ERL Status and Plans at Jefferson Lab

Stephen V. Benson,
On behalf of the Jefferson Lab FEL team

• Current status
• Next Generation Soft X-ray Sources
• JLab Plan – Harmonics of UV lasing, Soft X-ray Amplifier

March 1, 2010
JLab’s Existing 4th Generation Light Source

E = 150 MeV
135 pC pulses @ 75 MHz
(20 μJ/pulse in 250–700 nm UV-VIS)
120 μJ/pulse in 1-10 μm IR
1 μJ/pulse in THz

(UV system is presently under construction) Commissioning of FEL this year. Beam line has already transported CW beam.
IR Upgrade Specifications

- Average Power $> 10000$ W
- Wavelength range 0.9 to 10 $\mu$m
- Micropulse energy $> 100$ $\mu$J
- Pulse length $\sim 0.1$-2 ps FWHM nominal
- PRF $74.85$ MHz $\div 2x$ down to 4.68 MHz
- Bandwidth $\sim 0.2$–3 %
- Timing jitter $< 0.2$ ps
- Amplitude jitter $< 10\%$ p-p
- Wavelength jitter 0.02% RMS
- Position/Angle jitter $< 100$ um, 10 $\mu$rad
- Polarization linear, $> 100:1$
- Transverse mode $< 2x$ diffraction limit
- Beam diameter at lab 2 - 6 cm
What Have We Learned Recently about ERLs

• Have derived new methods for reducing CSR induced emittance growth.
• We have been exploring new ways to get the injected beam into the linac.
• Have developed new processing methods to improved accelerator performance.
• ERL operation required careful system integration of all components utilizing advanced accelerator technologies
  — High order magnetic corrections
  — Suppression of chromatic aberrations
  — Elimination of beam breakup instabilities
  — RF feedback control to levels never before achieved
BES Grand Challenges

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, ARPES*

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

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, ARPES*

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, ARPES*

5. How do we characterize and control matter away -- especially very far away -- from equilibrium?

Ultrafast, ultrabright, tunable THz/IR/UV/X-Ray light from next generation light sources

Report - Graham Fleming and Mark Ratner (Chairs).
Linac-based light source practical challenges

Linacs are expensive!

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

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

10 GeV means > 800m of linear accelerator, >$500M 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, ...

Brightness preservation:

Solutions to CSR, LSC, pulse compression - would like 1 nC in < 100 fs = 10 kA

Is recirculation feasible while retaining brightness? Cut linac cost by 2x-3x!

Halo control essential for CW

HOM & BBU control in cavities

Wakefield and propagating mode damping

Better for you to determine where the heat goes than the electrons!
JLab Conversion to JLAMP

- 4 steps
- 600 MeV, 2 pass acceleration
- 200 pC, 1 mm mrad injector
- Up to 4.68 MHz CW repetition rate
- Recirculation and energy recovery
- 10 eV – 100 eV fundamental output, harmonics to 2nm
- Pulse widths down to 50 fs
## Specifications, photon output, fundamental

<table>
<thead>
<tr>
<th></th>
<th>Oscillator</th>
<th>Amplifier</th>
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<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Wavelength (nm)</td>
<td>12</td>
<td>124</td>
<td>12</td>
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<tr>
<td>Wavelength (eV)</td>
<td>100</td>
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<tr>
<td>Pulse Length FWHM (fs)</td>
<td>100</td>
<td>100</td>
<td>50**</td>
<td>200</td>
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<tr>
<td>Pulse energy (μJ)</td>
<td>10</td>
<td>100</td>
<td>10</td>
<td>100</td>
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<tr>
<td>Photons/pulse @λ_{min,max}</td>
<td>6 x 10^{12}</td>
<td>6 x 10^{12}</td>
<td>6 x 10^{12}</td>
<td>6 x 10^{12}</td>
</tr>
<tr>
<td>dλ/λ_{@λ_{min,max}} (rms)</td>
<td>10^{-4}</td>
<td>10^{-3}</td>
<td>10^{-4}</td>
<td>10^{-3}</td>
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<tr>
<td>Brightness (average) (ph/s/0.1%BW/mm^2/mrad^2)</td>
<td>10^{26}</td>
<td>10^{24}</td>
<td>2 x 10^{25}</td>
<td>2 x 10^{23}</td>
</tr>
<tr>
<td>Brightness (peak) (ph/s/0.1%BW/mm^2/mrad^2)</td>
<td>2 x 10^{32}</td>
<td>2 x 10^{30}</td>
<td>2 x 10^{32}</td>
<td>2 x 10^{30}</td>
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<tr>
<td>prf (MHz)</td>
<td>4.88*</td>
<td></td>
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<td>1.17</td>
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<tr>
<td></td>
<td>* + 50 μs macro pulses any prf</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>** +10 fs @ 1 kHz prf</td>
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## Harmonic output

<table>
<thead>
<tr>
<th>Harmonic of 12 nm</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
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<tbody>
<tr>
<td>λ (nm)</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>2.5</td>
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<tr>
<td>λ (eV)</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
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<td>Pulse energy (nJ)</td>
<td>100</td>
<td>100</td>
<td>10</td>
<td>10</td>
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Accelerator Physics and Technologies Addressed by JLAMP

- High gradient cryomodules
- RF separation of high brightness beams.
- High brightness guns
- High prf seed laser technology
- Preservation of high brightness, moderate average current beams through multiple passes.
- Bunch compression in a machine with recirculation
- CSR, LSC, wakes, in high brightness beams.
- Multipass BPMs.
- RF drive of multiple cavities.
- Halo control
Enabling Strategy 1

187 MHz LBNL VHF normal conducting gun. 20 MV/m gradient, 750 keV beam output energy. rf testing this year.
Alternate - High Brightness 500 keV DC Gun

• **Technical Need**
  – Reliable operation at 500kV
  – Cooled cathode: high average current
  – Fast replacement of various cathode wafers
  – Ultrahigh vacuum pumping

• **Approach**
  – Replace existing coaxial electrode/ceramic geometry with inverted insulator
  – Add a load-lock chamber
  – Merge with graded beta cavity

• **Benefit**
  – Significant brightness improvement
  – Valuable research source for high charge scaling
  – Improved cathode lifetime and short turnaround
  – In engineering design, insulators on order
Enabling Strategy 2 - 100 MeV High Gradient Module

- Multicell cavities
- Insulating vacuum
- 2K liq. He bath
Enabling Strategy 3

Three beamlines:
1. Normal incidence, < 30 eV
2. Grazing incidence to 1 keV
3. THz for pump/probe studies

....are collaborating with NSLS on this.
JLAMP - undulators/seed laser

RedDragon - Seed Laser
40 mJ, 25 fs, 1 kHz

THz Wiggler

Radiator

Electron Beam Direction

Diagnostics

Buncher

Modulator

XUUS – UV Source
Gain length calculations

Gain Length (cm) vs. Wavelength (µm)

- Blue line: Delta Und.
- Red line: Hybrid Und.
- Green dotted line: APLE II und.

Gain length calculations for various undulators.
Quantum Excitation

- Energy fairly low; synchrotron radiation excitation modest even relative to 10 nm target emittance
  - $\lambda/4\pi \sim 0.8$ nm-rad $\sim 1.4$ mm-mrad normalized
    - estimate $\Delta \varepsilon < 0.01$ nm-rad
  - $\delta p/p$ controlled by longitudinal match (e.g. 0.03% in example);
    - Estimate $\Delta(\delta p/p) \sim 3 \times 10^{-6}$

![Graphs showing required emittance and emittance growth vs. energy](image1)

![Graphs showing required and excited momentum spread vs. energy](image2)
Summary

• JLab research is already focused on many of the key technologies required for next generation light sources
• Existing FEL is an ideal test bed for the investigating physics and technology limits for such machines
• Soon-to-be-operational UV FEL offers short pulse capability not only in UV but, through harmonics, an average brightness at 100 nm and possibly shorter wavelengths exceeding other sources
• Modest upgrades can extend that capability quickly to fundamental lasing in amplifiers while studying physics of high charge production in injectors, brightness preservation in bends, etc.
The Jefferson Lab FEL Team

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1. While there are unique applications of the IR system most of the action is in the VUV/soft/hard X-ray region.

2. Many scientific case studies for 4th Generation Light Sources point towards similar light sources roughly divided into FELs and ERLs.

3. Such CW light sources cannot presently be built (CW injector, brightness preservation in ebeam, seed laser, cryogenics cost and efficiency, linac cost).

4. BESAC has now embraced the idea of research toward a 4GLS and has issued a position paper.
Embedded 300/600 MeV recirculator

- Modify existing linac back/front ends by moving extraction/injection hardware closer to linac (rearrange diagnostics/correctors)
- Add in vertical bend to/from recirculation transport lines lying above midplane of existing ERL
Third generation x-ray sources

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

Fourth generation x-ray sources

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

Energy-Recovery LINAC
\[ \text{bunch charge} < 100 \text{pC} \]

- Extremely high peak brilliance
- Full spatial coherence
- Ultrashort (fs) pulses
- Temporal synchronization with seeding
- Low pulse rep. Rate \( 10^2 \) to \( 10^5 \) Hz
- Few experiments

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

Next Generation Photon Sources for Grand Challenges in Science and Energy
W. Eberhardt, BESAC Feb. 2009
Gain length calculations

- **Energy 600 MeV**
  - Peak Current: 2.5 kA
  - Wiggler Wavelength: 2.7 cm
  - Gap: 1.4-0.7 cm
  - μ = 1.8 at 0.9 cm gap
  - Ep_norm = 1 μm/2 μm
  - dE = 600 keV

- **Energy 900 MeV**
  - Peak Current: 2.5 kA
  - Wiggler Wavelength: 2.7 cm
  - Gap: 1.4-0.7 cm
  - μ = 1.8 at 0.9 cm gap
  - Ep_norm = 1 μm/2 μm
  - dE = 600 keV