SASE Saturation at the SCSS Test Accelerator Ranging from 50 nm to 60 nm

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on behalf of SPring-8 Joint-Project for XFEL
• Overview of the Test Accelerator
• Commissioning History
• Observation of SASE Saturation
• Investigation of the Electron Beam Performance
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Overview of the Test Accelerator

Location

[Image showing the location of the Test Accelerator in relation to SPring-8 Storage Ring and XFEL.]
Layout of the Test Accelerator

• 250 MeV Accelerator
  – To prove the SCSS concept
  – Constructed in 2005 on an existing building with some extension
2008/08/24-29 FEL2008, Gyeongju

Undulator

VUV Spectrometer
• Overview of the Test Accelerator
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History of Commissioning (1)

2005
- 3 4 5 6 7 8 9 10 11 12
- Civil Construction
- Installation(1)
- RF Aging & Commissioning
- 1st Light (Spont.)

2006
- 1 2 3 4 5 6 7 8 9 10 11 12
- Commissioning toward SASE
- 1st Observation of FEL Amplification
- Installation(2)

2007
- 1 2 3 4 5 6 7 8 9 10
- Commissioning for Seeding (150MeV)
- Seeding at 150nm
- Repair of Electron Gun
- Repair of U2
- RF Feedback Improvement
- Tuning toward Saturation
- Saturation at 60 nm
First Light (2005/11/30)

First spontaneous radiation observed by CCD

$E=66\text{MeV}, \text{gap}=10\text{mm}, \lambda=480\text{nm}$
History of Commissioning (2)

2005
- Civil Construction
- Installation(1)
- RF Aging & Commissioning
- 1st Light (Spont.)

2006
- Installation(2)
- Commissioning toward SASE
- 1st Observation of FEL Amplification
- Commissioning for Seeding (150MeV)
- Seeding at 150nm
- Repair of Electron Gun
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2007
- Saturation at 60 nm
First Lasing (2006/06/20)

SASE

Spontaneous

Interference pattern by a double slit

Spectra for different electron charges

Counts/e-Charge

Wavelength (nm)

300 shots average

0.25 nC

0.23 nC

0.21 nC

0.18 nC

0.15 nC

0.08 nC

0.055 nC

x10^4
Injector RF Parameter Stabilization

**RF Phase**
- Before: $\sigma_{\phi} = 0.10^\circ$
- After: $\sigma_{\phi} = 0.02^\circ$
- $0.1$ deg.

**RF Voltage**
- Before: $\sigma_v = 0.17\%$
- After: $\sigma_v = 0.03\%$
- $0.21\%$
Repair of Undulator 2

• Radiation power did not reach saturation in terms of the pulse energy and fluctuation

• Magnetic error in the d.s. undulator (U2)
  – Bandwidth of spontaneous radiation from U2 was about 3 times broader than U1
  – No amplification was observed with U2 alone
  – Significant multipole (skew quadrupole) components was observed both by e- beam and magnetic measurement

⇒ Repair of U2 to Achieve Saturation
Modification of the Magnetic Design

45-deg. inclined Halbach

Hybrid (before TiN Coating)
History of Commissioning (4)

- Civil Construction
- Installation(1)
- RF Aging & Commissioning
- 1st Light (Spont.)
- Installation(2)
- Commissioning toward SASE
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Trajectory Correction

• High Gain/Segment
  – Use the FEL intensity a probe for trajectory correction
• Horizontal: Adjust Steering (1D)
• Vertical: Adjust Steering & Und. Height (2D)
Envelope Matching

- Envelope Matching Over the Undulator
  - Projected: Beam Profile Monitor
  - Sliced (Lasing Part): ??

- High Gain/Segment
  - Use the FEL intensity a probe for envelope matching

- Adjust Several Magnetic Lenses and Q. Magnets Empirically(!)
History of Commissioning (5)

- Civil Construction
- Installation (1)
- RF Aging & Commissioning
- 1st Light (Spont.)
- Installation (2)
- Commissioning toward SASE
- 1st Observation of FEL Amplification
- Commissioning for Seeding (150MeV)
- Seeding at 150nm
- Repair of Electron Gun
- Repair of U2
- RF Feedback Improvement
- Tuning toward Saturation
- Saturation at 60 nm
Saturation Achieved (2007/10)

- Radiation power measured after reinstallation of U2 was about 10 times larger than before.
- Pulse energy fluctuation was less than 10 %.
  - seems to saturate, but has to be verified
- It is not feasible to measure the gain curve (radiation power vs. undulator length) with just two undulator segments.

An alternative method has to be taken to verify saturation!
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How to Verify Saturation?

- FEL Radiation Power with Linear Theory

\[ P = P_0 \exp \left( \frac{z}{L_g} \right) \]

- Typical Measurement: \( L_g \) fixed, \( z \) varied
  - Exponential growth of the radiation power
  - Not applicable to SCSS test accelerator
How to Verify Saturation? (con’t)

- Alternative Method: z fixed, L_g varied

\[ P = P_0 \exp \left( L_g^{-1} z \right) \]

\[ \varepsilon = 1 \pi \text{mm.mrad} \]
\[ I = 300 \text{A} \]
\[ \Delta E/E = 5 \times 10^{-4} \]

L_g^{-1} depends almost linearly on \( \lambda \)

P(\( \lambda \)) shows exponential growth & saturation with \( \lambda \)
Pulse Energy and Fluctuation vs. $\lambda$

Energy/Pulse ($\mu$J)

Wavelength (nm)

K Value

Pulse Energy

exponential growth

saturation

Fluctuation

Fluctuation (%)

0.32 0.65 0.9 1.09 1.23 1.37 1.49

0 10 20 30 40 50

0 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2

30 35 40 45 50 55 60
Long-Term Stability of SASE Intensity

Intensity variation = 11%(1σ)

2/19/2008

Laser Intensity [a.u.]

19:30  20:00  20:30

Time

50 nm
<table>
<thead>
<tr>
<th>Item</th>
<th>Achieved Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>50~60 nm</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>≤ 20 Hz</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>~30μJ@60nm</td>
</tr>
<tr>
<td>Pulse Energy Fluctuation (σ)</td>
<td>~10%</td>
</tr>
<tr>
<td>Beam Size # (FWHM)</td>
<td>~3mm</td>
</tr>
<tr>
<td>Pointing Stability #</td>
<td>~5% to the beam size</td>
</tr>
<tr>
<td>Averaged Spectral Width (FWHM)</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

# 10m from the undulator exit
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Longitudinal Bunch Profile

C-band Linac C-4
Chicane
Undulator

conversion of the bunch profile from longitudinal to horizontal

Energy Chirp
Transverse Profile

Current (A)

-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0

0 50 100 150 200 250 300

-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0

Current (A)

2008/08/24-29 FEL2008, Gyeongju
Comparison with FEL Simulations

Experimental

\[ \Delta E/E = 5 \times 10^{-4} \]
\[ \varepsilon = 0.7 \pi \text{mm.mrad} \]

\[ \sigma_E/E = 5 \times 10^{-4} \]
\[ \varepsilon = 0.7 \pi \text{mm.mrad} \]

L_g \sim 0.4 \text{m}
Emittance & Energy Spread

Relation between ε and σₖ/E for Lₕ=0.4m

Emittance Measured Just after the E-Gun (Double Slit Method)
Summary

• The SCSS test accelerator constructed to demonstrate the concept of SCSS, has reached saturation in the wavelength region longer than 50 nm.

• Sliced emittance at the undulator section, deduced from the comparison with the FEL simulations, has been found to be at least better than $0.9\pi \text{mm.mrad}$.

• User experiments started in Oct. 2007, and several results have been presented and published.