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SIMULATIONS OF SPACE CHARGE IN THE FERMILAB MAIN INJECTOR

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Abstract

The Fermilab Project X plan for future high intensity operation relies on the Main Injector as the engine for delivering protons in the 60–120 GeV energy range. Project X plans call for increasing the number of protons per Main Injector bunch from the current value of 1.0×10^{11} to 3.0×10^{11}. Space charge effects at the injection energy of 8 GeV have the potential to seriously disrupt operations. We report on ongoing simulation efforts with Synergia, MARYLIE/Impact, and IMPACT, which provide comprehensive capabilities for parallel, multi-physics modeling of beam dynamics in the Main Injector including 3D space-charge effects.

INTRODUCTION

Project X is a high intensity proton facility[1] being developed to support a world-leading program in neutrino and flavor physics over the next two decades at Fermilab. The facility will have the capability to deliver protons at varying energies for the use of the different physics programs. The Main Injector is the highest energy portion of the Project X facility, accelerating protons to energies of 60–120 GeV. In the short term, these protons will be used for the high intensity neutrino program. Longer term uses could include a neutrino factory and a muon collider.

In order to supply sufficient protons to the envisioned physics programs, the charge in each Main Injector bunch will be increased from its current value of 1.0×10^{11} protons to 3.0×10^{11} protons. Space charge effects could become problematic at these higher intensities and may negatively interact with magnet fringe fields and aperture restrictions to cause unacceptably large losses. We have embarked on a program to simulate the transport of high intensity bunches in a realistic Main Injector lattice, eventually including as many of these effects as is computationally feasible in order to understand if losses will become a problem and if so, evaluate possible mitigation strategies.

SIMULATION CODES

For these simulations we use the codes Synergia, MaryLie/IMPACT (ML/I), and IMPACT. The codes share some common methods and components, such as the split-operator approach for combining space-charge effects and other physical phenomena[6, 7, 8], and a nonlinear rf cavity model[11], but have independentally developed implementations. Obtaining equivalent results from calculations of the same process with multiple codes gives us confidence in the results.

Synergia[2, 3] is a parallel framework for building and running simulations of particle dynamics within accelerators. The CHEF[4, 5] library is used in the Synergia framework for modeling the trajectories of particles through optical elements that can be described by Hamiltonian dynamics. IMPACT[8] is a space-charge simulation code for which significant effort has gone into parallelization strategies, scalability, and design optimization for efficient calculations. MaryLie/IMPACT (ML/I) is a parallel code that combines the high-order optics capabilities of MaryLie[10] with a subset of the space-charge capabilities of IMPACT. Synergia, ML/I, and IMPACT all use the parallel PIC approach to modeling space-charge effects. Taken together, Synergia, ML/I, and IMPACT provide comprehensive capabilities for parallel, multi-physics modeling of beam dynamics in the Main Injector.

Table 1: Parameters of the Main Injector

	Current	Projected
Length [m]	3319.42	
Harmonic number	588	
Horizontal tune	26.425	
Vertical tune	25.415	
Synchrotron tune	9.58×10^{-3}	
Slip factor	-8.844×10^{-3}	
Transverse emittance [π mm mrad]	18	25
Longitudinal emittance [eV sec]	0.35	0.5

MAIN INJECTOR LATTICE

The major parameters of the Main Injector are described in Table 1 The dominant part of the Main Injector lattice is made up of 104 pairs of focusing-defocusing quadrupoles. To first order, there is no coupling between the horizontal and vertical planes. The lattice description for the Main Injector is contained in a single MAD8[9] file. Synergia and ML/I have independentally developed parsers and beamline element models, but both simulation programs were able to read the lattice description file and calculate fractional tunes that were in agreement to five significant digits: 0.42528(Q_x) and 0.41528(Q_y). These values agree well with the parameters used by the machine operations staff. Lattice functions calculated with both programs agree to within 1 part in 10^{-4}.

There are 18 radio-frequency cavities energized with a peak voltage of 1 MV. The harmonic number is 588. The CHEF libraries calculate the slip factor to be -8.847×10^{-3} in agreement with the machine design value -8.844×10^{-3}. A simulated off-momentum par-

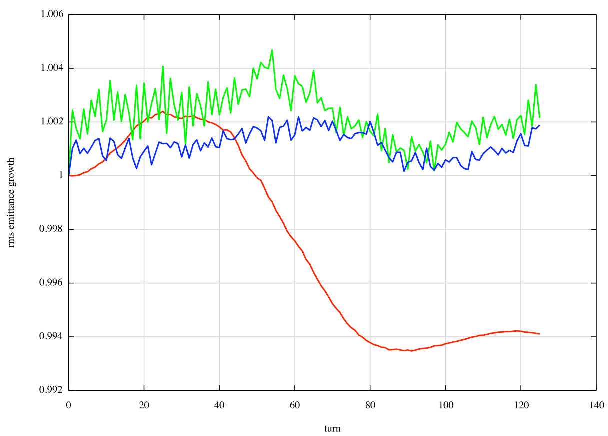

Figure 1: The RMS emittance growth as a function of turn number for a zero current, ML/I-generated bunch matched using a third order normal form. The horizontal, vertical, and longitudinal emittances are shown in green, blue, and red, respectively.

ticle executes 48 synchrotron oscillations in 4963 turns, for an approximate synchrotron tune of .00967. The actual machine synchrotron tune is 0.00958, giving us confidence that the simulation correctly describes the machine longitudinal dynamics. The Main Injector RF frequency at injection is 52.8 MHz giving a half period of $9.5\,\mathrm{ns}$. The bunch length extends to the edge of the RF bucket. Creating a matched bunch in longitudinal space that will propagate without emittance change requires a higher order matching procedure. The ML/I program can generate third order matched bunches using MaryLie's normal form capabilities. If A is the map that normalizes the 1-turn transfer map, $AMA^{-1} = N$, then a matched beam can be generated by applying A to the arguments of a 6D distribution that is a function of the quantities $(x^2 + p_x^2)$, $(y^2 + p_y^2)$, $(t^2 + p_t^2)$. Let g_{tori} be a function of these three quantities. Then a matched beam is given by

$$f_{matched}(\zeta) = g_{tori}(A\zeta), \tag{1}$$

where $\zeta = (x, p_x, y, p_y, t, p_t)$. Fig. 1 shows the evolution of the longitudinal and transverse rms emittances for the zero current case when a third order normal form is used. The distribution is seen to be well matched. The fact that there is more growth in the longitudinal plane than the transverse planes is to be expected given the large fraction of the rf bucket occupied by the beam. As mentioned, these results are for the zero current case. Though such a distribution will be less well matched in the finite current case, the zero current match provides a good starting point for simulation studies.

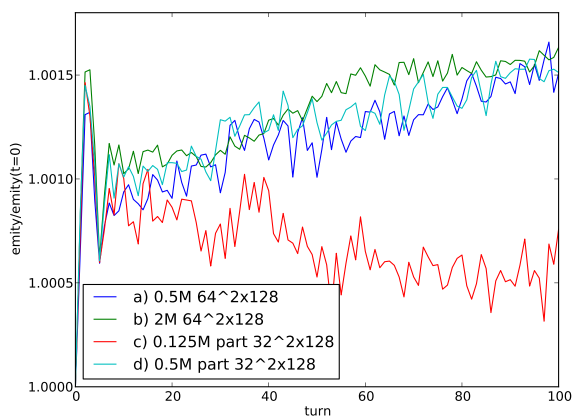

Figure 2: The emittance calculated over a 100 turn run for different numbers of macroparticles and grid size: a) 0.5 million, $64 \times 64 \times 128$; b) 2 million, $64 \times 64 \times 128$; c) 0.125 million, $32 \times 32 \times 128$; d) 0.5 million $32 \times 32 \times 128$.

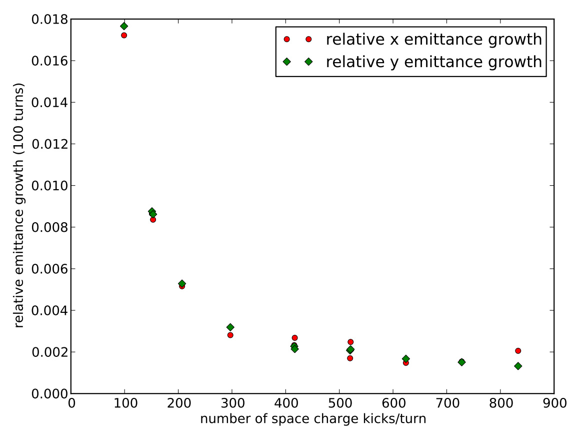

Figure 3: The relative space charge induced emittance growth $(\epsilon_f - \epsilon_i)/\epsilon_i$ over a 100 turn simulation varying the number of space charge kicks per turn.

COMPUTATIONAL ISSUES

A number of computational issues arise in doing PIC based space charge calculations. The common theme is the trade-off between computational time and the fidelity of the result. In PIC calculations, macroparticles representing many charges are deposited on a numerical grid. Calculations with larger numbers of macroparticles can resolve finer details of particle distributions. Calculations using a larger number of grid cells resolve finer details of the electric field. Increasing either of these parameters costs additional computational time. Fig. 2 shows a survey of emittance over a 100 turn run for different grid sizes and numbers of macroparticles. The emittance from the run using 0.5 million macroparticles closely follows the curve from the run using 2 million macroparticles. Also the curve from the run using a grid of $32 \times 32 \times 128$ is as good as the grid of $64 \times 64 \times 128$. Using the smaller grid, as well as 0.5 million macroparticles, results in a factor of 20 speedup of the calculation relative to one using the larger grid and more macroparticles.

Space charge is simulated via the split-operator technique in which each step through a section of the accelerator is modeled by a half-step, a kick representing the contribution of space-charge for the entire step, and a final half-step. Since the calculation of the space-charge kick is a relatively expensive computation, we try to minimize the number of them we do per turn consistent with achieving sufficient accuracy of the final calculation. Fig. 3 shows relative emittance growth after 100 turns for runs using different number of space-charge kicks/turn of the ring. As the number of kicks increases, the emittance growth approaches a limiting value. We would naively expect to only need 4 kicks/FODO cell or 416 kicks/turn , but it appears that 7 kicks/FODO cell (728 kicks/turn) is necessary for an accurate simulation.

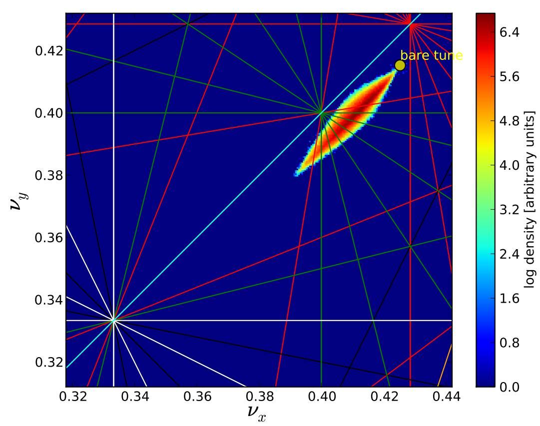

Figure 4: The tune footprint spread out by space charge at the current nominal settings.

SPACE CHARGE INDUCED TUNE SPREADING

Finally, we simulate a main injector beam bunch of nominal intensity for 2000 turns. For a representative sample of these particles, we calculate the tune. The tune footprint is plotted as a color density plot in Fig 4 along with the resonance lines up to 7^{th} order. Even at nominal intensity, space-charge spreads the bunch tunes over a large range. Particles that exceeded a modest transverse radius were removed. At this intensity, about 1000 particles out of 0.5 million were lost, all within the first 200 turns, indicating that they had been generated outside the machine acceptance.

FUTURE WORK

For future work, we will include effects of known order multipole fields in the main injector magnets as well as known apertures.

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