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EFFECT OF THREE-DIMENSIONAL QUADRUPOLE MAGNET MODEL ON BEAM DYNAMICS IN THE FODO LINE AT THE SPALLATION NEUTRON SOURCE BEAM TEST FACILITY*

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Abstract

The research program at the Spallation Neutron Source (SNS) Beam Test Facility (BTF) focuses on improving accelerator model accuracy. This study explores the effect of two different models of permanent magnet quadrupoles, which comprise a 9.5-cell FODO line in the BTF. The more realistic model includes all higher-order terms, while the simple, in use model, is a perfect quadrupole. Particular attention is paid to high-amplitude particles to understand how the choice of quadrupole model will affect beam halo distributions. In this paper, we compare particle tracking through a FODO line that contains only linear terms - a perfect quadrupole model - to a full 3D model.

INTRODUCTION

The Beam Test Facility (BTF) at the Spallation Neutron Source (SNS) is a functional duplicate of the Front End of the SNS accelerator. Current research at the BTF is focused on beam distribution, including full 6D measurements, and halo growth during beam transport. Of particular interest is how halo grows within a FODO line and accurately simulating this growth.

The FODO line at the Beam Test Facility consists of 19 permanent magnet quadrupoles [1]. Current simulations at Oak Ridge National Laboratory (ORNL) model the FODO line as perfect quadrupoles. However, in the aperture region of FODO lines it is known that the magnetic field becomes complex and differs from a perfect quadrupole. Understanding how much of an effect this difference causes is important for creating accurate simulations of halo distributions.

Recently, we developed an analytic model of the full magnetic field of the quadrupoles in the FODO line. The magnets being oriented in a Halbach Array made this possible as the field for each permanent magnet can be calculated and then combined with the fields of the other magnets. This analytic model along with the model for a perfect quadrupole can be used to create simulated quadrupoles for comparison. The quadrupole fields are similar (Fig. 1) but their field strengths increase differently in the transverse plane. This paper examines how the differences between these magnetic fields affect particle transport in the BTF FODO line.

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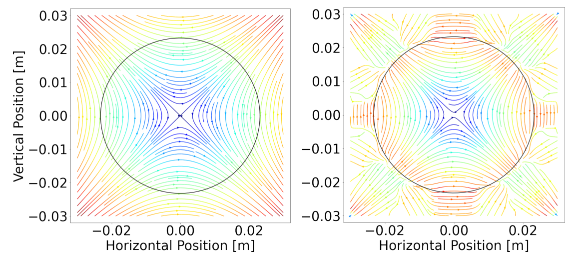

Figure 1: Magnetic field models of a perfect quadrupole (left) and full analytic solution quadrupole (right). The black circle in each shows the beam pipe aperture.

VIRTUAL FODO LINE

The strengths of the magnet models were scaled to create a realistic simulation of the BTF FODO lines. They were scaled to match the design integrated field strengths in the 1.817 T BTF magnets (Fig. 2)[1].

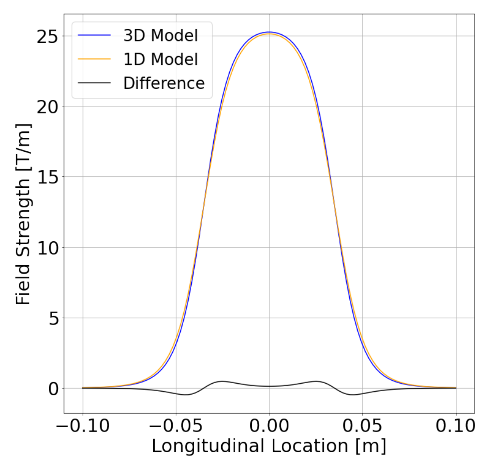

Figure 2: Longitudinal field profile of analytic models.

After scaling to match the strengths of the BTF magnets, two virtual FODO lines were created. Each line having the 19 quadrupoles in the same focusing order as the BTF with the same quadrupole length, spacing, and aperture as the design BTF FODO line[2].

TRACKING

The Runge-Kutta (RK4) method was used within PyORBIT[3] to track the particles through the virtual FODO lines using each particle's position and momentum. The particles were initially arranged in a circle in the normalized phase space then transformed using the matched Twiss parameters

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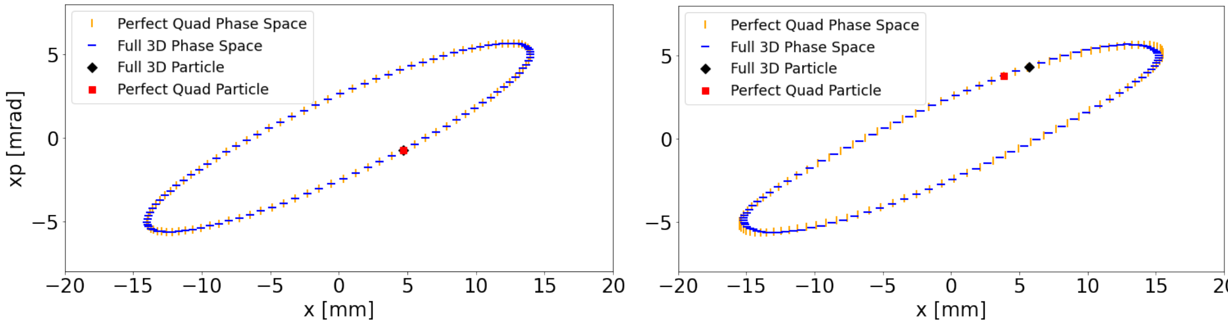

Figure 3: Phases spaces of magnet models before transport (left) and nine FODO cells later after transport (right).

of the midpoint of the first cell of the FODO line (Fig. 3). This was done so circular normalized phase space coordinates could be recovered at any position along the FODO line. The phase space distribution was aligned at the midpoint of the first cell so that at the end of the FODO line the particles had transported through an integer number of cells and had the same phase space as they had at the start.

The phase space distributions were transported down the FODO lines and maintained a near identical shape throughout (Fig. 3). Although the overall shape was maintained, the red and black dots representing the position of a single particle on each of the phase spaces reveal a difference in phase advance between the two models. While the particles start in the same position on their respective phase space ellipses, by the end of their transport, they occupy two different locations.

PHASE ADVANCE DIFFERENCES

To quantify the phase advance difference, the phase spaces were transformed back to normalized coordinates and the angle between a pair of particles was computed (Fig. 4). In normalized coordinates the particles perform simple harmonic motion, and the angle between a set of particles on either model is taken in the x, x' plane. The small abnormalities in the phase spaces of Fig. 3 and Fig. 4 are caused by a difference in z position between the particles as they were transported due to each particle's trajectory having a different path length and the same initial longitudinal velocity. This is accounted for by either selecting particles at one time step and different z positions, then normalizing according to each particle's z position's current Twiss parameters, or by selecting particles at one z position and multiple time steps, then normalizing using that z position's Twiss parameters. The second option is shown in Fig. 4.

To show how the phase advance evolves, the angle between particles can be taken at any position along the beamline. This is done after the particles have traveled one cell length for the whole line to generate a phase advance trend (Fig. 5). This results in a difference in phase advance of 36.6 ± 0.3 mrad/m in the near aperture region for the BTF FODO line. The result can be extended beyond the design length of the BTF FODO line to a virtual FODO line of ~10x the length. The result still holds with this line.

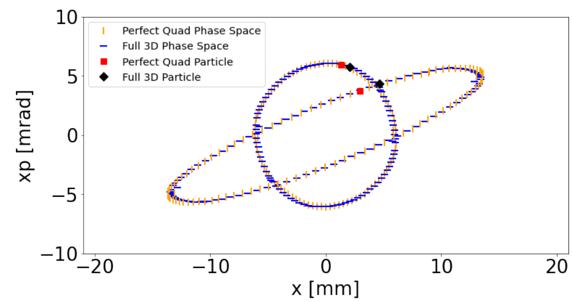

Figure 4: Normalized phase spaces at end of beam-line.

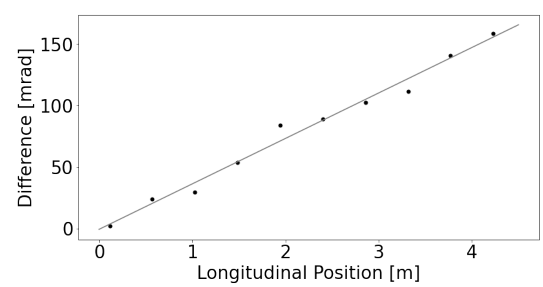

Figure 5: Particle phase advance difference using linear trend between magnet models.

The particles' maximum positional amplitude is controlled by adjusting the size of the normalized phase space circle before transportation along the beam-line. At a normalized radius of 6 the particles reach the near aperture region. Adjusting the radius makes it apparent that there is an amplitude dependence in the difference of the phase advance (Fig. 6). This difference is maximal at a normalized radius of 5.5 and trends towards zero as the particles are confined to the center.

CONCLUSION

The two magnet models for simulations of the BTF FODO line generate very similar linear trajectories but slightly different phase advances. The perfect quadrupole model generates a larger phase advance of 36.6 mrad/m than the full analytic model in the aperture region. The phase advance difference is amplitude dependant and is most notable in the

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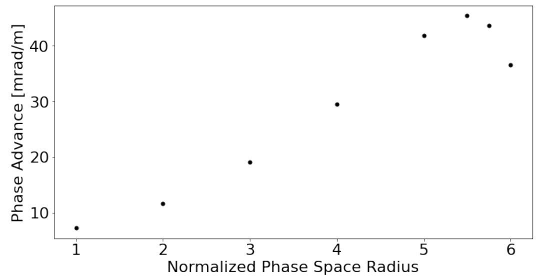

Figure 6: Particle phase advance difference trend at different normalized phase space radii.

near aperture region but falls off as the particles are confined to the center of the beam line.

Though the difference between the models is small, the effects are most notable where halo develops. This research only considered low particle density under no space charge effects, further research into these models is needed with high particle density and space charge effects. The current restriction to scaling these simulations is computational strain, with the simple model running in tens of seconds while the complex model runs in tens of minutes.

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