Slow feedback loops for a Landau cavity with high beam loading

Abstract

Equilibrium bunch shapes for bunches stretched with a higher-harmonic cavity are sensitive functions of beam and RF parameters. This paper gives results of calculations of equilibrium bunch shapes as a function of Landau-cavity voltage and phase and generator voltage and phase. The relationship between the stretched-beam phase and the (slow) feedback controls for the cavity is described and a control system capable of stretching, compressing, controlling the cavity phase arbitrarily (within the limits of the power amplifier), and operating without beam is proposed for use in the NSLS VUV ring. The latter is compared with the existing RF controls for the VUV-ring harmonic cavity [5].

I. INTRODUCTION

The sensitivity of the bunch shapes to the RF-system parameters of a Landau cavity has important implications to the RF controls of the cavity. Small shifts in the potential well shifts the bunch centroid by an exaggerated amount. In particular, shifts in the phase of the harmonic cavity voltage has an amplified effect on the beam phase through shifts in the equilibrium bunch distribution. Since beam loading is high, the effect is large. These effects made their impression on those of us in the RF group that attempted, on different occasions, to implement conventional amplitude and phase control loops. These attempts have resulted in beam-phase drifts in the cavity that were due to insufficient loop gain — the result of the beam loading, high cavity detuning, and, to be described here, the negative feedback resulting from the movement of the equibrium bunch distribution.

The original control system for the powered harmonic cavity, the one that is in use now, has worked remarkably well. There are three loops — the tuning loop, a loop that levels the forward power on the transmission line, and a loop that levels the cavity field by controlling the phase of the forward power. The tuning loop controls the phase of the cavity field relative to the forward wave on the transmission line **??**. The crossed level and phase loops work well with substantial beam loading because of the large beam loading and detuning of the cavity. The shortcoming of the existing system is that it is not able to vary the phase of the cavity over a sufficiently wide range due to the polar nature of the RF modulators and the fact that the cavity tuning is controlled through the incident RF wave on the transmission line. For this reason bunch shapes are not optimal (although bunch shapes are degraded for other reasons as well). In the proposed RF controls the cavity phase may be controlled arbitrarily (within the limits of the power amplifier), the crossed-loop feature is retained and an alternative scheme for the control of cavity tuning used.

The purpose of this paper is twofold. First, results of numerical calculations of bunch shapes as a function of harmonic cavity voltages and phases are shown. (This report assumes the the main-cavity field is fixed: this paper does not consider coherent instabilities.) The movement of the equilibrium bunch distribution and its effect on loop gains in uncrossed control loops is described. Second, a description of a control system capable of stretching, compressing, controlling the cavity phase arbitrarily (within the limits of the power amplifier), and operating without beam is given. Although the proposed system is not in operation it differs from the existing control system in finer details and is a modest extrapolation of our present experience.

Machine parameters are given in table I. A circulator is present on the harmonic-cavity transmission line.

II. BUNCH SHAPES OF STRETCHED BEAMS

In this section is considered the relationships among the generator current, cavity field, bunch shape, and bunch phase. In figure 1 is shown schematically these relationships. Branch A produces the bunch shape from the potential well determined by the cavity field. B is the Fourier transform and determines the beam-current phasor from the bunch shape (and centroid). D is cavity impedance giving the cavity field when multiplied by the total current in the cavity.

In the first part of this section branch C is cut in the sense that shifts in the beam phase are not transmitted although the fixed beam phasor is. Later, this branch is restored and the feedback provided by this branch is discussed. Now we consider branch D of figure 1 where beam loading unaffected by the harmonic-cavity field is the issue.

Due to the high beam loading, large detuning of the cavity is used [3] for compensation. As a result, the detuning angle Θ is large and the cavity largely cross-couples amplitude and phase. The component of the generator current that most strongly influences the cavity phase is the amplitude. The phasor diagram of figure 2 illustrates how the generator-current phase has little effect on the cavity phase.

Semi-quantitatively, in terms of the change in the generator-current phase $\delta\Psi_{I_g}$ and the beam loading parameter $Y = I_b R/V = 1/\cos\Theta$, the change in the cavity phase is

$$\delta\Psi_V = \delta\Psi_{I_T} \simeq (\delta I_g/I_b)^2 \simeq (\delta\Psi_{I_g}/Y)^2, \tag{2.1}$$

where the last approximate equality becomes an equality when the $\Psi_V = \Psi_{I_g} = -90°$. This equation expresses the quick rate at which beam loading reduces the influence of the generator phase on the cavity phase.

Similarly, figure 3 illustrates how the magnitude of the generator-current phasor most strongly influences the phase of the cavity voltage and hence the beam phase. In this case the generator current influences the cavity voltage as

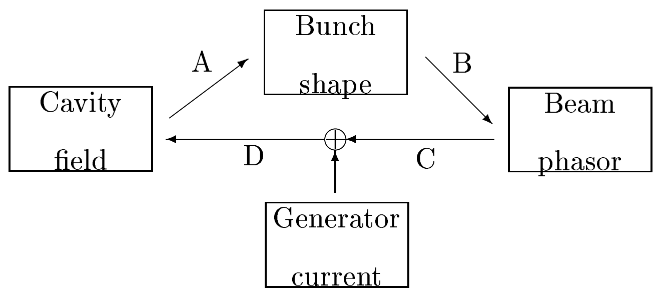

FIG. 1: Influences among the generator, cavity field, bunch shape, and beam phase.

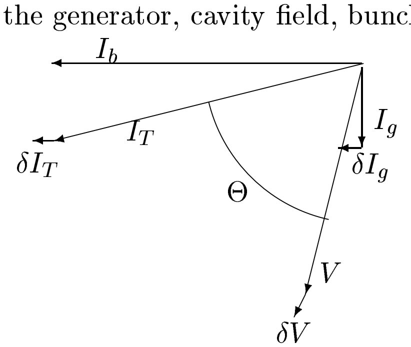

FIG. 2: Phasor diagram for the cavity voltage V, beam current I_b, generator current I_g, and total current I_T. The detuning angle Θ of the cavity is defined as the phase of $1/Z$. Responses of the cavity and beam to a change δI_g in the phase of the generator-current phasor are shown. The beam current is held fixed in spite of the small change in the cavity phase and the nominal generator current is set to $-90°$.

$$\delta\Psi_V \simeq \delta I_g/I_b \simeq \frac{1}{Y}\frac{\delta I_g}{I_g} \tag{2.2}$$

Now consider branch A of figure 1 where the sensitivity of stretched bunch shapes on cavity phase is considered. In the case of a stretched beam the bunch shapes [2] are a sensitive function of the harmonic cavity field—in particular the phase—when the bunches are optimally stretched. To see this, if the harmonic-cavity phase is shifted so that the voltage lags a small amount, the voltage is shifted upward locally. Since the waveform is locally flat, this shift moves the synchronous phase along the voltage waveform so that it leads the original bunch phase by an amount large compared to the original phase shift. The amount of the beam phase shift depends on the intrinsic energy spread in the beam.

In figure 4 is shown calculated bunches shapes for the VUV ring for the optimally

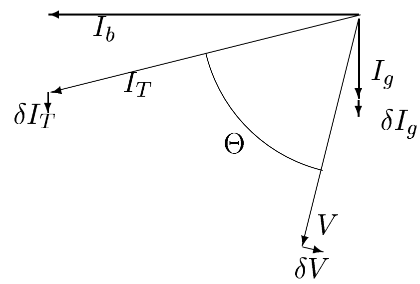

FIG. 3: Phasor diagram for the cavity voltage V, beam current I_b, generator current I_g, total current I_T, and detuning angle Θ and their responses to a change δI_g in the magnitude of the generator-current phasor. In this illustration the beam current is held fixed in spite of the change in the cavity phase.

stretched operation and in figures 5 and 6 the cavity phase has been shifted by -2° and $+2^\circ$, respectively. In the last two, the bunches are shifted by $\pm 9^\circ$.

Near the optimal harmonic-cavity field, the cavity phase shifts the beam phase by the factor -4.5. Since the beam phase shift opposes the shift in the cavity phase, branch C of figure 1 provides negative feedback from the beam to the cavity field and hence a mechanism by which perturbations of the cavity phase are suppressed. This is to say, e.g., that a perturbation of the generator current affecting the phase of the total current is largely cancelled by the shift in the beam's contribution to the total current in the cavity.

To see why the shift is negative consider the effect of a slight delay in the harmonic-cavity voltage. Because the slope of the harmonic-cavity voltage with respect to phase is positive (opposite the main-cavity field), the total RF voltage at the nominal phase is reduced. In order for the beam to remain synchronous it must shift positively in phase (earlier arrival time) to find a synchronous voltage. This occurs because, although the slope of the voltage is zero at the nominal phase, the voltage to second order in phase requires an earlier arrival time. Furthermore, because the slope of the total voltage is zero at the nominal phase, a large shift compared the cavity-phase shift results. So, the shift in beam phase is opposite the cavity phase shift and of larger magnitude.

An estimate of the degree to which this cancellation occurs, in the limit that $|I_b| \ll |I_g|$ and I_g is approximately orthogonal to I_T, goes as follows. One expresses the perturbation in the phase of the cavity voltage $\delta\Psi_V$ as

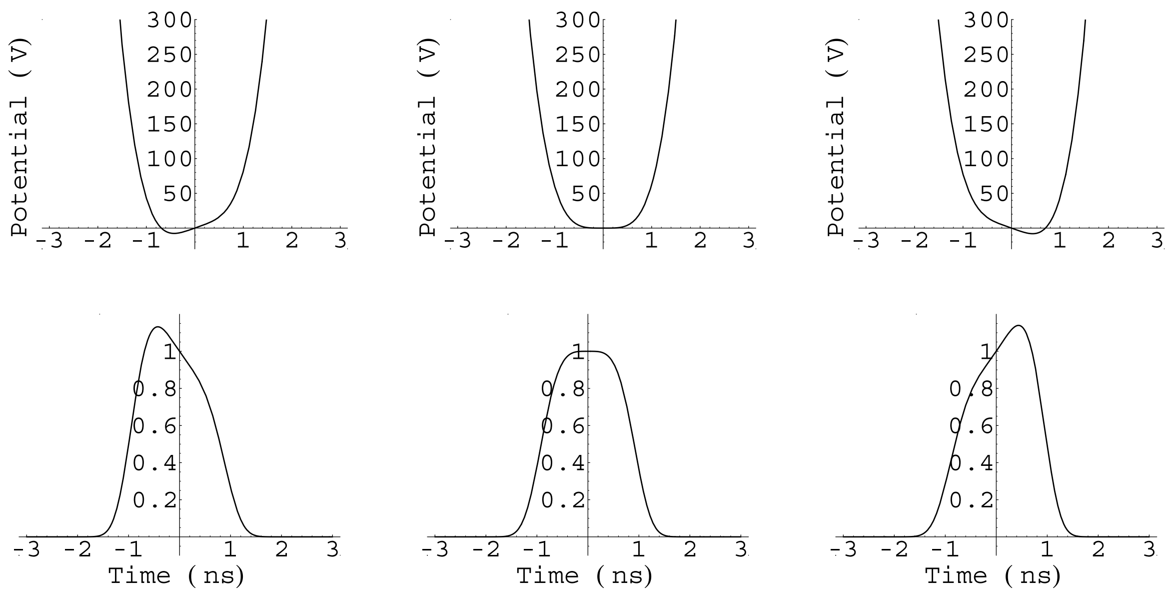

FIG. 4: Voltages (left), potential wells (center), and bunch shapes (right) for optimally stretched conditions. VUV energy spread is used in the bunch-shape calculation.

$$\delta\Psi_V = \delta\Psi_{I_T} \tag{2.3}$$

$$\simeq \delta\Psi_{I_b} + \delta\Psi_{V0} \tag{2.4}$$

$$\simeq G\delta\Psi_v + \delta\Psi_{V0}, \tag{2.5}$$

where Ψ_x is the phase of x, G is the phase multiplication factor obtained from figures 4, 5, and 6, and $\delta\Psi_{V0}$ is a shift in the phase of the cavity field that would be present in the absence of a shift in the beam phase, such as in equations 2.1 and 2.2. Solving this last equation for $\delta\Psi_V$, we have

$$\delta\Psi_V \simeq \frac{1}{1-G} \times \Psi_{V0}. \tag{2.6}$$

Thus, combining equations 2.1, 2.2, and 2.6, we have

$$\delta\Psi_V \simeq \frac{1}{1-G} \times \frac{1}{Y} \times \left(\frac{\delta\left|I_g\right|}{\left|I_g\right|} + \frac{1}{Y}\delta\Psi_{I_g} \right). \tag{2.7}$$

In summary, beam-loading dilution and the bunch-shape negative feedback reduce the effect of the generator current on the cavity phase and beam loading dilution reduces the effect of

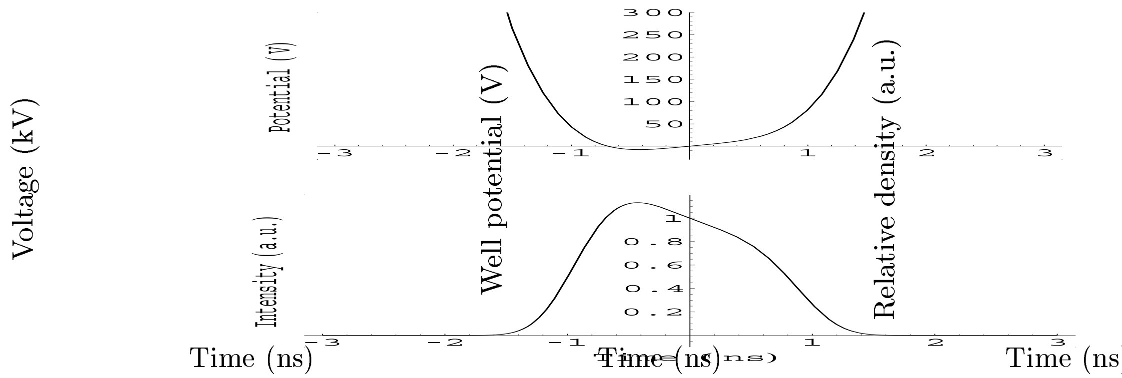

FIG. 5: Voltages (left), potential wells (center), and bunch shapes (right) with the harmonic cavity phase shifted by $-2°$. VUV energy spread is used in the bunch-shape calculation. The phase of the bunch is shifted by $9.1°$ from the nominal.

the generator-current phase beyond that of the generator-current amplitude. Note that, in the above discussion, the cavity voltage is fixed.

At this point is considered the fact that there is a circulator between the amplifier and the cavity. Assuming that the circulator is ideal, the quantity directly controlled by the input of the amplifier is the transmission-line forward-wave amplitude, where the forward-wave and reverse-wave amplitudes are functions of I_g and V defined by

$$a = \frac{1}{2}\left(\frac{V}{\sqrt{Z_0}} + I_g\sqrt{Z_0}\right) \tag{2.8}$$

$$b = \frac{1}{2}\left(\frac{V}{\sqrt{Z_0}} - I_g\sqrt{Z_0}\right), \tag{2.9}$$

where Z_0 is the impedance of the transmission line. (These quantities are normalized so that $|a|^2/2$ and $|b|^2/2$ are the powers carried in the forward and reverse directions.) In contrast, in the previous discussion the parameter controlled by the amplifier input is assumed to be the generator current I_g. It is not obvious that the earlier conclusions regarding the control of the cavity field using I_g transfers to the forward-wave amplitude. To show that the preceeding discussion is not qualitatively changed, in figure 7 are plotted contours of constant cavity voltage, beam current, and detuning on the complex-a plane. One can see in detail how the forward-wave phasor must change to generate varying cavity phases at cavity voltages near the optimal voltage. Even at 100 mA beam current the influence of the

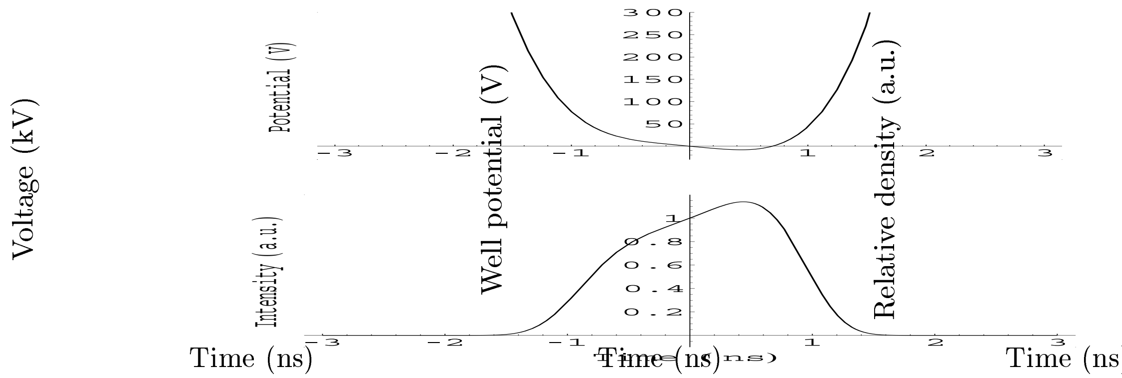

FIG. 6: Voltages (left), potential wells (center), and bunch shapes (right) with the harmonic cavity phase shifted by 2°. VUV energy spread is used in the bunch-shape calculation. The phase of the bunch is shifted by $-9.1°$ from the nominal.

forward-wave phase on the cavity phase is almost completely suppressed.

III. HARMONIC CAVITY CONTROLS

In this section is discussed the requirements of the control system for the harmonic cavity. Several major functions the system is required to perform are

- normal stretched operation,
- bunch compression,
- passive operation for injection, and
- offline or low-current operation.

In figure 8 is shown the basic configuration for normal (stretched) operation. In this configuration (and all active configurations) a complex-phasor modulator (CPM) is used to control the drive to the amplifier. The reason for this is that control through cartesian coordinates is more appropriate for this problem where the forward amplitude a must be able to go near zero into different quadrants of the complex-a plane.

Ordinary envelop detection is used to sense the cavity voltage and provide feedback to a_r; phase detection is through a mixer. The phase of the beam is used to generate the phase

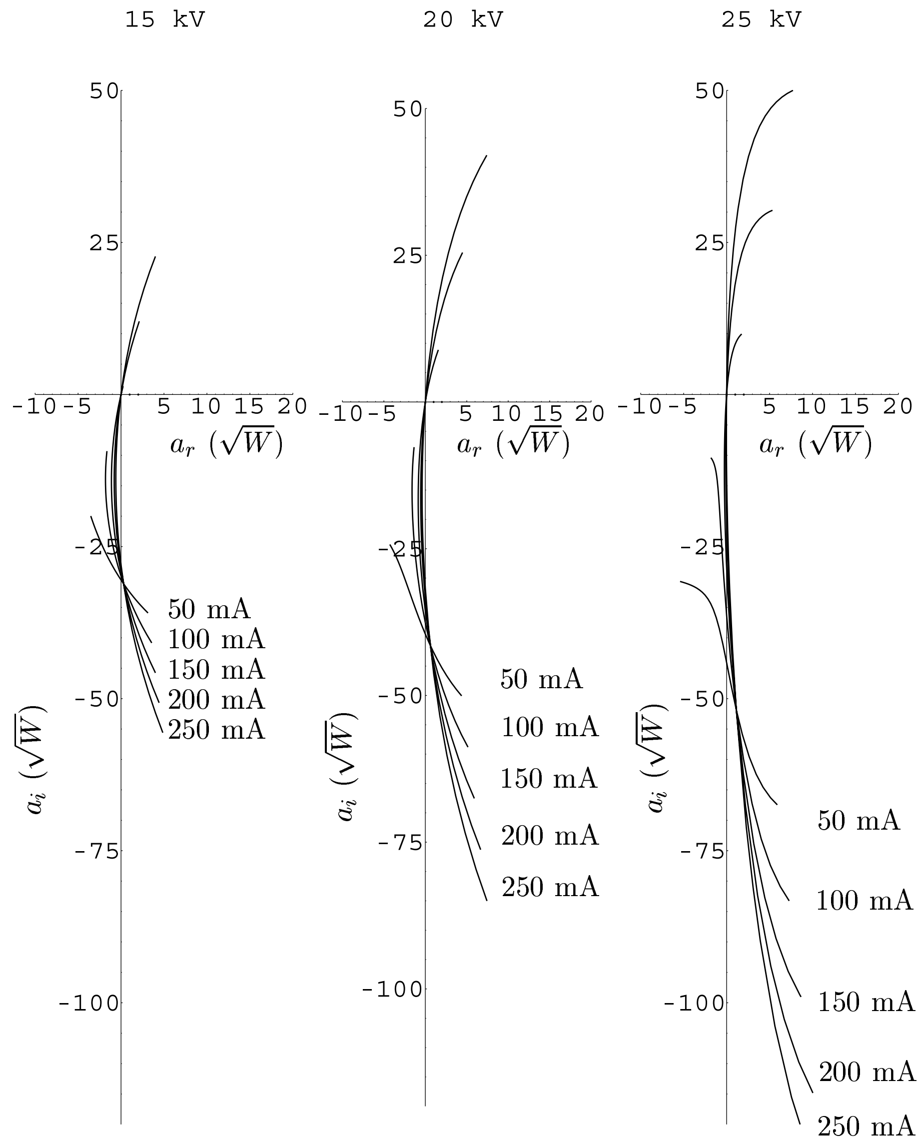

FIG. 7: Contours of constant cavity voltage on the generator-current (I_g) plane for the VUV ring. The cavity phase is swept along each curve from $-100°$ to $-85°$ (top to bottom). The effect of the cavity voltage on stretched beam phase and the beam phase on the cavity field are included in this calculation.

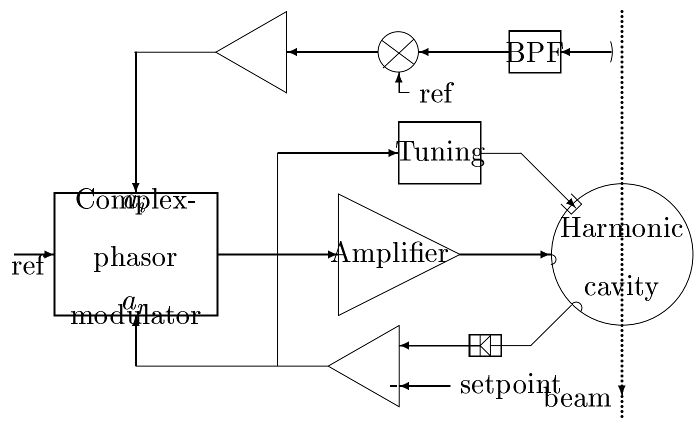

FIG. 8: Configuration of the harmonic-cavity rf system for normal (stretched) operation. BPF is a band-pass filter centered on the RF frequency that filter out other rotation harmonics of the beam.

error instead of the phase of the cavity. There are two reasons for doing this. The first is that the bunch-phase amplification factor G provides additional gain undoing the gain loss of the $1/(1-G)$ factor of equation 2.6. The second is that the beam phase is the quantity that needs to be regulated; it has the best chance of maintaining optimal bunch stretching.

Cavity detuning for beam-loading compensation is handled differently than in the usual method of detuning for beam-loading compensation [3]. In the usual method the tuning error signal is derived from the phase between the cavity field and the forward wave on the transmission line. This method is not applicable here because it is required that tuning control operate when the forward wave is zero. Consequently, this alternate method for beam-loading compensation is proposed. In this method the tuning block of figure 8 is required to move the cavity resonant frequency upwards for a given sign of a_r and limit the detuning to the high side of the rf frequency (this by some [possibly ambiguous] measure of the detuning). In this way the modulation amplitude a_r is kept at zero and the phase of a at $-90°$. In figure 9 is shown the forward amplitude and required power incident to the cavity for the tuning scheme described and to maintain the optimal stretching.

In figure 10 is shown the configuration for compressed operation. There are two main differences between the compressed and stretched configurations. The first is that, in bunch compression, the cavity phase is used as feedback in contrast to the use of beam phase in stretched operation. With beam-phase feedback in compressed mode the gain factor G is reduced to less than one so the gain advantage of beam feedback is no longer there. It

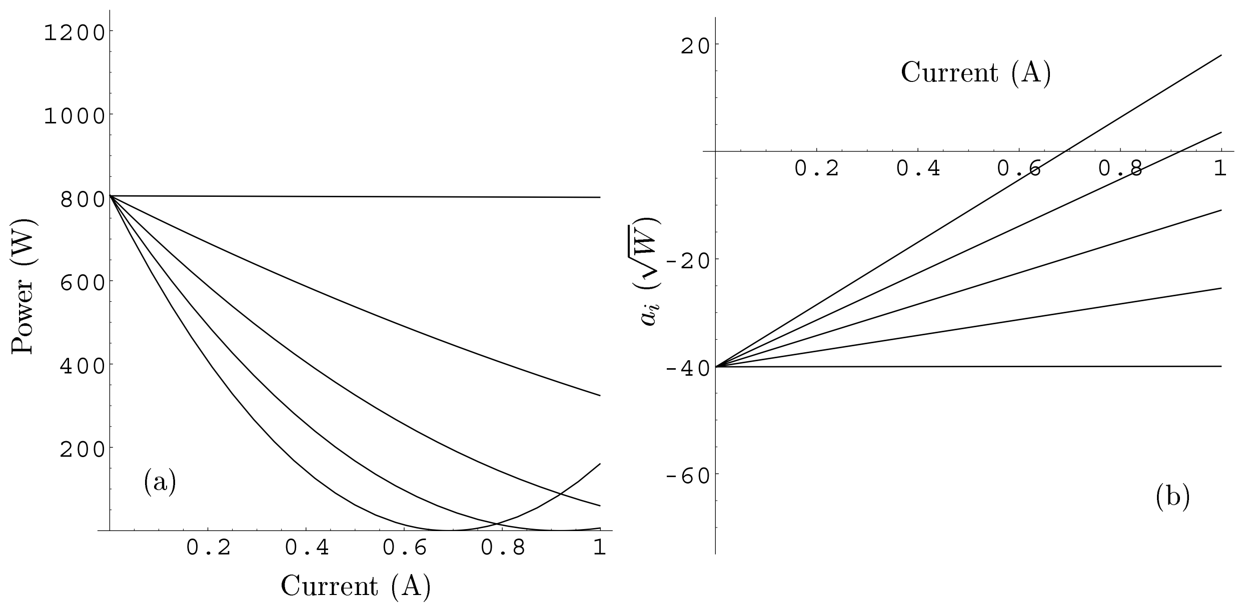

FIG. 9: Forward amplitude a_i and forward power required for nominal stretching as a function of beam current.

is preferable to use the cavity phase. The other difference is in the tuning control. In compressed mode tuning control is required to move the resonant frequency in the opposite direction and to confine the resonant frequency to the low side of the RF frequency.

In figure 11 is shown the configuration of the RF controls in passive operation. In this configuration the RF drive is switched completely off and one servo loop is used to level the RF field in the cavity. This is done by detuning the cavity sufficiently, when there is sufficient beam current, to provide the correct field in the cavity. The resonant frequency of the cavity must start near the RF frequency so that the beam excites the cavity. Passive operation in the compressed or stretched mode is determined by the tuning control as described for powered (active) operation. Passive operation is used during injection.

The transition to from passive to active operation occurs as follows. After the ring is filled and ramped the harmonic cavity control systems is switched to active. At this time there is a jump in the operating point of the CPM that brings the cavity phase to the optimum for stretching (when stretching). In this state a_i jumps to a new value and a_r becomes nonzero. In response to the latter condition the cavity tuning shifts to bring a_r to zero. When this is completed the CPM is at its normal active operating point.

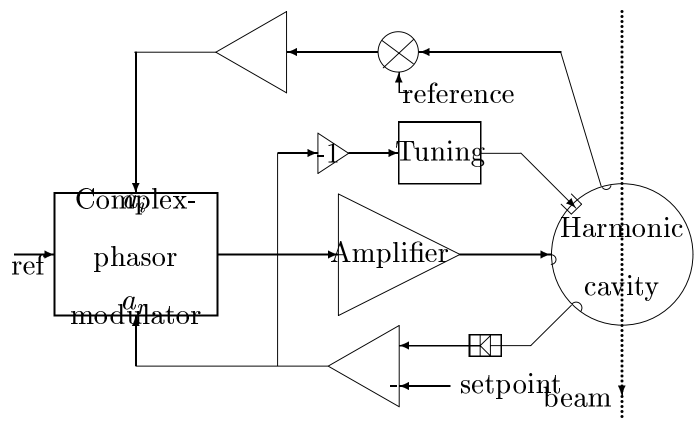

FIG. 10: Configuration of the harmonic-cavity rf system for compressed-bunch operation.

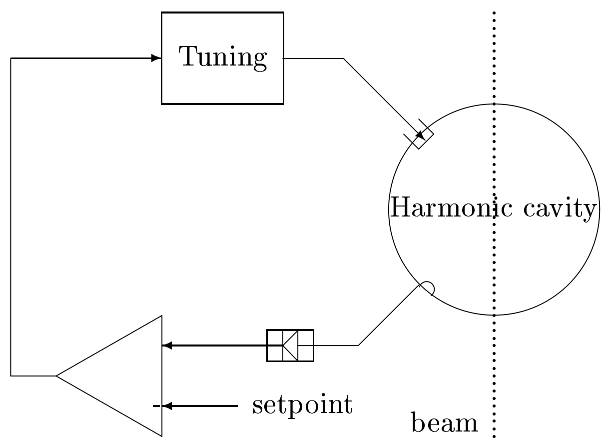

FIG. 11: Configuration of the harmonic-cavity rf system for passive operation.

Offline operation with cavity voltage levelled can be done with the configuration of figure 12. Here the cavity is tuned approximately on resonance. Open-loop operation can be done by applying constant or modulated signals to the a_r and/or a_i inputs of the CPM.

In figure 13 is shown the complete configuration for the system. This configuration can control the cavity phase arbitrarily within the power limit of the power amplifier.

The procedures to set phase shifters D1, D2, and D3 are described. Procedures for the setup of other elements of the system, such as autotune and RF signal levels, must also be done but are not described here.

- In passive mode (P), stretched mode (S), and with the ALC setpoint set to 250 W, seven-bunch beam is injected to 300 mA.

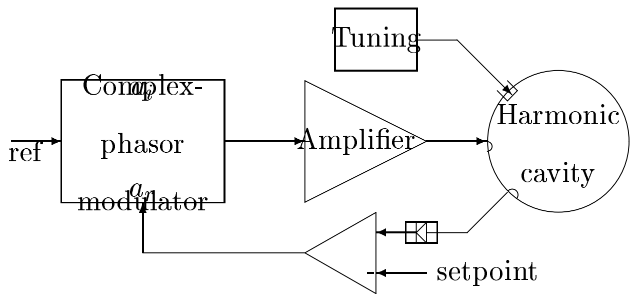

FIG. 12: Configuration of the harmonic-cavity rf system for offline operation.

- Delay D2 is set so that, with the passive setpoint M set to give 250 W of forward power, the autotune phase reads zero. The forward and cavity diagnostics should read approximately the same.
- Delay D1 is used to give a null in the output of the mixer. The correct slope is determined by other details of the system. With the wrong slope, the loop will run away when it is closed.

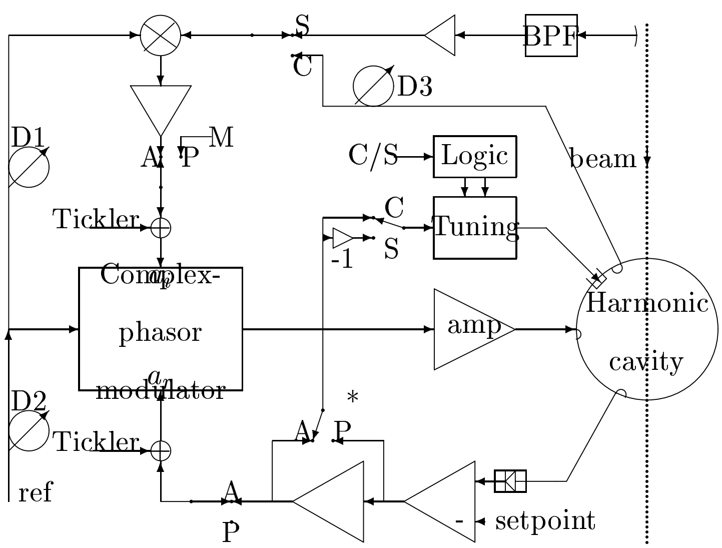

FIG. 13: Completed configuration for the harmonic-cavity control system. For the switch positions, 'A' represents active, 'P' represents passive, 'C' represents compress, and 'S' represents stretch. The ticker inputs are intended for open- and closed-loop gain measurements only. The active/passive switch marked with the asterisk selects a lower level-loop gain for the passive mode.

- With the autotune system set to manual so that the tuning does not change, switch to compress and adjust delay D3 to give a null in the mixer output with the same slope.
- With additional current one adjusts D1 so that, using bunch shape measurements, seven-bunch bunch shapes are optimal.

IV. CONCLUSIONS

The main result is that large changes in generator amplitude is required to vary the cavity phase significantly, a result known previously. The generator phase has only a weak effect on the cavity phase, even at currents below 100 mA. This occurs, not only because of the diluting effect of beam loading, but also because of negative feedback on perturbations of the cavity phase provided by the beam sloshing in a shallow potential well. These results explain the our repeated inability to implement stable conventional amplitude and phase control loops in the harmonic system. The control system proposed here includes the cross-coupled amplitude and phase control loops present in the existing control system.

This control system, intended to be slow compared to the coherent motion, has some new features. It provides passive and active operation for both stretched and compressed modes. Arbitrary cavity phases can be maintained, within the limits of the power amplifier. Cavity tuning does not require use of the forward wave on the transmission line. Beam phase has the best potential for maintaining optimal bunching and is used for phase-loop feedback. In compressed mode the cavity phase is used. Detailed plans for the new system are available and a construction timetable was drawn up.

External connections are available for making quick and easy open- and closed-loop gain-phase measurements. This may seem like a trivial point but it plays a pivotal role for the future evolution of the controls towards later upgrade to DSP- (digital signal processing) based controls where model validation is essential. As things stand there is no evolutionary path available in this operating RF system towards these methods where a quantum jump in the performance of the system may be made. This is why I consider the upgrade proposed here (and others like it) essential if we are to work towards the use of DSP-based methods in the RF system.

RF feedback applied to the harmonic system would ordinarily be useful for reducing the effect of beam loading of the cavity. However, it is not useful for the VUV harmonic cavity because the high loop delay limits the gain and bandwidth of the loop to the extent that at high current the detuning is large enough that there is little gain available, 14 dB without and 20 to 25 dB with gain equalization [6], at the RF frequency. Furthermore, since the maximum detuning required is 300 kHz (compressed) the RF-loop phase shift must track the detuning to remain stable. This considerably complicates the design of the controls.

V. ACKNOWLEDGEMENTS

J. Byrd

REFERENCES

[1] M. Sands, Laboratoire de l'Accélérateur Linéaire Report No. LAL-RT-2-76, 1976 (unpublished).

[2] Sands, M., "The Physics of electron Storage Rings: An Introduction", SLAC Report No. SLAC-0121 (UC, Santa Cruz), Nov 1970.

[3] A. Gamp, in *Proceedings of the 1991 CERN/RAL Accelerator School* p. 396-415, Oxford, England, (Cern, 1991); see also W. Broom, J. M. Wang, "Reactive Robinson Instability in the NSLS X-Ray Ring", BNL Report 62789 (1996).

[4] F. Pedersen, IEEE Trans. Nuc. Sci., Vol. NS-32 No. 5, p. 2138 (1985).

[5] R. Biscardi, S. L. Kramer, and G. Ramirez, Nuclear Instruments and Methods in Physics Research A 366 p. 26-30 (1995).

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TABLE I: Values of VUV ring, cavity parameters and symbols used in the text.

parameter	symbol	value
Beam energy	E_0	$= 800$ MeV
Energy loss per turn	U_0	$= 20.4$ keV
Momentum compaction	α	$= 0.0245$
Revolution frequency	ω_0	$= 2\pi \times 5.8763$ MHz
RF peak voltage	V	$= \simeq 20$ kV
RF harmonic number	h	$= 36$
RF mode normalized impedance	R/Q	$= 60/2\ \Omega$
Unloaded Q (including HOM loads)	Q_0	$= 7{,}900$
Unloaded harmonic-cavity impedance	R	$= 237$ kΩ
Input-port standing-wave ratio	κ	$= 1.36$