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An investigation of new regimes in laser-plasma interaction

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Contents

- Laser-wakefield acceleration in the bubble regime
- Wave breaking for relativistic plasma waves
- Photon acceleration in the laser modulational instability

Introduction

New regimes in laser-plasma and beam-plasma interaction have opened up recently:

- ‘Blow-out’ regime for laser-driven and beam-driven wakefields
- Production of mono-energetic electron bunches in laser-plasma interaction
- 100 GeV electrons produced in the beam-wakefield experiment at SLAC

Lasers of record-breaking power are being built today:

- Astra Gemini: 2*500 TW, 50 fs
- Vulcan upgrade: 10 PW, 30 fs

We need matching simulations to explore all these new possibilities.
We used the Osiris 2.0 Framework for this task.

Bubble acceleration

We simulated the following cases:

15 TW, to match today's Astra

→ some particle trapping, no bubble formation

40 TW, to match the Berkeley laser

→ significant particle trapping, two-period bubble

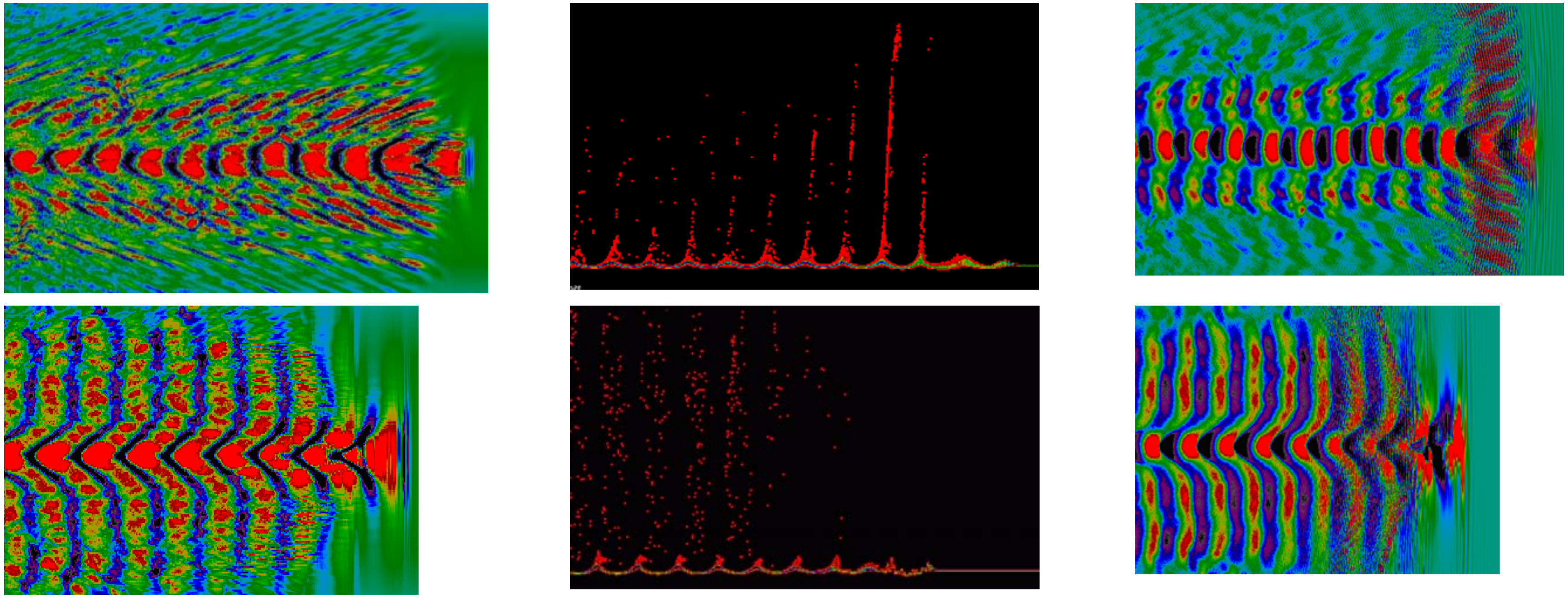
500 TW, to match Astra Gemini

→formation of a large, persistent bubble

→bunch with large charge and energy, small energy spread

15 TW simulation

At 15 TW laser power, there is some particle trapping, and a bubble is almost formed after 1 mm, but is lost after 2 mm.



Electron density

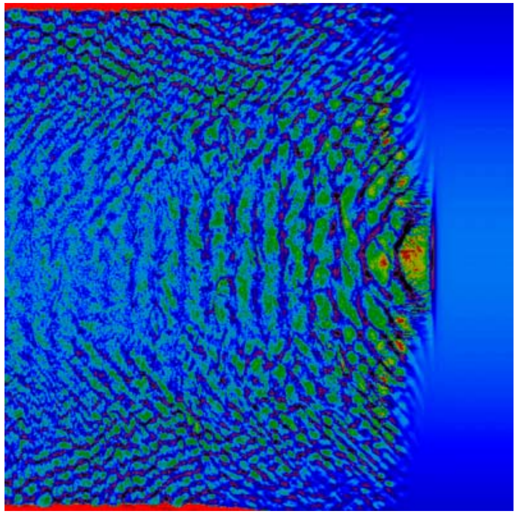
Electron phase space

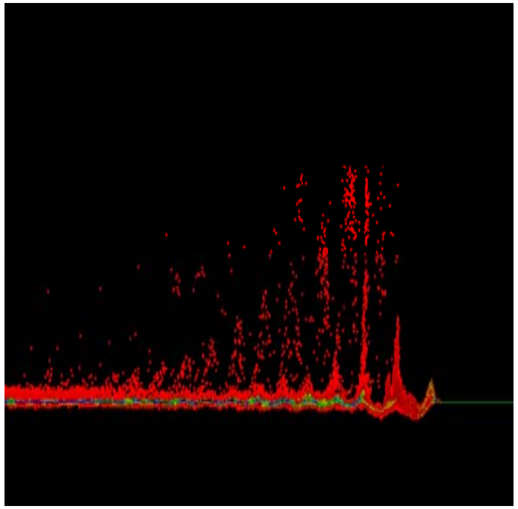
Long. electric field

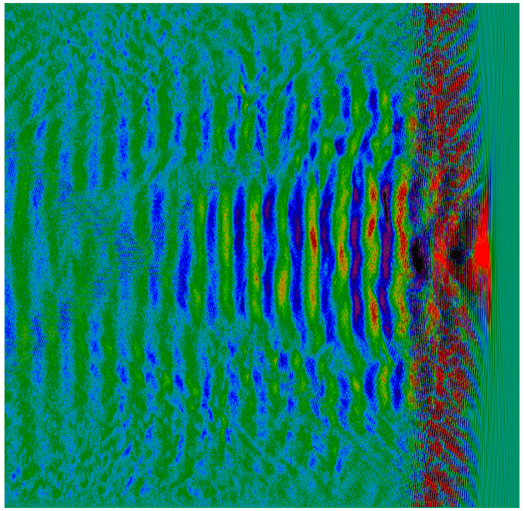
Laser: $I_0 = 6.4 \cdot 10^{18}$ W/cm^2; 50 fs duration; 20 μm spot size; $\lambda = 800$ nm
Plasma: $n_0 = 7.5 \cdot 10^{18}$ cm^{-3}; channel profile
Channel: parabolic, $r_0 = 23$ μm; width = 200 μm; 53% density increase (bottom to edge)

40 TW simulation

At 40 TW laser power, a two-period bubble is formed, lasting throughout the simulation, accompanied by significant electron trapping. (Snapshots taken after 2 mm of propagation.)


Electron density


Electron phase space

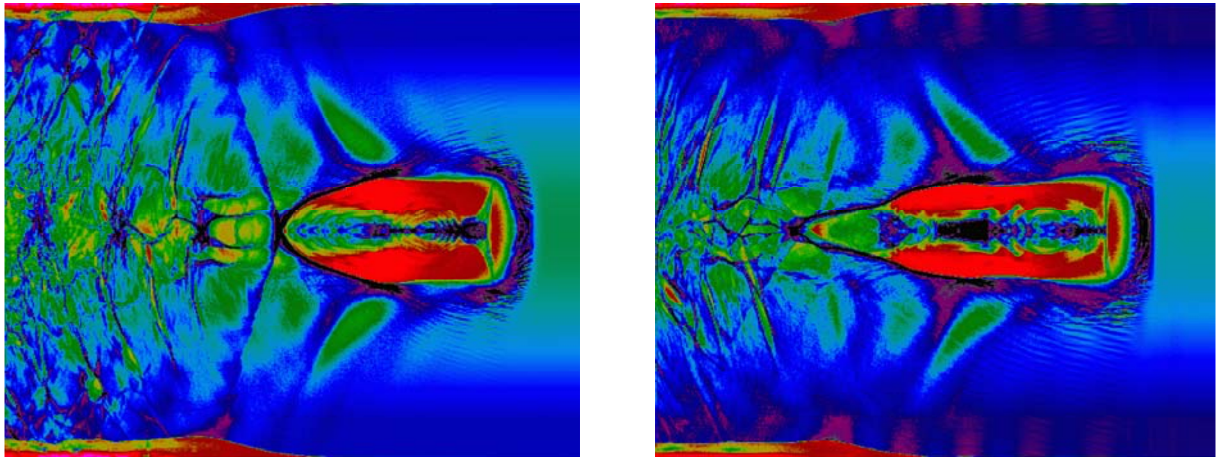

Long. electric field

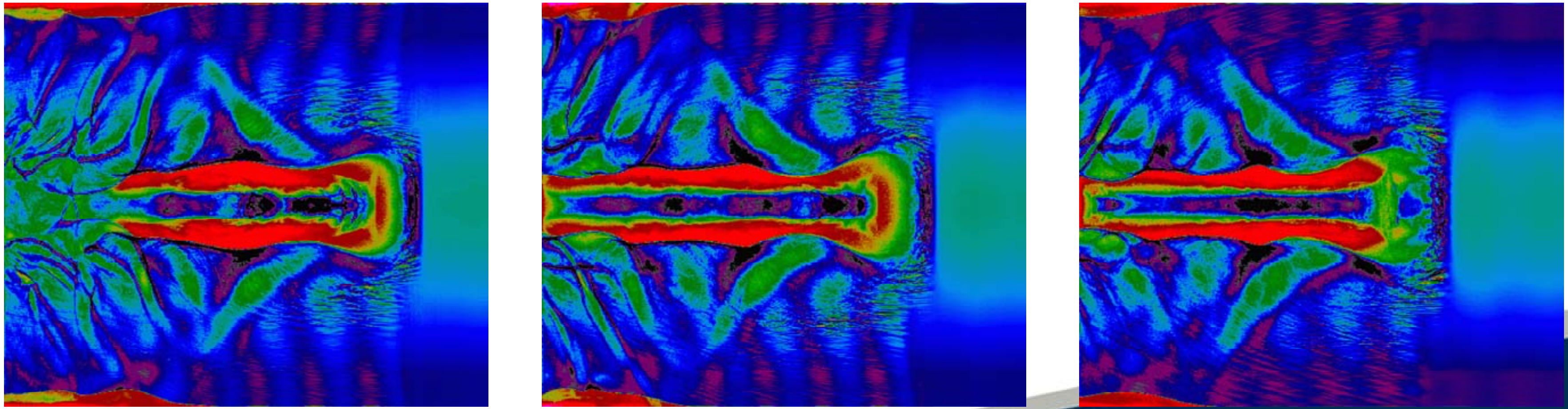
Laser: $I_0 = 1.7 \cdot 10^{19}$ W/cm^2; 50 fs duration; 20 μm spot size; $\lambda = 800$ nm
Plasma: $n_0 = 7.5 \cdot 10^{18}$ cm^{-3}; channel profile
Channel: parabolic, $r_0 = 23$ μm; width = 200 μm; 53% density increase (bottom to edge)

Charge dens. at 500 TW

At 500 TW, there is the formation of a persistent bubble with massive particle trapping. Snapshots after 1-5 mm.

Laser: $I_0 = 1.7 \cdot 10^{19}$ W/cm^2; 50 fs duration; 20 μm spot size; λ = 800 nm
Plasma: $n_0 = 7.5 \cdot 10^{18}$ cm^{-3}; channel profile
Channel: parabolic, r_0 = 23 μm; width = 200 μm; 53% density increase (bottom to edge)





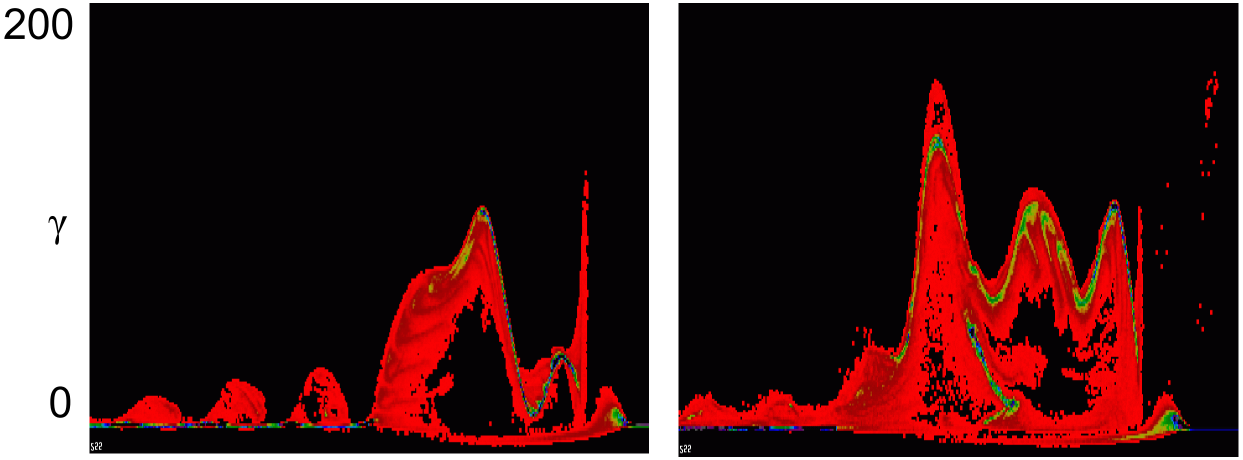
Phase space at 500 TW

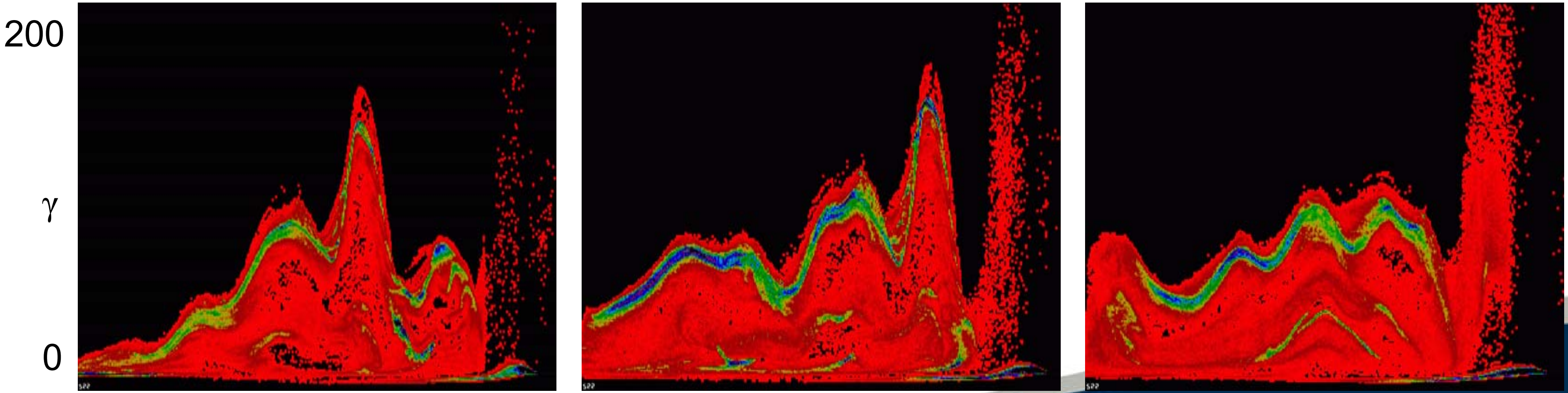
Phase space plots show the trapping of an electron bunch with high charge and small momentum (i.e. energy) spread

Laser: $I_0 = 1.7 \cdot 10^{19}$ W/cm^2; 50 fs duration; 20 μm spot size; λ = 800 nm

Plasma: $n_0 = 7.5 \cdot 10^{18}$ cm^{-3}; channel profile

Channel: parabolic, r_0 = 23 μm; width = 200 μm; 53% density increase (bottom to edge)

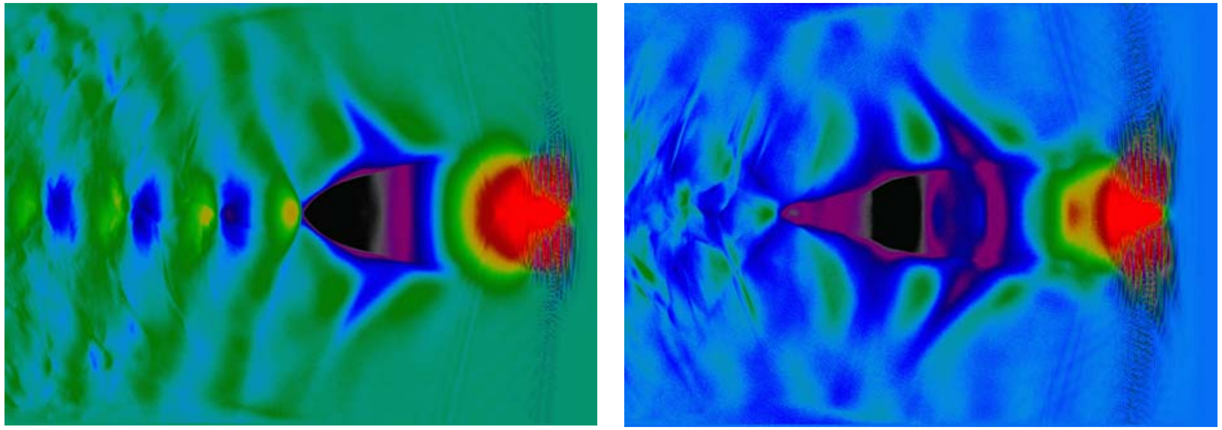


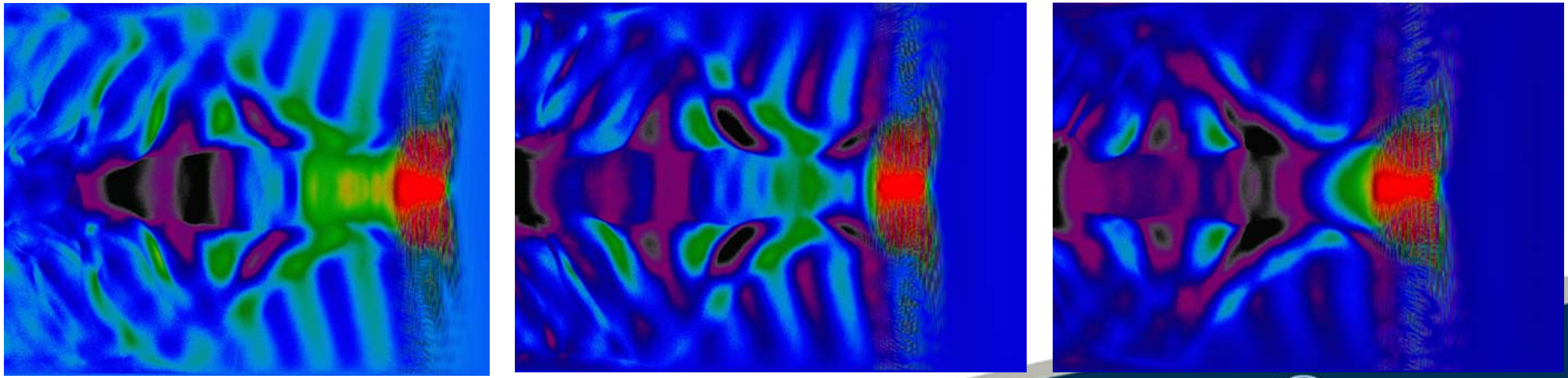


Long. E-field at 500 TW

The E-field in the bubble turns more homogeneous as time progresses, providing a favourable accelerating structure.

Laser: $I_0 = 1.7 \cdot 10^{19}$ W/cm^2; 50 fs duration; 20 μm spot size; λ = 800 nm
Plasma: $n_0 = 7.5 \cdot 10^{18}$ cm^{-3}; channel profile
Channel: parabolic, r_0 = 23 μm; width = 200 μm; 53% density increase (bottom to edge)





Open questions

From 2D to 3D: what will happen?

- Larger self-focusing, stronger bubble formation
- Should yield mono-energetic el. bunches at lower power

What bunch charge/energy can we reach?

- Higher energies will be reached at 10^{16}-10^{17} /cm^3
- Need to optimise density for maximum charge

What about scaling laws?

- Two sets of scaling laws exist: Lu et al. versus Pukhov et al.
- Need to either reconcile these or investigate which set provides the best description
- May there be an overarching scaling law that includes both sets as special cases?

Bubble: summary

Accessing the “bubble regime” with Astra Gemini should be relatively straightforward

With proper tuning, el. bunches with high charge and small energy spread will be produced

Need to increase pulse speed to reach high energies → lower the plasma density

Need better understanding of transverse behaviour, in-channel propagation, nonlinear effects,…

However, given the results of recent experiments, 10 GeV should be within reach!

Contents

- Laser-wakefield acceleration in the bubble regime
- Wave breaking for relativistic plasma waves
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Motivation

There is a lot of confusion regarding wave breaking in warm, relativistic, 1-D plasma:

9 different papers

4 different models

4 different wave breaking limits

This cannot go on. We must get 1-D right before we can proceed to 2-D/3-D

Plan of attack

Ingredients needed for the study of wave breaking:

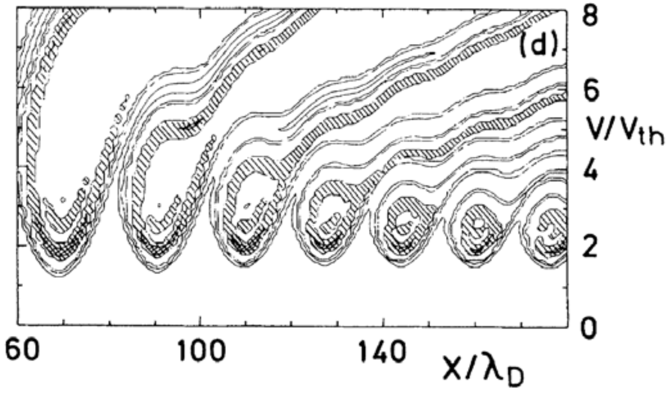
- Proper definition of wave breaking in warm plasma that relates wave breaking and particle trapping
- Correct relativistic hot fluid model for the plasma
- Find wave amplitude at which model breaks down
- Verify this situation against the original definition

Few papers consistently follow this scheme all the way to the end.

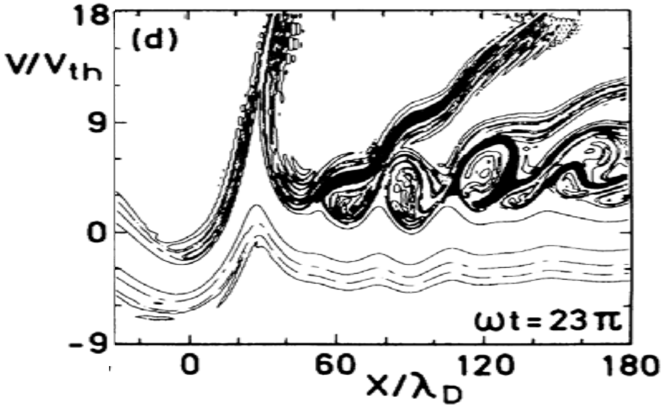
Definition of wave breaking

Wave breaking implies heavy particle trapping

trapping only



trapping and wave breaking



Definition: a wave breaks when it can trap particles at the electron sound speed: $s_0^2 = 3kT/m_e$

A. Bergmann and P. Mulser,
Phys. Rev. E **47**, 3585 (1993)

Two main models

Relativistic waterbag model

T. Katsouleas and W.B. Mori, Phys. Rev. Lett. **61**, 90 (1988)

W.B. Mori and T. Katsouleas, Physica Scripta **T30**, 127 (1990)

(J.B. Rosenzweig, Phys. Rev. A **40**, 5249 (1989))

Warm-plasma approximation

J.B. Rosenzweig, Phys. Rev. A **38**, 3634 (1988)

J. Krall, G. Joyce and E. Esarey, Phys. Rev. A **44**, 6854 (1991)

Z.M. Sheng and J. Meyer-ter-Vehn, Phys. Plasmas **4**, 493 (1997)

C.B. Schroeder, E. Esarey and B.A. Shadwick, Phys. Rev. E **72**, 055401(R) (2005)

C.B. Schroeder, E. Esarey, B.A. Shadwick and W.P. Leemans, Phys. Plasmas **13**, 033103 (2006)

Characteristics

Relativistic waterbag model

–Based on the fully relativistic fluid models of Eckart and Taub

–Wave breaks when upper boundary of waterbag gets trapped (coincides with fluid model breakdown)

–Wave breaking limit: $E_{wb} \propto \sqrt{\ln\left(\gamma_\varphi^2 \beta\right)} \Big/ \beta^{1/4}$ *for* $\gamma_\varphi^2 \beta >> 1 \quad \left(\beta = 3kT \big/ \left(mc^2\right)\right)$

C. Eckart, Phys. Rev. **58**, 919 (1940)
A.H. Taub, Phys. Rev. **74**, 328 (1948)

Warm-plasma approximation

–Based on the approximate models of Newcomb, Amendt and Siambis, who assume a plasma with a relativistic mean flow but non-relativistic temperature

–Wave breaks when the resulting fluid model breaks down

–Wave breaking limit: $E_{wb} \propto 1 \big/ \beta^{1/4}$ *for* $\gamma_\varphi^2 \beta >> 1$

J.G. Siambis, Phys. Fluids **22**, 1372 (1979)
W.A. Newcomb, Phys. Fluids **25**, 846 (1982)
P. Amendt, Phys. Fluids **29**, 1458 (1986)

Comparison

Models will be compared using the following criteria:

- Conformance to Taub's fundamental inequality
- Correspondence between wave breaking (model breakdown) and particle trapping
- Behaviour of the wave breaking limit for $\gamma_\varphi \rightarrow \infty$

The Taub test

Taub's fundamental inequality relating thermal energy U and pressure P: $1+U \geq P/2+\sqrt{1+(P/2)^2}$

	$\beta n^2 << 1$	$\beta n^2 >> 1$
Taub's prediction	$P_{ad} \sim n^3$	$P_{ad} \sim n^2$
Waterbag $P \sim \sqrt{\beta n^2}\sqrt{1+\beta n^2} - \operatorname{asinh}\left(\sqrt{\beta n^2}\right)$	$P_{ad} \sim \beta n^3/3$ O	$P_{ad} \sim \beta n^2$ O
Warm-plasma approx. $P \sim \beta n^3/3$	$P_{ad} \sim \beta n^3/3$ O	$P_{ad} \sim \beta n^3/3$ X

Warm-plasma approx. not meant to be used for $\beta n^2 >> 1$.

A.H. Taub, Phys. Rev. **74**, 328 (1948)

Wave breaking and particle trapping

Insert warm plasma wakefield potential into the model of Ruth and Chao.

Does wave breaking (model breakdown) correspond exactly to trapping of particles at speed $s_0=\sqrt{\beta}$?

- Waterbag model: yes, exact correspondence for any γ_φ.
- Warm-plasma approx.: only for $\gamma_\varphi^2\beta << 1$, not for $\gamma_\varphi^2\beta >> 1$

Waterbag model matches particle trapping and wave breaking; warm-plasma approx. fails to do so.

R.D. Ruth and A.W. Chao, AIP Conf. Proc. **91**, 94 (1982)
R. Trines and P. Norreys, Phys. Plasmas **13**, 123102 (2006)

Wave breaking limit for $\gamma_\varphi \rightarrow \infty$

A wave with $v_\varphi=1$, i.e. $\gamma_\varphi = \infty$, cannot accelerate particles to $v=v_\varphi$, so cannot break at all.

Thus, $\gamma_\varphi \rightarrow \infty$ must imply $E_{wb} \rightarrow \infty$

- Waterbag model: $\sqrt{\ln\left(\gamma_\varphi^{1/2}\beta^{1/4}\right)}\big/\beta^{1/4} \leq E_{wb} \leq \sqrt{\ln\left(2\gamma_\varphi^{1/2}\beta^{1/4}\right)}\big/\beta^{1/4}$
- Warm-plasma approx: $E_{wb} \sim 1\big/\beta^{1/4}$

The warm-plasma approx. allows a wave with $v_\varphi=1$ and finite amplitude to “break”, which is physically impossible.

T. Katsouleas and W.B. Mori, Phys. Rev. Lett. **61**, 90 (1988)
R. Trines and P. Norreys, Phys. Plasmas **13**, 123102 (2006)

Wave breaking: summary

Relativistic waterbag model beats warm-plasma approx. on three counts:

- relativistic effects are better covered in waterbag model
- Correspondence between wave breaking and particle trapping
- Lower limit for E_{wb} also tends to infinity

Some order created in the chaos

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Background

Modulational instability in long pulse-plasma interaction will lead to:

— Bunching of photons in both real and momentum space

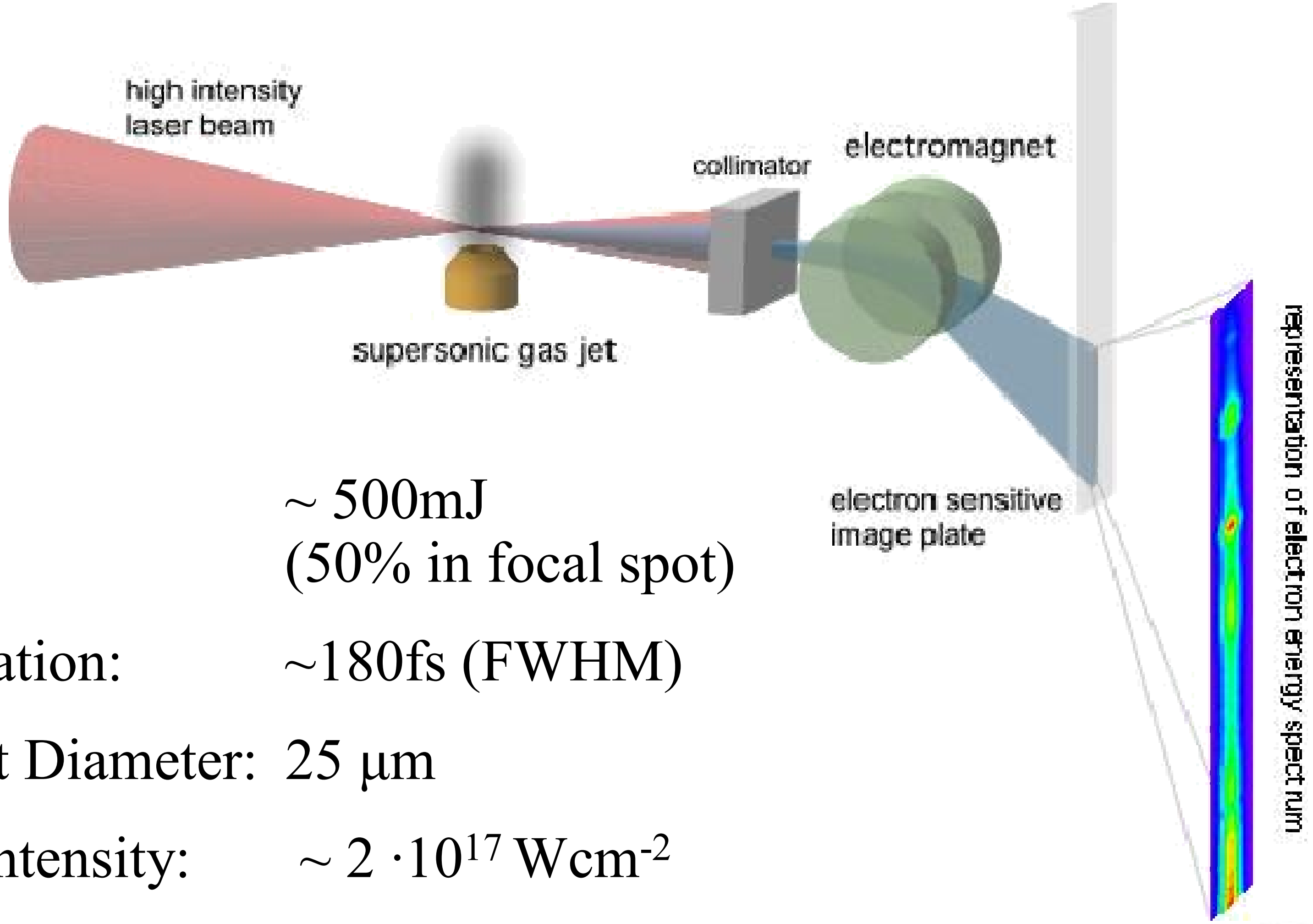
— Redshift of some parts of the pulse, blueshift of other parts

— Spectral peaks unrelated to Raman scattering

This should be visible in both experiments and simulations

Modulations to a probe pulse can be used to diagnose wakefield

Experimental Set-Up



Energy: ~ 500mJ
(50% in focal spot)

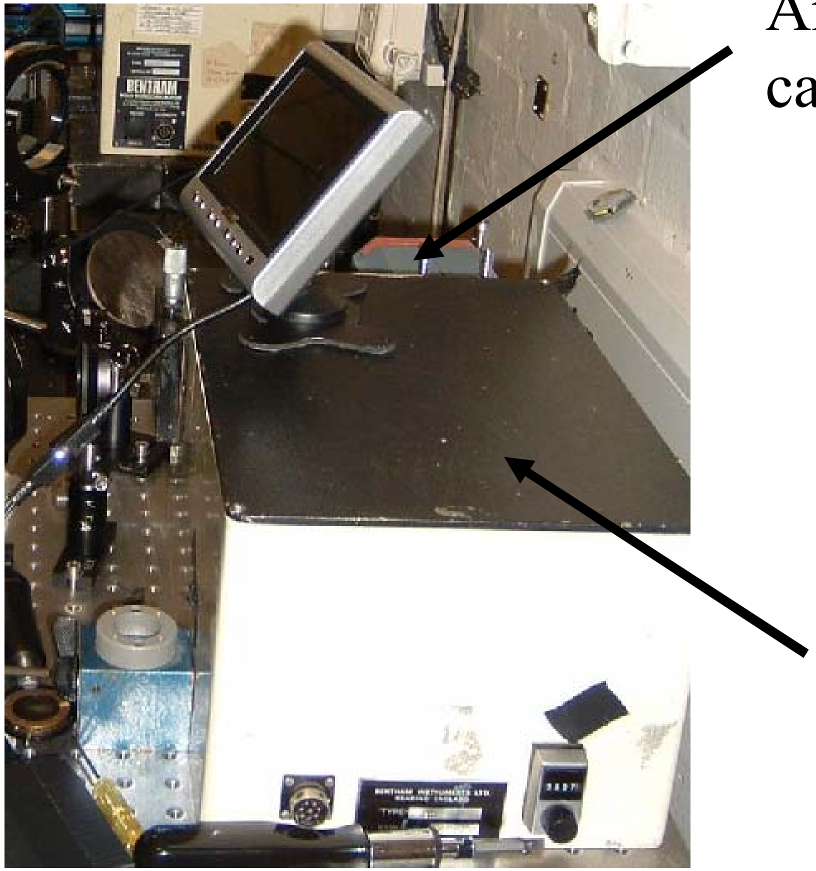
Pulse Duration: ~180fs (FWHM)

Focal Spot Diameter: 25 µm

Vacuum Intensity: ~ $2 \cdot 10^{17}$ $\mathrm{Wcm^{-2}}$

Plasma Density: $2 \cdot 10^{18}$ - $1.6 \cdot 10^{19}$ $\mathrm{cm^{-3}}$

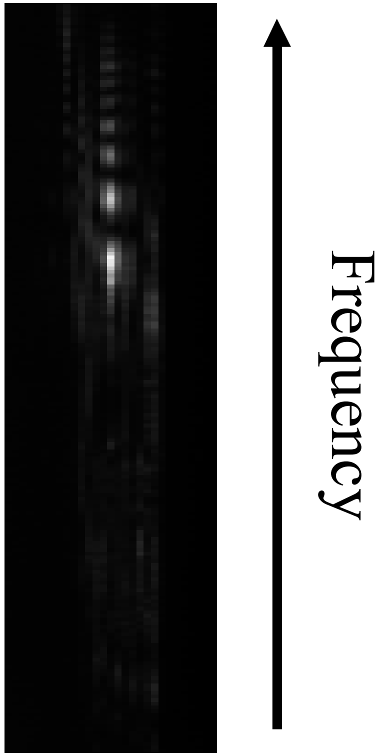
Data Acquisition



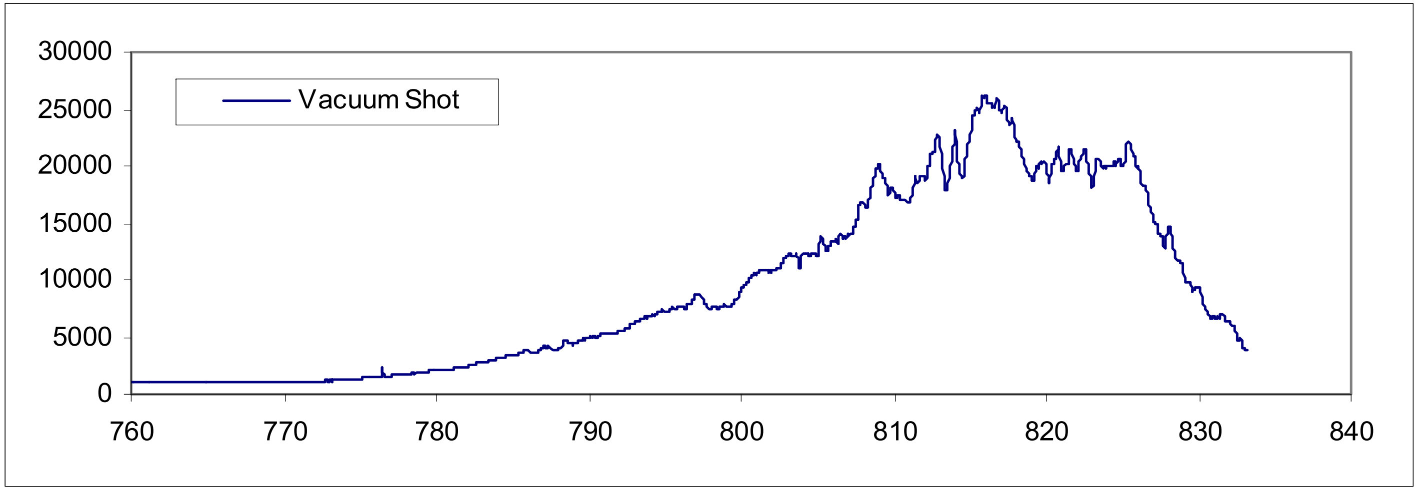
Andor CCD camera

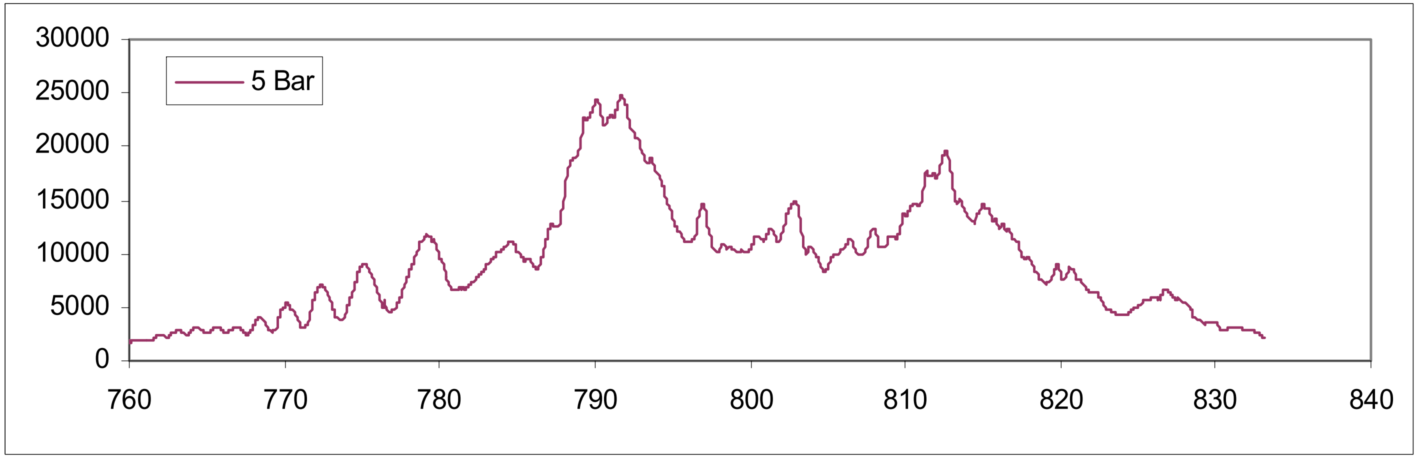
Bentham optical spectrometer

Output from the CCD



Results

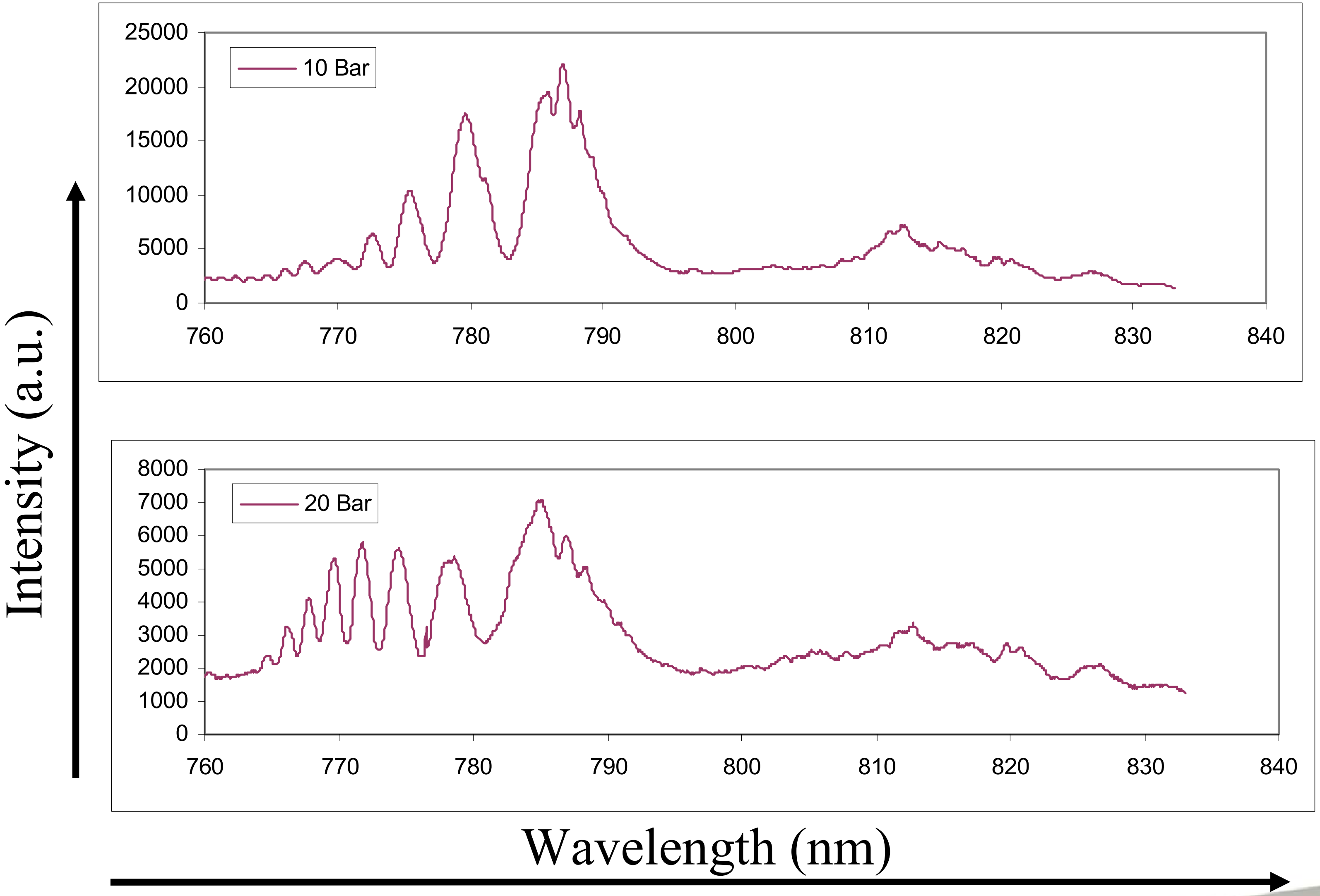




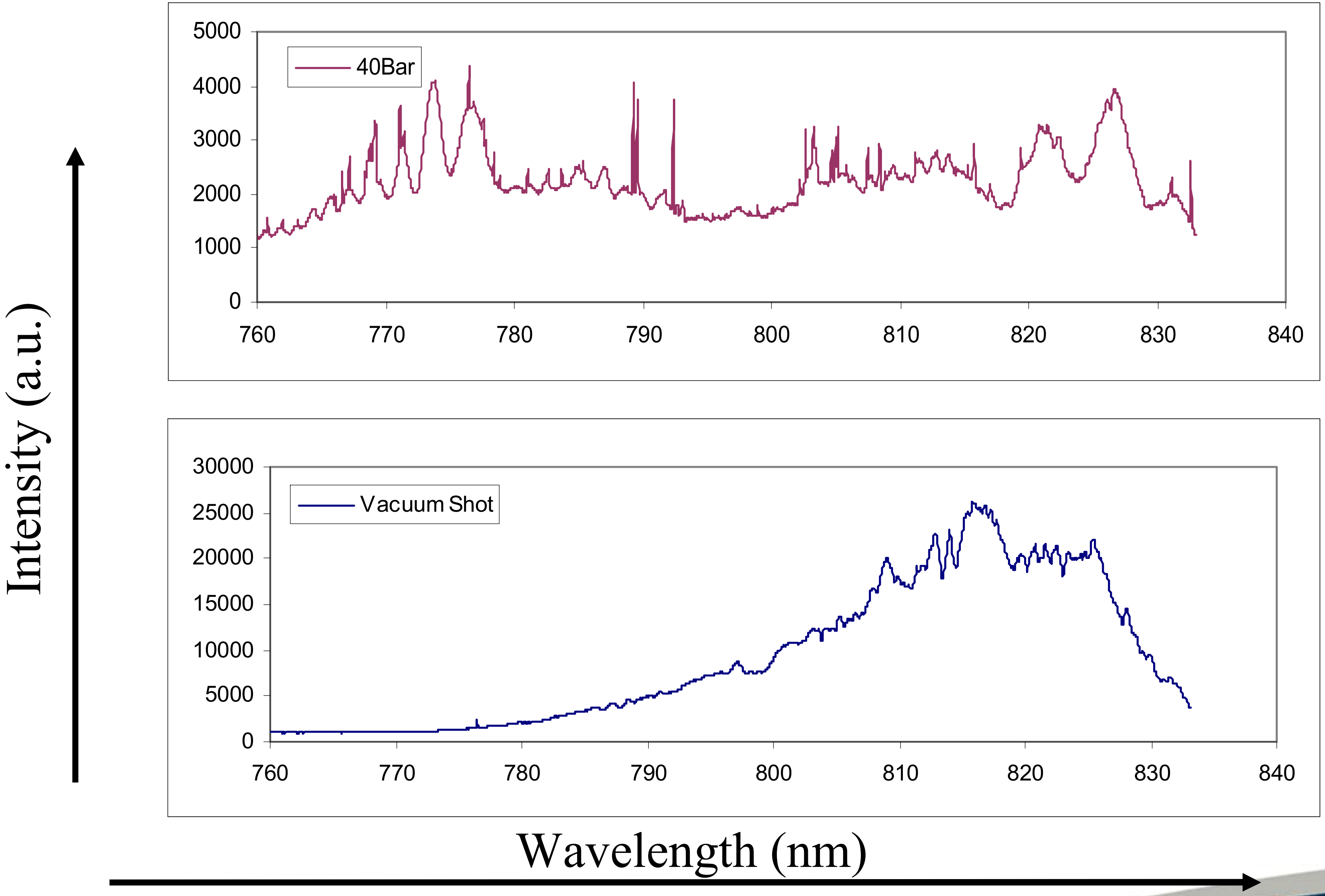
Intensity (a.u.)

Wavelength (nm)

Results

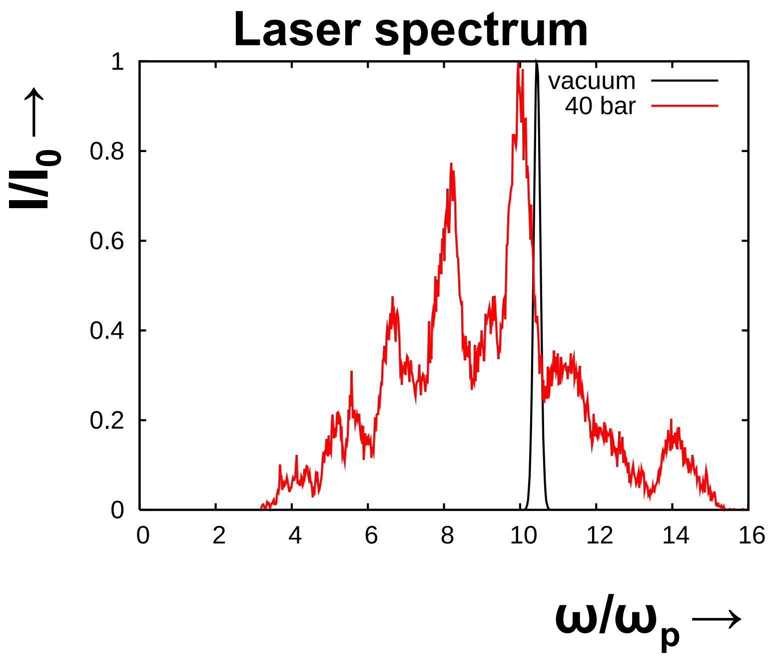

Intensity (a.u.)
Wavelength (nm)
10 Bar
25000
20000
15000
10000
5000
0
760
770
780
790
800
810
820
830
840
20 Bar
8000
7000
6000
5000
4000
3000
2000
1000
0
760
770
780
790
800
810
820
830
840

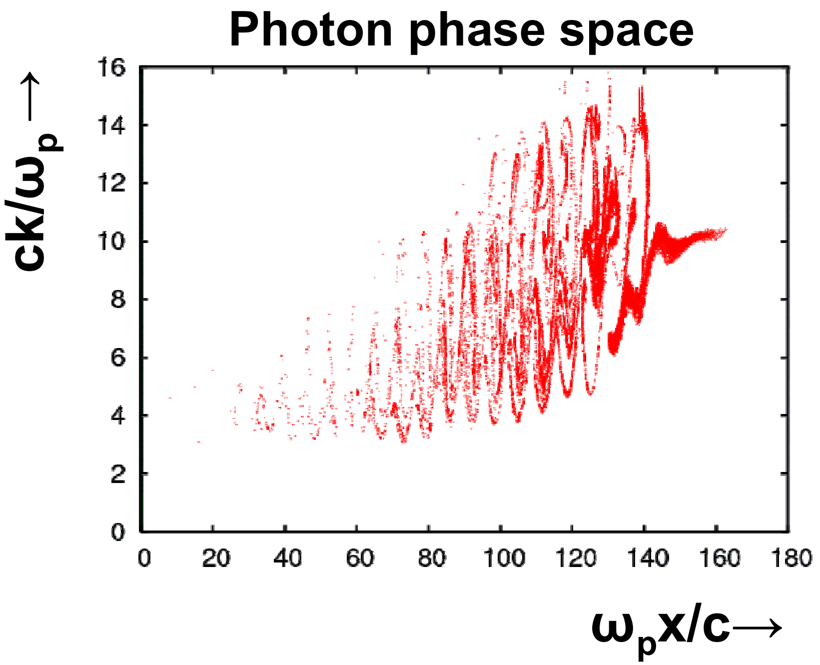
Results


Intensity (a.u.)
Wavelength (nm)
40Bar
5000
4000
3000
2000
1000
0
760
770
780
790
800
810
820
830
840
Vacuum Shot
30000
25000
20000
15000
10000
5000
0
760
770
780
790
800
810
820
830
840

Simulations

Photon kinetic simulations nicely reproduce spectral structure

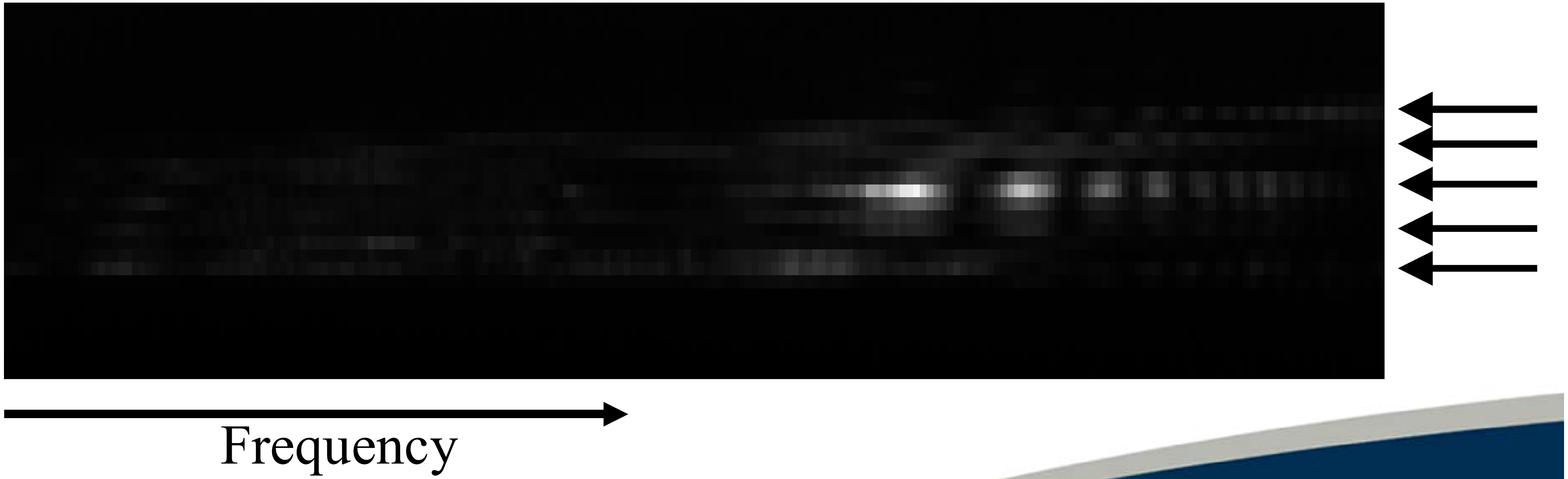

Laser spectrum


Photon phase space

Simulations don't explain everything, e.g. blueshift of entire spectrum (ionisation effect?)

Photon acceleration: summary

- The laser spectrum was shifted to the blue by about 30nm in each case – this is most likely due to blue shift occurring during the ionisation process
- Modulations in the spectral envelope vary with plasma density
- Modulations appear to vary in the transverse direction; caused by the Airy pattern in the pulse envelope?
- Amplitude of modulations are indicative of plasma wakefield amplitude



Photon acceleration: Future Work

- Use a long pulse to characterise the wakefield produced by a second pulse
  - Ionisation blue shift would not occur if the pulse was trailing a more intense pulse
  - Variations in the modulations would give information on wave amplitude, position of wave breaking and the extent of beam loading
- Obtain numerical estimates of wave amplitudes
- Simulations – implement photon kinetic and PIC codes to further analyse the mechanism

Summary and conclusions

Bubble acceleration

- Multi-GeV electron energy within reach for Astra Gemini
- Need lower plasma densities and longer interaction lengths
- Need better understanding of the trapping process

Relativistic wave breaking

- Conflict resolved in favour of relativistic waterbag
- New lower bound found for ultra-relativistic regime
- 1-D now understood; next step: 2-D

Photon acceleration and modulational instability

- Spectral modulations caused by repeated photon acceleration in the laser's wakefield, and ionisation blueshift
- Use "witness" pulse to diagnose driving pulse's wakefield
- Need further simulations for quantitative analysis