Consequences of Kicker Failure During HEB to Collider Injection and Possible Mitigation

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I. INTRODUCTION

In the injector chain for the Superconducting Super Collider (SSC) [1], the High Energy Booster (HEB) is the final stage injector. HEB is a bipolar machine located 14 m above the Collider bottom ring. A schematic representation of the transfer lines from HEB to Collider rings is shown in Figure 1.

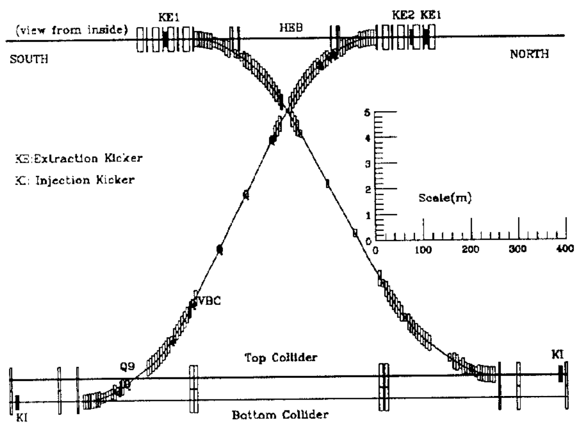

Figure 1. Schematic representation of the transfer lines.

The HEB beam extraction involves introducing a closed orbit bump at the extraction Lambertson magnets and deflecting the beam by kicker magnets. The HEB magnets guide this beam into the field region of the extraction Lambertson magnets. Rolling the first Lambertson provides a horizontal bend in addition to the vertical bend needed to direct the beam down the vertical transfer line. The extraction system for the clockwise beam is shown in Figure 2. Counter clockwise extraction system is similar in principle but differs in detail. The extraction kicker rise time is ~1.7 μs and the flat top is ~ 36 μs.

At the collider level, the beam from the transfer line travels through the field region of the collider injection Lambertson magnets and levels horizontally with the Collider closed orbit. Rolling the last injection Lambertson initiates a horizontal bend. The off-centered beam is bent further by the Collider quadrupoles. Finally, the injection kickers guide the beam back towards ring center and onto the closed orbit of the Collider.

From experience, it is known that there is a finite probability that a kicker may fail, that is, either prefire without triggering or misfire when required to fire. The probability of one kicker failure is high enough that it can occur about once a month [2]. The probability of simultaneous failure of two extraction kickers or two injection kickers is very low. Clean beam transfer depends also on the correct timing between the HEB extraction and Collider injection kickers.

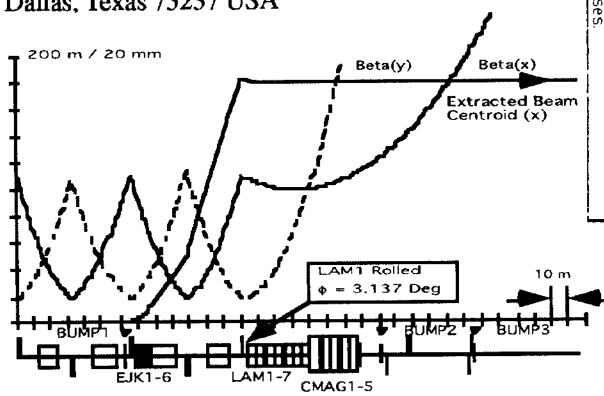

Figure 2. The HEB extraction system for the clockwise beam.

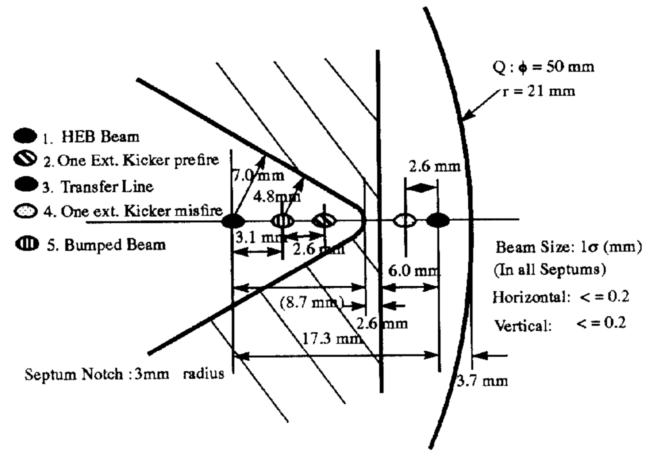

Figure 3. The interface cross section of HEB extraction Lambertson magnet and quadrupole Q1.

The limiting aperture of the HEB at 2 TeV is ~ 40 σ. The transfer line aperture is limited by the extraction and injection Lambertsons and the neighboring quadrupole magnet. The interface cross section of the HEB extraction Lambertson and quadrupole Q1 is shown schematically in Figure 3. A corresponding schematics for the injection Lambertson and qudrupole QU3B is given in Figure 5 of Ref. [3]. The arc represents part of the vacuum chamber through the quadrupole. The iron of the Lambertson magnet is shaded. The septum notch has a curvature of 3 mm radius instead of sharp edge. This enables the straight edge to move towards the field free region and increases the field region by few σ. Note that the circulating beam in each ring passes through the field free region of the Lambertson magnets. The Collider aperture at injection energy is limited by the abort Lambertson to ~ 16 σ.

In the following sections we discuss the three failure modes, namely, single kicker failure, two kickers failure and timing error between the extraction and injection kickers. We propose possible means of protecting the accelerator components.

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II. SINGLE KICKER FAILURE

The extraction and injection kickers are segmented to reduce the kick per module so that beam from a single kicker prefire circulates with little or no beam loss before being aborted.

If a single extraction kicker misfires, the extracted beam is in the field region ~ 3.4 mm (~ 17σ, σ = 0.2 mm) from the edge of the HEB septum. In the injection Lambertson it is ~ 2.7 mm (~ 10 σ, σ = 0.25 mm) from the edge of the septum. In tracking this beam around the Collider ring for the maximum three turns abort, we find that less than 0.01% of the beam is intercepted by the collimators in the interaction regions, and poses no problem to any components.

A single injection kicker misfire produces the same effect as that of prefire and the beam from a kicker misfire will be aborted safely.

III. TWO KICKERS FAILURE

Even though the probability of two extraction kickers failure (prefire or misfire) is very small, it is not insignificant to be ignored. At the HEB extraction Lambertson, the beam resulting from two kickers prefire is in the field free region ~ 0.6 mm (~ 3 σ) from the edge of the septum. As for the misfire, the beam is in the field region ~ 1 mm (~ 5 σ) from the septum. Thus we expect the extraction Lambertson to intercept less than 1% of the HEB beam in the event of two kickers failure. Energy deposition simulation with the MARS12 code [4] reveals that a 1% loss in the septum would produce a maximum temperature rise of ~ 420 °C, which is within the tolerable region. Thus there is no cause for concern at the HEB level as the HEB ring has large enough aperture to accommodate the beam from two kickers prefire with small loss before abort.

In the case of misfire, however, the beam will hit the Collider injection Lambertson directly. Energy density deposited by 2 TeV HEB beam in steel (high Z and high density material) septum is high enough to melt a long section of the septum and to even vaporize part of it. Thus it is necessary to intercept the beam before it reaches the septum using a low Z, low density material like pyrolytic graphite or carbon-carbon composite (C-C). For the purpose of energy deposition they are identical as they have the same density and Z.

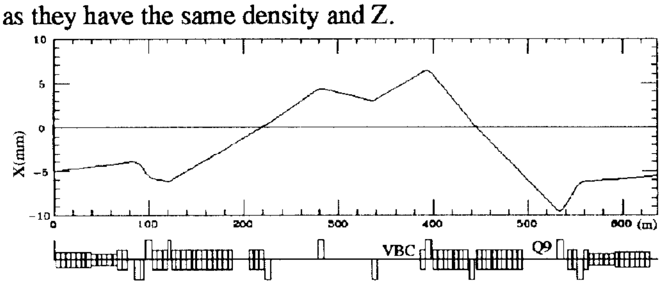

Figure 4. A stretched out transfer line and the beam displacement from two kicker misfire relative to nominal trajectory.

In the transfer line there are only two possible locations with both a large beam excursion from the nominal beam orbit and long free space (see Figure 4) for collimation. The first location is upstream of the first upward bending magnet VBC. The second location is upstream of the quadrupole Q9. Beam sizes and two kicker misfire positions near these two locations are given in Table 1. The last column gives the separation between the beam positions due to two and one misfire in unit of beam size.

Table 1
Beam Sizes and Excursions at the Chosen Locations

Location	σ_x (mm)	σ_y (mm)	x_2 (mm)	x_2-x_1 (σ)
VBC	0.227	0.120	5.50	12.2
Q9	0.394	0.124	8.07	10.2

The first location has three advantages: 1) at this location the collimator will intercept much less beam if a single kicker misfire occurs (last column in the Table 1); 2) this is farther away from the superconducting components and thus the secondaries will have minimum effect; 3) no interference with other beam lines. But it is highly disadvantageous since the interior of a graphite collimator can reach up to 4500 °C (assuming no sublimation) compared to 1750 °C, if placed at the second location (see Figure 5).

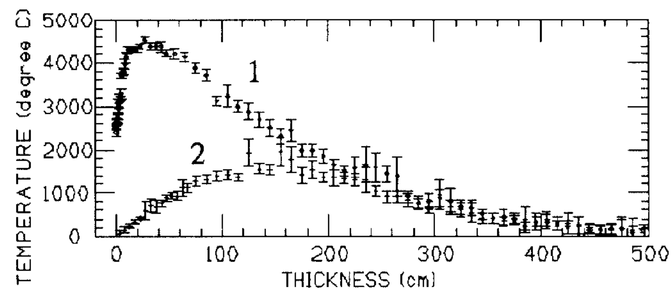

Figure. 5. Temperature distribution along a 1σ cross section of a graphite collimator at location 1 (diamonds) and location 2 (cross).

Graphite in vacuum begins to sublimate at ~ 1750 °C [5]. Since a surface can cool radiatively and the energy deposition peaks in the interior, sublimation will occur in the interior before anywhere else. We estimate the instantaneous pressure to be ~ 20000 atm. using ideal gas laws and the fact that the instantaneous vapor density is equal to the solid density. Laminating the collimator can minimize the effect of such a high instantaneous pressure or even eliminate the possibility of vaporization. The separation between laminations should be few σ (beam size) to allow radiative cooling and the thickness of the laminations should be as small as practically possible considering that the effective length of graphite required is ~ 5 m.

Hence, baring other technical difficulties, the second location, upstream of Q9, is the best place for the collimator to intercept the beam. Considering the fact that the MARS12 simulation can have ~ 20% uncertainty, and that there is some uncertainty in the assumptions such as beam profile and size, we would like to have at least a 50% safety margin; which means that the maximum temperature reached in the simulation should be kept below 750 °C.

Reduction of temperature in the collimator can be achieved by placing a short piece of graphite or C-C at the first location as a beam spoiler. As shown in Figure 6, a 30 cm graphite beam spoiler will reduce the maximum temperature in the collimator well below 750 °C.

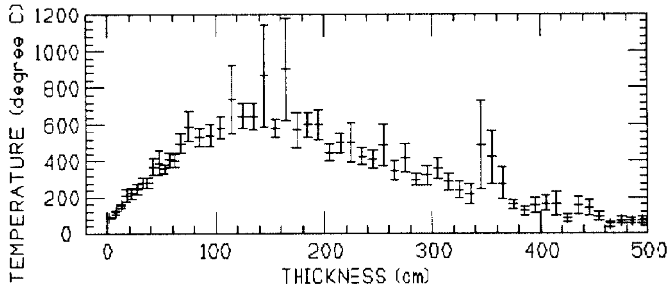

Figure 6. Temperature distribution along the 1σ cross section of a graphite collimator at location 2 with a 30 cm beam C-C spoiler at the location 1.

The beam spoiler will itself be spoiled by the beam. However, if it is only a short piece in an isolated region, it can be regarded as a sacrificial piece with a special vacuum chamber to be replaced if and when such a failure occurs.

An alternative approach is to rotate the beam spoiler fast enough to spread the beam and keep the maximum temperature in the spoiler below the 750 °C. This means that the maximum energy deposited in a 1σ x 5 cm volume of C should not exceed 10 J. From the MARS12 simulation the maximum energy deposited in that volume per proton is 5×10^{-12} J. Thus the maximum number of protons in 1σ cross section should not exceed 2×10^{12} protons, which is 1/8 or 4.5 μs of HEB beam. Hence the spoiler should be rotated by full with half maximum ($2.345\sigma_y$) of the beam in 4.5 μs. This corresponds to the rim speed of 70 ms^{-1}. The required minimum rotation speed for a 35 cm radius spoiler is then 2000 rpm.

Mechanically tolerable rim speed depends on the tensile strength and the density of the material. For graphite, the tensile strength is ~ 25 MPa allowing maximum rim speed of ~ 54 ms^{-1} that is well below our requirement. C-C material has ~ 11 times higher tensile strength and tolerable rim speed is then ~ 180 ms^{-1}. Thus a 30 cm thick C-C composite cylinder of 35 cm radius rotating at ~ 5000 rpm can survive two kickers failure and spoil the beam enough to protect the downstream collimator also. It should be noted that a 35 cm radius C-C system rotating at 40000 rpm is currently in operation[6].

Two injection kickers failure, also a serious problem for the collider, is currently under investigation.

IV. TIMING ERROR

The most serious failure related to the HEB extraction and Collider injection kickers is that the injection kickers may fire either before the HEB beam arrives at the kickers or after it has passed the kickers. Should this failure occur, the HEB beam continues into the Collider ring in the trajectory as shown in Figure 7. Further, an equivalent HEB length of circulating beam will be kicked off the closed orbit in the opposite direction giving rise to a mirror image trajectory about the vertical plane through the closed orbit. Tracking and energy deposition simulations indicate that the two superconducting dipoles in the dispersion suppressor region will be melted with yet unknown consequences related to the cryogenic systems.

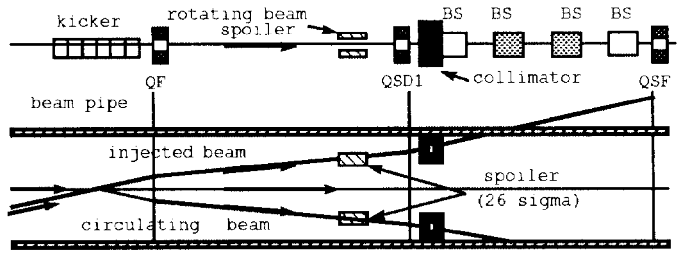

Figure 7. Collider components in the vicinity of injection kickers and the trajectories of the injected and circulating beam due to timing failure.

A logical choice of location for intercepting both the beam is upstream of the dispersion suppressor quadrupole QSD1. The beam sizes near this region are $\sigma_x = 0.18$ mm and $\sigma_y = 0.34$ mm, similar to that at the collimator in the transfer line. Maximum temperature in a graphite collimator will reach up to ~ 1750 °C. A system of a rotating beam spoiler upstream and a long fixed aperture collimator downstream of the quadrupole is a feasible option and is under investigation.

During the rise (~ 1.7 μs) and fall time (~ 4 μs) of the injection kickers an additional ~ 16% of HEB length equivalent circulating beam will be sprayed off the closed orbit. Only ~ 12% will be lost around the Collider ring, and most of it in the collimators. Few dipole magnets in the dispersion suppressor may quench due to excessive beam loss in them from the spray.

V. CONCLUSION

Failure of a single HEB extraction or Collider injection kicker poses no problem to the components in the two rings or in the transfer line. Consequences of two HEB extraction kickers failure or of timing error between the Collider injection and HEB extraction kickers can be minimized if not eliminated by use of a rotating C-C beam spoiler and graphite collimator.

VI. REFERENCES

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