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DAMPING THE Π-MODE INSTABILITY IN THE SLC DAMPING RINGS WITH A PASSIVE CAVITY*

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1 INTRODUCTION

Operating the Stanford Linear Collider (SLC) at 120Hz repetition rate requires the presence of two bunches in both the electron and the positron damping ring. The π-mode instability, a coupled bunch instability where the two bunches oscillate with a phase difference of 180°, had been observed in both rings with low current thresholds of $7*10^9$ particles per bunch. To avoid the instability, the RF system had to be operated in ways which in general reduced the cavity gap voltages and required constant operational attention. For the 1992 running cycle a passive cavity was installed and successfully tested. It is tuned to the frequency of the lower synchrotron oscillation sideband of an odd revolution harmonic. The impedance of the cavity then damps π-mode oscillations very similar to the Robinson damping provided by the main RF cavities which damps 0-mode synchrotron oscillations. In this report we describe the motivation and physical considerations that led to the final design parameters and the experience obtained from the performance of these cavities.

The longitudinal coupled bunch instability arises in the Damping Rings due to the coupling between the normal modes of the 2 bunch system and the higher order cavity modes. A schematic of the electron damping ring with its slightly asymmetric bunch spacing is shown in Figure 1, the positron damping ring has symmetric bunches. The 2 cavities diametrically across from each other are powered by a single RF source. That decouples RF manipulation from the normal mode in which the 2 bunches execute synchrotron oscillations with opposite phases. Table 1 sums up the relevant machine and RF parameters of the damping rings.

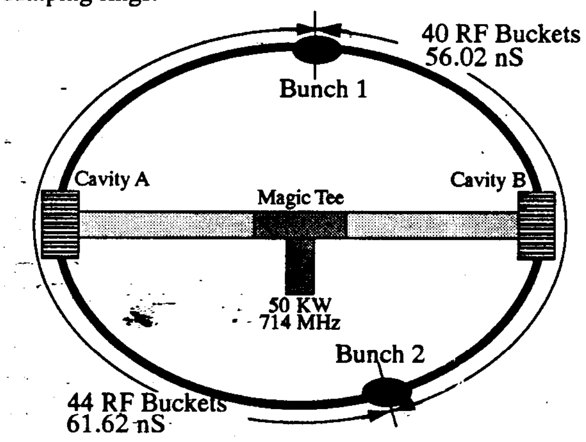

Figure 1 Electron Damping Ring Configuration

Table 1. Damping Ring Main RF Parameters

Momentum compaction (α)	0.01814	
Revolution frequency	8.5	MHz
Energy	1.15	GeV
Particles per bunch	5 & 5	10**10
Harmonic number	84	
Unloaded Q	24000	
Coupling factor (β)	2.5	
Synchronous angle	10	degree
Cavity detuning angle	68.3	degree
Shunt impedance	17.5	MΩ
Generator power/cavity	25.0	kW

For two evenly spaced bunches, impedance at the higher synchrotron oscillation sidebands of odd harmonics of the revolution frequency drives the π-mode instability. Such instability was demonstrated in Figure 2, which displays a damping ring position monitor located at a high dispersion point picking up the growing amplitude in the energy oscillations throughout the cycle. The signals from individual bunches are added (upper trace) or subtracted (lower trace) to manifest the 0-mode and the π-mode. The frequency is aliased by the digital scope we used. It is seen that as the growth in the π-mode progresses, there is an accompanying growth in the 0-mode. Very similar phenomenon has been observed in our simulation program, caused by the nonlinearity in the RF potential. The zero mode in turn reaches a limiting value due to Robinson damping /1/. The rise time of the instability was estimated to be of the order of 1 ms.

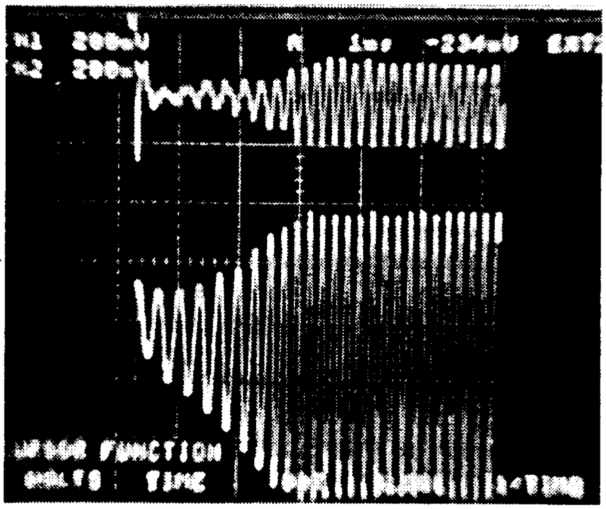

Figure 2 0-mode (upper trace) and π-mode oscillation in a store cycle (8.3 ms)

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Since the hardware configuration of the damping ring RF made it nearly impossible to feed back on the π-mode oscillations with the help of the main cavities, we decided to install an additional idling cavity. P. Wilson had calculated the damping provided by such a cavity to be:

$$\frac{1}{\tau_d} = \frac{N_{pc}}{N_h} \cdot \frac{V_{br}\,\omega_s}{V_c \sin\phi} \cdot \frac{-\xi\,\eta}{[1+(\xi+\eta)^2]\,[1+(\xi-\eta)^2]}$$

where

$$\xi = -\tan\psi = (n\,\omega_0 - \omega_r)T_f\,, \quad \eta = \omega_s T_f$$

and

N_{pc} : harmonic number of passive cavity
N_h : harmonic number of main cavity
V_{br} : beam induced voltage
V_c : peak RF voltage
ϕ: synchronous angle
ω_s : synchrotron frequency
ψ : cavity tuning angle
T_f : $2\,Q_0/\omega_r(1+\beta)$
ω_0 : revolution frequency
ω_r : cavity resonant freque
β : cavity coupling factor

2. IDLING CAVITY DESIGN PARAMETERS

To be confident of damping the π-mode oscillation it was decided to build idling cavities capable of damping growth rates of 100 μs, 10 times faster than the observed rate. The size of the cavities was restricted by the amount of space available in the damping rings. To maintain the aperture of the damping rings the bore of the cavities had to be 2 inches. Using URMEL, we designed a single cell cavity with nose cones having a Q of 15000 and shunt impedance of 1.8 MΩ (see Figure 3). This design provided damping times of less than 50 μs. Two tuners in different locations were included to allow differential tuning of higher order modes. Two RF probes allow voltage monitoring and power input if necessary.

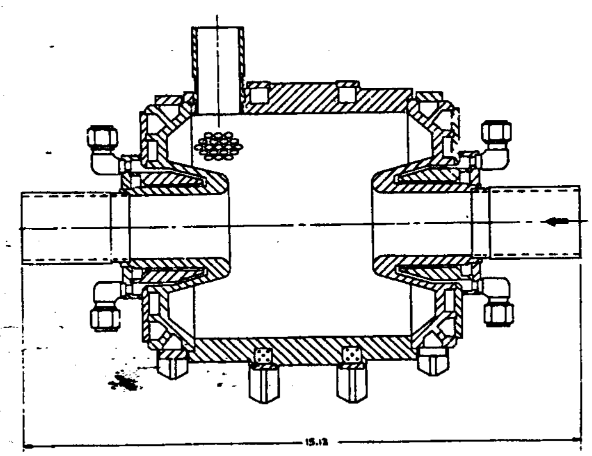

Figure 3 Cross section of cavity.

The cavity frequency was determined by the uneven bunch spacing in the electron damping ring (Figure 1). This spacing is required by the frequency of the SLC injector sub-harmonic buncher. The positron damping ring has equal bunch spacing allowing any odd harmonic to be used to damp the π-mode. The frequency spectrum I(S) of the two unevenly spaced bunches can be calculated by summing the two impulse trains from each bunch with the appropriate delay.

$$I(S) = [1 - e^{-i2\pi(61.62\times10^{-9})S}]\left[\frac{III}{8.5\times10^6}\left(\frac{S}{8.5\times10^6}\right)\right]$$

The last term is a "comb" function producing impulses at 8.5MHz intervals. This function is perturbed by the first term, which is the result of the bunch spacing/2/. Figure 4 shows the relative amplitudes of the odd and even harmonics.

The frequency for both cavities was chosen to be 1062.4 MHz, where the amplitude of the odd harmonic is at minimum and the amplitude of synchrotron sidebands due to the π-mode oscillation is maximized.

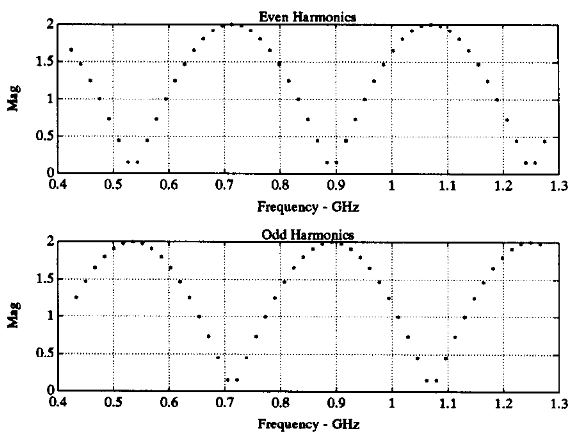

Figure 4 Bunch Spectrum in Electron Damping Ring

The thermal design was challenging due to the fact that the rings are sometimes operated with a single bunch. Under this condition each 8.5 MHz harmonic carries large amounts of power. If the cavity were erroneously tuned exactly to a beam harmonic instead of the synchrotron sideband, 28 KW could be dissipated in the cavity (Figure 5 and Table 2). We decided to design the cavities to withstand all possible operating conditions.

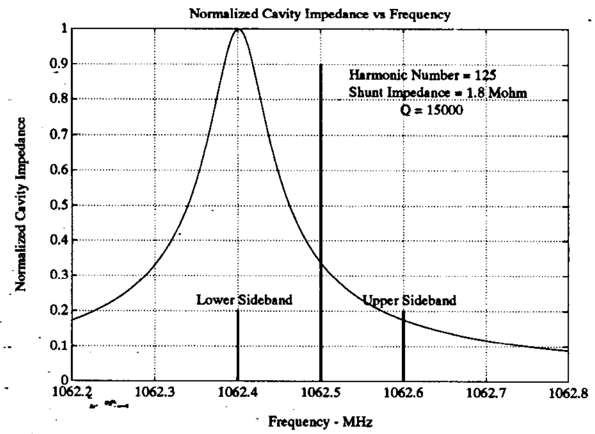

Figure 5 Cavity Impedance and Bunch Spectrum

Table 2. Cavity Power for Various Conditions

Number of Bunches	Normal Power	Maximum Power
($6x10^{10}$ particles per bunch)		
1	3.1 KW	28.4 KW
2	270 W	2.5 KW

Thermal calculation based on URMEL data were performed using the finite element analysis package IDE-AS.The initial design was entirely inadequate, having a maximum temperature of 370° C. The final design incorporating a novel high velocity nosecone cooling configuration in conjunction with end cap, annular body, and tuner cooling circuits requiring a total of 15 GPM. Maximum temperature was reduced to 145° C at the tip of the nosecone.

Fabrication of the cavities required some advanced operations including electrical discharge machining (EDM) of the inner nosecone cooling passages. A frequency shift later attributed to a slight distortion of the nose cones by the high pressure cooling water was observed. Hardening the annealed copper before pressure testing will be considered for future cavities.

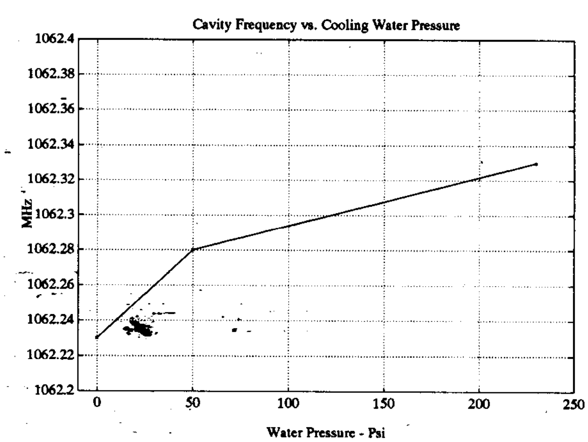

Figure 6 Cavity Tuning by Water Pressure

3 COMMISSIONING

The commissioning of the π-mode cavities was as unspectacular as it was successful. After installation, they were tuned to the desired frequency of 1062.4 MHz. The frequency was monitored with a network analyzer while it was adjusted with the manual tuners. Remotely controlled tuners were installed at a later time.

The π-mode instability disappeared immediately. To check the stability of the cure, we varied the main cavity temperature and RF frequency in both rings.

Changing the RF frequency moves the revolution harmonic and its synchrotron side bands underneath the impedance curve of the idling cavity and ultimately renders it ineffective or even driving the instability. The RF frequency could be moved in both rings by more than 60 kHz, before the instability was detected. That corresponds to changing the idling cavity's frequency by that amount multiplied with the ratio of the harmonic numbers. The following table list the results:

	Idle Cavity Frequency [MHz]	Equivalent Upper Frequency Shift [kHz]	Equivalent Lower frequency Shift [kHz]	Equivalent Stable Frequency Range [MHz]
NDR	1062.42	+90	-107	1062.31-1062.51
SDR	1062.38	+148	-90	1062.29-1062.53

Changing the temperature of the main RF cavities varies the frequencies of their higher order modes, which are the main driving force of the π-mode instability. These temperatures could be changed by more than +/- 5 degrees F, which exhausts our adjustable range, without any sign of instability. Since the damping ring cooling water temperature is stable within +/- 1 degree F, the result is more than sufficient.

The frequency of the cavities drifted in the first weeks by about a hundred kHz (see the previous chapter), so the tuners had to be adjusted a few times.

4 REFERENCES

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