IMPERIAL

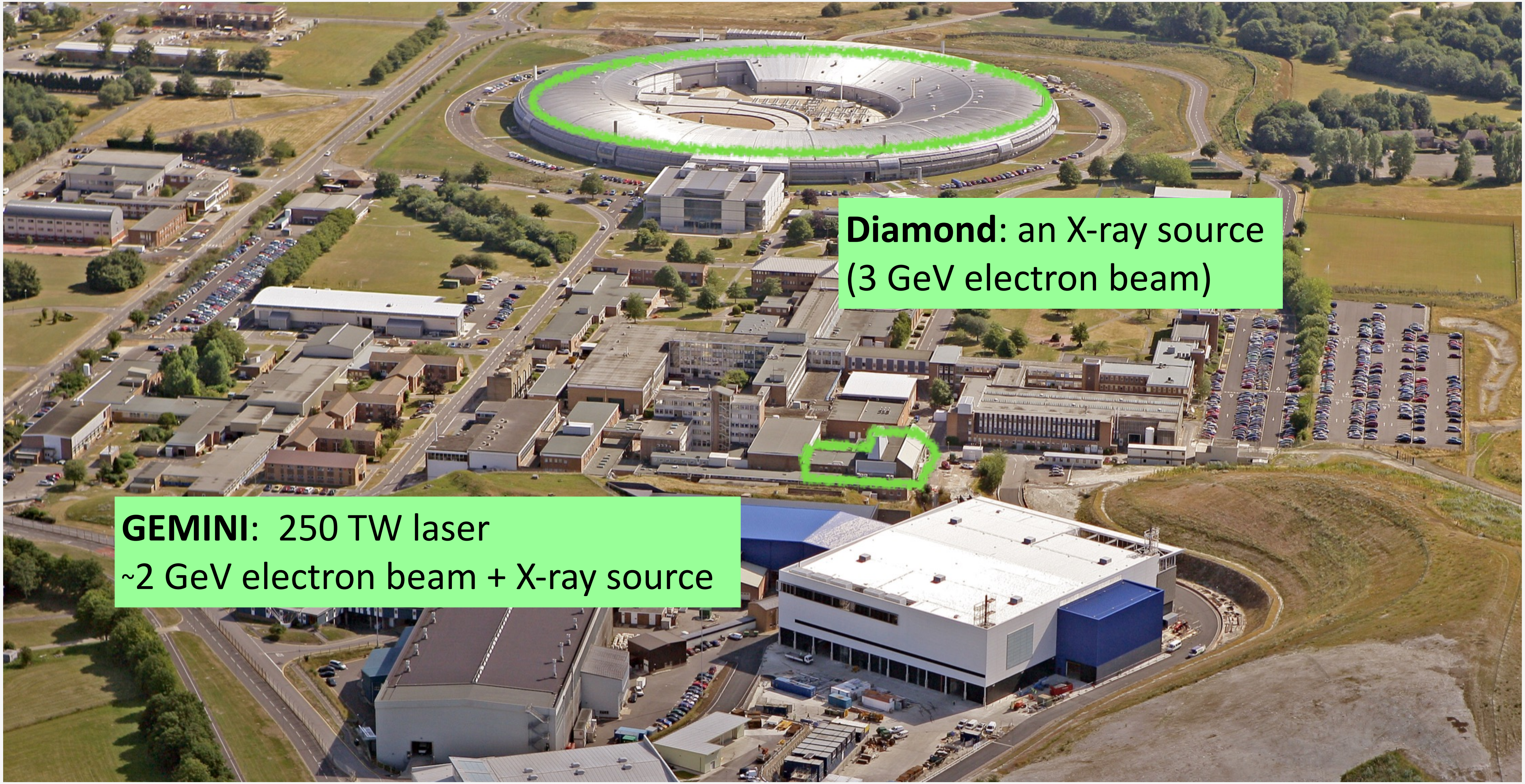
Laser Wakefield Accelerators:

Tools for Time-Resolved X-Ray Imaging and Spectroscopy

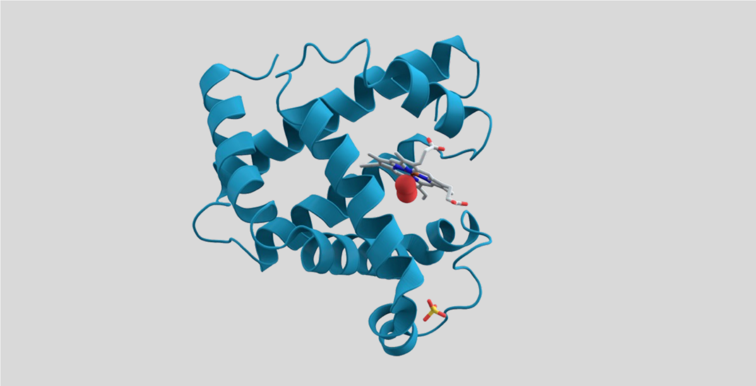
Stuart Mangles
23/04/2024

Outline

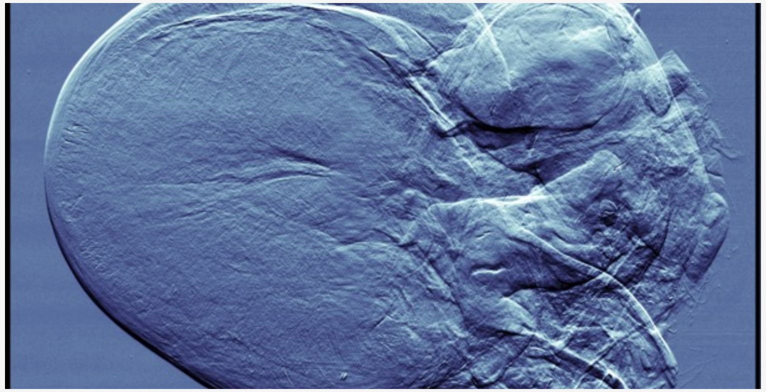
1 Intro to laser wakefield accelerators
2 Basic concepts of X-ray generation
3 Synchrotron radiation from Laser Wakefield Accelerators
4 Applications of X-rays from Laser Wakefield Accelerators


Diamond: an X-ray source
(3 GeV electron beam)
GEMINI: 250 TW laser
~2 GeV electron beam + X-ray source

X-rays are amazing tools for science



Myoglobin structure calculated using x-ray crystallography, wikipedia.org

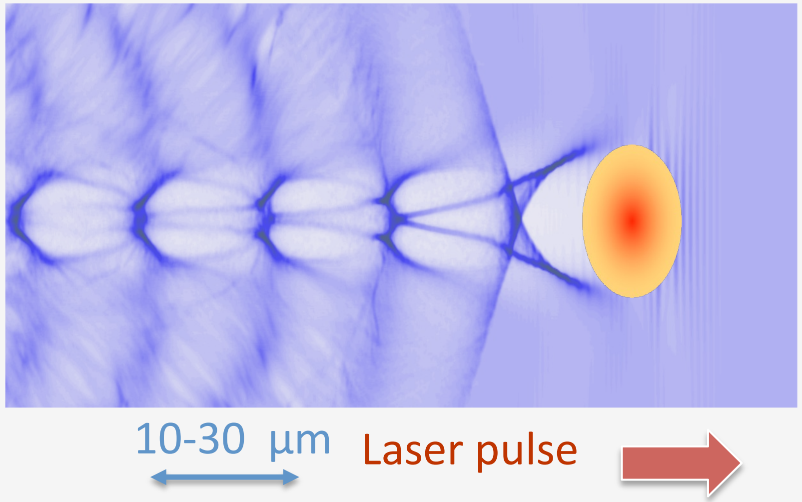


High resolution phase contrast x-ray imaging of a rat's heart
F. Pfeiffer. C. David, www.cimst.ethz.ch

Bright x-rays produced by particle accelerators are used a tool by a huge variety of scientists

- X-ray diffraction used to work out structures of proteins vital for discovery of new drugs, magnetic materials …
- Advanced x-ray imaging techniques to improve medical diagnosis
- X-ray tools used in palaeontology and archaeology

Laser wakefield accelerators



Laser wakefields are compact laser-plasma accelerators

- Plasma wave driven by very intense laser pulse travelling through a plasma
  - Plasma waves can support fields > 100 GV m^{-1}
  - conventional accelerators are limited to <100 MV m^{-1}

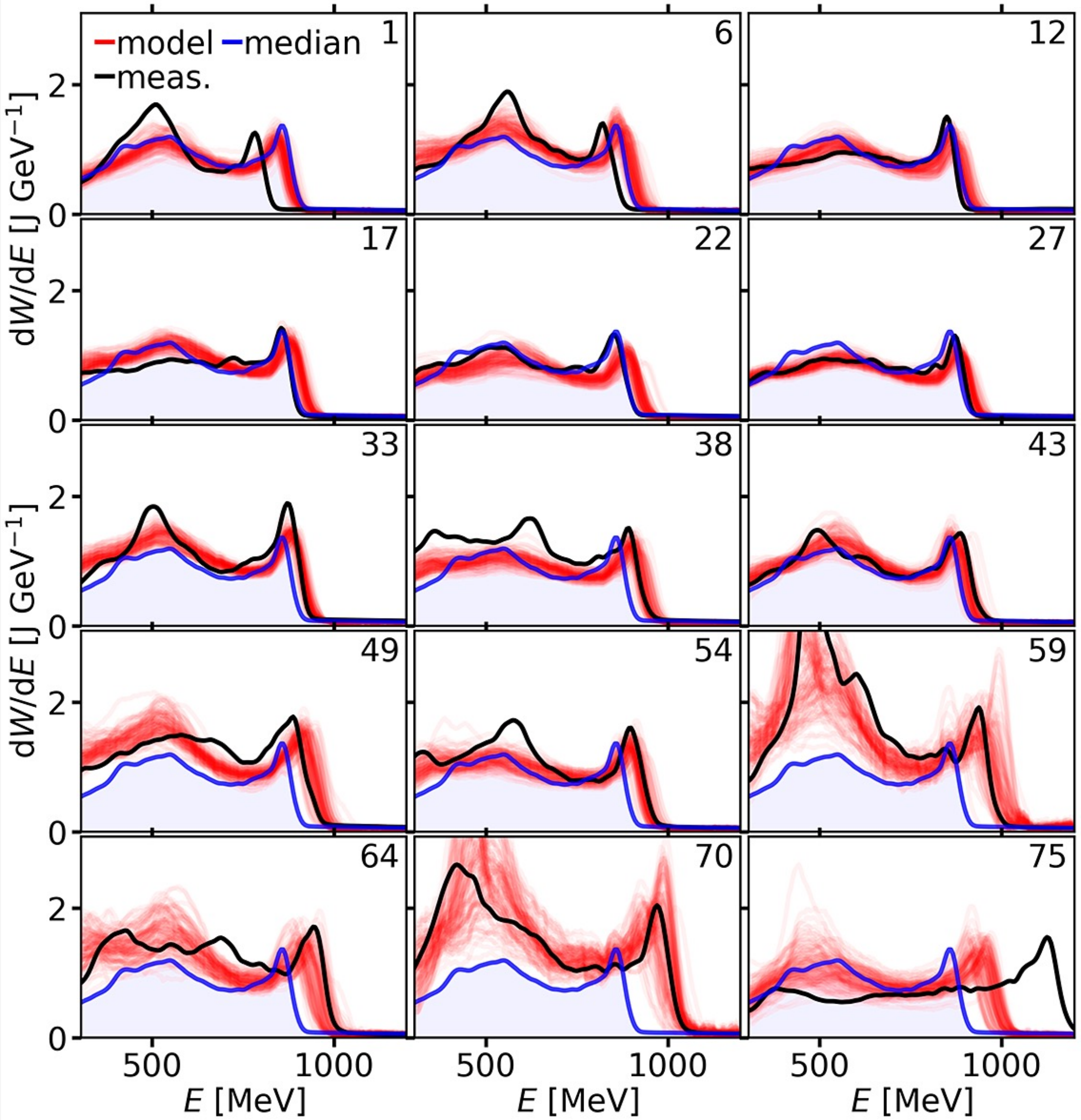
Laser wakefield accelerators

What sort of electron beams can we get?

Electron beam properties:

- gigaelectronvolt energy
- femtosecond duration

- Image shows selection of electron spectra from Gemini
  - Black: measured spectrum
  - Red: predictions of spectrum predicted by neural net based on other diagnostics of laser + plasma
  - Blue: average spectrum



Streeter et al, HPLSE 2023

Basic Concepts of X-ray Generation

X-ray Generation Mechanisms

There are many mechanisms for X-ray generation

- Bremsstrahlung
- Characteristic radiation (K-alpha etc)
- Synchrotron Radiation
- Thomson scattering
- Free Electron Lasers

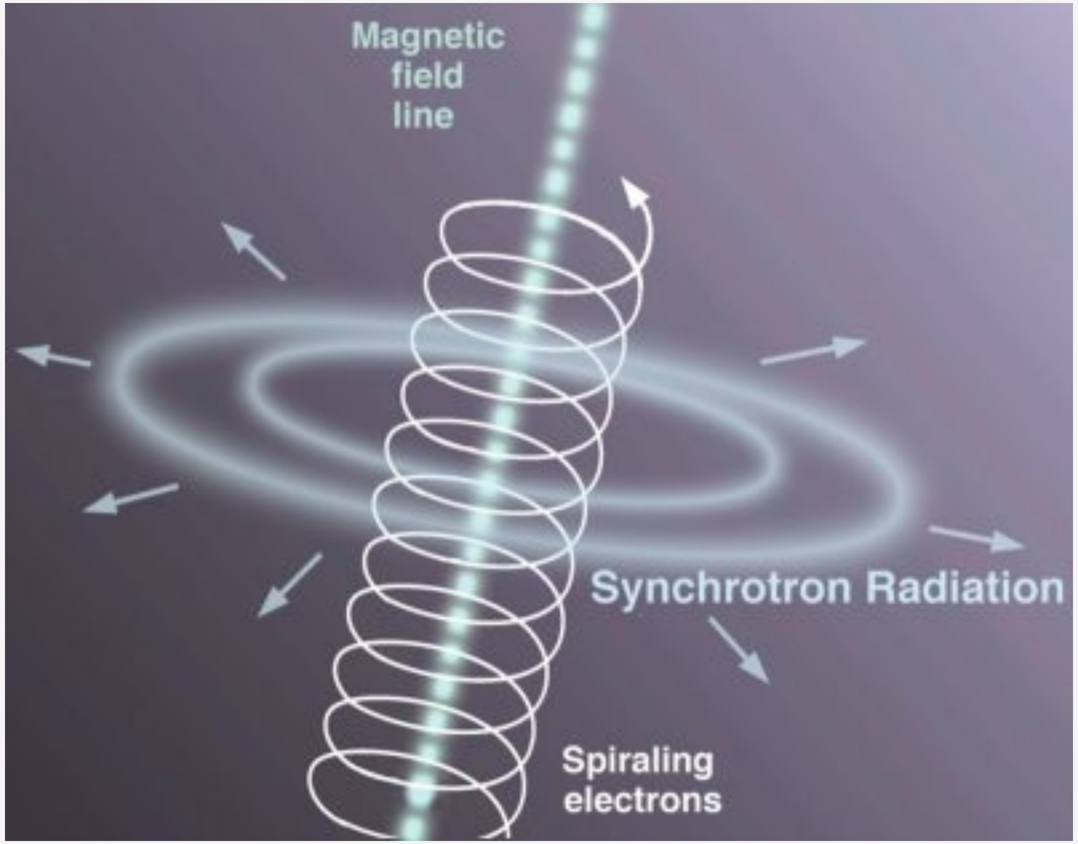


Image: Jon Lomberg/Gemini Observatory.

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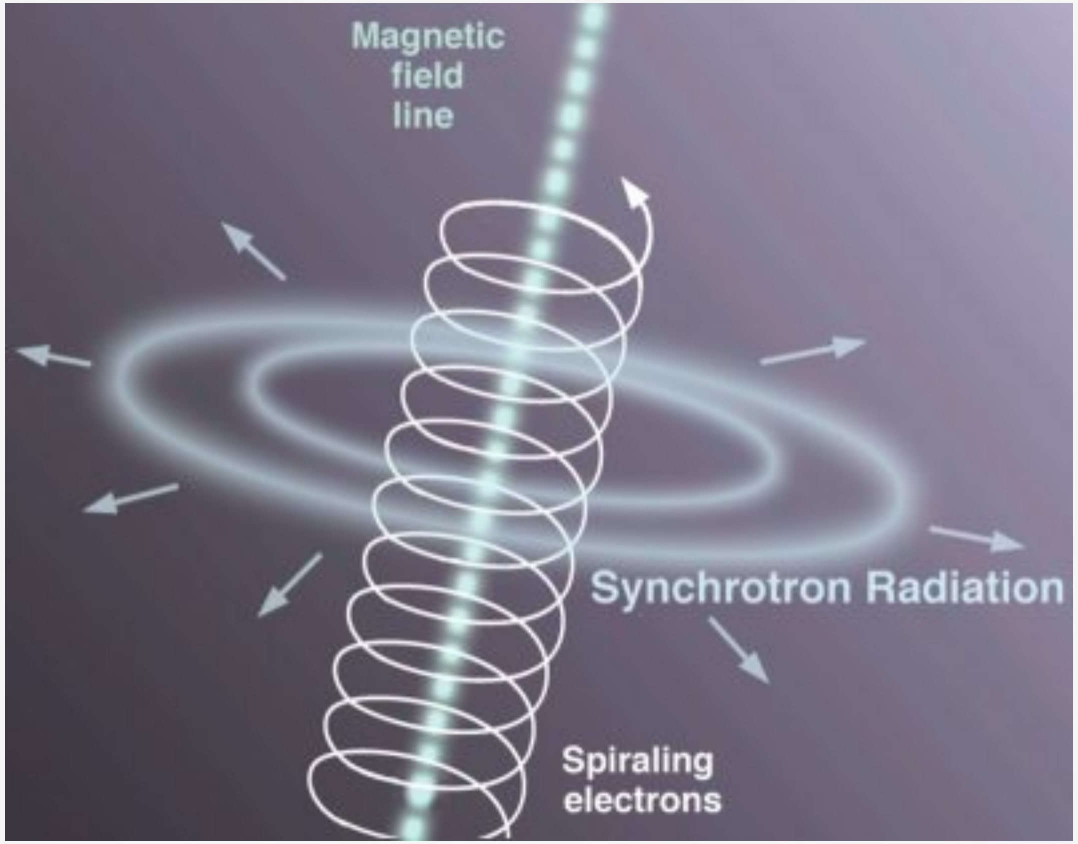


Image: Jon Lomberg/Gemini Observatory.

X-ray generation with high-energy electron beams

For high-energy electron beams ($E \gg m_e c^2$)

- Radiated power given by relativistic Larmor formula
- High energy particles radiate ***a lot***
- High energy particles have $|\underline{\boldsymbol{\beta}}| \to 1$: radiation is generated by bending the beam
- For constant circular motion (radius R) the expression is simpler

$$P = \frac{q^2}{6\pi\epsilon_0 m^2 c^3}\gamma^6\left[(\dot{\underline{\beta}})^2 - (\underline{\beta} \times \dot{\underline{\beta}})^2\right]$$

$$P = \frac{e^2 c}{6\pi\epsilon_0}\frac{\beta^4\gamma^4}{R^2}$$

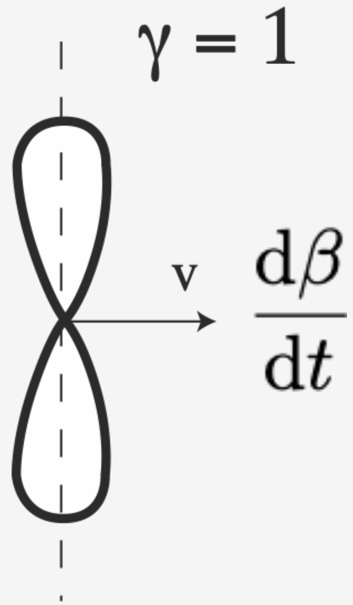
Power radiated by moving charge (Jackson chapter 14)

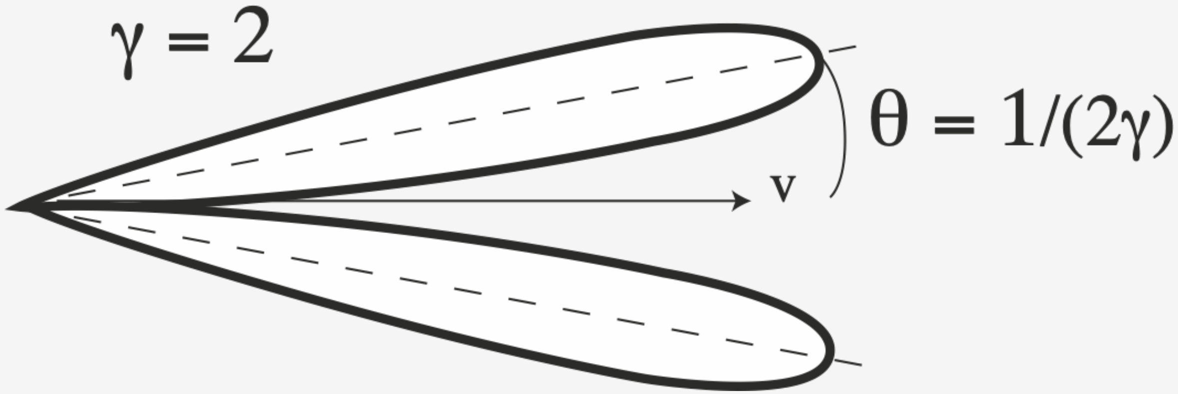
X-ray generation with high-energy electron beams

Radiation from ***low-energy*** electrons is emitted perpendicular to beam direction

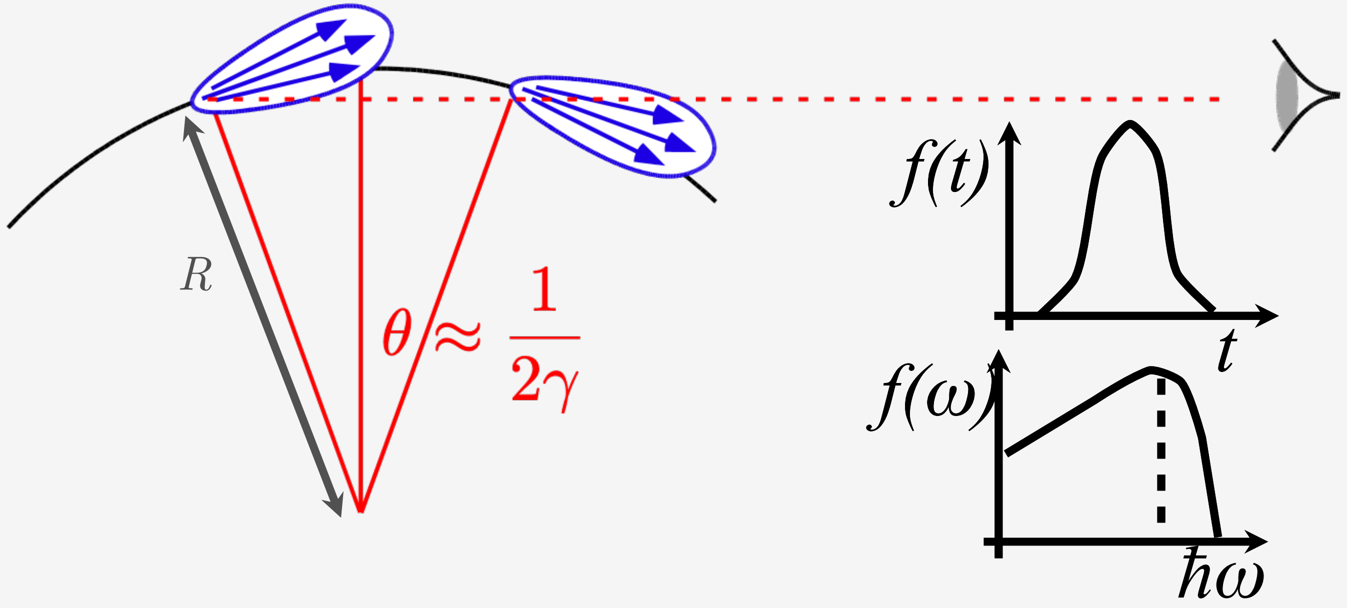
Radiation from ***high-energy*** electrons is "beamed" into narrow cone

- beam of X-rays pointing along the electron beam trajectory





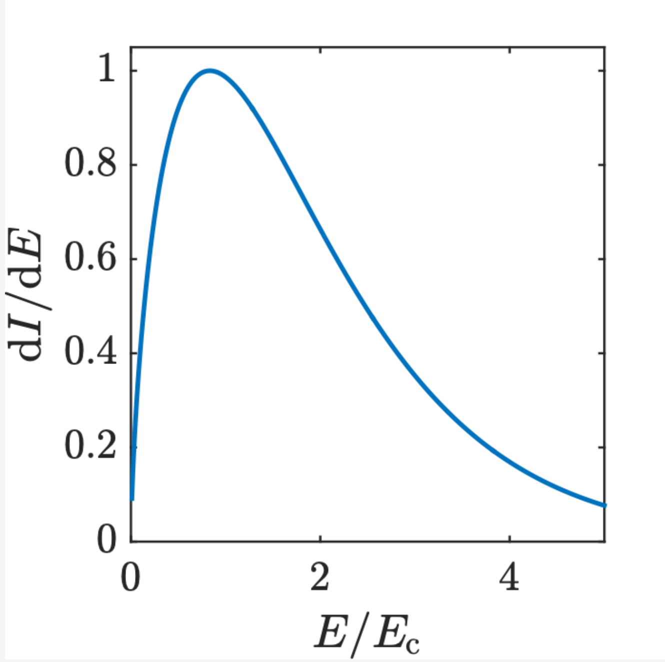
Radiation from particle in circular motion

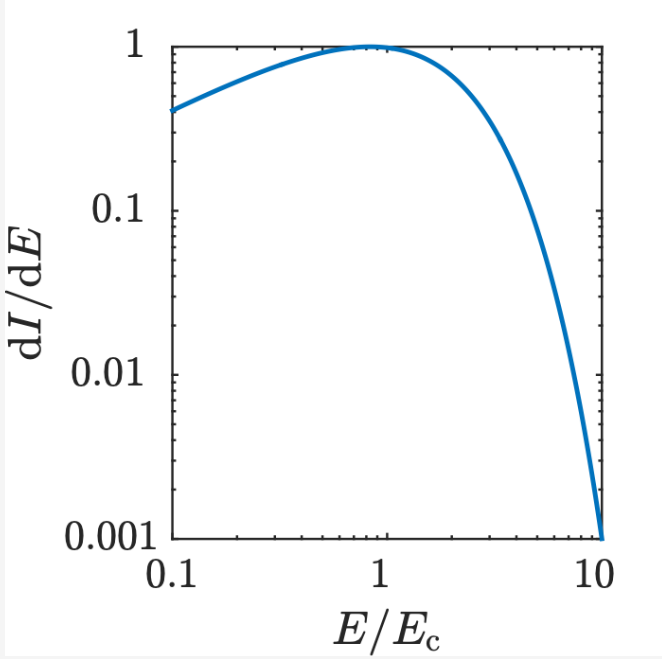


- Observer sees radiation flick on and off as beam sweeps past
- Duration of "flash" determined by radius of circle, R and the electron Lorentz factor, γ
- Spectral bandwidth of the radiation found from time bandwidth product
  - This determines the critical photon energy, E

for high-energy X-rays we need high γ and small R

Synchrotron Radiation Spectrum





Critical energy, E_c is a single parameter that defines shape of Synchrotron radiation

Radiation "on-axis"

$$\frac{d^2 I}{dE d\Omega} = \frac{3e^2}{16\pi^3 \epsilon_0 c}\gamma^2 \left(\frac{E}{E_c}\right)^2 K^2_{2/3}\left(\frac{E}{2E_c}\right)$$

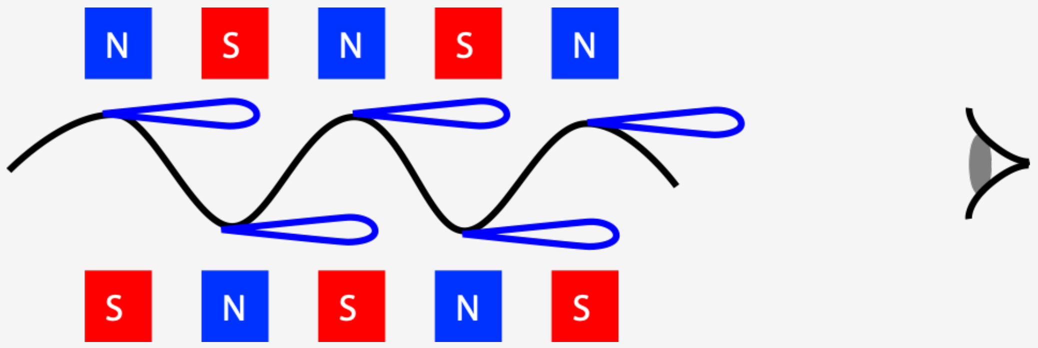
$$E_c = \frac{3}{2}\hbar c \gamma^3 / R$$

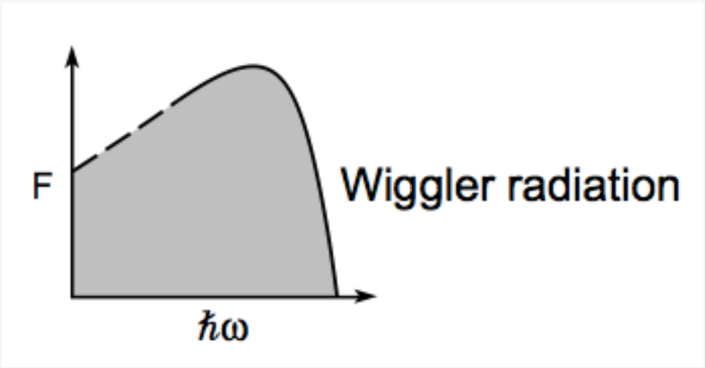
Wigglers and Undulators radiation

To get more X-rays add more bends

Define K parameter: $$K = \gamma k_0 r_0$$

Wiggler: if $K \gg 1$: spectrum is still synchrotron-like



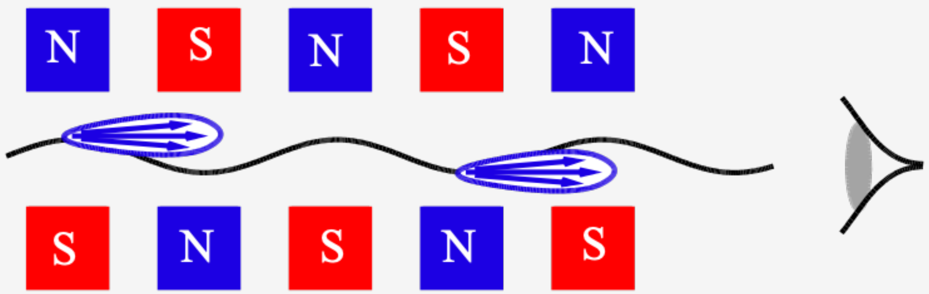


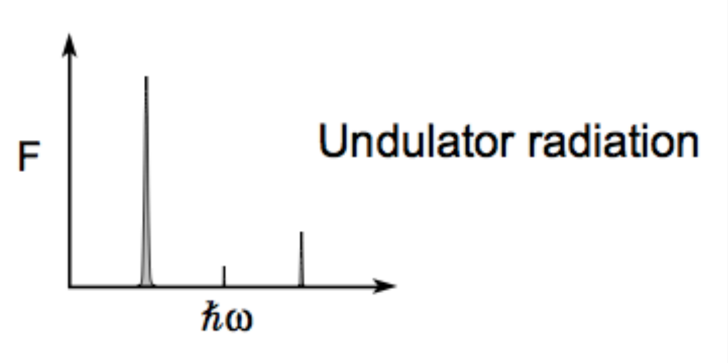
Wigglers and Undulators radiation

To get more X-rays add more bends

Define K parameter: $$K = \gamma k_0 r_0$$

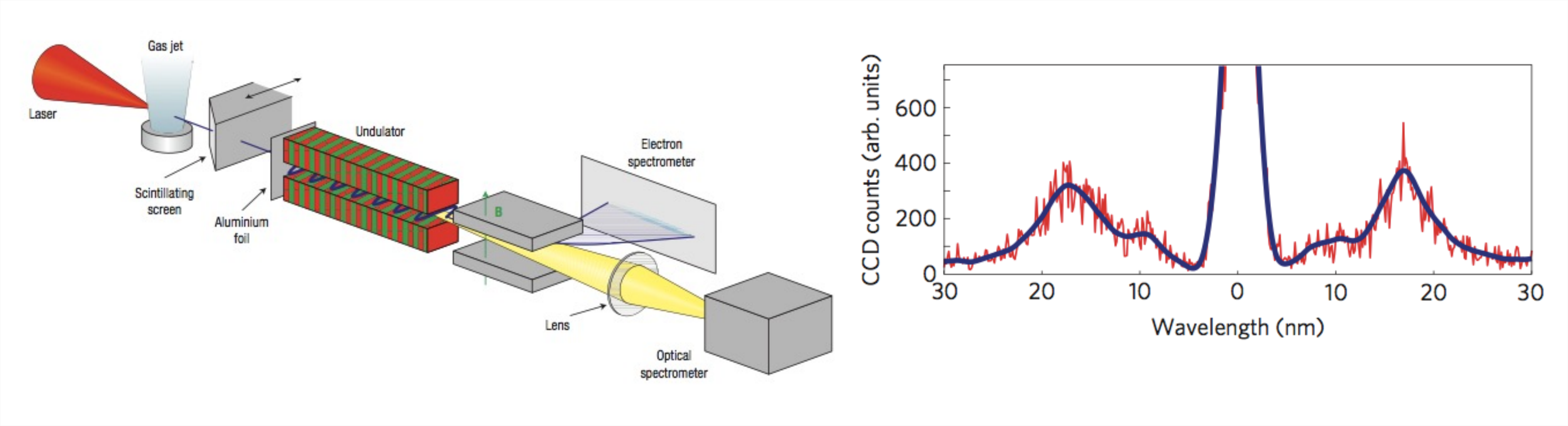
Undulator: if $K \ll 1$: spectrum is monochromatic





Synchrotron radiation from laser wakefield accelerators

Radiation using conventional undulator



Fuchs Nature Phys 2009
Schlenvoigt Nature Phys 2008

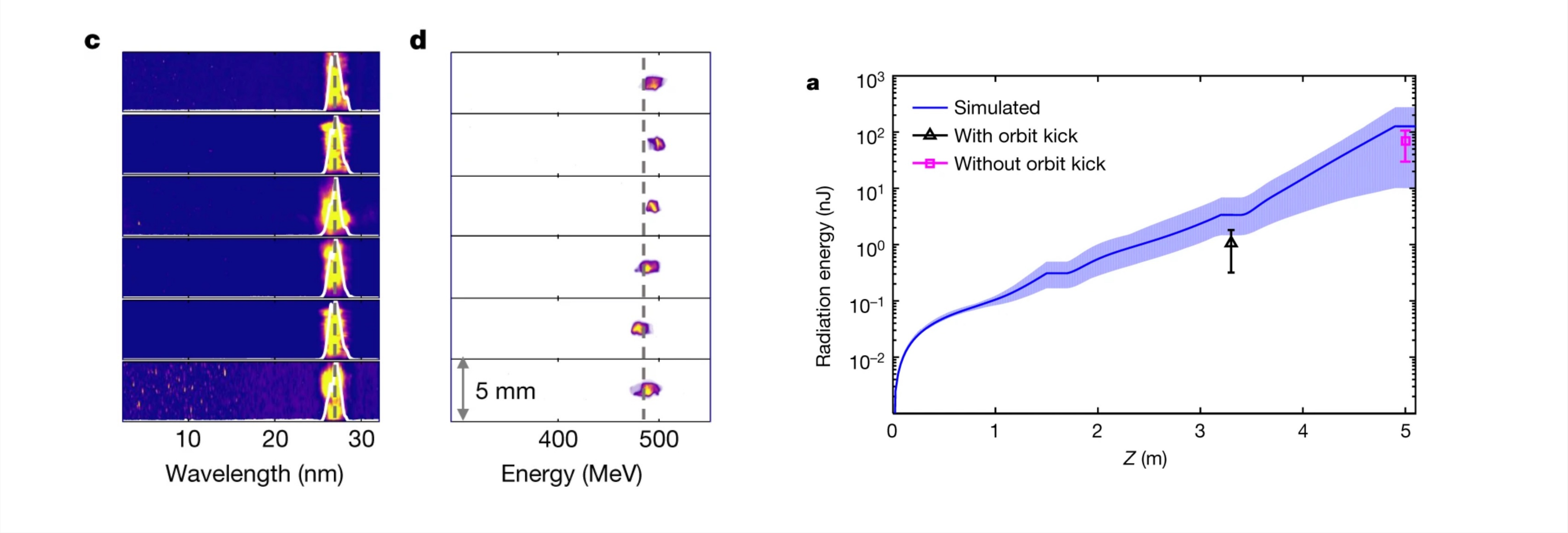
LWFA producing ≈200 MeV beams used in conventional undulator

- few centimetre period
- soft X-rays (< 100 eV)

Need shorter period to reach keV X-rays
But these are the route to LWFA FELs

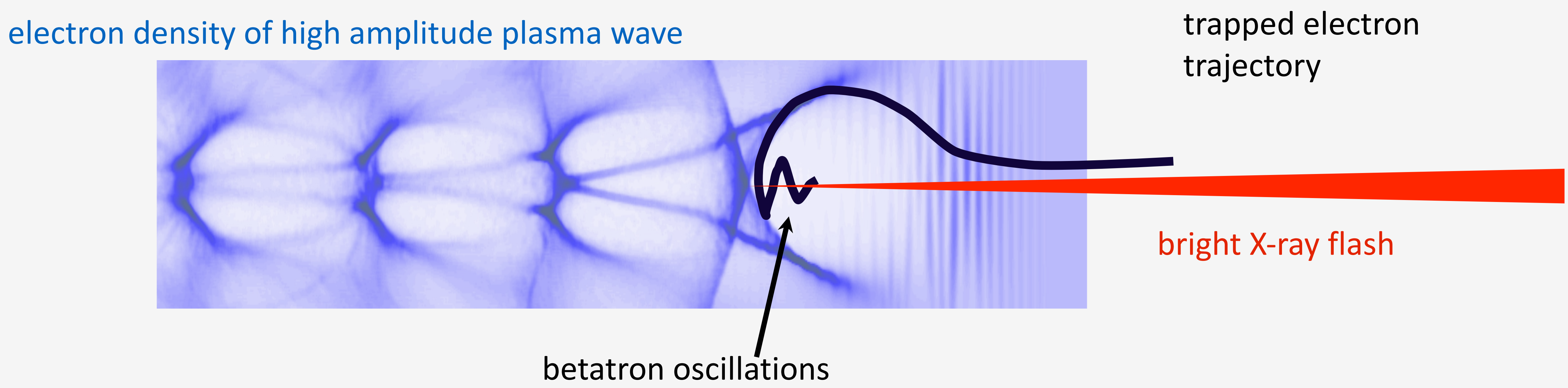
2021/22 was the year of the plasma FEL

2.7 nm FEL at SIOM: Wang et al Nature **595**, 516 (2021)
0.8 μm FEL at Frascati: Pompili et al Nature **606**, 659 (2022)
270 nm seeded FEL at HZDR: Labat et al Nature Photonics (2022)



But can we use LWFA to reach keV X-rays?

Laser Wakefield as accelerator and wiggler



Strong transverse fields inside bubble make electrons oscillate while being accelerated

- “betatron oscillations”

- wavelength of oscillations can be very short compared to conventional wigglers
  - for $n_e = 10^{19}$ cm^{-3} and 200 MeV electrons this is 300 μm

$$\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}} \qquad \lambda_\beta = \sqrt{2\gamma}\, c/\omega_p$$

Energy of X-rays from a Laser Wakefield Accelerator

Energy of X-rays in synchrotron:

$$E_c = \frac{3}{2}\hbar c\gamma^3/R$$

We can rewrite R in terms of the wiggler wavelength and amplitude

$$R \approx 1/(k_\beta^2 r_\beta) \qquad \omega_\beta = \frac{\omega_\mathrm{p}}{\sqrt{2\gamma}}$$

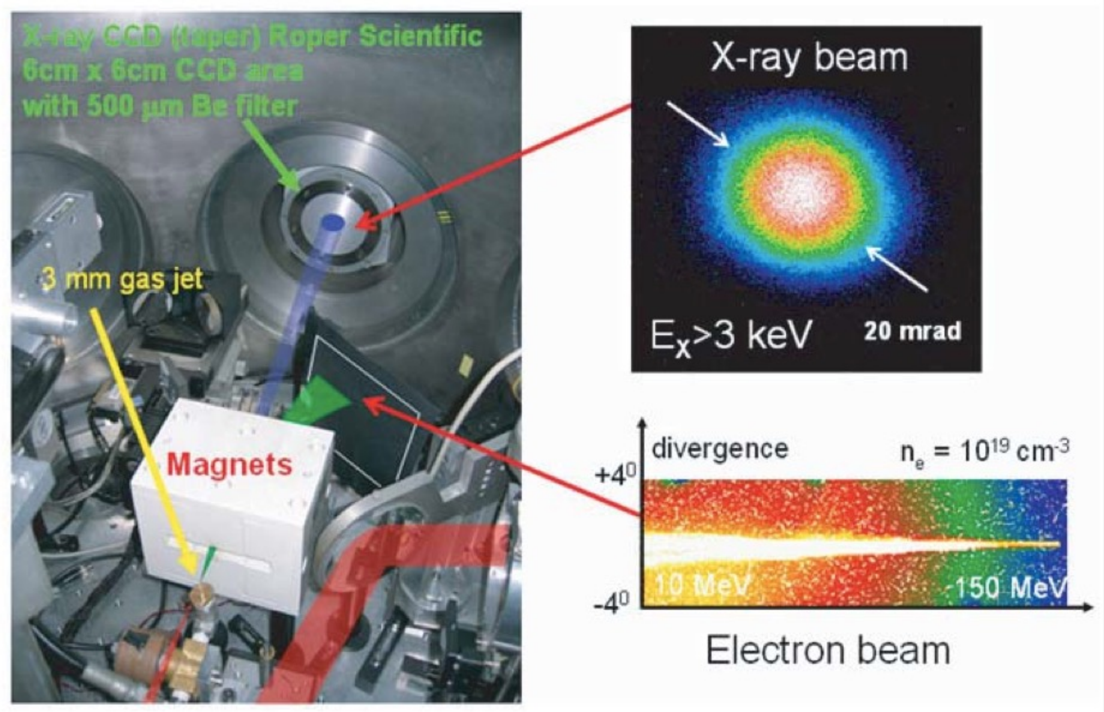
Result is expression for critical energy for x-rays from a LWFA:

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

Typical values for a laser wakefield accelerator:

- $r_\beta \simeq 1$ µm, $\gamma \simeq 2000$, $n_e \simeq 10^{18}$ cm^{-3} → $E_c \simeq$ 10s keV

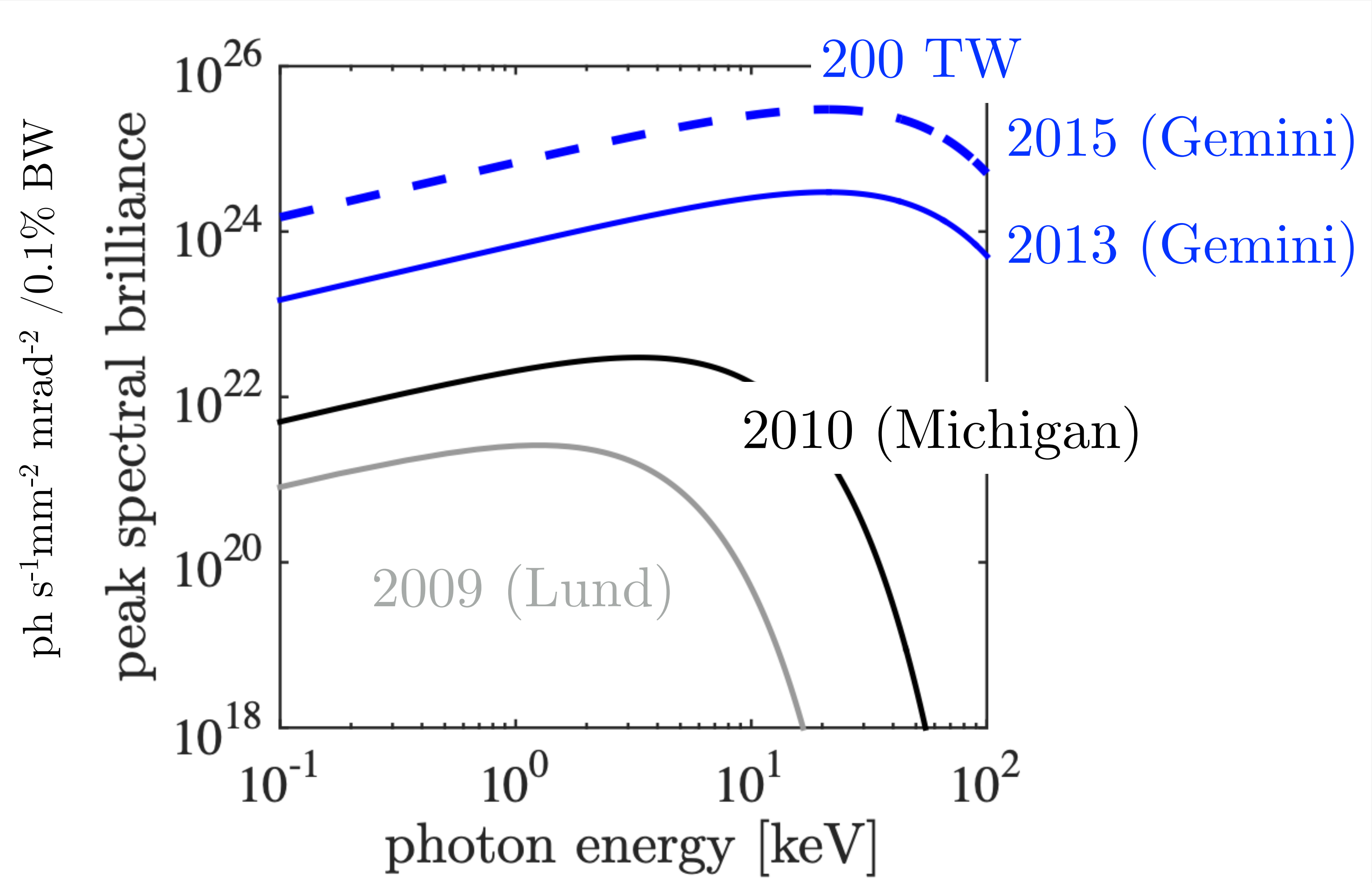
X-rays from a laser wakefield accelerator



First observed by Rousse *et al*. at LOA (PRL 2004)

- 30 TW laser
- broad band ≃100 MeV electrons
- X-ray radiation at ≃1 keV

X-ray energy and brightness scale with electron beam energy



Experiments have rapidly increased X-ray flux and photon energy

Applications of X-rays from Laser Wakefield Accelerators

What properties do X-rays from LWFA have that we can exploit?

Co-location of electron / X-ray source with other high-power lasers

- ns pulses for shock compression
- fs and ps pulses to produce hot / warm dense matter

Natural synchronization of electron / X-ray source with these lasers

- fs synchronization routinely achieved

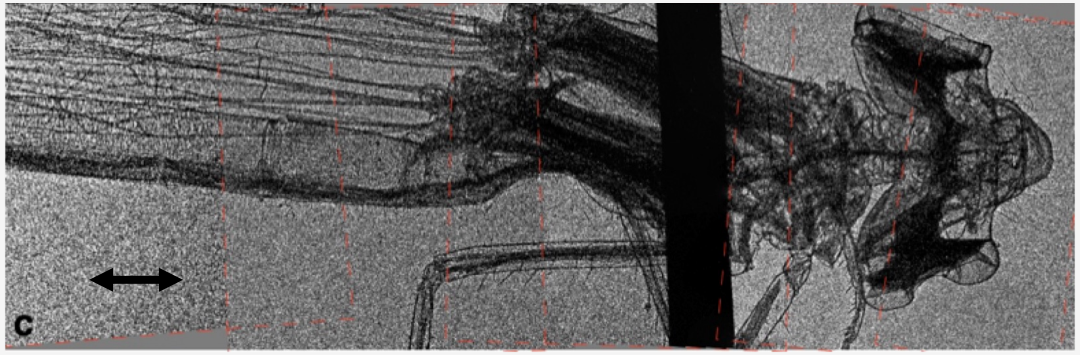
Unique properties of LWFA source

- X-ray source is small (≈1 µm)
- X-rays are both broadband and ultra-fast (≈10s fs)

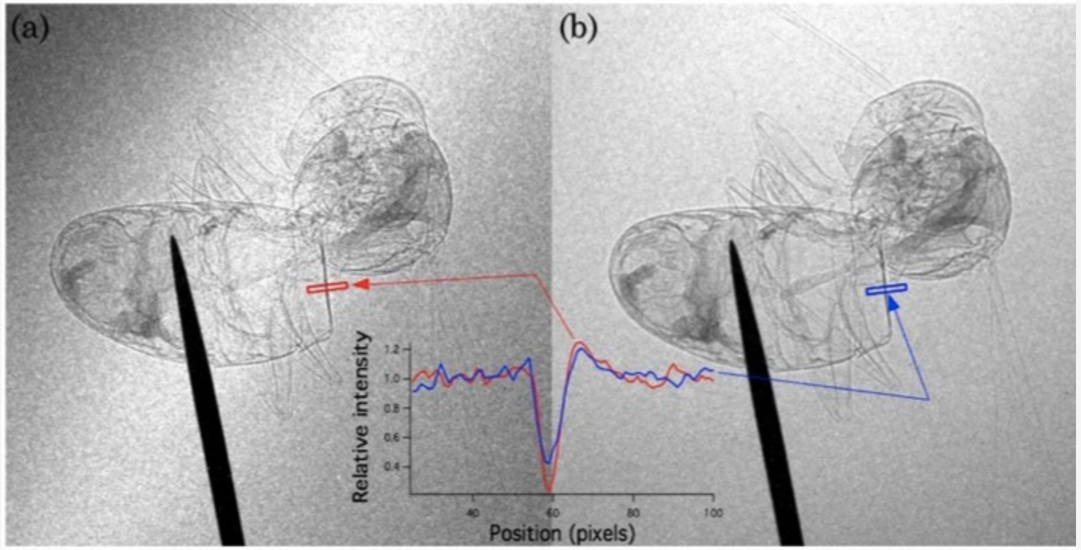
Small Source size good for imaging

high definition, high resolution imaging using phase contrast or absorption contrast

- possible because of the very small source size
- images possible in a single shot (30 fs exposure)

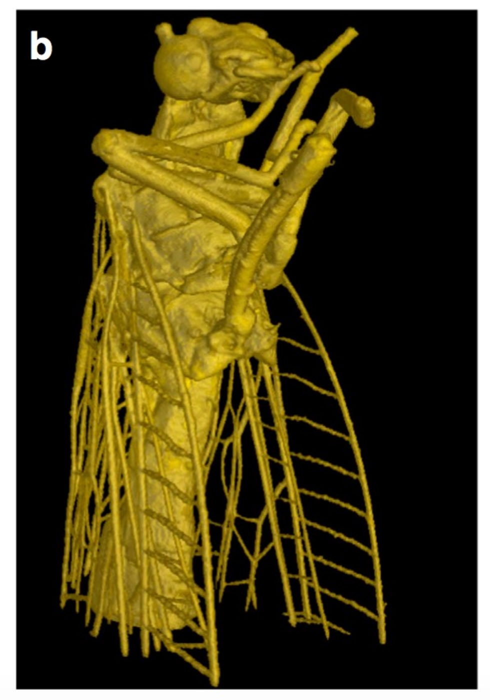


Kneip Applied Physics Letters 2011



Fourmaux Optics Letters 2011

X-rays now stable enough to perform 3D tomography



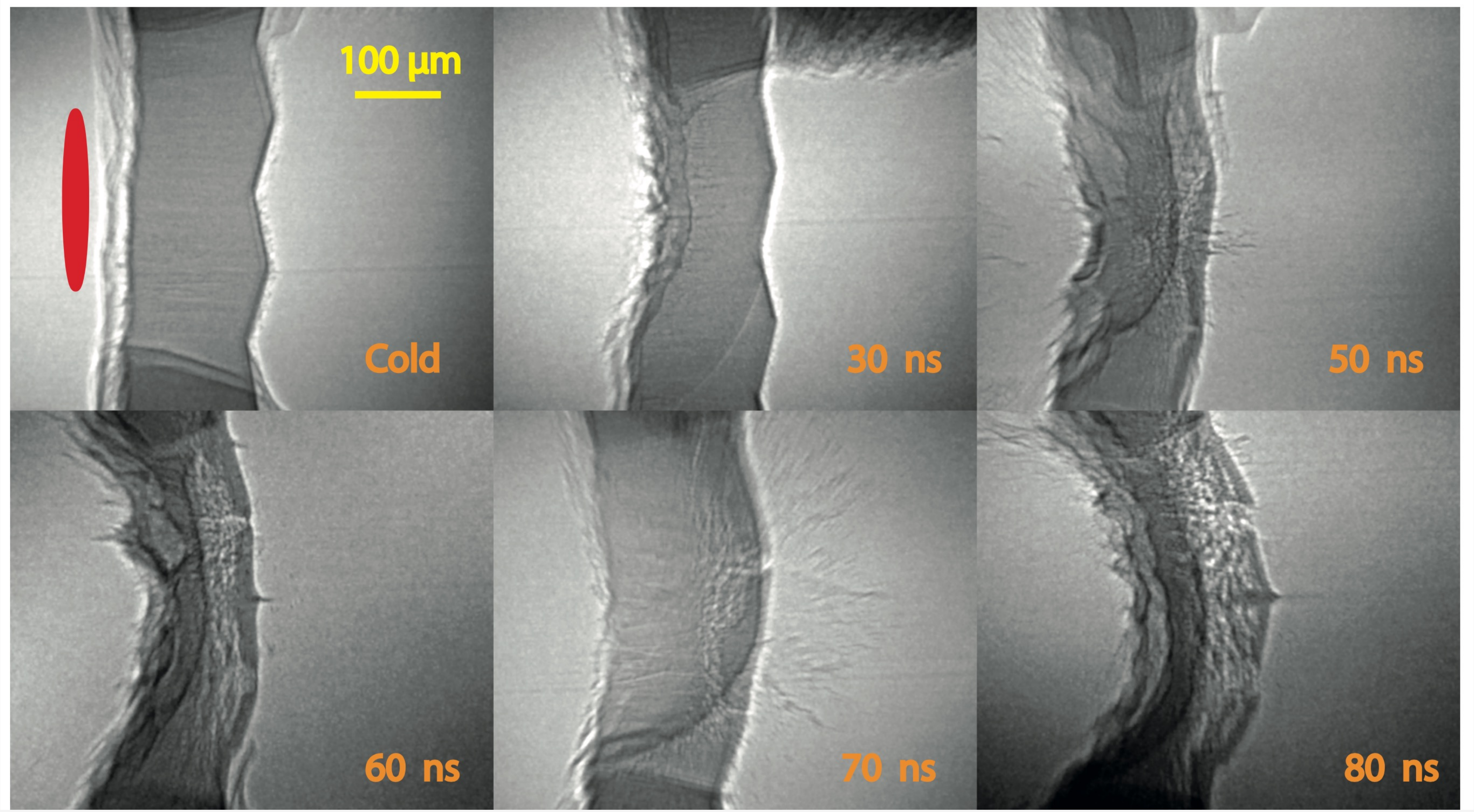
Wenz et al, Nature Comms 2015

Cole et al, Sci. Rep. 2015

- Tomography requires acquisition of 100s images per sample
- LWFA sources already competitive with state of the µCT
- High rep rate LWFA an exciting prospect for rapid tomography scans

Imaging rapidly evolving phenomena:

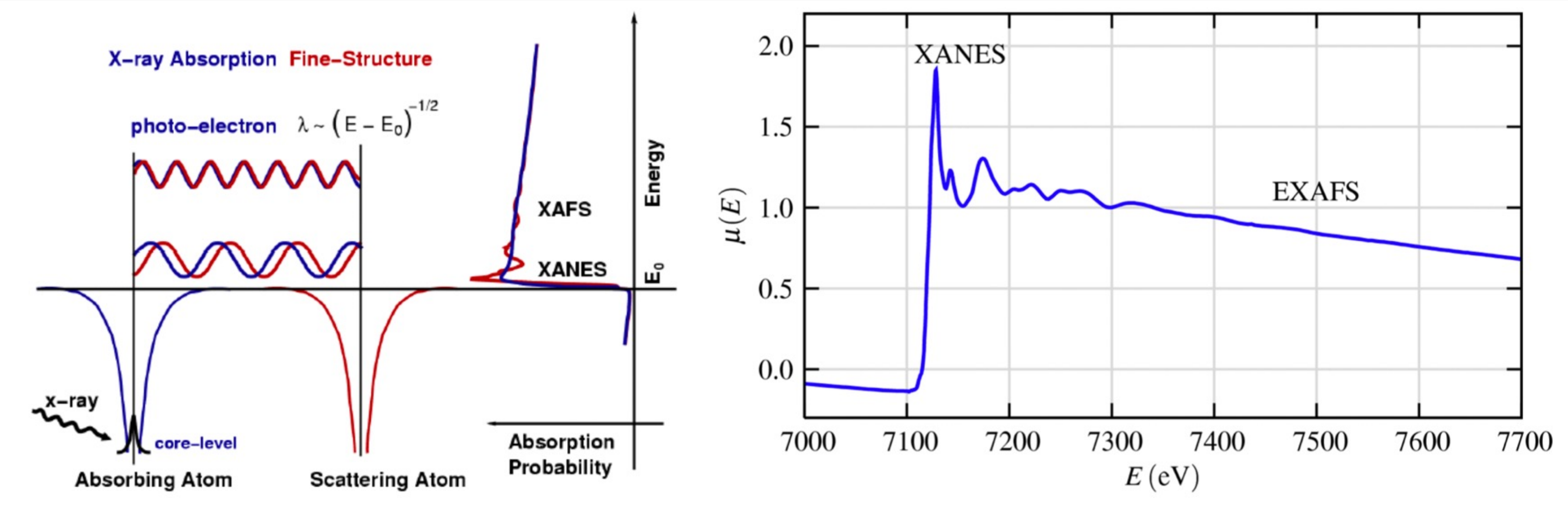
laser driven shocks on Gemini



See J Wood Sci Rep 2018

J Wood PhD Thesis https://doi.org/10.25560/58282

An ultrafast XANES / EXAFS diagnostic based on LWFA?



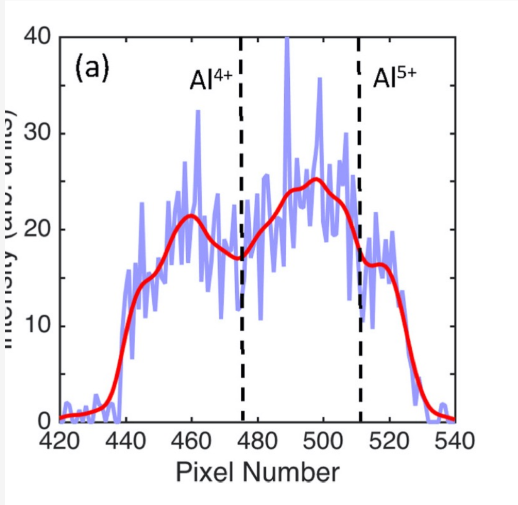
A Practical Introduction to Multiple Scattering Theory, Bruce Ravel, 2005

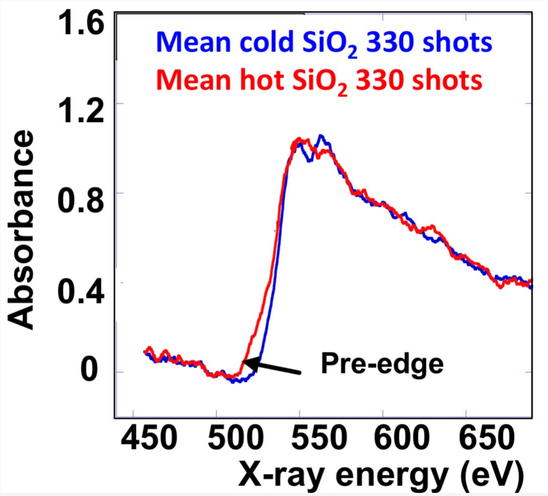
X-ray Absorption Spectroscopy is a powerful technique that provides a wealth of data about the properties of condensed matter

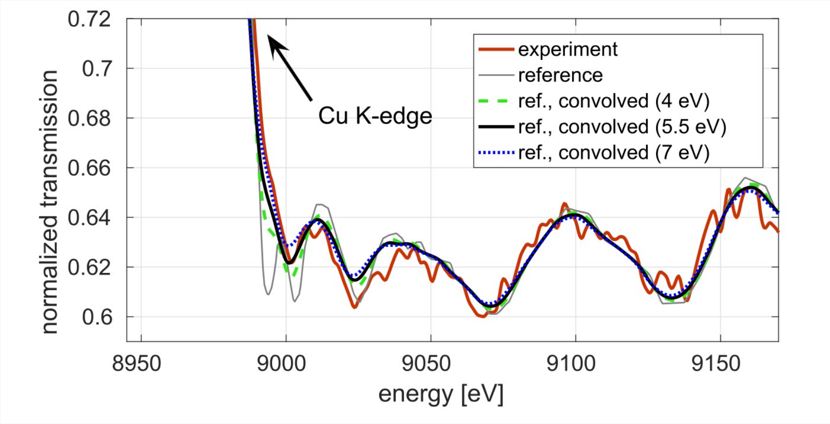
- X-ray is absorbed, produces photo-electron
- If Debroglie wavelength of photo-electron larger than spacing between absorbing atom and nearest neighbours, interference leads to peaks and troughs in absorption

Unique combination of broad spectrum and fs duration makes LWFAs ideal

X-ray absorption spectroscopy using LWFA







Mo PRE 2017
- 80 TW laser pulse
- 150 shots per spectrum

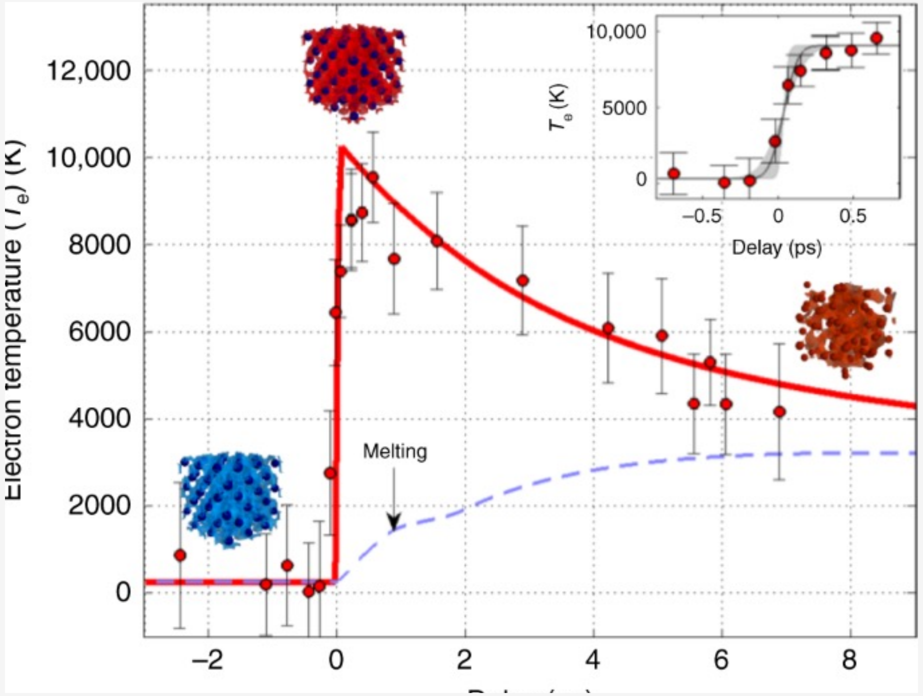
Albert IPAC 2018
- 20 TW laser pulse
- 300 shots per spectrum

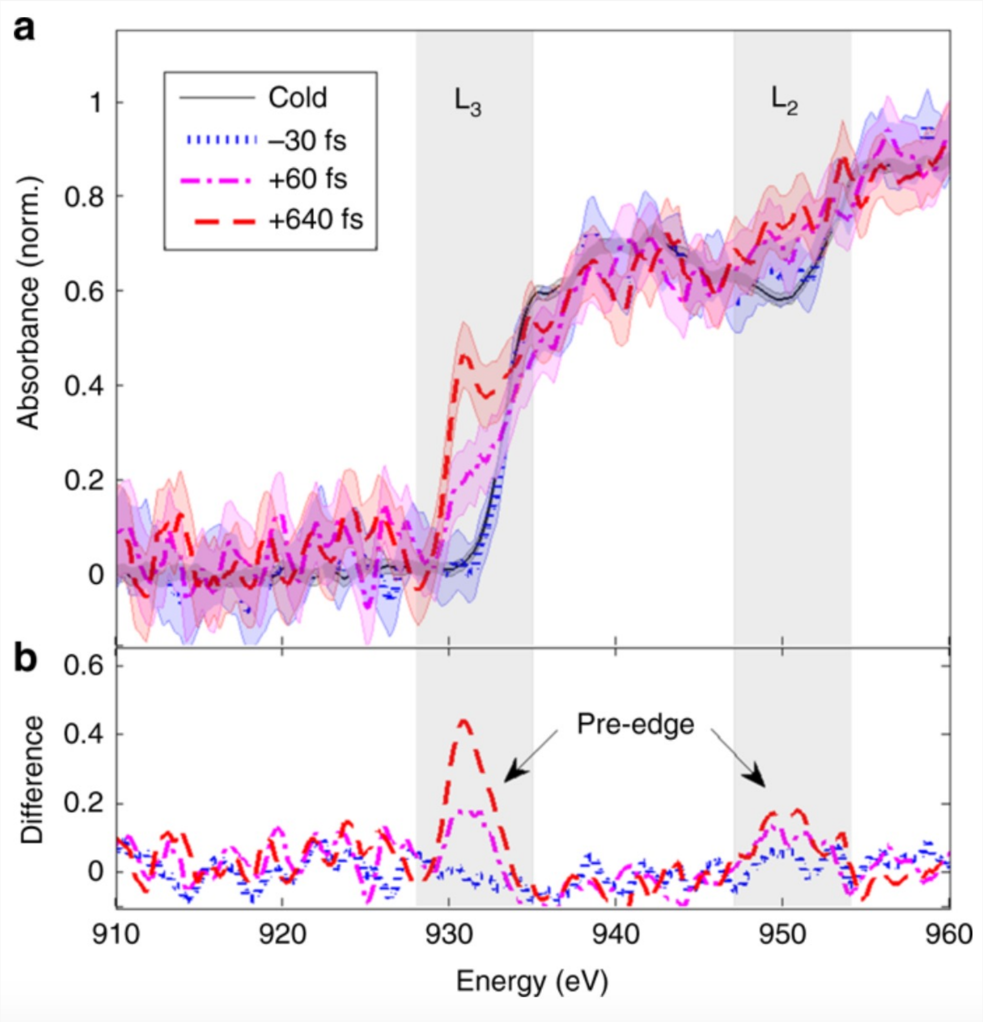
Smid Rev Sci Inst 2017
- 20 TW laser
- 150 shots per spectrum

X-ray absorption spectroscopy using LWFA

Mahieu Nat Comms 2018

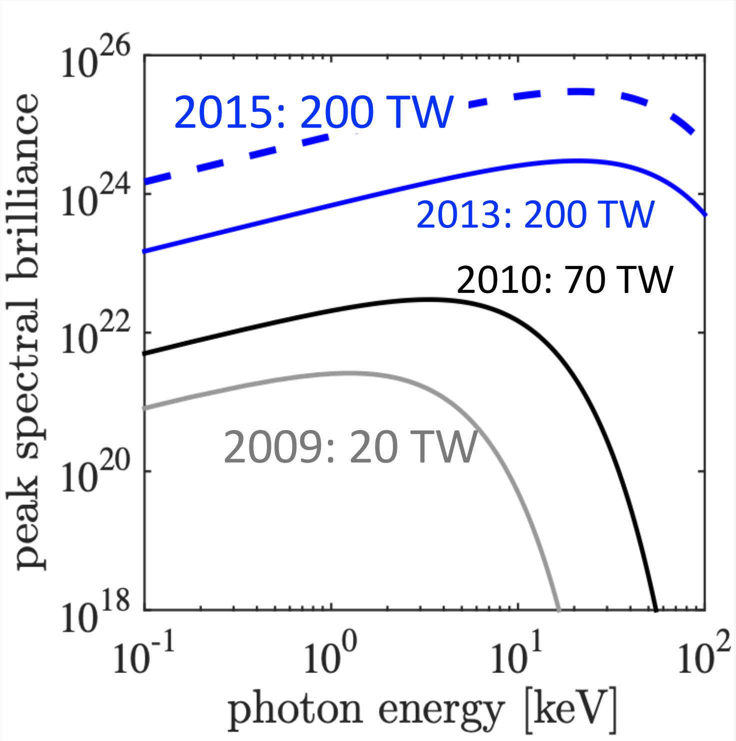
- 50 TW laser
- 50 shots per spectrum

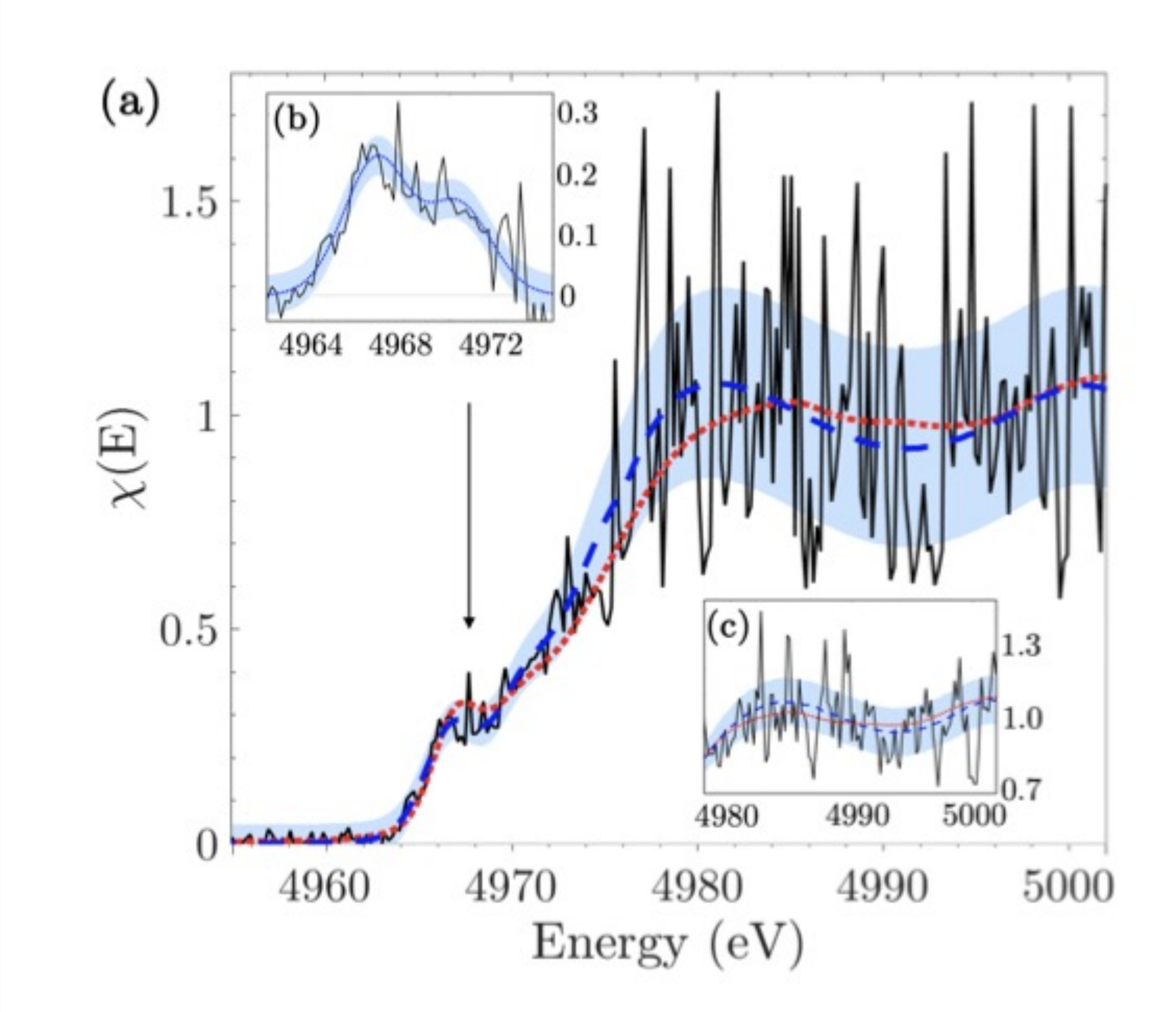




Single shot X-ray absorption spectroscopy

Single shot XANES

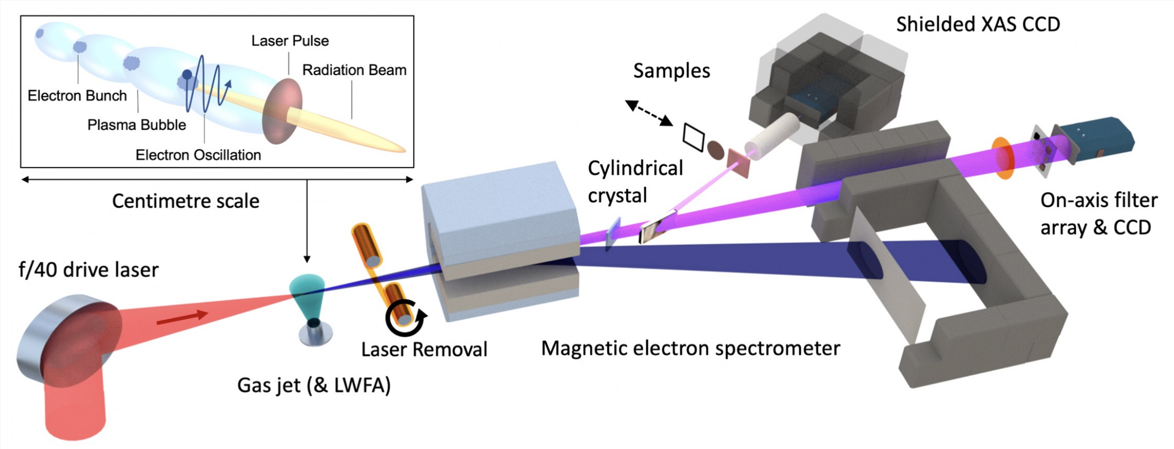


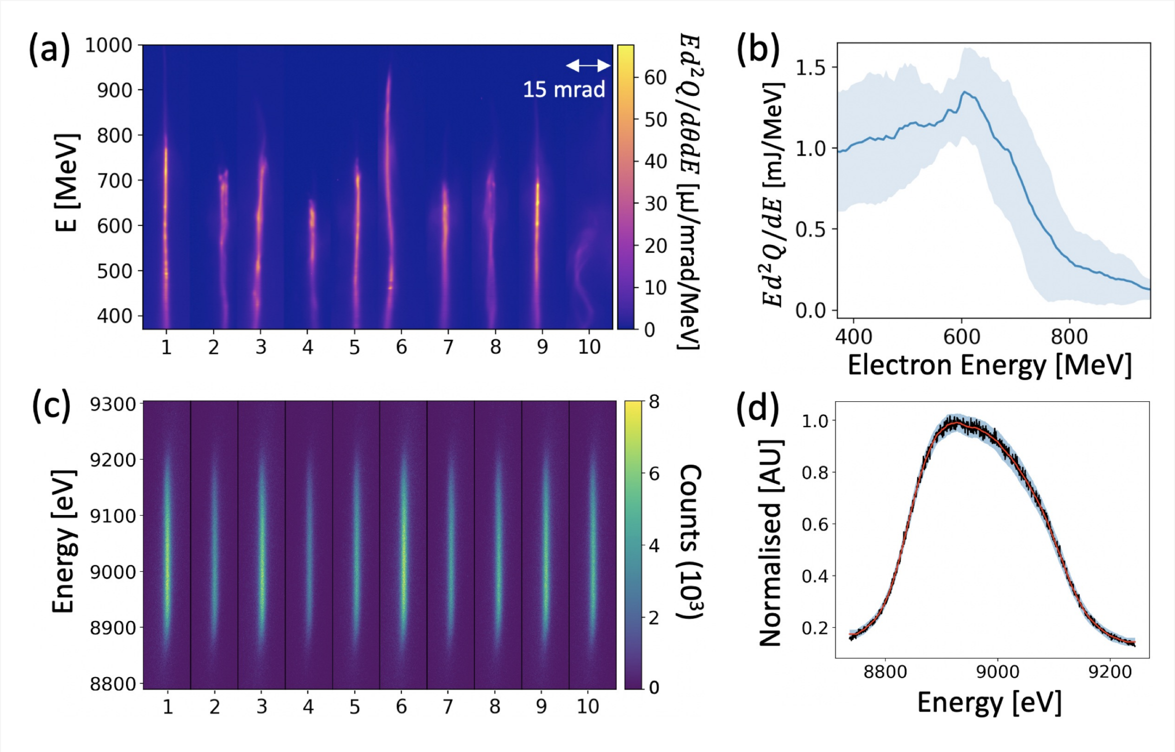


Kettle PRL 2019

- 250 TW laser pulse
- Single shot XANES

Single shot X-ray absorption spectroscopy





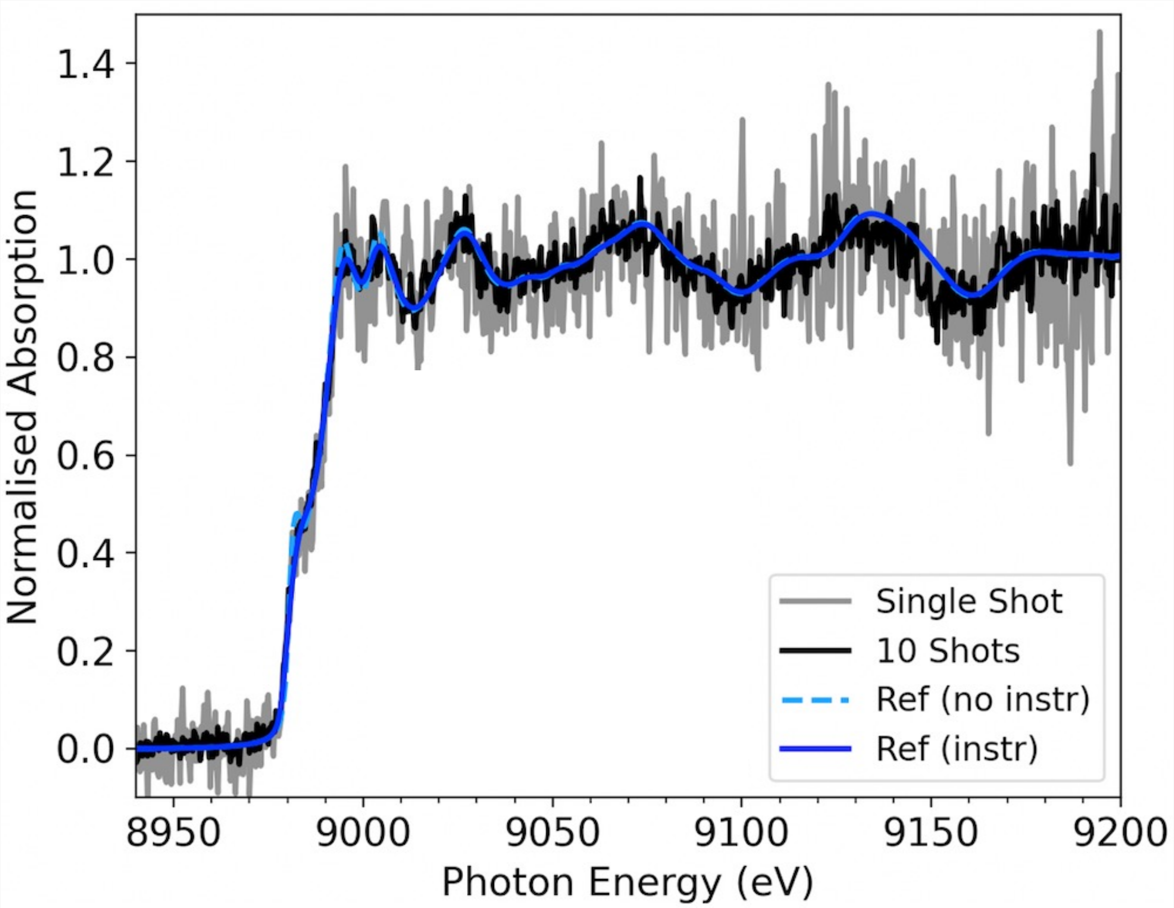
Kettle 2023 arXiv:2305.10123

- New geometry to improve signal:noise
- Stable x-rays (despite electron beam fluctuations)

Single shot X-ray absorption spectroscopy
Single shot EXAFS and XANES

Kettle 2023 arXiv:2305.10123

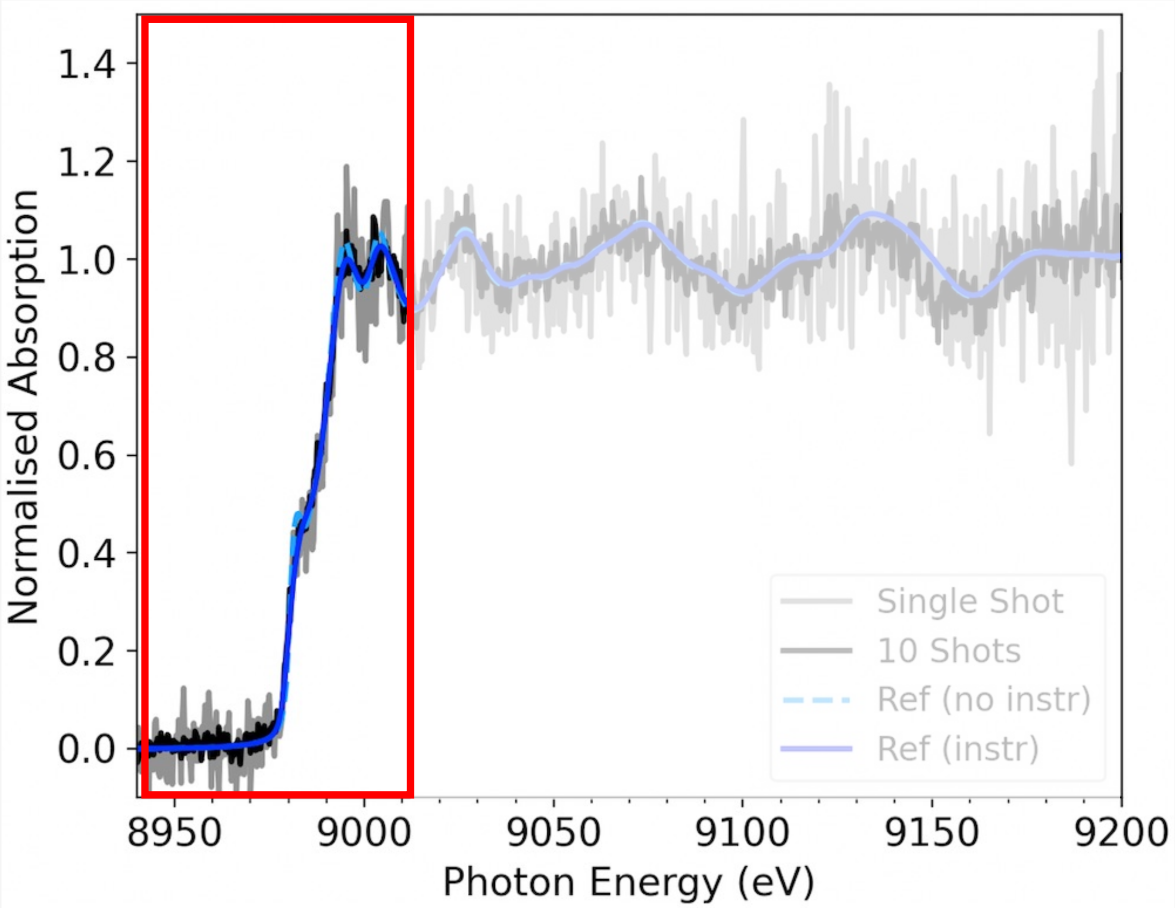
- 250 TW laser pulse
- Single shot XANES ***and*** EXAFS



Single shot X-ray absorption spectroscopy
Single shot EXAFS and XANES

Near edge

- information about the electrons (XANES)
  - electron distribution function, density of states, electron temperature

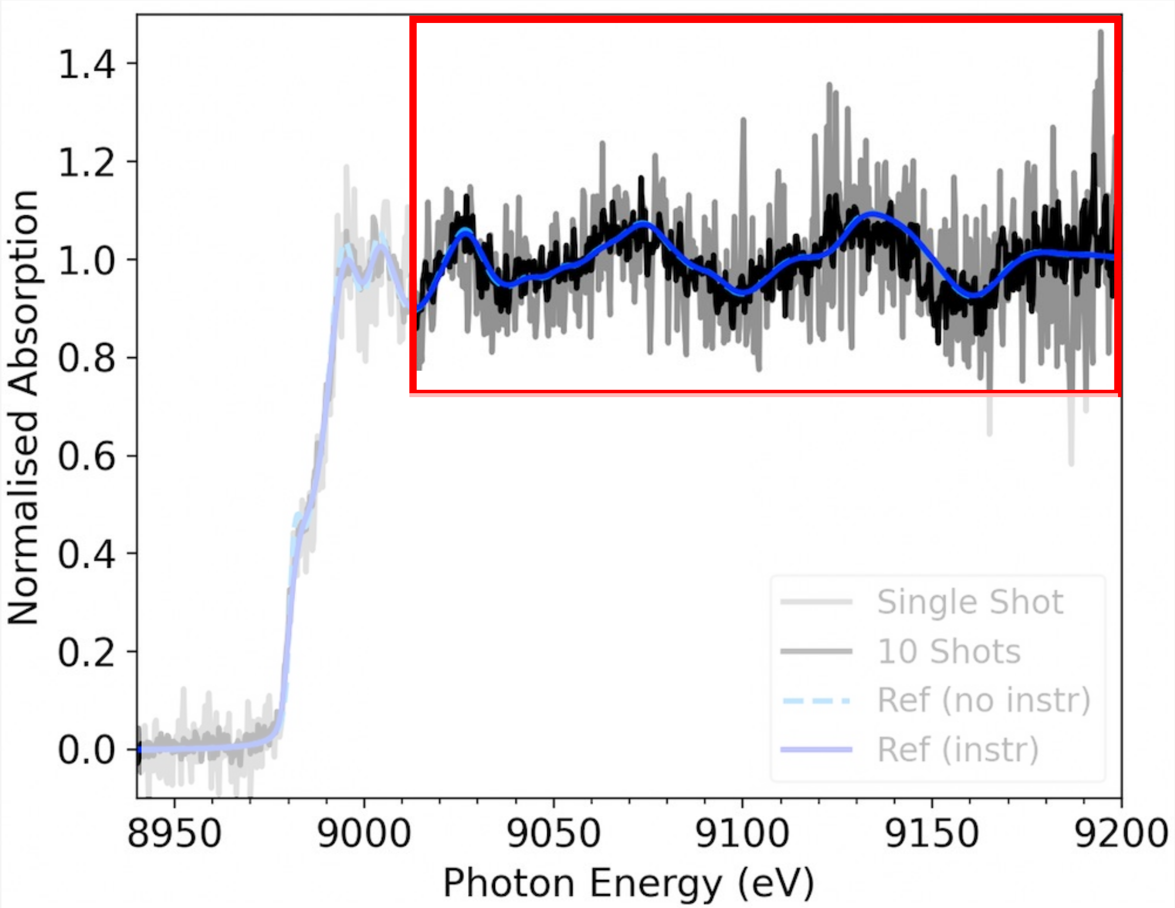


Single shot X-ray absorption spectroscopy

Single shot EXAFS and XANES

Next to the edge

- information about the ions
- Ionic structure, ion temperature

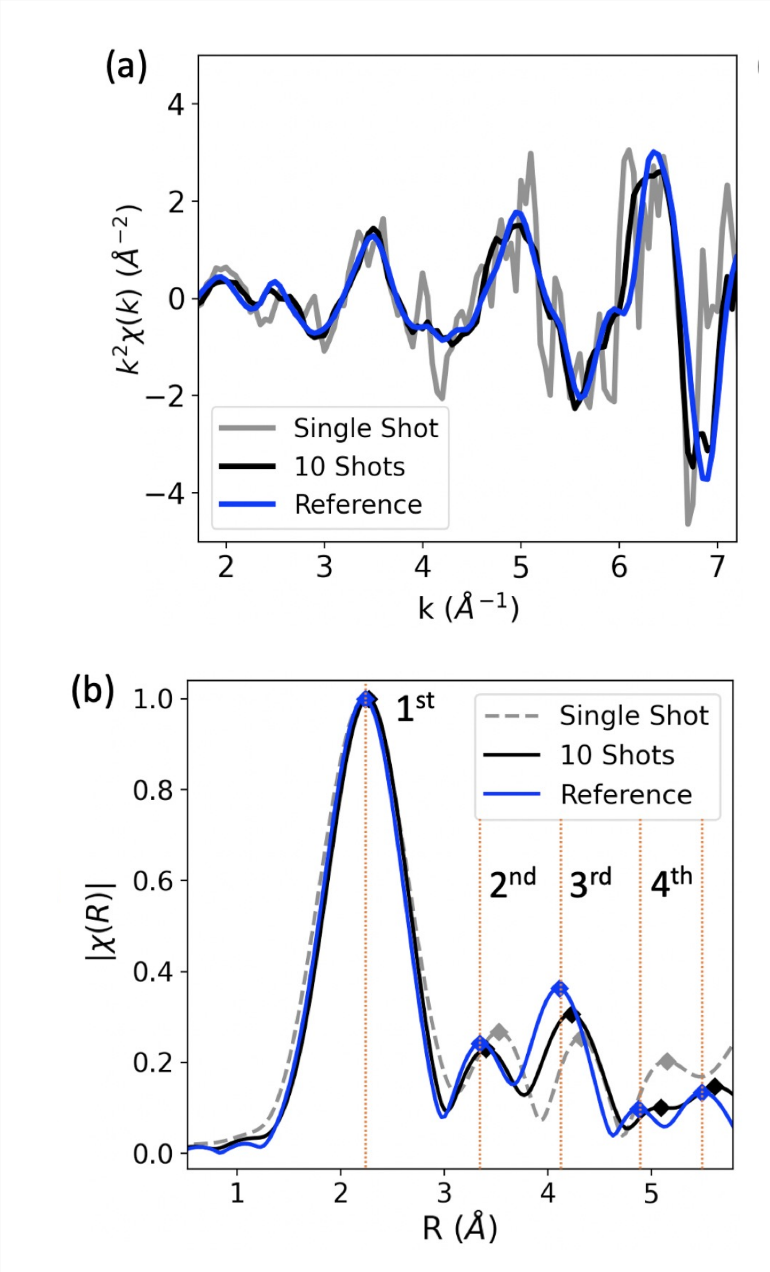


Single shot X-ray absorption spectroscopy
Single shot EXAFS and XANES

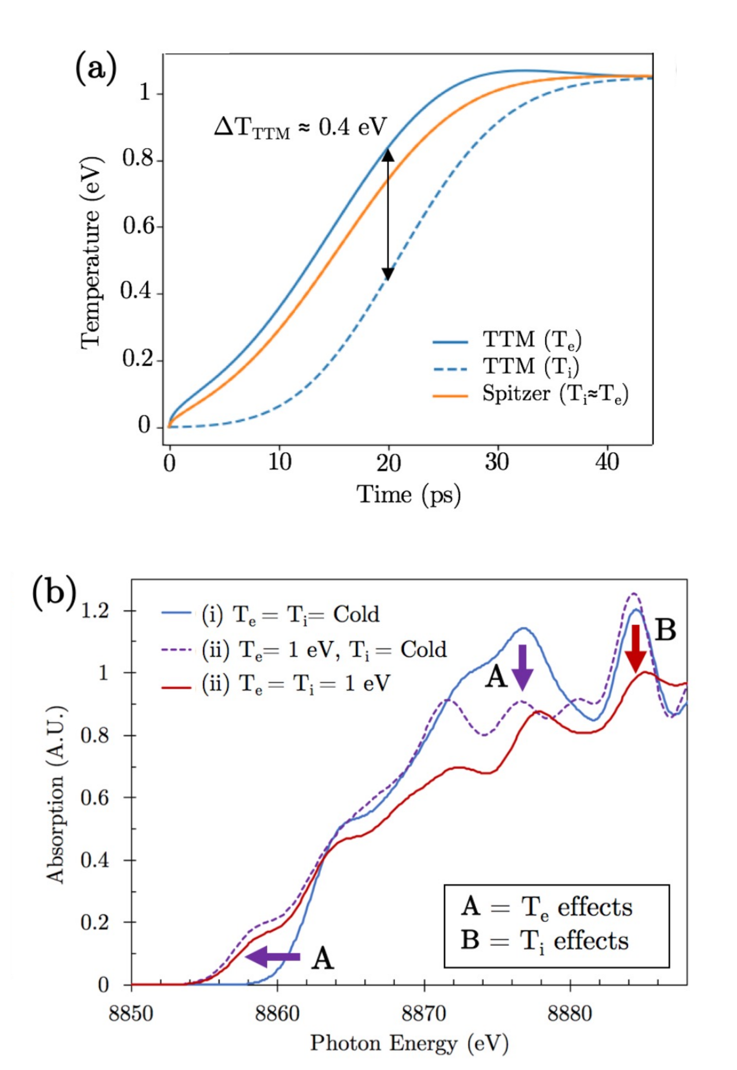
Next to the edge

- information about the ions
- Ionic structure, ion temperature

- Here we show measurement of position of first four nearest neighbours (coordination shells)
  - Single shot accuracy of 1.5% (shells 1) and 5% (shells 2 – 4)



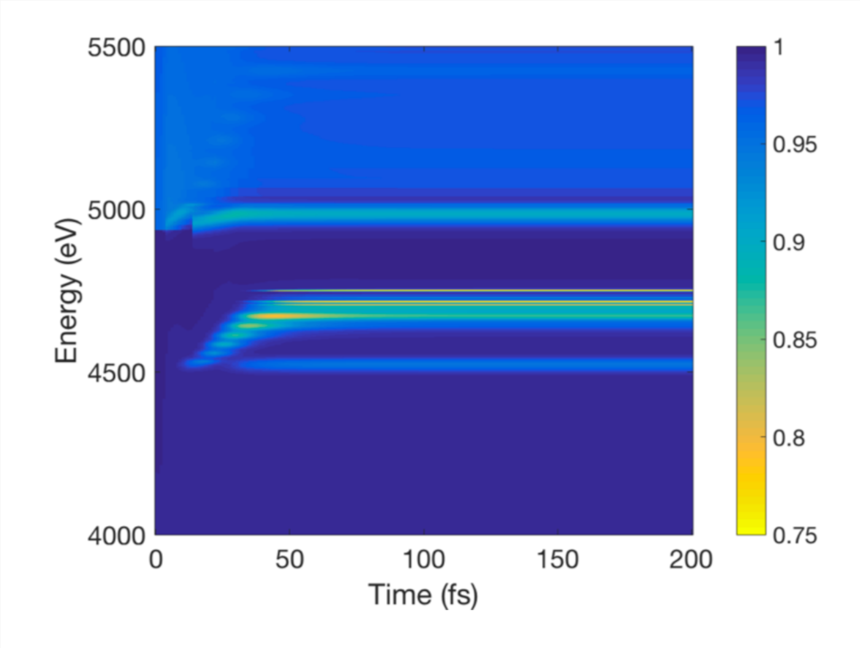
What's next?
Pump Probe Experiments



Pump-probe experiment to measure rate of heat flow between ions in warm dense matter

- warm dense matter created by picosecond x-ray heating (picosecond laser drive)
- investigate coupling between ions and electrons
  - Ion density fluctuations – phonons
  - Ion charge fluctuations (see Baggott PRL 2021)

What’s next?
Pump Probe Experiments



Pump-probe experiment to measure rate of ionization in hot dense plasma

- Hot dense plasma created by fast electron heating (femtosecond laser drive)
  - Measure change in opacity on route to equilibrium: testing NLTE codes
  - Time-resolved measurements of plasma opacity in conditions relevant to solar interior

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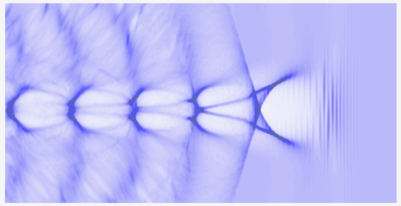
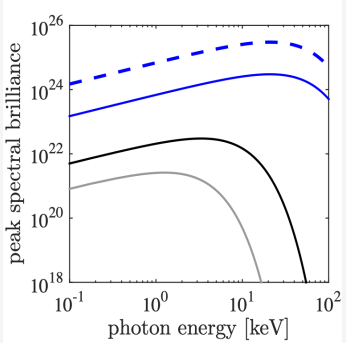
Summary:

1 Intro to laser wakefield accelerators



- GeV electron beams
- femtosecond beam

2 Basic concepts of X-ray generation

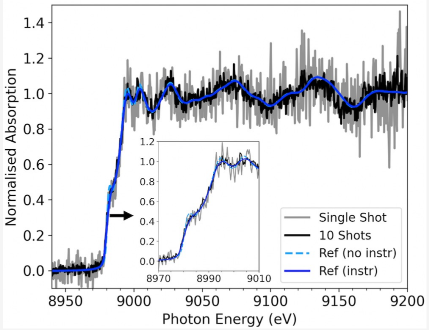


- synchrotron radiation
- wigglers, undulators and FELs

3 Synchrotron radiation from Laser Wakefield Accelerators

- betatron oscillations
- femtosecond, broadband x-rays

4 Applications of X-rays from Laser Wakefield Accelerators



- ultrafast imaging
- ultrafast XAS

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Thank you

LWFA: Tools for Time-Resolved X-Ray Imaging and Spectroscopy
23/04/2024

stuart.mangles@imperial.ac.uk