SYNCHRONOUS TRANSFER OF BEAM FROM THE NAL FAST CYCLING BOOSTER SYNCHROTRON TO THE NAL MAIN RING SYSTEM

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Summary

Beam from successive cycles of the 15-Hz booster synchrotron is stacked end to end in the main synchrotron with constant magnetic field. Beam already injected into the main ring is held in stationary rf buckets, and the rest field is determined by the circulating beam. To capture beam from subsequent booster cycles into the empty buckets in the main ring, the phase and frequency of the rf beam bunches in the booster are locked to the main ring rf system before beam is transferred. The magnetic fields in the booster and the main ring are regulated separately and tuned for the correct orbit radii and particle momentum. The azimuth of the beam circulating in the main ring is monitored by counting main ring rf cycles, and the beam transfer system is timed to inject beam from successive booster cycles in the correct sequence around the main-ring circumference.

Introduction

Beam is injected into the 1-km radius main synchrotron at NAL from an 8-GeV fast cycling booster synchrotron.[1] The 8-GeV beam is extracted from the booster with a fast kicker magnet system which produces a batch of beam whose length is equal to the circumference of the booster. However, the circumference of the main ring is 13.25 times larger. To fill the main ring with beam, the magnetic field in the main ring is held constant at the injection value for 0.8 sec. at the beginning of each main-ring cycle. The booster cycling frequency is 15 Hz so that batches of 8-GeV beam are injected every 66.6 msec. During the 0.8 sec. injection time, up to 13 batches of beam from successive cycles of the booster can be stacked in azimuth around the main ring. This process is illustrated schematically in Figure 1.

The harmonic numbers of the booster and the main ring are 84 and 1113, respectively, in the ratio of 1:13.25. Each "batch" of protons injected from the booster occupies 84 of the 1113 main-ring rf "buckets" so that thirteen batches may be injected in head-to-tail order with 21 empty buckets available as spaces between the batches.

When batches of 8-GeV beam are transferred from the booster to the main ring, the frequencies of the rf accelerating cavities in both synchrotrons must be identical and the rf bunch structure in the booster beam must be in phase with the main-ring rf "buckets" so that the beam can be captured in the stationary buckets. In addition, the momentum of the beam from the booster must be identical to the synchronous momentum of the main ring at the instant beam is transferred from one accelerator to the other.

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The booster magnetic field varies according to a biased sine wave. Thus, $\dot{B}$ is zero and the beam is in stationary rf buckets at the extraction energy. If the rf accelerating voltage which creates the stationary buckets in the main ring has its design value of 1.5 mV/turn, an rf voltage of 0.31 mV/turn is required in the booster to match the shape of booster beam bunches to that of the main-ring buckets.[2] The momentum width of the main-ring buckets is 6.8×10^{-3} and the matched bunches of the booster beam have a phase width of 0.74 radians and a momentum width of 1.26×10^{-3}. Placing the beam into an rf bucket with an accuracy of ±10% of each beam bunch dimension requires the error in phase between the booster beam bunches and the main-ring buckets to be less than ±4.2°, and the central momentum of the booster beam must equal synchronous momentum of the main ring to within $\pm 1.3 \times 10^{-4}$.

Several schemes based on different logic for achieving this "synchronous" transfer of beam were investigated. The scheme adopted and described here is to regulate the parameters in the main ring to predetermined values and to adjust the parameters in the booster to match. The main-ring rf frequency is set to a fixed value by a signal generator, and the main-ring field is regulated to a constant value by feedback from the radial position of the beam. For transfer, the booster beam-bunch phase, hence the bunch frequency, is synchronized to that of the main-ring buckets by a phase-lock loop. The momentum match is ensured by extracting the beam from the booster at a preadjusted peak field intensity. The stability and repeatability of the peak field of the booster is regulated to better than 10^{-4}.

Phase Matching

In the booster rf system, an approximate rf frequency program is generated by a digital stored-program function generator. During acceleration, corrections to the frequency program are made by a slow feedback loop which keeps the beam at the correct radial position in the aperture and by a fast feedback loop which damps coherent phase oscillations.

In the beam-control system, only one dc coupled loop is used--radial position. A high-pass filter with a cutoff of 300 Hz in the phase loop removes the dc component of the synchronous phase ϕ_s. In this form the loop serves to damp coherent phase motion. During acceleration, the dc component of ϕ_s is established by radial feedback only. The beam can be steered during the acceleration cycle by comparing the position voltage to that of a "model" produced by the digital, stored-program waveform generator. The error between actual position and the model shifts the frequency to bring ϕ_s to the value required to maintain the desired radius. Loop gains are programmed throughout the acceleration cycle by the stored-program function generator.

To synchronize the two rf systems, the main-ring rf signal is transmitted to the phase-lock unit in the booster low-level rf system. The phase-lock circuit monitors the instantaneous phase difference between the main-ring rf signal and the rf structure of the beam bunches in the booster. The main-ring rf frequency remains fixed at 52.8126 MHz during the entire beam transfer process.

Prior to extraction, the booster radius is programmed to the inside. Since it is operating above transition, its rf frequency will match that of the main ring several msec before extraction. At this point, the control of the booster frequency is determined by the main-ring frequency via the phase-lock circuitry instead of the booster radial position system. With its revolution frequency fixed, the beam then sweeps outward with the rising magnetic field. When the field has reached the 8-GeV value, the beam is extracted. Since injection into the booster, the beam size has shrunk sufficiently that there is adequate radial aperture available for the 1-cm radial excursion required.

For the moment, consider that during the interval before phase lock, $\dot{f}$ is essentially constant (9 MHz/sec), we can describe the instantaneous phase difference between booster bunches and main-ring buckets by:

$$\phi = \dot{f}\,(t^2/2) + \theta \qquad (1)$$

where $\dot{f} = 9 \times 10^6$ Hz/sec and θ is the residual phase error when the frequencies are equal. From this relation, plotted in Figure 2a, we see that booster bunches and main-ring buckets are aligned at t_1, t_2 .... The phase comparator translates the curve of Figure 2a into a voltage which "folds over" or changes sign every $2N\pi$ to give the characteristic voltage waveform shown in Figure 2b.

The phase-lock system must provide a smooth transition from the basic characteristic of Figure 2a to an arbitrary fixed phase of $2N\pi$ as indicated by the dashed curve. This is required to keep beam within the booster buckets during the phase shifting process. The transition starts π radians ahead of the final value with an initial slope made to approximate the slope of the phase characteristic at the start of the phase lock. This approximates a frequency match at the start of phase lock.

The phase detector monitors the instantaneous phase difference between the main-ring LLRF and the output of a beam current transformer located in the booster. A phase shifter is employed in the line between the main-ring LLRF and the phase detector. This enables the operator to adjust the length of this line so that in-phase voltages at the detector correspond to the booster bunches being aligned azimuthally with the main-ring bucket centers as the beam passes through the main-ring inflector. Because the frequencies are fixed at the time of extraction, this requires little adjustment once it is set.

With reference to Figure 3, we see that the main-ring rf and the booster beam are compared in phase twice. The first phase detector generates the characteristic of Figure 2b except that it "folds over" every π radians. Its output provides a measure of the difference frequency between the two input voltages to be used by the frequency discriminator. It also provides data to logic circuits which indicate the slope of the phase-voltage characteristic. The second phase comparator receives inputs at half the fundamental frequencies. This scaling is done to provide a zero volt output when the two fundamental references are in phase. This phase detector also supplies data to the logic circuits. The logic circuits perform two important functions; they synchronize the start of the phase lock π radians before the beam is aligned with the empty buckets, and they indicate what the sign should be when the phase lock is turned on. Sign changing is required to compensate for the "fold over" characteristic of the phase detector. The frequency discriminator measures the time interval between consecutive zero crossings. When this exceeds some value set by the operator, the discriminator enables the phase lock to begin.

At the onset of phase lock, the output of the second phase detector is held to serve as the initial value for a "model" to which we would like the phase to conform during its transition to zero. This model is presently an exponential decay with the time constant chosen to provide a fair match to $\dot{\phi}$ at the start of phase lock. The model and phase detector are compared to provide an error voltage for the booster LLRF. The appropriate sign is given to this error by the logic. At the start of phase lock, the gain of the booster radial position feedback is programmed off and in its place the phase-lock error voltage takes control. The transition is quite smooth since initially the model and the phase detector have the same value and no error voltage is developed. Oscilloscope traces of pertinent booster parameters are shown in Figure 4 for a typical booster pulse. This system presently brings the phase within ±6° of the bucket center.

Momentum Matching

During the injection process, the voltage controlled oscillator (VCO) in the main-ring rf system is locked to a signal generator whose frequency is set to

$$f_t = h\beta c/2\pi R = 52812.6 \text{ kHz}$$

where βc is the velocity of 8 GeV protons, $2\pi R$ is the main ring orbit length and h, the harmonic number, is 1113. The main-ring injection field is set by the operator to achieve a momentum match between the two machines within 10^{-3}. Once the first batch is injected, radial position information is derived from a pair of diagonally split induction electrodes. This information is normalized to render an intensity independent voltage proportional to $\Delta R/R$, a small deviation about the equilibrium radius R. This voltage is used to trim the field seen by the beam to keep it in the center of the aperture ($\Delta R = 0$). In other words, the main-ring magnet is automatically tuned to match the momentum of the first batch transferred from the booster. It is required that the momentum error be maintained to less than 10^{-4} on successive batches transferred from the booster.[2] The transfer process is initiated at a fixed time in the booster cycle and the peak magnetic field of the booster is regulated to have jitter of less than 0.5 G out of 7 kG from cycle to cycle.[3]

Following injection of the last booster batch, the main ring rf phase-lock reference is transferred from the reference oscillator to the beam pick-up electrode thus locking the VCO to the beam rf structure. At the same time, the radial position monitor output is applied to an electronic phase shifter to shift the phase of the cavity voltage relative to the VCO to establish the synchronous phase angle required for acceleration. The error voltage required to trim the field is maintained at the value which existed following the last injection.

Azimuthal Stacking of Successive Batches

The transfer of from 12-13 successive booster cycles must be timed in such a way that the beam is stacked head to tail around the circumference of the main ring. (See Figure 6.) The booster extraction system and main-ring injection system must be synchronized with a reference point on the main-ring circumference which indicates where beam is to be placed. A marker pulse is derived by counting cycles of the main-ring rf voltage and scaling by the main ring harmonic number. The result is a pulse train occurring at the main-ring revolution frequency. When transfer time is reached in the booster cycle, a pulse from the booster clock enables the timing system to synchronize with the marker pulse train. This synchronization results in a jitter in the booster extraction time from cycle to cycle of up to 21 μsec, the time of one revolution of beam around the main ring. $\dot{B}$ in the booster is sufficiently low at this point that the momentum jitter caused by this is insignificant. Following each transfer of beam to the main ring, the marker is delayed by 1.6 μsec, the time of one revolution of beam around the booster. Thus, the injection of beam from one booster cycle starts just after beam from the previous cycle has passed through the main-ring inflector. The revolution marker initiates the transfer of the first batch in the same way as the later ones.

As can be seen by the sequence of events shown in Figure 6, both septums must be triggered long before the kickers are fired. The timing jitter between the pulsed components in the transfer system must be less than 5 μsec. In this system, the required delay is achieved with a 10-bit shift register which is clocked by the train or reference pulses from the main ring. This, of course, provides drift-free increments of 21 μsec, but finer trimming is carried out with conventional one-shot delay elements.

Future Improvements

At the present time, the transition "model" for phase lock is a simple exponential decay which can cause large phase oscillations if not well adjusted. The booster rf cavities must therefore be operated at a higher voltage than the matched value to prevent particles from spilling out of the bucket during phase locking. Other "models" will be evaluated to see if they offer any improvement.

Work is being done to synchronize the kick by the extraction kicker magnets with a 2-3 bunch gap in the booster beam. This will prevent radioactivity induced by beam hitting the septum in the booster extraction system during the rise time of the kicker magnets.

With the present configuration of the main-ring low-level rf system, there is little, if any, damping of coherent synchrotron oscillations. Work is under way to provide damping by the use of information from the cavity-beam phase comparator.

Work is also under way to develop a "zero beat" detector. This will enable us to eliminate manual adjustment of the frequency discriminator.

References

1. Booster Synchrotron, NAL Report TM-405 (1973).

2. Matching and Synchronization during Transfer from Booster to Main Ring at 8-GeV, L. C. Teng, NAL Report TM-281.

3. The NAL Booster Synchrotron Power Supply Supply Servo, A. R. Donaldson and R. A. Winje, 1973 Particle Accelerator Conference.

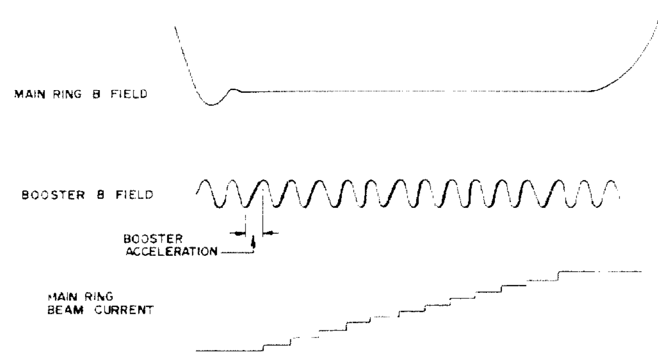

Fig. 1. Multiple pulse injection into the main ring.

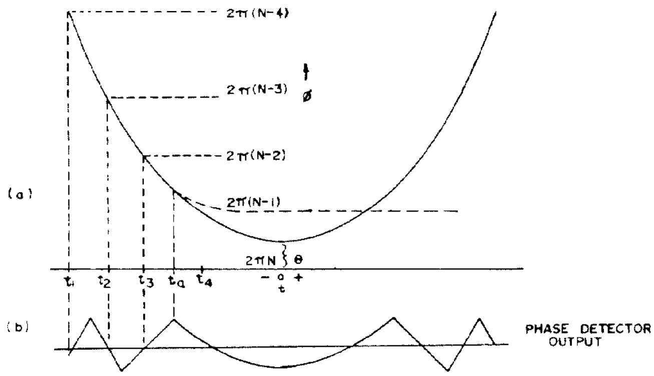

Fig. 2. Booster beam - Main ring bucket phase for constant $\dot{f}$.

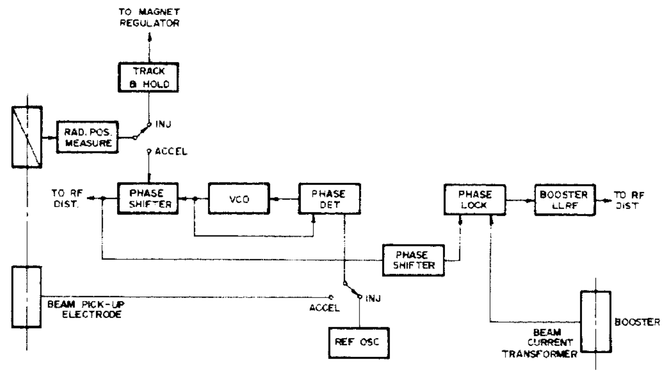

Fig. 5. Main ring low level rf system.

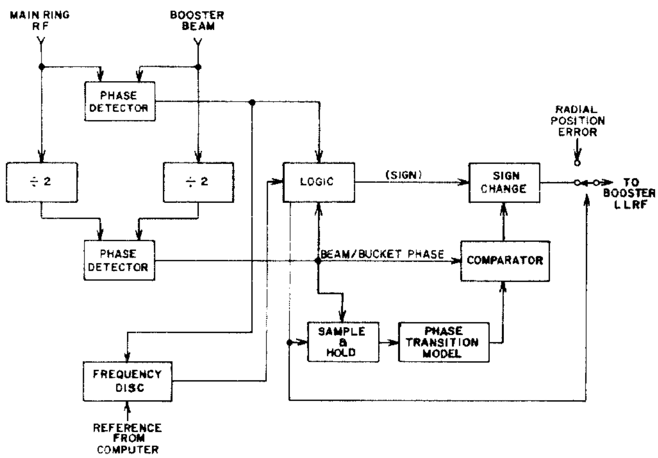

Fig. 3. Phase lock block diagram.

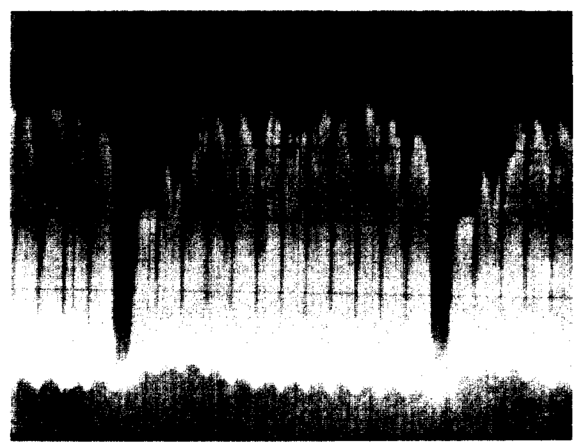

Fig. 6. Multiple batches of beam circulating in the main ring.

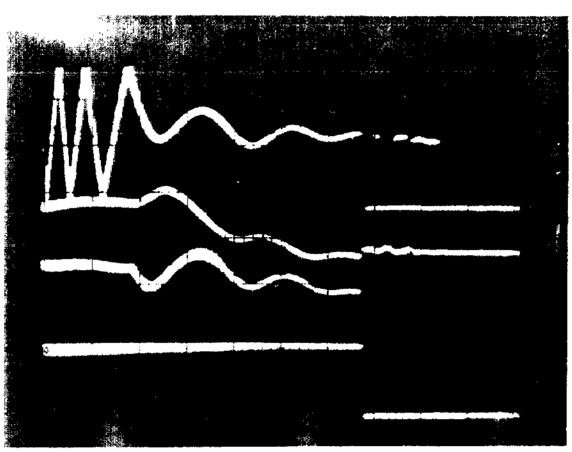

Fig. 4. Booster rf parameters at extraction
Top trace--booster bunch/main ring rf phase
Upper middle--booster radial position
Lower middle--booster bunch/cavity phase
Bottom--booster beam current.

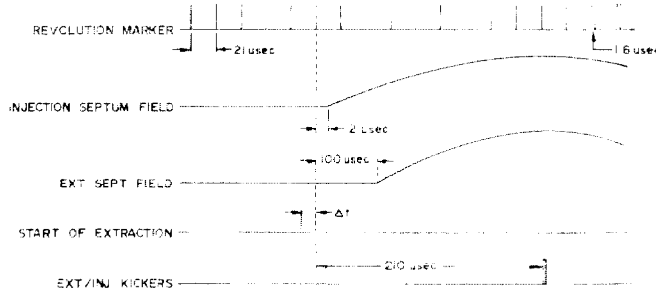

Fig. 7. Beam transfer timing for multiple pulse injection.