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# RF BEAM LOADING IN THE BROOKHAVEN AGS WITH BOOSTER INJECTION*

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## ABSTRACT

Multi-batch bunched beam loading during injection from the Booster to the AGS will be discussed. The full intensity beam injection to the upgraded AGS rf system with beam phase and radial feedbacks will be studied. It is shown that a beam phase feedback is necessary in order to guarantee a predictable beam behavior after the first batch injection, otherwise the initial phase deviation for the following batch injections cannot be controlled. However, the effectiveness of the phase feedback control of the transient beam loading may be limited by an associated emittance blow up in the process. It is shown that a fast power amplifier feedback with a moderate gain can significantly reduce the transient effect of the bunched beam injection.

## 1. INTRODUCTION

The operation of the AGS with beam injection from the Booster will result in two changes in its mode of operation. One is that the proton beam intensity at the AGS will be increased from 1.5 x $10^{13}$ to 6 x $10^{13}$ per cycle, and another is that the AGS ring will directly receive the bunched beam from the Booster. One of the possible problems is the repetitive transient beam loading during batched beam injection into the AGS.

The AGS rf cavities and power amplifier will be upgraded to accommodate the increase of the beam intensity by reducing the shunt impedance and introducing fast feedback of the power amplifiers. During the period of 1992 to 1994, however, the existing AGS rf system still has to be used. Therefore, it is of interest to understand the performance and limitations of both the old and the new rf systems under multi-batch beam injection from the Booster into the AGS.

In Ref. [1], the general static and transient beam loading effect has been discussed. In this note, repetitive transient beam loading of the AGS during injection will be discussed. The notations and the results in Ref. [1] will be followed and used in this note.

Table I lists the beam and rf parameters for the old and the upgraded AGS rf systems at injection.

Table I. AGS BEAM-LOADING PARAMETERS

| FUNCTION | NOTATION | OLD | NEW | UNIT |
|---|---|---|---|---|
| RF Frequency | f | 4.2 | 4.2 | MHz |
| RF Voltage Amplitude | V | 32 | 40 | kV |
| Loaded Cavity Quality Factor | Q | 21 | 19 | 1 |
| Cavity Capacitance | C | 82 | 175 | pF |
| Loaded Cavity Shunt Resistance | R | 9.7 | 4.2 | KΩ |
| Generator Current Without Beam | $I_{Go}$ | 3.3 | 9.52 | A |
| Beam Fundamental Current | $I_B$ | 7.91 | 7.91 | A |

The AGS rf harmonic number is 12, and there are 10 rf cavities in the AGS ring. The parameters shown are for each cavity. In this study, the number of protons in one bunch, *n*, is assumed to be 0.75 x $10^{13}$, 50 percent larger than the design number. It is assumed that the tuning and AVC loops will be in operation in order to guarantee a proper working condition for the generators and cavities. The generator current in the absence of beam, $I_{Go}$ = V/R, is important in determining the beam loading effect for a given beam current.

## 2. FULL INTENSITY BEAM INJECTION IN THE UPGRADED AGS RF SYSTEM

The full intensity beam injection in the AGS rf system is of interest, not only because it will be a typical operating condition in the future, but also that the resulting beam loading parameters under this condition are very close to that of the proton beam injection to the existing rf system with the intensity of 2 x $10^{13}$. Before the fast power amplifier feedback is available, the beam phase feedback and the beam radial feedback will provide control of the repetitive transient beam loading effect.

It takes four batch injections to fill the AGS ring. Since the cavity detuning condition will be changed from one injection to another, each batch injection has to be treated separately.

## 2.1 First Batch Injection

In Ref. [1], the beam loading effect from the beam current to the induced beam phase deviation, $\Delta\phi$, is described by,

$$\Delta\phi = Z_1(s)Z_{01}I_{B0} , \qquad (1)$$

where $I_{B0}$ represents the injected beam current, which is shown in Figure 1 for the periodic beam injection at the AGS. The transfer function $Z_1(s)$ represents the dynamic aspect of the effect,

$$Z_1(s) = \frac{\sigma}{s + \sigma} , \qquad (2)$$

where $\sigma$ is the half bandwidth of the cavity,

$$\sigma = \frac{1}{2RC} . \qquad (3)$$

The scaling factor $Z_{01}$ is determined by the generator current, it can be simplified as follows,

$$Z_{01} = \frac{1}{I_{Go}} \qquad (4)$$

under the assumption that the stable phase $\phi_s$ is small, and $I_B \leq I_{Go}$.

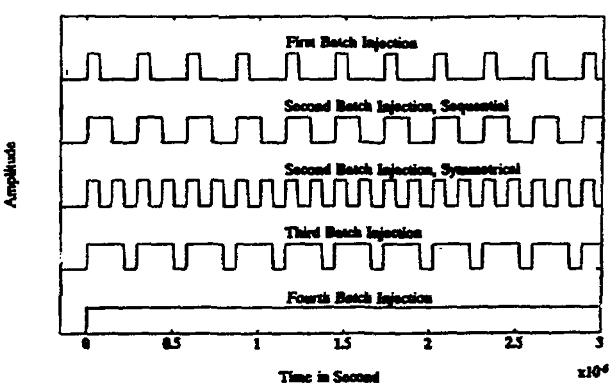


Figure 1. Waveforms of $I_{B0}$ for various batch injections.

With beam phase and radial feedbacks, the model of the beam loading is shown in Figure 2, where $\Delta R$ is the beam radius deviation[2]. In the absence of amplifier fast feedback, $K_0$ is set to 0 in Figure 2. At injection, the beam dynamic parameters are a = $1.89 \times 10^6$ and b = -74. The loop encircling b/s, a, and 1/s represents the synchrotron oscillation, the loop encircling $Z_1(s)$, $k_1$, and 1/s is the phase feedback, and the loop encircling $Z_1(s)$, b/s, $k_2$, $k_1$, and 1/s is the radial feedback. *In the case of choosing* phase feedback gain $k_1 = 4 \times 10^4$, and radial feedback gain $k_1k_2 = 12 \times 10^6$, the resultant radius deviation as a function of time under three conditions is shown in Figure 3. Effects on the phase deviation can also be calculated.

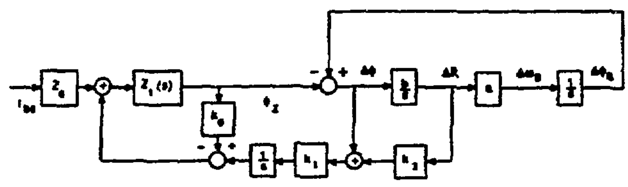

Figure 2. Model of transient beam loading, with fast feedback and phase plus radial feedback.

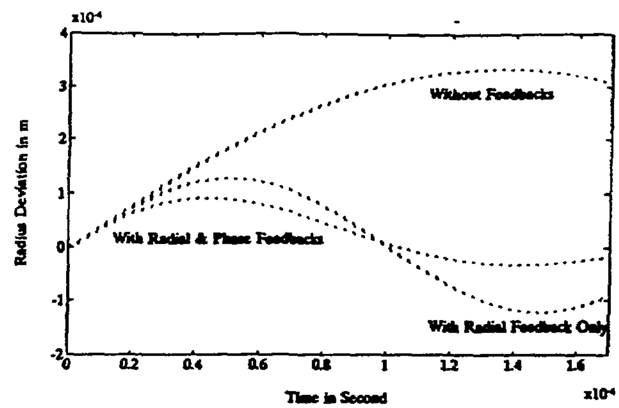


Figure 3. Beam radial deviation under various feedback conditions.

## 2.2 Second Batch Injection

Before the second batch injection, the rf cavities have been detuned by the tuning loop. The detuned angle is,

$$\phi_{Z1} = \tan^{-1}\left(\frac{I_{B1}}{I_{Go}} \cos\phi_s\right) , \qquad (5)$$

where $I_{B1}$ is the averaged fundamental component of the beam current due to the first batch injection.

Similar to Equation (1), the second batch injection will affect the beam phase deviation by,

$$\Delta\phi = Z_2(s)Z_{02}I_{B0} . \qquad (6)$$

The dynamic aspect of the transfer function, $Z_2(s)$, is the same as the transfer function of the voltage amplitude of the detuned cavity to the beam current, which can be shown to be [3],

$$Z_2(s) = \frac{\alpha s + \sigma^2(1 + \tan^2\phi_{Z1})}{s^2 + 2\alpha s + \sigma^2(1 + \tan^2\phi_{Z1})} . \qquad (7)$$

Since the cavity impedance with the detuning angle $\phi_{Z1}$ becomes,

$$Z = R \cos \phi_{Z1} e^{-j\phi_{Z1}} , \qquad (8)$$

the cavity voltage amplitude is changed by a factor of $\cos\phi_{Z1}$ for the same beam current. Again, a small stable phase $\phi_s$ is assumed, then it can be shown that if the beam current is comparable to $I_{Go}$. The scaling factor for the second batch injection becomes,

$$Z_{02} = \frac{\cos^2\phi_{Z1}}{I_{Go}} . \qquad (9)$$

The radius deviation of the sequential injection, i.e., the second batch is located adjacent to the first injected batch, and the symmetrical injection, i.e., the second batch is placed diametrically opposed to the first batch, are shown in Figure 4. It is shown that the radius deviation is about 2 mm at the end of 30 μsec for both cases. The calculation also shows that the phase deviation is about 20 degrees for both cases. Under the influence of the phase feedback, the initial beam phase deviation before second batch injection is at -7 degrees. Without phase feedback, this initial phase deviation will be large and varying, resulting in unpredictable beam loading behavior after second batch injection. Therefore, a phase feedback is needed for repetitive beam injection at the AGS.

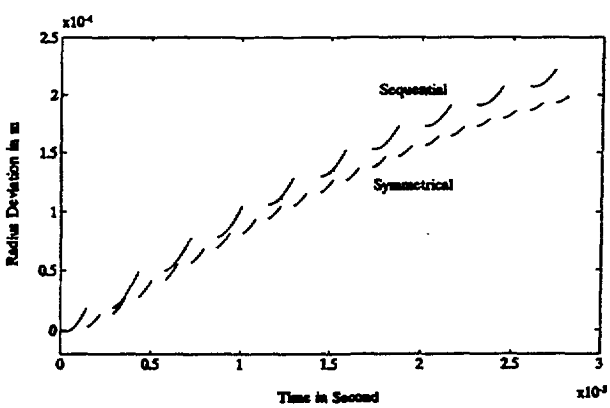


Figure 4. Beam radial deviations under second batch sequential and symmetric injection.

Additional repetitive transient beam loading effects on the third and final batches have also been calculated and the maximum radius deviation is found to be about 5 mm and that the phase deviation is about 25 degrees.[4]

## 3. FULL INTENSITY INJECTION WITH FAST POWER AMPLIFIER FEEDBACK

From the above analysis, it is clear that phase and radial feedback alone cannot solve the transient beam loading effect of periodic batch injection from the Booster. The fast feedback of the power amplifier has to be introduced. The model of the beam loading effect with the fast power amplifier feedback is shown in Figure 2, where $k_0$ is the fast feedback gain.

Following the same method shown above to study the beam loading effect of the repetitive beam injection, with a moderate fast feedback gain of 5, the situation is significantly improved. The beam phase deviation is now reduced to 5 degrees and the radius deviation is reduced to 0.5 mm for the first batch injection. Furthermore, the beam loading effects of subsequent injections can also be controlled to this low level without accumulative effect. It is clear that fast feedback is the ultimate solution to the transient beam loading effect caused by the periodic injection from the Booster. The only limiting factor is the time delay which has to be kept to below 150 nsec to provide sufficient damping. Fast feedback will be implemented in 1994 with the AGS rf upgrade.

An obvious means to reduce the beam loading effect is to increase the gain of the phase feedback, $K_1$. It is shown in [2] that under a rapid change of the beam phase deviation $\Delta\phi$, the rf bucket will move rapidly in the energy axis. This motion produces a displacement of the bunches in the bucket, and it is proportional to the phase feedback gain. It is calculated in [4] that under the above chosen $K_1$, the fourth batch injection will produce a bunch motion in the bucket up to 55% bucket half height. Therefore, there is an upper limit for the phase feedback gain, $K_1$. Alternatively, a narrow band feedforward[5] compensation signal ($f_{rf}$ only) can be added. This could actually reduce the necessary phase loop gain, as well as the beam radial excursions.

## 4. REFERENCES

[1] S.Y. Zhang and W.T. Weng, Static and Transient Beam Loading of a Synchrotron, BNL Informal Report AGS/AD/92-1 (1992).

[2] S.Y. Zhang and W.T. Weng, Topics on RF Beam Control of a Synchrotron, BNL Informal Report AGS/AD/92-3 (1992).

[3] F. Pedersen, Beam Loading Effects in the CERN PS Booster, IEEE Trans. on Nucl. Sci. NS-22, 1906-1909 (1975).

[4] S.Y. Zhang and W.T. Weng, Analysis of Periodic Transient Beam Loading of the AGS, BNL Informal Report AGS/AD/92-2 (1992).

[5] D. Boussard, Control of Cavities with High Beam Loading, Proc. IEEE Particle Accel. Conf., p. 1852, Vancouver, BC (1985).

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