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MODIFICATIONS TO THE FERMILAB BOOSTER-MAIN RING BEAM TRANSFER PHASE LOCK CIRCUIT

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Summary

Modifications have been made to the circuit which phase locks the Booster Accelerator beam to the Main Ring Accelerator RF oscillator used during injection time. The improvement in the transient response allowed the Booster RF voltage amplitude to be lowered to match the bucket shape to the Main Ring bucket shape. Effects of the RF cavity bandwidth and the delay time in the Booster RF system are discussed.

Introduction

Synchronization of the Booster beam to the Main Ring RF bucket before transfer of beam from the Booster to the Main synchrotron at Fermilab has been previously described.[1] One of the future developments listed there is the improvement of phase lock of the Booster beam to the Main Ring crystal controlled oscillator. Photographs in that paper clearly show the phases are not really locked but actually undergoing damped oscillations at the booster synchrotron frequency.[2] Figure 1 shows the phase difference between the Booster beam and the Booster RF accelerating voltage (upper trace) and the phase difference between the Main Ring injection oscillator and the booster beam for eight booster cycles. The lower trace also shows some small 80 KHz oscillations which makes the trace appear unfocused.

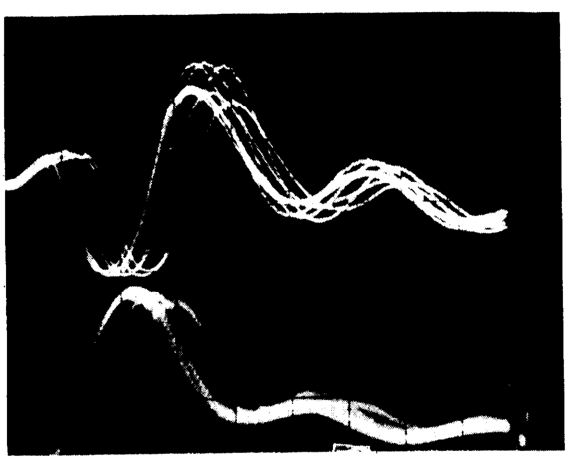

Fig. 1 Signals before circuit modifications

Top: booster beam - booster RF phase difference (15 /div)

Bottom: booster beam - Main Ring RF phase difference (25 /div)
10 booster cycles shown

The first half-cycle in the beam-RF phase error (upper trace) has a maximum deviation of about 30°. Lowering the RF voltage amplitude caused this deviation to become larger - i.e., more phase shift needed to reach the same accelerating voltage. The beam was then lost due to the nonlinearity of the RF combined with the underdamped feedback system.

Figure 1 also shows that the system is neither frequency nor phase locked, since the (ringing) transient has not died out at the time the beam is transferred to the Main Ring. So neither the momentum nor the phase is matched. Additionally, since the start of the phase lock process varies by several hundred microseconds from cycle to cycle in the Booster accelerator, each of the thirteen batches injected into the Main Ring has a different momentum and phase error.

Description of Feedback Loops

During acceleration there are two feedback loops from the beam to the low-level RF system, the phase loop which forces the cavity phase to follow the beam phase and the radial position loop which keeps the beam in the center of the aperture, i.e., forces the beam to have the synchronous energy. During extraction the phase error between the Main Ring oscillator and the Booster beam is substituted for the radial position error.[1] The block diagram for the system during this synchronizing time is shown in Figure 2.

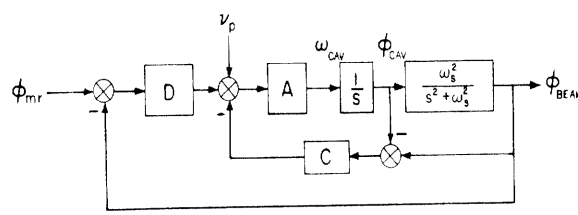

Fig. 2 Block diagram of booster phase feedback system (inner loop) and booster to Main Ring phase lock loop (outer loop)

The s-domain transfer function from the frequency program voltage (v_p), to the beam phase ($\emptyset_b$) is

$$\frac{\emptyset_b}{v_p} = \frac{A}{s} \frac{\omega_s^2}{s^2 + ACs + \omega_s^2}$$

where A is the voltage controlled oscillator transfer function and C is the phase detector transfer function. Critical damping is obtained when the product of these two is equal to twice the synchrotron frequency (ω_s)

$$AC = 2\omega_s$$

then

$$\frac{\emptyset_b}{v_p} = \frac{A}{s} \frac{\omega_s^2}{(s + \omega_s)^2} \triangleq G(s)$$

The transfer function from the main ring injection oscillator ($\emptyset_{mr}$) to the beam phase is

$$\frac{\emptyset_b}{\emptyset_{mr}} = \frac{G(s)\, D(s)}{1 + G(s)\, D(s)}$$

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$$\frac{\phi_b}{\phi_{mr}} = \frac{A\omega_s^2 D(s)}{s(s + \omega_s)^2 + A\omega_s^2 D(s)}$$

Where D(s) is a second phase detector.
For the unmodified circuit

$$D(s) = D_0 \frac{s + \omega_s}{\omega_s}$$

$$\frac{\phi_b}{\phi_{mr}} = \frac{A\omega_s D_0}{S(s + \omega_s) + A\omega_s D_0}$$

$$\frac{\phi_b}{\phi_{mr}} = \frac{A\omega_s D_0}{S^2 + \omega_s S + A\omega_s D_0}$$

For AD_0 larger than half the synchrotron frequency, this system will ring. From Figure 1, the ringing is about the same as the synchrotron frequency so AD_0 must be about equal to ω_s.

The roots of denominator can be approximated from Figure 1 as

$$s = \sigma \pm jw \simeq 2\pi\,(0.8 \pm j\,1.6)\,10^3 \text{ Hz}$$

D(s) was actually a "phase advance" network with a zero at ω_s and a pole at 10 ω_s. At frequencies above 10 ω_s the open loop gain changed at -60 db/decade. The small 80 kHz oscillations in Figure 1 are caused by 180° phase shift before the open loop gain reaches unity. Additional phase shift is introduced by the bandwidth of the RF cavities. At 53 MHz their Q is about 1000, so they introduce another pole at about

$$f = \frac{f_{rf}}{2Q} = 26 \text{ kHz}$$

Modifications

Since the model signal is an exponential with a 200 μ sec time constant, the closed loop gain should have zero phase shift to beyond 800 Hz. Thus a phase error at the input makes a phase correction (not the integral of phase) at the output. The phase advance network was changed to have a zero at 300 Hz and a pole at 3 KHz, and a second phase advance network with a zero at 10 KHz and a pole at 45 KHz was added. This combination makes a pseudo-differentiation network over the range of 300 Hz to 45 KHz.

Results

Figure 3 shows the beam-RF voltage phase error, the Main Ring phase to beam phase error and the radial position during the last two milliseconds of 13 booster accelerator cycles. Frequency lock takes place at the transient peak. During the remaining time before extraction the phase error is reduced, but not to zero because of finite open loop gain and the frequency program (v_p). Figure 4 shows the error signal and also the compensated error signal which is clearly not the derivative of the error but does have some phase advance.

The top trace of Figure 3 shows that the acceleration of the beam to final energy takes place in about 250 μ sec and the maximum phase shift is 18 to 30 degrees depending on the switching time. The booster RF voltage has been lowered and is about 280 kv at the

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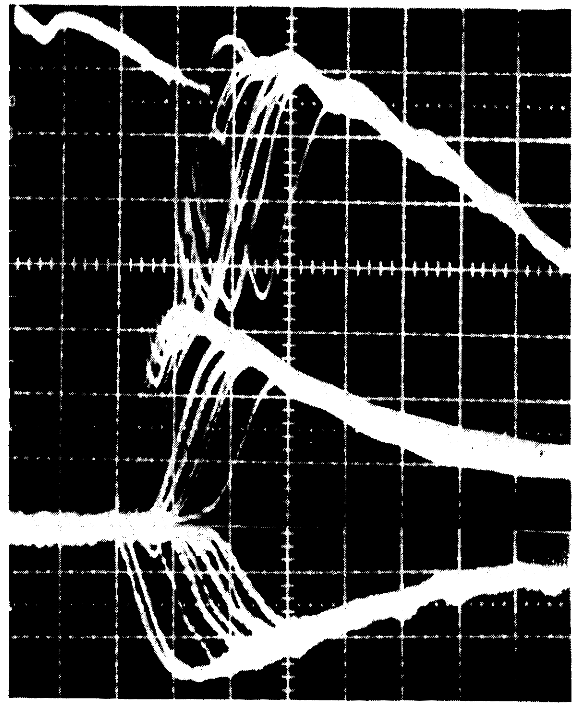

Fig. 3 Signals after circuit modifications

Top Trace: booster beam - booster RF phase (6° per division)

Middle Trace: Main Ring-RF booster beam phase (25° per division)

Bottom Trace: booster beam radial position (1.2 mm per div)

Time Axis: 200 μ sec/div

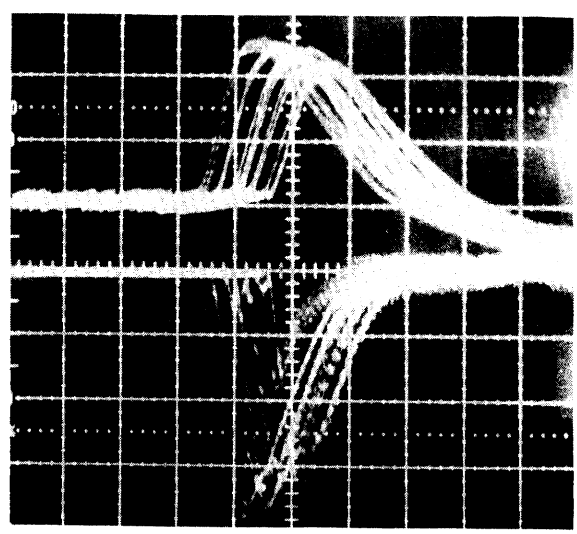

Fig. 4 Top: Main Ring RF to booster beam error

Bottom: compensated error signal

beginning of the traces and 200 kv at extraction at the right side of the figure.

Figure 5 shows the RF voltage during the booster cycle. The upper trace has a constant 300 kv for the last 2.5 m sec while the lower trace shows the modified voltage with 200 kv at extraction, the correct value for phase space matching to the Main Ring.[2]

Fig. 5 Booster RF voltage during one booster cycle

Upper: voltage 300 kv for final 2.5 m sec of cycle

Lower: voltage reduced to change linearly to 200 kv at extraction

Horizontal Axis: 5 m sec/div

Conclusions

The modification of the phase lock circuit between the Main Ring RF oscillator and the booster beam has eliminated ringing and decreased the acquisition time to about 250 μ sec. This improves the Main Ring beam in three ways:

(1) Momentum matching - the booster beam is frequency locked to the Main Ring injection frequency

(2) RF phase matching - the booster beam bunches are locked to the Main Ring RF buckets

(3) Phase space shape matching - the booster RF voltage amplitude was lowered to match Booster buckets to the Main Ring buckets.

Further improvements in open-loop gain and stability could not be made due to the large number of operational amplifiers in the circuit. A new low-level RF system is described elsewhere.[4] This system is somewhat simpler and further improvements will be easier to implement. The voltage controlled oscillator has a wide modulation bandwidth[5] and op-amps have been kept to a minimum. It may be possible to cancel the poles due to the beam and RF cavities, but one of them may be kept to suppress the multiple poles of $(1+e^{s\tau})$ due to the 1.4 μ sec delay time through the Booster RF system.[6]

References

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