Design work of the ERL-FEL as the high intense EUV light source

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The design study has been done under collaboration with a Japanese company.
Outline

• Introduction
• Injector Design
• Main Linac Design
• Bunch Compression & Decompression Scheme
• Design of Arc & Chicane
• Bunch Compression Simulation
• FEL Performance
• Summary and Outlook
Motivation

- 10-kW class EUV sources are required in the future for lithography

- The order of EUV-FEL size and cost can be acceptable

- ERL-FELs have merits of energy recovery, low dumped beam power and activation
Design Concept

• Target: 10kW power @ 13.5 nm, 800 MeV

• Use available technology without too much development

• Make the most of the cERL designs, technologies and operational experiences
Injector Design

- DC Photocathode gun with the same structure of 2\textsuperscript{nd} gun at cERL
- Two cERL cryomodules with six 2-cell SC cavities for $E_{\text{inj}} = 10.5$ MeV
- Two solenoid magnets and one buncher cavity
- New merger (under design)
Injector Parameters

Optimization of injector parameters before merger

60pC/bunch
1 ps : 0.30 mm mrad, 0.25 % → $\varepsilon_n = 0.60 \text{ mm}\cdot\text{mrad}$, $\sigma_p/p = 0.25 \%$ @ merger exit
2 ps : 0.25 mm mrad, 0.25 % → $\varepsilon_n = 0.55 \text{ mm}\cdot\text{mrad}$, $\sigma_p/p = 0.25 \%$ @ merger exit

100pC/bunch
1 ps : 0.57 mm mrad, 0.35 % → $\varepsilon_n = 0.80 \text{ mm}\cdot\text{mrad}$, $\sigma_p/p = 0.35 \%$ @ merger exit
2 ps : 0.35 mm mrad, 0.16 % → $\varepsilon_n = 0.60 \text{ mm}\cdot\text{mrad}$, $\sigma_p/p = 0.16 \%$ @ merger exit

The results are used as initial values for simulations including bunch compression.
Design of Main Linac Cavity

ERL-EUV cavity (Model 1) – TESLA-type 9-cell cavity + 108φ beam pipe

Under design. A large-aperture beam pipe will be also applied to the left side.

cERL cavity (Model 2) – stably operated at ~8.5 MV/m

Parameters for acceleration mode

<table>
<thead>
<tr>
<th></th>
<th>Model 2</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>1300 MHz</td>
<td><strong>1300 MHz</strong></td>
<td>80 mm</td>
<td>70 mm</td>
</tr>
<tr>
<td>Iris diameter</td>
<td></td>
<td></td>
<td>289 Ω</td>
<td>272 Ω</td>
</tr>
<tr>
<td>R_{sh}/Q</td>
<td>897 Ω</td>
<td><strong>1007 Ω</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qo×R_s</td>
<td></td>
<td></td>
<td>42.5 Oe/ (MV/m)</td>
<td>42.0 Oe/ (MV/m)</td>
</tr>
<tr>
<td>E_p/E_{acc}</td>
<td>3.0</td>
<td><strong>2.0</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_p/E_{acc}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Stable operation at 12.5 MV/m seems achievable due to reduced E_p/E_{acc}.
Main Linac Optics

- Main Linac
  - 64 cavities in 16 cryomodules (4 cavities/cryomodule)
  - $E_{\text{acc}} \approx 12.5 \text{ MV/m}$

- Optics
  - Focusing of quadrupole triplet at every two cryomodules
  - Body/edge focusing of cavities
  - Betatron function optimization against BBU $\Rightarrow I_{th,\text{BBU}} > 190 \text{ mA}$
  - Symmetric for acceleration and deceleration
HOM BBU

HOM-BBU threshold current is calculated by Simulation code \( bi \).

HOM parameters of Model 1 cavity

<table>
<thead>
<tr>
<th>( f ) [GHz]</th>
<th>( Q_e ) [Ω/cm(^2)]</th>
<th>( R/Q ) [Ω/cm(^2)/GHz]</th>
<th>( (R/Q) Q_e/f )</th>
<th>ModeType</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.866</td>
<td>7732</td>
<td>6.43</td>
<td>26659</td>
<td>( TM_{110} ) 6( \pi )/9</td>
</tr>
<tr>
<td>1.874</td>
<td>11655</td>
<td>8.77</td>
<td>54526</td>
<td>( TM_{110} ) 5( \pi )/9</td>
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<tr>
<td>1.879</td>
<td>18360</td>
<td>1.95</td>
<td>19089</td>
<td>( TM_{110} ) 4( \pi )/9</td>
</tr>
<tr>
<td>2.575</td>
<td>4899</td>
<td>21.32</td>
<td>40557</td>
<td>( TE_{121} ) ( \pi )/9</td>
</tr>
<tr>
<td>3.082</td>
<td>33608</td>
<td>0.98</td>
<td>10676</td>
<td>( TM_{121} ) 5( \pi )/9</td>
</tr>
</tbody>
</table>

Calculation of BBU threshold current

Scan over the betatron phase advance (0-2\( \pi \)) and return loop length (in one period of the base mode). Minimum BBU current is found to be about 195 mA. (478mA maximum).

Considering a Gaussian frequency distribution between linac cavities, the average BBU threshold current grows with the frequency spread \( \sigma_f \) increases, reaching about 1.1A when \( \sigma_f = 2 \)MHz.

BBU threshold current is well above the expected average current.
HOM Heating

Non-resonant heating
Parasitic loss absorbed at HOM damper

\[ P_{\text{loss}} = k_{\text{loss}} Q_b^2 f_b \]

- \( k_{\text{loss}} \): Loss factor
- \( Q_b \): bunch charge
- \( f_b \): bunch frequency

Estimation of loss factor
\[ k_{\text{loss}} \sim 20 \text{ V/pC} @ 1 \text{ ps} \]
\[ \sim 15 \text{ V/pC} @ 2 \text{ ps} \]

Examples of parasitic loss power

<table>
<thead>
<tr>
<th>Bunch length @cavity</th>
<th>9.75mA x 2 60pC 162.5MHz</th>
<th>8mA x 2 100pC 81.25MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ps</td>
<td>23.4 W</td>
<td>32 W</td>
</tr>
<tr>
<td>2 ps</td>
<td>17.6 W</td>
<td>24 W</td>
</tr>
</tbody>
</table>

Max. absorption power of HOM damper: 30 W (first target), 100 W (final goal)

Heating resonant to monopole HOMs
Difference between monopole HOM frequency and harmonics of bunch frequency

<table>
<thead>
<tr>
<th>monopole f_{HOM} [MHz]</th>
<th>Bunch frequency f_b [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>325</td>
</tr>
<tr>
<td>2393</td>
<td>207</td>
</tr>
<tr>
<td>2427</td>
<td>173</td>
</tr>
<tr>
<td>2442</td>
<td>158</td>
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<tr>
<td>2447</td>
<td>153</td>
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<td>2452</td>
<td>148</td>
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<td>147</td>
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<td>2459</td>
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<td>3848</td>
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</tr>
<tr>
<td>3851</td>
<td>49</td>
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<tr>
<td>3852</td>
<td>48</td>
</tr>
<tr>
<td>3853</td>
<td>47</td>
</tr>
</tbody>
</table>

: frequency difference within 10 MHz

Max. absorption power of the HOM damper restricts the bunch charge, length and frequency. The bunch frequency should be selected so as to avoid the resonant heating.
FEL power at saturation
\[ P_{\text{sat}} \approx \rho_{\text{FEL}} P_{\text{electron}}, \quad P_{\text{electron}} = EI_{\text{av}} \]

Pierce parameter
\[
\rho_{\text{FEL}} = \left[ \frac{1}{16} \frac{I_p}{I_A} \frac{K^2 [JJ]^2 \lambda_u^2}{\gamma^3 \sigma_x \sigma_y (2\pi)^2} \right]^{1/3}
\]
\[ I_p = \frac{Q_b}{\sqrt{2\pi\sigma_t}}, \quad I_A = 17 \text{kA} \quad \sigma_x = \sqrt{\gamma \varepsilon_{nx} \beta_x}, \quad \sigma_y = \sqrt{\gamma \varepsilon_{ny} \beta_y} \]
\[ [JJ] = J_0(\xi) - J_1(\xi), \quad \xi = K^2 / (4 + 2K^2) \quad \text{Planar undulator} \]
\[ [JJ] = 1 \quad \text{Helical undulator} \]

Photon wavelength and undulator parameters
\[ \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \quad K = K_y \quad \text{Planar undulator} \]
\[ K = \sqrt{2K_x} = \sqrt{2K_y} \quad \text{Helical undulator} \]

High peak current and low emittance are important for FEL power.
Bunch compression and decompression scheme (1)

1. **Bunch compressor**: 1st Arc
   - $R_{56} > 0$, $T_{566} > 0$
   - ($R_{56} < 0$, $T_{566} < 0$)

2. **EUV Source (ERL)**
   - **1st turn**: $R_{56} > 0$, $T_{566} > 0$
   - ($R_{56} < 0$, $T_{566} < 0$

3. **Bunch decompressor**: 2nd Arc
   - $R_{56} < 0$, $T_{566} < 0$
   - ($R_{56} > 0$, $T_{566} > 0$

4. **Main Superconducting Linac**

5. **Undulator (FEL)**

6. **Beam Dump**

7. **Injector**
Bunch compression and decompression scheme (2)

Main Superconducting Linac

Beam Dump

EUV Source (ERL)

Bunch compressor: Chicane
1st Arc + Chicane

Bunch decompressor: 2nd Arc

2nd Arc

$R_{56} < 0, T_{566} < 0$

$R_{56} > 0, T_{566} > 0$
Design of Arc Sections (1)

2-cell TBA lattice and optics ($R_{56}=0.0$ m)

$\rho = 3$ m, $\theta = \pi/8$ rad, $L_B = 1.178$ m, $L_Q = 0.4$ m, $L_{SX} = 0.2$ m

$R_{56} = 4\rho(\theta - \sin \theta) + 2\eta_c \sin \theta$

B: Bending magnet, Q: Quadrupole magnet, SX: Sextupole magnet

Eight sextupole magnets can be inserted in the arc to optimize $T_{566}$. 
The 2-cell TBA lattice has a wide dynamic range of $R_{56}$.
Momentum acceptance is more than 4% for horizontal half-aperture of ~5cm.
Design of Chicane

Four-magnet chicane

$$R_{56} = -\frac{4L_B}{\cos \theta} - \frac{4L_B^2L_D}{\rho^2 \cos^3 \theta} + 4\rho \theta$$

Chicane optics for $L_B=1\text{m}$ and $L_D=d=0.51\text{m}$

$R_{56}=-0.30\text{ m}, \rho=3\text{ m}, \theta=0.34\text{ rad}$

$R_{56}=-0.15\text{ m}, \rho=4.1\text{ m}, \theta=0.246\text{ rad}$
Bunch Compression by Arc

Main Linac + 1st Arc ($R_{56}=0.30$ m)

$Q_b=60$ pC

$E=10.5$ MeV

$E=800$ MeV

Main Linac + 1st Arc ($R_{56}=0.30$ m)

RF phase and sextupole strengths maximizing the Pierce parameter

$K_2$ (SX1) = -54.6 [m$^{-3}$], $K_2$ (SX4) = 26.4 [m$^{-3}$], $\phi_{RF}=96.7$ [deg]
Bunch Compression by Chicane

Main Linac + 1st Arc ($R_{56}=0.0 \text{ m}$) + Chicane ($R_{56}=-0.3 \text{ m}$)

- $Q_b=60 \text{ pC}$
- $E=10.5 \text{ MeV}$
- $E=800 \text{ MeV}$

- $\beta_x$, $\beta_y$, $\eta_x$

- $\sigma_t=1.00 \text{ ps}$
- $\sigma_p/p=0.250 \%$
- $\varepsilon_{nx}=0.60 \text{ mm mrad}$
- $\varepsilon_{ny}=0.60 \text{ mm mrad}$

- $\sigma_t=0.997 \text{ ps}$
- $\sigma_p/p=0.104 \%$
- $\varepsilon_{nx}=0.60 \text{ mm mrad}$
- $\varepsilon_{ny}=0.60 \text{ mm mrad}$

- $\sigma_t=43.8 \text{ fs}$
- $\sigma_p/p=0.110 \%$
- $\varepsilon_{nx}=1.72 \text{ mm mrad}$
- $\varepsilon_{ny}=0.60 \text{ mm mrad}$

RF phase and sextupole strengths maximizing the Pierce parameter

$K_2(\text{SX1})=-91.2 \text{ [m}^3\text{]}$, $K_2(\text{SX4})=23.6 \text{ [m}^3\text{]}$, $\phi_{RF}=82.4 \text{ [deg]}$
Bunch Compression by Arc & Chicane

Main Linac + 1st Arc ($R_{56}=-0.15$ m) + Chicane ($R_{56}=-0.15$ m)

Q_b=60 pC

$K_2^{(SX1)}=-110.5$ [m$^3$], $K_2^{(SX4)}=41.4$ [m$^3$], $\phi_{RF}=82.4$ [deg]

RF phase and sextupole strengths maximizing the Pierce parameter
Compensation of CSR effects (1)

Minimization of CSR-induced horizontal emittance growth

Phase ellipse angle vs beam/FEL parameters at chicane exit
(bunch compression by chicane)

Q_b=60 pC

The phase ellipse and CSR kick directions can be matched at chicane exit.
Such optics adjustment is difficult for bunch compression by arc.
Compensation of CSR effects (2)

Minimization of CSR-induced horizontal emittance growth

The phase ellipse and CSR kick directions can be matched at chicane exit.
Such optics adjustment is difficult for bunch compression by arc.
Slice emittance at high peak currents is lower than the projected emittance.

$$Q_b = 60 \text{ pC}$$

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projected normalized horizontal emittance
Electron beam parameters: $E=800 \text{ MeV}, Q_b=60 \text{ pC}, f_b=162.5/325 \text{ MHz}$
Helical undulator parameters: $K=1.652, \lambda_u=28 \text{ mm}, L_u=2.8 \text{ m (x 40)}$
Bunch compression scheme: 1$^{\text{st}}$ Arc + Chicane

FEL power without tapering: $9.0/18.0 \text{ kW @ 9.75/19.5 mA}$
FEL power with 10% tapering: $11.0/22.0 \text{ kW @ 9.75/19.5 mA}$

FEL pulse energy [µJ]:
- Untapered: 55.5 µJ
- Tapering 10%: 67.6 µJ

FEL peak power [GW]:
- Peak current
- FEL power

Power spectrum [a.u.]:
- Wavelength [nm]

Graphs showing the relationship between FEL pulse energy and undulator section length, and FEL peak power and wavelength.
Image of ERL-EUV Design

1st Arc

Chicane

Beam Dump

~200 m

Undulators (FEL)

Main Linac

~20 m

2nd Arc

Injector Diagnostic Line

Merger

Injector Linac

Gun
Summary & Outlook

• Design of ERL-EUV
  – Injector (gun, SRF cryomodule, tracking)
  – Main linac (cavity, optics, HOM BBU and heating)
  – Arcs and chicane (lattice, optics)
  – Bunch compression simulation

• Performance of the designed ERL-EUV
  – 9 kW power at 9.75 mA without tapering
  – 11 kW at 9.75 mA with tapering

• Further design work and optimization
  – Improvement of FEL power
    (tapering, optics, beam&undulator parameters etc.)
  – Bunch decompression simulation → S2E simulation
Thank you for your attention!
Bunch Compression and Decompression at cERL

\[ \sigma_t = 0.86 [ps], \sigma_p/p = 0.00388 \]

\[ \sigma_t = 1.20 [ps], \sigma_p/p = 0.00115 \]

\[ \sigma_t = 1.02 [ps], \sigma_p/p = 0.001 \]

\[ \sigma_t = 0.86 [ps], \sigma_p/p = 0.00388 \]

\[ K_2(SXIF2) = -52.29 \text{ [m}^{-3}\text{]} \]

\[ K_2(SXIF4) = -34.97 \text{ [m}^{-3}\text{]} \]

\[ \phi_{RF}(ACC) = 24.62 \text{ [deg]} \]

\[ K_2(SXIR2) = -64.41 \text{ [m}^{-3}\text{]} \]

\[ K_2(SXIR4) = -40.76 \text{ [m}^{-3}\text{]} \]

\[ \phi_{RF}(DEC) = 205.95 \text{ [deg]} \]

Initial Condition at ①:
- Bunch charge: 7.7 pC
- Initial bunch length: 1 ps
- Initial momentum spread: 0.1%
- Initial norm. emittance: 1 mm·mrad

Initial Condition at ②:
- Bunch charge: 3.4 pC
- Initial bunch length: 1 ps
- Initial momentum spread: 0.1%
- Initial norm. emittance: 1 mm·mrad

Initial Condition at ③:
- Bunch charge: 1.34 ps
- Initial bunch length: 1 ps
- Initial momentum spread: 0.1%
- Initial norm. emittance: 1 mm·mrad

Initial Condition at ④:
- Bunch charge: 4.52 fs
- Initial bunch length: 1 ps
- Initial momentum spread: 0.1%
- Initial norm. emittance: 1 mm·mrad

Bunch compression and decompression are successfully simulated at cERL.