TRACKING STRIPPED PROTON PARTICLES IN SNS RING INJECTION MOMENTUM DUMP LINE *

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Abstract

3D computer simulations are performed to study magnetic field distributions and particle trajectories along the SNS ring injection momentum dump line. Optical properties and transfer maps along the dump line are calculated. The stripped proton particle distributions on the dump window are analyzed. The study has provided useful information for the redesign of the SNS ring injection beam dump.

INTRODUCTION

An important source of particle losses in the SNS accumulator ring would be the momentum spread of the H^- beam coming from its superconducting linac. The beam particles with an energy difference of more than 4 MeV from the nominal design energy of 1 GeV would not be captured by the RF bucket and would end up in the gap between consecutive bunches, inducing intolerable losses during extraction.

A momentum collimation is designed by the SNS/BNL team to eliminate momentum tails of the H^- beams before they are injected into the ring [1-2]. The collimation employs a momentum scraper, consisting of two movable foils, at a maximum dispersion point in the HEBT line. Figure 1 shows the schematics of the momentum collimation, containing two horizontal stripping foils, a quadrupole magnet and a dipole corrector, and a bending dipole followed by a transport line to a dump. The foils strip the H^- beam that has a momentum spread of $0.2\% < \delta p/p_0 < 0.6\%$ into H^+, which is subsequently bent by a dipole DD4 (8D533) and directed to the beam dump. The unstrapped H^- beam is bent to the ring by 8D533 in the opposite direction.

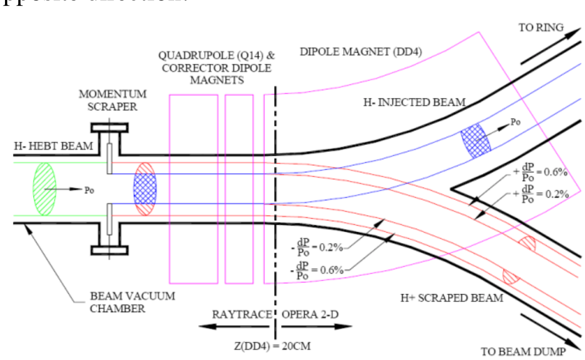

Figure 1: SNS ring injection momentum collimation (courtesy of P. He et al of BNL [2]).

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3D SIMULATION MODEL

In this study we employ a full 3D simulation code: OPERA3D/TOSCA v. 12 [3]. The 3D simulation model is shown in Fig. 2. It consists of three magnets: an HEBT dipole 8D533, a ring quad 21Q40, and the steel core of a dipole correct 27CD30. The positions of these magnets follow the design dimensions and are verified with our survey data. A coordinate translation and rotation from the SNS global coordinates is made for the convenience of simulations. The new coordinate origin in the simulation model is set at the quad center. The z-axis is chosen to coincide with the quad axis. The dipole pole-center is located at x = 22.209, y = 0, and z = 340.351 cm in the new coordinates, and the dipole axis is rotated by 5.625^o with respect to the quad axis.

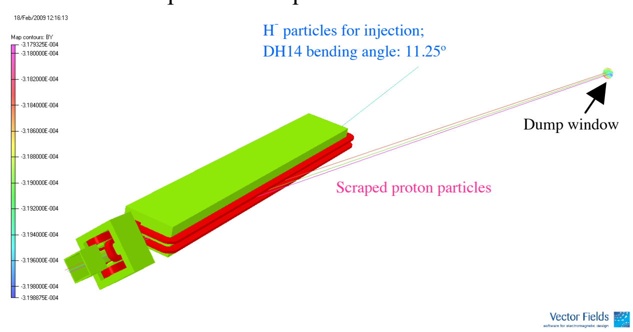

Figure 2: 3D model of momentum collimation dump line.

The background in the simulation model is a rectangular box of x = y = ±200 and z = -300 to 1550 cm, which includes the dump window. The model contains fine meshes with a total of 7275147 nodes and 17205349 elements, resulting in a post processor file of 3.325 GB. In order to ease the volume mesh, we have added four artificial cuts: two vertical ones at z = 45 and z = 900 cm; and two horizontal ones at y =±100 cm.

MAGNETIC FIELD DISTRIBUTIONS

Three-dimensional multipole expansion of the magnetic field has been made around a reference trajectory for the stripped proton beams. The reference trajectory is obtained for a 1 GeV proton particle launched upstream of quadrupole 21Q40 on its axis. This trajectory is fairly a planar curve on the y = 0 plane and is plotted in Fig. 3. The minimum curvature radius of the reference track is about 27.7 m. We expand the fields about the reference track in the same way as we developed in reference [4]. Note that this reference track does not exactly go through the designed dump window center, which is indicated by a red dot in the figure.

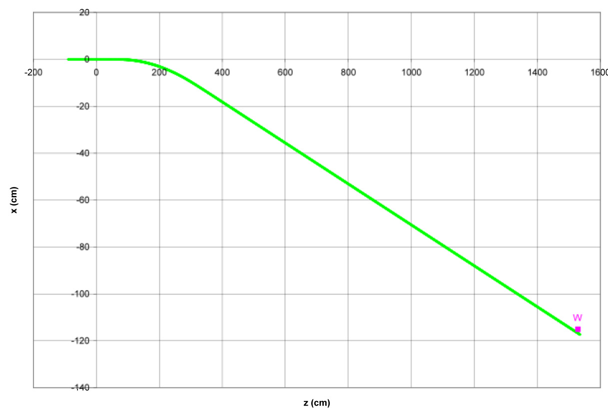

Figure 3: Reference trajectory for stripped proton beams.

Figure 4 shows the normal dipole term B_1 at a radius of 4 cm along the reference track. The linear component of the normal dipole term is $b_1(z)$, as indicated by the red curve. The linear component is a good representation of the dipole field. Figure 5 shows the quadrupole terms. Dipole 8D533 contains a small quad component at its entrance due to edge focusing, as well as a strong quad component in the fringe region due to its C-structure. Other higher-order field components exist as well. Due to the up-down symmetry about the mid-plane, all the skew terms should vanish.

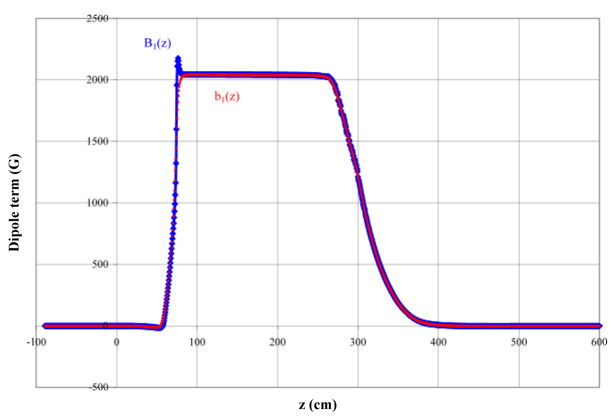

Figure 4: Dipole field B_1 at R = 4 cm and its linear term $b_1(z)$.

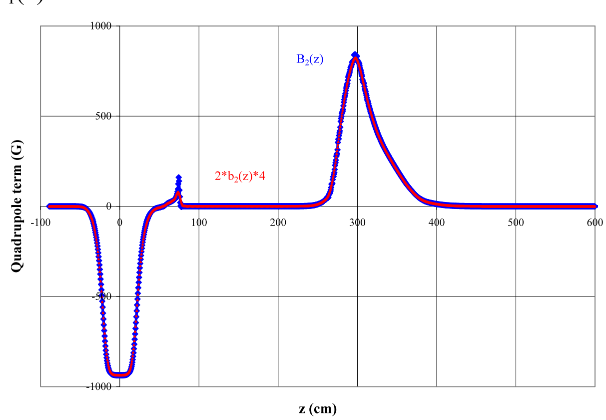

Figure 5: Quadrupole fields B_2 at R = 4 cm and its linear term $2*b_2(z)*4$.

PARTICLE TRAJECTORIES AND OPTICS

The linear particle optics of the momentum dump line, i.e. the transfer matrix from the stripping foils to the dump window, can be obtained in two different ways: one is by analyzing test particle trajectories through the dump line; another is by solving the trajectory equations. Since the coupling between the two transverse planes is negligibly small and can be neglected, we can express the solutions for x, x', y, y' in terms of matrix equations [5]

$$\begin{bmatrix} x_2 \\ x_2' \\ \delta_2 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{16} \\ R_{21} & R_{22} & R_{26} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_1' \\ \delta_1 \end{bmatrix}, \qquad (1a)$$

and

$$\begin{bmatrix} y_2 \\ y_2' \end{bmatrix} = \begin{bmatrix} R_{33} & R_{34} \\ R_{43} & R_{44} \end{bmatrix} \begin{bmatrix} y_1 \\ y_1' \end{bmatrix} \qquad (1b)$$

Here R_{16} and R_{26} are the dispersion coefficient and its derivative; δ_1 and δ_2 denote the fractional deviation of the particle momentum from that of the reference trajectory at the entrance and exit of the system. In a magnetic field, δ_1 and δ_2 should be the same as indicated by the matrix element $R_{66} = 1$.

For the linear optics, one can employ the first-order trajectory equations:

$$x'' + (k(s) + h(s)^2)x = h(s)\delta\ , \qquad (2a)$$

$$y'' - k(s)y = 0\ . \qquad (2b)$$

Here k(s) is the linear focusing function and h(s) is the curvature of the reference trajectory with s being its length. In this problem, z and s are fairly close. Thus, we simply use z instead of s as an approximation. The linear focusing function k(z) is then obtained by $2*b_2(z)/B_\rho$, with $b_2(z)$ as the generalized gradient shown in Fig. 5. The curvature h(z) of the reference trajectory is determined by the bending field as $b_1(z)/B_\rho$. The effect of $h(z)^2$ on the x-motion is much smaller than that of k(z).

Numerical solutions of the first-order trajectory equations yield

$$\mathbf{R}_x = \begin{bmatrix} 0.158 & 7.99 & 0.916 \\ -0.119 & 0.287 & 0.0667 \\ 0 & 0 & 1 \end{bmatrix},\ \mathbf{R}_y = \begin{bmatrix} -0.937 & 22.3 \\ -0.110 & 1.55 \end{bmatrix}.$$

Both the $\mathbf{R}_x$ and $\mathbf{R}_y$ matrices are for focusing. This is consistent with the field distribution in Fig. 5 where a normal quadrupole doublet exists in the dump line. The dispersion function $d_x(s)$ and its derivative $d_x'(s)$ are obtained from the inhomogeneous equation for the x-motion with the initial conditions: x(0) = x'(0) = 0 and δ = 1. At z = 15.2892 m, which is the dump window position, one has $d_x = 0.916$ m and $d_x' = 0.0667$.

In the test particle approach, the calculation is done in a moving coordinate centered on the reference track. A rectangular patch through the dump window and perpendicular to the reference trajectory is created. Three test particles on the x-z plane and two test particles on the y-z plane are launched at the stripper and tracked to the patch at the dump window. These yield all the matrix elements in Eq. (1). The numerical results of the **R**-matrix are fairly close to what obtained from the first method.

TRACKING PARTICLE DISTRIBUTIONS

The distributions of the stripped proton beams on the dump window can be obtained with either the matrices above or directly tracking test particles. The former is easier and more convenient, but it is limited to the linear approximation. The later is more involved in applications, but it could provide better accuracy since all the non-linear effects and even the very small x-y coupling are automatically included.

Figure 6 shows in blue color six test particles in the x-x' phase space at the stripping foils. The test particle distributions at the dump window are obtained in both the particle tracking approach (red points) and the matrix method (purple points). They are plotted together in the relevance to the local coordinate system (LCS) of a moving frame. It appears that the phase space is rotated clockwise by about 0.47 mrad. In practice, the stripping foils are inserted at predetermined x-positions. Thus, only those particles, which are outside these x-positions, are stripped and transported to the dump window. A similar calculation for twelve test particles in the y-y' phase space is made and plotted in Fig. 7.

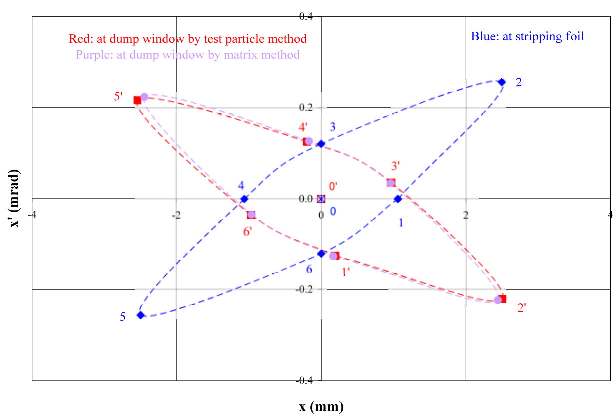

Figure 6: Particle distribution in the x-x' phase space at the scrapper and dump window.

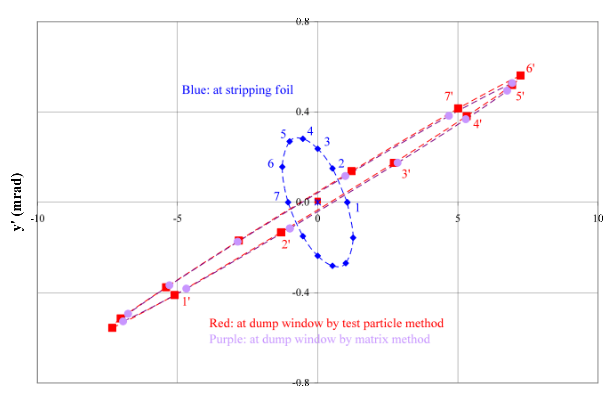

Figure 7: Particle distribution in the y-y' phase space at the scrapper and dump window.

To map test particles in the configuration space, we employ six of them with their initial phase-space parameters at the stripping foils, as shown in Fig. 8. By tracking these particles downstream one obtains their positions in the configuration space at the dump window, as also shown in the figure. All the plots are made in the LCS of a moving frame. These results plus those shown above can be used to estimate the power density distributions of the stripped protons at the dump window.

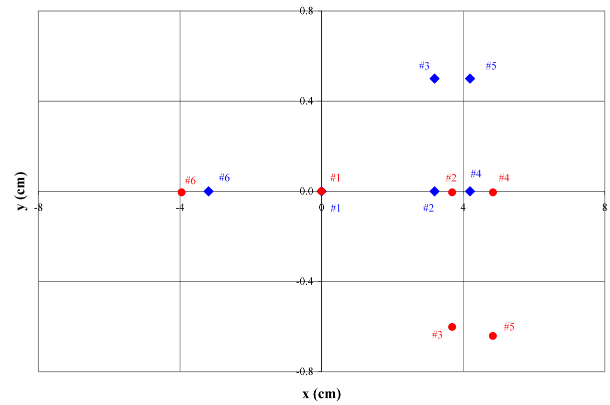

Figure 8: Initial particle positions at the scrapper (blue) and final positions at dump window (red).

SUMMARY

The momentum collimation beam dump line has been studied in a full 3D simulation model. The magnetic field distributions along the beam line are analyzed. The particle trajectories and particle optics are computed. The test particle distributions are tracked from the scrapper to the dump window. Based on the information provided from this study, the particle density distribution of the stripped protons on the dump window can be obtained. The method developed in this work can be applied to other applications.

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REFERENCES

[1] N. Catalan-Lasheras and D. Raparia, in Proc. of PAC2001, Chicago, 2001, p. 3263.
[2] P. He, H. C. Hseuh, D. Raparia, N. Tsoupas, and D. Weiss, in Proc. of PAC2001, Chicago, 2001, p. 3329.
[3] OPERA-3d/TOSCA, Vector Fields, England.
[4] J. G. Wang, Phys. Rev. ST Accel. Beams **9**, 012401 (2006). (http://prst-ab.aps.org/abstract/PRSTAB/v9/i1/e012401).
[5] D. C. Carey, *The Optics of Charged Particle Beams*, Hardwood Academic Publishers, Paris, 1987.