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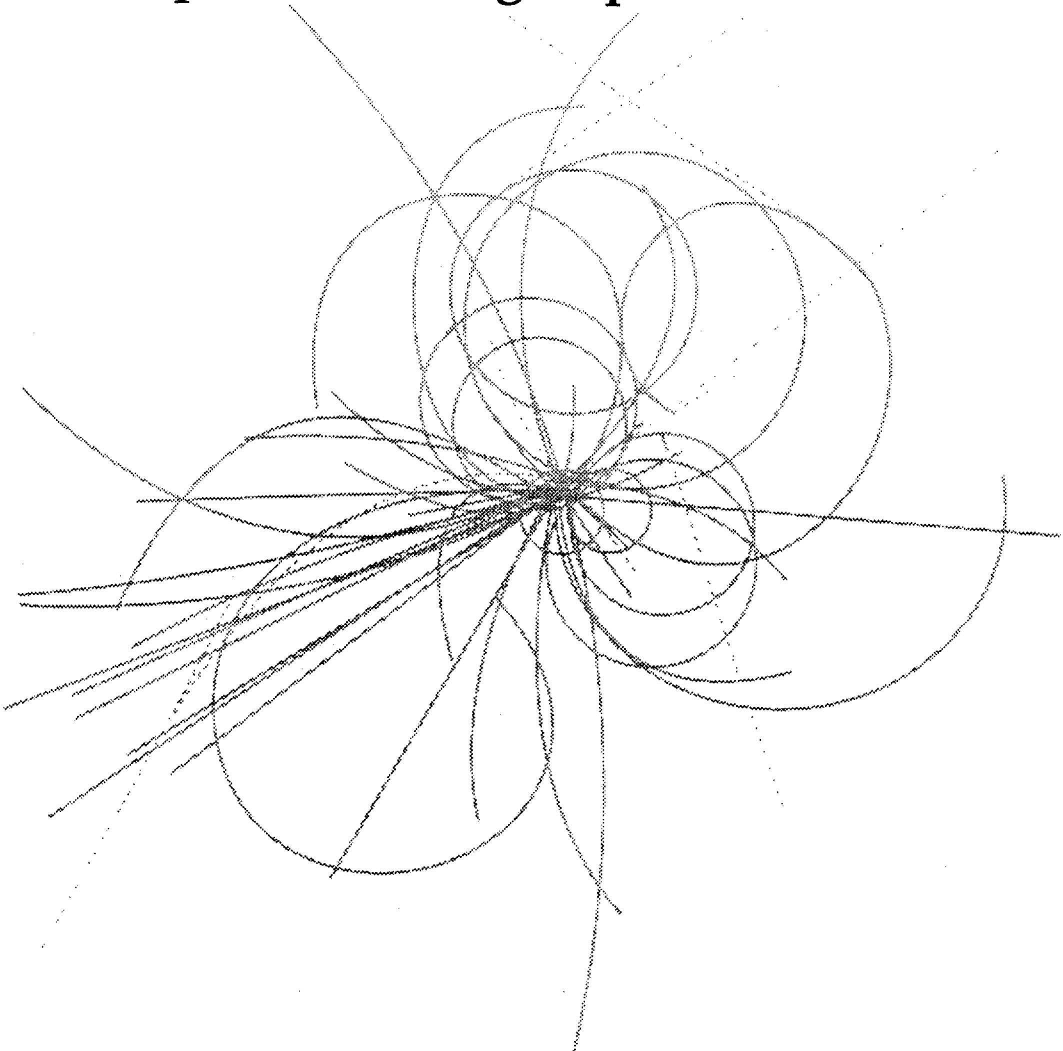

Super Slow Extraction at the SSC Using Channeling in a Bent Crystal

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Super Slow Extraction at the SSC Using Channeling in a Bent Crystal*

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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.

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1 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) experiment[1] 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 bent 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 μrad.

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. With a vertical deflection, the

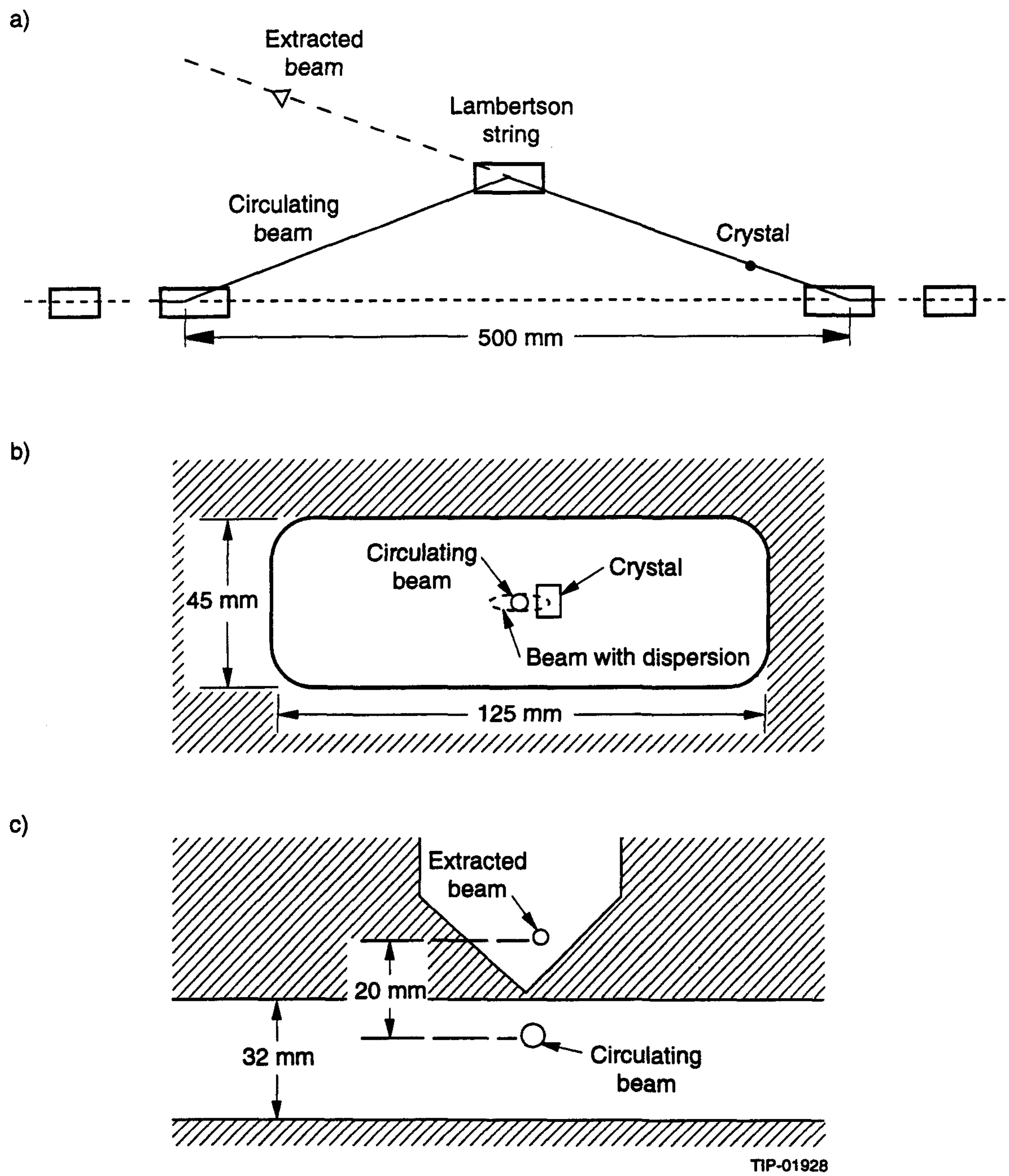

Figure 1. Schematic Illustration of the Extraction Utility. (a) Extraction closed orbit bump. (b) Cross-section at the crystal. (c) Cross-section at the Lambertsons.

channeling occurs in a thin layer at the crystal edge perpendicular to channeling planes. The issues associated with this will be discussed at the end of Section 3.

2 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 bent 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 $\approx 1\,\mu$rad. At the proposed crystal position in the SSC lattice, the beam divergence is $\approx \frac{1}{3}\ \mu$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 $\approx (0.30\ \mu\text{rad})^2$. 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 μrad 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_o and O_i respectively. A full discussion of the theory appears there. We use 2.5 ρ_1 as our dechanneling criterion as discussed in Reference 7. Here $\rho_1 = 0.075$ Å is the one-dimensional rms lattice vibration amplitude at room temperature. There is both experimental and computer simulation evidence for the 2.5 ρ_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 a real 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 ($z_1 = 1$, $z_2 = 14$, $n = 0.096$ Å^{-2}, $e^2 = 14.4$ eV-Å, $\Gamma = 5.48 \times 10^{-2}$), we find 78% initially channeled and 64% fully deflected.

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 $\approx 6.44 \times 10^{-23}$ rad^2/Å giving a scattering angle of ≈ 0.14 μrad 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 ≈ 0.40 μrad 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.

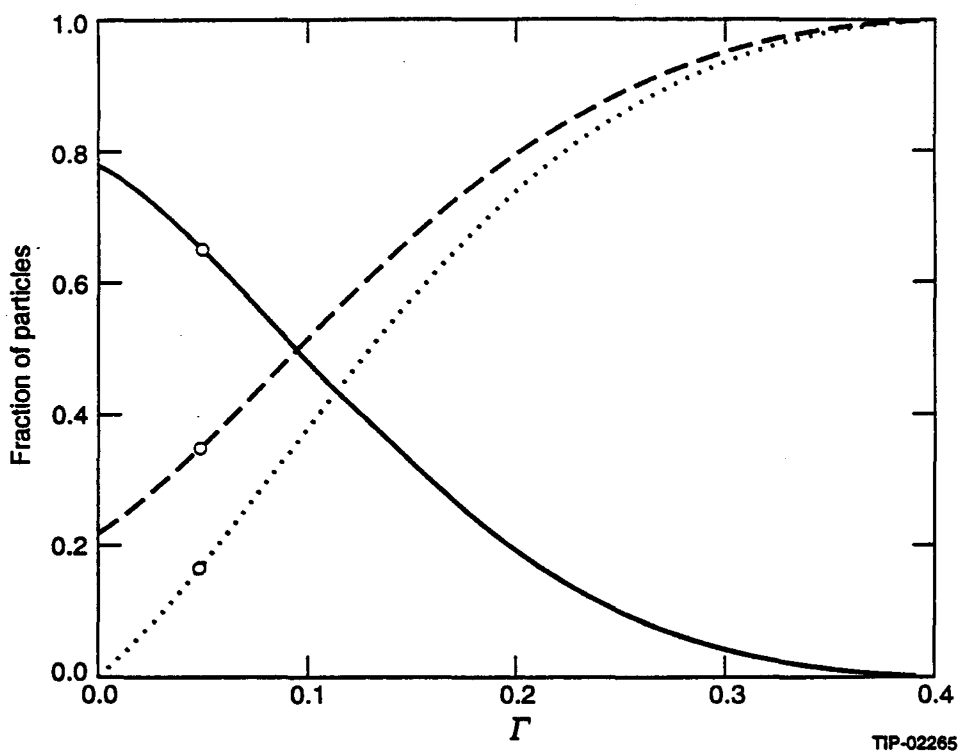

Figure 2. Planar Bending Dechanneling Curves as a Function of Γ. Dotted curve: fraction dechanneled in bent section, dashed curve: net fraction dechanneled, solid curve: net fraction channeled. The circles correspond to SSC parameters.

3 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 SFT 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 periphery of the beam.) We have been investigating the use of noise injected into the rf system as a mechanism for doing this, since the crystal will be located in a region where dispersion is nonzero and thus momentum displacements can be translated 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 enough to interfere with collider operations and the hit distribution on the crystal must lead to the desired extraction rate. In the results to be presented here, 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 rf noise simulated by a Monte Carlo scheme. The theoretical model is based on work at CERN and Brookhaven.[10,11] The longitudinal motion is governed by a coupled set of difference equations describing the evolution of the particle momentum and phase relative to the rf:

$$\phi_{n+1} - \phi_n = P_{n+1} + \psi_{n+1} - \psi_n, \tag{1}$$

$$P_{n+1} - P_n = -K_0(1 + a_n)\sin\phi_n, \tag{2}$$

with $P_n = \omega_{\rm rf}T_0\alpha_c(\Delta p_n/p_s)$ and $K_0 = \omega_{\rm rf}T_0\alpha_c(eV/p_s v_s) = \Omega^2 T_0^2$. Here n is the turn number, ϕ the phase relative to the synchronous phase, ψ the phase noise, a the amplitude noise, $\omega_{\rm rf}/2\pi$ the rf frequency, T_0 the beam revolution frequency, α_c the momentum compaction factor, e the electron charge, V the rf peak voltage, p_s and v_s the momentum and velocity of the synchronous particle, and $\Omega/2\pi$ the small oscillation synchrotron frequency;

Δ refers to a variation relative to the synchronous particle. If we define $P = P_n/T_0$, then the continuous time approximation of Eqs. (1) and (2) is:

$$\dot{\phi} = P + \dot{\psi}(t), \quad (3)$$

$$\dot{P} = -\Omega^2(1 + a(t)) \sin \phi. \quad (4)$$

A synchronous particle passes through the rf cavity at the zero crossing of the noise-free rf wave ($\phi = 0$) and its momentum is constant.

The horizontal dynamics determines the interaction of the circulating beam with the crystal. The horizontal position of a particle relative to the design orbit, x, is the superposition of its betatron motion and its closed orbit:

$$x = x_\beta(s) + x_{co}(s) \quad (5)$$

where s is the position in the ring. The closed orbit is periodic by definition and is given in terms of the particle momentum deviation by

$$x_{co}(s) = \eta(s)\Delta p/p_s. \quad (6)$$

The dispersion $\eta(s)$ is a lattice function and is given for a specified machine design. Therefore, by locating the crystal at a point in the machine where η is large, a particle with sufficient $\Delta p/p_s$ will strike the crystal.

Noise in the rf system induces a slow "diffusion" in the longitudinal phase space which repopulates the portion of phase space cut by the crystal. Because the rf cavity is in a dispersion free region ($\eta = 0$), the longitudinal dynamics there evolve by iteration of Eqs. (1) and (2). However, to account for the coupling at the crystal due to the dispersion there, the full six dimensional motion is followed in our Monte Carlo tracking.[9,12] While the tracking is a realistic representation of the process, it is computationally intensive. Fortunately, it has been shown[10,13] that the invariant action, $J = \oint P d\phi$, of the noise-free pendulum equations (Eqs. (3) and (4) with $a = \psi = 0$) evolves approximately as a diffusion process, in the presence of noise. The diffusion equation for the action density, $\rho(J,t)$, is

$$\frac{\partial \rho}{\partial t} = \frac{\partial}{\partial J}\left(D(J)\frac{\partial \rho}{\partial J}\right). \tag{7}$$

The natural auxiliary conditions are

$$\rho(J,0) = \rho_0(J),$$

$$\rho(J_b,t) = 0,$$

where $\rho_0(J)$ is the initial density, and the second condition is an absorbing boundary condition at $J = J_b$, an appropriately chosen boundary. The diffusion coefficient is determined from the noise spectral densities.[10] Phase noise typically has a larger effect on the core than does amplitude noise. For a white noise spectrum, the diffusion coefficient for small action is linear for phase noise while quadratic for amplitude noise. Our results for amplitude noise will be described elsewhere.[13] The distribution in action at 10^6 turns is shown in Figure 3a for white phase noise. The diffusion coefficient is presented as an insert and the dotted curve gives the initial distribution in action. The solid curve and histogram respectively show the results from theory and simulation. In the simulation, a particle is removed when its action exceeds J_b. The agreement between the two is good. At 10^6 turns there is considerable broadening of the beam, and this is unacceptable for concurrent collider experiments. However, we will see that by filtering the noise spectrum, the diffusion coefficient can be reduced for small action, with a concomitant reduction in diffusion of

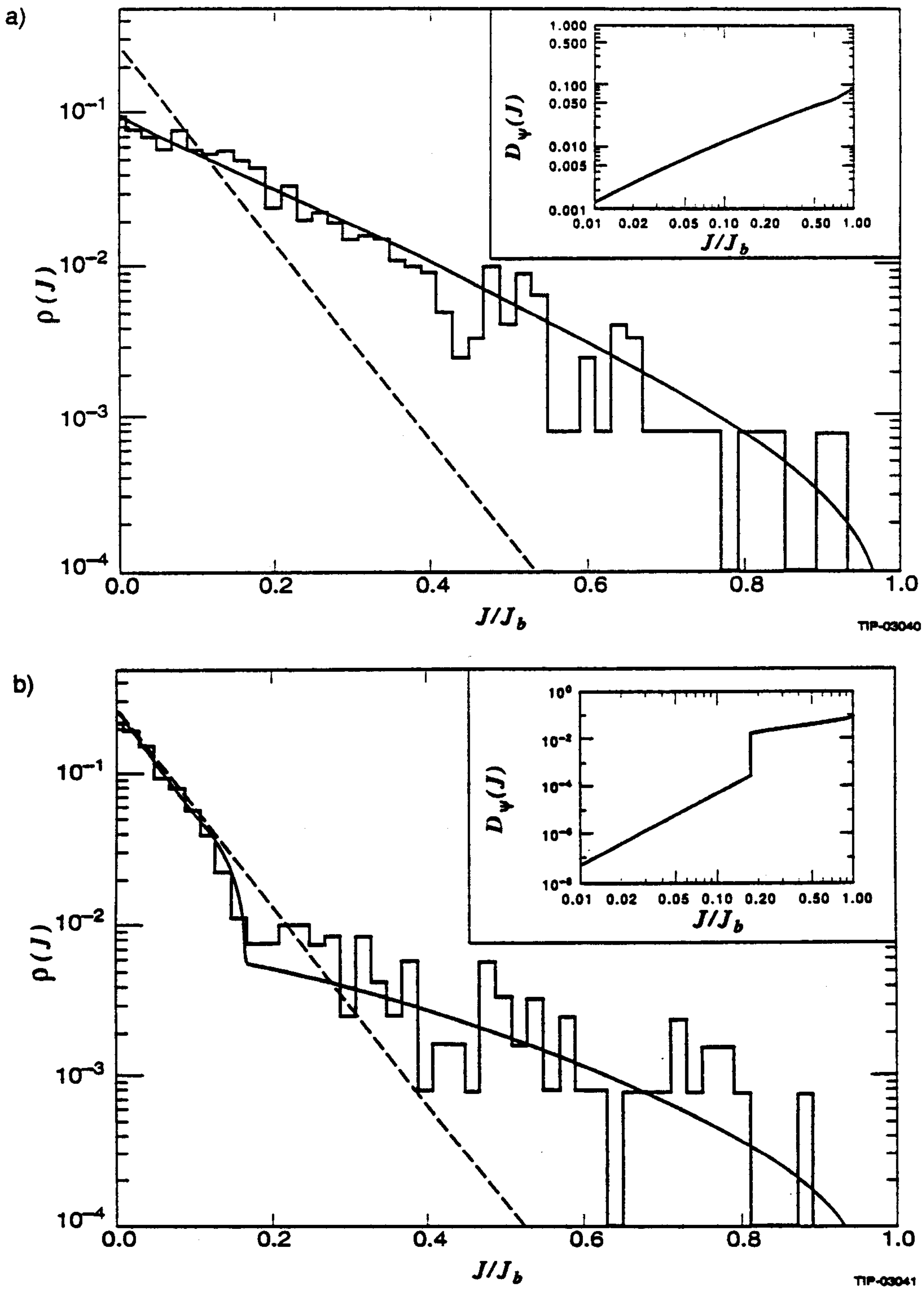

Figure 3. Distributions in Longitudinal Action. Initial distribution is dotted. Distribution at 10^6 turns from diffusion theory is given by solid line and that from tracking simulation by histogram. The diffusion coefficient is shown in the insert. The noise variance is $(0.1 \text{ rad})^2$. (a) White phase noise. (b) Notched phase noise.

the beam core. This is shown in Figure 3b for phase noise with a notch filtered spectrum. Our notched filter removes frequency components near the small amplitude synchrotron frequency from the spectrum, and the diffusion coefficient for small J is now proportional to J^3. Here the agreement between theory and simulation is also good.

However, the boundary condition warrants a closer look. In the simulations above, particles were removed from the beam when they reached the critical action $J = J_b$. The critical action, J_b, is defined by $\phi = 0$ and $\Delta p/p_s = x_c/\eta_c$ where x_c is the crystal horizontal position and η_c is the dispersion at the crystal. This action is also used as the absorbing boundary in the diffusion model. However, this is only an approximation to the effect of the crystal: tracks which strike the crystal are essentially removed from the beam. In reality, due to the betatron motion, the crystal does not actually define a distinct boundary in action. The above choice of boundary condition gives a lower bound on the number of hits on the crystal. As Eq. (5) implies, a particle with a betatron oscillation can hit the crystal before its action grows to J_b. The histograms in Figure 4 illustrate the difference. This is from a simulation in which the particles were removed from the beam when their x-position exceeds x_c. Comparing with Figure 3, we see that only the tail of the longitudinal distribution is affected and, consistent with the argument above, that Figure 4 gives more hits on the crystal. It is important to note that the final distribution is close to the initial for small action so that the beam core is not affected. Additional insight into the core preservation is seen in the longitudinal phase space scatter plots for the white and notched cases shown in Figures 5a and 5b respectively. Here the initial phase coordinates of the tracks which strike the crystal are shown. Figure 5a confirms the unsuitability of white phase noise discussed earlier. In contrast, the hole in the phase space shown in Fig. 5b in

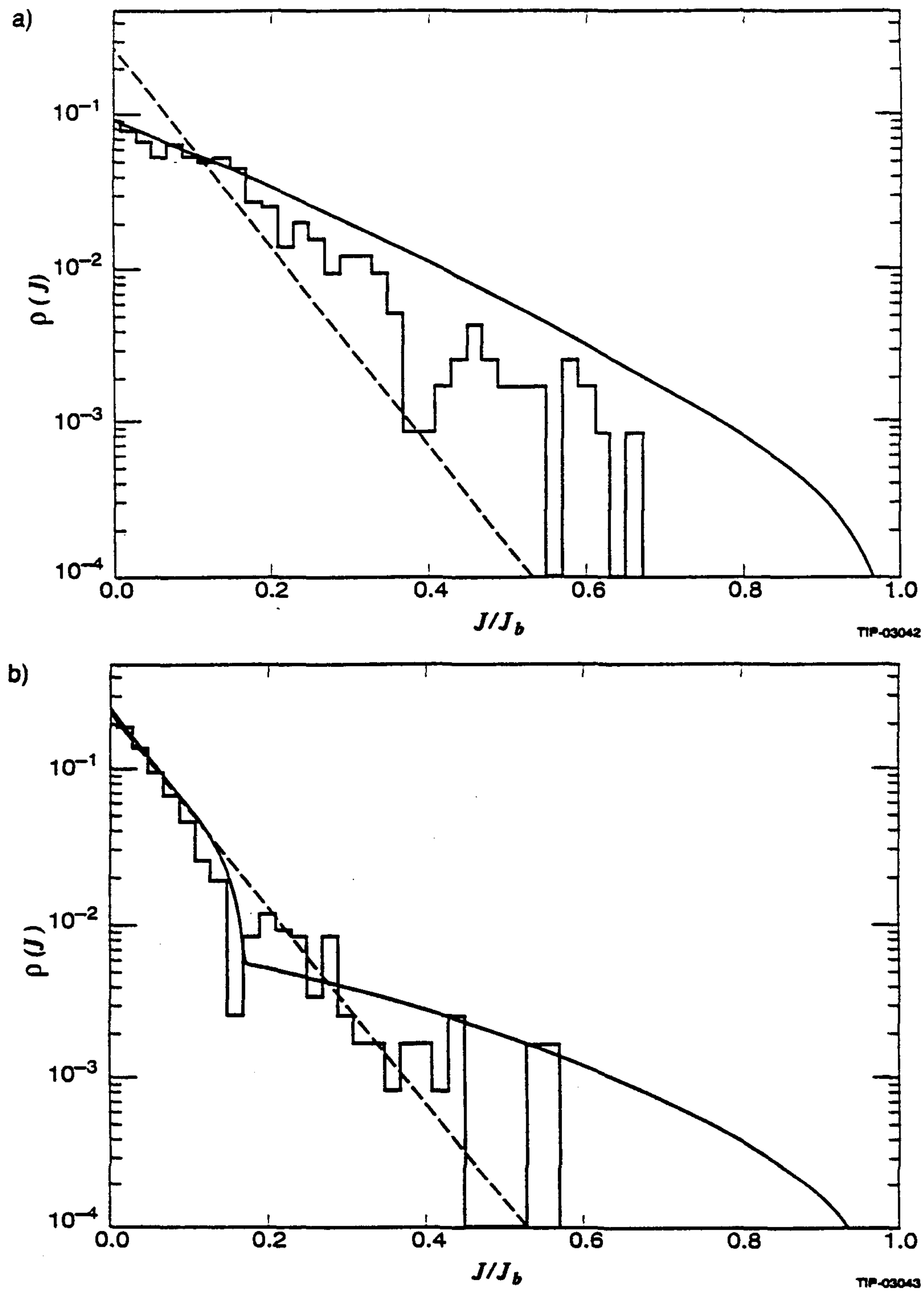

Figure 4. Same as Figure 3, Except that the Histogram Represents Simulation in Which Particles are Removed from the Beam When They Strike the Crystal.

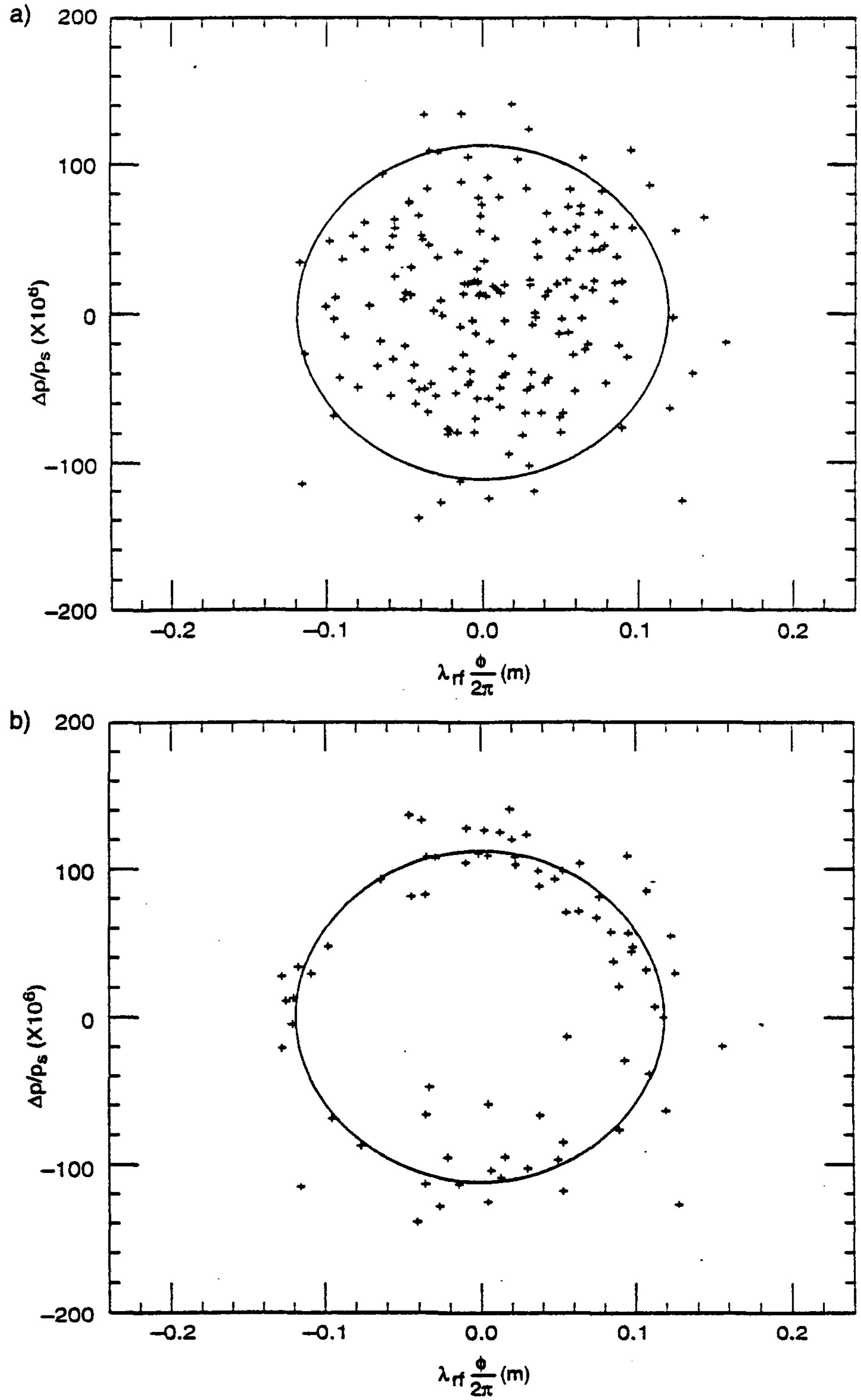

Figure 5. Scatter Plots of Initial Coordinates in Longitudinal Phase Space of Tracks Which Strike the Crystal. λ_{rf} is the rf wavelength. The circle is the orbit whose synchrotron frequency is 0.95Ω. (a) White phase noise. (b) Notched phase noise.

the filtered noise case is a dramatic illustration of the preservation of the longitudinal core. Filtering is seen to be an effective way to reduce the diffusion from the core. Computational constraints require reduced numbers of turns and tracks in the tracking, so the variance of the noise is chosen to give an adequate number of strikes on the crystal. Nevertheless, the noise variance is small, and would be smaller still at the desired extraction rate at the SSC, 1-2$\times 10^8$ pps.

The distribution of hits on the crystal is of considerable interest for the design of the deflecting crystal. To understand the hit process, we note that three time scales are represented in Eq. (5). The slowest, on the scale of many synchrotron periods, is the diffusion in the longitudinal phase space. Because of the dispersion, the noise induces a diffusion of the closed orbit, and this is, in effect, what continuously feeds particles into a neighborhood of the crystal. This has no other role. The intermediate time scale is the synchrotron period. On this time interval the center of the betatron ellipse goes through one oscillation and comes closest to the crystal when $\Delta p/p$ is a maximum. In addition the particle is moving on its betatron ellipse; this is the fast time scale. At the SSC, the synchrotron period is roughly $800T_0$ and the betatron period is roughly $T_0/100$. In summary, each particle moves rapidly on a betatron ellipse with slowly oscillating center. The amplitude of this slow oscillation increases very slowly due to the diffusion. Now, 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 determined by the betatron phase advance, that is, the fractional tune. Therefore, during this time, the net displacement of the closed orbit due to the momentum change, 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 6a are shown the hits for two values of β_x, 346 m and 1385 m. The first value is representative of our earlier results[12] and corresponds to the value of β_x before the recent interchange of the direction of the two counterpropagating beams at the SSC. We see that the distribution of hits is not especially sensitive to β_x but the total number of strikes increases significantly. This is a consequence of being able to reach deeper into the longitudinal distribution. 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 6b where the distribution is shown for a case in which the fractional part of the horizontal tune was (unrealistically) chosen close to 1/2. That is, the particle returns to the crystal after only two turns and the center of the betatron ellipse moves only slightly giving a smaller step size. Thus, 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 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 Ångstroms is consistent with fabrication of single crystal Si optical elements in other applications.[14] However, energy deposition and radiation damage in such a relatively small volume of crystal may impact the system design.

4 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

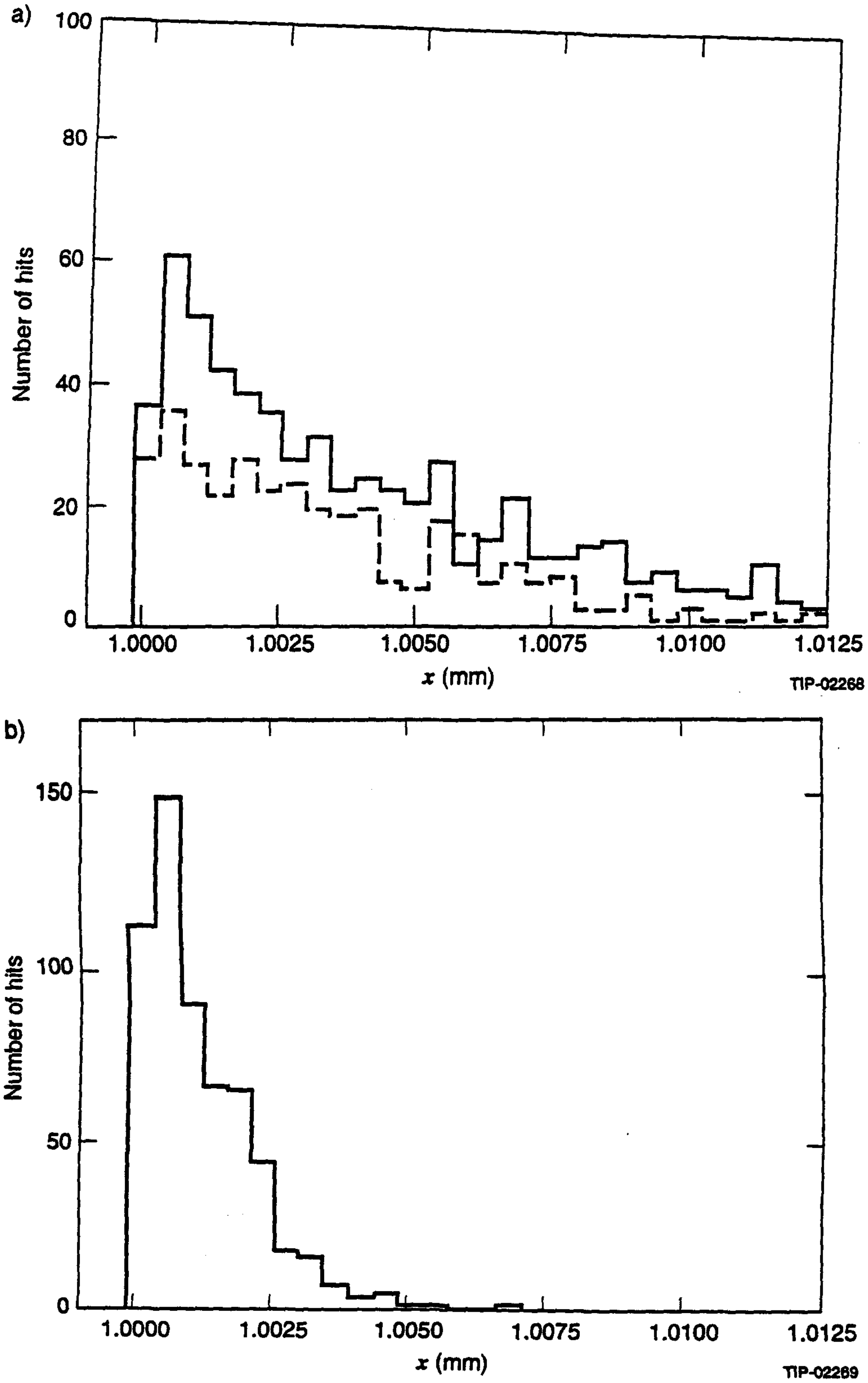

Figure 6. Distribution of Hits on Crystal. (a) $\nu_x = 122.784$, dashes: $\beta_x = 346\,\mathrm{m}$, solid: $\beta_x = 1385\,\mathrm{m}$ (b) $\nu_x = 122.501$, $\beta_x = 1385$ m.

SFT as well as provide 20 TeV test beams. While the initial concept is several years old,[15] substantial progress has been made subsequent to the Snowmass Summer Study[16] in 1990. Furthermore, interest in pursuing a similar idea at the proposed Large Hadron Collider (LHC) at CERN[17] 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.[18,19] 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 Tevatron[20] beginning in 1992.

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