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**The HEB at Flat Top:
Arranging for the HEB to Collider Beam Transfer**

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The HEB at Flat Top: Arranging for the HEB to Collider Beam Transfer

D. J. Larson

Abstract

The flat top for the High Energy Booster (HEB) is planned to last for only 6.5 seconds, yet during this time the beam must be made to: 1) have the correct central momentum; 2) have the correct bunch-to-bunch spacing; 3) have the correct central phase; and 4) have the correct momentum spread and longitudinal length. All of these attributes must match what the Collider expects or unwanted emittance growth will occur. This paper outlines the techniques necessary to achieve a proper HEB-to-Collider beam transfer within the 6.5 s time constraint. A novel means for cogging is proposed and evaluated. The hardware necessary to implement the beam manipulation and to achieve the four goals is specified, and tolerances on the hardware are evaluated.

Key Words: High Energy Booster, HEB, flat top, longitudinal dynamics, cogging, bunch rotation, rf, phase locking, bucket manipulations.

1.0 INTRODUCTION AND STATEMENT OF THE PROBLEM

Transfer of the protons from the High Energy Booster (HEB) to the Collider involves four conditions that must be met at flat top relevant to longitudinal dynamics:

1. The momentum of the protons must be at a level appropriate for storage in the collider.

$$P_{\text{HEB}} = P_{\text{COLLIDER}} \quad (1)$$

2. The bunch separation must be the same in the HEB as it is in the Collider so that each bunch sees the correct phase of the rf voltage when it recirculates around the Collider.

$$\Delta S_{\text{HEB}} = \Delta S_{\text{COLLIDER}} \quad (2)$$

3. Each bunch must be transferred at the correct time so that it occupies its correct place within the Collider. (This third issue of correct timing for the center of the bunches is termed "cogging.")
4. The momentum spread and longitudinal length of the proton bunches must be adjusted just before they leave the HEB so that they match into the longitudinal environment of the Collider. (A "bunch rotation" must be done that shortens the longitudinal length and increases the momentum spread of the proton beam just prior to ejection from the HEB.)

Since any given machine operates poorest at its lowest momentum, the machine that ejects the beam must be assigned the responsibility for preparing the appropriate beam characteristics prior to ejection. Thus, just prior to ejection from the HEB, beam manipulations within the HEB must be done so that the above four criteria are met simultaneously.

2.0 AN OVERVIEW OF THE HEB CYCLE

Since the Super Collider is designed to collide proton bunches with other proton bunches, some proton bunches must circulate around the Collider clockwise (CW), while other proton bunches must circulate counter-clockwise (CCW). In order to provide both CW and CCW beams, the HEB has been designed as a bipolar device. During one half of the HEB cycle protons will be accelerated CW, and during the other half of the HEB cycle the magnetic fields will all be reversed, with protons accelerated CCW.

During injection of the protons from the Medium Energy Booster (MEB), the magnetic field will remain constant. Injection from the MEB will take 20 s.

The majority of the cycle time of the HEB is used to ramp the superconducting magnets, as the current within the magnets can only be changed at a limited rate. During the acceleration of the proton beam, the proton momentum increases, and the magnetic field required to keep the beam contained increases. The increase in the magnetic field from the injection level to the extraction level requires 100 s. At the end of the 100-s acceleration cycle the magnetic field remains constant for 6.5 s. It is this 6.5-s interval, called the "flat top," that can be used for the beam manipulations required for the HEB to Collider beam transfer.

The entire HEB magnet cycle is shown in Figure 1. In addition to the portions already discussed, there is a magnetic downramp that takes 112 s, a 2.5-s pause at zero magnetic field, and a 10.5-s ramp to achieve the proper field for the next injection. Only the transitions to and from the pause at zero are done instantly. Parabolas of 1.5-s duration link the other various linear portions of the field.

Figure 1. The HEB Magnet Ramp.

3.0 GETTING THE MOMENTUM RIGHT

In order to get the momentum right, the beam must simply be accelerated to the correct value. This will be done during the initial ramp.

4.0 GETTING THE BUNCH TO BUNCH SPACING RIGHT

Within any synchrotron the particles will have a revolution frequency determined by their velocity divided by the circumference of the machine,

$$f_0 = v/C . \quad (3)$$

The rf frequency of the acceleration cavity is set to be an integral multiple of the revolution frequency so that the center of the proton bunch will always experience the same phase of the rf on each revolution. The value of the integer multiplier is called the harmonic number, h , of the machine.

$$f_{RF} = hf_0 . \quad (4)$$

In principle there could be up to h bunches recirculating in each machine. The space in longitudinal phase space capable of containing protons is called a bucket. The rf frequency of the Collider has been chosen to be six times greater than that of the HEB. Hence, only every sixth bucket in the Collider will contain particles. Therefore the bunch separations in the HEB and Collider are determined by the following expressions.

$$\Delta s_{\text{HEB}} = C_{\text{HEB}}/h_{\text{HEB}} ; \Delta s_{\text{COLLIDER}} = 6 \times C_{\text{COLLIDER}}/h_{\text{COLLIDER}} . \quad (5)$$

If all of the bunches are to be transferred correctly, the bunch-to-bunch separation in the HEB at ejection, Δs_{HEB} , must be equal to the six-bucket separation in the Collider, $\Delta s_{\text{COLLIDER}}$. At first glance it might appear difficult to arrange equality between the bunch spacing in the HEB and the bucket spacing in the Collider. Some small value of construction errors is inevitable during construction, and therefore, even though the machine design uses the appropriate values, in reality there will be some error. It is, however, relatively straightforward to correct for small circumference construction errors.

While the physical circumference of a trajectory through the center of the installed magnets will contain an error, it is possible to move the particle trajectories radially away from the center of the installed magnets. If the radius of the particle trajectory is moved outward (inward) the circumference of the particle trajectory will be increased (decreased). It is important to note that one cannot move the particle trajectory too far radially, as the magnetic field quality deteriorates as one moves away from the center. But some adjustment of the particle trajectory can be done by radial displacement. This radial displacement is accomplished by arranging the beam energy to be slightly different than the value required to have the beam centered.

The bunch spacing in the HEB can be made equal to the six-bucket separation in the Collider to within a very small error by simply phase locking the rf cavities of the HEB and Collider to a constant relative phase so that the rf frequency of the HEB is exactly six times less than the rf frequency of the Collider. This is clearly seen when one appreciates that the bucket separation is equal to the particle velocity divided by the rf frequency.

$$\Delta s = C/h = v/hf_0 = v/f_{\text{RF}} . \quad (6)$$

Since the particle velocity remains constant during the transfer, locking the ratio of rf frequencies to six leaves the six-bucket separation in the Collider equal to the HEB bunch separation up to an accuracy determined by the locking technique. This leads to a bunch separation in the HEB that is equal to the appropriate bunch separation in the Collider.

Thus, a simple phase locking of the HEB and Collider rf cavities results in identical bunch separations in the two machines in spite of construction errors. In reality one does not choose the rf frequency to be an integer multiple of the revolution frequency, rather there is just an rf frequency and a series of magnets that act to return the beam. If the circumference of the particle trajectories, which is determined by the magnets, leads to a condition where the revolution frequency is equal to the rf frequency divided by an integer, the particles will all remain in phase with the rf cavity. In the case of the nonaccelerating buckets that exist during the beam transfer, this phase is 180 degrees so that the particle energy does not change. But, if the magnets determine a return path that leads to a revolution frequency slightly greater (less) than the rf frequency divided by the harmonic number, the particles will arrive too early (late) on the next rf cycle. If the particles arrive too early (late) they will see an electric field in the cavity that is accelerating (decelerating). An accelerating (decelerating) electric field will increase (decrease) the particle trajectory, resulting in a revolution frequency closer to the rf frequency divided by the harmonic number.

This is the same process that is responsible for phase stability in particle accelerators. The phase stable region will always be established at a circumference that leads to a revolution frequency, f_0 , that is equal to the rf frequency, f_{RF} , divided by some integer, h .

If the beam is accelerated in a way where it always arrives at the rf cavity at the correct time, the revolution frequency will always be equal to the rf frequency divided by the harmonic number. If the rf frequency reached at the flat top is not six times less than the rf frequency of the Collider, the rf frequency will need to be changed in order to phase lock it. For Eq. (4) to remain valid during a change in f_{RF} , f_0 must also change. If f_{RF} is changed slowly enough, the required change in f_0 will occur automatically. If the frequency needs to be increased (decreased) to phase lock it, on each turn the particles will arrive at the rf cavity a little too late (early) and they will be slightly decelerated. A slight deceleration of the particles causes their frequency to be slightly increased. By continuing this process the energy and hence, revolution frequency of the particles can be changed until it is at the correct value. This is clearly the reason that phase locking of the rf cavities results in identical bunch separations—the beam energy in the HEB is changed during the process until the circumference of the particle trajectories exactly matches what is needed.

4.1. Longitudinal Dynamics Associated With Changing the Rf Frequency

The above discussion is qualitative. The rf frequency is said to be changed “slowly,” and the amount of acceleration and deceleration resulting from such changes is not quantitatively evaluated. A quantitative evaluation of this process will now be done.

At flat top, before any change of frequency, the synchronous particle will have a revolution frequency of $f_0 = f_{RF}/h$, and it will pass through the rf cavity with a phase $\phi = 180$, and therefore the synchronous particle will have no increase in energy on each pass at flat top. If now the rf frequency is changed linearly over time by an amount

$$\delta f_{RF} = B \delta t, \quad (7)$$

a particle will need to undergo an energy change to stay synchronous. In order for a particle to remain synchronous with the now changing rf frequency it is necessary that the revolution frequency of such a particle change by

$$\delta f_0 = \delta f_{RF}/h = (B/h) \delta t. \quad (8)$$

The original revolution frequency is given above in Eq. (3) as

$$f_0 = v/C, \quad (3)$$

and, as shown elsewhere (for one derivation see Reference 1),

$$\delta f_{RF}/f_{RF} = \delta f_0/f_0 = \delta v/v - \delta C/C = -\eta \beta^{-2} (\delta E/E_S) \quad (9)$$

where $\eta = \gamma_t^{-2} - \gamma^{-2}$ and $\beta = v/c$. Here c is the speed of light, $\gamma = (1 - \beta^2)^{-1/2}$ and γ_t is equal to the transition energy of the machine in rest-mass units. Therefore, to remain synchronous, a particle must experience an energy change of

$$\delta E_S = -E_S \beta^2 \delta f_0 / \eta f_0 = -E_S \beta^2 B \delta t / \eta h f_0 \quad (10)$$

or,

$$\delta E_S / \delta t = -E_S \beta^2 B / \eta h f_0 . \quad (11)$$

Assuming a voltage across the gap of the rf cavity of $V \sin \phi$, the energy gained by a particle during one transit of the machine will be $QV \sin \phi$, and since the particles go around once every $1/f_0$ s, the energy gained per unit time is

$$\delta E / \delta t = f_0 Q V \sin \phi . \quad (12)$$

Equating expressions (11) and (12) for the synchronous particle results in the definition of a synchronous phase associated with a linear change in frequency

$$\sin \phi_S = -E_S \beta^2 B / \eta h Q V f_0^2 . \quad (13)$$

Therefore, starting a linear change in frequency has the effect of creating an accelerating or decelerating bucket around the synchronous phase given in Eq. (13).

(Note that a nonlinear frequency change program could also be used. Such a program would result in a synchronous phase still defined by Eq. (13) provided that $B = \delta f_{RF} / \delta t$ is used, where B is no longer a constant but must be evaluated throughout the frequency change program. This results in an ever-changing value for ϕ_S which is a more complicated case for analysis than is presented here.)

4.2 Adiabatic Change in the Rf Frequency

A quantitative estimate of the effect of phase locking in the presence of construction errors is now possible. Again referring to Eq. (6)

$$\Delta s = C/h = v/hf_0 = v/f_{RF} , \quad (6)$$

it is seen that the bunch spacing depends on the circumference of the particle trajectory within the machine. Assuming the beam will be kept in the center of the machine magnets during acceleration, construction errors will lead to a circumference slightly different than the design value. The present survey accuracy is expected to result in a circumference error of $\delta C/C = 1 \times 10^{-7}$, which would lead to a bunch separation error of $\delta \Delta s / \Delta s = 1 \times 10^{-7}$, which can be corrected by changing the rf frequency by an amount $\delta f_{RF} / f_{RF} = -1 \times 10^{-7}$. (Actually, $\delta C/C = \gamma_t^{-2} \delta p/p$, $\delta v/v = \gamma^2 \delta p/p$, and $\delta f_{RF} / f_{RF} = \delta v/v - \delta C/C$. At flat top in the HEB $\gamma_t = 2000$ and $\gamma = 34.475$, so to a very good approximation $\delta f_{RF} / f_{RF} = -\delta C/C$ at flat top in the HEB.) Thus the required frequency change is $\delta f_{RF} = -1 \times 10^{-7} f_{RF}$. Setting the amount of time required for the frequency change as a variable, $\delta t = x$, the coefficient B is

$$B = \delta f_{RF} / \delta t = -1 \times 10^{-7} f_{RF} / x , \quad (14)$$

and therefore the synchronous phase determined by Eq. (13) is

$$\sin\phi_S = -E_S\beta^2 B/\eta h Q V f_0^2 = E_S\beta^2 1 \times 10^{-7}/\eta x Q V f_0. \quad (15)$$

At flat top in the HEB the parameters are approximately $E_S = 2 \times 10^{12}$ eV, $\beta = 1$, $\eta = 8.4 \times 10^{-4}$, $Q = e$, $V = 40\,000$ V, $h = 2160$, $f_{RF} = 60$ MHz and $f_0 = f_{RF}/h$. For $x = 20$ s, $\sin\phi_S = 0.01$, or $\phi_S = 180 - 0.6$ degrees. At flat top the one sigma width of the bunch is 22 degrees, and the phase space smearing caused by changing the frequency over 20 s to arrange a phase lock is thus acceptable. But flat top in the HEB is designed to be only 6.5 s and therefore an adiabatic change in rf frequency cannot be used to lock the phase at flat top.

4.3 Nonadiabatic Change in the Rf Frequency

While a sudden increase in $B = \delta f_{RF}/\delta t$ will result in a discontinuous jump of ϕ_S , a planned stepping of B can result in a fast change of rf frequency without incurring longitudinal emittance growth. This can be done by noting that an initial sudden change from $B = 0$ to $B = C_1$, where C_1 is some arbitrary constant, results in a sudden jump in synchronous phase from $\phi_{S0} = 180$ to $\phi_{S1} = 180 - \theta_1$, where θ_1 is some arbitrary angle determined through Eq. (13). Since the phase jump occurs suddenly, the center of the bunch distribution will be at a phase $\phi = 180$ immediately after the phase jump, and the center of the bunch distribution will begin to oscillate around ϕ_{S1} . After one half of a synchrotron oscillation the center of the bunch distribution will be at a phase $\phi = 180 - 2\theta_1$. If, at the moment the center of the bunch distribution reaches $\phi = 180 - 2\theta_1$, a second sudden change from $B = C_1$ to $B = C_2$ is made to occur, a sudden jump in synchronous phase from $\phi_{S1} = 180 - \theta_1$ to $\phi_{S2} = 180 - \theta_1 - \theta_2$ will follow. By properly choosing C_2 , $\theta_2 = \theta_1$ can be arranged leaving $\phi_{S2} = 180 - 2\theta_1$ and since the center of the distribution is also at $\phi = 180 - 2\theta_1$, the distribution will now be centered on the new synchronous phase and no significant longitudinal emittance growth should occur in this process. At this point the frequency is now increasing at a rate of $B = \delta f_{RF}/\delta t = C_2$, but the goal here is to change the frequency to a new constant value; therefore it is necessary to reduce B to zero once the proper frequency has been reached. B can be reduced to zero without much longitudinal phase space growth in the beam by following the inverse of the process that led to $B = C_2$. At the correct time (determined below) B must suddenly change from $B = C_2$ to $B = C_1$, resulting in a sudden jump in synchronous phase from $\phi_{S2} = 180 - 2\theta_1$ to $\phi_{S1} = 180 - \theta_1$, after one half of a synchrotron period the center of the beam distribution will be at $\phi = 180$ and when this occurs B must suddenly change from $B = C_1$ to $B = 0$, resulting in a sudden jump in synchronous phase from $\phi_{S1} = 180 - \theta_1$ to $\phi_{S0} = 180$, and now both the synchronous phase and the center of the bunch distribution are at $\phi_{S0} = \phi = 180$ although the frequency has been changed. Figure 2 shows an illustration of the frequency change process just described, while Figure 3 shows an "artistic" conception of what happens to the phase space during the frequency change process.

The above description is qualitative. A quantitative description of the process will now be done to determine required parameters for stipulated goals. The bucket area is determined by (for one derivation see Reference 1),

$$A = (1 - \Gamma^{0.79})^{1.27} (\beta/\pi f_{RF}) \{32 E_S Q V T / |\eta| \pi h \Gamma\}^{1/2}, \text{ where } \Gamma = \sin\phi_S. \quad (16)$$

Jim Griffin of Fermilab has suggested that it is best to keep the bucket area constant throughout as much of the HEB operation as possible. Prior to bunch rotation, a value of $A = 3.5$ eV-s has been chosen. Noting that $\beta, f_{RF}, E_s, |\eta|$ and h are constant at flat top leads to the conclusion that Eq. (16) provides a relationship between the synchronous phase, ϕ_s , and the rf voltage, V . The frequency of synchrotron oscillations is determined by (for one derivation see Reference 1),

$$f_s = \omega_s/2\pi = (f_0/\beta)(-h\eta QV\cos\phi_s/2\pi E_s)^{1/2} . \quad (17)$$

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Figure 2. A frequency change ramp that should result in a minimum of longitudinal emittance growth. The frequency starts out at f_{RF1} , and then at $t = 0$ begins increasing linearly at a rate $df_{RF}/dt = C_1$. At $t = T_s/2$ the rate of increase of frequency increases to $df_{RF}/dt = C_2$. At $t = T_s/2 + T_2$ the rate of increase of frequency decreases back to $df_{RF}/dt = C_1$. At $t = T_s + T_2$ the frequency becomes constant again at the new value f_{RF2} .

Figure 3. "Artistic" conception of longitudinal phase space evolution during the frequency change program depicted in Figure 2. (a) Prior to $t = 0$ the beam resides in a non-accelerating bucket with $\phi_s = 180$. One standard deviation beam size is about 22 degrees. (b) At $t = 0$ the rf frequency begins ramping at a rate $df_{RF}/dt = C_1$, which is equivalent to the synchronous phase jumping to $\phi_{s1} = 160$ and an accelerating bucket is formed. (c) One half of a synchrotron period after $t = 0$, when $t = T_s/2$, the beam rotates in the accelerating bucket to be centered at $\phi = 140$. (d) At $t = T_s/2$ the rf frequency ramp increases at a new, faster rate, $df_{RF}/dt = C_2$, which is equivalent to the synchronous phase jumping to $\phi_{s2} = 140$. A new accelerating bucket is formed and the beam distribution and synchronous phase are now matched. The beam can be accelerated, and frequency changed, for an arbitrary amount of time T_2 . At the end of this arbitrary time the frequency ramp can decrease back to $df_{RF}/dt = C_1$ (back to picture (c)), remain at that rate of increase for half a synchrotron period (back to picture (b)), and then decrease back to $df_{RF}/dt = 0$ (back to picture (a)). This process should allow a frequency and momentum change with little longitudinal emittance growth.

The rate of frequency change is determined through B via Eq. (14), and B is determined by rearranging Eq. (15),

$$B(\phi_{s1}) = -\eta h Q V f_0^2 \sin \phi_{s1} / E_S \beta^2. \quad (18)$$

The amount of frequency change for the process described here is $[B(\phi_{s1})]/[2f_s(\phi_{s1})]$ (which is the change during the first half synchrotron oscillation) plus $B(\phi_{s2})T_2$ (which is the change occurring during an arbitrary time T_2), plus $[B(\phi_{s1})]/[2f_s(\phi_{s1})]$ (which is the change during the second half synchrotron oscillation), or,

$$\Delta f_{RF}(\phi_{s1}, \phi_{s2}, T_2) = [B(\phi_{s1})]/[f_s(\phi_{s1})] + B(\phi_{s2})T_2. \quad (19)$$

In the above expression T_2 can take on any value. (Note that $T_2 = 0$ corresponds to the special case where the center of the beam distribution makes one full synchrotron oscillation in the accelerating bucket and when the oscillation is complete, and the center of the distribution returns to $\phi = 180$, ϕ_s is suddenly changed to 180.)

The largest possible value for ϕ_s corresponds to the case where V is at the limit of the rf system. For the present HEB design this leads to a maximum deviation of ϕ_s from π of about 40 degrees. Thus, the maximum frequency change possible with very little longitudinal emittance growth should occur if ϕ_s is stepped to $\phi_{s1} = 180 - 20 = 160$ degrees, and one half of a synchrotron oscillation later ϕ_s is stepped to $\phi_{s2} = 180 - 40 = 140$ degrees. ϕ_s can remain at 140 degrees for an arbitrary amount of time, and when the time is right ϕ_s can be stepped back to $\phi_{s1} = 160$ degrees for one half a synchrotron period and then stepped to 180 degrees to end the frequency change process.

A computer code using Eqs. (16), (17) and (18) has been written that evaluates V , ϕ_s , f_s and B for various values of the quantity $V \sin \phi_s$. The code assumes values for the remaining variables that correspond to the situation for HEB at flat top, $h = 2160$, $A = 3.5$ eV-sec, $E_s = 2 \times 10^{12}$ eV, $\beta = 1$, $\eta = 8.4 \times 10^{-4}$, $Q = e$ and $f_{RF} = 60$ MHz. For the case of $\phi_{s1} = 160$ degrees, $V(160) = 160$ 000 V, $f_s(160) = 4$ Hz and $B(160) = 38.5$ Hz². For the case of $\phi_{s2} = 140$ degrees, $V(140) = 860$ 000 V, $f_s(140) = 8.6$ Hz and $B(140) = 387$ Hz². Therefore, at these maximum values for ϕ_{s1} and ϕ_{s2} the frequency change is

$$\Delta f_{RF}(120, 140, T_2) = [38.5 \text{ Hz}^2]/[4 \text{ Hz}] + 387 \text{ Hz}^2 T_2. \quad (20)$$

The minimum frequency change under these maximum conditions occurs when $T_2 = 0$, and $\Delta f_{RF}(120, 140, 0) = 9.625$ Hz. Therefore, if the required frequency change is greater than or equal to 9.625 Hz, Eq. (20) can be used to determine T_2 and the procedure outlined here can be followed with $\phi_{s1} = 160$ degrees and $\phi_{s2} = 140$ degrees. For a required frequency change less than or equal to 9.625 Hz different values of ϕ_{s1} , ϕ_{s2} and T_2 will be needed. The simplest way to choose an appropriate value of ϕ_{s1} and ϕ_{s2} for the case where the required frequency change is less than 9.625 Hz is to set $T_2 = 0$. Such a choice leaves

$$\Delta f_{RF}(\phi_{s1}, \phi_{s2}, 0) = [B(\phi_{s1})]/[f_s(\phi_{s1})] = [-f_0 \sin \phi_{s1} / \beta] / [(-E_s \cos \phi_{s1} / h \eta Q V 2\pi)]^{1/2}. \quad (21)$$

Since f_0 , β , E_s , h , η , Q , and 2π are constants at flat top, substituting the required frequency change Δf_{RF} into Eq. (21) thus results in an expression relating V and ϕ_s . Requiring a constant bucket area through Eq. (16) results in a second expression relating V and ϕ_s . Rearranging Eq. (16) leaves

$$V = [|\eta| \pi h / 32 E_s Q] [(\pi f_{RF} A / \beta) (1 - \Gamma^{0.79})^{-1.27}]^2, \text{ where } \Gamma = \sin \phi_s. \quad (22)$$

Thus, substituting the expression for V in Eq. (22) into Eq. (21) leaves an expression that enables a determination of the desired ϕ_{s1} required to change the rf frequency by an amount Δf_{RF} with a minimum of longitudinal emittance growth and a minimum of time devoted to the process.

4.4 Getting the Bunch to Bunch Spacing Right – Time Requirement

It is shown above that an adiabatic change in rf frequency is not possible given the assumed magnitude of frequency change demanded from foreseen construction errors and the amount of time available at flat top. However, it is possible to non-adiabatically change the rf frequency by suddenly changing from the non-accelerating constant frequency associated with flat top to a linearly increasing rf frequency. It is shown above that such an operation amounts to suddenly

changing the synchronous phase. A sudden change in the synchronous phase will result in a motion of the longitudinal phase space about the new synchronous phase. By waiting until the longitudinal phase space evolves to a third stable synchronous phase and then suddenly changing the slope of the rf change, the rf frequency can be changed with little longitudinal phase space growth. Reversing the process brings the slope of rf change back to zero.

The nonadiabatic change in rf frequency proposed is made possible by suddenly changing the slope of rf frequency change and the voltage across the rf cavities. As discussed above, there are two possible cases of rf frequency change to be considered. Both cases start and end with constant rf frequencies but employ different ramp scenarios to change the rf frequency.

Case I. Required rf frequency change greater than or equal to 9.625 Hz.

In this case three linear ramps of the rf frequency are needed. The first and third ramps last for one half of a synchrotron period. $V = 160\,000\text{ V}$ and $B = 38.5\text{ Hz}^2$ for the first and third rf frequency ramps. In between the first and third rf frequency ramps is a second ramp with $V = 860\,000\text{ V}$ and $B = 387\text{ Hz}^2$. The amount of time devoted to the second ramp is found from the desired frequency change by evaluating Eq. (20).

Case II. Required rf frequency change less than 9.625 Hz.

In this case only one linear ramp of the rf frequency is needed, and the temporal duration of the ramp is one synchrotron period. For this case Eqs. (21) and (22) can be used to determine the appropriate values of V and ϕ_s required to lead to the desired frequency change. Eq. (18) can be used to determine the rate of change of the rf frequency. Note that Eqs. (21) and (22) are not analytically solvable, and either a computer code or a computer-code-generated look-up table can be used to solve the equations.

It is estimated that construction errors will result in a need to change the HEB rf frequency by about 6 Hz, which falls under Case II. The amount of time to non-adiabatically adjust the rf frequency under Case II is one synchrotron oscillation period. The longest synchrotron period is associated with the smallest value of V , and a limiting value for V occurs when no frequency change is required, calculated elsewhere¹ to be 0.5 s.

Getting the bunch spacing right thus consists of: 1) Determining the amount of frequency change required to make $f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}}$; 2) Changing f_{RFHEB} to the correct value via either Case I or Case II as appropriate; and 3) Locking the HEB and Collider rf frequencies to a constant relative phase once $f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}}$. The maximum time needed to change the frequency (and get the bunch spacing right) is thus the maximum synchrotron period, calculated elsewhere¹ to be 0.5 s.

4.5 An Alternative Way of Getting the Bunch to Bunch Spacing Right

Up to now it has been assumed that the beam is kept in the center of the HEB magnets right up to flat top. Since construction errors will result in a circumference slightly different than what is needed for phase locking the HEB and Collider rf cavities to a constant relative phase, it is necessary to move the beam radially in order to achieve the locking. Therefore, the desired position of the beam at flat top will not be in the center of the HEB magnets, but rather someplace else. During commissioning of the HEB-to-Collider beam transfer it will become apparent just how much radial displacement is needed to exactly match the HEB-to-Collider circumference. Rather than keeping the beam in the center of the magnets throughout the HEB cycle until flat top, it will be easier to simply allow the beam to drift over to the eventual correct (off center) place during each HEB cycle. Thus, the electronics can be set to assure that the HEB and Collider are

locked to a constant relative phase simply by programming the beam to drift an appropriate amount away from center during the acceleration cycle. This latter approach will almost certainly be used in actual operation, but one purpose of this note is to evaluate the alternatives, one of which is discussed in Sections 4.1 through 4.4.

5.0 GETTING THE TIMING OF THE TRANSFER RIGHT – COGGING

Since the Collider is about a factor of eight larger than the HEB, and yet the bunch separations in the two machines are the same, it will take eight batches of protons to fill the Collider in both the clockwise and counterclockwise directions. (A total of sixteen batches must be transferred.) Each batch of protons must go into the Collider in the correct place. (If a batch is sent into a place where another batch was sent previously, the previous batch will be expelled from the Collider.) The process of getting the timing correct so that each batch will go into the correct place is called cogging.

In practice not all of the places capable of storing particles will actually contain particles. Each machine must kick the particles into the next machine, and it takes a certain small amount of time to turn on the physical apparatus that does the kicking. No particles should be within the kicking apparatus when it is not fully on or off, since any particles not completely kicked will hit something somewhere and cause unnecessary radiation. For this reason there are gaps in the stream of protons. The goal of the cogging process is to set the timing of the recirculation so that the first bunch of protons immediately following the gap will be transferred to the correct place within the Collider.

In addition to getting the timing correct for the transfer of the first proton bunch, it is required that the other bunches in the transferred batch also be transferred at the correct time. This will automatically be accomplished if the bunch separation in the HEB exactly matches the six-bucket separation in the Collider. A proper setting of the bunch separation can be done by equating the rf frequency of the HEB to one sixth of the rf frequency of the Collider, as just discussed in Section 4.

The cogging process actually involves two sub-processes. A coarse cogging must be done so that the first proton bunch is timed so that it will be transferred into the correct 144-bunch region of the Collider. A fine cogging must be done so that the first proton bunch is transferred into the specific single bucket (out of the 144) and exact phase that is desired.

5.1 Coarse Cogging for the HEB to Collider Transfer

Figure 4 is helpful in describing the goal of the cogging process. (Figure 4 has been copied from SSC-N-685, aka SSCL-A-5, a note prepared by Jack Peterson and Miguel Furman.) The position of the first bunch to be transferred from the HEB (A) could be anywhere in the ring at the time the desired position within the Collider (B) reaches the transfer point. The goal of the cogging is to align A and B so that a kicker can be energized to completely and correctly transfer the beam.

The circumference of the Collider is $C_{\text{COLLIDER}} = 87\,120$ m. The circumference of the HEB is $C_{\text{HEB}} = 10\,800$ m. Since the bunch separation is five meters in both cases, this corresponds to a bunch-harmonic number of 17 424 for the Collider and 2160 for the HEB. The bunch-harmonic number for the Collider is defined here as the number of bunches that can be stored with a five-meter bunch separation. Since the HEB bunch separation is six times larger than the Collider bucket separation, only every sixth Collider bucket will contain particles. Thus, the harmonic number for the Collider is six times larger than the bunch harmonic number. Every sixth bucket in the collider will be called a "six-bucket" in this note. (The one to one transfer of HEB buckets to Collider six-buckets is much easier to follow than a discussion that always includes an additional factor of six.)

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Figure 4. Schematic of the Cogging Process. Copied from SSC-N-685, aka SSCL-A-5, a note prepared by Jack Peterson and Miguel Furman.

The coarse cogging will be done with the rf frequencies of the HEB and Collider locked together to a constant relative phase. As described above in Section 4.0, the phase locking also locks the bunch separation of the HEB to equal the six-bucket separation in the Collider, and this in turn locks the relative circumferences of the two machines into an integer relationship. Due to the relative circumferences of the two machines, when a bunch in the HEB goes around once, a bucket in the Collider will have advanced 2160 six-bucket spacings. After eight revolutions of a bunch in the HEB a bucket in the Collider will have advanced 17 280 six-bucket spacings. This is equivalent to the bucket in the Collider moving backward by 144 six-bucket spacings. Thus, during every eight revolutions in the HEB the relative Collider bucket will move backward by 144 six-bucket spaces. After one HEB revolution the original collider bucket will have advanced 2160 six-bucket positions; after $1+8$ HEB revolutions the original collider bucket will have advanced $2160-144$ six-bucket positions; and after $1+n8$ HEB revolutions the original collider bucket will have advanced $2160-144n$ six-bucket positions. For $n = 15$, or 121 revolutions in the HEB the original Collider bucket will be back at the starting point. The revolution time in the HEB is $10\,800\text{ m/c} = 36\text{ }\mu\text{s}$, and therefore the collider bucket will return to its original position every 0.0044 s. It is thus possible to align the first HEB bunch into any single 144 desired-bucket section of the Collider simply by waiting up to 0.0044 s.

5.2 Fine Cogging for the HEB to Collider Transfer

The first HEB bunch will align with any single 144 six-bucket section of the Collider simply by waiting, but within each 144 six-bucket section the first HEB bunch will always align with the same specific Collider six-bucket on each successive alignment. This situation is a result of the integer relationship that exists between the HEB and Collider circumferences. Unlocking the integer relationship will allow the alignment position to move to another place within any single 144 six-bucket section of the Collider.

Since the phase locking requires that the beam be radially displaced in one direction, it is desirable to allow the option of moving either way to get from the nearest 144 six-buckets to the exact six-bucket required for the transfer. (During the cogging it is desired to have the option of radially displacing the beam in the opposite way as that required by the phase lock so as to use the most good field aperture of the magnets.) Thus, we want to allow the capability of moving the Collider six-bucket the full 144 spaces.

5.2.1 Changing the Rf Phase

We desire to change the relative phase of the HEB rf cavities by an amount sufficient to move the HEB bucket up to 144 six-bucket spacings in the Collider. This is a phase shift of 144 HEB rf cycles. Defining the phase to be zero at the instant a relative phase change operation begins results in the phase of the HEB rf cavity being defined as

$$\phi_{\text{HEB}} = \int_0^T dt f_{\text{RFHEB}}, \quad (23)$$

and the six-bucket phase of the collider rf cavity being defined as

$$\phi_{\text{COL}} = (1/6) \int_0^T dt f_{\text{RFCOL}}, \quad (24)$$

and therefore the relative phase difference between the HEB rf and Collider six-bucket rf is

$$\Delta\phi = \phi_{\text{HEB}} - \phi_{\text{COL}} = \int_0^T dt [f_{\text{RFHEB}} - (1/6) f_{\text{RFCOL}}]. \quad (25)$$

Getting the bunch spacing right, as discussed above in Section 4.0 is accomplished by setting the HEB rf frequency equal to one sixth the collider rf frequency, $f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}}$, and this locks the relative phase. To change the phase to a new value, it is necessary to change the HEB rf frequency away from its locked value, and then, when the correct phase change has occurred, the HEB rf frequency must be relocked to $f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}}$.

5.2.2 The Rf Phase Change During a Non-adiabatic Rf Frequency Change

Section 4 presents two cases for a non-adiabatic rf frequency change without a significant longitudinal emittance growth. It will be shown that the best way to cause phase shifts is to deal with Case I only, that is a required rf frequency change greater than or equal to 9.625 Hz will be used. For that case, defining $t = 0$ as the time a frequency change operation begins, the rf frequency can be changed with a time profile determined by the following equations, (which describe an rf frequency time dependence similar to that shown in Figure 2).

$$f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}}; \quad t < 0, \quad (26)$$

$$f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}} + B(160)t; \quad 0 < t < T_S/2, \quad (27)$$

$$f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}} + B(160)(T_S/2) + B(140)(t - T_S/2); \quad T_S/2 < t < T_S/2 + T_2, \quad (28)$$

$$f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}} + B(160)(T_S/2) + B(140)T_2 + B(160)(t - T_S/2 - T_2); \quad T_S/2 + T_2 < t < T_S + T_2, \quad (29)$$

$$f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}} + B(160)(T_S + B(140)T_2); \quad t = T_S + T_2. \quad (30)$$

As discussed more fully in Section 4, the first (Eq. (27)) and third (Eq. (29)) ramps last for one half of a synchrotron period. During these ramps the synchronous phase is 160 degrees, one synchrotron period is $T_S = 0.25$ s, the rf voltage is $V = 160\,000$ V and the rate of frequency change is $B(160) = 38.5$ Hz². In between the first and second rf frequency ramps is a second ramp (Eq. (28)) with $V = 860\,000$ V and $B(140) = 387$ Hz².

The amount of time devoted to the second ramp, T_2 , can arbitrarily range from 0 to the value associated with the maximum allowable frequency change. Note that in each temporal range f_{RFHEB} has the form

$$f_{\text{RFHEB}} = (1/6)f_{\text{RFCOL}} + C_1 + C_2(t - T_A); \quad T_A < t < T_A + T_B. \quad (31)$$

Therefore the integrated phase advance in each temporal range is,

$$\Delta\phi_{AB} = \int_{T_A}^{(T_B - T_A)} dt [C_1 + C_2(t - T_A)] = C_1 T_B + C_2 (T_B)^2/2. \quad (32)$$

Therefore, the phase change resulting from the first half synchrotron oscillation (Eq. (27), (the first frequency ramp) is $\Delta\phi_1 = B(160)(T_S)^2/8$, the phase change resulting from the second frequency ramp (described by Eq. (28)) is $\Delta\phi_2 = B(160)(T_S/2)T_2 + B(140)(T_2)^2/2$, and the phase change resulting from the second half synchrotron oscillation (Eq. (29), the third frequency ramp) is $\Delta\phi_3 = B(160)(T_S/2)^2 + B(140)(T_S/2)T_2 + B(160)(T_S)^2/8$.

The phase change associated with changing the rf frequency is $\Delta\phi_{\text{RAMP}} = \Delta\phi_1 + \Delta\phi_2 + \Delta\phi_3$,

$$\Delta\phi_{\text{RAMP}} = B(160)(T_S)^2/2 + [B(160) + B(140)](T_S/2)T_2 + B(140)(T_2)^2/2. \quad (33)$$

5.2.3 The Rf Phase Change During a Complete Rf Frequency Change Cycle

In the proposed phase change process, the frequency will begin at the desired value given in Eq. (26), be changed according to the frequency ramps specified in Eqs. (27), (28) and (29), and then remain at the new, changed frequency given by Eq. (30) for an arbitrary amount of time T_3 . After the time T_3 has elapsed the frequency will be ramped back to the value of Eq. (26) in a return ramp that is symmetric to the ramps given in Eqs. (27), (28) and (29). (Note that the deceleration ramp will use the symmetric decelerating phases $\phi_{S1} = 200$ degrees and $\phi_{S2} = 220$ degrees.) The phase change occurring during T_3 is $\Delta\phi_4 = B(160)T_S T_3 + B(140)T_2 T_3$ and the phase change occurring during the symmetric return ramp is the same as that given in Eq. (33), and therefore the total phase change during a complete rf frequency change cycle is

$$\Delta\phi_{\text{CYCLE}} = B(160)(T_S)^2 + [B(160) + B(140)] T_S T_2 + B(140)(T_2)^2 + B(160)T_S T_3 + B(140)T_2 T_3. \quad (34)$$

5.2.4 The Maximum Allowable Rf Frequency Change; an Expression for T_{2MAX}

In order to change the relative phase of the HEB rf cavities by an amount sufficient to move the HEB bucket up to 144 six-bucket spacings in the Collider it will be necessary to move the protons radially in the HEB in order to change their HEB recirculation circumference. It is desirable to keep the radial displacement less than or equal to two millimeters, in order to avoid beam loss. (If the radial displacement is greater than two millimeters the field quality in the magnets deteriorates to an extent large enough to cause beam loss.) The circumference of the HEB is related to an average radius by the following expression.

$$C_{HEB} = 2\pi r_{HEB} \quad (35)$$

Thus, the differential radius is related to the differential circumference by

$$\Delta C_{HEB}/C_{HEB} = \Delta r_{HEB}/r_{HEB}, \text{ or } \Delta C_{HEB} = C_{HEB}(\Delta r_{HEB}/r_{HEB}) . \quad (36)$$

With $C_{HEB} = 10\,800\text{ m}$, $r_{HEB} = 1719\text{ m}$, and since we wish to keep the maximum value of $\Delta r_{HEB} = 2\text{ mm}$, the maximum value of the differential circumference is $\Delta C_{HEB} = 1.25\text{ cm}$.

Arranging a displacement in the radial position of the HEB beam can be done by accelerating (decelerating) the beam. The differential circumference is related to the differential momentum by

$$\Delta C_{HEB}/C_{HEB} = (\gamma_{THEB})^{-2} \Delta p_{HEB}/p_{HEB} . \quad (37)$$

In Eq. (37) γ_{THEB} is the transition energy of the HEB divided by the rest mass of the proton, $\gamma_{THEB} = 34.475$. Thus, the differential momentum required to move the beam radially by the maximum allowable 2 mm is

$$\Delta p_{HEB}/p_{HEB} = (\gamma_{THEB})^2 \Delta C_{HEB}/C_{HEB} = (\gamma_{THEB})^2 \Delta r_{HEB}/r_{HEB} = 1.38 \times 10^{-3} . \quad (38)$$

The required momentum change can be arranged by changing the rf frequency. Recalling Eq. (9) from Section 4.1,

$$\delta f_{RF}/f_{RF} = \delta f_0/f_0 = \delta v/v - \delta C/C = -\eta\beta^{-2}(\delta E/E_S) , \quad (9)$$

and combining Eq. (9) with equation (38) and doing some rearranging leaves an expression for the frequency change required to move the beam radially by two millimeters,

$$\Delta f_{RFMAX} = -f_{RF}\eta\beta^{-2}(\Delta E/E_S) = -f_{RF}\eta(\Delta p/p_S) = -1.16 \times 10^{-6} f_{RF} = 70\text{ Hz} . \quad (39)$$

Since the frequency change in Eq. (39) is the change that results in the maximum allowable radial displacement, Eq. (39) is the maximum allowable frequency change that can occur at flat top. Since we desire to change the phase of the HEB cavity relative to the Collider cavity, Eq. (39) represents an upper bound on the amount of frequency change we can employ in changing the phase.

Equating the frequency change given in Eq. (30) to the magnitude of the maximum allowable frequency change as determined in Eq. (39) leaves an expression for evaluating T_{2MAX} , which is the maximum allowed value of T_2 ,

$$\Delta f_{RFMAX} = 70\text{ Hz} = B(160)T_S + B(140)T_{2MAX} . \quad (40)$$

5.2.5 A Numerical Estimate of the Time Required for Fine Cogging

It is noted above in Section 4.3 that for HEB at flat top, $h = 2160$, $A = 3.5$ eV-sec, $E_S = 2 \times 10^{12}$ eV, $\beta = 1$, $\eta = 8.4 \times 10^{-4}$, $Q = e$, $f_{RF} = 60$ MHz and $f_0 = f_{RF}/h = 27.8$ KHz. For the case of $\phi_{S1} = 160$ degrees, $V(160) = 160\,000$ V, $f_s(160) = 4$ Hz and $B(160) = 38.5$ Hz². For the case of $\phi_{S2} = 140$ degrees, $V(140) = 860\,000$ V, $f_s(140) = 8.6$ Hz and $B(140) = 387$ Hz². Thus, Eq. (40) can be solved for T_{2MAX} ,

$$T_{2MAX} = (70 \text{ Hz} - B(160)T_S)/B(140) = [70 - (38.5)(0.25)]\text{Hz}/[387 \text{ Hz}^2] = 0.155 \text{ s} . \quad (41)$$

Substituting $B(160) = 38.5$ Hz², $B(140) = 387$ Hz², $T_2 = T_{2MAX} = 0.155$ s and $T_S = 0.25$ s into Eq. (34) leaves

$$\begin{aligned} \Delta\phi_{CYCLE} (T_2 = T_{2MAX} = 0.155 \text{ s}, T_S = 0.25 \text{ s}) &= B(160)(T_S)^2 + \\ [B(160) + B(140)] T_S T_2 + B(140)(T_2)^2 + B(160)T_S T_3 + B(140)T_2 T_3 &= 38.5 (0.25)^2 \\ + [38.5 + 387](0.25)(0.155) + 387 (0.155)^2 + [38.5(0.25) + 387(0.155)]T_3 &= 28.2 + 69.6 T_3 . \end{aligned} \quad (42)$$

The fine cogging must be capable of moving an HEB bucket by a relative phase of between $\Delta\phi_{CYCLE} = \Delta\phi_{CHMIN}$ and $\Delta\phi_{CYCLE} = \Delta\phi_{CHMIN} + 144$ in order for the HEB bucket to be able to visit all possible Collider six-buckets. With $\Delta\phi_{CHMIN} = 28.2$, varying T_3 between 0 and

$$T_{3MAX} = 144/69.6 = 2.1 \text{ s} \quad (43)$$

will allow every possible Collider six-bucket to be aligned with the first HEB bucket for a possible transfer. The total time required to complete the fine cogging is

$$T_{FINECOGGING} = T_{3MAX} + 2T_{2MAX} + 2T_S = 3 \text{ s} . \quad (44)$$

5.3 Non-adiabatic Fine Cogging – A Discussion

As discussed in Section 4.5, during commissioning of the HEB it is likely that a determination of construction errors will be made, and that the HEB and Collider rf cavities can be phase locked to a constant relative phase immediately upon the start of flat top. While the cavities are locked together, a determination must be made as to how much of a phase advance is required by the fine cogging. Once the amount of fine cogging is known, Eq. (42) can be used to determine the amount of time, T_3 , that the beam must spend at its maximum frequency offset in order to arrange for the fine cogging. Once the required T_3 is known, the rf voltage can be suddenly increased to 160 kV and the frequency of the HEB increased linearly at a rate of 38.5 Hz² for one half of a synchrotron period, followed immediately by a sudden increase in the rf voltage to 860 kV and an increase in the HEB rf frequency of 387 Hz² for 0.155 s, followed immediately by a sudden decrease of the rf voltage back to 160 kV and an increase of the HEB rf frequency of 38.5 Hz² for another half synchrotron period, followed immediately by a decrease of the rf voltage to 38.5 kV and a constant rf frequency. The rf frequency should remain constant at the new value for a time equal to T_3 , and then the rf voltage can be suddenly increased to 160 kV and the frequency of the HEB decreased linearly at a rate of 38.5 Hz² for one half of a synchrotron period, followed immediately by a sudden increase in the rf voltage to 860 kV and a further decrease in the HEB rf frequency of 387 Hz², followed immediately by a sudden decrease of the rf voltage back to 160 kV and a final decrease of the HEB rf frequency of 38.5 Hz² for another half synchrotron period. At this point the

fine cogging will be complete, and the HEB and Collider rf cavities can be locked to a constant relative phase. Coarse cogging will be accomplished simply by waiting. The proper cogging instant will occur every 0.0044 s once the fine cogging is complete.

Here it has been calculated that the synchrotron period during the change in rf frequency of 38.5 Hz^2 (when the rf voltage is 160 kV) is 0.25 s. During commissioning the rate of frequency change and the voltage during the ramps can be varied somewhat from what is described here to obtain the minimum experimentally observed longitudinal emittance growth. The important point is that once the first, second and third frequency ramps are determined in such a way that leads to minimum longitudinal emittance growth, from Eq. (42),

$$\Delta\phi_{\text{CYCLE}} = \dots 28.2 + 69.6T_3,$$

which can be altered to be

$$\Delta\phi_{\text{CYCLE}} = \phi_0 + KT_3, \quad (45)$$

where ϕ_0 and K are an experimentally determined constants dependent only on the frequency change ramps. Thus, as long as the same frequency change ramp is used on every cycle, a unique, experimentally determined, expression can be used to determine the amount of time, T_3 , required to achieve the desired fine cogging phase advance $\Delta\phi_{\text{CHANGE}}$.

Analysis is easier using time as a variable, but instrumentation may be easier using phase advance as a variable. The process of frequency change will likely be accomplished by taking a reference signal that is generated to be synchronous with the beam in the Collider (or, if there is no beam in the Collider the signal will be synchronous with the Collider rf), and adding to such a signal a frequency generated by a phase shifter. The phase shifter will supply the change ramps and phase advance. Once the change ramps are specified it will be established how much phase advance occurs in the change ramps. Thus, rather than specifying a length of time that the fully changed frequency remains constant, it will probably be easier to determine how much phase advance is needed to align the beams, subtract the phase advance known to occur in the ramps, and then send a signal to the phase shifter to advance the remaining phase during the maximum frequency offset.

This entire process must be simulated (with ESME) to determine how well the proposed process maintains longitudinal emittance. Included in the ESME study should be a realistic limit as to how fast the rf voltage can be increased.

It may be desirous to decrease the rf frequency prior to the wait of T_3 , and increase it afterward, rather than the order mentioned in the first paragraph of this subsection. The goal will be to move the beam radially in the direction opposite to that required by the construction errors.

Also note that the physical picture behind this proposal (see Figure 3 above) is to suddenly switch to an accelerating bucket (by imposing a linear rf frequency change and a stepped rf voltage), wait half of a synchrotron oscillation and then switch to a second accelerating bucket (by changing again the frequency ramp and voltage) which is now centered on the displaced beam distribution. This process could be subdivided by making many such changes. The example chosen here steps the phase by 20 degrees and then by another 20 degrees. Variations of the process can use more steps, with the important idea to use the synchrotron oscillation to minimize longitudinal emittance growth, a multistep process would simply take more time to complete. Nonetheless, if sufficient longitudinal emittance dilution is caused by the two step process proposed here, a multi-step process should be investigated.

Lastly note that there are at least four other ways to accomplish the fine cogging.

1. The same radial displacement can be achieved by "adiabatically" changing the rf phase. This option would require more time, four 1.5-s parabolas, or an additional 6 s, than the process proposed here.
2. The rf systems of the entire SSC complex can be synchronized so that the fine cogging occurs automatically. This option requires relaxation of some feedback loops. If the magnet ramp is different than planned, a predetermined fine cogging requirement on the rf cavity would lead to radial beam wandering.
3. The cogging can be done during the ramp. This option has the same drawback as option 2.
4. The acceleration (deceleration) can be done by jumping the phase to form an accelerating (decelerating) bucket. This option results in a frequency change with little emittance growth and results in flexibility during the ramp and is discussed more in the following subsection.

5.4 An Optional Acceleration Scheme for the Fine Cogging

Rather than following several linear ramps appropriately timed in order to accelerate the beam to provide the radial displacement required for the fine cogging, it may be desirable to accelerate the beam in a single frequency ramp. Such a situation can result when it is realized that what causes emittance dilution is a situation where the center of the beam distribution no longer coincides with the synchronous phase. This emittance dilution causing situation can arise if a frequency ramp is started, as just discussed. But the previous discussion assumed that the frequency ramp was always continuous. If, when the frequency ramp starts and the voltage is suddenly increased, a phase jump is also made to occur, the center of the beam can remain at the synchronous phase throughout the frequency change process. This option can be used to accelerate the beam by doing three things simultaneously: 1) jumping the phase by 40 degrees so that the synchronous particle suddenly sees a phase of 140 degrees; 2) jumping the rf voltage to 860 000 V; and 3) starting a linear frequency ramp of 387 Hz^2 . These conditions should remain in effect for 0.18 s so that the full two millimeter radial excursion is in place, and once the 0.18 s has elapsed three things must be done simultaneously: 1) jumping the phase by 40 degrees so that the synchronous particle suddenly sees a phase of 180 degrees; 2) jumping the rf voltage to 38 700 V; and 3) stopping the frequency ramp.

This optional acceleration scheme fits into the fine cogging scenario in the same way as the acceleration scheme discussed above. The timing measurements will determine how much phase advance is required, and the amount of phase advance occurring during the acceleration and deceleration ramps will be subtracted leaving the amount of phase advance that must occur while the frequency is at its maximum displacement. The hardware will be set to advance the phase by just this amount.

This optional scheme clearly is easier to understand and calculate, but it is not clear which scheme will be easier to implement. There are therefore two viable options to consider for the acceleration required to complete the fine cogging.

5.5 Summary of the Cogging Process

During commissioning it will be determined what radial position offset results in a condition where the HEB and Collider circumferences are related by their design harmonic numbers. Acceleration cycles will then reach flat top with the beam in such a radial offset, and the HEB and Collider rf cavities can therefore be locked to a constant relative phase immediately at the onset of flat top. Once locked, electronics must be able to determine how much phase advance is required to fine-cog the beam. The beam will then be accelerated to a new radial displacement so that the phase can advance and then be decelerated back to the locked radial position. The acceleration can be accomplished in one of two ways, as discussed in the preceding sections.

Once the fine cogging is complete, coarse cogging will happen automatically, with the proper transfer conditions being met every 0.0044 s. The exact amount of time between proper conditions is impossible to determine in advance, due to the presence of construction errors. Once the machines are built, however, this time will be fixed and determinable experimentally. The important point is to arrange the kickers to fire when proper conditions are met, and that once fine cogging is complete these conditions regularly and predictably appear.

6.0 GETTING THE CORRECT ENERGY AND LONGITUDINAL SPREAD

The present design of the Super Collider incorporates a 60 MHz rf system into the HEB and a 360 MHz rf system into the Collider. As a result of this, and other machine parameters, the equilibrium bunch length in the HEB is too long for matching into the Collider, and consequently the equilibrium energy spread is too small. In order to arrange for the correct energy and longitudinal spatial spreads, the voltage of the rf cavity will be varied programmatically just prior to ejection. The specific programmed voltage variation leads to what is called a "bunch rotation" of the beam.

When plotted in phase space (energy along one axis, temporal spread along the other axis) the beam particles will occupy some area, called the bunch area. Ellipses can be drawn that surround various numbers of particles, such as the ellipse containing 95% of the particles. Individual particles will traverse elliptical paths in phase space, due to an interaction between their arrival time at the rf cavity and the timing of their recirculation. (If a particle arrives at the cavity too early (late), it will get too much (little) of accelerating voltage. Since it gets too much (little) of a kick, it is accelerated (decelerated) and it will take longer (shorter) for it to return to the rf cavity. Thus, over time the particle will arrive too late, then too early, *etc.* Viewed in phase space, such a pattern is described by an elliptical trajectory.)

The height (the energy spread) of an ellipse in phase space is determined by the voltage on the rf cavity. After all cogging is complete the rf voltage will be 38.7 kV as determined in Reference 1. It is also determined in Reference 1 that under this low voltage condition the beam has a relatively low momentum spread of $\sigma_p/p = 1.65 \times 10^{-5}$ and a relatively long longitudinal spatial spread of $\sigma_z = 318$ mm. The ellipse surrounding the particles and the ellipse of the containing bucket are both very short (small momentum spread) and fat (large longitudinal spatial spread). If the voltage of the cavity is now suddenly increased to 860 kV, the bucket containing the particles will suddenly become much taller (the momentum spread associated with the separatrix will become much larger) and the individual particles in the short fat ellipse will follow trajectories associated with the new bucket. This process has the effect of rotating the original ellipse until it is tall and thin; *i.e.*, it leads to a shortening of the longitudinal spatial spread and an increase in the energy spread.

Reference 1 presents the results of calculations of the matched values of σ_p/p and σ_z . After the increase in rf voltage to 860 kV the matched momentum spread of the beam increases to $\sigma_p/p = 3.58 \times 10^{-5}$ while the longitudinal spread of the beam decreases to $\sigma_z = 147$ mm. But the beam is not matched to the bucket here, rather there is a rotating ellipse. Nonetheless, the matched case can be used to arrive at an estimate of σ_p/p and σ_z for the unmatched case. Near the center of the bucket all of the ellipses will be nested. On each such ellipse the ratio of σ_p/p to σ_z is a constant, and this ratio for the matched case is $3.58 \times 10^{-5}/147$ mm. The unmatched ellipse starts out with $\sigma_z = 318$ mm prior to the onset of bunch rotation, and the height of its matched trajectory is thus

$$\sigma_p/p = (3.58 \times 10^{-5}/147 \text{ mm})(318 \text{ mm}) = (7.74 \times 10^{-5}). \quad (46)$$

The phase space area should not change much during the short time the bunch is allowed to rotate. Since the initial phase space area associated with the one standard deviation quantities is $\epsilon = (\sigma_p/p)(\sigma_z) = (1.65 \times 10^{-5})(318 \text{ mm})$, the longitudinal spread of the rotated bunch will be

$$\sigma_z = \epsilon/(\sigma_p/p) = (1.65 \times 10^{-5})(318 \text{ mm})/(7.74 \times 10^{-5}) = 67.8 \text{ mm}. \quad (47)$$

The time required for this process is one quarter of a synchrotron period. One synchrotron period corresponding to the case after the voltage increase is calculated in Reference 1 to be 9.8 Hz. Thus, bunch rotation will take 25.5 ms.

Note that the bunch rotation process should be simulated with ESME as a check to see that the approximation of nested phase space trajectories is adequate and also to determine the amount of longitudinal emittance dilution expected to result from the process.

7.0 REQUIRED HARDWARE CAPABILITIES

This note has assumed that all of the beam quantities are known but, in practice, hardware must be used to determine the values of the beam properties. Also, this note assumes that manipulations of the rf cavity can be done instantly, if desired, but in actuality such manipulations will require some finite time. This section will discuss the tolerances of the hardware needed to arrange for proper transfer of the proton beam from the HEB to the Collider. Note that these specs are derived from what is required for flat top manipulations only. Other considerations may lead to more stringent tolerances than those given here.

1. The tolerance on the acceptable momentum error for the batch comes from the capability of the longitudinal damper of the Collider. A momentum error will lead to a dipole oscillation of the bunches in the Collider, and these oscillations can be damped. The presently planned longitudinal damper can damp away two degrees of 60 MHz phase offset, or a longitudinal position error of 28 mm. Since the bunch spread at transfer time is $\sigma_z = 68$ mm, this implies that the dampers can accommodate injection errors of 40% of the transferred beam spreads. The relative momentum spread at transfer time is $\sigma_p/p = 7.74 \times 10^{-5}$, and therefore it is required that the central momentum be set to a tolerance of $\Delta p/p = 0.4\sigma_p/p = 3 \times 10^{-5}$.

In a dipole magnetic field the particle momentum is $p = eBr$ where e is the proton charge, B the magnetic field in the dipole and r the particle radius in the dipole. By keeping the beam centered in the dipole so that $\Delta r/r = 0$, the relative error in momentum is $\Delta p/p = \Delta B/B$. In the superconducting magnets of the HEB the magnetic field is predominantly determined by the current through the coils, $\Delta p/p = \Delta B/B = \Delta I/I$. Thus, it is needed that the hardware be capable of setting the current in the magnets to a relative error of $\Delta I/I = 3 \times 10^{-5}$ for proper transfer of beam from the HEB to the Collider.

2. The above spec on the magnet current was derived assuming that the beam is kept in the center of the magnets, and to accomplish such a feat it is necessary that the position of the beam be detected. In a dispersive region the beam will obtain a horizontal offset given by the dispersion function multiplied by the momentum offset, $\Delta r = D\Delta p/p$. With a typical value for the dispersion function of $D = 2$ m, and an observable Δr of 10 microns, this implies that a pickup monitor will be able to detect a relative momentum error of $\Delta p/p = 5 \times 10^{-6}$. Since this relative momentum detection capability is much less than the tolerance allowed for the relative current error, spec 1 is adequate provided the Beam Position Monitors (BPMs) at a place in the HEB where there is a 2-m dispersion are capable of detecting beam position to 10 microns.
3. The requirement of phase locking of the rf cavities so that emittance growth is avoided during transfer is determined by the longitudinal damping system. The planned Collider longitudinal damping system can handle an input phase error of 15 degrees of the 360 MHz rf, so the HEB and Collider rf systems must be lockable to a constant relative phase plus or minus two degrees of the 60 MHz rf.
4. The hardware must be capable of determining the position of the desired bucket in the Collider to which the first proton bunch is to be transferred, as well as the position of the first proton bunch in the HEB to such an accuracy that it is known which individual bucket the transfer will be made to. This must be done to about 1/10 of a bucket size; the timing of arrival of the first HEB proton bunch and the desired Collider bucket must be known to about 400 ps. This constraint is discussed more fully in Section 7.1.
5. Once the timing of the first proton bunch and the desired Collider bucket are known, the hardware must be capable of programming the rf to accelerate (or decelerate) the beam and then advance the relative phase by the correct amount to get the timing right to the 400-ps level. Note that a counter on a properly programmed phase shifter can accomplish this task.

(Note that requirements 4 and 5 can be relaxed from 400 ps to 10 ns if the procedure outlined in Section 7.2 is followed. However, to assure that each bunch goes to the correct Collider bucket, the 400 ps spec must be obtained.)
6. Assuming that 1 mm is the maximum tolerable deviation from the design for the longitudinal spatial bunch spread, and noting that the one standard deviation longitudinal spread varies as $V^{-1/4}$ (which implies that the logarithmic error in V can be four times larger than the tolerated logarithmic error in longitudinal spread), $\Delta V/V$ must be less than about 5%.
7. If the bunch rotates too far or not far enough it will not have the longitudinal spatial extent desired for transfer. The time the bunch is allowed to rotate before extraction is determined in advance from coggling considerations. Therefore, if the beam rotates too fast or too slowly there will result an emittance dilution. During the bunch rotation the longitudinal size varies from 318 mm to 67.8 mm in one quarter of a synchrotron period. Assuming this change to occur linearly a one-mm error will occur if the synchrotron oscillation advances by 90.4 degrees rather than the planned 90 degrees. Thus, the allowed logarithmic tolerance in the synchrotron frequency is $0.4/90 = 0.0044$. Since the synchrotron frequency is proportional to $V^{1/2}$, which implies that the logarithmic error in V can be two times larger than the tolerated logarithmic error in synchrotron frequency, $\Delta V/V$ must be less than about 1%.

8. Beam ejection must be done when the proper timing conditions are met for transfer. Transfer of the beam involves timing of bunch rotation and timing of kicker turn on.
 - a) A determination that proper transfer conditions are met must be done by processors associated with the hardware described in requirement 4.
 - b) When the proper conditions are met for the first time 1) the time to begin bunch rotation and 2) the time to eject the beam are specified. These times should be determinable to 400 ps using the hardware required for requirement 4.

(Note that since fine cogging must be complete prior to beam ejection the proper timing conditions will reappear about every $\tau_{CC} = 0.0044$ s as described in Section 5.1. The exact value of τ_{CC} , which will be somewhat different than 0.0044 s, must be determined experimentally. Then, the beam can be transferred at any instant of n times τ_{CC} after the first occurrence of proper timing conditions.)

9. Since the bunch rotates 360 degrees in about 100 ms, and the tolerance for the rotation is plus or minus 0.4 degrees, the rapid increase in rf voltage must begin within plus or minus 100 μ s of the correct value.
10. It is desired to increase the rf voltage by about a factor of 22 very quickly to begin the bunch rotation. The amount of time taken to increase the voltage must be similar to the tolerance for when the increase starts. The rf voltage must be increased by a factor of 22 in less than 100 μ s.
11. The signal to turn on the kickers must be done within a tolerance such that none of the bunches are only partially kicked. The extraction (and abort) gap in the HEB is 103 buckets, or 515 m, or 1.72 μ s. The extraction kicker rise time is 1.7 μ s, so the tolerance on the signal to turn the kickers on is plus or minus 10 ns of the correct value.

(Note that the "correct values" specified in requirements 9 and 11 will be experimentally determined. The correct value for requirement 11 will be $n\tau_{CC}$ where n is some integer large enough to ensure that the bunch rotation is complete, and the correct value for requirement 9 is $n\tau_{CC}$ minus one quarter of a synchrotron oscillation.)

7.1 Required Hardware Capability to Determine Where Specific Bunches and Buckets Are

The present design of the Super Collider calls for a 60-MHz rf system for the HEB and a 360-MHz rf system for the Collider. This leads to a situation where the bunch separation in the HEB is six times greater than what could be achieved in the Collider. Thus, the design intends to fill every sixth bucket in the Collider, with the remaining 5/6ths of the buckets empty. (A bucket is an area in longitudinal phase space capable of storing particles.) This scenario places a large burden on the system used to get the timing of the beam transfer correct.

If the Collider used a 60-MHz system, and the beam was transferred to the wrong bucket, the Collider operation would not be seriously deteriorated, since, with every bucket filled, the offset of a few positions results in a situation where only a few of the buckets intended to be filled remain empty. The Collider operation is thus diminished by the few empty buckets out of the 2000 that are to be transferred.

However, since the present design calls for 5 of every 6 buckets to be empty, if the batch of protons from the HEB is sent to the Collider with an error of just one Collider bucket, none of the transferred batch will participate in Super Collisions, as they will reach the crossing point at the wrong time.

Since the first bunch in each batch must be transferred from the HEB into the single correct Collider bucket, we must have some way of knowing where the bunch is within the HEB. And, since the relevant point is to send in new batches so that they collide with batches already in the Collider, we must also know where the occupied Collider buckets are. It is assumed here that phase locking of the HEB and Collider cavities will assure that the batches are sent to the center of a Collider bucket. The concern here is that the control electronics are sufficient to assure that the bunches are sent to the correct buckets.

The total error in the transfer will be the sum of the error in the HEB timing system plus the error in the Collider timing system. Assuming that the errors have a Gaussian occurrence, the total standard deviation of the error is the sum of the individual standard deviations of the errors added in quadrature, and thus the total standard deviation of the error is the square root of two times the individual standard deviations of the errors of the timing equipment.

Here it will be assumed that we desire the right Collider bucket to be filled 99% of the time. The probability of an error greater than "a" occurring with the assumed Gaussian distribution is defined as

$$f(E > a) = \left(\frac{2}{\pi\sigma^2}\right)^{1/2} \times \int_a^{\infty} \exp\left((-x^2)/(2\sigma^2)\right) dx, \quad (48)$$

where $f(E > a)$ is defined as the probability of an error greater than "a" and σ is the standard deviation of the combined errors. The integral in Eq. (48) can not be evaluated analytically, but is related to the error function, $\text{erf } x$, defined as

$$\text{erf}(b) = \left(\frac{2}{\pi^{1/2}}\right) \times \int_0^b \exp(-t^2) dt. \quad (49)$$

By making the substitution $t^2 = \frac{x^2}{2\sigma^2}$, and hence $dt = \frac{dx}{2^{1/2}\sigma}$, it can be noted that $f(E > a) = 1 - \text{erf}(b)$ if $b = \frac{a}{2^{1/2}\sigma}$. Looking up the value of $\text{erf}(b)$ in a table it is found that $\text{erf}(b) = 0.99$ for $b = 1.83$. The transfer will be a failure if the batches are transferred to the next or preceding Collider bucket relative to the desired Collider bucket. The wrong bucket will be chosen if the error, a , is equal to half the bucket width, since that is the distance from the bucket center (the desired point) to the edge of the next bucket. Thus,

$$a = (1/2)(5/6)m/3 \times 10^8 \text{ m/s} = 1.4 \text{ ns}, \quad (50)$$

where the 1/2 comes from the half bucket width, (5/6) m is the Collider bucket spacing, and $3 \times 10^8 \text{ m/s}$ is the speed of light. We can now solve for the required σ ,

$$\sigma = \frac{a}{2^{1/2}b} = \frac{1.4 \text{ ns}}{1.414 \times 1.83} = 0.537 \text{ ns} \quad (51)$$

The σ just calculated is the total σ for the combined errors of the HEB and Collider timing systems. As discussed above, the individual errors must be a factor of the square root of two less than the combined value, or

$$\sigma_{\text{HEB}} = \frac{\sigma}{2^{1/2}} = 0.38\text{ns} = \sigma_{\text{Collider}} \quad (52)$$

Thus, in order to assure proper transfer of the beam from the HEB into the Collider, it is required that the timing system have a one sigma error of 380 ps.

7.2 Additional Hardware to Assure Proper Bunch Transmission

Section 7.1 has just calculated the requirement on the hardware that determines the position of bunches within the ring under the assumption that such hardware will be the sole determinant in getting the beam timing conditions correct for transfer. But, to insure proper transfer, additional hardware should be added to the Collider that picks up the 60-MHz signal of the recirculating Collider beam and outputs a CW sine wave phase locked to the recirculating beam. Clearly, the phase of such a signal is locked with the Collider rf cavity but the advantage here is that if phase locking of the HEB rf is done to a specific relative phase difference with the 60-MHz signal rather than the 360-MHz signal, if there is an error of one full cycle the bunches will still be transferred to the correct 1/6th subset of Collider buckets that will participate in Super Collisions; they will be sent to a bucket 6 positions away from what is desired. This system should lock the HEB rf cavities to the 60-MHz Collider-beam-generated signal to a constant relative phase plus or minus two degrees so that the planned Collider longitudinal damping system can damp any phase error that occurs during transfer.

Note that cables must be used to transfer the 60-MHz signal from the Collider beam tube to the HEB low level rf system, and that the phase length of the cable will vary with temperature. To compensate for this a round trip, cable should be sent out from the HEB end, with the round trip cable tied together with the signal cable. A 60-MHz signal should be sent down the round trip cable and one half of any additional phase delay observed in the round trip cable should be subtracted from the phase of the signal cable.

With the hardware described here a much more relaxed specification comes about on the hardware that determines when the individual buckets cross a given point. Since missing by 6, 12 or 24 buckets would not seriously affect luminosity, it becomes acceptable to tolerate timing system errors of about 10 ns.

7.3 Required Hardware Specifications – Summary

The required hardware must be able to:

1. Set and monitor the drive current in the main dipole magnets to within a relative error of $\Delta/I = 3 \times 10^{-5}$;
2. Set the momentum induced radial beam displacement at a known place of 2-m (or more) dispersion within the HEB to a desired value plus or minus ten microns;
3. Lock the HEB rf cavities to a 60-MHz signal sourced from the stored Collider beam to a known, constant relative phase within plus or minus two degrees (Note that this can only be done when there is beam in the Collider. For injection of the first batches into the Collider in either the CW or CCW direction the HEB rf cavities should be locked directly to the Collider rf cavities to a known, constant relative phase within plus or minus two degrees);

4. Determine the time a single bunch passes a known Collider reference point to within 400 ps;
5. Determine the time a single bunch passes a known HEB reference point to within 400 ps;
6. Determine how much phase advance is required from the measurements of 4 and 5 in order to obtain the proper fine cogging conditions for transfer and then implement that phase advance to an accuracy of 400 ps;
7. Rapidly increase the rf voltage over less than a 100- μ s interval;
8. Maintain the rf voltage to a value within 1% of what is specified for the bunch rotation;
9. Determine when bunch rotation should begin and when beam ejection should begin. This can be done to within 400 ps using the hardware used to achieve requirements 4 and 5.
10. Begin the voltage increase within 100 μ s of the specified bunch rotation start time; and
11. Turn on the extraction kickers within 10 ns of the specified value.

These specs are driven by the need to have minimal longitudinal phase space growth during transfer. Toward that end, the specs described here have assume that a 1-mm error in longitudinal position of the bunch spread is the maximum tolerable, that the longitudinal dampers in the Collider can accommodate a maximum tolerable injection error of 15 degrees, and that every bunch must be sent to the correct bucket at transfer time. These assumptions are good guesstimates of what will be required, but should any of the above tolerances require great increase in cost or effort over what would be needed for a spec somewhat more lenient, decision makers may decide to relax the spec. Lastly, note that non-flat-top considerations might require more stringent tolerances than those given here.

8.0 SUMMARY AND SYNTHESIS OF LONGITUDINAL GYMNASTICS OF THE HEB AT FLAT TOP

The longitudinal gymnastics required at the flat top of the HEB cycle are needed so that the particle bunches can achieve the correct parameters for injection into the Collider. The particle bunches must:

1. have the correct central momentum;
2. have the correct bunch to bunch separation;
3. have the correct timing; and
4. have the correct energy spread and longitudinal spatial spread.

Section 7 has outlined the hardware specifications required to achieve these goals, while Sections 3 through 6 present the detailed calculations and discussion of the individual processes needed to achieve these goals. The purpose of this section is to sum up the processes by which the goals are reached, and state the amount of time each process will require.

The method of obtaining the four requirements simultaneously will involve:

1. accelerating the protons to the correct momentum;
2. phase locking the rf cavities of the HEB and Collider to assure correct bunch to bunch separation;
3. determining the timing error;
4. unlocking the rf, accelerating (or decelerating) the beam to unlock the HEB and Collider circumferences;
5. allowing the HEB beam to align itself with the Collider buckets;
6. decelerating (or accelerating) the beam back to the correct momentum, and re-locking the rf systems;
7. quickly increase the voltage of the HEB rf at the correct time;
8. wait $1/4$ of a synchrotron period and inject into the Collider.

The maximum time it takes to complete these operations and the process involved (as discussed in detail in the earlier sections of this report) are:

1. The momentum of the beam is specified by the radial offset of the beam at a point of finite (~ 2 m) dispersion and the current through the magnets. The correct values for these conditions will be determined during machine commissioning. The correct momentum will be set just at the beginning of flat top. Flat top time required is 0;
2. Phase locking of the HEB and Collider rf cavities can be done when the HEB and Collider particle circumferences are related by an integer relationship. Construction errors will lead to a situation where this integer relationship can only be established if the HEB beam is allowed to be radially offset. The amount of offset will be determined during commissioning so that the HEB and Collider rf cavities can be phase locked immediately upon reaching of flat top. Flat top time required is 0;
3. Beam pickups will determine when bunches pass known points in the Collider and HEB and electronics will determine how much rf phase advance is needed to achieve proper conditions for transfer. The amount of flat top time needed will be determined by the hardware and electronics—presumably this will be less than 0.1 s. Flat top time required is 0.1 s;
4. Acceleration (deceleration) of the beam at constant magnetic field in order to achieve radial displacement can be done as described in Section 5 by changing the rf frequency and voltage in such a way as to minimize longitudinal emittance growth. The rf voltage will be suddenly increased to 160 kV and a phase shifter will begin a linear change in rf frequency of 38.5 Hz^2 for 0.125 s, followed immediately by a sudden increase in the rf voltage to 860 kV and a linear change in the HEB rf frequency of 387 Hz^2 for 0.155 s, followed immediately by a sudden decrease in the rf voltage to 160 kV and a linear change in the HEB frequency of 38.5 Hz^2 for 0.125 s. Flat top time required is 0.405 s;
5. Once the beam is radially displaced, the phase shifter can continue to run at the constant frequency described in process 4 until proper fine cogging conditions have been reached. Section 5 calculates that the maximum time required is 2.1 s;

6. The HEB and Collider rf cavities can be relocked to the correct constant phase by reversing the frequency changes specified in process 4 but keeping the time durations and voltages constant for the operations. Flat top time required is 0.405 s;
7. Correct coarse timing conditions occur every 0.0044 s once fine cogging is complete. The rapid increase in rf voltage needed to begin bunch rotation must occur at a precise moment in between proper timing conditions. At most one must wait 0.0044 s to get the first proper timing conditions after fine cogging (processes 4, 5 and 6) is complete to get a marker, and an additional 0.0044 s for proper bunch rotation onset timing to be correct based on that marker. Flat top time required is 0.0088 s;
8. Once initiated the one-quarter bunch rotation will take 0.0255 s. At the end of the bunch rotation the kickers should be fired to inject beam into the Collider. Flat top time required is 0.0255 s.

Total flat top time required is thus about 3.1 s.

As mentioned in Section 5, processes 4 and/or 6 above can be replaced with a process that uses a phase and voltage jump at the beginning and end of a single frequency ramp in order to do the acceleration and/or deceleration. This alternative can result in a time savings of half a second over that discussed in the preceding paragraph.

References

1. D. J. Larson, "A Study of the HEB Longitudinal Dynamics," SSCL-655, December 1993, Distribution Category 414.

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