Superconducting Accelerator for ERL based FEL EUV light source at KEK/Japan

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1. Introduction for high-power EUV Light source
2. Learn from cERL cryomodule
3. EUV main linac cavity & cryomodule design
4. Development for EUV main linac cavity
5. Summary
Introduction

- 10-kW class EUV sources are required in the future for Next Generation Lithography

In order to realize 10-kW class EUV light source, ERL-FEL is the most promising light source (High repetition rate (≤1.3 GHz) and high current linac system).

LPP of 13.5 nm
→ 250W level now
Need breakthrough for higher EUV light (>1kW)

Breakthrough for EUV light by using FEL (with ERL)

X-ray pulse duration ~ 50 ps

Micro-bunching -> SASE lasing → high peak power

X-ray pulse duration ~ 10 fs

G. Dattoli et al., NIM-A (2001)

In case of normal conducting accelerator,
The repetition rate of FEL is less than 100Hz
→ High repetition with SC cavity is needed for kW laser
### EUV/X-ray FELs

<table>
<thead>
<tr>
<th></th>
<th>LCLS</th>
<th>SACLA</th>
<th>FLASH</th>
<th>Euro-XFEL</th>
<th>LCLSII</th>
<th>EUV-FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of linac</strong></td>
<td>Normal</td>
<td>Super</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operation mode</strong></td>
<td>Pulse</td>
<td>Long pulse</td>
<td>CW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Country</strong></td>
<td>US</td>
<td>Japan</td>
<td>Germany</td>
<td>Germany</td>
<td>US</td>
<td>--------</td>
</tr>
<tr>
<td><strong>ERL scheme</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>120</td>
<td>30~60</td>
<td>&lt;5000</td>
<td>&lt;27000</td>
<td>1M</td>
<td>162.5M</td>
</tr>
<tr>
<td><strong>Beam energy (MeV)</strong></td>
<td>14300</td>
<td>6000~8000</td>
<td>1250</td>
<td>17500</td>
<td>4000</td>
<td>800</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>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 Power (W)</strong></td>
<td>~1</td>
<td>~1</td>
<td>&lt;0.6</td>
<td>~100</td>
<td>~1000</td>
<td>&gt;10000</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>
</tbody>
</table>

ERL helps to make high power CW FEL and reduce the beam dump power (important in future)
Design Concept for high repetition high current EUV-FEL

- Target: 10kW power @ 13.5 nm, (800 MeV, 10mA)
- Use available technology (based on SASE-FEL) without too much development
- Make ERL scheme by cERL designs, technologies and operational experiences

Energy recovery is needed for accelerating more than 10 mA to reduce beam dump and save RF power.

This operational experience with high current is studied in Compact ERL (cERL) at KEK.
Learn from Compact ERL (cERL) in KEK (cERL cryomodules)

See details by [K. Umemori; "Long operational experience with beam in Compact-ERL cryomodules". July 20th 12:00 (THYA06)]

Compact ERL Layout

Recirculation (return) loop

20MeV

2-cell Cavity Tuner E.Kako MOPB097

Injector module

2-cell cavity × 3 Double coupler

RF frequency: 1.3 GHz
Input power:
10kW/coupler (10mA, 5MeV)
180kW/coupler (100mA, 10MeV)

$E_{acc}$: 7.6MV/m (5MeV)
15MV/m (10MeV)

Unloaded-Q: $Q_0 > 1 \times 10^{10}$

Requirement was satisfied at V.T. Heavy F.E was met @9-10MV/m after string assembly.

Main linac module

HOM damped (for 100mA circulation to suppress HOM-BBU in design)
9-cell cavity (ERL-model2) × 2

RF frequency: 1.3 GHz
Input power: 20kW CW (SW)

$E_{acc}$: 8.3 MV/m (operational)

Unloaded-Q: $Q_0 > 1 \times 10^{10}$

Requirement was satisfied at V.T. Heavy F.E was met @9-10MV/m after string assembly.

Success 1mA operation 100% Energy recovery without HOM-BBU.

Operated from 2013. Current increased.
<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>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 (main linac)</td>
</tr>
<tr>
<td>Number of SRF cavity</td>
<td>9-cell cavity × 64</td>
</tr>
<tr>
<td>Beam repetition</td>
<td>162.5 MHz</td>
</tr>
<tr>
<td>Beam current</td>
<td>9.75 mA</td>
</tr>
</tbody>
</table>

Design strategy (main linac)

$E_{peak}/E_{acc}$ is 1.5 times reduced from cERL cavity to overcome field emission.

8.3 MV/m $\rightarrow$ 12.5 MV/m

10kW FEL output

Acceleration/Deceleration to 800 MeV/10 MeV

Energy recovery of 790 MV × 10 mA $\sim$ 8 MW

Energy recovery is needed.
FEL Performance by simulation

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

Helical undulator parameters: \( K=1.652 \), \( \lambda_u=28 \text{ mm} \), \( L_u=4.9 \text{ m (18 units)} \), \( L_g=1.12 \text{ m} \)

Bunch compression scheme: 1\(^{st}\) Arc(DBA), \( R_{56}=0.3115 \text{ m} \)

FEL power without tapering: \( 12.9/25.8 \text{ kW} \) @ \( 9.75/19.5 \text{ mA} \)

FEL power with 2% tapering: \( 14.4/28.8 \text{ kW} \) @ \( 9.75/19.5 \text{ mA} \)

10 kW class high power EUV light source is NOT just a dream!
Injector & Merger Design

Cryomodule design

- Vacuum Vessel
- 5K Panel
- 5K Support
- 80K Shield
- 2K He Jacket
- 5K Duct
- Input Coupler
- 2K Gas Return Pipe
- 2-cell Cavity
- HOM Coupler
- Six cw input couplers

B : Bending magnets (θ=15°, ρ=1m)
Q : Quadrupole magnet

Injector part of cERL will be used for EUV-FEL light source.

ref. E.Kako “MOPB097” poster in SRF2017
Design of Main Linac Cavity

How to overcome field emission

EUV cavity – TESLA-type 9-cell cavity + Large beam pipes (100φ & 110φ)

Only end cell was modified to match the impedance to beam pipe.

EUV cavity

HOM damper

HOM damper

HOM damper

Parameters for acceleration mode

<table>
<thead>
<tr>
<th></th>
<th>ERL Model 2</th>
<th>EUV</th>
<th>ERL Model 2</th>
<th>EUV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1300 MHz</td>
<td>1300 MHz</td>
<td>Iris diameter</td>
<td>80 mm</td>
</tr>
<tr>
<td>$R_{sh}/Q$</td>
<td>897 Ω</td>
<td>~1000 Ω</td>
<td>$Q_o \times R_s$</td>
<td>289 Ω</td>
</tr>
<tr>
<td>$E_p/E_{acc}$</td>
<td>3.0</td>
<td>~2.0</td>
<td>$H_p/E_{acc}$</td>
<td>42.5 Oe/(MV/m)</td>
</tr>
</tbody>
</table>

From cERL stable beam operation of 8.3 MV/m in 3 years with less trip ratio. Stable operation at 12.5 MV/m seems achievable due to reduced $E_p/E_{acc}$. 
Detailed calculated parameters of EUV main linac cavity

- Ep/Eacc is 2.0 because the center cell is TESLA shape.
- EUV monopole HOM is lower than cERL because the cERL was optimized for dipole HOMs

<table>
<thead>
<tr>
<th>Cavity Parameters</th>
<th>KEK-EUV (MHz)</th>
<th>KEK-cERL (MHz)</th>
<th>TESLA (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>Iris diameter (mm)</td>
<td>70</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td>R/Q (Ω)</td>
<td>1009</td>
<td>897</td>
<td>1036</td>
</tr>
<tr>
<td>G (Ω)</td>
<td>269</td>
<td>289</td>
<td>270</td>
</tr>
<tr>
<td>Ep/Eacc</td>
<td>2.0</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Hp/Eacc (mT/(MV/m))</td>
<td>4.23</td>
<td>4.25</td>
<td>4.26</td>
</tr>
<tr>
<td>BBU limit</td>
<td>&gt;190 mA</td>
<td>~600 mA</td>
<td>~10 mA</td>
</tr>
</tbody>
</table>

Monopole HOM

- EUV cavity satisfied our requirement of 10 mA beam operation by keeping Ep/Eacc ~ 2.

Norio NAKAMURA
ERL2015
(https://www.bnl.gov/erl2015/)

Calc by Superfish

Calc by MW-Stdio (cERL case calc by MAFIA)
- EUV module consists 4 cavities and the design based on STF and ERL module.
- Coupler position is opposite direction each cavity, because the beam pipe sizes are different.
- Input coupler and tuner are same type of ERL and STF.
- HOM damper needs new development.
Input coupler
- cERL main linac coupler is working well up to CW 15 kW power (double windows)
- Qext=2x10^7 require 4~5 kW input power for Eacc=12.5 MV/m
- We could apply for EUV main linac cavity by using cERL main linac coupler.

Frequency tuner
- Rough tuning by Slide-Jack tuner controlled by motor
  - Full stroke 3mm (~1MHz)
- Fine tuning by piezo tuner
  - Precision <nm
- Working very well at cERL and STF
- Apply for EUV
Test of HOM damper for EUV cavity

- **cERL HOM absorber** (ferrite) has **cracks during cool down and not bakable** ⇒ not good for SRF usage.
- **AlN** (Sienna Tec. : STL-150D) is a candidate for absorber. ⇒ AlN is already tested at Jlab and DESY
- We started the measurement of **RF parameter @ low temperature, outgassing and testing the brazing.**

**RF parameter measurement @ 80K**

We have enough absorption by using AlN material @80K.
Outgassing rate of AlN ring was measured after 48h x150 °C baking. After 1000h, outgassing rate is lower than $10^{-8}$ Pa*m³/s/m²

Outgassing rate of AlN ring

AlN ring

20160523AlN

Surface area 0.020724

Outgassing rate of AlN ring

AlN (STL-150D) damper is bakeable and easy for cleaning. It is enough for installation inside the cryomodule.

cERL damper is not bakeable. So water rinse is not allowed.

~ Measured by Shinji Terui (KEK)
Brazing test of AlN based HOM damper prototype

- Two AlN cylinders were brazed in the copper cylinder which has the comb pattern.
- Brazed by Silver at 750 degree under Hydrogen Furnace.
- We tried thermal test. Unfortunately, AlN cylinder is broken after first 80K thermal cycle.
- Ultrasonic testing in the water bath was done after brazing. AlN ring of 2\textsuperscript{nd} prototype much tighter connected than that of 1\textsuperscript{st} one. But not all area of AlN ring was connected.
- We need to search more tighter brazing condition including thermal cycle.

1\textsuperscript{st} : Test piece of brazing

2\textsuperscript{nd} : HOM damper prototype

Connection was not tight and crack occurred under cooling to 80 K (but very fast (1 hour)).

T. Ota et al., “Development of HOM absorbers for CW Superconducting cavities in Energy Recovery LINAC” (MOPB062)
For reliable operation after assembly work

Toward the reliable operation,
- We made the horizontal test stand for testing the performance after cryomodule assembly including HOM damper, input coupler, tuner and magnetic shield.
- Furthermore, now we try to establish the local clean boose and slow pumping system in this horizontal test stand to overcome field emission after string assembly.

Horizontal test stand was build and already carried out high power test in KEK.

For making very clean local boose

Open clean bench KOACH (ISO class 1)

Slow pumping system
EUV-FEL Light Source Study Group for Industrialization

since 2015

By all Japan association to realize EUV-FEL light source
• EUV-FEL-ERL is promising to open the era to the highest EUV light source and can make more than 10 kW@ 13.5nm EUV light in design.

• We learned that most severe problem is field emission on long beam operation.
• EUV cavity has been designing by including cERL beam operation experience for EUV-ERL/FEL accelerator.
  • Cavity based on KEK-cERL + TESLA cavity to reduce Epk/Eacc.
  ⇒ TESLA center cell + beam line damper with modified end-cell & beam pipe
  • This designed cavity could make 10 mA beam operated without HOM BBU instability and large HOM heat load with 12.5 MV/m accelerating field by extrapolated from cERL operation.
• Cryomodule has been designing based on STF+ERL cryomodule.
• HOM damper was newly developed for EUV cavity. We found AlN material is suitable for our cryomodule HOM damper on RF parameters and outgassing. Unfortunately, we did not find good brazing condition.
• For a reliable cryomodule operation, we made horizontal test stand for study of more reliable string assembly work to prevent the dust coming into the cavity.
• We also do the nitrogen doping/infusion work for future high-Q operation. (See poster; T. Konomi, et, al., “Trial of Nitrogen Infusion and doping by using J-PARC Furnace”, THPB021 poster)
• Finally, all Japan association with KEK promote to build EUV-FEL light source.
Thank you for your attention!