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VOLTAGE REQUIREMENTS FOR THE TRANSVERSE DAMPERS

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Technical Note

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I. INTRODUCTION

In order to control the transverse resistive wall instability that is expected to be present in the AGS Booster when operating at the maximum design intensity of 1.5×10^{13} protons per pulse, vertical and horizontal feedback damping systems will be installed. A conceptual design for such a system is contained in Booster Technical Note 137 (Revised).

The resistive wall instability in the AGS has been controlled by a narrow band feedback system since early 1973 (see Accelerator Division Technical Note 118). However, with the advent of multi-batch injection of three bunches at a time from the Booster, the need to damp injection errors of individual bunches, as well as control the instability at three or more times the present intensity cannot be met with this system. A conceptual design of a bunch-to-bunch feedback system capable of performing this task is contained in Accelerator Division Technical Note 209. This design has undergone some modifications and the current status is described in Accelerator Division Technical Note 352.

The purpose of this report is to discuss the voltage/ power requirements of the amplifier/drivers that will be used to excite the 50 Ω strip line kickers that will be used in both the Booster and AGS Systems.

II. BOOSTER KICKER REQUIREMENTS

The maximum expected growth rate of the instability on a 1.5 GeV kinetic energy flattop with $Q = 4.75$ is $1500\ \text{sec}^{-1}$ in the vertical plane[1] at zero chromaticity. In order to suppress this instability, one would need an $\epsilon > 2.2 \times 10^{-3}$ where[1]

$$\epsilon_{eff} = 8/\pi^2 \sqrt{\beta_k/\beta_p}\ (\Delta p/p)_\perp\ /(\Delta y/\beta_p) \qquad (1)$$

Here β_k, β_p are the beta functions at the kicker and pickup electrodes, Δy is the oscillation amplitude, and $(\Delta p/p)_\perp$ the corresponding transverse angular kick given by

$$\left(\frac{\Delta p}{p}\right)_\perp = \frac{(1+\beta)}{\beta}\ \frac{e\sqrt{Z_o\ P}}{\beta\gamma_o c}\ \frac{\ell k}{c} \qquad (2)$$

We have assumed a "square wave" kick so that the peak power $P = V^2/50$. For the geometrical factor k, we use a value about 20% greater than given in Reference [1] since it is now known that the expression given there overestimates the image current effect. Thus, we obtain for $\ell = 0.635$ M

$$\left(\frac{\Delta p}{p}\right)_\perp = \frac{1.923}{0.923}\ \frac{V_k\ 0.635}{2.6\ m_o c^2}\sqrt{\frac{377}{50}}\ 4.85\ M^{-1} = 7.22 \times 10^{-9} V_k \qquad (3)$$

Putting this into Equation (1) gives

$$V_k \geq 2.2 \times 10^{-3}\ \frac{\pi^{-2}}{8}\ \frac{\Delta y(\mathrm{mm})\ 10^{-9}}{7.22 \times 12.2 \times 10^3 (\mathrm{mm})} = 30.7\ \Delta y(\mathrm{mm}) \qquad (4a)$$

or $$P_k > 18.85(W)\ \Delta y^2(\mathrm{mm}) \qquad (4b)$$

In order to assure stability, one should have a damping rate at least twice the growth rate. Hence, if the peak power available were 50 watts, $V_{peak} = 50$ volts and this would be obtained if $\Delta y = 0.8$ mm. Now, if we assume eight-bit digitization of the position signal with full scale being ± 0.51 cm, then the LSB would correspond to a 40 micron displacement. It would be desirable to keep the residual closed orbit error after subtraction and noise (digitization error included) to much less than 0.8 mm. Then one could inhibit the kicker pulse so that only errors greater than this residual signal produce a deflection. Then, in principal, the peak power requirement would be reduced since growth beyond this limit would be curtailed. Once this "dead band" is exceeded, the kick should be proportional to the absolute error in order to insure adequate damping. Now the rotation frequency at injection is 800 kc and if we assume $Q_V \approx 4.9$, then the low frequency component of the kicker signal would be 80 kc. Since the maximum bunch frequency will be 4.14 MHz the high frequency component of a reasonable "square" pulse will be several times this. Hence, the bandwidth of the strip line driver should be at least 20 kc to 16 MHz. The peak power requirement into a 50 Ω load should be 25-50 watts in order to allow for some finite residual error signal level as discussed above.

III. BOOSTER LOW LEVEL SIGNAL CONSIDERATIONS

If we assume that the standard pickup electrode signal electronics will be used, then we can estimate the signal level of the integrator for a single bunch at 1 mm displacement. Using signal levels given in Booster Technical Note 170, we assume a peak signal of 3 volts for 0.5×10^{13} protons in a "cosine squared" bunch at the center of the pickup electrode. This implies that a factor of ten attenuation has been employed in the front end termination. Another factor of four is lost in driving the sum and difference hybrid in a matched manner and in its insertion loss. However, since the difference output is the sum of two inputs and because there is a 2:1 step-up transformer at the hybrid output, this factor of four is recovered. That is, if V is the peak signal, from one electrode, to the hybrid driver, then the difference signal arriving at the base line restoration circuit will be δ V, where $\delta \cong 0.1$/cm is the PUE position sensitivity relative to the signal at the center.

Now for the cosine squared distribution $V = 2\bar{V}/B$, where $\bar{V}$ is the average voltage and B the bunching factor. The 3 volt signal given above is for a B = 1/3 while we anticipate a B = 0.5 for a maximum intensity bunch. Hence $\bar{V} = (2/3) \times 3/4 = 0.5$ volts so that the output of the integrator at 1.5 GeV kinetic energy with $C = 33 \times 10^{-12}$ $\mu\mu$f, R = 4k would be (τ_{int} = CR)

$$V_i = 0.1 \frac{\bar{V}\,\Delta t}{CR} = \frac{0.5 \times 0.1/\text{cm}}{4.1\times10^{6} \times 2 \times 33\times10^{-12} \times 4\times10^{3}} =$$

$$0.046 \text{ volts/cm} \tag{5}$$

or 4.6 mV/mm. Thus, if full scale were 5.1 mm, the output would be about 23.5 mV and a gain of 42 would be required to give ± 1 volt for an ADC. This could be obtained by removing the input attenuation factor of ten and reducing the 4K integration resistor to 1K. However, there are other options which can be explored. Our purpose here is to present a set of parameters based on existing data that can be used to aid in the prototype design.

IV. <u>AGS HORIZONTAL KICKER REQUIREMENTS</u>

Injection is in the horizontal plane where the growth rate is expected to be small even for moderate values of the chromaticity. Hence, we assume that the horizontal kicker power requirements will be set by the allowed injection errors. Now the AGS kicker plates will be about 0.92 meters long so $(\Delta p/p)_\perp \cong 1.1 \times 10^{-8}\, V_k$ for this system since the chamber size, plate widths, and spacing are essentially the same as for the Booster, i.e., $k \cong 4.85\ M^{-1}$ also. Let us take a $\Delta x = 1.5$ mm, with $\sqrt{\beta_p\, \beta_k} = 15$ M and assume $\epsilon_{eff} = 0.02$, then

$$\left(\frac{\Delta p}{p}\right)_\perp = \frac{0.02 \times 1.5}{1.5 \times 10^3} = 2 \times 10^{-6} \tag{6}$$

So that $V_k \cong 182$ volts, the initial damping rate would be $(\epsilon\Delta\, x/2)$ per turn for proportional damping, i.e., 15 microns/turn.

Next let us determine if this value of t is sufficient to prevent significant phase space dilution. First we use the criterion given by Lambertson[2]

$$\frac{\epsilon\ f_o}{2} > 0.94\ \Delta\omega a_o/\sigma \tag{7}$$

where f_o is the rotation frequency, a_o the initial position error, σ the rms transverse beam size and $\Delta\omega$ is the betatron tune spread (FWHH). We assume the emittance of the Booster to be 30 π mm mrad normalized and obtain a $\sigma = 13.6/\sqrt{6} = 5.6$ mm. We also assume that the line charge of a bunch is proportional to $(\phi_o^2 - \phi^2)^2$ which leads to a $[\phi'/\omega_s] = 0.54(\phi'/\omega_s)_{max}$. Then if the tune spread is due only to chromaticity, we would have $\Delta\omega = 2\pi\ f_o \times 0.54 \times \Delta Q$. Taking $a_o = 1.5$ mm and assuming $\Delta Q = 10^{-2}$, we obtain

$$\frac{\epsilon\ f_o}{2} > 2\pi \times 0.94 \times \frac{1.5}{5.6} \times \frac{2\ f_o}{2} = 0.017\ \frac{f_o}{2} \tag{8}$$

Another criterion is that the error should be damped to e^{-1} in $(\Delta Q)^{-1}$ turns (assuming proportional damping). This leads to the requirement that $\epsilon > 2\,\Delta Q = 0.02$. Both of these limits lead to some dilution (less than 10% for the Lambertson case) while a more stringent requirement of $\epsilon > 40\,\sigma_\phi$ would result in essentially no dilution.[3] For the present case,

$\sigma_Q = \Delta Q/2\sqrt{2}$ so that $\epsilon > 0.076$ which is quite large. Although this criterion was used in Accelerator Division Technical Note 209, it was assumed there that $\Delta Q \cong 10^{-3}$ so that essentially the same value of ϵ was obtained there also, i.e., 0.02.

Here, we have assumed a 180° wide bunch which results in a $(\Delta p/p) \cong 2 \times 2.38 \times 10^{-3}$ full width. Thus, in order to obtain a ΔQ of 10^{-2}, the chromaticity $\xi = (\Delta Q/Q) / (\Delta p/p)$ must be $\cong 0.15$. this in turn implies a head-tail phase shift of

$$X = 2\pi\, f_o\, \tau_e\, \xi/\eta = \frac{\pi}{12}\,\frac{8.75 \times 0.15}{0.1345} = 0.81\,\pi \qquad (9)$$

and should result in a reduction of the growth rate of the resistive wall instability by about a factor of two from the $\xi = 0 = X$ value. Hence, if one wishes to reduce the ΔQ to make the dilution less for a given ϵ, it should be possible as long as the growth rate is less than say $\epsilon\, f_o/4$ or 1700 sec^{-1}.

V. AGS VERTICAL KICKER REQUIREMENTS

For this system, the requirements are primarily determined by the expected instability growth rate. If $X = 0$ at injection (1.5 GeV kinetic) and we have 0.5×10^{13} protons/bunch, a value of 6000 sec^{-1} is anticipated based on measurements with 9×10^{12} total protons. Thus, $\epsilon_{eff} > 2 \times 6{\times}10^3/f_o = 0.035$ so that

$$\left(\frac{\Delta p}{p}\right)_\perp > 0.035\,\frac{\pi^2}{8}\,\frac{\Delta y}{\bar{\beta}} = 2.87 \times 10^{-6}\ \Delta y(\mathrm{mm}) \qquad (10a)$$

$$V_k > 262\ \text{volts}\ \Delta y(\mathrm{mm}) \qquad (10b)$$

If we limit V_k to 200 volts peak, then one could in principal correct an injection error of ≈ 0.75 mm since the growth rate for each group of bunches would be less than 1500 sec^{-1}. The net damping rate would be $D > (\epsilon\, f_o/2 - 1500\ sec^{-1})$ which is greater than in the horizontal plane, i.e., 3400 sec^{-1}.

Actually as far as the component of the (9 - Q) mode present in three bunches oscillating with no phase shift between them, as would be the case for equal injection errors, it is only one-third of the error. Hence, in principal the growth of this mode would effectively be driven by only one bunch oscillating at the injection amplitude. We assume, of course, that any other bunches present prior to injection have negligible coherent amplitudes.

Now if the vertical chromaticity was always ≥ 0.15, then the growth rate of the (9 - Q) mode would be at least a factor of two below the X = 0 value. This would enable one to provide adequate proportional damping, i.e., $D > 2/\tau_g$ where $1/\tau_g$ is the growth rate, and still correct some amount of injection error with a maximum power requirement of 800 watts per deflection plate. A method of extending these capabilities without an increase in peak power requirements will be presented next.

VI. <u>CONSTANT AMPLITUDE DAMPING</u>

For proportional damping, the maximum change in amplitude per turn is $\epsilon\ \Delta y$, but the average rate of reduction is proportional to $\overline{\cos^2 \varphi}$, where φ is the betatron phase advance per turn at a fixed point. Hence, it is really $\epsilon\ \Delta y/2$ and it decreases with decreasing amplitude. However, if we keep the amplitude of the correction fixed as long as the error exceeds some nominal value, then the average is proportional to $\overline{\cos \varphi} = 2/\pi$. So if the kick amplitude of the two systems were the same initially, then the damping rate for the constant amplitude case would be $4/\pi$ times that of the proportional system[4] and would not change as long as the error threshold was exceeded. It has been shown[5] that if one wishes to damp a given injection error by e^{-1} in a given time, then the peak power required is reduced by a factor of four since the required kicker voltage is reduced by about a factor of two.

If the constant amplitude option were employed on the AGS at injection, then the allowable injection errors could be increased by a factor of two for the same peak kicker voltage assuming no other parameter changes. Alternately, the peak voltage requirement could be reduced by a factor of two for the same injection error tolerances. If the latter were exceeded, then in general the principal result would only be some additional dilution.

Let us consider a vertical error of 0.75 mm with $X \cong 0.8\ \pi$ and $V_{max} = 100$ volts. Then the initial damping rate would be $[(4/\pi)\ 3000\ \text{sec}^{-1} - 3000\ \text{sec}^{-1}/12] \times 0.75\ \text{mm} = 3570 \times 0.75$ mm/sec and this would increase as the position error and hence the driving force decreased. Even if X = 0, the rate would be 3.32 x 0.75 M/sec resulting in a 1/e reduction in amplitude in 66 revolutions or a 75% reduction in less than 80 revolutions ($\approx$ 226 μsec). However, if X = 0 and the damping rate for all twelve bunches was required to be twice the growth rate or 12000 sec^{-1}, then for V_{max} = 100 volts

$$\Delta y_{max} = \frac{4}{\pi} \frac{100}{2 \times 262} = 0.24 \text{ mm} \qquad (11)$$

That is, the loop gain would correspond to an $\epsilon = 0.035(\pi/2)$ in a proportional damping system. In order to have the system function properly at this level of error, the residual position error due to closed orbit offset and noise (including digitization effects) should be considerably smaller. Hence, a limit of < 0.1 mm would be desirable. A reduction in growth rate, i.e., a $X \geq 0.8\ \pi$ or a larger V_{max} would, of course, allow a larger residual error.

Since the horizontal growth rate, even with all twelve bunches present, is expected to be much less than 6000 sec^{-1} at X = 0 operation with V_{max} = 100 volts in the constant amplitude mode, should permit injection errors greater than 1.5 mm to be controlled. The damping rate would remain fixed so that the time required to reach the threshold amplitude (defined by the residual position error) will increase with the initial error. In principal, if X = 0, there will be no dilution and hence the increase in the time will not present a problem. However, if there is some non-linearity in the magnetic field, then the resulting amplitude-dependent tune shift could, over a period of time, "smear" out the beam in transverse phase space.

In conclusion then, operation with a constant amplitude kick above some residual position error can reduce the required kicker power by a factor of four. In the horizontal plane, the "residual error" can be greater since the loop gain required for stability against the resistive wall impedance is expected to be quite modest. In the vertical plane, the tolerance on the residual error and on the injection error will be much smaller because of the required loop gain. Since injection is in the horizontal plane, the smaller tolerance in this plane should not present a great problem. Also, the vertical closed orbit at the pickup should be subject to less variation than the corresponding horizontal case. This leaves the "electronic" noise as an area for scrutiny.

Wideband power amplifiers (10 kc - 200 MHz) in the 250-400 watt range such as the Amplifier Research 250L or the IFI M404 should be suitable for this application.

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