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BEAM-LOADING TRANSIENTS AND BUNCH SHAPE IN THE OPERATION OF PASSIVE HARMONIC CAVITIES IN THE ALS-U

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Abstract

The ALS-U is a major upgrade of the LBNL ALS to a diffraction limited light source. The current plan is to replace all the vacuum and magnet components while retaining the existing 500 MHz main and third-harmonic, passively operated, rf cavities, but replacement of the existing rf cavities is also being considered. A new feature, is represented by beam-loading transients associated with a beam consisting of 11 bunch trains separated by 10 ns gaps as needed to enable on-axis swap-out injection. In this paper we study these transients and the associated bunch-to-bunch phase, length, and profile variations.

INTRODUCTION

Passively operated harmonic cavities to lengthen the bunches and increase the Touschek lifetime will be an essential feature of the Advanced Light Source upgrade (ALS-U) [1][2]. Two options are being considered for the upgrade, entailing either re-use of the existing 3rd order cavities already operating in the ALS or the installation of newly designed cavities. While we believe that both options can deliver the goal of stretching the natural bunch length by about a factor 4, for this study we restrict our analysis to the latter, in which case the bunch profile at the design average beam current can be made closer to the 'optimal', i.e. maximally, flat shape. Passive operation of the harmonic cavities has obvious advantages in terms of hardware reduction and operation costs but, in general, limits the flexibility of controlling the bunch length and makes the effect of the cavities on the beam depend on the beam filling structure. The presence of a long gap in the beam filling is known to induce beam-loading transient effects that may compromise our ability to control the beam as intended. The goal of this paper is specifically to study the beam-loading transient effects associated with the time-structure of the ALS-U beam. Because of the aggressive small emittance goal and resulting small dynamic aperture and relatively short lifetime, ALS-U will adopt on-axis injection where portions of the beam are frequently swapped in and out of the storage ring into an adjacent Accumulator ring. The beam will consist of 11 trains separated by 10 ns gaps, the latter determined by the minimum raising/fall time of the fast kicker enabling the swap-out, with two trains having 25 and nine trains having 26 bunches. (With $h = 328$ harmonic number the number of circulating bunches is 284, and because 328 is not divisible by 11, not all trains can have the same number of bunches.)

We conducted our study primarily with macroparticle simulations (using the code Elegant [3]) but we end this section by outlining a semianalytical approach, which we used to determine the parameters for the optimal harmonic cavity design and benchmark the simulations for the test case of uniform beam filling.

The interaction of the beam with the cavity is well described by the impedance of the cavity fundamental mode[4]

$$Z(\omega) = \frac{R_s}{1 + iQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)} = R_s e^{-i\Psi}\cos\Psi, \qquad (1)$$

where the detuning angle is defined by: $\tan\Psi = Q\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right) \simeq 2Q\frac{\omega_r - \omega}{\omega_r}$ and R_s is the shunt impedance of the cavity, Q is quality factor. ω_r is the resonant frequency for the cavity.

In the presence of a beam with uniformly bunch separation T, we expect the profile $\rho(\tau)$ to be the same for all bunches. The induced voltage on the cavity can then be written as $V(\tau) = -eN(2\pi)^{-1}\sum_{m=-\infty}^{\infty}\int_{\infty}^{\infty} d\omega\tilde{\rho}(\omega)e^{-i\omega(\tau - mT)}Z(\omega)$, where $\tilde{\rho}(\omega)$ is the FT of $\rho(\tau)$. Retaining only the harmonic $\omega_3 = 3\omega_{rf}$ close to the cavity resonant frequency on the assumption of a high Q, we find ([5]), $V(\tau) \simeq V_3(\tau)$ with

$$V_3(\tau) = -2I_{avg}R_s F\cos\Psi\cos(\omega_3\tau + \Psi - \Phi_F), \qquad (2)$$

where $I_{\text{avg}} = N/T_{rf}$, is the average current, and the amplitude F and phase Φ_F are related to the bunch form factor at $\omega = \omega_3$: $\tilde{\rho}(\omega_3) = Fe^{i\Phi_F}$.

With the total rf potential given by $V_T(\tau) = V_1\sin(\omega_{rf}\tau + \phi_1) + V_3(\tau)$ and the scaled total potential defined as $u(\tau) = -(\alpha\sigma_\delta^2 E_0 T_0)^{-1}\int_0^\tau [eV_T(\tau') - U_0]\,d\tau'$, the bunch equilibrium distribution normalized to unity is given by [6]

$$\rho(\tau) = \frac{e^{-u(\tau)}}{\int_{-\infty}^{+\infty} e^{-u(\tau')}d\tau'}. \qquad (3)$$

This equation can be regarded as a functional equation in the unknown ρ, similar to a Haissinski equation or as an algebraic equation in the two unknowns F and Φ_F. Here we take the latter view using a Newton method to find numerical solutions. Solutions are searched to determine a value of the shunt impedance R_s for which an appropriate detuning angle can be found so that the resulting rf voltage and bunch profile is maximally flat at the ALS-U design 500 mA current, see Table 1. Relevant ALS-U parameters are $\alpha = 2.1 \times 10^{-4}$ momentum compaction factor, $\sigma_\delta = 9.4 \times 10^{-4}$ relative energy

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spread, $E_0 = 2$ GeV beam energy, $C = cT_0 = 196.5$ m circumference, $U_0 = 217$ keV energy loss/turn (dipoles only).

In the presence of a beam filling pattern consisting of a single train of n_b bunches separated by T_{rf}, followed by n_e empty rf buckets with $n_e + n_b = h$, it can be shown that the voltage induced by the beam as seen by a particle belonging bunch n ($n = 0, 1, \ldots, n_b - 1$) can be written as $V_{3,n}(\tau) \simeq -\frac{eN}{T_0} \sum_{n'=0}^{n_b-1} \tilde{\rho}_{n'}(\omega_3) \sum_{l=-l_{max}}^{l_{max}} e^{i2\pi l(n'-n)/h} \times e^{-i(\omega_3+l\omega_0)\tau} Z(\omega_3 + l\omega_0) + cc$, where T_0 is the revolution period, $\omega_0 = 2\pi/T_0$, and $2l_{max}\omega_0$ is the width of the cavity resonance peak, and where now the profiles $\rho_n(\tau)$ of the bunches in the train are allowed to be all different. One can then proceed as in the case of uniform beam filling to write a system of equations to identify the form factors of the n_b bunches and the resulting profiles. Further extension of the formula can be made to account for any arbitrary fill pattern.

SIMULATION RESULTS

The Elegant [3] simulations were based on the machine parameters reported in the previous section and the main and harmonic cavities parameters shown in Table 1. The calculated bunch form factor for the parameters below is 0.9. We used 10k macroparticles to represent each individual bunch in the train and tracked the beam for a few damping times to reach equilibrium, starting from a gaussian distribution for the bunches. The simulations include beam-loading effects in the harmonic but not in the main cavities. With these parameters, we found that radiation damping is sufficient to suppress the Robinson instability naturally associated with the operation of the harmonic cavities.

Table 1: Parameter Setting for Cavity

Main Cavity Parameters		**3rd Cavity Parameters**	
Voltage	0.6 MeV	Q	20 000
Phase	161.79 deg	R_s	1.39 $M\Omega$
Freq.	500.1469 MHz	Detuning Freq.	250.2 kHz

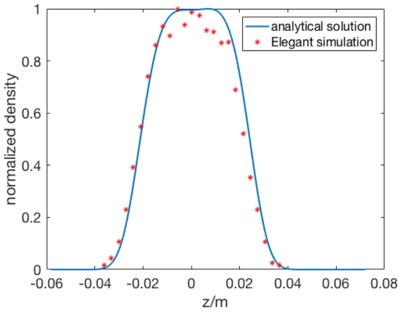
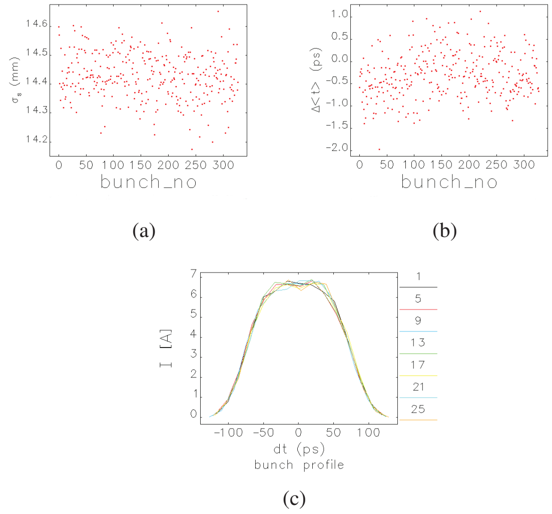


Figure 1: Bunch profile for uniform beam-fill pattern: simulations vs. analytical model.

We benchmarked the macroparticle simulations against the semi-analytical model discussed in the previous section for the case of uniform beam filling, and found good agreement, in Fig. 1. We then proceeded by studying variants of the beam filling pattern and exploring slightly modified simulation parameters.

Specifically, we considered the following settings, labeled C1 through C4: *i)* ALS-U fill pattern where the two shorter trains wtih 25 bunches are adjacent (C1); *ii)* ALS-U fill pattern where the two shorter trains (6th and 11th train) are the farthest away from each other (C2); *iii)* same fill pattern as C1 but with modified choice of shunt impedance $R_s = 1.42$ MΩ to yield slightly overstretched bunches (C3); *iv)* same fill pattern as C2 but with slightly overstretched bunches as in C3 (C4).

For reference, Fig. 2 shows the result for a uniform fill pattern. Bunch length and centroid variations are within 0.4 mm (or about 3%) and 3 ps respectively, within the noise.



(a)

(b)

(c)

Figure 2: Bunch centroids, bunch length and profile for uniform beam-fill pattern

Fig. 3~5 show the simulation results for bunch centroid, bunch length, and selected bunch profiles for the other cases we investigated. The observed variations of the bunch centroid along a train is on the order of tens of ps.

In addition to the bunch-to-bunch variations along a train one can also observe train-to-train variations apparently caused by the irregularity introduced by the two shorter trains. The latter variations are stronger when the two shorter trains are adjacent. Over-stretching the bunches also appears to have an effect on enhancing the transients.

The bunch lengths are reported in Fig.4, also showing visible transient effects, with bunch-length variations that in the worst case can reach about 20%.

Fig. 5 reports the equilibrium distribution profiles for selected bunches along the first train of the beam, indicating apparent deviations from the optimal flat-top profile seen in the uniform fill pattern.

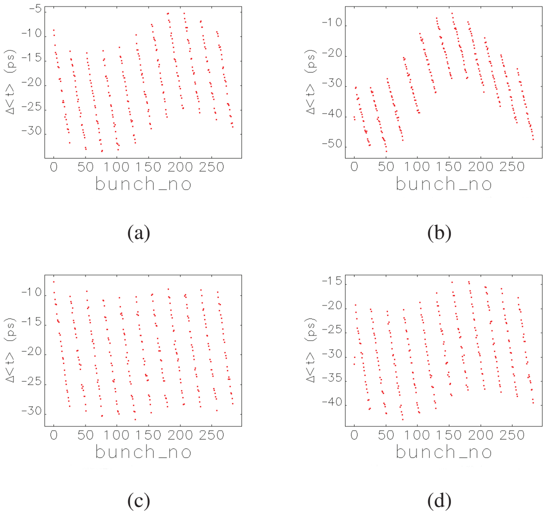


Figure 3: Bunch centroid for every bunch. Fig.3a is for C1 setting, Fig.3b is for C3, Fig.3c is for C2, Fig.3d is for C4.

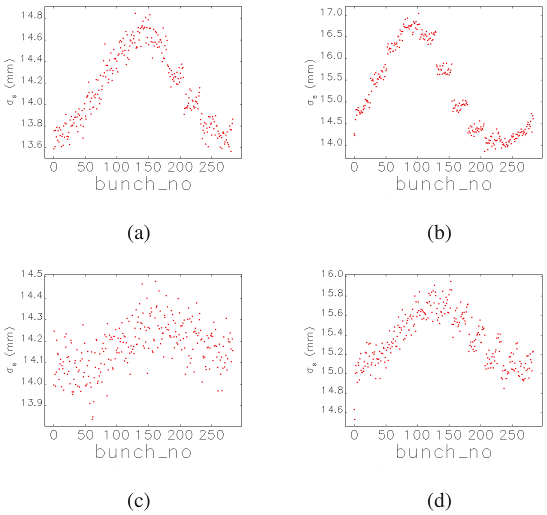


Figure 4: Bunch length for every bunch. Fig.4a is for C1 setting, Fig.4b is for C3, Fig.4c is for C2, Fig.4d is for C4.

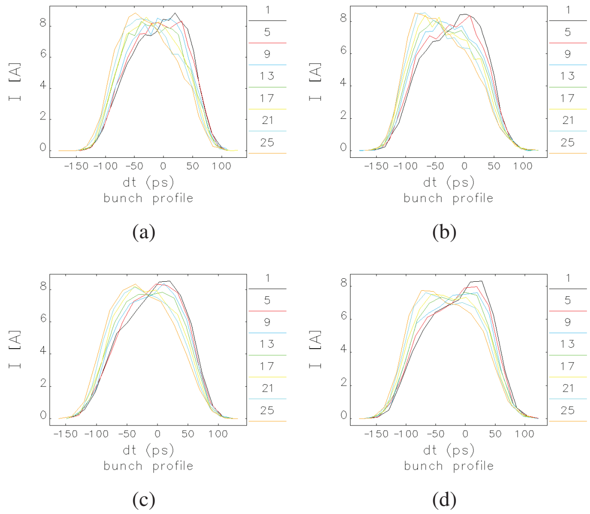


Figure 5: Bunch profile for selected bunches along the first train. Fig.5a is for C1 setting, Fig.5b is for C3, Fig.5c is for C2, Fig.5d is for C4.

CONCLUSION

Beam-loading transient effects caused by the harmonic cavities have been investigated for the ALS-U lattice parameters and beam-fill pattern. We find that the presence of 10 ns gaps between the bunch trains is responsible for a shift in the bunch centroid of about 20 ps from head to tail of each train. While noticeable, the magnitude of this shift is acceptable. In addition, we observe a train-to-train modulation induced by the non-uniformity of the number of bunches per train. This modulation, however, can be greatly reduced by appropriately placing the two shorter trains at the largest distance from each other. Bunch length variations are on the order of a few percent; overstretching the bunches, as would be desirable to lengthen the beam lifetime, tends to increase the observed bunch-to-bunch variations. The determination of the optimal bunch lengthening will be the topic of further studies.

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