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TRANSIENT BEAM LOADING AND RF POWER DISTRIBUTION IN THE SSC*

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E.C. Raka
AGS Department, Brookhaven National Laboratory
Associated Universities, Inc., Upton, New York 11973 USA

Introduction

Transient beam loading will occur in the SSC at injection as the fifteen individual batches from the High Energy Booster are loaded box-car fashion into the main rings. Periodic transient beam loading will be present also at injection due to the gaps between the successive batches as well as the gap that remains to be filled. Even after the rings have been "filled" there will remain the abort gap of 3.1 μsec. This can produce significant modulation of the phase and amplitude of the rf voltage seen by those bunches immediately following it unless corrective measures are taken. Two different methods of reducing this modulation will be discussed, each of which put certain requirements on the rf power distribution system.

Periodic Transient Modulation Effects

First we will calculate the maximum amount of phase modulation that a bunch will see due to the 3.1 μsec abort gap while in the storage mode. We shall ignore the effects due to the much smaller gaps between successive groups of bunches injected from the HEB. The following parameters will be used in our calculation; $Q_\ell = 10^4$; $R_s = 1.25$ MΩ/gap; β(coupling) = 3; $I_b = 73$ mA; $V_{gap} = 500$ kV $= V_c$. Then, if one had every sixth bucket filled, the simple diagram shown in Figure 1 would hold (ignoring the effects of synchrotron radiation losses). Here

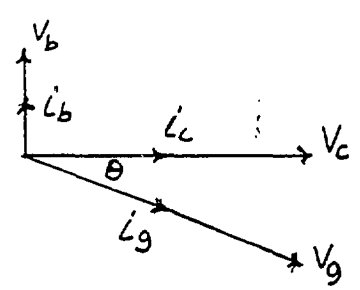

Fig. 1

V_c is the total gap voltage, V_b the beam induced voltage, V_g the generator voltage as it appears across the accelerating gap and θ the angle between V_c and V_g. We have assumed that the cavity(ies) are tuned on resonance with f_{rf} as is proposed in the CDR. Then $\tan\theta = V_b/V_c$ which would be $2 \times 0.074 \times 1.25 \times 10^6 \div 0.5 \times 10^6 = 0.37$. The AGC loop would keep V_c constant and the phase and radius (frequency) loops would control θ. However, by design neither of these loops would have any response at f_0 (3.614 KC) or its harmonics. Hence, they could not correct for transient effects, i.e., the fact that i_b the beam current contains components at f_0 and its harmonics as well as at the nominal bunch frequency of 62.45 MHz and its harmonics plus sidebands at multiples of f_0.

In order to calculate the effect of the 3.1 μsec gap, we need $\tau_c = 2Q_\ell/\omega_{res}$ for an individual cell of the five-cell cavity. We obtain $\tau_c = 2 \times 10^4 / 2\pi\, 374.74 \times 10^6 = 8.5$ μsec so that the beam induced voltage will decrease to 182.5 kV $e^{-3.1/8.5} = 126.7$ kV or $\Delta V_b = -55.75$ kV. From Figure 1 it can be shown easily that the change in the angle θ seen by the first bunch after the abort gap will be $\delta\theta \cong \Delta V_b/V = -0.111$ rad. Thus, if uncorrected, this bunch will oscillate at this amplitude in synchrotron phase space or with an amplitude $\delta Z = 1.4$ cm in real space. Since $\sigma_z = 7.3$ cm at 20 TeV, this modulation at ω_s is not small and would show up as a modulation of the beam-beam interaction. One can calculate the approximate change in V_c for this bunch. We find $\Delta V_c = 15.5$ kV or $\Delta V_c/V_c \cong 0.03$ which in principal could result in a coherent quadrupole oscillation of the bunch. We note that since $\tau_c \ll \tau_0 = 276.7$ μsec the above analysis is very close to the actual steady state case.

Before we discuss the correction schemes, let us consider the periodic transient case at injection after the first batch has been accepted. The slow phase, radial, and amplitude loops act as if this batch represents the entire ring. The beam induced voltage will vary from essentially zero to 182.5 kV $(1 - e^{-18.1/8.5}) = 161$ kV, since $\tau_c \ll (276.7 - 18.1)$ μsec where we assume the batch length is 18.1 μsec not 17.5 as given in the CDR[4] (this keeps the abort gap at 3.1 μsec and the spacing between batches at 0.15 μsec). This means that θ for the bunches would vary over a range of 17.8° if not corrected. The corresponding momentum error would be $\Delta p/p = 0.115 \times 10^{-3}$, while the bucket height at injection with 20 MV is 0.75×10^{-3}. We note that this momentum error is more than seven times greater than the 1.5×10^{-4} error the longitudinal injection damping system is designed to correct for.

Transient Correction Methods

We consider first the use of fast feedback loops to control the phase and amplitude of the cavity voltage seen by the individual bunches. As pointed out by Kerns and Flood,[1] the principal parameters that will determine the loop performance are the time delay and the transfer function of the cavity for phase or amplitude modulation. We use the standard low pass analogue representation of the cavity for phase or amplitude modulation $(1/1 + s\tau_c)$, which is valid if there is no detuning. The time delay is

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made up of the propagation delay of the waveguide between the klystrons and the cavities, the signal delay from the sensing electronics to the klystron and its driver plus the delays in the circuits themselves. If the total delay is τ_d, the one can show[1] that the maximum d.c. gain is limited to $A_{max} = (\pi/2)(\tau_c/\tau_d)$. In order to provide suitable damping of a transient, the open loop gain must be reduced to $A_o \cong (2/3)\ \tau_c/t_d$.[1] Since $\tau_c = 8.5$ µsec, we consider $\tau_d = 1$ µsec as a possible value for the time delay. This leads to an $A_o = 5.67$ or $(A_o + 1) = 6.67$ and hence a reduction in phase or amplitude modulation transients by the same factor.

We note that if the coupling were reduced so that $\beta = 2$ then $R_s = (5/3) \times 10^6\ \Omega$, but $\tau_c = 11.33$ µsec. Then we would have $\delta\theta = 0.116$ rad at 20 TeV, but the loop gain could be increased so that the reduction factor would be 8.56 for a net gain in error reduction of 18% over the $\beta = 3$ case. It is evident that the usefulness of this method depends critically upon minimizing the time delay τ_d around the feedback loop. This implies relatively short runs for the power distribution waveguides and wide-band circuitry to process the error signals and modulate the drive and phase to the 1 MW klystrons.

Next, we shall discuss the so-called feedforward correction method.[2] The signal from a single pick-up electrode is filtered to obtain the frequency components of the beam current at $f_{rf} \pm k_{fo}$ where $k = 1, 2, \text{---}\ k_m$ with $k_m \gtrsim 2\ f_{rf}/Q_\ell f_o$ say. Hence, with $\beta = 3$, $Q_\ell = 10^4$, $f_o = 3.614$ KC; $f_{rf} = 374.7$ MHz; $k_m \gtrsim 21$. This signal after appropriate delay and amplification is summed with the rf signal necessary to produce the required V_c in the absence of beam loading. Its phase is adjusted to inject a current into the cavity opposite to i_b so that the net beam induced voltage is zero. As can be seen from Figure 1, the total required generator voltage or current remains the same, i.e., $\|i_g^2\| = \|i_b^2\| + \|i_c^2\|$, but the slow phase and amplitude loops control only that part if i_g corresponding to i_c. Hence, in addition to compensating for the periodic transient beam loading, this method removes the coupling between these loops. In order for the former to occur, the time delay between pickup and cavity must be equal to the transit time of a bunch between the same two points on the ring. Whether a one-turn delay or some fraction of τ_o is employed would depend upon a detailed design study. In any event, this method would require a modification of the proposed rf power distribution system which will be discussed below.

Since the feedforward method is open loop, there could be not coupled interaction with the longitudinal injection error damping system or the bunch-to-bunch dipole and quadrupole mode damping systems proposed for the SSC. The compensation will not be perfect, but one should be able to keep the residual phase and amplitude modulation effects small enough so that these other closed loop systems could reduce the remaining errors to the noise level. The fast phase and amplitude loops on the other hand could possibly interact both with the main phase and amplitude loops as well as with the other damping systems referred to above. Any such interaction could, of course, be taken into account in the overall system design and should not represent a significant limitation.

RF Power Distribution

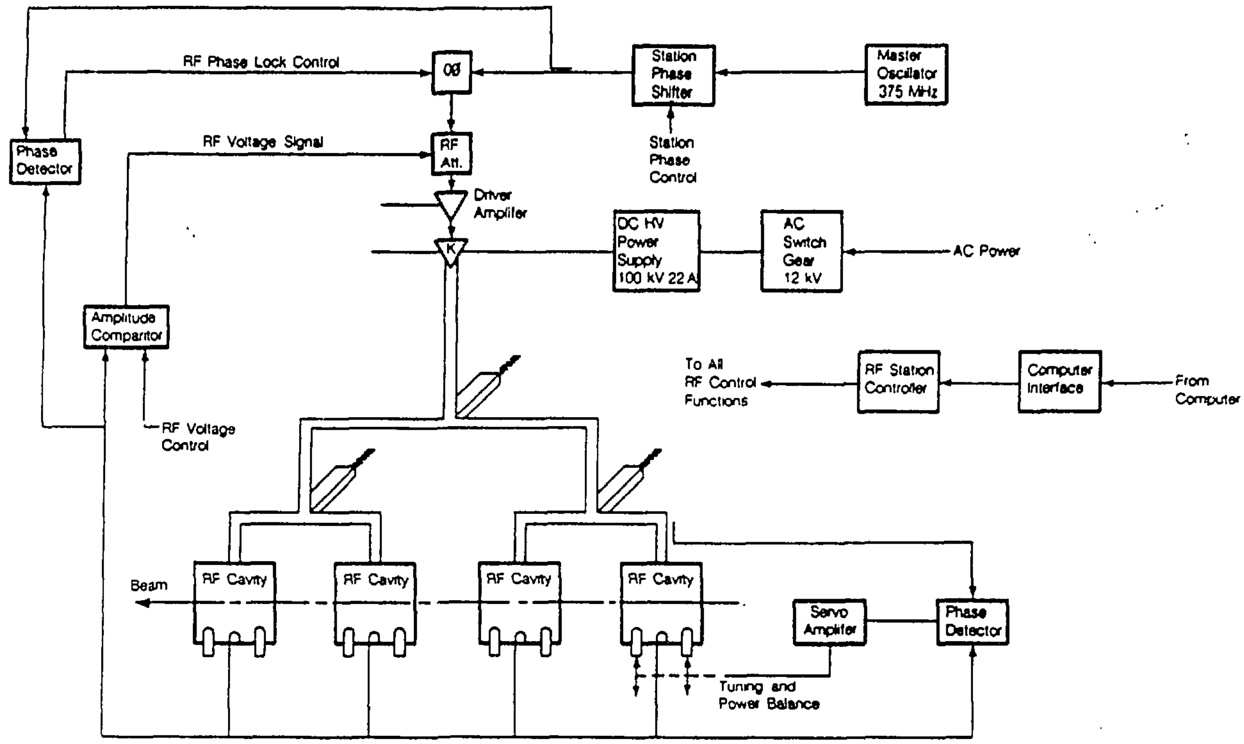
Figures 2 and 3 taken from the CDR[4], show the proposed rf power distribution system. Magic T's are used to split the power from a single klystron so as to feed four five-cell cavities. In Figure 3, which is to scale, one finds that the ends of the cavities are 5 $\lambda/4$ apart where $\lambda = 0.8$ m and since each cavity is 5 $\lambda/2$ long, the spacing between the centers of a pair of cavities is 15 $\lambda/4$. If one adjusts the length of the feed lines from the magic T nearest to the cavities so that they differ by $\lambda/4$,[3] then the reflected power from the two cavities will be absorbed in the load connected to the 0° port (the feed in this case is at the 180° port, i.e., the two lines to the cavity are 180° out of phase). This scheme can be used with the fast feedback loop compensation method. However, it is not suitable for the feed-forward method because the signal delay could only be matched to the beam delay at one cavity. The distribution system sketched in Figure 4 would solve this problem at the expense of furnishing a circulator at the input to each cavity. The latter is necessary to absorb the reflected power since it would no longer be possible to arrange the phasing so as to have the reflections from a pair of cavities cancel each other. One could then use ordinary power splitters to divide the drive signal. In principle, there is not tight limitation on propagation delay for this system since one has overall a time budget that could be as large as τ_o. However, if only a fraction of τ_o is to be used, then again the length of the waveguide run should be minimized.

Conclusion

Transient beam loading in the SSC can be compensated using existing techniques. However, the implementation of a given method will put certain restrictions on the design of the rf power distribution system. The choice of which scheme to use will, of course, have to await detailed design studies.

References

1. Q. Kerns, W. Flood, Proc. IEEe Trans. on Nucl. Sci., Vol. NS-12, June, 1965, pg. 58.
2. D. Boussard, Proc. IEEE Trans. on Nucl. Sci., Vol. NS-32, No. 5, October, 1985, pg. 1852.
3. M.A. Allen, H.D. Swarz, P.B. Wilson, Proc. IEEE Trans. on Nucl. Sci., NS-30, No. 4, August, 1983, pg. 3447.
4. SSC Conceptual Design Report, SSC-SR-2020, March 1986.



Master circuit diagram of rf system, indicating servo-loops to stabilize the amplitude and phase of the cavity fields.

Figure 2

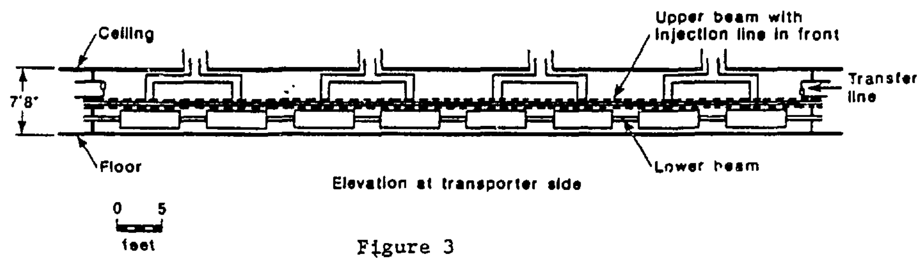


Figure 3

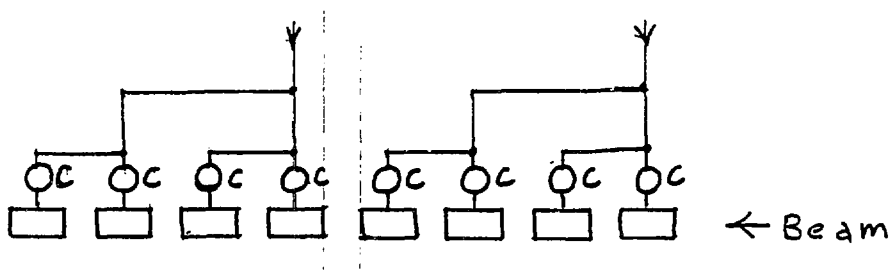


Figure 4

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