Excitements and Challenges for Future Light Sources Based on X-Ray FELs

26th ADVANCED ICFA BEAM DYNAMICS WORKSHOP ON NANOMETRE-SIZE COLLIDING BEAMS

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and
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Lausanne, Switzerland
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SASE FELs

- Electron bunch
- X-ray emission

1% of X-Ray Pulse

Electron Bunch Micro-Bunching

Exponential Gain Regime

Saturation

Undulator Regime

Avg. Field Power vs. Z

Power (watts)

Z (m)

Time (fs)
Transverse Coherence

Z=25 m

Z=37.5 m

Z=50 m

Z=62.5 m

Z=75 m

Z=87.5

Courtesy of Sven Reiche, UCLA
## Peak Brightness Enhancement From Undulator To SASE

\[ B = \frac{\text{# of photons}}{\Omega_x \Omega_y \Omega_z} \quad (\Omega_i - \text{phase space area}) \]

<table>
<thead>
<tr>
<th></th>
<th>Undulator</th>
<th>SASE</th>
<th>Enhancement Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td># of photons</td>
<td>( \alpha N_e )</td>
<td>( \alpha N_e N_{lc} )</td>
<td>( N_{lc} \sim 10^6 )</td>
</tr>
<tr>
<td>( \Omega_x \Omega_y )</td>
<td>((2\pi \varepsilon_x) (2\pi \varepsilon_y))</td>
<td>((\lambda/2)^2)</td>
<td>10^2</td>
</tr>
<tr>
<td>( \Omega_z )</td>
<td>( \frac{\Delta \omega}{\omega} \cdot \left( \frac{\sigma_z}{c} \right) = 10^{-3} \times 10 \text{ps} )</td>
<td>( \frac{\Delta \omega}{\omega} \cdot \left( \frac{\sigma_z}{c} \right)_{\text{compressed}} = 10^{-3} \times 100 \text{fs} )</td>
<td>10^2</td>
</tr>
</tbody>
</table>

\( I_c \) - coherence length
How bright are different light sources?
Projects:

TESLA

The Superconducting Electron-Positron Linear Collider
with an Integrated X-Ray Laser Laboratory

Technical Design Report

Part I Executive Summary
Part II The Accelerator
Part III Physics at an e⁺e⁻ Linear Collider
Part IV A Detector for TESLA
Part V The X-Ray Free Electron Laser
Part VI Appendices

TESLA Brochure (PDF document, 537 MB)
### LCLS: Parameters & Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEL Radiation Wavelength</td>
<td>15.0 Å</td>
<td>1.5 Å</td>
</tr>
<tr>
<td>Electron Beam Energy</td>
<td>4.54 GeV</td>
<td>14.35 GeV</td>
</tr>
<tr>
<td>Repetition Rate (1-bunch)</td>
<td>120 Hz</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Single Bunch Charge</td>
<td>1 nC</td>
<td>1 nC</td>
</tr>
<tr>
<td>Normalized rms Emittance</td>
<td>2.0 mm-mrad</td>
<td>1.5 mm-mrad</td>
</tr>
<tr>
<td>Peak Current</td>
<td>3.4 kA</td>
<td>3.4 kA</td>
</tr>
<tr>
<td>Coherent rms Energy Spread</td>
<td>&lt;2 x 10(^{-3})</td>
<td>&lt;1 x 10(^{-3})</td>
</tr>
<tr>
<td>Incoherent rms Energy Spread</td>
<td>&lt;0.6 x 10(^{-3})</td>
<td>&lt;0.2 x 10(^{-3})</td>
</tr>
<tr>
<td>Undulator Length</td>
<td>100 m</td>
<td>100 m</td>
</tr>
<tr>
<td>Peak Coherent Power</td>
<td>11 GW</td>
<td>9.3 GW</td>
</tr>
<tr>
<td>Peak Spontaneous Power</td>
<td>8.1 GW</td>
<td>81 GW</td>
</tr>
<tr>
<td>Peak Brightness *</td>
<td>1.2 x 10(^{32})</td>
<td>12 x 10(^{32})</td>
</tr>
</tbody>
</table>

* photons/sec/mm\(^2\)/mrad\(^2\)/0.1%-BW
Performance Characteristics

Peak and time averaged brightness of the LCLS and other facilities operating or under construction.
Self Seeding Scheme for Full Longitudinal Coherence
Two-stage undulator for shorter pulse

Also a DESY scheme which emphasizes line-width reduction (B. Faatz)

Mitigates $e-$ energy jitter and undulator wakes

$Si$ monochromator ($T = 40\%$)

SASE Saturation (23 GW)
LCLS - The First Experiments

Femtochemistry
Dan Imre, BNL

Nanoscale Dynamics in Condensed Matter
Brian Stephenson, APS

Atomic Physics
Phil Bucksbaum, Univ. of Michigan

Plasma and Warm Dense Matter
Richard Lee, LLNL

Structural Studies on Single Particles and Biomolecules
Janos Hajdu, Uppsala Univ.

Report developed by international team of ~45 scientists working with accelerator and laser physics communities
Accelerator System

- RF Photo-cathode gun

Emittance Preservation in Linacs
- transverse wakefields
- CSR microbunching instability
- misalignments & chromaticity

Machine Stability
- jitter tolerance budget
- simulation of budget
LCLS: System Components

- **7 MeV**
  - \( \sigma_z \approx 0.83 \text{ mm} \)
  - \( \sigma_\delta \approx 0.2 \% \)

- **150 MeV**
  - \( \sigma_z \approx 0.83 \text{ mm} \)
  - \( \sigma_\delta \approx 0.10 \% \)

- **250 MeV**
  - \( \sigma_z \approx 0.19 \text{ mm} \)
  - \( \sigma_\delta \approx 1.8 \% \)

- **4.54 GeV**
  - \( \sigma_z \approx 0.023 \text{ mm} \)
  - \( \sigma_\delta \approx 0.76 \% \)

- **4.54-14.35 GeV**
  - \( \sigma_z \approx 0.023 \text{ mm} \)
  - \( \sigma_\delta \approx 0.02 \% \)

- **1.5 Å**
  - 8 GW
  - \( \sigma_z \approx 0.023 \text{ mm} \)

- **15 Å**
  - 17 GW
  - \( \sigma_z \approx 0.023 \text{ mm} \)

- **2525-14.35 GeV**
  - \( \sigma_z \approx 0.023 \text{ mm} \)
  - \( \sigma_\delta \approx 0.02 \% \)
RF Photo-Cathode Gun

Normalized Slice Emittance: 1 \mu m rad (rms)
Max Bunch Charge: 1 nC
Bunch Length: 0.8 mm

“Half” Cell
Laser Port
Full Cell
Electron Beam Exit
Photocathode

Scale
0 1" 2" 3"
X-band RF used to Linearize Compression
\( (f = 11.424 \text{ GHz}) \)

S-band RF curvature and 2\textsuperscript{nd}-order momentum compaction cause sharp peak current spike

\[
e V_x = -E_0 \left[ 1 - \frac{1}{2\pi^2} \frac{\lambda_x^2 T_{566}}{R_{56}^3} \left( 1 - \sigma_z / \sigma_{z_0} \right)^2 \right] - E_i
\]

X-band RF at decelerating phase corrects 2\textsuperscript{nd}-order and allows unchanged \( z \)-distribution

0.6-m section, 22 MV available at SLAC (200-\( \mu \)m alignment)
Coherent Synchrotron Radiation (CSR)

- Induced energy spread breaks achromatic system
- Causes bend-plane emittance growth (short bunch is worse)
- Powerful radiation generates energy spread in bends

\[ \Delta E / E < 0 \]
\[ \Delta x = R_{16}(s) \Delta E / E \]

Overtaking length:
\[ L_0 \approx (24 \sigma_z R^2)^{1/3} \]

Coherent radiation for \( \lambda > \sigma_z \)
CSR Micro-bunching and Projected Emittance Growth

14.3 GeV at undulator entrance 230 fsec

Projected emittance growth is simply ‘steering’ of bunch head and tail.

0.5 µm

‘slice’ emittance is not altered

Workshop in Berlin, Jan. 2002 to benchmark results (www.DESY.de/csr/)

Courtesy Paul Emma, SLAC
Cell structure of the LCLS undulator line

- UNDULATOR
- X-Ray Diagnostics
- Quadrupoles
- Horizontal Steering Coil
- Vertical Steering Coil
- Beam Position Monitor

Dimensions:
- 3420 mm
- 187 mm
- 421 mm
- 11055 mm
Start-to-End Tracking Simulations

- Track entire machine to evaluate beam brightness & FEL

- Track machine many times with jitter to test stability budget (M. Borland, ANL)

Diagram:

- **Parmela**
- **Elegant**
- **Genesis**

Steps:
- space-charge
- compression, wakes, CSR, ...
- SASE FEL with wakes
Magnetic Measurement of the Prototype
Potential for Damage to X-Ray Optics

- In Hall A, low-Z materials will accept even normal incidence. The fluences in Hall B are sufficiently low for standard optical solutions. Even in the Front End Enclosure (FEE), low Z materials may be possible at normal incidence above ~4 keV, and at all energies with grazing incidence. In the FEE, gas is required for attenuation at < 4 keV
SASE Demonstration Experiments at Longer Wavelengths

• IR wavelengths:
  UCLA/LANL ($\lambda = 12\mu$, $G = 10^5$)
  LANL ($\lambda = 16\mu$, $G = 10^3$)
  BNL ATF/APS ($\lambda = 5.3\mu$, $G = 10$, HGHG = $10^7$ times S.E.)

• Visible and UV:
  TESLA Test Facility (DESY): $E_e = 390$ MeV, $L_u = 15$ m, $\lambda = 42$ nm
  VISA (BNL-LANL-LLNL-SLAC-UCLA): $E_e = 70$ MeV, $L_u = 4$ m, $\lambda = 0.8$ $\mu$
  APS LEUTL: $E_e \leq 700$ MeV, $L_u = 25$ m, $120$ nm $\leq \lambda \leq 530$nm

All successful!
LOW-ENERGY UNDULATOR TEST LINE PARAMETERS

PROJECT GOALS

- Perform experiments with the SASE FEL output
- Assess the challenges associated with producing a SASE FEL in preparation for an x-ray regime machine

PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Regime I 530</th>
<th>Regime II 120</th>
<th>Regime III 51</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon Beam Radiation Classification</td>
<td>Visible (green)</td>
<td>Vacuum ultraviolet</td>
<td>Vacuum ultraviolet</td>
</tr>
<tr>
<td>Electron energy (MeV)</td>
<td>217</td>
<td>457</td>
<td>700</td>
</tr>
<tr>
<td>Normalized emittance (mm mrad)</td>
<td>5π</td>
<td>3π</td>
<td>3π</td>
</tr>
<tr>
<td>Energy spread (%)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td>100</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>Undulator period (mm)</td>
<td>33</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Magnetic field (T)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Undulator gap (mm)</td>
<td>9.3</td>
<td>9.3</td>
<td>9.3</td>
</tr>
<tr>
<td>Cell length (m)</td>
<td>2.73</td>
<td>2.73</td>
<td>2.73</td>
</tr>
<tr>
<td>Gain length (m)</td>
<td>0.81</td>
<td>0.72</td>
<td>1.2</td>
</tr>
<tr>
<td>Undulator length (m)</td>
<td>9 x 2.4</td>
<td>9 x 2.4</td>
<td>10 x 2.4</td>
</tr>
</tbody>
</table>
Properties of SASE FEL radiation:

1) transv. coherence
2) long. coherence
3) fluctuations

1) Transverse coherence should be almost 100% at saturation

Observation of diffraction pattern at TTF FEL:
TTF2: Soft-X ray User Facility / Overview

TTF Phase II

experimental area bypass 1000 MeV 450 MeV 150 MeV 4 MeV

undulators seeding collimator # 7 # 6 // # 4 # 3 # 2 module # 1 RF gun
Future Light Sources based on X-ray FELs

- A leap in electron beam and photon beam technology
- A leap in x-ray science
- Proposals around the world for UV and x-ray facilities
- LCLS turns on in 98
Acknowledgement

• I thank my colleagues at SLAC, DESY, and ANL for making these excellent VGs available to me!