Recent Progress and Operational Status of the Compact ERL at KEK

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E. Cenni [on leave]
Future Plan: ERL Light Source Project at KEK

Staged plan:
1. 3-GeV ERL as synchrotron light source
2. 6-7 GeV XFEL Oscillator (XFEL-O)

RF frequency: 1.3 GHz
Beam current: 10-100 mA
Bunch charge: 7.7-77 pC
Normalized emittance: 0.1-1 mm·mrad

The Compact ERL (cERL)

To demonstrate technologies for the ERL light source.

Parameters of the cERL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>In operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy $E$</td>
<td>35 MeV</td>
<td>20 MeV</td>
</tr>
<tr>
<td>Injector energy $E_{\text{inj}}$</td>
<td>5 MeV</td>
<td>2.9 - 6 MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>10 mA</td>
<td>80 μA</td>
</tr>
<tr>
<td>Normalized emittance [mm-mrad]</td>
<td>0.1 @7.7 pC</td>
<td>1 @77 pC</td>
</tr>
<tr>
<td>Repetition frequency of bunches</td>
<td>1.3 GHz</td>
<td>1.3 GHz (usual)</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>1-3 ps (usual)</td>
<td>1-3 ps (usual)</td>
</tr>
<tr>
<td>$E_{\text{acc}}$ in main linac</td>
<td>15 MV/m</td>
<td>8.2 MV/m</td>
</tr>
<tr>
<td>Gun high voltage</td>
<td>500 kV</td>
<td>390 kV</td>
</tr>
<tr>
<td>Max. heat load at 2K</td>
<td>80 W</td>
<td>100 - 80 W</td>
</tr>
</tbody>
</table>
Beam Optics of cERL

Injector (gun → exit of main linac). Using GPT.

Recirculation loop (exit of main linac → beam dump). Optics for LCS experiment is shown. Using elegant.
Time Structure of Beams

**CW beam**
(for high currents)

Expand

\[ \sigma_t = 1-3 \text{ ps} \]

1.3 GHz
769.2 ps

Bunch charge: 7.7 pC → average current: 10 mA

Typical repetition rate of macro-pulses: 5 Hz

**Burst beam**
(for beam tuning)

1.3 GHz
769.2 ps

Initial conditions are determined by the gun-drive laser.
## Construction and Commissioning

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Refurbishment of building</td>
</tr>
<tr>
<td>2009</td>
<td>Clearing radioactive materials</td>
</tr>
<tr>
<td>2010</td>
<td>Construction of radiation shielding</td>
</tr>
<tr>
<td>2011</td>
<td>Construction of injector</td>
</tr>
<tr>
<td>2012</td>
<td>Commissioning of injector</td>
</tr>
<tr>
<td>2013</td>
<td>Construction of recirculation loop</td>
</tr>
<tr>
<td>2014</td>
<td>Commissioning of cERL (with loop)</td>
</tr>
<tr>
<td>2015</td>
<td>Construction of LCS system</td>
</tr>
<tr>
<td></td>
<td>Commissioning of LCS system</td>
</tr>
</tbody>
</table>

**Construction**

**Commissioning/Operation**

*May, 2015*
Picture of the cERL

- Photocathode DC gun
- Main-linac cryomodule
- Injector cryomodule
- Injector diagnostic beamline
- Recirculation loop
Beam Operation Time

The time while the beam was ON.

Japanese fiscal year: April - March
LCS: Laser Compton Scattering

Commissioning of injector
Commissioning of recirculation loop
Beam-current upgrade, LCS experiment

Construction of loop
Installation of LCS system

Beam Operation Time (h)

Japanese Fiscal Year

2013 Apr.

2014 Apr.

2015 Apr.
Beam Current of 80 μA (CW) was Recirculated

Measured at the beam dump

April 2, 2015

Beam Current (μA)

Time

21:20 21:30 21:40 21:50

0 10 20 30 40 50 60 70 80 90 100
Beam Currents: Achievement and Prospect

At present

- 1 mA
- 10 mA
- 100 μA

Prospect

- 10 mA
Gun and SC Cavities worked very stably

**Gun voltage**

0 - 500 kV

**Main-linac Cavities**

(ML-1, ML-2)

Accelerating voltage/cavity (MV)

- **Conditioning**
- **Dispersion measurement**

**Operation of Photocathode DC Gun (Feb. 16 - Mar. 2)**

During 2 weeks

**Operation of Main-Linac Cavities (Feb. 16 - Mar. 2)**

During 2 weeks
Beam Emittance (under study)

At an injector energy of $E = 6.1$ MeV

<table>
<thead>
<tr>
<th>Bunch charge</th>
<th>At injector</th>
<th>Normalized emittance: $\varepsilon_n [\text{mm} \cdot \text{mrad}] = \beta\gamma\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02 pC</td>
<td>0.17 mm·mrad</td>
<td></td>
</tr>
<tr>
<td>0.77 pC</td>
<td>$\approx 0.3$ mm·mrad</td>
<td></td>
</tr>
<tr>
<td>7.7 pC</td>
<td>0.5 - 0.8 mm·mrad</td>
<td></td>
</tr>
</tbody>
</table>

At an injector energy of $E = 2.9$ MeV

<table>
<thead>
<tr>
<th>Bunch charge</th>
<th>At injector ($E=2.9$ MeV)</th>
<th>At recirculation loop ($E=19.9$ MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02 pC</td>
<td>-</td>
<td>0.14 / 0.14</td>
</tr>
<tr>
<td>0.5 pC</td>
<td>-</td>
<td>0.32 / 0.28</td>
</tr>
<tr>
<td>7.7 pC</td>
<td>2.5 / 2.9</td>
<td>5.8 / 4.6</td>
</tr>
</tbody>
</table>

Study to reduce the beam emittance is in progress.
Demonstration of Energy Recovery ($I_0 = 30 \, \mu A$)

**ERL operation**
Cavities 1 and 2: acceleration (1st pass) and deceleration (2nd pass)

**Non-ERL operation**
Cavity 2: deceleration  
(b) Cavity 1: acceleration  
(c) (Vc=8.57 MV/cavity)

E=2.9 MeV

**No beam loading**
Energy recovery: 100-98.6%  
(within accuracy of the measurement)

**Beam loading (+ and -)**

Cavity 1: $P_{in} - P_{ref}$

Power lost in cavity = ($P_{in}$ : input power to cavity) - ($P_{ref}$ : reflected power from cavity)
Laser Compton Scattering (LCS)

R. Nagai et al., Demonstration of High-flux Photon Generation from an ERL-based Laser Compton Photon Source, TUPJE002
A. Kosuge et al., Development of a High Average Power Laser for High Brightness X-ray Source and Imaging at cERL, TUPWA066

Work is supported by:
A government (MEXT) subsidy for strengthening nuclear security (R. Hajima, JAEA), and Photon and Quantum Basic Research Coordinated Development Program from the MEXT (N. Terunuma, KEK)

The principal parameters

<table>
<thead>
<tr>
<th>Electron beams:</th>
<th>Laser enhancement cavity and 45W laser</th>
<th>Experimental hut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>20 MeV</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>162.5 MHz</td>
<td></td>
</tr>
<tr>
<td>Max. current</td>
<td>80 μA</td>
<td></td>
</tr>
<tr>
<td>Laser:</td>
<td>1064 nm</td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>1064 nm</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>162.5 MHz</td>
<td></td>
</tr>
<tr>
<td>Produced X-ray</td>
<td>6.9 keV</td>
<td></td>
</tr>
<tr>
<td>Photon energy</td>
<td>6.9 keV</td>
<td></td>
</tr>
</tbody>
</table>
Beam Optics for the LCS

- Low-beta insertion for small beam sizes at IP
- Transport beams to the dump with small beam losses

Beam optics was established

IP: interaction point

Design optics (example: “70% middle” optics)

\[ \sigma_x^* = 21 \, \mu m, \quad \sigma_y^* = 33 \, \mu m \text{ at IP} \]

Beam sizes at IP were estimated from Q-scan data

\[ \sigma_x^* \sim 13 \, \mu m, \quad \sigma_y^* \sim 25 \, \mu m \text{ (example)} \]

Beam size at the screen monitor

\[ \beta_x^* \sim 0.037 m, \quad \beta_y^* \sim 0.11 m \]

K-value of QMLC04

\[ \sigma_x^*, \sigma_y^* < \text{(resolution of the screen monitor)} \]

Bunch charge: 0.5 pC/bunch,
Normalized emittances: \((\epsilon_{nx}, \epsilon_{ny}) = (0.47, 0.39) \, \text{mm-mrad}\)
X-ray was Successfully Produced by LCS

Parameters of electron beams:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [MeV]</td>
<td>20</td>
</tr>
<tr>
<td>Bunch charge [pC]</td>
<td>0.36</td>
</tr>
<tr>
<td>Bunch length [ps, rms]</td>
<td>2</td>
</tr>
<tr>
<td>Spot size [μm, rms]</td>
<td>30</td>
</tr>
<tr>
<td>Emittance [mm mrad, rms]</td>
<td>0.4</td>
</tr>
<tr>
<td>Repetition Rate [MHz]</td>
<td>162.5</td>
</tr>
<tr>
<td>Beam current [μA]</td>
<td>58</td>
</tr>
</tbody>
</table>

Parameters of laser (enhanced by cavity):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center wavelength [nm]</td>
<td>1064</td>
</tr>
<tr>
<td>Pulse energy [μJ]</td>
<td>64</td>
</tr>
<tr>
<td>Pulse length [ps, rms]</td>
<td>5.65</td>
</tr>
<tr>
<td>Spot size [μm, rms]</td>
<td>30</td>
</tr>
<tr>
<td>Collision angle [deg]</td>
<td>18</td>
</tr>
<tr>
<td>Repetition rate [MHz]</td>
<td>162.5</td>
</tr>
</tbody>
</table>

Results:

- Photon energy = **6.9 keV**
- Detector count rate = **1200 cps @φ4.66mm**
- Source flux = **4.3 x 10^7 ph/s** (*)

(*) calculated by CAIN/EGS simulations

An X-ray image of a hornet which was taken using LCS-produced X-ray. Detector: HyPix-3000 from RIGAKU. Detector was apart from the sample by approx. 2.5 m.
The Second Photocathode DC Gun

M. Yamamoto, to be presented at ERL2015.

- Vacuum pressure: $4 \times 10^{-10}$ Pa
- Conditioned up to 550 kV
- 500 kV was hold for 50 h without any trips
- Ready for beam-extraction test
Summary and Outlook

- The Compact ERL was commissioned and is in stable operation.
- Learned many lessons from the commissioning.
- The photocathode DC gun and both (injector and ML) SC cavities are operating very stably.
- Achieved beam current of 80 μA.
- X-ray of 7 keV was successfully produced from laser Compton scattering.
- We have established many important technologies for the ERL light source.
  We continue to conduct R&D effort on remaining issues such as:
  - Improved cavity-assembly technique for higher accelerating gradient
  - Mass-production technique for main-linac cavities

Subjects in FY2015

- Lower emittance at high bunch-charges ($q_b \geq 7.7$ pC)
- Beam current: 1 mA
- Bunch compression ($\sigma_t \sim 100$ fs)
- Higher X-ray flux in LCS experiment
Acknowledgment

We would like to thank the people of ERL community, especially, the members of the Jefferson Lab. and the Cornell University, for useful information and discussions.