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A MULTI-HARMONIC CAVITY SYSTEM FOR BUNCH LENGTHENING FOR THE NSLS-II UPGRADE

G. Bassi*, A. Khan, V. Smaluk, F. Gao, J. Rose
Brookhaven National Laboratory, Upton, NY, USA

Abstract

In the next generation of light sources, to improve the beam lifetime of the bunches and mitigate collective effects such as intrabeam scattering, Higher-Harmonic Cavity (HHC) systems are commonly used to increase the equilibrium bunch length without an increase of the energy spread. Present HHC systems are based on HHCs of the same order. To increase the bunch lengthening factor induced by the HHC system, we investigate a scheme based on the combination of HHCs of different order. In the present contribution we investigate bunch lengthening conditions for a multi-harmonic cavity system consisting of a passive third order harmonic cavity and an active fifth harmonic cavity. Numerical simulations are performed with Vlasov-Fokker-Planck solver SPACE, with parameters of the NSLS-II upgrade.

INTRODUCTION

We investigate a multi-Harmonic Cavity (multi-HC) system to increase the bunch length in the low-emittance rings. In this contribution we consider a passive normal conducting cavity of order three combined with an active normal conducting cavity of order five. With parameters of the NSLSII-U [1], we show that a bunch lengthening factor $u \approx 10$ is theoretically possible. Conditions for normal conducting cavities are determined. The case of a combined active multi-HC system of order m and n has been investigated in [2], while the case of a multi-HC system using a passive superconducting third harmonic cavity will be studied in a future work.

BUNCH LENGTHENING CONDITIONS

Sextic Potential (Passive HC of Order m and Active of Order n)

In the case of equally spaced stationary bunches, the total voltage induced by a passive harmonic cavity of order m and an active cavity of order n reads

$$\begin{aligned} V(\tau) &= V_{rf}\sin(\omega_{rf}\tau + \phi_s) \\ &- i_m R_m \cos\psi_m \cos(m\omega_{rf}\tau + \psi_m) \\ &+ rV_{rf}\sin(n\omega_{rf}\tau + \psi_n) - V_{rf}\sin\phi_{s0}, \qquad (1) \\ \sin\phi_{s0} &= \frac{U_0}{eV_{rf}} \end{aligned}$$

where $i_m = 2I_0\tilde{\lambda}(m\omega_{rf})$ and $\tilde{\lambda}(\omega) = e^{-\frac{1}{2}(m\omega_{rf}\sigma_t)^2}$, and where we used a Gaussian approximation for $\tilde{\lambda}(\omega)$. The total potential reads therefore

$$\begin{aligned} U(\tau) = \frac{eV_{rf}}{T_0E_0\omega_{rf}}\Big[&\cos(\omega_{rf}\tau + \phi_s) - \cos\phi_s \\ &+ \frac{r}{n}(\cos\psi_n - \cos(n\omega_{rf}\tau + \psi_n)) \\ &+ i_m R_m \frac{\cos\psi_m}{m\omega_{rf}}(\sin(m\omega_{rf}\tau + \psi_m) - \sin\psi_m) \\ &+ \omega_{rf}\tau\sin\phi_{s0}\Big]. \end{aligned} \qquad (2)$$

Small Oscillations ($\tau \ll 1$) Performing a Taylor series expansion, we obtain a sextic potential via setting to zero the coefficient of the expansion up to order five. Solving for ϕ_s, R_m, ψ_m, r and ψ_n we obtain

$$\begin{aligned} \sin\phi_s &= \frac{m^2n^2}{a_{mn}}\sin\phi_{s0}, \\ R_m &= -\frac{V_{rf}a_{mn}(n^2-1) + m^2n^4\sin^2\phi_{s0}}{i_m m^2n^2(m^2-n^2)\sin\phi_{s0}}, \\ r &= \frac{\sqrt{a_{mn}(m^2-1) - n^2m^4\sin^2\phi_{s0}}}{n(m^2-n^2)\sqrt{n^2-1}}, \\ \tan\phi_m &= \sqrt{(m^2-1)(a_{mn}(n^2-1) - m^2n^4\sin^2\phi_{s0})} \\ &\times \frac{\sqrt{-a_{mn}^2 + m^4n^4\sin^2\phi_{s0}}}{mn^2\sin\phi_{s0}\sqrt{-(a_{mn}^2 + (m^2-1)m^2n^4\sin^2\phi_{s0})}}, \\ \tan\phi_n &= \frac{m^2n\sin\phi_{s0}(a_{mn}^2 - (m^2-1)m^2n^4\sin^2\phi_{s0})}{\sqrt{-(m^2-1)^2(a_{mn}(n^2-1) - m^2n^4\sin^2\phi_{s0})^2}} \\ &\times \frac{1}{\sqrt{-a_{mn}^2 + m^4n^4\sin^2\phi_{s0}}}, \end{aligned} \qquad (3)$$

where $a_{mn} = (m^2-1)(n^2-1)$.

Bunch Lengthening Factor

The bunch lengthening factor u for a sextic potential reads [2]:

$$\begin{aligned} u &:= \frac{\sigma_\tau}{\sigma_{\tau 0}} \qquad (4) \\ &= \sqrt{\frac{\Gamma(1/2)}{\Gamma(1/6)}}\left(\frac{720\cos\phi_{s0}}{(a_{mn} - 2(m^2-1))\omega_{rf}^4\cos\phi_s}\right)^{1/6}\frac{1}{\sigma_{\tau 0}^{\frac{2}{3}}}. \end{aligned}$$

BUNCH LENGTHENING IN THE NSLS-II-U

With parameters of the NSLS-II-U, as shown in Table 1, we determine the conditions for operating a combined passive third order and active fifth order HC system. Numerical

* gbassi@bnl.gov

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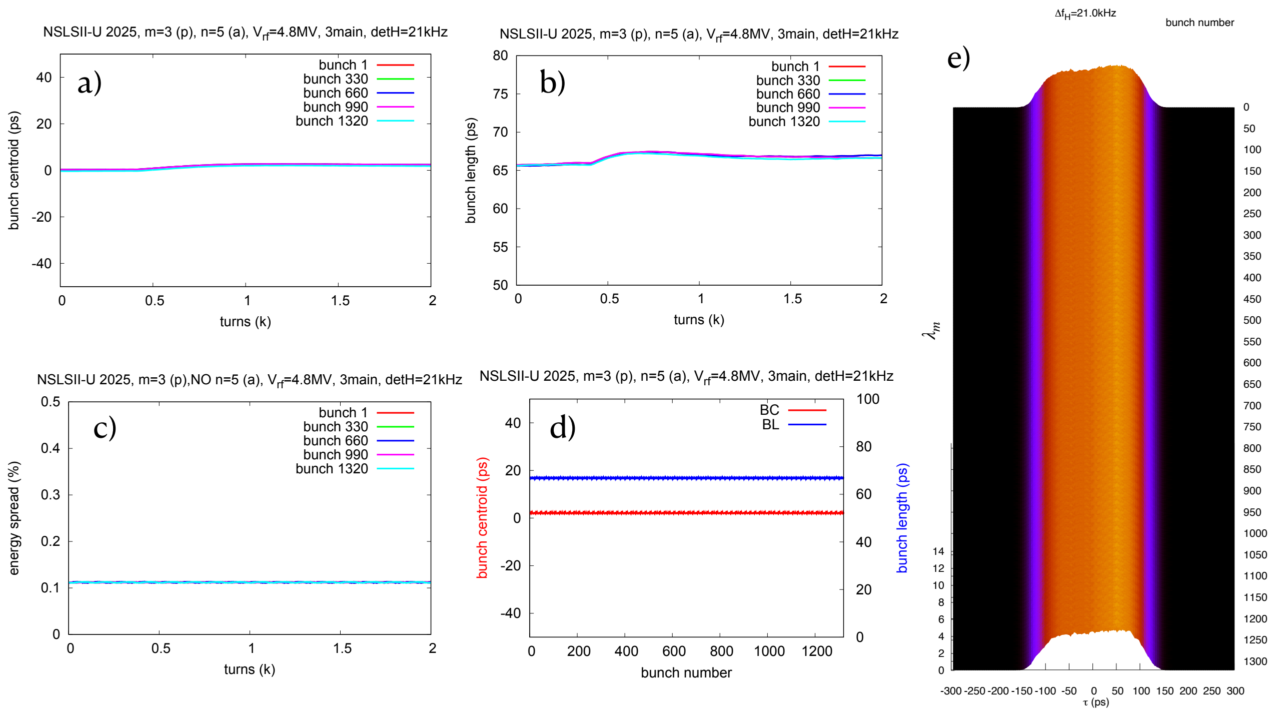

Figure 1: To force the equilibrium, we decreased the longitudinal damping time by 100 times, i.e τ_z = 0.0685. Fig. 1a) shows the bunch centroid, Fig.1b) the bunch length, Fig. 1c) the energy spread, Fig. 1d) the bunch centroid and bunch length as function of bunch number after 2000 turns, and Fig. 1e) the longitudinal density as a function of bunch number after 2000 turns. The detuning frequency of the third harmonic cavity is 21kHz.

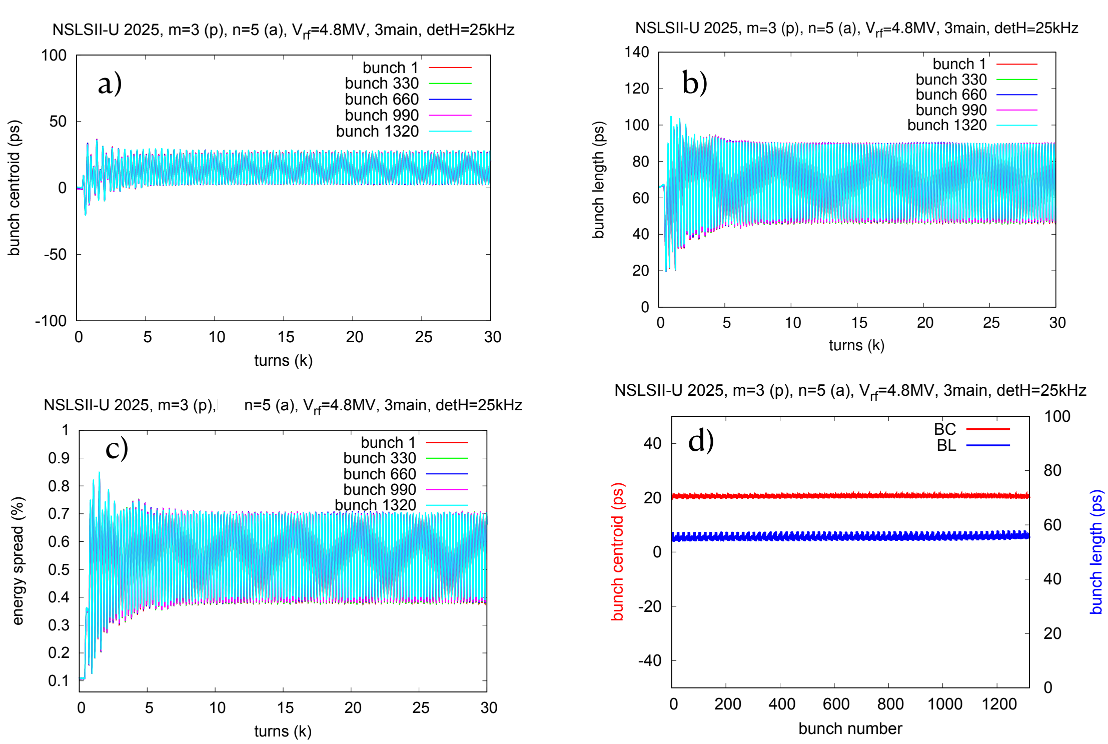

Figure 2: Instability for a detuning frequency of 25 kHz. Fig. 2a) shows the bunch centroid, Fig.2b) the bunch length, Fig. 2c) the energy spread, Fig. 2d) the bunch centroid and bunch length as function of bunch number after 30000 turns.

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Table 1: NSLS-II-U parameters corresponding a low-emittance complex bend lattice [1]. *bunch length achievable under optimal conditions with two HHCs. ** Unloaded value. *** Loaded values of active cavity

Parameter	Symbol	Value	Unit
Circumference	C	791.72	m
Revolution frequency	$\omega_0/2\pi$	378.66	kHz
Beam energy	E_0	4	GeV
Average current	I_0	0.4	A
Momentum compaction	α	6.67	10^{-5}
Natural energy spread	σ_δ	1.1	10^{-3}
Energy loss per turn	U_0	1940.3	keV
Synchrotron tune	ν_s	3.92	10^{-3}
Harmonic number	h	1320	
RF frequency	$\omega_{rf}/2\pi$	499.8	MHz
RF voltage	V_{rf}	4.8	MV
Bunch length w/o HHC	σ_{t0}	7.87	ps
Bunch length with HHC*	σ_t	72	ps
Longitudinal damping time	τ_z	6.85	ms
Main cav. shunt impedance**	R_s	33375	MΩ
Main cav. quality factor**	Q_0	750	10^6
Beta coupling	β_c	11236	
3HC frequency	$\omega_H/2\pi$	3×499.8	MHz
3HC shunt impedance**	R_H	18.9	MΩ
3HC quality factor**	Q_H	200	10^3
5HC frequency	$\omega_n/2\pi$	5×499.8	MHz
5HC shunt impedance***	R_n	1.4	MΩ
5HC quality factor***	Q_n	20	10^3

Table 2: Beam loading per cavity parameters (three main, one passive 3HC and one active 5HC) for numerical simulations with SPACE.

Parameter	Symbol	Value	Unit
Main cavity voltage	V_c	1.6	MV
Detuning frequency main cavity	$\Delta\omega_r/2\pi$	-4.8	kHz
3HC detuning frequency	$\Delta\omega_H/2\pi$	21	kHz
5HC detuning frequency	$\Delta\omega_n/2\pi$	-97	kHz

simulations are performed with SPACE (Table 2). According to Eq.(3), the parameters for a combined HC system of order $m = 3$ and $n = 5$ read $\phi_s = 2.648$, $R_m = 18.9\,\mathrm{m}\Omega$, $\psi_m = -1.39339$, $r = 0.08858$ and $\phi_n = 3.03443$. The corresponding bunch lengthening factor reads $u = 8.4$. Preliminary simulations show an instability. To force the equilibrium, we decreased the longitudinal damping time by 100 times, i.e $\tau_z = 0.0685$, as shown in Fig. 1: Fig. 1a) shows the bunch centroid, Fig. 1b) the bunch length, Fig. 1c) the energy spread, Fig. 1d) the bunch centroid and bunch length as function of bunch number after 2000 turns, and Fig. 1e) the longitudinal density as a function of bunch number after 2000 turns. The detuning frequency of the third harmonic cavity is 21kHz. The instability for a detuning frequency of 25 kHz is shown in Fig. 2. We observe an instability with saturation, with the bunch centroid, bunch length and energy spread performing an oscillatory motions. We are investigating the nature of such instability.

CONCLUSION

We discussed the option to operate the NSLS-II-U with a multi-harmonic cavity system consisting a passive third-harmonic cavity and an active fifth-harmonic cavity. We considered a normal conducting passive third harmonic cavity that allows to operate under optimal conditions (sextic potential). We are also considering the option to operate with a superconducting passive third harmonic cavity. For a study with a single third harmonic superconducting cavity, see [3]. With numerical simulations we plan also to study transients effects and performance reduction effects driven by non-uniform filling patterns [3, 4].

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