Optics Simulations of the 5 MeV NPBSE FOX Telescope

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Abstract

The far-field optics experiment (FOX) is a proposed design for the neutral particle beam space experiment (NPBSE) program. This 425 MHz straight beam line includes a 4.3 meter large-bore telescope. It is designed to deliver an 8 mA, 5 MeV neutral hydrogen beam with a transverse divergence of approximately 30 micro-radians to a target space vehicle (TSV) located up to 5 km away. We present zero current simulations, made with Grumman's TOPKARK code, of the telescope optics and the resulting 5 km target footprint. These simulations demonstrate the need for momentum compactation to minimize chromatic aberrations and for the careful use of octupoles to correct geometric aberrations. TOPKARK uses a novel line dipole model for the large-bore, combined function telescope objective lenses, constructed with rods of permanent magnet material, proposed for use in the FOX. We describe this model and its effect on the dynamics.

I. OVERVIEW OF FOX

The far-field optics experiment (FOX) design is largely due to the AT division at LANL [1]. It is a proposed design for the neutral particle beam space experiment (NPBSE) program.

It is a straight device, as seen in Fig. 1 approximately 11 meters long consisting of a 1 meter ion source, a 1.58 meter RFQ, a 1.74 meter DTL, a 4.31 meter telescope, a 0.25 meter WAFFOG and a 1.46 meter neutralizer. It operates at a frequency of 425 MHz and is designed to deliver an 8 mA, 5 MeV neutral hydrogen beam with a transverse divergence of approximately 30 micro-radians to a target located up to 5 km away.

The telescope section includes an RF cavity for momentum compactation. In the absence of any appreciable drift space, the RF phase is reversed in the last few cells of the DTL to longitudinally stretch the beam in preparation for this compactor.

The quadruplet eyepiece matches the beam from the DTL into the telescope objective. The objective itself is a quadrupole triplet. The last two quads of the eyepiece and the three objective quads control the beam focus and magnification in both transverse planes and match the maximum beam excursion in these planes in order to minimize

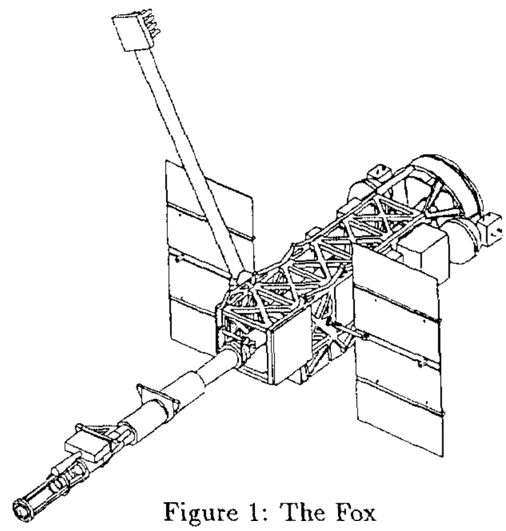

Figure 1: The Fox

the required beam pipe radius.

The large-bore objective lenses have a nominal diameter of 35 cm and are made of some 32 individual rods of suitably oriented permanent magnet material. Since each rod can be individually oriented, it is possible to control the multipole content of the objective, in particular the quadrupole and octupole content are thus determined. Still, because of the discrete nature of the rods, high order multipoles are seen by particles that approach them too closely.

II. THE TOPKARK CODE

The Topkark code is a Grumman reworking of a previous LBL-BNL-Grumman code developed for modeling a compact storage ring [10]. It exists in both a Taylor map version and a tracking version. Topkark incorporates both canonical [9],[11] and non-canonical integration techniques, automatic differentiation [7], and uses the LIELIB routines of Forest [8]. The code incorporates the usual array of iso-magnetic accelerator elements as well as a combined function bending element to dodecapole order. Topkark has been benchmarked against Marylie 3.0 [4] and TLIE [5].

Recent additions to the code include fitting routines for obtaining desired Taylor map coefficients and several space charge models which depend only on second moments of the distribution function [6]. The space charge models have been benchmarked against the TRACE3D code to linear

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order and are discussed in more detail in this proceedings.

III. LARGE-BORE OBJECTIVE MODEL

The large-bore objective lenses are made of individual rods of suitably oriented permanent magnet material. In Topkark, each permanent magnet rod is modeled by a long, thin, rectangular loop of current carrying wire. The vector potential from each piece of straight wire is easily calculated analytically. These are added up and the limit of loop width d going to zero as the current I goes to infinity is taken so that the dipole moment Id remains constant. The resulting vector potential, equivalent to a line of equally oriented point dipoles, is obtained analytically.

$$A_z(x,y,z) = \frac{\mu_0 Id}{4\pi}\frac{(x-a)\cos\mu+(y-b)\sin\mu}{(x-a)^2+(y-b)^2} \left[\frac{z-z'}{\sqrt{(x-a)^2+(y-b)^2+(z-z')^2}}\right]_{z_1}^{z_2} \quad (1)$$

$$A_x(x,y,z) = \frac{\mu_0 Id}{4\pi}\cos\mu \left[\frac{1}{\sqrt{(x-a)^2+(y-b)^2+(z-z')^2}}\right]_{z_1}^{z_2} \quad (2)$$

A_y is given by replacing $\cos\mu$ by $\sin\mu$ in Eq. 2. Here, $\mu+\pi/2$ is the angle of orientation of the dipole moment, while $Id \approx M\sigma$, where M is the magnitization and σ the cross sectional area of the rod. The variables a and b are the x, y coordinates of the rod. z_1 and z_2 are the longitudinal positions of its endpoints.

To obtain quadrupole symmetry, we choose N, the number of rods, to be a multiple of 4. Fox uses 32 rods spaced at angles a uniform distance apart. To obtain a desired multipole with quadrupole symmetry, we choose

$$\mu_i = (m+1)\,\theta_i + \pi/2 \quad (3)$$

Then $m = 2,4,6$ yields quadrupole, octupole and duodecapole respectively. Mixtures of multipoles may be obtained by suitable superposition of orientations. The first spurious multipole to appear is of order $N+m$. This model is a close analog of the REQ magnet design described by Halbach [12]

IV. OPTICS SIMULATIONS

The single particle Hamiltonian dynamics of the large-bore objective lenses incorporating the formula for the vector potential given above are integrated using a non-symplectic, adaptive Runge-Kutta technique since canonical integration is not an issue in the FOX.

The tracking code version of Topkark does not use a perturbative expansion but rather the exact form of the Hamiltonian. Thus, there is no limit to the perturbative order of the dynamics. The only errors made are related to the time step and order of integration.

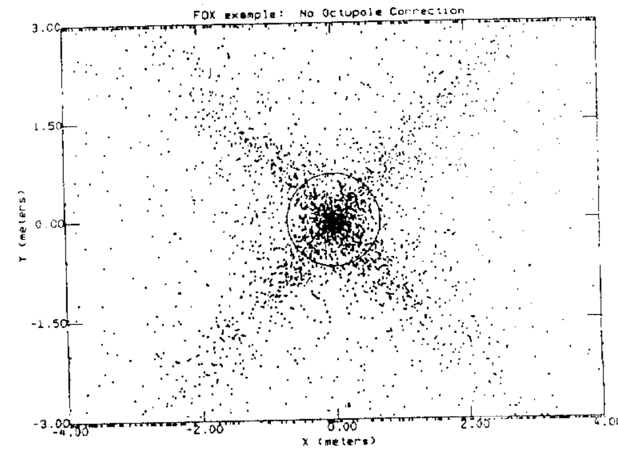

Figure 2: Uncorrected Fox design footprint at 5 km.

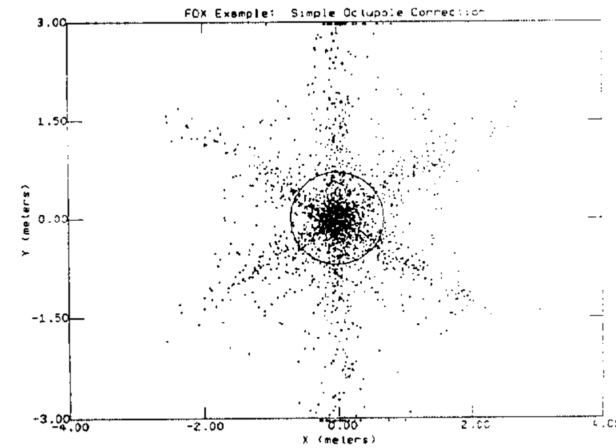

Figure 3: Simple Octupole correction Fox design footprint at 5 km.

However, the Taylor map version of the code is most useful in correcting aberrations. The fringe fields of quadrupole magnets directly feed third order geometric aberrations. These arise from a Lie polynomial of the form [2], [3],

$$f_4 = A\,x^4 + B\,x^2y^2 + C\,y^4, \quad (4)$$

and generate the following kicks in the momentum,

$$\begin{aligned} p_x = \partial_x f_4 &= 4Ax^3 + 2Bxy^2 \\ p_y = \partial_y f_4 &= 4Cy^3 + 2Bx^2y. \end{aligned} \quad (5)$$

The coefficients A, B, C scale with telescope aspect ratio as radius over length to the third power. The uncorrected footprint is shown in Fig. 2

Simple octupole correction depends on the fact that A, B and C are linear in the strength of any octupole magnets. Then three octupole magnets can be used to zero all of A, B and C, dramatically reducing the third order geometric aberrations. However, this simple correction results in octupoles which feed up strongly into fifth order aberrations as shown in Fig. 3.

By using more than three independent octupoles (FOX uses seven), one can zero the third order coefficients while

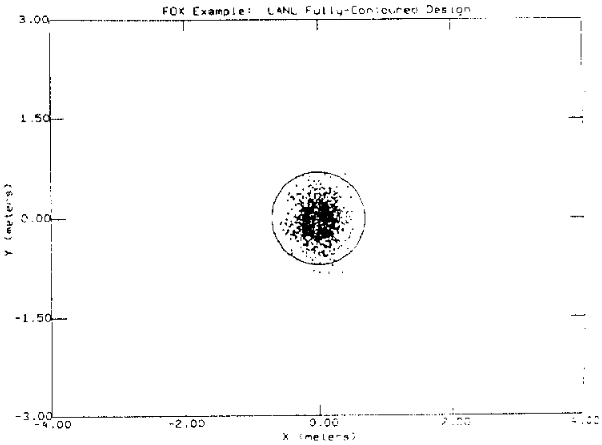

Figure 4: Contoured Fox design footprint at 5 km.

simultaneously minimizing the octupole strengths in the least squares sense. This greatly reduces feed-up to fifth order.

In the fully "contoured" LANL approach one explicitly minimizes the appropriate coefficients of the fifth order map with these extra octupoles, yielding a small but significant improvement over the least-squares approach. The footprint due to a fully contoured FOX objective is shown in Fig. 4

One further outcome of the FOX simulations was the necessity of increasing the objective bore diameter to 35 cm. Initial FOX designs used a bore diameter of 25 cm, while the beam had a nominal two sigma diameter of 20 cm. Reduced performance resulted because of the close approach of many particles to the permanent magnet rods. There, they were subject to the high order "spurious" multipoles due to the discrete number of the rods.

V. CONCLUSIONS

The particle tracking code Topkark, developed at Grumman, was used to simulate the beam optics of the FOX. These simulations demonstrated the following requirements, all of which are satisfied by the final optics design.

High order geometric aberrations must be carefully controlled through the use of "contoured" octupoles. Chromatic aberrations must be minimized through momentum compaction provided by an RF gap. The telescope objective bore must be significantly larger than the beam size in order to reduce the impact of very high multipole contributions from their 32 rod-like permanent magnets.

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