Upgrade plan of cERL for the POC as a first stage of the
development on EUV-FEL high power light source

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High Energy Accelerator Research Organization (KEK),
Tsukuba, Ibaraki 305-0801, Japan
6.6 to 1 nm wavelength from EUV-FEL?

Dear Kawata-san;

Thank you for your submission. We will have acceptances later go out after the final submission date.

In regards to topics of your talk, one quick question and request. We are now looking for potential reduction of wavelength for extension of EUVL. Is it possible to obtain 6.6 to 1 nm wavelength from EUV-FEL? If so what will be the challenges of this work? I believe finding a high power light source at smaller wavelengths may be a challenge for plasma sources and FEL may have a good opportunity. May be you can cover this topic as well in your talk, in addition to your update of 13.5 nm FEL.

Thank you for your consideration.

Best Regards

Vivek Bakshi
Contents

• Introduction from the point of view of EUV Lithography
• Design study on high power EUV-FEL light source
• 2\textsuperscript{nd} EUV-FEL Workshop
• Update of the accelerator performance in cERL
• Detail of the studies on the upgrade plan for the POC as a first stage of the development on EUV-FEL high power light source
• Summary1
• Possibility about BEUV
• Summary2
Technology node trend of Logic LSI and expected power on EUV light source
Prototype design of the EUV-FEL

ERL test machine for developing ERL technologies

<table>
<thead>
<tr>
<th>Items</th>
<th>Achieved values in cERL</th>
<th>Design Values at the EUV-FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy for injector (MeV)</td>
<td>2.9-6</td>
<td>10.5</td>
</tr>
<tr>
<td>Energy of Accelerator(MeV)</td>
<td>20</td>
<td>800</td>
</tr>
<tr>
<td>Charge /bunch (pC)</td>
<td>0.7-5</td>
<td>60</td>
</tr>
<tr>
<td>Repetition rate (MHz)</td>
<td>162.5-1300</td>
<td>162.5</td>
</tr>
<tr>
<td>Average Current (mA)</td>
<td>1.0</td>
<td>9.75</td>
</tr>
<tr>
<td>Emittance for electron beam (mm mrad)</td>
<td>0.3-1</td>
<td>~0.7</td>
</tr>
<tr>
<td>Gradient of the accelerated energy (MV/m)</td>
<td>8.6</td>
<td>12.5</td>
</tr>
<tr>
<td>Wavelength of EUV-FEL (nm)</td>
<td>/</td>
<td>13.5</td>
</tr>
<tr>
<td>Average power of EUV-FEL (kW)</td>
<td>/</td>
<td>Higher than 10 kW</td>
</tr>
</tbody>
</table>
We concentrate the Reduction of Source Size last year

- Higher field gradient of Main SC cavities
  - Increase of power consumption $\propto E_{\text{acc}}^2/Q$
  - Development of High-Q SC cavity is essential.

- Lower Beam Energy
  - Shorter undulator period and stronger magnetic field
  - Increase of current or energy conversion efficiency for the same FEL power

- 2-loop/2-turn ERL
  - Optics design for CSR effect suppression
  - Increase of current for the same FEL power
2nd EUV-FEL Workshop

Date: 12/ Dec. /2017  10:00-17:00
Site: Surugadai-kinenkan, Tokyo
Participants : 103 (Source group, tool & material venders, end users etc.)
http://pfwww.kek.jp/PEARL/EUV-FEL_Workshop2/program_eng.html

Invited Speakers

Michael Lercel (ASML)
"EUV industrialization for HVM and future outlook"

Tetsuya Ishikawa (RIKEN SPring-8 Center)
“Laser plasma amplification of SACLA XFEL beam and its extension to EUV-FEL applications”

Masaharu Nishikino (QST)
“Research on the interaction of a SXFEL with matter for EUV ultra-precision nano-fabrication”
Staging to realize the EUV-FEL light source

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

Upgrade plan of cERL for the POC

2\textsuperscript{nd} stage Phase 1:  
Establishment of the EUV-FEL Lithography system

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

Clean room with EUV exposure system

The above concept should be important to realize the EUV-FEL high power light source for EUV Lithography.
Upgrade plan of cERL for the POC
Outline of the accelerator specification on the upgrade plan

<table>
<thead>
<tr>
<th>Items</th>
<th>Achieved values in cERL</th>
<th>Upgrade on cERL</th>
</tr>
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<tr>
<td>Energy for injector (MeV)</td>
<td>2.9</td>
<td>5</td>
</tr>
<tr>
<td>Energy of Accelerator (MeV)</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>Charge /bunch (pC)</td>
<td>0.7-5</td>
<td>60</td>
</tr>
<tr>
<td>Repetition rate (MHz)</td>
<td>162.5-1300</td>
<td>162.5</td>
</tr>
<tr>
<td>Average Current (mA)</td>
<td>1.0</td>
<td>9.75</td>
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<td>Emittance for electron beam (mm mrad)</td>
<td>0.3-1</td>
<td>3.0</td>
</tr>
<tr>
<td>Gradient of the accelerated energy (MV/m)</td>
<td>8.6</td>
<td>12.5</td>
</tr>
<tr>
<td>Wavelength of IR-FEL (nm)</td>
<td>/</td>
<td>1350</td>
</tr>
<tr>
<td>Average power of IR-FEL (kW)</td>
<td>/</td>
<td>&gt;1 kW</td>
</tr>
</tbody>
</table>

1. Installation of additional SRF cavities for IR-FEL to increase the beam energy up to 80 MeV.
2. Installation of undulator to create near infrared FEL light
3. Beam development of high bunch charge and high current operation
Outline of the upgrade plan

Beam Energy: 80 MeV (5 MeV @ Injector & Dump line)

- New Undulator for FEL
- New SRF cavities
- Demonstration of the higher field gradient with high Q
FEL power

- High ave. power > 1 kW@162.5MHz
- A few picosecond pulse duration
FEL spectrum

- SASE FEL is quasi-monochromatic
- Short Pulse FEL has a slightly broad spectrum with a sideband structure
Point of issue

- Energy spread is increased after FEL
  - For Short Pulse FEL, $\Delta E/E \sim 3\%$
  - For SASE FEL, $\Delta E/E \sim 1.5\%$

- Large energy acceptance required!
Items to be consider for cERL FEL from the view points of beam operation

1. Operation of high current beam
   - Average current of 10 mA
   - Bunch charge of 60 pC with low emittance
   - Bunch repetition rate of 162.5 MHz

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
Beam transportation after FEL

Beam Energy: 80 MeV (5 MeV @ Injector & Dump line)

Energy spread increase due to FEL lasing

Dispersion function of cERL (from 2nd arc to dump)

Energy spread due to FEL may cause beam loss in the dispersion sections (2nd arc, dump line (DL)).

The beam loss can be overcome by enlargement of the aperture in DL from the consideration.
Summary1

• Upgrade plan of cERL for the POC as a first stage of the development on EUV-FEL high power light source has been studied.
• We organized EUV-FEL Workshop at last year and discussed about the staging development procedure.
• Present planning is a full version to demonstrate the FEL power and also the performance of the SRF accelerator.
• Even though the budget will not be enough to demonstrate both of them, we will make a effort to demonstrate low energy FEL production as a POC.
Possibility about BEUV

- Wavelength of FEL is proportional to $1/E_{\text{acc}}^2$.
- Dr. R. Hajima has already presented as the next slide of “Possible upgrade to 6.5 nm” in the source workshop at 4/November/2014 at Dublin.
Possible Upgrade to 6.5 nm

Main linac ~ 12 MV x (66 + 28) cavity

1130 MeV, 8 mA

undulator (same as 13 nm)

6.5 nm FEL, 8 kW

After Ryoichi Hajima: 2014 International Workshop on EUV and Soft X-Ray Sources; November 3-6, 2014, Dublin · Ireland
Recent study about the power and spectrum

FEL pulse energy

FEL spectrum

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

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

Accelerator Parameters: \( E_{\text{acc}} = 1131 \text{ MeV} \) \((800 \times \sqrt{2})\),
The other conditions are almost same to these of EUV-FEL
Summary2

• Is it possible to obtain 6.6 to 1 nm wavelength from EUV-FEL? → Absolutely Yes!

• If so what will be the challenges of this work?
  → There is no big challenge from the viewpoint of accelerator technology. We just increase the accelerator energy up to ~1131 MeV from 800 MeV. The size reduction is always very important.

• It is necessary to examine whether the acceptance of the wavelength on the Multi-layer reflectivity curve at the 6.X nm is wide enough to accept the whole FEL light ($\Delta\lambda/\lambda = 6 \times 10^{-3}$).
We will organize 3rd EUV-FEL Workshop with source group, tool and material vendors, and end users.

Date: 11/ Dec. /2018  13:00-17:00
Site: Surugadai Kinenkan, Tokyo
Registration fee: Free
Thank you for your attention!