

# ORBIT BENCHMARK OF SPACE-CHARGE-INDUCED EMITTANCE GROWTH IN THE CERN PS \*

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## Abstract

Particle tracking codes provide an invaluable tool in the design and operation of high intensity machines. An important task in the development of these codes is the validation of the space charge models through benchmark with experimental data. Presented here are benchmarks of the ORBIT particle tracking code with recent measurements of space-charge-induced transverse emittance growth in the CERN PS machine. Benchmarks of two experimental data sets are performed: A benchmark of transverse emittance growth during an integer resonance crossing, and a benchmark of transverse emittance growth during a Montague resonance crossing.

## INTRODUCTION

One of the challenges in building the next generation of high intensity accelerators is understanding and controlling collective effects that lead to beam loss and residual radiation. Simulation codes are an invaluable tool in this effort, and can be used for realistic modeling of beams under the influence of a multitude of collective effects. Because these codes are assuming an increasingly central role in machine design and optimization, it is becoming more and more important to validate the simulation results with data from existing machines.

The work presented here is part of an ongoing effort to benchmark the ORBIT particle tracking code with experimental data. ORBIT is a particle-in-cell code developed for realistic modeling of beams in rings and transport lines [1, 2]. The code is designed to model collective effects associated with high intensity beams, and is parallelized to provide high computing efficiency. ORBIT has previously been benchmarked with both transverse and longitudinal profile measurements for a number of different scenarios [3, 4, 5]. Though these benchmarks were successful, profile data provides a limited characterization of the beam state. A more general and inclusive parameter is the transverse beam emittance, which is sensitive to collective effects. In this paper we present the first results of a benchmark of ORBIT with CERN Proton Synchrotron (CERN PS) emittance data. Two independent sets of emittance measurements are under study: One taken during an integer resonance crossing [6], and one taken during a Montague reso-

nance crossing [7]. The experiments and the initial simulation results are described in the following sections.

## HALF-INTEGER RESONANCE CROSSING

In this experiment, a 180 ns, 1.4 GeV proton beam was single-turn injected from the CERN Booster into the 628 meter CERN PS ring. The beam intensity was  $1.7 \times 10^{12}$  protons and the initial lattice tunes were set to ( $Q_x = 6.16, Q_y = 6.24$ ). After 15 ms of storage, the RF was ramped from 25 kV to 200 kV over a 15 ms period, and the lattice tune was changed to ( $Q_x = 6.14, Q_y = 6.21$ ). The beam was stored for  $\sim 1000$  ms in this state, after which the RF and tunes were restored to their initial settings. Emittance measurements were made at several stages of the experiment: at the beginning of the storage, 100 ms after the RF ramp-up, 300 ms after the RF ramp-up (horizontal only), 500 ms after the RF ramp-up, and 100 ms after the RF ramp-down. The total storage time was  $\sim 1130$  ms, or about 500,000 turns. The measured emittance data is shown in Figure 1. A more complete description of the experiments can be found in reference [6].

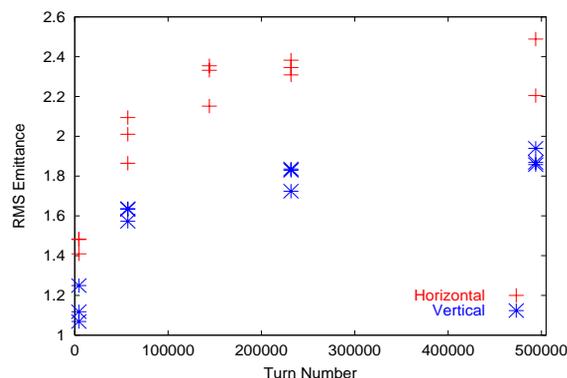


Figure 1: The measured rms emittance (un-normalized) in the horizontal (red +’s) and vertical (blue \*’s) planes. The RF ramp-up and tune change occurred at 6555 turns, and the RF ramp-down and restoration of original tunes occurred at 456,000 turns.

The ORBIT code was used with the experimental parameters listed above to simulate the beam storage. The CERN PS MAD file was used to create the machine lattice, and symplectic tracking was adopted to avoid artificial emittance growth caused by numerical truncation errors. A longitudinally parabolic beam distribution with energy spread

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$\Delta p/p_{(2\sigma)} = 2.15 \times 10^{-3}$  was injected over one turn to simulate the injection from the PS Booster, and the transverse distribution was taken as a Gaussian with emittance matched to the first measured point in the data set. A sequence of beam storage, RF ramps, and tune changes was prescribed to match the experimental setup. A longitudinal impedance of 20.0 Ohms was assumed [8], and 2.5D transverse space charge along with separate longitudinal space charge was applied.

Because the space charge algorithms and symplectic tracking are computationally expensive, thus far only the first 110,000 turns of the experiment have been simulated. At this point, only the second set of emittance measurements, taken 100 ms (47,000 turns) after the RF ramp-up, can be compared with the simulation (the first set was used to match the initial beam in the simulation). Figure 2 shows the simulated rms beam emittance for the vertical and horizontal directions. Comparing with the experiment at the available data point, the simulated emittance in the horizontal direction is in good agreement with the experiment, and the simulated emittance in the vertical direction is about 10% high. However, the growth rate of the emittance in the simulation is noticeably larger than that of the experiment. More computation time is needed to determine if this rate will reduce with storage time, or if the simulation will over-estimate the amount of emittance growth in the experiment.

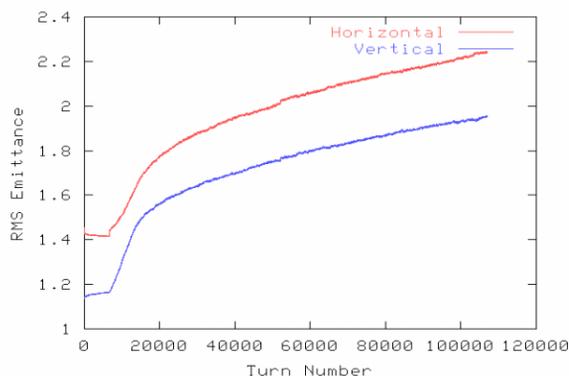


Figure 2: The simulated rms horizontal (red curve) and vertical (blue curve) emittances.

Though only one experimental point is available for benchmark at this stage of the simulation, it is nonetheless interesting to investigate the beam evolution simulated thus far. The longitudinal profile of the beam before the RF-ramp up is shown in Figure 3, along with the profile of the beam after the ramp-up. Note that the beam is much more bunched after the ramp, resulting in higher space charge forces. The increase in space charge is also visible in the tune footprint of the beam, shown at the beginning of the RF ramp-up, at the middle of the ramp-up, and at the end of the ramp-up, in Figures 4(a) - 4(c), respectively. Before the RF ramp-up and tune change, the beam is above the integer resonance in the vertical direction, and just be-

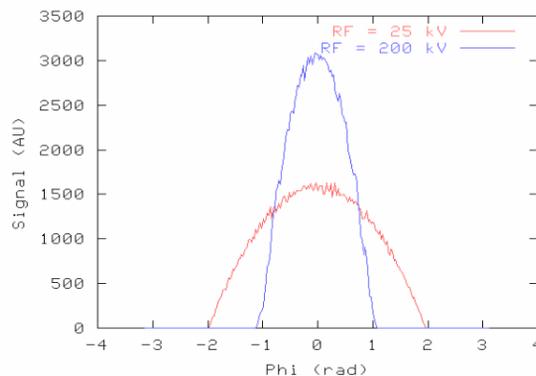


Figure 3: The initial simulated longitudinal beam profile before the RF ramp-up (red curve), and the simulated longitudinal beam profile at the end of the RF ramp-up (blue curve).

low the integer in the horizontal direction; no emittance growth is present at this stage. After the RF ramp-up, the beam is 0.025 below the integer in the horizontal direction, and 0.05 below the integer in the vertical direction. The crossing of the integer resonance results in space-charge-induced emittance growth, as shown in Figure 2, with the steepest growth rate occurring during the RF ramp-up. Figure 4(d) shows the tune footprint of the beam after 110,000 turns of storage (90,000 turns after completion of the RF ramp-up). Note that the tunes are mostly above the integer at this stage, though the shape of the footprint is different than before the RF ramp-up, due mainly to the increase in energy spread. Even with tunes above the integer, the emittance continues to increase. Slow growth during the high RF storage period is also observed in the experiment data shown in Figure 2. The growth may be due to a coherent response of the beam to the integer stopband, which has previously been noted to cause emittance growth [5]. This possibility is currently under investigation.

Though many more turns of storage are needed before the next change in experimental parameters, it is likely that the beam will reach an equilibrium state before this time, and it will be possible to eliminate the remaining turns of high-RF storage and proceed directly to the RF ramp-down and tune change. However, if the beam state does not reach equilibrium, it will be necessary to simulate the entire storage, which would amount to unreasonably long computation times.

## MONTAGUE RESONANCE CROSSING

In this 2002 experimental data set, the emittance of a  $1 \times 10^{12}$  proton, 1.4 GeV beam was measured as a function of the lattice tunes. The lattice tunes were adjusted to pass the beam through a Montague difference resonance, where significant emittance exchange between the two transverse planes can be observed. For each point in the data set, the lattice tunes were set and the beam was single-turn injected

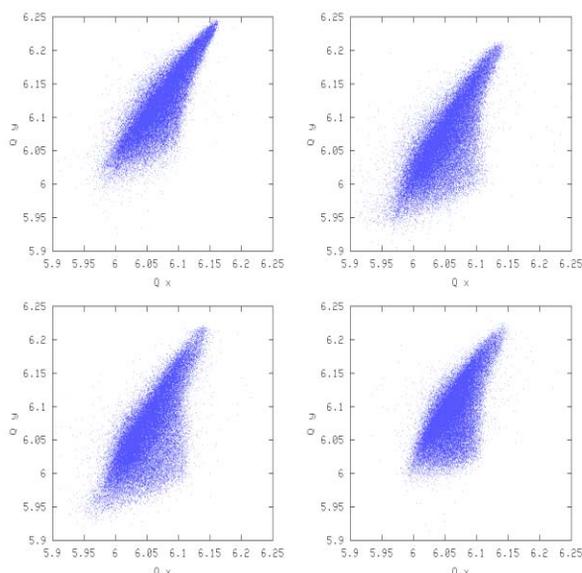


Figure 4: a) The tune footprint before the RF ramp-up and tune change. b) The tune footprint at the middle of the RF ramp-up. c) The tune footprint at the end of the RF ramp-up. d) The tune footprint 90,000 turns after the end of the RF ramp-up.

into the CERN PS and stored for 10 ms (4370 turns), after which the emittance was measured. The vertical lattice tune was fixed at  $Q_y = 6.21$ , while the horizontal tune was varied from  $Q_x = 6.25$  to  $Q_x = 6.15$  in steps of  $\Delta Q_x = 0.01$ ; each set of tunes corresponded to a separate injection, storage, and emittance measurement. The beam was rematched to the new lattice in each case.

For our simulations, we assume that the initial emittance of the beam for each point corresponds to the initial experimental emittance at the point  $Q_x = 6.15$ , where there is no experimentally-measured emittance exchange due to the resonance. As in the experiment, the beam in the simulation is rematched to the lattice for each different working point; this eliminates emittance growth due to mismatch with the lattice. Again, separate 2.5D transverse space charge and longitudinal space charge were used, along with symplectic tracking.

Thus far, 5 of the experimental data points have been simulated. The simulated points correspond to  $Q_x = 6.15, 6.16, 6.17, 6.19$  and  $6.21$ . The results are shown along with the experimental measurements in Figure 5. In the experimental data, there is no emittance exchange for the data points  $Q_x = 6.15 - 6.17$ . The initial emittance in the simulations was matched to the first of these points,  $Q_x = 6.15$ . After  $\sim 4000$  turns of storage, we see that the simulation predicts a small amount of emittance exchange in the points  $Q_x = 6.15, 6.16$ . Sizable emittance exchange begins to occur in the simulation around  $Q_x = 6.17$ . Defining the resonance stopband half-width as distance between the beginning of a nonzero slope in the data, and the point of maximum exchange, we can conclude

that the simulated resonance half-width is  $\Delta Q_x = 0.05$ . For the experimental data, by the same definition the half-width of the resonance in the region  $Q_x = 6.15$  through  $Q_x = 6.21$  is  $\Delta Q_x = 0.03$ , and the half-width in the region  $Q_x = 6.21$  through  $Q_x = 6.25$  is somewhat larger,  $\Delta Q_x = 0.04$ . Therefore, we observe that the simulation somewhat over-predicts the amount of coupling between the two directions. However, the simulation results are in close enough agreement to merit their use in studying the underlying physics of the Montague resonance. This work is ongoing.

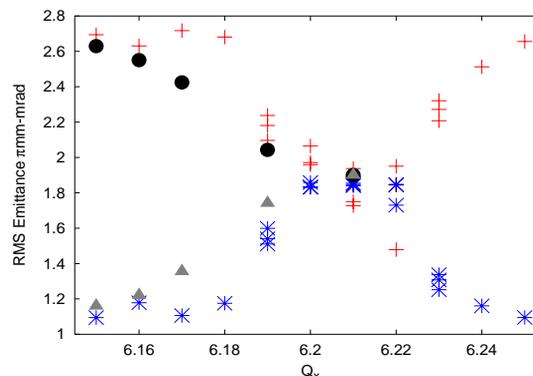


Figure 5: The simulated rms horizontal (solid black circles) and vertical (solid gray triangles) emittances, along with the horizontal (red crosses) and vertical (blue stars) experimental data.

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