MULTI-PASS, MULTI-BUNCH BEAM BREAK-UP OF ERLS WITH 9-CELL TESLA CAVITIES*

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Abstract

In this paper, multi-pass, multi-bunch beam break-up of some small-scale Energy Recovery Linac(ERL) configuration using 9-cell Tesla cavity is discussed. The threshold currents of different cases are investigated and some factors that influence the threshold currents are discussed.

INTRODUCTION

Multi-pass, multi-bunch beam break-up (BBU) caused by higher order modes (HOMs) field in RF cavities is one of the main limitations to the beam current of ERLs. In order to suppress HOMs more efficiently, various types of superconducting cavities have been designed, e.g., the 5-cell cavity at BNL, 7-cell cavity at Cornell University and 9-cell ERL cavity at KEK/JAEA, etc. Compared with those cavities, 9-cell Tesla cavities are rather mature after years of development and some facilities like ILC and European XFEL have decided to adopt 9-cell Tesla cavity.

Due to the BBU effect, 9-cell Tesla cavities are not applicable for the ERL synchrotron light source [1]. Nevertheless they can be used in some small-scale ERL configuration with the average current around 10 mA. In this paper, we discuss the HOMs and BBU threshold current for small-scale ERLs which employ 9-cell Tesla cavities.

MULTI-PASS, MULTI-BUNCH BBU

When an electron bunch enters a cavity with excited HOM field, it experiences a transverse kick and returns to the cavity with a transverse offset after traversing the recirculating loop. This offset leads to an energy exchange between HOM and bunch. If the energy gain from bunches is beyond the suppression ability of HOM coupler, HOM energy grows and then larger transverse kick will be experienced by subsequent bunches, which in turn leads to further growth of HOM energy. Then, a feedback loop establishes and BBU occurs finally. In case of single HOM in single cavity, the BBU threshold current can be calculated by [2]

$$I_{th} = -\frac{2pc^2}{e\omega(\frac{R}{Q})Q_e M_{12}^* \sin(\omega T_r)} \quad (1)$$

where R/Q is the shunt impedance of HOM; Q_e is the HOM's external quality factor; ω is the HOM frequency and M_{12}^* is the transport line parameter:

$$M_{12}^* = T_{12}\cos^2\theta + \frac{1}{2}(T_{14}+T_{23})\sin 2\theta + T_{34}\sin^2\theta \quad (2)$$

where T_{ij} is the transport matrix element of the whole transport line; θ is the HOM polarization angle. For ERLs with more cavities and more HOMs, simulations should be adopted. In this paper the code "bi"[3] developed by Cornell University is used to calculate the threshold current.

BBU SIMULATION

According to Eq. 1, the most threatening HOMs to BBU should be the dipole modes with larger $(R/Q)Q_e$. Typical simulation results for the 100 mA high-current cavity calculated by Cornell University show that the dipole HOMs should meet the demands of Eq. 3

$$(R/Q)Q_e/f < 1.4 \times 10^5 \Omega/cm^2/GHz \quad (3)$$

In the 9-cell Tesla cavity, there are several dipole HOMs with $(R/Q)Q_e/f > 1.4 \times 10^5$ and they are presented in Table 1.

Table 1: 4 most threatening dipole HOMs in Tesla cavity

Mode No.	f GHz	Q_e	R/Q Ω/cm^2	$(R/Q)Q_e/f$ $\Omega/cm^2/GHz$
1	1.7074	5×10^4	11.21	3.28×10^5
2	1.7343	2×10^4	15.51	1.79×10^5
3	1.8738	7×10^4	8.69	3.25×10^5
4	2.5751	5×10^4	23.80	4.62×10^5

For simulation we assume that all cavities are installed in a cryomodule with no additional focusing between them. It is also assumed that the recirculating loop has equal betatron phase advance in horizontal and vertical planes and β-function is the same at the start and the end.

For PKU-ERL test facility, which employs two 9-cell Tesla cavities, 4-MeV injected beams are accelerated to 30 MeV at the first pass, the betatron phase advance in $(0, \pi)$ is scanned and the BBU current is calculated. The results for such a scheme are presented in Fig. 1

As shown in Fig. 1, the most threatening modes in the 9-cell Tesla cavity are mode 1 and mode 4. Both of them have $(R/Q)Q_e/f$ larger than other HOMs and therefore determine the threshold current of 9-cell Tesla cavity. BBU current due to some HOMs is sensitive to the betatron phase advance so that a slight shift of betatron phase advance leads to obvious change of BBU current. The maximum value of BBU current that can be achieved by lattice

adjustment for this case is about 300 mA and the minimum value is about 35 mA.
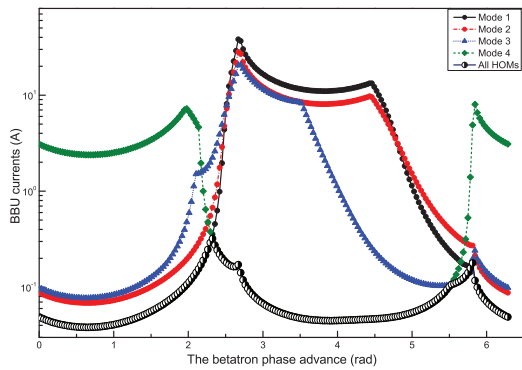

Figure 1: The BBU current vs. the betatron phase advance of recirculating loop.

For an ERL with higher energy, more 9-cell Tesla cavities are required. With increasing number of cavities, electron beam suffers more kicks and the offset after recirculating will be larger so that more energy exchange will occur between HOMs and beam. We calculate BBU currents for ERLs with different number of cavities. The simulation results are shown in Fig. 2.
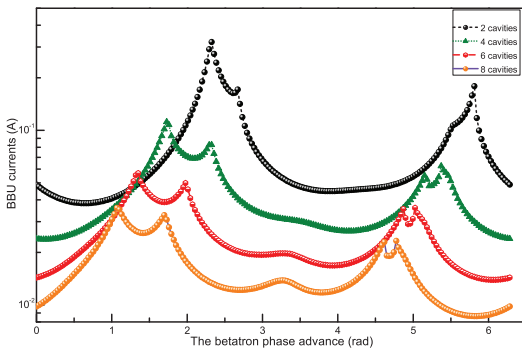

Figure 2: The BBU current vs. the betatron phase advance of recirculating loop for different cavity numbers.

From Fig. 2 we can find that in the case of 8 cavities (in an ILC cryomodule), accelerating injected beam from 4 MeV to 100 MeV (blue squares in Fig. 2, the BBU threshold current is about 31 mA. To achieve average current higher than 31 mA, some additional methods should be taken.

INFLUENCE OF INHOMOGENEOUS HOMS TO BBU

Dipole HOMs in real cavities slightly differ from those in ideal cavities due to fabrication errors. According to [4], the frequency spread of dipole HOM due to the fabrication error is of the order of 10 MHz. For an ERL with several Tesla cavities, this frequency spread may interrupt the coupling of HOMs in different cavities and increase

the BBU current. Fig. 3 shows the BBU current vs. HOM frequency spread of mode 1 in an 8-cavity scheme. The optics are chosen correspondingly to both the minimum and maximum current values from Fig. 2 and the frequency are uniformly distributed.
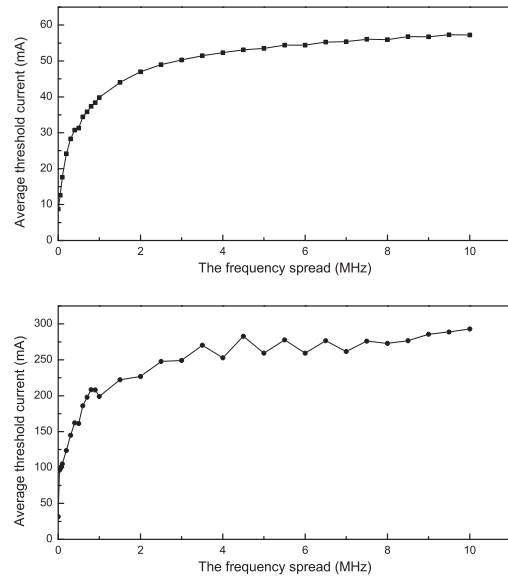

Figure 3: The BBU current vs. the frequency spread. The lattice are relatively corresponding to the BBU current $I_{th} = 8.7$ mA (top) and $I_{th} = 31$ mA (bottom)

Clearly the worst case is that all cavities have the same HOM frequency. The HOM frequency spread between cavities leads to larger BBU current for $\sigma > 3.5$ MHz, arriving at about 50 mA for this case. It also indicates that when $\sigma > 3.5$ MHz, the BBU current does not increase as fast as $\sigma < 3.5$ MHz; that means the ability of increasing BBU current by HOM frequency spread is limited.
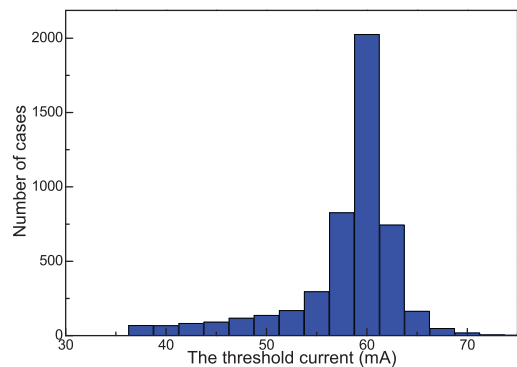

Figure 4: Statistics of the BBU current for 10 MHz frequency spread.

Fig. 4 shows the statistics of BBU current against different cases of frequency spread in the 8-cavity scheme. The HOM frequency spread is uniformly distributed with

$\sigma = 10$ MHz around $mode$ 1. BBU current is calculated 5000 times and the average current of this case is about 60mA, compared to the original BBU current of 8.7mA.

Q_e spread of HOMs will also be introduced in cavity fabrication, e.g., slightly adjustment of the depth of HOM coupler antenna causes an obvious change on Q_e. The shift of Q_e due to cavity assembling uncertainties might be as large as one order of magnitude. Fig. 5 shows the statistics of the BBU current against the Q_e spread. BBU current is calculated by determining the thresholds in 1000 random seeds that have Q_e randomly distributed between 2.5×10^4 and 2.5×10^5. Betatron phase advance of lattice is chosen corresponding to the lowest value of BBU current 8.7mA. The average BBU current of the statistical result is about 3.1mA.
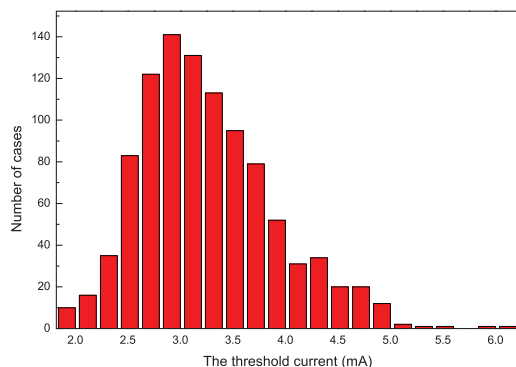

Figure 5: Statistics of the BBU current for different cases of Q_e distribution. HOM parameters: $f \approx 1.7074$GHz, $R/Q = 87.54\Omega$, Q_e is chosen within $(2.5 \times 10^4, 2.5 \times 10^5)$.

Typically fabrication uncertainties of cavities will cause the Q_e of HOM larger than nominal value so that the BBU current will be smaller than that of the ideal cavities. Eq. 1 indicates that cavities at lower energy section contribute more to the instability since bunches in these cavities are easier to be deflected. Therefore, it is beneficial to set the first and last cavities in ERL to have lower Q_e.

METHODS TO SUPPRESS BBU

For ERLs with 9-cell Tesla cavities, not-well-damped HOMs may increase the risk of beam break-up of ERLs. Some methods can be applied to reduce this risk, such as a random frequency distribution introduced to HOMs among cavities [5], or a dedicated section to adjust the betatron phase advance of recirculating loop [6]. With the former method, as shown in Fig. 3, the ability of increasing the threshold current is limited. With the latter method, it is hard to assure $M_{12}^* \sin \omega T_r \approx 0$ for each HOM in each cavity so that for ERLs with more cavities and HOMs the ability of suppressing BBU is also limited.

Some other beam optics manipulation can also be applied to suppress BBU, e.g., interchanging the horizontal and vertical planes betatron motion with reflection transport, or rotating the betatron phase plane by 90° [2]. These functions can be realized by a solenoid or a set of skew-quadruples. Two configurations, employing a reflection section and a rotation section in the recirculating beamline of a 8-cavity scheme respectively are simulated. The results are shown in Fig. 6.
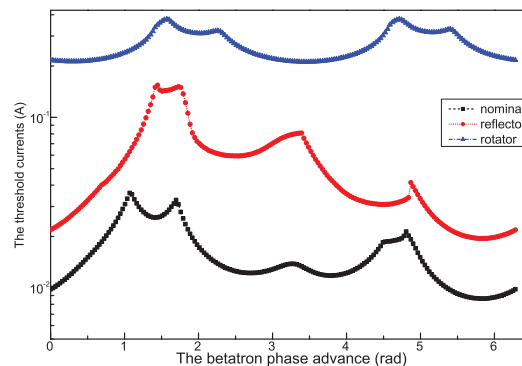

Figure 6: The 8×9cell Tesla cavities scheme with a reflector (red squares) or a rotator (green triangle) in the transport line.

As shown in the figure, the threshold current is increased by about 5 times with reflection configuration while 10 times with rotation configuration. In principle these methods will lead to an infinite threshold current for single HOM in single cavity. However, for larger ERL machine with more cavities and cryomodules, complicated situation of HOMs may lead to destructive mode coupling and degrade the performance of suppression. What's more, for ERLs of more than 2 turns, the coupling induced by these two methods will increase the difficulty of beam transport.

CONCLUSION

The threshold currents of multi-pass, multi-bunch beam break-up for small-scale ERLs with 9-cell Tesla cavities are investigated. By adjusting the betatron phase advance of recirculating lattice and introducing frequency spread between different cavities, BBU effect can be effectively suppressed. For an small-scale ERL test facility with 9-cell Tesla cavities, BBU threshold current up to tens mA can be obtained.

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