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CHALLENGES TOWARDS INDUSTRIALIZATION OF THE ERL-FEL LIGHT SOURCE FOR EUV LITHOGRAPHY

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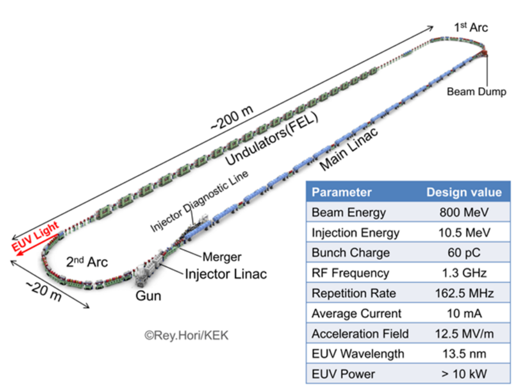
Abstract

Energy-recovery linac based free-electron lasers (ERL-FELs) are possible candidates of a high-power EUV light source for lithography. In Japan, an ERL-FEL light source has been designed to demonstrate generation of high EUV power for lithography and the EUV-FEL Light Source Study Group for Industrialization has been established since 2015. For industrialization, high availability is essential as well as high power and reduction of the light source size is also required. In this paper, we will show overview of the ERL-FEL light source and describe considerations and developments for obtaining high availability and size reduction of the light source.

OVERVIEW OF THE ERL-FEL LIGHT SOURCE FOR EUV LITHOGRAPHY

EUV Lithography is going to high volume manufacturing (HVM) stage with 250-W-class laser-produced plasma sources [1] and 1-kW-class EUV light sources will be required in future to realize the production for less than 3-nm node [2]. ERL-FELs are possible candidates of a high-power EUV light source and can distribute 1 kW power to multiple scanners simultaneously.

An ERL-FEL light source has been designed in Japan to demonstrate generation of EUV power more than 10 kW [3-7]. Figure 1 shows design and specification of the designed ERL-FEL light source for EUV lithography. In addition, the EUV-FEL Light Source Study Group for Industrialization has been established since 2015 to realize industrialization of the light source and the related items. As shown in Fig. 2, this group consists of 12 companies, 3 national laboratories and 5 universities.



Parameter	Design value
Beam Energy	800 MeV
Injection Energy	10.5 MeV
Bunch Charge	60 pC
RF Frequency	1.3 GHz
Repetition Rate	162.5 MHz
Average Current	10 mA
Acceleration Field	12.5 MV/m
EUV Wavelength	13.5 nm
EUV Power	> 10 kW

Figure 1: Design and specification of the ERL-FEL light source for EUV lithography.

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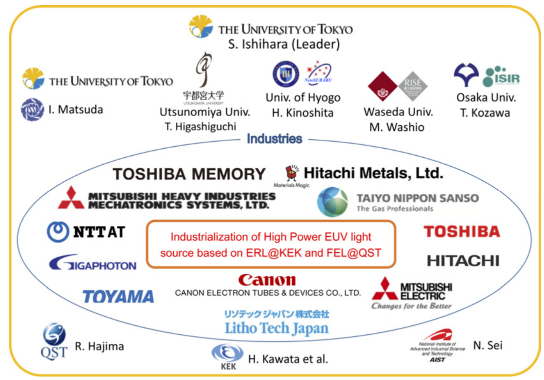

Figure 2: EUV-FEL Light Source Study Group for Industrialization.

AVAILABILITY

Required availability for the light source is more than 98 %, which means that the total non-operating time must be kept within a week for a year. We have to consider the followings to ensure high availability.

Photocathode Preparation System

A multialkali photocathode has a relatively long lifetime of the quantum efficiency and is expected to be used for the gun of the ERL-FEL light source. However, the lifetime is still short and about two weeks for 10-mA operation. Therefore, a lot of photocathodes should be prepared and exchanged for a year. Figure 3 shows the photocathode preparation system developed at KEK [8]. All the processes including cleaning, activation, storage and exchange should be remote-controlled for industrialization to reduce the exchange time. The remote-controlled photocathode preparation system is achievable without much difficulty.

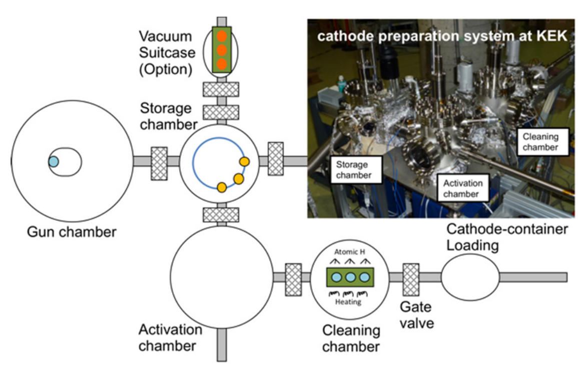

Figure 3: Photocathode preparation system for the DC gun developed at KEK.

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Trips and Field Emission of SRF Cavities

Trips of superconducting RF (SRF) cavities decrease availability of the light source. For the two main-linac (ML) cavities in the Compact ERL (cERL) [9] at KEK, the trip rate became sufficient low when the LLRF feedback gain was optimized and the accelerating gradient was set to a moderate value [10]. In addition, most trips can be automatically recovered in a few to several minutes. Trips of SRF cavities seems not a serious problem.

Field emission (FE) of the cERL SRF cavities has increased in the long-time operation [10-12]. Strong FE induces cavity trips and vacuum troubles and as a result reduces availability. To reduce FE, the pulse processing method has been applied to the cavities [10, 12]. In this method, pulse power was input to the cavities. Figure 4 shows that the pulse processing much reduced the FE of the ML cavity No. 2 (ML2) of the cERL. Introduction of short-time pulse-processing can considerably recover the degraded cavity performance. Other in-situ processing methods [13-14] will also be studied.

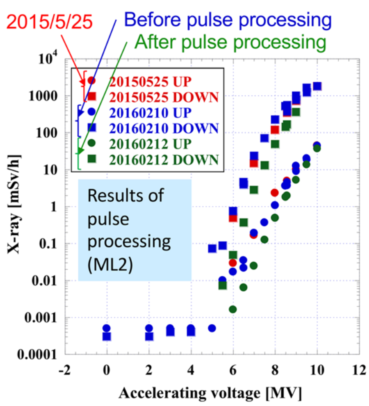

Figure 4: Pulse processing effect on the ML2 cavity. The FE is reduced by the pulse processing method.

Redundant System

Redundancy of the light source is necessary for ensuring high availability against safety inspection of the cryoplant for the SRF cavities and serious troubles of the system components. Figure 5 shows an example of a redundant system. In this figure, two light sources are prepared for redundancy. A more detailed redundant system configuration should be designed for industrialization.

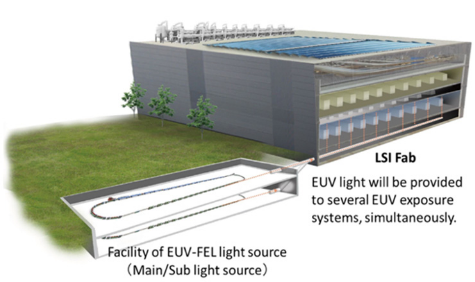

Figure 5: Redundant system of the EUV-FEL light source. The entire light source is duplicated.

LIGHT SOURCE SIZE

Reduction of the light source size is also required. The present light-source size is mainly decided by the ML length. Reduction of the ML length is necessary for the light-source size reduction. Possible solutions for reduction of the ML length are:

1. Higher accelerating gradient of the ML SRF cavities
2. Lower beam energy with shorter-period undulators
3. Double-loop configuration of the light source

It is briefly discussed below whether these solutions are effective or not.

Higher Accelerating Gradient of SRF Cavities

The following issues should be considered for achieving higher accelerating gradient of the ML SRF cavities.

- Suppression of FE
- Achievement of higher Q-value

Suppression of FE is important for higher accelerating gradient of the SRF cavities. FE is caused by dust particles or contaminants during cavity assembly work. We are introducing a particle measurement system in vacuum and a slow pumping and venting system for control of particle movement [15]. Furthermore a test bench with a horizontal cryostat was constructed to check the cavity performance after the assembly work [16].

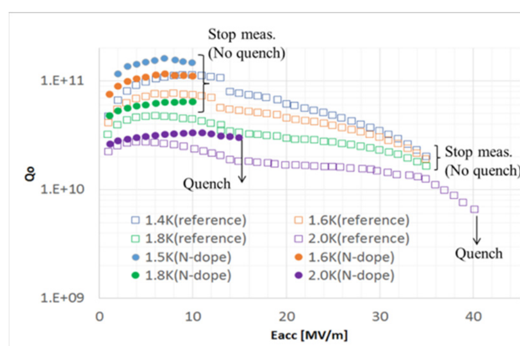

Figure 6: Comparison of Q-values between normal treatment (reference) and N_2 doping treatment.

Power loss of cavities is proportional to the square of the accelerating gradient and inversely proportional to the Q-value. A high Q value is crucial for reducing the power loss in high accelerating gradient. Methods of achieving higher Q values are reduction of a residual magnetic field and nitrogen (N_2) doping treatment. The two methods were tested with a single-cell SRF cavity. The Q value was doubly increased by cancelling the residual magnetic field by a solenoid coil [17]. Figure 6 shows the result of N_2 doping. The Q value is increased by a factor of 1.5 at 15 MV/m and 2 K compared to the normal treatment [18]. Further study on N_2 doping is necessary for searching more optimum condition because the achieved maximum accelerating gradient became lower than in the normal treatment. The recent R&D result of Q > $3\text{x}10^{-10}$ @ 35 MV/m with N_2 doping [19] greatly encourages us.

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Lower Beam Energy

Shorter period undulators for reducing beam energy can be achieved by in-vacuum undulators (IVUs) or cryogenic permanent magnet undulators (CPMUs). We roughly estimate the effects of the shorter period undulators by using the assumed beam parameter values in Table 1. For simplicity, the undulators are assumed to be planar and NMX-S38EH [20] and NMX-68CU [21] from Hitachi Metals, Ltd. are used for permanent magnets of IVUs and CPMUs. Figure 7 shows the calculated beam energy. The beam energy is reduced by 30 % at maximum due to the shorter period undulators. Figure 7 also shows the saturation FEL output power calculated by using the approximate formula [22]. The FEL output power is much decreased by the shorter period undulators. Reducing the beam energy is not suitable if the FEL power is the most important.

Table 1: Beam Parameters for the Calculation

Energy spread	0.1 %
Bunch charge	60 pC
Bunch length	100 fs
Peak current	600 A
Average current	9.75 mA
Normalized emittance	1 mm·mrad
Betatron function	5 m

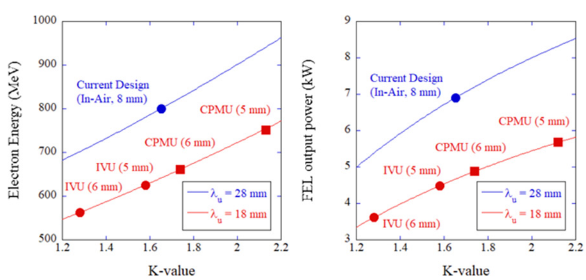

Figure 7: Calculated electron beam energy (left) and FEL output power (right) as a function of the undulator K-value. The values in the parentheses are the assumed undulator magnetic gaps.

Double-Loop Configuration

Two types of double-loop configurations are shown in Fig. 8. In the Type-A configuration, the beam is accelerated twice by the same main-inac cavities and the main-linac length is reduced by half. But the total beam current and the generated higher-order-mode (HOM) power in the main linac becomes double. The cavity heat load becomes more severe. In the Type-B configuration, the main linac is divided into two parts and each length becomes half. The beam current and the HOM power in the main linac are the same as in the single-loop configuration and the number of the cavities is doubly larger than that of the Type-A. For both types, the source size is significantly reduced. Designing these double-loop configurations should be studied so as to keep the same FEL power because the beam passes more bending sections such as arc and joint sections, which might degrade the beam quality.

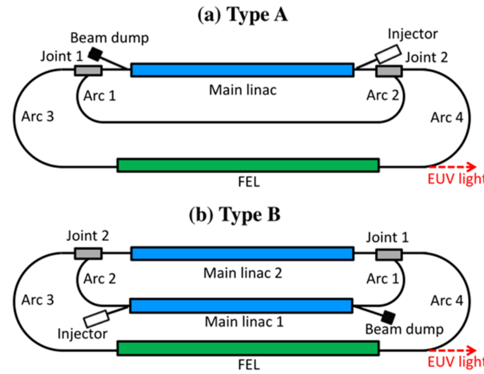

Figure 8: Schematic view of two types of double-loop configurations, (a) Type A and (b) Type B.

SUMMARY

ERL-FEL light sources can provide high-power EUV light that meets future demand for lithography. A high-power ERL-FEL light source for EUV lithography was designed and the EUV-FEL Light Source Study Group for Industrialization was organized in Japan. We showed and discussed some considerations and developments on industrialization of the ERL-FEL light source.

A remote-controlled photocathode preparation system can much reduce photocathode exchange time to ensure high availability of the light source. Trips of SRF cavities are expected not to be serious for availability because of the low trip rate at the cERL. FE of SRF cavities increased for a long-time operation is in situ recovered considerably by the pulse processing method. However, a redundant system of the light source should be designed and prepared.

Higher accelerating gradient of SRF cavities and a double-loop ERL configuration can reduce the light-source size. For the former solution, clean assembly and N_2 doping techniques of SRF cavities are key issues and being developed. In the latter solution, design study should be done to confirm whether the FEL power are significantly decreased or not. Reducing the beam energy is not a good solution because it substantially decreases the FEL power.

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