FEASIBILITY STUDY OF AN ACTIVE HARMONIC CAVITY FOR BUNCH LENGTHENING IN AN ELECTRON STORAGE RING

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Abstract

Bunch lengthening from a double radio-frequency (rf) system combining fundamental and harmonic cavities (HCs) is essential to achieve the extremely low emittance which is required for ring-based fourth generation synchrotron light sources in low-to-medium energy range. The relatively low required rf voltage in these machines as compared to third generation ones, makes the use of normal conducting (NC) cavities more attractive. We report here some results of the feasibility study of such a double rf system using NC active HCs for the SOLEIL Upgrade case. Particle tracking simulations have been performed, taking into account the instabilities related to the fundamental impedance of the cavities, and the results suggest that relevant bunch lengthening factors can be achieved for all the operating modes, even at the lowest stored current of 10-20 mA in a single bunch. The use of NC instead of superconducting (SC) HCs should result in significant cost savings for comparable performance in terms of bunch lengthening at the same HC frequency.

INTRODUCTION

Double rf systems combining fundamental and passive HCs have been used for over 20 years in a number of third generation light sources to lengthen the electron bunches in order to improve the beam lifetime and stability [1–4]. Such systems are even more relevant in fourth and future generation synchrotron light rings since bunch lengthening is essential to preserve the extremely low emittance, especially for the storage rings of low-to-medium energy range. Besides, the relatively low required rf voltage in the latter makes the use of NC cavities more attractive.

For this purpose, a powered HC, so-called "active HC", has some advantages as compared to the more commonly used passive HC:

- The external generator of an active HC allows to provide sufficient voltage to lengthen the bunches even at low stored current (operation with a single or few bunches)
- A proper control of the rf external generator may circumvent unstable beam motions
- An adaptive feedforward technique on both main and harmonic cavity generators may mitigate voltage fluctuations due to transient beam loading (TBL) [5].

The first point is important to maintain in the next generation light sources a wide exploitation of the synchrotron radiation by preserving all the operation modes existing in the third generation light sources. New concepts of synchrotron radiation sources that emphasize flexibility are proposed by KEK [6] and SOLEIL [7].

As for the second and third points, it has been reported that these phenomena limit the bunch lengthening during multi-bunch operation [2–4, 8, 9], and overcoming them is an important milestone in achieving extremely low emittance.

For active HCs, the TM020 cavity has been proposed because of its intrinsic high Q and low R/Q values [5]. Two different NC-TM020 cavities are being developed at KEK [10] and ESRF [11] with resonant frequencies of 1.50 GHz and 1.41 GHz respectively.

In this note, the feasibility study of active HCs, assuming both the SOLEIL Upgrade v0356 lattice [7] and ESRF-type NC-TM020 HCs, is numerically carried out. The tracking code mbtrack [12] is used to evaluate the beam stability and bunch lengthening performance.

ACTIVE HC SYSTEM

The total rf voltage $V(\phi)$ seen by the beam is given by

$$V(\phi) = V_{c,1}\cos(\phi + \phi_1) + V_{c,n}\cos(n\phi + \phi_n), \quad (1)$$

$$V(0) = U_0/\mathrm{e}, \quad (2)$$

where ϕ is the phase angle of the beam with respect to the main rf wave, ϕ_1 and ϕ_n are the synchronous phases with respect to the main and nth harmonic rf waves; $V_{c,1}$ and $V_{c,n}$ are the main and harmonic rf voltage amplitudes, respectively; U_0 is the energy loss per turn.

Here, we introduce a variable ξ,

$$\xi = \frac{-nV_{c,n}\sin\phi_n}{V_{c,1}\sin\phi_1}. \quad (3)$$

$V'(0)$ and $V''(0)$, the first and second derivative of the total rf voltage, can be expressed as functions of ξ as follows:

$$V'(0) = -(1-\xi)V_{c,1}\sin\phi_1, \quad (4)$$

$$V''(0) = -V_{c,1}\left(\cos\phi_1 - \xi n\frac{\sin\phi_1}{\tan\phi_n}\right). \quad (5)$$

The bunch lengthening is "optimal" at the so-called flat potential (FP) condition, when $V'(0) = V''(0) = 0$, which is met by setting the parameters such that $\xi = 1$ and $\phi_n = \arctan(n\tan\phi_1)$. Once $V_{c,1}$, U_0/e and n are fixed, all the system parameters are determined from the above equations, (1) to (5), regardless of the stored current or operating mode.

In general, the complex cavity voltage $\tilde{V}_c$ can be considered as the superposition of a generator-induced component $\tilde{V}_g$ and a beam-induced component $\tilde{V}_b$: $\tilde{V}_c = \tilde{V}_g + \tilde{V}_b$. Ignoring the bunch form factor (assumed to be equal to 1), the HC beam-induced voltage is given by

$$V_{b,n} = \frac{2I_0R_{s,n}}{(1+\beta_n)}\cos(\psi_n)\cos(\pi + \psi_n + n\phi), \quad (6)$$

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where I_0 is the stored current, $R_{s,n}$, β_n and ψ_n are the HC shunt impedance, coupling factor and detuning angle ($-\pi/2 < \psi_n < \pi/2$). Its detuning frequency Δf is calculated from its resonant frequency $f_{r,n}$ and loaded-Q $Q_{L,n}$:

$$\Delta f = f_{r,n}/(2Q_{L,n}) \tan\psi_n, \tag{7}$$

$$Q_{L,n} = Q_{0,n}/(1+\beta_n). \tag{8}$$

In the passive HC case, $\tilde{V}_{g,n} = 0$, the HC voltage is only the beam-induced component, and ψ_n (or Δf) becomes the only operational "knob" for adjusting the HC voltage and phase. Then the FP condition can be only met for a single value of the product $I_0.R_{s,n}$ and the power lost by the beam in the HC must be fully supplied by the MC generator.

In the active HC case, since the HC generator amplitude and phase are also used as operational "knobs", the FP condition can be fulfilled regardless of I_0 or $R_{s,n}$ as far as instabilities do not occur.

In both cases, active or passive, approaching the FP condition means that the longitudinal restoring force is reduced, and it is necessary to be careful about the occurrence of instabilities, especially at high beam current.

INVESTIGATION SETUP

The investigation has been performed for the SOLEIL Upgrade, whose parameters are listed in Table 1. A combination of four EU-type 351.6 MHz main cavities (MCs) [13, 14] and one to three ESRF-type 2-cell HCs [11] at the harmonic number $n = 4$, is considered. The cavity parameters are listed in Table 2. It is assumed that both MCs and HCs are "HOM free". For the SOLEIL Upgrade, not only 500 mA in multi-bunch but also 20 mA in a single bunch and 100 mA in 8 bunches are requested. The double rf system should be therefore compatible with all these operation modes.

As a result of the double rf potential analysis, based on Ref. [15] with the parameters listed in Table 1, the FP condition is met when ϕ_1=1.296, $V_{c,4}$=434 kV and ϕ_4=-1.641. In this case, the bunch length and lengthening factor (BLF) are expected to be 40 ps and 4.7, respectively.

Using a single ESRF-type HC with a voltage of 434 kV corresponding to the FP condition leads to a power dissipation P_c of about 40 kW, which is close to the limit of what could be handled [16]. That would be relaxed in using a second HC, however in return it will double the total R/Q hence increasing the parasitic effects of the TBL and limiting the bunch lengthening [5, 17]. Therefore we have investigated and compared the following three cases: one HC (1-HC), two HCs (2-HC) and three HCs (3-HC) but one of them detuned in the opposite direction for bunch shortening (BS) instead of bunch lengthening (BL).

Table 1: SOLEIL Upgrade Parameters (v0356)

Parameter	Unit	Value
Energy, E_0	GeV	2.75
RF frequency	MHz	351.6
Energy loss per turn (no ID), U_0	keV	458
Main RF voltage, $V_{c,1}$	MV	1.80
Energy spread		8.9×10^{-4}
Momentum compaction factor, α		1.1×10^{-4}
Longitudinal damping time, τ_e	ms	12.2
Synchrotron frequency w/o. HC	kHz	1.78
Natural rms bunch length	ps	8.5

Table 2: Cavity Parameters of the Double Rf System

Parameter	MC	HC (2 cell)
Harmonic number, n	1	4
Shunt Impedance, $R_s = V_c^2/2P_c$	5.0 MΩ	2.4 MΩ
Unloaded-Q, Q_0	35,000	27,000
Cavity coupling coefficient, β	5.0	1.0
Cavity number	4	1~3

The mbtrack simulations are performed in one-dimension (longitudinal) and both MC and HC impedance's are considered as instability sources. A broad band impedance of 0.069 Ω/GHz/m (pure copper vacuum pipe) is assumed and taken into account with the calculation technique described in the Ref [18]. In the tracking simulation, the cavity voltage and phase vary as the bunch distribution changes until the steady-state condition is reached. Therefore, it is difficult to anticipate the setting that will lead to the target voltage and phase.

For the active HC case, the parameter set is determined in advance to provide the specified cavity voltage and phase under the predicted bunch distribution (a Gaussian distribution with the rms bunch length of 30 ps), which minimize the required generator power for both MC and HC, and they are treated as constant during each tracking simulation.

In the mean time, for both cases, the setting of the MC is slowly changed to achieve the specified voltage and phase with the accuracy of 1×10^{-3}.

The tracking results for the various parameter sets were systematically compared after several series of simulations. Typically, 0.5 to 1 million turns were required to converge towards a steady solution. The deviations from the target values were about 4% in amplitude, 0.1% in phase and the statistical accuracy of the calculated bunch length was estimated to be 0.1 ps.

HIGH CURRENT MULTI BUNCH MODE

In the bunch lengthening operation of a double rf system, the resonant frequency of the HC is higher than the nth harmonic of the rf frequency, that is positive detuning. In this case, one needs to be careful as regards to the occurrence of coupled-bunch instabilities and in particular the +1 mode, when the detuning is large. It has been well studied for the case of a single rf system. In the Ref. [19], the analytical equation of the growth rate $\mathbf{GR}_l$ for each mode number l is derived with the assumptions of a point charge, equally spaced M bunches and a coherent frequency close to the

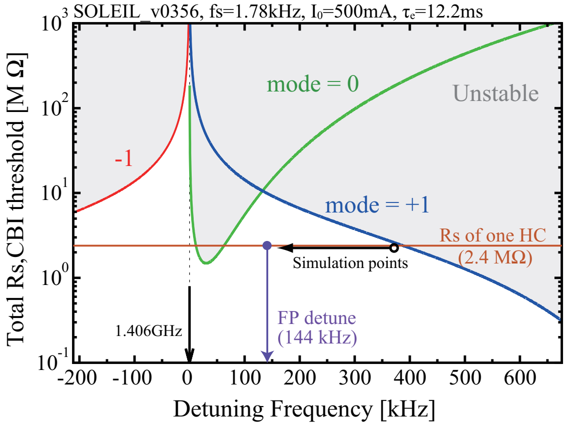

Figure 1: HC R_s threshold for coupled-bunch instabilities (1-HC case), taking into account the MC R_s and the parameters in Table. 1. The threshold plots for coupled-bunch modes : -1 (red), 0 (green) and 1 (red). Unstable beam motions are expected in the grey-colored area.

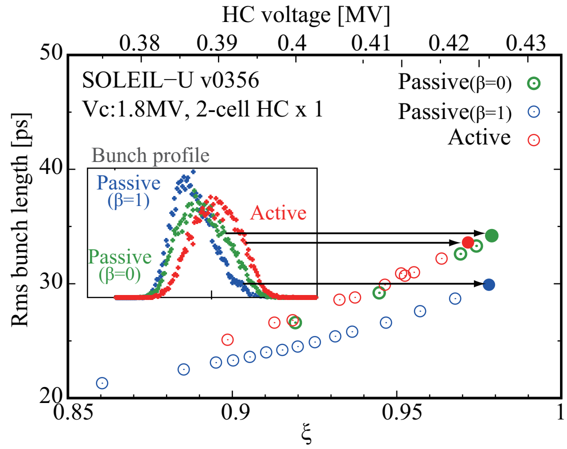

Figure 2: Rms bunch length as a function of ξ, obtained from the mbtrack simulations, for the active and passive (β_4 = 0 and 1) 1-HC cases. In the inset, the bunch profiles at maximum bunch length are compared for the three cases.

incoherent one (synchrotron frequency), as follows:

$$\mathbf{GR}_l = \frac{\alpha I_0}{2\nu_s E_0} \left\{ \sum_{\mu=0}^{\infty} f_{l,\mu}^{+} \mathrm{Re}\left[Z(f_{l,\mu}^{+})\right] - \sum_{\mu=1}^{\infty} f_{l,\mu}^{-} \mathrm{Re}\left[Z(f_{l,\mu}^{-})\right] \right\} \quad (9)$$

$$f_{l,\mu}^{\pm} = \{\mu M \pm (l + \nu_s)\} f_0$$

$$Z(f) = \frac{(R/Q)\, Q_L}{1 + iQ_L\,(f_r/f - f/f_r)}$$

where ν_s and f_0 are the synchrotron tune and revolution frequency.

By extending the Eq. (9) to the case of multiple cavities, the thresholds of the HC shunt impedance R_s are calculated for the coupled-bunch modes +1, 0 and -1, and plotted in Fig. 1 as a function of the HC detuning frequency. In the calculation, the synchrotron frequency without HC is used and the contributions from the MC and the longitudinal radiation damping are taken into account. Although, these assumptions become no longer valid when ξ approaches unity, due to the reduction and spread of the synchrotron frequency, we can use this type of plot as a guideline for the following complicated tracking simulations.

1-HC case

Considering the 1-HC case with a shunt impedance of 2.4 MΩ, the detuning frequency that satisfies the FP condition is 144 kHz, indicated as "FP detune" in Fig. 1. So, the stable domain is expected within the detuning frequency range from 350 kHz to the vicinity of "FP detune."

The mbtrack simulations have been carried out along the parameter set shown as "Simulation points" in Fig. 1 and the obtained rms bunch lengths are plotted versus ξ in Fig. 2 for three 1-HC cases : active (in red), passive with β_4=1 (generator "OFF", in blue) and passive with β_4=0 (in green). ξ is calculated from Eq. (3) using the steady values of each simulation result.

In the active case with the generator "ON", the maximum bunch length of 33.6 ps (BLF of 4) is obtained for ξ=0.97 and a detuning of 142 kHz. With the generator "OFF", although it is reduced, one can still achieve a bunch length up to 29.9 ps (BLF of 3.4) for ξ=0.98 and a detuning of 132 kHz. It is confirmed that the longer bunches are achieved with the HC generator "ON" despite its slightly smaller ξ. Moreover, comparing the bunch profiles in the inset of Fig. 2, one can see that the active case has a more symmetric shape. That is an advantage of the active HC, which allows to cancel not only V' but also V''.

The bunch lengthening and profile for the more usual passive case with a coupling β_4=0 are also shown in Fig.2. The achieved performance is rather similar to that of the active case : maximum bunch length of 34.2 ps (BLF of 4.0) for ξ=0.98 with a detuning of 138 kHz and an almost symmetric profile. However, it should be mentioned that the passive 1-HC case is not compatible with bunch lengthening in the operation modes at lower current.

In all the above studied cases, unstable beam motion with bunch length fluctuations along the bunch train, prevents further bunch lengthening at the vicinity of "FP detune." The analysis of the bunch mass center motion suggests the occurrence of mode +1 oscillations, however it is found that the growth rate is much larger than that given by the extension of the Eq. (9). This instability is considered to be of the same nature as the one reported in Ref. [8] and [9] under the name, "coupled bunch mode l = 1 instability" and "periodic transient beam loading instability", respectively.

2-HC case

The instability thresholds for the 2-HC case are plotted as dashed lines in Fig. 3. Considering the detuning frequency of 287 kHz that satisfies the FP condition, there is no stable operating point to perform bunch lengthening for this case.

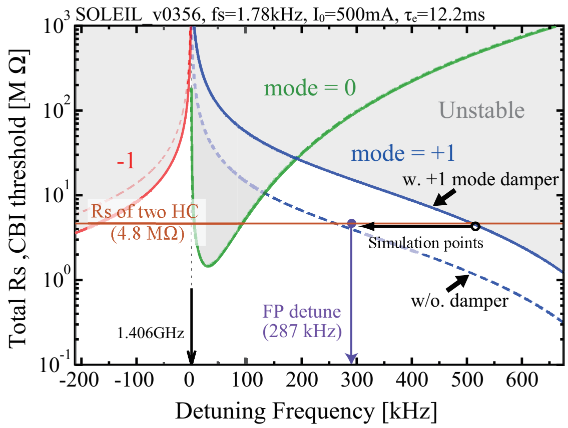

Figure 3: HC R_s thresholds for coupled-bunch instability (2-HCs case). The dashed and solid lines are obtained with and without +1 mode damper, respectively.

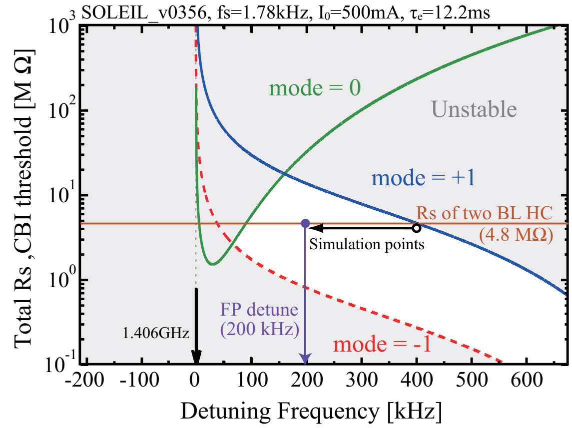

Figure 4: HC R_s thresholds for coupled-bunch instability (2BL & 1BS HCs case).

Then the thresholds were re-calculated after including a +1 mode damper [20] with a center frequency of 352.4 MHz and a bandwidth of 881 Hz. The result is shown as solid lines in Fig. 3. A maximum damping rate of 666 s^{-1} is expected for the coherent frequency at 1 kHz, where the feeding rf amplitude of 240 V is technically feasible.

The results of the mbtrack simulations show that the maximum bunch length is limited at 19.6 ps (BLF of 2.3) for ξ = 0.81 and a detuning of 350 kHz. Beyond this ξ value, one observes an unstable beam motion whose property is similar to that of 1-HC case. The unstable motion cannot be suppressed by increasing the damper voltage within a practical range. The ξ limit is lower than that of 1-HC case, which is likely due to the 2-fold increase of the HC R/Q.

3-HC (2BL & 1BS) case

According to the previous investigation, it is found that the unstable beam motion having the couple-bunch mode +1 and large growth rate reduces the bunch lengthening performance in the 2-HC case. Then we have introduced a third HC with negative detuning as a counter force to the instability, a configuration that we called 2BL & 1BS.

In this case, the detuning of the BS HC is set to -400 kHz leading to a beam induced voltage around 150 kV. Therefore, in order to meet the FP condition, the 2BL HCs must provide about 580 kV, which corresponds to a detuning of 200 kHz.

Although the presence of the BS HC tends to decrease the damping from the 2BL HCs on the coupled-bunch mode -1, the global contribution remains a damping effect and therefore the stability of mode -1 should be insured from 390 kHz to the FP tune, as shown in Fig. 4.

The results of mbtrack simulations show that the maximum bunch length of 28.4 ps (BLF of 3.3) is obtained at ξ=0.95 and a detuning of 219 kHz. The cavity voltage for the 2BL HCs is 558 kV; the dissipation is then 16.2 kW for each BL HC and 4.7 kW for the BS HC, which is quite relaxed as compared to the 1-HC case. The bunch lengthening performance is in between the 1-HC and 2-HC cases and it is confirmed that the introduction of the BS cavity has a significant effect on suppressing the mode +1 instability that occurs near the FP.

Table 3: Summary of Bunch Lengthening Performance

HC setup	Bunch length	BLF
Multi bunch 500 mA		
one HC	33.6 ps	4.0
one Passive HC (β = 0)	34.2 ps	4.0
one Passive HC (β = 1)	29.9 ps	3.4
two HCs	19.6 ps	2.3
2BL & 1BS HCs	28.4 ps	3.3
Single bunch 20 mA		
one HC	38.8 ps	4.6
8-bunch 100 mA		
one HC	30.0 ps	3.5

DISCUSSION

From the comparison of the active HC results for the SOLEIL Upgrade multi-bunch 500 mA mode, one finds that the best performance is obtained with a double rf system that consists of four EU-type 352MHz-MCs and one active ESRF-type 1.41GHz-HC. The obtained bunch length of 33.6 ps (BLF of 4) is comparable to that of the SC passive HC case for the same HC frequency [21].

Although it is not discussed in this paper, the bunch lengths in single-bunch and 8-bunch modes have been also evaluated for the 1-HC active configuration. The obtained BLF is 4.6 in single bunch-20 mA and 3.5 in 8-bunch-100 mA. In single bunch mode, it is considered that the FP condition is met without the occurrence of the mode +1 instability, as ξ values higher than unity can be reached (double hump bunch shape). On the other hand, the bunch length in 8-bunch 100 mA mode is limited owing to the mode +1 instability at ξ=0.94.

From these results, summarised in Table 3, it is numerically confirmed that BLFs > 3.5 can be achieved for all requested operation modes, using one active HC with a power dissipation of about 40 kW, which is rather close to the estimated hardware limit. It is worthwhile mentioning that a larger number of passive HCs would be needed to achieve bunch lengthening in the lower current modes : three (1 BS & 2 BL) at 100 mA in 8 bunches and more than five at 20 mA in a single bunch.

Furthermore, the impact of the TBL should be investigated if empty buckets are introduced in the bunch train to avoid ion trapping.

Finally, the authors continue to investigate the impact of rf techniques such as mode damper, direct rf feedback and feedforward TBL compensation [5, 22]. As pointed out in "INTRODUCTION", the possibility of applying these techniques is another advantage of the active HC option as they may allow for further enhancement of the BLF.

CONCLUSION

The feasibility of an active HC system for bunch lengthening is numerically investigated for the SOLEIL Upgrade storage ring. The threshold of the coupled-bunch instabilities driven by the cavity fundamental impedance's is analytically calculated for each possible parameter set. Then the maximum stable bunch length is evaluated by simulations using the particle tracking code mbtrack.

The maximum stable bunch lengths are obtained by using a single 2-cell 1.41GHz-HC having a shunt impedance of 2.4 MΩ, combined with four EU-type 352MHz-MCs. Relevant BLFs are anticipated for all the requested operating modes: 4.0 at 500 mA in 416 bunches, 3.5 at 100 mA in 8 bunches and 4.6 at 20 mA in a single bunch. The HC power dissipation will be around 40 kW, which is close to the estimated hardware limit. R&D's are ongoing at the ESRF to demonstrate its feasibility in terms of power dissipation and required HOM damping for the SOLEIL Upgrade case [16]. In the 3-HC (2BL & 1BS) case, the power dissipation is relaxed however the maximum BLF is smaller (3.3 at 500 mA), which is nevertheless better than the factor of 2.3 in the 2-HC case, since the third HC with opposite detuning can reduce the effective shunt impedance that causes instability and limits the bunch lengthening.

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