ZGS FEEDBACK SYSTEM

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Summary

In this paper, we investigate the beam phase damping techniques employed in the ZGS. Phase oscillation frequencies have been measured at various times during acceleration. Response data taken on all systems involved with phase and radial position measurement have been used to calculate the phase and radial position responses. These results compare favorably with responses measured on the ZGS with accelerated beam.

Phase Oscillations

Phase or energy oscillations initially arise from the energy and phase spread of the injected beam. After the beam is captured and bunched, the presence of FM and AM noise on the accelerating cavity voltage may excite these oscillations and spill beam from within the phase stable region. Although it is not possible to damp phase oscillations of individual particles on the ZGS, it is quite feasible to damp the coherent oscillation of all of the particles in the eight bunches using the feedback system.

Phase Feedback in the ZGS

In considering transient motion of a single particle due to acceleration, we use the following linear approximations.[1]

$$\frac{d(\Delta\phi)}{dt} = -h\Gamma\Lambda\,(\Delta x) + (\omega_o - \bar{\omega}) \qquad (1)$$

and:

$$\frac{d(\Delta x)}{dt} = \frac{\bar{V}_o \cos\phi_s}{2\pi\Lambda}(\Delta\phi) + \frac{\sin\phi_s}{2\pi\Lambda}(V - \bar{V}) \qquad (2)$$

where $\Gamma = \frac{\omega_o^2}{\beta\eta}\left[\frac{1}{\gamma^2} - \frac{1}{\alpha}\right]$ and

$$\Lambda = \frac{\alpha\eta}{c}$$

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The phase error ($\Delta\phi$) is a small deviation from the synchronous phase ϕ_s which is defined by:

$$\phi_s = \arcsin \bar{V}/V_o$$

where V_o is the peak RF cavity voltage and $\bar{V}$ is the average voltage gain per turn required to accelerate the beam. The radial deviation (Δx) is a small displacement from the desired radius x_s. The RF angular frequency ω_o and the average particle angular frequency $\bar{\omega}$ are related to the frequency of the accelerating cavity by the harmonic number h. In other words, the voltage across the gaps of the accelerating cavity change polarity eight times during the time required for a particle to complete one turn. The remaining terms used in the expressions for transient motion due to acceleration are as follows:

$$\eta = \frac{\text{momentum}}{\text{rest mass x c}}$$

$$\beta = \frac{\text{velocity}}{c}$$

$$\gamma = \frac{\text{total energy}}{\text{rest mass x c}^2}$$

$$\alpha = \frac{R}{\eta}\frac{d\eta}{dR}$$

where R is the radius of orbit.

V = cavity voltage seen by the beam.

From these equations, we see that FM noise is equivalent to radial position error and AM noise is equivalent to phase error. To simplify matters, we may neglect amplitude modulation of the cavity voltage, i.e. $(V - \bar{V}) = 0$, and let $\Delta\omega = (\omega_o - \bar{\omega})$. We then solve equations (1) and (2) to obtain relations between frequency and position:

$$\Delta\omega = \frac{2\pi\Lambda}{V_o\cos\phi_s}\left[\frac{d^2(\Delta x)}{dt^2} + \Omega^2(\Delta x)\right] \qquad (3)$$

and frequency and phase:

$$\frac{d(\Delta\omega)}{dt} = \frac{d^2(\Delta\phi)}{dt^2} + \Omega^2(\Delta\phi) \qquad (4)$$

where:

$$\Omega^2 = \frac{h\,\Gamma\, V_o \cos\phi_s}{2\pi} \quad . \tag{5}$$

Equations (3) and (4) might well describe a series tuned circuit resonant at Ω driven by a voltage proportional to $\Delta\omega$ and having a circulating current proportional to $\Delta\phi$. The voltage across the capacitor would then be analogous to ΔX.

The frequency program for acceleration in the ZGS is derived from the magnetic field as opposed to a phase shifted signal from a beam pickup electrode. In a system such as this, a transient frequency error between accelerating cavity and beam rotation will excite phase oscillations which can cause particles to move out of the phase stable region and be lost against the inner wall of the vacuum chamber due to the rising magnetic field. In equations (3) and (4) we observe that no damping terms exist for these oscillations other than the non-linearities of large amplitude oscillations. To damp phase oscillations in the ZGS, we let $\Delta\omega = -A(\Delta\phi) + (\Delta\omega')$ in equations (3) and (4) with the results:

$$\Delta\omega' = \frac{2\pi\Lambda}{V_o\cos\phi_s}\left[\frac{d^2(\Delta x)}{dt^2} + A\,\frac{d(\Delta x)}{dt} + \Omega^2(\Delta x)\right] \quad . \tag{6}$$

$$\frac{d(\Delta\omega')}{dt} = \frac{d^2(\Delta\phi)}{dt^2} + A\,\frac{d(\Delta\phi)}{dt} + \Omega^2(\Delta\phi) \quad . \tag{7}$$

This is shown as a feedback system in Figure 1. The phase between the accelerating cavity and the beam is converted to an analog voltage by the phase measuring system. A hi-pass filter with cut-off set at 200~ removes the ϕ_s component. The $\Delta\phi$ component is given a gain β, then injected into the master oscillator along with E_o, the accelerating program voltage which generates ω_o and e_1, an input perturbation. Since our phase feedback is AC coupled, ϕ_s is not determined by the feedback loop. Instead, the beam itself will automatically seek its own synchronous phase angle, ϕ_s, for a given RF voltage to enable $V - \overline{V} = 0$.

The response of this phase loop as shown in Figure 1 in terms of the responses of its constituents is given by:

$$\frac{\Delta\phi}{e_1}\underline{\left|\psi_\phi\right.} = \frac{K_1\underline{\left|\theta_1\right.}K_2\underline{\left|\theta_2\right.}K_3\underline{\left|\theta_3\right.}}{1+\beta\underline{\left|\theta\right.}K_1\underline{\left|\theta_1\right.}K_2\underline{\left|\theta_2\right.}K_3\underline{\left|\theta_3\right.}} \quad . \tag{8}$$

Position response of the beam with this loop is described by:

$$\frac{\Delta x}{e_1}\underline{\left|\psi_x\right.} = \frac{K_1\underline{\left|\theta_1\right.}K_4\underline{\left|\theta_4\right.}\Omega^2}{h\,\Gamma\,\Lambda\left(\Omega^2 - \alpha^2 + \alpha K_1\underline{\left|\theta_1\right.}K_3\underline{\left|\theta_3\right.}\beta\underline{\left|\theta+90\right.}\right)} \quad . \tag{9}$$

In order to achieve optimum position response using RF programming and maximum damping of phase oscillations, gain A should be set for critical damping of equations (6) and (7). This is achieved when:

$$\beta = \frac{2\Omega}{K_1K_3} \tag{10}$$

where $K_1K_3\beta$ has replaced A in equation (7) and phase angles are small throughout the range of Ω. The results of equation (10) vs. time are presented in Figure 2. The high initial value of β required for critical damping results from the gain change in the master oscillator required to maintain a constant $\Delta f/f$ during acceleration. Aside from this, the curve follows that of Ω vs. time given in Figure 4.

System Response Measurements

In order to adequately appraise the entire loop, each system involved required accurate measurement of gain and phase. To investigate the phase detector K_3, two frequencies, f_o and $f_o + \alpha$ were injected into the cavity RF and beam RF inputs. This caused the system to roll through its phase angle-to-voltage characteristic at a rate α. This phase angle-to-voltage characteristic is linear and reverses slope at $\pm 90^o$. Zero crossings occur at 0^o and 180^o. The output for two different frequency inputs therefore appears as a triangular waveform representing 180^o peak-to-peak. Phase shift within the phase detector appeared as a time delay between the DC output and the difference between the two RF inputs.

Master oscillator and power amplifier response K_1 was measured by injecting an audio frequency, α, into the phase correction input on the oscillator and measuring the resulting frequency deviation at the cavity with a wide band frequency-to-voltage converter. Phase delays in the measuring equipment and cables were subtracted from the results to give corrected readings. The combined response of these two systems is given in Figure 3. The large phase shift results from filters in the phase detector, long cable runs between systems, and the slow response of the cavity tune.

Measurement of the radial position (X) measuring system was accomplished by driving the pickup electrodes with a balanced modulator to simulate sinusoidal radial beam motion. The basic modulator was a beam deflection tube with an RF carrier injected into the control grid circuit and the modulation signal driving the deflection electrodes. Output signals modulated 180° apart were taken from the two plates via filters and amplifiers to provide the proper RF simulation inputs to the radial position pickup electrodes. The response of this system was essentially flat-out to 10 kc.

Experimental Results

With the ZGS accelerating during a normal run, an input $E_1 \sin \alpha t$ was gated into the oscillator at a given guide field. The gate used here was designed to open and close only at zero crossings of the signal to be gated. With such a gate, only one small discontinuity occurred during turn-on. Fortunately, this did not rattle the beam enough to affect the data. A discontinuity caused by gating $E_1 \sin \alpha t$ on at $\alpha t = n\pi$ may be removed by placing an integrator between the gate and the oscillator. Both the output of the beam phase detector and the radial position measuring system were compared with the gated input as to amplitude and phase. Phase angles were measured from Lissajous patterns with the quadrant determined from the time delay between input and output. During the course of this experiment, E_1 was adjusted to limit the beam motion to only 1 to 2 inches either side of beam center.

It was found that the measured Ω values did not agree with those calculated by equation (5). We therefore found it necessary to measure Ω at a number of points by letting α approach Ω, in which case K_3 would approach infinity and equation (8) would reduce to:

$$\frac{\Delta \phi}{e_1} = \frac{1}{\beta \underline{|\theta}} \quad . \tag{11}$$

Since $\underline{|\theta}$ was 0° in the range of phase oscillation frequencies, this point was easily found by observation of a Lissajous pattern of $\Delta\phi$ and e_1. The measured values for Ω are compared with those calculated from equation (5) in Figure 4. The calculations assumed a momentum compaction factor of 0.6 and a rate of ring magnetic field rise of 21kG/sec. The lower measured value of Ω is quite understandable if we remember that equations (1) and (2) are linear approximations valid for small values of (Δx) and $(\Delta \phi)$ and therefore represent an upper limit for Ω. The measured Ω was an average of the oscillations of all particles, some with small amplitude oscillations and high Ω values, others with large amplitude and low Ω values. Adiabatic anti-damping of individual particle phase oscillations increases their amplitudes which also reduces Ω, particularly during the first 50 msec. The momentum compaction factor α was not constant as assumed in the calculations. With our measured values for Ω, we were able to calculate K_3 and hence the response of the loop for a given value of β using our measured responses in equation (8). Typical measured gain and phase data for the phase loop are compared to calculated values in Figure 5. The data show that if β is increased from 0.0095 to 0.116, the system will oscillate at approximately 20 kc. This value of β, however, is quite in excess of that required for critical damping.

As a general rule, the ZGS does not employ direct radial feedback to the oscillator since better long-term position stability may be obtained without this. Radial feedback, however, does have the effect of increasing the zero order term in equations (6) and (7) and decreasing the position response time to an input command. However, one must be mindful that the rate at which a beam undergoing acceleration may be moved is limited by the voltage across the accelerating cavity. Beam radial position response to e_1 was measured and has been compared to the calculated values in Figure 6. Additional phase and position response data taken 30 msec and 950 msec after injection showed harmony between calculated and measured data.

The results of our experiment indicate that equations (6) and (7) do accurately describe transient beam phase and radial position due to acceleration.

References

(1) L. C. Teng, "General Formulation of RF Self-Tracking in a Synchrotron." Argonne National Laboratory Particle Accelerator Division Report, ANLAD-62 (March 1961).

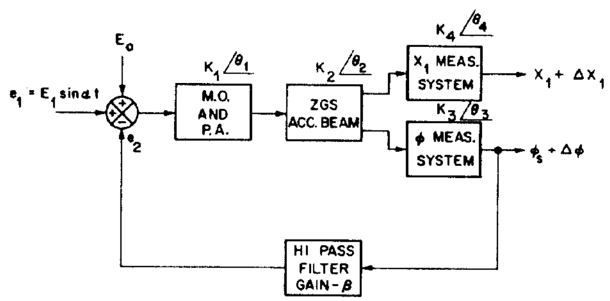

Fig. 1. Block Diagram of the ZGS Phase Feedback Loop.

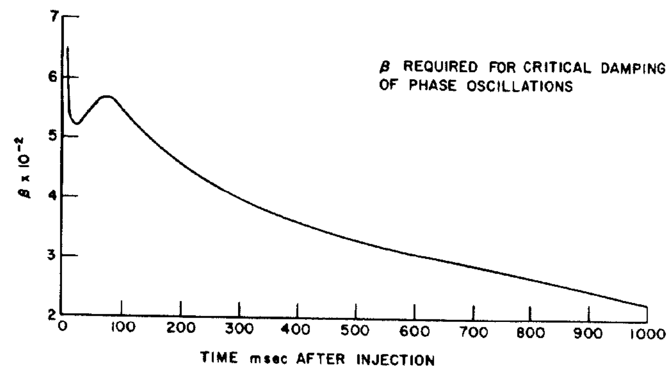

Fig. 2. β Required for Critical Damping of Phase Oscillations During Acceleration on the ZGS.

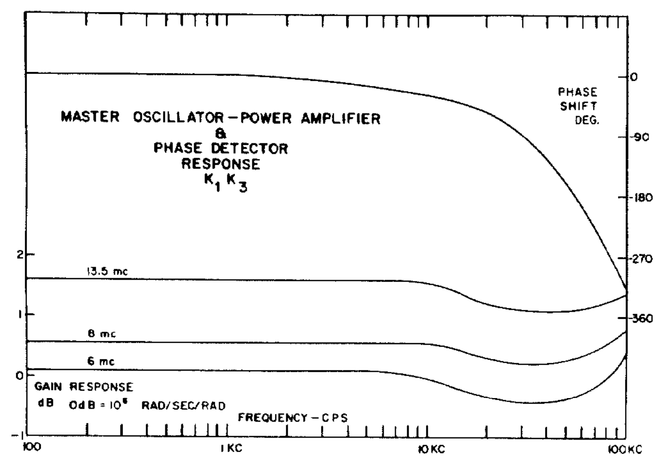

Fig. 3. Gain-Phase Response of the Master Oscillator, Power Amplifier, and Phase Detector.

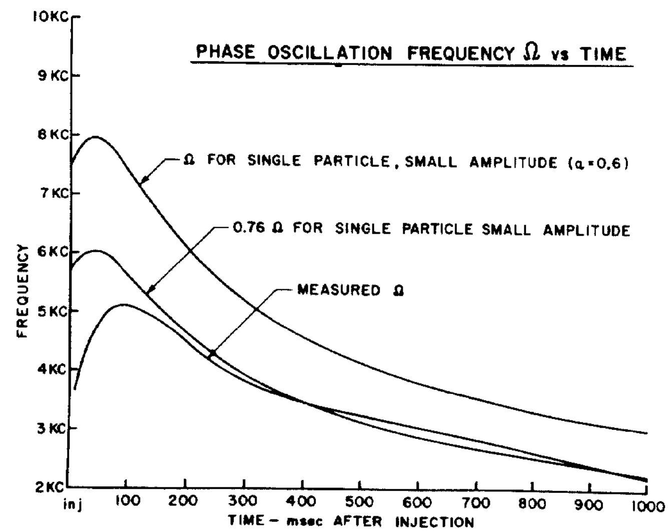

Fig. 4. Comparison of Measured and Calculated Ω During the Course of Acceleration.

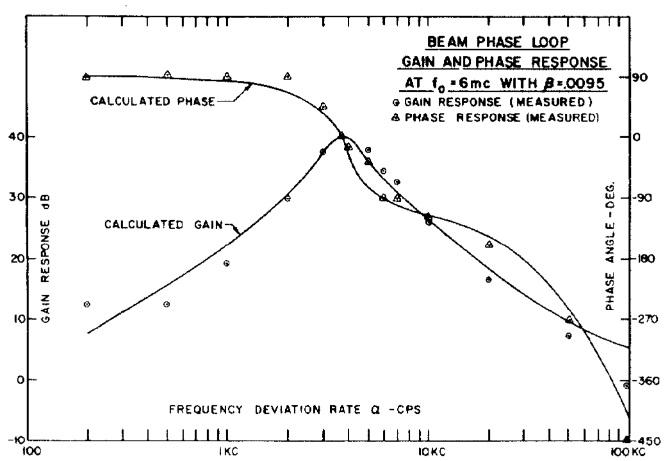

Fig. 5. Beam Phase Loop Response to an Accelerating Frequency Deviation 13 msec After Injection.

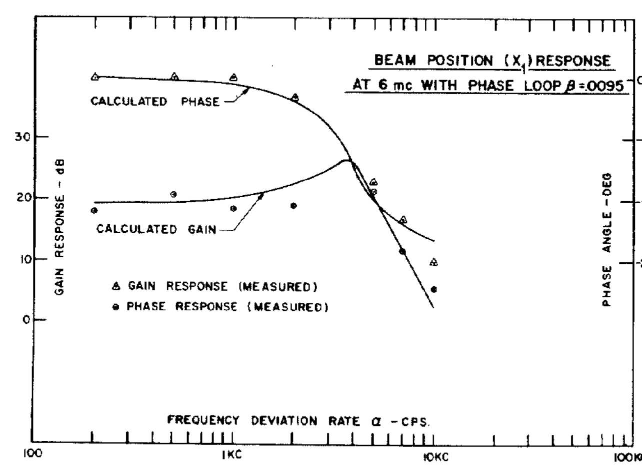

Fig. 6. Beam Position Response of the ZGS Beam to an Accelerating Frequency Deviation 13 msec After Injection.