BENCHMARK OF SPACE CHARGE SIMULATIONS AND COMPARISON WITH EXPERIMENTAL RESULTS FOR HIGH INTENSITY, LOW ENERGY ACCELERATORS

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Abstract

Space charge effects are a major contributor to beam halo and emittance growth leading to beam loss in high intensity, low energy accelerators. As future accelerators strive toward unprecedented levels of beam intensity and beam loss control, a more comprehensive understanding of space charge effects is required. A wealth of simulation tools have been developed for modeling beams in linacs and rings, and with the growing availability of high-speed computing systems, computationally expensive problems that were inconceivable a decade ago are now being handled with relative ease. This has opened the field for realistic simulations of space charge effects, including detailed benchmarks with experimental data. A great deal of effort is being focused in this direction, and several recent benchmark studies have produced remarkably successful results. This paper reviews the achievements in space charge benchmarking in the last few years, and discusses challenges that remain.

INTRODUCTION

Recently, a great deal of effort has been dedicated to benchmarking space charge simulations with experimental data. Whereas a decade ago realistic benchmarks of this type were virtually nonexistent, nowadays rigorous benchmarking of space charge algorithms is routine practice for simulation codes which model high intensity, low energy accelerators. Additionally, the last few years have marked an important transition from qualitative to quantitative benchmarks, and many successful quantitative benchmarks have been achieved for a variety of machine parameters.

A few key factors have contributed to the recent emergence of successful space charge benchmarks with experimental data. First, though space charge has been an important effect in machines for many years, the design and planning of new high intensity, low energy machines such as the SNS, JPARC, RIA, and ESS, which require unprecedented control of beam losses, has provided additional incentive for understanding space charge effects. Second, great advances in computer power during the mid to late 1990's allowed the development of codes that could produce realistic, particle-in-cell style simulations on personal pc's and pc-based parallel computer environments, with reasonable run times. This convenience has made the problem much more attractive to accelerator physicists who do not specialize in computational physics. Finally, a third factor that contributed to the recent fruition of space charge benchmarks is a paradigm shift, i.e., the realization that the coherent beam dynamics are more relevant in determining space charge effects than the incoherent dynamics [1, 2]. As a case-in-point, the incoherent tune is no longer considered to be the space charge limitation of a machine. This revised understanding of the problem has clarified the relevant signatures of space charge resonances, and has helped identify quantities to target experimentally. For example, a few recent experiments have focused on measuring envelope oscillations and coherent tunes in accelerators [3, 4].

This paper presents the history of space charge benchmarks with experimental data for high intensity, low energy hadron accelerators. Here, a benchmark is defined as a quantitative comparison of simulated data with the same property measured experimentally, in an experiment where space charge is a primary effect. This manuscript is organized as follows. First, the computational aspects of space charge simulations are discussed. Next, data compiled from a literature survey of journal articles, PAC and EPAC conference proceedings, and ICFA workshop proceedings is presented. The data then is systematically analyzed to look for trends in the number of benchmarks produced over the last several years, and in the types of benchmarks performed. A number of examples of successful benchmarks are presented, and finally in the last section, future challenges and directions are discussed.

THE COMPUTATIONAL PROBLEM

Before the 1990's boom in computer power, space charge was studied mainly through theoretical models such as the envelope model, which rely on idealized machine parameters, fixed emittances, and rms quantities. These models are inherently incapable simulating real experiments. Due to the advances in computer resources, the focus has now shifted to particle-in-cell (PIC) simulations, where space charge is treated in a self-consistent fashion for realistic particle distributions, and where the entire accelerator environment, including the nonlinear magnetic lattice, RF cavities, and injection regions, are accurately modeled.

Mathematically, simulating space charge effects in a beam with a PIC code amounts to solving Poisson's equation, $\nabla^2\phi = \rho/\epsilon$, for the beam in the accelerator environment. Though qualitatively a simple problem, the implementation of this calculation generally involves solving the system on a grid, and implementating and optimizing a variety of numerical methods. Additionally, for many codes, parallelization is required to accomplish reasonable run times with numerically converged routines. Because

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there are a number of ways to approach the problem, space charge algorithms vary from code to code. Many new solvers are being developed which optimize speed, parallelization, or gridding techniques [5]. However, the biggest advances in PIC simulations thus far are linked to increases in computer power, allowing simulations with progressively smaller mesh sizes and more macroparticles, and consequentially better resolution of space charge effects. Most benchmark simulations are now performed with anywhere between 10^5 and 10^6 macroparticles. In machines where the bunch length is long compared to the width of the beam, it is often sufficient to treat the problem with a two-dimensional transverse space charge solver, and a separate one-dimensional longitudinal solver, which is numerically less expensive than running a full three-dimensional treatment. On the other hand, simulating short bunch lengths or including transverse impedances in the simulation generally requires a full three-dimensional treatment of space charge. Additionally, three-dimensional solvers usually require the inclusion of image charges and matching at the beam pipe boundary.

SUMMARY OF BENCHMARKS

One of the challenges associated with performing space charge benchmarks with experimental data is to obtain a complete set of data where the machine conditions are known and recorded at the time of the experiment. In addition to this, it is necessary to isolate the space charge effect, either by suppressing any interfering effects, or by properly identifying and accounting for these effects in the simulation. To some extent, these challenges are addressed by performing dedicated space charge experiments, where the intent of the experiment is to obtain data appropriate for a benchmark. Preliminary simulations of the experiment are also helpful to understand the parameter space and potential problems that may arise.

Tables 1 and 2 summarize the results of a literature survey of benchmarks which fall within the aforementioned definition of a space charge benchmark with experimental data. Though some benchmarks may have been overlooked in the survey, the information gathered is comprehensive enough to elucidate the overall trends in the area. Generally, just as there are more ring codes than linac codes in existence, there are also a greater number of space charge benchmarks for rings than for linacs. This is because rings have tighter beam loss constraints than linacs, and are more sensitive to beam losses through collective effects, such as space charge. The ratio of total ring to linac space charge benchmarks performed in the last decade is about three to one.

Figure 1 is a histogram of the total number of space charge benchmarks with experimental data published in the last decade. Two notable observations from this figure are that no benchmarks were published before 1998, and that there is a substantial increase in the number of benchmarks produced in the last three years, with a major jump occurring in the year 2003.

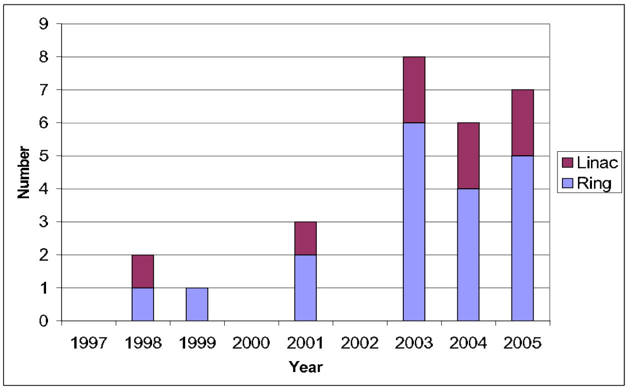

Figure 1: Histogram of the number of space charge benchmarks with experimental data in the last decade, broken down into rings and linacs.

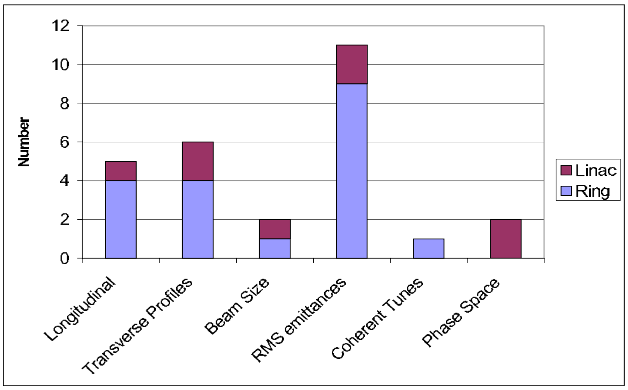

Figure 2: Histogram of the type of space charge benchmarks performed, broken down into rings and linacs.

Figure 2 is a histogram of the type of benchmarks which have been performed. In terms of pure numbers, the most benchmarked quantity is the rms emittance of the beam. This is due in large part to a cross-code benchmark with CERN PS experimental data which is currently underway. Note from Table 1 that many of the rms emittance benchmarks are currently in progress, with results expected later this year; seven different codes are participating in this benchmark, and thus seven of the ten ring benchmarks shown are due to this collaboration. More discussion is dedicated to this effort in a later section. Alternatively, if we consider the number of different machines used in a given type of benchmark, then the transverse profile becomes the most benchmarked quantity to date, having been done for a total six different machines - four rings, and two linacs.

BENCHMARK EXAMPLES AND DISCUSSION

In this section a representative sampling of the benchmarks presented in Tables 1 and 2 are presented. The intent here is not to discuss the physics under study in the vari-

Table 1: Summary of space charge benchmarks with experimental data for ring machines. In the first column, ”Long.” refers to any longitudinal parameter, ”T. Profiles” refers to transverse profiles, and ”Emittance” refers to the rms emittance of the beam

Quantity	Machine	Code	Year	Reference
Long.	PSR	ACCSIM	1998	ICFA Workshop [6, 7]
Long.	TRIUMF	SPUNCH	2003	PAC 2003 [8]
Long.	PSR	ORBIT	2004	PRST-AB, [9]
Long	Fermilab Booster	Synergia	2003	PAC 2003 [10]
T. Profiles	PSR	ORBIT	2001	PRST-AB [11]
T. Profiles	CERN PS Booster	ACCSIM	1999	PAC 99 [12]
T. Profiles	KEK PS Main Ring	ACCSIM	2003	PAC 2003 [13]
T. Profiles	Fermilab Booster	Synergia	2004	ICFA Workshop 2004 [14]
Emittance	KEK Booster	SIMPSONS	2001	PAC 2001 [15]
Emittance	KEK PS Main Ring	ACCSIM	2003	PAC 2003 [13]
Emittance	CERN PS	Micromap	2003	PRST-AB [16]
Emittance	CERN PS	IMPACT	2004	EPAC 2004 [17]
Emittance	CERN PS	ORBIT	2004	ICFA 2004 [18]
Emittance	CERN PS	ACCSIM	2005	F. Jones, in progress
Emittance	CERN PS	Synergia	2005	P. Spentzouris, in progress
Emittance	CERN PS	SIMPSONS	2005	S. Machida, in progress
Emittance	CERN PS	ORBIT (BNL)	2005	A. Luccio, in progress
Beam Width	Fermilab Booster	Synergia	2003	PAC 2003 [10]
Coherent tune	Fermilab Booster	Synergia	2005	P. Spentzouris [4]

Table 2: Summary of space charge benchmarks with experimental data for linac machines. In the first column, ”Long.” refers to any longitudinal parameter, ”T. Profiles” refers to transverse profiles, and ”Emittance” refers to the rms emittance of the beam

Quantity	Machine	Code	Year	Reference
Long.	SNS	Parmilla	2005	PAC 2005 [19]
T. Profiles	LEDA	IMPACT	2003	PAC 2003 [20]
T. Profiles	SNS	Parmilla	2005	PAC 2005 [21]
Emittance	LANSCE	Parmilla	1998	ICFA 1998 [22]
Emittance	SNS	Parmilla	2005	PAC 2005 [23]
Phase Space	HCX	WARP	2003	PAC 2003 [24]
Phase Space	SNS	Parmilla	2005	PAC 2005 [26]
Beam Width	LEDA	IMPACT	2001	SNS Mini-Workshop 2001 [25]

ous experiments, but to highlight the progress and achievements in the area of space charge benchmarking.

Longitudinal

Longitudinal benchmarks have possibly been the most successful class of space charge benchmarks performed. Compared with transverse benchmarks, the algorithms for handling space charge are simpler, and the numerics are less expensive. Moreover, longitudinal benchmarking does not require detailed knowledge of the lattice optics, and data measurements often rely on standard diagnostic equipment such as beam or wall current monitors. For this reason, most codes have at one point or another benchmarked against longitudinal data.

Figure 3 shows one of the first, or possibly the very first, published longitudinal space charge benchmark with experimental data. In this benchmark, the ACCSIM code was used to reproduce the effect of space charge compensation via inductive inserts in the PSR ring. Since this time, computer power has increased and the ability to resolve effects on a finer scale has enabled space charge benchmarks of high frequency longitudinal features [9].

Transverse Profiles and Beam Widths

Profile benchmarks have in many ways been the hallmark of transverse space charge benchmarks. Most codes have attempted and been successful with this benchmark. Transverse benchmarks are inherently more complicated than longitudinal benchmarks, as they require detailed knowledge of the lattice and a more complicated space charge solver with larger numerics. A successful space charge profile benchmark is a good indication that the

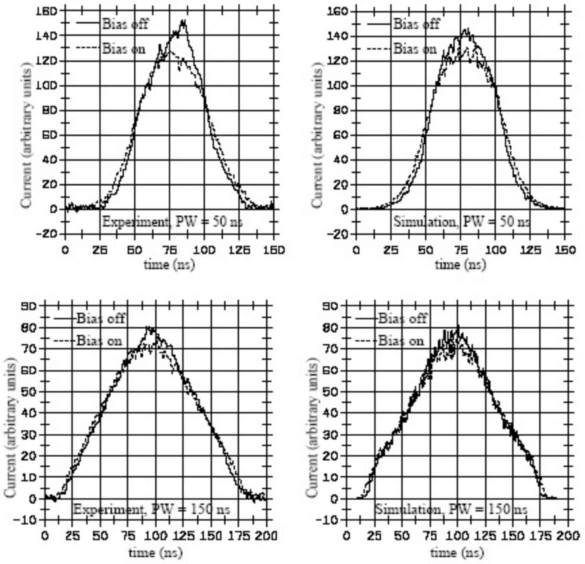

Figure 3: Top: Experimental longitudinal profiles for a low intensity beam with the inductive insert bias on and off (the left side is experimental measurements, and the right side is simulated data). Bottom: The same as top, but for a high intensity beam.

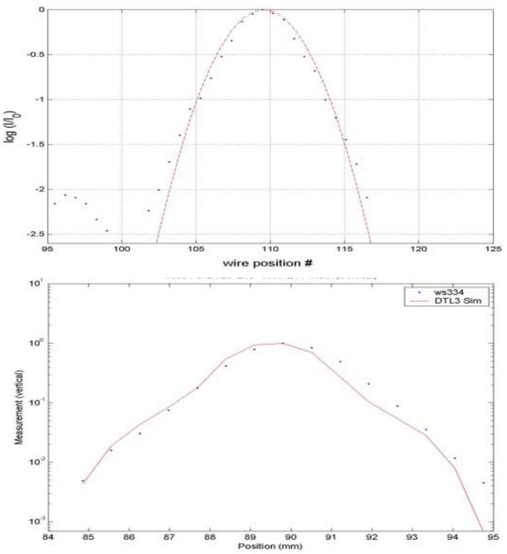

Figure 4: Top: Measured wire scan data (points) and simulated data (lines) for one set of quadrupole strengths. Bottom: Measured wire scan data (points) and simulated data (lines) for a different set of quadrupole strengths.

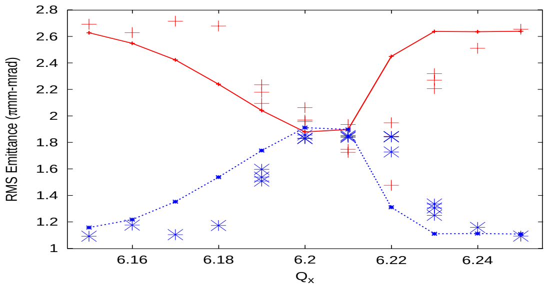

Figure 5: ORBIT benchmark of the Montague emittance exchange measurement. The solid lines are the simulated data, and the points are the measured data (red is horizontal, blue is vertical).

space charge model in the code is correct at least in the gross approximation, and that the fundamental machine parameters (injection scheme, machine optics, etc) are well-represented. Futhermore, transverse profiles are quite sensitive to space charge effects, and some information about halo growth can be derived from profile measurements.

Shown in Figure 4 are preliminary results of matching studies in the SNS warm linac [19]. In this study, matching quads were varied about the nominal value, and profiles were recorded on downstream wire scanners. The data was simulated using the Parmilla code. For the two profiles shown, the simulated data agree very well with the experimental data, and reproduce the space-charge-induced beam tails seen in the measured data. However, not all profiles in this study exhibited the same level of agreement, though the qualitative trends were very similar; this work is still in progress.

Emittances

The benchmark quantity that has received the most attention in recent years is the rms emittance. Much of this is due to an experimental measurement of emittance exchange in a Montague resonance crossing experiment in the CERN PS. This data set is an outstanding example of an experiment which was performed with benchmarking explicitly in mind [17]. The effort has matured into a seven code, cross-code benchmark of the experiment. As shown in Table 1, three codes have completed the full benchmark with experimental data, and four more codes are in the process of this work. The cross-code benchmark is broken down into several steps, progressing from simplified to realistic simulations of the experiment. This step-by-step process helps to identify the relevant physical processes at hand in the experiment, and to highlight the differences in the space charge solvers being used. A more detailed explaination of this project is available in reference [27]. Shown in Figure 5 is the ORBIT result of the benchmark with experimental data. ORBIT reproduces the emittance exchange seen in the measured data, though there is some discrepancy in the resonance width. Similar results were found with the Micromap and IMPACT codes.

Coherent Tune

The coherent tune of the machine is probably the most direct indicator of the level of space charge in the beam, and is the quantity with the strongest link to theoretical models of space charge. Measurements of this parameter have been

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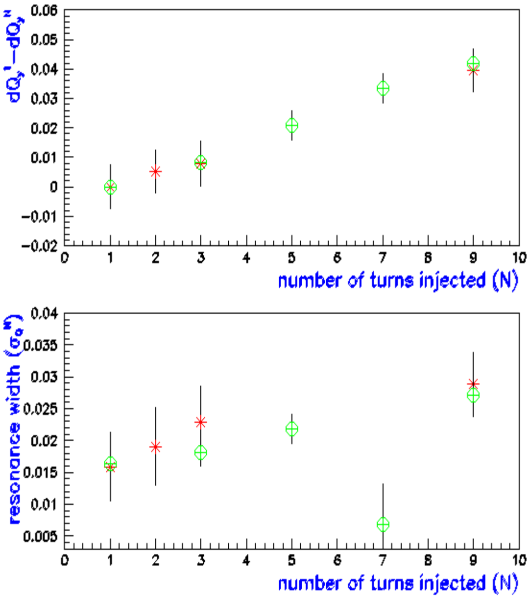

Figure 6: Synergia benchmark of the coherent tune and resonance width measurement in the Fermilab Booster.

made on only a few machines so far, and only one realistic benchmark with experimental data was found in the literature survey presented in Table 1. This benchmark is shown in Figure 6, where both the coherent tune of the beam and the resonance width were successfully measured in the Fermilab Booster and subsequently benchmarked with Synergia. As seen in the figure, the agreement between the simulation and the data is very good. The details of this experiment are available in reference [4].

FUTURE CHALLENGES

Remarkable achievements have been made in the area of space charge benchmarks with experiment in the last decade. In this short timespan, the field has progressed from having never before done this type of work, to routinely producing successful, quantitative space charge benchmarks for a variety of experimentally measurable quantities. There is currently a great deal of momentum in this type of work, with more and more codes joining the effort, and stronger collaborations between groups. The net result of this effort is a large suite of comprehensive, well-benchmarked codes which can be used in the design and optimization of existing and future machines.

A major challenge for these codes, which has not yet been addressed, is to benchmark beam loss in the accelerator. In terms of space charge effects, this task requires one to accurately and consistently reproduce the beam distributions to within fractions of a percent, a capability not yet demonstrated by any simulation code. Another challenge is to simulate beams during long ring storage times, on the orders of hundreds of thousands of turns. This requires completely symplectic tracking, which is computationally expensive. Currently, most simulations are performed for no more than a few thousand turns of a beam. Simulating long-storage experiments is mainly a technical limitation tied to the current available computer power and will resolve itself in the future as computer power increases and code infrastructures are adapted to make use of it.

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