SSCL-A-5

Beam Synchronization and SSC Filling Time Considerations

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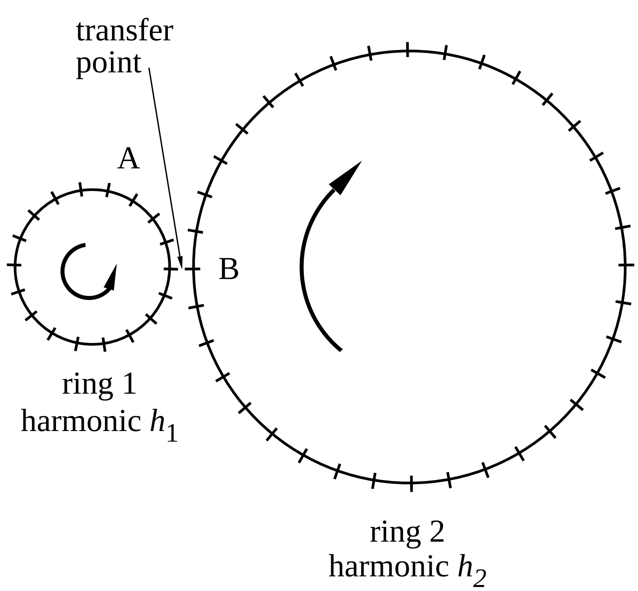
August 1989

General

In beam transfers between the booster rings and into the Supercollider it will generally be necessary to position each injected beam train into specific buckets in the receiving ring. The simplest and cheapest method of arranging flexible bucket synchronization between two adjacent accelerator rings is through choice of the ratio of harmonic numbers of the two rings. Such a method imposes no constraints on the details of the acceleration cycle.

Coarse Synchronization Through Choice of Harmonic

Consider the relative positions of the RF buckets when the beam in ring 1 is available for transfer to ring 2 in the figure below. Assume that the two frequencies are locked at 60 MHz, corresponding to a bunch spacing and RF wavelength of 5 meters. The two RF harmonic numbers are h_1 and h_2. (The collider RF frequency will be 6 times higher, but only every sixth bucket will be used, so that when "ring 2" is the collider ring, the harmonic h_2 will be the "beam" harmonic in the collider, not the RF harmonic.) Let the synchronization objective be to position bucket A in ring 1 alongside bucket B in ring 2 at the point of transfer. Let time t = 0 sometime when bucket B in ring 2 is at the transfer point and bucket A in ring 1 is at some arbitrary azimuth:



At $t = T_2$, which is the revolution period in ring 2, bucket B is back at the transfer point, but bucket A will have moved r bucket positions, where r is the remainder in the division h_2/h_1. That is, express h_2 as

$$h_2 = I_{21} h_1 + r \tag{1}$$

where I_{21} is the integer part of the ratio h_2/h_1. Then after h_1 revolutions of ring 2, the bucket A will have visited each of the h_1 possible bucket positions, provided that h_1 and r do not have a common factor. Thus within the period $h_1 T_2$, bucket A in ring 1 will match up at the transfer point with bucket B in ring 2, which is the required condition for beam transfer.

If h_1 is a prime number, then the condition that r and h_1 have no common factor is, of course, satisfied, but such a requirement would be too restrictive—i.e., sufficient but not necessary.

The condition that r and h_1 have no common factor leads to a second condition, namely that h_1 and h_2 have no common factor also, as consideration of equation (1) can easily show. This second condition (that h_1 and h_2 have no common factor) is certainly necessary and we suspect that it is also sufficient for this synchronization method to work. The present design, however, does not meet this requirement in any of the three transfers, as can be seen from the table below.

Synchronization Times

For the injector chain described in the memorandum "Parameters as of 8/9/89" the maximum required synchronization time $h_1 T_2$ for each inter-ring transfer is listed below. (We assume that the nominal harmonics listed will be adjusted slightly to avoid having common factors in any transfer.)

Ring	$2\pi R$(m)	nominal h	T(μsec)	$h_1 T_2$(sec)	cycle time(sec)
LEB	500	100	1.67	0.0014	≥ 0.1
MEB	4,120	824	13.7	0.030	≥ 4
HEB	10,800	2,160	36.0	0.63	≥ 60
SSC	87,120	17,424	290.4	—	—

We note that the maximum synchronization period $h_1 T_2$ in each ring is only about 1 percent or less of the cycle time of that ring.

We should note that in normal operation all of the buckets in the LEB are full, so that no coarse synchronization is required, in which case the no-common-factor condition on h_1 and h_2 need not be applied. However, in order to allow operation of the LEB with only every nth bucket full, or even with just one bucket full, it will probably be necessary to apply the no-common-factor condition.

The synchronization technique just described provides only the "coarse" synchronization, i.e., it positions bucket A in ring 1 to be roughly opposite bucket B in ring 2. However, there is still the problem of the "fine" synchronization, i.e., the precise centering of bucket A on bucket B. The fine synchronization is to be accomplished through phase slippage of up to one-half an RF period. We will return to this problem after considering the phase-slippage technique in a more general context.

An Alternative Method of Synchronization

An alternative method of adjusting the relative positions of the RF buckets in the two rings involved in a beam transfer is to utilize phase slippage produced by a shift in the radio frequency in one or both rings. It turns out, however, that for coarse synchronization this method is much slower and has the further disadvantage of exposing the beam to dangers associated with the momentum shift involved.

The fractional change in revolution period $\Delta T/T$ associated with a fractional change in momentum $\Delta p/p$ is

$$\frac{\Delta T}{T} = \left(\alpha - \frac{1}{\gamma^2}\right)\frac{\Delta p}{p} ,$$

where α is the compaction factor, and γ the total beam-particle energy in units of the proton rest mass. Therefore, to shift bucket A in ring 1 to any given position in ring 1 requires at most a shift of one half the revolution period. The corresponding number of turns is $1/2(\alpha - 1/\gamma^2)\Delta p/p$, and the total synchronization time required for the frequency-shift method is

$$T_{\Delta f} = \frac{T_1}{2\left(\alpha - \frac{1}{\gamma^2}\right)\frac{\Delta p}{p}} .$$

For illustration, using $\Delta p/p = 10^{-3}$ we arrive at the following estimates for these synchronization times:

Ring	α	γ	$T_{\Delta f}$(sec)
LEB	8.3×10^{-3}	12.8	0.38
MEB	2.9×10^{-3}	213.2	2.4
HEB	1.2×10^{-3}	2132.2	15.

Thus, the required times for coarse synchronization using the frequency shift method corresponding to $\Delta p/p$ of 10^{-3} are for each ring comparable to the nominal cycle time of that ring and thus would significantly increase the filling time of the SSC.

Fine Synchronization

For fine synchronization relative phase shifting of up to one-half an RF period is required. This is a standard problem in all existing booster/main ring systems. At the Fermilab booster-main ring transfer, the phase match is approached adiabatically. At a time well in advance of the desired transfer time, the relative phases and frequencies of the two RF systems are measured. Then a frequency excursion of the booster RF can be calculated which can produce the ideal phase and frequency match at transfer. The process is continually monitored so as to correct small deviations.

If the fine synchronization is delayed until the last possible moment, the minimum required times for fine synchronization in each ring can be obtained by dividing the maximum coarse synchronization times above ($T_{\Delta f}$) by the harmonic number

Ring	$T_{\Delta f}/h$ (msec)
LEB	3.8
MEB	2.9
HEB	6.9

Such periods for fine synchronization would be acceptable for the MEB and HEB extraction scenarios, but not for the LEB because of the concomitant variation of the beam energy (at least 0.3 percent for the LEB running at 10 Hz), as Sam Penner has pointed out.

SSC Filling Time

The filling time of the SSC is dominated by the ramping time of the HEB. Consider the following filling scenario:

(1) The LEB is loaded via multi-turn injection from the linac in 20 or 30 μsec.

(2) The MEB is loaded with 7 beam trains from the LEB, each LEB train containing about 98 bunches. The seven LEB trains are separated in the MEB by 6 gaps of about 2 empty buckets each due to the rise time of the MEB injection kicker magnet. The fall time must be less than the MEB abort gap, which in this case is 126 empty buckets (2.1 μsec).

(3) The HEB is loaded with 3 beam trains from the MEB, each MEB train containing 686 filled buckets and 6 MEB-injection-kicker gaps. Such a loading produces 2,058 filled buckets in the HEB, plus 18 MEB-injection kicker gaps, plus 2 HEB-injection-kicker gaps (6 empty buckets each) and an abort gap of 54 empty buckets (0.90 μsec).

(4) The SSC is loaded with 8 beam trains from the HEB, resulting in 16,464 filled buckets, plus 144 MEB-injection-kicker gaps, plus 16 HEB-injection-kicker gaps, plus 7 SSC-injection-kicker gaps (9 empty buckets each) and an SSC-abort gap of 513 empty buckets (8.5 μsec).

This scenario produces a filling factor of 94.5 percent in the SSC. (The filling factor could be increased to 96.2 percent by adding a special train of 3 LEB batches to be accelerated through the injector chain, thereby shortening the SSC abort gap to 204 empty buckets (3.4 μsec). However, this small addition would lengthen the SSC filling time by about 12.5 percent.)

The total filling time corresponding to the four-step scenario listed above can be expressed in terms of the ramping times of the cycles t_L, t_M, t_H of the LEB, MEB, and HEB, respectively:

$$FT_{SSC} = (7 \times 3 \times 8)\, t_L + (3 \times 8)\, t_M + 8\, t_H$$

which for ramping times of 0.1 sec, 4 sec, and 120 sec, respectively, e.g., evaluates to:

$$\begin{aligned} FT_{SSC} &= 16.8 + 96 + 960 && \text{seconds} \\ &= 0.28 + 1.6 + 16 && \text{minutes.} \end{aligned}$$

Thus, the ramping times of the LEB and the MEB could be appreciably lengthened without significant effect on the total filling time of the SSC.

It must be kept in mind, however, that other considerations, such as beam quality degradation during injection, make it desirable to have short cycle times, especially at low energies.