X-ray sources from laser-plasma acceleration: development and applications for high energy density sciences

HEDS Center Seminar

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LLNL
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X-ray sources are widely used to probe high energy density science experiments

**X-ray sources – Picosecond phenomena**

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

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

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

- X-ray opacity

Jarrott et al, POP 21 031201 (2014)
We are developing x-ray sources based on laser-plasma acceleration to fill a gap in HED science

X-ray sources – Picosecond phenomena

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

Photon energy [keV]

Photons/eV/Sr/ps

10^13
10^11
10^9
10^7
10^5
10^3
10^1
1
2
5
10
20
50
100

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

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

  - X-ray opacity

Jarrott et al, POP 21 031201 (2014)

Albert et al, PRL 118, 134801 (2017)
Albert et al, PRL 111, 235004 (2013)
Lemos et al, PPCF 58 034108 (2016)
Lemos et al, PRL (in review)
Outline

- Laser-plasma acceleration: an alternative for high brightness x-ray sources
- Self modulated and blowout laser-wakefield acceleration regimes for high brightness x-ray source development
- X-ray source development at LLNL and applications
- Betatron x-ray source development at LCLS and applications
- Conclusion and perspectives
Outline

- Laser-plasma acceleration: an alternative for high brightness x-ray sources
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Conventional x-ray light sources are large scale national facilities

- X-ray free electron laser: LCLS
- Synchrotron: APS

SLAC, CA
Argonne Nat. Lab., IL
Sources driven by laser-plasma accelerators offer an alternative

<table>
<thead>
<tr>
<th>Synchrotron</th>
<th>Free Electron Laser</th>
<th>Laser-plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="APS" /></td>
<td><img src="image" alt="LCLS" /></td>
<td><img src="image" alt="LCLSAPS" /></td>
</tr>
<tr>
<td>Electrons from storage ring wiggled by undulators</td>
<td>Electrons from linac wiggled by undulators</td>
<td>Electrons from laser-produced plasma wiggled by plasma</td>
</tr>
<tr>
<td>✓ Hard X-rays</td>
<td>✓ Soft X-rays (8 keV)</td>
<td>✓ Hard X-rays (up to MeV)</td>
</tr>
<tr>
<td>✓ High brightness</td>
<td>✓ Very High brightness</td>
<td>✓ High brightness</td>
</tr>
<tr>
<td>✓ Multiple beamlines</td>
<td>✓ One beamline</td>
<td>✓ Small scale</td>
</tr>
<tr>
<td>✓ Not ultrafast (ps)</td>
<td>✓ Ultrafast (fs)</td>
<td>✓ Ultrafast (fs)</td>
</tr>
<tr>
<td>✓ Not coherent</td>
<td>✓ Coherent</td>
<td>✓ Some spatial coherence</td>
</tr>
</tbody>
</table>

Plasmas can naturally sustain large acceleration gradients

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

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

\[ n_e = 10^{18} \text{ cm}^{-3} \rightarrow E_0 = 96 \text{ GV/m} \]
Intense laser pulses drive electron plasma waves

Wake behind a boat

Plasma wave behind a laser

Nuno Lemos, LLNL
Intense laser pulses drive electron plasma waves

Wake behind a boat

Plasma wave behind a laser

Nuno Lemos, LLNL

~50 µm
Intense laser pulses drive electron plasma waves

Wake behind a boat

Plasma wave behind a laser

Nuno Lemos, LLNL

~50 µm

Beam divergence $\theta \sim r_0 \sqrt{\frac{n_e}{\gamma}}$
Laser wakefield acceleration can produce x-ray and gamma-ray sources using several processes

1. **Betatron x-ray radiation**
   - keV

2. **Compton scattering**
   - keV – MeV

3. **Bremsstrahlung**
   - MeV
X-ray sources from LWFA have unique properties compared to conventional light sources

- Broadband (keV - MeV)
- Ultrafast (fs-ps)
- Collimated (mrad)
- Small source size (µm)
- Synchronized with drive laser or XFEL within <ps
X-ray sources from LWFA have unique properties compared to conventional light sources

- Broadband (keV - MeV)
- Ultrafast (fs-ps)
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- Small source size (μm)
- Synchronized with drive laser or XFEL within <ps
The sources and techniques we are developing are important for applications in HED science.

Applications

- High pressure and shock physics
  - Equation of state
  - Material strength
  - Phase transitions
    - Opacity
- Laboratory astrophysics

![Graph showing average X-ray flux (photons/s/0.1% BW)](Image)

**Equation of state**

\[
\rho \propto \frac{1}{\sqrt{a}} \left( \frac{2}{a} \right) \left( \frac{E_0}{E} \right)^{3/4}
\]

**Material strength**

\[
\frac{d}{d} = \frac{d}{\sqrt{a}} \left( \frac{E_0}{E} \right)^{3/4}
\]

**Opacity**

\[
\alpha \propto \frac{1}{\sqrt{a}} \left( \frac{E_0}{E} \right)^{3/4}
\]
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LWFA light 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 $c\tau \sim 1/n_e^{1/2}$

To drive a wake we need $P > P_c \sim 1/n_e \sim \tau^2$

- 30 fs $n_e \sim 10^{19} \text{ cm}^{-3}$
- 1 ps $n_e \sim 10^{16} \text{ cm}^{-3}$
- 30 fs $P_c \sim 2 \text{ TW}$
- 1 ps $P_c \sim 2 \text{ PW}$
Self modulated laser wakefield acceleration (SMLWFA) is easier to achieve with picosecond scale lasers ($c\tau \gg \lambda_p$)

To drive a wake we need $P > P_c \sim 1/n_e$

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

1 ps $n_e \sim 10^{19}$ cm$^{-3}$

1 ps $P_c \sim 2$ TW
The laser propagates in the plasma and decays into an electron plasma wave and forward scattered waves.

Plasma wave:
\[ \lambda_p = c/\omega_p \sim 1/n_e^{1/2} \]

Matching conditions:
\[ \omega_0 = \omega_s +/-% \omega_{\text{plasma}} \]
\[ k_0 = k_s +/-% k_{\text{plasma}} \]
The index of refraction variations due to the plasma wave cause the laser to focus/defocus

\[ \lambda_p = \frac{c}{\omega_p} \approx \frac{1}{n_e^{1/2}} \]

- Plasma wave
- Laser pulse envelope
- Electron density

\[ cT_{\text{Laser}} \]
This beat pattern exerts a force on the plasma electrons and the plasma wave amplitude grows until wave breaking.

\[ \lambda_p = \frac{c}{\omega_p} \approx \frac{1}{\sqrt{n_e}} \]
Upon wave breaking electrons are trapped into the plasma wave

\[ \lambda_p = \frac{c}{\omega_p} \sim \frac{1}{n_e^{1/2}} \]
Trapped electrons undergo acceleration in the longitudinal field of the plasma wave.

\[ \lambda_p = \frac{c}{\omega_p} \sim \frac{1}{n_e^{1/2}} \]

Where:
- \( \lambda_p \) is the laser pulse wavelength.
- \( c \) is the speed of light.
- \( \omega_p \) is the plasma frequency.
- \( n_e \) is the electron density.

The diagram illustrates the relationship between the plasma wave and the laser pulse envelope, showing how electrons are accelerated in the longitudinal field of the plasma wave.
Electrons trapped in plasma wave are accelerated to relativistic energies

Electrons overlap with laser field: **direct laser acceleration (DLA)**\(^2\), dominant if \(I > 10^{20}\) W/cm\(^2\)

Electrons trapped into several plasma wave periods: **continuous energy spectrum**

---

**Electron acceleration**

Longitudinal E field from plasma wave: **self-modulated wakefield acceleration (SMLWFA)**\(^1\)

\[ \lambda_p = c/\omega_p \approx 1/n_e^{1/2} \]
Electrons trapped off-axis undergo betatron oscillations, reinforced by overlap with laser field

Electron acceleration

Longitudinal E field from plasma wave: **self-modulated wakefield acceleration (SMLWFA)**

Electrons overlap with laser field: **direct laser acceleration (DLA)**, dominant if I > 10^{20} W/cm^2

Electrons trapped into several plasma wave periods: **continuous energy spectrum**
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Our work is part of a plan to develop LWFA-driven sources on large picosecond lasers

<table>
<thead>
<tr>
<th></th>
<th>Titan</th>
<th>OMEGA-EP</th>
<th>NIF-ARC</th>
<th>LMJ-PETAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy:</strong></td>
<td>150 J</td>
<td>400 J</td>
<td>250 J /beamlet</td>
<td>2 kJ</td>
</tr>
<tr>
<td><strong>Pulse duration:</strong></td>
<td>0.7 ps</td>
<td>1 ps</td>
<td>1 ps</td>
<td>0.5 ps</td>
</tr>
<tr>
<td><strong>F/10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Experiments done</strong></td>
<td>yes</td>
<td></td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td><strong>2 Shot days 2019</strong></td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Proposal short listed</strong></td>
<td></td>
<td></td>
<td></td>
<td>yes</td>
</tr>
</tbody>
</table>

Collaboration with CEA
Titan Laser
150 J
0.7 ps

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

Self modulated

Laser Wakefield Acceleration on Titan

F/10 OAP
2.5 m focal length

86 % in 28 \mu m
I = 5 \times 10^{18} \text{ W/cm}^2
We have demonstrated the production of betatron radiation in the blowout and self-modulated regimes.

We have demonstrated the production of radiation in the SMLWFA regime.

We have characterized these processes producing keV – MeV photons from SMLWFA electron beams

These sources provide opportunities for new x-ray diagnostics development
Electron and forward laser spectra confirm that we are in the SMLWFA regime

Particle-in-cell simulations performed with OSIRIS

osiris v2.0

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST

New Features in v2.0

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Parallel I/O

Ricardo Fonseca: ricardo.fonseca@ist.utl.pt
Frank Tsung: tsung@physics.ucla.edu
2D PIC simulations of electron and forward laser spectrum also confirm signatures of SMLWFA

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

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

\( E_c = 20 \text{ keV} \)
Electrons accelerated in the SMLWFA regime produce betatron x-rays

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

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

\( Ec = 5 \text{ keV} \)

[Graph showing the x-ray intensity distribution vs. energy]

[Graph showing the yield distribution vs. filter number]
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
Electrons accelerated in the SMLWFA regime produce betatron x-rays with critical energies of 10-40 keV

Electrons accelerated in the SMLWFA regime produce betatron x-rays with critical energies of 10-40 keV

Measured/calculated x-ray spectrum

Betatron - Experiment
PIC simulation

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

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

Noise level

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

Betatron, $E_c = 10$ keV

$n_e = 1.5 \times 10^{19}$ cm$^{-3}$

$E_{\text{laser}} = 150$ J

$a_0 \sim 3$
Compton scattering allows for increased photon flux up to a few 100 keV

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

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

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

\( E_{\text{laser}} = 120 \text{ J} \)

\( a_0 \sim 3 \)

N. Lemos et. al Phys. Rev. Lett. (in review)
Compton scattering allows for increased photon flux up to a few 100 keV

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

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

\( n_e = 4 \times 10^{18} \text{ cm}^{-3} \)
\( E_{\text{lasers}} = 120 \text{ J} \)
\( a_0 \sim 3 \)

A multi-temperature Compton scattering distribution is consistent with predictions from measured electron beam energy.

**Electron beam spectrum**

Counts [arb. unit]/MeV

- Detection threshold

**Compton scattering spectrum**

Photons/keV/shot

10^{11} photons/shot

\[ E_x \propto 4\gamma^2 E_L \]

N. Lemos et al Phys. Rev. Lett. (in review)
LWFA-driven bremsstrahlung produces the most photons at MeV energies

\[ f(E) \propto \exp[-E/T] \]

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

N. Lemos et. al, PPCF, 60, 054008 (2018)
N. Lemos et. al, PRL (in review)
P. M. King et. al, RSI 90, 033503 (2019)
The combined target can be varied to control the photon flux and temperature of the emitted x-rays.

Foil
CH, 100 µm

Laser
Gas
Nozzle

Compton

\[ \text{Photons/keV/Sr} \]

\[ 10^8 \quad 10^9 \quad 10^{10} \quad 10^{11} \]

\[ 10^2 \quad 10^3 \]

\[ E_\gamma \ [\text{keV}] \]

P. M. King et. al, In preparation (2019)
The combined target can be varied to control the photon flux and temperature of the emitted x-rays.
The combined target can be varied to control the photon flux and temperature of the emitted x-rays

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**Diagram:**
- **Laser**
  - **Gas**
  - **Nozzle**
  - **Foil**
    - CH, 100 µm
  - **Foil**
    - W 50 µm
  - **Foil**
    - CH, 100 µm
    - W 250 µm

**Graph:**
- **Phonons/keV/Sr**
- **$E_\gamma$ [keV]**

**References:**
- Compton + Brem
- P. M. King et. al, In preparation (2019)
We can radiograph typical NIF targets with this source.

30 um thick gold half hohlraum

~5.75 mm

~4.72 mm
We can radiograph typical NIF targets with this source.
We can radiograph typical NIF targets with this source
We can tune the source to provide the radiograph with the best contrast and resolution.
We can tune the source to provide the radiograph with the best contrast and resolution.
First Results at the OMEGA-EP laser show similar electron beam properties in SMLWFA conditions

$a_0=3$

$n_e=5 \times 10^{18} \text{ cm}^{-3}$

Electron spectrum

Image Plate 1

2:1 SNR

Electrons/sr/MeV

20 40 60 80 100 120 140 160 180 200

MeV

10^{12}

10^{10}

10^{12}

10^{10}

160 mrad

160 mrad

TCC'

Laser Parameters

• Appodizing Beams
  • f/8, f/10 on 2/BL
  • f/6 on 1/SL
  • Alternate SL, BL
• Scan energy
• All shots BC

Gas Jet

• 100% He
• Vary PHe, Φ nozzle

Electron spectrum

E-spectrometer
We have DS shots at NIF (9/11/2019) to develop the SMLWFA platform

ARC Parameters
1 beamlet
Shortest pulse duration: 1 ps
Energy: Maximum (>250 J)
Intensity: 0.5 – 1 x 10^{18} W/cm
We will use gas tubes and a modified version of NEPPS to produce and characterize electrons up to 150 MeV.
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- Conclusion and perspectives
We performed experiments at LCLS MEC end station

MATTER IN EXTREME CONDITIONS (MEC)

- Colocation of three laser systems
  - XFEL (8 keV, 70 fs, 3 mJ)
  - ns optical laser (20 J, ns)
  - fs optical laser (1-7 J, 40 fs)

- Type of experiments
  - ns laser pump / Betatron x-ray probe
  - fs laser pump / Betatron x-ray and LCLS probe
  - LCLS pump / Betatron x-ray probe
Betatron x-ray experiment at LCLS-MEC
Characterization of electron beam and betatron beam profile

- **Electrons**
  - Electron spectrum graph
  - Electron energy distribution

- **X-rays (IP)**
  - Beam profile
  - 40 mrad fwhm

- **X-rays (CCD + Filters)**
  - 30 mrad

**Diagram:**
- MEC short pulse
- OAP
- Electron spectrometer
- Filters
- X-ray CCD/IP
- Electron energy [MeV]
- Electron energy [MeV]
- dN/dE

**Details:**
- 1J, 45 fs
Electron beams and betatron x-rays are produced every shot

**Electrons**
- Dispersed on LANEX screen
- \( n_e = 10^{19} \text{ cm}^{-3} \)
- 90% He, 10% N\(_2\) mix

**Betatron x-rays**
- > 4 keV on PI-MTE CCD
- 3 x 12.5 µm Al filters
- 60 µm Ag wires grid

![Energy (MeV) plot](image)

Energy (MeV)

- 50
- 100
- 200

30 mrad

![Image of grid](image)
Characterization of betatron x-ray focus shows 16 % rms intensity stability.

X-ray focus scan

Ray tracing betatron focus

Electron spectrometer

X-ray CCD
Al 25 µm

Ellipsoidal mirror

14 mrad tangential slope error
100 mrad sagittal slope error

Courtesy P. Heimann
Betatron x-ray spectrum characterized with grating spectrometer

Reference spectra registered during the delay scan => high stability

CCD signal (int. 30 pix vert. & 30 shots)

Intensity stability ~ 9 % rms

Reference 30 shots

9 % rms intensity stability

CCD counts/30 pix vert 30 shot

Spectrometer

Ellipsoidal mirror

X-ray CCD

Electron spectrometer

Electron energy (eV)

450

500

550

600

650

0

5 10^3

1 10^4

1.5 10^4

2 10^4

2.5 10^4

X-ray energy (eV)

0 5 10 150 70 90 150 MeV

→ B

650

450

Energy (eV)
We have probed nonthermal melting in SiO$_2$ using x-ray absorption spectroscopy.
We performed absorption spectroscopy of SiO$_2$ at the O K-edge (535 eV)
No absorption of x-ray probe photons below O K-edge energy

- Betatron photon <535 eV
- Conduction band
- Valence band
- SiO$_2$ 300 K
- O K-edge

Photon Energy [eV]

Absorbance

No absorption of x-ray probe photons below O K-edge energy
Sharp transition corresponds to strong absorption of x-ray photons for energies above the O K-edge.

Betatron photon
>535 eV

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

SiO₂ 300 K

Conduction band
Valence band

9 eV

O K-edge

Absorbance

Photon Energy [eV]

510 520 530 540 550 560

0 0.2 0.4 0.6 0.8 1

535 eV

1848.6 eV
Multiphoton absorption causes electrons to cross the bandgap and leave vacancies in the valence band.
1s-valence band transitions are now authorized: strong absorption peak 9 eV below the edge
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

Photon Energy [eV]

Absorbance

0

0.2

0.4

0.6

0.8

1

Photon Energy [eV]

510

520

530

540

550

560

0.2

535 eV

510 eV

1848.6 eV

Si 1s

Si 2s

Si 2p

O 1s

O 2s

K-edge

Cold

Warm
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

<9 eV

535 eV

1848.6 eV

Photon Energy [eV]

Absorbance

O K-edge

Cold

Warm
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 the use of betatron x-rays as a tool for absorption spectroscopy with sub ps resolution.

- Electron spectrometer
- Ellipsoidal mirror
- X-ray CCD
- Energy (eV)
- Pump 10^{15} W/cm^2
- 200 nm SiO_2
- Delay scan on am-SiO_2 sample
- XANES spectra normalized then subtracted to avg cold and integrated over ≠ spectral range
- Cold over [500-545] eV
- Cold over [500-535] eV
- Hot over [500-545] eV
- Hot over [500-535] eV

Integrated spectra hot - avg cold (eV)

- Delay (ps)
- \( y = 6 \times (0.5 + 0.5 \times \text{erf}((m_0 - m_1)/m_2)) \)

Error

- Value
- m_1
- m_2
- Chisq
- R

Without #568, erf fit gives:
- \( t_0 = 0.0 \pm 0.1 \text{ ps} \) (good sync.)
- temp. res. = 0.68 ± 0.18 ps
- (0.48 ± 0.13 ps rms)
- (1.13 ± 0.30 ps FWHM)

0.48 +/- 0.18 ps rms rise time
Other applications in progress

Phase contrast imaging of laser-driven shocks

Relaxation of metals driven by XFEL x-rays

Courtesy of S. Mangles and J. Woods, Imperial College
Conclusions and future work

- We have demonstrated the production of novel x-ray sources from laser-plasma accelerators.
- They are broadband (keV - MeV), ultrafast (fs - ps), collimated (mrad), synchronized with drive laser.
- They enable new applications:
  - Study of ultrafast non-thermal melting in SiO2
  - Phase contrast imaging of laser-driven shocks
  - 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

X-ray sources – Picosecond phenomena

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)
N. Lemos et. al, PRL (in review)
It is an exciting time for short pulse laser science – LaserNetUS established in August 2018

https://www.lasernetus.org