EUV-FEL Light Source for Lithography

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Outline

• Introduction
• Design and Performance
• Considerations and Developments for Industrialization
  – Availability
  – Size Reduction
• Summary
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Status & Prospect of EUV Lithography

Present Status
• EUV Lithography system based on 200-W-class LPP source is progressing and at starting point of HVM.

Future Requirement
• 1-kW-class EUV light sources will be required to realize the production for less than 3-nm node.

It is important to develop a new-type light source such as an ERL (energy recovery linac)-based EUV FEL, which has a potential of providing 1-kW-class EUV power, even to multiple scanners simultaneously.
Compact ERL (cERL)

Test machine for developing ERL technologies in operation at KEK since 2013

Next targets:
(1) High bunch charge operation
(2) Bunch compression

Beam Energy: 20 MeV
RF Frequency: 1.3 GHz
Acceleration field (ML): 8.3 MV/m

History of achieved beam current:
- 0.1 mA
- 1 mA
- 10 mA

cERL technologies and resources are available for EUV-FEL light sources.
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Design of EUV-FEL Light Source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>800 MeV</td>
</tr>
<tr>
<td>Injection Energy</td>
<td>10.5 MeV</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>60 pC</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>162.5 MHz</td>
</tr>
<tr>
<td>Average Current</td>
<td>10 mA</td>
</tr>
<tr>
<td>Acceleration Field</td>
<td>12.5 MV/m</td>
</tr>
<tr>
<td>EUV Wavelength</td>
<td>13.5 nm</td>
</tr>
<tr>
<td>EUV Power</td>
<td>&gt; 10 kW</td>
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</tbody>
</table>
Light Source Components

Circularly-polarizing undulator developed at KEK-PF

2\textsuperscript{nd} arc
bunch decompression
TBA cell x 2

Photocathode DC gun

2\textsuperscript{nd} DC gun developed for cERL

FEL system

1\textsuperscript{st} arc (new design)
bunch compression
DBA cell x 3
Blue: Bending magnet
Red: Quadrupole magnet
Yellow: Sextupole magnet

Main linac
64 superconducting cavities in 16 cryomodules
Main cavity – TESLA-type 9-cell cavity + 108φ beam pipe
Under design. A large-aperture beam pipe will be also applied to the left side.

stable operation at $E_{\text{acc}}=12.5$ MV/m

Injector linac

2-cell SRF cavity for cERL

2-cell SRF cavity for cERL cERL injector cryomodule cERL cryomodule structure
Simulation Study

FEL power without tapering: 12.9/25.8 kW @ 9.75/19.5 mA (162.5/325 MHz)
FEL power with 2% tapering: 14.4/28.8 kW @ 9.75/19.5 mA (162.5/325 MHz)

\( P_{\text{FEL}} = 88.5 \, \mu J \times 162.5 \, MHz = 14.4 \, kW, \, I_{av} = 60 \, pC \times 162.5 \, MHz = 9.75 \, mA \)

Energy spread is increased.

\( \langle \gamma \beta \rangle = 1561.1 \)
\( \sigma_t = 48.5 \, fs \)
\( \sigma_p/p = 0.299 \% \)
\( \epsilon_{nx} = 1.98 \, \text{mm} \cdot \text{mrad} \)
\( \epsilon_{ny} = 0.71 \, \text{mm} \cdot \text{mrad} \)

\( P_{\text{FEL}} > 10 \, kW \) at 10 mA without beam loss
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Availability Issues

Required availability for industrialization: $\geq 98\%$

( non-operation time $\leq \sim 1$ week per year)

- Electron Gun
  - Photocathode exchange/preparation time
- SRF Cavity
  - Trip rate
  - Increase of field emission in long-term operation
- Cryoplant
  - High pressure gas safety law
  - Safety inspection (once a year in Japan)
Cathode Preparation System

- Cathode preparation system should and can be remote-controlled.
- Activate & storage 6~9 cathodes per day.
- Short dead time for exchange cathode during gun operation.

Courtesy of M. Yamamoto

Cathode preparation system at KEK

Gun chamber

Storage chamber

Activation chamber

Cathode Cleaning

Gate valve

Cathode-container Loading

NEA Activation

Vacuum Suitcase (Option)

Cathode Cleaning

Gun chamber

Activate & storage 6~9 cathodes per day.

Short dead time for exchange cathode during gun operation.
Trip of SRF Cavities

Trip statistics of two cERL Main Linac Cavities

- **E_{acc} = 8.3MV/m (ML1 & 2)**
- **ML1: 9.6MV/m, ML2: 6.9MV/m**

- **3rd run (5 weeks)**
  (2014/5/20-6/20)
- **4th run (9.5 weeks)**
  (2015/1/26-4/4)
- **5th run (5 weeks)**
  (2015/5/25-6/27)
- **6th run (7 weeks)**
  (2016/2/15-3/31)

**LLRF Feedback**
- High gain → Medium gain
- **E_{acc} = 8.3MV/m (ML1 & 2)**
- ML1: 9.6MV/m, ML2: 6.9MV/m

**No trip (2/9~3/23)**

- Trips due to LLRF disappeared

**Trip rate of SRF cavities is very low and not a serious problem.**

- **cavity**
- **coupler2 (warm)**
- **vacuum outside cavity**
- **LLRF**
- **miss operation**
- **earthquake**
- **other hardware**
- **unknown**

**Courtesy of H. Sakai**
Pulse Processing of SRF Cavities

Field emission (FE) of the cERL cavities increased in the long-time operation. High peak pulse RF power is input to the cavities to reduce FE.

ML2 Pulse Aging (10Hz)
Vc=8.57MV(CW)+2.3MV(10Hz x 4ms)=10.9 MV
40min pulse aging was done.

Before pulse processing
After pulse processing

Results of pulse processing (ML2)

ML2 Vc vs ALOKA monitor
- Onset moved up 0.5 MV.
- Radiation reduced half on same acc. field.
  \(\rightarrow\) Pulse processing works well.

Short-time pulse processing can recover the degraded performance. Other in-situ processing methods are also studied to reduce FE.
Redundant System

Redundant System for ensuring high availability
- Critical parts (Cryoplant, Injector, Main Linac, Undulator, …)
- Entire light source system

Redundant system configuration should be designed.
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Reduction of Light Source Size

The present size is mainly decided by the main linac length.

Possible solutions of reducing the main-linac length

• Higher acceleration field of main linac
  - Suppression of field emission
  - Higher-Q SRF cavity
• Lower beam energy
  - Shorter-period undulators with stronger magnetic field
    ➢ In-vacuum undulators
    ➢ Cryogenic permanent magnet undulators
• Double-loop configuration
  - Two-times acceleration with half the main linac
  - Division of the main linac into two parts
Suppression of Field Emission

Suppression of field emission is a key issue for higher acceleration field of main-linac SRF cavities in CW operation.

Improvement for clean environments with dust free during assembly work

Test bench to confirm the higher field performance of cavities

Introduction of a particle measurement system in vacuum and a slow pumping and venting system for suppression of particle movement

Horizontal cryostat to check cavity performance after assembly work

Courtesy of E. Kako, K. Umemori, H. Sakai
Higher-Q SRF Cavities

Power loss in SRF cavity: $P_{\text{loss}} \propto \frac{E_{\text{acc}}^2}{Q}$

Methods of achieving higher Q values
(1) Reduction of residual magnetic field by a solenoid magnet and so on
(2) Introduction of nitrogen ($N_2$) doping treatment

$Q=\sim 1 \times 10^{10} \rightarrow 2 \times 10^{10} @ E_{\text{acc}}=15 \text{ MV/m, 2K}$

$Q=2 \times 10^{10} \rightarrow 3 \times 10^{10} @ E_{\text{acc}}=15 \text{ MV/m, 2K}$

Cancellation of the residual magnetic field by a solenoid coil

Improvement of Q values by nitrogen doping treatment

Further study on $N_2$ doping is necessary for more optimum condition.

Courtesy of E. Kako, K. Umemori, H. Sakai
Shorter Period Undulators (1)

Shorter period undulators for reducing beam energy
(1) In-vacuum undulators (IVUs)
(2) Cryogenic permanent magnet undulators (CPMUs)

Beam parameters assumed in the calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy spread</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Charge</td>
<td>60 pC/bunch</td>
</tr>
<tr>
<td>Bunch length</td>
<td>100 fs</td>
</tr>
<tr>
<td>Peak current $I_p$</td>
<td>600 A</td>
</tr>
<tr>
<td>Average current</td>
<td>9.75 mA</td>
</tr>
<tr>
<td>Normalized emittance ($\varepsilon_x = \varepsilon_y$)</td>
<td>1 mm mrad</td>
</tr>
<tr>
<td>Beta func. ($\beta_x = \beta_y$)</td>
<td>5 m</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>162.5 MHz</td>
</tr>
</tbody>
</table>

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

\(\lambda\): radiation wavelength (13.5 nm)
\(\lambda_u\): undulator period
\(K\): K-value of undulator
\(\gamma\): Lorentz factor

Reduction of beam energy

Courtesy of R. Kato
Shorter Period Undulators (2)

FEL Output Power

\[ P_{FEL} = \eta P_b \quad (P_b = E_b I_b) \]

\[ \eta = 1.6 \rho / (1 + \Lambda)^2 \]

\[ \rho^3 = \frac{1}{64\pi^2} \left( \frac{K\lambda_u}{\gamma} \right)^2 \frac{I_p}{I_A} \left[ JJ \right]^2 r_b^2 \gamma \]

- \( P_{FEL} \): FEL output power
- \( P_b \): beam power
- \( E_b \): beam energy
- \( I_b \): average beam current
- \( \eta \): energy conversion efficiency
- \( \rho \): one-dimensional FEL parameter
- \( \Lambda \): correction term for three-dimensional effects
- \( I_p \): peak current
- \( I_A \): Alfven current
- \( r_b \): transverse beam size
- \( JJ \): \( J_0(\xi) - J_1(\xi) \), \( \xi = K^2 / (4+2K^2) \)

Conclusions:
(1) The beam energy and the main-linac length are reduced.
(2) The FEL output power is also decreased (without current increase).

Courtesy of R. Kato
Double-Loop Configuration

Type A:
Beam is accelerated twice by the same main-inac(ML) cavities and the ML length is reduced by half. The beam current and the higher-order-mode(HOM) power in ML become double.

Type B:
Main linac(ML) is divided into two and each ML length becomes half. The beam current and the HOM power in ML are the same. The number of the ML cavities is doubly larger than that of Type-A configuration.

Joint 1 & 2 consist mainly of bending magnets.

- Light source size is significantly reduced.
- Design study is needed to keep the same EUV output power.
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• ERL-based EUV-FEL light sources have a potential of providing high-power EUV light that meets future demand for lithography.

• It is demonstrated in simulation that our designed EUV-FEL light source can generate EUV power of more than 10 kW at 10 mA without serious beam loss.

• High availability required for lithography can be achieved without too much technology development and with a redundant system.

• Reduction of the light source size is also possible and requires further R&D and design work.
EUV-FEL Light Source Study Group for Industrialization

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Industrialization of High Power EUV light source based on ERL@KEK and FEL@QST
The design study has been done under collaboration with a Japanese company.
Thank you for your attention!