ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB265

BUNCH LENGTHENING OF THE HALF STORAGE RING IN THE PRESENCE OF PASSIVE HARMONIC CAVITIES

Tianlong He*, Zhenghe Bai, Weiwei Li, Gangwen Liu,
Hongliang Xu, Shangcai Zhang, Guangyao Feng, Lin Wang, Weimin Li
National Synchrotron Radiation Laboratory, USTC, Hefei, China

Abstract

A passive 3rd harmonic RF system, being necessary for the Hefei Advanced Light Facility (HALF) storage ring under design, will be employed to lengthen the bunches for suppressing the intrabeam scattering and improving the beam lifetime. However, the transient beam loading due to the fundamental mode may significantly reduce the bunch lengthening. Since the scale of transient effects is proportional to R/Q, the effects of R/Q on bunch lengthening, in uniform fill pattern with the near-optimum condition fulfilled, are analyzed by multibunch multiparticle tracking simulation. It indicates that the passive superconducting harmonic cavity with a lower R/Q is preferred by HALF.

INTRODUCTION

The Hefei Advanced Light Facility (HALF) storage ring, being designed as a diffraction-limited storage ring, will has natural emittance lower than 100 pm·rad and nominal beam current of 350 mA [1]. To assure its performance, the passive 3rd harmonic cavity (3HC) will be used to stretch the bunches for mitigating the intrabeam scattering effect and improving the Toucheck lifetime. However, the transient beam loading effect can dramatically degrade bunch lengthening. As is known that the scale of transient effects is proportional to the value of R/Q which only depends on the geometry structure of RF cavity. Generally, there are two types of cavities: superconducting (SC) and normal conducting (NC). Considering the voltage requirement and power limitation, one SC cavity like Super-3HC of SLS/Elettra type (R/Q = 90 Ω) or three NC cavities like ALS type (R/Q = 80 Ω) are required. From the beam point of view, the main difference between both of them is the total R/Q. It means that their related transients will be much different. Although the NC case will cause more severe transients than the SC case, it is still considered to be employed for HALF due to the unnecessary complex SC infrastructure. To make the proper choice of the 3HC, it is better to evaluate the effect of different schemes with different R/Q on bunch lengthening.

Recently, we have developed a tracking code on the platform of MATLAB which utilizes a graphics-processing-unit card [2]. This code can be used for bunch lengthening under arbitrary bunch trains and arbitrary charge configuration. It is worth noting that both fill pattern and charge configuration are represented by one dimensional matrix, so as to be very easily set. In addition, the post-processing of the tracking results is also convenient.

NEAR-OPTIMUM LENGTHENING CONDITION

Optimum lengthening condition (also called flat-potenital condition) is usually fulfilled by zeroing the first and second derivative of the total rf voltage [3], in which the bunch profile can be stretched symmetrically to flat-top. However, in most cases for passive HC, this condition can not be met for the specific beam current and HC parameters, since the optimum voltage amplitude and phase can not be satisfied at the same time by adjusting only one variable of detuning frequency. Therefore, for second best, only the optimum voltage amplitude is chosen to be achieved, which can assure a still nice bunch lengthening. We call this condition as near-optimum lengthening condition [4]. Assuming an uniform fill pattern with equal charges, the near-optimum condition can be achieved by

$$\tan(\psi_h) = -\frac{2Q\Delta f}{f_r}, \tag{1}$$

$$\cos(\psi_h) = -\frac{k_{fp}V_{rf}}{2FI_0R}, \tag{2}$$

where ψ_h is the detuning phase ranged in 90−180 deg, Δf is the detuning frequency, F∼1 for short bunches, R, Q and f_r are the shunt impedance, quality factor and resonant frequency of HC, respectively, V_{rf} is the main voltage, and k_{fp} is the optimum ratio of the harmonic voltage relative to the main voltage and is given by

$$k_{fp} = \sqrt{\frac{1}{n^2} - \frac{1}{n^2-1}\left(\frac{U_0}{eV_{rf}}\right)^2}, \tag{3}$$

in which n is the harmonic order, U_0 is the energy loss per turn and e is the elementary charge. With Eqs. (1) and (2), the required detuning frequency can be determined.

BUNCH LENGTHENING

We will study the bunch lengthening for different cases with different R/Q by tracking simulation. The latest HALF parameters [1] used for calculation are listed in Table 1, where the energy loss per turn consists of radiation loss from the insertion devices, and the damping time is set to 12 ms considering the contribution from the damping wigglers. Note that the R/Q is given by the circuit definition, and the detuning of main cavity (MC) is set to achieve the load angle

* htlong@ustc.edu.cn

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB265

of ~ −20 deg. Parameters of different passive HC cases used for calculation are summarized in Table 2, where the detuning Δf_h is determined by the near-optimum lengthening condition as mentioned above.

Table 1: HALF Parameters Used for Calculation

Parameter	Symbol	Value
Circumference	C	480 m
Beam energy	E_0	2.2 GeV
Harmonic number	h	800
Nominal beam current	I_0	350 mA
Longitudinal damping time	τ_z	12 ms
Momentum compaction	α_c	8.1×10^{-5}
Natural energy spread	σ_δ	6.45×10^{-4}
Energy loss per turn	U_0	600 keV
Voltage of MC	V_{rf}	1.4 MV
RoverQ of MC	R_m/Q_m	90
Quality factor of MC	Q_m	40 350
Load angle of MC	θ_L	−20 deg

Table 2: Parameters of Six 3HC Cases Used for Calculation

	Current (mA)	R/Q (Ω)	Q	Δf_h (kHz)	Δf_m (kHz)
Case 1	350	45	5×10^5	56.78	-14.15
Case 2	500	45	5×10^5	81.13	-19.25
Case 3	350	90	5×10^5	113.58	-14.15
Case 4	500	90	5×10^5	162.27	-19.26
Case 5	350	160	2×10^4	198.44	-14.07
Case 6	350	240	2×10^4	300.59	-14.10

In all below calculations, we consider that all buckets are filled with equal charges. The macroparticle numbers per bunch and the tracking turn are set to 4×10^3 and 1×10^5, respectively. For SC cases (cases 1-4), Q is set to 5×10^5 rather than the real value of 2×10^8, so that the tracking results can be convergent within less turns. Only the statistical results of 80 bunches, uniformly distributed along the bunch train, will be displayed.

Cases 1 and 2: One Cell Superconducting Cavity

The results of cases 1 and 2 are shown in Figs. 1 and 2, respectively. These two cases have R/Q of 45 Ω which may be achieved with one cell SC cavity. We can see that for the nominal beam current of 350 mA (case 1) and even the larger current of 500 mA (case 2), all bunches can be equally stretched to have rms length of ~ 24 ps.

Cases 3 and 4: Two Cell Superconducting Cavity

The results of cases 3 and 4 are shown in Figs. 3 and 4, respectively. These two cases have R/Q of 90 Ω which may be achieved with two cell SC cavity such as the Super-3HC of SLS/Elettra. For case 3 with 350 mA, we can also see that the rms lengths of all bunches are lengthened to ~24 ps. While

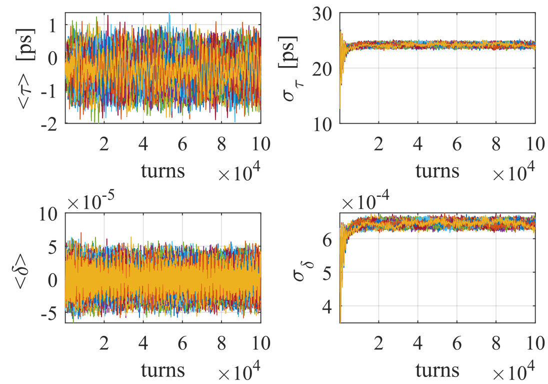

Figure 1: Statistics of the bunches vs turns for case 1, including bunch centroid (upper-left), rms length (upper-right), average of relative energy deviation (lower-left) and energy spread (lower-right).

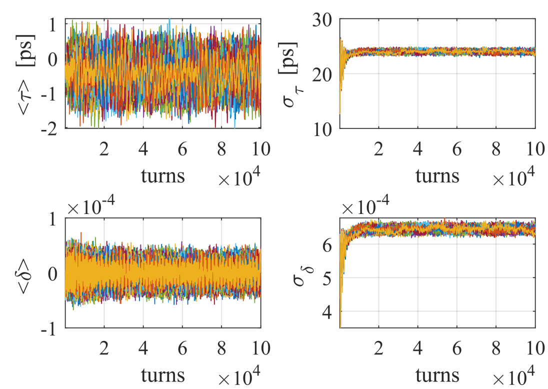

Figure 2: Statistics of the bunches vs turns for case 2.

for case 4 with 500 mA, most bunches have rms lengths ranged in 11−13 ps, several bunches have rms lengths larger than 80 ps, which means they are over-stretched into two separately sub-bunches. Note that their centroids vary over the bunch train even with the uniform fill pattern. It is obvious that this centroid transient is different from that induced by the introduction of gaps.

Compared with case 2, it is clear that if we would like to raise the target current up to 500 mA, the R/Q should be reduced to 45 Ω (actually 60 Ω is also feasible, which has been checked by tracking simulation) in order to ensure sufficiently long bunches.

Cases 5 and 6: Normal Conducting Cavities

For NC cases, two and three cavities of ALS type are taken into account respectively. Note that the former has a risk of encountering excessive power loss which exceeds the cavity limit. Nevertheless, it can still be calculated in theory to evaluate the effect of R/Q on bunch lengthening. The results of cases 5 and 6 are shown in Figs. 5 and 6 respectively. Obviously, we can not obtain satisfactory bunch lengthening for both NC cases, since most bunches have rms length

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB265

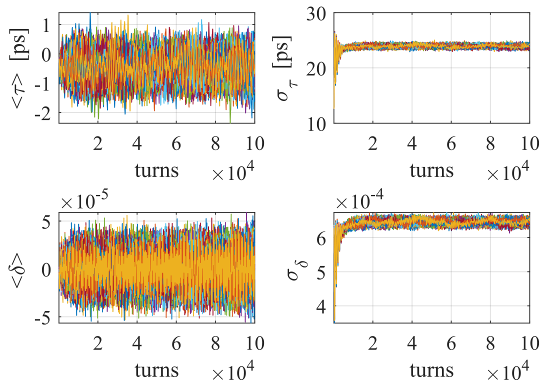

Figure 3: Statistics of the bunches vs turns for case 3.

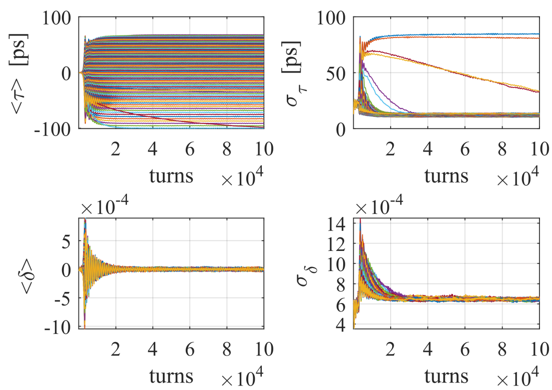

Figure 4: Statistics of the bunches vs turns for case 4.

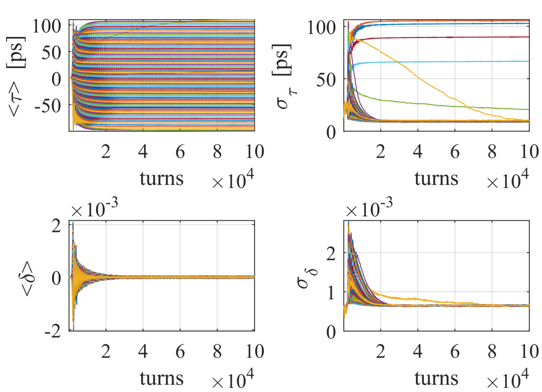

Figure 5: Statistics of the bunches vs turns for case 5.

of ~10 ps for case 5 and ~6 ps for case 6. Compared to case 5, we found more severe centroid transients for case 6. It indicates that the transients increase with the value of R/Q. Due to the large R/Q, passive NC cavities are not suitable for HALF.

DISCUSSION

More calculations show that for a specific R/Q, there is a current threshold (conversely, for a specific current, there

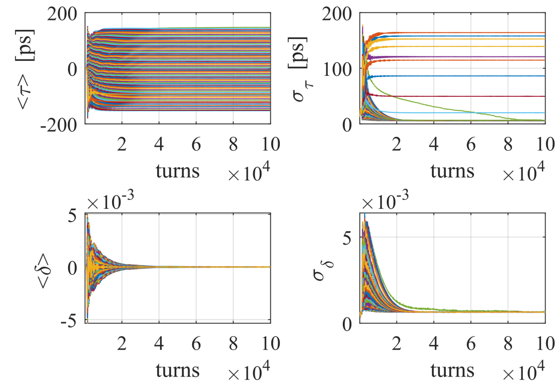

Figure 6: Statistics of the bunches vs turns for case 6.

is a R/Q threshold), when the threshold is exceeded, all bunches can not be stretched uniformly, but encounter a severe centroid transients. One apparent conclusion can be drawn that the threshold increase with the cavity voltage amplitude and the momentum compaction factor. However, for a storage ring to attain ultra-low emittance, it generally leads to a low momentum compaction factor and thus a lower main voltage, which resulting in a lower threshold of R/Q for a given beam current.

From the tracking point of view, the loading voltage phasor induced by a bunch charge q passing through an RF cavity is given by

$$\widetilde{V}_b(\tau) = \frac{Fq\omega_r R}{Q} e^{(j-1/2Q)\omega_r \tau}, \quad (4)$$

where $\omega_r \sim 6\pi h f_0$ for 3HC, and f_0 is the revolution frequency. So $q\omega_r \sim 6\pi I_0$, and I_0 is the total beam current. When substituting it into Eq.(4), we know that the loading voltage is proportional to the product of R/Q and I_0. It indicates that the effect of R/Q = 90 Ω at 350 mA on bunch lengthening is equivalent to that of R/Q = 63 Ω at 500 mA, which actually has been verified by tracking simulation.

CONCLUSION

For HALF, in order to obtain satisfactory bunch lengthening under the beam current of 350 mA or higher current of 500 mA, it is necessary to have a sufficiently small R/Q for 3HC, e.g., a SC cavity with only one cell. Unluckily, the passive NC cavities can not meet the requirement of HALF for bunch lengthening owing to the large R/Q.

ACKNOWLEDGEMENTS

This work was supported by the Fundamental Research Funds for the Central Universities (No. WK2310000090).

REFERENCES

[1] Z. H. Bai *et al.*, "A Modified Hybrid 6BA Lattice for the HALF Storage Ring", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB112, this conference.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB265

[2] T. He and Z. Bai, "Graphics-processing-unit-accelerated simulation for longitudinal beam dynamics of arbitrary bunch trains in electron storage rings", unpublished.

[3] J. M. Byrd and M. Georgsson, "Lifetime increase using passive harmonic cavities in synchrotron light sources", *Phys. Rev. ST Accel. Beams*, vol. 4, p. 030701 Mar. 2001. doi:10.1103/physrevstab.4.030701

[4] T. He, W. Li, Z. Bai, and L. Wang, "Longitudinal equilibrium density distribution of arbitrary filled bunches in presence of a passive harmonic cavity and the short range wakefield", *Phys. Rev. Accel. Beams*, vol. 24, p. 044401, Apr. 2021. doi:10.1103/physrevaccelbeams.24.044401