SLAC-PUB-15105

STUDIES OF SPACE CHARGE EFFECTS IN THE PROPOSED CERN PS2*

J. Qiang#, R. D. Ryne, LBNL, Berkeley, CA94720, U.S.A.
U. Wienands, SLAC, Menlo Park, CA 94025, U.S.A.
A. Macridin, P. Spentzouris, FNAL, Batavia, IL 60510, U.S.A.
R. D. Maria, Y. Papaphilippou, CERN, Geneva, Switzerland

Abstract

A new proton synchrotron, the PS2, is under design study to replace the current proton synchrotron at CERN for the LHC upgrade. Nonlinear space charge effects could cause significant beam emittance growth and particle losses and limit the performance of the PS2. In this paper, we report on studies of the potential space-charge effects at the PS2 using three-dimensional self-consistent macroparticle tracking codes, IMPACT, MaryLie/IMPACT, and Synergia. We will present initial benchmark results among these codes. Effects of space-charge on the emittance growth, especially due to synchrotron coupling, aperture sizes, initial painted distribution, and RF ramping scheme will also be discussed.

INTRODUCTION

Space-charge effects have been identified as the most serious intensity limitation in the CERN PS and PS Booster [1], since nonlinear space-charge effects in high intensity hadron beams can cause significant emittance growth and particle losses. These effects put a strong limit to the attainable intensity for a proposed synchrotron accelerator, PS2 [2], which is expected to replace the existing 26 GeV PS machine with a 50 GeV final output energy machine for future accelerator complex upgrade at CERN. Exploring the space-charge effects through long-time self-consistent particle tracking will help shed light on the source of emittance growth and particle loss (e.g. space-charge driven resonance) and help provide means to overcome these effects through improved lattice design or compensation schemes.

COMPUTATIONAL MODELS

The following computer codes were used in this study:

IMPACT is a parallel particle-in-cell code that was originally developed to model the dynamics of multiple charged particle beams in linear accelerators [3]. The code includes the effects of externally applied fields from magnets and accelerating cavities as well as the effect of self-consistent space charge fields. It has been applied to a number of studies such as beam dynamics studies in the SNS linac, JPARC linac, RIA driver linac, CERN superconducting linac, and LEDA halo experiment. For the purpose of studying space-charge effects in a synchrotron ring, the IMPACT code was extended to include thin lens kicks for multipole elements and RF cavities, multi-turn simulation, RF ramping, etc.

MaryLie/IMPACT (ML/I) [4] is a hybrid code that combines the beam optics capabilities of MARYLIE with the parallel 3D space-charge capabilities of IMPACT. In addition to combining the capabilities of these codes, ML/I has a number of additional features including a fifth-order rf cavity model, a variety of magnet models, and wakefield effects. The code allows for map production, map analysis, particle tracking, and 3D envelope tracking, all within a single, coherent user environment.

Synergia [5] is a framework for simulation of linear and circular accelerators with a fully 3D treatment of space charge, and the capability to use arbitrary order maps for the single-particle optics modeling. The code itself is a hybrid system based on the IMPACT space-charge code and the *mxyzptlk*/*beamline* libraries [6], which includes a MAD parser. Synergia includes enhancements to these codes as well as new modules. Synergia has multi-turn injection capabilities and can follow multiple bunches longitudinally.

SIMULATION RESULTS

Using the above-mentioned computer codes, we carried out simulation studies of the proposed PS2 lattice. Our initial study was based on a 2009 lattice design [7]. We adopted the MAD lattice input file and checked the agreement of the single particle tracking without space-charge effects. Figures 1 and 2 shows the transverse beta function and coordinates from the above three codes. They all agree with each other even though the underlying tracking methods are quite different.

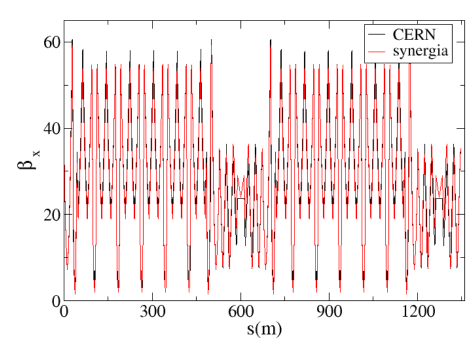

Figure 1: Horizontal beta function evolution in PS2 from MAD output and from the Synergia output.

*Work partially by the US Department of Energy through the US LHC Accelerator Research Program (LARP) under Contract No. DE-AC02-05CH11231
#jqiang@lbl.gov

Presented at the 1st International Particle Accelerator Conference (IPAC 2010)
Kyoto, Japan, May 23 - 28, 2010

Work supported by US Department of Energy contract DE-AC02-76SF00515.

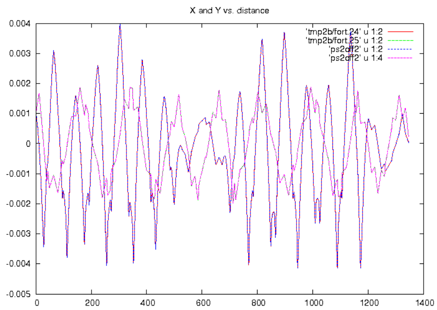

Figure 2: Tranverse single particle trajectories from the MaryLie/IMPACT code and from the IMPACT code.

Next, we studied 3D space-charge effects in the proposed lattice using the IMPACT code. Figures 3 and 4 show the transverse tune footprint without space-charge effects, and with space-charge effects but with/without longitudinal synchrotron motion. It is seen that the tune footprint is significantly enlarged due to the space-charge effects. The space-charge effects cause some particle tunes to cross the 5th and the 6th order resonances. Without including the synchrotron motion, the footprint shows a regular necktie shape distribution as expected. Including longitudinal synchrotron motion in the space-charge simulation shows three overlapping necktie tune footprints. This is due to the coupling between the longitudinal synchrotron motion and the transverse betatron motion from the three-dimensional space-charge effects. This coupling causes some particle tunes to cross over the lower 4th order resonance and result in larger emittance growth as shown in Figure 5.

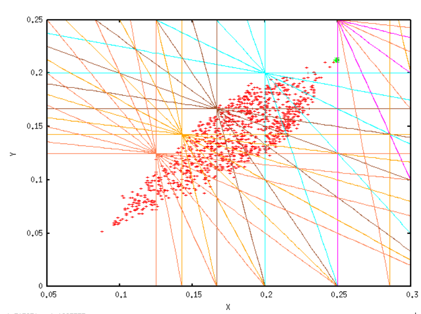

Figure 3: Transverse tune footprint without synchrotron motion.

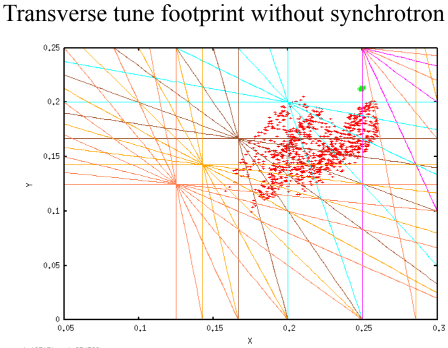

Figure 4: Transverse tune footprint including synchrotron motion.

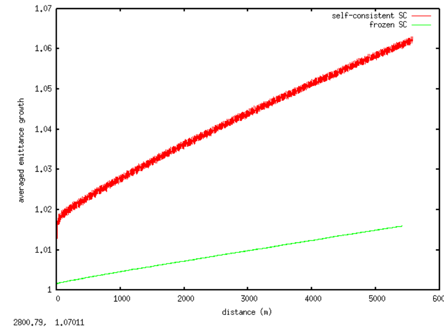

Figure 5: Transverse emittance growth with/without synchrotron motion.

In 2010, a new lattice design was proposed [8]. In this new lattice, the working point was moved from below half integer to above half integer. The chromaticity of the new lattice is set to zero. The beam is painted longitudinally for the first 150 turns. At the end of the painting, an RF program is used to ramp the voltage and the phase of the RF cavity to accelerate the beam. In the first study, the RF voltage is ramped following a parabolic time dependent function from 0.65 MV to 0.9 MV within 100 milli-seconds. This makes the beam kinetic energy reach 6 GeV at the end of ramping. The initial longitudinal density distribution at the end of painting has a trapezoidal shape. Using this initial longitudinal distribution and a transverse waterbag distribution, we carried out 3D space-charge simulation for 4×10^{11} proton beam in the new PS2 lattice. Figures 6 and 7 show the transverse emittance growth and the fractional particle loss as a function of turns. There are about 2-6% emittance growth and 0.24% particle losses after six thousand turns. A new painting scheme was used to

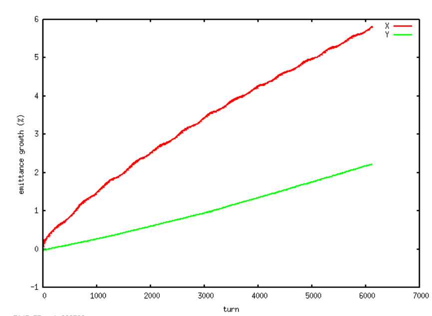

Figure 6: Transverse emittance growth vs. turns.

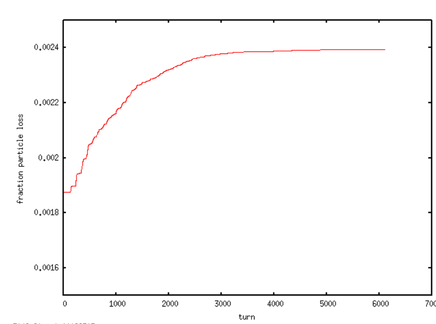

Figure 7: Fractional particle losses vs. turns.

generate an initial longitudinally waterbag like phase distribution with a parabolic transverse density profile. Using such an initial distribution, we carried out another space-charge simulation. The transverse emittance growth of the beam and the fractional particle loss are given in Figures 8 and 9. It is seen that such an initial distribution results in lower emittance growth than the previous initial longitudinal distribution. The horizontal emittance reaches 5% at the end of 21,000 turns and shows a tendency of saturation while the vertical emittance growth reaches 7% with no sign of saturation yet. However, both the transverse rms sizes and maximum amplitudes decrease due to the accelerating damping. The fractional particle losses in Figure 9 is about 10^{-6}, which is much less than the previous trapezoidal painted distribution.

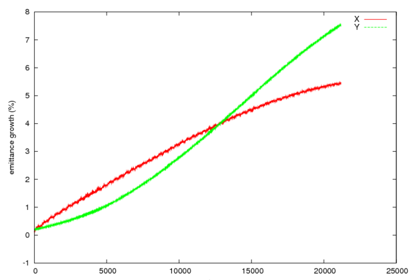

Figure 8: Transverse emittance growth vs. turns with initial parabolic density distribution.

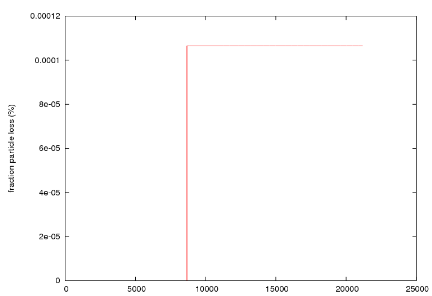

Figure 9: Fractional particle losses vs. turns with initial parabolic density distribution.

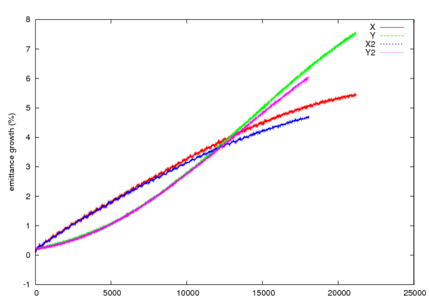

Figure 10: Transverse emittance growth vs. turns with nominal and two centimeter larger aperture size.

Aperture size of the beam pipe directly affects the particle loss and accelerator machine cost. A larger aperture size could result in less particle loss but also higher machine construction cost. In this study, we carried out space-charge simulations using half aperture sizes of 5.5 x 3.0 centimeters and 6.5 x 4.0 centimeters. Figure 10 shows transverse emittance growth as a function of turn for both aperture sizes. The larger aperture size does result in slightly smaller emittance growth due to the smaller effects of image charges in the conducting wall. However, this reduction of emittance growth with two centimeter larger aperture size is small. Meanwhile, the particle losses for both aperture sizes are the same. This suggests that 5.5 x 3.0 centimeter half aperture size might be sufficient. In the nominal design, the half aperture size is chosen as 6.3 x 3.25 centimeters.

Different RF ramping schemes could lead to changes in particle loss and emittance growth. A faster ramping will help reduce space-charge effects but make longitudinal RF capture worse. Figures 11 and 12 show the transverse emittance growth and the particle loss from previous 100 ms ramping and the new 50 ms ramping. It is seen that by ramping the RF voltage faster, more particles get lost. The emittance growth becomes also somewhat larger.

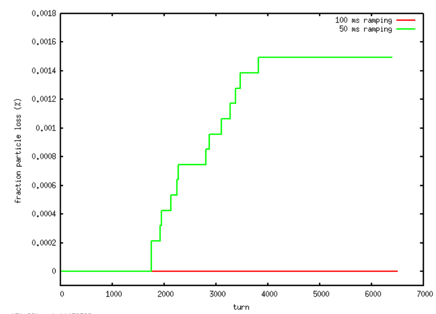

Figure 11: Fractional particle losses vs. turns with 100 ms and 50 ms RF ramping.

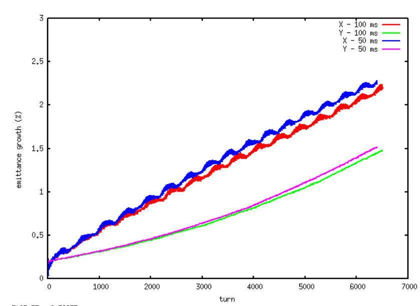

Figure 12: Transverse emittance growth vs. turns with 100 ms and 50 ms RF ramping.

REFERENCES

[1] M. Aiba, et al, in proceedings of PAC07, 3390, 2007.
[2] https://twiki.cern.ch/twiki/bin/view/Main/PS2Collaration.
[3] J. Qiang, R. Ryne, S. Habib, and V. Decyk, J. Comp. Phys. 163, 434 (2000).
[4] R. D. Ryne, et al., in proceedings of ICAP06, 157, 2006.
[5] P. Spentzouris, J. Amundson, D. D. Dechow, in proceedings of PAC05, 3490, 2005.
[6] L. Michelotti, FERMILAB-CONF-91-159..
[7] Y. Papaphilippou et al., to appear in proceedings of PAC09, Vancouver, Canada, 2009.
[8] H. Bartosik et al., “Linear optimization and tenability of the PS2 lattice,” this conference.