Laser Wakefield Accelerators: Tools for Time-Resolved X-Ray Imaging and Spectroscopy

Stuart Mangles
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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

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

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
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
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.
X-ray Generation Mechanisms

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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 \(|\beta| \to 1\): radiation is generated by bending the beam
- For constant circular motion (radius \(R\)) the expression is simpler

\[
P = \frac{q^2}{6\pi \varepsilon_0 m^2 c^3} \gamma^6 \left[ (\dot{\beta})^2 - (\beta \times \dot{\beta})^2 \right]
\]

\[
P = \frac{e^2 c}{6\pi \varepsilon_0} \frac{\beta^4 \gamma^4}{R^2}
\]

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, $\gamma$
- 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 $\gamma$ and small $R$
Synchrotron Radiation Spectrum

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

Radiation “on-axis”

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

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

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

Fuchs Nature Phys 2009
Schlenvoigt Nature Phys 2008
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 $n_e = 10^{19} \text{ cm}^{-3}$ and 200 MeV electrons this is 300 µm

\[
\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}} \quad \lambda_\beta = \sqrt{2\gamma} \frac{c}{\omega_p}
\]
Energy of X-rays from a Laser Wakefield Accelerator

Energy of X-rays in synchrotron:

\[ E_c = \frac{3}{2} \frac{\hbar c \gamma^3}{R} \]

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

\[ R \approx \frac{1}{(k^2 \beta r_\beta)} \quad \omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}} \]

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

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

Typical values for a laser wakefield accelerator:

- \( r_\beta \approx 1 \mu m, \ \gamma \approx 2000, \ n_e \approx 10^{18} \text{ cm}^{-3} \Rightarrow E_c \approx 10^9 \text{ keV} \)
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)
X-rays now stable enough to perform 3D tomography

- 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

Wenz et al, Nature Comms 2015
Imaging rapidly evolving phenomena: laser driven shocks on Gemini

See J Wood Sci Rep 2018

https://doi.org/10.25560/58282
An ultrafast XANES / EXAFS diagnostic based on LWFA?

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

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

![Graph showing normalized absorption vs photon energy]
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
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
Thank you