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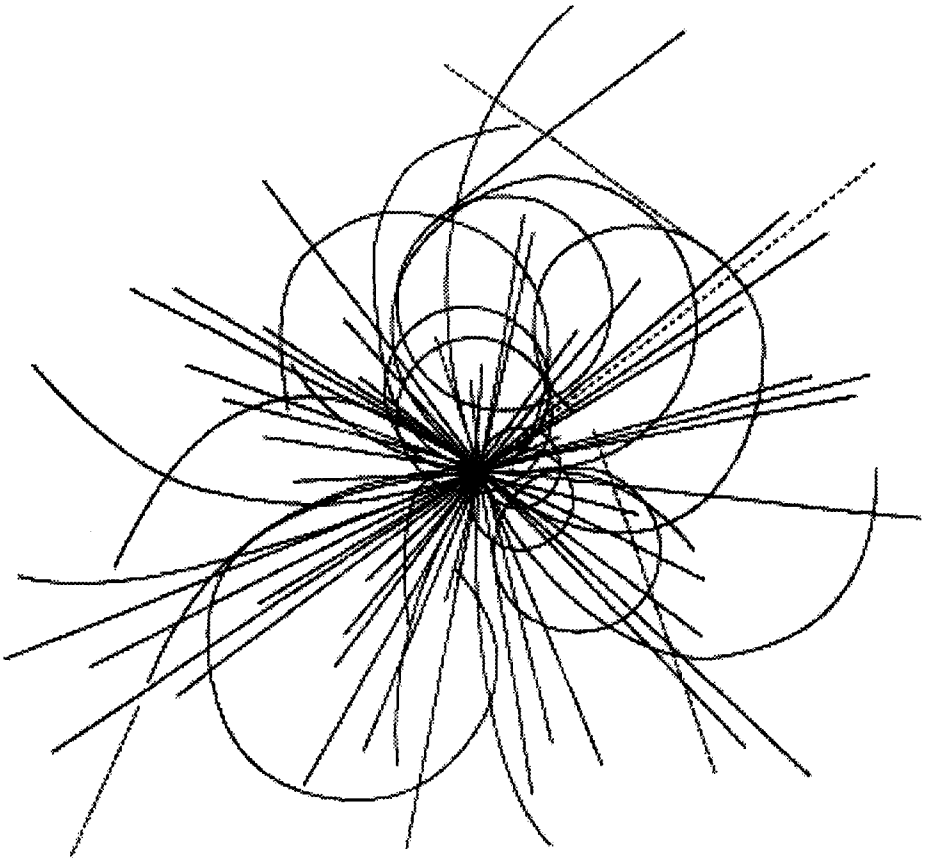

Superconducting Super Collider Laboratory

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Hardware Capabilities Required for Bunch Rotation and HEB to Collider Transfer

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Abstract

This paper derives tolerances for much of the hardware associated with longitudinal beam manipulations in the High Energy Booster (HEB).

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

1.0 INTRODUCTION AND OVERVIEW

This report 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.

Background material for this report can be found in References 1 and 2. SSCL-655 discusses the longitudinal dynamics of the HEB and SSCL-665 discusses the HEB at flat top.

The hardware specifications derived in this note are made under the assumption that each individual error will either 1) be dampable or 2) cause an emittance growth of less than 10%. Most such emittance growths will be added in quadrature, and therefore the net effect of all of the errors described below will be that the longitudinal emittance will increase about 20–30% during the bunch rotation.

All derivations assume that the particles are in the linear portion of the rf bucket, an approximation that should be good in practice, as the bucket to beam area ratio is six prior to bunch rotation and it is 34 during bunch rotation.

Many of the tolerances are quite loose, and it may be that essentially zero cost is associated with order of magnitude tolerance reductions. If an order of magnitude reduction in tolerance can be achieved with additional component costs of less than 1% such reductions should be implemented.

The derivation of each tolerance will now be specified. Following each derivation a single sentence will specify the derived tolerance. Following all the derivations the 3B spec language will be repeated.

2.0 TOLERANCE DERIVATIONS

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 $\sigma_z = 53$ mm, this implies that the dampers can accommodate injection errors of 50% of the transferred beam spreads. The relative momentum spread at transfer time is $\sigma_p/p = 9.89 \times 10^{-5}$, and therefore it is required that the central momentum be set to a tolerance of $\Delta p/p = 0.5\ \sigma_p/p = 9.89 \times 10^{-5}$.

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 $\Delta I/I = 5 \times 10^{-5}$ for proper transfer of beam from the HEB to the Collider.

Hardware must be capable of setting the current in the magnets to a relative error of $\Delta I / I = 5 \times 10^{-5}$ for proper transfer of beam from the HEB to the Collider. (Note that this requirement is for setting of the main bus current values in the Collider and HEB at transfer time. This is not a ripple requirement.)

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 30 microns, this implies that a pickup monitor will be able to detect a relative momentum error of $\Delta p/p = 1.5 \times 10^{-5}$. Since this relative momentum detection capability is much less than the tolerance allowed for the relative current error, spec 1 is adequate provided at least one Beam Position Monitor (BPM) at a place in the HEB where there is at least a 2-m dispersion is capable of detecting beam position to 30 microns.

At least one BPM, preferably near the rf cavities, at a place in the HEB where there is at least a 2-m dispersion must be capable of detecting beam position to 30 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 2 degrees of the 60 MHz rf.

The HEB and Collider rf systems must be lockable to a constant relative phase plus or minus 2 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 400 ps.

The timing of arrival of the first HEB proton bunch and the desired Collider bucket must be known to within plus or minus 400 ps.

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.

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 within plus or minus 400 ps.

6.) If the bunch rotates too far or not far enough it will not have the longitudinal spatial spread desired for transfer. The time the bunch is allowed to rotate before extraction is determined in advance from cogging considerations. Therefore, if the beam rotates too fast or too slowly there will result an emittance dilution. The amount of dilution can be calculated by assuming that, prior to the onset of the bunch rotation process, 95% of the beam particles reside in a matched ellipse in phase space that has:

$$\text{semi-minor axis } a = \Delta p/p = 1.76 \times 10^{-5}\ ;\ \text{semi-major axis } b = \sigma_Z = 298 \text{ mm}\ . \tag{1}$$

(These values for $\Delta p/p$ and σ_Z correspond to a bunch which is matched to the bucket prior to bunch rotation as calculated by the standard formula in the ELVIRA code.[1] If the $\Delta p/p$ axis is scaled to obtain the proper units, the ellipse will not distort (its semi-major and semi-minor axes will not change) as it rotates. The proper scaling of the $\Delta p/p$ axis is the scaling that results in circular trajectories for all of the beam particles. For a hypo-thetical bunch matched to the voltage after bunch rotation begins the ellipse axes are:

$$\text{semi-minor axis } a' = \Delta p/p = 4.18 \times 10^{-5}\ ;\ \text{semi-major axis } b' = \sigma_Z = 126 \text{ mm}\ . \tag{2}$$

A particle within this hypothetical bunch that starts out at $\sigma_Z = 126$ mm and $\Delta p/p = 0$ will arrive at $\sigma_Z = 0$ mm and $\Delta p/p = 4.18 \times 10^{-5}$ after one quarter of a synchrotron oscillation. For this motion to be a circle of radius 126, it is necessary to scale σ_Z in mm and scale the values of $\Delta p/p$ also in mm by multiplying all values by the factor

$$f = (126 \text{ mm}/4.18 \times 10^{-5})\ . \tag{3}$$

Thus the phase space ellipse in the new units has

$$\text{semi-minor axis } A = fa = 53 \text{ mm};\ \text{semi-major axis } B = \sigma_Z = 298 \text{ mm}\ . \tag{4}$$

Using axes aligned with the semi-major and semi-minor axes, the equation for the rms ellipse is

$$\xi^2/A^2 + \psi^2/B^2 = 1 \tag{5}$$

where ξ and ψ are orthogonal coordinates related to σ_Z and $\Delta p/p$ by

$$\sigma_Z = \xi\cos\theta - \psi\sin\theta \ \text{ and } \ f\Delta p/p = \xi\sin\theta + \psi\cos\theta\ , \tag{6}$$

where θ is the angle formed between the ξ (ψ) and σ_Z ($f\Delta p/p$) axes. θ will increase linearly with time during the bunch rotation process.

The quantity of interest is the amount of emittance increase that will be caused by an overshoot (or undershoot) of the ellipse past (or prior to) $\theta = 90$ degrees. If the ellipse goes too far so that the maximum value of its projection onto the σ_Z axis exceeds the desired value $\sigma_{Z0} = 53$ mm by an amount $\Delta\sigma_Z$, particles with $\sigma_{Z0} + \Delta\sigma_Z$ within the Collider buckets will traverse phase space ellipses that have a phase space area larger than the desired amount, and phase space filamentation will eventually lead to a situation where the longitudinal emittance is increased from $\varepsilon_0 = k\pi(\sigma_{Z0})^2$ to $\varepsilon = \varepsilon_0 + \Delta\varepsilon = k\pi(\sigma_{Z0} + \Delta\sigma_Z)^2$. (This expression results from looking at the case where the phase space

trajectories are circular in the Collider rf bucket, hence the phase space area is equal to the area of the circle. k is a constant related to the scaling of the $\Delta p/p$ axis. Since the momentum spread is a maximum when the beam is properly rotated, only an increased longitudinal size can contribute to a larger emittance during an over (or under) rotation.) Logarithmically, $\Delta\varepsilon/\varepsilon_0 = 2\Delta\sigma_Z/\sigma_{Z0}$. Specifying the maximum tolerable $\Delta\varepsilon/\varepsilon_0$ during the bunch rotation as 10% leaves a tolerable $\Delta\sigma_Z/\sigma_{Z0}$ during the bunch rotation of 5%.

The value of $\Delta\sigma_Z/\sigma_{Z0}$ that is achieved during the bunch rotation is determined by the rf voltage accuracy that can be achieved during the bunch rotation operation. The rate of advance of θ is governed by the synchrotron frequency, ω_S, $\theta = \omega_S t$, which is proportional to $V^{1/2}$. Thus $\Delta\theta/\theta = (1/2)\Delta V/V$. However, the relationship between $\Delta\sigma_Z/\sigma_{Z0}$ and $\Delta\theta/\theta$ is complicated. The way to determine that relationship is to form the ellipse governed by Eq. (4) and then look for the maximum value of σ_Z as determined from Eq. (5). σ_{Z0} can then be subtracted from σ_Z at each value of θ to get $\Delta\sigma_Z$, and the maximum tolerable value of $\Delta\theta$ obtained. A computer code (source code in the Appendix) was written to generate such calculations with the result that if a $\Delta\sigma_Z/\sigma_{Z0}$ of 5% is tolerable (which implies that $\sigma_Z = 53 + 2.7$ mm = 55.7 mm) the tolerable value of $\Delta\theta$ is 3.4 degrees, and $\Delta\theta/\theta = 3.4/90 = 3.8\%$ and that therefore the tolerable value of logarithmic voltage error is $\Delta V/V = 7.6\%$.

During bunch rotation, the rf voltage must be 1.6 MV plus or minus 120 kV.

7.) A second contribution to the value of $\Delta\sigma_Z/\sigma_{Z0}$ that is achieved as a result of peak voltage error comes from the error in the matched trajectory that results from an incorrect peak voltage. But the axes of the matched ellipse expressed in Eq. (2) are dependent on $V^{1/4}$, so voltage errors of $\Delta V/V = 7.6\%$ result in errors in the axes of the rotating ellipse of $\Delta A/A = \Delta B/B = (1/4)\Delta V/V = 7.6\%/4 = 1.9\%$. This error results in effects that are smaller than those of item 6) above and therefore item 6) drives the peak voltage tolerance specification. (Also, the effect of $\Delta A/A$ tends to offset the effect of $\Delta B/B$, further reducing the errors caused by this mechanism.)

No tolerance is derived from this emittance growth mechanism.

8.) There is a contribution to the value of $\Delta\sigma_Z/\sigma_{Z0}$ that is caused as a result of low voltage error. The axes a and b of Eq. (1) at low voltage are proportional to $V^{1/4}$, so $\Delta a/a = \Delta b/b = (1/4)\Delta V/V$. Since we desire $\Delta\sigma_Z/\sigma_{Z0} < 5\%$, and with $\Delta\sigma_Z/\sigma_{Z0}$ proportional to $\Delta a/a$, this implies that at low voltage we must have $\Delta V/V < 20\%$.

Prior to bunch rotation the rf voltage must be 54 kV plus or minus 10 kV.

9.) There is a contribution to beam emittance growth if a bunch is at an incorrect phase while at low voltage. Here, the emittance growth simply extends the bunch from an initial spread of $b = \sigma_Z = 298$ mm centered on zero to a spread centered on 5 m $(\Delta\theta_{rf}/2\pi)$. For a 5% growth in the longitudinal spread axis of the ellipse containing 95% of the particles,

$$5 \text{ m } (\Delta\theta_{RF}/2\pi) = (0.298 \text{ m})(0.05)(6^{1/2}) \Rightarrow \Delta\theta_{RF} = 0.046 \text{ radians} = 2.6 \text{ degrees.} \quad (7)$$

In the above expression the square root of six comes from the fact that the 95% ellipse contains 6 times the rms area, and therefore each ellipse axis is the square root of 6 times larger than the rms value.

Prior to bunch rotation the rf phase must be held to within 2.6 degrees of its design value for each and every bunch.

10.) At peak voltage the beam size is 53 mm rather than 298 mm, and the requirement for phase stability scales with this size: $\Delta\theta_{RF}$ = 0.046 radians(53/298) = 0.47 degrees.

During bunch rotation the rf phase must be held to within 0.47 degrees of its design value for each and every bunch.

11.) Since the bunch rotates 360 degrees in about 100 ms, and the tolerance for the rotation is plus or minus 3.4 degrees, the rapid increase in rf voltage must begin within plus or minus 1 ms of the correct value. However, timing accuracies much more accurate than this are easily obtainable, so it is reasonable to decrease this particular tolerance by an order of magnitude, so that it will contribute less than 1% to the emittance growth.

The rapid increase in rf voltage must be triggered to start within plus or minus 100 μs of the correct time. (The correct time is one quarter of a synchrotron oscillation period prior to a transfer time that is determined by cogging considerations.)

12.) It is desired to increase the rf voltage from 0.054 MV to 1.6 MV 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 in less than 1 ms.

The rf voltage must be increased in less than 1 ms to start bunch rotation.

13.) In addition to rf hardware requirements, the controls group must provide an rf voltage and phase program which the rf hardware is obliged to follow. This program should be much more accurate than the hardware requirements, since the program itself should not contribute appreciably to transverse emittance growth.

The rf voltage control program must be able to program the rf voltage to any value between 11 kV and 1.6 MV to within 0.5%, and must be able to specify any of these values at any time within the cycle to within 100 μs.

The rf phase control program must be able to program the rf phase to any value between 0 and 360 degrees to within 0.01 degree, and must be able to specify any of these values at any time within the cycle to within 100 μs.

14.) 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 μs. The extraction kicker rise time is 1.7 μs, so the tolerance on the signal to turn the kickers on is plus or minus 10 ns of the correct value.

The tolerance on the signal to fire the kickers on the correct turn is plus or minus 10 ns relative to the beam bunches on either side of the abort gap.

(Note that the "correct values" specified in requirements 11 and 14 will be experimentally determined. The correct value for requirement 14 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 11 is $n\tau_{CC}$ minus one quarter of a synchrotron oscillation. See Reference 2 for more details.)

3.0 3B SPECIFICATIONS

Background material for the hardware specifications of this section can be found in SSCL-667 "Hardware Capabilities Required for Bunch Rotation and HEB to Collider Transfer."

The hardware specifications below were derived under the assumption that each individual error will either 1) be dampable or 2) cause an emittance growth of 10%. Most such emittance growths will be added in quadrature, and therefore the net effect of all of the errors described below will be that the longitudinal emittance will increase about 20–30% during the bunch rotation.

Many of the tolerances are quite loose, and it may be that essentially zero cost is associated with order of magnitude tolerance reductions. If an order of magnitude reduction in tolerance can be achieved with additional component costs of less than 1% of system costs such reductions should be implemented.

1. Hardware must be capable of setting the current in the magnets to a relative error of $\Delta I/I = 5 \times 10^{-5}$ for proper transfer of beam from the HEB to the Collider. (Note that this requirement is for setting of the main bus current values in the Collider and HEB at transfer time. This is not a ripple requirement.)
2. At least one BPM, preferably near the rf cavities, at a place in the HEB where there is at least a 2-m dispersion must be capable of detecting beam position to 30 microns.
3. The HEB and Collider rf systems must be lockable to a constant relative phase plus or minus 2 degrees of the 60 MHz rf.
4. The timing of arrival of the first HEB proton bunch and the desired Collider bucket must be known to within plus or minus 400 ps.
5. 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 within plus or minus 400 ps.
6. The rf voltage, V, must be within plus or minus 7% plus or minus 6 kV from its desired value over the range between 50 kV and 1.6 MV.
7. The rf voltage, V, must be within plus or minus TBD% plus or minus TBD kV from its desired value over the range between 11 kV and 50 kV.
8. After reaching full energy and prior to bunch rotation the rf phase must be held to within 2.6 degrees of its design value for each and every bunch.
9. During bunch rotation the rf phase must be held to within 0.47 degrees of its design value for each and every bunch.
10. The rapid increase in rf voltage must be triggered to start within plus or minus 100 μs of the correct time. (The correct time is one quarter of a synchrotron oscillation period prior to a transfer time that is determined by cogging considerations.)

11. The rf voltage must be capable of being changed from any value in the range between 10 kV and 1.6 MV to any other value in that same range in less than 1 ms, and the voltage tolerances of items 5) and 6) met by the end of such a change.

12. The rf voltage control program must be able to program the rf voltage to any value between 11 kV and 1.6 MV to within 0.5%, and must be able to specify any of these values at any time within the cycle to within 100 μs.

13. The rf phase control program must be able to program the rf phase to any value between 0 and 360 degrees to within 0.01 degree, and must be able to specify any of these values at any time within the cycle to within 100 μs.

14. The tolerance on the signal to fire the kickers on the correct turn is plus or minus 10 ns relative to the beam bunches on either side of the abort gap.

References

1. Larson, "A Study of the HEB Longitudinal Dynamics," SSCL-655.

2. Larson, "The HEB at Flat Top: Arranging for the HEB to Collider Beam Transfer," SSCL-665.

Appendix

Source Code for the Program Ellipse

```
C       PROGRAM ELLIPSE
        DOUBLE PRECISION PI,A,B,Z,DZ,X(1000),Y(1000)
        DOUBLE PRECISION THETA,DTHETA,XMAX,XTEST,THETAP
        INTEGER NDX,NTHETA,I,J,K
0002    PI=3.141592653589793238
0010    OPEN (UNIT=10,STATUS='OLD',FILE='ellipse.in')
        READ (10,*) A,B,NDX,NTHETA
        CLOSE (10)
0030    OPEN (UNIT=30,STATUS='NEW',FILE='ellipse.out')
        Z=0.0
        DZ=A/(NDX-1)
        DO 0100 I=1,NDX
        X(I)=Z
        Y(I)=-1*B*( (1- ((Z/A)**2) )**0.5 )
        Z=Z+DZ
0100    CONTINUE
        THETA=0.0
        DTHETA=PI/(2*(NTHETA-1))
        DO 0300 J=1,NTHETA
        XMAX=0.0
        DO 0200 K=1,NDX
        XTEST=X(K)*COS(THETA)-Y(K)*SIN(THETA)
        IF (XTEST.GT.XMAX) XMAX=XTEST
```

```
0200  CONTINUE
      THETAP=THETA*180./PI
      WRITE (30,*) 'THETA = ',THETAP,' XMAX = ',XMAX
      THETA=THETA+DTHETA
0300  CONTINUE
      CLOSE (30)
9999  CONTINUE
      STOP
      END
```