Demonstration of high-repetition FEL using cERL and beyond EUV-FEL

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• Why is Energy Recovery required?

• Project of IR-FEL based on the cERL
  - Demonstration of high-repetition FEL -

• Is it possible to obtain a wavelength of several nm from EUV-FEL?

• Summary
Part 1:

Why is Energy Recovery required?
Efficiency of FEL

• Assuming this square area is the power of the electron beam, how much area is converted to light by FEL?

Maybe ...
this red square

• FEL conversion efficiency is $\sim 10^{-2}$ in the infrared region and $10^{-3}$ to $10^{-4}$ in the EUV/X-ray region
Efficiency of FEL

• Assuming this square area is the power of the electron beam, how much area is converted to light by FEL?

• Low conversion efficiency of FEL is not a serious problem for academic use.

• However, for industrial use ... we need improvement!
To make the efficiency better

• There are 2 ways to improve conversion efficiency

(1) Increase efficiency itself

(2) Reduce dump power

Tapered FEL, TESSA*, …

Energy Recovery

*Alex Murokh, EUVL workshop, LBNL, June 15 - 2016, P44
Energy Recovery Linac

Energy exchanged between fresh bunches (from injector) and old bunches (from circulation) in the main SC Cavities.

- Increase average beam power
- Reduce dump power (small radiation)
# EUV/X-Ray FELs

<table>
<thead>
<tr>
<th></th>
<th>LCLS</th>
<th>SACLA</th>
<th>FLASH</th>
<th>Euro-XFEL</th>
<th>LCLS II</th>
<th>EUV-FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Normal conduct.</td>
<td></td>
<td></td>
<td>Super con.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Configuration</strong></td>
<td>Linac</td>
<td></td>
<td>Linac</td>
<td>Linac</td>
<td>ERL</td>
<td>ERL</td>
</tr>
<tr>
<td><strong>Operation Mode</strong></td>
<td>Pulse</td>
<td></td>
<td>Long-pulse</td>
<td>CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Country</strong></td>
<td>US</td>
<td>Japan</td>
<td>Germany</td>
<td>EU</td>
<td>US</td>
<td>---</td>
</tr>
<tr>
<td><strong>Repetition rate (pulse/sec)</strong></td>
<td>120</td>
<td>60</td>
<td>&lt;5000</td>
<td>&lt;27000</td>
<td>1M</td>
<td>162.5M</td>
</tr>
<tr>
<td><strong>Beam energy (GeV)</strong></td>
<td>14.3</td>
<td>6~8</td>
<td>1.25</td>
<td>17.5</td>
<td>4</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Wavelength (nm)</strong></td>
<td>0.15</td>
<td>0.08</td>
<td>4.2-52</td>
<td>0.05</td>
<td>~0.3</td>
<td>13.5</td>
</tr>
<tr>
<td><strong>FEL Pulse energy (mJ)</strong></td>
<td>~10</td>
<td>~10</td>
<td>&lt;0.5</td>
<td>~10</td>
<td>~1</td>
<td>~0.1</td>
</tr>
<tr>
<td><strong>Average FEL power (W)</strong></td>
<td>~1</td>
<td>~1</td>
<td>&lt;0.6</td>
<td>~100</td>
<td>~1k</td>
<td>&gt;10k</td>
</tr>
<tr>
<td><strong>Beam dump power (W)</strong></td>
<td>~1.5k</td>
<td>~0.5k</td>
<td>~6k</td>
<td>~0.5M</td>
<td>~1M</td>
<td>~0.1M</td>
</tr>
<tr>
<td><strong>FEL / Dump (%)</strong></td>
<td>0.07</td>
<td>0.2</td>
<td>0.01</td>
<td>0.02</td>
<td>0.1</td>
<td>10</td>
</tr>
</tbody>
</table>

ERL helps to make high-power CW FEL and reduce the beam dump power.
Prototype design of the EUV-FEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>13.5 nm</td>
</tr>
<tr>
<td>Output power</td>
<td>&gt; 10 kW</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>60 pC</td>
</tr>
<tr>
<td>Beam energy</td>
<td>800 MeV</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>12.5 MV/m</td>
</tr>
<tr>
<td>Number of SRF cavity</td>
<td>9-cell cavity × 64</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>162.5 MHz</td>
</tr>
<tr>
<td>Beam current</td>
<td>9.75 mA</td>
</tr>
</tbody>
</table>

Acceleration/Deceleration to 800MeV/10MeV
Energy recovery of 790MV × 10mA ~ 8MW

10kW FEL output
10MeV, 10mA
500kV DC
10MeV, 10mA
800MeV, 10mA
Staging to realize the EUV-FEL light source

1st stage:
Development of the feasible technologies

Upgrade plan of cERL for the PoC

2nd stage Phase 1:
Establishment of the EUV-FEL Lithography system

2nd stage Phase 2:
International Development Center on the processing of EUV-FEL lithography

Clean room with EUV exposure system

IR-FEL project as a PoC is important to realize the EUV-FEL light source for future EUV Lithography.
Part 2:

Project of IR-FEL based on the cERL
- Demonstration of high-repetition FEL -
Organic materials (Resin, Engineering plastic) : light-weight, low-cost, high-functional

Recently, the use of organic materials has been increasing.

Processing methods : Machining, Molding, Laser processing (CO₂, Fiber)

These organic materials have vibration absorption in the mid-infrared region

<table>
<thead>
<tr>
<th>Absorbance</th>
<th>Wavelength (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>0.1</td>
<td>4</td>
</tr>
<tr>
<td>0.2</td>
<td>6</td>
</tr>
<tr>
<td>0.3</td>
<td>8</td>
</tr>
<tr>
<td>0.4</td>
<td>10</td>
</tr>
<tr>
<td>0.5</td>
<td>12</td>
</tr>
<tr>
<td>0.6</td>
<td>14</td>
</tr>
<tr>
<td>0.7</td>
<td>16</td>
</tr>
</tbody>
</table>

Absorption spectrum of polypropylene

Peak①: δ declination of side chain methyl group
Peak②: Stretch vibration of main chain C-C bond
Peak③: Twist of main chain C-C bond

Considering the process of cutting the resin, the absorption wavelength of ② and ③ seem to be more suitable than ①,

However, there is no database of easy-to-process wavelengths and required laser power.
Main high-power laser in MIR range is CO₂ laser only
→ Insufficient understanding of basic phenomena required for processing

A tunable high-power laser is required to create a database for processing!

Project theme founded by NEDO (Ministry of Economy, Trade and Industry)
“Development of high-power mid-infrared lasers for high-efficiency laser processing utilizing photo-absorption based on molecular vibrational transitions.”

KEK’s mission
1. Development of high-power IR-FEL
2. Creation of processing database
3. Processing demonstration
High average power IR-FEL Project

New Undulators for FEL

Beam Energy: 17.5 - 19.0 MeV
Injector Energy: 3.0 - 4.0 MeV
E-Gun Energy: 500 keV
Bunch repetition: 1.3 GHz → 81.25 MHz
Average current: 1 mA (→ 5 mA)
Operation mode: CW or Burst

FEL wavelength

©Rey. Hor i/KEK
Layout and parameters of IR-FEL

Beam parameter
- Energy: 17.5 – 19.0 MeV
- Bunch charge: 60 pC
- Repetition: 81.25 MHz
- Bunch length: 0.5 – 2 ps (FWHM)
- Energy spread: 0.1%
- Norm. emittance: $3\pi$ mm mrad

Undulator parameter
- Type: APU (Planar)
- Gap: 10 mm (Fixed)
- K: 1.42
- Period $\lambda_u$: 24 mm
- Total length: 3 m
- No. of Undulator: 2

Undulator #1
- FEL monitor port #1

Undulator #2
- FEL monitor port #2

Design of undulators.
By changing the energy, average power exceeding 1 W can be obtained in the range of 13 – 20 μm. A large density modulation is formed in front of the electronic bunch due to the slippage effect.
Items to be consider for cERL-FEL from the view points of beam operation

1. Operation of high current beam
   - Average current of 5 mA (10 mA @ EUV-FEL)
   - Bunch charge of 60 pC with low emittances
   - Bunch repetition rate of 81.25 MHz (162.5 MHz @ EUV-FEL)

2. Beam transportation after FEL
   - Large energy spread due to FEL lasing
   - Beam loss in the dispersion sections (dump line, 2\textsuperscript{nd} arc)

3. Bunch compression & decompression
   - Essential to EUV-FELs
   - Increased peak currents for FEL
   - Reduced energy spread after deceleration
Staging to realize the EUV-FEL light source

1\textsuperscript{st} stage:
Development of the feasible technologies

Upgrade plan of cERL for the PoC

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Clean room with EUV exposure system

IR-FEL project as a PoC is important to realize the EUV-FEL light source for future EUV Lithography.
Expected LSI Fab with EUV-FEL

LSI Fab

EUV light will be provided to several EUV exposure systems, simultaneously.

Facility of EUV-FEL light source
(Main/Sub light source)
Part 3:

Is it possible to obtain a wavelength of several nm from EUV-FEL?
Redundancy of EUV-FEL (13.5 nm)

FEL output power: 10 kW x 2 (13.5 nm, redundant)
Rearrangement of EUV-FEL (3.4 nm)

EUV Source 1+2

Main Superconducting Linac #1

Main Superconducting Linac #2

FEL light

FEL output power : ~10 kW (3.4 nm)
SASE-FEL formula (1D model)

- **FEL wavelength**
  \[ \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \]

- **FEL parameter (1D)**
  \[ \rho = \frac{1}{\gamma} \left\{ \frac{1}{64\pi^2} \frac{I_p}{I_A} \frac{K^2 \lambda_u^2 \left[J J \right]^2}{\sigma_x \sigma_y} \right\}^{\frac{1}{3}} \]

- **Gain Length (1D)**
  \[ L_{gain} = \frac{\lambda_u}{4\sqrt{3}\pi\rho} \]

- **Saturation Length**
  \[ L_{sat} \approx 20 \times L_{gain} \]

- **FEL power**
  \[ P_{FEL} = \rho P_{beam} = \rho EI_{beam} \]

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<table>
<thead>
<tr>
<th></th>
<th>13.5 nm</th>
<th>6.7 nm</th>
<th>3.4 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td>( \lambda )</td>
<td>( \lambda/2 )</td>
<td>( \lambda/4 )</td>
</tr>
<tr>
<td><strong>Beam Energy</strong></td>
<td>( \gamma )</td>
<td>( \sqrt{2}\gamma )</td>
<td>( 2\gamma )</td>
</tr>
<tr>
<td><strong>FEL Parameter (1D)</strong></td>
<td>( \rho )</td>
<td>( \rho/\sqrt{2} )</td>
<td>( \rho/2 )</td>
</tr>
<tr>
<td><strong>Gain Length (1D)</strong></td>
<td>( L_{gain} )</td>
<td>( \sqrt{2}L_{gain} )</td>
<td>( 2L_{gain} )</td>
</tr>
<tr>
<td><strong>Saturation Length</strong></td>
<td>( L_{sat} )</td>
<td>( \sqrt{2}L_{sat} )</td>
<td>( 2L_{sat} )</td>
</tr>
<tr>
<td><strong>Beam Power</strong></td>
<td>( P_{beam} )</td>
<td>( \sqrt{2}P_{beam} )</td>
<td>( 2P_{beam} )</td>
</tr>
<tr>
<td><strong>FEL Power</strong></td>
<td>( \rho P_{beam} )</td>
<td>( \rho P_{beam} )</td>
<td>( \rho P_{beam} )</td>
</tr>
</tbody>
</table>
Issues beyond the EUV-FEL

• Stochastic effect
• Low reflectivity of multilayer mirror
• Narrow bandwidth of multilayer mirror
Issues beyond the EUV-FEL

• Stochastic effect
• Low reflectivity of multilayer mirror
• Narrow bandwidth of multilayer mirror
Issues beyond the EUV-FEL

Low reflectivity & Narrow bandwidth of multilayer mirrors were shown at 2018&2019 Source Workshop from optiX fab.

<table>
<thead>
<tr>
<th>λ, nm</th>
<th>1.4</th>
<th>2.4</th>
<th>2.7</th>
<th>4.4</th>
<th>6.7</th>
<th>9.0</th>
<th>12.0</th>
<th>13.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>R, %</td>
<td>0.02</td>
<td>18.1</td>
<td>26.2</td>
<td>16.8</td>
<td>61.0</td>
<td>36.0</td>
<td>49.2</td>
<td>70.1</td>
</tr>
<tr>
<td>FWHM, nm</td>
<td>0.002</td>
<td>0.005</td>
<td>0.008</td>
<td>0.02</td>
<td>0.05</td>
<td>0.11</td>
<td>0.12</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Issues beyond the EUV-FEL

Low reflectivity & Narrow bandwidth of multilayer mirrors were shown at 2018&2019 Source Workshop from optiX fab.
Issues beyond the EUV-FEL

Low reflectivity & Narrow bandwidth of multilayer mirrors were shown at 2018&2019 Source Workshop from optiX fab.
Recent study about the power and spectrum

FEL power with 2% tapering:
12.7/25.4 kW @ 9.75/19.5 mA (162.5/325 MHz)

$\Delta \lambda / \lambda = 6 \times 10^{-3}$

Beam energy: $E = 1131$ MeV ($800 \times \sqrt{2}$),
The other parameters are almost same to these of EUV-FEL
Summary
Summary

• By using ERL technology, FEL can be operated in high repeat rate, and the beam dump power can be reduced.

• KEK will install two undulators in the cERL and develop an infrared FEL with high average power. With the IR-FEL, mid-infrared light can be obtained average power exceeding 1 W in CW operation.

• IR-FEL can demonstrate many of the challenges for the realization of EUV-FEL.

• From the viewpoint of compatibility with the bandwidth of multilayer mirrors, the EUV-FEL's critical wavelength is expected to be about 3.5 nm.

• In the 6.7 nm wavelength range, the FEL spectrum is well within the bandwidth of the multilayer mirror, and an output of 10 kW or more can be expected.
Core members for IR-FEL and Acknowledgement

Team leader of cERL: Hiroshi Sakai
EUV-FEL coordinator: Hiroshi Kawata
Undulator design: Kimichika Tsuchiya
Vacuum system: Yasunori Tanimoto
FEL production: Yosuke Honda
Beam dynamics: Tsukasa Miyajima, Miho Shimada, Norio Nakamura

This presentation is based on results obtained from NEDO project "Development of advanced laser processing with intelligence based high-brightness and high-efficiency laser technologies (TACMI project)."
Thank you for your attention!