A NEXT GENERATION LIGHT SOURCE FACILITY AT LBNL


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Technology of a Next Generation Light Source

- High brightness electron beams
- X-ray free electron lasers
- High-power optical lasers
- FEL seeding
- Optical manipulations
- CW superconducting accelerator
- High repetition rate injector
  - Intense X-ray pulses from VUV to hard X-ray
  - High average power X-ray beams
  - Control of pulse duration
  - Control of pulse energy
  - Spatial coherence
  - Temporal coherence
  - Generation of shorter wavelengths in harmonic stages
  - Precise synchronization
  - Shorter undulators
Next Generation Light Source (NGLS) – a new class of X-ray laser

Array of (ultimately 10) configurable FEL beamlines
100 kHz CW pulse rate
Capability of one FEL having MHz rate
Independent control
Each FEL configured for experimental requirements

Injector

Laser heater

Bunch compressor

~2 GeV CW superconducting linac

Beam transport and switching

Laser systems, timing & synchronization

Low-emittance, MHz bunch rate
≤ 1 nC
≤1 mm-mrad

Photo-gun
Next Generation Light Source (NGLS) – a new class of X-ray laser

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- ≤ 1 mm-mrad

Laser systems, timing & synchronization

Upgrade potential
NGLS – unprecedented power, ultrafast pulses, high repetition rate

Today’s storage ring x-ray sources
- ~ nanoseconds
- Weak pulses at high rep rate
- ~ picoseconds

Today’s x-ray laser sources
- ~ milliseconds
- Intense pulses at low rep rate
- ~ femtoseconds

Tomorrow’s NGLS
- ~ microseconds
- Intense pulses at high rep rate
- ~ attoseconds to femtoseconds
Science-driven accelerator design

• We have worked with a broad community over four years to develop a proposal for a Next Generation Light Source
NGLS high repetition rate X-ray laser: a transformative tool for energy science

- **Imaging**
  Take pictures from stills to movies while identifying the chemical species, on ultrafast timescales

- **Structure**
  Track the changes in positions of the atoms in proteins as they act, relating structure to function

- **Spectroscopy**
  Multiple pulse and non-linear techniques
NGLS – operating characteristics

- High repetition rate FEL array
  - X-ray energy range ~0.25 – 1.2 keV
    - Fundamental, harmonics may also be used
  - Pulse length ~0.25 – 250 fs
  - Bandwidth $5 \times 10^{-5}$ – ~1% (FWHM at ~1 nm)
  - Peak power ≤1 GW
  - Average power ≤100 W
Baseline electron beam parameters

- Baseline parameters reflect single point design study
  - Chosen to meet science needs
  - At minimal machine costs
  - Flexibility around these choices
    - Performance range will be further refined in future studies

- Parameters have been achieved or are close to demonstrated performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge (pC)</td>
<td>300</td>
</tr>
<tr>
<td>Repetition rate (MHz)</td>
<td></td>
</tr>
<tr>
<td>Out of linac</td>
<td>1</td>
</tr>
<tr>
<td>Into FEL</td>
<td>0.1-1</td>
</tr>
<tr>
<td>Average current (mA)</td>
<td>0.3</td>
</tr>
<tr>
<td>Bunch length (fs)</td>
<td></td>
</tr>
<tr>
<td>Out of injector (FWHM)</td>
<td>~5000</td>
</tr>
<tr>
<td>Into FEL (usable bunch core)</td>
<td>250</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td></td>
</tr>
<tr>
<td>Out of injector</td>
<td>&gt;40</td>
</tr>
<tr>
<td>Into FEL (in usable bunch core)</td>
<td>&gt;500</td>
</tr>
<tr>
<td>Emittance (slice, normalized, mm-mrad)</td>
<td></td>
</tr>
<tr>
<td>Out of injector</td>
<td>&lt;0.6</td>
</tr>
<tr>
<td>Into FEL</td>
<td>0.6</td>
</tr>
<tr>
<td>Emittance (projected, normalized, mm-mrad)</td>
<td></td>
</tr>
<tr>
<td>Out of injector</td>
<td>0.7</td>
</tr>
<tr>
<td>Into FEL</td>
<td>0.73</td>
</tr>
<tr>
<td>Energy spread (slice, rms, keV)</td>
<td></td>
</tr>
<tr>
<td>Out of injector</td>
<td>&lt;4</td>
</tr>
<tr>
<td>Into FEL (in usable bunch core)</td>
<td>50</td>
</tr>
</tbody>
</table>
R&D: MHz rep-rate photocathode gun

Successful low-power RF and vacuum tests
Cavity now installed in test area
**R&D: MHz rep-rate photocathode gun**

Successful low-power RF and vacuum tests
Cavity now installed in test area

<table>
<thead>
<tr>
<th>Parameter</th>
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</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>187 MHz</td>
</tr>
<tr>
<td>Operation mode</td>
<td>CW</td>
</tr>
<tr>
<td>Gap voltage</td>
<td>750 kV</td>
</tr>
<tr>
<td>Field at the cathode</td>
<td>19 MV/m</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>30887</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>6.5 MW</td>
</tr>
<tr>
<td>RF Power</td>
<td>90 kW</td>
</tr>
<tr>
<td>Stored energy</td>
<td>2.3 J</td>
</tr>
<tr>
<td>Peak surface field</td>
<td>24 MV/m</td>
</tr>
<tr>
<td>Peak wall power density</td>
<td>25 W/cm²</td>
</tr>
<tr>
<td>Accelerating gap</td>
<td>4 cm</td>
</tr>
<tr>
<td>Diameter/Length</td>
<td>70/35 cm</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>$&lt; 10^{-11}$ Torr</td>
</tr>
</tbody>
</table>
R&D: High quantum efficiency photocathodes

- Alkali antimonides eg. K$_2$CsSb
- Cs$_2$Te

80 MHz Ti:S Oscillator

VIS UV mono

Sample transfer

5 axis manipulator; motor scanned theta, LN2 – 1100 K

Low Energy Electron Diffraction + Auger

Time of Flight Electron Analyzer

Tunable 2$^{\text{nd}}$, 3$^{\text{rd}}$, 4$^{\text{th}}$ harmonic generation + pulse picker
R&D: APEX – Advanced Photoinjector EXperiment

Cathode mounting & vacuum load-lock mechanism
Diagnostic beamlines
30-40 MeV booster
Laser systems on roof
Beam dump
Cathode mounting & vacuum load-lock mechanism

Diagnostic beamlines

30-40 MeV booster

Laser systems on roof

Beam dump

Currently funded for Phase-I: gun & photocathode

R&D: APEX – Advanced Photoinjector EXperiment
- Ballistic bunching
- Velocity bunching
- Emittance compensation
Injector beam dynamics modeling

Current profile

Normalized slice trans. emittance

Long. Phase Space

Slice rms energy spread
Injector beam dynamics modeling

D. Filipetto et al, “Low Energy 6D Beam Diagnostic for APEX, the LBNL VHF Photo-injector,” WEP222

C. F. Papadopoulos et al, “Photoinjector Beam Dynamics for the APEX Project,” THP200

J. Feng et al, “Drive Laser System for APEX the Advanced Photo-injector Project at the LBNL,” THP222
Linac schematic and beam dynamics modeling

- IMPACT model with full physics

- 10^9 macroparticles

- ELEGANT model
Linac schematic and beam dynamics modeling

M. Venturini et al, “Studies of a Linac Driver for a High Repetition Rate X-rays FEL,” THP180

• IMPACT model with full physics
  • $10^9$ macroparticles

• ELEGANT model
R&D: beam spreader kicker
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R&D: beam spreader kicker

- Bend angle 3 mrad
- Magnet length 2 m
- Pulser voltage 12 kV
- Pulser current 240 A
- B field 60 G
- E field 1.8 MV/m
- Rise/fall times 5 ns
- Pulse width 10 ns
- Repetition rate 100 kHz
Three initial FEL beamlines to span the science case

- **Seeded**
  - 5 – 150 fs
  - 10 μs
  - High resolution
  - ~Time-bandwidth limited
  - $10^{11} - 10^{12}$ ph/pulse
  - $10^{-3} - 5 \times 10^{-5}$ bandwidth
  - **High-resolution spectroscopy**
  - **Diffract-and-Destroy (with harmonics)**

- **2 Color Seeded**
  - 0.25 – 25 fs
  - 10 μs
  - Ultra-fast
  - 250 as pulses
  - 2 color
  - $10^{8}$ ph/pulse
  - **Multidimensional spectroscopy**

- **SASE**
  - 5 – 250 fs
  - ≤1 μs
  - Highest rep rate
  - High flux
  - $10^{11} - 10^{12}$ ph/pulse
  - 100 W
  - **Diffract-and-Destroy (at highest rate)**
  - **Photon correlation spectroscopy**
Beamline 1: ECHO seeded

- ECHO experiments under way at SLAC, SINAP
- Additional R&D program under development
Beamline 2: ECHO seeded 2-color attosecond

# Initial performance of first 3 beamlines

<table>
<thead>
<tr>
<th></th>
<th>Beamline 1</th>
<th>Beamline 2</th>
<th>Beamline 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Seeded, narrow-bandwidth</td>
<td>2-color seeded</td>
<td>SASE</td>
</tr>
<tr>
<td><strong>Feature</strong></td>
<td>Short coherent pulses</td>
<td>2-color X-ray pump/probe with adjustable delay and attosecond pulses</td>
<td>High average flux and brightness</td>
</tr>
<tr>
<td><strong>Pulse length</strong></td>
<td>5 – 150</td>
<td>0.25 – 25</td>
<td>~5 – 250</td>
</tr>
<tr>
<td>(fs, FWHM)</td>
<td>(1.0 – 0.28 keV)</td>
<td>(1.0 – 0.28 keV)</td>
<td>(1.2 – 0.38 keV)</td>
</tr>
<tr>
<td><strong>Wavelength range</strong></td>
<td>1.2 – 4.5</td>
<td>1.2 – 4.5</td>
<td>1.0 – 3.3</td>
</tr>
<tr>
<td>(fundamental, nm)</td>
<td>(1.0 – 0.28 keV)</td>
<td>(1.0 – 0.28 keV)</td>
<td>(1.2 – 0.38 keV)</td>
</tr>
<tr>
<td><strong>Maximum repetition rate (kHz)</strong></td>
<td>100</td>
<td>100</td>
<td>1,000</td>
</tr>
<tr>
<td><strong>Total photons/pulse</strong></td>
<td>$\sim 10^{11}$ (150 fs, 1.2 nm)</td>
<td>$\sim 10^9$ (sub-fs)</td>
<td>$\sim 10^{11}$ (250 fs, 1 nm)</td>
</tr>
<tr>
<td></td>
<td>$\sim 10^{12}$ (150 fs, 4.5 nm)</td>
<td>$\sim 10^{12}$ (250 fs, 3.3 nm)</td>
<td></td>
</tr>
<tr>
<td><strong>Photons per 6D coherence volume</strong></td>
<td>$\sim 10^{11}$</td>
<td>$\sim 10^8$</td>
<td>$\sim 10^{10}$</td>
</tr>
<tr>
<td><strong>Peak power (GW)</strong></td>
<td>$\sim 0.1$ (1.2 nm)</td>
<td>$\sim 0.05$ (1.2 nm)</td>
<td>$\sim 0.1$ (1 nm)</td>
</tr>
<tr>
<td></td>
<td>1 (4.5 nm)</td>
<td>0.1 (4.5 nm)</td>
<td>1 (3.3 nm)</td>
</tr>
<tr>
<td><strong>Average power (W)</strong></td>
<td>$\sim 1$ (150 fs, 1.2 nm)</td>
<td>$\sim 0.001$ (sub-fs)</td>
<td>$\sim 0.1$ (5 fs, 1 nm)</td>
</tr>
<tr>
<td></td>
<td>10 (150 fs, 4.5 nm)</td>
<td>0.1 (fs)</td>
<td>100 (250 fs, 3.3 nm)</td>
</tr>
<tr>
<td><strong>Power in 3rd harmonic relative to fundamental (%)</strong></td>
<td>$\sim 0.1$ (1.2 nm)</td>
<td>~ 1</td>
<td>$\sim 0.1$ (1 nm)</td>
</tr>
<tr>
<td></td>
<td>1 (4.5 nm)</td>
<td></td>
<td>1 (3.3 nm)</td>
</tr>
<tr>
<td><strong>Relative bandwidth (%)</strong></td>
<td>$\sim 0.005$ (150 fs, 1.2 nm)</td>
<td>$\geq 1.4$ (sub-fs)</td>
<td>~ 0.2 (1 nm)</td>
</tr>
<tr>
<td></td>
<td>0.02 (150 fs, 4.5 nm)</td>
<td></td>
<td>0.5 (3.3 nm)</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>Variable, linear/circular</td>
<td>Variable, linear/circular</td>
<td>Variable, linear/circular</td>
</tr>
</tbody>
</table>

![Graph showing photons per pulse vs. wavelength for different beamlines]
NGLS project status

• Pre-conceptual design studies

• LBNL submitted “Proposal for approval of Conceptual Design” to US Department of Energy, December 2010

• DOE presented “Mission Need” for an NGLS in March 2011
  – Hoping for confirmation of “CD0”
  – LBNL would lead the writing of a Conceptual Design Report, due around October 2013
A Next Generation Light Source facility at LBNL – Summary

- Pre-conceptual design studies for a high repetition rate FEL array
  - High repetition rate injector (1 MHz)
  - CW Superconducting linear accelerator
  - Bunches spread to an array of independent soft X-ray FELs
  - Control of X-ray pulses using a variety of FEL designs
  - High average X-ray power (up to ~100 W)
    - Flexible platform for future expansion

- R&D in critical technologies supported by DOE BES and LDRD
  - Gun
  - Photocathodes
  - Kickers
  - FEL seeding (at SLAC)

- Conceptual design approval is hoped for in the near future
Thank you for your attention

NGLS – other papers at this conference

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