AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

o

TITLE: RECENT RESULTS IN ANALYSIS AND SIMULATION OF BEAM
HALO

AUTHOR(S): Robert D. Ryne AOT-1
Thomas P. Wangler AOT-1

SUBMITTED TO: ADTT Conference, Las Vegas, NV, July 25-29, 1994

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Form No. 836 R5
ST 2629 10/91

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

875

Recent Results in Analysis and Simulation of Beam Halo *

Robert D. Ryne and Thomas P. Wangler

AOT-1, MS H817

Los Alamos National Laboratory, Los Alamos, NM 87544, USA

Abstract. Understanding and predicting beam halo is a major issue for accelerator driven transmutation technologies. If strict beam loss requirements are not met, the resulting radioactivation can reduce the availability of the accelerator facility and may lead to the necessity for time-consuming remote maintenance. Recently there has been much activity related to the core-halo model of halo evolution [1-5]. In this paper we will discuss the core-halo model in the context of constant focusing channels and periodic focusing channels. We will present numerical results based on this model and we will show comparisons with results from large scale particle simulations run on a massively parallel computer. We will also present results from direct Vlasov simulations.

INTRODUCTION

Several countries are now involved in efforts aimed at utilizing accelerator-driven technologies to solve problems of national and international importance. These technologies have both economic and environmental implications. The technologies include waste transmutation, plutonium conversion, neutron production for materials science and biological science research, neutron production for fusion materials testing, fission energy production systems, and tritium production. All of these projects require a high-intensity accelerator that operates with extremely low beam loss (approximately one part in 10^8 per meter). It is now known that a major source of beam loss is the formation of a very low density beam halo at a displacement exceeding several *rms* beam radii. Understanding the nature of this halo and finding ways to minimize it is crucial to the future of the above mentioned technologies. We are using both analytical and numerical tools to study beam halo.

CORE-HALO MODEL: CONSTANT FOCUSING CHANNEL

In the core-halo model of beam halo evolution [1-5], halo particles interact with a beam core of an assumed density profile, whose *rms* radius is governed by envelope equations. We begin by considering a uniform linear focusing channel with no acceleration; the channel and the beam are assumed to have axial symmetry. We will assume that the beam core has a uniform density, though the main features of the core-halo model have been observed to be insensitive to the choice of the core density profile. Figures 1 and 2 show stroboscopic plots of 32 test particles in the core-halo model; points are plotted in (x, p_x) -space each time the core radius reaches a minimum. The main features of the plots are: (1) a central region that has an extent of slightly more than the core radius; (2) a large amplitude region where particles exhibit betatron motion perturbed by the core space charge; (3) a period-2 resonant structure (associated with the fixed points to the left and right of the central region); and (4) a separatrix with an inner branch that encloses the central region and outer branches that separate the period-2 resonance from the betatron-like trajectories. The period-2 resonance is a parametric resonance corresponding to the fact that resonant particles have an oscillation frequency which is one half the envelope frequency [5]. In these figures the separatrix is actually a narrow chaotic band, and the outer edge of the chaotic band

***Work supported by: (1) U.S. Department of Energy, Defense Programs; and (2) U.S. Department of Energy, Office of Energy Research (Office of High Energy and Nuclear Physics and Office of Scientific Computing)**

Figure 1: Stroboscopic phase space plot based on the core-halo model (uniform density core, tune depression=0.4). The initial core mismatch is 1.5 (*i.e.* the beam oscillates with a maximum amplitude 1.5 times the matched value). The location of 32 test particles is plotted every time the beam envelope reaches a minimum, for a total of 1000 oscillations.

has the approximate shape of a peanut. This “peanut diagram” provides a useful picture for describing halo formation: if particles in an initially well-defined uniform core reach the separatrix (by transport mechanisms not included in this model¹), then they will be carried to large amplitudes along the outer branch of the separatrix. Also, deviations from an exact uniform core, in which a low-density tail extends into the resonance region, will produce the same result. Figure 1 (with the obvious chaotic region) corresponds to a system with a core mismatch of 1.5 and a space-charge tune depression of 0.4; Figure 2 corresponds to a slightly less intense beam with a tune depression of 0.5 and the same mismatch as in Figure 1. Features of the core-halo model agree well with detailed particle simulations run on the massively parallel CM-5 at the Advanced Computing Laboratory. Figure 3 shows simulation results of an initial Kapchinskij-Vladimirskij (KV) distribution with a mismatch of 1.5 and a tune depression of 0.5. For these parameters the system is unstable, and Figure 3 shows the distribution after the instability has set in. The simulation was run with 2 million particles. The first curve bounding the chaotic band in Figure 2 is also shown in Figure 3 for comparison. For this configuration (an axially symmetric beam in a solenoid channel), the CM-5 results show that the maximum particle amplitudes will be approximately confined within the outer separatrix of the core-halo model.

¹Two examples of processes beyond the scope of the core-halo model which could lead to transport from the core toward the inner branch of the separatrix are (1) nonlinear instabilities of the core and (2) particle collisions inside the core. The presence of observable chaos, and its effect on the rate of diffusion toward the inner branch of the separatrix, is a topic that is presently being studied.

Figure 2: Stroboscopic phase space plot based on the core-halo model (uniform density core, tune depression=0.5, mismatch=1.5).

Figure 3: Beam phase space from a 2 million particle simulation on the CM-5 (65536 points are plotted). The outer peanut-shaped set of points were obtained from the core-halo model shown in Figure 2.

CORE-HALO MODEL: ALTERNATING GRADIENT CHANNEL

As shown above, the mismatch of intense beams in constant focusing channels can result in large amplitude growth for the particles. This leads naturally to the following question: Can the envelope oscillation of a matched beam in an alternating gradient channel have similar deleterious effects? The study of the core-halo model for beams in periodic focusing systems was first performed by Lagniel [3]. Consider, for example, a matched uniform beam in a FODO channel with a zero-current phase advance per focusing period of 70 degrees/cell which is depressed by space charge to 35 degrees/cell. A stroboscopic plot for an array of particles in such a system is shown in Figure 4; the data points are recorded at the center of a horizontally focusing quadrupole, where the matched horizontal beam size is $x_{edge} = 4.6\text{mm}$ (*i.e.*, $x_{rms} = 2.3\text{mm}$). It is clear that the period-2 resonance that was such an important feature for a mismatched beam in a constant focusing channel is not present here. This is to be expected, since a halo particle in this example oscillates with a period roughly one tenth the quadrupole period (*i.e.*, the period of the drive in the single particle equation of motion). Though resonant structure and weak chaos are present, this does not appear to be a major source of halo formation, since the resonance structure does not provide a path by which particles can be transported to large amplitudes. Figure 5 shows simulation results for an initially *rms* matched Gaussian beam in this channel after 22 periods. A large amplitude halo is *not* present. A low amplitude halo is present due to charge redistribution (since the initial Gaussian beam was not an equilibrium distribution in this channel), accompanied by a small emittance growth of approximately 7 percent. In contrast, Figure 6 shows the same system as Figure 5, but the beam is *rms* mismatched by a factor of 1.5. Now a significant halo is present; the emittance growth in this case is approximately a factor of two.

DIRECT VLASOV/POISSON SIMULATIONS

Particle simulations provide a means of modeling the Vlasov equation by following the trajectories of a large number of interacting particles. (Since the Vlasov equation does not include the effects of two-particle collisions, the above statement assumes that collisions between particles in the simulation have a negligible effect). With the advent of large-memory computers, another approach is now possible: the direct numerical solution of the Vlasov/Poisson equations. In this approach, the distribution function is specified on a grid in phase space, and the values of the function on the grid are stepped forward in time. At present we have developed a 2-dimensional (x, p_x, y, p_y) code that runs on the CM-5 [6]. An example output is shown in Figure 7, which corresponds to an initially mismatched 4-dimensional Gaussian beam in a quadrupole channel. The figure, which shows the beam density, was obtained by integrating the 4-dimensional distribution over the variables p_x and p_y . This simulation utilized a 128^4 grid, for a total of 268 million grid points. At present, we see no clear advantage to using direct Vlasov simulations: though the resulting data are smoother than that obtained from particle simulations (because binning the output of a particle simulation generally results in noise from poor statistics), a high resolution Vlasov code requires a very large amount of memory. We will continue to develop both particle simulations and Vlasov/Poisson simulations so that we can make further comparisons of these two approaches.

Figure 4: Stroboscopic phase space plot based on the core-halo model for a matched uniform beam in a quadrupole channel. Zero-current phase shift/cell and depressed phase shift/cell are $\sigma_0 = 70$ deg, $\sigma = 35$ deg, respectively.

CONCLUSIONS AND FUTURE WORK

There is strong evidence that core breathing oscillations due to transverse mismatch of intense charged particle beams can lead to significant halo formation. This is evident in the core-halo model, and it is supported by large scale particle simulations. In contrast, it appears that the flutter associated with matched beams in quadrupole channel does not lead to serious halo formation. Based on our experience with the CM-5, we believe that particle simulations with 10 million particles are easily achievable, and simulations with 100 million particles are possible but with some difficulty. Though such simulations will provide high precision beam loss estimates of linac designs, it is worth stressing that understanding the physics of halo formation and propagation through analytical models is essential for the systematic design and optimization of linacs for accelerator driven technologies.

Figure 6: Simulation results showing the beam phase space after 22 focusing periods in a FODO channel. The initial distribution is an *rms* mismatched Gaussian beam. ($\sigma_0 = 70$ deg, $\sigma = 35$ deg)

Figure 5: Simulation results showing the beam phase space after 22 focusing periods in a FODO channel. The initial distribution is an *rms* matched Gaussian beam. ($\sigma_0 = 70$ deg, $\sigma = 35$ deg)

Figure 7: Output from a direct Vlasov/Poisson simulation. The 4-dimensional distribution function was integrated over p_x and p_y to obtain the beam density on a 128x128 grid.

ACKNOWLEDGEMENT

This research was performed in part using the resources located at the Advanced Computing Laboratory of Los Alamos National Laboratory, Los Alamos, NM 87545

REFERENCES

- [1] J.S. O'Connell, T.P. Wangler, R.S. Mills and K.R. Crandall, "Beam Halo Formation from Space-Charge Dominated Beams in Uniform Focusing Channels," Proceedings of the Particle Accelerator Conference, Washington, DC, p. 3657 (1993).
- [2] J.M. Lagniel, "On Halo Formation in Space-Charge Dominated Beams," Nucl. Inst. Meth A345, No. 1, p. 46 (1994).
- [3] J.M. Lagniel, "Chaotic Behaviour and Halo Formation from 2D Space-Charge Dominated Beams," Nucl. Inst. Meth A345, No. 3, p. 405 (1994).
- [4] T.P. Wangler, "Dynamics of Beam Halo in Mismatched High Current Charged Particle Beams," Los Alamos preprint, LA-UR-94-1135 (1994).
- [5] R.L. Gluckstern, "Analytic Model for Halo Formation in High Current Ion Linacs," to appear in Phys. Rev. Lett. (1994).
- [6] S. Habib and R. Ryne, in preparation.

**DATE
FILMED**

10/18/94

END