Bunch Length Control in the VUV Light Source [1]

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Abstract-

The VUV storage ring at the National Synchrotron Light Source has for several years had a fourth harmonic rf cavity operating in the passive bunch lengthening mode. This has provided an increase in bunch length and beam lifetime that varies with beam current. Recently a 10 kWatt transmitter was added to this rf system allowing operation with a constant bunch length at all currents throughout the entire beam decay of the ring. Beam stability with the two active power sources has been obtained by working with a conservative bunch lengthening that counters the influence of bunch lengthening in the higher order modes of the rf cavities. The existence of an rf power circulator separating this transmitter and cavity, has helped make it possible to operate this system over a wide range of conditions from bunch lengthening to bunch shortening. In addition to making the bunch length almost independent of beam current, the present operation has helped stabilize the existing phase noise on the beam and has been a benefit to experiments requiring precise timing and constant shape of the bunches.

1. INTRODUCTION

Quadrupoles are installed in storage rings not only to provide the focusing for transverse stability of the beam, but also to control the beam size of the synchrotron light. Some increase in beam size with current is observed due to wakefields or ions, but for the most part beam size remains fairly constant with beam current. The bunch length, however, will typically vary by several factors [1] to an order of magnitude with current, due to wakefield affects. For timing and fluorescent lifetime measurements this change in temporal distribution of the source (excitation) is important and makes experiments difficult [2]. To counter this change, the experimenters must simultaneously measure the excitation function and deconvolve it as it changes.

Several years ago a 4th harmonic cavity was added to the VUV ring, primarily to increase the bunch length and beam lifetime [3]. This cavity has been operated in a passive mode using the beam's current to create the field to lengthen the bunch. This has proved quite useful in increasing the beam lifetime at high currents where the lifetime is short, but has had little effect at low currents, see Figure (1). For a few users this proved to be more of a problem, since variation of the bunch shape and length was even greater than without the harmonic cavity operating. Since the fall of 1993, the ring has been operating with the 4th harmonic cavity powered by an external source, providing increase bunch lengthening and lifetime at all currents. The added benefit has been that the shape and length of the bunches has remained more constant throughout the current range. Operation is also possible where the bunch will be shortened for timing experiments.

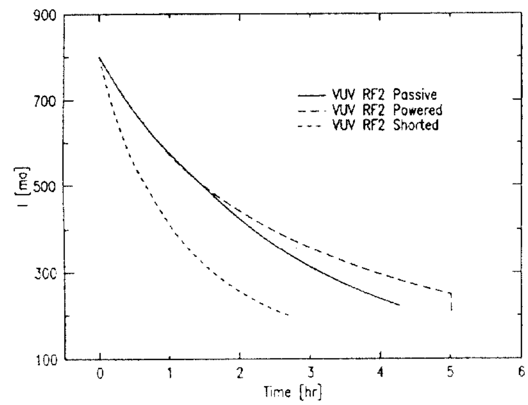

Figure (1) Current versus time for the VUV ring during operational fills for: one rf system (short dashed) plus a 4th harmonic cavity in passive mode (solid) and powered mode (long dashed curve).

2. THEORY OF THE HARMONIC CAVITY OPERATION

The basic theory of harmonic cavity operation for bunch lengthening has been described by A. Hofmann et al. [4]. In their description the optimum bunch lengthening was obtained by determining the voltage gained by a bunch [5] with energy loss per turn U_0 , that satisfies the conditions:

$$V_T = V_1\cos\phi_1 + kV_1\cos(n\phi_n) = U_0 \qquad (1a)$$

$$-V_T' = V_1\sin\phi_1 + kV_1 n \sin(n\phi_n) = 0 \qquad (1b)$$

$$-V_T'' = V_1\cos\phi_1 + kV_1 n^2\cos(n\phi_n) = 0 \qquad (1c)$$

where V_1, ϕ_1 are the voltage and synchronous phase for the main rf system and ($kV_1=V_n$), ($n\phi_n$) are the voltage and synchronous phase for the nth harmonic rf system.

These equations can be solved for a given n and V_1 to yield:

$$\cos\phi_1 = \frac{n^2}{n^2-1}\left(\frac{U_o}{V_1}\right) \qquad (2a)$$

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[1]Work performed under the auspices of the U.S.Dept. of Energy.

$$\tan(n\phi_n) = n \tan \phi_1 \qquad (2b)$$

$$k = \frac{-\sin\phi_1}{n \sin(n\phi_n)} \qquad (2c)$$

In the VUV ring this optimum bunch lengthening condition for n=4 and V_1 = 80kV yields:

$$\phi_1 = 78.7°, \quad (4\phi_4) = -92.9° \text{ and } k = 0.246$$
$$\text{or } V_4 = kV_1 = 19.68\text{kV}.$$

Figure (2a) shows the calculated bunch current distribution for the natural energy spread of the beam with the main rf cavity alone, and with the 4th harmonic system operating at the optimum bunch lengthening conditions. This yields quite a flat distribution with a factor of four increase in the FWHM to 1.44 nsec.

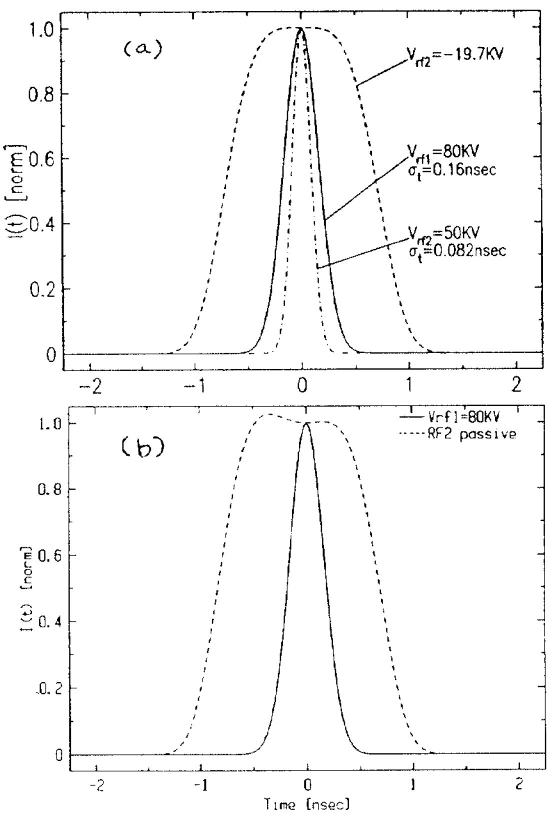

Figure (2) (a) Calculated bunch shape for a single rf system operating with 80KV gap voltage (solid), and with a 4th harmonic system operating at maximum bunch lengthening (dashed) V_4 = 19.7 KV and bunch shortening with V_4 = 50KV (dot-dashed).
(b) Calculated bunch shape for the passive operation of the 4th harmonic cavity at θ_c =+88° and $I_0 \approx$ 850 mA.

For passive operation of the cavity, the beam current frequency component (I_b) at $4*f_{rf}$ generates the voltage for bunch lengthening [6] given by:

$$V_4 = I_b R_{sh} \cos\theta_c \, e^{i(\theta_c - \pi)}.$$

where $\theta_c = \tan^{-1}(-2Q\delta)$ is the cavity detune angle and $\delta = (4f_{rf} - f_c)/f_c$ is the frequency shift from the cavity resonant frequency, f_c with the quality factor Q and shunt impedance R_{sh}. The optimum phase angle requires the cavity to be tuned very inductively with a cavity detune angle of $\theta_c \approx +88°$. With the cavity phase set by this detune angle the optimum bunch lengthening can occur only at one current value. However, this passive operation mode has the advantage that it's simple to implement and doesn't require complicated servo loops to stabilize the amplitude and phase. Figure (2b) shows the bunch lengthening for passive operation at high current. Except for a slight distortion the bunch length is comparable to the optimum.

Powering of this cavity will allow optimum bunch lengthening at all currents. To stabilize the bunch shape and length as a function of current, parameters for this system will need to be adjusted empirically to counter the bunch lengthening due to self fields, as observed in reference [1]. This will be done by giving up the condition in Eq. (1b) and maintaining the symmetric potential Eqs. (1a) and (1c). By shifting the phase of the 4th harmonic voltage $\approx$ 180°, bunch shortening is also possible. Significant bunch shortening is not possible with passive operation since the cavity must operate with $\theta_c \approx -90°$ and the voltage is not very large. Powering the 4th harmonic cavity to V_4 = 50 kV and $4\phi_4$=+90°, yields a factor of two shortening of the bunch as shown in Figure (2a).

3. OPERATIONS WITH THE POWERED HARMONIC CAVITY

During initial operations with the powered harmonic cavity near its optimum bunch lengthening, it proved difficult to achieve stable beam conditions. This was due to phase oscillations of the beam and to higher order modes in the main rf cavity. The latter caused the bunch focusing potential to shift beyond the optimum and develop microbunches within the bunch, as shown in Figure (3).

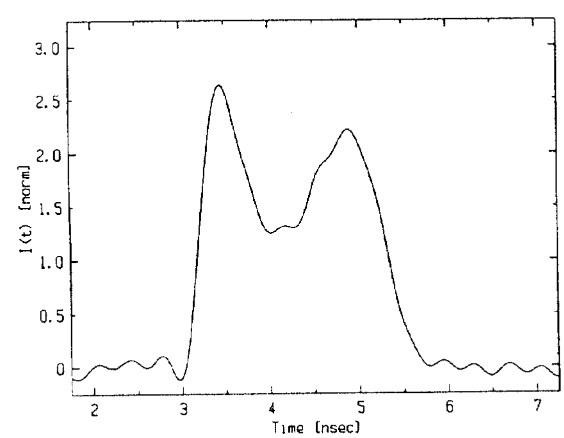

Figure (3) Reconstructed bunch current distribution for one bunch out of a 7 bunch train with the 4th harmonic cavity operating close to optimum bunch lengthening.

In order to deal with this instability, a simplified feedback system was developed which does not reference directly to the beam phase. This system operates with a synchronous phase for the 4th harmonic cavity of $4\phi_4$ = -90°, i.e. the zero crossing of the 211 Mhz gap voltage waveform. Under these conditions there is no net power given to or taken from the beam. A cavity tune servo system compensates for the reactive beam load while an amplitude loop keeps the forward power constant. The beam is kept at the zero crossing by a loop which compares the amplitude of the forward power to the cavity field and adjusts the phase of the 211 MHz drive to keep the powers equal. This requires that the cavity tune be resonant at the drive frequency at zero current. A circulator in the system isolates the reflected power from the drive amplifier. Despite operating at the non-optimum phase, the system provided at least a factor of two increase in the bunch length and lifetime.

Figure (4) shows the reconstructed bunch current distribution [1] for two bunches in an asymmetric train of seven bunches, at two different currents I_o = 760 and 370 mA and with the harmonic cavity powered as described above. Clear differences in the bunch length and shape are observed between the bunches. This results from potential well distortions due to higher order modes in the main rf cavity that are not harmonics of the rf frequency. Since the potential well has been made flatter, with the harmonic cavity operational, these modes have a clearer affect on the bunch shape. Despite the variation between the bunches the FWHM bunch length remains constant to within 15% over this current range.

Shifting the synchronous phase to $4\phi_4$ = +90° and using a similar pair of feedback loops, yields bunch shortening. Although operation with the shortened bunch has not begun, Figure (5) shows the result of a bunch shortening test with about V_4 = 20kV. This yielded a reduction in bunch length from σ_t = 180 to 118 psec for a total current of 188 mA. Additional power is available to reduce the bunch by at least a factor of two.

Future work will continue to explore changes in the feedback loops that could allow increases in the bunch lengthening and stability.

4. ACKNOWLEDGMENTS

This system was made possible by the dedicated efforts of many people in the RF Group especially J. Keane and R. D'Alsace. Some of the early calculations on the stability of this system were performed by J. Wachtel.

5. REFERENCES

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[4] A. Hofmann, S. Meyers, Beam Dynamics in a Double RF System, Proc. 11th Int. Conf. HE Acceler. CERN, p. 610 (1980).
[5] Note the shift of 90° in the definition of potential which simplifies the phase relationship for passive operation.
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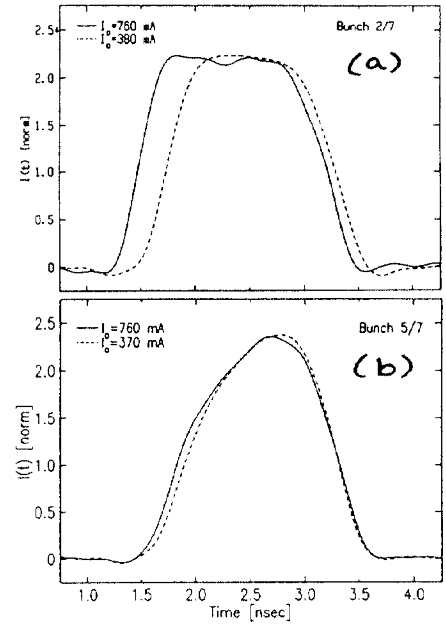

Figure (4) Bunch current distribution for two bunches (No. 2 and 5) in a seven bunch train with the 4th harmonic cavity powered as described in the text. The current distribution is shown for two currents I_0 = 760 and 370 mA, the solid and dashed curves respectively.

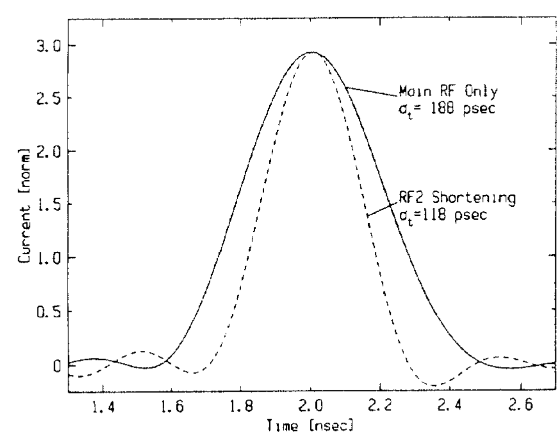

Figure (5) Bunch current distribution measured with the main rf system alone (solid) and with the 4th harmonic cavity powered for bunch shortening (dashed curve).