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Abstract

The possibility of a high-precision B -physics experiment in a fixed target configuration has stimulated considerable interest in the extraction of a low-intensity proton beam from the SSC during collider operation. The candidate scheme which has received the most attention uses a bent crystal of Si to deflect protons into the extraction line. In this paper, we present results on deflecting efficiency of Si (110) planes and on the feeding of the crystal by controlled injection of noise into the collider rf system. These results are important in establishing the viability of simultaneous collider and fixed target operation.

1.0 INTRODUCTION

As its name implies, the Superconducting Super Collider is a hadron storage ring whose principal objective is to explore TeV mass scale physics in high- p_t collisions of intersecting counter-rotating proton beams. However, the high energy of the stored protons, 20 TeV, the highest value of any machine now contemplated, makes possible other interesting physics. One concept which has been receiving attention is a fixed target experiment for the investigation of heavy flavors, particularly high-statistics B meson physics. The Super Fixed Target (SFT) experiment¹ as it has come to be called exploits the relatively long decay length of a B meson in the laboratory frame to simplify reconstruction of the candidate events. Detector data handling limits determine the proton extraction rate into the beamline. This is small, of the order of 10^8 pps, which is comparable to the rate at which protons would be removed at a high luminosity IR ($\mathcal{L} = 10^{33} \text{cm}^2 \text{sec}^{-1}$) and is a fraction of the rate of conventional slow spill on hadron storage rings like the Tevatron. It is conceivable then, to operate such an experiment in conjunction with collider operations. This precludes the usual slow spill techniques like resonant extraction and, at SSC energies, conventional extraction hardware would be difficult to implement in any case. For these reasons, we have been exploring the possibility of a novel approach using the phenomenon of planar channeling of charged particles in curved single crystals of Si.² The original suggestion that channeling in such crystals might be applied to the optics of particles in accelerators is due to Tsyganov.³ Subsequently, this has been demonstrated in several applications most of which are reviewed in Reference 2. The most recent example has been at the SpS H8 beamline.⁴ In this paper, we discuss our recent theoretical and computational results on the extraction of the low intensity beam. The two fundamental issues which must be confronted are the efficiency of the channeling and the repopulation of the beam phase space cut by the crystal which, of necessity, must lie in the tail of the beam distribution.

In the remaining part of the introduction, we provide a brief description of the extraction geometry as it is now envisioned relative to the SSC footprint. We then turn to the questions of dechanneling and phase space repopulation in the subsequent two sections. A concluding section discusses the direction of future work.

The SSC lattice includes two utility straights, one in the west campus which provides space for injection, acceleration and beam dumping, and one in the east campus. At one stage of the conceptual design, it was anticipated to allow for beam dumps in both utility straights. While the site-specific design provides for beam absorbers only in the West campus the companion utility straight with its closed orbit bump remains in the East campus lattice. This is a natural location for the low-intensity extraction line. Planar

channeling in a bent crystal of Si is used to provide the kick into the field-free region of the Lambertson string, as illustrated in Figure 1. To deflect the extracted protons into the gap in the distance shown requires an angular kick of slightly less than $100 \mu\text{rad}$.

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Figure 1. Schematic Illustration of the Extraction Utility. (a) Extraction closed orbit bump. (b) Cross-section at the crystal. (c) Cross-section at the Lambertsons.

In our extraction geometry, the channeling crystallographic planes are horizontally oriented with the bend in the vertical direction; that is, the radius of curvature lies in a

vertical plane tangent to the closed orbit. While this fits naturally into a horizontal machine, it was originally suggested,⁵ as a way to alleviate a concern with the ability to orient the channeling crystallographic planes with the physical surface of the crystal. This could be a difficulty with a deflection in the horizontal plane. The quantitative requirements which are imposed on the extractor will be included in our discussion of the extraction mechanics to which we now turn.

2.0 CRYSTAL CHANNELING

The unique feature of the approach to extraction in the SFT is the use of channeling in a bent single crystal of Si to provide the kick which allows the extracted protons to clear a magnetic septum. There has been much work done on the channeling of relativistic particles of various "species" in both axial and planar channels and in both straight and curved crystals. (A review of the subject is provided in the collection of papers "Relativistic Channeling," cf. Reference 2). Space does not permit a detailed discussion and, in any case, most of the new results we wish to report do not involve the channeling process.

It is reasonable to use the (110) planes of Si to deflect the particles and the critical angle for 20 TeV protons is $\approx 1 \mu\text{rad}$. At the proposed crystal position in the SSC lattice, the beam divergence is $\approx \frac{1}{3} \mu\text{rad}$ so one expects a significant fraction of the protons which hit the crystal to be channeled. To obtain an estimate of this fraction as well as the fraction of the particles which hit the crystal and are fully deflected, we use the model presented in Reference 6 and further discussed in Section 4 of Reference 7. Particles striking the crystal are uniformly distributed in space between two adjacent crystal planes and Gaussian distributed in angle with variance $\approx (0.30 \mu\text{rad})^2$.² We consider the crystal to be bent with a constant curvature with a very short straight section preceding the bend. We take a radius of curvature of 300 m corresponding to $100 \mu\text{rad}$ over 3 cm. The fraction of particles channeled in the straight portion is then calculated by assuming a particle dechannels if it penetrates too close to a plane. This defines a boundary in the transverse phase space of the channeled particles inside of which all channeled particles lie. The boundary is an energy surface. The channeled fraction is given by the density integrated over this phase area. In the region of constant curvature, the boundary is contracted due to the centrifugal potential and the phase area of channeled particles is reduced. The fraction of particles fully deflected is given by the density integrated over this phase area. These are illustrated in Figure 1b of Reference 6 where they are referred to as O_0 and O_1 respectively. A full discussion of the theory appears there. We use $2.5 \rho_1$ as our dechanneling criterion as discussed in Reference 7. Here $\rho_1 = 0.075 \text{ \AA}$ is the one-dimensional rms lattice vibration amplitude at room temperature. There is both

experimental and computer simulation evidence for the $2.5 \rho_1$ criterion. In Figure 2, we show both of these as a function of $\Gamma = \frac{1}{2\pi z_1 z_2 n e^2} \left(\frac{pv}{R} \right)$ assuming beam divergence and momentum are fixed. Here p is the particle momentum, v its velocity ($\approx c$), R the bend radius, z_1 and z_2 the atomic numbers of the particle and channeling medium respectively, and n the areal number density ($= Nd_p$, with d_p the interplanar spacing and N the atomic density). Γ is roughly the ratio of the centrifugal potential to the channel potential. For our parameters ($z_1 = 1$, $z_2 = 14$, $n = 0.096 \text{ \AA}^{-2}$, $e^2 = 14.4 \text{ eV-\AA}$, $\Gamma = 5.48 \times 10^{-2}$), we find 78% initially channeled and 64% fully deflected.

Figure 2. Planar Bending Dechanneling Curves as a Function of Γ . Dotted curve: fraction dechanneled in curved section, dashed curve: net fraction dechanneled, solid curve: net fraction channeled. The circles correspond to SSC parameters.

The next dechanneling process to consider is that due to electron multiple scattering (ems). If we assume an average electron density of $z_2 N$ in the (110) planes of Si then the mean square scattering angle per unit length due to ems is $\approx 6.44 \times 10^{-23} \text{ rad}^2/\text{\AA}$ giving a scattering angle of $\approx 0.14 \text{ } \mu\text{rad}$ in 3 cm of Si.⁸ Thus the ems dechanneling should be small. (For comparison, we note that the combined nuclear and electron multiple scattering in a random direction gives an rms scattering angle of $\approx 0.40 \text{ } \mu\text{rad}$ for 3 cm). Other factors such as defects (e.g. dislocations) should be small in the Si sample sizes required. The effects of radiation damage and local heating depend on the details of the extraction

and we will say more about this in the next section. In any case, they can be mitigated against. Thus it seems a 50% efficiency represents a not unreasonable expectation. This analysis is consistent with the CERN experiment at 450 GeV. Another approach to the investigation of channeling can be found in Reference 9.

3.0 NOISE IN THE RF SYSTEM

The particles which are removed from the circulating beam by the crystal occupy a volume of phase space which must be repopulated if extraction is to be continuous. There is a slow growth of beam halo which occurs both from interactions at the collision points as well as from scattering on the residual gas in the beam pipe. The rate is dependent on the luminosity and does not appear to be adequate at $\mathcal{L} = 10^{33} \text{cm}^2 \text{sec}^{-1}$ for the physics to be done. (For $\mathcal{L} = 10^{34}$, the halo rate is likely to be sufficient but it might still be desirable to have a controlled way to move particles to the edge of phase space.) We have been investigating the use of noise injected into the rf system as a mechanism for doing this. Dispersion at the position of the crystal translates momentum displacements into transverse displacements. Two important requirements which any scheme used to bring protons onto the crystal must satisfy are considered here. The beam core in the longitudinal phase space must not be disturbed and the hit distribution must lead to the desired extraction rate. In the results to be presented, we will demonstrate that injection of suitably tailored noise can satisfy both of these.

We have investigated the effect of rf noise on the circulating SSC beam for extraction using both a diffusion theory in longitudinal action and tracking studies in the linear lattice with the noise in the rf simulated by a Monte Carlo scheme. The theoretical model is based on work at CERN and Brookhaven.^{10,11} Our own contributions to the development of the theory will appear soon.¹² A concise description of both the theory and the simulation technique appears in Reference 13. The theory considers only the longitudinal degree of freedom while the tracking studies follow the full six-dimensional motion until a given track strikes the crystal. Nevertheless, we find good qualitative agreement between the two. We have considered both phase and amplitude noise. Phase noise typically has a larger effect on the core than does amplitude noise. For a white noise spectrum, the diffusion coefficient for the small amplitude particles is linear in the action for phase noise while quadratic for amplitude noise. However, we will see that by filtering the noise spectrum, the diffusion coefficient can be made to have a higher order tangency for these protons, with a concomitant reduction in diffusion, even for phase noise. Our results for amplitude noise will be described elsewhere.¹⁴ Tracking studies are important to interface the evolving halo with the crystal channeling. We now turn to a discussion of the important results.

The distribution in action is shown in Figure 3a for phase noise with a notch filtered spectrum. The dashed curve gives the initial distribution in action. The solid curve and histogram respectively show the results from theory and simulation at 5×10^6 turns, the end of the run. The agreement between the two is good. Detailed discussion of the theoretical model and results therefrom will appear in Reference 14. Computational constraints require a reduced number of turns in the tracking, so the variance of the noise is chosen to give an adequate number of strikes on the crystal. Nevertheless, the noise is small and at the desired extraction rate at the SSC, $1\text{-}2 \times 10^8$ pps, the variance would be smaller still. It is important to verify that the core of the longitudinal distribution is preserved. A scatter plot of the longitudinal δ - ℓ phase space appears in Figure 3b, where δ is the relative momentum deviation and ℓ is the path length deviation. Here the initial phase coordinates of the tracks which strike the crystal are shown. The hole in the phase space in the filtered noise is a dramatic illustration of the preservation of the longitudinal core. This is also seen in Figure 3a where the change in distribution is seen to be small for $j \lesssim 0.24$. Filtering is seen to be an effective way to reduce the diffusion from the core. By contrast, white noise transports particles from the longitudinal core and would not be acceptable.¹³

The distribution of hits on the crystal is of considerable interest for the design of the deflecting crystal. Due to the dispersion, the noise induces a diffusion of the closed orbit. A diffusion in the horizontal position then results from a superposition of this on the betatron motion. Consider a proton which just skims the crystal when its x -betatron ellipse is moving toward the crystal. It next encounters the crystal at a subsequent turn which is tune dependent. Therefore the net displacement of the closed orbit, which is approximately the step size, also depends on the tune. Thus the number of hits and their distribution on the crystal are expected to depend on the size of β_x and on the tune. In Figure 4a are shown the hits for two values of β_x , 346 m and 1385 m. The first value is representative of our earlier results¹³ and corresponds to the value of β_x before the recent interchange of the direction of the two counterpropagating beams. The difference in β_x at the location of the crystal is a consequence of the asymmetry of the utility straight with 4 m dispersion. We see that the distribution of hits is not especially sensitive to β_x but the total number of strikes increases significantly. In both cases, the extraction rate is larger than needed in practice and the actual noise variance would be smaller. The tune dependence is illustrated in Figure 4b where the distribution is shown for a case in which the fractional part of the horizontal tune was (unrealistically) chosen close to $1/2$. As expected, the hit distribution became considerably narrower. Since machine operation avoids low order rationals, the effect of tune is not anticipated to be a problem. It is

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Figure 3. (a) Longitudinal Distribution in Normalized Action $j = J/J_c$ Where J_c is the Action at the Image of the Crystal Position. Initial distribution is dashed. After 5×10^6 turns, with phase noise of variance $\sigma_e = 0.155$ and spectrum notched in a small band around small amplitude synchrotron frequency, the solid curve gives the theory and the histogram the result of tracking simulation in six-dimensional phase space initially following 1000 particles. (b) Scatter Plot of Initial Longitudinal Phase Coordinates of 128 Tracks Which Strike Crystal. The ellipse is centered at (0,0) with major and minor axes given by $\sigma_\delta = 5.0 \times 10^{-5}$ and $\sigma_l = 5.1 \times 10^{-2}$ m.

Figure 4. Distribution of Hits on Crystal. (a) $\nu_x = 122.784$, dashes: $\beta_x = 346$ m, solid: $\beta_x = 1385$ m
 (b) $\nu_x = 122.501$, $\beta_x = 1385$ m.

understood that the extraction will take place in a thin strip of material at the edge of the crystal. This does not appear to lead to any fundamental problems. Finishing the edge to optical accuracy with disruptions of the lattice on the scale of Ångströms is consistent with fabrication of single crystal Si optical elements in other applications.¹⁵ However, energy deposition and radiation damage in such a relatively small volume of crystal may impact the system design.

4.0 SUMMARY

The physics potential of a fixed target capability for Beauty physics at the SSC has stimulated the interest in the extraction of a low intensity beam from the circulating proton bunches. The extracted beam could serve other fixed target experiments besides SFT as well as provide 20 TeV test beams. While the initial concept is several years old,¹⁶ substantial progress has been made subsequent to the Snowmass Summer Study¹⁷ last year. Furthermore, interest in pursuing a similar idea at the proposed Large Hadron Collider (LHC) at CERN¹⁸ has grown as a result. We have described in this paper some of our recent results which contribute substantially to the demonstration of the feasibility of the concept. However, there are considerations in addition to the extraction rate and preservation of the longitudinal emittance which are important to a working extraction scheme. We have already mentioned the distribution of hits on the crystal. It is also desirable from the perspective of the physics objectives that the extraction duty factor be close to unity. That is, the time dependence of the extraction rate should be close to the optimum mean rate of one proton/bunch/turn. It is reasonable to expect that some variation with time of the parameters such as the noise spectral density and filter bandwidths may be useful to maintain this ratio. This research will be part of our continuing investigation of the extraction process. Furthermore, other ideas for manipulating the rf system to move protons onto the crystal are now beginning to be investigated.^{19,20} These could also be useful in developing an optimized system. A significant part of future research will be devoted to gaining a sufficient understanding of the longitudinal dynamics in the presence of these complex modulations in anticipation of the proposed experiments at the Tevatron²¹ beginning in 1992.

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