COMPARISON OF SIMULATION, THEORY AND MEASUREMENT FOR
THE MARYLAND TRANSPORT EXPERIMENT*

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The evolution of measured beam characteristics such as emittance and radius, as well as details of the beam cross section, have been compared with both theory and simulation, and substantial agreement has been obtained. Simulations have also been employed to identify those deviations from an idealized transport system, such as mismatch and misalignment, which are likely to be the cause of emittance growth in excess of what was expected for the ideal system.

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1. Introduction

Because the propagation of a space charge dominated beam in a focused channel is often characterized by strongly nonlinear dynamics, computer simulations have become an important tool in the design of these transport systems, as well as in understanding the underlying nonlinear phenomena. However, it is difficult to know, a priori, how detailed a numerical model is required to adequately describe a particular physical system. It is often similarly difficult to determine how detailed the experimental diagnostics must be, in order to explain why quantities such as the beam emittance, which is usually conserved unless nonlinearities are significant, behave in the observed manner.

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The University of Maryland Transport Experiment [1] because it is relatively low cost, easily modified, and is well diagnosed, promises to be a particularly suitable platform for comparison with simulations. An extensive program of comparisons of simulation to the experiment, as well as to applicable theory, is therefore in progress, and we will summarize some of the recent findings which have emerged from this work.

2. Numerical Model

Because many of the observed characteristics of the Maryland Transport Experiment may be explained only if the details of lens nonlinearities are included, it is important to incorporate an accurate representation of the magnet characteristics into the simulation model. Fortunately for this purpose, a comprehensive series of detailed measurements of the lens characteristics has been made by Loschialpo [2]. He found that the longitudinal magnetic fields, along the axis of a single lens could be accurately modelled by the analytic form,

$$B_z(0,z) = \frac{B_0 e^{-\frac{1}{2}\left(\frac{z}{b}\right)^2}}{1 + \left(\frac{z}{a}\right)^2},$$

where $b = 2.29$ cm, and $a = 4.4$ cm. The off-axis magnetic field at a point (r,z) is then found numerically from the expansion,

$$B_z(r,z) = B_z(0,z) - \frac{r^2}{4} B''(0,z) + \frac{r^4}{64} B''''(0,z)$$

$$B_r(r,z) = -\frac{r}{2} B'(0,z) + \frac{r^3}{16} B'''(0,z).$$

Figure 1 is a plot of the measured values of the radial magnetic field 1.0 cm off-axis, which is approximately the outer limit of the field typically sampled by beam particles. Also plotted for comparison, is the field calculated from the truncated series. The value of B_0 was calculated from the

magnet current using Loschialpo's measurements on the axis, and there are no other free parameters in this comparison, except that the experimental data were symmetrized by slightly shifting the vertical axis to account for hysteresis in the field measurement.

The simulations described below use the SHIFT-XY two-dimensional particle-in-cell code[3], with the particle orbits advanced in the magnetic field using the half-field algorithm described by Boris[4]. The analytic expressions for the derivatives of the magnetic field are evaluated at each longitudinal position, and the magnetic field is then calculated using the radius of each particle. It was found numerically that 32 leapfrog steps per magnet period were adequate for integrating the particle orbits, even in the presence of the relatively rapidly varying magnetic field at the beam edge.

3. Solid Beam

Experimental data have been obtained using the full transport system, of 38 lenses spaced 13.6 cm apart, with the first two lenses used to match the beam. Measurements were obtained for two different operating currents of 160 mA and 240 mA respectively, both at 5.0 kV. Simulations, seeking to reproduce the experimental data for both cases, were first performed for the nominal operating conditions of a perfectly aligned system, with a uniform initial cross section, and an initial temperature, uniform across the beam at the measured cathode temperature. This corresponds to unnormalized, four times rms, emittances of $8.5 \cdot 10^{-5}$ m-rad, and $8.8 \cdot 10^{-5}$ m-rad for the two operating currents. Matching lens magnetic field settings in these cases were calculated from the measured lens currents.

Measured emittances at the end of the channel were generally higher than the minimum values which were obtained from simulations using the nominal parameter set. Deviations from the nominal set were therefore explored with a view towards varying those quantities for which there were experimental

uncertainties, or for which small errors in the measured values could result in a substantial change in final beam emittance, as in the details of the matching section.

Simulation of the 160 mA experiment using the nominal values, which in this case included the use of matching lens settings based on a linear envelope code, resulted in a 22% emittance growth compared with 70% in the experiment. The importance of lens nonlinearities was demonstrated when artificially reducing them in the simulation, resulted in the absence of any emittance growth [5]. Reducing the nonlinearities in the transport system magnets, but not in the matching lens section, reduced the growth in the simulation to 7%.

A 2% change in the current in the first matching lens was found to eliminate the 20% mismatch which characterized the nominal parameter set and also resulted in a reduction of the emittance growth to 7%. The primary cause of the 22% emittance growth therefore appears to be the thermalization of the mismatch energy by the lens nonlinearities [6]. Also noteworthy, is the sensitivity of the amount of beam mismatch, and the emittance growth it causes, to the matching lenses settings.

A 2 mm offset of the initial 6.8 mm radius beam resulted in only a few percent emittance growth, so that moderate beam misalignment did not seem a likely cause of the 70% emittance growth observed in the experiment. Other attempts to investigate this unexpectedly high emittance growth were limited by a shift to operation at 240 mA, and the careful realignment and matching of the system to minimize any associated emittance growth. As a result, an emittance, at the end of the transport system, of only 40% above the initial inherent emittance was measured, despite the much higher current.

A simulation using the new nominal parameters resulted in emittance growth of about 130%, however the beam was somewhat mismatched. Since location of the beam waist was not precisely known, the beam waist was moved

slightly to minimize the mismatch, and the two matching lenses adjusted by +1.8% and -3% respectively to match the beam. Adjustment of the matching lens currents is reasonably justified, because the matching lenses are actually placed at slightly different positions than assumed in the simulations.

Figure 2 is a plot of the evolution of the x and y rms emittances in the matched beam simulation. An emittance growth of 11% was observed.

Figure 3 is a plot of the evolution of the x and y rms emittances resulting from an initial 2 mm offset of the matched beam. Probably because of the higher current, and the resulting larger equilibrium radius, approximately a 34% emittance growth is observed. The beam image at the downstream end of the experimental transport system is, in fact, observed to be off center by approximately 3 mm. While the detailed cause of the beam offset at the downstream end is not yet known, a misalignment of this magnitude is a good candidate as the cause of the observed emittance growth.

Measurements of the beam profile at the downstream end of the transport system show an asymmetry which is further evidence of misalignment. The observed hollowing of about 20% of the current at the beam center compared with the edges is, however, in fairly close agreement with the profile observed in the simulation. Detailed comparisons are difficult however, because a steady state profile has not yet been reached. Though any rms emittance growth from the lack of detailed force balance between the initially uniform profile and the nonlinear focusing forces, occurs quickly, as expected from the behavior of the homogenization of a nonuniform beam [7,8], localized sloshing-like motion within the beam can persist for a much longer time, especially in view of the nearly linear lens fields at the axis of the transport system.

Further simulation of the consequences of lens misalignments as well as more detailed measurement of the beam characteristics entering the transport

system will probably both be required to further refine detailed understanding of the source of the measured emittance growth.

4. Multiple Beam Transport

Experiments and simulations were also performed to examine the recombination of five beamlets produced by placing a mask at the exit of the gun. While detailed comparisons have been made between measured and simulated evolution of the beam profile as well as comparisons to the theoretical predictions [9], a comprehensive description is beyond the scope of this report, except for those aspects directly relevant to the comparisons between simulation and experiment described above.

The unexpected finding of a reemergence of images of the initial beam configuration, is an indication that the orbits of some subset of the beam particles is close to linear. If these particles are viewed as test particles, then the depressed phase advance derived from the image location is an estimate of the beam emittance. The emittance growth measured this way of 2.6 is approximately the same as 2.6 predicted from the conversion of field energy to kinetic energy [7,9] and compares to 2.7 in the simulations. The emittance growth of 3.3 measured at the end of the transport system is therefore experimental evidence that a component of emittance growth is occurring past the first few lenses. This is consistent with the gradually increasing emittances observed in simulations of emittance growth from an initial mismatch. It also suggests that if misalignment is a significant cause of the emittance growth, that misalignment is more likely to be away from the gun end of the transport system, or could possibly result from an initial aiming error which causes the beam to slowly drift off-axis.

Another area of agreement with the simulations worth noting is that the final beam profile in the multi-beam experiment is peaked at the center rather

than being hollowed as in the solid beam case. This too is observed in the simulations.

5. Conclusions

A substantial degree of detailed agreement has been obtained between computer simulation and the measured behavior of the Maryland Transport Experiment. There are many promising areas to look into for further and more detailed agreement. For example, the initial beam current cross section emerging from the gun is slightly hollow, instead of uniform as assumed and this can be incorporated into the simulations. A more detailed examination of the consequences of different types of beam misalignment should also be worthwhile.

In many cases, such as the sensitivity of final beam emittance to initial rms match, the simulations can examine aspects of the transport system which are difficult to measure. Further comparisons between simulation and experiment appear a very promising avenue for the investigation of details of the nonlinear beam dynamics in space charge dominated transport systems, as well as in resolving any remaining discrepancies between simulation and experiment.

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FIGURE CAPTIONS

- Fig. 1. Comparison, as a function of the axial distance, of the radial magnetic field at 1 cm radius with the field calculated from the truncated series expansion.
- Fig. 2. Evolution of the x and y rms emittances of the beam at 240 mA after the matching lens values have been adjusted to match the rms envelope.
- Fig. 3. Evolution of the x and y rms emittances of the matched 240 mA beam with an initial 2 mm offset. The greater emittance growth is in the direction of the offset.

Figure 2

Figure 3