# FIELD DISTRIBUTIONS OF INJECTION CHICANE DIPOLES IN SNS RING*

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*Abstract*

3D computing simulations have been performed at ORNL to study the magnetic field distributions of two injection chicane dipoles in the SNS ring. The simulation studies have yielded the performance characteristics of the dipoles and generated magnetic field data in three dimensional grids. Based on the simulation data, a 3D multipole expansion of the chicane dipole field, consisting of generalized gradients and their derivatives, has been made. The expansion is quasi-analytical by fitting numeric data into a few interpolation functions. A 5th-order representation of the field is generated, and the effects of even higher order terms on the field representation are discussed.


## INTRODUCTION

In the Spallation Neutron Source (SNS) being built in Oak Ridge National Laboratory (ORNL) a 1 GeV $H^-$ beam from its linac is injected into an accumulator ring to produce a proton beam by stripping off electrons in low magnetic field. In the injection region there are four DC magnetic dipoles (D1 to D4) in a chicane structure, which controls the beam orbit. The striping foil is located at the edge of the second dipole (D2), whose field is very critical to the injection operation. D2 and D3 are very close, and they have complementary pole tip structures.

The dipoles are designed by BNL (Brookhaven National Lab) [1] and their design simulation file does exist. It is to our convenience to start independent simulations of the dipoles at ORNL, which yield their performance characteristics and generate field distribution in 3D grids for tracking study of beams. But, the data file occupies a few hundred meg-bytes memories and it is hard to manage the data in subsequent work. Therefore, we expand the magnetic field into 3D multipoles based on the simulation data. The 3D multipole expansion describes the magnetic field in terms of harmonic and pseudo-harmonic components and is analytical in nature. The field at any point within a cylindrical volume about the z-axis of the magnets can be calculated by approximate formula, such as a 5th-order representation presented in this paper.

## 3D COMPUTING SIMULATIONS

The simulation code is OPERA3D/TOSCA [2]. The simulation model as shown in Fig. 1 is built by the OPERA3d package "Modeller" rather than "Pre-Processor", and is constructed according to the BNL design drawings and parameters [3]. In the setup the dipoles D2 and D3 are energized at 2140 A and 1690 A, respectively. These currents should be close to the operation values for a 1 GeV beam.

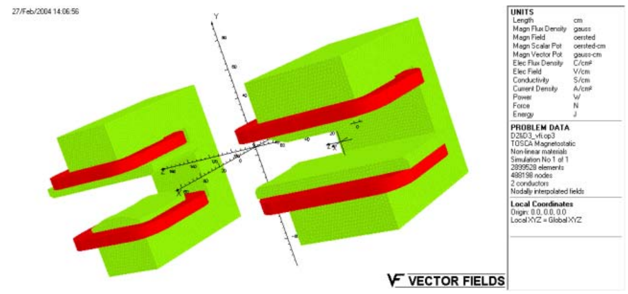

Figure 1: Simulation model of chicane dipoles.

The magnetic field on the z-axis from the simulation is plotted in Fig. 2. The integrated field and the harmonic contents are analyzed by a rotating Cartesian patch, similar to an un-bucked winding in a Halbach coil in accelerator magnet measurements [4]. Figure 3 shows the harmonic distribution. The blue and green bars are calculated for the D2 region and D3 region respectively with a separation point at z=93.87 cm. The red bars are calculated for the entire length of both D2 & D3, which are much smaller due to opposite phases of the quadrupole, octupole, and sextupole in the two dipoles,

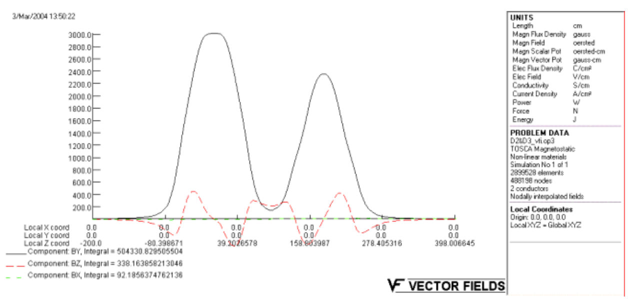

Figure 2: Magnetic field along the z-axis.

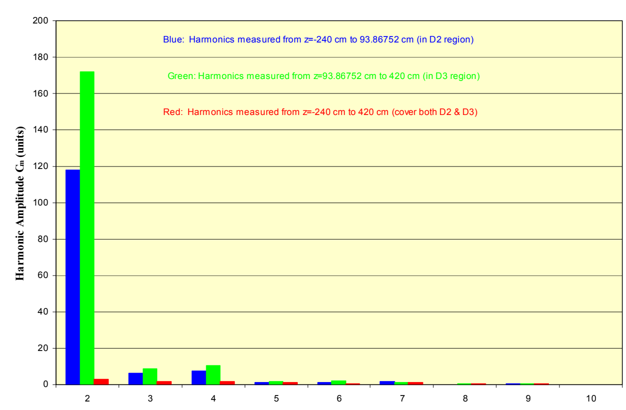


Figure 3: Harmonic amplitudes of chicane dipoles.

The stripping foil is located at x=0, y=2 cm and z=30.7 cm, which is around the edge of D2. In Table 1 we list these parameters and compare the simulation results between ORNL and BNL [5]. The agreement looks good.

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Table 1: Field distribution around stripping foil

| | ORNL | BNL |
|---|---|---|
| D2 Current (A) | 2140 | 2168 |
| D3 Current (A) | 1690 | 1716 |
| $B_y$ (kG) | 2.5244 | 2.50 |
| $B_z$ (kG) | -0.5256 | -0.532 |
| $B_{total}$ (kG) | 2.5785 | 2.556 |
| $Tan^{-1}(B_z/B_y)$ (rad.) | -0.2053 | -0.2 |
| $B_y$ integral (G-cm) ( - infinity to foil) | 241463.53 | 237997 |
| $B_y$ integral (G-cm) ( foil to + infinity) | 263163.88 | 261751 |

## 3D MULTIPOLE EXPANSION

### *Technique [6,7]*

First, from OPERA3d postprocessor we calculate and Fourier-decompose a field component, say $B_r$, on the surface of a cylinder of radius R, co-axial with the dipoles axis:

$$B_r(R,\theta,z)=\sum_{m=0}^{\infty}\mathcal{B}_m(R,z)Sin(m\theta)+\mathcal{A}_m(R,z)Cos(m\theta).$$

We then can obtain the generalized gradients according to

$$C_{m,s}(z)=\frac{1}{2^m m!}\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}dk\,\exp(\mathrm{ikz})\frac{k^{m-1}}{I_m'(kR)}\tilde{\mathcal{B}}_m(R,k),$$

$$C_{m,c}(z)=\frac{1}{2^m m!}\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}dk\,\exp(\mathrm{ikz})\frac{k^{m-1}}{I_m'(kR)}\tilde{\mathcal{A}}_m(R,k).$$

Here $\tilde{\mathcal{B}}_m(R,k)$ and $\tilde{\mathcal{A}}_m(R,k)$ are the Fourier transforms of $\mathcal{B}_m(R,z)$ and $\mathcal{A}_m(R,z)$, and $I_m(x)$ is the modified Bessel function of the first kind of order m. The field components at any point within the cylinder can be constructed as

$$B_r=\sum_{m=0}\sum_{\ell=0}^{\infty}(-1)^{\ell}\frac{m!(2\ell+m)}{2^{2\ell}\ell!(\ell+m)!}C_{m,\alpha}^{[2\ell]}(z)r^{2\ell+m-1}\begin{Bmatrix}Sin(m\theta)\\Cos(m\theta)\end{Bmatrix},$$

$$B_\theta=\sum_{m=0}\sum_{\ell=0}^{\infty}(-1)^{\ell}\frac{m!m}{2^{2\ell}\ell!(\ell+m)!}C_{m,\alpha}^{[2\ell]}(z)r^{2\ell+m-1}\begin{Bmatrix}Cos(m\theta)\\-Sin(m\theta)\end{Bmatrix}.$$

$$B_z=\sum_{m=0}\sum_{\ell=0}^{\infty}(-1)^{\ell}\frac{m!}{2^{2\ell}\ell!(\ell+m)!}C_{m,\alpha}^{[2\ell+1]}(z)r^{2\ell+m}\begin{Bmatrix}Sin(m\theta)\\Cos(m\theta)\end{Bmatrix}.$$

Here α is either s for the sine term or c for the cosine term, and the two terms add together for each component.

### *On-axis gradients*

The generalized gradients $C_0'(z)$, $C_{1,s}(z)$, and $C_{1,c}(z)$ represent the on-axis magnetic field components $B_z(z)$, $B_y(z)$, and $B_x(z)$ at x=y=0, respectively. This property can be employed to verify the validity of the 3D multipole expansion by comparing the generalized gradients directly to the simulation data of the on-axis fields. As shown in Figs. 4-6, the agreement is very good.

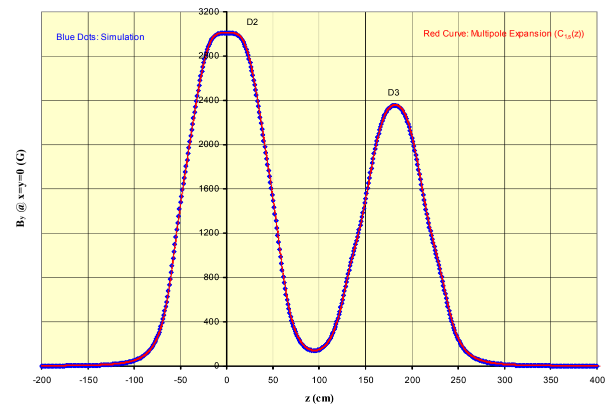


Figure 4: $B_y$ at x=y=0 versus z.

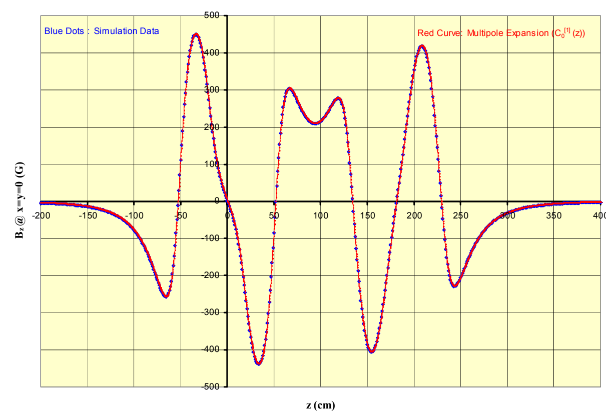


Figure 5: $B_z$ at x=y=0 versus z.

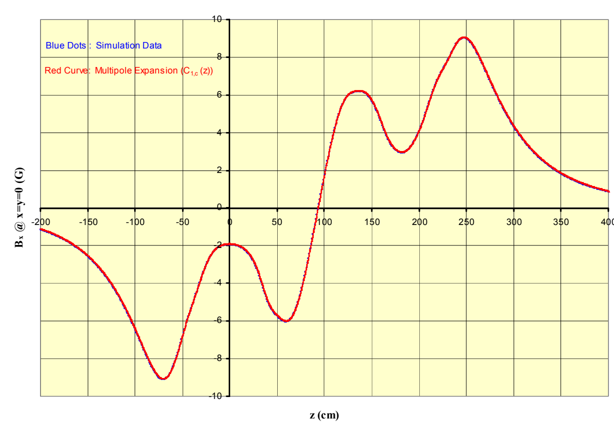


Figure 6: $B_x$ at x=y=0 versus z.

### *A $5^{th}$-order representation*

The magnetic field at any point inside the cylinder can be calculated from the generalized gradients. In practice, a cut to a certain order has to be made. A $5^{th}$-order representation of the magnetic field covers the multipoles up to the regular dodecapoles and pseudo-dodecapoles. The explicit expressions for this representation are left out due to the page limit, but they can be obtained in a straight forward way by keeping only m=0-6 terms in the field equations given above. In this case, a total of 13 generalized gradients are required and they can be stored in computer as interpolation functions for subsequent calculations. In this way much less memories are needed and the field calculations become quasi-analytical. A comparison between the expansion results and the simulation data are shown in Figs. 7-10. In general, the agreement is very good for small radius. When it is far away from the axis, the discrepancy for some field components may get larger, and higher-order terms, such as up to 9th order, is required for better agreement, as shown in Fig. 10.

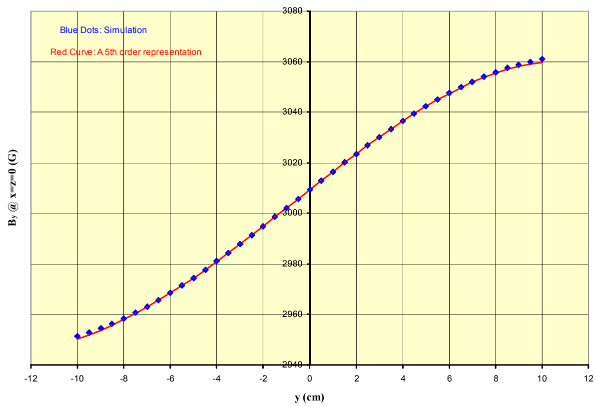


Figure 7: $B_y$ versus y at x=z=0.

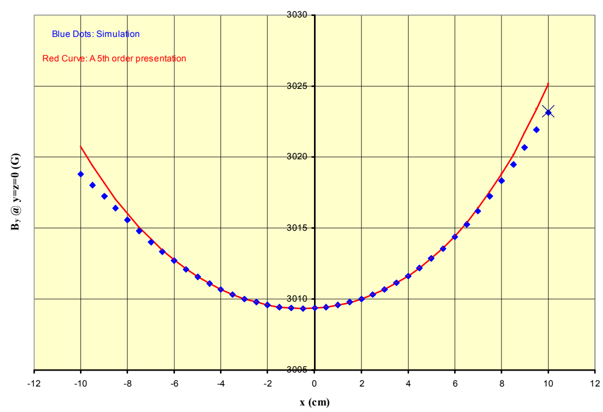


Figure 8: $B_y$ versus x at y=z=0.

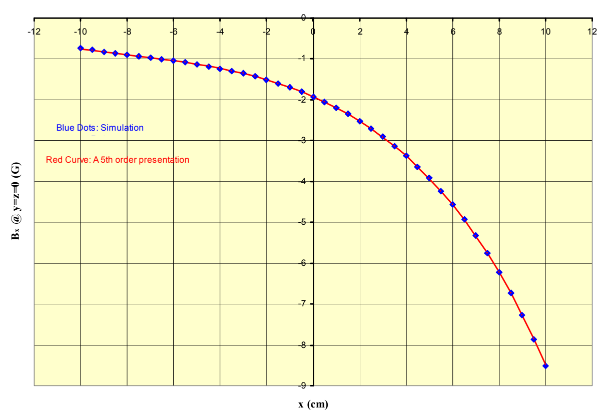


Figure 9: $B_x$ versus x at y=z=0.

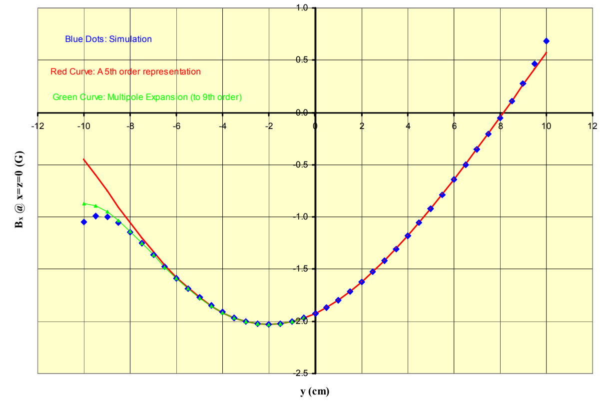


Figure 10: $B_x$ versus y at x=z=0.

## ACKNOWLEDGEMENTS

The author would like to thank W. Z. Meng of BNL, who performed the 3D simulation of D2 & D3 a few years ago and provided us with his OPERA input file. The help from J. Simkin of Vector Field, England, in many details of the OPERA code and simulation technique is highly appreciated. The author also would like to acknowledge the initiation of this task by S. Henderson, and communications on this matter with J. Holmes.

## REFERENCES

[1] The injection chicane dipoles were designed at BNL by Y.Y. Lee, W. Meng, et al. See “Injection into the SNS Accumulator Ring: Minimizing Uncontrolled Losses and Dumping Stripped Electrons”, D.T. Abell, Y.Y. Lee, W. Meng, in Proc. of EPAC 2000, p.2107.

[2] OPERA-3d (an **OP**erating environment for **E**lectromagnetic **R**esearch and **A**nalysis) is the pre and post processing system for electromagnetic analysis programs such as TOSCA (for non-linear magnetostatic or electrostatic field and current flow problems) developed by Vector Fields Limited, England.

[3] http://dwg-server.c-ad.bnl.gov/eng-arch/source.htm

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[6] M. Venturini and A. Dragt, “Accurate Computation of Transfer Maps from Magnetic Field Data”, NIM (A) 427 (1999) 387-392.

[7] M. Venturini, Ph. D. Dissertation, University of Maryland at College Park, Physics Department, 1998.

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