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Longitudinal damping rates in RHIC

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Introduction

It has been proposed to damp the longitudinal oscillations of individual bunches arising from injection errors in time or energy by a pulsed wideband cavity system that deliver a fixed amplitude kick [1]. Such a system could also control coupled bunch instabilities arising from parasitic resonant mode present in the storage and accelerating cavities. We shall discuss the damping rate for injection errors assuming a 2 KV kick that can be applied once per revolusion and the instability growth rate that such a kick could control.

Injection Error Damping

D.P. Deng in RF Technical Note 17 [2] has shown that for a 0.2 ev sec/amu gold bunch and a $10^{-4}(\Delta p/p)$ injection error or 0.13 rad (7.6°) phase error the resulting phase space dilution would be the same for a 1 KV or 5 KV kick. Hence he concluded that a 1 KV kick would be necessary to keep the resulting dilution below 10%. If we double the bunch area to 0.4 ev sec/amu then the decoherence time would be reduced by $\approx \sqrt{2}$ and one would have to increase the damping rate to keep the dilution under control. It seems safe to assume that if the kick is increased to 2 KV then the resulting dilution will still be less than 10%.

We note that a 10^{-4} error in $(\Delta p/p)$ for Au will be damped in 0.027 sec with a 2 KV per turn kick. This would insure that if the bunches are extracted from the AGS at a 30 Hz rate with phase or momentum errors $\leq 10^{-4}$ only a single kicker would be required.

For protons the decoherence time $\Delta t = \pi/\Delta\omega_s = 1/2\Delta f_s$ is 0.29 sec for a 0.5 ev sec bunch area. ($\Delta\omega_s = \omega_{s0}\hat{\varphi}\delta\hat{\varphi}/4$ with $\delta\hat{\varphi} = \omega_{rf}\eta\delta p/p\omega_{s0}$). At injection ($\gamma = 31$) the 2 KV kick would also damp a $(\delta p/p)$ error of 10^{-4} in 0.029 sec. Since the error would be eliminated in 1/10 the decoherence time very little phase space dilution would occur.

The injection parameter for the Au beam have been revised [3]. It is now assumed that the bunch area could be as large as 0.5 ev sec and in order to minimize additional area growth due to IBS the injection voltage will be raised to 600 KV the maximum available. This will require bunch rotation in the AGS prior to extraction. With an area of 0.5 ev sec, 600 KV and an injection error of 10^{-4} in $\delta p/p$ we obtain a $\Delta\omega_s = 0.0236\omega_{s0}$ or a decoherence time Δt of 0.12 sec. This should be compared to the 0.15 sec value for a 0.2 ev sec bunch at $V_{rf} = 185$ KV obtained in reference 2 where a 1 KV kick was found to be sufficient to minimize bunch dilution. Since a 2KV kick would reduce a 10^{-4} error in < 0.03 sec the ratio of damping time to decoherence time is even more favorable here. Hence again dilution should be minimal.

Coupled Bunch Instability Damping

Since the pulsed cavity system waveform would have a longer fall time than rise time, i.e., not symetric it can only be used to damp dipole bunch oscillations. A second limitation as far as controlling coupled bunch oscillation modes is the once per revolution kick rate. Thus the effective damping rate will be $1/N$ that of a true bunch to bunch damper with a 2 KV capacity. Here N is number of bunches whch in RHIC would be at most 120.

Now the rate of change of momentum at injection is given by ($\beta \approx 1$) (for protons),

$$\left(\frac{\Delta \dot{p}}{p}\right) = \frac{V_d f_0 D}{E} = \frac{2\times10^3 \times 78.2\times10^3 \times 6.37}{31\times0.938\times10^9} = 3.4\times10^{-3}/\text{sec}$$

where V_d is the kicker voltage, f_0 the rotation frequency and $D = 0.637 = \overline{|\sin\varphi|}$ since the amplitude of the kick does not change (for proportional damping $D = 0.5 = \overline{\sin^2\varphi}$). The value of 3.4×10^{-3}/sec will be the same for Au at injection. Now on a per turn basis one would have $(\Delta p/p) = 3.4\times10^{-3}/78.2\times10^3 = 4.34\times10^{-8}$/turn.

Next let us consider a bunch oscillating with a growth rate α, i.e.

$$\Delta p/p = \left(\frac{\Delta p}{p}\right)_0 e^{\alpha t}$$

or

$$(\Delta\dot{p}/p) = \alpha\,(\Delta p/p)_0\, e^{\alpha t}$$

where $(\Delta p/p)_0$ is some initial amplitude which can be detected. Since $\Delta r = X_p(\Delta p/p)$ where $X_p = 1.5$ M at most, then the minimum detectable $(\Delta p/p)_0$

depends upon the Δr resolution of a radial pickup electrode. We shall assume this to be 20 microns [3] so that $(\Delta p/p)_0 = 20 \times 10^{-6}/1.5 = 1.33 \times 10^{-5}$. We note that this would correspond to a phase amplitude of

$$\delta\hat{\varphi} = \frac{\omega_{rf}}{\omega_{s0}}\left(\frac{\Delta p}{p}\right)_0 = \frac{28 \times 10^6}{45} 8.73 \times 10^{-4} \times 1.33 \times 10^{-5} = 7.2 \times 10^{-3}\text{rad}$$

or 0.4° at the injection voltage of 196 KV or 0.32° at 300 KV accelerating voltage. This is well below the anticipated 1° of phase error resolution at 28 MHz. Hence a position error measurement on a bunch to bunch basis is desirable. We note that at 300 KV for Au at injection $\delta\hat{\varphi} = 0.75°$.

Returning to bunch oscillations we would have for $\alpha = 1 \text{ sec}^{-1}$

$$\left(\frac{\Delta\dot{p}}{p}\right) = \frac{1.33 \times 10^{-5}}{\text{sec}} = \frac{1.33 \times 10^{-5}}{78.2 \times 10^3} = 1.7 \times 10^{-10}/\text{turn}$$

when the oscillation is first detected. Now for a 2 KV/turn kick we have since for $\beta \approx 1$ $\Delta p/p = \Delta E/E$

$$\frac{\delta p}{p} = \frac{2 \times 10^3}{31.2 \times 0.938 \times 10^9} = 6.8 \times 10^{-8}/\text{turn}$$

for a single bunch at maximum oscillation amplitude. Since in principle a given bunch would receive the kick only once per 120 turns the average $\delta p/p$ change would then be $6.8 \times 10^8 \div 120 = 5.67 \times 10^{-10}$. This is 3 1/3 times greater than the 1.7×10^{-10}/turn growth rate obtained above for $\alpha = 1 \text{ sec}^{-1}$ and 20 micron position resolution. Hence the oscillation would be damped since a factor of two is usually considered a safe margin for damping. This result would also apply to Au at injection since the $(\delta p/p)$/turn would be the same.

It is obvious then how the damping rate would scale with the position resolution for fixed kick. Of course the damping rate would decrease with the beam momentum as p_0/p. It has been shown [4] that the growth rate for the dipole mode driven by a single parasitic cavity resonance would not change for the Au beam from $\gamma = 26$ to $\gamma = 108$ assuming that the mode is unstable to begin with. Hence an unstable mode with a growth rate $> 0.06 \text{ sec}^{-1}$ at top energy could appear. However this means an e folding time of 16 2/3 sec which is about 1/3 or the 52 sec acceleration time from $\gamma = 26$ to $\gamma = 108$. Using Baartman's [5] criteria of 4-5e folding times as being safe one could tolerate considerably larger growth rates since transfer to the 200 MHz system, if not already performed, will ensure stability at much greater intensities than the design value [4].

Finally we note that at top energy

$$\delta\hat{\varphi} = \frac{2.8 \times 10^6}{27.7} \times 1.91 \times 10^{-3} \times 1.33 \times 10^{-5} = 2.56 \times 10^{-2} \text{ rad} \simeq 1.5^\circ$$

for protons with $V_{rf} = 300$ KV and about 1.4° for Au. Hence it might be possible to use phase error information at or near the top energy for the damping loop if a 1° resolution is obtained at 28 MHz. Of course there would have to be a 90° phase shift at ω_s to obtain damping.

References

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