ANALYSIS OF HOM-BBU WITH NEWLY DESIGNED CAVITIES FOR A MULTI-GEV ERL LIGHT SOURCE

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Abstract

A collaborative project towards an ERL light source has been launched in Japan. In this project, we are developing a superconducting cavity optimized for a high-average current beam. The latest design is a 9-cell cavity of 1.3 GHz with enlarged beam pipes and on-axis HOM absorbers. In this paper, beam breakup instabilities for the newly designed cavity are investigated. Threshold current of beam breakup at a 5 GeV ERL, and possible extension to 2-turn configuration, are presented.

INTRODUCTION

An energy-recovery linac (ERL) is a promising device for next-generation X-ray light sources, because an ERL is able to generate an electron beam of high-average current with ultimately small emittance. In the research and development towards the future ERL light source, beam breakup (BBU) caused by higher-order modes of superconducting cavities (HOM) is one of the critical issues to resolve. In order to suppress the HOM-BBU and increase the accelerating beam current, several studies have been conducted, which are beam optic optimization, x-y coupling in a return loop and utilization of polarized cavities [1][2]. Although these procedures indeed increase the BBU threshold current to some degree, the most straightforward solution to the HOM-BBU is development of ERL-oriented cavities with strong damping of HOMs.

Recently, a collaborative project for a future X-ray ERL facility has been established in Japan [3]. In the project, we are developing a superconducting cavity optimized for a high-average current ERL. Design of the cavity shape has been completed and fabrication of the prototype is under way [4][5].

In the present paper, we analyse HOM-BBU with our newly designed cavities. Threshold current of HOM-BBU at a 5-GeV ERL, the effect of HOM frequency randomization and possible extension to a 2-turn configuration are discussed.

CAVITY DESIGN

In the Japanese collaboration team (KEK/JAEA/ISSP), we are developing superconducting cavities for a 5 GeV-class ERL light source. We have chosen a 9-cell 1.3-GHz structure and two types of cavity have been designed: we call them Model-1 and Model-2. Figure 1 shows the Model-2 cavity, the latest model, which has optimized cell shape and enlarged beam pipes for efficient damping of HOMs. HOMs excited in the cavity are extracted through the beam pipes and damped by on-axis HOM absorbers installed at both ends of the cavity. The detail of the cavity is described elsewhere [4].

Parameters of major HOMs, which have large Q_L or large (R/Q), for Model-1, Model-2 and TESLA cavities are listed in Table 1. We use these parameters in the following BBU simulations.

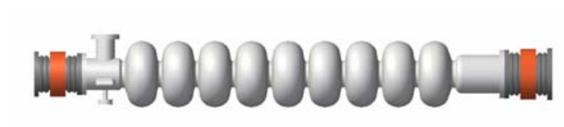

Figure 1: Model-2 cavity for the ERL light source in Japan.

In a previous study, a criterion of HOM properties to achieve 100-mA operation in an ERL is presented:

$$(R/Q)Q_L/f < 1.4 \times 10^5 [\Omega/cm^2/GHz]. \qquad (1)$$

Although all the HOMs in the Model-2 cavity fulfill this criterion, we need to confirm the detail performance of the cavity by numerical simulations.

SIMULATION CODES

In our study, two kinds of BBU simulation codes have been used, `bi` developed at Cornell and `BBU-R` at JAEA. These two codes are based on the same algorithm of particle tracking, but have different features [1]. In all the simulations in this study, we assume HOMs are polarized in x and y directions, and no $x-y$ coupling in the beam optics. The two codes, in this situation, can be applied equally to HOM-BBU analysis.

Optimization of beam optics is necessary in HOM-BBU simulations, because the threshold current of HOM-BBU is a function of beam optics—beam envelope inside the linac and betatron phase advance of the return loop. The simplest scheme for the linac focusing optimization is setting quadrupoles strength K_1 so that the lower energy beam feels constant focusing strength along the linac. This is called 'graded gradient focusing with a constant K_1'. The

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Table 1: Major HOMs for Model-2, Model-1 and TESLA cavities.

f (GHz)	(R/Q) **(Ω/cm^2)**	Q_L	$(R/Q)Q_L/f$ $(\Omega/cm^2/GHz)$
	Model-2		
4.011	3.210	11410	9.131E3
1.856	7.311	1698	6.689E3
2.428	6.800	1689	4.730E3
4.330	0.01800	60680	2.523E3
3.002	0.3250	29990	3.247E3
1.835	8.0877	1101	4.853E3
	Model-1		
2.575	21.32	4899	4.056E4
1.874	8.770	11660	5.454E4
1.866	6.434	7732	2.666E4
1.879	1.953	18360	1.909E4
3.082	0.9791	33610	1.068E4
3.085	0.9631	31860	9.946E3
	TESLA		
2.575	23.80	50000	4.621E5
1.875	8.801	51100	2.399E5
1.865	6.500	50600	1.763E5
1.811	1.668	95100	8.761E4
1.887	0.2002	633000	6.716E4

value of focusing strength, K_1, and the phase advance in the return loop are chosen to maximize the BBU threshold current. Another optimization scheme of linac focusing is making the transverse size of two beams minimum by changing Twiss parameters at the linac entrance, strength of quadrupole magnets and phase advance of the return loop. This scheme is called 'minimum beam size'. We apply these two optimization schemes in the following simulations.

LINAC CONFIGURATION

We assume a 5-GeV linac consisting of 31 cryomodules, each of which contains 8 cavities as shown in Fig.2. Since the cavities have beam pipes with different diameters for each side, they are connected with coupler-side to coupler-side. The cavity length measured from the center of the HOM absorber is assumed to be 1.568 m = 0.235 m + 1.038 m + 0.295 m (the shorter end is the coupler side).

A quadrupole triplet is installed between two cryomodules as shown in Fig.2. The total length of the linac including 31 cryomodules and 30 triplets becomes 466.864 m. The total recirculation length including the linac and the return loop is 1466.1 m corresponding to 6357.5 RF periods. Assuming the injection energy of 10 MeV, and the accelerating voltage per cavity of 20 MV, we have the final energy of 4.97 GeV.

In the simulation we assume two polarizations of HOMs, horizontal and vertical (x and y), for each HOM listed in Table 1, and that the two polarized HOMs have the same frequency, (R/Q) and Q_L.

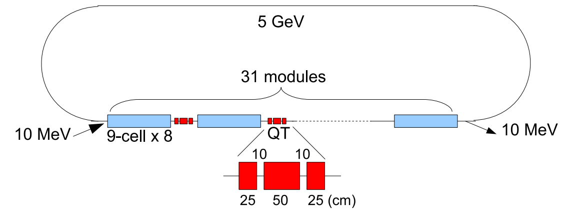

Figure 2: A 5 GeV ERL light source.

RESULTS OF BBU SIMULATIONS

Optimization of Beam Optics

The threshold current of HOM-BBU for the 5-GeV ERL with Model-2 cavities is calculated. Figure 3 shows the BBU threshold current obtained by `bi` with the graded gradient focusing. In this calculation, HOM frequency randomization is not included. As seen in Fig.3, the threshold current depends on both focusing strength of the quadrupole triplet and the phase advance of the return loop. Here the linac FODO becomes unstable in the region $K_1 > 2.55m^{-2}$. The threshold current has a maximum value, 0.683 A, at $\Psi = 210°$ and $K_1 = 2.4m^{-2}$.

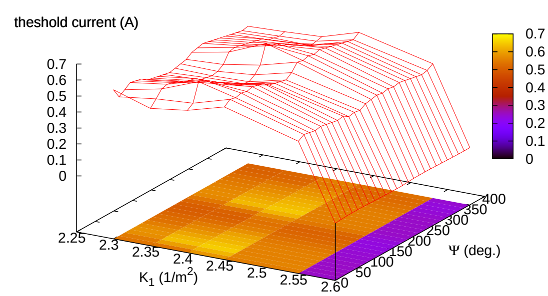

Figure 3: BBU threshold current for the 5 GeV ERL with Model-2 cavities as a function of beam optics, strength of the linac quadrupoles, K_1, and phase advance of the return loop, Ψ.

The other optimization scheme, 'minimum beam size', gives a threshold current of 0.600 A by `BBU-R`, and 0.659 A by `bi`. Figure 4 shows optimum strength of quadrupole triplets along the linac, where optimum values are around $K_1 \sim 2.4m^{-2}$, which is consistent with the result from 'graded gradient focusing'. Betatron envelopes along the acceleration and the deceleration after the optimization are shown in Fig.5.

Comparison of 3 Types of Cavities

Figure 6 is a comparison of BBU threshold current obtained for 3 types of cavities, Model-1, Model-2 and

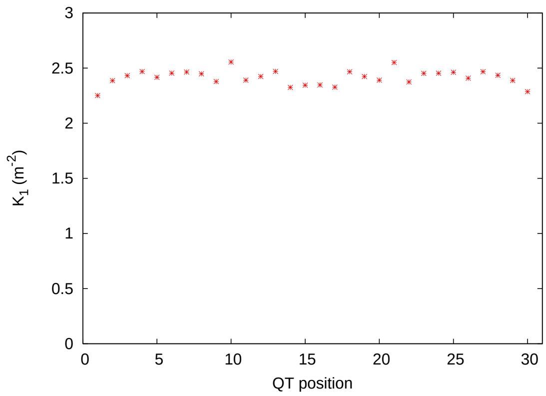

Figure 4: Optimum focusing strength of quadrupoles obtained from the ‘minimum beam size’scheme.

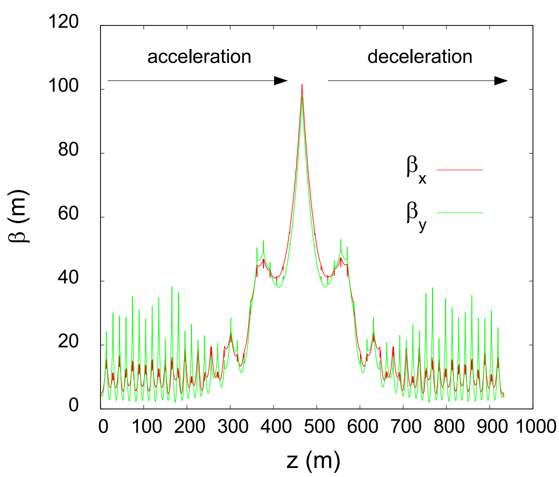

Figure 5: Optimum betatron envelopes obtained from the ‘minimum beam size’scheme.

TESLA. These calculations have been made by `bi` with the graded gradient focusing scheme, and the focusing strength K_1 is chosen to maximize the threshold current for each type of cavity.

The maximum BBU threshold current is found to be 23 mA for TESLA cavity, 140 mA for Model-1 cavity and 680 mA for Model-2 cavity. These results are consistent with a prediction by Eq.(1) with the HOM parameters listed in Table 1. We can conclude that Model-2 cavity is competent enough for a multi-GeV ERL light source.

HOM Frequency Randomization

It is known that randomization of HOM frequency is effective in enlarging the BBU threshold current. The randomization of HOM frequencies is introduced naturally in the cavity fabrication processes, and has a spread of several MHz at TESLA cavity [6].

Figure 7 shows HOM-BBU threshold current with HOM frequency randomization for the 5 GeV ERL with Model-2

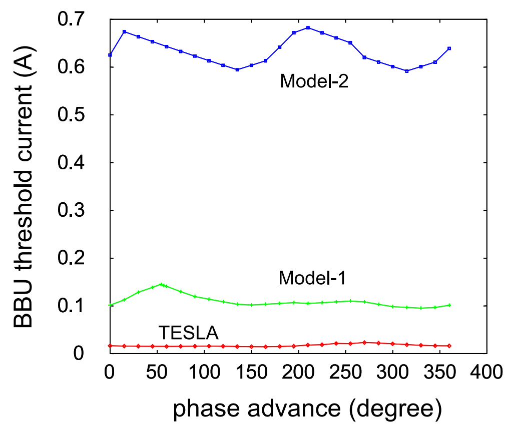

Figure 6: Threshold current for 3 types of cavities: TESLA, Model-1, Model-2.

cavities. In the simulations, we assume the frequencies of HOMs have a Gaussian distribution among many cavities. The error bars indicate maximum and minimum values of 10 simulations with a different seed of random number generation. The simulations have been made by combination of a BBU code and an optics optimization scheme: (1) `bi` and graded gradient focusing, (2) `bi` and minimum beam size, (3) `BBU-R` and minimum beam size. We can see that the threshold current increases with the HOM frequency randomization, and becomes about 1.5 A for the randomization of 1 MHz. The difference of the threshold current in three curves is not as large as the variation due to random numbers.

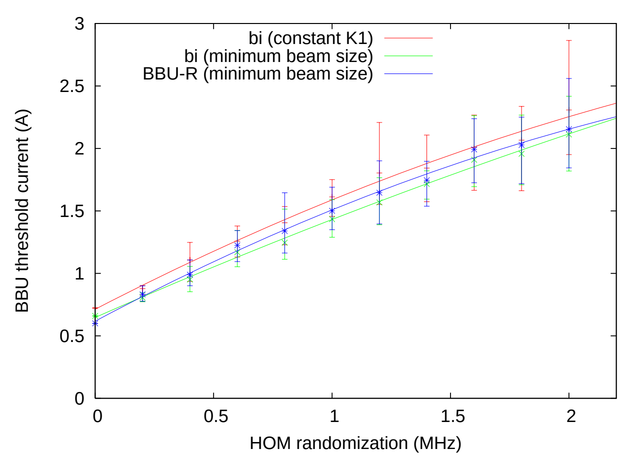

Figure 7: Threshold current with HOM frequency randomization for the 5 GeV ERL with Model-2 cavities.

Return Loop Length

In a single-cavity single-HOM case, the HOM-BBU threshold current is a function of the return loop length [1]. The loop-length variation is expected to affect the HOM-BBU even in a multi-cavity multi-HOM ERL. We investigate the effect of loop-length variation in our 5 GeV ERL with Model-2 cavities. Figure 8 shows BBU threshold current with varying return loop length in the 5 GeV ERL, where we use BBU-R with an optimization scheme of minimum beam size. The periodic oscillation of the BBU threshold current seen in the upper figure is due to the most harmful HOM, whose frequency has a fractional relation with the fundamental, $f = 4.011GHz \simeq (37/12) \times 1.3GHz$.

The periodic oscillation disappears by HOM frequency randomization as seen in the lower figure.

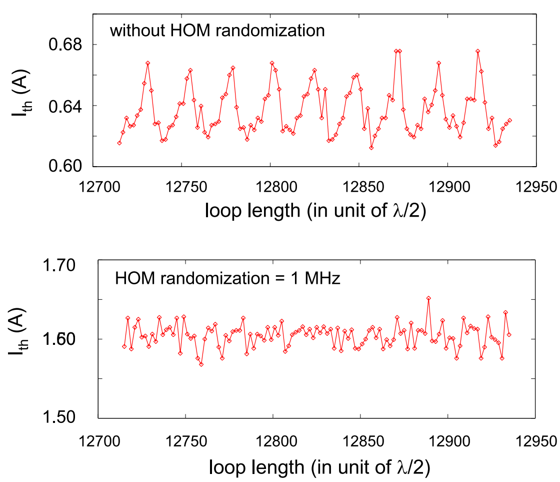

Figure 8: Threshold current against the variation of return-loop length.

HOM-BBU IN A 2-TURN ERL

As the HOM-BBU threshold has been increased by improvement of cavity performance, a multi-turn configuration becomes a practical option of an ERL light source. If a 5-GeV ERL light source is built in a 2-turn configuration, construction and operation costs of the linac, the refrigerator and the RF system can be reduced to a half of the 1-turn configuration. Thus the 2-turn ERL is attractive from an economic viewpoint, but we need detailed investigation of electron beam dynamics in the 2-turn ERL before adopting the 2-turn configuration. We, therefore, study growth of emittance and energy spread due to CSR in the 1st loop as well as HOM-BBU in the 2-turn configuration.

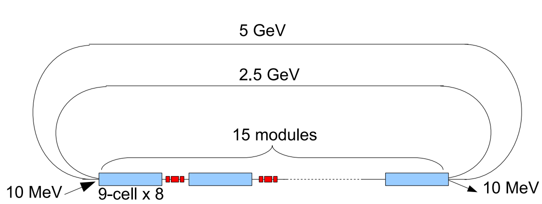

Figure 9: A 5 GeV ERL light source with a 2-turn configuration.

We study a simple 2-turn ERL shown in Fig.9, where the 1st loop consists of 180-degree FODO arcs and a FODO channel straight section. The arc has the same lattice as FODO arcs in KEK-PF, a 2.5 GeV storage ring. Each FODO arc has 14 bending magnets and a pair of QD and QF between bending magnets. The bending radius is 8.66 m. In order to minimize the CSR effects in the arcs, we set betatron phase advance per cell, $\Psi_x = 12\pi/14$. The 1st loop is non-isochronous and $R_{56} = 0.697m$ (sign of R_{56} is same as a DBA arc). Figure 10 shows betatron envelopes for the 1st loop.

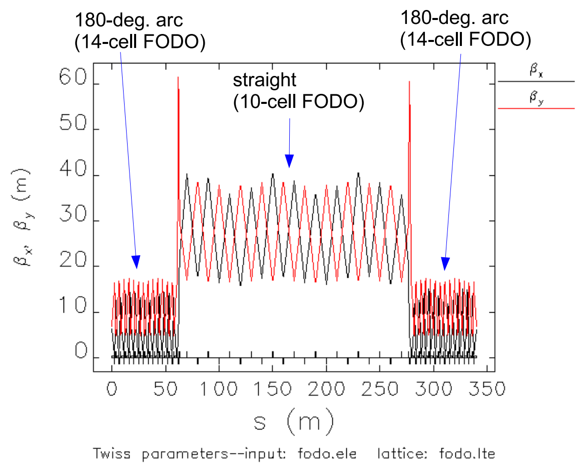

Figure 10: Betatron functions for the 1st loop.

The linac consists of 15 cryomodules and 14 quadrupole triplets, and the total length is 224.56 m. We choose the loop lengths including the linac: 619.994 m for the 1st loop, 1020.101 m for the 2nd loop. The bunch repetition rate is 0.65 GHz, a half of the fundamental frequency. The accelerating voltage per cavity is 20 MV.

In the 2-turn configuration, 4 electron beams exist in the linac. In the optimization of beam optics by graded gradient focusing, we set the quadrupole strength so that the lowest energy beam feels a constant focusing strength, K_1. The betatron phase advance of the loops are chosen to maximize the BBU threshold current.

Figure 11 shows calculation results of the BBU threshold obtained by bi as a function of HOM frequency randomization, where the optimization of beam optics has been made by graded gradient focusing: quadrupole strength $K_1 = 2.3m^{-2}$, phase advance of the 1st loop $\Psi_1 = 0$, phase advance of the 2nd loop $\Psi_2 = 122°$. We assume a Gaussian distribution of HOM frequencies same as the simulations for the single turn ERL. The simulation result shows that the BBU threshold is about 300 mA for HOM frequency randomization of 1 MHz, which is sufficiently large for the standard operation of 5 GeV-ERL light sources, 100 mA (154 pC, 0.65 GHz).

In a previous study, the BBU threshold current for a 1 GeV-ERL was estimated at 750 mA for 1-turn and 300 mA for 2-turn configuration with an ideal cavity which has strong HOM damping [8]. Here, we have shown that the 2-turn 5-GeV ERL is really possible with our newly designed cavity.

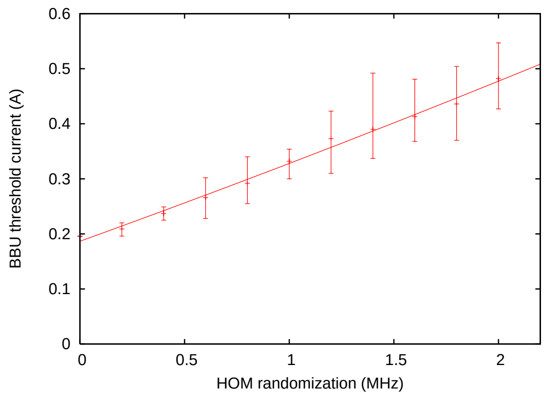

Figure 11: BBU threshold current of the 2-turn ERL with HOM frequency randomization.

Degradation of the electron beam quality due to CSR is calculated by particle tracking simulations with `elegant` [9]. We define emittance growth in the 1st loop as

$$\Delta\varepsilon_n = \sqrt{\varepsilon_f^2 - \varepsilon_i^2}, \tag{2}$$

where ε_i and ε_f are normalized emittances at the entrance and the exit of the 1st loop, respectively. From the linear analysis, the emittance growth defined above is proportional to the bunch charge and independent of initial emittance [7]. The growth of energy spread is also defined in the same manner.

Figure 12 shows growth of emittance and energy spread in the 1st loop. For a 100 mA beam current (154 pC) and 3 ps bunch duration, the growth of emittance and energy spread are found to be 0.053 mm-mrad and 1.89×10^{-5} (47 keV), which are fairly acceptable for a 5-GeV ERL light source. The beam degradation is still modest even for a 1 ps, 100 mA case, in which growth of emittance and energy spread are 0.240 mm-mrad and 8.55×10^{-5} (210 keV), respectively. In the simulation with 1 ps bunches, the emittance growth moves to a nonlinear regime at large bunch charge, $Q \gtrsim 0.3\ nC$. This nonlinear emittance growth at the large bunch charge seems due to chromatic aberration and can be compensated by appropriate sextupole corrections which are not included in the simulation.

CONCLUSIONS

We have seen HOM-BBU analysis of a 5 GeV ERL with our newly designed cavities. The BBU threshold current has been calculated by `BBU-R` and `bi` with two kinds of beam optics optimization. It has been found that Model-2 cavity can accelerate a 100 mA beam keeping enough margin of safety, and is competent for future ERL light sources. We have also studied possible extension to a 2-turn configuration. The HOM-BBU and the CSR effects in a 2-turn 5-GeV ERL can be handled without any fatal effects.

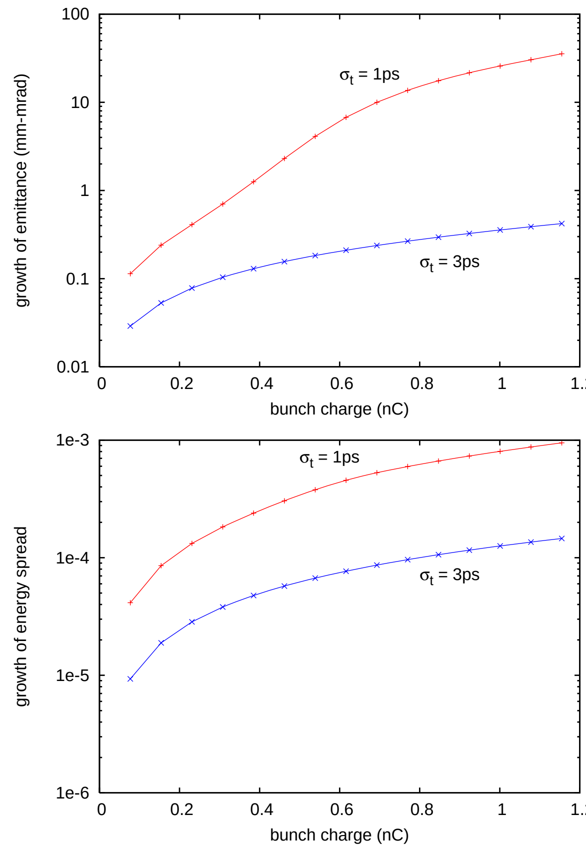

Figure 12: Growth of emittance and energy spread due to CSR effects in the 1st loop.

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