COLLECTIVE EFFECTS AND INSTABILITIES IN SPACE CHARGE DOMINATED BEAMS*

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Abstract

This paper will illustrate the use of computer simulations to study collective beam dynamics in high intensity proton rings. More and more, computer codes are used to perform desktop experiments that provide the experimenter thorough control and visualization capabilities. In this role, the simulation code confirms and demonstrates the limits of theoretical and computational analysis, aids in the understanding of experimental results, and provides guidance on design and operational issues. Examples will be presented for several different collective phenomena and, where possible, comparisons to both theoretical and experimental results will be made. Examples will be taken from PSR and SNS.

INTRODUCTION

High intensity accelerators, characterized by strong collective and space charge effects, are essential components of many present and planned accelerator projects. The necessity of operating and controlling such machines in a robust manner without excessive losses has motivated much study of collective phenomena. An increasingly important component of research into collective beam dynamics is the computer simulation. Because of the ability to model a wide range of conditions, ranging from the highly idealized and simple scenarios of theoretical calculations to the complicated geometries and numerous physical effects found in experiments, computer simulation is increasingly being used to bridge theory and experiment. Simulation provides the additional advantages of a high level of control and availability of detailed and precise diagnostic information.

This paper will illustrate the use of simulation in the study of collective phenomena by drawing on a number of examples from high intensity proton rings. Specifically, we will consider a number of space charge driven resonances, an inductive longitudinal instability in PSR, the stabilization of a transverse instability at ~10 MHz in SNS, electron cloud studies for long bunch machines, and a self sustaining longitudinal bunched beam distribution in PSR.

COLLECTIVE PHENOMENA

We will now consider a variety of collective phenomena in which computer simulation has played an illuminating role.

Parametric Resonance for Mismatched Beams

The parametric resonance has been intensively studied as a candidate for halo generation (see [1-4] and references therein). Although the parametric resonance is present in all beams with space charge and has been studied computationally for high intensity rings [5], it is of most concern in proton and ion linear accelerators. The parametric resonance involves an interaction between the collective beam envelope oscillation and the individual particles. Thus, the details of the lattice structure are not involved. Because the particle tune distribution is sheared, there are surfaces in the single particle phase space on which the incoherent tunes are resonant with the collective envelope oscillation frequency. Several such surfaces may exist for strongly tune depressed beams, but the m=2 surface is always present. For matched beams, these resonant surfaces are thin and have no effect, but with mismatch an island structure with separatrix forms. Beam particles in the vicinity of the separatrix can be jostled across at the x-points and move to large amplitudes outside the island structure. Such particles form the beam halo.

Early studies of the parametric resonance [1,2] were carried out in 2D with uniform external focusing. Subsequent generalizations were made to 3D axismmetric bunches [3], to nonuniform phase space distributions [3], and to the incorporation of real external lattices [4,5]. The simulations carried out in these studies fall into two categories: 1) Particle core model calculations were done to track individual particles in the potential of the oscillating core in order to map the phase space topology. 2) Self consistent PIC simulations were done to examine the halo formation due to the mismatched beam distribution. Ambitious 3D calculations of the latter type for short bunches have been carried out by Ryne using in excess of 10^6 macroparticles as described in Ref. [3]. These calculations show significant halo formation in both longitudinal and transverse directions together with the result that significant mismatch in one plane enhances halo formation in the other.

Intrinsic Resonances of Anisotropic Beams

Another class of collective phenomena that is independent of the details of the accelerator lattice involves intrinsic resonances driven by multipolar perturbations in the space charge distribution in anisotropic beams having different emittances and/or focusing strengths in different planes. These resonances are sensitive to the beam emittances and intensity, but they depend on the lattice only through the average focusing strengths. A detailed theoretical description in terms of linearized Vlasov theory has been provided by Hofmann [6] and computational studies have been conducted by a number of groups both for linacs [6] and for rings [6-8]. The intrinsic coupling resonances are accompanied by emittance exchange and by halo formation in the direction receiving energy. Because of this, these resonances are a concern in linacs, but stability diagrams have been derived [6] that provide guidance in their avoidance. In rings, intrinsic coupling resonances can occur when the betatron tunes are nearly equal, $\nu_x \sim \nu_y$, if the average transverse energies differ. As with linacs, such resonances can be avoided and, unless the tune depressions are so large as to give beam turbulence, there are substantial regions of stability for anisotropic beams.

Envelope Integer Resonance

The envelope integer resonance is activated when the beam envelope tune approaches an integer value at which there is also some lattice perturbation. The envelope integer resonance is more commonly called a half integer resonance because the envelope tune is roughly double those of the individual particles. This resonance is, however, a collective phenomenon that was initially studied Sacherer [9] using an envelope equation analysis and elaborated by others [10-13]. Sacherer found that, as a tune is brought near a half integer value from above, the coherent oscillation frequency of the beam envelope approaches the integer that is double that value. If the lattice contains perturbations at this integer value, a standing envelope modulation develops at that periodicity. This modulation can be thought of as a space charge induced adjustment of the lattice functions.

One of the interesting features of the envelope integer resonance comes from the relationship between the incoherent particle tunes and the envelope coherent frequency: incoherent tunes can cross the half integer resonance, in apparent violation of the single particle resonance condition, before the resonance of the collective mode significantly affects the beam. The lack of resonant single particle activity is discussed in detail by Baartman [11].

A critical limitation of an envelope equation analysis is the inability to explain the emittance growth observed in association with the envelope integer resonance. The beam emittances occur as specified input parameters in the envelope equations. Computational PIC studies of beam broadening at high intensity in PSR [14-16] demonstrate excellent systematic agreement between calculated and experimentally observed beam profiles, and the calculations show that the broadening is accompanied by emittance growth. The behavior of the emittance growth associated with the integer envelope resonance has been studied by Cousineau [17] using both particle core and PIC models. She determined that with increasing intensity, coherent envelope oscillation frequencies decrease until the collective envelope motion encounters an integer stopband. The response of the beam to this stopband is to increase its emittance (broaden) in order to weaken space charge forces just enough to maintain the position at the edge of the stopband. This is shown in Fig. (1), where Fig. (1a) shows the vertical emittance evolution, as calculated using ORBIT, for three different beam intensities during injection. All other injection parameters are fixed, including the bare vertical tune, which equals 2.19. Figure (1b) shows the perturbed envelope oscillation tunes calculated using the envelope equations for the same emittances and intensities as in Fig. (1a). For the two lower intensity cases the emittance evolution is entirely due to the painting scheme and space charge plays no part. For these cases, the envelope tunes continue to decrease throughout injection as more beam is added. For the highest intensity case, there is significant profile broadening as space charge forces the emittance to grow well beyond the level dictated by the injection scheme. For this case, the envelope tunes are seen to drop quickly to a constant level and then remain there at the edge of a stopband as the beam broadening balances the space charge force due to the additional injected beam. This broadening involves the entire beam. It is not a halo forming process. The stopband is driven by lattice harmonics and can be corrected by removing those harmonics, in which case space charge has little effect in enhancing the emittance.

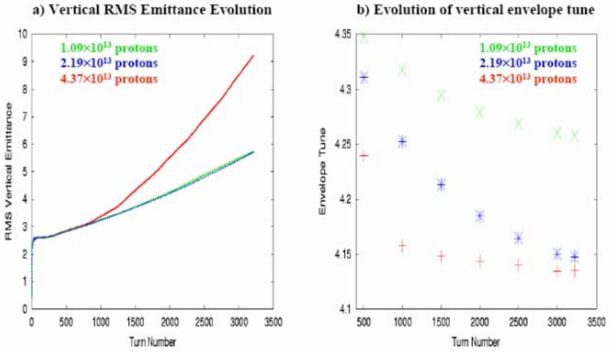

Figure 1. a) Calculated vertical emittance evolution for injection into PSR at three different intensities, and b) corresponding calculated vertical envelope oscillation tunes.

Resonance Correction with Space Charge

One topic of particular interest in high intensity rings is the correction of lattice imperfection resonances in the presence of significant space charge forces. The effect of space charge on linear coupling and gradient errors has been studied analytically using a linearized Vlasov approach by Aslaninejad and Hofmann [18], and the correction of a variety of errors through fourth order has been studied computationally for the SNS ring by Fedotov, Parzen, and coworkers [19]. In their work, it was found that resonances occur when collective, not individual particle, modes are excited by the lattice imperfections. PIC simulations show that these resonances lead to a significant enhancement of the beam tail, but that most of this undesirable beam growth can be removed through resonance correction. Fedotov and Parzen carried out the resonance correction by eliminating the appropriate islands observed in single particle tracking. Thus, they found that correcting the single particle resonance stopband was sufficient to significantly reduce the beam growth with space charge present.

Inductive Longitudinal Instability in PSR

The physics of collective instabilities due to wake fields has been intensively studied to the degree that there are now a number of excellent textbooks on the subject [20,21]. Longitudinal beam dynamics in high intensity rings has been addressed computationally by a number of researchers [22-24]. Although the physics model for tracking in longitudinal codes is a simple 2D phase space, these codes contain many sophisticated features for acceleration, transition crossing, and beam manipulation, as well as models for wake fields and space charge.

An excellent illustration of a longitudinal instability in which simulation and experiment are in agreement is provided by an inductively driven instability at 72 MHz (harmonic number 26) in PSR. The instability is caused by the impedance of an inductive insert, when the insert is not heated. Independent calculations were performed by Indiana graduate student C. Beltran as part of his PhD thesis [25] using ESME [23] and by S. Cousineau [26] using the ORBIT Code [27] with impedance taken from Beltran [25] and experimental data from R. Macek. The longitudinal current profiles at various stages in both the ESME and ORBIT simulations gave good agreement with the measured data. For the peak harmonic, the ESME simulations obtained n = 27 and the ORBIT result agreed with the experimental value of n = 26. The growth times for the instability were found to be 30 μs with ESME and 42 μs with ORBIT, compared with the measured growth time of 33 μs, so that reasonable agreement was again obtained. Finally, the threshold value determined using ORBIT was found to occur at about 65 nCoulombs compared to an experimental value of 80 nCoulombs. This level of agreement between experiment and simulation is adding to the credibility of computer modeling of collective beam dynamics.

Stabilization of Transverse Instability in SNS

As with longitudinal beam dynamics, the analytic study of transverse collective effects has received much attention [20,21]. Typical analytic approaches involve simplified macroparticle models or the more detailed linarized Vlasov equation techniques. An accurate description of instabilities for the SNS ring will require mode coupling analysis because increments and tuneshifts are much larger than the synchrotron tune. A coasting beam model would provide a reasonable starting point because of the long bunch length and small synchrotron tune, but bunch factor effects yield different space charge tuneshifts between the center and ends of the bunch. In computational studies, the incorporation of transverse wakefields into simulations was carried out by Blaskiewicz to study the head-tail instability with space charge [28]. More recently, Danilov developed a transverse impedance formulation which has been implemented in ORBIT and UAL [29]. Computer calculations with transverse impedances and space charge are very expensive because 3D space charge models are necessary to correctly describe the interaction between space charge and external impedance with longitudinally dependent beam centroids. Except for the 3D linac space charge calculations by Ryne and Qiang, the simulations described so far were all carried out using, at most, 2D space charge models.

Transverse impedance stability calculations with ORBIT and UAL have been used in the design of SNS. The dominant impedance in the SNS ring is that of the extraction kicker. With the original design, ORBIT predicted an instability threshold due to this impedance of about 1×10^{14} protons. At the full intensity of 2×10^{14} protons consistent with 2 MW operation, the growth time for the instability was about 200 turns with a broad spectrum peaking at about 8 MHz, resulting in significant halo by the end of beam accumulation. As a result of this prediction, the extraction kicker was redesigned to reduce the impedance and, as a result, the predicted threshold was doubled. Additional computational studies for the stabilization of this instability were carried out by Danilov with an active feedback approach using ORBIT and by Fedotov with octupoles to introduce tune spread using UAL. Both mechanisms were found to be effective in stabilizing this mode.

Electron Cloud Studies in Long Bunch Machines

Transverse instabilities driven by clouds of ambient electrons have been observed in several proton and positron rings. Much theoretical and computational work [30-33] has been done to analyze the observations for short bunches, which applies to most of these machines. However, PSR and SNS have long bunches and require independent analysis. Studies have been carried out for these machines using both coasting [34] and bunched [35-37] beam analysis. A variety of computer codes have been developed to simulate electron cloud instabilities. A complete simulation of the electron cloud physics must include 1) electron generation and cloud formation models such as residual gas ionization, emission from walls, or synchrotron radiation; 2) electron tracking in external, self, and beam fields; and 3) beam particle tracking in external, self, and electron fields. A full PIC code simulation for a real ring, such as PSR, will be computationally intensive, requiring dedicated massively parallel computing resources. Detailed phenomenological models of electron sources have been developed by Pivi and Furman [38]. Their secondary emission package includes models for elastic scattering, rediffusion, and true secondary emission as functions of incident electron energy and angle for a variety of surface materials. Although the dynamics of the electron cloud buildup have been examined computationally by several groups (for example [38-39]), most of these simulations fail to include the beam response to the electrons and are thus not fully self consistent. Recently, some groups have begun to include the beam response. Blaskiewicz [37] developed a simplified model for interacting proton and electron beams suitable for calculations on a single processor and Rumolo and coworkers [40] and the ORBIT group [41] have created fully interacting electron cloud – beam PIC models. The ORBIT group is just starting application of its code to PSR, but benchmarking with an analytic coasting beams model [42] with uniform charge distributions shows agreement of growth rates to within about 15% (see Fig. 2).

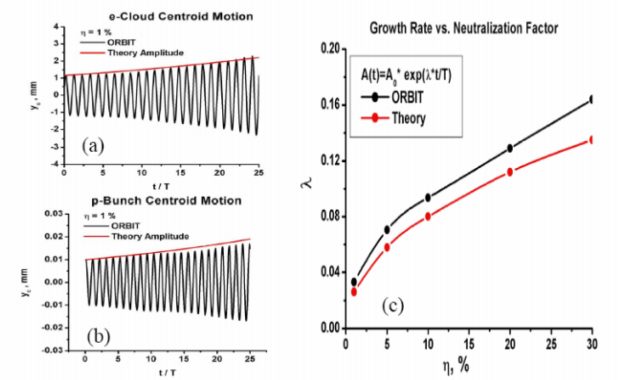

Figure 2. Benchmark of ORBIT electron cloud module with analytic case: a) electron centroid motion, b) proton centroid motion, and c) growth rates.

Self Sustaining Longitudinal Bunched Beam Distribution in PSR

Stationary longitudinal bumps and holes have been observed in a number of accelerators including the CERN PSB, SPS, and Tevatron. These solitons can not be predicted using linearized Vlasov analysis [43]. Recently, Koscielniak [44] has derived conditions for the existence of stationary holes maintained by space charge in a longitudinal Hamiltonian system; and Blaskiewicz [45] has demonstrated that a defocusing impedance can support humps in bunched beams. A clear illustration of a self sustaining bunched space charge distribution has been observed in PSR. Key to observing this phenomena are the facts that the linac injection frequency is a multiple (n = 72) of the ring frequency and that the ring RF focusing was turned off during the experiment. Protons bunches were injected with their natural energy spread from the linac at the same locations, turn after turn, for 559 turns. Individual bunches in the PSR ring will decohere due to energy spread and space charge forces in about 30 turns. Thus, one would expect any bunch structure at the linac frequency to disappear by 30 turns after injection (say 600 turns). Observations, however, show this structure not only to persist for more that 1000 turns following injection, but to actually strengthen during this time. The details of the behavior are intensity dependent, indicating collective phenomena are involved. The experiments were carefully simulated by Cousineau and coworkers [46], using ORBIT, and the computational results agreed with the experiment. They established that the observed phenomenon was a space charge effect by independently turning on and off the external impedance, which made no difference to the linac signature, and the space charge, without which decoherence occurred in less than 50 turns following injection. As the particles move longitudinally, they accelerate away from the density peaks due to space charge forces, moving quickly across the density holes. Again, due to space charge forces, they slow down as they approach the peaks, thus sustaining the structure. In one numerical experiment the structure persisted for 10000 turns, when the calculation was finally stopped. The group also derived an infinite number of exact bunched space charge supported steady state solutions of the Vlasov equation in longitudinal phase space (see Fig. 3).

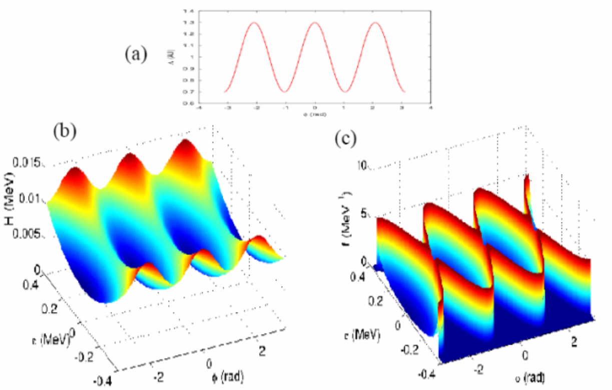

Figure 3. Example of steady state distribution: a) Longitudinal density profile, b) Hamiltonian function, and c) distribution function.

CONCLUSIONS

A number of collective phenomena in which space charge plays an important part have been discussed with an emphasis on the use of computer simulation. Drawing primarily from high intensity proton rings, it was shown how experimental and theoretical results are used to benchmark and give confidence to the simulations and how the simulations, in turn, are used to provide insight into the physics and guidance in issues involving design and operation.

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