X-ray Science at the Femtosecond to Attosecond Frontier

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Workshop information

• SUMMARY OF SESSION HOURS (exclusive of meals):
  • Monday AM 08:30 – 12:00 Royce Hall
  • Monday PM 13:45 – 17:45 P&A-Knudsen Buildings
  • Tuesday AM 08:40 – 12:00 Royce Hall
  • Tuesday PM 13:45 – 17:45 P&A-Knudsen Buildings
  • Wednesday 08:40 – 12:00 Royce Hall
SUMMARY OF MEAL HOURS & EVENTS:

- Sunday Reception 18:00 – 21:00 CNSI
- Monday Registration 07:30 – 08:30 Royce
- Monday Breakfast 07:30 – 08:30 Royce
- Monday Lunch 12:00 – 13:45 PAB Patio
- Monday Dinner 18:00 – 20:00
- Tuesday Breakfast 08:00 – 08:40 Royce
- Tuesday Lunch 12:00 – 13:45 PAB Patio
- Tuesday Dinner 18:00 – 20:00
- Wed. Breakfast 08:00 – 08:40 Royce
- Wed. Lunch 12:00 – 13:45 PAB Patio
- Wed. Museum 14:00 – 17:00
Welcome to the workshop

Thank you for coming to the “Workshop on X-ray Science at the Femtosecond to Attosecond Frontier”.

This is a very exciting time for the new area of science with high brightness, coherent X-rays made possible by FELs. The two operating FELs, FLASH and LCLS, and the new ones to come in the near future, promise to revolutionize the exploration of the properties of matter at the atomic and molecular level, reaching a new level of space and time resolution.

In this workshop we want to discuss and examine one important near future FEL development, the production of femtosecond to attosecond coherent X-ray pulses, and the science that can be done with them, in the 0.1 to about 10 nm wavelength region.
Peak brightness of existing X-ray FELs, Flash and LCLS

X-ray FELs work and we know how to build them.

An old plot with superimposed FLASH and the very new LCLS data. **Good predictions.** Peak power in the 1-10 GW range.
LCLS first lasing at SLAC, April 2009, at 0.15 nm

Courtesy LCLS group, SLAC
• Pulse trains of up to 800 μs duration
• Up to 10 Hz repetition rate (currently 5 Hz)
• Fixed gap undulators (Tune with electron beam energy)
• Wavelength range (fundamental): 6-47 nm
• Pulse energy average: 100 μJ
• Peak power: ~ 5 GW
• Pulse duration (FWHM): 10-50 fs
• Spectral width (FWHM): 0.5-1 %
X-ray FELs next developments: the wish list

Flash, LCLS, and the next FELs, as XFEL, SCSS, Fermi, are only the beginning of the road. Present and next generation FEL capabilities can be extended to parameters like:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy, keV</td>
<td>0.1-100</td>
</tr>
<tr>
<td>Pulse repetition rate, Hz</td>
<td>100-10^5</td>
</tr>
<tr>
<td>Pulse duration, fs</td>
<td>&lt;1-1000</td>
</tr>
<tr>
<td>Coherence, transverse</td>
<td>Very good</td>
</tr>
<tr>
<td>Coherence length</td>
<td>L_{Bunch} to L_{Cooperation} (300-0.1µm)</td>
</tr>
<tr>
<td>Peak Brightness</td>
<td>10^{30} - 10^{34} ph/mm^2 mrad^2 s 0.1%bw</td>
</tr>
<tr>
<td>Average brightness</td>
<td>10^{18} - 10^{27} ph/mm^2 mrad^2 s 0.1%bw</td>
</tr>
<tr>
<td>Polarization</td>
<td>Variable, linear to circular</td>
</tr>
</tbody>
</table>
Workshop mission: fs-as coherent X-ray pulses

Recent theoretical and experimental progress in the physics and technology of electron beams has shown the possibility of producing low charge, pC range, ultra-short, sub-micrometer, electron bunches with small emittance and high brightness. This development opens new possibilities to design and build compact, lower cost free-electron lasers, to produce high intensity, femtosecond long, coherent X-ray pulses.

The workshop is organized to stimulate a timely discussion between the FEL and photon scientists, and to consider the scientific opportunities offered by these new developments.

Notice: many other methods have been proposed and studied before to produce fs-as x-ray pulses. However here we would like to focus on the possibilities offered by low charge bunches.
Workshop Goals

In particular the workshop can explore:

A. The design of soft X-ray FELs, optimized to produce high peak power, coherent soft X-ray pulses in the 1 to 10 nm region, with pulse duration of about 0.5 to 5 fs and variable polarization.

B. The areas of science where such FELs can yield new, exciting results.

C. The entry-level X-ray performance specifications and plans to expand the FEL performance, for instance the pulse repetition rate, in a staged approach.

D. The technologies, such as beam and photon diagnostics, X-ray optics, timing systems, instrumentation, and short period undulators, required by the FELs.
The road to the new FELs is made easier by recent advances in electron sources

1. Low charge operation of LCLS/SPARC/Ferrario type photoinjectors increases electron beam brightness, reduces the emittance and the pulse length. The scaling laws, in simplified form at low charge, $\varepsilon \sim Q^{1/3}$, have been studied with simulations, and partially verified by experiments.

2. Velocity compression, also recently demonstrated on SPARC, makes it easier to obtain large current for small charge, and to compress the bunch lengths to the micrometer range.

These advances are important for the production of femto-attosecond electron bunch duration and X-ray pulses.
FEL benefits of low charge electron bunches for femto-attosecond X-ray pulses

- Reducing the emittance we can reduce the electron beam energy for the same wavelength.
- The two effects combine to give a larger FEL parameter and a shorter gain length.
- Velocity + magnetic compression can be used to reduce the bunch and photon pulse duration to the femtosecond range.
- Reducing the bunch length to a value smaller than the cooperation length gives full transverse and longitudinal coherence of the photon pulse.
- Lower energy and shorter gain length reduce the length of the linac and undulator, and minimize the FEL cost.
Example: a compact soft X-ray FEL using off the shelf components

- Beam energy 1.4 GeV
- S-band injector+X or C-band linac, length <35 m
- 1.5 cm period, K=1, undulator, length 15 m
- Bunch charge, 1-20 pC
- Pulse length, 1 to few fs
- Number of coherent photons/pulse, $10^{10}$-10$^{12}$
- Linac repetition rate, 120 Hz
- X-ray Pulses in one linac pulse, 1 to 100
- Synchronization to external laser using the signals from the photoinjector laser and the coherent radiation from the electron bunch after compression.
Recent studies show that a smaller emittance (x 0.1), larger electron beam brightness (x 10-100) and very short, ~ 1fs or less, electron bunches can be produced by reducing the bunch charge from about 1nC to few, 1 to 10 pC, and using velocity and magnetic bunching.

SPARX: $E=2$ GeV, $\lambda=3$ nm, Single spike $\sigma_B=0.48$ $\mu$m (1.6 fsec), $2\times10^{10}$ photons in the pulse.
LCLS 1pC example: attosecond pulses.

Single spike at saturation, with $10^{10}$ photons.

Beam brightness~ $4 \times 10^{17}$ A/m$^2$ rad$^2$ compared to $6 \times 10^{15}$ A/m$^2$ rad$^2$ for the 1 nC design case.

$\lambda = 0.15 \text{nm}$,

$\sigma_E = 10^{-4}$,

$\sigma_L = 160 \text{nm} (530 \text{as})$. 

Beam current profile

Peak power vs. $z$
LCLS at low charge, short pulses

20 pC $\lambda = 0.15\, nm$  
20 pC $\lambda = 1.5\, nm$

Workshop charge

Consider a fs-as FEL in the 1-10 nm range using low, pC charges, and discuss the following questions.

1. Is the scientific interest large enough to justify building the system? What are the minimum requirements on pulse intensity, polarization and repetition rate to make it interesting?

2. What are the critical technical developments needed to realize a near term, dedicated FEL for femtosecond and sub-femtosecond X-ray science?

3. What is the time scale and budget for designing and building the FEL using off-the shelf photoinjector-linac components?
What are the tolerances required for optimum low charge operation?

Can the FEL be designed to be upgradable in stages? As an example one could start using the LCLS/SPARC type injector and later upgrade to a high repetition injector, going from about 100Hz to 100kHz.
Workshop charge

I am sure you will find more questions to ask, and more answers to give.
Thank you again for coming and I hope you will enjoy UCLA and the workshop.