# 3D FIELD QUALITY STUDIES OF SNS RING EXTRACTION LAMBERTSON SEPTUM MAGNET *

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*Abstract*

The SNS ring Extraction Lambertson Septum magnet contains a strong skew quadrupole term, which has been identified as the source of causing a beam profile distortion on the target. We have performed 3D computer simulations to calculate the skew quad term, to analyze its origin, and to devise a solution of minimizing the skew quad term by modifying the magnet in situ. Particle tracking is performed to verify the beam profile evolution through the existing and modified septum.

## INTRODUCTION

The SNS accumulator ring extraction system is built in one of its four straight sections. Figure 1 shows a part of the straight, containing an Extraction Lambertson Septum (ELS) magnet followed by a quad doublet assembly. During the ring accumulation, the circulating beam passes through a well-shielded aperture in the upper yoke of ELS. The ring extraction takes place in a single turn and two steps after the beam is fully accumulated. The AC kickers upstream (not shown in figure) are first fired, that pushes the beam down to the dipole entrance of ELS, which in turn bends the beam horizontally out of the ring.

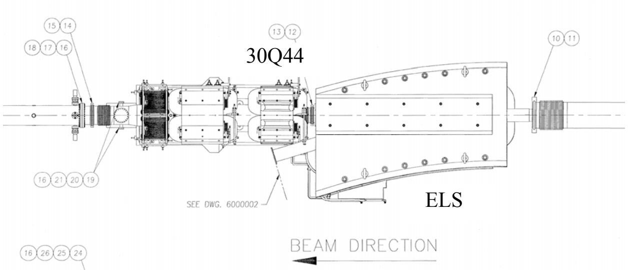


Figure 1: Extraction septum and quad assembly (courtesy of BNL/SNS design drawing and specifications).

The ELS was designed and developed at Brookhaven National Lab (BNL) [1-3]. Its structure is quite complex and its field qualities are very critical to the extracted beam as well as to the circulating beam. Though the ELS extraction line was measured with a flip coil on grids before delivery, there were no official test data of harmonic contents provided. Since the SNS ring commissioning, we have found that the extracted beam profile on the target is slightly "tilted", as shown in Fig. 2 [4]. This distorted beam profile does not match the target geometry and has been an issue of concern for high power operation. A considerable amount of effort has been devoted to finding the source of the beam profile distortion. Finally, 3D simulation studies of the ELS field qualities show a strong skew quadrupole term in the ELS extraction line, and this has been identified to be responsible for the beam profile "tilt" on the target. This has motivated us to carefully model the magnet in 3D computer simulations in order to accurately calculate the skew quad term and to improve its field quality by minimizing the skew quad term.

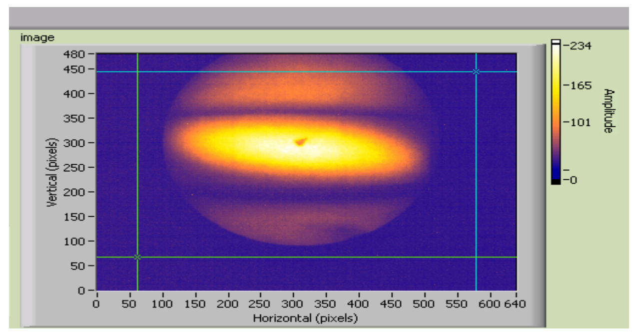


Figure 2: Beam image from the target view screen [4].

## 3D MODEL OF ELS

The simulation environment is OPERA3D/TOSCA [5]. The model is built with the OPERA package "Modeller" rather than the "Pre-processor". A single ELS model is shown in Fig. 3. The circulating beam passes through the upper, round, straight aperture within the iron yoke. A shielding box upstream and a shielding cap downstream are also attached. These parts are critical for shielding the circulating beam from the ELS stray field. The extracted beam goes through the lower, curved ELS pole-tips. On the pole-tip, two longitudinal shims are added to improve the bending field uniformity. In the model, the mechanical dimensions follow the BNL/SNS design drawings and specifications. The coordinate system origin is that z=0 is at 12.116 cm from the pole-tip end, y=0 is at the mid-plane of the bending dipole, and x=0 is at the circulating beam axis. The magnet is energized at 1890 A in the model, which is for a nominal 1 GeV proton beam.

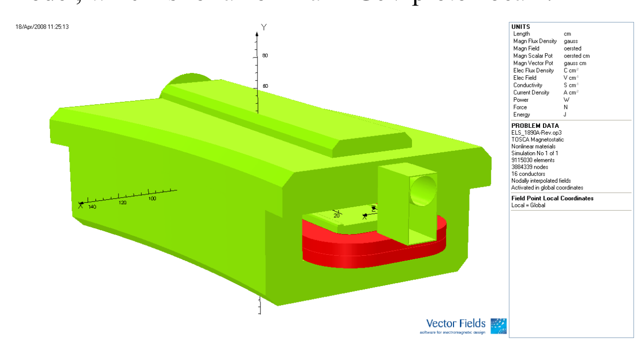


Figure 3: 3D simulation model for ELS.

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## ELS SKEW QUAD TERM

### *Computation*

The skew quad term in the ELS is computed with three different methods for cross-check and comparson with measurements. The first method is the patch rotation, which calculates the magnetic flux through a rotating patch. Since the reference trajectory inside the hard edge magnet is curved, we have to use piece-wise straight patches. A Fourier decomposition of the total magnetic flux yields the skew quad term and higher harmonics. The second method is so-called surface field analysis, which calculates the magnetic field component $B_r$ or $B_\theta$ on a cylindrical surface in order to obtain the z-dependent harmonic distribution of magnetic field along a reference trajectory. An integration over the entire surface length yields the integrated harmonics, including the skew quad term. The third method calculates the bending field along different, parallel trajectories, which form a pattern of grids on a cross section, and fits the results to a harmonic notation. The method mimics the BNL flip coil measurement. The results of calculations with a reference radius of R=8 cm are listed in Table I. The integrated skew quad term ($A_2$*L) from the first two methods accounts for 126 units, which is too large for a transport line magnet. The results from the third method and the measurement contain more errors.

Table I: Integrated ELS Harmonics

| | Patch rotation | | Surface field | |
|---|---|---|---|---|
| m | $B_m$*L | $A_m$*L | $B_m$*L | $A_m$*L |
| 1 | -1.6925 | -0.0022 | -1.6926 | -0.0017 |
| 2 | -0.0059 | -0.0214 | -0.0066 | -0.0215 |
| 3 | 0.0027 | -0.0007 | 0.0027 | -0.0001 |
| 4 | 0.0001 | -0.0050 | 0.0002 | -0.0050 |
| 5 | 0.0001 | -0.0001 | 0.0001 | -0.0001 |

| | Dipole field on grid | | BNL test | |
|---|---|---|---|---|
| m | $B_m$*L | $A_m$*L | $B_m$*L | $A_m$*L |
| 1 | -1.6916 | | -1.7055 | |
| 2 | 0.0008 | -0.0221 | -0.0005 | -0.0166 |
| 3 | 0.0023 | 0.0001 | 0.0077 | 0.0011 |
| 4 | 0.0002 | -0.0051 | -0.0012 | -0.0022 |
| 5 | 0.0002 | 0.0001 | -0.0025 | -0.0001 |

### *Origin*

The integrated skew quad term in the ELS has two constituents. The first one comes from the ELS central region due to the up-down asymmetry of the pole tip & coil configuration and un-optimized compensation by the longitudinal shims. A 2D model of the central ELS cross section, as shown in Fig. 4, is built to study the effect of the longitudinal shims. The existing shims yield a skew quad term of 56.5 units in the ELS central region. By varying the shim geometry, we are able to vanish the skew quad term completely. On the other hand, it is also possible to change both the amplitude and polarity of the skew quad term by specially designed shim cross sections.

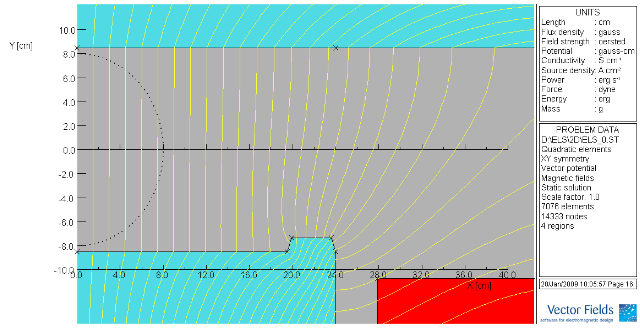


Figure 4: The central area of a 2D ELS model.

The second constituent of the ELS skew quad term results from the end effect of the magnet, which uses a longer septum plate to shield the circulating beam from the fringe field of the dipole below. This structure naturally contributes to the skew quad term. A chamfer angle at the pole-tip end would alleviate the problem, but it was overlooked in the original design. For the existing ELS, we have noticed that there is a gap of more than 10 cm between the pole-tip end and the coil. This space could be utilized for the insertion of z-blocks with appropriate chamfer angles. A simplified 3D ELS model with various z-blocks is tested for the end effect. The results are shown in Fig. 5 for three cases. The z-blocks could vanish the integrated skew quad term completely, or to make it with a different amplitude and opposite sign.

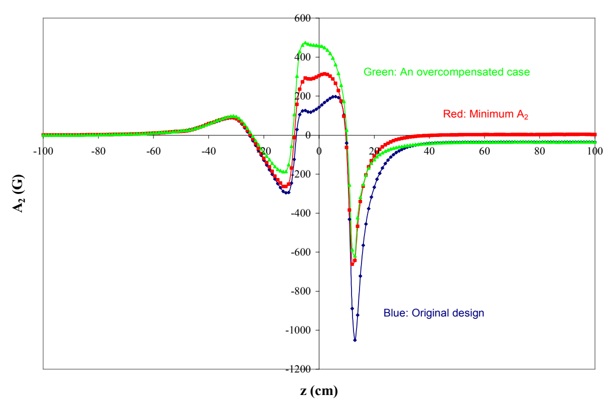


Figure 5: Skew quad term at the ELS end.

### *Minimization*

There are a few options to modify the existing ELS in situ in order to minimize its integrated skew quad term. The simplest way is to replace the longitudinal shims with a new design geometry, which produces a positive skew quad term in the ELS central region to cancel the contributions at the two ends. A modified ELS model with new shims is built. The skew quadrupole term of the magnetic field on a cylindrical surface of radius 8 cm is shown in Fig. 6, where we also plot the result for the existing ELS. The integrated skew quad term for the modified ELS is now 0.00054 T-m, or 3.2 units. The corresponding integrated gradient is 0.0067 T. This is about 40 times smaller than that in the existing magnet.

The integrated skew quad term would be further reduced when an adjacent quadrupole downstream of the ELS is taken into account.

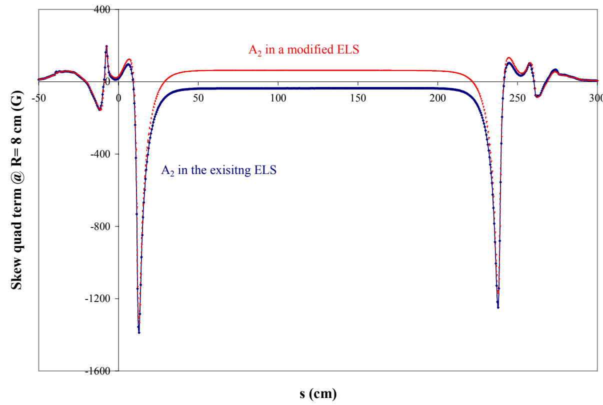


Figure 6: Skew quad term of the field on a cylindrical surface surrounding a reference track.

## BEAM PROFILE THROUGH ELS

We study the extracted beam trajectories and profiles through the ELS before and after the modification of the magnet. A laminar beam of an elliptical cross section without space charge is launched upstream of the magnet. The particles initially move in the direction of the z-axis. We select a reference particle on the axis and 36 more on the surface of the ellipse. OPERA TRACK command is employed to calculate the trajectories, as shown in Fig. 7. At the output end, we create a Cartesian patch, which is perpendicular to the reference trajectory. The intersection of all the particle trajectories on the patch is recorded. This yields the beam profile downstream of the ELS.

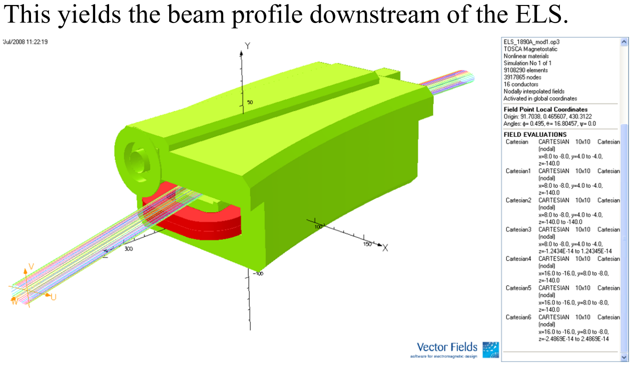


Figure 7: Trajectories of a laminar beam without space charge through the ELS.

Figure 8 shows the beam profiles from the study. The dotted blue curve is the beam profile upstream of the ELS entrance. It is a perfect, right ellipse. The red curve indicates the beam profile from the existing septum at its output. It is clear that the extracted beam profile is distorted and looks like to be "tilted". The test particle upstream at A(4, 0) on the elliptical surface is moved to A' downstream of the existing ELS. The angle between OA and OA' is 9.7°. The beam profile "tilt" appears to be even larger than this angle. This extracted beam profile resembles what observed in the early experiment, as shown in Fig. 2, though there are differences due to different beam parameters, location of evaluation, etc. The green curve in Fig. 8 shows the extracted beam profile from the modified septum at the same output location. The test particle at A is moved to point A''. Very little beam profile "tilt" can be seen. Indeed, the extracted beam profile cross section is a fairly good ellipse. The profile distortion is corrected with the ELS modification.

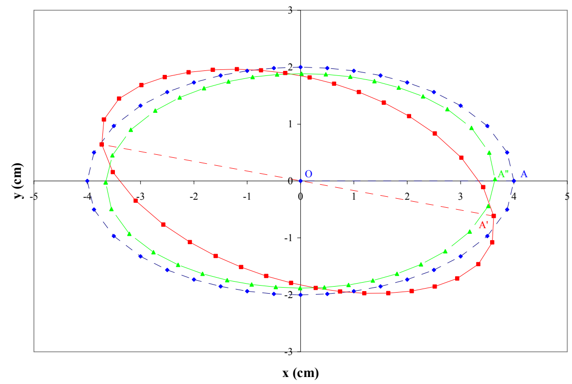


Figure 8: Extracted beam profiles through the existing and modified ELS.

## SUMMARY

3D computer simulations have been performed to calculate the ELS skew quad term, to study its origin, and to find a way of modifying the ELS in situ. The detailed description of this work can be found in [6, 7]. During the machine outage in February, 2009, the two longitudinal shims in the existing ELS were replaced in situ with a new pair of different geometry. The subsequent beam diagnostics showed that the beam profile distortion was corrected and the problem was indeed solved [8].

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