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Hydrodynamics Driven by Intense short-pulse lasers

(and two slides relevant to laser plasma accelerators!)

John Pasley

Presented at the LPA Conference, Bangalore, 14/3/2017

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Acknowledgments

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TIFR: Sudipta Mondal, Amit Lad, Saima Ahmed, V. Narayanan, Prashant Singh, Gourab Chaterjee, Amitava Adak, G. Ravindra Kumar

Rutherford Appleton Laboratory: Alex Robinson , Peter Norreys, James Green, M. Notley, P. P. Rajeev, Chris Spindloe, Trevor Winstone, Rob Clarke, Dave Neely

+ Other collaborators (see citations) from **Lawrence Livermore National Laboratory**, **Imperial College London, Ohio State University, University of California San Diego, General Atomics, LLE, University of Oxford, ILE- Osaka, University of Reno, Cranfield University,** and the **University of Michigan**.

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- **STFC**
- **TIFR-DAE**

Talk outline

- Brief intro to IFE
- Relevance of short pulse hydro to IFE
- Experimental and simulation based studies
- Future work
- Conclusions

What is ICF/IFE?

Deuterium and tritium isotopes of hydrogen are imploded violently by laser or x-ray drive

Lasers or X-rays symmetrically irradiate pellet

Implosion results in compression, heating and finally thermonuclear ignition + burn


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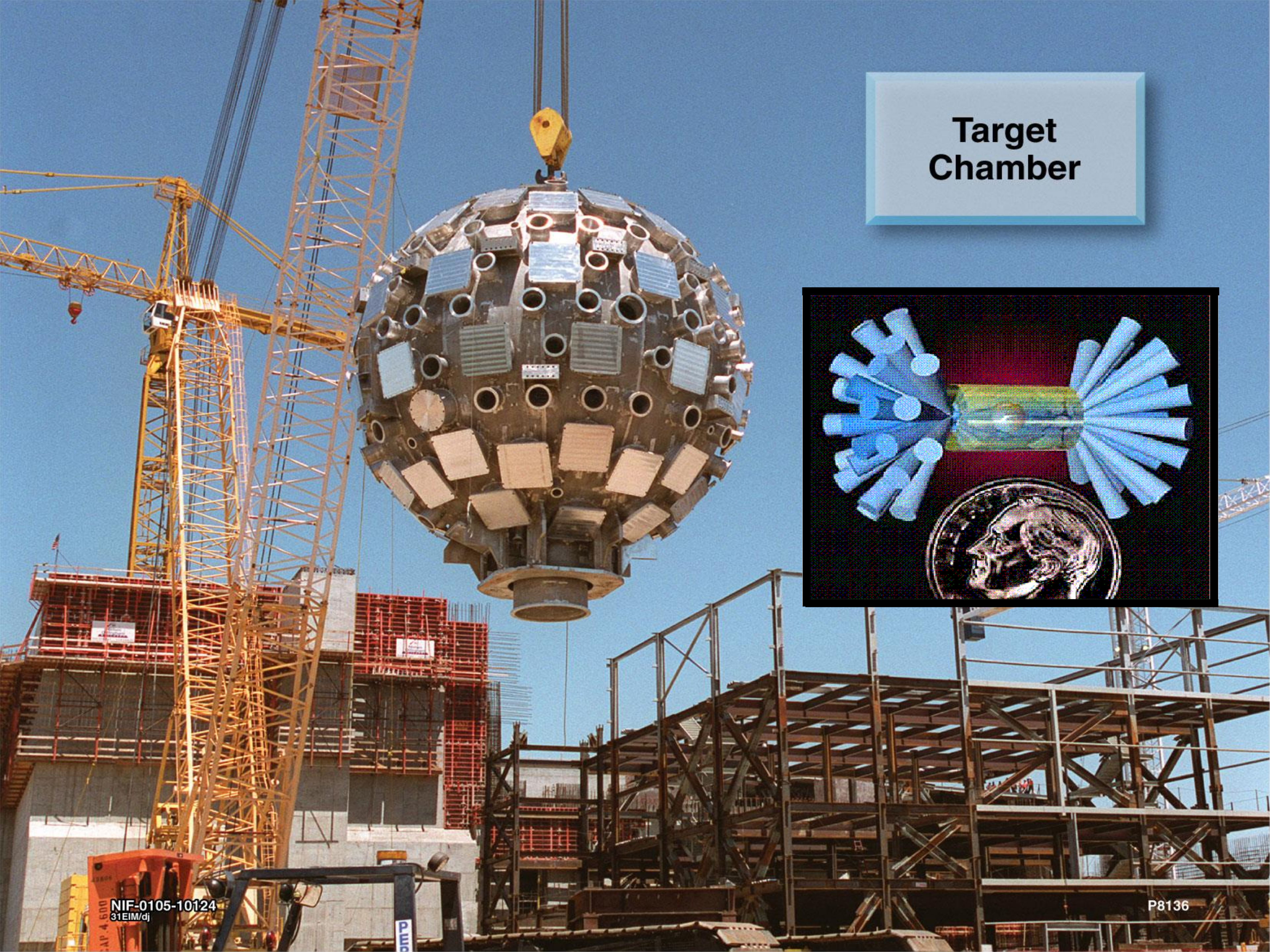
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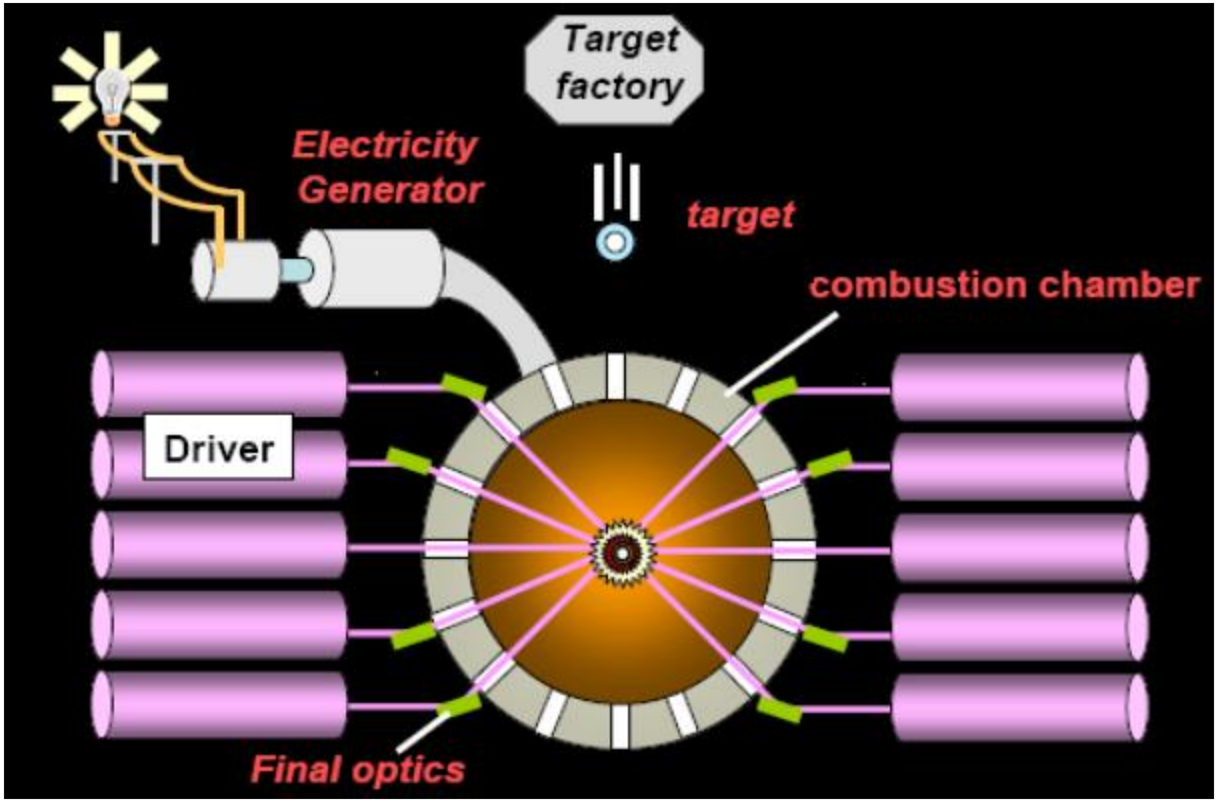
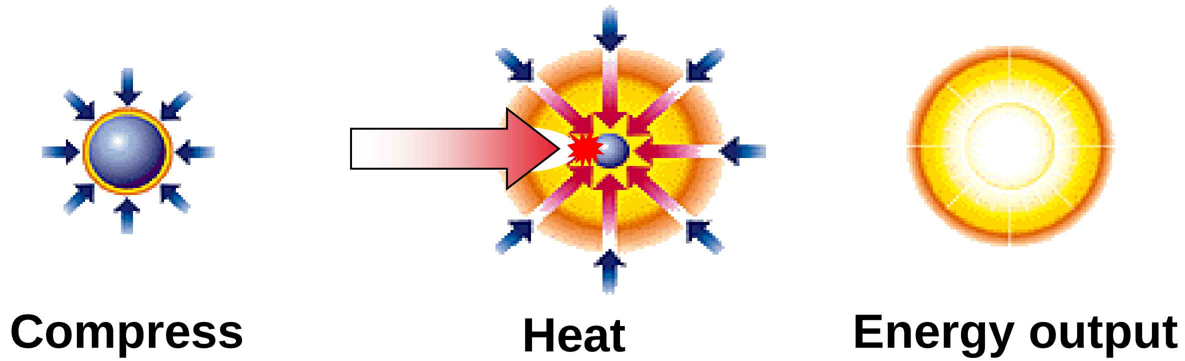
Inertial Fusion Energy



What is Fast Ignition?

A suggested aternative ICF scheme…

- Heating by implosion is inefficient (<1% of driver energy goes into heating fuel)
- Fast ignition uses a separate laser for heating, hoping to achieve much higher efficiency
- Significantly less energy is required to drive the implosion if it is not required to heat, only to compress



Short pulse hydro relevance to Inertial Fusion Energy (IFE)

Can divide roughly into two areas:

- Hydro driven directly by the laser (e.g. hole-boring/ Radiation pressure (RP) driven)
- Hydro driven indirectly by pressure gradients induced by heating

This has **direct** relevance to IFE in the following areas:

- Fast Ignitor hotspot
- Fast Ignitor cone-tip
- Structured collimators

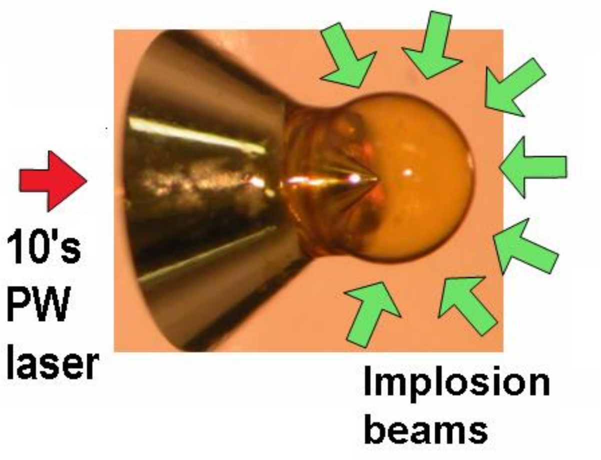
Short pulse hydro relevance to Inertial Fusion Energy (IFE)

In addition, short pulses enable us to create extreme conditions which may be relevant to issues in IFE and elsewhere in HEDP:

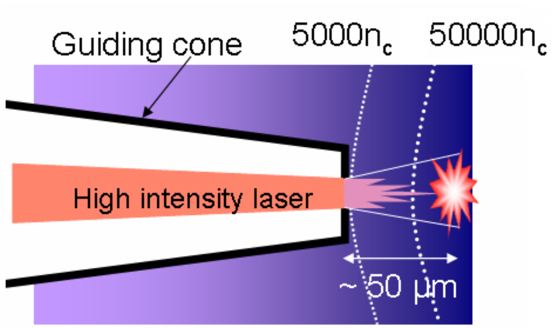
- ICF hotspot dynamics
- Studies of high temperature opacity and EOS

In these cases the hydro may, or may not, be a desirable feature of the short-pulse interaction. Understanding the hydrodynamic behaviour under the influence of a short pulse is however vital to designing such experiments.

Cone-tip evolution



On timescale of ~20ps, plasma cannot be treated as static, given the pressures involved (which may reach Tbar levels in the hotspot, and be tens or hundreds of Gbar elsewhere)



Density gradient in cone guided FI

Heating is driven by electron current, so rad-hydro alone maybe insufficient. Need to consider MHD evolution of plasma in concert with the electron transport problem

Challenging area experimentally

Few diagnostics are capable of resolving hydrodynamic behaviour occuring on picosecond timescales (be this a problem of spatial resolution, temporal resolution, or both!)

High-energy short-pulse laser plasma interactions generate intense competing “noise” signal, further complicating diagnosis

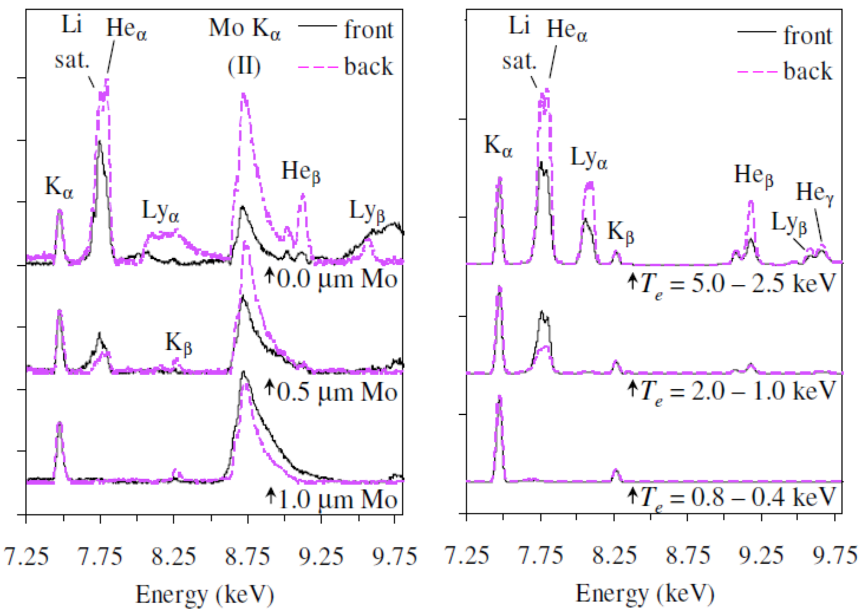
Short-pulse drivers large enough to replicate conditions in full-scale fast ignition, from a hydrodynamic standpoint, do not yet exist

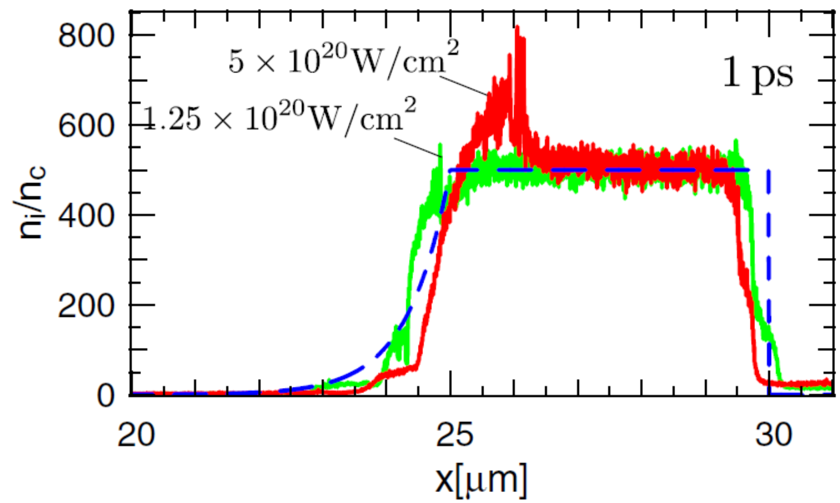
Early experiment in this area

Laser: Vulcan PetaWatt, 1.05μm, 400J, 0.8ps, 5×10^{20} W/cm^2
Target: (front) Mo/Ni/V(back), target (0m-1μm/ 0.5μm/1μm)

Experiment (HOPG)

Simulation (CR- SCRAM)





Collisional PIC Calculations suggest that a strong shock is being driven into the target
P_{shock} ~ 1GBar

*K.U. Akli, S.B. Hansen, … , **J.Pasley**, …, and M.H. Key, Phys. Rev. Lett. **100**, 165002, (2008)*

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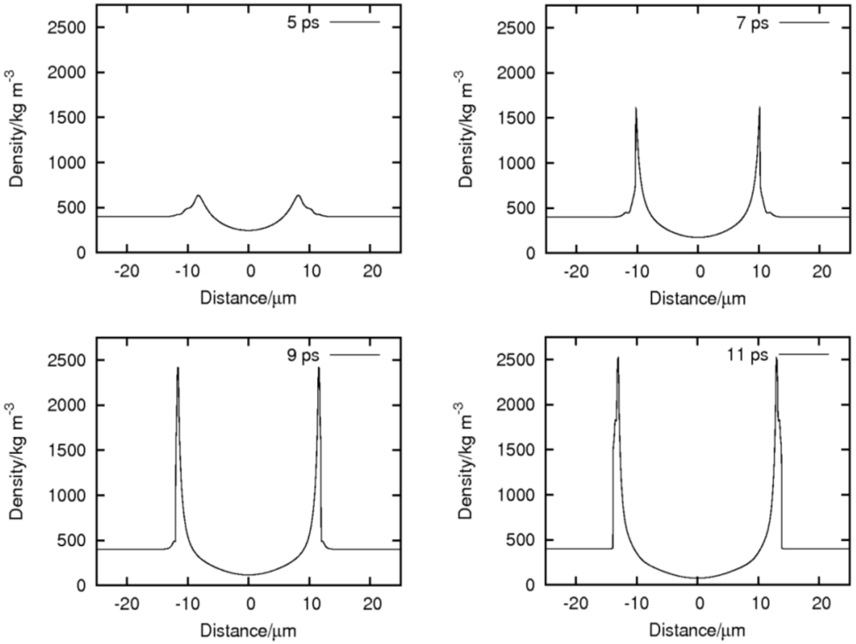
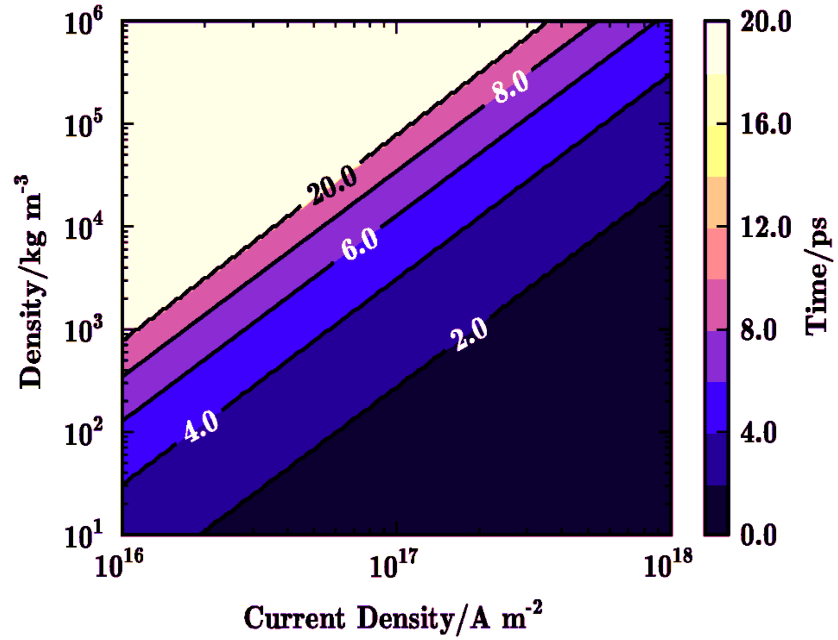
nkT pressure gradients tend to dominate hydro at sub-10^{20}W/cm^2 or at depth





- We have performed both 1 and 2-D MHD calculations of the effect of intense beams of hot electrons propagating through matter
- Ohmic heating found to be dominant effect (compared to jxB)
- Shocks can be generated; most easily at lower densities. j_0^2/ρ ratio determines rate at which shocks form

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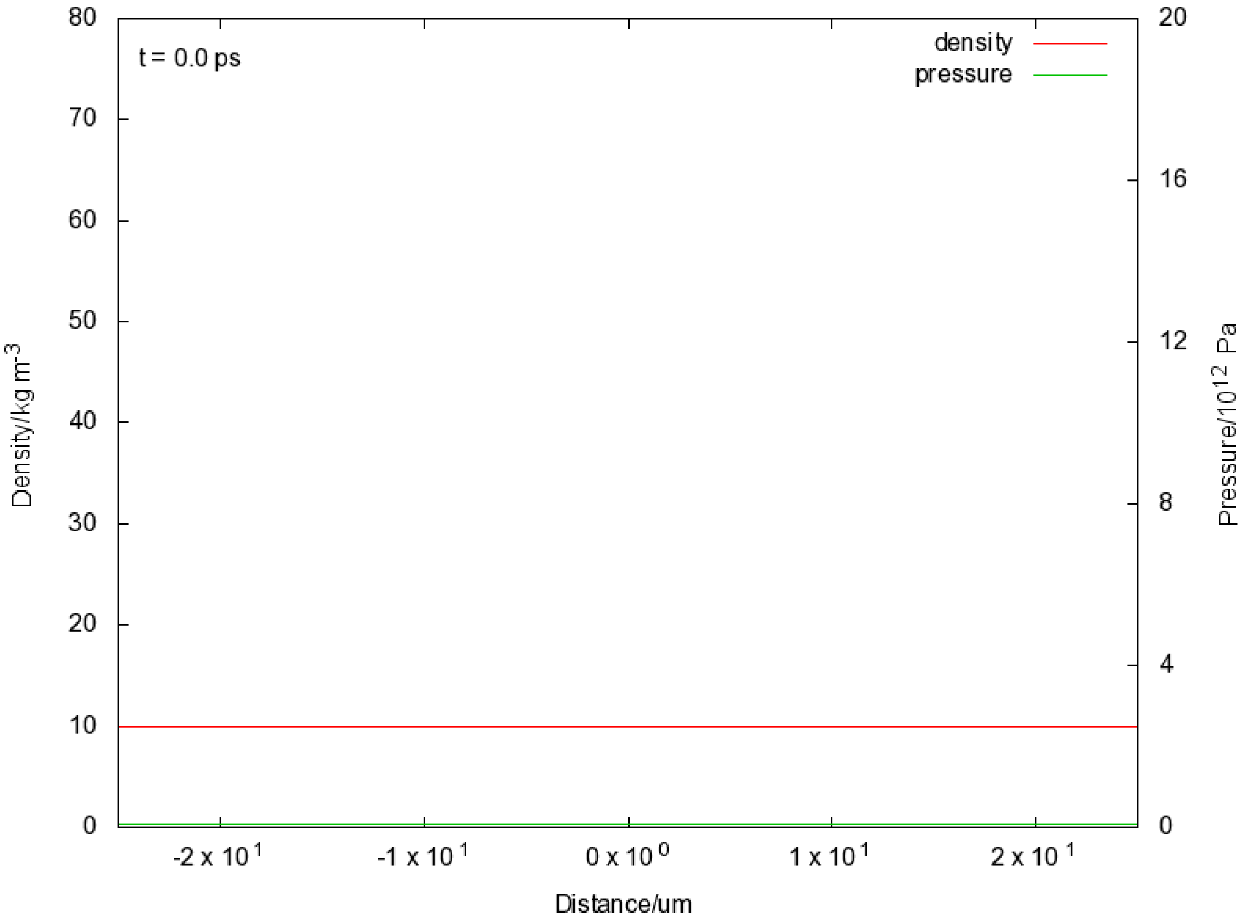
*I.A. Bush, A.P.L. Robinson, R. Kingham and **J.Pasley**, PPCF **52**, (2010)*

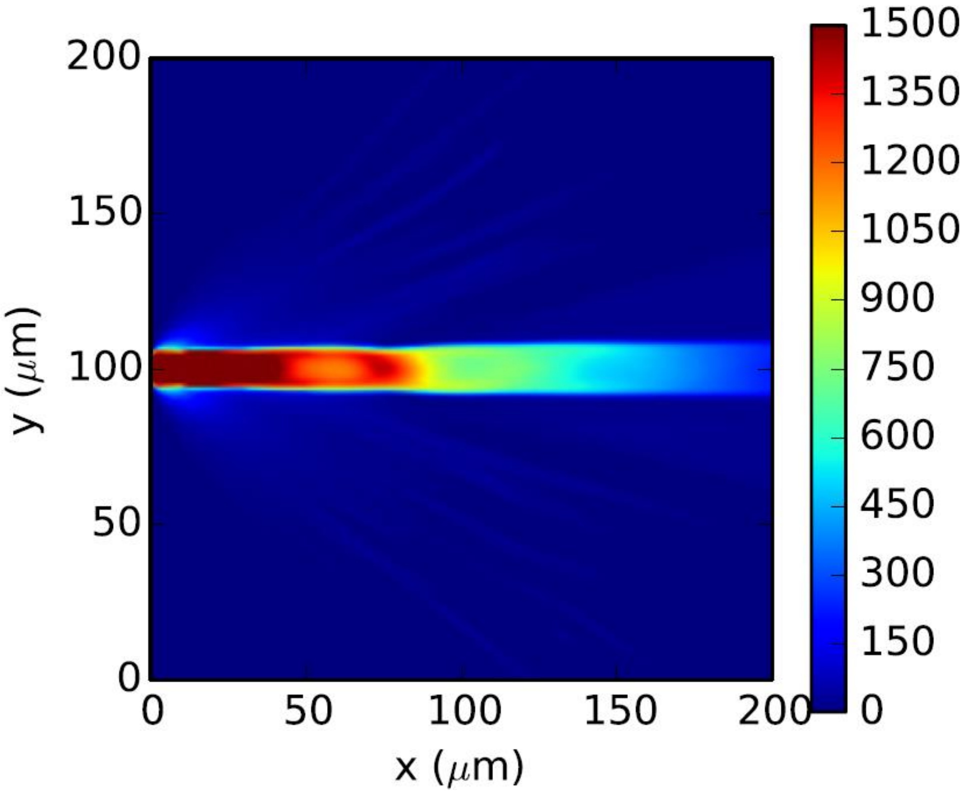
Time evolution of an electron beam driven shock



$j_0 = 10^{17}$ A m^{-2} $\rho_0 = 10$ kg m^{-3}

I.A. Bush, A.P.L. Robinson, R. Kingham and ***J.Pasley****, PPCF* ***52****, (2010)*

Short pulse heated shaped pressure sources



- Al guiding structure in CH substrate
- Wire tapered near laser interaction site to capture maximum energy from divergent beam

- *A.P.L.Robinson, H.Schmitz, and* ***J. Pasley****, Phys. Plasmas* ***20****, (2013)*
- *A.P.L. Robinson, H. Schmitz, J.S. Green, C.P. Ridgers, N. Booth, and* ***J. Pasley****, Phys. Plasmas* ***22****, (2015)*

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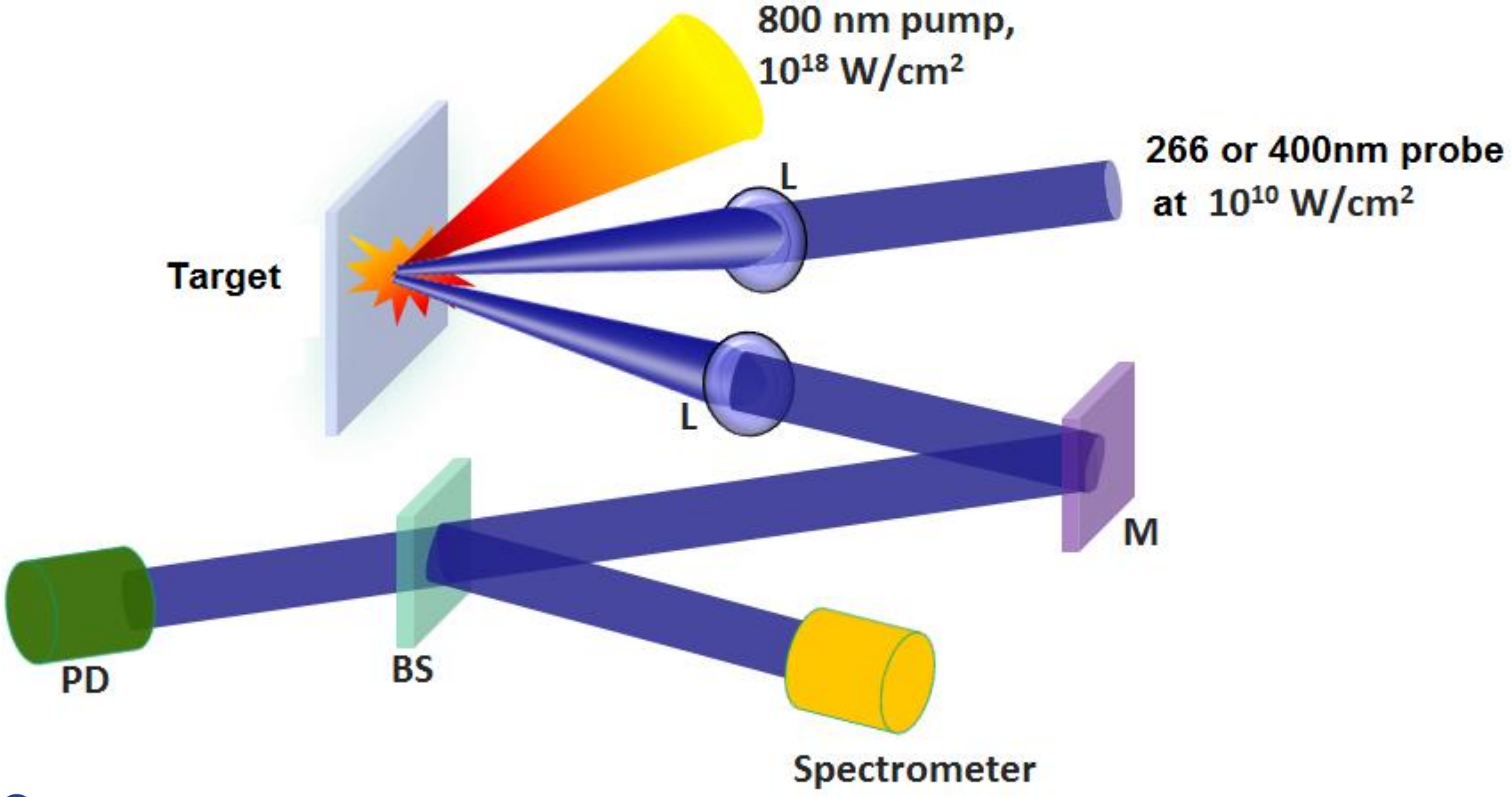
Measuring short-pulse driven hydro directly in the lab



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Initial experiments probed Al target at 400nm

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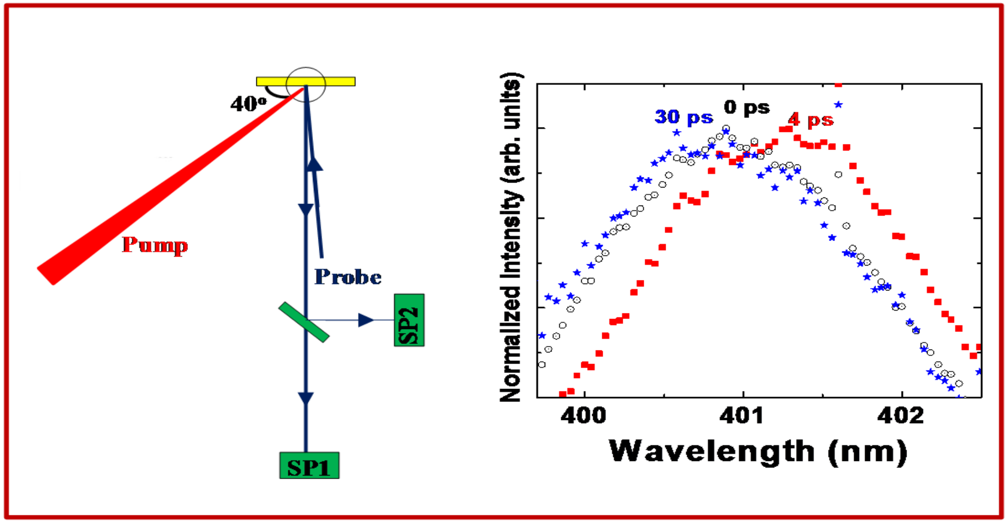
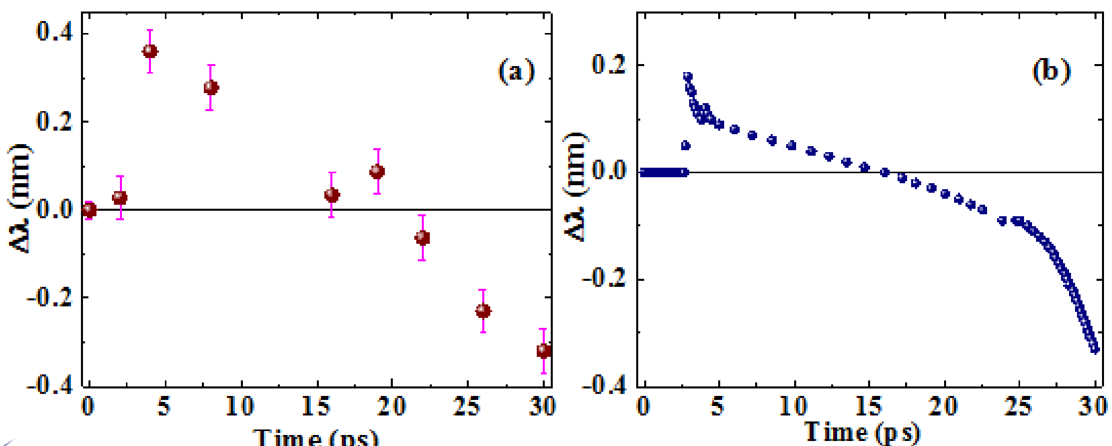


Pump-probe experiment employed, using Doppler shift of 2 ω (400nm) probe to record hydrodynamics driven by interaction of 1 ω pump beam (30fs)



1-D electromagnetic PIC calculation coupled to simple hydrodynamics model shows a reasonable match to the experimental measurements

Similar diagnostic used (Y. Ping et al, Phys Rev. Lett., 2012) to investigate hole-boring during the laser pulse

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*S. Mondal, Lad, S. Ahmed, V.Narayanan, **J. Pasley**, P.P. Rajeev, A.P.L. Robinson, G. Ravindra Kumar, Phys. Rev. Lett. **105**, (2010)*

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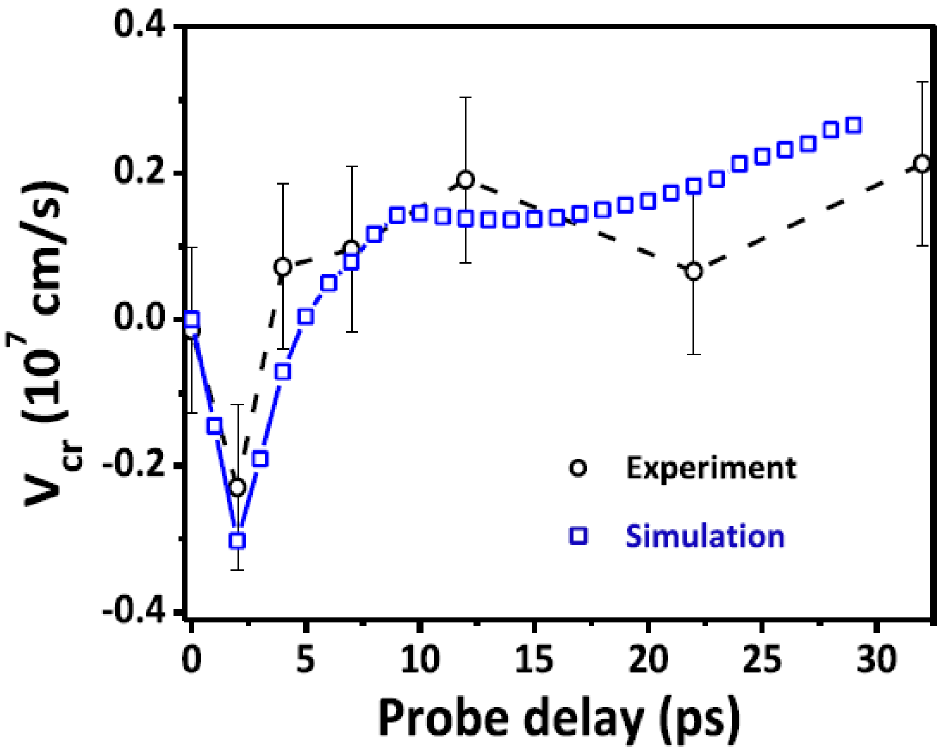
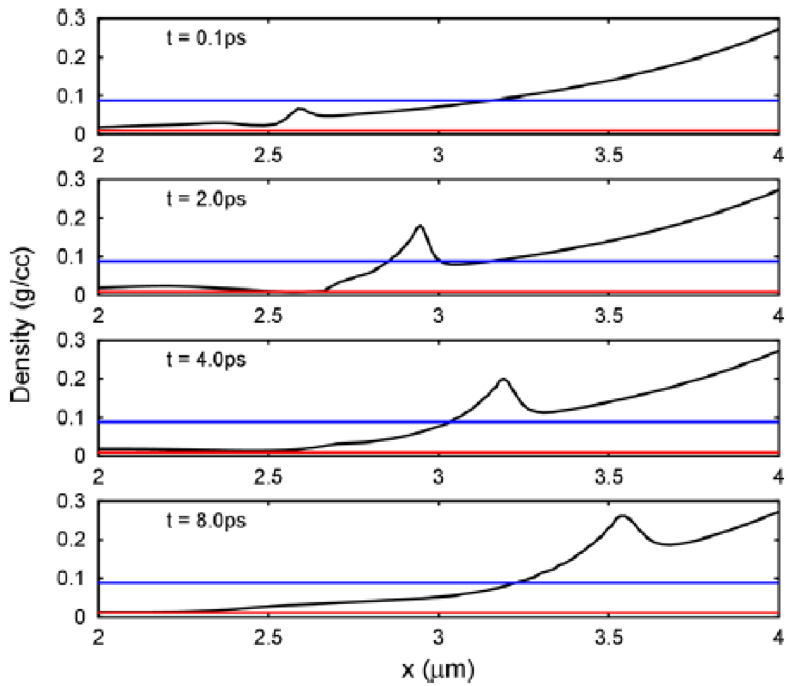
Fused silica probed at 266nm

Use of a UV probe enables moderately dense plasma dynamics to be recorded





*Amitava Adak, David R. Blackman, Gourab Chatterjee, Prashant Kumar Singh, Amit D. Lad, P. Brijesh, A. P. L., Robinson, **John Pasley**, and G. Ravindra Kumar, Phys. Plasmas **21**, (2014)*

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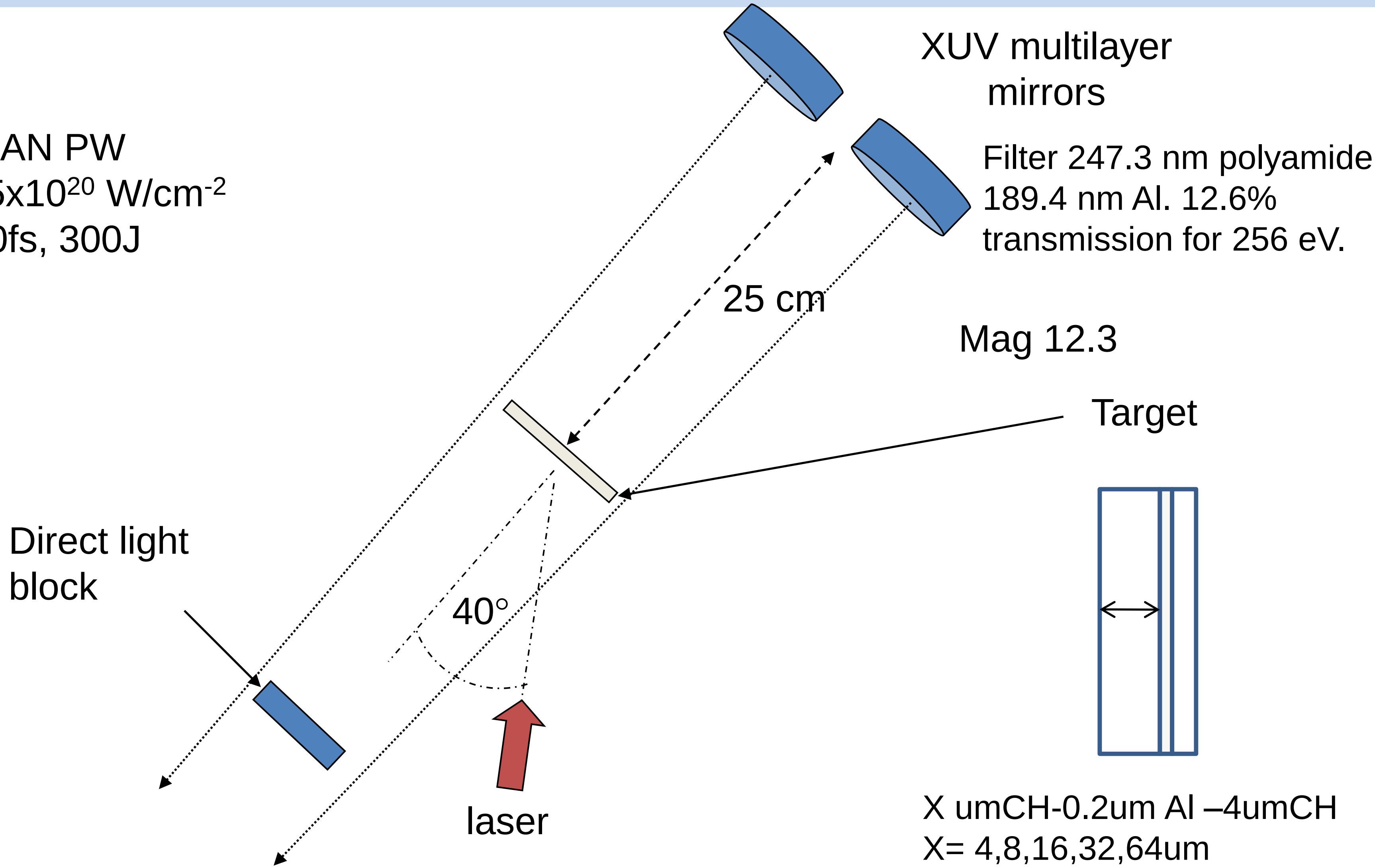
"Holey" emission experiment

VULCAN PW
I ~ 2.5x10^{20} W/cm^{-2}
T=700fs, 300J



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"Holey" emission experiment and modelling

A.P.L.Robinson, [1] K.L.Lancaster, [1] J. Pasley,[1,2] P. Hakel,[3] T. Ma,[4] K.Highbarger,[5] F.N.Beg,[6] S.N.Chen,[6] R.L.Daskalova,[5] R.R.Freeman,[5] J.S.Green,[1,7] H.Habara,[8] P. Jaanimagi,[9] M.H.Key,[9] J. King,[10,8] R.Kodama,[10,8] K.Krushelnick,[11] H.Nakamura,[10] M.Nakatsutsumi,[10] A.J.MacKinnon,[12] A. McPhee,[12] R.B.Stephens,[12] L.Van Woerkom,[13] and P.A.Norreys[1,7]

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[3]University of Reno
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[13]Department of Physics, Ohio State University, Columbus, Ohio, OH 43210-1117, USA

Results with 4μm CH at front show particularly striking "holey" emission

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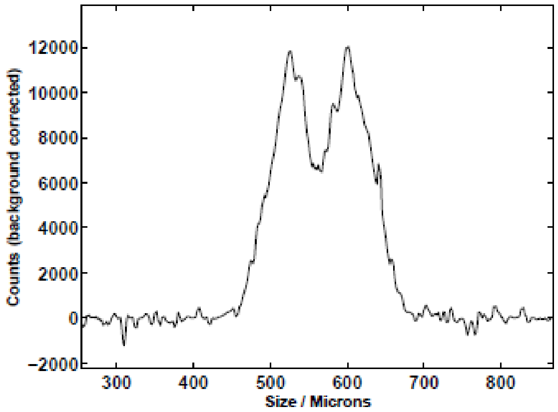
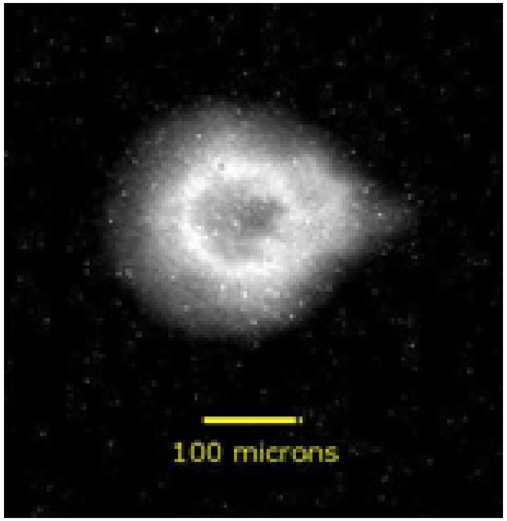
Such ring-like structures have in the past been put down to electron transport phenomena

- Hybrid simulations were carried out using the 3D hybrid code ZEPHYROS (Alex Robinson).
- The code could never produce ring like structure of the correct spatial scale from a centrally peaked temperature distribution
- Even choosing extreme temperature distributions did not produce ring structures of the correct spatial scale.





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3 step approach to hydro-modelling

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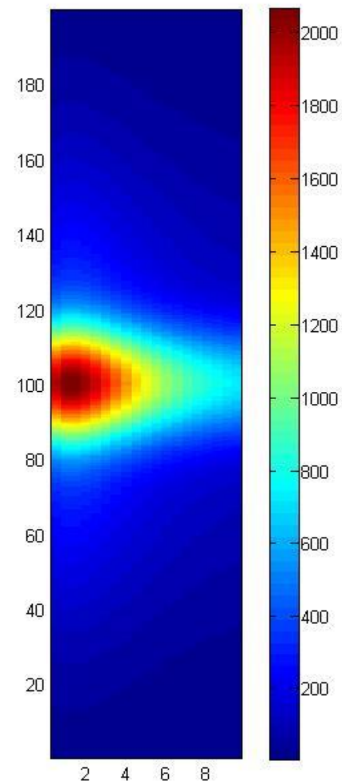
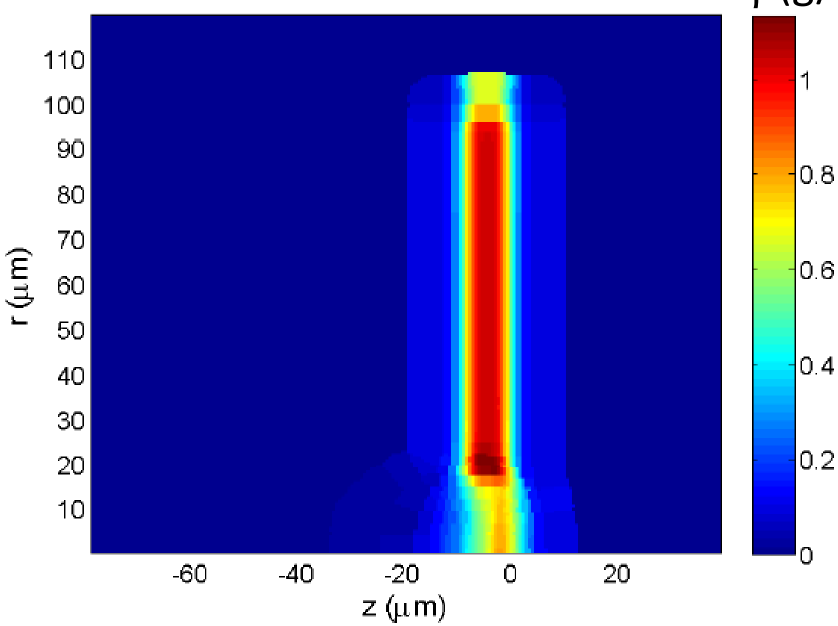
ZEPHYROS (Robinson)

Te (eV)

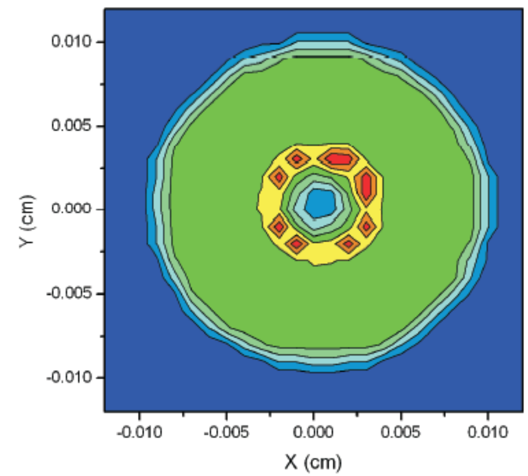


h2d radiation hydrodynamics

ρ(g/cc)



SPECT3D collisional radiative atomics code (run initially by Hakel and later by Robinson)



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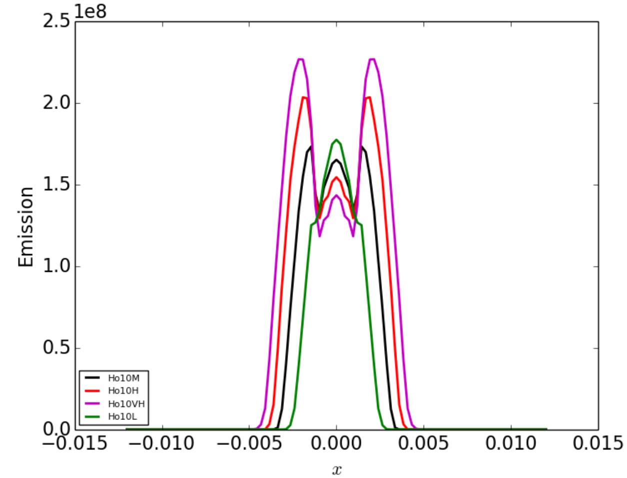
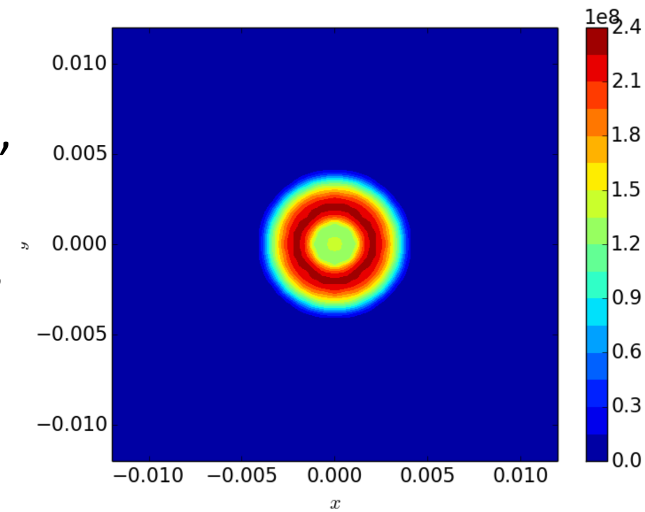
Early calculations show promise of reproducing holey emission pattern of appropriate scale

Holey work on-going!

- Formation of a ring-like emission pattern is a stable feature of these calculations
- We have tried using hyades, h2d and FLASH for the rad-hydro modelling
- Ring-like emission is most pronounced (and similar to the experiment) when a compression wave is formed: **pressures in these waves can be of order 200Mbar!**
- Formation of compressive disturbance is quite sensitive to the exact temperature profile used, and also to the code / set-up employed
- Radius of ring-like emission structure formed is dependent on injection properties of the electron beam
- Paper recently submitted to Phys. Plasmas





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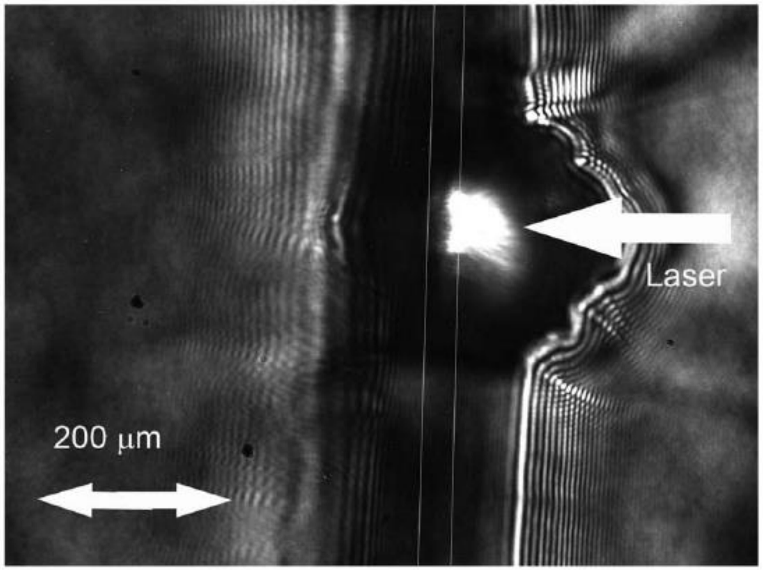
Short Pulse driven Rayleigh-Taylor Instability studies



Vulcan PW interacts with 25μm CH with a 1μm Cu back-layer

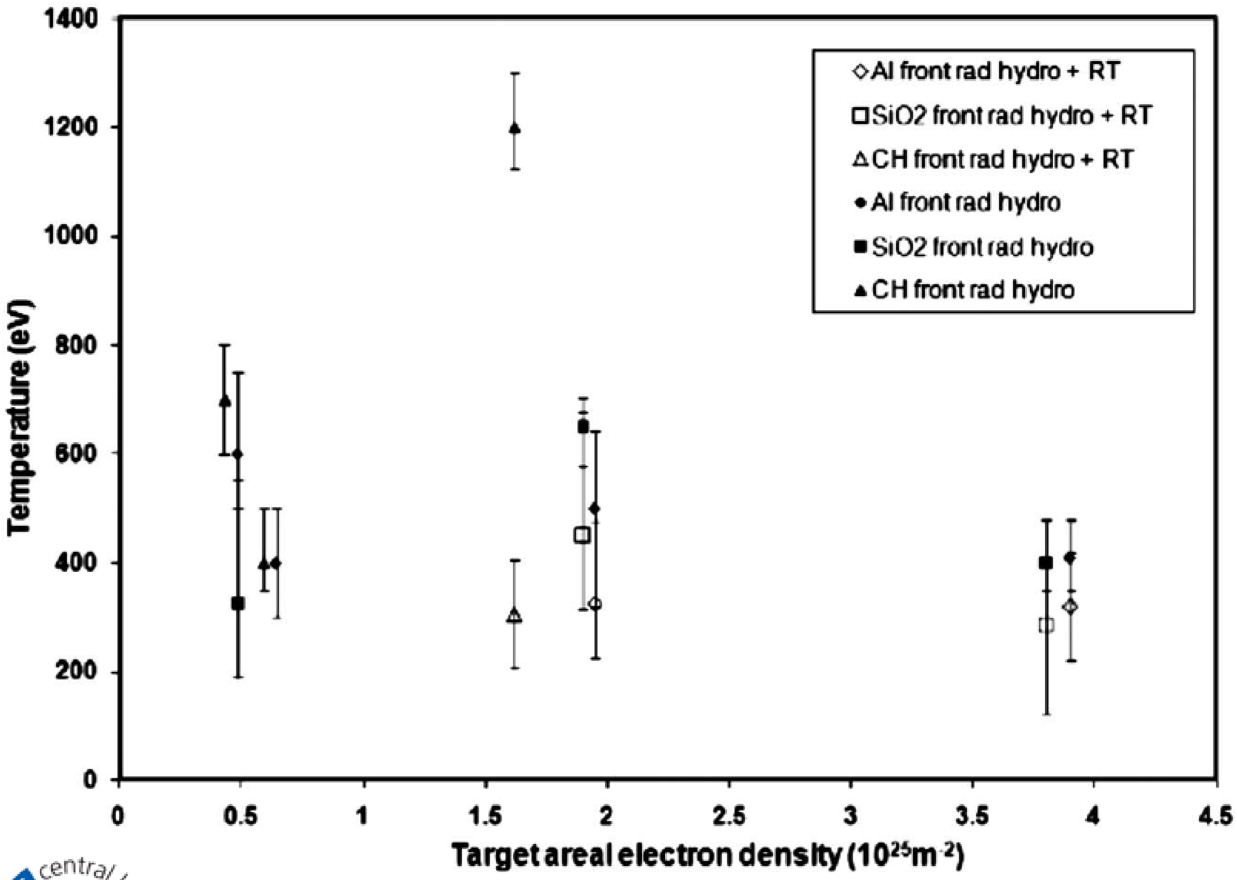
K. L. Lancaster, ***J. Pasley,*** *J. S. Green, D. Batani, S. Baton, R. G. Evans, L. Gizzi, R. Heathcote, C. Hernandez Gomez, M. Koenig, P. Koester, A. Morace, I. Musgrave, P. A. Norreys, F. Perez, J. N. Waugh, and N. C. Woolsey, Phys. Plasmas* ***16****, (2009)*

- We came to consider RT experiments driven by short-pulse lasers after surprising results from a Vulcan PW experiment on layered targets

- Transverse optical probing showed Cu back surface moving much further than seemed possible based on 1-D rad-hydro calculations. Naïve calculations suggested unphysically high temperatures needed to match experiment

- Results fell into line with expectations when it was realised that Cu/CH interface would be unstable from early times: CH motion dictating rear-surface expansion after penetration of Cu layer

Measurements suggested RT growth

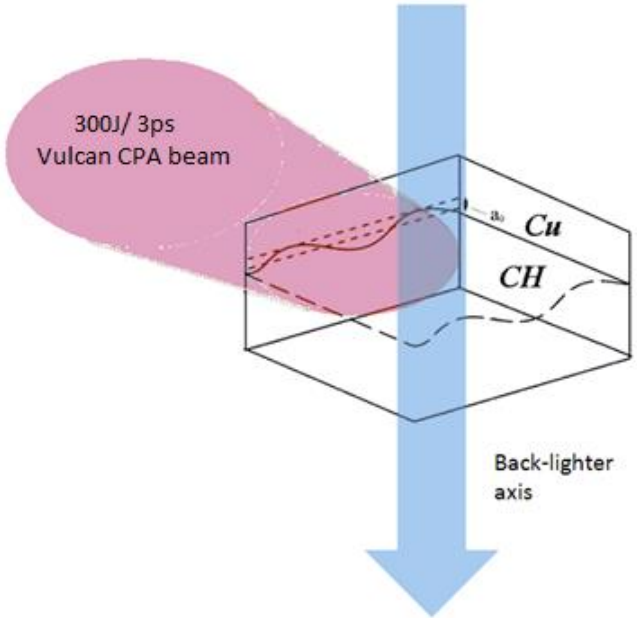


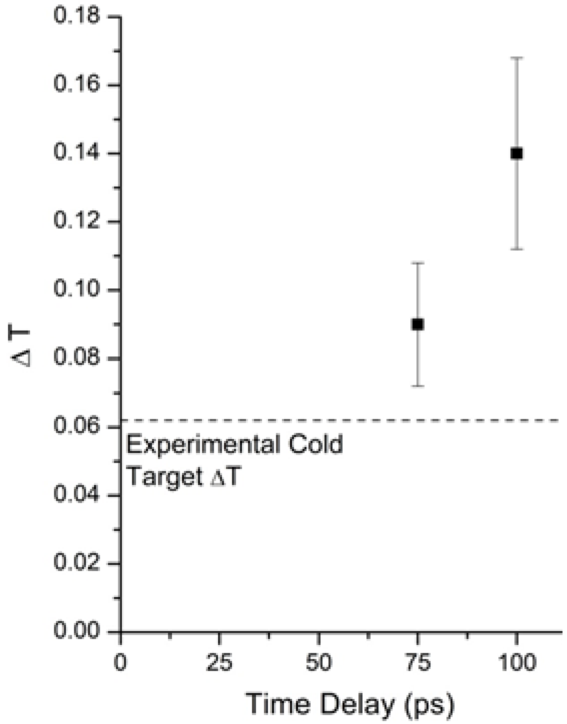
Results suggested that RT growth caused penetration of Cu back layer in thicker targets after ~100ps

*K. L. Lancaster, **J. Pasley,** J. S. Green, D. Batani, S. Baton, R. G. Evans, L. Gizzi, R. Heathcote, C. Hernandez Gomez, M. Koenig, P. Koester, A. Morace, I. Musgrave, P. A. Norreys, F. Perez, J. N. Waugh, and N. C. Woolsey, Phys. Plasmas **16**, (2009)*

RTI driven by radiative cooling in short pulse heated targets

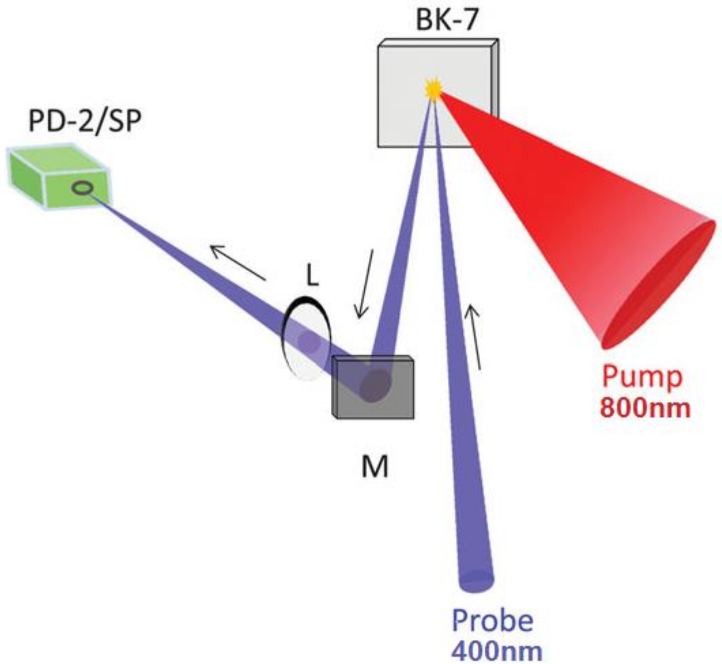
Follow-up experiment with sinusoidal interface perturbation at RAL





Measured growth rate ~10x higher than previously measured in any laser-solid target experiment.

Acoustic generation



- Continuation of earlier pump-probe experiments carried out at the Tata Institute
- 400nm probe beam interrogates interaction site of 800nm pump beam (30fs) of moderately high intensity (5 x 10^{16}W/cm^2 to 1.5 x 10^{17}W/cm^2)
- Doppler spectroscopy measurements of the interaction were carried out with a temporal resolution of around 100 femtoseconds

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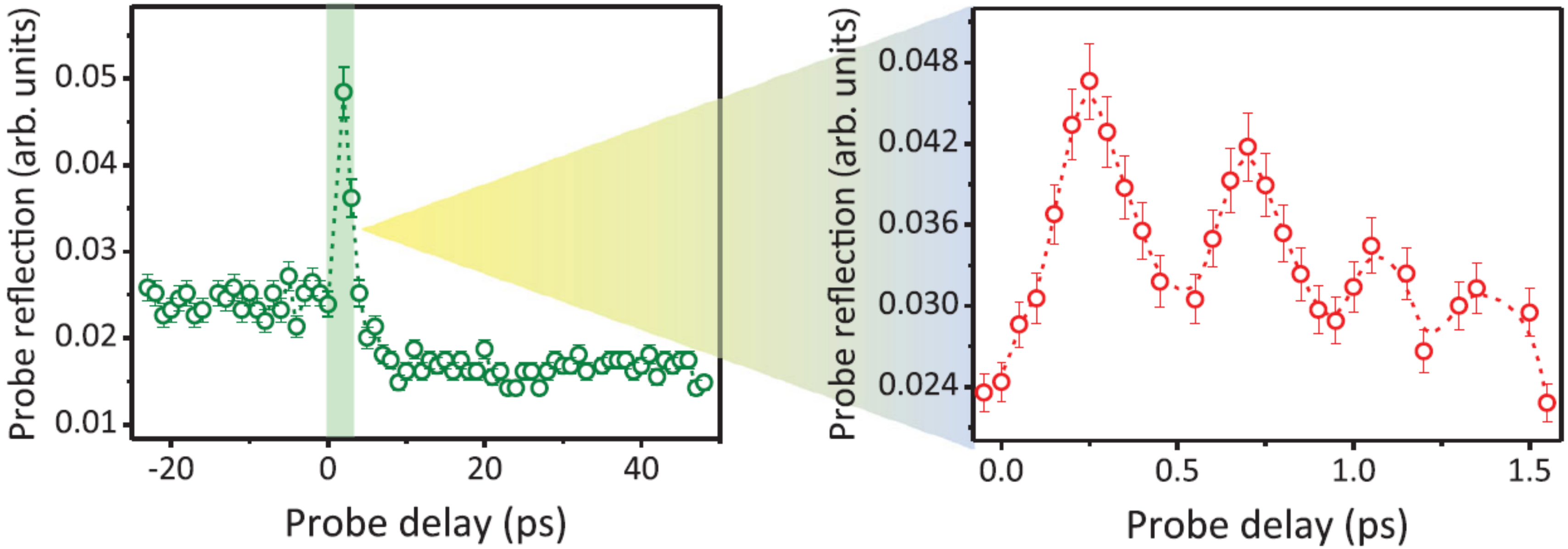
A. Adak, A. P. L. Robinson, P.K. Singh, G. Chatterjee, A. D. Lad, ***J. Pasley,*** *and G. Ravindra Kumar, Phys. Rev. Lett.* ***114****, (2015)*

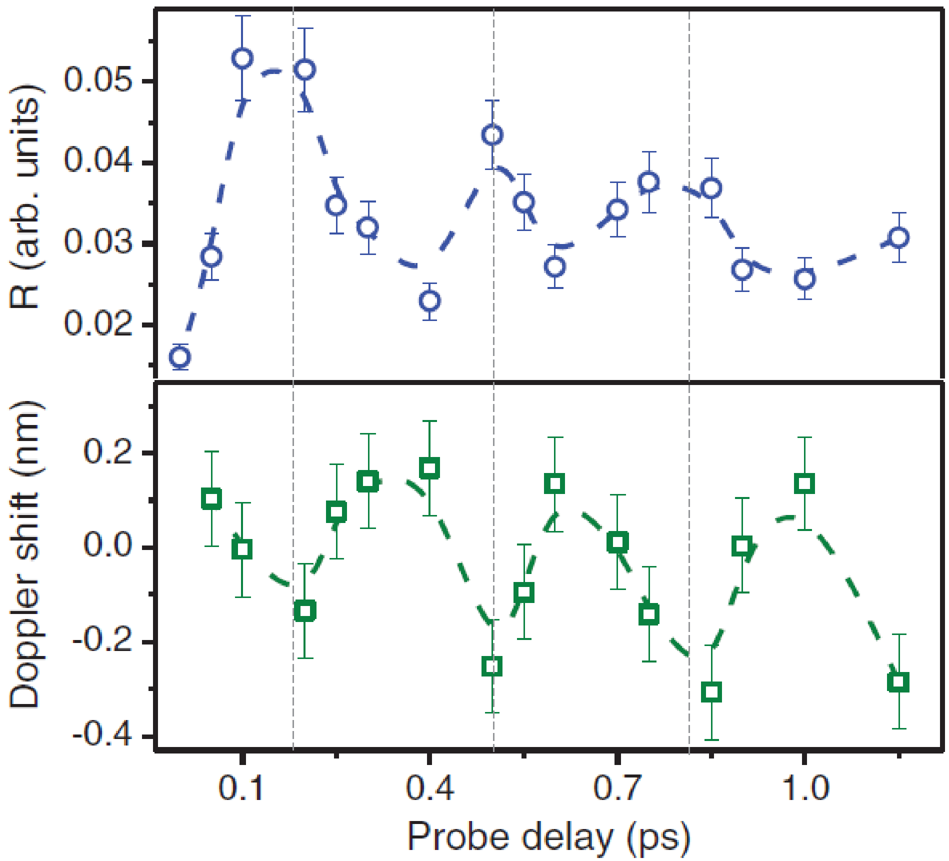
Acoustic generation



Measurements with very high temporal resolution reveal unexpected oscillatory behaviour in the reflectivity.

A. Adak, A. P. L. Robinson, P.K. Singh, G. Chatterjee, A. D. Lad, ***J. Pasley,*** *and G. Ravindra Kumar, Phys. Rev. Lett.* ***114****, (2015)*

Acoustic generation



- Further investigations revealed an out-of-phase modulation in the Doppler shift of the probe
- These measurements were unexpected and it took some time to adequately explain them

A. Adak, A. P. L. Robinson, P.K. Singh, G. Chatterjee, A. D. Lad, ***J. Pasley,*** *and G. Ravindra Kumar, Phys. Rev. Lett.* ***114****, (2015)*

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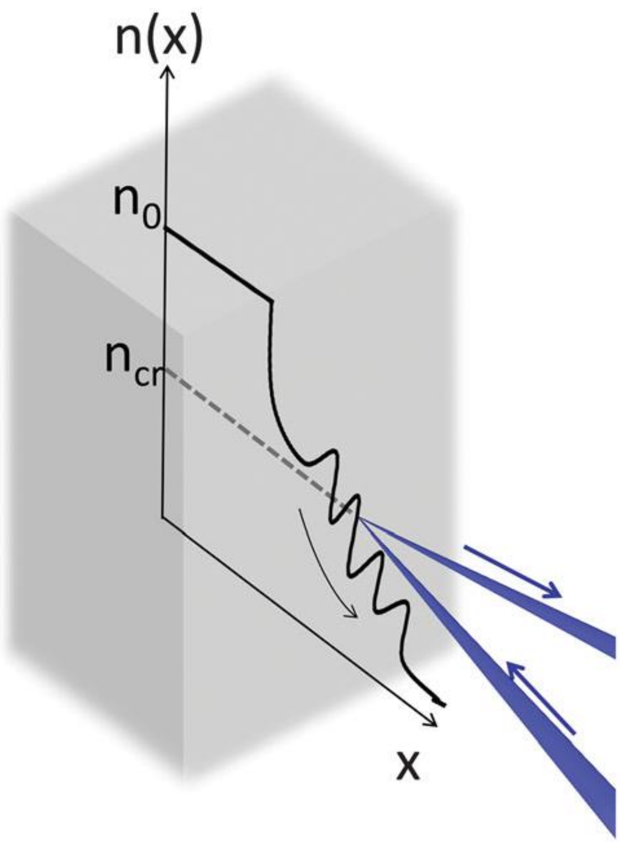
Acoustic generation



- I proposed an explanation that the combined reflectivity and Doppler measurements could be explained by an approximately sinusoidal density disturbance propagating down the density gradient through the probed density contour

- However, if this was the explanation, we also needed to find a source of such a disturbance at the appropriate frequency (hundreds of GHz)

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A. Adak, A. P. L. Robinson, P.K. Singh, G. Chatterjee, A. D. Lad, ***J. Pasley,*** *and G. Ravindra Kumar, Phys. Rev. Lett.* ***114****, (2015)*

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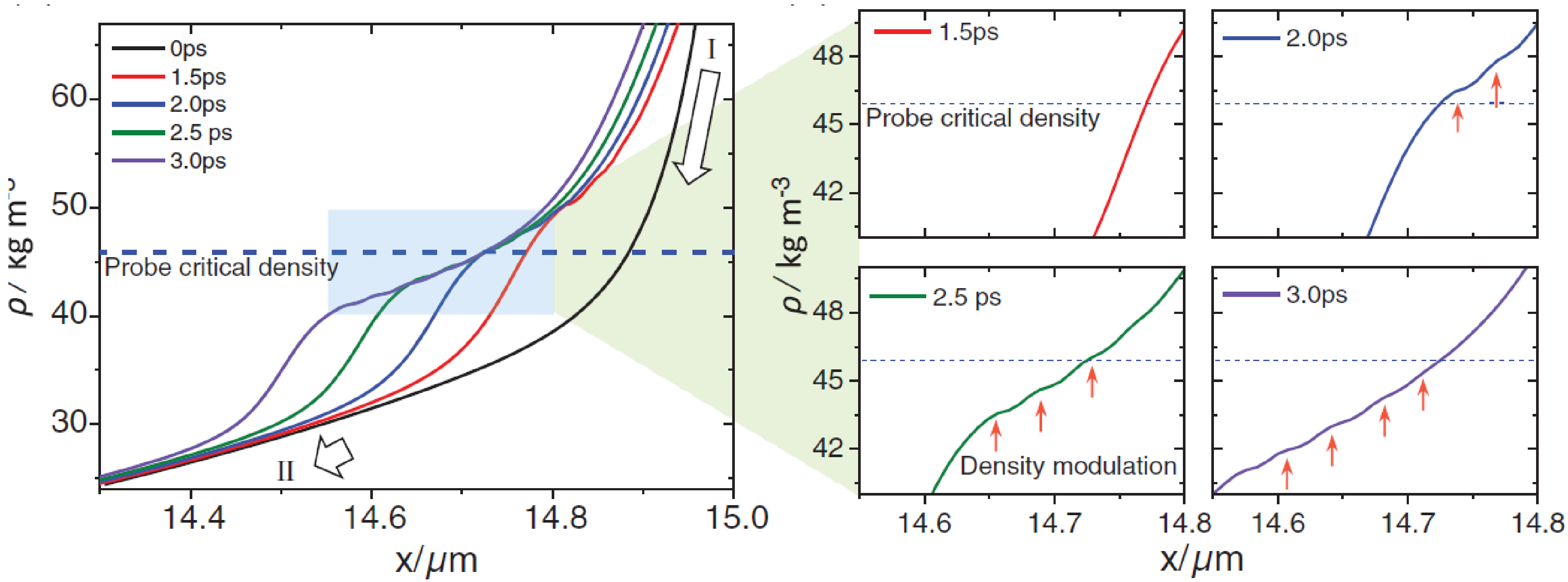
Acoustic generation



Simulations revealed that the prompt heating of the preformed plasma (picosecond contrast is ~ 10^{-4}, nanosecond contrast is ~ 10^{-8}) results in a velocity flow gradient. This drives modulations

A. Adak, A. P. L. Robinson, P.K. Singh, G. Chatterjee, A. D. Lad, ***J. Pasley,*** *and G. Ravindra Kumar, Phys. Rev. Lett.* ***114****, (2015)*

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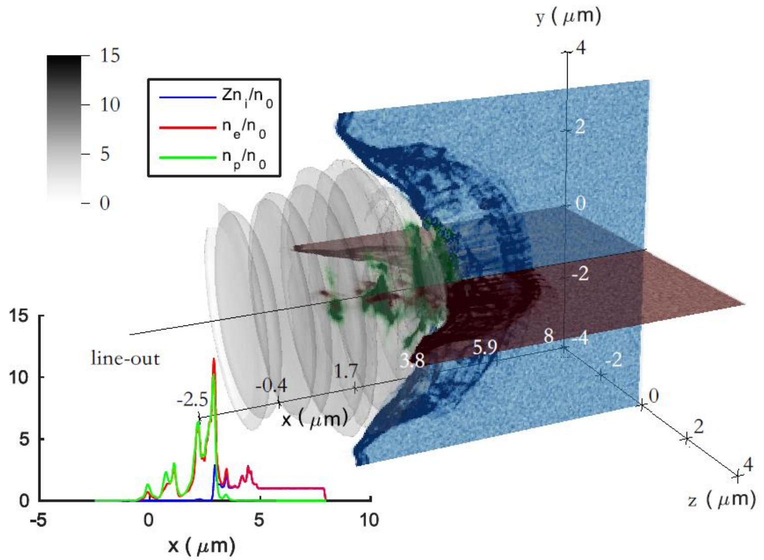
Finally, since this is Laser Plasma accelerator workshop…



Hole-boring simulation including non-linear Compton effect and pair-production. t = 6T, I = 5 x 10^{24} W/cm^2 , λ = 1μm, circular polarisation

Laser intensity 10^{23}W/cm^2 + can drive processes not seen at lower intensities

Non-linear Compton effect produces γ-rays as electrons are accelerated in the laser field and these decay to e+ e- pairs resulting in a pair cascade

Pair plasma density can exceed the relativistically-corrected critical density resulting in the quenching of the laser field

D. Del Sorbo, D. R. Blackman, R. Capdessus, K. Small, C. Slade-Lowther, W. Lou, M. Duff, A. P. L. Robinson, P. McKenna, Z.-M. Sheng, ***J. Pasley,*** *and C. P. Ridgers, submitted to Phys. Rev. Lett. 2017*

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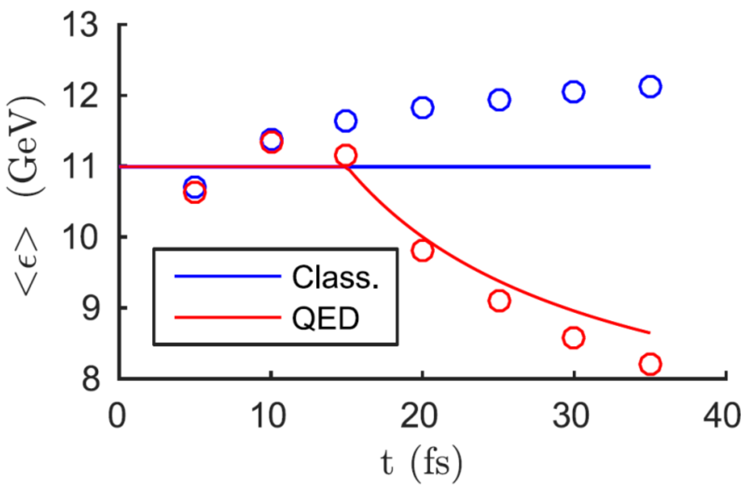
Results suggest e- e+ pair plasma saps energy from laser pulse at high I



Accelerated ion energy and production efficiency respectively reduced by 30-50% & 50-65% from values expected in absence of QED effects in conditions given on previous slide

Questions: dario.delsorbo@york.ac.uk

- Simulations are performed with the PIC code EPOCH
- Plasma is described as a collection of macroparticles (electrons, ions and, eventually, positrons and gamma-ray photons), with a statistical weight.
- The electromagnetic fields are split into two components: (i) low frequency fields, from the laser and collective processes in the plasma; (ii) high frequency gamma-ray photons.
- The high frequency fields are modelled as macroparticles moving on null geodesics and the low frequency fields are represented on a spatial grid and updated by solving Maxwell's equations.
- The acceleration of electrons, ions and positrons is included by solving the Lorentz force law.
- QED effects (emission of a gamma-ray photon by an electron or positron and the decay of a gamma-ray photon to an electron-positron pair in the laser fields) are modelled stochasticially with a Monte-Carlo algorithm, where the rates are derived in the Furry picture. Here the classical low-frequency electromagnetic field 'dresses' the electron and positron states. The interactions between the 'dressed' particles and the gamma-ray photons is treated perturbatively, as an expansion of the S-matrix, in powers of the fine structure constant.

D. Del Sorbo, D. R. Blackman, R. Capdessus, K. Small, C. Slade-Lowther, W. Lou, M. Duff, A. P. L. Robinson, P. McKenna, Z.-M. Sheng, ***J. Pasley,*** *and C. P. Ridgers, submitted to Phys. Rev. Lett. 2017*

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Future work

- Investigating such physics adequately on large facilities with high energy pulses of greater relevance to Fast Ignition is challenging due to the large amounts of background/ noise signals present and the limited shot availability
- In the near term we are further investigating the acoustic generation process and studying its relevance to various astrophysical systems
- Review article invited by AIP Phys. Plasmas - this is currently being prepared

Conclusions

- A range of different hydrodynamic effects that may arise due to the illumination of a target with a short-pulse laser
- Hydrodynamics in dense plasmas at sub- RP intensities driven predominantly by nkT pressure gradients
- Modelling is challenging requiring a range of different codes to tackle the different stages of the interaction (prepulse, main-pulse, later motion)