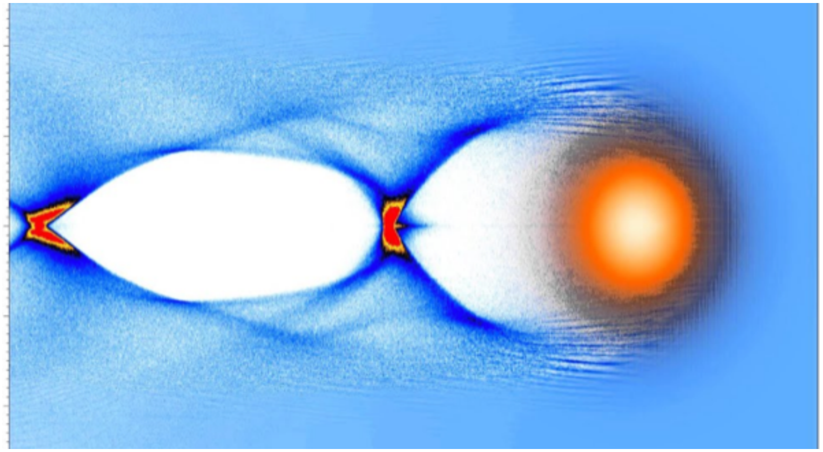
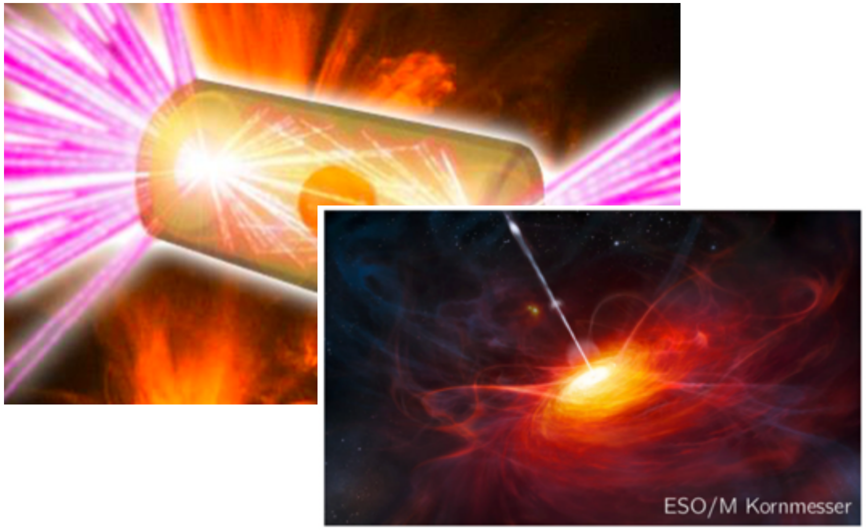
Using X-rays from a laser wakefield accelerator to perform ultrashort multi-Kev absorption spectroscopy

Brendan Kettle
John Adams Institute for Accelerator Science, Imperial College London

JAI Fest 2019, 6th December, Oxford University





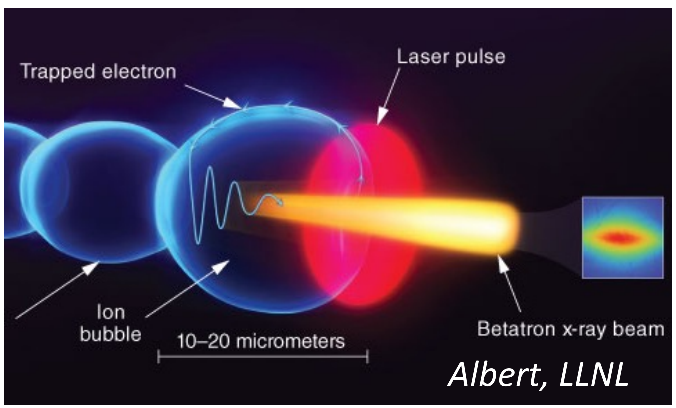
Imperial College London

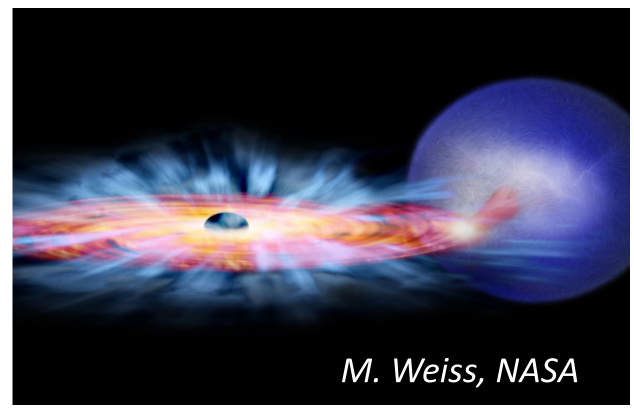
John Adams Institute for Accelerator Science

erc

The *TeXMEx* Project

Time resolved X-ray probing of Matter under Extreme conditions



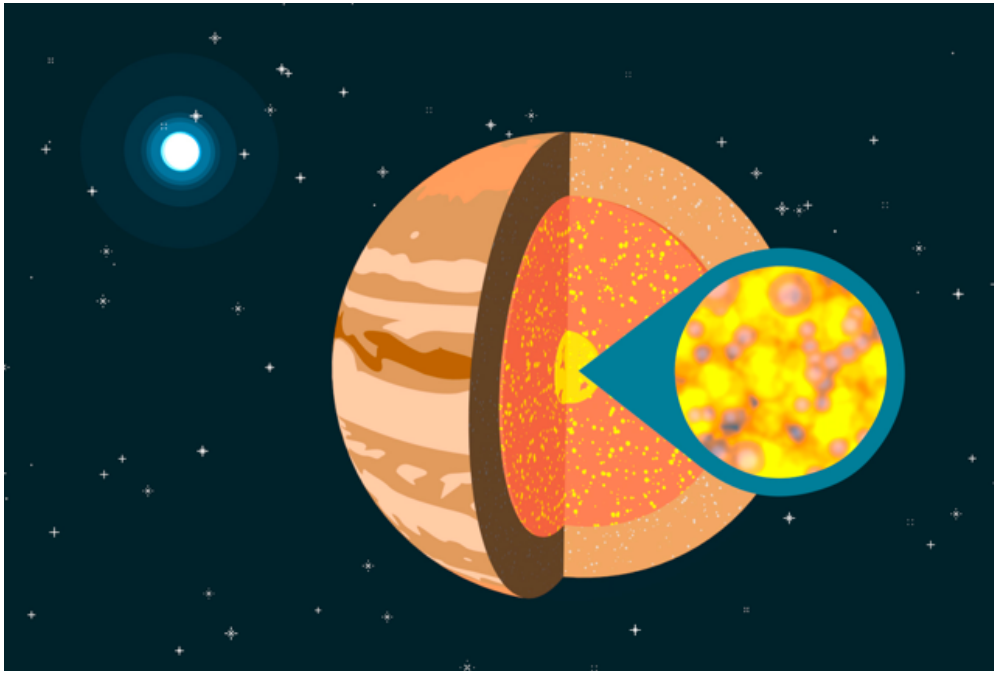


Academics: Stuart Mangles, Steven Rose

Post-docs: Brendan Kettle, Rory Baggott

PhD's: Robbie Watt, Cary Colgan, Eva Los, Wei Wu

Extreme conditions? …. High Energy Density Matter



Densities > 1 g/cc

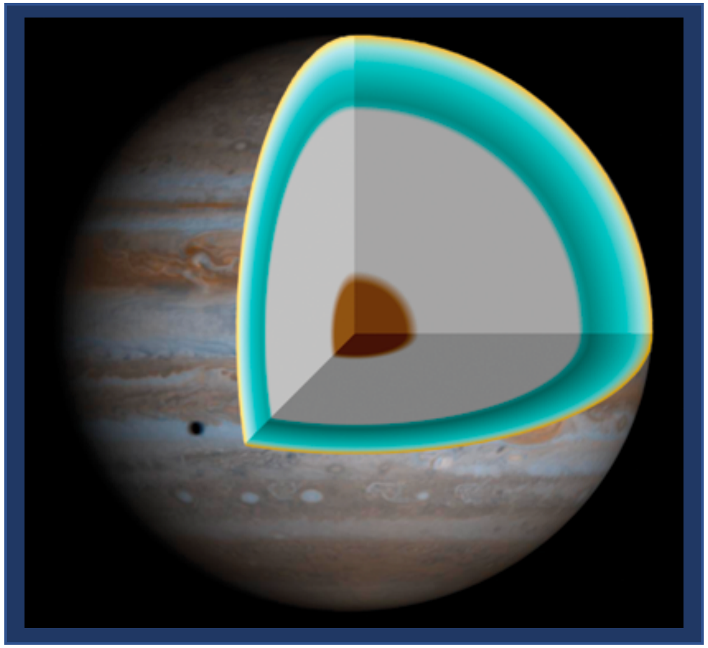
Warm Dense matter (WDM):
1-100 eV. E.g. planets, ICF

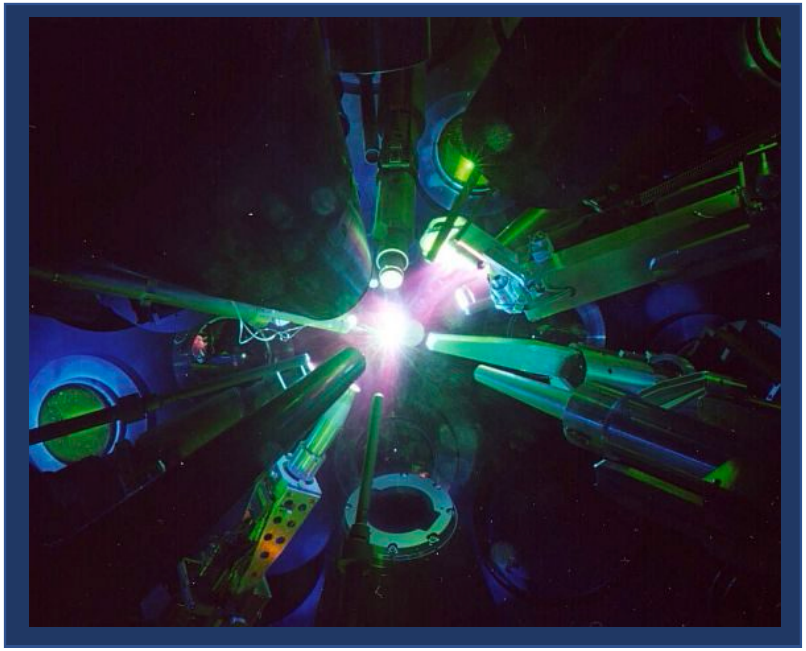
$$\Gamma = \frac{(Z^* e)^2}{R_i k T_i}$$

Hot Dense matter (HDM):
> 100 eV. E.g. stars.

Many processes governing dense energetic plasmas remain untested/unquantified due to **<u>theoretical complexity and experimental difficulties</u>.**

Why perform ultrafast X-ray absorption measurements?





- **X-rays:** Samples too dense for optical probing. Allows access to core electrons.
- **Ultrafast:** Transient states (in the lab) and rapid processes; sub-picosecond timescales.

Ultrafast X-ray absorption measurements

Processes & Techniques

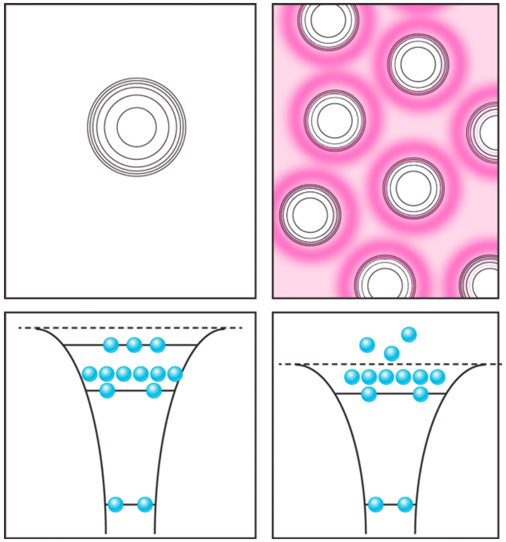
- X-ray Absorption Near-Edge Structure (XANES)
- Extended X-ray Absorption Fine Structure (EXAFS)
- Ionisation Potential Depression (IPD).
- Excited state absorption lines.
- Non-thermal processes.

Etc.

Provide

- Temperature
- Electronic and local atomic structure
- Ionisation energies/rates
- Electron-Ion equilibration rates

Etc.



Umstadter, *Physics* 5, 88 (2016)

Recent publications

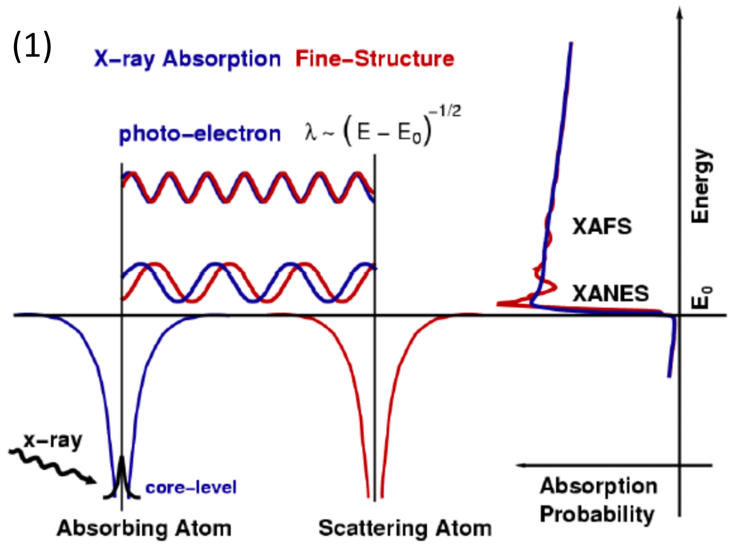
Mahieu et al. Nat. Comms, 9, 3276 (2018)
Dorchies et al. Phys. Rep. 657, 1-26 (2016)
Cho et al. PRL 106, 167601 (2011)
Mančić et al. PRL 104, 035002 (2010)
Engelhorn et al. PRB 91**,** 214305 (2015)
Hoarty et al. PRL 110, 265003 (2013)
Circosta et al. PRL 109, 065002 (2012)
Iglesias. HEDP 12, 5-11 (2014)
Vinko et al. Nat. Comm 6, 6397 (2015)

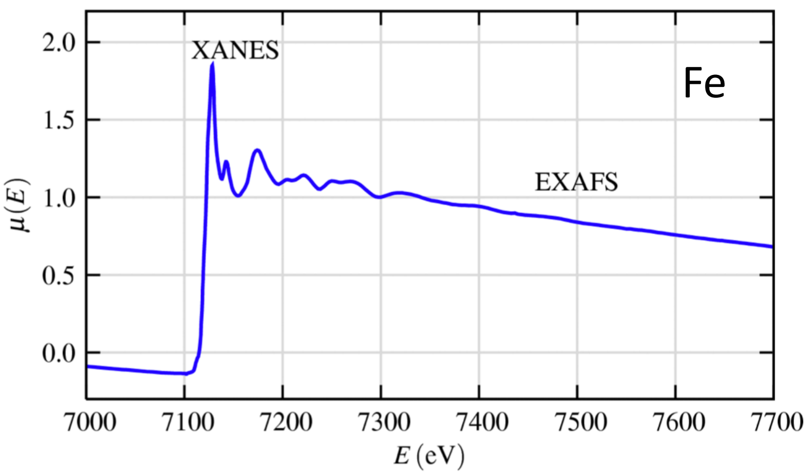
Imperial College London

John Adams Institute for Accelerator Science

erc

X-ray Absorption Near Edge Structure (XANES) & Extended X-ray Absorption Fine Structure (EXAFS)





Local scattering of ejected photoelectrons cause modulations in absorption close to resonant edge.

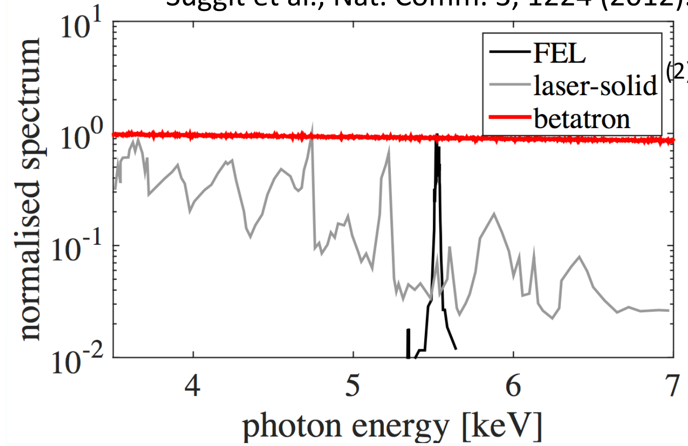
Slope and peak positions detail **electronic & atomic structure** and broadening of features reveal **electron & ion temperature**.

[1] *A Practical Introduction to Multiple Scattering Theory*, Bruce Ravel, 2005

What type of X-ray source do we need?

- High photon flux from small source – single shot if possible
- Multi-keV photon energies
- Short sub-picosecond duration
- Broadband and smooth spectrum
- High rep-rate is desirable
- Temporal matching to pump?

[2]Suggit et al., Nat. Comm. 3, 1224 (2012).



	Synchrotrons	XFELs	Laser-plasmas	LWFA
Duration	10 – 100 ps	< 100 fs	1 -10 ps	< 100 fs
Spectrum	Broad and Smooth	Narrow	Broad Not Smooth	Broad and Smooth

Experiment Results

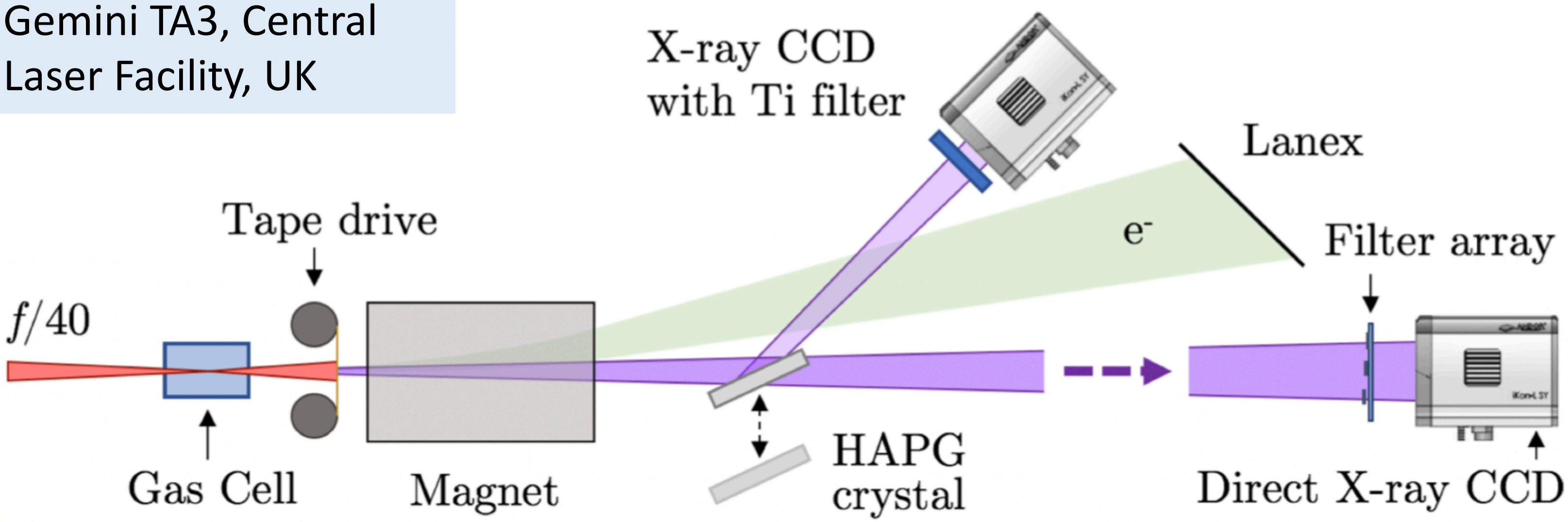
Stuart Mangles[1], Steven Rose[1], Rory Baggott[1], Robbie Watt[1], Jason Cole[1], Elias Gerstmayr[1], Nelson Lopes[1], Alec Thomas[2,3], Matthew Streeter[2], Stephen Dann[2], Yong Ma[2], Amina Hussein[3], Dan Symes[4], Chris Spindloe[4], Olle Lundh[5], Isabel Gallardo Gonzalez[5], Kateřina Falk[6], Michal Šmíd[6], Felicie Albert[7], Nuno Lemos[7]

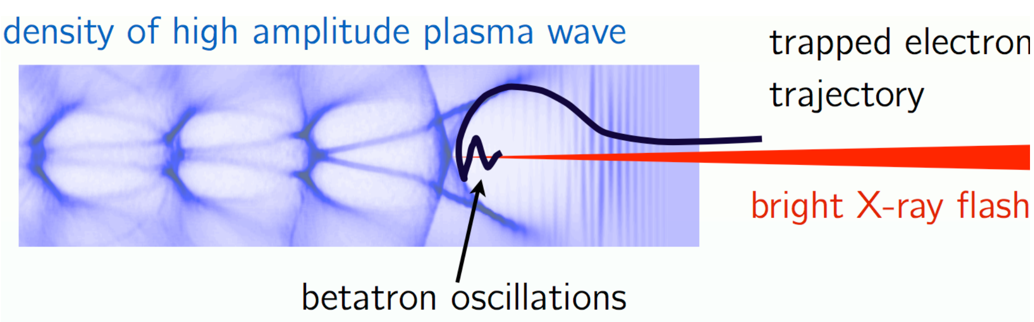
[1] Imperial College London, U.K.
[2] Lancaster University, U.K.
[3] University of Michigan, USA
[4] Central laser Facility, U.K.
[5] Lund University, Sweden
[6] ELI Beamlines, Czech Republic
[7] Lawrence Livermore National Laboratory, USA

The Cockcroft Institute of Accelerator Science and Technology
Science & Technology Facilities Council Central Laser Facility
Lund University
The University of Michigan
Lancaster University
eli beamlines
Lawrence Livermore National Laboratory

Campaign in August 2017

Gemini TA3, Central Laser Facility, UK

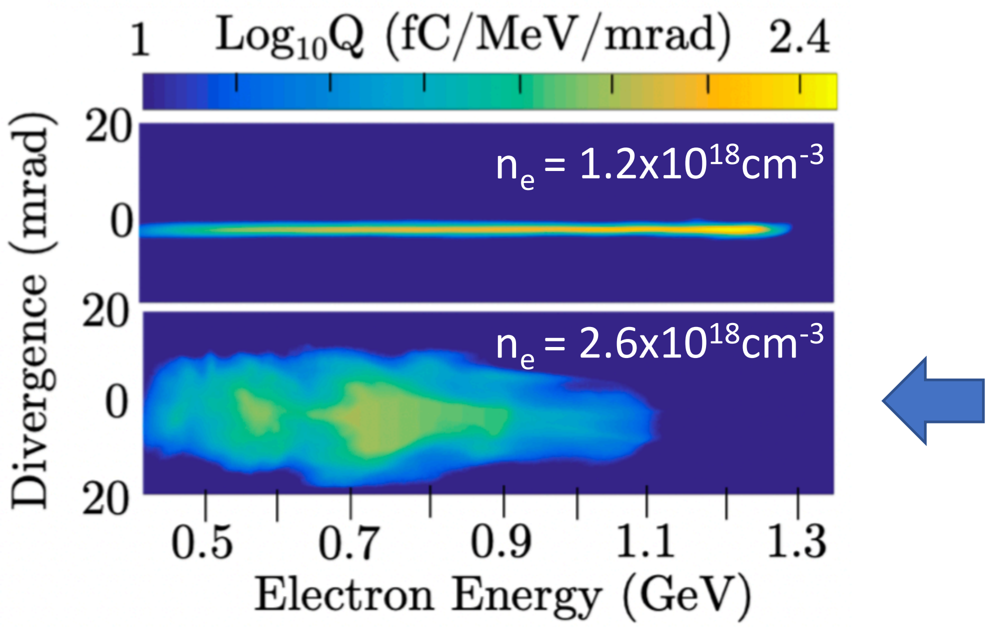




Drive laser
Duration = 47 ± 5 fs
Energy = 9 ± 0.3 J (43% in FWHM)
Intensity = $4.9 \pm 0.6 \times 10^{18}$ W/cm^2
($a_0 \approx 1.5$)

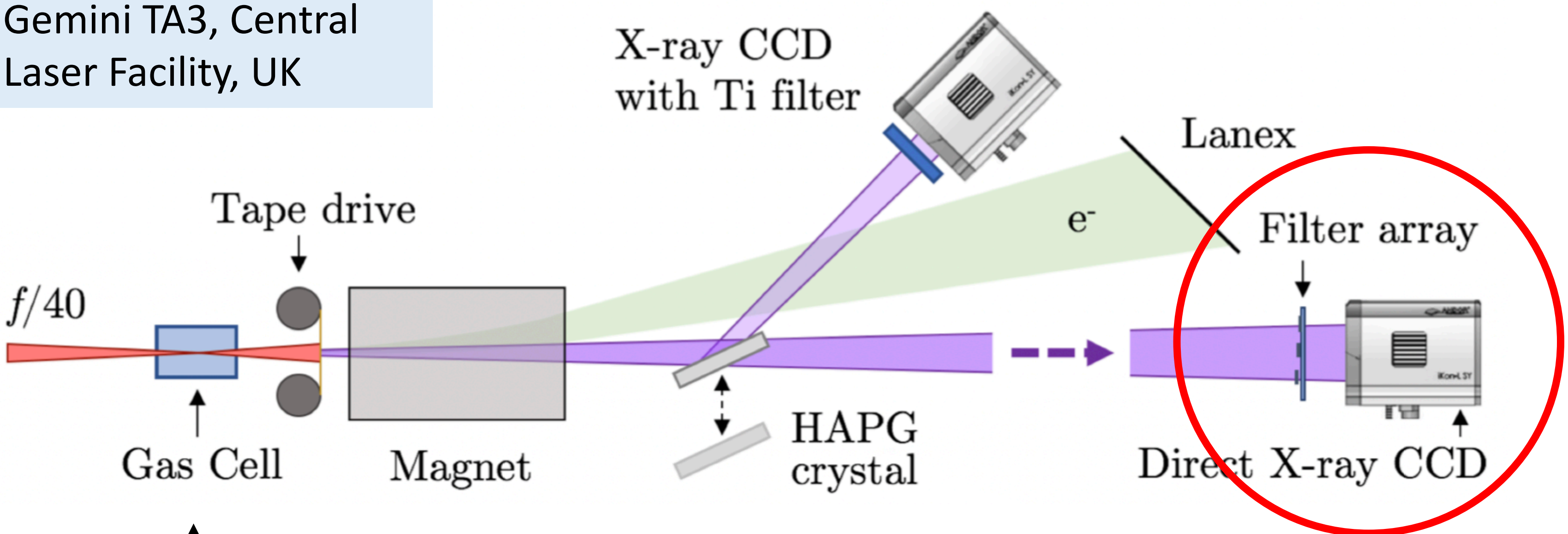
Laser-wakefield accelerator performance

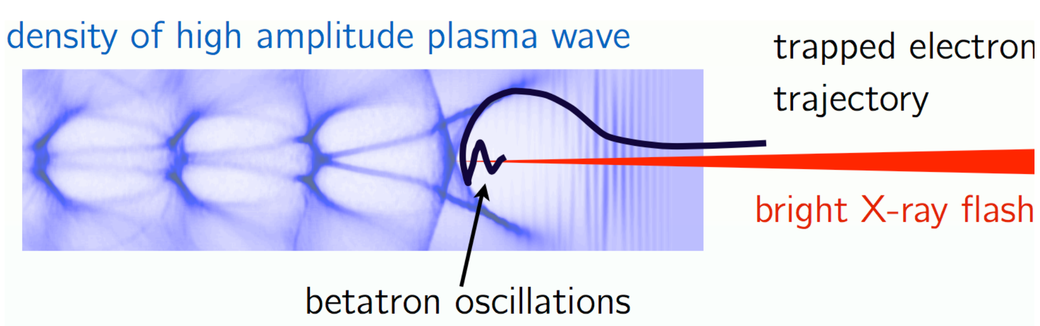
- Two stage gas cell. First stage (3mm long) 2% Nitrogen mix for **ionisation injection**, second stage ≈20mm long, pure helium.
- Went for **high charge** (and **high X-ray flux**) "messy" electron beams (using increased density in first cell).



Campaign in August 2017

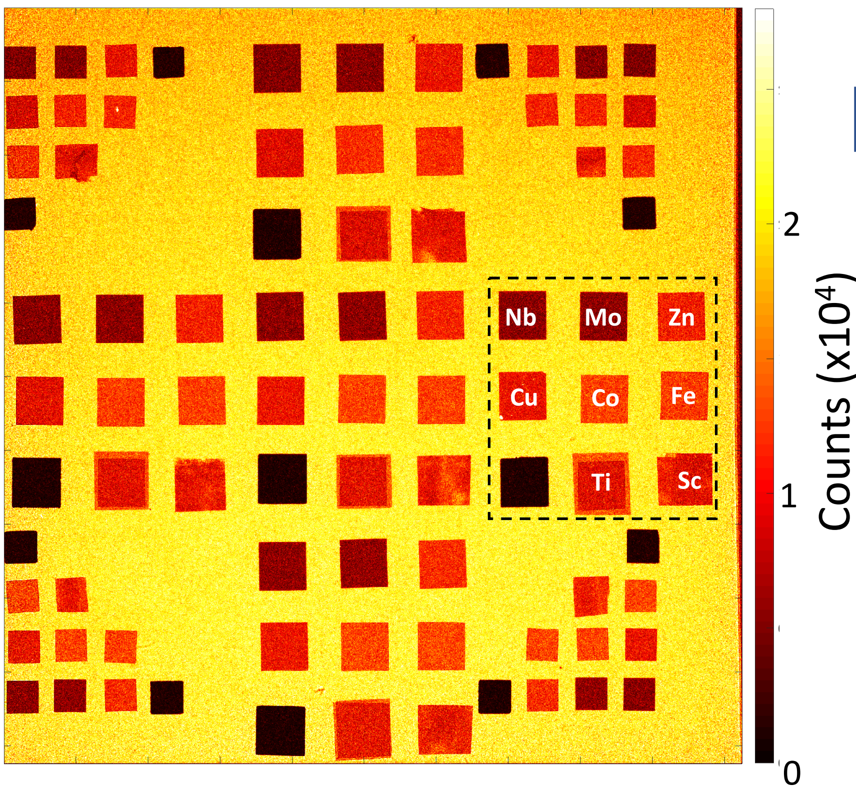
Gemini TA3, Central Laser Facility, UK

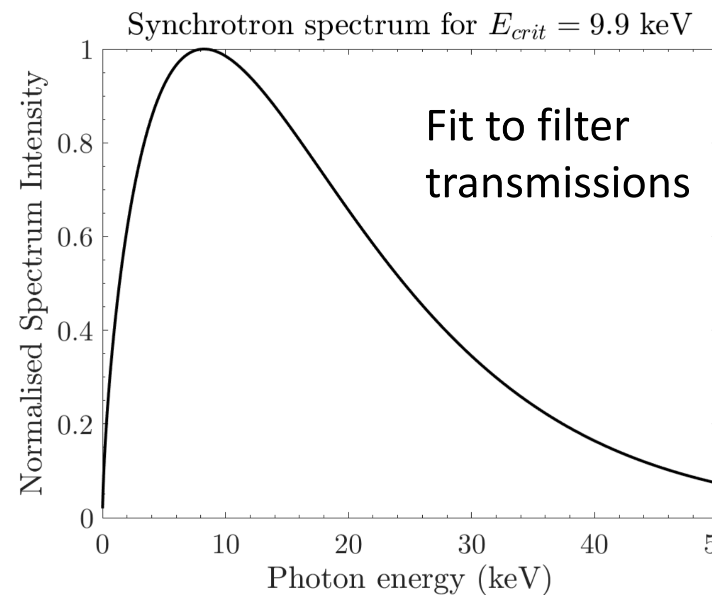




Drive laser
Duration = 47 ± 5 fs
Energy = 9 ± 0.3 J (43% in FWHM)
Intensity = 4.9 ± 0.6 x 10^{18} W/cm^2
($a_0 \approx 1.5$)

LWFA X-ray results – broad spectrum using filter array





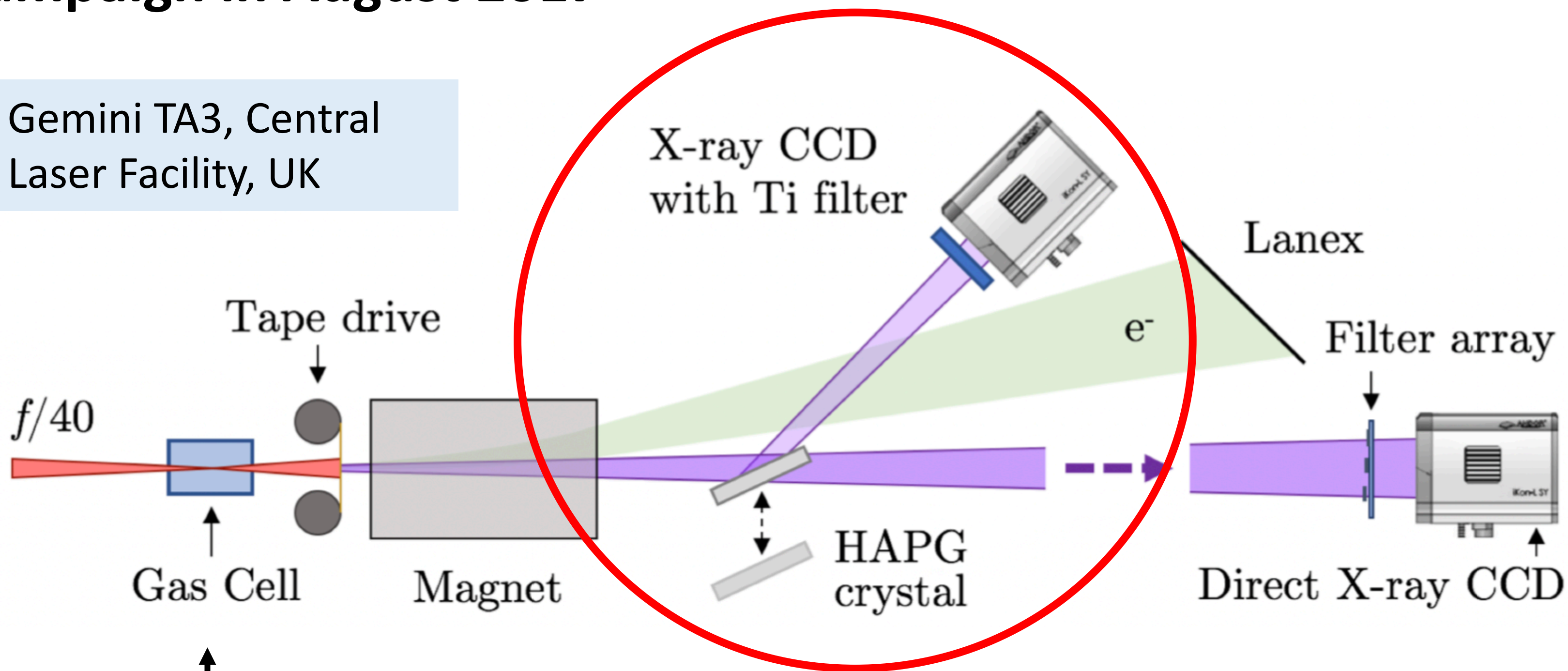
$$\left.\frac{d^2 I}{dE d\Omega}\right|_{\theta=0} \propto \gamma_e^2 \left(\frac{E}{2E_{crit}}\right)^2 \mathcal{K}_{2/3}^2\left(\frac{E}{2E_{crit}}\right)$$

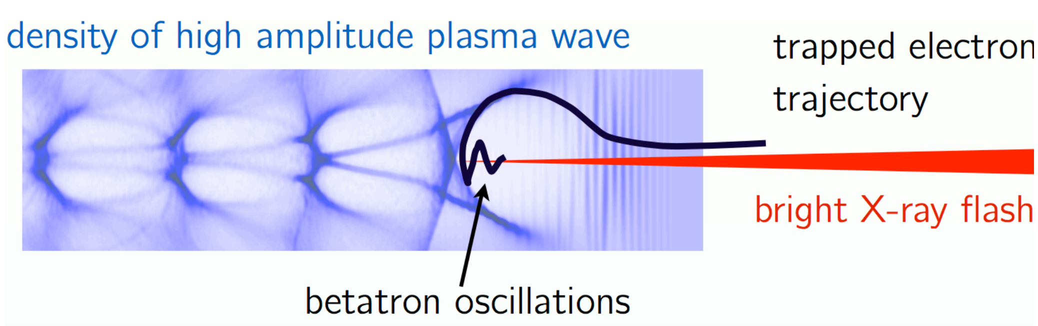
E_{crit} = 9.9 ± 1.5 keV, and the entire beam contained **7.2 ± 2.8 × 10^5 photons/eV at 5 keV**

(≈10^{22}-10^{23} photons/s/mm^2/mrad^2/0.1% BW)

Campaign in August 2017

Gemini TA3, Central Laser Facility, UK





Drive laser
Duration = 47 ± 5 fs
Energy = 9 ± 0.3 J (43% in FWHM)
Intensity = 4.9 ± 0.6 x 10^{18} W/cm^2
($a_0 \approx 1.5$)

LWFA X-rays – High resolution using crystal spectrometer

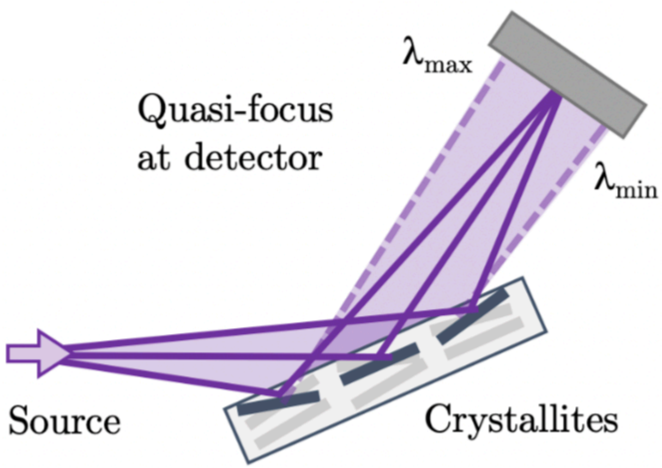
Bragg's law

$$2d \sin\theta = n\lambda$$

2d = Crystal lattice spacing (fixed)
θ = Incident ray angle
λ = Diffracted X-ray wavelength

Graphite 2d = 6.708 Å
Range of energies ≈ **2 - 10 keV**

1-to-1 Mosaic "focusing"



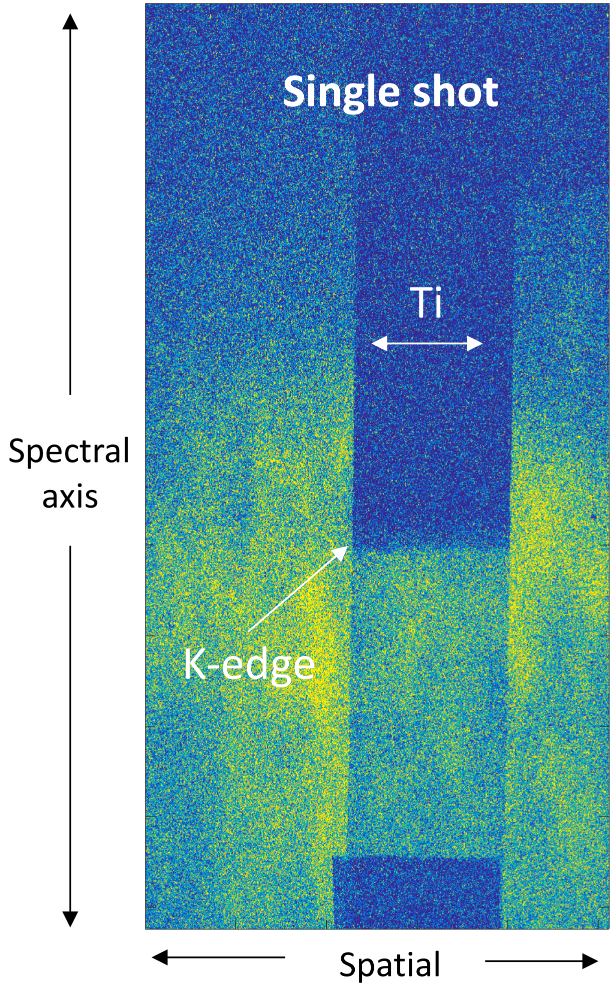
Solid rays: Single wavelength
Dashed rays: Min/max wavelength

- Bragg reflections provide sweep of X-ray energies on detector.
- **Mosaic**: Random orientation of crystallite planes allow more rays to be diffracted to detector - **10 times more efficient** than "perfect" crystal, with small sacrifice in resolution.

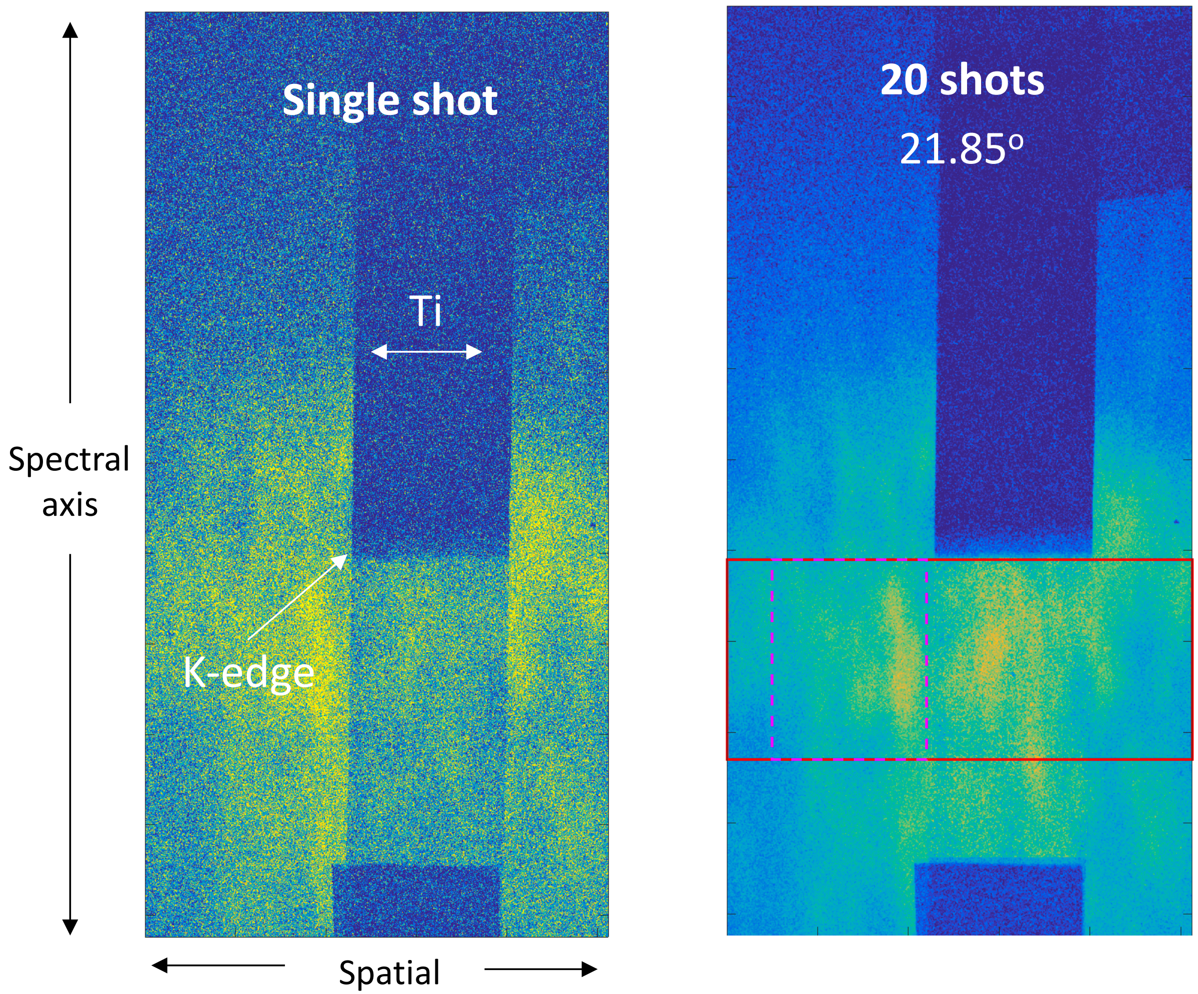
Resolution:
dE/E ≈ 2000

Zastrau et al. J.Inst. 8 P10006 (2013)

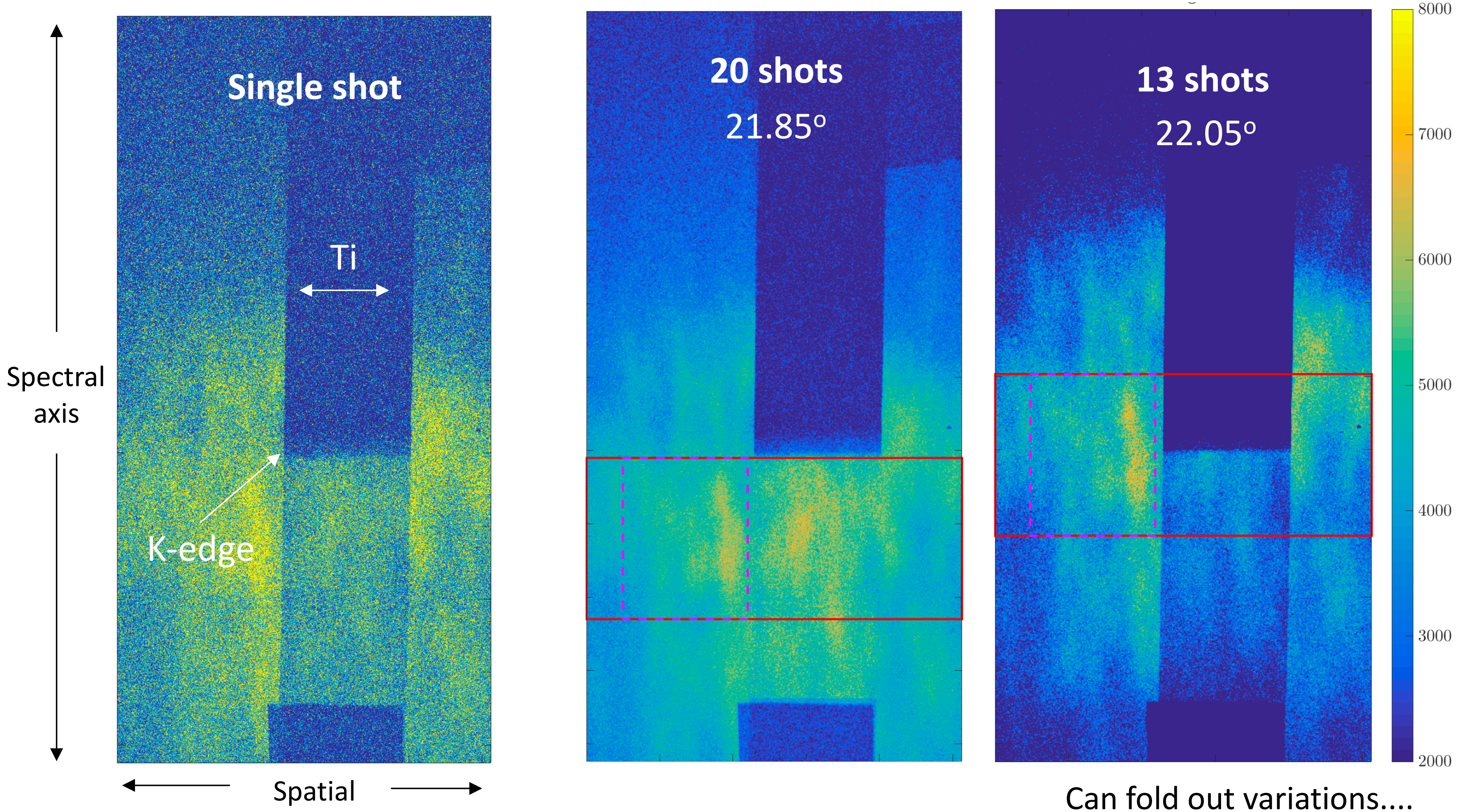
Crystal spectrometer results



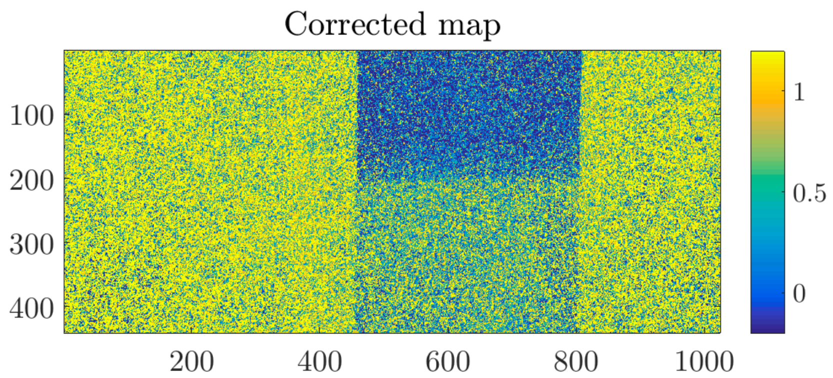
Crystal spectrometer results

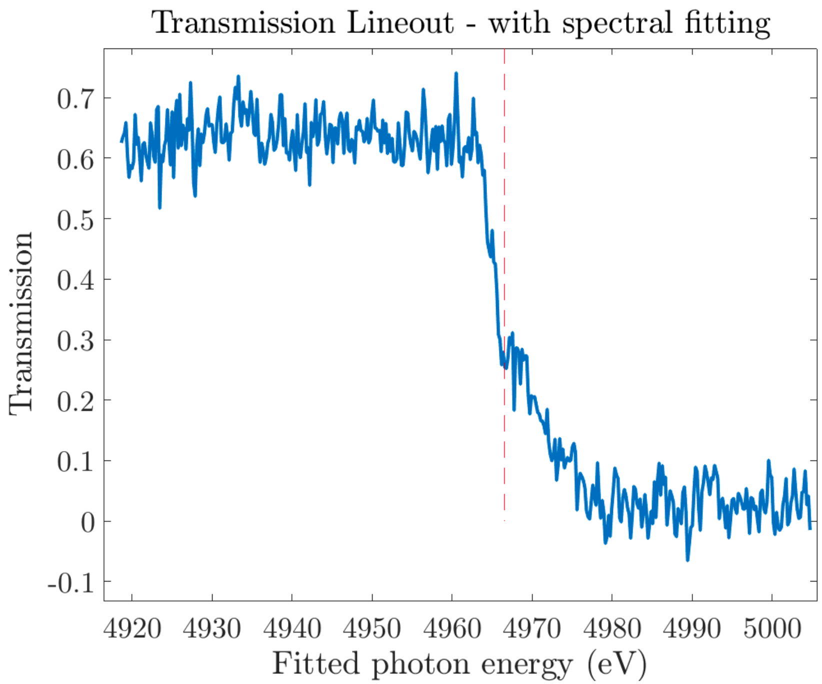


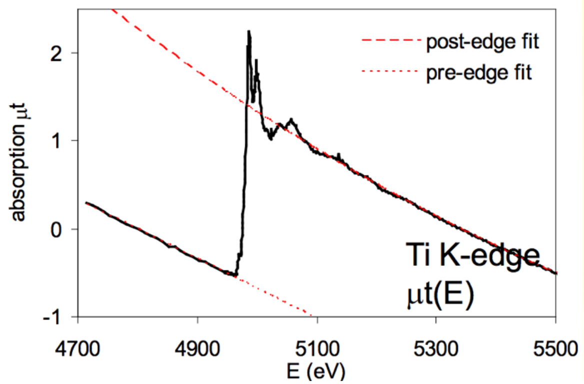
Crystal spectrometer results



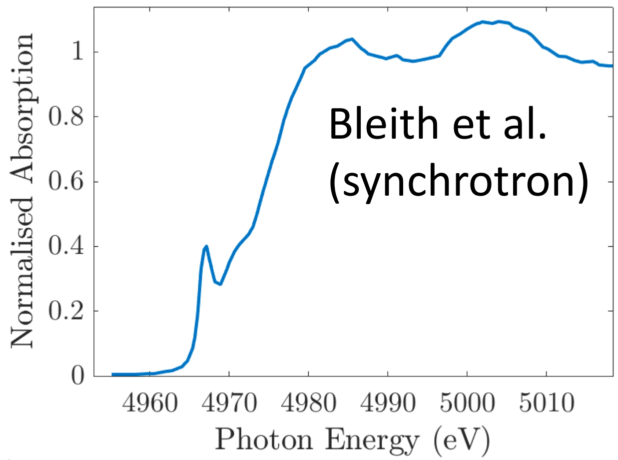
Can fold out variations....







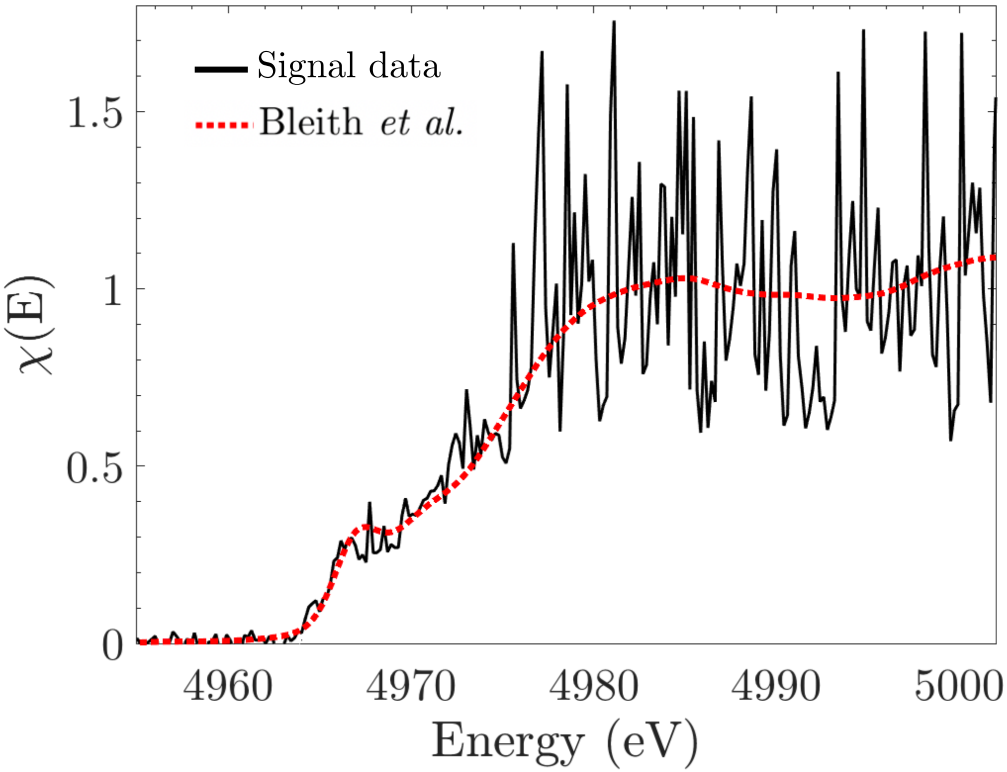
$$\chi(E) = \frac{\mu(E) - \mu_0(E)}{\mu_1(E)}$$



[1] *A Practical Intro. to Multiple Scattering Theory*, B. Ravel, 2005
[2] *Bleith et al. J. Mater. Chem. A, 2014, 2, 12513*

Titanium K-edge XANES measurements

Normalised absorption, 10µm Ti Foil



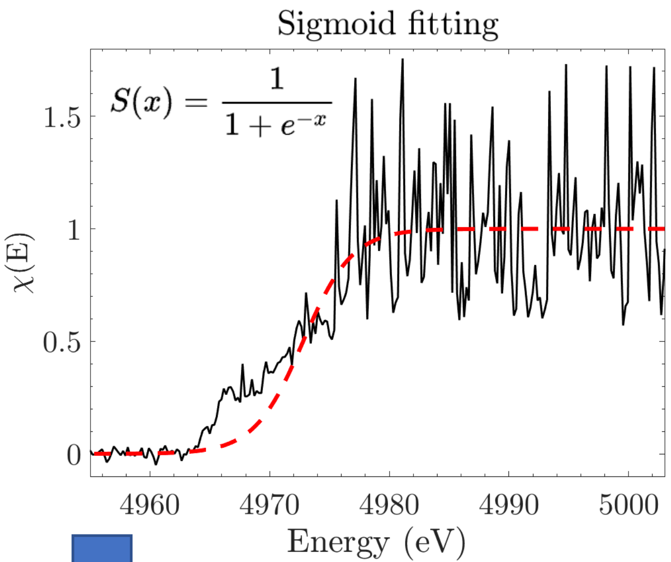
(<u>Single Shot</u>)

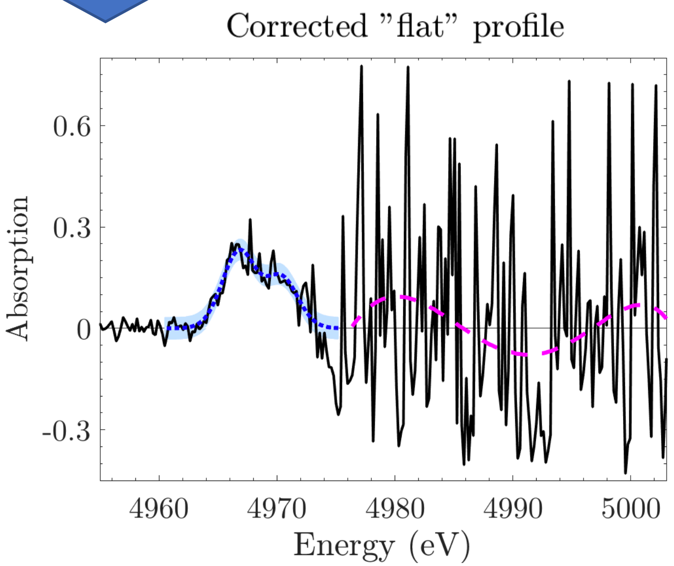
Direct spectral measurement of X-rays with approximately 2.2 eV resolution over an 80 eV window.

Signal-to-noise = 300:1

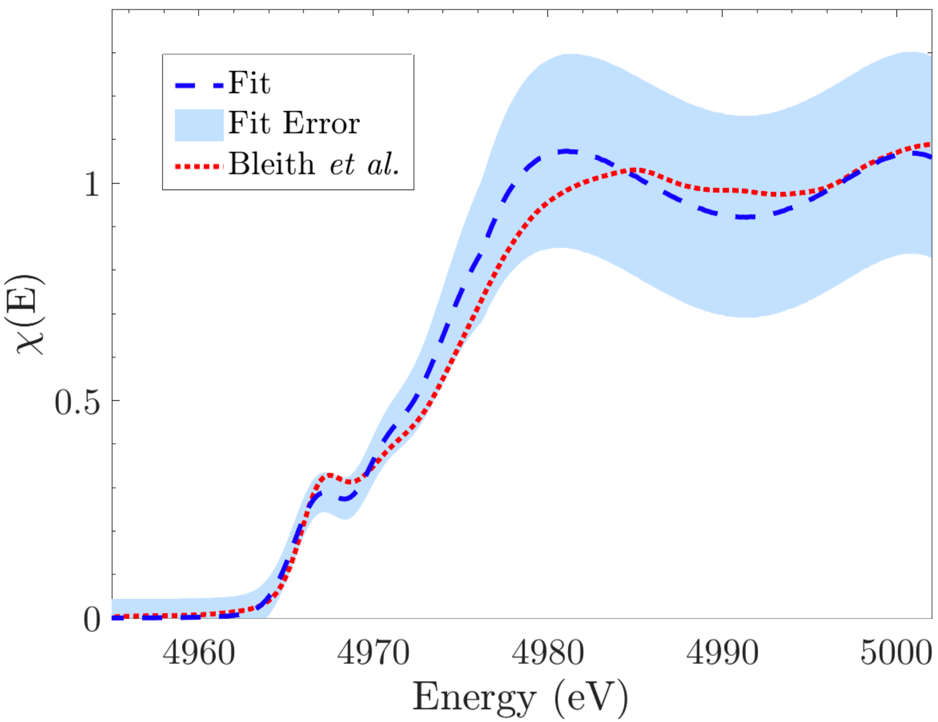
Poisson? …. should be 1100:1

… Noise is mostly from electron dump, <u>not X-ray source</u> and can be improved…





Reconstructed fit

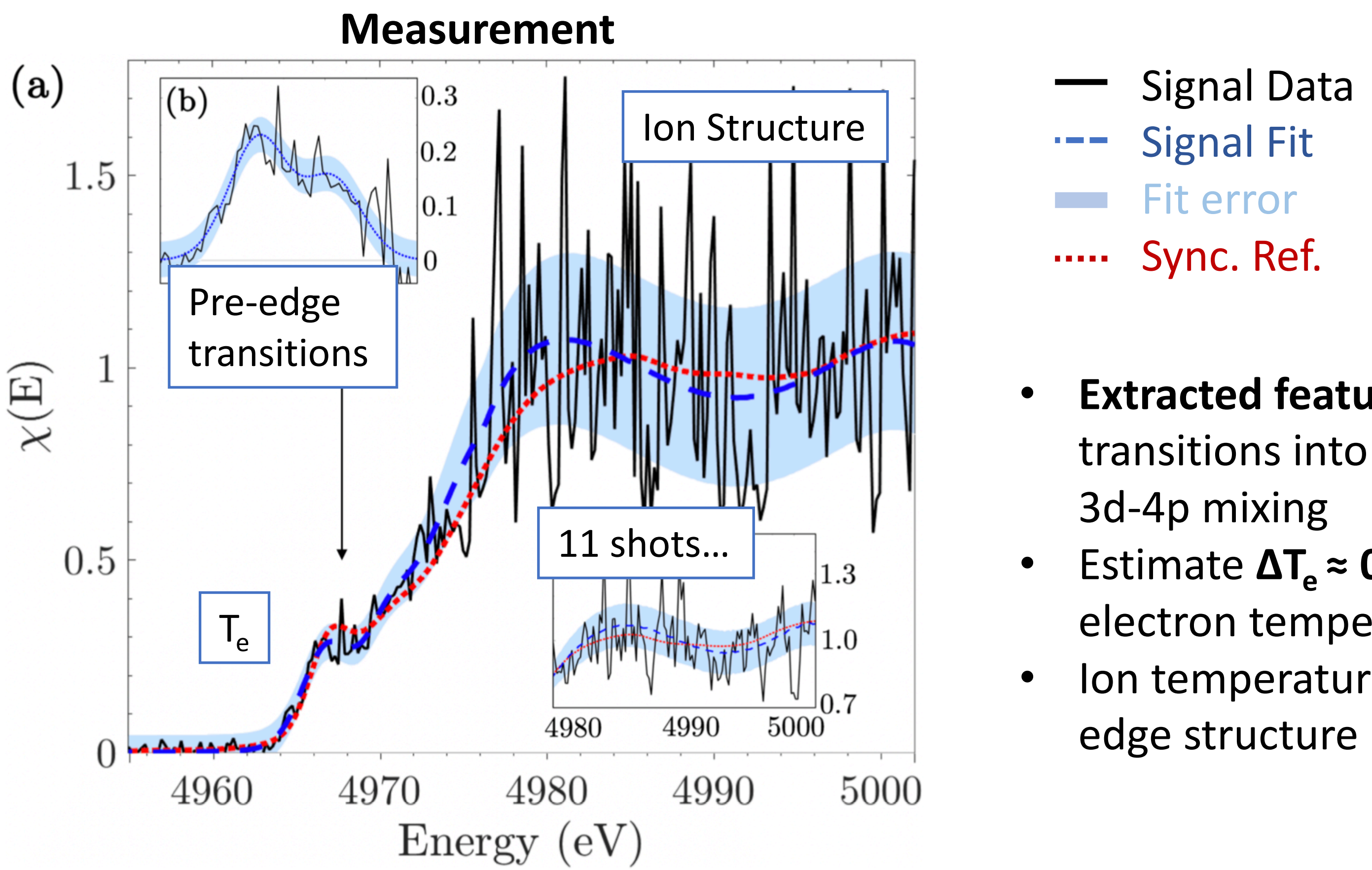


Imperial College London

John Adams Institute for Accelerator Science

erc

Single Shot XANES measurement

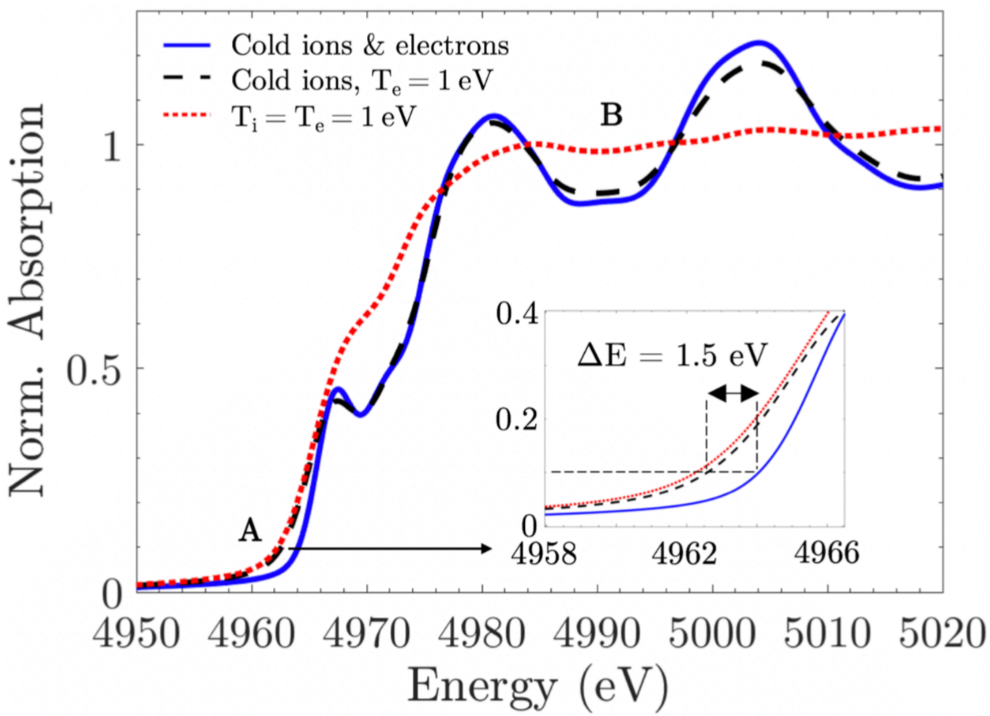


- **Extracted features** - forbidden transitions into 3d shell (allowed by 3d-4p mixing
- Estimate $\Delta T_e \approx$ **0.4 eV** resolution in electron temperature change
- Ion temperature/structure in post edge structure

Recently accepted for PRL: https://arxiv.org/abs/1907.10167

Model predictions for electron-ion equilibration in dense plasmas

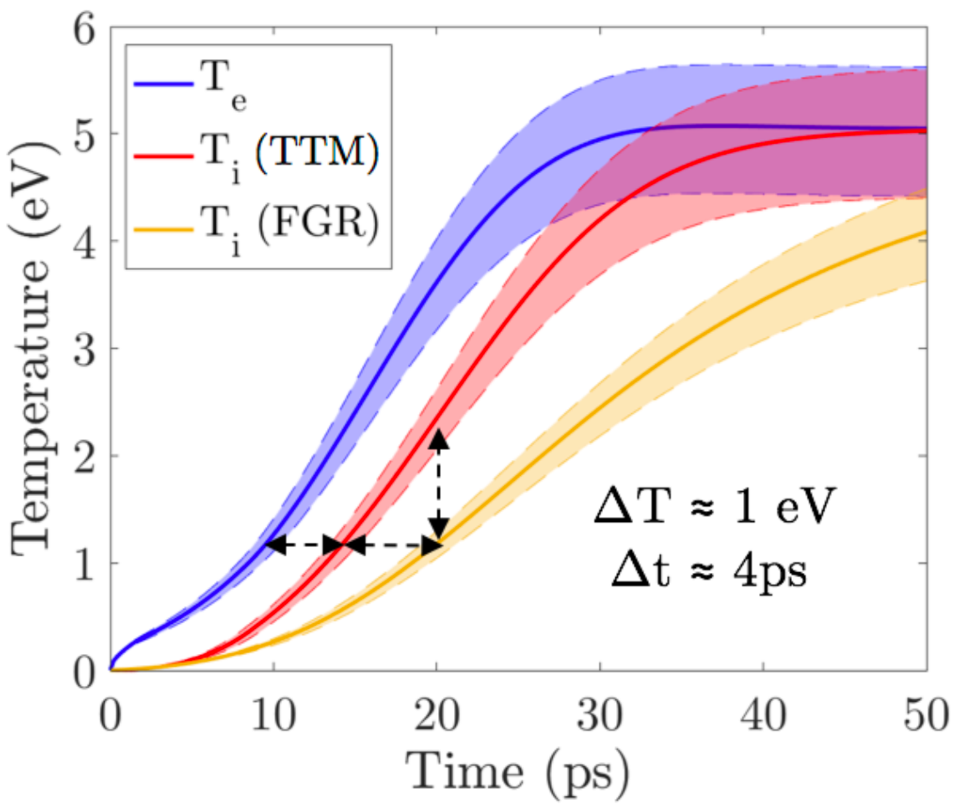
Copper DFT simulations (GPAW)



Simulations by Rory Baggott

- Electron and ion temperatures have individual signatures
- Can **independently measure the electron and ion temperature** on a single shot.
- Very interesting for high energy density samples due to ultrashort pulse duration of X-rays.

Model predictions for electron-ion equilibration in dense plasmas

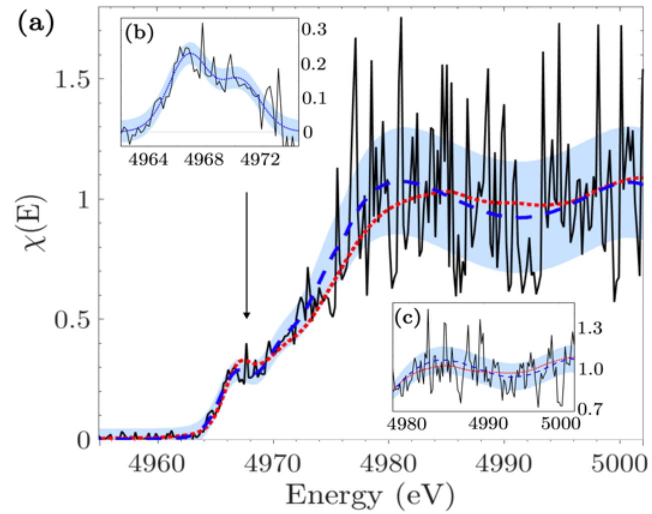


- Temperature equilibration estimates for Copper
- 20ps X-ray driver
- Comparing Two-temperature model with plasma based model

<u>Possible to measure equilibration rates of WDM and HDM</u>.

In conclusion

- High resolution direct spectral measurement of LWFA X-rays
- Single-shot multi-keV absorption of Ti K-edge.
- With shielding/improved geometry this can be even better – post-edge leads to ion information.
- With appropriate heating scheme; Measurements of ultrafast processes in high energy density matter.

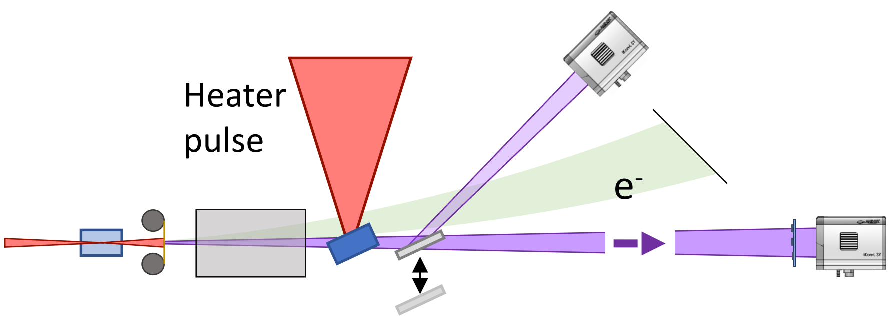


Single-shot multi-keV X-ray absorption spectroscopy using an ultrashort laser wakefield accelerator source

B. Kettle,[1,*] E. Gerstmayr,[1] M.J.V. Streeter,[2,†] F. Albert,[3] R.A. Baggott,[1] N. Bourgeois,[4] J.M. Cole,[1] S. Dann,[2,‡] K. Falk,[5,6] I. Gallardo González,[7] A.E. Hussein,[8] N. Lemos,[3] N.C. Lopes,[9] O. Lundh,[7] Y. Ma,[2,§] S.J. Rose,[1] C. Spindloe,[4] D.R. Symes,[4] M. Šmíd,[5] A.G.R. Thomas,[8,2] R. Watt,[1] and S.P.D. Mangles[1]

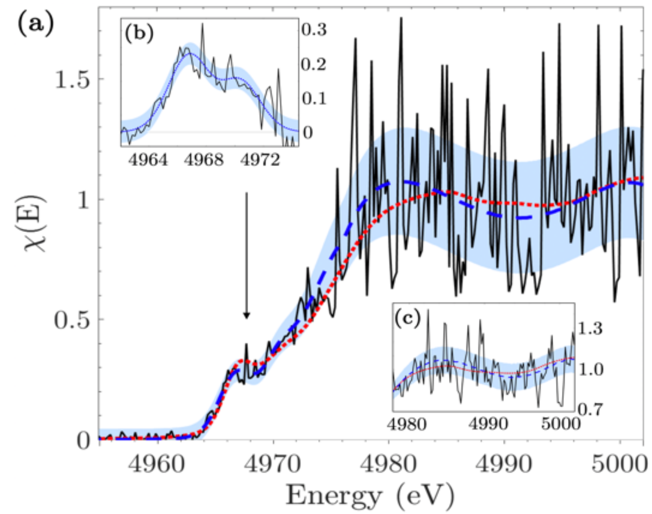
[1] *The John Adams Institute for Accelerator Science, Imperial College London, London, SW7 2AZ, UK*
[2] *Physics Department, Lancaster University, Lancaster LA1 4YB, United Kingdom*
[3] *Lawrence Livermore National Laboratory (LLNL), Livermore, California 94550, USA*
[4] *Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot OX11 0QX, UK*
[5] *Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstrasse 400, 01328 Dresden, Germany*
[6] *Institute of Physics of the ASCR, Na Slovance 1999/2, 182 21 Prague, Czech Republic*
[7] *Department of Physics, Lund University, P.O. Box 118, S-22100, Lund, Sweden*
[8] *Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109-2099, USA*
[9] *GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, U.L., Lisboa 1049-001, Portugal*

Single-shot absorption measurements have been performed using the multi-keV X-rays generated by a laser wakefield accelerator. A 200 TW laser was used to drive a laser wakefield accelerator in a mode which produced broadband electron beams with a maximum energy above 1 GeV and a broad divergence of ≈ 15 miliradians FWHM. Betatron oscillations of these electrons generated $1.2 \pm 0.2 \times 10^6$ photons/eV in the 5 keV region, with a signal-to-noise ratio of approximately 300:1. This was sufficient to allow high-resolution XANES measurements at the K-edge of a titanium sample in a single shot. We demonstrate that this source is capable of single-shot, simultaneous measurements of both the electron and ion distributions in matter heated to eV temperatures by comparison with DFT simulations. The unique combination of a high-flux, large bandwidth, few femtosecond duration X-ray pulse synchronised to a high-power laser will enable key advances in the study of ultra-fast energetic processes such as electron-ion equilibration.



In conclusion

- High resolution direct spectral measurement of LWFA X-rays
- Single-shot multi-keV absorption of Ti K-edge.
- With shielding/improved geometry this can be even better – post-edge leads to ion information.
- With appropriate heating scheme; Measurements of ultrafast processes in high energy density matter.



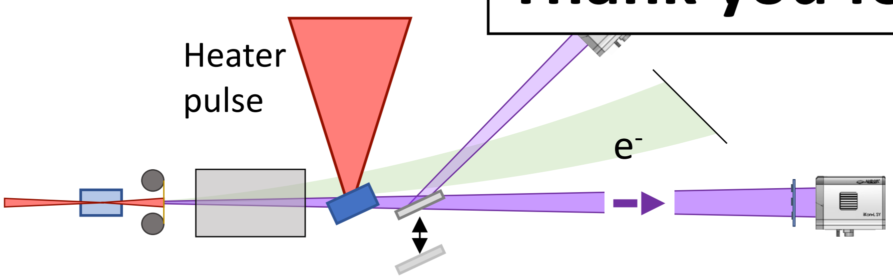
Single-shot multi-keV X-ray absorption spectroscopy using an ultrashort laser wakefield accelerator source

B. Kettle,[1,*] E. Gerstmayr,[1] M.J.V. Streeter,[2,†] F. Albert,[3] R.A. Baggott,[1] N. Bourgeois,[4] J.M. Cole,[1] S. Dann,[2,‡] K. Falk,[5,6] I. Gallardo González,[7] A.E. Hussein,[8] N. Lemos,[3] N.C. Lopes,[9] O. Lundh,[7] Y. Ma,[2,§] S.J. Rose,[1] C. Spindloe,[4] D.R. Symes,[4] M. Šmíd,[5] A.G.R. Thomas,[8,2] R. Watt,[1] and S.P.D. Mangles[1]

[1] *The John Adams Institute for Accelerator Science, Imperial College London, London, SW7 2AZ, UK*
Lancaster University, Lancaster LA1 4YB, United Kingdom
ational Laboratory (LLNL), Livermore, California 94550, USA
STFC Rutherford Appleton Laboratory, Didcot OX11 0QX, UK
n-Rossendorf, Bautzner Landstrasse 400, 01328 Dresden, Germany
he ASCR, Na Slovance 1999/2, 182 21 Prague, Czech Republic
cs, Lund University, P.O. Box 118, S-22100, Lund, Sweden
ience, University of Michigan, Ann Arbor, Michigan 48109-2099, USA
[9] *GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, U.L., Lisboa 1049-001, Portugal*

Single-shot absorption measurements have been performed using the multi-keV X-rays generated by a laser wakefield accelerator. A 200 TW laser was used to drive a laser wakefield accelerator in a mode which produced broadband electron beams with a maximum energy above 1 GeV and a broad divergence of ≈ 15 miliradians FWHM. Betatron oscillations of these electrons generated $1.2 \pm 0.2 \times 10^6$ photons/eV in the 5 keV region, with a signal-to-noise ratio of approximately 300:1. This was sufficient to allow high-resolution XANES measurements at the K-edge of a titanium sample in a single shot. We demonstrate that this source is capable of single-shot, simultaneous measurements of both the electron and ion distributions in matter heated to eV temperatures by comparison with DFT simulations. The unique combination of a high-flux, large bandwidth, few femtosecond duration X-ray pulse synchronised to a high-power laser will enable key advances in the study of ultra-fast energetic processes such as electron-ion equilibration.

Thank you for listening



Acknowledgements

Stuart Mangles[1], Steven Rose[1], Rory Baggott[1], Robbie Watt[1], Jason Cole[1], Elias Gerstmayr[1], Nelson Lopes[1], Alec Thomas[2,3], Matthew Streeter[2], Stephen Dann[2], Yong Ma[2], Amina Hussein[3], Dan Symes[4], Chris Spindloe[4], Olle Lundh[5], Isabel Gallardo Gonzalez[5], Kateřina Falk[6], Michal Šmíd[6], Felicie Albert[7], Nuno Lemos[7]

[1] Imperial College London, U.K.
[2] Lancaster University, U.K.
[3] University of Michigan, USA
[4] Central laser Facility, U.K.
[5] Lund University, Sweden
[6] ELI Beamlines, Czech Republic
[7] Lawrence Livermore National Laboratory, USA

The Cockcroft Institute of Accelerator Science and Technology

Lancaster University

Science & Technology Facilities Council Central Laser Facility

eli beamlines

The University of Michigan

erc

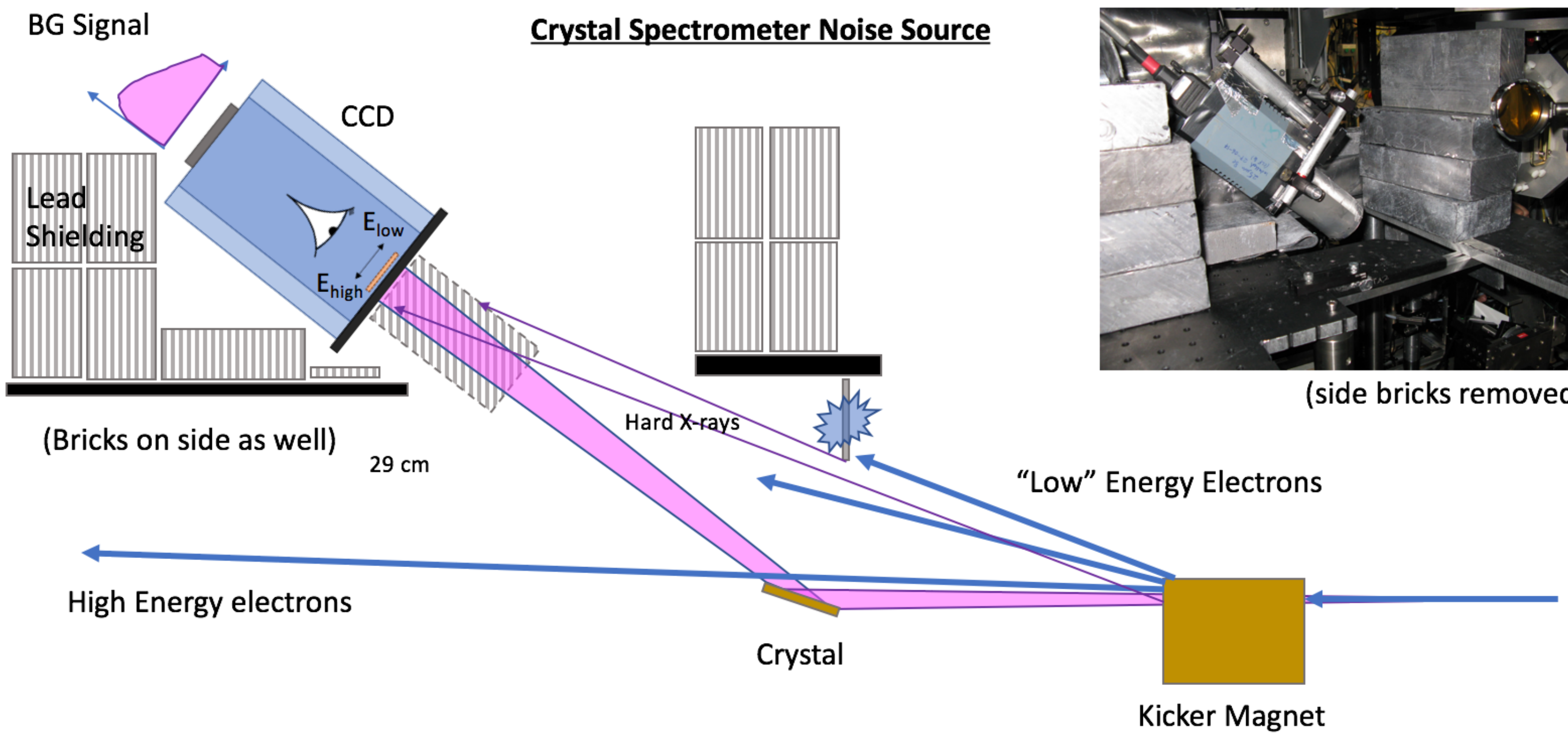
Part funded by
ERC TeXMex Grant
(Ref: 682399)

Lund University

Lawrence Livermore National Laboratory

Error/Noise contributions

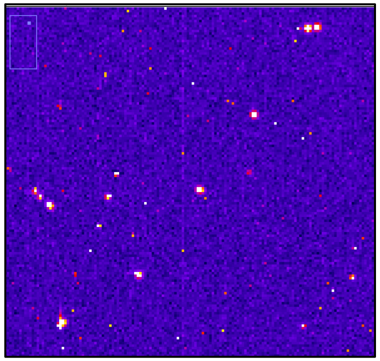
- Hard photon background from electron dump. Dominates. Can be significantly reduced by sweeping electrons in other direction and improving shielding.
- Reference map errors. Give larger scale fluctuations. Can be reduced by a full crystal characterisation.
- Inherent source fluctuations.

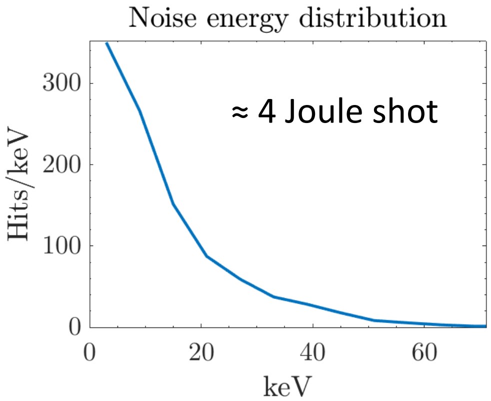


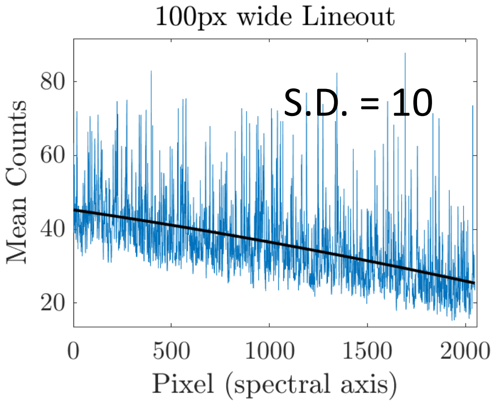
(side bricks removed)

▹ Crystal spectrometer noise issue

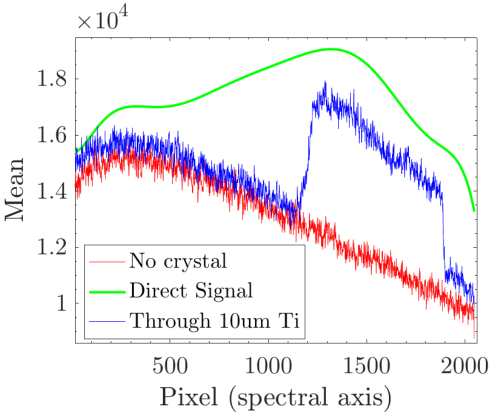
Looking at low power shots with ”single hit” noise.
Run charge recombination routine and gauge spectrum.

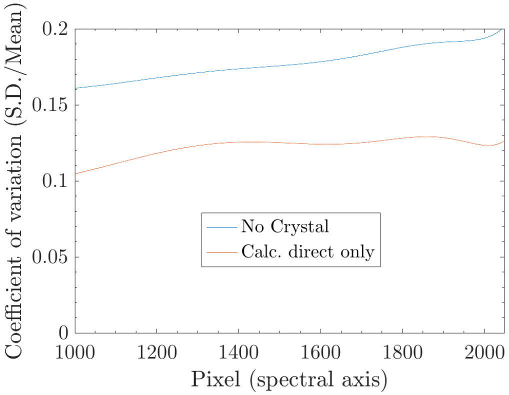






On full power shots, this becomes ≈x200





Can improve

- Shielding
- Electron dumping
- Detector geometry (including curved crystal)

To reduce noise and move closer to single shot measurements.

BACKGROUND NOISE

We assess the background level on the crystal spectrometer by summing the CCD counts on shots where the crystal is moved out of the direct path of the X-ray beam, and hence no signal is being reflected towards the detector. For each of these shots we also sum the total electron charge simultaneously detected on the electron spectrometer. Fig. 3 (a) depicts a linear correlation for the number of CCD counts as a function of electron charge.

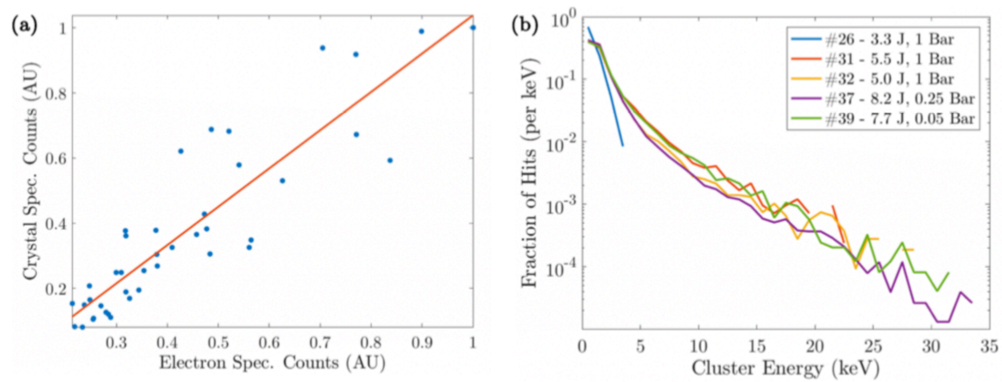
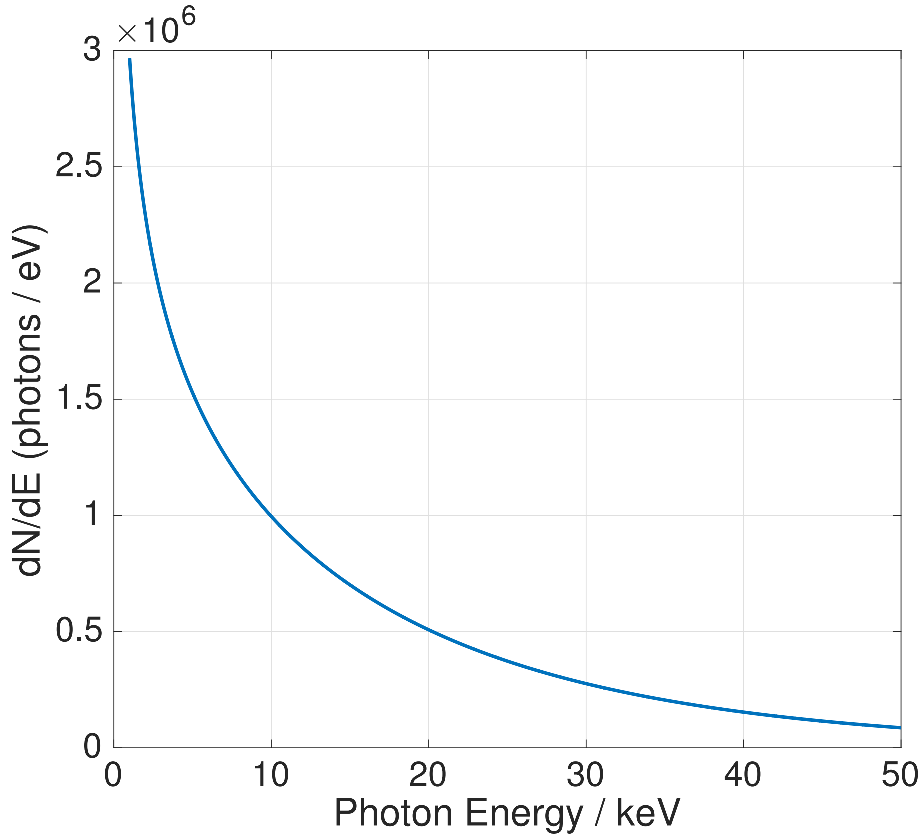


FIG. 3: (a) Crystal spectrometer CCD counts as a function of measured electron charge for shots with no crystal in place. (b) Single-hit cluster energies for various background shots at low background flux.

In an attempt to further characterise this background signal we perform a single-hit cluster analysis of the individual CCD strikes on shots with a low enough level of flux (thus avoiding strike pile-up). Less than 3% of CCD pixels registered a value above threshold for all shots used in the single-hit analysis. A cluster combining algorithm was used to calculate the total freed energy for each individual identifiable strike on the CCD. Fig. 3 (b) depicts the number of strikes as a function of total contained energy in each cluster. For the shots depicted, various plasma densities and laser energies were used, corresponding to varying levels of electron charge being generated from the LWFA. Shot 26 in the blue has no detectable electron charge driven, and represents the dark current of the CCD. All shots apart from 26 show a broadband spectra of cluster energies tailing out to 30 keV (which is also where the quantum efficiency of the CCD falls off).

These results indicate that in the current configuration the background noise is being produced by the accelerated electrons interacting with the target chamber and creating secondary noise sources. Importantly, it should therefore be possible to significantly reduce the background with improved shielding and appropriate electron beam dumping, away from the CCD.



$\times 10^6$
3
2.5
2
1.5
1
0.5
0
dN/dE (photons / eV)
0
10
20
30
40
50
Photon Energy / keV