I. INTRODUCTION

The new 1.5 GeV Booster synchrotron completes the injector chain for the Relativistic Heavy Ion Collider, RHIC. It enables the AGS to accelerate all heavy ions to 14 GeV/c for collider operation and also increases the intensity of the AGS for fixed-target experiments by a factor of four. The ultra-high vacuum ensures acceleration of partially stripped ions from the Tandem Van de Graaff to energies sufficient for complete stripping. For high intensities, it accelerates the 200 MeV linac beam in four batches of three bunches per AGS cycle. At $1.5 \times 10^{13}$ protons per batch, it has the same space charge tune spread as the AGS at 200 MeV. This variety of applications means the Booster must accommodate a very wide range of particle masses and intensities. Since it operates in a Pulse-by-Pulse Modulation mode at 7.5 Hz, the computer controlled functions of time and magnetic field, and the 64 timing triggers of the beam control system take on unique values for each of four PPM users. Beams of $^{197}$Au and protons have been accelerated in the same PPM cycle.

The revolution frequency of heavy ions increases by up to a factor of 16 during acceleration. To keep the rf frequency range within 2.3 to 4.8 MHz, the harmonic number is reduced four times by factors of two by coalescing bunches pairwise during acceleration.

II. OVERVIEW

The beam control system is basically a servo that causes the beam to follow a reference function of time for the orbit radius. As the magnetic field of the synchrotron changes, the servo changes the momentum of the beam through the high level system to maintain the specified radius. No a priori knowledge of the magnetic field is assumed, other than providing sufficient rf voltage from the acceleration cavities. Proper rf frequency and phase are determined by a combination of feedforward and feedback.

Feedforward is based on a measurement of the magnetic field in an on-line reference magnet with the "Gauss clock" ($\pm 0.100$ Gauss/tick, 100 kg/sec bandwidth). The field measurement addresses a RAM containing the revolution frequency which, multiplied by the harmonic number (volatile), controls a direct digital synthesizer (STEL 1175) to produce the rf frequency program. The accuracy is better than 0.1%. Digital frequency data are also used to feedforward the proper drive level to the cavities (inside the AVC loop) and to apportion the total rf voltage among the four cavities which operate to two frequency bands. A feedforward value for the phase between the beam bunches and the rf voltage is obtained from a measurement of dB/dt, via a pole tip winding, and from the reference function for the rf voltage. The value includes the effect of the harmonic number on the electrical phase between the beam pick-up and cavities.

The heart of the beam control system is the feedback loops illustrated in Figure 1. This is the classical configuration for hadron machines with a dc coupled Voltage Controlled Oscillator and a radial loop. Signals from the transverse pick-up are processed with AM-to-PM circuits located in the tunnel. The amplified radial error signal controls a phase shifter, $\psi$, which serves as a

![Figure 1. The concept of the beam control system.](image-url)
reference to the inner feedback loop, the phase loop, which
locks the rf voltage to the beam. A wall current monitor is
used for the longitudinal pick-up. The phase loop
strongly damps any coherent synchrotron motion that may be
stimulated by changes in the frequency program, 
$\Delta f(t)$, injection errors, or the radial loop. The beam
transfer functions, $B_r$, $B_m$, and $B_h$ relate modulations in
the rf frequency to modulations in the beam phase,
frequency, and radius. The stable phase program, $\varphi_s$, is
another reference for the phase loop such that the output of
the phase detector, $\varphi$, is nominally zero. The accuracy of
the phase program is determined by the phase shifter, ($\pm 2^\circ$), not the phase detector (a double balanced mixer).

III. FEEDBACK LOOPS

The phase loop should have high open loop gain at
the synchrotron frequency (1 to 7 kHz) in order to provide
strong damping. The response time of the cavity and delays
within the loop limit the gain. The frequency modulation
response function of the cavities was measured and found
to be well fit by a single-pole roll off at 20 kHz together
with a delay of 1.5 $\mu$s, irrespective of rf frequency or
time (the Q is approximately proportional to frequency).
Additional delays occur in the cables and VCO (2 $\mu$s) and
in the group delays of the narrowband filters (2 $\mu$s) used in
the phase measurement circuit. Gain at low frequency is
also important since the radial loop and the stable phase
program rely on the phase error, $\varphi$, being zero. A PID
characteristic for the loop amplifier, $D_s(s)$, fulfills the
requirements. The transfer function can be written in terms
of a pole at the origin and two zeros,

$$D_s(s) = \frac{k}{s} (s + z_1)(s + z_2).$$

One zero is chosen to roughly cancel the pole of the cavity
response and the other is placed below the synchrotron
frequency and offsets the 90$^\circ$ phase shift from the pole at
zero.

The radial loop amplifier is simply a proportional
gain up to a one pole corner frequency of 1 kHz. The open
loop gain curves were measured with beam on a magnetic
field flattop, Figure 2. The data were actually taken with
the loops closed and the transformation $T/(1-T)$ reveals the
open loop response from the closed loop measurement. 7

One sees the synchrotron frequency resonance in the phase
curve and the 1/s behavior of the radial loop which
provides accurate tracking by the radius servo. The
transient response of the phase loop is illustrated in Figure
3. The chopped linac beam is injected off-center in the
bucket and oscillates until the phase loop is closed.

IV. HETERODYNE SYSTEM

The measurement of the beam phase should be
insensitive to the details of the bunch shape and intensity.
Some form of averaging of the bunch signal is necessary.
Extracting the phase of a single Fourier component
typically the fundamental rf frequency is well defined and
technically convenient. It is done here by translating the
bunch and cavity signal to an Intermediate Frequency (10.7
MHz) and narrowband filtering to select a single line from
the discrete spectrum. The filter bandwidth is $\pm 150$ kHz,
which discriminates between revolution lines for protons,
where unequal bunch populations are possible, and between
rf lines for heavy ions, where all buckets are filled
(adamping capture). The heterodyne system that does
the frequency translation is illustrated in Figure 4.

The Local Oscillator is generated from the
frequency program by adding 10.7 MHz to the frequency
control word of the Direct Digital Synthesizer. The DDS
generates quadrature outputs ($90^\circ \pm 1^\circ$) that are used in the
single-sideband output mixer. The output mixer uses four-
quadrant multipliers (Analog Devices AD834) instead of
diode mixers. The good linearity of the multipliers and the
quality LO signals leads to RF spectra with spurious lines
down by >45 dB across the band 0.5 to 5.0 MHz. The
input mixers are optimized for wide dynamic range using
high level double balanced mixers in the double-sideband
configuration, since their output is filtered at the IF before
the phase detector. The phase detector employs a very fast
comparator (AD96685, 2.5 ns delay) as a limiter giving
over 70 dB of dynamic range. The AM-to-PM processing
circuits for the radius measurement operate at the IF and
use the same limiters. The phase shifters for $\varphi_r$, and $\varphi_s$, not
shown in Figure 4, also operate at the IF.
cycle with extraction suspended (the beam is decelerated to injection energy) and under radial loop control. The offset frequency, which begins at about 100 kHz and winds down to zero Hertz, then up-converts the beam signal to the target frequency, \( f_{MR} = \Delta f(t) + f_{BEAM} = f_{AGS} \). The synchronization circuits lock \( f_{MR} \) to \( f_{AGS} \) by modulating \( f_{BEAM} \). The key ingredient to this scheme is the DDS that generates \( \Delta f(t) \). It must be precise so that \( f_{BEAM} \) is reproducible, start and end at the same phase each time, and provide quadrature outputs down to dc so that the phase relation between \( f_{MR} \) and \( f_{AGS} \) is unambiguously determined at extraction time. Figure 5(a) shows the output of the \( \Delta f(t) \) DDS for the last 2 ms of its sweep.

To effect synchronization, radial control is replaced with phase error with respect to the external reference. Since the phase is arbitrary when control is switched, a significant transient, causing excursions in the bunch to bunch phase, would occur. The transient is avoided by preceding the synchronization loop with a frequency loop with two zones. First, a specified beat frequency is established which gives a sawtooth waveform from the phase detector with the desired slope. See figure 5(b). A circuit that detects the desired slope then transfers the reference of the frequency loop from a dc value to a value proportional to square root of the phase. The loop thus synthesizes the equation \( \frac{d\phi}{dt} = \left( f_1 / \sqrt{\phi_0} \right) \phi(t) \). The phase, therefore, approaches zero quadratically and the frequency linearly. They reach zero at the same time and control is finally changed to the synchronization loop with no phase or frequency transient. The phase signal during the synchronization process is shown in Figure 5(b), along with the triggers that advance to the \( \sqrt{\phi(t)} \) zone and finally to phase locking.

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REFERENCES

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