SIMULATION OF SPACE-CHARGE EFFECTS IN THE PROPOSED CERN PS2*

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Abstract

A new proton synchrotron, the PS2, was proposed to replace the current proton synchrotron at CERN for the LHC injector 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 simulation studies of the potential space-charge effects at the PS2 using three-dimensional self-consistent macro-particle tracking. We will present the computational model used in this study, and discuss the impact of space-charge effects on the beam emittance growth, especially due to synchro-betatron coupling, initial longitudinally painted distribution, and RF ramping schemes.

INTRODUCTION

The PS2 with higher injection energy (4 GeV) was proposed to replace the current protron sychrotron with 1.4 GeV injection energy for LHC upgrade at CERN [1]. Space-charge effects have been identified as the most serious intensity limitation in the PS and PS Booster [2], 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 the proposed synchrotron accelerator. Exploring the space-charge effects through long-time self-consistent particle tracking will help shed light on the source of emittance growth and particle losses (e.g. space-charge driven resonance) and help provide means to overcome these effects through improved accelerator design or compensation schemes.

COMPUTATIONAL MODELS

In this study, we have used the IMPACT code and the MaryLie/IMPACT (ML/I) code developed at Lawrence Berkeley National Laboratory for simulation studies. The IMPACT code is a parallel particle-in-cell code suite for modeling high intensity, high brightness beams in RF proton linacs, electron linacs and photoinjectors [3]. It consists of two parallel particle-in-cell tracking codes IMPACT-Z and IMPACT-T (the former uses longitudinal position as the independent variable and allows for efficient particle advance over large distances as in an RF linac, the latter uses time as the independent variable and is needed to accurately model systems with strong space charge as in photoinjectors), an RF linac lattice design code, an envelope matching and analysis code, and a number of pre- and post-processing codes. Both parallel particle tracking codes assume a quasi-electrostatic model of the beam (i.e. electrostatic self-fields in the beam frame, possibly with energy binning) and compute space-charge effects self-consistently at each time step together with the external acceleration and focusing fields. The 3D Poisson equation is solved in the beam frame at each step of the calculation. The resulting electrostatic fields are Lorentz transformed back to the laboratory frame to obtain the electric and magnetic self-forces acting on the beam. There are six Poisson solvers in the IMPACT suite, corresponding to transverse open or closed boundary conditions with round or rectangular shape, and longitudinal open or periodic boundary conditions. These solvers use either a spectral method for closed transverse boundary conditions [4], or a convolution-based Green function method for open transverse boundary conditions [5]. The parallel implementation includes both a 2D domain decomposition approach for the 3D computational domain and a particle-field decomposition approach to provide the optimal parallel performance for different applications on modern supercomputers. Besides the fully 3D space-charge capability, the IMPACT code suite also includes detailed modeling of beam dynamics in RF cavities (via field maps or z-dependent transfer maps including RF focusing/defocusing), various magnetic focusing elements (solenoid, dipole, quadrupole, etc), allowance of arbitrary overlap of external fields (3D and 2D), structure and CSR wake fields, tracking multiple charge states, tracking multiple bin/bunches, Monte-Carlo simulation of gas ionization, an analytical model for laser-electron interactions inside an undulator, and capabilities for machine error studies and correction. 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, dynamic RF ramping, and lumped space-charge kicks.

The MaryLie/IMPACT (ML/I) [6] 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 powerful features, including a choice of Poisson solvers, a fifth-order RF cavity model, multiple reference particles for RF cavities, a library of soft-edge magnet models, representation of magnet systems in terms of coil stacks with possibly overlapping fields, and wakefield

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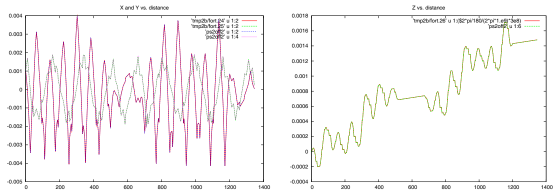

Figure 1: Single particle trajectories from the MaryLie/IMPACT code and from the IMPACT code.

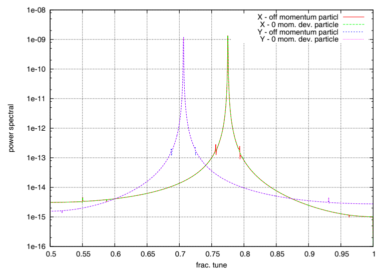

Figure 2: Power spectra of the single particle trajectory of 0 momentum deviation particle and off-momentum particle.

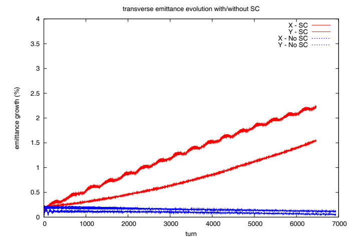

Figure 3: Transverse emittance evolution with and without including space-charge effects.

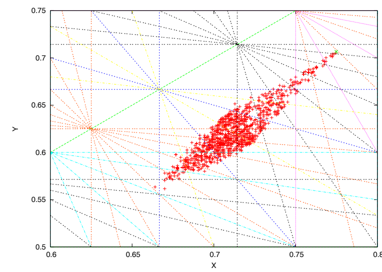

Figure 4: Tune footprint without sychrotron motion.

effects. The code allows for map production, map analysis, particle tracking, and 3D envelope tracking, all within a single, coherent user environment. ML/I has a front end that can read both MARYLIE input and MAD lattice descriptions. The code can model beams with or without acceleration, and with or without space charge. The code inherits the powerful fitting and optimizing capabilities of MARYLIE augmented for the new features of ML/I. The combination of soft-edge magnet models, high-order capability, space charge effects, and fitting/optimization capabilities, make ML/I a powerful code for a wide range of beam optics design problems.

SINGLE PARTICLE BEAM DYNAMICS TEST

Using the above-mentioned computer codes, we carried out simulation studies of the proposed PS2 lattice. Our initial study was to test the single particle beam dynamics using 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 between the IMPACT code and the MaryLie/Impact code. Figure 1 shows the transverse and longitudinal coordinates from the two codes. Both codes agree with each other very well even though the underlying tracking methods are quite different. To check the single particle tracking results against the MAD-X output, we also calculate the power spectrum of the single particle trajectory of a zero momentum deviation particle and an off-momentum particle using a 2010 new lattice design [8]. The results are shown in Fig. 2. Both particles give the same tunes within the numerical accuracy. This also results in the zero first-order chromaticity that is obtained from the MAD-X output.

SPACE-CHARGE SIMULATION RESULTS

We studied 3D space-charge effects in the proposed 2010 lattice using the IMPACT code. Figure 3 shows the transverse emittance growth from the simulation with and without including space-charge effects. It is seen that the space-charge effects drive significant emittance growth of the beam. Such a growth of emittancce is caused by the nonlinear fields of the space-charge forces. The space-charge forces also result in the synchro-betatron coupling of the beam. Figure 4 and 5 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 particle tunes to cross the 4th, the 5th, and the 7th 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 enlarge of 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 more particle tunes to cross over the lower 4th order and 6th order resonance and results in larger emittance growth as shown in Fig.6.

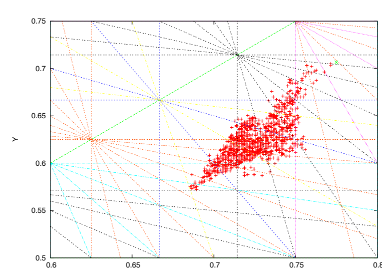

Figure 5: Tune footprint with sychrotron motion.

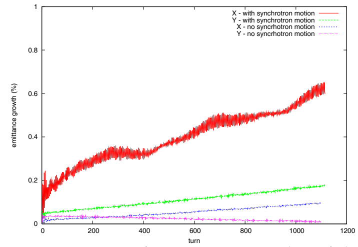

Figure 6: Transverse emittance growth with and without sychrotron motion.

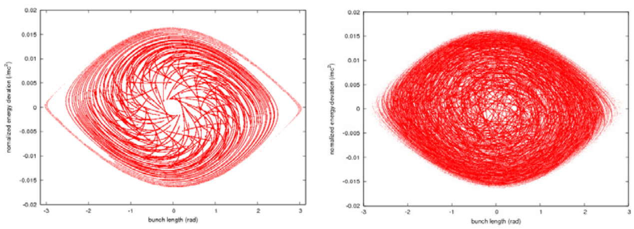

Figure 7: Initial longitudinal phase distribution in case 1 and in nominal case.

Effects of Initial Painted Distributions

The initial longitudinal distribution at the end of painting has impact to the beam emittance growth and particle losses during the rest of acceleration. Figure 7 shows the initial longtudinal phase space distribution from longitudinal painting case 1 and from the nominal painting. The case 1 initial distribution has a wider phase distribution and a hallow shape of current distribution. The nominal case has a narrower phase distribution and a closer to parabolic shape of current distribution. Using those initial longitudinal distributions and assumed transverse waterbag distribution, we carried out 3D space-charge simulation for 4×10^{11} proton beam in the new 2010 PS2 design lattice. Figure 8 shows the fractional particle loss as a function of number of turns using the initial longitudinal particle distribution from the case 1 and from the nominal case. There is about 0.24% particle loss after six thousand turns from the case 1 initial distribution while there is only one macroparticle loss out of about one million particles from the nominal case initial distribution.

Recently, a new painted longitudinal initial distribution (case 3) was proposed with trapezoid and smaller initial phase amplitude than the nominal case. The longitudinal phase space distribution is given in Fig. 9. Using above initial longitudinal distribution, we carried out space-charge simulation in the nominal PS2 2010 lattice. Figure 10 shows the fractional particle loss evolution using the new case 3 initial distribution and the nominal case initial distribution. It is seen that new initial painted longitudinal distribution actually has a much larger particle loss than the nominal case. Figure 11 shows the maximum longitudinal phase amplitude evolution in both cases. Even though the new initial longitudinal distribution starts with a smaller initial maximum phase amplitude, it grows quickly beyond the boundary of RF bucket. This might be due to the stronger space-charge effect associated with this initial distribution since it has smaller bunch length than the nominal case.

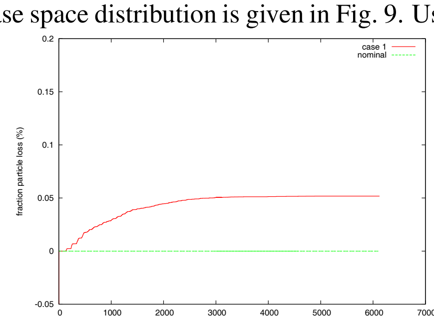

Figure 8: Fractional particle loss evolution in the case 1 and the nominal case.

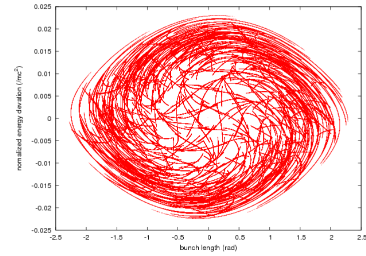

Figure 9: Initial longitudinal phase distribution in case 3.

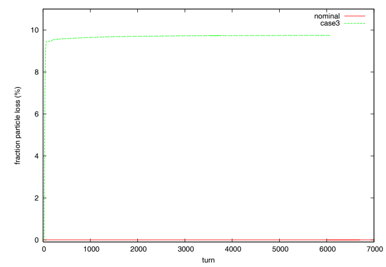

Figure 10: Fractional particle loss evolution in the case 3 and the nominal case.

Effects of RF Ramping Schemes

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. 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.

Figure 12 shows the two voltage ramping schemes: In the first case, the RF voltage is ramped following a

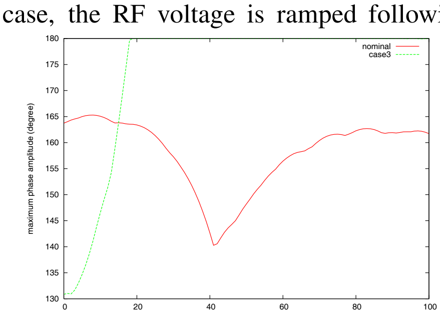

Figure 11: Maximum longitudinal phase amplitude in the case 3 and the nominal case.

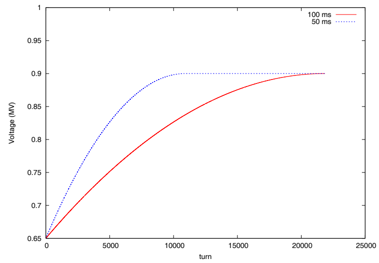

Figure 12: RF voltage evolution with 100 ms and 50 ms ramping schemes.

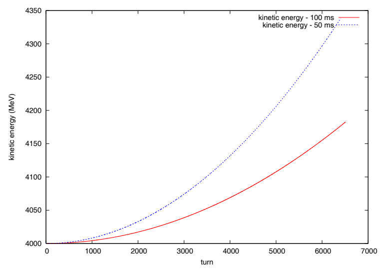

Figure 13: Beam kinetic energy evolution with 100 ms and 50 ms ramping schemes.

parabolic time dependent function from 0.65 MV to 0.9 MV within 100 milli-seconds; In the second case, this ramping is done within 50 milli-seconds. Figure 13 shows the beam kinetic energy growth from the two schemes. The faster voltage ramping leads to a faster beam kinetic energy increase. Figure 14 show the fractional particle loss from the 100 ms ramping and the 50 ms ramping scheme. It is seen that by ramping the RF voltage faster, more particles get lost. Figure 15 shows the maximum longitudinal phase amplitude evolution from the two ramping schemes. The faster ramping scheme results in larger oscillation of maximum amplitude and particle losses. Figure 16 shows the emittance evolution of the beam from the two ramping schemes. The faster ramping scheme also leads to larger emittance growth due to the stronger space-charge effects. The stronger space-charge effects results from the faster acceleration damping of longitudinal phase amplitude (i.e. rms bunch length) from the faster voltage ramping.

A new RF ramping scheme is tested recently. Figures 17 and 18 show the ramping voltage evolution and the beam kinetic energy evolution from the new scheme and the nominal scheme. The new scheme has a slower voltage ramping than the nominal case but a faster phase ramping than the nominal case to keep the kinetic energy increase to be the same. Figure 19 shows emittance evolution from the new and the nominal ramping scheme. It is seen that emittance growth starts to saturate after 30000 turns. In the nominal ramping case, there is about 10% emittance growth after 40000 turns. Using the new RF ramping scheme, such a grown is only about 8%. The new ramping scheme leads to less emittance growth in both horizontal and vertical plans after 40000 turns. The larger vertical emittance growth in both cases could be due to the smaller vertical aperture size in the design, which results in stronger space-charge effects. Figure 20 shows the longitudinal rms phase evolution from both ramping schemes. The new scheme leads to a slower phase amplitude damping and hence weaker space-charge effects. The stronger space-charge effects in the nominal ramping attributes to more transverse emittance growth.

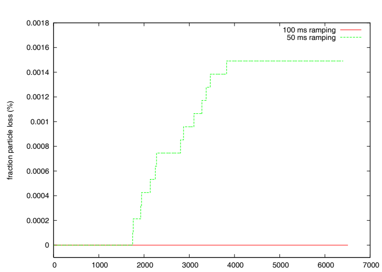

Figure 14: Particle loss evolution with 100 ms and 50 ms ramping schemes.

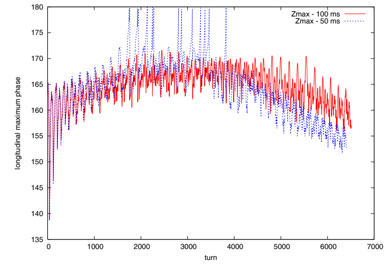

Figure 15: Maximum longitudinal phase amplitude with 100 ms and 50 ms ramping schemes.

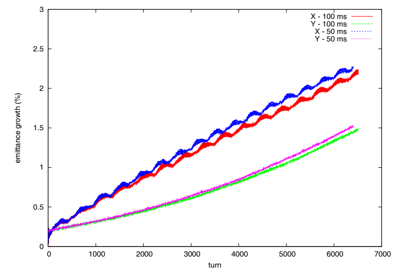

Figure 16: Transverse emittance growth with 100 ms and 50 ms ramping schemes.

Effects of Initial Emittances

The emittance growth of the beam also depends on the initial emittance at the injection due to space-charge effects. Figure 21 shows transverse normalized emittance evolution with 2, 2.5 and 3 mm-mrad initial normalized emittances. Using a smaller injection emittance results in

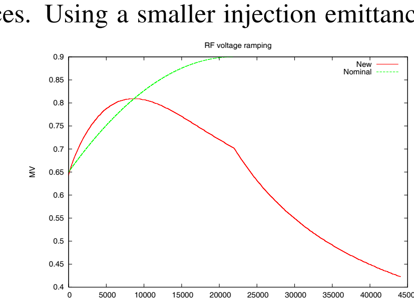

Figure 17: RF voltage evolution with the nominal 100 ms ramping scheme and the new ramping scheme.

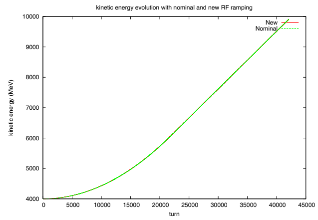

Figure 18: Beam energy evolution with the nominal 100 ms ramping scheme and the new ramping scheme.

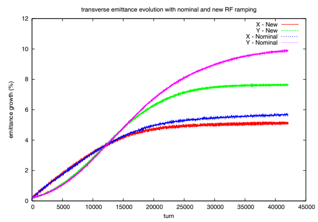

Figure 19: Transverse emittance evolution with the nominal 100 ms ramping scheme and the new ramping scheme.

larger relative emittance growth in the accelerator due to stronger space-charge effects. However, given the larger growth of the emittance, the final emittance with smaller initial emittance down to 2 mm-mrad is still better than the final emittance with larger initial emittance.

Effects of Bunch Intensities

The nominal design of PS2 assumes an intensity of 4×10^{11} proton per bunch. From previous simulations, we can see that final emittance can be kept below 3 mm-mrad if the beam is injected with an initial emittance below 3 mm-mrad using the nominal bunch intensity. In order to check the maximum bunch intensity that can be achieved while keeping the final beam emittance below 3 mm-mrad, we carried out simulations using 1.25, 1.5, and 2 times the nominal intensity. Figure 22 shows the emittance evolution of the beam using those bunch intensities. It is seen that the transverse emittance increases a lot and reaches beyond 3 mm-mrad even with 25% increase of bunch intensity. This suggests that the nominal bunch intensity 4×10^{11} might be close to the maximum limit of intensity for the given lattice design.

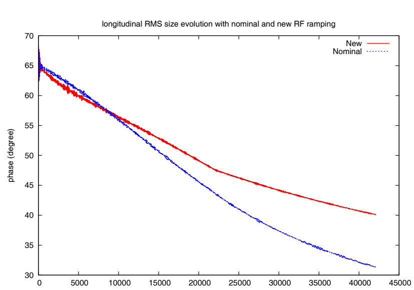

Figure 20: Longitudinal rms phase evolution with the nominal 100 ms ramping scheme and the new ramping scheme.

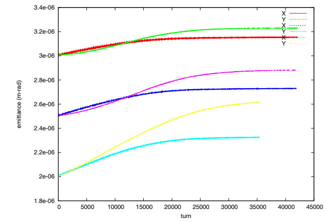

Figure 21: Transverse emittance evolution with the different initial emittances.

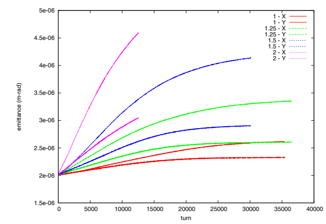

Figure 22: Transverse emittance evolution with the nominal bunch intensity, 1.25 times, 1.5 times, and 2 times the nominal intensity.

SUMMARY

In this paper, we have shown that space-charge effects can cause significant beam emittance growth and particle losses at PS2. These effects are worsen with the presence of sychro-betatron coupling. Using a better painted longitudinal phase space distribution and optimizing the RF ramping scheme for acceleration help mitigate the adversary space-charge effects and lower the beam emittance growth and particle losses. This results in potential final beam emittance below 3 mm-mrad as required by the design goal of PS2 with 4×10^{11} protons per bunch.

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