

# 3D SIMULATION STUDIES OF BEAM DYNAMIC ISSUES IN SNS RING INJECTION AND EXTRACTION \*

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## Abstract

We have performed 3D particle tracking in realistic magnetic field configurations to study particle losses in the SNS ring injection dump beam line and beam profile tilt in an extraction Lambertson septum. The technique is based on accurate 3D modeling of magnet assemblies or beam lines and 3D particle trajectory calculations through simulated fields. The studies have discovered a number of design and operation issues that cause particle losses in the injection region and beam profile tilt through the extraction septum. The remedies to all the problems are also devised. This paper reports our simulation techniques and major findings.

## PARTICLE LOSSES IN SNS RING INJECTION

The Spallation Neutron Source (SNS) ring injection dump beam line suffered high particle losses during commissioning and early operation. We performed 3D modeling of the injection region. The particle trajectories in the models and particle optics further downstream were calculated. The studies clearly showed the waste beam loss mechanisms and led to the remedies to the problems. This section highlights our results, and more details can be found in reference [1].

### 3D simulation models

The simulation environment employed in the studies is OPERA-3d/TOSCA v.11 [2]. The models consist of four magnets, i.e., three chicane dipoles D2, D3, D4 and an Injection Dump Septum Magnet (IDSM), as shown in Fig. 1. The models are a realistic, full 3D representation of the real injection configuration, taking into account the fringe field, interference, nonlinear effect, etc. A model typically contains about 14 million total elements, which is close to the maximum allowed by the software [3]. The TOSCA solutions yield a post-processor file of 4.132 GB, from which we obtain the field distributions and 3D particle trajectories.

The chicane dipole settings are critical to the injection performance. In this paper we report the results only from an early production setting, which was employed since the ring commissioning and typically showed all the waste beam loss mechanisms.

After IDSM, a single quadrupole is installed to transport the waste beams to an Injection Dump (IDump), which is 19.5 m away further down stream. The particle optics method is employed to map the waste beams from the quad entrance to the IDump.

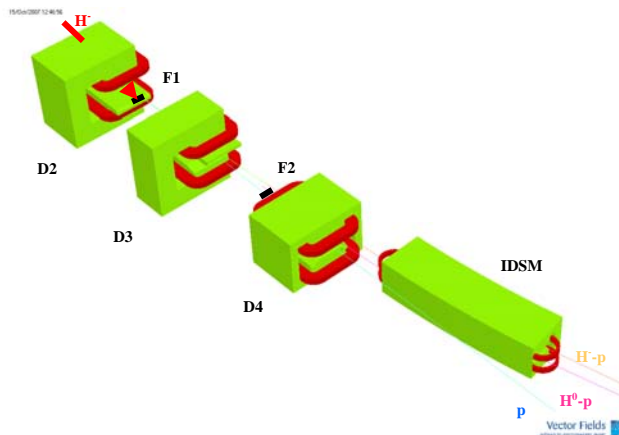


Figure 1: 3D simulation model.

### 3D particle trajectories through IDSM

OPERA3D has a build-in TRACK command for calculating trajectories of charged particles by directly integrating the equations of motion in simulated magnetic fields. We launch waste beam particles of 1 GeV in energy at the primary foil F1. The initial locations and slopes of these particles are determined by the size and emittance of the linac-injected H<sup>-</sup> beam.

Figure 2 shows the H<sup>-</sup> particle trajectories (in between F1 and F2) and H<sup>-</sup>-proton particle trajectories (after F2) in the y-z plane. Three chicane dipoles D2, D3, and D4 are depicted by their axial positions, and IDSM is indicated by the inner surface of its vacuum chamber. It is clear that all the H<sup>-</sup>-proton particles have significant y-motion in D4 and IDSM, and some H<sup>-</sup>-proton particles are lost to the upper surface of the IDSM vacuum chamber. These losses are much more serious in the design setting and the delivered setting of the chicane dipoles.

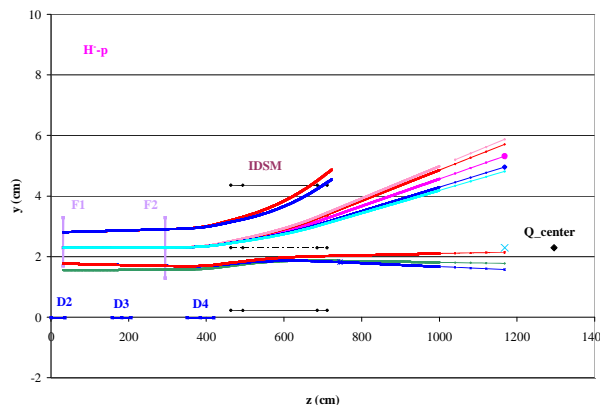


Figure 2: H<sup>-</sup> and H<sup>-</sup>-proton trajectories in y-z plane.

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Figure 3 shows the waste beam trajectories in the  $x$ - $z$  plane. The two bundles of the  $H$ -proton and  $H^0$ -proton beams include their centroids and two more tracks in the maximum  $x$ -extension. We can see that the  $H^0$ -proton beam is too close to the IDSM vacuum chamber wall, and some particles already hit the middle of the IDSM vacuum chamber. This is consistent with what was observed in operation. These horizontal losses for the  $H^0$ -proton particles are not seen in the two other settings since they have stronger bending angles in D4.

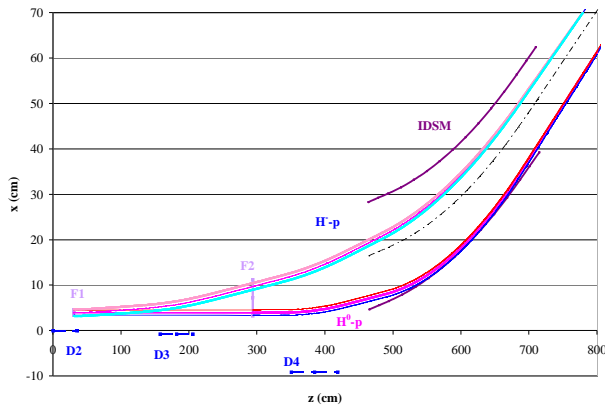


Figure 3: Waste beam trajectories in  $x$ - $z$  plane.

### Particle optics through quad to IDump

We first use the quad transfer matrices to map the waste beam particles through the quad, and then to use the drift space matrices to map the particles further downstream. A number of different quadrupole magnet currents are used in calculations. We have found that a single quadrupole magnet can not transport all the waste beam particles even through a shielding wall, let alone the dump window which is still more than ten meters downstream.

### Remedies

The excessive  $y$ -motion of the  $H$ -proton particles was mainly caused by incorrect D4 position. The  $H$ -proton trajectories passed through the D4 pole-tip boundary, where the magnetic field was very non-uniform and there was a significant  $B_x$  component. We have moved D4 in the positive  $x$ -direction by  $\Delta x=8$  cm. Thus, the  $H$ -proton tracks now get back towards the D4 center into a more uniform field region. The  $B_x$  component is then much reduced, and the  $y$ -motion of the  $H$ -proton particles is greatly mitigated.

The  $H^0$ -proton particle losses in ELS were mainly due to inadequate bending in D4. The waste beam trajectories are very sensitive to the chicane dipole settings. With the early production setting, where the D4 field strength was weaker, many  $H^0$ -proton particles were lost in the horizontal direction around the middle of IDSM. New chicane dipole settings have been developed, where the D4 strength is increased and F1 is moved further beam left. Thus, the  $H^0$ -proton particles are kept clear of the

IDSM vacuum chamber wall and their losses in IDSM are much reduced.

We have also modified a spare IDSM for the improvement of its performance [4]. First, the vertical gap is increased by 2 cm, which provides the  $H$ -proton particles more clearance in the  $y$ -direction. Second, good field region for the  $H^0$ -protons is further extended from the pole-tip edge toward the septum plate, where it happens that there is some space available. Thus, the vacuum chamber can be accordingly enlarged by 3 cm, which gives the  $H^0$ -proton particles significantly more clearance in the horizontal direction. Third, we add specially designed  $z$ -bumps on the IDSM entrance face for the  $H^0$ -proton beam that further pushes these particles inward in IDSM. All of these efforts reduce the waste beam losses in IDSM to the lowest level.

A C-dipole has been added just after IDSM [5]. This provides more control of two waste beams. It also makes the phase space areas of the two waste beams much closer than in the original design. Nevertheless, the waste beam losses around the quad and further downstream still remain. More actions should be taken.

## BEAM PROFILE TILT IN EXTRACTION SEPTUM

Since the SNS ring commissioning it has been found that the beam profile on the target is tilted. Figure 4 shows a beam image from the target view screen for  $5.3 \times 10^{13}$  ppp extracted from the ring during commissioning [6]. More recent beam diagnostics upstream of the target have also shown a tilted beam. This would mismatch the target cross section and becomes an important issue for higher power operation.

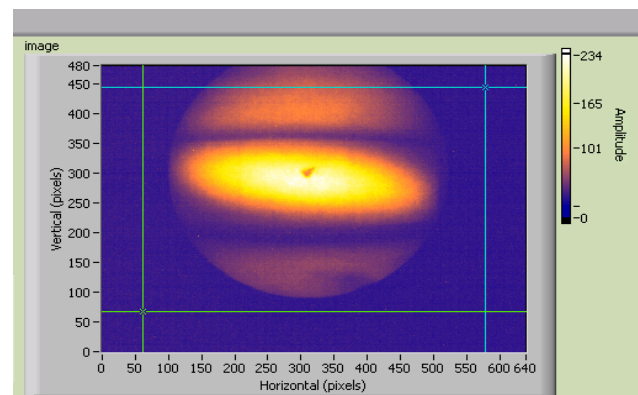


Figure 4: Beam image from the target view screen.

Many possible sources of causing the beam profile tilt have been analyzed. Our final attention is focused on the ring Extraction Lambertson Septum magnet (ELS). It contains a strong skew quadrupole component, which distorts the beam profile. We have performed 3D modeling of ELS to study the problem. The skew quad term in ELS is carefully calculated. The origin for the excessive skew quad component has been identified. And the options to minimize the skew quad term are proposed. 3D particle tracking in our simulation models clearly

shows the beam profile tilt in the existing ELS. The beam profile tilt would disappear if we follow the devised modification options.

*Simulation models*

A single ELS model built by OPERA-3d/TOSCA v. 12 is shown in Fig. 5. The model has fine meshes with more than nine million elements. Its post-processor file occupies more than 2 GB. The magnet is energized at 1890 A in the model, which is for a 1 GeV proton beam.

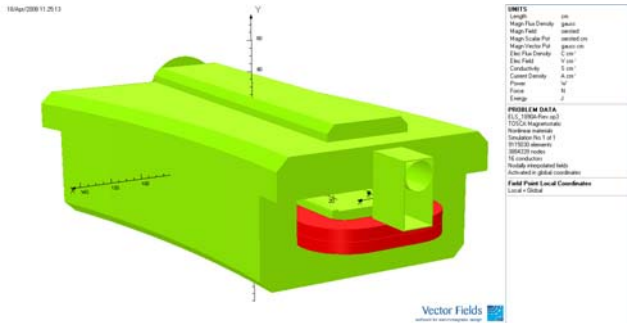


Figure 5: Entrance view of ELS simulation model.

*Skew quad term in ELS*

The radial field on a cylindrical surface of radius  $R=8$  cm co-axial with the reference trajectory in ELS is calculated and Fourier decomposed. Figure 6 shows the normal (B2, red) and skew (A2, blue) quad term over the entire length of the reference track. The integrated skew quad term is  $A_2 * L = -0.0215$  T-m, corresponding to an integrated gradient of 0.27 T. This accounts for 127 units, in comparison with the integrated dipole field of 1.693 T-m.

The skew quad term in the central ELS region is due to the up-down asymmetry of the gap geometry. With proper compensation by two longitudinal shims, this component can be eliminated or be made with an opposite sign. At the two ends of the magnet, the integrated skew quad term can also be reduced by adding z-bumps with appropriate chamfer angles.

*Minimization of skew quad term*

One option to minimize the integrated skew quad term in the ELS is to replace the existing longitudinal shims by new ones, which produce a positive skew quad term to compensate the negative ones from the two ends. The right cross section of new shims can be found from 2D models. A full 3D modified ELS model with the new shims is built in this way. The surface field method yields a skew quadrupole term, also shown in green in Fig. 6. The integrated skew quad term is now 0.000537 T-m, or 3.2 units. The corresponding integrated gradient is 0.0067 T. This is a reduction by a factor of about 40.

*Verification by particle tracking*

We study the beam trajectories and profiles in ELS before and after the modification. A laminar beam of an elliptical cross section without space charge is launched at

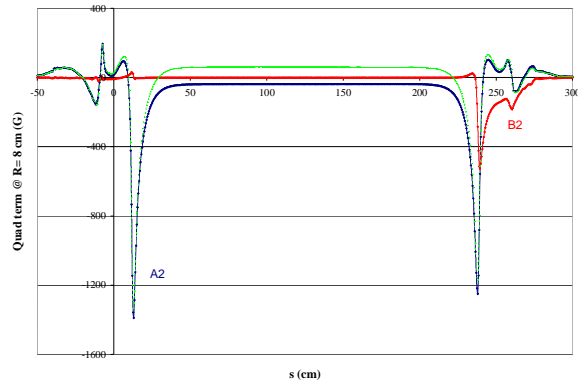


Figure 6: Skew and normal quad term vs. s.

upstream of the magnet. OPERA TRACK command is employed to calculate the particle trajectories through ELS. Figure 7 shows the beam profiles from the study. The dotted blue curve is the beam profile at upstream of ELS. It is a perfect, up-right ellipse. The red dots indicate the beam profile from the existing septum at its downstream. It is clear that the beam profile is tilted. The tilt angle is about  $9.7^\circ$ . The green dots show the beam profile from the modified septum at the same location. Indeed, the beam cross section is fairly an up-right ellipse. The profile tilt is corrected.

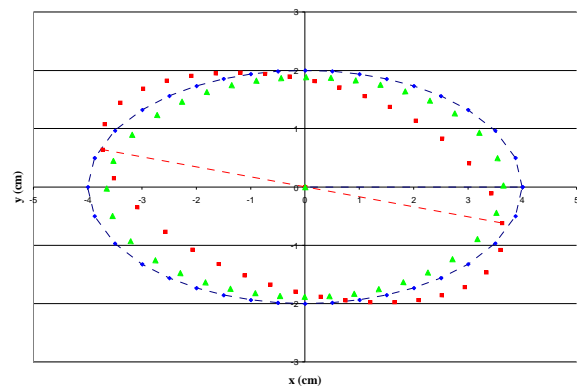


Figure 7: Beam profiles through ELS.

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**REFERENCES**

- [1] J. G. Wang and M. Plum, Phys. Rev. ST Accel. Beams **11**, 014002 (2008).
- [2] OPERA-3d/TOSCA is developed by Vector Fields, England.
- [3] J. Simkin of Vector Fields, private communication.
- [4] J. G. Wang, SNS-NOTE-MAG-0181, March 28, 2008.
- [5] M. Plum, in SNS injection dump beam line review, Nov. 2006.
- [6] M. Plum, in Proceedings of PAC07, p. 2603.