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BUNCH-LENGTHENING RF SYSTEM USING ACTIVE NORMAL-CONDUCTING CAVITIES

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Abstract

A normal conducting (NC) harmonic cavity (HC) bunch-lengthening system, powered with an external rf generator, is attractive for future generation synchrotron light rings. This system is expected to improve the bunch lengthening performance even at low stored currents. As a result of recent particle tracking simulations, a proper control of the external rf generator is also expected to be a countermeasure for reduction in bunch lengthening efficiency due to the transient beam loading (TBL) and for unstable beam motions in the vicinity of the "flat-potential" condition. In order to realize such a system, a low R/Q 1.5GHz-TM020 HC and a broadband kicker cavity with a bunch phase monitor integrated in the digital rf control for the TBL compensation, are being developed.

INTRODUCTION

Bunch lengthening using a double RF system with fundamental and harmonic cavities (FC and HC) [1] is essential in preserving the extremely low emittance in fourth and future generation synchrotron light rings. For these rings, the relatively low required rf voltage makes the use of normal conducting (NC) cavities quite attractive.

For more than 20 years, double rf systems with passive HCs have been used in a number of third-generation light sources to lengthen the electron bunches for improving the beam lifetime and stability [2–5]. These previous works have revealed that the transient beam loading (TBL) reduces the bunch lengthening efficiency when bunch gaps are introduced in the fill pattern, especially for systems consisting of HCs having their resonant frequency higher than 1 GHz. It has also been reported that reducing the total R/Q of the HCs is essential in mitigating such transient effects [6].

In addition, recent studies have shown that in many cases, unstable beam motions, such as the so-called "mode-0" [7, 8] and the "periodic transient beam loading (PTBL)" [9–11] instabilities, prevent one from reaching the optimum bunch lengthening condition at low and high beam current, respectively, even with symmetric filling patterns. While reducing the R/Q will help the latter, it will worsen the former.

To realize an efficient bunch lengthening system, the KEK team proposed a promising solution relying on a powered TM020 HC with RF feedbacks (RF-FBs) [12], as reported at FLS2018. Based on this concept, we are developing a HC using the TM020 resonant mode [13], a kicker cavity with a bandwidth > 5 MHz [14], a bunch phase monitor (BPhM) and RF-FBs. In this paper, we describe our complete bunch lengthening system including the cavity and BPhM designs.

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ACTIVE NC DOUBLE RF SYSTEM

A feature of our proposed system is the use of powered TM020 HCs, also called "active HCs". The use of the higher frequency TM020 resonant mode instead of the lowest TM010 mode allows to reduce the R/Q by about 40% [13] and active HCs have some advantages over the more commonly used passive HCs:

- The external generator of an active HC can provide sufficient voltage to lengthen the bunches even at a low stored current (operation with a single or few bunches) [15]
- A proper control of the external generator by using advanced low-level rf (LLRF) techniques can mitigate the voltage fluctuations due to the TBL effect and circumvent unstable beam motions.

The first point is important to maintain a wide use of the synchrotron radiation in the future light sources by preserving all the operating modes available in third-generation light sources. New concepts of synchrotron radiation sources that emphasize flexibility are proposed by KEK [16] and SOLEIL [17].

As shown in Ref. [12], transient rf voltage compensation can be achieved by using the generators of both FC and HC or by using a separate broadband kicker cavity. Besides, particle tracking simulations, performed with the mbtrack2 code [18], have shown that an advanced feedback, such as a direct RF-FB (DRFB) loop can help to push back the PTBL instability threshold in the vicinity of the "flat-potential" condition [19].

In the following section, the development progress of hardware components, needed to realize our active NC double RF system is reviewed.

HARDWARE DEVELOPMENT STATUS

1.5GHz-TM020 Harmonic Cavity

The 508MHz-TM020 cavity was originally developed as a HOM-damped accelerating cavity for the SPring-8 II project [20], and four such cavities have already been installed as fundamental accelerating cavities at the new 3-GeV synchrotron radiation facility NanoTerasu in Japan [21].

In their design, two shallow coaxial slots are located on both end plates of the cavity, where the magnetic field of the accelerating mode vanishes (i.e., at its magnetic field node). By placing microwave absorbers on these slots, most of the harmful parasitic modes can be strongly damped without

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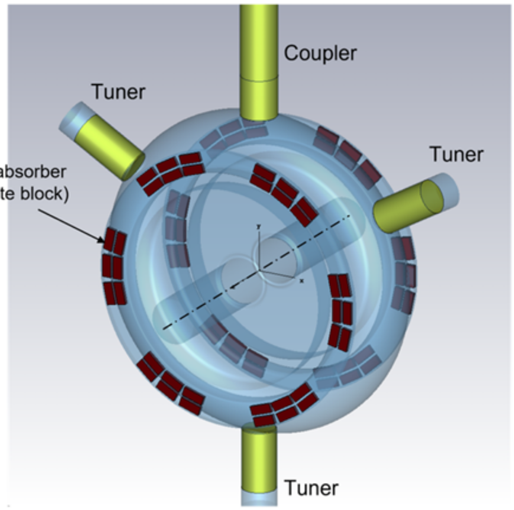

Figure 1: Inner structure of the TM020 HC.

significantly affecting the TM020 accelerating mode and while maintaining a compact longitudinal size of the cavity.

Another advantage of this cavity is its intrinsically high unloaded Q due to the use of a higher frequency mode for the beam acceleration. Compared to a typical TM010 cavity at the same frequency of 1.5 GHz, which is the third harmonic of the KEK-PF FC, a TM020 cavity has a higher unloaded Q (by factors of 1.5–2.2) and a lower R/Q (by about 40%).

Based on these advantages, which are particularly suitable for HCs, we have been developing a 1.5GHz-TM020 HC since 2018, separately from the pioneering work described above. A similar 1.41GHz-TM020 two-cell cavity is also under development for ESRF-EBS [22].

The design work of our 1.5GHz-TM020 HC is almost completed [13]. After optimizing the cavity shape to maintain a low R/Q and a strong HOM-damping, we made a concerted effort to minimize the leakage power of the TM020 mode into the microwave absorbers over a reasonable tuning range. As a result of the numerical investigations and experimental studies with a low power cavity model, we found that maintaining the axial symmetry of the cavity is essential for minimizing the leakage power of the accelerating mode. To this end, we have symmetrically arranged three frequency tuners and designed an input coupler loop that produces only a small perturbation on the accelerating mode, as shown in Fig. 1.

The main computed parameters of our 1.5GHz-TM020 HC are listed in Table 1. The assumed total wall-loss power of 11.3 kW corresponds to an RF voltage of 155 kV. The computed parasitic mode loss factor is 0.83 V/pC at an rms bunch length of 3 mm (i.e., without HCs).

Broadband Kicker Cavity

As reported in Ref. [12], the mitigation of the voltage fluctuations due to the TBL effect can be expected by introducing an adaptive feedforward technique to both FC and HC. However, the compensation performance is limited by the narrow bandwidth of these cavities. For the purpose of increasing the bandwidth, we consider developing a dedicated kicker cavity [23] with a 3dB bandwidth of about 5 MHz, while a cavity voltage of tens of kV is sufficient. To meet these requirements, one uses a single-mode (SM) cavity concept [24], strongly loaded by means of two external wave-guides, connected through large coupling slots, as shown in Fig. 2. The harmful HOMs are attenuated by rf absorbers located on the beam pipes.

The practical design of the kicker cavity was performed using CST MW-studio and a model cavity with a resonant frequency of 1.5 GHz was fabricated to confirm the computed performance. The main parameters of the kicker cavity are listed in Table 1. Assuming a generator power of 40 kW and a beam current of 500 mA, a cavity voltage of 44 kV is obtained with a wall dissipation of 2.59 kW and a reflected power of 7.85 kW to each wave-guide, the remaining 21.7 kW being the beam loading power. The 3dB-bandwidth of the cavity is 5.1 MHz.

Table 1: 1.5GHz-TM020 HC Main Parameters

Parameter	Value
Resonant frequency	1.5 GHz
R/Q, ($R_s = V_c^2/2P_c$)	34.0 Ω
Unloaded Q	31400
Tuning range, $(P_{\mathrm{abs}}/P_{\mathrm{wall}})^1 < 2\%$	-0.5 ~ 0.5 MHz

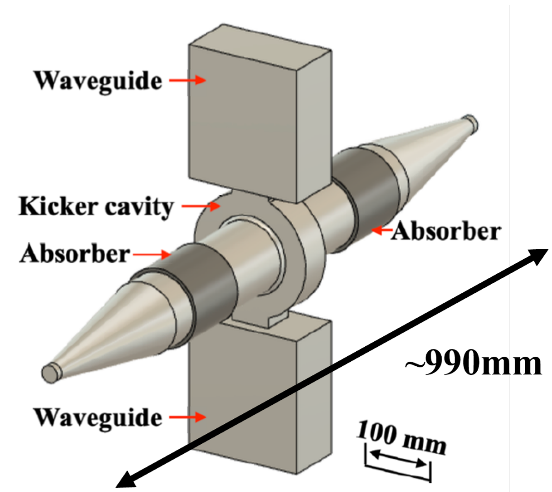

Figure 2: Schematic of the broadband kicker cavity.

Bunch Phase Monitor (BPhM)

To realize the TBL compensation system, it is necessary to develop not only the dedicated cavity, but also the associated advanced digital LLRF control system. To calculate and control the additional RF voltage aimed at compensating the TBL, we use the information of the bunch center-of-mass

[1] Ratio of the power lost into the absorbers over the cavity wall loss for the accelerating mode

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Table 2: Broadband Kicker Cavity Main Parameters

Parameter	Value
Resonant frequency	1.5 GHz
R/Q, ($R_s = V_c^2/2P_c$)	30.0 Ω
Unloaded Q	17937
Loaded Q	292

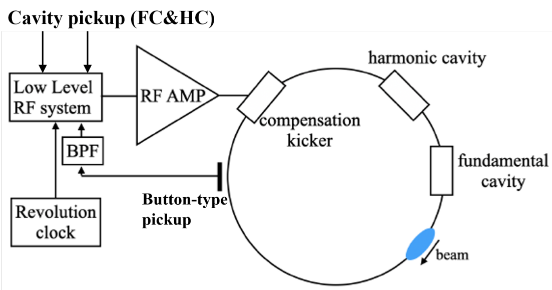

Figure 3: Schematic of the bunch phase monitor (BPhM).

phase along the bunch train together with a monitoring of the transient variations of the cavity voltage.

As shown in Fig. 3, both the FC and HC pickup signals and the bunch signal from the button-type pickup on the vacuum chamber are fed into analog inputs of the digital LLRF system. These signals are sampled by a fast ADC in synchronization with the revolution clock. For the signal sampling, we plan to measure the bunch phase by a IQ conversion applying the direct sampling method. In order to eliminate noise and harmonics, the bunch signal will be pre-processed using an appropriate band pass filter (BPF).

We intend to integrate this system in the digital LLRF system being developed for the Photon Factory upgrade project [25] to achieve a TBL compensation by measuring and feeding back the bunch phase information at a sampling frequency of more than 1 kHz.

The results of the preliminary tests of the BPhM at KEK-PF, where the HC is not yet installed, are reported hereafter. The rf and revolution frequencies at KEK-PF are 500.1 and 1.6 MHz, respectively. In the tests, a direct sampling frequency of 307.8 MHz and a BPF of 470~520 MHz were used. The IQ sampling was performed every 13 bunches, and 24 samples were obtained during one revolution period. The fill pattern was consisting of a multi-bunch train with 250 bunches and a gap of 62 unoccupied RF buckets.

The measured bunch phase with the prototype BPhM is indicated as black circles in Fig. 4, which shows the bunch phase shift due to the TBL. The results averaged over 100 turns are plotted, but no difference was observed when averaging over 100 kTurns. The significant changes in the absolute value of the bunch phase in the first part of the bunch train is suspected to be due to the frequency dispersion caused by the long transmission cable (~100 m) from the button-type pickup.

The bunch phase obtained from the BPhM prototype is compared to that from the "integrated General purpose signal processors (iGP)" (red) [26, 27], which is averaged over 40 kTurns with a synchronous detection at 1.5 GHz. Although the measured bunch phase slopes are slightly different, we expect that it is good enough for a correct TBL compensation.

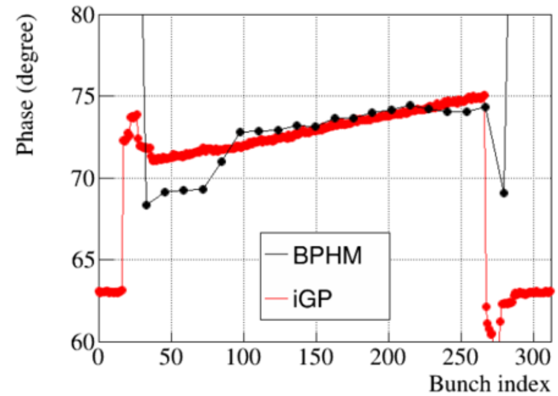

Figure 4: Measured bunch phases with the prototype BPhM (black), compared to those with iGP (red).

CONCLUSION

We are developing a bunch lengthening system of high performance for future synchrotron light sources. We aim to improve the bunch lengthening efficiency by using a powered NC-TM020 HC, a broadband kicker cavity and a sophisticated LLRF control system.

In the development of the TM020 HC, the symmetrical arrangement of three frequency tuners has made possible the achievement of the required operational frequency tuning range as well as the preservation of the axial symmetry, which is essential for limiting the accelerating mode power leak into the absorbers. The design of the high power model is almost completed.

The broadband kicker cavity for the TBL compensation is a SM-mode cavity concept with two rf input waveguide strongly coupled to the cavity by means of large slots in order to achieve the required wide bandwidth. The HOM attenuation is complemented by absorbers on the beam pipes.

We have also designed and confirmed the feasibility of a BPhM for bunch phase control, which is one of the required functions of the LLRF system for the TBL compensation.

We intend to further proceed with more sophisticated hardware designs and realistic tracking simulations in parallel to the design of a practical bunch lengthening system using NC active HCs.

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