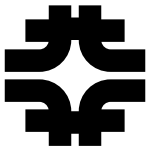

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Trigger Delay Compensation for Beam Synchronous Sampling

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Trigger Delay Compensation for Beam Synchronous Sampling*

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Abstract. One of the problems of providing beam feedback in a large accelerator is the lack of beam synchronous trigger signals far from the RF signal source. If single bucket resolutions are required, a cable extending from the RF source to the other side of the accelerator will not provide a synchronous signal if the RF frequency changes significantly with respect to the cable delay. This paper offers a solution to this problem by locking to the RF, at the remote location, using a digital phase locked loop. Then, the digitized frequency value is used to calculate the phase shift required to remain synchronized to the beam. Results are shown for phase lock to the Fermilab Main Ring RF.

INTRODUCTION

Most fast, wideband beam instrumentation and control require some kind of reference signal which remains stable and in phase with the beam. For storage rings or rings with highly relativistic beam, a stable fixed oscillator would provide the necessary signal. For lower energy accelerators, however, one needs a source which tracks the changing velocity of the beam. The Fermilab Main Ring is such an accelerator, and it derives beam synchronous triggers from the RF acceleration system. These triggers are then used to control dampers (1), kickers, and diagnostics equipment. Although the position of the beam relative to these triggers remains constant from cycle to cycle at a given time in the cycle, they do not remain in the same position relative to beam throughout one cycle. This paper discusses the reason for this phenomenon as well as offering solutions to counteract the problem.

* Operated by the University Research Association, Inc. under contract with the US Department of Energy.

MAIN RING RF TIMING

The Main Ring RF system is used to accelerate the beam, therefore it must remain phase locked to the beam in order to remain effective. The phase of the voltage controlled oscillator (VCO) must lead the phase of the beam by the same amount of time it takes for the signal to get to the amplifiers, through the cavities, and across the gap at the correct phase for the beam. By providing a delay in the feedback loop of the VCO, the phase error between the beam and the VCO can be reduced by a factor of the open loop gain of the system. This delay must be short enough, however, to maintain the stability of the loop. Figure 1 shows a simplified diagram of the Main Ring phase loop. With the configuration shown, the phase error at the phase detector will equal the phase error at the accelerating cavity. Thus, the signal coming out of the VCO is not synchronous with the beam until 500 ns after it is created.

The triggers used to control synchronous events are derived from the VCO signal. The Main Ring Beam Synch system (MRBS) divides the VCO frequency by seven and distributes this clock signal around the ring. Encoded on this clock are different timing critical events such as the event for firing Booster extraction kickers, the event for firing Main Ring extraction kickers, and events marking the

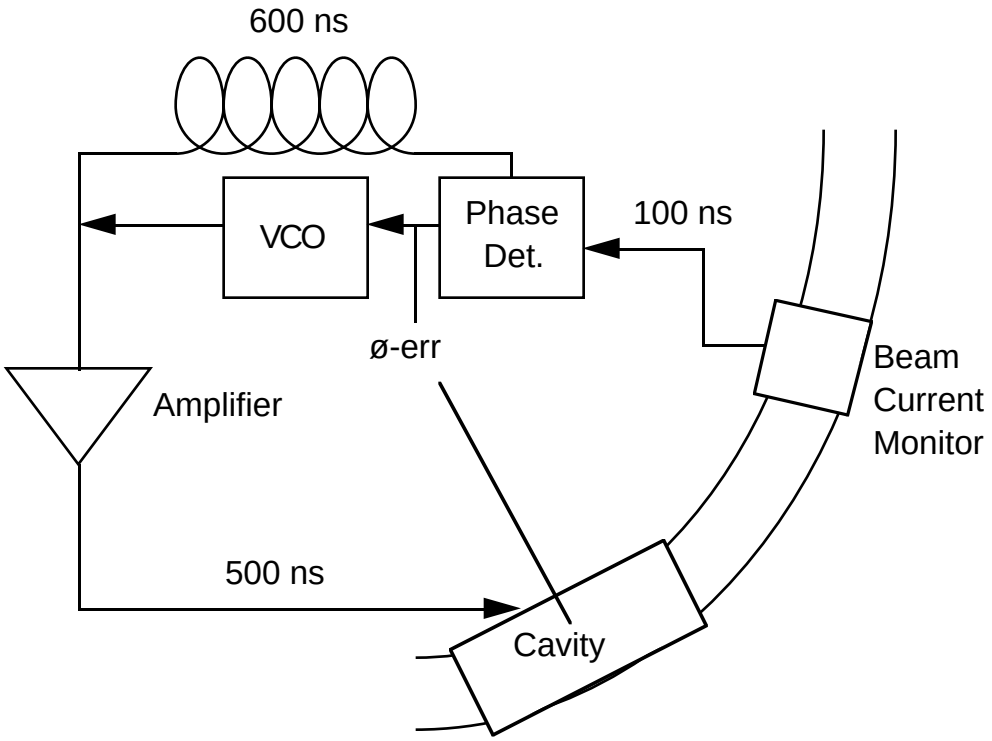

Figure 1. Block diagram of the Main Ring beam phase feedback system. Notice that the phase error at the phase detector will match the phase difference between the VCO and the beam at the cavity.

first bunch every revolution for a partially filled machine. The events for the kickers can be calibrated at a particular point in the acceleration cycle (usually the beginning and end of the cycle) and remain precise to a beam bucket on each cycle. The events for marking a bunch, however, only remain precise at short distances from the VCO.

Effects of Delay Errors

Using the MRBS system as a beam synchronous trigger requires careful monitoring to ensure that the trigger is delayed properly with respect to the beam. If the signal is not delayed properly, phase errors between the trigger and the beam will develop as the velocity of the beam increased. One way to simulate the effect is to drive two cables of unequal delay with an RF source. At any one frequency, the phase difference between the two cables are fixed, but as the frequency changes, the phase difference between the two cables changes according to equation (1). The last approximation in equation (1) assumes that we perform the integration where the frequency slew appears relatively flat over a time span equal to the difference in the delays.

$$\begin{aligned}\Delta\phi &= \int_0^t (\omega_{rf}(t') - \omega_{rf}(t' - \Delta t))dt' \\ &= \int_{t-\Delta t}^{t} \omega_{rf}(t')dt' - \int_{-\Delta t}^{0} \omega_{rf}(t')dt' \\ &\cong (\omega_{rf}(t) - \omega_{rf}(0))\Delta t\end{aligned} \tag{1}$$

The Main Ring RF changes its frequency by about 300 kHz over the entire cycle. For triggering applications close to the VCO, the delay error will be on the order of the total delay of the acceleration system. This corresponds to a maximum phase error of about 300 kHz * 600 ns = 65°, which is too large a phase error to ignore even close to the VCO.

A real problem exists for synchronization at any location other than someplace close to the RF system. About two miles of cable is require to send the VCO signal to the other side of the ring. This comes out to a delay of about 16μs, which corresponds to a phase error of almost five complete cycles. This means that a trigger you set up to be synchronous with the start of every batch at injection will be off by five buckets at extraction.

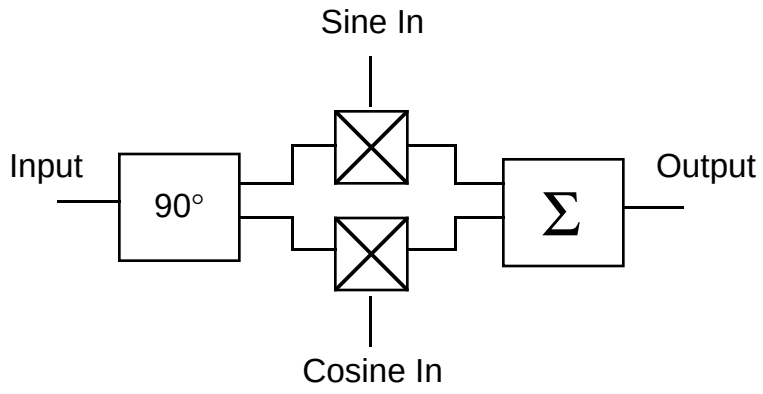

Figure 2. I & Q Phase Modulator. The cosine and sine inputs are driven by a voltage which is proportional to the real and imaginary parts of the output signal desired.

DELAY DIFFERENCE COMPENSATION

For any application which relies on a synchronous trigger signal to sample or kick the beam throughout the Main Ring cycle, the phase errors caused by differences in delays are unacceptable. One way to correct the problem is to delay the beam signal by an amount equal to the extra delay of the trigger signal from the VCO. Unfortunately, this could be as much as two miles of cable at a place in the ring far from the VCO. Compensations of this type would be impossible for kickers because an equal negative delay would be required.

Open Loop Compensation

Another possibility for compensating the delay difference is to use an I & Q phase modulator and two arbitrary function generators. Figure 2 shows a block diagram of the phase modulator. The function generators drive the multipliers which control the ratio of the real and imaginary components of the RF drive. These function generators are programmed to provide a phase shift equal and opposite to the phase shift induced by the difference in delay. One draw back to this method is that the generators be reprogrammed every time the acceleration cycle program is changed. The generators must also be programmed accurately relative to each other, or they could cause phase and amplitude modulations on the output of the modulator.

A more versatile method of correcting the phase errors is to replace the function generators with a signal derived from the VCO frequency. If a table of digital frequency values which tracks the VCO can be created, then the configuration shown in fig. 3 will compensate for delay differences. The

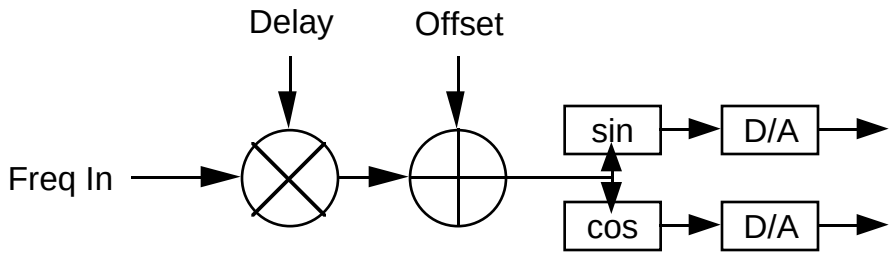

Figure 3. I & Q modulator driver circuit. A digital frequency input will produce two analog signals which are proportional to the real and imaginary parts of the phase shift required.

frequency value is multiplied by a delay value (positive or negative), and a phase offset is added. Then, this phase value is passed through sine and cosine look-up tables and converted to analog signals to drive the I & Q phase modulator mentioned above. The advantage of this over the function generators is that only one function needs to be programmed (frequency), and the sine and cosine look-up tables are calibrated to reduce phase and amplitude modulations. Unfortunately, this method will still require a different frequency table every time the acceleration cycle program is changed.

Phase Locked Loop Compensation

Ideally, there should be a way to measure the VCO frequency throughout the cycle and send the value to the phase shifters without some kind of fixed table. A commercial frequency counter could provide the needed digital frequency value. The value would drive the frequency input of phase shifter, and the VCO itself would drive the other phase shifter input. This works fine if the actual VCO signal is distributed around the ring.

Another way to solve the problem is by using a digital phase locked loop, which drives a direct digital synthesizer (DDS). Figure 4 shows a block diagram of the phase locked loop. The value of the RF wave is sampled by a digitizer which is triggered by the MRBS clock. The digital value is scaled and summed with an integrated signal. Both the scalar and the integration constants are controlled digitally, so the poles of the phase locked loop filter can be adjusted easily. The primary feature of this system is that the circuit provides a filtered digital value equal to the VCO frequency. Another feature of this system is that it provides a new RF signal, which makes it unnecessary to distribute the actual VCO signal.

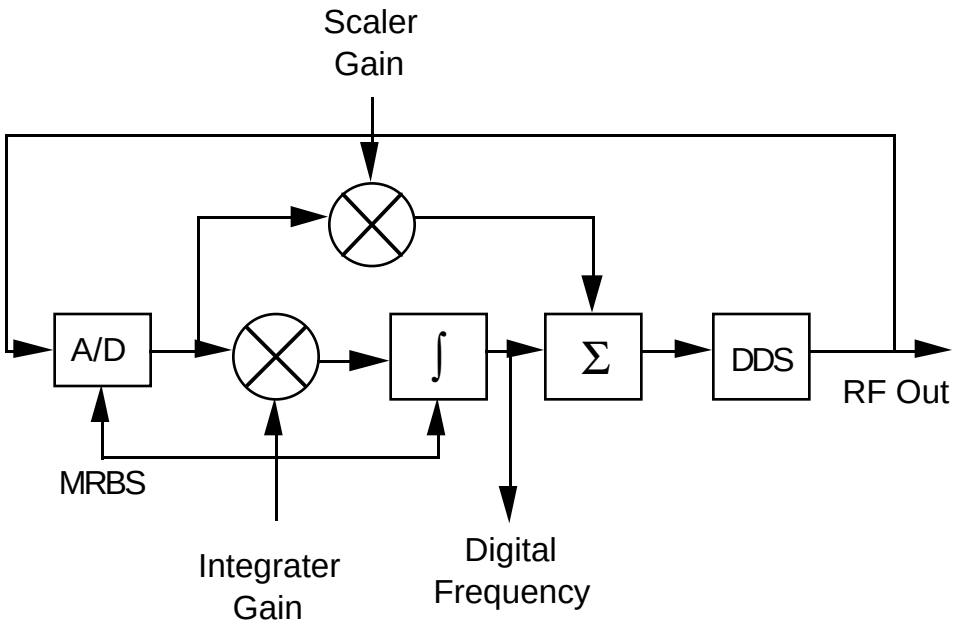

Figure 4. RF regeneration circuit. RF phase locks to the MRBS and produces the digital frequency signal necessary to drive the phase shifter.

Measurement Results

The entire circuit including the RF regeneration circuit, the I & Q modulator driver, and the I & Q modulator was constructed. A Sciteq® ADS-431-203 was used as the DDS. It is capable of being clocked at 1600 MHz, and can output frequencies up to 400 MHz. The digitizer is 8 bits wide and drives an Altera® erasable programmable logic device (EPLD) which acts as the digital filter and delay processing unit. For a clock frequency of 803 MHz and an input frequency of 53 MHz/7, the scalar value of the filter is 3.91E5 s^{-1}, and the integrator value is 3.61E8 s^{-2}. With these settings, the delay precision is about 40 ns, and the maximum possible delay is about 41μs.

The system was then tested on the bench using a network analyzer and a divide by seven RF counter. The network analyzer swept through the Main Ring operating frequencies from 52.8 MHz to 53.1 MHz, and the sweep time was adjusted to provide the maximum frequency slew rate that the Main Ring will require (about 2 MHz/s). Tracking errors were less than half of a degree at this slew rate. The system does have repeatable errors in the phase shift circuitry, though. As the programmed delay causes the phase shifter to shift the signal through 360°, there is a ±0.2 dB error in amplitude and a ±3° error in phase. These errors can be calibrated out by reprogramming the sine/cosine look up tables.

Random errors are much more detrimental to the operation of the system than the fixed errors. Phase modulation noise was measured, and it was usually about -110 dBc/Hz out to 15 MHz. Amplitude modulation noise measured about -120 dBc/Hz out to 400 kHz, but the amplitude modulation spectrum also contained spurs at about -57 dBc. These values are typical values. One can measure the worst case noise properties by setting the input frequency to a point where 21 bits on the DDS are toggling to sustain lock. In this case, there are phase modulation spurs at -54 dBc and amplitude modulation spurs at -49 dBc. Also, the AM noise floor is increased to -80 dBc/Hz.

Future Plans

This system will certainly be applied to the operation of the Main Ring dampers, and it may also be applied to other beam synchronous applications. Hopefully, though, the days of the RF regeneration circuit are numbered. The entire accelerator will be converting its analog VCO and accelerating system into a digital DDS system. When this happens, the value of the DDS frequency could be distributed around the ring with a carrier at the DDS frequency itself. Once the RF signal and frequency value are extracted, the only necessary components are the I & Q modulator and the I & Q modulator driver. Plans are currently being discussed for maintaining ring wide beam synchronous signals in the Main Injector.

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