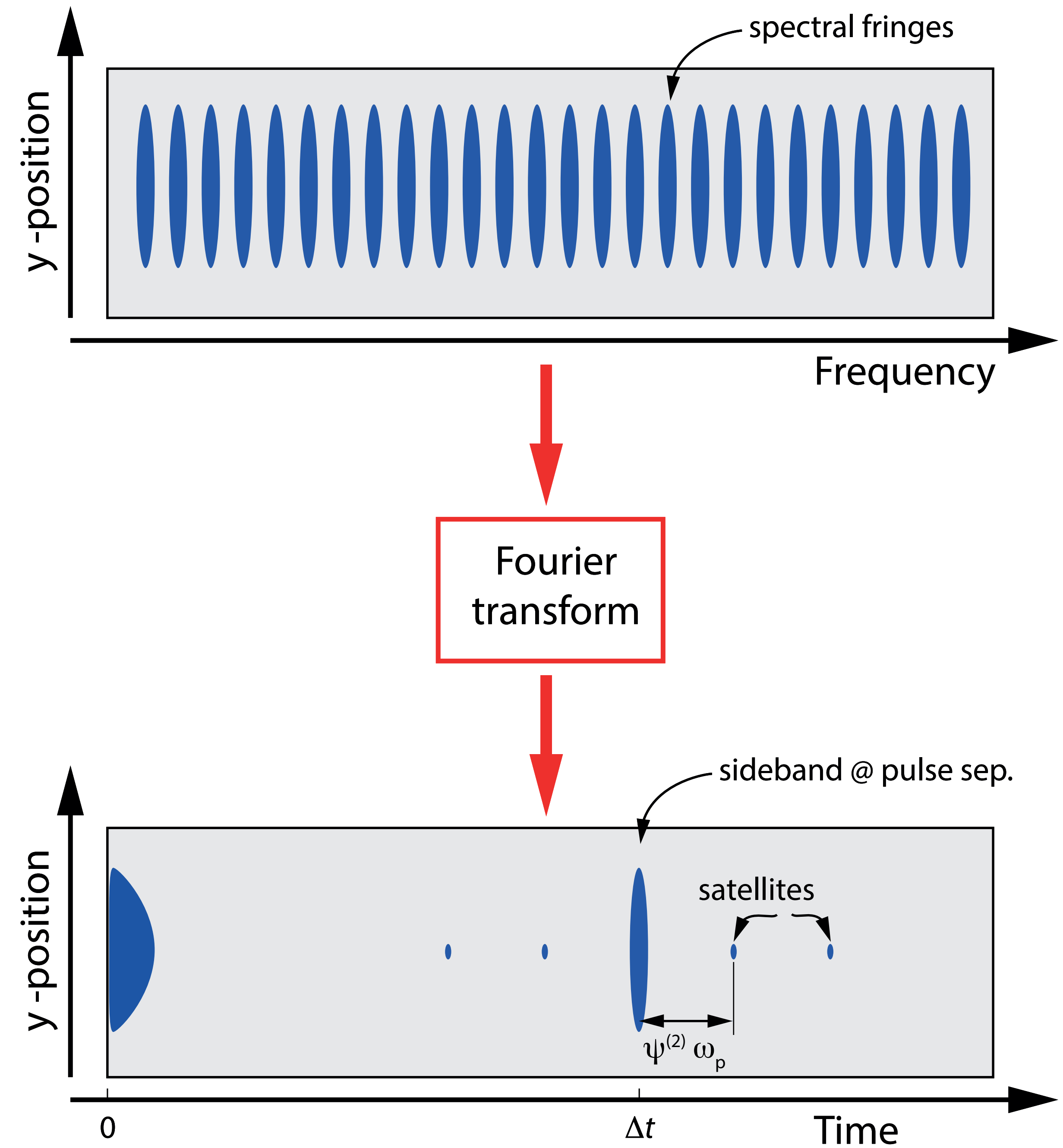
- Temporally-encoded spectral shifting (TESS)
- Assume plasma wave is sinusoidal

$$\Delta\phi_\mathrm{p} \approx \frac{\omega_\mathrm{p0}^2}{2\omega_\mathrm{probe}} \frac{\ell}{c} \frac{\delta n_\mathrm{e}}{n_\mathrm{e0}} \sin\left(\omega_\mathrm{p0}\zeta + \theta\right)$$

- Probe contains terms of form,

$$\begin{aligned} \exp\left(i\Delta\phi_\mathrm{p}\right) &= \exp\left[i\beta \sin\left(\omega_\mathrm{p0}\zeta + \theta\right)\right] \\ &= \sum_{m=-\infty}^{\infty} J_m\left(\beta\right) \exp\left[im\left(\omega_\mathrm{p0}\zeta + \theta\right)\right] \end{aligned}$$

- Fourier transform of interferogram:
  - Sideband at probe-ref pulse spacing: $t = T$
  - Satellites at $t = T \pm m\,\omega_\mathrm{p} \times \psi^{(2)}$ **give plasma period**
  - Ratio of satellite(s) to sideband **gives wake amplitude**



John Adams Institute for Accelerator Science

TESS

N. H. Matlis *et al.* *Opt. Lett.* **41** 5503 (2016)

- Temporally-encoded spectral shifting (TESS)
- Assume plasma wave is sinusoidal

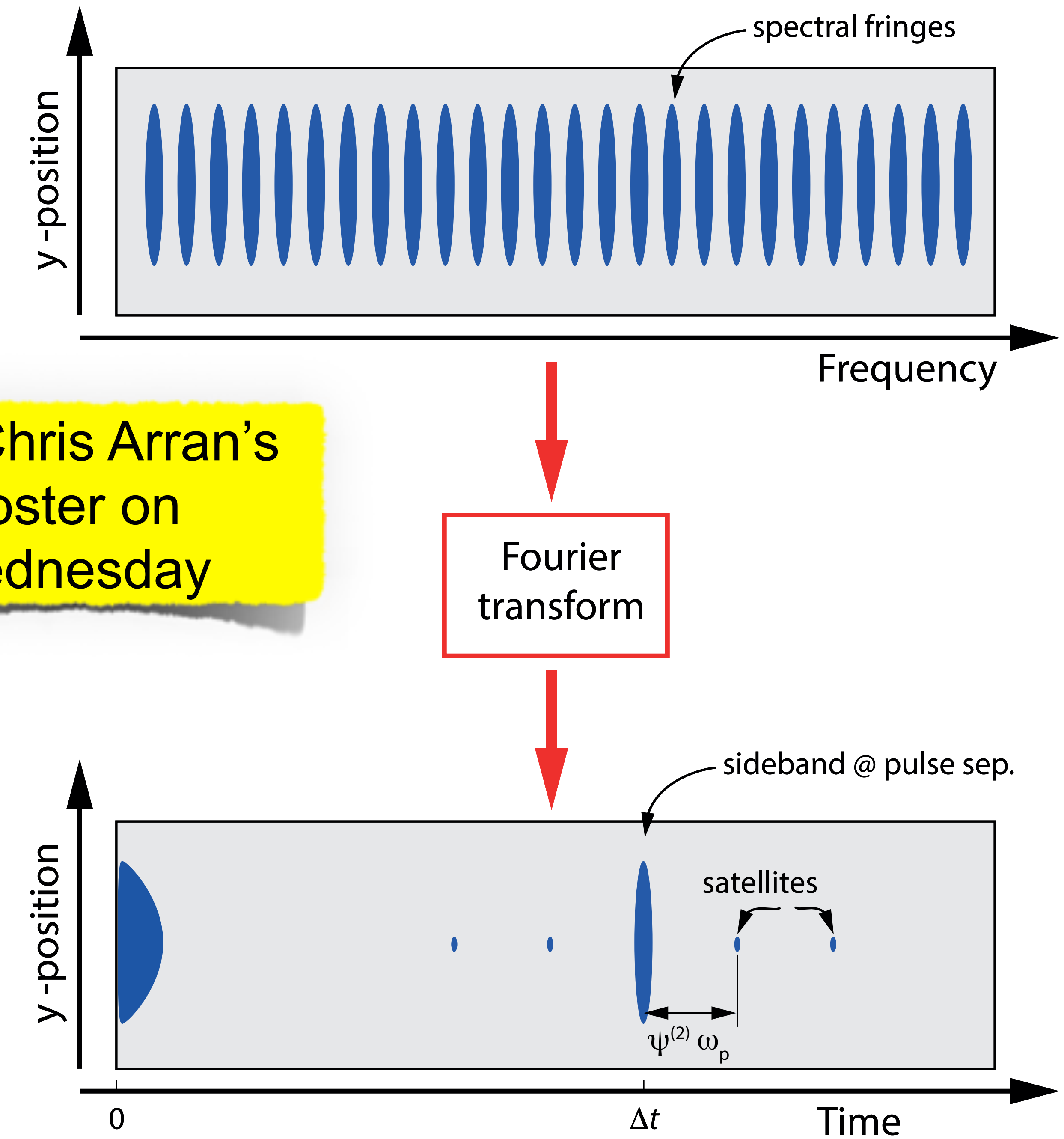
$$\Delta\phi_{\mathrm{p}} \approx \frac{\omega_{\mathrm{p0}}^2}{2\omega_{\mathrm{probe}}} \frac{\ell}{c} \frac{\delta n_{\mathrm{e}}}{n_{\mathrm{e0}}} \sin\left(\omega_{\mathrm{p0}}\zeta + \theta\right)$$

- Probe contains terms of form,

$$\begin{aligned}\exp\left(i\Delta\phi_{\mathrm{p}}\right) &= \exp\left[i\beta\sin\left(\omega_{\mathrm{p0}}\zeta + \theta\right)\right] \\ &= \sum_{m=-\infty}^{\infty} J_m\left(\beta\right)\exp\left[im\left(\omega_{\mathrm{p0}}\zeta + \theta\right)\right]\end{aligned}$$

- Fourier transform of interferogram:
  - Sideband at probe-ref pulse spacing: $t = T$
  - Satellites at $t = T \pm m\, \omega_{\mathrm{p}} \times \psi^{(2)}$ **give plasma period**
  - Ratio of satellite(s) to sideband **gives wake amplitude**

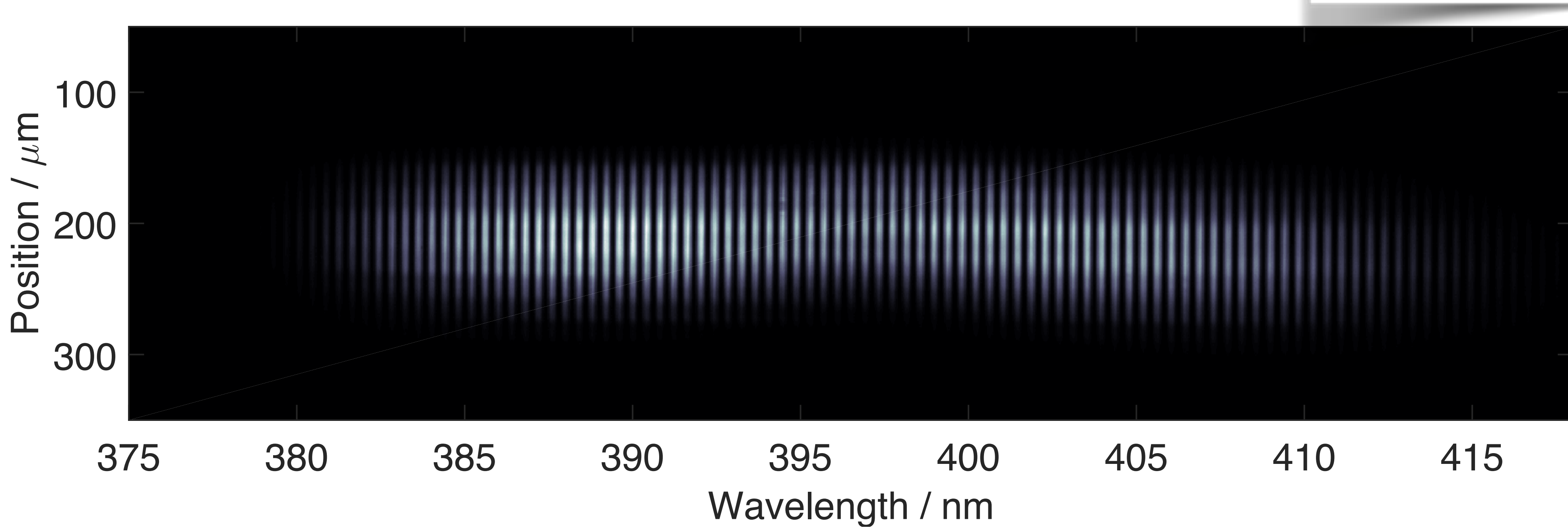
See Chris Arran's poster on Wednesday



UNIVERSITY OF OXFORD

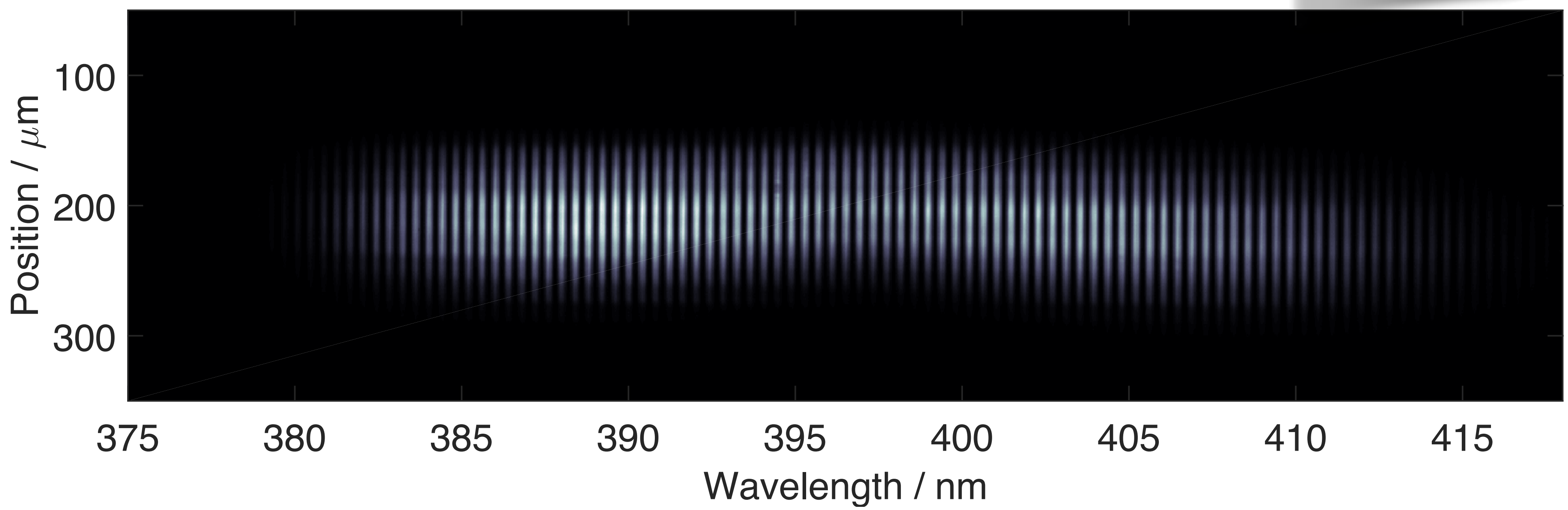
TESS with real data

Raw spectrum (no gas)

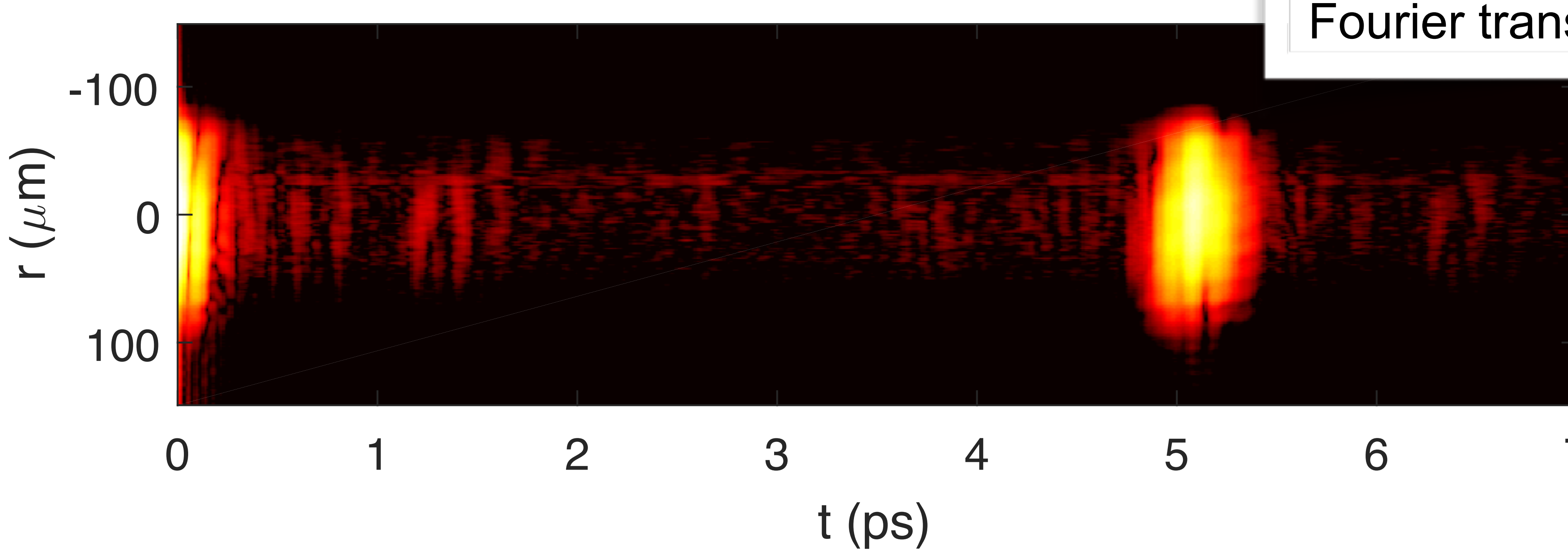


TESS with real data

Raw spectrum (no gas)

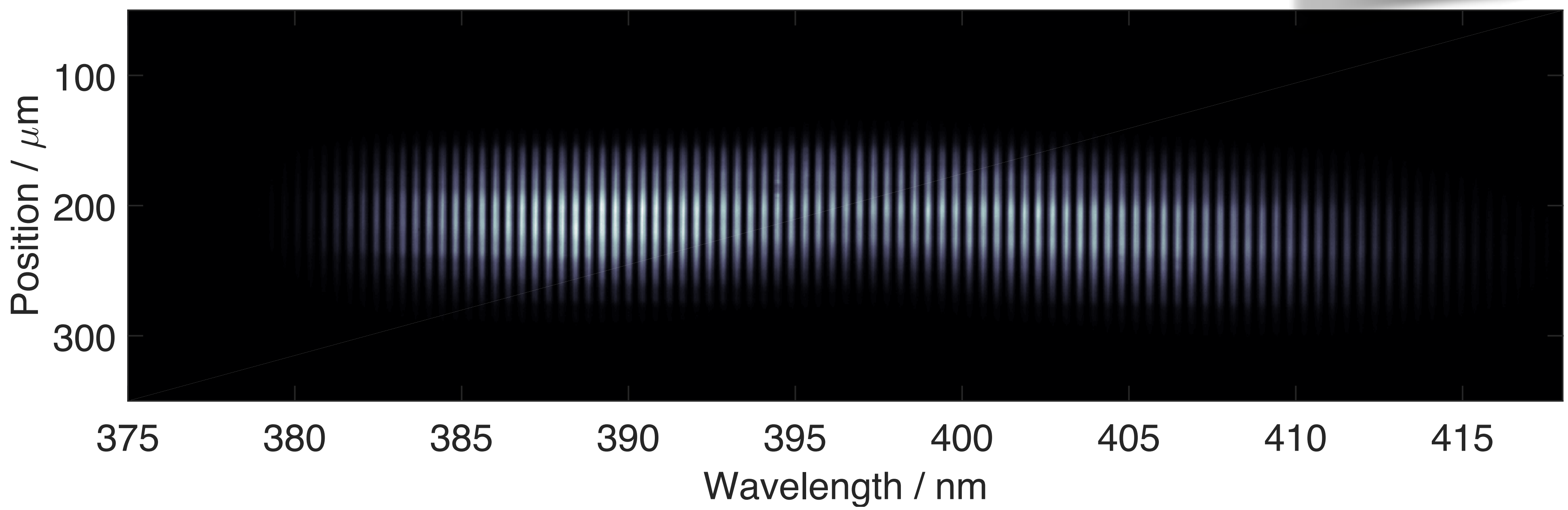


Fourier transform (no gas)

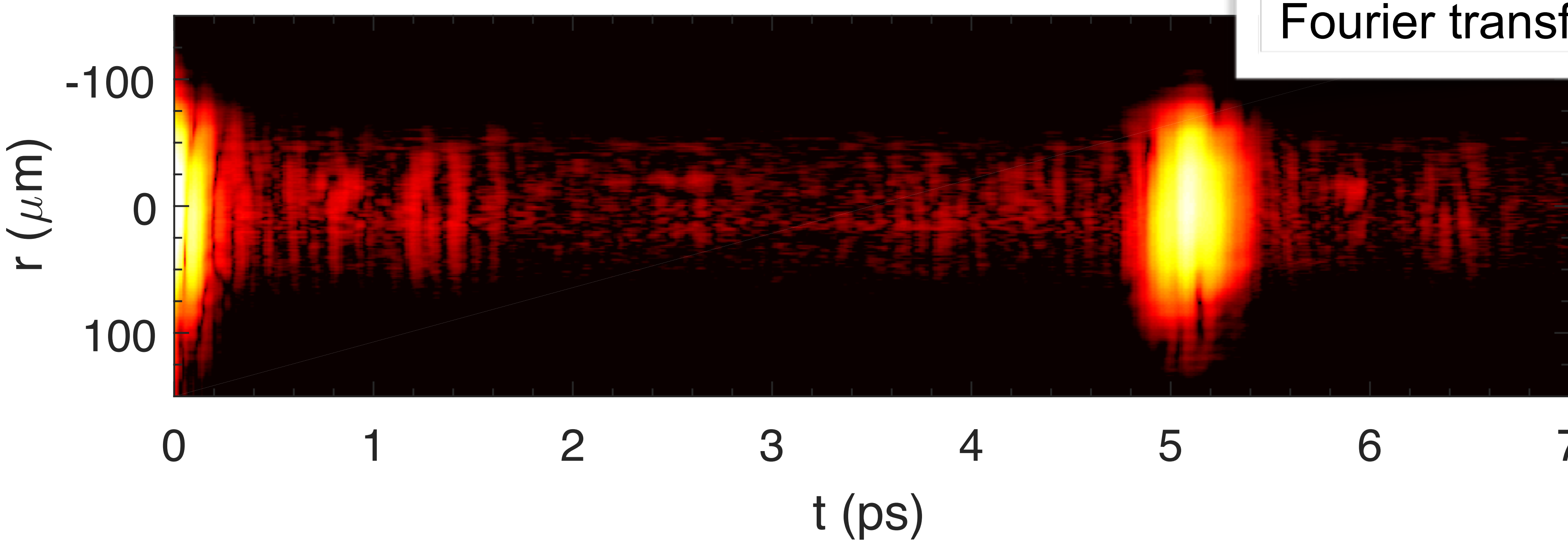


TESS with real data

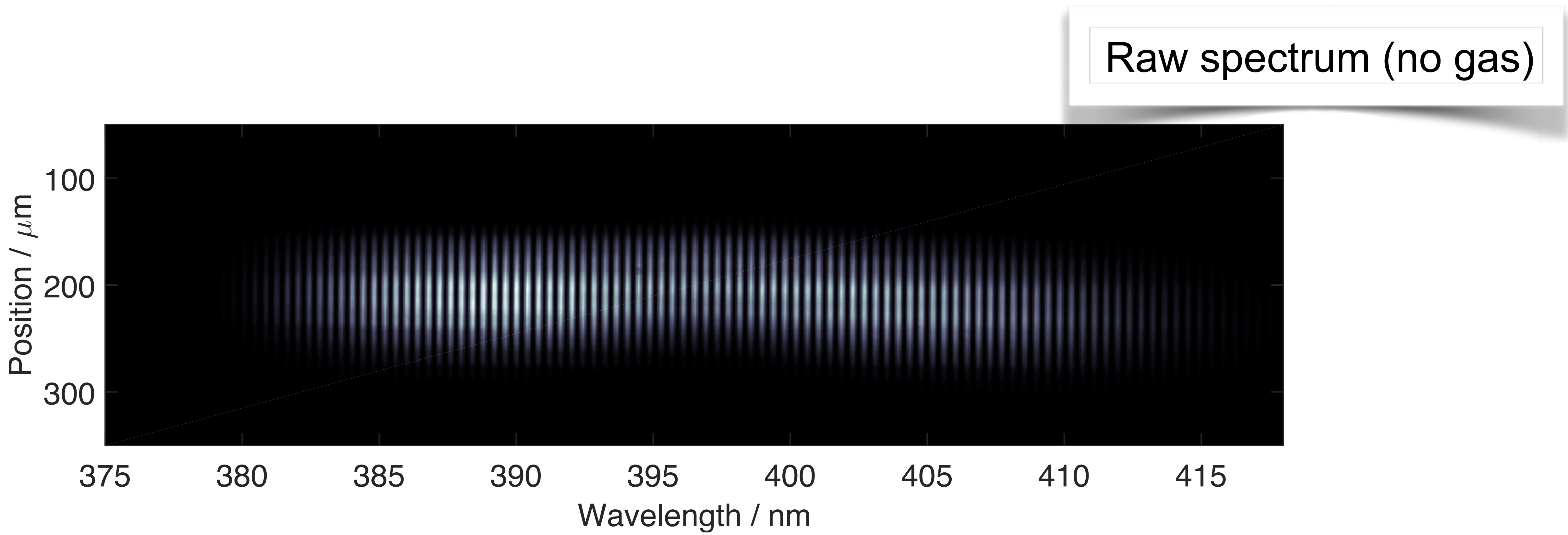
Raw spectrum (no gas)

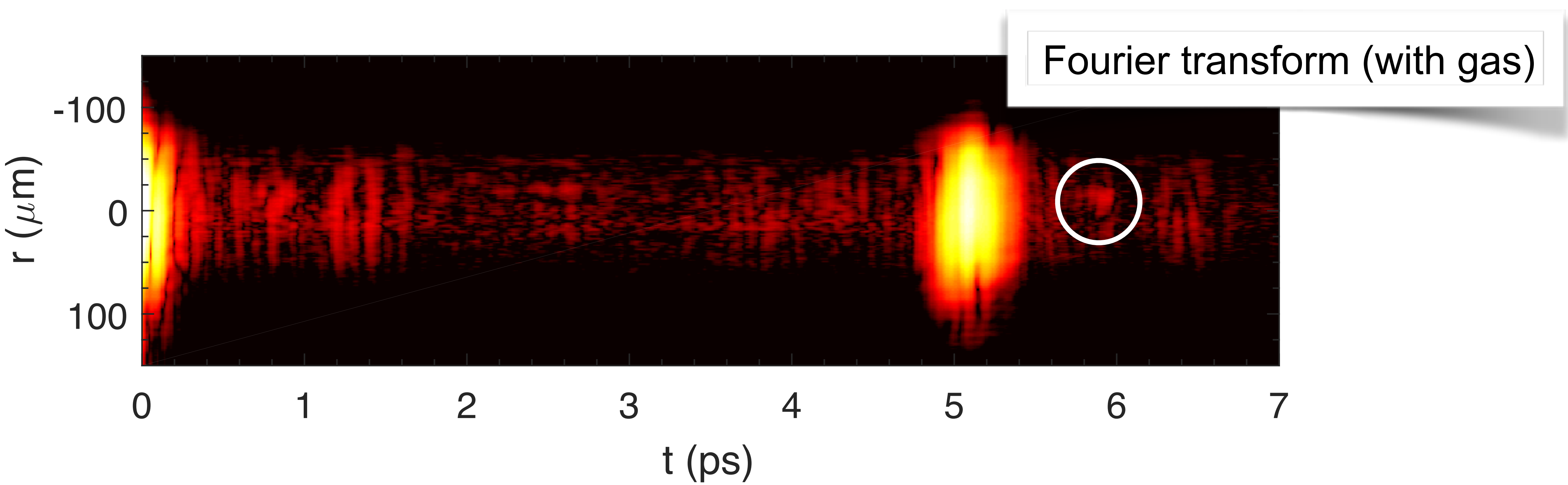


Fourier transform (with gas)



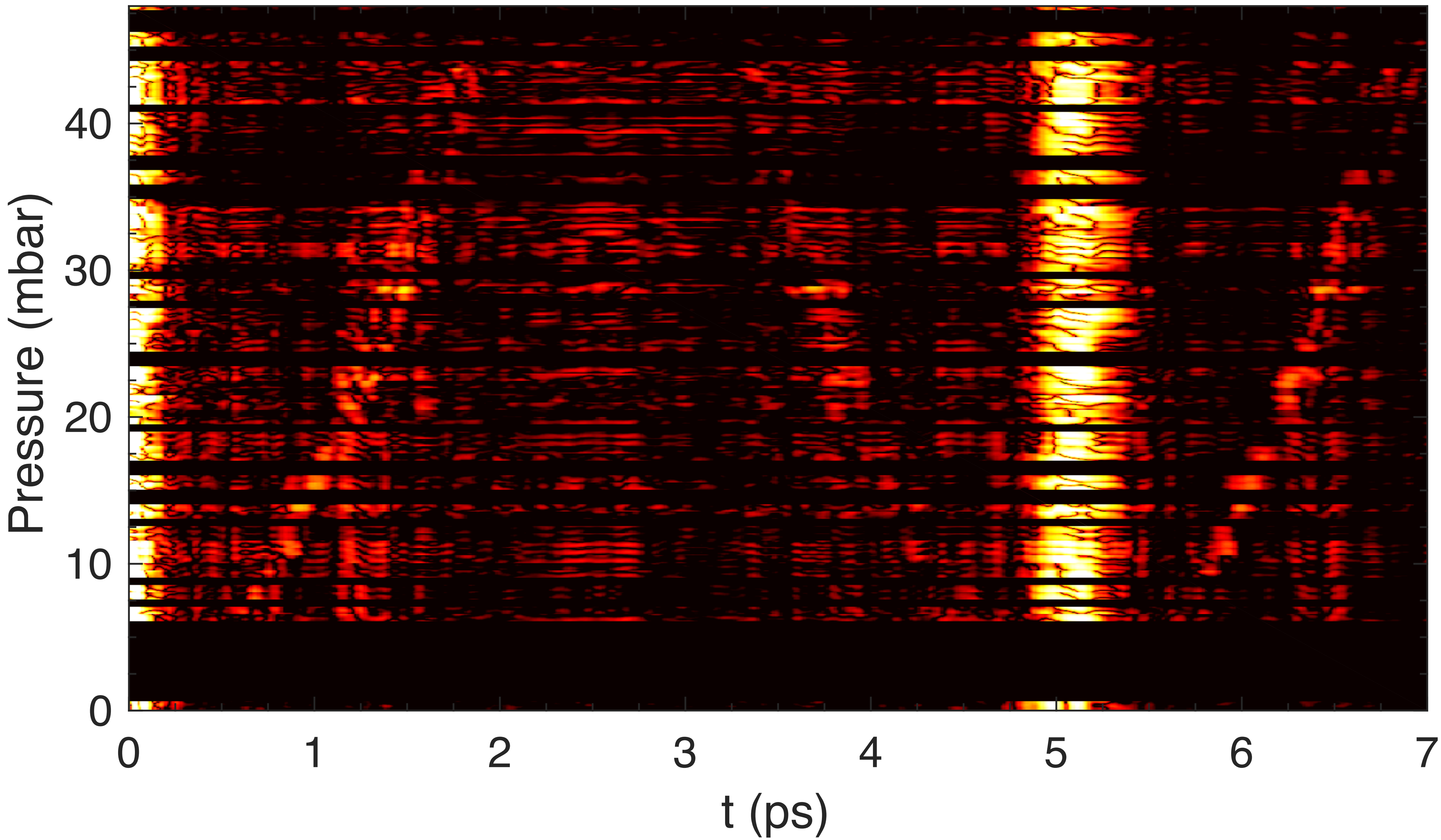
TESS with real data





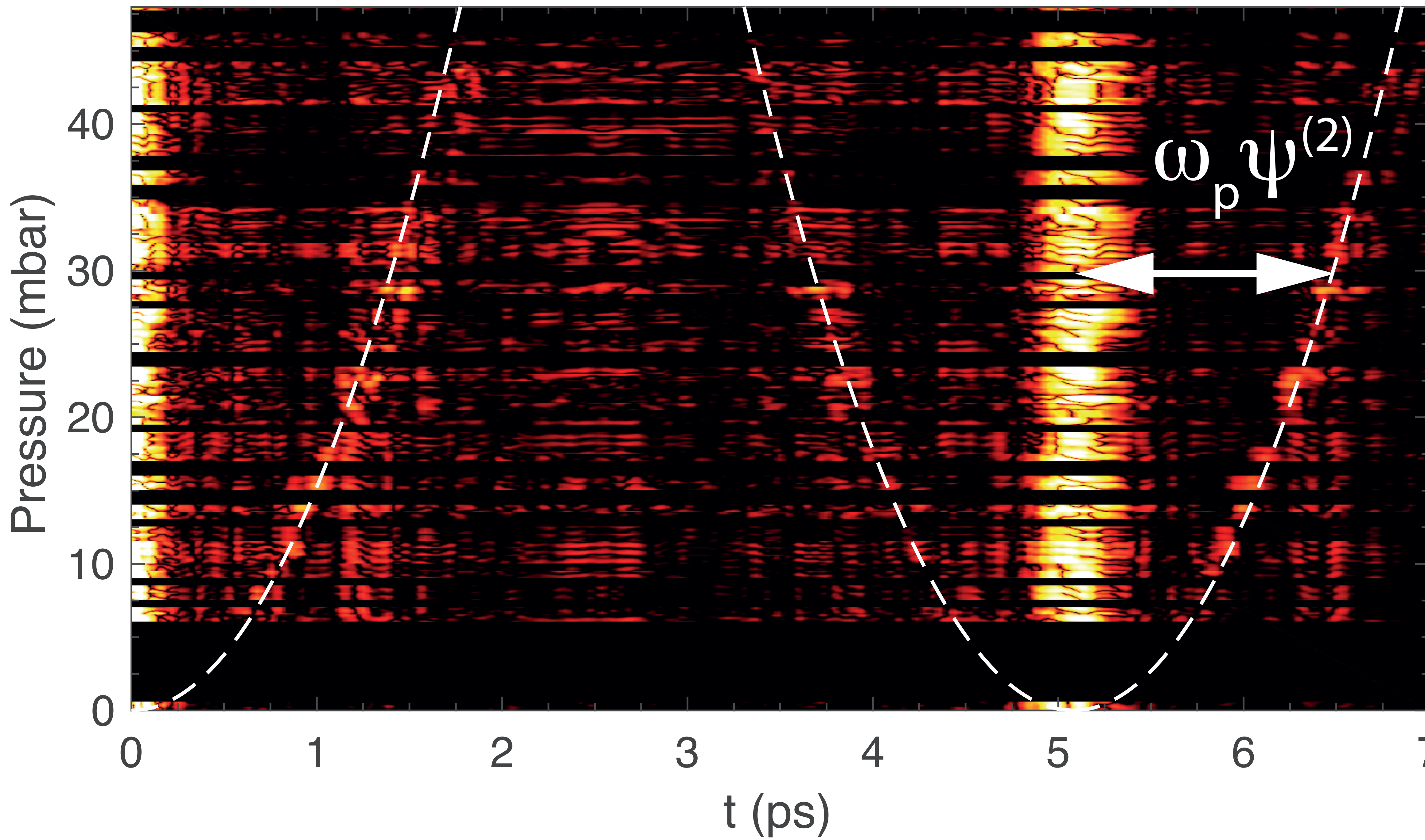
TESS waterfall

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



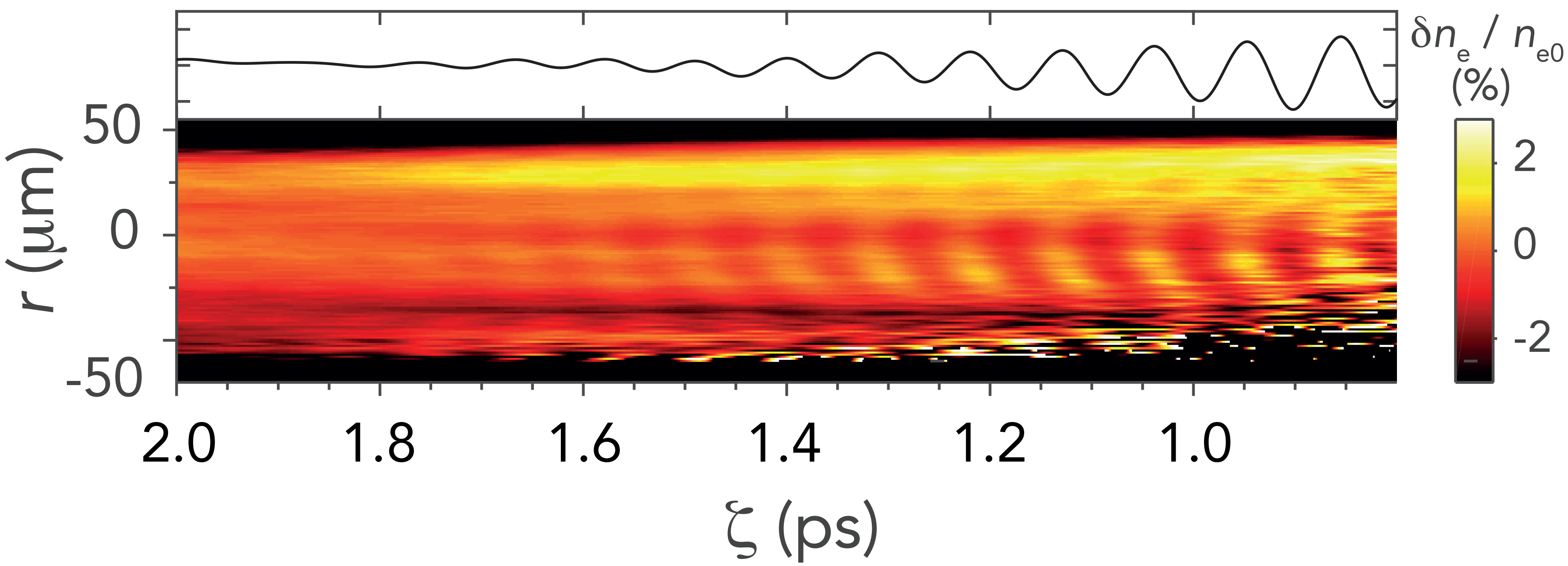
TESS waterfall

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



Single drive pulse: FDH retrieval of wakefield

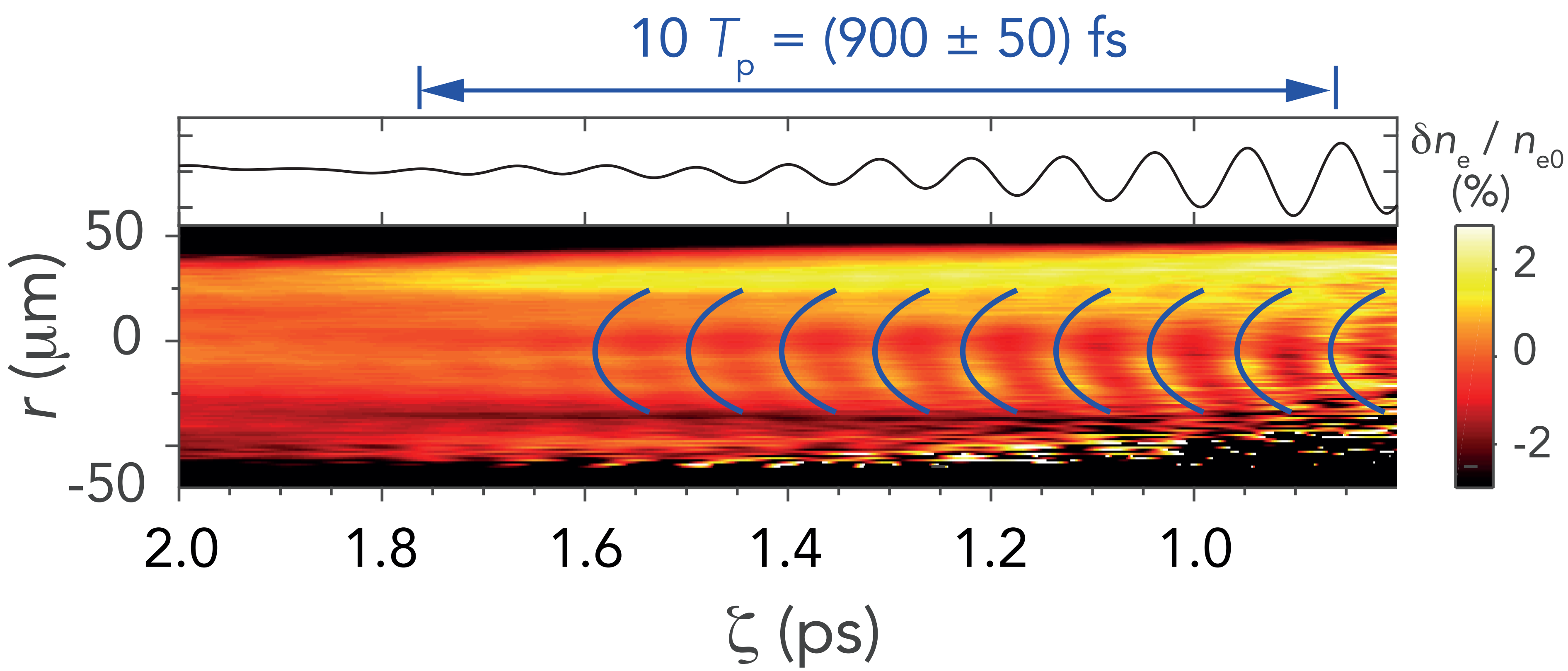
J. Cowley *et al.* *Phys. Rev. Lett.* **119** 044802 (2017)



- Wakefield clearly observed!

Single drive pulse: FDH retrieval of wakefield

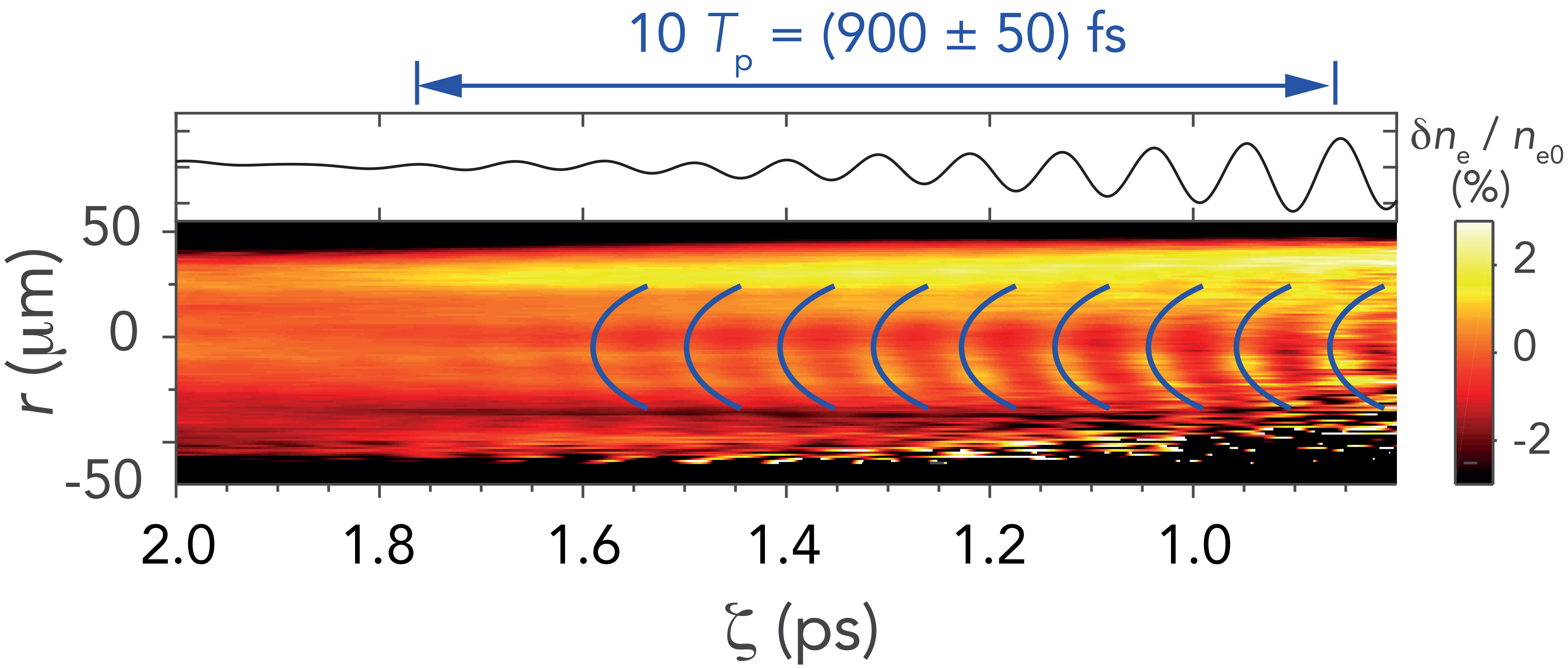
J. Cowley *et al. Phys. Rev. Lett.* **119** 044802 (2017)

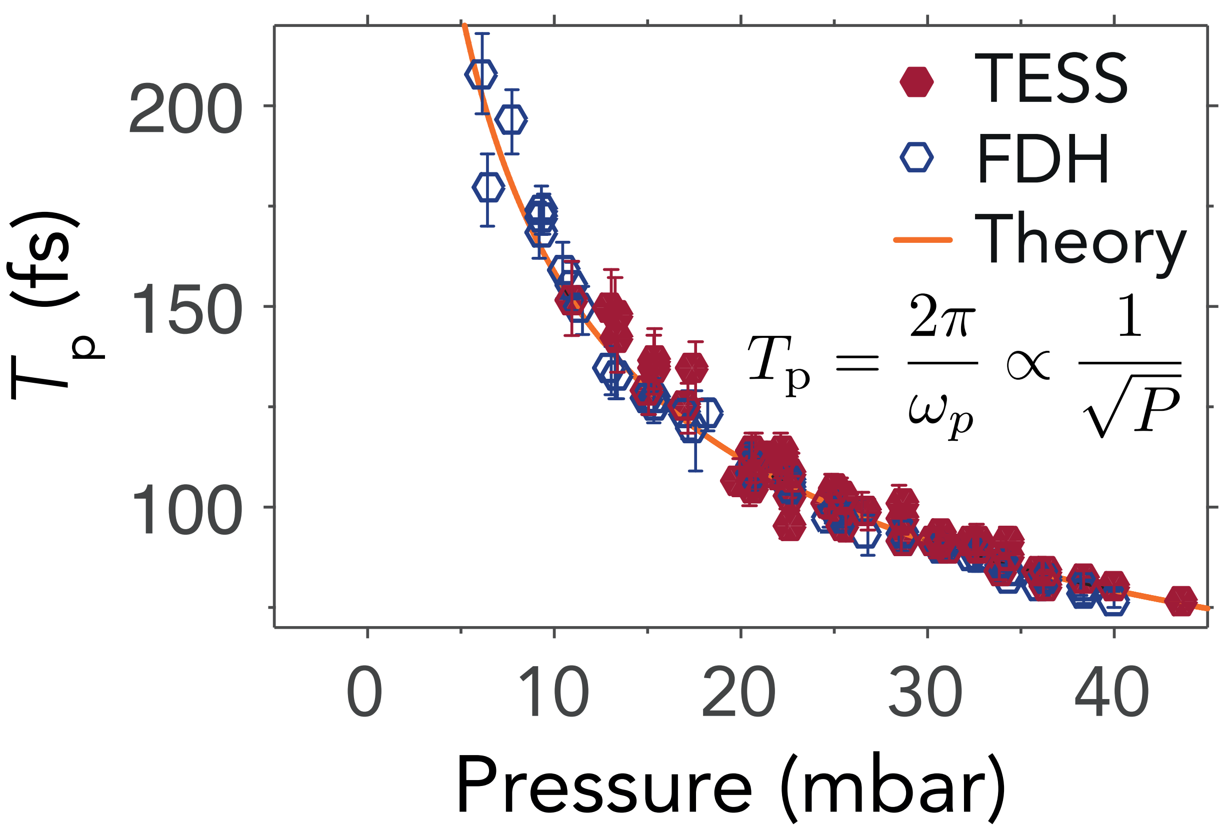


- Wakefield clearly observed!
- Measured plasma period agrees with expected value
  - P = 31 mbar ⇒ T_p = 90 fs

Single drive pulse: FDH retrieval of wakefield

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



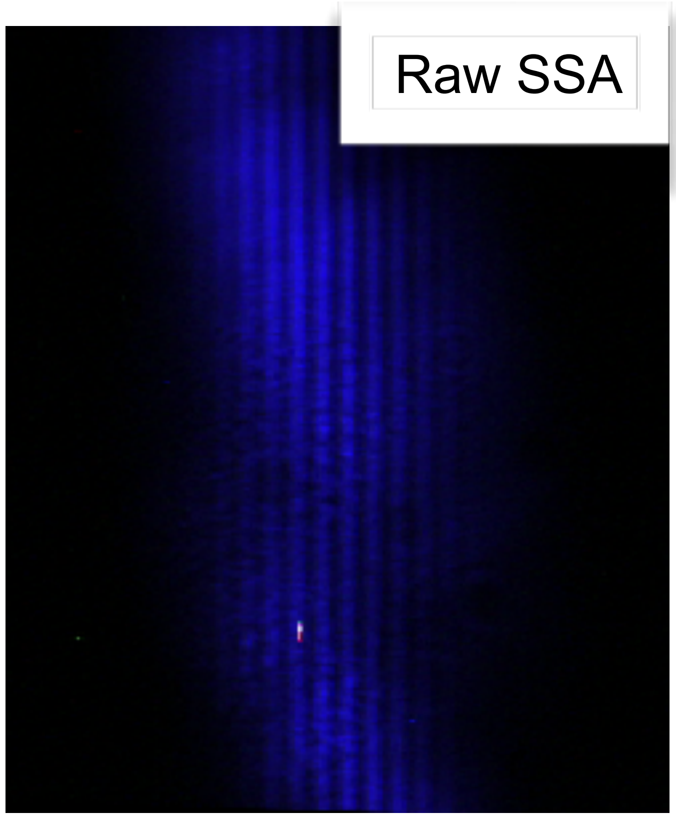


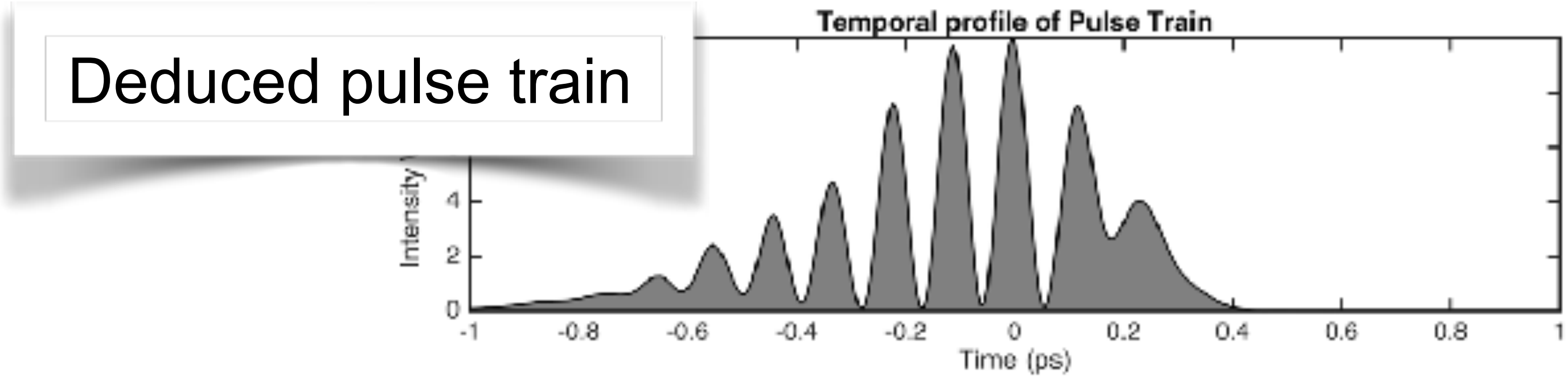
- Wakefield clearly observed!
- Measured plasma period agrees with expected value
  - P = 31 mbar ⇒ T_p = 90 fs
- FDH and TESS measurements consistent & agree with theory (no free parameters)

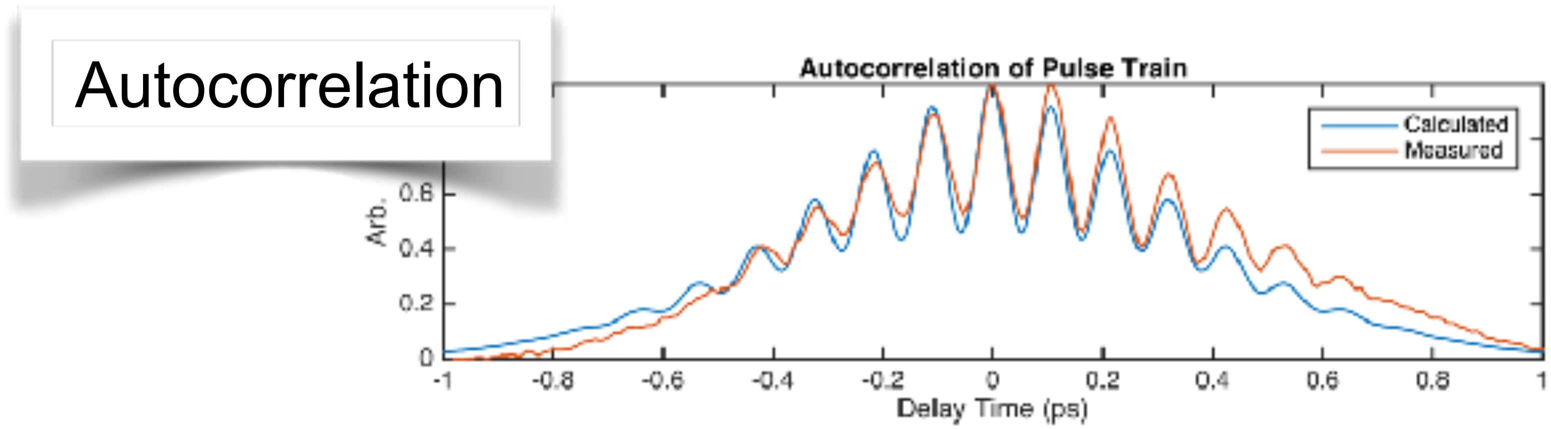
Wakefields excited by trains of pulses

Pulse train characterization

R. J. Shalloo *et al. Nucl. Instr. Meth. A* **829** 383 (2016)



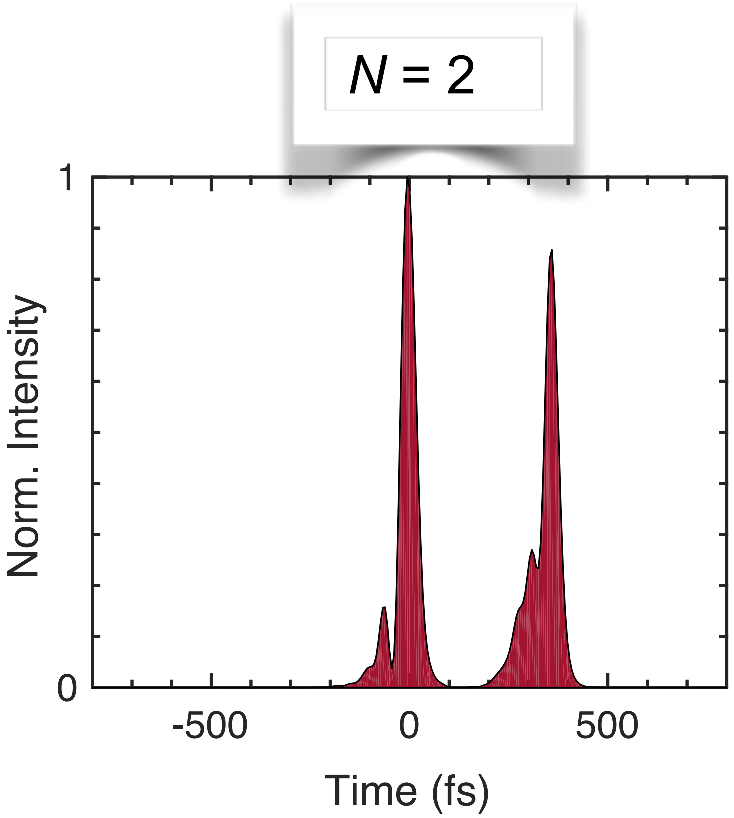




- Pulse trains characterized by comparing measured single-shot autocorrelation …
- with SSA calculated from
  - Measured laser spectrum
  - Compressor geometry

Two-pulse driver

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

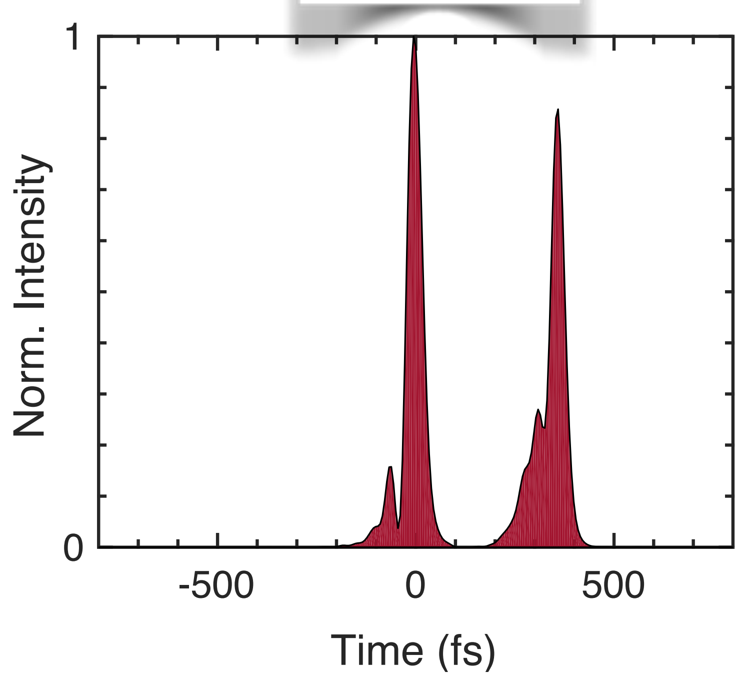


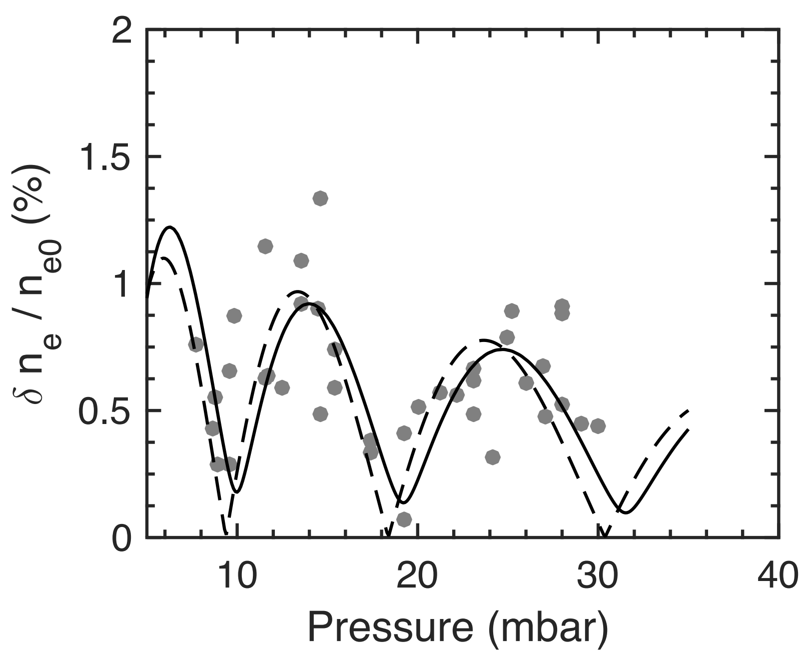
$$\frac{\delta n_e}{n_{e0}} = \left[\frac{\delta n_e}{n_{e0}}\right]_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{p0}\delta\tau\right)}\right|$$

Two-pulse driver

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

N = 2

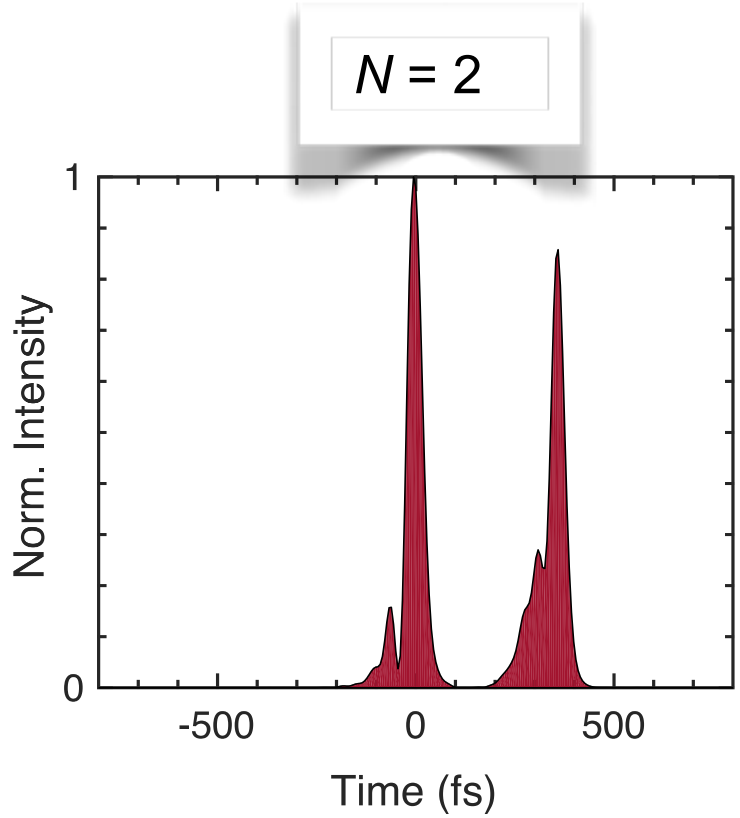


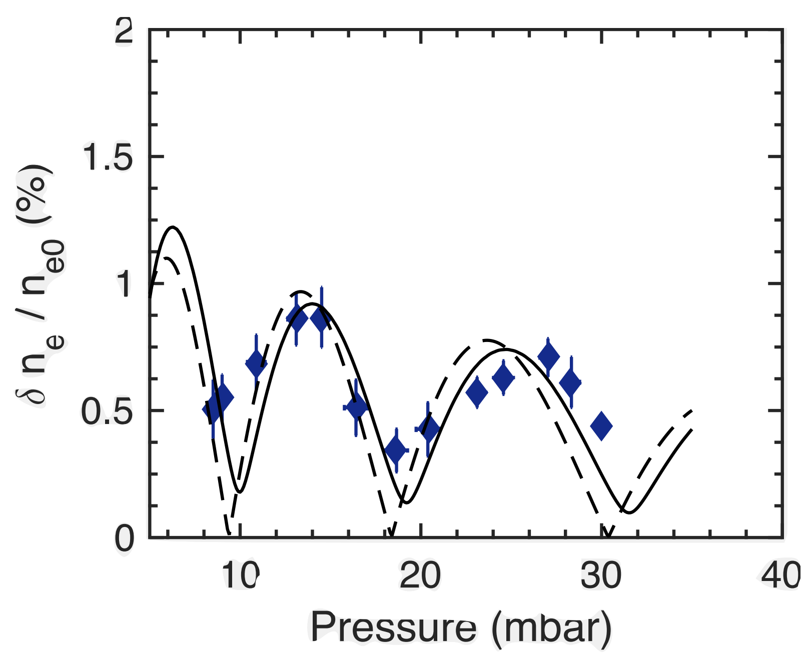


$$\frac{\delta n_e}{n_{e0}} = \left[\frac{\delta n_e}{n_{e0}}\right]_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{p0}\delta\tau\right)}\right|$$

Two-pulse driver

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





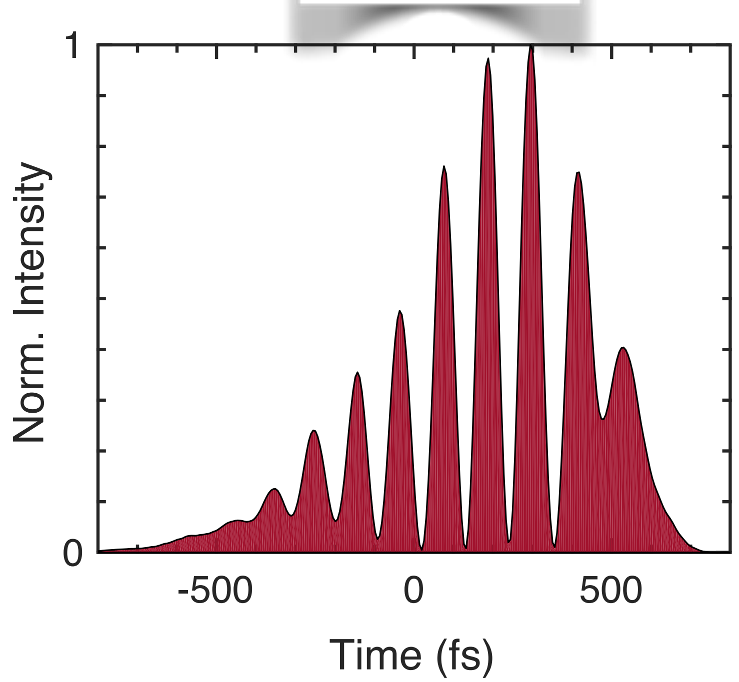
$$\frac{\delta n_e}{n_{e0}} = \left[\frac{\delta n_e}{n_{e0}}\right]_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{p0}\delta\tau\right)}\right|$$

- Excellent fit to analytic expression for *N* = 2
  - $\delta\tau$ = (407 ± 6) fs
  - SSA: $\delta\tau$ = (365 ± 40) fs
  - Spectra interference $\delta\tau$ = (420 ± 20) fs
- Even better agreement with fit of wake calculated from measured pulse train with $\zeta \rightarrow \alpha\zeta$
- Find α = 1.1 ± 0.02
- **Energy recovery!**
  - Wake amplitude reduced by (44 ± 8)%

Multi-pulse driver

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

$N \approx 7$

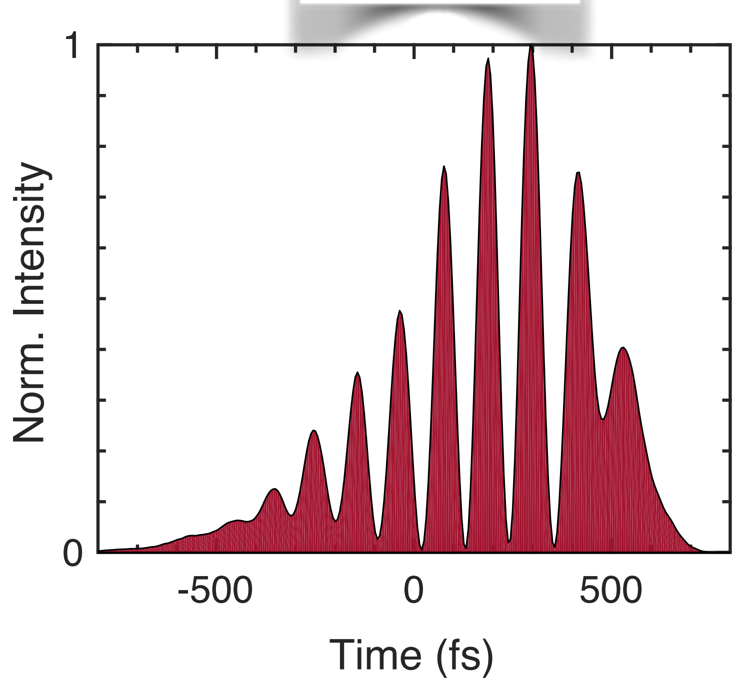


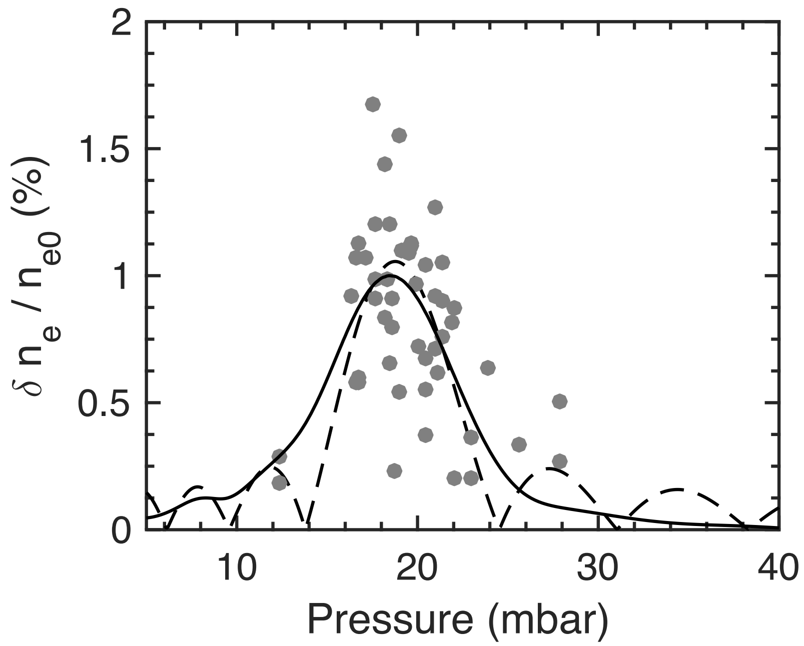
$$\frac{\delta n_e}{n_{e0}} = \left[\frac{\delta n_e}{n_{e0}}\right]_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{p0}\delta\tau\right)}\right|$$

Multi-pulse driver

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

$N \approx 7$



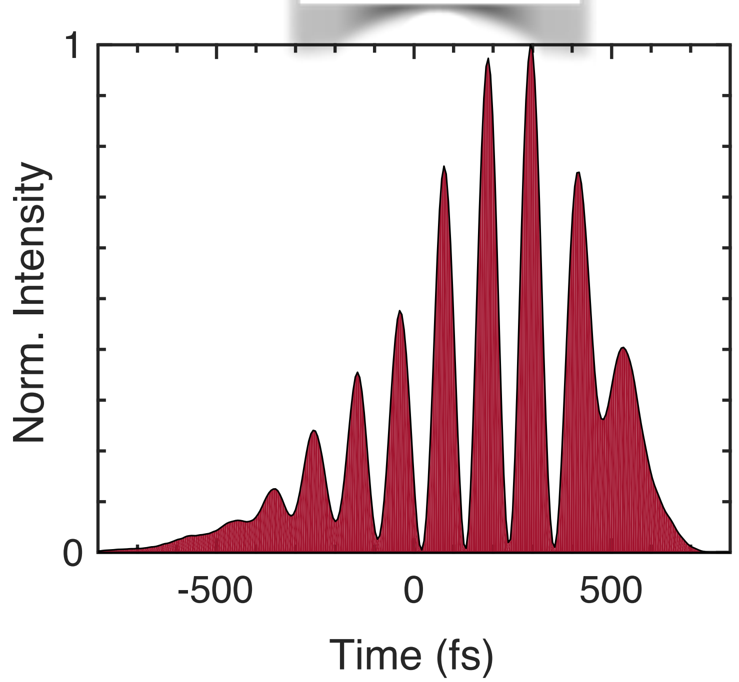


$$\frac{\delta n_e}{n_{e0}} = \left[\frac{\delta n_e}{n_{e0}}\right]_{N=1} \times \left| \frac{\sin\left(\frac{1}{2} N \omega_{p0} \delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{p0}\delta\tau\right)} \right|$$

Multi-pulse driver

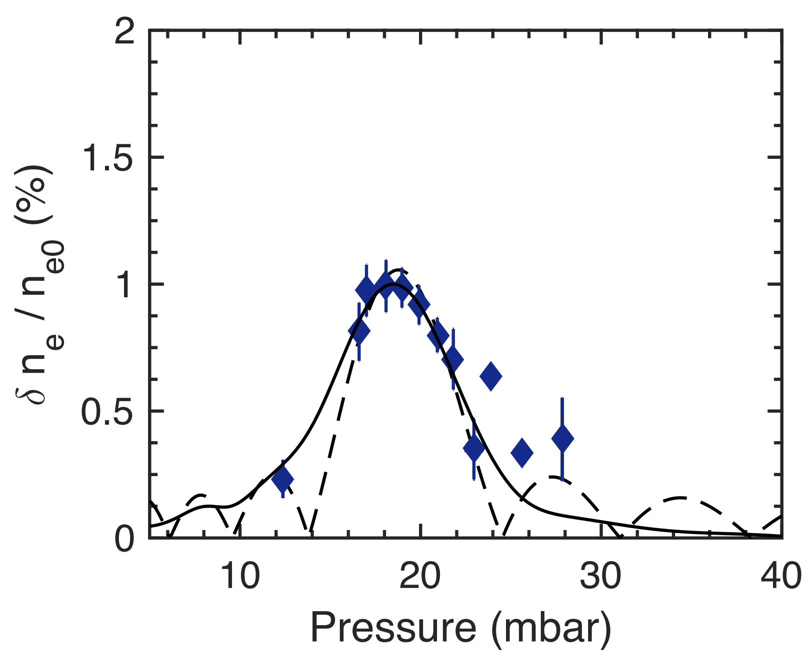
J. Cowley *et al. Phys. Rev. Lett.* **119** 044802 (2017)

$N \approx 7$



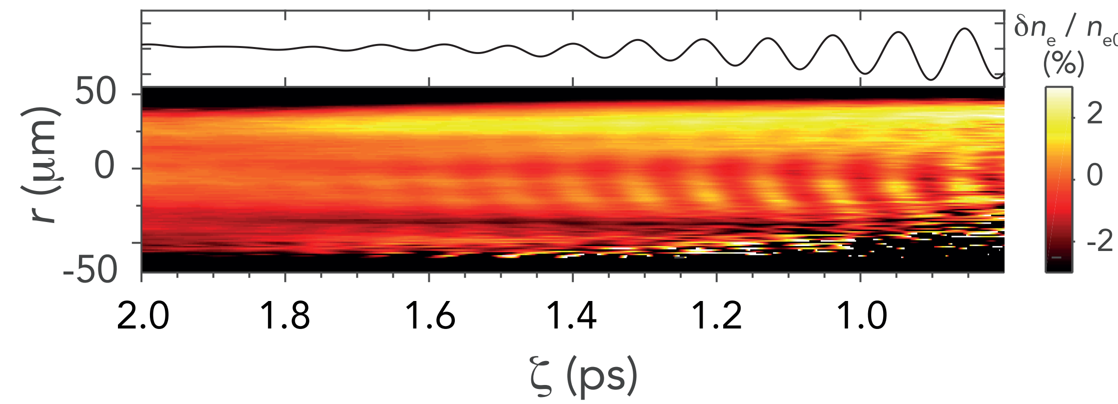
$$\frac{\delta n_e}{n_{e0}} = \left[\frac{\delta n_e}{n_{e0}}\right]_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{p0}\delta\tau\right)}\right|$$

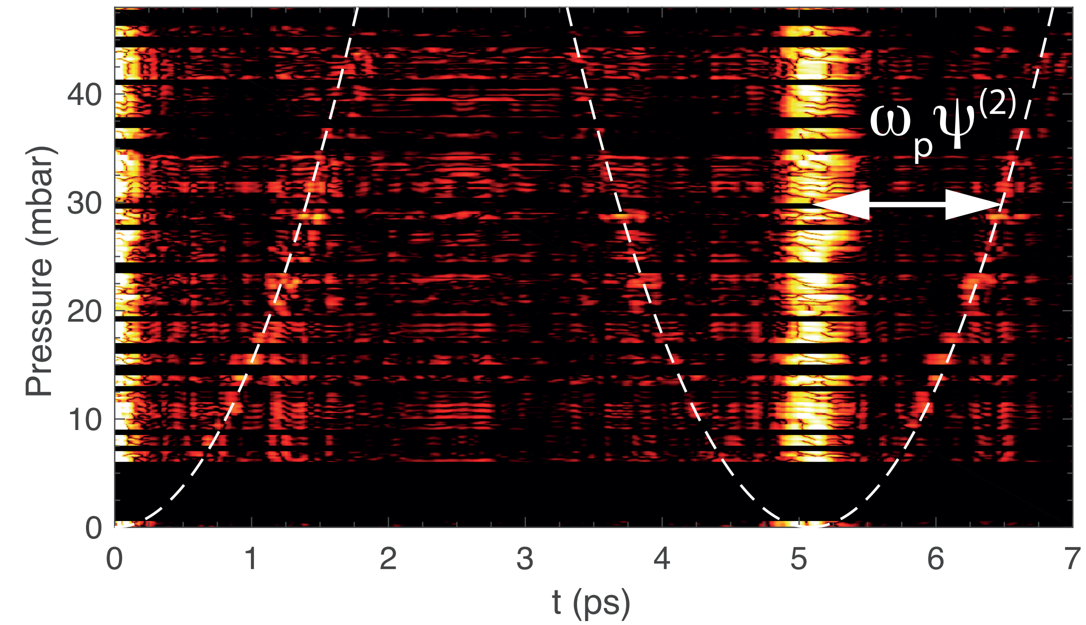
- Excellent fit to analytic expression for $N = 7$
  - $\delta\tau = (116 \pm 2)$ fs,
  - SSA: $\delta\tau = (112 \pm 6)$ fs
- Excellent agreement with fit of wake calculated from measured pulse train with $\zeta \rightarrow \alpha\zeta$
- Find $\alpha = 1.04 \pm 0.02$



Summary

- First demonstration of MP-LWFA OR first demonstration of beat-wave with chirped driving pulses
- First step to energy recovery
- Demonstrated TESS measurements consistent with FDH & measured wake amplitudes as low as 1%
- Future
    - Adjust pulse chirp to maintain resonance at large wake amplitudes
    - Accelerate electrons!





This work was supported by:

- Science and Technology Facilities Council (Grant Nos ST/J002011/1, ST/P002048/1, and 1507620)
- Engineering and Physical Sciences Research Council (Grant Nos 1378575 and 1093881)
- Helmholtz Association of German Research Centres (Grant No. VH-VI-503)
- Air Force Office of Scientific Research, Air Force Material Command, USAF [Grant No. FA8655-13-1-2141]