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STRETCHED BUNCH SHAPES IN THE NSLS VUV RING

N. Towne*, National Synchrotron Light Source
Brookhaven National Laboratory, Bldg. 725B, Upton, NY 11973-5000†

Abstract

For bunches stretched with a higher-harmonic cavity, longitudinal bunch shapes are influenced by small variations in the potential wells of the buckets of the bunch train. This paper discusses three things that perturb the bunch shapes in the NSLS VUV ring: the $-90°$ (non-optimal) phase of the harmonic cavity maintained by the RF controls [1], higher-order modes (HOM) of the main cavity, and the effect of unfilled buckets on the RF fields in the accelerating modes of the two cavities. The suppression of the lowest-lying HOM in an experiment using RF feedback applied to two HOM damping-probe ports is described and results of calculations of the effect of unfilled buckets are given. Measured bunch shapes are shown and discussed.

1 INTRODUCTION

Operation of an RF system with a higher-harmonic cavity (HHC) provides two benefits. The addition of synchrotron-frequency spread provides Landau damping of coupled-bunch modes [2] and bunch lengthening increases the Touschek-scattering lifetime. Both are important in the NSLS VUV ring where a near-ϕ^4 potential is used. A consequence of the use of this potential is that bunch shapes are sensitive to perturbations of the potential well on the order the intrinsic energy spread of the ring. A number of such perturbations are present in the VUV ring. First, near the optimum voltage of the HHC, the bunch shape is especially sensitive to the HHC phase. Second, higher-order modes affect the potential wells of the different buckets differently. Third, the use of empty buckets for the control of ion trapping again provides asymmetric distortion of the potential wells. All of these effects can be seen in the VUV bunch shapes (figure 1) and it is the purpose of this paper to describe these influences. Although the first two effects have been reported previously [1], additional information is provided here. The third effect is assessed for the VUV ring for the first time and occupies the majority of this paper. Bunch lengthening through the broad-band impedance is a substantial effect, although it is not discussed here.

Machine parameters are given in table 1.

2 HARMONIC-CAVITY PHASE

Stretching the bunches is, in part, an exercise in the control of the voltages and phases of the main and harmonic cavities. The ideal condition for bunch stretching [3] has, in the VUV ring, cavity phase of $-94°$ and voltage ratio near h_1/h_2, where h_1 and h_2 are the harmonic numbers of the two cavities. Some HHC power is provided by the beam. The RF controls for the HHC do not attempt to meet this condition but instead maintain a relative phase of $-90°$ [1]. The bunch shapes, in spite of this, are nearly optimal (figure 2) because a shift of the cavity phase much smaller than the four degrees is required to meet this condition—a consequence of the near-ϕ^4 potential. Reference [4] explains this more fully.

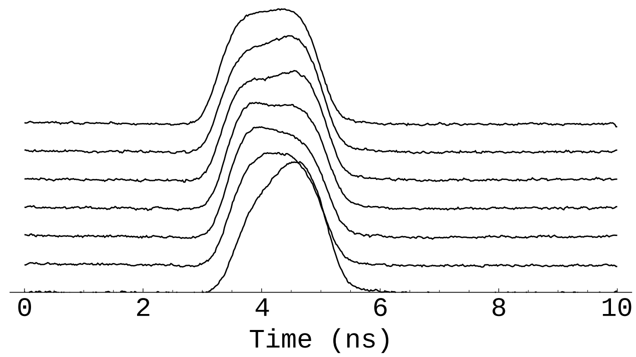

Figure 1: Longitudinal bunch shapes for a 620-mA seven-of-nine bucket fill in the NSLS VUV ring. The first bunch is at the bottom.

Table 1: Values of VUV ring, cavity parameters and symbols used in the text.

Revolution frequency	$\omega_0/2\pi$	5.8763 MHz
Energy spread	σ_ε	5×10^{-4}
Momentum compaction	α	0.0245
Cavity voltages	V_1/V_2	80/20 kV
Cavity harmonics	h_1/h_2	9/36
Cavity loss factors	k_1/k_2	10/20 GΩ/s

3 HIGHER-ORDER MODES

Higher-order mode (HOM) losses in the cavities of the VUV ring are not, in most cases, known with any accuracy. The oscillation of bunch shapes visible in figure 1 voltages at non-RF revolution harmonics are at work. In only the case of the lowest monopole HOM of the main cavity at 270 MHz is the Q known and the influence assessable. This mode has center frequency only a few hundred kilohertz above the 46th revolution harmonic, which is once removed from a bucket harmonic, and significant voltage is generated. In an experiment RF feedback centered

* Email: towne@bnl.gov
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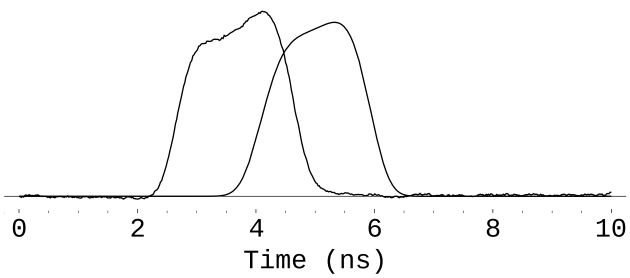

Figure 2: Measured bunch shape in the VUV ring for a symmetric nine-bunch fill (left) and calculated assuming ideal stretching but with the HHC phase set so that the net power transfer between the HHC and the beam is zero ($-90°$ condition, right).

on the 270 MHz mode was applied to the cavity through two damping probes fitted with high-pass filters to reject the pickup from the powered accelerating mode. Feedback gain sufficient to reduce the strength of the mode by a factor of two at the revolution harmonic was applied and the result, in figure 3, verifies that there is some voltage in this HOM affecting the bunch shapes. Remaining oscillation of the bunch shapes shows that there is a voltage in the ring at least one other revolution harmonic.

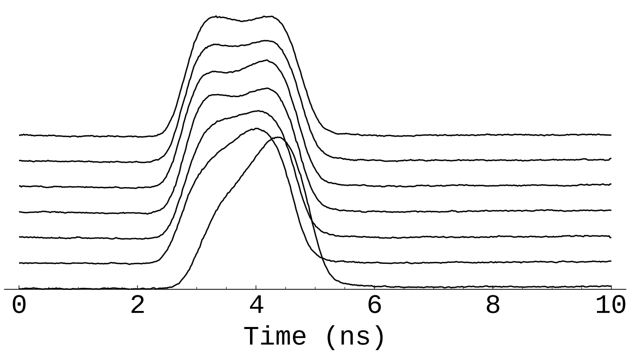

Figure 3: Bunch shapes for a 570-mA seven-bunch fill with 7.2 dB of gain applied to the 270-MHz mode of the main cavity. There is 5.3 dB gain at the 46th revolution harmonic a few hundred kilohertz below the resonance (the revolution harmonic is displaced one from a bucket harmonic).

This result, that the 270 MHz mode is responsible for only part of the distortion of the buckets, and the result that suppressing the impedance of the mode had little effect on the coupled-bunch modes, dictated the conclusion that the mode suppression is of little utility in the VUV ring.

4 THE BUNCH TRAIN [5]

Empty buckets break the periodicity, at the RF frequency, of the beam current. As a result the voltage in the ring induced by the beam current has Fourier components at revolution harmonics other than harmonics of the bucket frequency. This has the effect of introducing non-uniformity, perhaps very small, of the bucket potentials. Ordinarily this non-uniformity is not of concern but, when one considers stretched bunches of electrons in a storage ring where the RF potential may approximate a ϕ^4 potential, small changes become significant. In the NSLS VUV ring the effect of this potential-well distortion is significant. It is the task of this section to give a calculation of the shifts of the bunch shapes, apply the calculation to the VUV ring, and compare the results with measurements.

To begin, consider a ring of b buckets with beam current I_b due to an asymmetric fill of n empty buckets and $b - n$ bunches in a train. Imagine that the beam current I_b is the sum of a part where all buckets are filled $\bar{I}_b$ and a part δI_b where empty buckets are filled with charge opposite the others. Furthermore, assume that the current I_b due to the fictitious charge in the n empty buckets is lumped into the center of the train of empty buckets and that its Fourier component at the RF frequency $\omega_{RF} = h\omega_0$ (h is the harmonic number of the cavity and ω_0 is the revolution frequency) is canceled by another voltage:

$$\delta I_b = eN \sum_{p=-\infty}^{\infty} \delta(t - pT_0) - \kappa \cos(h\omega_0 t), \qquad (1)$$

where $\kappa = 2I_{av}/(b/n - 1)$, $eN = \kappa T_0/2$, I_{av} is the average beam current, and T_0 is the revolution period. It is assumed that a nominal potential well is generated by the RF cavities driven by a combination of generator current and beam current so that the voltage in the cavities generated by $\bar{I}_b$ is (conceptually) absorbed into the voltage in the cavities for ideal bunch stretching. δI_b is regarded as a perturbation without a Fourier component at $h\omega_0$.

One then models the cavity as a resonator with resonant frequency ω_r, detuning $\Delta = \omega_r - h\omega_0$ from the cavity's harmonic h of ω_0, quality factor Q, and impedance R. The voltage $V_{\delta I_b}$ induced by δI_b has two terms corresponding to the terms on the right-hand side of equation 1,

$$V_{\delta I_b} = V_1 + V_2. \qquad (2)$$

The result of Kramer and Wang [6] gives

$$V_1 = eNke^{-i\Omega\tau}/(e^{-i\Omega T_0} - 1) + \text{c.c.}, \qquad (3)$$

where k is the loss factor (the product of the damping rate $\Gamma = \omega_r/2Q$ and the impedance R) of the cavity, $\Omega = \omega_r - i\Gamma$, and $\tau = t \bmod T_0$. The term V_2 is the negative of the wake potential $-W(t) = -2k\cos(\omega_r t)e^{-\Gamma t}$ for the cavity convolved with the second term of equation 1

$$V_2(t) \simeq -\frac{k\kappa}{2}\frac{e^{-h\omega_0 t}}{-i(\Delta - i\Gamma)} + \text{c.c.} \qquad (4)$$

Summing V_1 and V_2,

$$\begin{aligned} V_{\delta I_b} &\simeq k\left(\frac{eNe^{-i\Omega\tau}}{-i(\Delta - i\Gamma)T_0} - \frac{\kappa e^{-ih\omega_0 t}}{-2i(\Delta - i\Gamma)}\right) + \text{c.c.} \\ &\simeq \frac{\kappa k}{2} e^{-ih\omega_0 t}\frac{e^{-i(\Delta - i\Gamma)\tau} - 1}{-i(\Delta - i\Gamma)} + \text{c.c.} \\ &\simeq \kappa k \cos(h\omega_0 t)\tau. \qquad (5) \end{aligned}$$

Note that this is a small quantity, it has a Fourier component at the RF frequency due to the approximations made, and it adds a locally constant voltage to each bucket. We add a term at the RF frequency $h\omega_0$, borrowed from the prescribed RF voltage, to remove this locally constant voltage so $V_{\delta I_b}$ meets the periodic boundary condition $eNk = V_{\delta I_b}(0_+ + pT_0) = -V_{\delta I_b}(0_- + pT_0)$, where $p = \ldots, -1, 0, 1, \ldots$. This gives

$$V_{\delta I_b} \simeq \kappa k \cos(h\omega_0 \tau)(\tau - T_0/2). \tag{6}$$

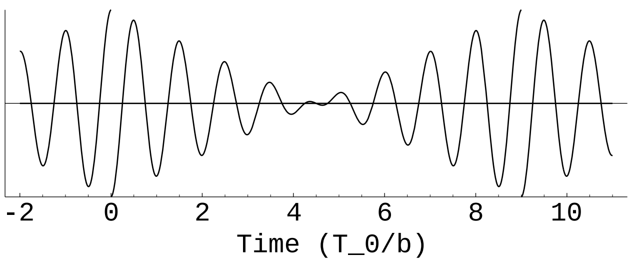

Figure 4: Equation 6 for $h = 9$ and time in units of the RF period.

The solution is illustrated in figure 4. Bunches are located at the either the minima or maxima on the first half of the train and on the maxima or minima, respectively, on the second half. The RF voltage at a bucket are, to first order in phase, shifted by $V_{\delta I_b}$ evaluated at the time of the bucket. To remind the reader, a shift of the RF voltage upward makes the synchronous phase later while a shift downward has the opposite effect. The first leading and the first lagging bucket with respect to the kick receive the largest shifts and of opposite signs with respect to each other. The signs of the shifts depend on the number of empty buckets. To see this consider the phase of $V_{\delta I_b}$ for the first bunch after the kick.

$$\varphi = 2\pi \frac{n+1}{2} \frac{h}{b}. \tag{7}$$

By inspection one can see that the cases where the shift for this bunch, proportional to $-\cos\varphi$, is positive and negative are:

- negative when n is odd or h is an even multiple of b and
- positive when n is even and h is an odd multiple of the b.

To illustrate with the VUV ring, there are nine RF buckets and, in normal operation, there are two empty buckets ($n = 2$ and $b = 9$). The main cavity has $h = 9$ determining the bucket frequency and the harmonic cavity has $h = 36$ (table 1). The shift in the total RF voltage at the phase of the first bunch following the kick due to the main cavity is positive while the shift due to the harmonic cavity is opposite the shift of the main cavity. Since the loss factor of the harmonic cavity is larger than that of the main cavity, the effect of the harmonic cavity prevails and the net shift of the RF voltage at the first bunch after the kick is negative (figure 5). When comparing this conclusion with the first bunch in figure 1 we see that it is shifted slightly later in time suggesting that the potential for that bunch is locally high instead of low. Based on this observation we conclude that the actual perturbation of the RF voltage at that bunch is dominated by a higher-order mode(s) pushing the voltage upward.

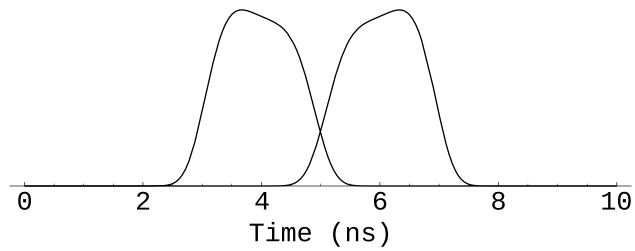

Figure 5: Calculated bunch shapes for the leading (left) and trailing (right) bunches of a seven-bunch train and two empty buckets in the VUV ring given the ideal RF voltages for stretching.

5 CONCLUSION

Bunch shapes in the NSLS VUV ring are influenced uniformly by the harmonic cavity phase, asymmetrically by the HOMs not near bucket harmonics, and the presence of, in normal operation, a gap in the fill. The unusually asymmetric shape of the first bunch (figure 1) is a result of the combination of the voltages from the HOMs and HHC phase; the affect of the empty buckets is a moderating but minor influence. Near ideal bunch shapes are obtained for the other bunches.

6 REFERENCES

[1] R. Biscardi, S. L. Kramer, and G. Ramirez, Nucl. Instrum. Methods **A** 366 (1995), p. 26-30.

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[5] The work of this section was made possible by discussions held at ALS with J. Byrd and others.

[6] S. L. Kramer and J. M. Wang, Nucl. Instrum. Methods **A** 423 (1999), p. 260, equation 22.