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Title: LOS ALAMOS BEAM HALO EXPERIMENT: COMPARING THEORY, SIMULATION, AND EXPERIMENT

Author(s): Thomas P. Wangler, LANSCE-1
Ji Qiang, LBNL

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Los Alamos Beam Halo Experiment: Comparing Theory, Simulation, and Experiment

Thomas P. Wangler[1], and Ji Qiang[2]

[1]*Los Alamos National Laboratory, Los Alamos, NM 87544*
[2]*Lawrence Berkeley National Laboratory, One Cyclotron Road, University of California, Berkeley, CA 94720*

Abstract. We compare macroparticle simulations with measurements from a proton beam-halo experiment in a 52-quadrupole periodic-focusing channel. Three different initial distributions with the same Courant-Snyder parameters and emittances, but different shapes, predict different beam profiles in the transport system. Input distributions with greater population in the tails produce larger rates of emittance growth, a result that is qualitatively consistent with the particle-core model of halo formation in mismatched beams. The simulations underestimate the growth rate of halo and emittance for mismatched beams. Better agreement between simulations and experiment may require an input distribution that represents more accurately the tails of the real input beam.

INTRODUCTION

We present the results of self-consistent macroparticle simulations including space-charge forces using the macroparticle simulation code IMPACT[1] for comparison with experimental measurements of the beam profiles in a high-current proton beam. The measurements were made in a beam-transport channel using a 6.7-MeV proton beam at the Low Energy Demonstration Accelerator (LEDA) facility at Los Alamos National Laboratory. A major goal of the experiment was to validate the beam-dynamics simulations of beam halo, using simulation codes such as IMPACT. Of particular importance was the validation of the space-charge routine [2].

BEAM HALO EXPERIMENT

The LEDA facility consists of a 75-keV dc injector, a low-energy beam transport (LEBT) system, and a 350-MHz radiofrequency quadrupole (RFQ), which accelerates the proton beam to 6.7 MeV. A schematic diagram of the LEDA beam-halo experiment transport system, which follows the RFQ, is given in Fig. 1[3]. The transport system consists of 52 magnetic quadrupoles with alternating polarity to provide strong periodic transverse focusing. Transverse beam profiles were measured using beam-profile detectors[4], located in the middle of the drift space after quadrupoles 4, 20, 22, 24, 26, 45, 47, 49 and 51. The first four quadrupole gradients are independently adjustable to match the beam, producing equal rms sizes in the beam-profile detectors, or to produce mismatches to excite a breathing mode or a quadrupole mode. The beam current was varied over a range from 16 mA and 100 mA. In this paper we report on results at 75-mA.

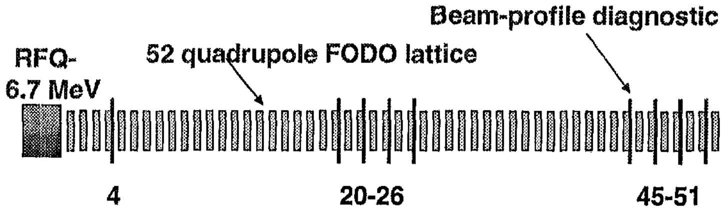

FIGURE 1. Block diagram of the 52-quadrupole-magnet lattice showing the nine locations of beam-profile scanners.

SIMULATIONS

The lack of detailed knowledge of the initial distribution in phase space is an important issue. Our approach to the simulations has been to generate three different initial distributions with the same Courant-Snyder ellipse parameters and emittances, which were deduced from the measurements. These three distributions are: 1) 6D Waterbag, 2) 6D Gaussian, and 3) a distribution called LEBT/RFQ, generated from a simulation through the LEBT and RFQ, starting at the plasma surface at the exit of the ion source. The particle coordinates of the LEBT/RFQ distribution were scaled to produce the correct Courant-Snyder parameters and emittances.

The transverse phase-space plots of these distributions are given in Fig.2. Figure 2 shows qualitatively an increasing input beam halo as we progress from the Waterbag to the Gaussian to the LEBT/RFQ distribution. Using these three initial distributions for a 75-mA input beam, we have simulated the beam transported through the matched LEDA experiment. We have used about 2.8 million macroparticles with a computation grid of 65 X 65 X 129. Poisson's equation is solved in cylindrical coordinates with transverse perfect-conducting-wall boundary conditions and a longitudinal periodic boundary condition.

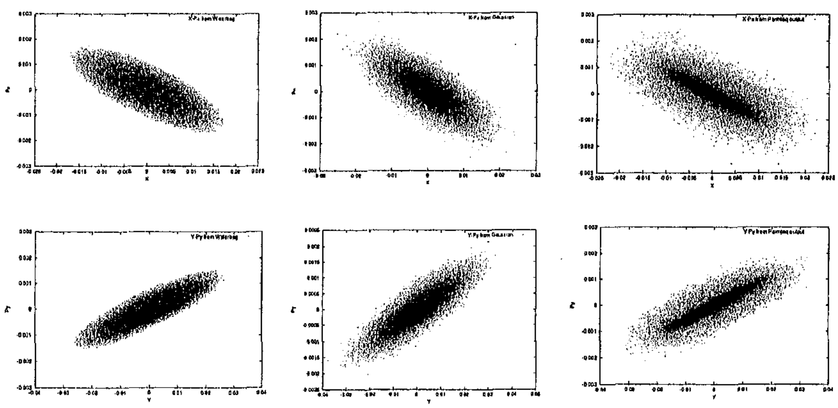

FIGURE 2. Transverse phase-space projections for three initial simulation distributions for the matched beam: 6D Waterbag (left), 6D Gaussian (middle), and RFQ/LEBT (right). The upper plots show x-x' phase space, and the lower plots show y-y' phase space.

All three distributions predict a nearly matched transverse rms beam size, in good agreement with the matched-beam measurements. The Waterbag distribution generates the best matched solution with a nearly uniform rms size through the channel. The next best match corresponds to the Gaussian distribution. The rms beam sizes from the simulation using the LEBT/RFQ distribution fluctuate over a range of about 10% from the average value. The matched rms sizes from measurements at the detector locations in the transport channel showed a similar fluctuation.

In addition to the rms sizes, the LEDA experiment also obtained the projected density distributions, i.e. beam profiles in x and y at nine locations along the transport channel. The density profiles from the simulations of the matched beam, are compared with measurements in Fig. 3. The LEBT/RFQ simulation agrees best with the measured profiles, especially in the core region. However, none of the distributions reproduce the tails observed in the measured profiles.

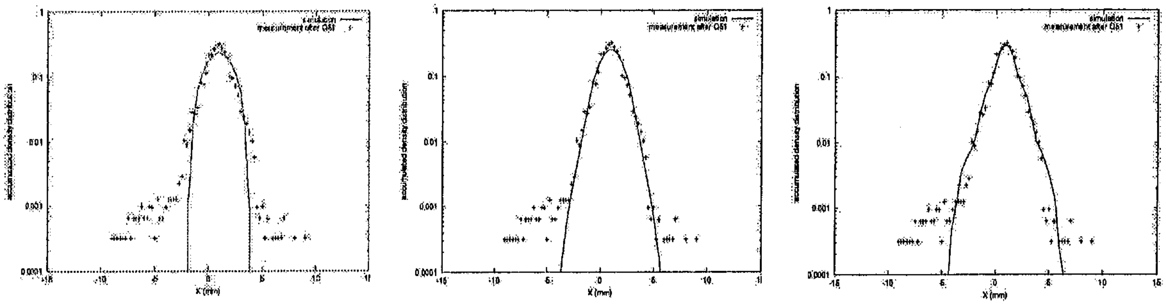

FIGURE 3. Horizontal profiles from measurements (points) and simulations (curves) at the final profile detector for 75-mA matched beam. The initial distributions for the simulations are: 6D Waterbag (left), 6D Gaussian (center), and LEBT/RFQ (right).

The first four quadrupole magnets were also adjusted to produce breathing- and quadrupole-mode rms mismatches. All three simulations fail to reproduce the broad shoulders, which are induced in the measured beam profiles by the mismatches (see Fig. 4 for LEBT/RFQ case). The broader shoulders are evidence of a more rapid halo growth rate in the mismatched beams, which is not reproduced by the simulations.

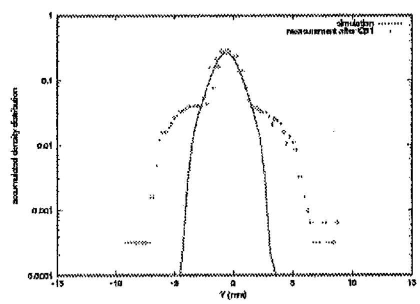

FIGURE 4. Horizontal profile from measurements (points) and the LEBT/RFQ simulation (curve) at the final profile detector for a 75-mA breathing-mode mismatched beam.

Figure 5 compares the rms emittances calculated from the measurements at 75 mA for a breathing-mode mismatched beam, with those from the three simulations. We find that the emittance growth rate from simulations increase as we progress from the 6D Waterbag to 6D Gaussian to LEBT/RFQ, i.e. with increasing halo population in the initial distribution. This is a result that would be expected qualitatively from the particle-core model [5], because the resonant particles that form the halo lie outside the beam core. The emittance growth rate calculated from measurements is larger than those from any of the three simulations. This result is also consistent with the explanation that the initial distributions assumed for the simulations do not adequately populate the tails, which are main source of the halo and emittance growth.

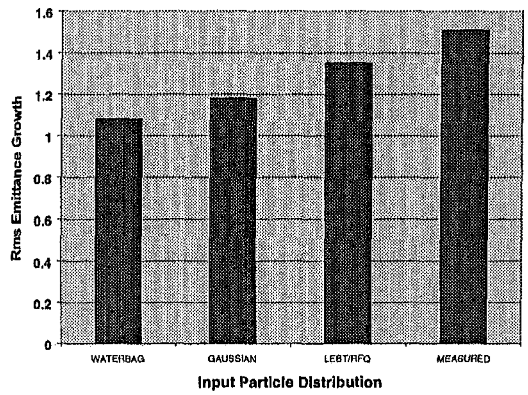

FIGURE 5. Emittance growth at scanner 45 from three simulations and from the experiment, for a breathing-mode mismatch at 75 mA.

CONCLUSIONS

Benchmarking multiparticle simulation codes against experimental measurements is a challenge, especially when the details of the initial 6D phase-space distribution are not known. We conclude that using only the known Courant-Snyder parameters and the emittances as input parameters is not sufficient for reliable simulations of beam halo. Using the IMPACT code, we have carried out simulations of the LEDA beam-halo experiment using three different initial particle distributions, 6D Waterbag, 6D Gaussian, and LEBT/RFQ (generated from simulation through the LEBT and RFQ), all scaled to produce initial ellipse and emittance parameters deduced from the measurements. These three distributions differ qualitatively with respect to their initial halo content. Based on the particle-core model, we expect that initial particle distributions with greater halo population will exhibit greater resonant halo growth. While all three initial distributions give fair agreement with the measured profiles for the matched case, the LEBT/RFQ does the best, as would be expected. However, none of these distributions describe well the observed halo density in the matched beam. The measured mismatched beam profiles exhibit a rapid halo growth rate, which is underestimated by all three simulations. These results can be explained by the hypothesis that the higher growth rate for the real beam is caused by a higher density in the initial halo, and consequently, a greater population of the region of phase space that leads to resonant halo growth. We conclude that knowledge of the initial particle distribution, especially the density in the tails, is important for accurate simulations of the beam halo.