ERL2015 SUMMARY OF WORKING GROUP 4 RF AND SUPERCONDUCTING RF

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Abstract

The 50th ICFA Advanced Beam Dynamic Workshop on Energy Recovery Linac (ERL2015) was held on June 7-12, 2015 at Stony Brook University in U.S.A. Working Group 1-5, were organized in the workshop. Working Group 4 mainly covered the topics and issues about RF and Superconducting RF cavity for ERLs. This paper summarizes WG4 presentation and activities.

INTRODUCTION

The WG4 charge is to identify the critical issues of each component in cryomodule construction, assembly works and beam operation for ERL. Especially, we need to evaluate what is the critical issues of SRF cryomodules for high current and high charge with low emittance beam operation. Following themes was discussed in WG4.

A) Recent progress of each laboratory for ERL from ERL2013.
B) Cavity and cryomodule design for ERL.
C) Cavity fabrication technique and cavity testing.
D) HOM damping design/simulation and HOM damper/coupler development.
E) RF control for stable beam operation.
F) SRF Gun.
G) High Q R&D for SRF challenge.

18 oral presentations were contributed to WG4 in total. The topics of SRF Gun were discussed at joint session of WG1 and WG4. The topics of HOM BBU simulation and impedance issues were discussed at joint session of WG2 and WG4. The topics of RF control were discussed at joint session of WG3 and WG4.

Among these WG4 presentation and discussion, we pick up the critical issues and progresses in this paper.

SRF CHALLENGE

Recent most interesting and exciting topic about SRF field is to study new approaches for obtaining higher-Q of more than $1x10^{10}$. Fumio review the recent progress to obtain higher Q-value about SRF cavities all over the world in this plenary session.

High-Q R&D for SRF Challenge for ERL (Fumio Furuta, Cornell Univ.)

The two approaches to obtain the higher-Q value of SRF cavities were presented. One is done by Cornell Univ. for ERL project; the other is by FNAL for LCLS-II project. Table 1 shows the summary of two approaches. The former surface treatment was based on the normal cavity treatment. But by applying the slow cooling to 2 K, we would reduce the thermo-current in Nb and the higher-Q was achieved. The latter case is the new approach for SRF challenge to get higher-Q. Nb surface properties was changed by adding N2 gas with optimum pressure in a few minutes when Nb cavity was annealed in furnace; this procedure was named as “N2-dope”. It is recently found that this “N2-dope” procedure tend to increase the unloaded-Q of Nb cavity [1]. Comparing with former approach, this “N2-doped” cavity do not need slow cooling but fast cooling because the magnetic flux was easily trapped so that residual loss was increased.

Finally, it was concluded that higher-Q of more than $3x10^{10}$ at 2 K in medium field is in hand now with high yield at horizontal test by recent dramatic high-Q study of both procedures in this plenary talk.

Table 1: Summary of High-Q Approaches

R&D program	Cornell ERL	LCLS-II
SRF cavity	1.3GHz 7-cell	1.3GHz 9-cell
Highest Q0 in HT at 16MV/m,2K	$3.5x10^{10}$	$3.2x10^{10}$
Surface finish	120C bake + HF rinse	N2-dope
Cool down	Slow cool	Fast cool
Trapped flux effect	Not sensitive	High sensitive

PROGRESS FROM ERL2013 AT EACH SRF FACILITY FOR ERL

In this session, we review the recent progress at each laboratory and company.

Completion of the Cornell High Q CW Full LINAC Cyromodule (Ralf Eichhorn, Cornell Univ.)

Cornell University has finished building a 10 m long superconducting accelerator module as a prototype of the main linac of a proposed ERL facility. This module houses 6 superconducting cavities- operated at 1.8 K in continuous wave (CW) mode - with individual HOM absorbers and one magnet/ BPM section [2].

Cavity Production and Results: For the cavities, a 7-cells, 1.3 GHz design was made while an envisaged Q of $2x10^{10}$ was targeted at a gradient of 16 MV/m. All 6 cavities for the MLC module have been produced in-house starting from flat metal niobium sheets. All cavities were tested vertically, the summary of these test are given in Figure 1. All six cavities exceeded the design quality

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factor, averaging to 2.9×10^{10} at 1.8 K. At 2 K, the average Q was 1.8×10^{10}, at 1.6 K we found 4.3×10^{10}[3].

The reproducibility of the Q versus E curves for all cavities is remarkable, also the fact that none of the cavities needed additional processing- giving a 100 % yield.

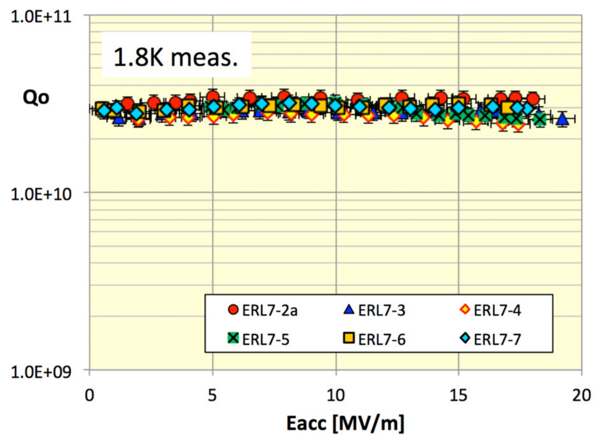

Figure 1: Vertical test results for all 6 ERL cavities. All cavities exceeded the design specifications for the ERL ($Q=2 \times 10^{10}$ at 1.8 K). The reproducibility of the results, gained without any reprocessing of a cavity, is remarkable. The cavities were not N2-doped!

Preparation for Testing: In preparation for the testing of the MLC, the module was transported across the Cornell campus (Figure 2). Currently, cryogens and instrumentation is getting connected and the first cool-down is scheduled for early July.

Figure 2: The MLC crossing Cornell campus on a truck in preparation for testing at Wilson Lab.

Operational experience of CW SRF injector and Main-linac cryomodules at the Compact ERL (Hiroshi Sakai, KEK)

CW injector and main linac cryomodules were developed for Compact ERL (cERL) project [4] and constructed at 2012. The injector cryomodule [5] includes three 2-cell 1.3 GHz superconducting cavities. The main linac cryomodule [6] includes two 9-cell 1.3 GHz superconducting cavities. After construction of the injector and the recirculation loop, the CW operation was started with 20 MeV beam in Dec. 2013 [7]. After precise beam tuning, energy recovery operation was achieved with more than 90 uA at present. Injector and main linac cavity were stable for ERL beam operation with Digital LLRF system, which stability has $\Delta A/A < 0.01\%$ and $\Delta\theta < 0.01$ degree.

Q-values of Main-linac cavities were several times measured. Results are shown in Figure 3. Although radiation existed and Q-values were low from the first high power test at 2012, after some period of beam operation, Q-values became further worse. However, pulse processing method worked effectively to suppress field emissions. Finally, we kept same performance within error-bars after degradation from May 2014 to Mar. 2015. At present, Reason why field emission became worse and stopped is not clear. We will continue measuring the cavity performances.

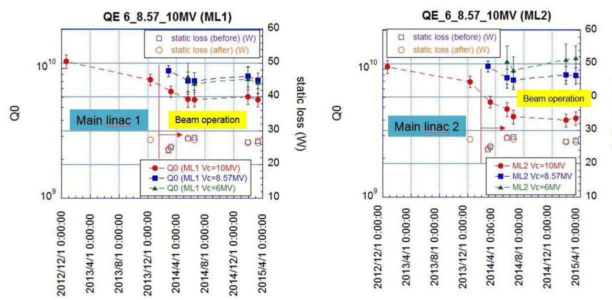

Figure 3: Measurement of the cavity performances of 6, 8.57 and 10 MV cavity voltage, which almost equals with MV/m, during long-term beam operation including high power test of Main linac 1(left) and 2 (right).

The Development of the High Current Superconducting Cavity at IHEP (Zhenchao Liu, IHEP)

High current superconducting cavity, slotted cavity, was developed at IHEP [8]. The aim of the cavity is delivering ampere-class beam current for the GeV ERLs [9]. Although the fabrication of the cavity is challenging, we have fabricated a 1.3 GHz 3-cell slotted cavity. The room temperature RF test and the vertical test at 4.2 K were taken and the results show that the cavity is available to reach the design goal. Figure 4 shows the 1.3 GHz 3-cell slotted cavity. The heavy damping of the slotted cavity for dipoles were performed in low level RF test up to 2.5 GHz. The cavity has extremely low HOM impedance and the HOMs power can be easily extracted from the waveguide structure.

The cavity has few hard multipacting barriers, however, the gradient is limited by the RF power. The gradient of the cavity reached 2.4 MV/m at 4.2 K with a Q_0 of 1.4×10^8 limited by power. 2K vertical test will be done soon. And further study will begin. The cavity shows a great potential in the high current and high HOM damping application such as ERL and circular collider.

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Figure 4: 1.3GHz 3-cell slotted cavity.

Development for Mass Production of Superconducting Cavity by MHI (Kohei Kanaoka, Mitsubishi Heavy Industry)

MHI has improved our superconducting technology to take part in the production design and manufacturing of the cryomodules including the superconducting cavities. MHI produced the injector module of cERL shown in Figure 5(right) which contains three 9-cell cavities. We performed the production design and fabrication of the parts and assembly of the cryomodule at KEK. We also fabricated the main accelerator module for cERL shown in Figure 5 (left) [10,11].

We designed the 1.3GHz 1.5-cell elliptical cavity for the superconducting RF electron gun and fabricated the Prototype#1.

MHI has developed the manufacturing process of superconducting cavities for a long time. For example, we perform the welding of the stiffener rings by the laser welding. The 2-cell cavity shown in Figure 6(left) was fabricated by using the seamless dumbbell. MHI has the EBW machine which can contain four 9-cell cavities by vertical position and weld them in one batch. We succeeded in welding all seams of equator of four cavities in one batch shown in Figure 6(right)[12].

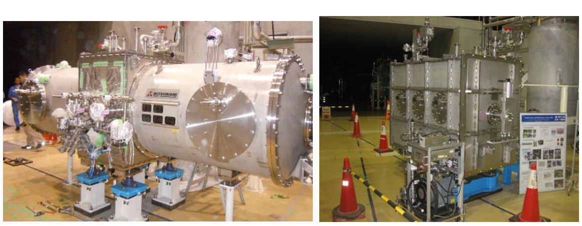

Figure 5: Main accelerator module(left), Injector module of cERL (right).

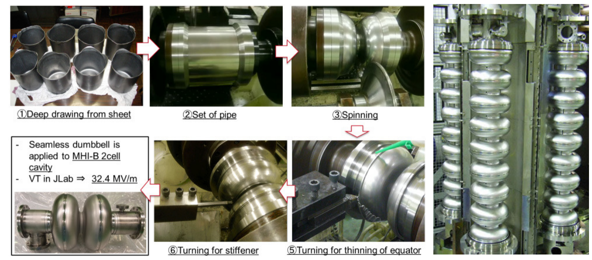

Figure 6: Process of the manufacture of the seamless dumbbell and 2-cell cavity (left), batch process (right).

Ultra-Fast Harmonic Resonant Kicker Design for the MEIC Electron Circular Cooler Ring (Yulu Huang, IMP (Jlab))

Electron cooling is essential for the proposed MEIC to attain low emittance and high luminosity [13].The present MEIC design utilizes a scheme of multi-stage cooling, a DC cooler in the booster and bunched electron beam cooler ERL in the collider ring. To achieve a very high electron beam current for bunched beam cooling in the future high luminosity upgrade, we adopt a circulator ring to reuse the electron bunches. The electron bunches will recirculate for 25 turns, thus the current in the ERL can be reduced by a factor of 25. An ultra-fast kicker is required for this circulator ring, with a pulse width less than 2.1ns (1/476.3MHz) and a high repetition frequency of 19.052MHz (1/25 of 476.3MHz). JLab started an LDRD proposal to develop such a kicker. Our approach is to generate a series harmonic mode with RF resonant cavities [14], electron bunches passing through the cavity will experience an integral effect of all the harmonic field, thus every 25th bunch will be kicked while all the other bunches un-kicked.

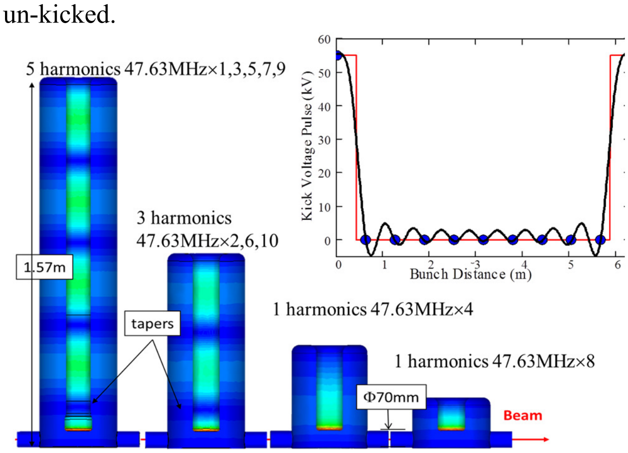

Figure 7: Harmonic modes in four cavity system with the highest harmonic electric field distribution shown in each cavity. Ideal kick voltage pulse (red square pulse) and bunch train scheme (blue point) to kick every 10th bunch, and the reconstructed kicker pulse with the first 10 harmonic modes (black).

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Here we present a design of a simplified prototype with every 10th bunch kicked, using four Quarter Wave Resonator based cavities to generate 10 harmonic modes, as shown in Figure 7. Cavity structure is optimized to get the highest shunt impedance, and the total power dissipated on the four cavities for copper material is 87.72W, two to three orders of magnitude lower than a strip-line kicker [15].

Recent progress of PKU DC-SRF gun and future prospect were also presented. Furthermore, design work for SRF cavities for high current ERLs at BNL were also presented in this session

RF CONTROL OF SRF CAVITIES FOR STABLE BEAM OPERATION

The joint session with WG3 were held to discuss the RF control for SRF cavities and RF sources.

Performance of Digital LLRF System at cERL (Feng Qiu, KEK)

A compact energy recovery linac (cERL), which is a test machine for the next generation synchrotron light source 3-GeV ERL, was constructed at KEK [7]. In the cERL, a normal conducting (NC) buncher cavity and three superconducting (SC) two-cell cavities were installed for the injector, and two nine-cell SC cavities were installed for the main linac (ML). The radio-frequency (RF) fluctuations for each cavity are required to be maintained at less than 0.1% rms in amplitude and 0.1° in phase. These requirements are fulfilled by applying digital low-level radio-frequency (LLRF) systems. During the beam-commissioning, the LLRF systems were evaluated and validated. A measured beam momentum jitter of 0.006% indicates that the target of the LLRF systems is achieved (see Figure 8). To further improve the system performance, an adaptive feedforward (FF) control-based approach was proposed and demonstrated in the beam-commissioning as well [16]. Based on the new adaptive FF approach. The microphonics in the cavity of the ML has been rejected successfully as shown in Figure 9. The current status of LLRF system and the adaptive FF approach for LLRF control in the cERL are presented in this paper.

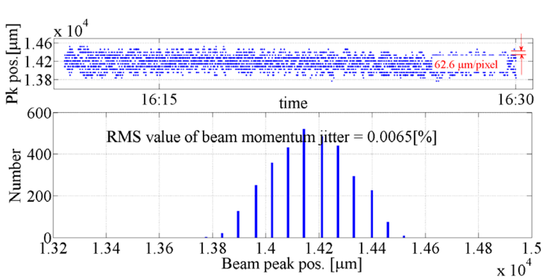

Figure 8: Beam momentum jitter measurement. The measured beam momentum jitter was 0.0065% rms, which is in agreement well with RF stability.

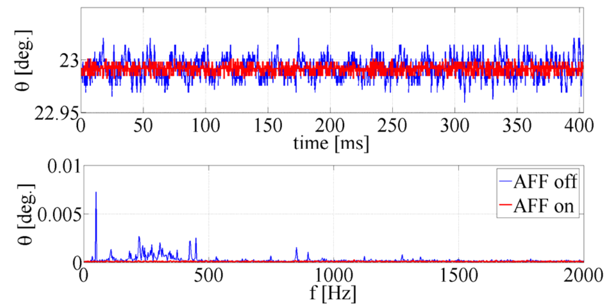

Figure 9: Measured RF phase of the ML2 cavity pickup signal in the case of with and without adaptive FF control. Both waveform (top) and spectrum (bottom) are presented.

Resonance Control for Narrow-Bandwidth, Superconducting RF Applications (J. P. Holzbauer, FNAL)

Many of the next generation of particle accelerators (ERLs, XFELs) are designed for relatively low beam loading. The cavities are designed to operate with narrow cavity bandwidths to minimize capital and operational costs of the RF plant. With such narrow bandwidths, cavity detuning from microphonics becomes a significant factor, and in some cases can drive the cost of the machine [17]. Piezo actuators have been successfully used to actively stabilize cavity resonant frequencies. This paper will present the results of ongoing detuning compensation efforts at FNAL using prototype 325 MHz SRF single spoke resonators designed for the PIP-II project at Fermilab [18].

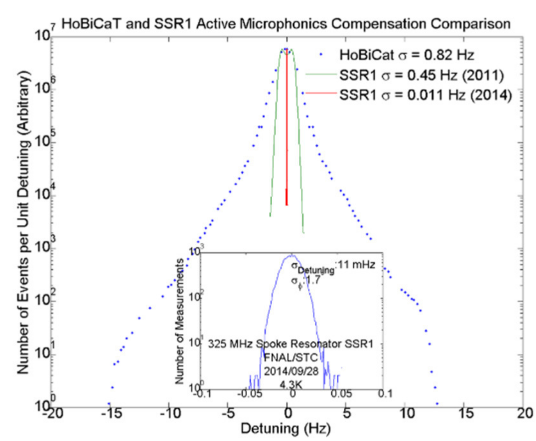

Figure 10: A comparison detuning distributions following active compensation at HoBiCaT and FNAL.

Using an FPGA system developed at FNAL, the cavity was controlled and calibrated on-line. Static and dynamic measurements were used to calibrate relative gains and phases of cavity signals along with cavity Lorentz Force Detuning coefficients. This coefficient was used to correct

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this detuning in a feedforward configuration on the piezo. Careful calculation of cavity detuning was calculated online and feed into the piezo for active compensation of fast cavity detuning. Over a two hour run, the cavity resonance was stabilized to an RMS detuning of 11 mHz with a peak to RMS ratio of 6 as shown in Figure 10. Active efforts to improve this and include amplitude and phase stability are ongoing.

Using a 1.3 GHz 20 kW Solid State Amplifier as RF Power Supply for DC-SRF Photo-Injector (Fang Wang, Peking Univ.)

An upgraded DC-SRF injector with a 3.5-cell cavity was designed and constructed at Peking University [19]. Taking into account the regulation reserve for phase and amplitude control and losses in the waveguide distribution, a 20 kW CW amplifier at 1.3 GHz is needed and we manufactured a solid state amplifier (SSA) under the collaboration with BBEF.

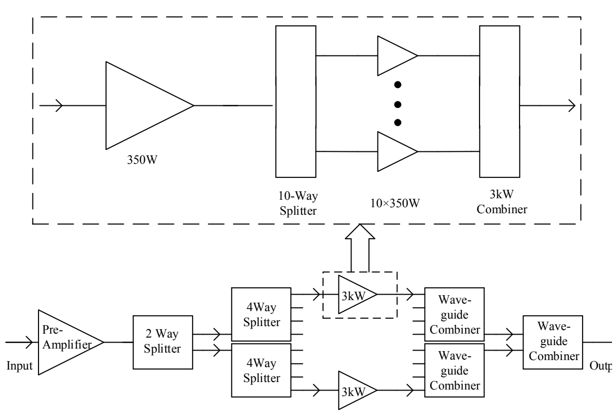

Figure 11 : Structure of 20kW SSA.

Table 2: Technical Specification of the Power Amplifier

Parameter	Required	Results
Frequency Range /MHz	1300±0.05	1300±0.05
CW & Pulsed Output Power (1dB Compression) /kW	≥ 20	20
Linear Gain /dB	≥73	~85
Output Harmonics 2nd/3rd Order /dBc	≤-30 ≤-30	-70 -57
RF Phase Shift vs. Output/°	≤10	9.5
Gain Change vs. Output/ dB	≤2.0	1.6
Efficiency at 20kW output	≥40%	34%

The overall structure of the SSA is illustrated in Figure 11. It consists of 8 transistor banks. Each bank generates 3 kW and in which, there are 11 elementary modules with individual power supplies and one module is used as a preamplifier to drive the other ten.

It has been tested after the installation. The technical specification is shown in Table 2. Full reflection test was carried out with a short waveguide terminal, and we got 16 kW over 16 kW in CW for ten minutes without problem. It has been used for routine operation of the DC-SRF photo-injector successfully since 2012.

DISCUSSION

To clarify the present status and future prospect for establishing the high current and high charge with low emittance ERL beam operation. We discuss the following subjects.

A) How is the present status for high current ERL of each component ?
  i. Cavity design and test results are OK to meet the more than 100mA operation. However, we need to care not to contaminate the field emission source in string assembly especially for mass production phase.
  ii. HOM damper/coupler development for high current beam operation were continuously proceeded at each labs. Recently, HOM damper works well with CW 40 mA of 2.7 ps bunch length at Cornell injector beam line.
  iii. Fundamental power coupler (FPC) gives the transmitted more than CW 40kW of 1.3 GHz at Cornell Univ and KEK. BNL FPC give the CW 500 kW of 700 MHz. These results enable CW beam operation 100mA at injector.

B) How to obtain and keep the optimum and stable CW operation field with High-Q for a long time for beam operation ?
  i. Recent high-Q R&D including “N2 doped” cavity gives the Q0 > 3x10^{10} at 16 MV/m. We need to push high-Q R&D more.
  ii. Degradation during beam operation is one of the problem for stable beam operation. KEK cERL main linac cavities met the degradation come from field emission (FE) during beam operation at 8.3MV/m field. Furthermore, CEBAF and SNS also meet the degradation during beam operation. We need to keep measuring the cavity performance and collect the experience of degradation of cavities with long-term beam operation.
  iii. We discuss about how to stop the FE (Dark) current from cavity in operation. By using collimator and Q-magnet between cryomodule, we can separate the dark current and main beam. However, we conclude that we need the careful simulation and discuss with beam dynamics group (WG2) more.

C) RF and beam control issues. (WG3/4 joint session)
  i. By using Digital LLRF system, stability has $\Delta A/A < 0.01\%$ and $\Delta\theta < 0.01$ degree at KEK cERL. And tuner control with 0.011Hz was

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satisfied by cautious optimism by FPGA at FNAL. These are encouraging results, which satisfy our ERL requirements.

ii. We discuss the strategy to reach the high current beam more than 100 mA. By considering the space charge effects at injector parts, we support starting the beam tuning with nominal bunch charge and increase the beam current by changing the repetition ratio of beam. In reality, more discussion is needed.

iii. When we hit the worse HOM's, we basically need to detune the one cavity. We also discuss the possibility about de-Qing and feedback to HOM suppression.

iv. What we need to do and care if we met the failure during beam operation with high current beam ? Failure modes, which gives the not only stopping the injector beam but also ejecting beam, must to be considered before the beam operation. Clearing gap with beam was also suggested not to increase the beam instability and to identify the bunch train information.

SUMMARY

From ERL2013, the positive and steady advances are seen at every laboratories in these two years as follows.

A) Recent high-Q R&D including the "N2 dope" at FNAL, Cornell Univ. is a great work. This lead us to reach more higher gradient CW operation of ERL.

B) Cavity performance including cryomodule test has reached the ERL level and meet reququirments. On the other hand, we met the degradation with FE during long-term beam operation at KEK cERL main-linac.

C) HOM damper was performed with real high current beam with CW 40 mA at Cornell injector and gave the good performance.

D) More than 100 mA was achieved with BBU suppressed cavity design, which was done at BNL, Cornell, KEK, HZB, in the elaborate simulation work.

E) Cavity fabrication technique catch up with the mass production phase now.

F) LLRF with tuner control of stable power source reach the very high stability of $\Delta A/A < 0.01\%$ and $\Delta\theta < 0.01$ degree, which satisfy our ERL requirements.

G) New SRF guns starts in operation at HZDR and BNL. Dark current is severe problem at present.

All key components are in the level of practical use expect for HOM damper. Furthermore, we understand the difficulty of SRF operation with high gradient in CW mode because of FE and other disturbance. We note that construction of new ERLs like BERLinPro is underway and new test facility of FFAG-ERL at Cornell/BNL and CERN are proposed. As the next step, we will accumulate the cavity & cryomodule test including new ERL facility and operation experiences so that we can meet for stable operation at the next ERL2017.

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