FEL oscillation with a high extraction efficiency at JAEA ERL FEL

Japan Atomic Energy Agency (JAEA) ERL group

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1. Configuration and recent upgrade
2. FEL efficiency measurement in the return arc
3. Magnetic bunch compression in the first arc
Original JAEA FEL without energy recovery

- Superconducting linear accelerator (SCA)
- Electron beam energy 17 MeV,
  Bunch charge 0.5nC
- FEL wavelength 22μm
- Pulsed operation of 1ms macropulse x 10Hz

2.5MeV Injector

Two single-cell 500 MHz SCAs

83 MHz sub harmonic buncher (SHB)

230kV DC gun equipped with a thermionic cathode driven by a grid pulser
High efficiency FEL without ERL in 2001

1. achieved high FEL efficiency of 6%.
2. observed FEL oscillation at zero detuning length of an optical cavity.
3. generated an intense few-cycle FEL pulse.

R. Nagai et al., NIM A 483, 129 (2002).
A high-power ERL FEL at JAEA

The same injector as the original JAEA FEL

17 MeV loop consists of a merger chicane, two five-cell 500 MHz SCAs, a triple-bend achromat arc, half-chicane, undulator, return-arc, and beam dump.

First lasing in August, 2002.

JAEA ERL upgrade

1. Doubled bunch repetition rate of the gun grid pulser to 20.8 MHz
2. Increase of power supplies for injector SCAs from 8 kW to 50kW
   Improvement of low-level RF controller
3. Doubled energy acceptance of the return arc from 7% to 15%

N. Nishimori et al., APAC2004, 625
(R. Nagai et al., TUPPH005.

A grid pulse developed at BINP is used.

Two 50 kW IOT RF power supplies are used.

Merits of a high-efficiency FEL

\[ P_{\text{FEL}} = P_{\text{beam}} \eta_{\text{fel}} \]

1. Saves the total beam current needed for high-power lasing.
2. Generates broadband ultrashort optical pulses.

Quantum control of chemical reaction  
H. Iijima et al., TUPPH002.

![Graph showing FEL efficiency and Ti:sap. signal against \(\delta L\) (\(\mu\m\)).](image)
FEL efficiency experiment in the return arc

A hole in 2 mm diameter on the mirror

a) FEL ($\lambda = 22\mu m$)

b) wire scanner
c) beam dump
d) current transformer

Beam profiles at a dispersive point

Non-destructive beam profile monitors.
1. Synchrotron radiation monitor
2. Beam position monitor
3. Wire scanner
The wire scanner

Based on a linear movement of a Cu wire in 0.6 mm diameter at a speed of 0.39 mm/s by 100 mm-stroke.

The secondary electron emission current is measured with a current meter (TR8641 electronic picoammeter, ADVANTEST).

Al fork with a gap of 26 mm.
Beam envelopes in the return arc

Electron beam from undulator

\[ \beta_x = 0.33 \text{ m} \]
\[ \beta_y = 1.7 \text{ m} \]
\[ \alpha_x = 0 \]
\[ \alpha_y = -1 \]

\[ \eta_x = 0.4 \text{ m} \]

To merger chicane

From undulator
FEL power detuning curve

- 230 μs macropulse
- 18.5 μA (average)
- 8 mA during macropulse
- 0.7 kW during the macropulse
Beam profiles measured with WIRE #1

$\eta_x = 0.38$ m from measurement
$\eta_x = 0.41$ m from calculation

no FEL

FEL maximum power

sharp edge

$\delta L = +10 \mu m$
$0 \mu m$
$-1 \mu m$
$-2 \mu m$
$-4 \mu m$
$-6 \mu m$
$-10 \mu m$
$-20 \mu m$
$-30 \mu m$
FEL efficiency detuning curve

- Bore of Q is 100 mm in diameter.
- $\eta_x = 0.6 \text{ m from cal.}$
Integrated secondary emission electron current

Secondary electron production rate:
\[1.5 \mu A / 18.5 \mu A = 8\%\]

Beam loss due to the presence of wire:
\[0.08 \mu A / 1.5 \mu A = 5\%\]

Area of profile is proportional to the incident beam current
Beam loss may occur if the return arc is not achromatic, if energy compression in the arc is insufficient, if energy acceptance of the dump is not large enough.
Beam macropulse after the return arc

\( \delta L = 0 \) \( \mu m \) eff. = 2.8%

\( \delta L = -4 \mu m \) eff. = 1.9%

\( \delta L = +10 \mu m \) eff. = 0%

\( \delta L = -6 \mu m \) eff. = 1.4%

\( \delta L = 0 \mu m \) eff. = 2.8%

Beam profiles measured with WIRE #2

![Graph showing beam profiles measured with WIRE #2.](image)

- Integrated current (μA) against wire position (mm).

- insets showing secondary emission electron current (μA) against δL (μm) for different δL values: +20μm, 0μm, -2μm, -6μm, -10μm, -30μm.

Magnetic bunch compression in the first arc

CSR power from the last bending magnet is much higher than the remaining two, indicating another bunch compression in the first arc.

Measured horizontal beam profiles with a wire scanner at a dispersive point in the first arc as a function of the RF phase of the last SCA.
Wire scanner in the first arc

$M_{56} = 0.6 \, \text{m}$ at the exit of the first arc from calc.

Electron beam from the SCAs
Beam profiles measured with WIRE #3

Beam loss due to the presence of wire: $0.1 \mu A / 1.4 \mu A = 7\%$

FEL power loss $10\%$

FEL maximum power

Phase of the last SCA

$\theta = -17^\circ, -12^\circ, -8^\circ, -4^\circ, -2^\circ, 0^\circ, 2^\circ$
Energy spread, energy of beam centroid, and total secondary electron current

- Energy spread (%)
- Energy of beam centroid (
- Total secondary electron current (μA)

Graph showing:
- FWHM energy spread (%)
- Integrated current
- Beam centroid energy
- Energy spread
- FEL maximum power

θ (deg.) phase of the last SCA
Temporal profiles at the undulator center

30 μs macropulse

phase of the last SCA

\[ \theta = \{-14.2^\circ, -10^\circ, -5^\circ, 0^\circ, 5^\circ, 10^\circ\} \]

counts/ch

-60 -40 -20 0 20 40 60 80
time (ps)
Bunch length and bunch arrival time

- Bunch length: $M_{56} = 0.38 \text{ m from the measurement}$
- Bunch arrival time: $M_{56} = 0.6 \text{ m from the calculation}$

- FEL maximum power: 0.8% (10 deg.)
Poster presentations by JAEA ERL group in FEL06

[TUPPH005] R. Nagai et al.,
``Beam current doubling of JAEA ERL-FEL”’

[TUPPH006] R. Nagai et al.,
``Performance of a conventional analog φ-A type low-level RF controller”’

[TUPPH002] H. Iijima et al.,
``Development of frequency-resolved optical gating for measurement of correlation between time and frequency of chirped FEL”’

[TUPPH007] T. Nishitani et al.,
``JAEA photocathode DC-gun for an ERL injector”’
Summary

- We have doubled the electron bunch repetition rate by upgrading the gun grid pulser and RF power supply for injector SCA modules.
- The energy acceptance of the triple bend achromatic return arc has been increased from 7% to 15% by replacing quadrupole magnets and beam ducts.

- We have achieved 0.7 kW FEL oscillation during 230 $\mu$s macropulse at 22$\mu$m wavelength using 8 mA electron beam.
- The FEL extraction efficiency has been measured with a wire scanner and the peak efficiency reaches 2.8%.
- We have found that a magnetic bunch compression in the first arc with off crest acceleration in main SCA modules is indispensable to realize the high-efficiency FEL.

- We will continue our experimental study on the beam dynamics in the triple bend achromatic arcs under high-efficiency FEL oscillation.
1st arc dispersion function

WIRE #3  $\eta = 0.5$ m

$M_{56} = 0.6$ m

$M_{56} = 0.07$ m

half chicane

One-dimensional time-dependent FEL simulation

Triangular bunch
Colson's dimensionless current $J_0 = 25$
Optical cavity loss of 4.2%
## JAEA ERL FEL parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy at undulator</td>
<td>17 MeV</td>
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<tr>
<td>Average current at undulator</td>
<td>8 mA</td>
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<tr>
<td>Bunch charge at undulator</td>
<td>0.4 nC</td>
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<tr>
<td>Bunch length at undulator (FWHM)</td>
<td>12 ps</td>
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<td>Peak current</td>
<td>35 A</td>
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<td>Energy spread before undulator (FWHM)</td>
<td>1.5%</td>
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<tr>
<td>Energy spread after undulator (full width)</td>
<td>&gt;15%</td>
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<tr>
<td>Normalized emittance (rms)</td>
<td>40 mm mrad</td>
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<tr>
<td>Bunch repetition</td>
<td>20.8 MHz</td>
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<tr>
<td>Macropulse</td>
<td>1 ms X 10 Hz</td>
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<td>Undulator period</td>
<td>3.3 cm</td>
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<tr>
<td>Number of undulator periods</td>
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<tr>
<td>Undulator parameter (rms)</td>
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<td>Optical cavity length</td>
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<td>Rayleigh range</td>
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<td>Cavity mirror radii</td>
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<tr>
<td>FEL wavelength</td>
<td>22 µm</td>
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<tr>
<td>FEL extraction efficiency</td>
<td>&gt;2.5%</td>
</tr>
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</table>
17MeV ERL loop

first arc

Five-cell SCA

undulator

Merger chicane

triple-bend achromat return-arc

2.5 MeV injection beam