# RF BEAM CONTROL SYSTEM FOR THE BROOKHAVEN RELATIVISTIC HEAVY ION COLLIDER, RHIC*

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*Abstract*

The Relativistic Heavy Ion Collider, RHIC, is two counter-rotating rings with six interaction points. The RF Beam Control system for each ring will control two 28 MHz cavities for acceleration, and five 197 MHz cavities for preserving the 5 ns bunch length during 10 hour beam stores. Digital technology is used extensively in: Direct Digital Synthesis of rf signals and Digital Signal Processing for, the realization of state-variable feedback loops, real-time calculation of rf frequency, and bunch-by-bunch phase measurement of the 120 bunches. DSP technology enables programming the parameters of the feedback loops in order to obtain closed-loop dynamics that are independent of synchrotron frequency.

## 1 SYSTEM OVERVIEW

The beam control system for each ring controls the three storage cavities in that ring and two of the four storage cavities that are common to both rings. Figure 1. shows a block diagram of the main subsystems. A DSP ("Program") calculates the approximate rf frequency from a measurement of the current in the ring dipole magnets plus a command function for the beam radial position. The calculated frequency controls a Direct Digital Synthesizer that generates 1024 x the revolution frequency (80 MHz) which is the digital clock for all the other synthesizers in the system. The frequency control word for the 1024Frev synthesizer is corrected by another DSP ( "State Variable Feedback") which makes small, fast corrections to implement phase and radial feedback loops. These discrete-time feedback loops sample and output at the revolution frequency. The bunch-by-bunch phase measurement system measures the phase of each bunch on each machine turn. This is done by fanning out the analog bunch signals from the longitudinal pick-up into eight parallel channels via an analog DeMux circuit.

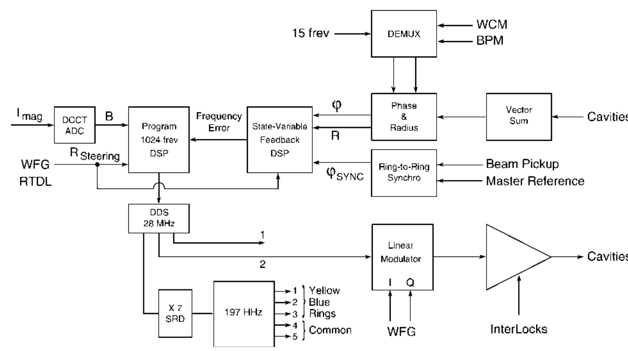


Figure 1. Block diagram of beam control system. Two DSPs calculate the frequency program, and the feedback algorithms. Each ring has two 28 MHz cavities and five 197 MHz cavities. A Step Recovery Diode generates the 197 MHz from the 28 MHz. Standard RHIC Wave Form Generators update at 720 Hz.

The amplitude and phase of each cavity are controlled by a linear modulator in the rf drive line. Since all cavities are equipped with rf feedback systems with >40 dB of loop gain[1] no AVC or phase tracking loops are used.

## 2 RF DRIVE

### 2.1 *RF Source*

A DDS generates 28 MHz as the source of the rf drive chain. The digital clock of this synthesizer carries the 0.35 % frequency variation needed to accelerate from 12 GeV/nucleon to $\beta$=1. The frequency control word is just a constant, proportional to the harmonic number. This minimizes (to one) the number of write operations that are performed for each frequency step. The frequency steps are kept small compared to the bucket height. With the synchrotron frequency ranging as low as 30 Hz the step size is kept below 0.6 Hz so that the discrete steps are always less than 1% of the bucket height. With a peak ramp rate of 22 kHz/s this step size requires a frequency update interval of <28μs.

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The 28 MHz signal drives the acceleration cavities directly and is multiplied by seven with a step-recovery-diode comb generator and bandpass filter to provide drive at 197 MHz for the storage cavities.

### 2.2 *Linear modulator*

The linear modulators effect an amplitude dynamic range of 60 dB and a phase set ability of one degree. The core of the modulators is a pair of four-quadrant rf analog multipliers (AD834) used in an I/Q configuration. Sixteen-bit DACs convert I/Q data from standard RHIC Wave Form Generators [2]. The WFGs compute I and Q on line at 720 Hz from cavity amplitude and phase functions that are generated off-line and downloaded to on-board RAM.

The linear modulators have internal PROM that is used when faster control is needed. Specialized functions (ramps, cosine, exp…) can modify the I/Q data from the WFG at up to 10 MHz by complex multiplication before they are applied to the rf multipliers. These ramps are selected by a serial line (NIM_LINK) and triggered by pulses from the RHIC system-wide Event Link.

## 3 DIGITAL SIGNAL PROCESSORS

Four TMS320C40 50 MHz DSPs (Texas Instruments) reside on a VME card (Spectrum CV6) which communicates with the accelerator control system via a Power3E PC and Ethernet. Real-time calculations for generation of the frequency program and beam control feedback loops are handled by two DSPs while I/O internal and external to the VME crate is handled by the other two. DSPs communicate via shared memory and communications ports. High bandwidth data for real-time control use the VME Subsystem Bus (VSB). The availability of mature software tools (C compiler, debugger, optimized application libaries) was a major factor in the card choice. Programs are written in C.

### 3.1 *Frequency Program*

The RF Beam Control system is structured in the conventional fashion [3] for hadron synchrotrons. That is, an accurate open-loop generation of the rf frequency (Program) is augmented by corrections determined from beam parameter measurements (feedback). Accuracy is determined by measurement error of the beam energy which is inferred from the current in the arc dipoles. Because the machine ramps slowly ($d\gamma/dt < 1\ s^{-1}$), eddy current effects are small and the current is a reliable indicator of average dipole field. A Direct-Current Current Transformer (Danfysik 861R, < 5ppm) converts magnet bus current to a voltage that is sampled at 80 kHz to 16 bits (Pentek 1602). Resolution is improved by a digital filter before the frequency calculation is performed The desired radial position of the beam is received from the Real Time Data Link system [4] of RHIC at 720 Hz. From the current and radius the Program DSP calculates the rf frequency to 32 bits, giving a frequency resolution of 6 mHz at 28 MHz.

The VSB bus handles the rf phase jump at transition. The Program DSP calculates the synchronous phase, $\varphi_s$, from dp/dt and the vector rf voltage. When triggered by a interrupt at transition the Program DSP advances the phase of the Digital Synthesizer which generates cavity drive by $\pi-2\varphi_s$. It also tells the feedback DSP that the new stable phase angle is $\pi-\varphi_s$.

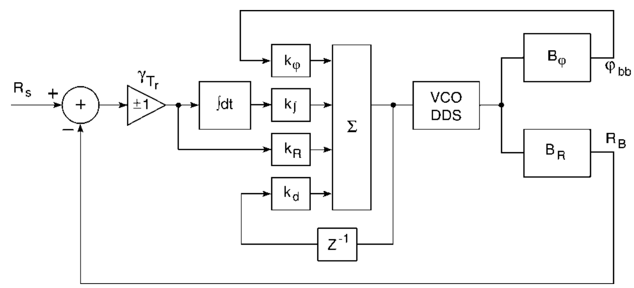


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Figure 2. State variable feedback. $B_R$ and $B_\varphi$ are beam transfer functions. There are four states, including an integral of the radial error and a delay compensator. At transition the sign of the radial feedback is changed.

### 3.2 *State Variable Feedback DSP*

The heart of the beam control system is the feedback loops that damp the coherent synchrotron oscillations (phase loop) and regulate the beam radial position (radial loop). The loops are designed with state variable formalism [5] and realized in the State Variable Feedback DSP. Figure 2 shows the block diagram. $B_\varphi$ and $B_R$ represent the beam transfer functions for rf frequency to phase and amplitude. The phase and radius are measured once per turn. This makes the revolution frequency the sample clock of the discrete-time control system. The design includes an additional state to serve as an estimator of the measurement delay.

At transition the sign of the radial feedback must change and it is essential that the value of the radius state variable is zero then. The actual radius may not be zero, however, because it follows a command function. To implement this "radial steering" capability a new state is created by integrating the difference between the measured radius and the command function. It is this difference, which is nominally zero, that supplies the radial feedback state variable. A pre-filter on the command function that matches the closed-loop response of the radius prevents a transient caused by a fast change in the command function.

A benefit of the DSP is convenient adjustment of the feedback gains. This is done 200 times during the acceleration cycle to maintain constant closed-loop dynamics as the synchrotron frequency changes.

The gains are obtained in a two step process. First an LQR [6] optimization is done which weights heavily the phase oscillation damping. From the resulting gains the closed-loop poles are determined and then by pole-placement, using Ackermann's formula, analytic expressions are derived for the gains as functions of the pole values and the synchrotron frequency.

## 5 BEAM PHASE MEASUREMENT

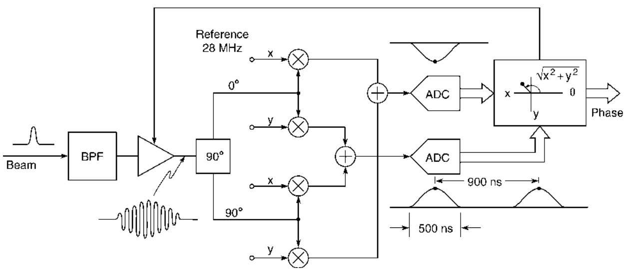


Figure 3. The bunch-by-bunch phase measurement circuit. The I/Q components of the response of the Bessel filter (Q=10) are demodulated with the components of the reference signal at 28 MHz. Digital rectangular-to-polar conversion supplies the phase and magnitude.

The phase of every bunch is measured on every turn by the phase detector illustrated in figure 3. The bunch signal from the wall current monitor longitudinal pickup is applied to a narrowband (Q=10) bessel filter centered at 28 MHz. The response of this filter, which is a burst lasting for about 500 ns, is demodulated in a double-sideband circuit with the 28 MHz cavity-drive signal. The resulting I and Q baseband signals are digitized to 12 bits, and a dedicated DSP chip (Pythagoras, Plessy ) performs the rectangular to polar transformation. The rectangular-to-polar conversion provides full zero to 360 degree unambiguous phase results.

The magnitude is used in an Automatic Gain Control circuit which keeps the signal levels in range for the ADCs. When RHIC has the full complement of 120 bunches the bunch spacing is less than the ringing time of the filter. So a parallel bank of eight filters is used and the bunch signals are de-multiplexed with GASFET switches into the eight channels. To reduce video feedthrough and achieve high dynamic range the control signal is bandlimited to a sin(x)/x-type shape so that any feedthrough is below the lower band edge of the filter.

The average phase over one turn is calculated in the phase detector electronics before the data is sent to the beam control DSP. During the injection process the new bunch is masked out of the average until the injection damper has corrected any phase or energy errors.

## 6 SYNCHRONIZATION, INJECTION AND COLLISION

RHIC is filled one bunch at a time from the four bunches in the AGS at 30 Hz repetition rate. The AGS cycles at 0.5 Hz, implying the nominal fill of 60 bunches can be loaded in 30 seconds. Single bunch transfer is advantageous because any fill pattern of the 360 buckets in RHIC is allowed. Typically the pattern is selected to yield equal collision rates at all six interaction points. The relative orientation of the gap between the two rings is controlled by the collision synchronization system.

### 6.1 *Bunch by bunch injection*

The injection synchronization system provides the triggers to the extraction and injection kickers, and also a reference signal to which the AGS bunches are locked. Between each injection the phases of the kickers trigger and the AGS reference signal must advance appropriately to fill the desired bucket and provide that the AGS bunch is at the kicker when it fires. The phasing of these signals is effected by precise ($2x10^{-10}$) control of the frequency of the DDS with which they are generated. By switching to a slightly (~30 Hz) offset frequency for a prescribed time (a counted number of revolution periods) the bunches and kickers trigger are aligned for filling the desired bunch pattern.

### 6.2 *Synchronization for collisions*

The two rings of RHIC accelerate independently and when the beam in each ring reaches full energy the radial feedback is replaced with a ring-to-ring synchronization system. The two rings are first synchronized to a master oscillator at 197 MHz . Then the missing bunch gaps are aligned by advancing the phase of the synchronization reference by the appropriate integral number of 197 MHz periods.

## REFERENCES

[1] J. Rose et al, PAC 1995, Dallas Texas, p.1669

[2] Private communication, V115 WFG,T. Kahn, Brookhaven National Laboratory, Upton NY 11973

[3] D. Boussard, Proc. CERN School on RF Engineering, Oxford England, April 1991.

[4] H. Hartmann, PAC 1997, Vancouver Canada

[5] E. Onillon and J.M. Brennan, EPAC Vol 3, June 1996, Sitges Spain, p1842

[6] Digital Control of Dynamic Systems, Franklin, Powell, and Workman, Addison-Wesley Publishing, 1990