Time Resolved Imaging of Shock Compressed Matter Using X-Rays from a Laser Wakefield Electron Accelerator

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Acknowledgements

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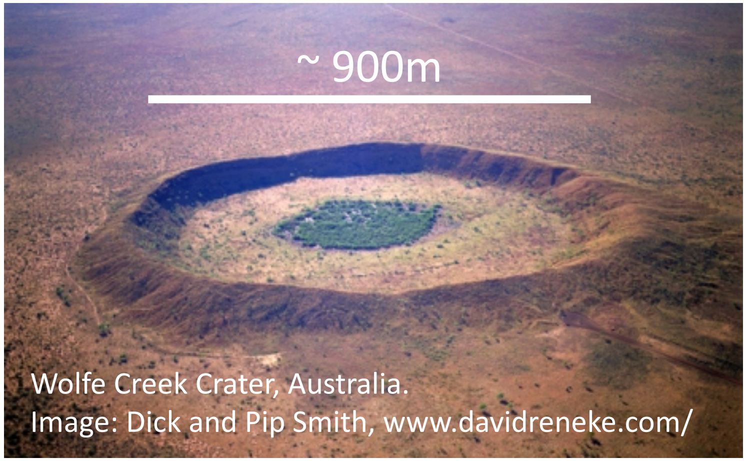
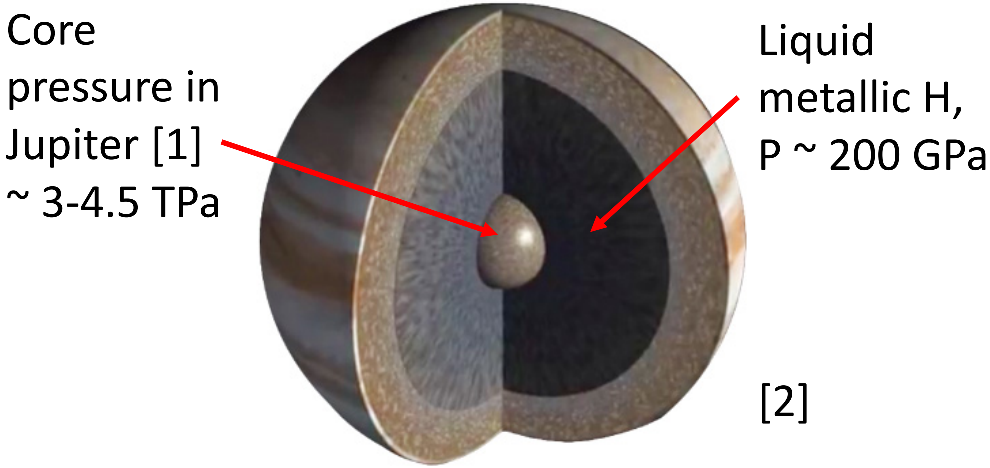
Contents

- Importance of high energy density physics (HEDP).
- Measuring materials in extreme conditions: challenges and conventional methods.
- X-rays from Laser Wakefield Accelerators: betatron radiation.
- Imaging laser driven shock waves in silicon and quantitative measurements.
- Overview: increasing the brightness of betatron radiation at 10-20 keV energies.
- Imaging shocks in aluminium with high signal-to-noise ratio and studies of spall.

Examples of High Energy Density Physics

Aim: Understand how materials behave in extreme conditions- usually high pressure.





Meteorite impacts: fluid flow, spallation, what happens to the meteorite?
Planetary defence.

Core existence suggested by gravitational measurements [3]. Composition? Phase? Planet radius can decrease with mass- implications for exoplanents.

Other examples: astrophysical shocks, ICF, material failure.

[1] Guillot, T. *et al*. "Chapter 3: The Interior of Jupiter". In Bagenal, F. *et al. Jupiter: The Planet, Satellites and Magnetosphere*. Cambridge University Press (2004). .
[2] Crockett, Christopher. "Juno is closing in on Jupiter". Science News, June 16 2016.
[3] Bodenheimer, P. *Icarus*. 23. **23** (3): 319–25 (1974).

Understanding HEDP

- Laboratory experiments informing simulations.
- Sometime it is suitable to use fluid or MHD codes (e.g. astrophysical shocks).
- With solids have inter-molecular forces: strength, crystallisation, phase changes. Full modelling requires molecular dynamics codes. Experiments on bulk matter are important (EOS).

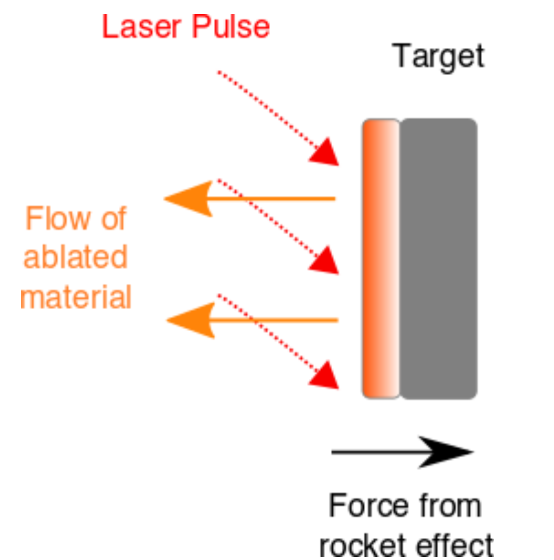
To get to very high pressure states in the lab we need dynamic compression experiments. Driven by high explosives, or more recently:

High velocity flyer plate:

Laser ablation:

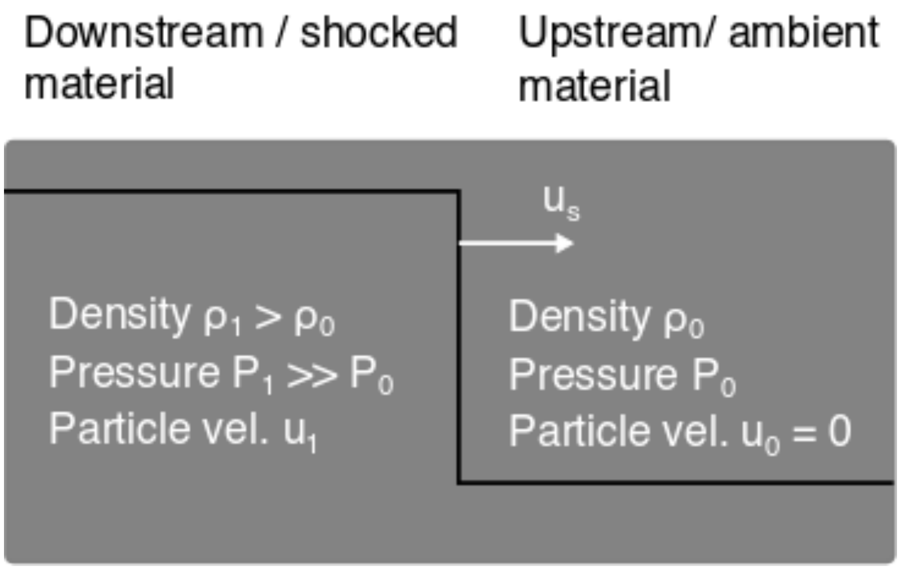
$$P \approx 800 \left(\frac{I_{14}}{\lambda_{\mu}}\right)^{2/3} \text{GPa}$$

[4]



[4] Drake, R. P. *High-Energy-Density Physics* (Springer-Verlag Berlin, Heidelberg,2006),1st edn.

Traditional Diagnostic Techniques in Shock Physics



Mass conservation:

$$\rho_o u_s = \rho_1 \left(u_s - u_1 \right)$$

Momentum conservation:

$$P_1 - P_0 = \rho_0 u_s u_1$$

- Can measure u_s, u_p with wire gauges (intrusive) or interferometrically with VISAR (surface data only).
- Can also measure P with strain gauges (intrusive).
- Conventional methods are *surface-based* or *intrusive*.

X-ray Based Measurements in Shock Physics

- X-rays: non-intrusive, subsurface measurements.
- Only way to observe the effects of material inhomogeneities.
- Also a measure of density.

- Source requirements:
  - ❑ Short pulse ($\ll$ 1ns).
  - ❑ High resolution.
  - ❑ Hard: few 10's keV to get good contrast for $Z \approx$ 10-20 solids.
  - ❑ Bright: single shot imaging is of fundamental importance- nonlinear processes and target destroyed every shot.

Imaging at Synchrotron and X-FEL sources

A hard, high brightness source is required:

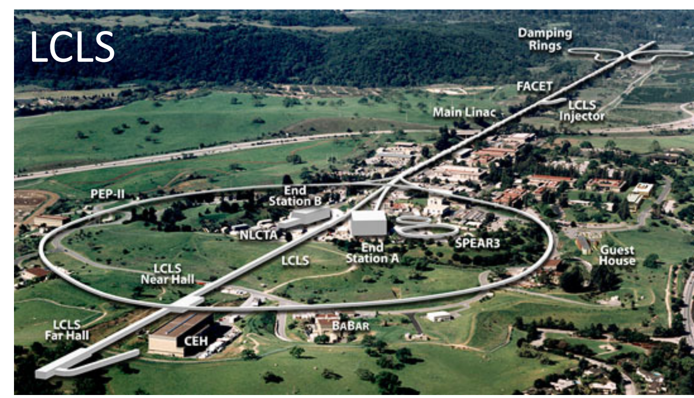
$$B/\mathrm{photons/s/mrad^2/mm^2/0.1\%BW}$$

Achievable with sources based on relativistic electron beams.

ESRF: B ≈ 10^{23} @ 10-20 keV
LCLS: B ≈ 10^{31}-10^{34} @ 10 keV [5]

Temporal resolution

Synchrotron short pulse beamlines: 10's – 100ps
XFELs: 10's fs



Single shot spatial resolution from dynamic experiments

Synchrotrons: 2-4 µm [6-8]
XFELs: ~ 0.5 µm [9]

[5] http://photon-science.desy.de/research/ studentsteaching/sr_and_fel_basics/fel_basics/tdr_spectral_characteristics/index_eng.html
[6] Ramos, K. J. *et al. J. Physics: Conf. Ser.* 500, 142028 (2014)
[7] Jensen, B. J. *et al. AIP Adv.* 2, 012170 (2012).
[8] Yeager, J. D. *et al. Compos. Part A: Appl. Sci. Manuf.* 43, 885–892 (2012).
[9] Schropp, A. *et al. Sci. Reports* 5, 11089 (2015).

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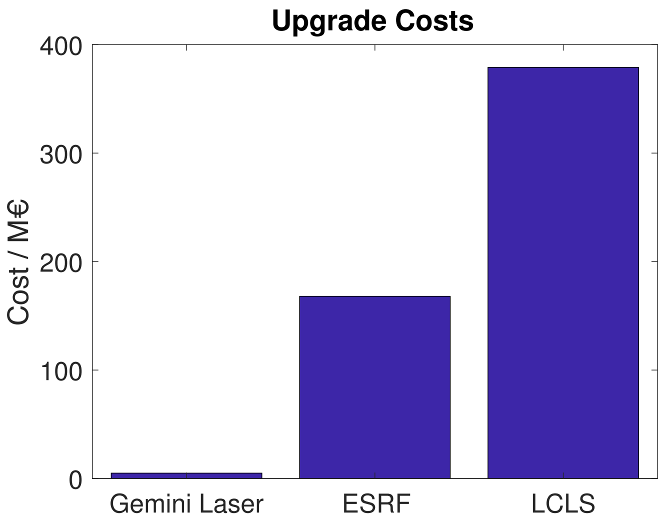
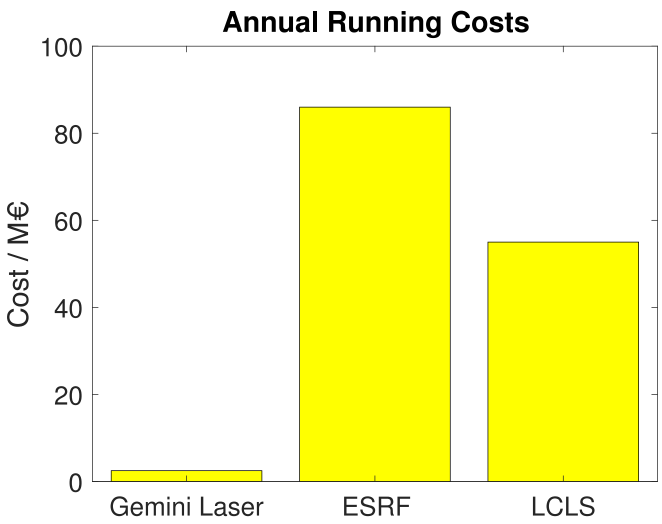
Is there a Laser-based Alternative?

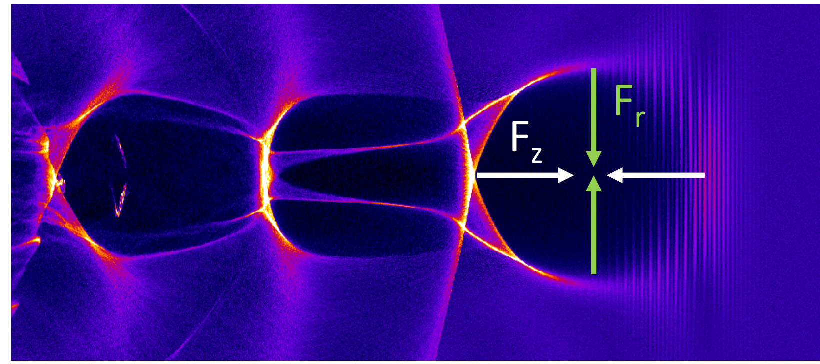




- High rep rate of conventional sources is not required for HEDP experiments: low rep. rate drivers.
- Laser pulse duration 10s fs
- Good synchronisation with optical drivers.

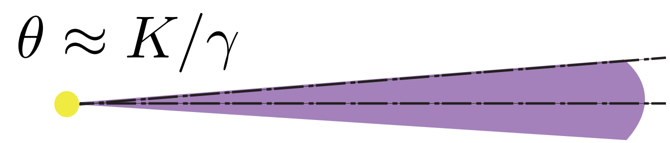
Generation of Betatron Radiation

Bubble focusing forces support oscillation: radiation.



Frequency boost of $2\gamma^2$.

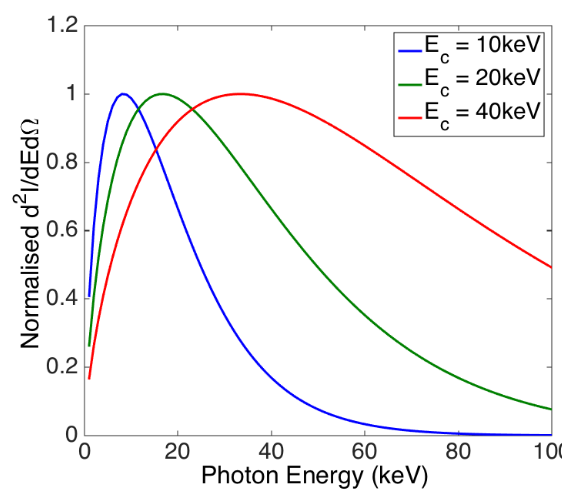
Narrow emission, $\theta \approx K/\gamma$ where $K = \gamma k_\beta r_\beta$.



$K \gg 1$: broadband radiation.

Approximated by on axis synchrotron spectrum [10], defined by critical energy E_C:

$$E_c = \frac{3\hbar}{4c}\gamma^2{\omega_p}^2 r_\beta$$



$$B = 10^{22} - 10^{23}/\mathrm{photons/s/mrad^2/mm^2/0.1\%BW}$$ [11]

[10] E. Esarey et al. Physical Review E, 65(5):056505, May 2002.

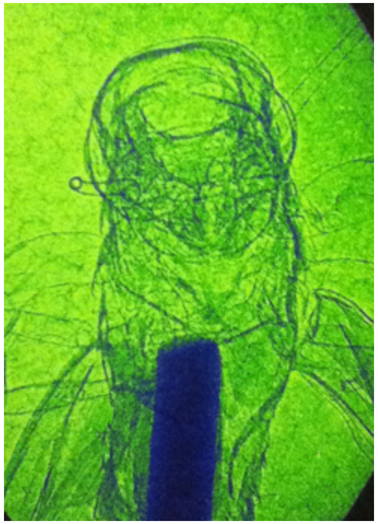
[11] Kneip, S. *et al., Nat. Phys.* 6, 980–983 (2010).

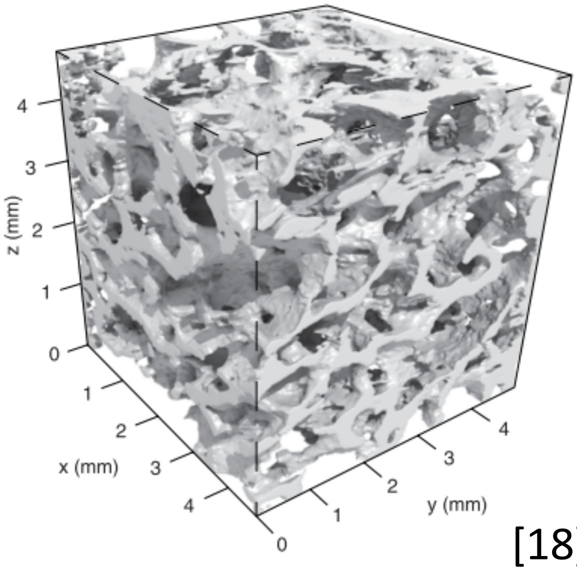
High Quality “Betatron Imaging”

High quality = high resolution (small source), high photon flux.

Spatial coherence may be desired for propagation based PCI.

It has been shown that betatron radiation can produce good quality images in absorption and phase contrast [14-18].





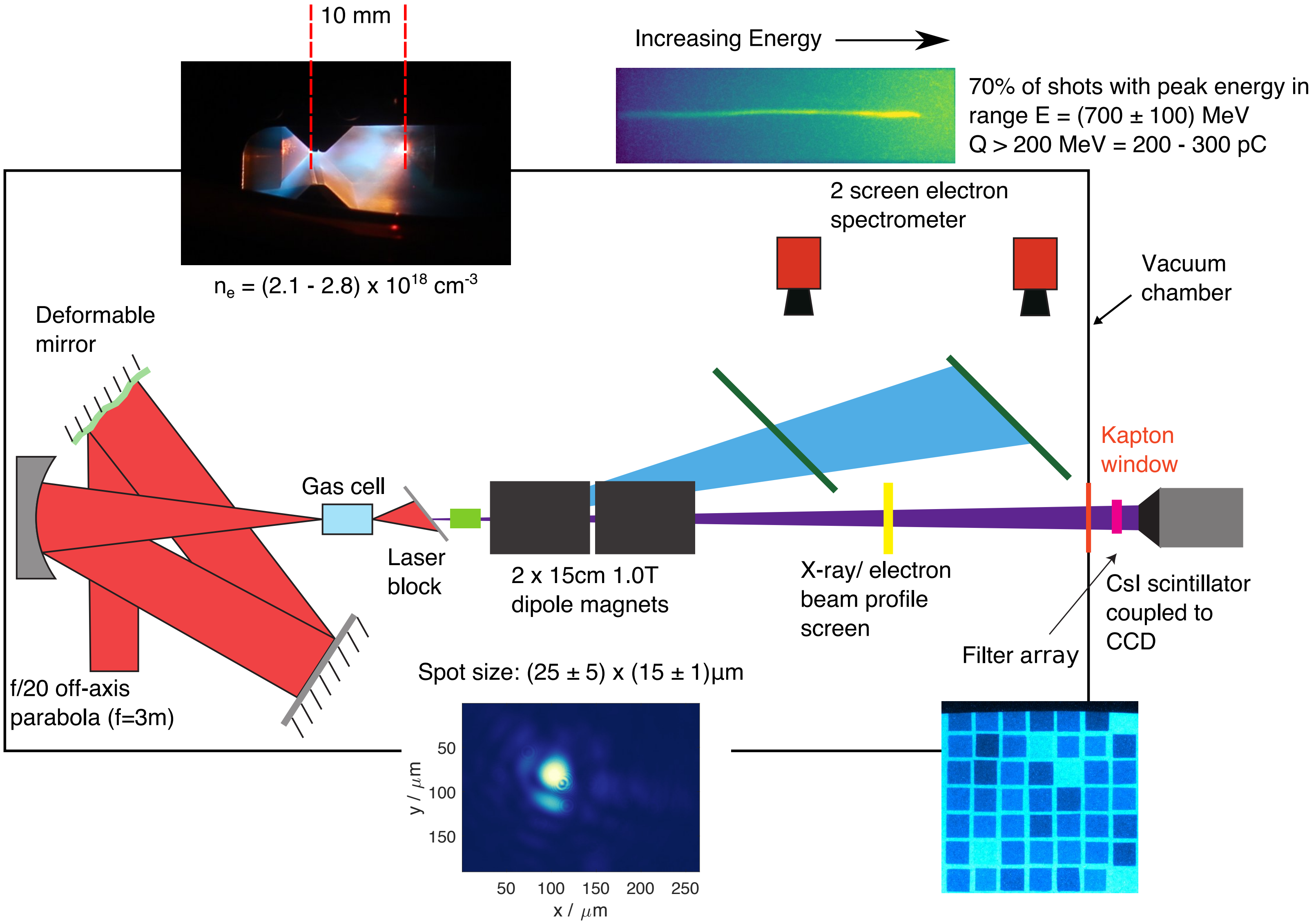
[18]

J. Cole talk WG4.

Should utilise short pulse nature of betatron radiation: Imaging of dynamic processes.

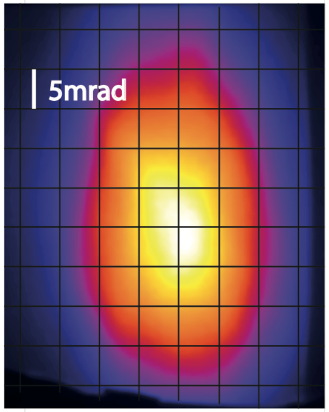
[14] S. Kneip et. al., Nat. Phys. 6(12):980-983, 2010 [15] S. Kneip et. al. Appl. Phys. Lett., 99(9):093701, 2011. [16] S. Fourmaux et. al., Opt. Lett., 36(13):2426, 2011.
[17] J. Wenz et. al., Nat. Commun. 6:7568, 2015 [18] J.M. Cole, J.C. Wood et. al. Scientific Reports 5:13244, 2015.

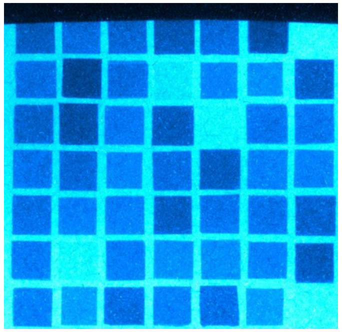
Experimental Set-up



Betatron Source Properties

FWHM divergence:
(20 ± 2) x (9 ± 1) mrad





Assume on-axis synchrotron spectrum.
E_c from differential filter transmission.

$$E_c = (20.4 \pm 0.8)\ \mathrm{keV}$$

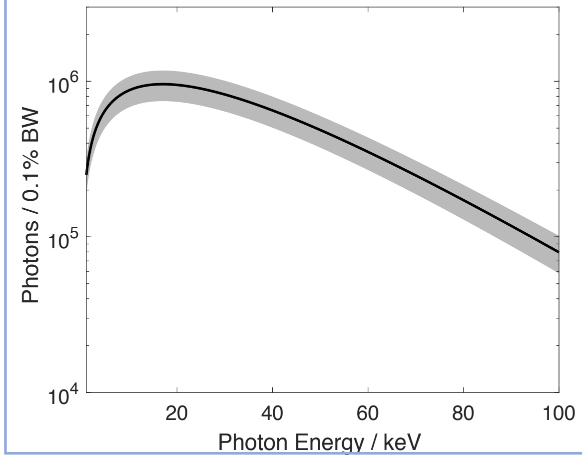
Standard error from 40 shots.

Estimate source size from $E_c = \frac{3\hbar}{4c}\gamma^2 {\omega_p}^2 r_\beta$

$$2r_\beta = (1.6 \pm 0.4)\ \mu\mathrm{m}$$

Knife edge measurements.

LSF FWHM = (4.7 ± 0.4) µm at target plane.

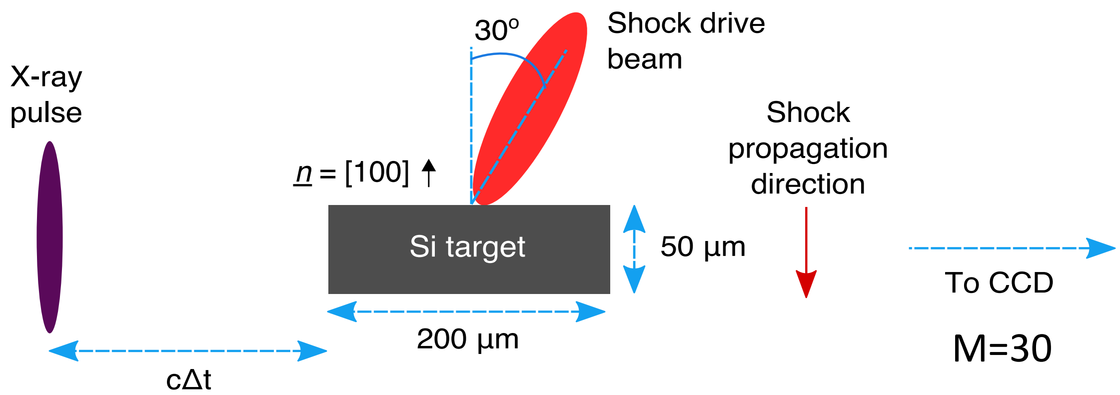


Detector calibrated with Fe-55 source.

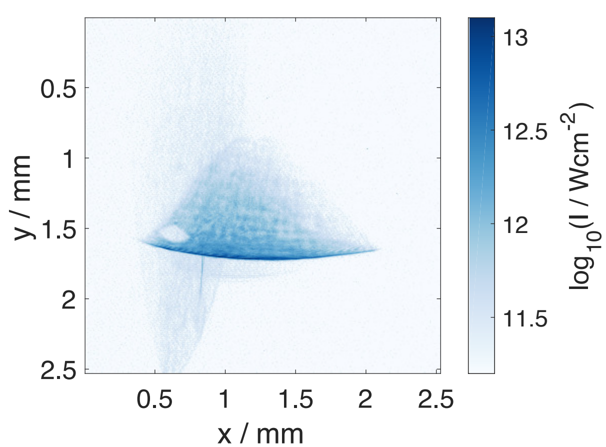
(5.5 ± 1.2) x 10^9 photons/shot with E > 1keV.

B(60fs) = (6 ± 1) photons/s/mm^2/mrad^2/0.1%BW.

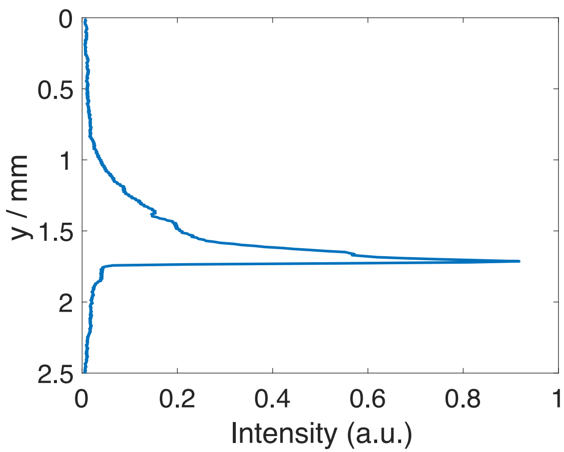
Shock Target Interaction Point



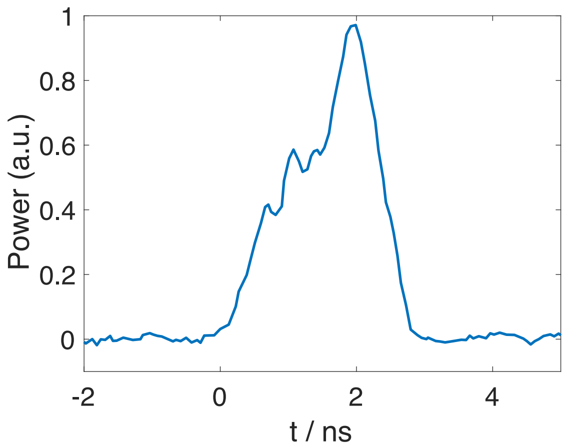
(14 ± 1) J delivered to target.
λ = 800nm.
Intensity on target
$I \approx (6.0 \pm 0.5) \times 10^{12}\,\mathrm{Wcm}^{-2}$



Spatial intensity profile.

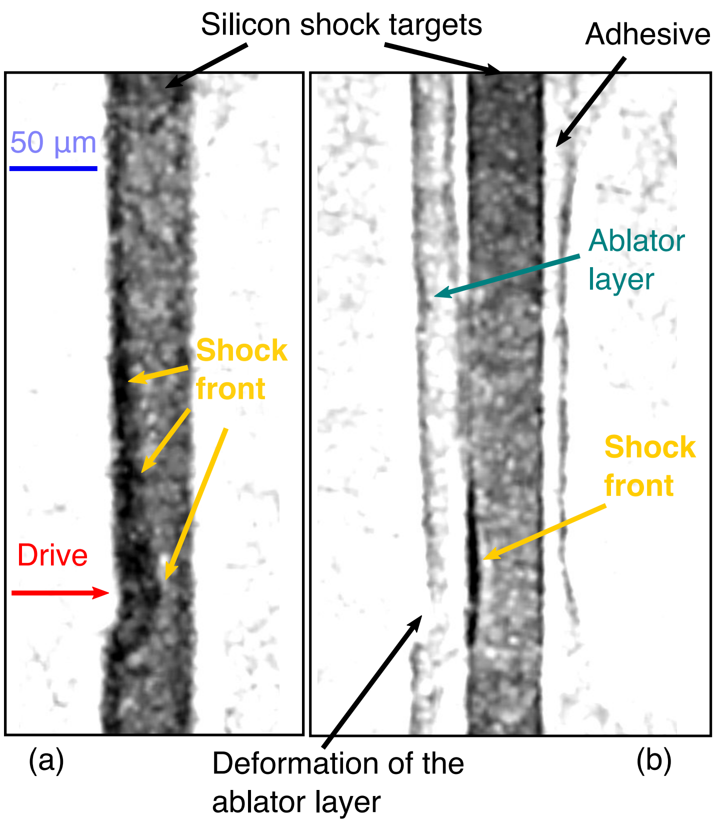


Intensity profile integrated over x.



Temporal profile of drive pulse.
Pulse length ≈ 3 ns.

Images of Shocked Silicon



$\Delta t = 5.2$ns $\Delta t = 6.5$ns

Bremsstrahlung noise from electrons reduced with filter smaller than PSF.

Can determine the position of the shock front- quantitative study of material properties.

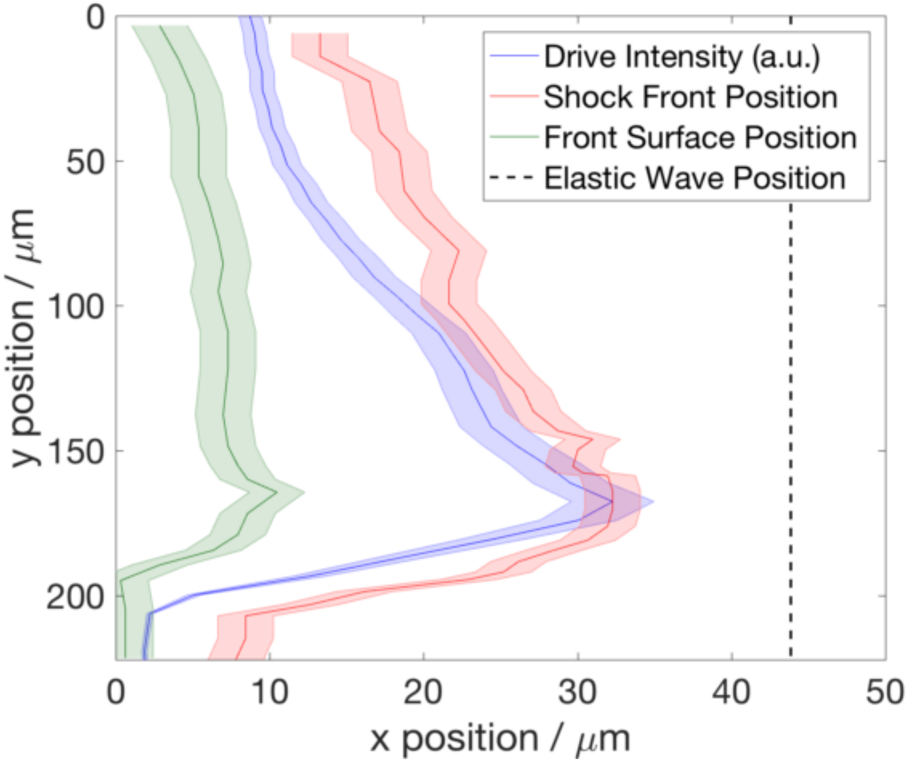
The ablator layer had a large effect on the shock propagation: clear because of PCI.

< 1% difference in detected x-ray intensity between the ablator layer and the vacuum.

Could study low-*Z* ablator dynamics while retaining the ability to probe medium-Z targets with betatron.

From now on: focus on target without ablator layer.

Shock Front and Surface Positions



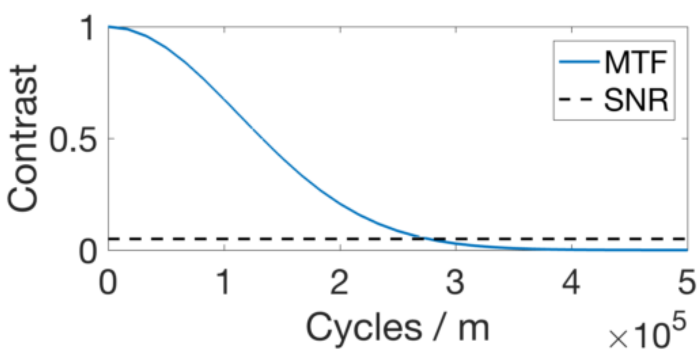
Shock shape follows laser intensity pattern.

Treat shock locally as quasi-1D. Lateral effects small. Jump conditions applicable.

Good measurements of u_s.

Drive surface not following laser intensity.

Unsupported shock at 5.2 ns- drive surface position not a measurement of u_p. But could be for longer drive.



Errors in distance from system resolution. MTF from PSF. Contrast vs spatial frequency.

Resolution ≈ 3.6 µm.

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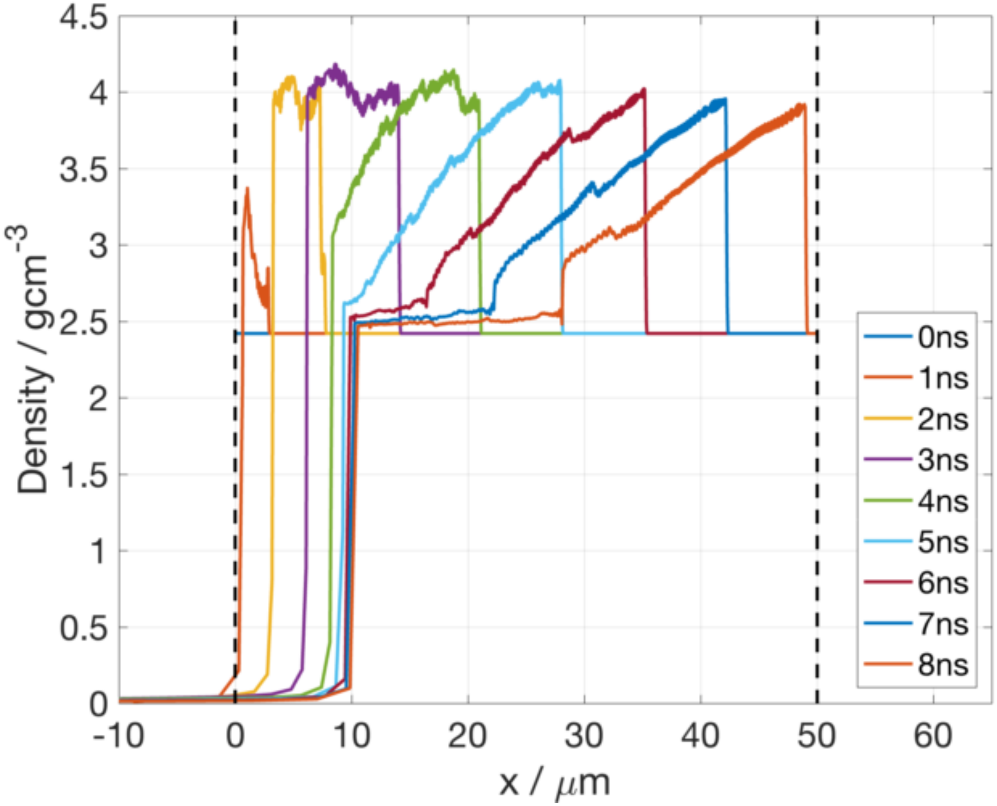
Insight from Simulations



Target density vs. x position.

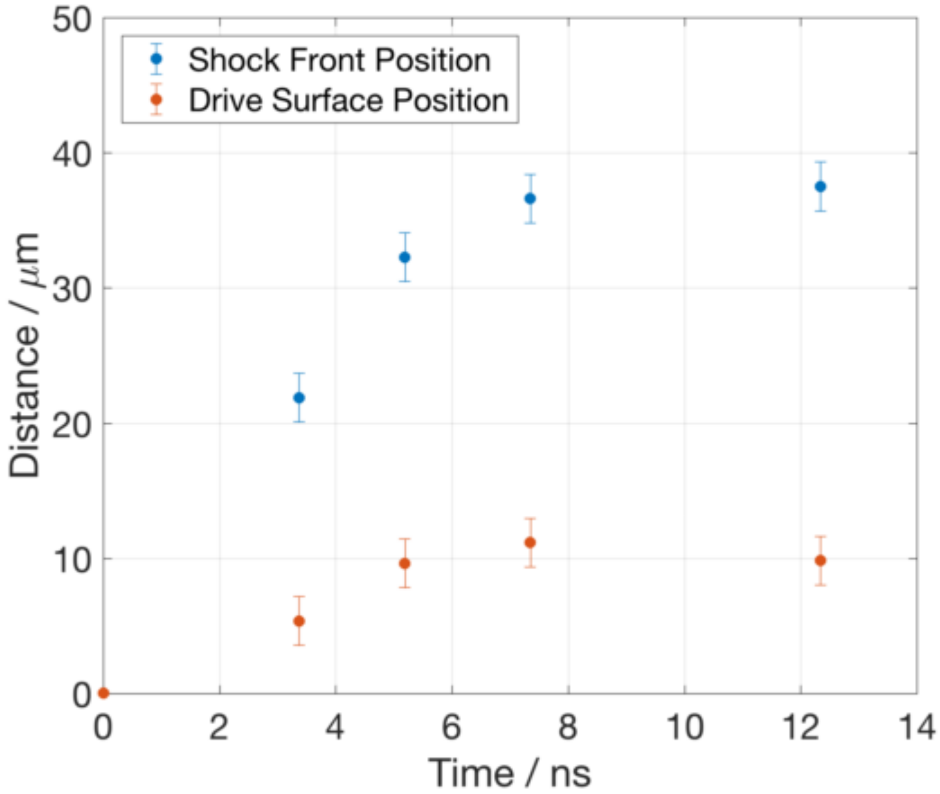
As expected, shock only supported for approx. 3 ns.

How do we know? Density at rear of shocked material = density at shock front.

Can compare front surface and shock front positions vs. time to experimental data.

Rad-hydro simulations using 1D HYADES code.
$I = 1 \times 10^{12}$ W/cm^2.

Results of Timing Scan I

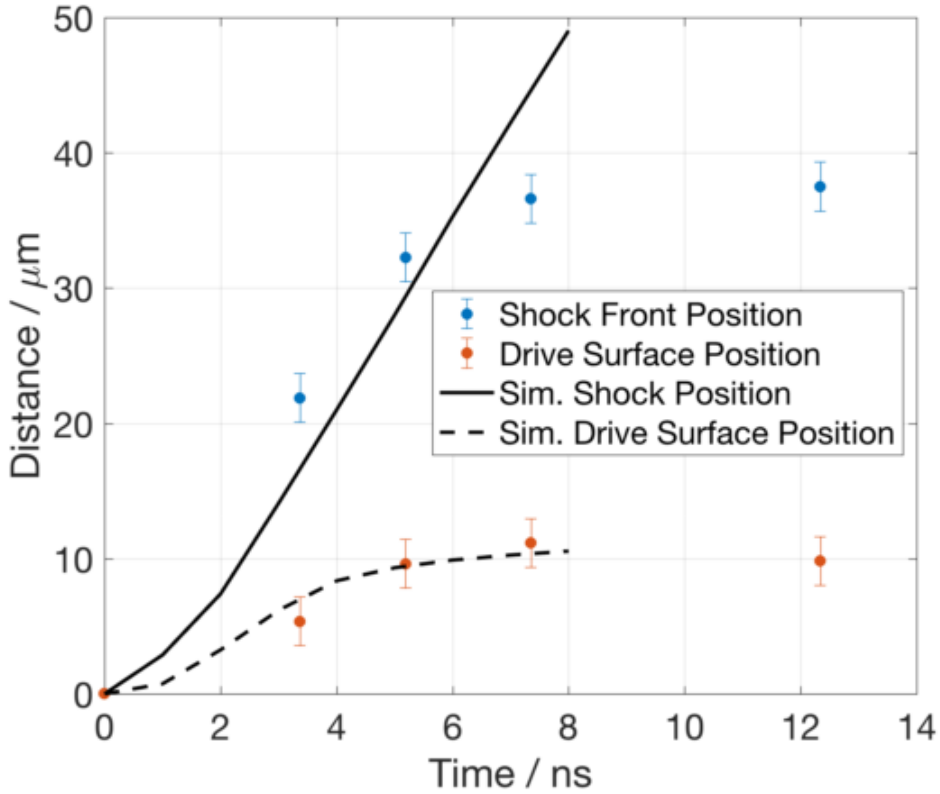


Looking at most intense part of laser/ strongest shock.

Suggests that shock velocity u_s is approx. constant over first 5ns.

From gradient of linear fit to data taken up to 5.2 ns, $u_s \approx (6.2 \pm 0.4)$ km/s.

Results of Timing Scan II



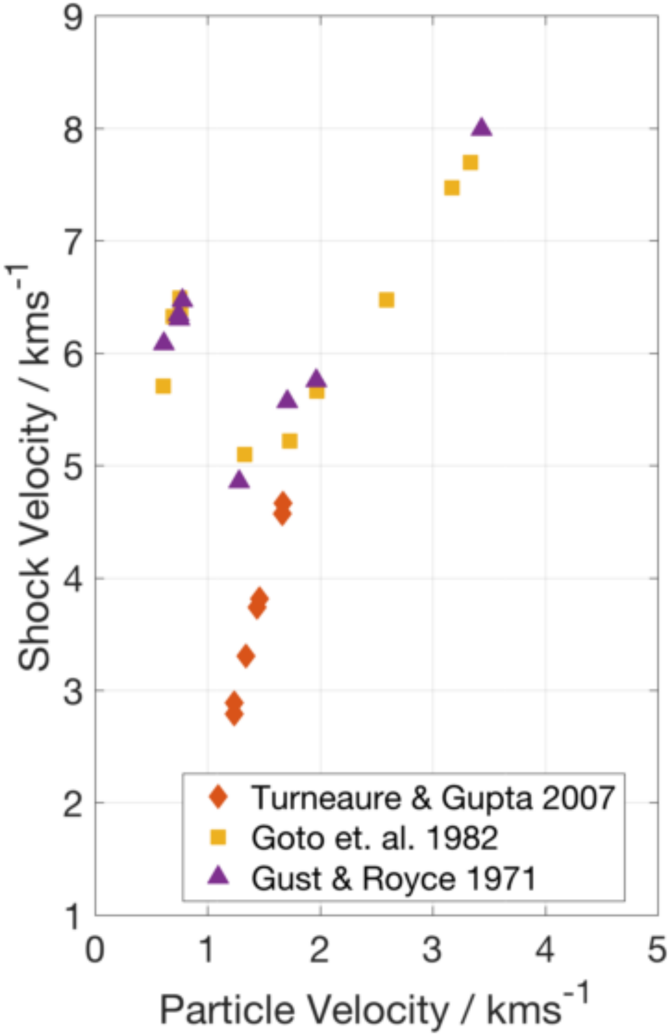
Good agreement between data and 1D simulations for the rear surface position (1x10^{12} W/cm^{2})

Up to approx. 7ns good agreement for shock position.

Simulated shock speed 7.0 km/s. ~10% above data.

At late times: have rarefaction wave, so its apparent distance from the front surface reduces.

u_s - u_p Hugoniot- Theory

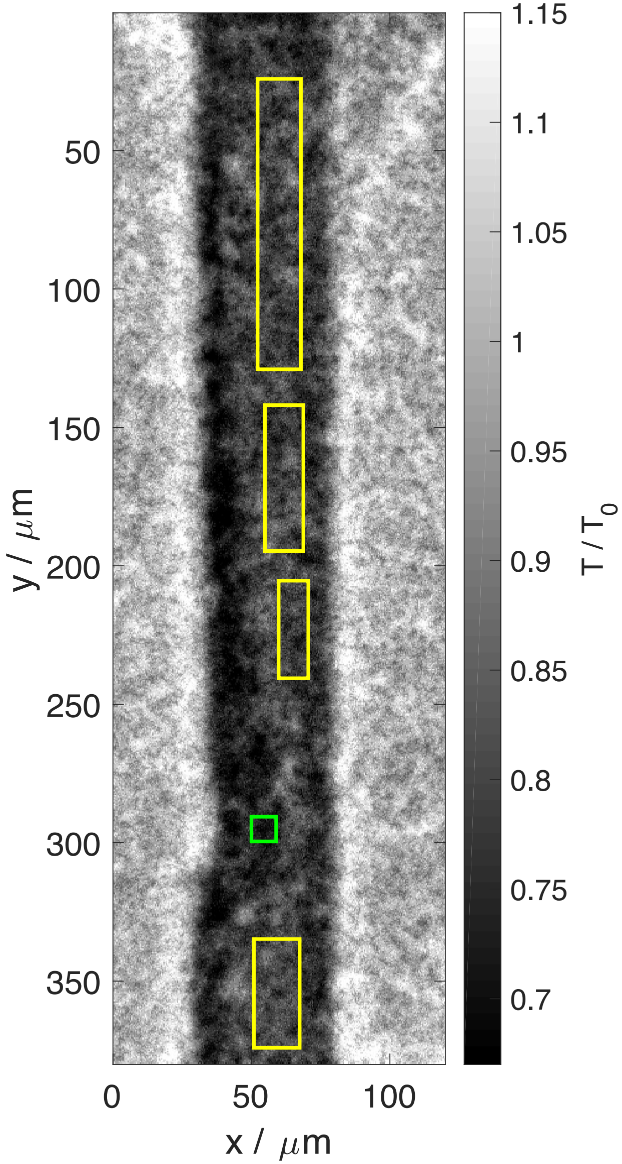


- Hugoniot: fundamental property of a material, if we shock to some u_p it tells us u_s.
- Data from work using flyer plate/ high-explosive drivers [19-21].
- Where does our data go? Need to calculate shocked density and find particle velocity u_1 from

$$\rho_o u_s = \rho_1 \left(u_s - u_1 \right)$$

[19] Goto, T., Sato, T. & Syono, Y. *Jpn. J. Appl. Phys.* 21,L369–L371(1982).
[20] Turneaure, S. J. & Gupta, Y. M. *Appl.Phys.Lett.*91,1–4 (2007).
[21] Gust, W. H. & Royce, E. B. *J. Appl. Phys.* 42, 1897–1905(1971).

Density Estimation



- Divide image by x-ray intensity pattern in the absence of the target.

- Image represented mathematically by:

$$\frac{T}{T_0} = \frac{\int_0^\infty I(E,E_c)\ M(E)\ Q(E)\ e^{-\frac{\mu(E)}{\rho_0}\rho_1 d}\ dE}{\int_0^\infty I(E,E_c)\ M(E)\ Q(E)\ dE}$$

- Assume *d* = constant = 200 µm. We don't know E_c or ρ_1.

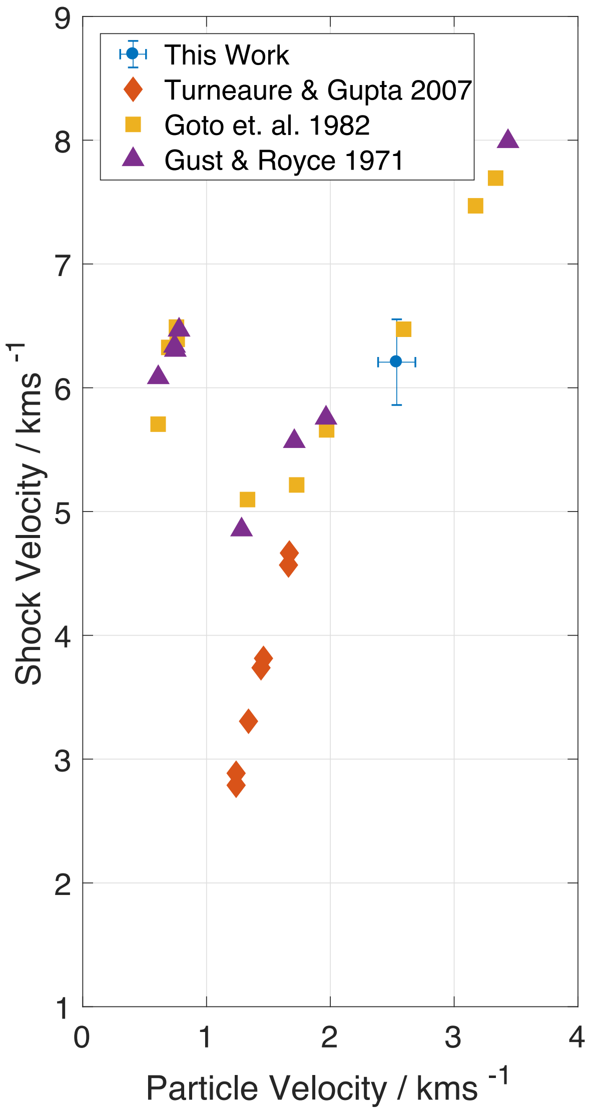
- Good noise removal important- exceptional pixel values only.

- Calculate E_c from ambient density Si: yellow regions.

- Calculate ρ_1 in green region just behind shock front:

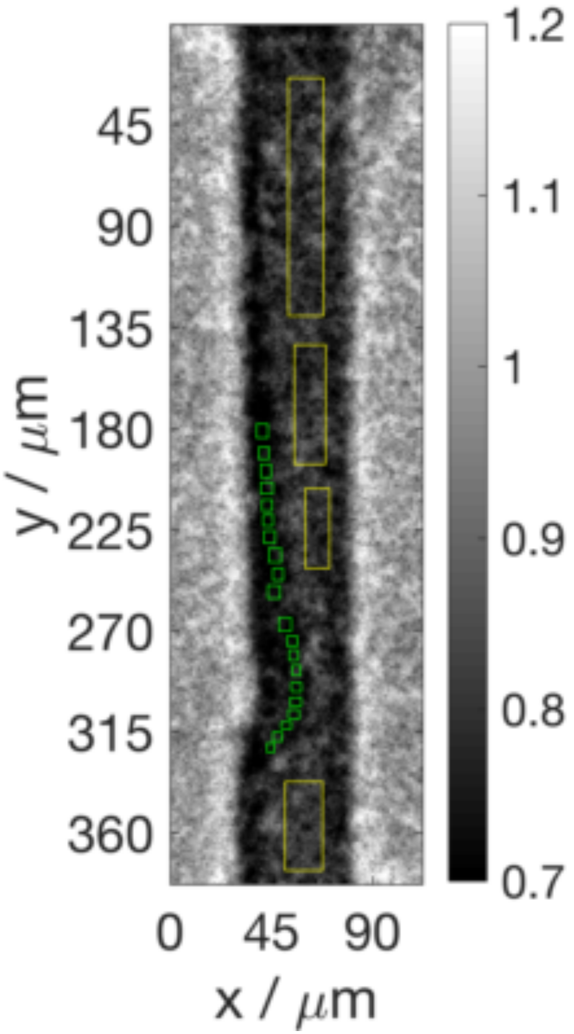
$$\rho_1 = (3.87 \pm 0.05)\ \mathrm{gcm}^{-3}$$

u_s - u_p Hugoniot- Data

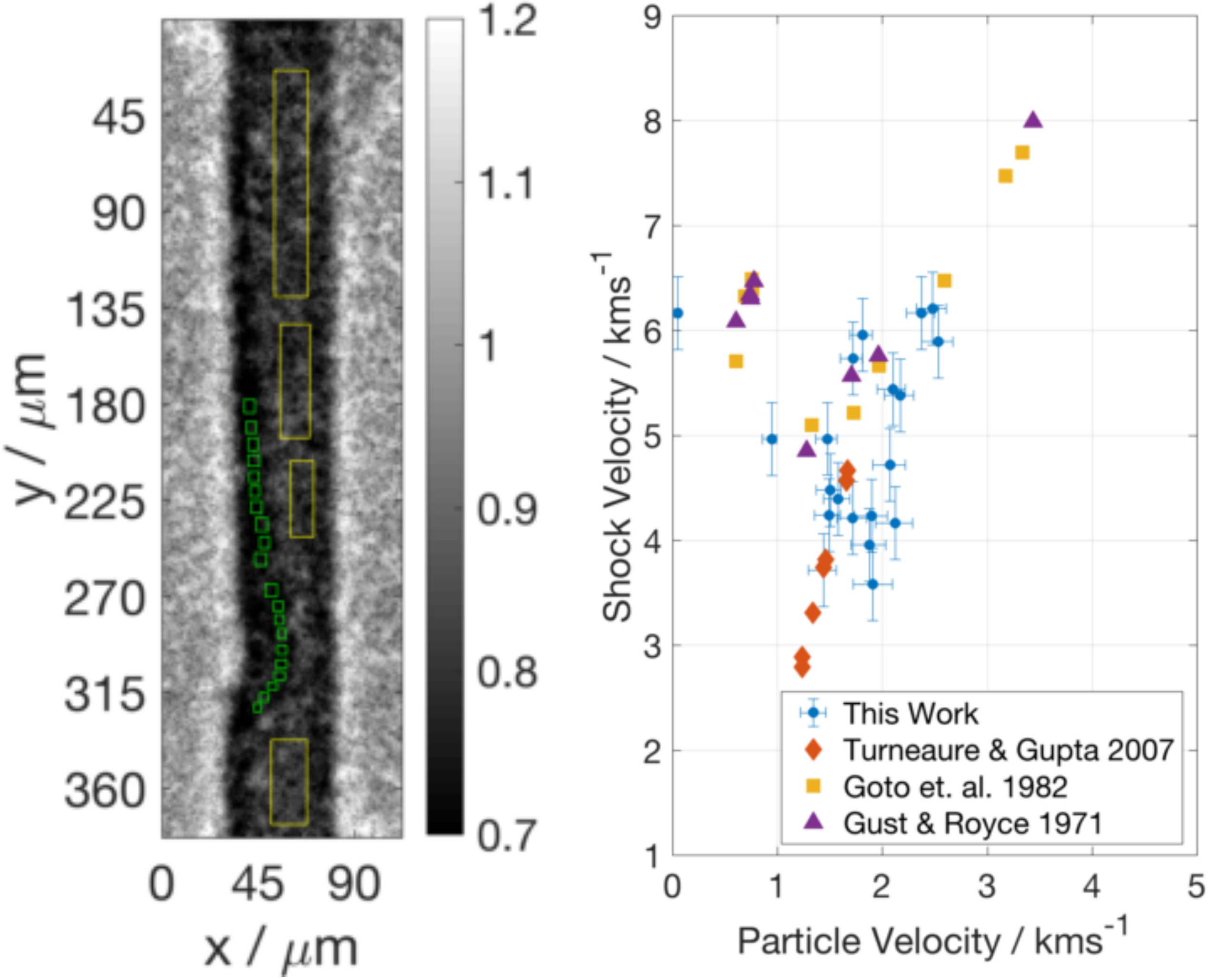


- Excellent agreement between this work and literature data.
- Betatron x-rays from a LWFA can be used to make accurate, quantitative measurements of shock physics/ HEDP experiments.

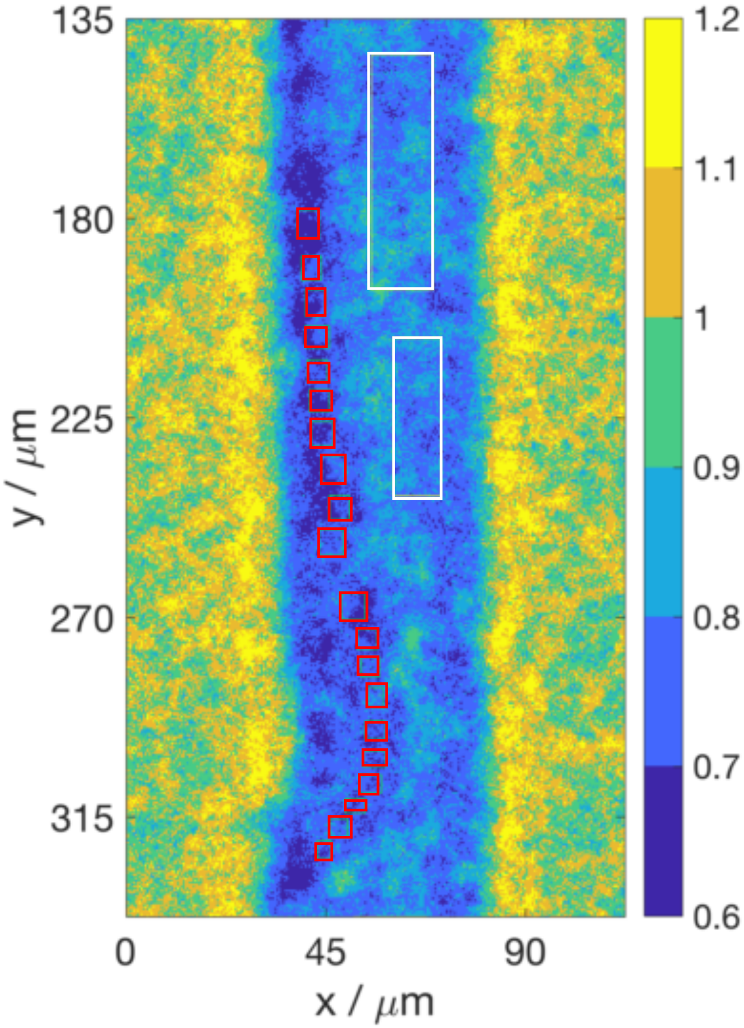
u_s - u_p Hugoniot- Multiple Data Points



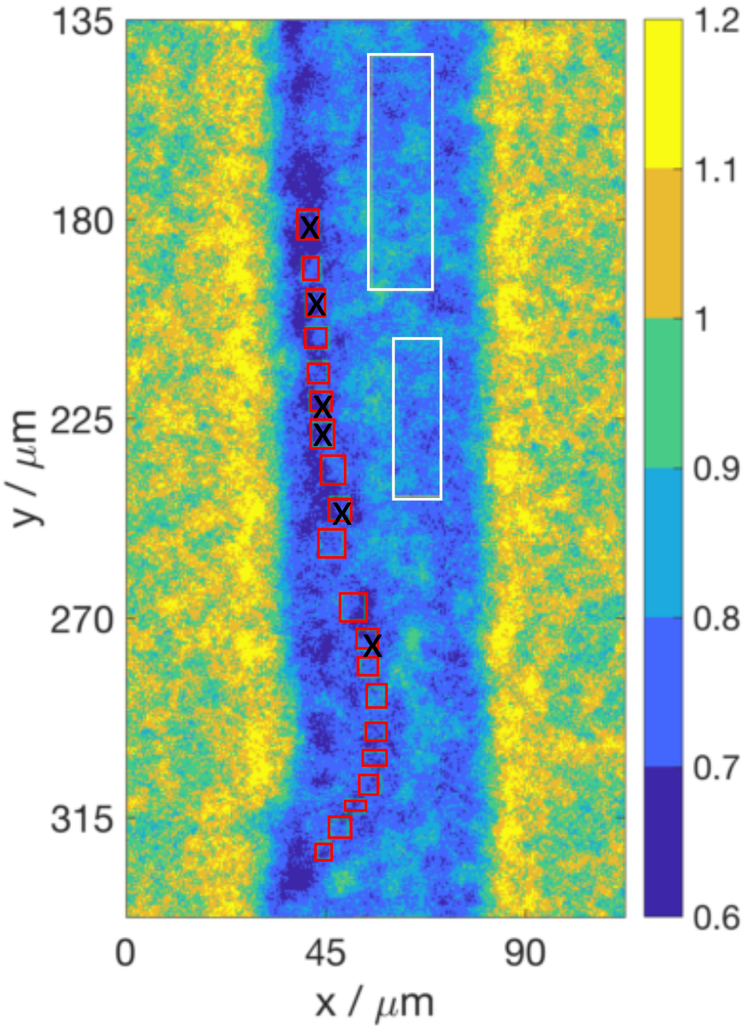
u_s - u_p Hugoniot- Multiple Data Points



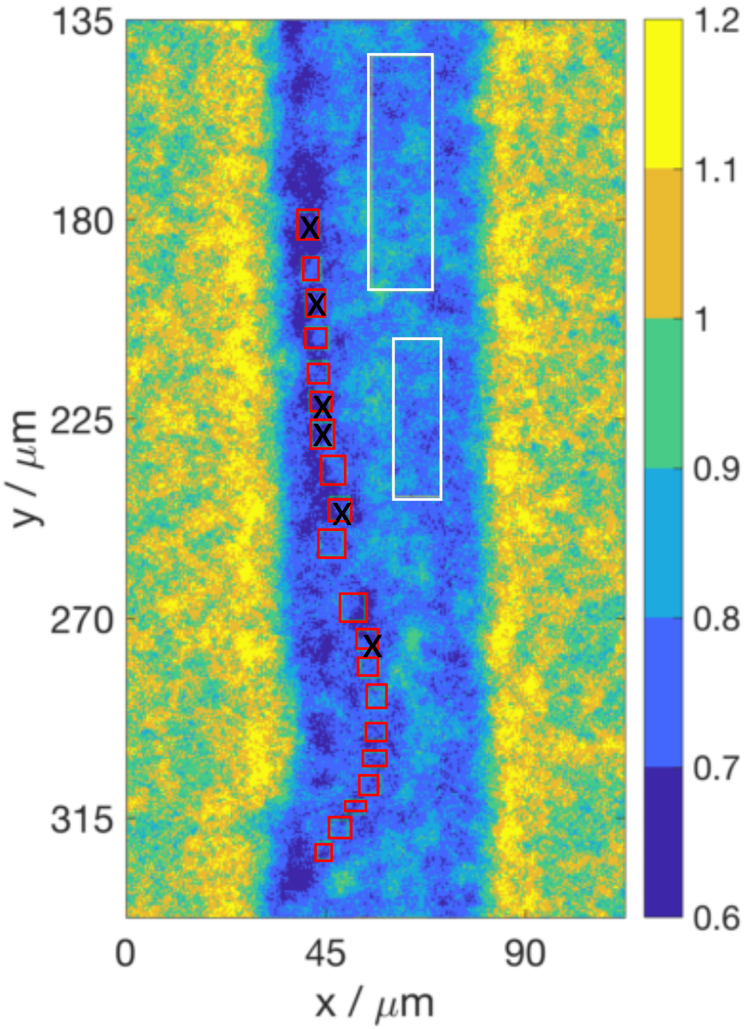
u_s - u_p Hugoniot- Refinement

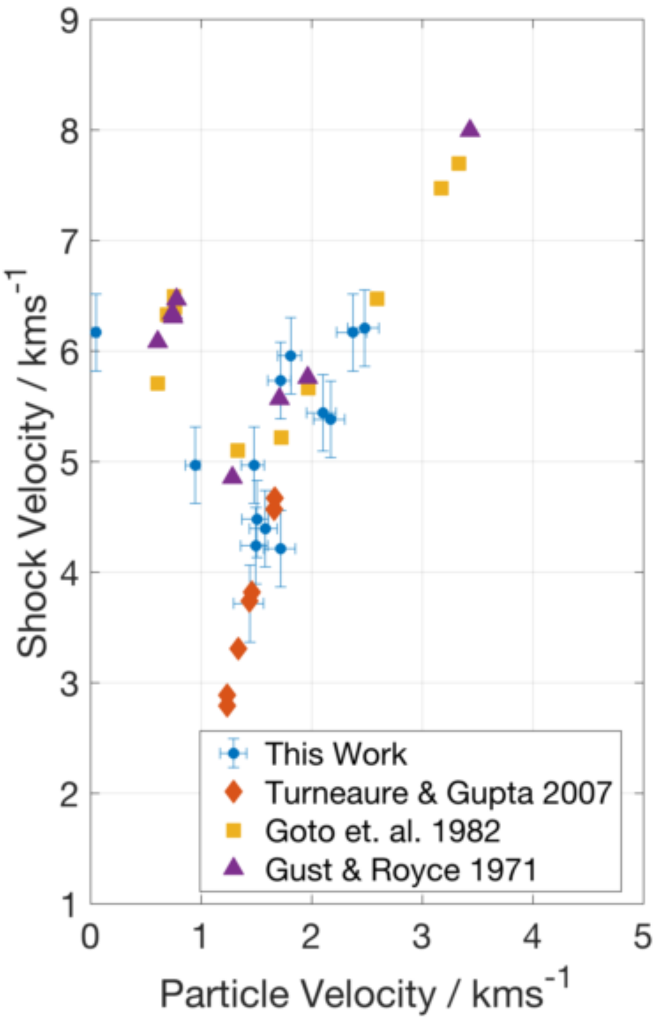


u_s - u_p Hugoniot- Refinement



u_s - u_p Hugoniot- Refinement



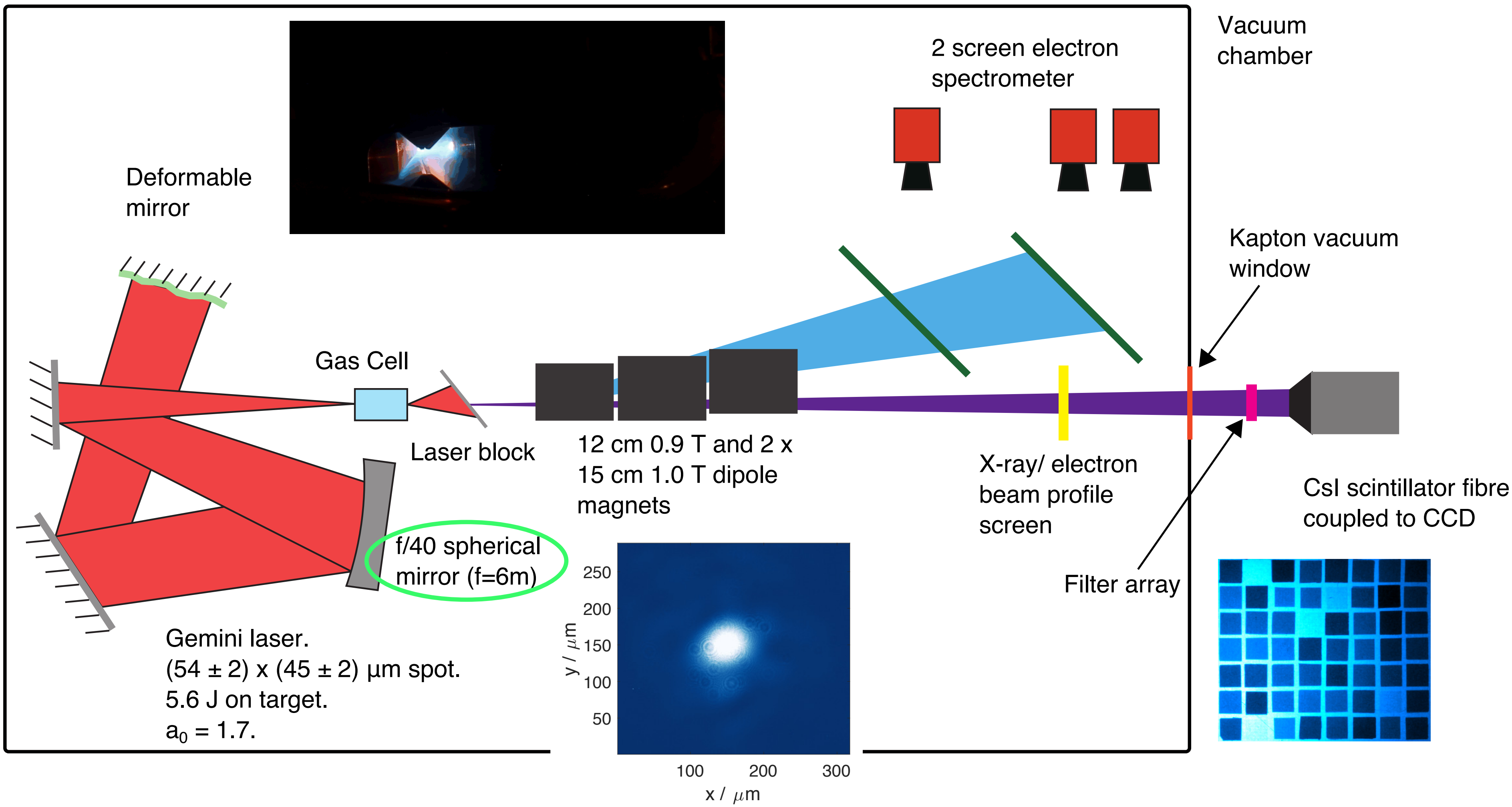


Summary so far

- Useful, quantitative, accurate measurements of multi-km/s shock waves in solid density material.
- 2 major limitations:
    1. Nonideal shock driver- too short
    2. Large errors driven by system resolution and poor signal to noise ratio.
- Limitation 1: “easily” solved.
- Limitation 2: not so easily solved. Next: brief aside on a recent experiment where we saw a significant brightness increase.

  J. Wood talk from Tuesday- Enhanced Betatron Radiation from a LWFA in a Long Focal Length Geometry

Experiment Set-up



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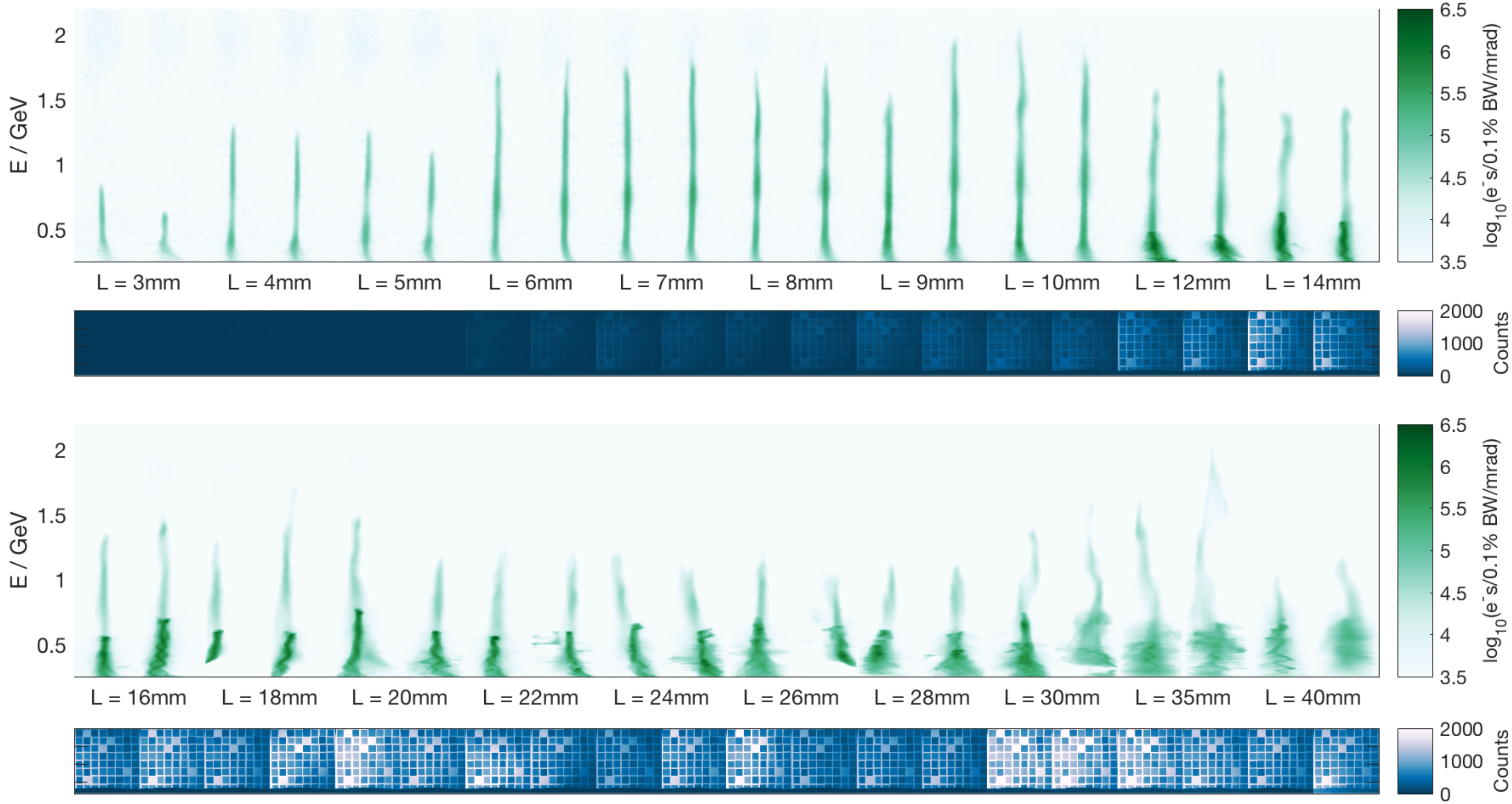
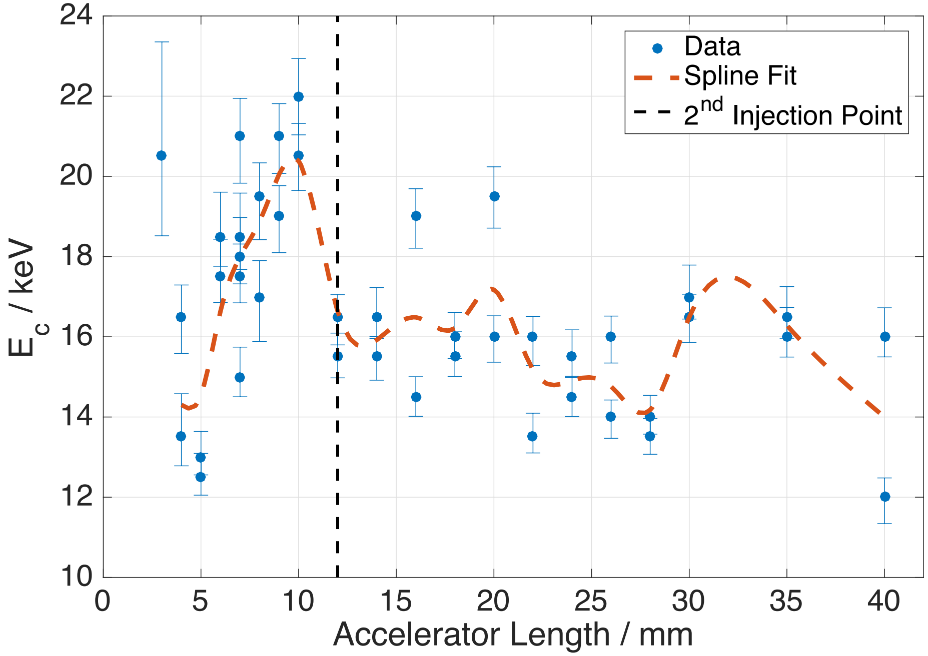
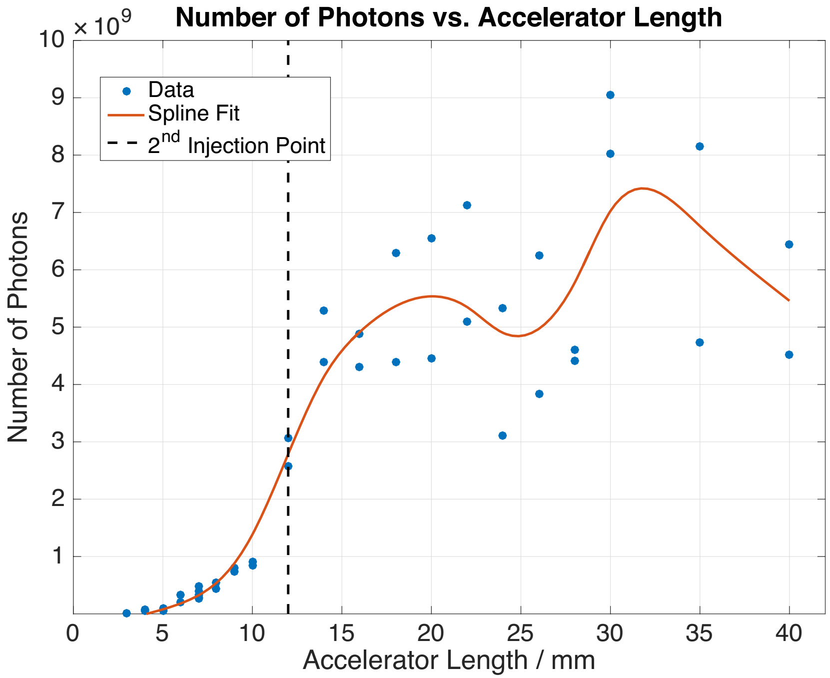
Electron and X-ray Results II



Injection of 2nd bunch with high charge per unit BW and large transverse momentum.
Second injection correlates with a large increase in the number of x-rays being detected.

Bright Betatron X-ray Results





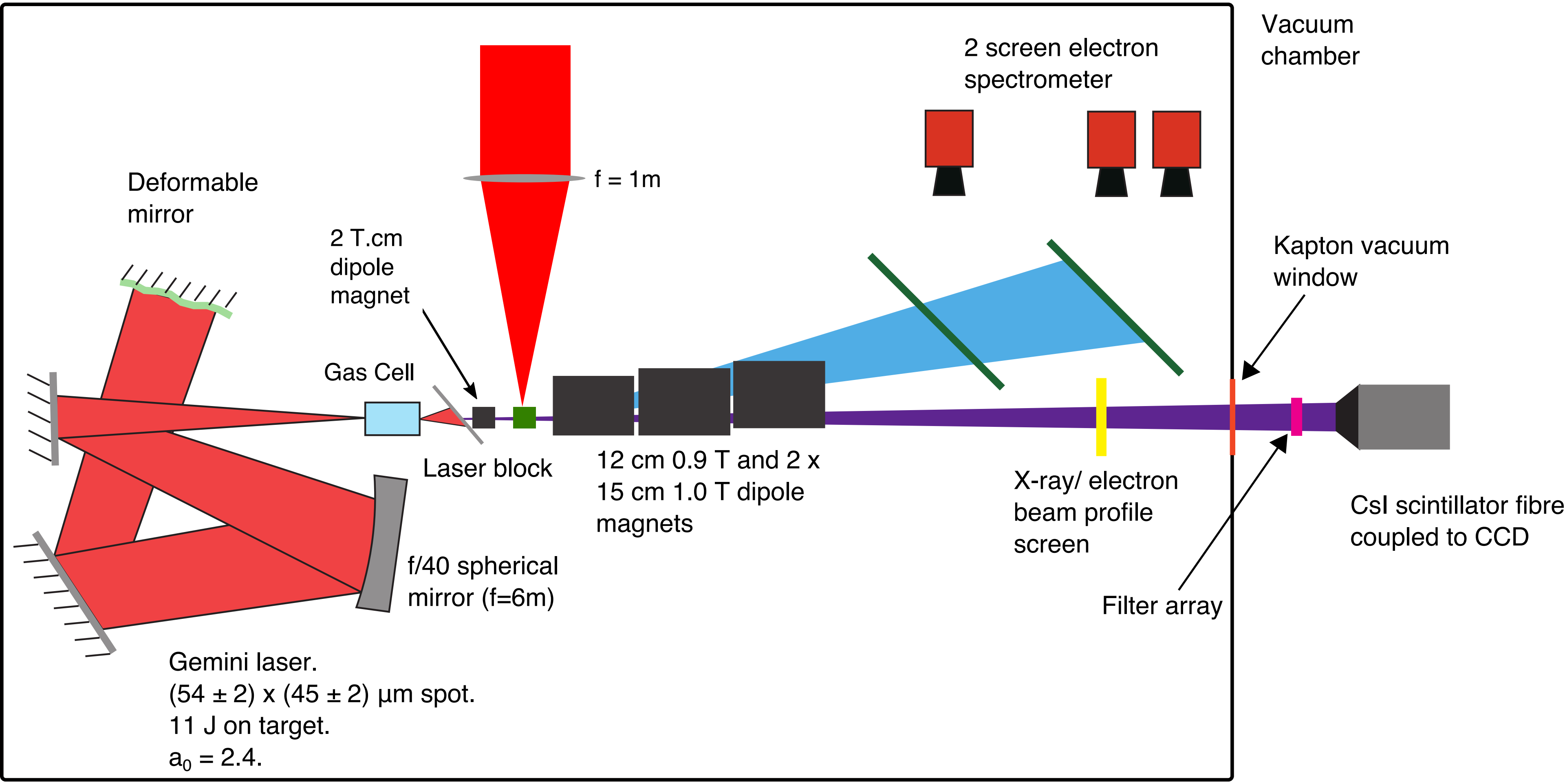
'Naïve' single spectrum fit- spectrum cools after 2nd injection. Suggests 2nd bunch dominating emission properties.

Large oscillation radius drives large increase in photon number at moderate energies.

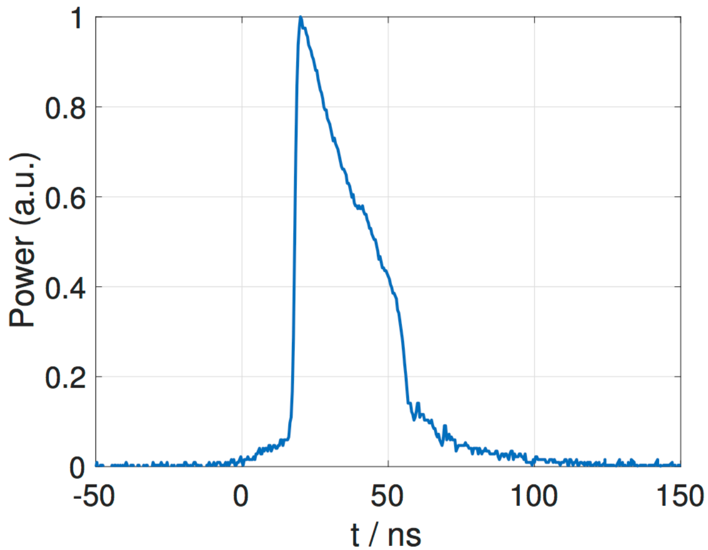
$$W_{tot} \propto N_e \gamma^{5/2} r_\beta^2$$

Later: Increase in laser energy: 5.6 J to 11.3 J. $a_{0,max}$ = 2.4.
Max of 3.4 x 10^{10} photons/shot, increase of 6x. B ≈ 3x10^{24} photons/s/mm^2/mrad^2/0.1%BW

New Shock Imaging Experiment



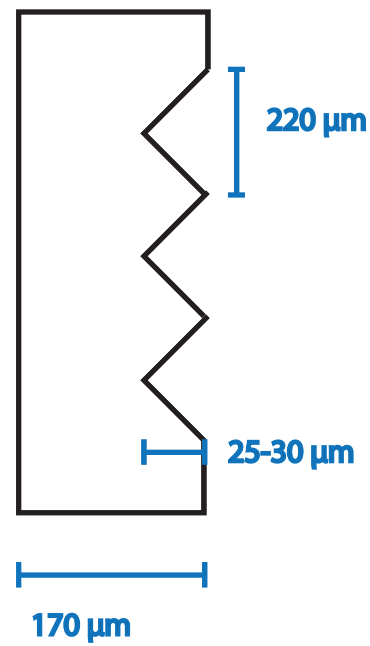
Target and Drive Details

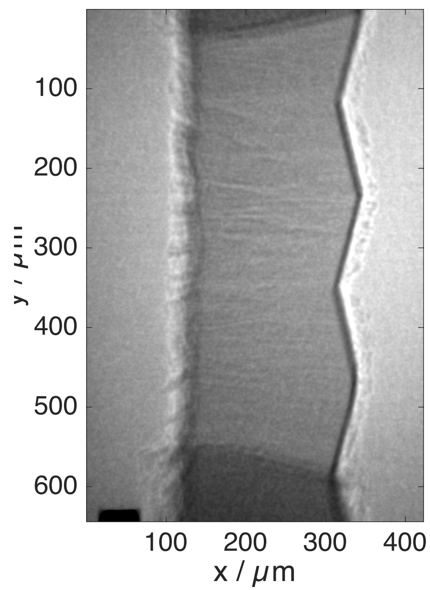


λ = 1053 nm. 20 – 25J on target.

High intensity: Gaussian spot, ~ 65µm FWHM, I = 3.5 x 10^{12} W/cm^2.

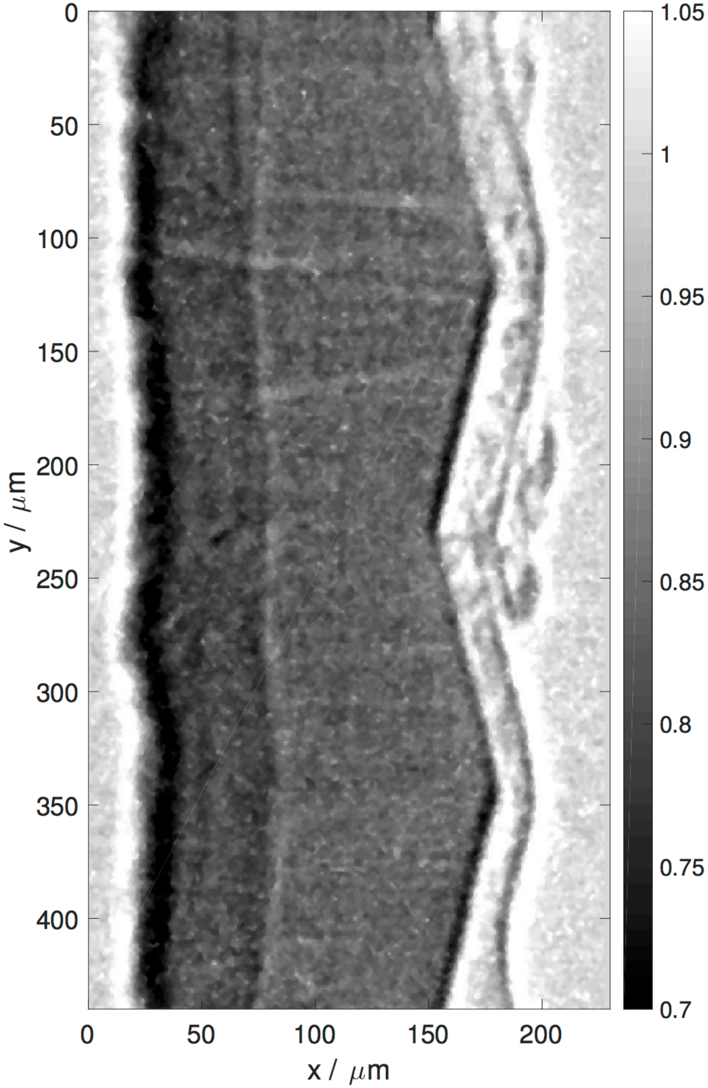
Low intensity: ~ Gaussian spot, ~ 330µm FWHM, I = 1.4 x 10^{11} W/cm^2.

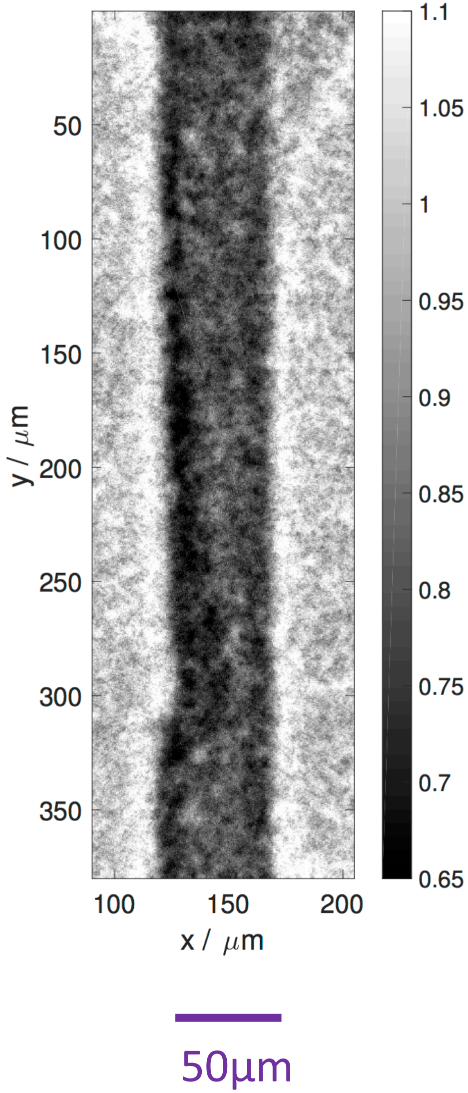




Target thickness: 200 µm.
Material: Aluminium.
Magnification: 22.5.

Comparison of Image Quality

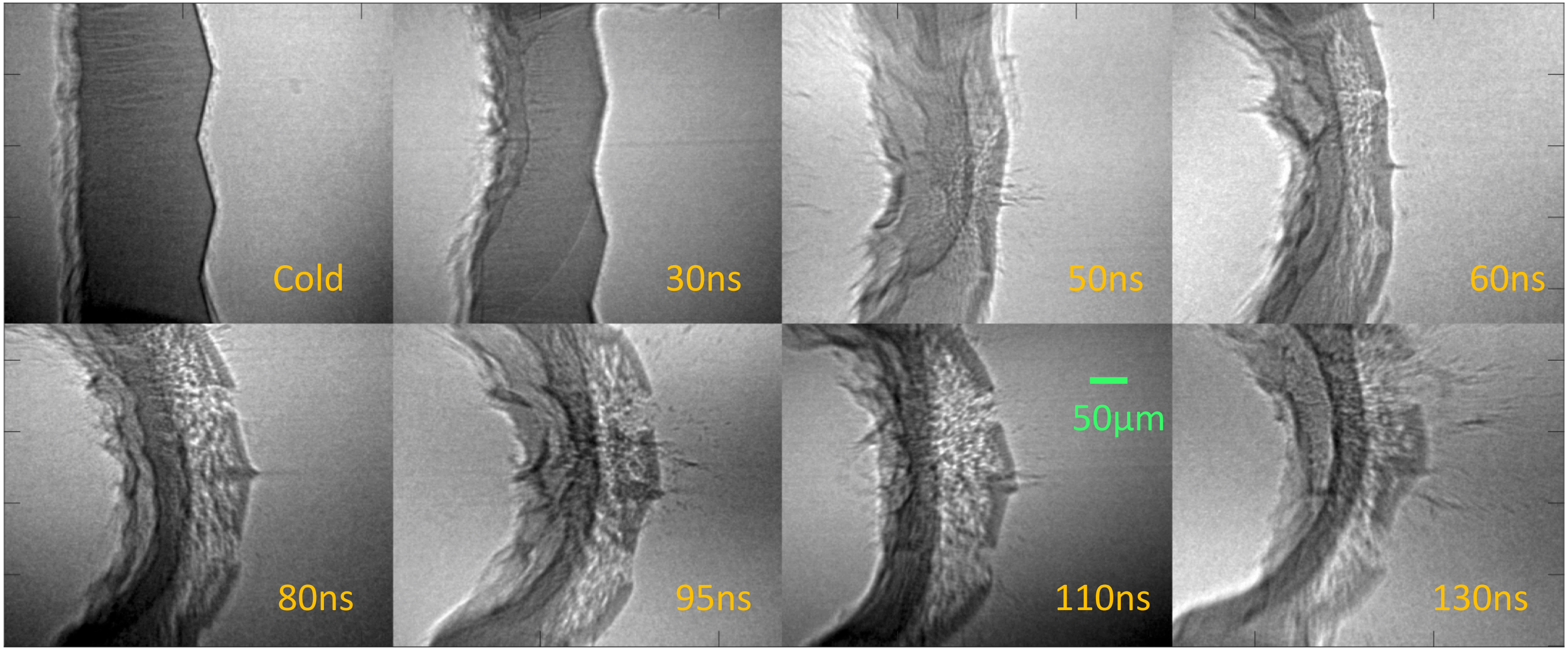




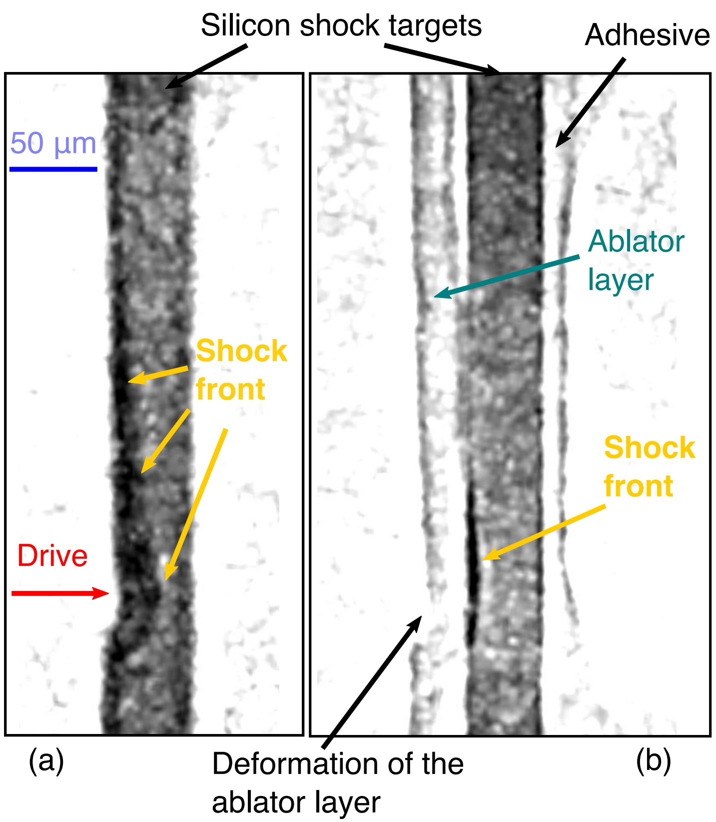
Left: shocked Al imaged by bright source. M=22.5. Some median filtering.

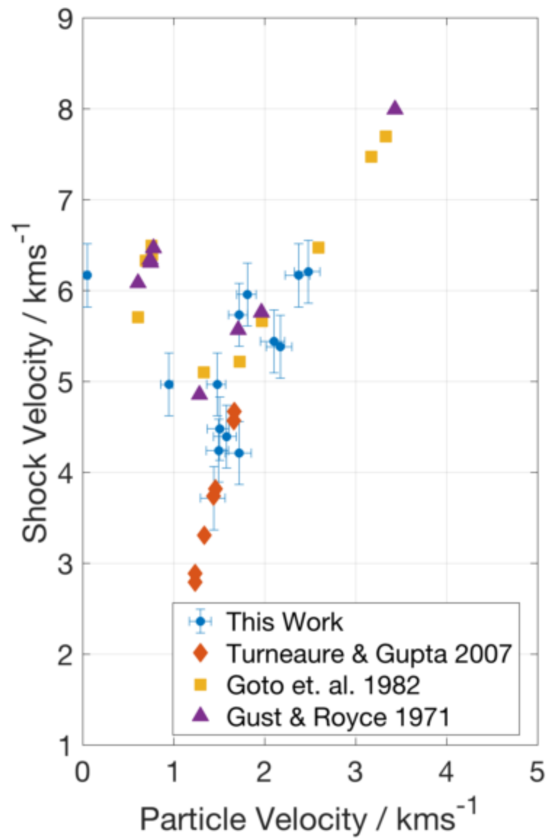
Right: shocked Si imaged by old source. M=30. Advanced noise removal.

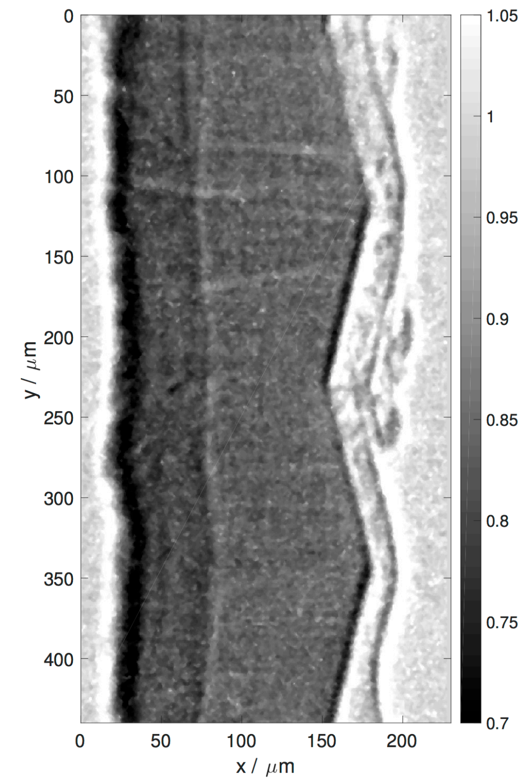
Time Series of Material Spall



Conclusions







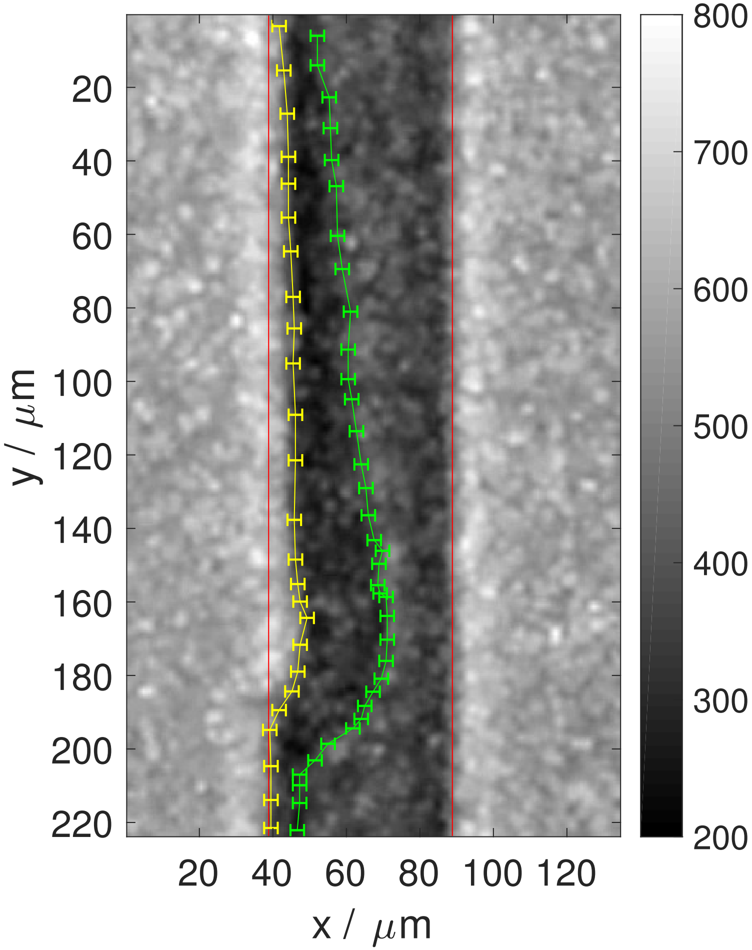
High resolution (4-5µm) imaging of shock waves travelling at 6.2kms^{-1} with betatron radiation.

Quantitative measurements in good agreement with previous work.

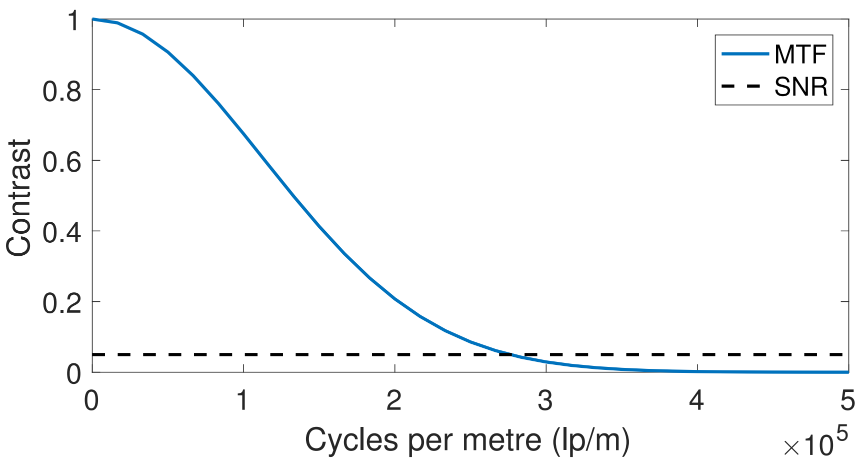
More recent work with much superior image quality.

Additional Information

Closer Examination of Shock Front



Δt = 5.2ns



Red lines: initial target edges, found with Sobel algorithm and reference image.

Green: shock front. Yellow: rear surface.

Errors in distance from system resolution. MTF derived from PSF. Contrast vs spatial frequency.

Equating MTF with SNR ⇒ error bar full width = 3.6 μm.

Noise removal

- Dark field correction- camera dark noise and read noise subtraction.
- Flat field correction- corrects for non-uniform pixel response.
- On most images, performed morphological opening- highlights slowly varying trends at expense of one or few pixel events (’noise’). Good for visualisation, but changes a lot of pixel values.
- We know remaining noise principally from 2 sources: hot pixels from bremsstrahlung from e-beam interactions, cold pixels from imperfect flat field correction.
- Only want to correct these exceptional pixel values- the rest is important signal.
- Compare the value of each pixel to the average of different size neighbourhoods around it, and if the ratio of the pixel value to these averages exceeds a trigger value, or for cold pixels was less than some lower trigger value, then the pixel value was replaced by the average.
- Repeat for decreasing trigger values until image details started to appear in the removed noise, which indicated that the process had gone one step too far.
- To remove multi-pixel noise, this filter was passed twice, so that in the second run exceptional pixel values could be excluded from averaging.
- Most pixel values remain unchanged as a result of the application of this filter.