PASSIVE LANDAU CAVITY EFFECTS IN THE NSLS-II STORAGE RING*

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Abstract

In middle-energy 3rd generation synchrotron light sources with small transverse emittance, higher harmonic cavities (Landau cavities) are installed for bunch lengthening to increase the Touschek lifetime, and to provide Landau damping for beam stability [1]-[5]. In this contribution we study the effects of passive Landau cavities in the NSLS-II storage ring for uniform fill-patterns with the OASIS tracking code [6],[7]. In our simulations we use an earlier set of parameters of the NSLS-II storage ring since our main purpose is to illustrate the basic mechanism of passive Landau cavity operations. It is on our agenda to study the actual parameters of the ring and discuss the case with non uniform fillings.

ACTIVE LANDAU CAVITY

Consider the rf voltage produced by the fundamental rf cavity and by a m-harmonic cavity (Landau cavity)

$$V(\tau) = V_{rf}[\sin(\omega_{rf}\tau + \phi_s) + K\sin(m\omega_{rf}\tau + \phi_n] - \frac{U_s}{e},$$

To compensate for the synchrotron radiation energy loss

Table 1: NSLSII Parameters

Parameter	Symbol	Value	Unit
Energy reference particle	E_0	3	GeV
Average current	I_0	500	mA
Number of bunches	M	1300	
Harmonic number	h	1300	
Circumference	C	780.3	m
Bunch duration	σ_τ	12	ps
Energy spread	σ_p	9.8×10^{-4}	
Energy loss per turn	U_s	1172	KeV
Momentum compaction	α	3.68×10^{-4}	
Revolution frequency	ω_0	$2\pi\times0.384$	MHz

U_s, we require $V(0) = 0$. In addition, we require $\frac{\partial V}{\partial\tau}\Big|_{\tau=0} = \frac{\partial^2 V}{\partial\tau^2}\Big|_{\tau=0} = 0$. These conditions lead to

$$V(\tau) = V_{rf}[\sin(\omega_{rf}\tau + \phi_s) - \sin\phi_s - \frac{\sin\phi_s}{m^2}\big(\cos m\omega_{rf}\tau - 1\big) - \frac{\cos\phi_s}{m}\sin m\omega_{rf}\tau]$$

In Fig.1 (top left) we show the phase space portrait with only the main rf cavity (red line) and with a third-harmonic Landau cavity (blue line) with parameters for the NSLS-II storage ring (see Table1). The optimal conditions satisfied by the voltage $V(\tau)$ induce a bunch lengthening without an increase of the energy spread.

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PASSIVE LANDAU CAVITY: GAUSSIAN BUNCHES

For passive Landau cavity operations, the total voltage is given by the sum of the voltage produced by the powered main rf cavity and the voltage induced by the beam traversing the Landau cavity. In the case of stationary Gaussian bunches uniformly distributed around the ring for a narrow-band resonator wake with frequency ω_R, shunt impedance R_s and quality factor Q, the total voltage reads (see Appendix A)

$$V(\tau) = V_{rf}\sin(\omega_{rf} + \phi_s) + i_b R_s\cos\psi\cos(\psi + m\omega_{rf}\tau).$$

where $i_b = 2I_0 e^{-\frac{1}{2}(m\omega_{rf}\sigma_\tau)^2}$ and the detuning angle ψ satisfies

$$\tan\psi = 2Q\delta, \qquad \delta = \frac{1}{2}\Big(\frac{\omega_R}{m\omega_{rf}} - \frac{m\omega_{rf}}{\omega_R}\Big). \qquad (1)$$

Imposing the same conditions as for the active Landau cavity ($V(0) = V'(0) = V''(0) = 0$) we have to satisfy

$$\begin{aligned} V_{rf}\sin\phi_s &= -i_b R_s\cos\psi^2 + \frac{U_s}{e}, \\ V_{rf}\cos\phi_s &= i_b R_s m\cos\psi\sin\psi, \\ V_{rf}\sin\phi_s &= -m^2 i_b R_s\cos\psi^2, \end{aligned}$$

which, solved for ϕ_s, ψ and R_s give

$$\begin{aligned} \sin\phi_s &= \frac{m^2}{m^2-1}\frac{U_s}{eV_{rf}} = \frac{m^2}{m^2-1}\frac{U_s}{\sin\phi_{s0}}, \\ \tan\psi &= -m\cot\psi, \\ R_s &= \frac{V_{rf}\sin\phi_s}{i_b m^2\cos\psi^2}. \end{aligned}$$

The optimal parameters for passive Landau cavity operations of the NSLS-II storage ring according to Table1 are thus

$$\begin{aligned} \sin\phi_s &= 0.2637, \\ \tan\psi &= 10.97 \Longrightarrow \psi = 84.79°, \\ R_s &= 17.77M\Omega. \end{aligned}$$

where the detuning frequency of the Landau cavity $\Delta\omega = \omega_R - m\omega_{rf}$ can be calculated from eq.1. According to Table2, $R_2 = 1800M\Omega$ is much bigger than R_s, so the optimal conditions for Landau cavity operations can not be met. Nevertheless, if we notice that $i_b R_s\cos\psi = 1.61MV$, roughly one third of $V_{rf} = 5MV$ and choose the detuning angle ψ to meet the condition $i_b R_2\cos\psi = 1.61MV$ it follows that the detuning frequency is $\Delta\omega = 2\pi\times 83.8$kHz for $Q_2 = 10^8$.

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Table 2: RF Parameters Main Cavity and Third-Harmonic (m=3) Landau Cavity

Parameter	Symbol	Value	Unit
RF frequency main/Landau	$\omega_{rf}/m\omega_{rf}$	$2\pi\times500/1500$	MHz
RF voltage main	V_{rf}	5	MV
Shunt impedance main/Landau	R_1/R_2	11.7/18000	MΩ
Quality factor main/Landau	Q_1/Q_2	65000/10^8	
Detuning main RF frequency	$\Delta\omega$	-$2\pi\times8.1$	kHz

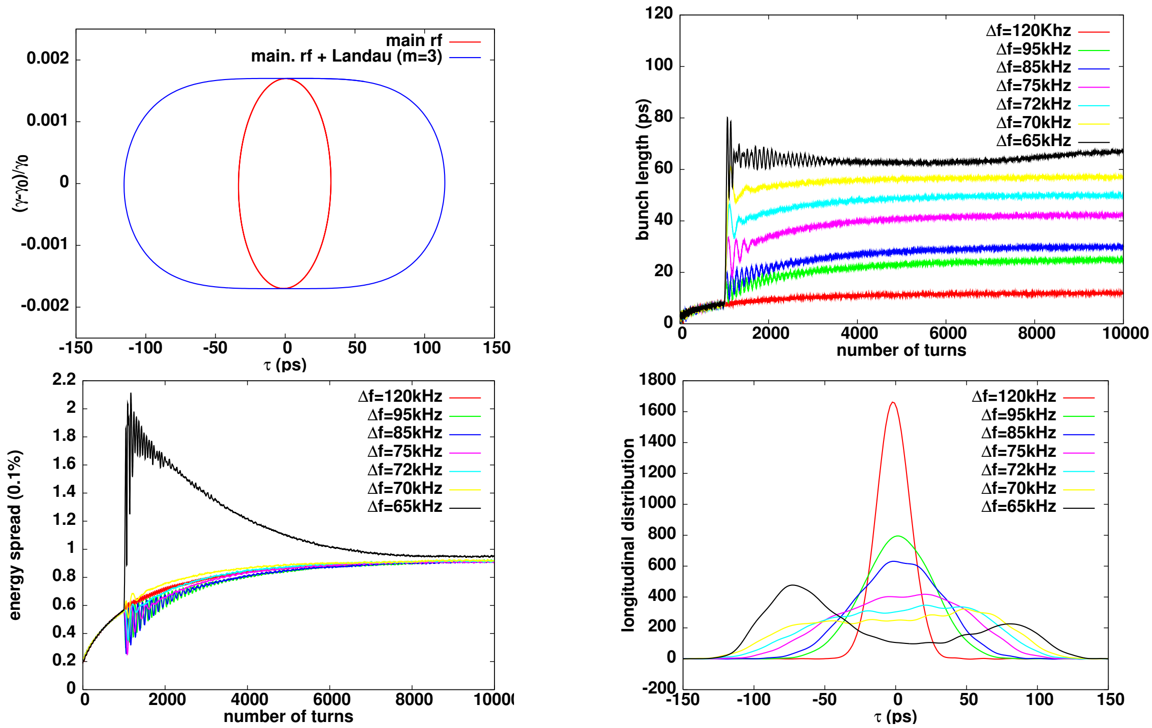

Figure 1: Top left: longitudinal phase space portrait with (blue line) and without (red line) a third-harmonic active Landau cavity. Top right: bunch lengthening vs number of turns for several values of the detuning angle Δf of the Landau cavity. Bottom left: the same as top right for the energy spread . Bottom right: longitudinal distribution for several values of Δf showing a doubled peaked structure for $\Delta f = 65$kHz.

PASSIVE LANDAU CAVITY: NUMERICAL SIMULATIONS

We discuss now self-consistent simulations of passive Landau cavity effects with the OASIS tracking code. The algorithm to calculate long range effects is briefly outlined in Appendix B. A more detailed discussion can be found in [6]. Since our calculation of the coupled-bunch interaction requires an integration over the history of the beam, it is very time consuming to simulate the Landau cavity with $Q_2 = 10^8$. We discuss here simulations with the smaller value $Q_2 = 260000$. In order to meet the requirements discussed at the end of the Section 2, we choose $R_2 = 46.8$MΩ. We plan to optimize our algorithm to discuss the case with $Q_2 = 10^8$. In Fig. 1 (top right) we show the bunch length as a function of the detuning frequency Δf. The optimal bunch lengthening for uniform fillings occurs for values of the detuning frequency in the range from 70 to 75kHz, not far from the value predicted by the calculation with stationary Gaussian bunches. For example the bunch lengthening for $\Delta f = 72$kHz is 50ps. For smaller values of Δf the energy spread begins to increase as shown in Fig.1 (bottom left) and the longitudinal distribution starts to show a doubled peaked structure, as shown in Fig.1 (bottom right).

CONCLUSIONS

We studied passive Landau cavity effects induced by a third harmonic rf cavity for uniform fillings. We simulated numerically the detuning angle for optimal bunch lengthening and found it to be in agreement with the analytical theory for Gaussian bunches. For smaller values of the optimal detuning angle the phase space is populated around two phase space points giving to the longitudinal distribution a doubled peaked structure. In the analysis to date we did not study non uniform fillings and we did not include transients effects induced by the impedance of the fundamental rf cavity. We plan to perform these studies together with the inclusion of a model to simulate the effects of a feedback system.

APPENDIX A: PASSIVE LANDAU CAVITY FOR STATIONARY GAUSSIAN BUNCHES

Consider the total voltage produced by stationary Gaussian bunches uniformly distributed around the ring for a narrow-band resonator wake

$$V(\tau) = \int_{-\infty}^{\tau} d\tau'\rho(\tau') \sum_{k=-\infty}^{+\infty} W\Big(k\frac{T_0}{M} + \tau - \tau'\Big), \quad (2)$$

where

$$W(\tau) = 2\alpha R_s e^{-\alpha\tau}\Big(\cos\bar{\omega}\tau - \frac{\alpha}{\bar{\omega}}\sin\bar{\omega}\tau\Big)\ (\tau > 0),$$
$$\rho(\tau) = \frac{Q}{\sqrt{2\pi}\sigma_\tau} e^{-\frac{\tau^2}{2\sigma_\tau}},$$

and $\alpha = \omega_R/2Q$, and $\bar{\omega} = \sqrt{\omega_R{}^2 - \alpha^2}$. The summation over k has been extended to $-\infty$ taking advantage of the causality property of the wake function. From

$$W(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\omega e^{-i\omega\tau} Z^{||}(\omega),\ \ \rho(\tau) = \int_{-\infty}^{\infty} d\tau e^{i\omega\tau}\tilde{\rho}(\omega),$$

it follows

$$V(\tau) = \frac{Q}{2\pi}\int_{-\infty}^{+\infty} d\omega\tilde{\rho}(\omega)e^{i\omega\tau} \sum_{k=-\infty}^{+\infty} e^{-i\omega k\frac{T_0}{M}} Z^{||}(\omega).$$

Using the following identity and changing integration variable

$$\sum_{k=-\infty}^{+\infty} e^{ikz} = 2\pi \sum_{p=-\infty}^{+\infty} \delta(z - 2\pi p), \quad y = \frac{\omega T_0}{M}, \quad (3)$$

we have

$$V(\tau) = \frac{\omega_0 M}{2\pi} \sum_{p=-\infty}^{+\infty} \tilde{\rho}(pM\omega_0)e^{-ipM\omega_0\tau} Z^{||}(pM\omega_0).$$

Assuming $M = h$ (h = harmonic number) and the narrow-band resonator impedance sharply peaked at $\omega = m\omega_{rf}$ ($\omega_{rf} = h\omega_0$)

$$Z^{||}(\omega) = \frac{R_s}{1 + iQ(\frac{\omega_R}{\omega} - \frac{\omega}{\omega_R})} \overset{\omega = m\omega_{rf}}{=} \frac{R_s}{1 + i2Q\delta},$$
$$\text{where} \quad \delta = \frac{1}{2}\Big(\frac{\omega_R}{m\omega_{rf}} - \frac{m\omega_{rf}}{\omega_R}\Big), \quad (4)$$

in the sum over p we keep only terms with $p = -m, m$

$$V(\tau) = \frac{\omega_0 M}{2\pi}\Big(\tilde{\rho}(-m\omega_{rf})e^{im\omega_{rf}\tau} Z^{||}(m\omega_{rf}) + \tilde{\rho}(m\omega_{rf})e^{-im\omega_{rf}\tau} Z^{||}(-m\omega_{rf})\Big)$$
$$= \frac{\omega_0 MQR_s}{\pi(1 + 4Q^2\delta^2)} e^{-\frac{1}{2}\omega^2\sigma_\tau^2}(\cos m\omega_{rf}\tau - 2Q\delta\sin m\omega_{rf}),$$

where we used $\tilde{\rho}(\omega) = Qe^{-\frac{1}{2}\omega^2\sigma_\tau^2}$. Using $I_0 = \omega_0 MQ/2\pi$ and defining $i_b = 2I_0 e^{-\frac{1}{2}(m\omega\sigma_\tau)^2}$, the result can be cast in the form

$$V(\tau) = i_b R_s \cos\psi \cos(\psi + m\omega_{rf}\tau), \quad (5)$$

where $\tan\psi = 2Q\delta$.

APPENDIX B: CALCULATION OF LONG RANGE WAKEFIELD INTERACTION

We outline the algorithm for the self-consistent calculation of the long-range wakefield interaction. For simplicity, we consider the case of one bunch interacting with the voltage $V(\tau)$ produced by the bunch itself after n turns. The total voltage $V(\tau)$ from the previous k revolutions is therefore

$$V(\tau) = \sum_{k=-\infty}^{n} \int_{-\infty}^{\tau} d\tau'\rho_k(\tau')W\big[(n-k)T_0 + \tau - \tau'\big],$$

Assuming that the long-range wakefield is slowly varying for $\tau \in [(n-k)T_0 - 5\sigma_\tau, (n-k)T_0 + 5\sigma_\tau], k < n$, and using $l = n - k$ we can calculate $V(\tau)$ by expanding W in Taylor series at lT_0

$$V(\tau) = \sum_{l=0}^{+\infty} \int d\tau'\rho_{n-l}(\tau')\Big(W(lT_0) + W'(lT_0)(\tau - \tau') + W''(lT_0)\frac{(\tau-\tau')^2}{2} + \cdots\Big)$$
$$= \sum_{l=0}^{+\infty}\Big[W(lT_0) + W'(lT_0)(\tau - \langle\tau\rangle_{n-l}) + W''(lT_0)\frac{(\tau^2 - 2\tau\langle\tau\rangle_{n-l} + \langle\tau^2\rangle_{n-l})}{2} + \cdots\Big).$$

Thus the calculation of $V(\tau)$ at turn n can be done by storing the moments $\langle\tau\rangle_k, \langle\tau^2\rangle_k, \cdots$ of the bunch over previous turns.

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