X-ray light sources driven by laser plasma accelerators for high energy density science experiments

Félicie Albert, PhD
Physicist
Deputy Director, LLNL High Energy Density Science center
Collaborators


**M. Sinclair**, K.A. Marsh, C.E. Clayton, and C. Joshi (UCLA)

E. Galtier, P. Heimann, E. Granados, H. J. Lee, B. Nagler, A. Fry (LCLS)

W. Schumaker, F. Fiuza, E. Gamboa, L. Fletcher, S.H Glenzer (SLAC)

**P. M. King, I. Pagano**, M. C. Downer, B. M. Hegelich (UT Austin)

A. Ravasio, F. Condamine, M. Koenig (LULI)

A.G.R. Thomas, C. Kuranz

B. Barbrel, J. Gaudin, F. Dorchies (CELIA)


D. Kraus, R.W. Falcone, C. Geddes (UCB/LBNL)

P. Zeitoun (LOA)

**J. L. Shaw**, D. H. Froula (LLE)
Outline

- X-rays: a powerful tool for high energy density science experiments
- Using high power lasers to generate laser plasma accelerators and x-rays
- Two applications of x-rays from laser plasma accelerators
  - Imaging complex high energy density science experiments
  - Understanding electron-ion equilibration in warm dense matter
- Conclusion
At LLNL we use the National Ignition Facility (NIF) and concentrate its 192 beams into a mm$^3$. 
Such experiments create extreme, transient conditions of temperature and pressure that are hard to diagnose.

- Temperature: 100 million degrees
- Density: 20x the density of lead
Many High Energy Density Science experiments rely on x-ray backlighters with unique properties

X-ray sources for HEDS experiments

- Radiography, X-ray diffraction
  - Barrios et al, HEDP 9, 626 (2013)

- X-ray absorption spectroscopy
  - Ping et al 84, RSI 123105 (2013)

- X-ray opacity

  - Jarrott et al, POP 21 031201 (2014)
Many High Energy Density Science experiments rely on x-ray backlighters with unique properties

X-ray sources for HEDS experiments

- Radiography, X-ray diffraction
- X-ray absorption spectroscopy
- X-ray opacity

- Sandia Z – 3 ns
- Broadband emission OMEGA – 100 ps
- NIF – 1 ns
- Bremsstrahlung Titan – 10 ps

Barrios et al, HEDP 9, 626 (2013)
Ping et al 84, RSI 123105 (2013)
Jarrott et al, POP 21 031201 (2014)

This work – x-rays driven by laser wakefield acceleration
Unique properties of sources driven by LWFA can enable applications

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Drive laser: Target

X-ray probe
X-ray sources with MeV photons and <10 µm resolution are required to understand some of the experiments done at the NIF.

Double shell implosion, 1800 g/cc

0.2 MeV radiography

1 MeV radiography

Fully imploded capsule
We use "pump-probe" experiments and x-ray measurement techniques to understand these conditions.
We use "pump-probe" experiments and x-ray measurement techniques to understand these conditions.
4th generation x-ray light sources used for scientific applications could be used but are billion dollar-scale national facilities

X-ray free electron laser: LCLS

Synchrotron: APS

3 km

Argonne Nat. Lab., IL

SLAC, CA
Laser plasma accelerators offer a compact alternative to these big machines

X-ray free electron laser: LCLS

Accelerating electrical field is 1000 times stronger than in a regular accelerator
Using high power lasers to generate laser plasma accelerators and x-rays
An intense laser pulses drives electron plasma waves.

Wake behind a boat

Plasma wave behind a laser

60 µm

Nuno Lemos, LLNL
Laser-produced plasmas can naturally sustain large acceleration gradients which makes laser plasma accelerators 1000 x smaller

\[ E_0 = \frac{mc\omega_p}{e} \]

\[ \omega_p = \sqrt{\frac{n_e e^2}{me \varepsilon_0}} \]

\[ n_e = 10^{18} \text{ cm}^{-3} \rightarrow E_0 = 96 \text{ GV/m} \]
Laser pulse

Trapped Electron

Electron plasma wave

Betatron X-ray beam

Laser wakefield acceleration can produce x-rays using several processes

1. **Betatron x-ray radiation**

   - ![Diagram of Betatron x-ray radiation]
   - Formula: $E_x \sim \gamma^2 n_e r_0$
   - Units: keV

2. **Compton scattering**

   - ![Diagram of Compton scattering]
   - Formula: $E_x \sim 4\gamma^2 E_L$
   - Units: keV - MeV

3. **Bremsstrahlung**

   - ![Diagram of Bremsstrahlung]
   - Formula: $E_x \sim \gamma$
   - Units: MeV
Most of these sources are typically produced with ultrashort laser pulses in the blowout regime \( (c\tau \sim \lambda_p/2) \)

Condition to be in the blowout regime \( c\tau \sim 1/n_e^{1/2} \)  

30 fs \( n_e \sim 10^{19} \text{ cm}^{-3} \)
Self modulated laser wakefield acceleration is easier to achieve with picosecond scale lasers ($c\tau >> \lambda_p$).

Condition to be in the self-modulated regime $c\tau >> 1/n_e^{1/2}$.

$\lambda_p = c/\omega_p \sim 1/n_e^{1/2}$

$1 \text{ ps } n_e \sim 10^{19} \text{ cm}^{-3}$
High charge, relativistic electron beams are accelerated through self-modulated laser wakefield acceleration

1. Creation of an electron plasma wave (EPW)
2. Raman forward and self-modulation instabilities
3. Wave breaking traps electrons in EPW potential

Laser pulse envelope

Laser pulse envelope

- Laser $I > 10^{18}$ W/cm²
- Gas $n_e \sim 10^{19}$ cm⁻³
- Nozzle

Electron plasma wave

- $\lambda_p = c/\omega_p \sim 1/n_e^{1/2}$
- $\lambda_p = 10 \mu$m

Wave breaking traps electrons in EPW potential

$\omega_0 = \omega_s +/\- m\omega_p$

$k_0 = k_s +/\- m k_p$

Laser pulse envelope

Electron plasma wave

Electron density

Electron plasma wave

Electron density

Electron plasma wave

Electron density

Electron plasma wave

Electron density

Electron plasma wave

Electron density
Imaging complex high energy density science experiments
Our project is developing laser plasma accelerators on large kJ-class picosecond lasers.

- **Titan, LLNL**
  - SMLWFA electrons
  - Betatron radiation

- **OMEGA-EP, LLE**
  - Compton scattering/Bremsstahlung

- **NIF – ARC, LLNL**
  - Radiography

- **LMJ – PETAL, CEA**
  - X-ray sources

2015: Titan, LLNL (SMLWFA electrons, Betatron radiation)

2016: Titan, LLNL (Compton scattering/Bremsstahlung)

2017: Titan, LLNL (Radiography)

2018: OMEGA-EP, LLE (SMLWFA electrons)

2019: OMEGA-EP, LLE (X-ray sources)

2020: NIF - ARC, LLNL (SMLWFA electrons)

2021: LMJ – PETAL, CEA (X-ray sources)

NIF – ARC, LLNL (SMLWFA electrons)

LMJ – PETAL, CEA (SMLWFA electrons)
Laser wakefield – betatron experiments – Titan LLNL

self-modulated regime

Titan Laser
150 J
0.7 ps

Target
3 mm He jet
$n_e = 10^{19} \text{ cm}^{-3}$

86% in 28 µm
$I = 5 \times 10^{18} \text{ W/cm}^2$
We have developed a platform to produce x-rays in the self modulated laser wakefield acceleration regime.

Electrons accelerated in the SMLWFA regime produce betatron x-rays
Electrons accelerated in the SMLWFA regime produce betatron x-rays

\[ \frac{d^2 I}{dE d\Omega} \propto \left( \frac{E}{E_c} \right)^2 K_{2/3}^2 \left[ \frac{E}{E_c} \right] \]

\( Ec = 20 \text{ keV} \)

\( \text{Yield} \text{ [Normalized]} \)

Filter
Electrons accelerated in the SMLWFA regime produce betatron x-rays

\[
\frac{d^2 I}{dE d\Omega} \propto \left( \frac{E}{E_c} \right)^2 K_{2/3}^2 [E/E_c]
\]
Electrons accelerated in the SMLWFA regime produce betatron x-rays

\[
\frac{d^2I}{dEd\Omega} \propto \left(\frac{E}{E_c}\right)^2 K_{2/3}\left[E/E_c\right]
\]

---

P.M. King et al, RSI (2019)
Electrons accelerated in the SMLWFA regime produce betatron x-rays

Best fit for $E_c = 10$ keV +/- 2 keV (least squares fit) – $10^9$ photons/eV/Sr
Betatron x-rays have critical energies of 10-40 keV

\[ E_c = 10 \text{ keV} \]

\[ E_c = 40 \text{ keV} \]

Measured/calculated x-ray spectrum

Optimized betatron radiation produces the most photons for energies <40 keV

\[ f(E) \sim \left( \frac{E}{E_c} \right)^2 K_{2/3} \left( \frac{E}{E_c} \right) \]

\[ n_e \sim 10^{19} \text{ cm}^{-3} \]

\[ n_e = 1.5 \times 10^{19} \text{ cm}^{-3} \]

\[ E_{\text{laser}} = 150 \text{ J} \]

\[ a_0 \sim 3 \]

Compton scattering allows for increased photon flux up to a few 100 keV.

Compton scattering

$$f(E) \propto \exp \left( -\frac{E}{T_1} \right) + \exp \left( -\frac{E}{T_2} \right)$$

$$T_1 = 36 \text{ keV (Filter wheel)}$$

$$n_e = 4 \times 10^{18} \text{ cm}^{-3}$$

$$E_{\text{laser}} = 120 \text{ J}$$

$$a_0 \sim 3$$

Ross pairs

N. Lemos et. al, Phys. Plasmas (2019)
Compton scattering allows for increased photon flux up to a few 100 keV

Compton scattering
$f(E) \propto \exp \left[ -\frac{E}{T_1} \right] + \exp \left[ -\frac{E}{T_2} \right]$

$T_2 = 78 \text{ keV (Step wedge)}$

$n_e = 4 \times 10^{18} \text{ cm}^{-3}$

$L_{\text{laser}} = 120 \text{ J}$

$a_0 \sim 3$
LWFA-driven bremsstrahlung produces the most photons at MeV energies

\[ f(E) \propto \exp\left[-\frac{E}{T}\right] \]

\[ T = 838 \text{ keV (Step wedge)} \]

\[ n_e \sim 10^{19} \text{ cm}^{-3} \]

\[ n_e = 4 \times 10^{18} \text{ cm}^{-3} \]

\[ E_{\text{laser}} = 120 \text{ J} \]

\[ a_0 \sim 3 \]
We can control the x-ray flux and energy by combining several processes.
Spectral and flux tuning allows for optimized radiography applications

Half hohlraum – 30 µm Au

W ball, \( r = 400 \mu m \)

W ball areal density
\( \sim 0.7 \text{ g/cm}^2 \)

\begin{align*}
\text{Laser} & \quad \text{Gas} \quad n_e \sim 10^{19} \text{ cm}^3 \\
\text{Nozzle} & \quad T \quad 71 \text{ keV} \\
\text{Laser} & \quad \text{Gas} \quad n_e \sim 10^{19} \text{ cm}^3 \\
\text{Nozzle} & \quad T \quad 331 \text{ keV} \\
\text{Laser} & \quad \text{Gas} \quad n_e \sim 10^{19} \text{ cm}^3 \\
\text{Nozzle} & \quad T \quad 641 \text{ keV}
\end{align*}

Magnification = 3

N. Lemos et al, In preparation
We can reproduce radiographs of test objects using the x-ray ray tracing code HADES.

I. Pagano et al., In preparation
SM-LWFA driven x-ray source shows 1.4x higher radiography SNR for the same conditions

I. Pagano et. al, In preparation

Areal density = 7.6 g/cm²
Understanding electron-ion equilibration in warm dense matter
Betatron x-ray source development at LCLS-MEC

\[ c \tau = \frac{c}{\omega_p} \approx 1/\sqrt{n_e} \]

Blowout regime
Application: detection of nonthermal melting in SiO₂

energy deposition

non-equilibrium structure A

non-equilibrium structure B

thermalized structure B

Non thermal transition

Thermalization

0 10-100fs 10-100ps
Absorption spectroscopy of SiO$_2$ at the O K-edge (535 eV)

- SiO$_2$ 300 K
- Conduction band
- Valence band

- O 2s
- Si 2p
- Si 2s
- O 1s: 535 eV
- Si 1s: 1848.6 eV

Photon Energy [eV] vs. Absorbance
No absorption of x-ray probe photons below O K-edge energy

Betatron photon <535 eV

- SiO\textsubscript{2} 300 K
- Conduction band
- Valence band
- O 2s
- Si 2p
- Si 2s
- O 1s: 535 eV
- Si 1s: 1848.6 eV

Absorbance vs. Photon Energy [eV]

O K-edge
Sharp transition corresponds to strong absorption of x-ray photons for energies above the O K-edge.

Betatron photon >535 eV

- SiO$_2$ 300 K
- Conduction band
- Valence band
- O 2s
- Si 2p
- Si 2s
- O 1s
- Si 1s

Photon Energy [eV]:
- 9 eV
- 535 eV
- 1848.6 eV

Absorbance:
- 0
- 0.2
- 0.4
- 0.6
- 0.8
- 1

O K-edge
Multiphoton absorption causes electrons to cross the bandgap and leave vacancies in the valence band.

Heating
Optical laser
$10^{15}$ W/cm²

SiO$_2$ 10,000 K

Conduction band

Valence band

9 eV

O 2s
Si 2p
Si 2s
O 1s
Si 1s

535 eV

1848.6 eV
1s-valence band transitions are now authorized: strong absorption peak 9 eV below the edge.

- **SiO$_2$ 10,000 K**
- **Conduction band**
- **Valence band**

- **Betatron photon**
- **Heating**
- **Optical laser $10^{15}$ W/cm$^2$**

**Energy Levels:**
- **Si 1s**: 1848.6 eV
- **Si 2s**: 535 eV
- **Si 2p**:
- **O 1s**: 535 eV
- **O 2s**

**Absorbance graph:**
- **O K-edge**
- **Photon Energy [eV]**
- **9 eV**
Defect states also allow absorption within bandgap upon heating, K-edge is broadened and red shifted.
Defect states also allow absorption within bandgap upon heating, K-edge is broadened and red shifted.

Heating
Optical laser
$10^{15}$ W/cm$^2$

Betatron photon

SiO$_2$ 10,000 K

Conduction band

Valence band

O 2s
Si 2p
Si 2s
O 1s

Si 1s 1848.6 eV

535 eV

$<9$ eV

$510$ $520$ $530$ $540$ $550$ $560$

Absorbance

Photon Energy [eV]

Cold

Warm

O K-edge

Heating
Optical laser
$10^{15}$ W/cm$^2$
We have demonstrated the use of betatron x-rays as a tool for absorption spectroscopy.
We have demonstrated the use of betatron x-rays as a tool for absorption spectroscopy.
We have demonstrated betatron x-rays absorption spectroscopy with sub ps resolution

![Diagram of betatron x-ray setup](image)

- Electron spectrometer
- Ellipsoidal mirror
- Pump: $10^{15}$ W/cm$^2$
- 200 nm SiO$_2$
- X-ray CCD

**Cold/warm absorption spectra**

- Integrated spectra hot – average cold (eV)
- Integrated 500 – 545 eV
- Integrated 500 – 535 eV

**Error estimated from cold data**
- 0.8 rms over [500-545] eV
- 0.6 rms over [500-535] eV

**Error**
- Value
  - 0.9553
  - -0.17005
- m1
  - 0.17909
  - 0.68532
- m2
  - NA
  - 2.9108
- Chisq
  - NA
  - 0.95702
- R
  - 0.8086

**Without #568, erf fit gives**
- “t0” = 0.0 ± 0.1 ps (good sync.)
- temp. res. = 0.68 ± 0.18 ps
  - (0.48 ± 0.13 ps rms)
  - (1.13 ± 0.30 ps FWHM)
We still have a lot of ongoing exciting projects

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<th>keV-MeV sources and applications</th>
<th>Platform development on larger HEDS lasers</th>
<th>LaserNetUS experiments using betatron source</th>
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<td><img src="image1" alt="Image" /></td>
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- Role of Direct Laser Acceleration in Self-modulated LWFA*
- 3D OSIRIS PIC simulations confirm observation (UCLA collaboration)

*P.M. King et al, PRAB (2021)

- Betatron, Bremsstrahlung, Compton sources for radiography applications
- LaserNetUS experiment at Texas Petawatt on radiography

N. Lemos (in prep)
2 new students: B. Pagano (UT Austin) and A. Aghedo (FAMU)

- 150 MeV, 700 nC beams at OMEGA EP*

W-NEPPS
- 150 MeV > μC at NIF- ARC
- Development of new targets and diagnostics


- Study of warm dense iron with XANES
- Phase contrast imaging of laser-driven shocks in water

*M. Berboucha, E. Galtier et al
**C. Kuranz et al
Conclusions and future work

- We have demonstrated the production of novel x-ray sources from laser-plasma accelerators on several laser facilities

- They are broadband (keV - MeV), ultrafast (fs - ps), small source size (µm), collimated (mrad), synchronized with drive laser

- They enable new applications
  - Study of ultrafast non-thermal melting in SiO2
  - Radiography of dense objects
  - Phase contrast imaging of laser-driven shocks and hydrodynamic instabilities
  - Study of opacity in HED matter

- Future work and challenges
  - Improving sources stability and flux
  - Applications from proof-of-principle to practical
  - LWFA sources as probes for HED science experiments, single shot and rep-rate

References:

N. Lemos et al, PPCF 58 034108 (2016)
F. Albert et al, PRL 118 134801 (2017)
F. Albert et al, POP 25 056706 (2018)
N. Lemos et al, PPCF 60, 054008 (2018)
F. Albert et al, Nuclear Fusion, 59, 032003 (2019)
P. M. King et al, PRAB, 24, 011302 (2021)
N. Lemos et al, PRL (in preparation)
Access to this type of research will be facilitated by networks.

Founded 2018