JLAMP Proposed 4th Generation Soft X-ray Light Source

George R. Neil, for the JLAB Team
Associate Director, Jefferson Laboratory

Nov. 17, 2009
What are (4th) Next Generation Light Sources?

Superconducting radio-frequency linac based, as opposed to rings

Significantly higher brightness than existing sources

Short pulse capability (< 100 fs)

High transverse coherence and ideally longitudinal coherence

Concept covers broad spectral range from THz through VUV to soft and hard X-rays but the push is toward X-rays

Complementary capability – they do not displace 3rd generation rings!

Configuration loosely divided into Free Electron Lasers or Energy Recovering Linacs
**Third generation x-ray sources**

Storage ring
\[ \varepsilon \sim \frac{E^2}{R} \]
\[ \tau_{\text{lifetime}} \gg \tau_{\text{relaxation}} \]
bunch charge 1nC

- Many experiments
- Ready tunability
- High flux
- ps pulses

**Fourth generation x-ray sources**

LINAC source
\[ \varepsilon \sim \frac{1}{E} \]
\[ \tau_{\text{lifetime}} \ll \tau_{\text{relaxation}} \]
bunch charge \( \leq 1 \) nC

- Extremely high peak brilliance
- Full spatial coherence
- Ultrashort (fs) pulses
- Temporal synchronization with seeding
- low pulse rep. Rate \( 10^2 \) to \( 10^6 \) Hz
- Few experiments

Energy-Recovery LINAC
bunch charge < 100 pC

- High avarage brilliance
- Full spatial coherence
- Many experiments
- Ready tunability
- Excellent energy resolution
- Flexible pulse characteristics
- Fs to ps pulse lengths
- \( 10^9 \) pulses/s

Courtesy W. Eberhardt

Next Generation Photon Sources for Grand Challenges in Science and Energy
W. Eberhardt, BESAC Feb. 2009
So why haven’t CW 4th Generation sources been built?

Linacs are expensive!
- Get 1 eV photon with energy of ~100 MeV
- Get 100 eV with ~1 GeV
- Get 1000 eV with 3 GeV
- Get 10 keV with 10 GeV

Linacs presently achieve <12 MV/m real estate gradient CW

3 GeV means >300m of linear accelerator, >$200M for the linac!

Undulators are also expensive >0.4M/m x 100m = $40M per undulator x 10? = $400M

Add in the cost of cryogenic refrigerator, conventional facilities, etc. and the total for 1Å output is well above $1B
Physics advances are also required

Injectors: ultimate brightness at low (100 pC) and high (1 nC) charge

Approaches: DC gun, copper RF gun, SCRF gun, ...

We don’t presently know how to make a high charge, high brightness CW gun.

Brightness preservation in transport:

Solutions to coherent synchrotron radiation (CSR) emittance degradation, longitudinal space charge (LSC) in pulse compression

Is recirculation feasible while retaining brightness? Cut linac cost by 2x!

Halo control essential for CW

High order mode & beam breakup control in cavities

Wakefield and propagating mode damping
JLAMP – 4th Generation VUV/Soft X-Ray Light Source

Operates from 7 eV table-top laser energy to 500 eV with harmonics
3 to 6 orders of magnitude brighter than FLASH

Scientific case focused on DOE-BES Grand Challenges from world-class committee
- materials science
- AMO (Atomic, Molecular, Optical Science)
- imaging

Secondary goals address BES R&D priorities (injector, srf, collective effects, seed lasers) for next generation hard X-ray photon facility

$70M and fast schedule since it builds on existing FEL infrastructure
Existing JLab 4th Generation IR/UV Light Source

\[ E = 120 \text{ MeV} \]
\[ 135 \text{ pC pulses @ } 75 \text{ MHz} \]

(20 \( \mu \) J/pulse in 250–700 nm UV-VIS
in commissioning)

120 \( \mu \) J/pulse in 1-10 \( \mu \)m IR

1 \( \mu \) J/pulse in THz

*The first high current ERL*

14 kW average power

**Ultra-fast (150 fs)**

**Ultra-bright**

\( 10^{23} \) ph/sec/mm\(^2\)/mrad\(^2\)/0.1\%BW

UV harmonics exceed FLASH
average brightness (\( 10^{21} \) average,
\( 10^{27} \) peak
ph/sec/mm\(^2\)/mrad\(^2\)/0.1\%BW)
## External JLAMP Collaborators

### Advisory Committee to Lab Director

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
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<tbody>
<tr>
<td>Wolfgang Eberhardt</td>
<td>Helmholtz-Zentrum Berlin (Chair)</td>
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<tr>
<td>Maury Tigner</td>
<td>Cornell</td>
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<tr>
<td>Roger Falcone</td>
<td>LBNL</td>
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<td>Peter Johnson</td>
<td>BNL</td>
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<tr>
<td>Erwin Poliakoff</td>
<td>LSU</td>
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<tr>
<td>Nora Berrah</td>
<td>Western Michigan U.</td>
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### Physics/Condensed Matter Working Group

<table>
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<tr>
<th>Name</th>
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<tr>
<td>Andrea Cavalleri</td>
<td>Max Planck/University of Hamburg (Chair)</td>
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<td>Peter Johnson</td>
<td>BNL</td>
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<tr>
<td>John Hill</td>
<td>BNL</td>
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<tr>
<td>Martin Wolf</td>
<td>FHI, Berlin</td>
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<tr>
<td>Norman Mannella</td>
<td>U. Tennessee</td>
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<tr>
<td>Aaron Lindenberg</td>
<td>Stanford</td>
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<tr>
<td>Harald Ade</td>
<td>NC State</td>
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<tr>
<td>Rick Osgood</td>
<td>Columbia U.</td>
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<tr>
<td>Henry Kapteyn</td>
<td>JILA, Colorado</td>
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### AMO/Chemistry Working Group

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<tr>
<td>Erwin Poliakoff</td>
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<tr>
<td>Eckart Ruehl</td>
<td>Free U., Berlin</td>
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<tr>
<td>Dan Rolles</td>
<td>U. Hamburg</td>
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<td>Markus Drescher</td>
<td>U. Hamburg</td>
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<tr>
<td>Lu Zheng-Tian</td>
<td>Argonne</td>
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<td>Mike White</td>
<td>BNL</td>
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### Imaging Working Group

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<td>Harald Ade</td>
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<tr>
<td>Henry Chapman</td>
<td>CFEL, DESY, Hamburg</td>
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<tr>
<td>John Spence</td>
<td>Arizona State</td>
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JLab’s IR/UV 4th Generation Light Source

Upgrade three cryomodules to new C100 design with >100 MeV/module

Add two recirculations up in energy and two down in energy recovery
JLAMP FEL designed for unparalleled 10-100 eV average brightness

- 600 MeV, 2 pass acceleration
- 200 pC, 1 mm mrad injector
- Up to 4.68 MHz CW repetition rate
- Recirculation and energy recovery
- 10 nm fundamental output, 10 nm/H harmonic
- 50 fs-1000 fs near-Fourier-limited pulses

- Baseline: seeded amplifier operation using HHG
- HGHG amplifier + oscillator capability
- THz Wiggler for synchronized pump/probe
CW operation gives high average brightness in both fundamental and harmonics.
JLAMP delivers important parameter space un-addressed in hard X-ray proposals, with chemical selectivity to measure atomic structure at the nanoscale, measurement of dynamics on the attosecond timescale of electron motion, and imaging.
## Summary of technical specifications for some of the proposed new light source facilities

Items in blue are estimates not from official project sources

<table>
<thead>
<tr>
<th>Facility</th>
<th>Wavelength (nm)</th>
<th>Photon Energy (keV)</th>
<th>Pulse duration (FWHM) (fs)</th>
<th>FEL beamline repetition rate (Hz)</th>
<th>Peak Brightness</th>
<th>Average Brightness (CW)</th>
<th>Average Brightness (bunch trains)</th>
<th>Photons per pulse coherent</th>
<th>Bandwidth</th>
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<tr>
<td>NGLS</td>
<td>1–10</td>
<td>1.2–0.12</td>
<td>0.3–500</td>
<td>105 +</td>
<td>10^{30–10^{32}}</td>
<td>10^{19–10^{25}}</td>
<td>10^{9–10^{13}}</td>
<td>10^{2–10^{6}}</td>
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<td>LCLS</td>
<td>0.15</td>
<td>8.2</td>
<td>80</td>
<td>120</td>
<td>2x10^{33}</td>
<td>2x10^{22}</td>
<td>10^{24}</td>
<td>2x10^{12}</td>
<td>2x10^{-3}</td>
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<td></td>
<td>1.5</td>
<td>0.82</td>
<td>240</td>
<td>120</td>
<td>3x10^{31}</td>
<td>8x10^{20}</td>
<td>5x10^{22}</td>
<td>2x10^{13}</td>
<td>4x10^{-3}</td>
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<td>JLAMP</td>
<td>10-100</td>
<td>0.1–0.01</td>
<td>50–100</td>
<td>4.7x10^{6}</td>
<td>10^{30–10^{32}}</td>
<td>10^{23–10^{26}}</td>
<td>10^{23–10^{26}}</td>
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<td>FLASH</td>
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<td>5</td>
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<td>10^{16–10^{17}}</td>
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<td>10^{-2}</td>
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<td>47</td>
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<td>5</td>
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<td>10^{16–10^{17}}</td>
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<td>2x10^{12}</td>
<td>10^{-2}</td>
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<td>XFEL</td>
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<td>12.4–0.2</td>
<td>100</td>
<td>10</td>
<td>10^{31–10^{33}}</td>
<td>10^{20–10^{21}}</td>
<td>10^{23–10^{25}}</td>
<td>10^{12–10^{14}}</td>
<td>~10^{-3}</td>
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<td>SPRing8</td>
<td>0.1</td>
<td>12.4</td>
<td>50</td>
<td>60</td>
<td>10^{33}</td>
<td></td>
<td></td>
<td>10^{11}</td>
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<tr>
<td>XFEL</td>
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<td>FERMI @elettra</td>
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<td>0.41–0.12</td>
<td>~40</td>
<td>50</td>
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<td>10^{20}</td>
<td></td>
<td>10^{11–10^{12}}</td>
<td>~10^{-4}</td>
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<tr>
<td>NLS</td>
<td>1.24–2.5</td>
<td>1–0.5</td>
<td>20</td>
<td>1000</td>
<td>10^{32}</td>
<td>10^{21}</td>
<td></td>
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<td>~10^{-4}</td>
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<tr>
<td>SwissFEL</td>
<td>0.1–7</td>
<td>12–0.17</td>
<td>0.6–28</td>
<td>100</td>
<td>10^{31–10^{33}}</td>
<td>10^{20–10^{21}}</td>
<td></td>
<td>10^{11–10^{13}}</td>
<td>10^{-3–10^{-4}}</td>
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*Items in italic font are measured on operational facilities*
Average Brightness vs Photon Energy

LCLS 1.5 Å, $4.2 \times 10^{22}$

High Rep Rate Injectors

Xray Cavity

SRF

Region of Partial Lasing in “Ultimate” Rings

3rd Generation Storage Rings

CW Linac Soft X-ray FELs

Pulse

Bunch Train

Single Bunch

3rd

PL 3rd

“Ultimate” Storage Rings and ERLs

PL 5th

Jefferson 10-2008 8777A23

ANL-08/39
BNL-81895-2008
LBNL-1090E-2009
SLAC-R-917
Many approaches for a CW High Brightness Gun – but none working yet

JLab Advanced DC Gun

LBNL Low Frequency RF Gun

F. Sannibale

Cathode

Beam exit aperture

Cathode insertion/extraction channel (load-lock mechanism not shown)

J. Bisognano

WiFEL/Niowave SRF Gun

F. Sannibale
HV DC Photoemission Guns for 4th Generation Light Sources
Carlos Hernandez-Garcia, Jefferson Lab

- The 4GLS accelerators need unprecedented average brightness electron beam (sub-micron emittance like the LCLS injector AND >10 mA CW beam like the Jefferson Lab FEL injector)
- Such an electron beam has not been demonstrated and represents a major technical challenge
- We need support for R&D on fundamental cathode physics (electron emission) and on electron beam dynamics near the cathode surface

Electron pulses are generated when the GaAs photocathode is illuminated with laser pulses operating at a sub-harmonic of the accelerator frequency.

The FEL gun has delivered a record 7000 Coulombs and over 900 hours of CW beam time between 2004 and 2007. At 10 mA and 350kV DC is the most powerful photoemission gun to ever power an FEL.

Field emission from electrodes represents one of the technical challenges of ultra-high brightness and high current photoguns.

Photocathode robustness at unprecedented average current is key for an user facility but has not been demonstrated yet.

The JLab FEL team is developing the next generation of High Voltage DC electron guns designed to meet the beam requirements for high repetition rate VUV and soft X-ray accelerator based light sources.
100 MeV High Gradient Module

Component procurements awarded for JLab 12 GeV Machine – 10 modules

- Multicell cavities
- Insulating vacuum
- 2K liq. He bath

Original CEBAF module
User Topic Summary

Condensed matter physics
- Ultrafast photoemission spectroscopy of coherently controlled complex materials
- Femtosecond Pump/Probe ARPES in artificial nanosystems
- Electronic states in strongly correlated systems using soft X-ray scattering

Chemical physics and Atomic, Molecular, Optical physics
- Matter at small dimensions
  - Atomic and electronic structure of size-selected clusters
  - Chemical reactivity of size-selected neutral clusters and nanoparticles
  - Time-resolved nanoscale “surface” dynamics
- Molecular movies
  - Electronic dynamics using time-resolved ESCA
  - Time-resolved photoelectron diffraction in gas-phase molecules
- Ultrasensitive trace analysis of noble gas isotopes

Imaging biological and soft condensed matter
- High resolution structural determinations of non-periodic materials and dynamic studies of soft matter
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  - materials science
  - AMO (Atomic, Molecular, Optical Science)
  - imaging

Secondary goals address BES R&D priorities (injector, srf, collective effects, seed lasers) for next generation hard X-ray photon facility

< $100M and fast schedule since it builds on existing FEL infrastructure
The Jefferson Lab FEL Team

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the DOE Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.
JLAMP addresses BES Grand Challenges in soft X-ray range

Directing Matter and Energy; 5 Challenges for Science & the Imagination

1. How do we control materials processes at the level of the electrons?
   *Pump-probe time dependent dynamics*

2. How do we design and perfect atom- and energy-efficient synthesis of new forms of matter with tailored properties?
   *PLD, photo-chemistry, XRS*

3. How do remarkable properties of matter emerge from the complex correlations of atomic and electronic constituents and how can we control these properties?
   *Pump-probe time dependent dynamics, XRS*

4. How can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living things?
   *Pump-probe time dependent dynamics, XRS*

5. How do we characterize and control matter away -- especially very far away -- from equilibrium?
   *Non-linear dynamics, ultra-bright sources*

Report - Graham Fleming and Mark Ratner (Chairs).

Ultrafast, ultrabright, tunable THz/IR/UV/X-Ray light from next generation light sources
Electrons determine macroscopic phenomena, their coupling can dominate behavior leading to novel effects with potential for energy and environmental applications: e.g. Mott insulators, High-Tc superconductivity, Colossal magnetoresistance, Metal-insulator transitions, other effects due to charge order, spin order, orbital order, stripes, etc.

Example: Oxides of transition metals (e.g. Cu. Mn, Ni, V...) show high temperature superconductivity not understood

Electron coupling can be stronger than binding energy
Need to study: Charge, spin, orbital and electron-lattice coupling, to learn about non-adiabatic behavior, validity of Born-Oppenheimer approximation.

Need tunable ultrabright (10^{12} ph/pulse), ultrafast (50 fs) coherent light in 7-100 eV range to excite electrons and study their response

Use multi-photon pulses to couple to electrons and phonons: high resolution, perturbation response

Pump/probe approach as a function of photon energy is used to study coupling time scales, energy resonances, phonon coupling, phase transitions

JLAMP has been defined by the user community to match these needs
Game-changing materials science in VUV/soft X-ray region

Critical applications:
- Magnetism
- Superconductivity
- Correlated electron systems
- Nanosystems
- Nanofabrication

Examples: real-space structure and dynamics of cuprate stripes, searches for hidden order parameters in the pseudogap phase and competing orders in the vortex phase, and detailed measurements of the spin Hamiltonian in low dimensional cuprates

Coherent diffraction (manganite) – 4 orders increase in flux makes time scales to microseconds accessible & fluctuations down to nsec scale


Dynamical coupling - magnetism

Laser pulse breaks long range electron spin coupling

High repetition rate allows rapid mapping of temporal decays

Narrow bandwidth allows accurate mapping of energy structure

Time-resolved Angle-Resolved Photoemission Spectroscopy (ARPES)

JLAMP provides tunable high average flux applied to static or dynamic targets

Spin resolved photoemission at high intensities improves time and spatial resolution

THz undulator + lasers for selecting excitations close to ground state: phonon pumping, phason excitations, Josephson Plasma Resonances, electronic gaps

Schematic diagram of time-resolved ARPES: An ultrashort pump pulse ($h\nu_1$) photoexcites a solid and changes the electron population of both occupied and unoccupied electronic states which are probed by a second, time-delayed UV pulse, exciting electrons above the vacuum level where their kinetic energy and momentum are detected. Right panel: Energy and momentum resolved snapshot of the electronic structure of the charge density wave system TbTe$_3$ at a time-delay of 200 fs after photoexcitation [F. F. Schmitt et al., Science 321, 1649 (2008).]
Electrons in atoms, molecules and small clusters determine chemical behavior. Understanding the electronic response has major impact for reactivity, and catalysis with potential for energy and environmental applications.

Response of atoms to light is not well understood

Need to study: time-dependent electronic wavefunctions for electrons emitted during ionization process


Need tunable ultrabright ($10^{12}$ ph/pulse), ultrafast (50 fs) coherent light in 7-100 eV range to excite electrons and study their response

Use multi-photon pulses for to provide coherent control of the excitations

Pump/probe approach as a function of photon energy is used to tag the electrons as they emerge

JLAMP has been defined by the user community to match these needs
Gas Phase Cluster Studies

JLAMP provides tunable high average flux applied to low density ion beams, gas-phase clusters of $10^4$-$10^6$ ions/cm$^3$ enabling much wider application of the techniques pioneered on FLASH: significantly higher count rates, energy resolution

- Enables direct inner-shell photoionization of size-selected neutral clusters with photon energies well above conventional laboratory lasers (10–300 eV with high harmonics) and at much higher photon fluxes than those available from laser- or arc-based XUV harmonic generation sources.

- Ability to access shallow core levels in metals and other elements will allow the application of powerful spectroscopic techniques using soft x-rays (XPS, NEXAFS) to probe the local atomic and electronic structure of small clusters with elemental specificity.

- General capability for mass selected clusters impossible without this brightness:
  (1) electronic and geometric structure, dynamics of size-selected clusters and nanoparticles
  (2) chemical reactivity of these species probing size-selected neutral clusters generated by photo-detachment from the corresponding anion clusters