ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOXA04

SUPERCONDUCTING ACCELERATOR FOR ERL BASED FEL EUV LIGHT SOURCE AT KEK

H. Sakai†, E. Kako, T. Konomi, T. Kubo, K. Umemori, KEK, Tsukuba, Japan
M. Sawamura, QST, Tokai, Naka, Ibaraki, Japan
T. Ota, Toshiba Corporation, Yokohama, Japan

Abstract

An energy recovery linac (ERL)-based free electron laser (FEL) is a possible candidate of a tens of kW EUV source and open the era for next generation EUV-lithography. We have designed the 10 mA class ERL-based EUV-FEL light source to generate more than 10 kW power [1]. One of the key technologies is the CW superconducting cavity to realize the energy recovery of high beam current of more than 10 mA by suppressing HOMs and high gradient acceleration of more than 12 MV/m. This CW superconducting cavity had been developed through the construction of the Compact ERL (cERL) facility in KEK and it successfully achieved the energy recovery of 1 mA CW beam until now [2,3]. However, the accelerating gradient of main linac was limited at 8.3 MV/m due to heavy field emission during the long-term CW beam operation [4]. In this paper, first we express our design strategies of SRF cavities of the main linac of ERL-EUV light sources not only to suppress the HOMs but also to overcome the field emission problem by modifying the main linac cavity of cERL more sophisticatedly. Next we show the recent development works for ERL-EUV superconducting cavity about HOM damper and the reliable cryomodule operation by using new horizontal test stand.

INTRODUCTION

Lithography for LSI needs shorter wavelength and high power to meet the Moore's law. The intense EUV (Extreme Ultra-violet) light source around 13.5 nm wavelength is the strongest candidate for new generation light source for Lithography. And high power EUV source is required for mass production. Up to now, 250 W high power EUV source of 13.5 nm wavelength by using LPP (Laser Produced Plasma) has been developed for 30 years. However, EUV light source of more than 10 kW is required for mass production of LSI.

In order to obtain more than 10 kW EUV light source, the accelerator-based EUV light source was proposed [1]. Figure 1 shows the conceptual design of 10 kW EUV light source. The design of this light source is based on SASE-FEL scheme. This accelerator consists of the high-brightness DC-gun that can produce ultra-low emittance beams with a high average current of about 10 mA with drive-laser system, superconducting RF cavities for injector that can provide high RF power to beam up to 10 MeV beam energy and main linac that can accelerate up to 800 MeV energy under the energy recovery condition, a recirculating loop to achieve the energy recovery and to maintain the beam quality and compress the bunch length to increase the peak current of beam, the long undulator section to make a SASE-FEL of more than 10 kW with EUV regime, and the beam dump of the decelerated beam. The detailed beam parameters are summarized in Table 1. The total beam power of 8 MW is needed from the RF power and it is difficult to damp this beam power of 8 MW if we do not apply energy recovery scheme. Therefore, energy recovery is necessary to save the RF power to the beam and much reduce the beam power to the damp. Therefore, it is necessary to use the well-designed superconducting RF cavities in main linac section.

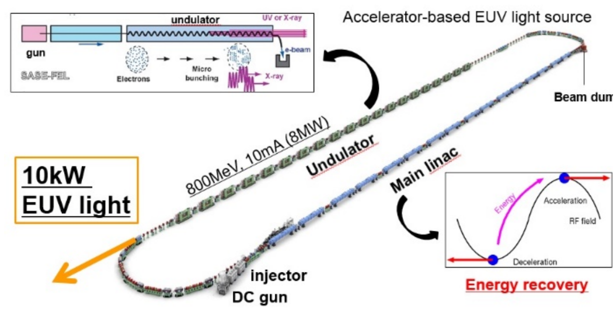

Figure 1: Conceptual layout of accelerator-based EUV light source of more than 10 kW.

Table 1: Main Parameters of Accelerator-based EUV Light Source of 10 kW

Wave length of light	13.5 nm
Power of EUV light	10 kW
Total beam energy	800 MeV
Bunch charge	60 pC
Beam current (CW)	9.75 mA (162.5MHz rep rate)
Normalized emittance	0.6 mm mrad
Bunch length	1 – 3 ps (usual) 100 fs (bunch compression)

To realize this high-power EUV light source, a stable beam operation is needed with this high CW current beam of more than 10 mA. It is important for main-linac superconducting cavities to not only achieve a high accelerating gradient (Eacc) in beam operation but to also strongly damp higher-order modes (HOMs), because the suppression of beam-breakup (BBU) instability and heat load due to the HOMs is one of the key issues for high-current operation. Furthermore, it is important to overcome

† hiroshi.sakai.phys@kek.jp

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOXA04

the degradation of the cavity performance during beam operation for a long time. Fortunately, we have developed ERL test facility named as Compact ERL (cERL) to study the feasibility of the future 3 GeV ERL light source. We carried out beam operation with energy recovery from 2013 and successfully achieve about 1 mA CW beam operation with 100 % energy recovery condition [2,3]. The main linac for ERL-based EUV light source should be designed from the experience of cERL beam operation.

DESIGN OF SUPERCONDUTING CAVITY

Learn from cERL Cryomodule Operation

We have already designed and fabricated 1.3 GHz 9-cell superconducting cavity, named as "KEK-ERL model-2 cavity" optimized for the ERL operations, especially for HOM damping by modifying from TESLA cavity. The requirement of this cavity is 15 MV/m accelerating field and more than 1×10^{10} of unloaded-Q (Q_0) for cERL main linac. The design strategy of our KEK-ERL model-2 cavity was reported in Ref. [5] in detail. By adopting enlarged beam pipes to extract the HOMs from the cavity to the HOM absorbers and changing the cell shapes and the iris diameter to 80 mm to reduce the impedances of the HOMs, this design of KEK-ERL model-2 cavity satisfies the >100 mA current ERL operation required to avoid HOM-BBU instability [5]. However, the ratio of the peak electrical field on the surface divided by the accelerating field (E_{peak}/E_{acc}) of our cavity is 1.5 times higher than that of the TESLA cavity. As a results, we suffered from the heavy field emission from 8 MV/m after cryomodule assembly [6], even though they satisfied our requirements of a high unloaded-Q of more than 1×10^{10} with an accelerating gradient of more than 15 MV/m at vertical tests [7].

Figure 2 shows the long-term cryomodule operation under cERL beam operation [8], that is the summary of Q-value measurements at 9.7, 8.3 and 5.8 MV/m of the cavity of this cryomodule from Dec.2012 to Mar.2016. After beam operation, the degradation was also observed. However, we could keep 8.3 MV/m accelerating field under 1 mA beam operation. Therefore, 8.3 MV/m is the operating point at cERL beam operation until now. However, we learned that we need to keep the cavity performance with higher Q-value and overcome from the heavy field emission under long-term beam operation. To reduce the effect of the field emission, E_{peak}/E_{acc} should be reduced. Furthermore, we need to escape installing the uncleaned components to the cryomodule. For example, HOM damper of cERL main linac, which was made by the ferrite with HIP bonding, was unfortunately fragile during cooling down to 80 K and not bakeable [9]. We should improve HOM damper not to be fragile and bakeable to be clean inside the cryomodule. Finally, in general, the construction of cryomodule must be done in the extremely clean circumference. This clean work should be carried out on not only string assembly but also the beam line installation. We need to establish more clean assembly technique to suppress the field emission for a long time.

We mention that the injector cryomodule worked well and accelerated 1 mA beam with the small emittance in the cERL for a long time [10]. Toward the design of the injector cryomodule of EUV light source, we will basically use this cERL injector cryomodule design even though some modification of HOM couplers are needed. Therefore, we only show the design strategy and R&D work of main linac of EUV light source as follows.

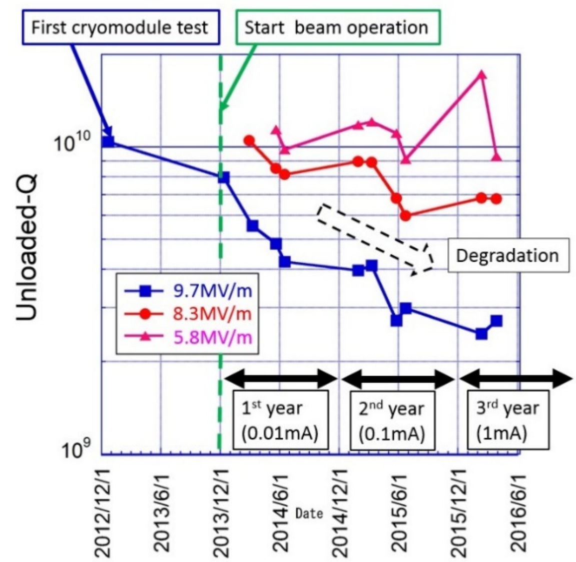

Figure 2: Cavity performance of cERL main linac under cERL beam operation for 3 years.

Design of Superconducting Cavity for Main Linac of EUV Light Source

From the cERL experience, we take the following concepts into accounts to design main linac cavity for EUV light source.

1. HOM suppression is based on KEK-cERL main linac concept as shown in Figure 3. Main frequency is 1.3 GHz and 9-cell cavity with large beam pipes and beam line HOM dampers are used.
2. The center cell shape applies TESLA cell to decrease E_{peak}/E_{acc} to around 2 for the reduction of the effect of field emission.
3. In order to reduce the impedances of HOMs, especially critical lower HOMs, we apply the frequency matching by changing only end cell shape and beam pipe shape because HOMs are passed through the end cells and damped at beam line damper.

The detailed strategy and calculation results are shown in Ref. [11,12]. The HOMs matching were mainly done below 3 GHz of both monopole modes and dipole modes.

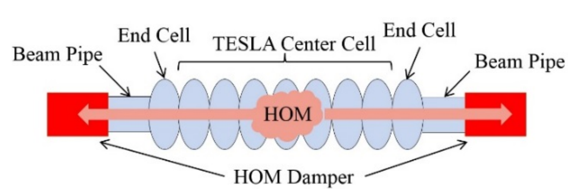

Figure 3: Cavity design scheme of main linac cavity.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOXA04

For designing of 100 mA ERL like cERL, KEK-ERL model-2 cavity (cERL) mainly supressed the impedance of dipole mode to obtain big margin of the BBU threshold. And finally we achieved less than 1×10^4 of impedance, which equals to the 600 mA of BBU instability by changing not only beam pipe but also cell shape itself. For EUV case, 10 mA is the requirement of the maximum beam current. To keep the $E_{peak}/E_{acc} \sim 2$, our design starts keeping center cell of TESLA shape and changing only end cell and beam pipe. We consider the design goal is 100 mA BBU threshold, which equals 5.5×10^4 of impedance of dipole mode, to obtain the margin of 10 mA beam operation. On the other hand, beam repetition is 162.5 MHz rep. rate, which is different of cERL of 1.3 GHz rep rate. Monopole mode must be reduced around the frequencies of the multiple of 162.5 MHz. Our design goal of monopole modes is 20 W heat load of monopole mode, which equals 5×10^4 of monopole mode impedance.

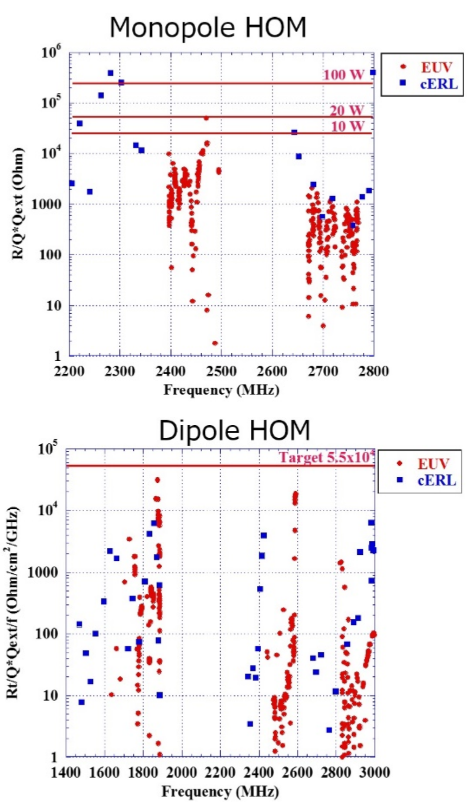

Figure 4: The calculation results of HOM impedances of both monopole modes (top) and dipole modes (bottom). The red (blue) points of both figures show the calculated impedances of EUV (cERL) main linac.

Figure 4 shows the calculation results of HOM impedances of both monopole modes and dipole modes. The red (blue) points shows the calculated impedances of EUV (cERL) main linac. The extracted HOMs are assumed to be perfectly absorbed by the HOM damper set outside of the cavity. Compared with cERL case, the impedance of dipole modes slightly increased due to the lack of change of center cell shape. However, we successfully reduce the impedances of HOMs to the target value of 5.5×10^4, which satisfied the BBU threshold of more than 100 mA [13]. We note that HOM monopole modes successfully reduce the impedance of less than 5×10^4, which equals to 20 W heat load of monopole mode during 10 mA beam operation with 162.5 MHz rep. rate.

Finally we summarize the parameters of our EUV main linac cavity in Table 2. The E_{peak}/E_{acc}, R/Q and Geometrical factor of the EUV main linac kept as same as those of TESLA because of no change from TESLA center cell shape. On CW beam operation, we learned that field emission is severe problem. Therefore, the target design accelerating field is needed to be set from the ratio of E_{peak}/E_{acc} between EUV and cERL of 1.5 (=3.0/2.0) and the real experience from the operating field of cERL of 8.3 MV/m. We start to set the target value of accelerating field of 12.5 MV/m for EUV-light source.

Table 2: Main Parameters of Main-linac Cavity of KEK-EUV Design, cERL and TESLA

Cavity Parameters	KEK-EUV	KEK-cERL	TESLA
Frequency (MHz)	1300	1300	1300
Accelerating field (MV/m)	12.5 (CW)	15 (design) (CW) 8.3 (operating) (CW)	31.5 (pulse)
Iris diameter (mm)	70	80	70
R/Q (Ω)	1009	897	1036
Geometrical factor (Ω)	269	289	270
E_{peak}/E_{acc}	2.0	3.0	2.0
H_{peak}/E_{acc} (mT/(MV/m))	4.23	4.25	4.26

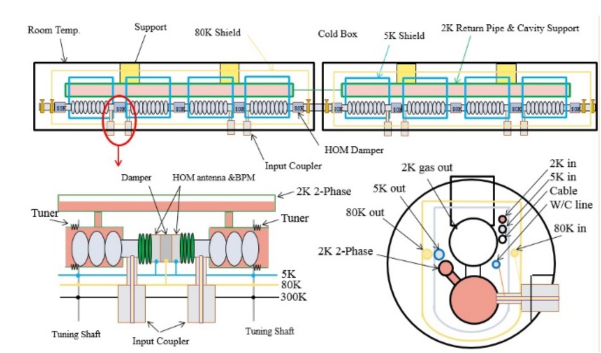

Figure 5: Conceptual design of EUV main linac cryomodule.

Finally, we briefly show the conceptual design of our main linac cryomodule in Fig. 5. This module consists of four 9-cell cavities and is based on STF cryomodule, which was constructed for ILC prototype cryomoudule with pulsed operation [14]. Therefore, 16 cryomodules will be installed to EUV light source. The differences between STF and EUV are number of cold boxes because EUV cryomodule operated under CW condition. The heat load to the cold box is much higher than STF case. So one

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOXA04

cryomoudule has one 2 K cold box. One input coupler equips one cavity to feed 5 kW CW RF power to the cavity with (1-2) × 107 of the loaded-Q, which was already achieved on cERL main linac cryomodule [6,15]. Tuner with piezo and coarse tuner are the same type of cERL and worked well under this loaded-Q during 1 mA operation with energy recovery [16,17]. Therefore, we need to develop new HOM damper, which will be set between cavities at 80 K, and develop new designed cavity for EUV main linac.

Furthermore, under CW operation with 12.5 MV/m, it is suitable to obtain higher unloaded-Q than the nominal value of 1 × 1010. Recently, we could achieve higher unloaded-Q of 3 × 1010 at 12.5 MV/m accelerating field under 2 K in V.T by applying nitrogen doping in furnace in KEK/JAEA [18]. The detailed cryomodule design is now under way. However, if we will apply the higher unloaded-Q value by adding nitrogen doping, the careful design of the magnetic shield and temperature control are needed for this EUV main-linac cryomodule.

Finally, the module assembly technique of not only cryomodule assembly but also the beam line installation need to be established to suppress the effect of the field emission for a long time. Some R&D for the clean work is needed before the installation to the beam line.

We express our recent R&D effort to develop the EUV main linac cavity and cryomodule as follows.

R&D FOR EUV MAIN LINAC CAVITY

Development of HOM Damper

HOM damper (HOM absorber) is one of the key components to determine the ERL cavity performance to reduce the HOM impedances for the high current operation. The absorption heat of HOM absorber is estimated to about 20 W. There are some candidates (SiC, AlN, Ferrite) for absorption material of HOMs. In cERL operation, ferrite had good absorption ability and were selected. However, this was not suitable to operate at 80 K in cryomodule because ferrite was finally broken under the thermal cycle and was difficult to bake itself. Therefore, the AlN is planning to be used as HOM absorber material for EUV main linac cryomodule because it has high RF absorption at 80 K and reliability in cryomodule operation in CEBAF and E-XFEL under low temperature of 80 K.

Prior to the fabrication of HOM damper, the permittivities and permeabilities of AlN (Sienna Tec. STL-150D) were measured at room temperature and 80K by Nicolson-Loss method. It was confirmed that the permittivities at 80 K kept high value at high frequency as shown in Fig. 6 [19]. We also measure the outgassing ratio of this AlN of HOM absorber. This outgassing ratio of AlN was also measured after 48 hours under 150 ℃ baking. The outgassing from AlN ring was finally reduced to less than 1 × 10-8 Pa m3/s/m2, which satisfy our clean vacuum condition to install cryomodule. Furthermore, we did not see the crack of AlN ring under 150 ℃ and cooldown to 80 K. This AlN material is suitable to absorb HOMs and install for our EUV main linac cryomodule.

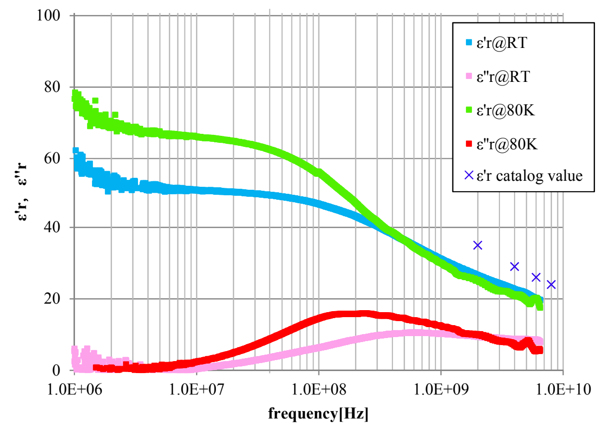

Figure 6: Measured permittivities of AlN at room temperature and 80 K.

Next we fabricated the prototype of HOM absorber to check the adhesion between the thermal anchor and the AlN material and the robustness of its material after brazing under thermal cycle between 80 K and room temperature. Figure 7 shows the prototype of HOM absorber for EUV main linac cryomodule. The silver brazing applied to adhere AlN ring to the copper ring anchor. In order to reduce the thermal stress under 80 K cooling, lattice-like slots was applied on the inner surface. The detailed study of this prototype of HOM damper is expressed in Ref. [20]. Unfortunately, after cooling, cracks occurred in the AlN cylinder after brazing. This was cooled in one hour from room temperature to 80 K. It was too fast to cool this uniformly. Furthermore, we found that the adhesion between AlN ring and copper ring of this prototype were not perfectly carried out. The touched area of AlN and copper is considered to be about 60 % of the brazed area by ultra-sonic testing. It is considered that about 40 % of the brazed area is not completely touched. We note that the adhesion between AlN material and copper was perfectly connected by using sliver and Ni-strike under the sample test. Material test was OK. However, the adhesion procedure between the AlN ring itself and copper ring with lattice-like slots was not established. To fabricate the actual HOM absorber for EUV main linac, we need to continue developing the brazing procedure and checking the adhesion with each other after thermal cycle.

Figure 7: The prototype of HOM absorber.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOXA04

Toward the Reliable Operation by Using EUV Main Linac Cavity

We found that the degradation was occurred after string assembly and during beam operation in both cERL operation and STF cryomodule test [14]. It is crucially important to check the cavity performance after the string assembly even though the cavity performance of V.T is good. In KEK, we made the horizontal test stand for testing the performance after cryomodule assembly including HOM damper, input coupler, tuner and magnetic shield. Figure 8 shows the picture of our new horizontal test stand [21]. One cavity with two HOM absorbers will be install into this horizontal test cryostat. We have already carried out the high power test by using this horizontal test stand. Therefore, we will carry out the feasibility test of cavity performance after string assembly with new HOM absorber by using this test stand in order to well-establish the clean assembly work. In addition, the cryomodule test for high-Q study can be carried out to check the magnetic shield and cooling condition.

Figure 8: Picture of new horizontal test stand at KEK.

Toward the realization of EUV light source, first of all, we will fabricate the prototype of EUV 9-cell cavity as expressed above. And we will carry out the V.T and 8horizontal test by using this test stand. After whole assembly work will be established by using this test stand with new HOM damper, input coupler, tuner and magnetic shield. The prototype cryomoudule with 4 cavities will be fabricated and installed into cERL to check the feasibility under 10 mA beam operation by using cERL beam and check the degradation under beam operation, too.

SUMMARY

After the explanation of the conceptual design of 10 kW EUV light source based on ERL-FEL scheme, we describe the design strategy and the calculation results of our EUV main-linac cavity. From the experience of cERL beam operation for a long time, not only the suppression of HOMs but also the reduction of Epeak/Eacc are required for EUV main-linac cavity. To satisfy these requirements, we separate the design strategies to our cavity. One is keeping the same shape of TESLA cavity into the center cell of EUV main-linac, the other is optimizing matching the end cell with beam pipe to efficiently extract HOMs to the outside. By using these methods, we established 100 mA HOM-BBU threshold by using the calculated HOM dipole mode and less than 20 W heat load by using the calculated HOM monopole mode with the beam repetition of EUV light source, which satisfy our requirements. We note that the 1.5 times reduction of Epeak/Eacc from cERL was achieved with this cavity. Therefore, the target of the accelerating field is set to be 12.5 MV/m.

HOM damper needs to be developed. AlN material were selected for the EUV HOM damper. We found a good absorption ability of AlN material under 80 K and low outgassing ratio after baking. We found that this AlN material is suitable to absorb HOMs and install for our EUV main linac cryomodule. Therefore, we proceed to fabricate the prototype of HOM damper. Unfortunately, we had a bad adhesion between the AlN ring and copper ring by using this prototype. We need to continue developing the brazing procedure to realize the HOM damper to EUV main linac cryomodule.

The horizontal test stand was already constructed and high power test was also done. By using this horizontal test stand, we will establish the clean assembly work not to degradate the cavity performance and high-Q cavity for realization of the reliable operation by using EUV main linac cryomodule with four 9-cell EUV cavities. We also plan to install this EUV main-linac cryomodule to cERL beam line to check 10 mA beam operation with ERL, which is needed to realize the EUV light source before the mass-production phase of EUV light source.

ACKNOLEDGEMENTS

We would like to express our gratitude to Shinji Terui of KEK for measuring the outgassing ratio of AlN material ring for a long time.

REFERENCES

[1] N. Nakamura *et al.*, "Design work of the ERL-FEL as the high intense EUV light source", in *Proc. ERL'15*, Stony Brook, NY, USA, p.4, MOPCTH010.

[2] T.Obina *et al.*,"Recent Developments and operational status of the Compact ERL at KEK",in *Proc. IPAC'16*, Busan, Korea, p.1835, TUPOW036.

[3] K. Umemori *et al.*, "Long-term operation experience with beams in Compact ERL cryomodules" in these proceedings.

[4] H. Sakai *et al.*, "Measurement of the cavity performances of Compact ERL main linac cryomodule during beam operation", in *Proc. SRF2015*, Whistler, 2015, p592, TUPB021.

[5] K. Umemori, *et al.*, in *Proc. APAC'07*, Indore, 2007, p. 570, paper THC2MA03.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-MOXA04

[6] H. Sakai, *et al*., in *Proc. SRF'13*, p. 849, paper THIOC02.

[7] K. Umemori *et al*., in *Proc. 16th Int. Particle Accelerator Conf*., New Orleans, 2012, p. 2227, paper WEPPC011.

[8] H. Sakai, *et. al*., in *Proc. SRF'15*, Whistler, 2015, p. 592, paper TUPB021.

[9] M. Sawamura, *et al*., in *Proc. SRF2011*, Chicago, p. 350, 2011, paper TUPO003.

[10] E. Kako, *et. al*., "Long term cavity performance in Compact-ERL injector Cryomodule.", in *Proc. of IPAC2016*, Busan, Korea, p2145, paper WEPMB013.

[11] T. Konomi *et al*., "Design of the 9-cell superconducting cavity for EUV light source accelerator", ICFA Mini Workshop on High Order Modes in Superconducting Cavities 2016.

[12] T. Konomi *et al*., to be submitted to NIM A.

[13] N. Nakamura, "ERL-based High-power FEL Source for EUV Lithography", OSA International Workshop on Compat EUV & X-ray Light Sources, Hiroshima, Japan (2016).

[14] Y. Yamamoto *et al*., "High Gradient cavity performance in STF-2 Cryomodule for the ILC at KEK", in *Proc. IPAC'16*, Busan, Korea, p2158, paper WEPMB017.

[15] H. Sakai, *et al*., in *Proc. SRF'11*, Chicago, p. 356, 2011, paper TUPO005.

[16] K. Enami, *et al*., in *Proc. IPAC'14*, Dresden, p. 2534, 2014, paper WEPRI027.

[17] F. Qiu *et al*., "Performance of the Digital LLRF systems at KEK cERL", in *Proc. of ERL'15*, Stony Brook, NY, USA, p84, WEIDLH2066.

[18] T. Konomi *et al*., "First trial of Nitrogen Infusion and Nitrogen Doping by using J-PARC Furnace", these conference.

[19] T. Ota *et al*., "Development of HOM dampers for superconducting cavities", in *proc. the 13th Annual Meeting of Particle Accelerator Society of Japan* (2016)

[20] T. Ota *et al*., "Development of HOM absorbers for CW Superconducting cavities in Energy Recovery LINAC" in these conference.

[21] K. Umemori *et al*., "Construction and 2 K cooling test of Horizontal test cryostat at KEK", in *Proc. IPAC'16*, Busan, Korea, WEPMB015.