Operational Progress in Compact-ERL and Development of ERL-FEL for EUV Light Source at KEK

ERL project Office, KEK

Hiroshi KAWATA

Contents

• Progress in Compact-ERL
• Design study of ERL-FEL for EUV light Source
cERL Team

High Energy Accelerator Research Organization (KEK)

Japan Atomic Energy Agency (JAEA)

Hiroshima University
M. Kuriki

The Graduate University for Advanced Studies (Sokendai)
E. Cenni [on leave]
Future Plan: ERL Light Source Project at KEK

3 GeV ERL (1st stage)
- Diffraction-limited X-ray source
- Ultra-short-pulse light source
- Driver for XFEL-O (2nd stage)

The Compact ERL
- Injector (low $\varepsilon$, high $I_0$)
- Main linac (CW, $\sim$15 MV/m)
- Beam dynamics
- Beam losses

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

The Compact ERL (cERL)

The cERL contains all important technologies.

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>Gun high voltage</td>
<td>500 kV</td>
<td>390 kV</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>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>See, page 21</td>
</tr>
<tr>
<td></td>
<td>1 @77 pC</td>
<td></td>
</tr>
<tr>
<td>Repetition frequency of bunches</td>
<td>1.3 GHz</td>
<td>1.3 GHz (usual)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>162.5 MHz (for LCS)</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>1-3 ps (usual)</td>
<td>1-3 ps (usual)</td>
</tr>
<tr>
<td></td>
<td>~ 100 fs (compress.)</td>
<td></td>
</tr>
<tr>
<td>Max. heat load at 2K</td>
<td>80 W</td>
<td>80 - 100 W</td>
</tr>
</tbody>
</table>

Circumference: ~ 90 m
### Construction and Commissioning of cERL

<table>
<thead>
<tr>
<th>Year</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refurbishment of building</td>
<td>Clearing radioactive materials</td>
<td>Construction of radiation shielding</td>
<td>Construction of injector</td>
<td>ERL2013</td>
<td>Construction of recirculation loop</td>
<td>Commissioning of cERL (with loop)</td>
<td>Construction of LCS system</td>
<td>Commissioning of LCS system</td>
</tr>
</tbody>
</table>

**Legend:**
- **Blue**: Construction
- **Red**: Commissioning/Operation
Picture of the cERL

- Photocathode DC gun
- Main-linac cryomodule
- Injector diagnostic beamline
- Injector cryomodule
- Recirculation loop
The First Transportation of Beams to the Dump (Feb. 6, 2014)

**Beam energy** ($E$)
- Injector: 2.9 MeV
- Recirculation loop: 19.9 MeV

**Parameters**
- Gun voltage: 390 kV  
- Buncher: OFF
- Injector cavities: $E_{\text{acc}} = (3.3, 3.3, 3.1) \text{ MV/m}$
- Main-Linac cavities: $V_c = (8.57, 8.57) \text{ MV}$

**Beam pulses (macropulse)**
- Peak current: $\sim 24 \mu\text{A}$
- Macropulse width: 1.2 $\mu\text{s}$
- Repetition of bunches: 1.3 GHz
- Repetition frequency: 5 Hz
- Average beam current: $\sim 140 \text{ pA}$

---

**Beam profiles on screen monitors.**

- MS11
- MS3
- MS1
- MS14
- MS31 (dump line)
- Dump FC
- MS26
- MS27
- MS29
- MS15
- MS17
- MS19
- Movable FC
- Dump line
- Main linac
- Injector
- The 1st arc
- The 2nd arc

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- Injector
- The 1st arc
- The 2nd arc
Correction of Path Length for Optimum Energy Recovery

- Two measures for path-length correction were prepared
- Path length was corrected so that the beam momentum took a minimum at the dump line

Path-length control chicane
- Tuning range: ±5 mm
- Large hysteresis
- Currently fixed

Orbit bump in the arc
- Tuning range: ±10 mm/arc
- Routinely used

Determination of an optimum path length

\[ \propto \text{(momentum at the dump line)} \]
Demonstration of Energy Recovery ($I_0 = 30 \, \mu A$)

ERL operation

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

- E=2.9 MeV
- E=19.9 MeV

Non-ERL operation

- Cavity 2: deceleration
  - (Vc=8.57 MV/cavity)
  - E=2.9 MeV
- Cavity 1: acceleration
  - (Vc=8.57 MV/cavity)
  - E=2.9 MeV

Beam current

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

- Cavity 2:
  - $P_{in} - P_{ref}$
  - 275W

- Cavity 1:
  - $P_{in} - P_{ref}$
  - -294W

Beam loading (+ and -)

No beam loading

Energy recovery: 100-98.6%
(within accuracy of the measurement)

Beam loading test with 30µA (2015/2/13 20:25-20:43)

(Power lost in cavity) = ($P_{in}$: input power to cavity) - ($P_{ref}$: reflected power from cavity)
Beam Current of 80 μA (CW) was Recirculated

Measured at the beam dump
April 2, 2015

Presented by Dr. Sakanaka
Beam Currents: Achievement and Prospect

At present:
- 1 mA
- 10 mA
- 100 mA

Prospect:
- 10 mA

Injector with recirculation loop:
- 100 μA
- 1 mA
Summary and Outlook for cERL

- 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.
- Achieved low beam emittance (< 1 mm·mrad) at low bunch charges (< 0.5 pC/bunch).
- X-ray production from Laser Compton Scattering was successfully demonstrated.

Subjects in the near future

- Lower emittance at high bunch-charges \( (q_b \geq 7.7 \ pC) \)
- Beam current: 1 mA \( (\rightarrow 10 \ mA) \)
- Bunch compression \( (\sigma_t \sim 100 \ fs) \) and THz production

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
Acknowledgment

We have learned much from designs and experiences of JLab IR-FEL and Cornell Injector. We appreciate useful information and advices from
JLab: George Neil, Steve Benson, Geoffrey Krafft, David Douglas, Kevin Jordan, Carlos Hernandez-Garcia, Pavel Evtushenko, Vashek Vylet, Andrew Hutton,
Cornell: Georg Hoffstaetter, Bruce Dunham, Ivan Bazarov, Christopher Mayes, and many other people.
We would also thank the people of ERL community for useful discussions and encouragement.
Design study for high power EUV light source based on ERL-FEL
The design study has been done under collaboration with a Japanese company.
Motivation

• 10-kW class EUV sources are required in the future for lithography

In order to realize 10-kW class EUV light source, ERL-FEL is the most promising light source (High repetition rate ($\leq 1.3$ GHz) and high current linac system).
X-ray free electron laser (XFEL)

RIKEN, Harima, Japan

SPring-8

SACLA
(SPring-8 Angstrom Compact X-ray Laser)

In case of normal conducting accelerator,
The repetition rate is less than 100Hz

X-ray pulse duration ~ 50 ps

I \propto N

Micro-bunching -> SASE lasing

X-ray pulse duration ~ 10 fs

I \propto N^2
Design Concept

• Target: 10kW power @ 13.5 nm, 800 MeV

• Use available technology without too much development

• Make the most of the cERL designs, technologies and operational experiences
FEL Performance

Electron beam parameters: \( E = 800 \text{ MeV} \), \( Q_b = 60 \text{ pC} \), \( f_b = 162.5/325 \text{ MHz} \)

Helical undulator parameters: \( K = 1.652 \), \( \lambda_u = 28 \text{ mm} \), \( L_u = 2.8 \text{ m} \) (segment length)

Bunch compression scheme: 1\(^{st}\) Arc + Chicane

FEL power without tapering: \( 8.9/17.8 \text{ kW} @ 9.75/19.5 \text{ mA} \)

FEL power with 8% tapering: \( 18.0/36.0 \text{ kW} @ 9.75/19.5 \text{ mA} \)
# ERL&FEL Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Energy</td>
<td>10.5 MeV</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>800 MeV</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>60 pC</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>162.5/325 MHz</td>
</tr>
<tr>
<td>Ave. Current</td>
<td>9.75/19.5 mA</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>0.1 % rms</td>
</tr>
<tr>
<td>Normalized Emittance*</td>
<td>0.6 mm mrad</td>
</tr>
<tr>
<td>Undulator Period</td>
<td>28 mm</td>
</tr>
<tr>
<td>Undulator Gap</td>
<td>7 mm</td>
</tr>
<tr>
<td>EUV Wavelength</td>
<td>13.5 nm</td>
</tr>
<tr>
<td>EUV output power</td>
<td>18/36 kW</td>
</tr>
</tbody>
</table>

* entrance of 1st arc
Presentation of the feasibility study

2014 International Workshop on EUV and Soft X-ray Sources  
2014/Nov./3-6  Kako, Hajima

AAA technical workshop  
2015/April/14  Kawata

ERL2015 at BNL (USA),  
2015/June 7~12  Nakamura

EUV-Litho WS in Hawaii (USA)  
2015/June 15~19  Nakamura

NGL Workshop  
2015/July/7  Kawata

Particle Accelerator Society of Japan  
2015/Aug./4-7 Miyajima

SRF2015 at TRIUNF (Canada)  
2015/Sept./13~18  Kawata  ←Today

EUV-Source WS in Dublin (Ireland)  
2015/Nov./9~12 Umemori

We also start to prepare a committee to establish the consortium to realize the EUV light source in Japan.
Summary & Outlook for EUV Light Source

• Design of ERL-EUV Light Source
  – Injector (gun, SRF cryomodule, tracking)
  – Main linac (cavity, optics, HOM BBU and heating)
  – Arcs and chicane (lattice, optics)
  – Bunch compression simulation

• Performance of the designed ERL-EUV
  – 8.9 kW power at 9.75 mA without tapering
  – 18 kW at 9.75 mA with tapering

• Further design work and optimization
  – Improvement of FEL power
    (tapering, optics, beam&undulator parameters etc.)
  – Bunch decompression simulation