3D MODELING OF SNS RING INJECTION DUMP BEAM LINE*

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Abstract

The SNS ring injection dump beam line has been suffering high beam losses since its commissioning. In order to understand the mechanisms of beam losses, we have built 3D simulation models consisting of three injection chicane dipoles and one injection dump septum magnet. 3D particle trajectories in the models are obtained. The study has clearly shown the design problems causing beam losses in the injection dump beam line. This paper reports our findings and proposed remedies

INTRODUCTION

The SNS accelerator employs an H^- charge exchange process to obtain high intensity proton beams in its accumulator ring [1, 2]. As shown in Fig. 1, a 1 GeV H^- beam from its linac is focused on a thin foil (F1) to produce a proton beam. A small portion of the H^- particles is only partially stripped and becomes H^0 particles after the thin foil. And some incoming H^- particles may miss the foil. The H^0 and H^- particles after F1 propagate forward through a chicane dipole D3 and strike on a thick foil (F2), after which they all should be stripped off the electrons and become proton particles. These particles are so called waste beams, which are bent by a chicane dipole D4 and an Injection Dump Septum Magnet (IDSM), and further transported to an injection dump (IDump) through a quadrupole. The waste beams are still called "H^-" beam or "H^0" beam, according to their origin.

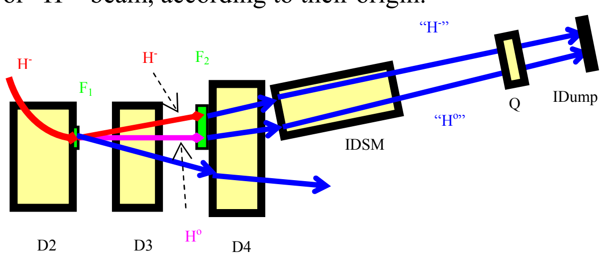

Figure 1: Injection dump beam line schematic.

Since the SNS ring commissioning the entire injection dump beam line, especially IDSM, has been suffering high beam losses. We have found that the injection dump line design was apparently based on 2D calculations, resulting in very small aperture of IDSM. We believe that 3D simulation models are very critical to reveal 3D particle trajectories in IDSM and to understand the beam loss mechanisms. In order to take into account the fringe field of these magnets and magnetic interference among them, good 3D models should include all the four magnets. The quad downstream can be separated in study.

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3D MODEL

The simulation environment is OPERA3D/TOSCA [3]. We have first simulated four individual magnets D2, D3, D4, and IDSM [4, 5] and compared the results with the BNL design simulations and measurements. Good agreements are found. We then combine the four magnets in final models, as shown in Fig. 2.

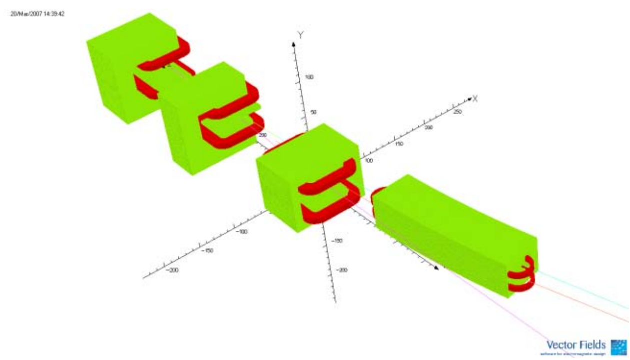

Figure 2: 3D simulation model for injection dump beam line (from left to right: D2, D3, D4, and IDSM).

The coordinate system origin is at the D2 center and the unit is in centimeters. The beams travel in the positive z-direction. The mechanical centers of D3 and D4 are at (-0.772, 0, 181.4) and (-9.155, 0, 384.3); the center of the IDSM entrance face is at (19.3958, 2.3, 493.1165), about which the magnet is rotated count-clockwise by 2.61285^o [6]. The coordinates of the two foil centers are at (3.9967, 2.3, 30.7092) and (7.29, 2.3, 293.5086).

There exist mainly three chicane dipole current settings for the SNS ring injection: "design setting" [7], "delivered setting" [8, 9], and "production setting" [10]. The first two settings had various problems and were abandoned during the ring commissioning, and the third one has been used ever since. We have studied all the three settings in our 3D models and compared their performances. In this paper we report the results only from the "production setting", where D2 and D3 are energized at 2126 A and 1449 A, while D4 and IDSM are at -1737 A and -2914 A, respectively. These currents in D2, D3, and D4 yield bending angles of 53.1, 28.3, and -39.4 mrad for a 1 GeV proton beam. The chicane dipole D1 on the left of D2 (not shown) has a bending angle of -42.0 mrad in this case.

The great difficulty of the models is its very large volume. It contains about 14 million total elements, which is close to the maximum allowed by the software [11]. Other model statistics include 8.3 million total nodes, 16 million edges, 9 million linear tetrahedral, 5 million quadratic tetrahedral, 8 million equations, etc. The TOSCA solution yields a typical post-processor file of 4.132 GB, from which we obtain the field distributions and 3D particle trajectories.

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3D PATICLE TRAJECTORIES

The OPERA3D build-in TRACK command is used for calculating trajectories of charged particles. We take the approach of test particles and launch them at F1. The incoming H^- beam has a normalized rms emittance of 0.5 π mm mrad. Its rms radius at F1 is about 1.5 mm and its spot size extends to more than 14 mm due to halo particles [12]. The initial test particles are determined by an equivalent beam of the same rms emittance and an effective radius of 3 mm. The particles outside a twelve-times rms emittance will be ignored. This results in an effective emittance of 3.3 π mm mrad for each waste beam. The scattering in the foils is not included.

Figure 3 shows the "H^-" particle trajectories in the y-z plane. Many of them are lost to the upper side of the IDSM vacuum chamber. These losses are more serious in the "design" and "delivered" settings. All the "H^0" particles have no problem in the y-direction. Figure 4 shows the waste beam trajectories in the x-z plane, where the three chicane dipoles are depicted by their axial positions, and IDSM is represented by the boundaries of its vacuum chamber inner surface. The two bundles of the "H^-" and "H^0" beams include their centroid and two more tracks in the maximum x-extensions. We can see that some "H^0" particles already hit the middle of the IDSM vacuum chamber. These horizontal losses for the "H^0" particles are not seen in the two other settings, which have stronger bending angle in D4.

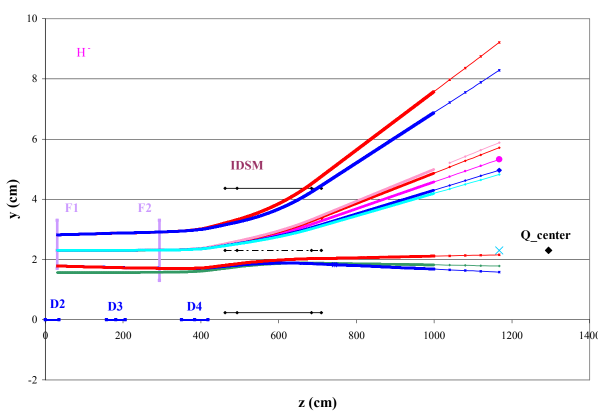

Figure 3: "H^-" particle trajectories in y-z plane.

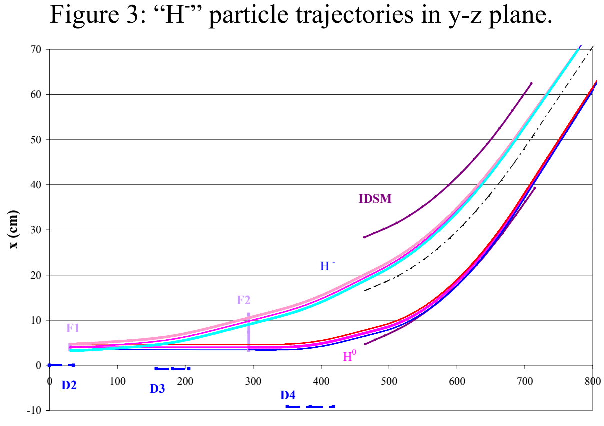

Figure 4: Waste beam trajectories in x-z plane.

PARTICLE OPTICS DOWNSTREAM

The waste beam transport through a quad to the injection dump is shown in Fig. 5. The region from z=-1.3 to z=1.3 m denotes the quadrupole 30Q58, including its fringe field. The remaining is just drift space. The initial conditions in the phase space at z=-1.3 m can be obtained from the output of the 3D simulation models.

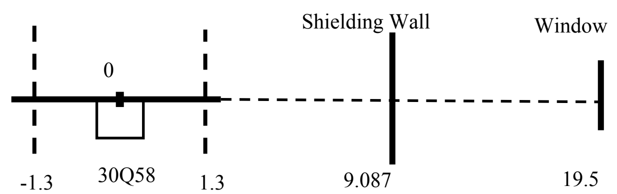

Figure 5: Waste beam transport downstream (# in meters)

The quadrupole 30Q58 data are already available [13]. By using its transfer matrices, as listed in Table 1, we map the waste beam particles from z=-1.3 to z=1.3 m, and then to employ the drift space matrices to map the particles further downstream. We have tried a number of different quad currents in calculations, and the best results are shown in Fig. 6. The quad 30Q58 can not transport all the waste beam particles even through the shielding wall, let alone the dump window. This is also true for the "design" and "delivered" settings.

Table 1: 30Q58 parameters at I=405 A.

	m_{11}	m_{12} (m)	m_{21} (1/m)	m_{22}	f (m)
F	0.7240	2.2508	-0.2114	0.7240	4.731
D	1.2893	2.9638	0.2235	1.2893	-4.475

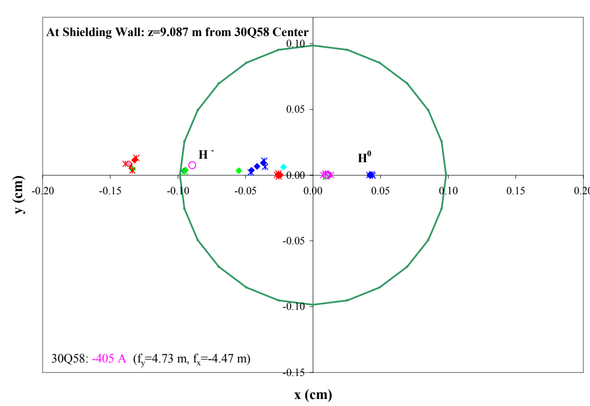

Figure 6: Waste beam particles at shielding wall.

The injection dump optics in the original design [14, 15] shows that the beta function for both x and y at the dump window reaches approximately 3500 m. With a 10" pipe for the transport channel, the acceptance is about 4.4 π mm mrad. Though this acceptance is significantly larger than the rms emittance of the linac injected H^- beam, it is far less than the equivalent phase space area occupied by both "H^0" and "H^-" waste beam particles. This makes the waste beam transport downstream to the dump window impossible.

REMEDIES

The 3D simulations have so far clearly shown the waste beam losses, caused by three major design problems. First, the y-motion was apparently overlooked. The vertical aperture of IDSM is too small, which blocks many "H^-" particles. Second, the horizontal aperture of IDSM is also very marginal, that intercepts some "H^0" particles in the "production setting". Third, it is practically impossible to transport all the waste beams to the injection dump by a single quad after IDSM. The proposed remedies to these problems are described below.

Move D4 by Δx=+8 cm

The y-motion of the "H^-" particles in the chicane region is mainly caused by D4 position. The simulation shows that the "H^-" trajectories pass through the D4 pole-tip boundary, where the magnetic field is very non-uniform and a significant B_x component exists. If we slide D4 in the positive x-direction, the "H^-" tracks would move towards the D4 center and get into more uniform field region where the B_x component would be much reduced.

Figure 7 shows the y-motion of the "H^-" particles after the chicane dipole D4 is moved in the positive x-direction by 8 cm. All the particles remain inside IDSM, in contrast to that in Fig. 3. This is true for all the three chicane dipole settings. Therefore, this action will be implemented during the next machine shutdown.

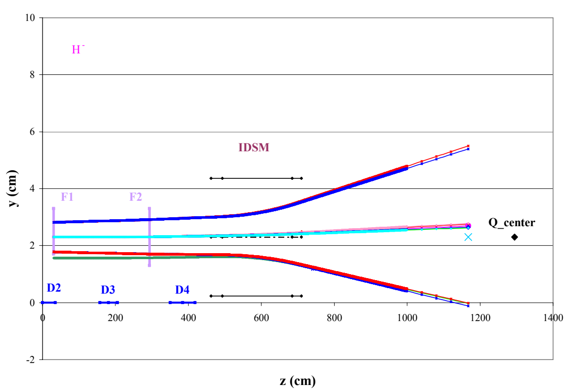

Figure 7: "H^-" tracks in y-z after D4 is moved by +8 cm.

Move F1 by +1 cm and Use New Chicane Setting

The "H^0" particle losses in the horizontal direction in IDSM happen only in the "production setting". This is because the D4 field is too low and can not bend enough the "H^0" particles. A way out is to move the injection foil (F1) in the positive x-direction. This requires an adjustment of the orbit bump amplitude accordingly. In one of the models, we move F1 by Δx=1 cm and use a new chicane dipole setting: -46.35, 58.60, 31.19, and -43.44 mrad for D1, D2, D3, and D4. The IDSM current remains at -2914 A.

Figure 8 shows the waste beam trajectories in the x-z plane when we implement these changes in the model. The "H^0" particles indeed are kept clear off the IDSM vacuum chamber. This figure is in contrast to Fig. 4.

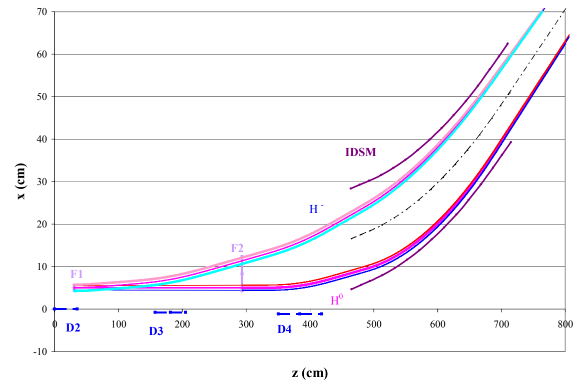

Figure 8: Waste beam trajectories in x-z plane after F1 is moved by +1 cm and new chicane setting is used.

Add Another Quad 30Q44 Downstream

The easiest and most effective way to solve the transport problem after the quad (30Q58) is to add another quad, such as a 30Q44 to form a doublet. The doublet would reduce the beta function amplitude downstream and make the beam transport there possible. This is straighter forward and we skip the details.

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