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NUMERICAL SIMULATIONS OF SPACE CHARGE COMPENSATION WITH AN ELECTRON LENS*

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Abstract

The future high energy physics program at Fermilab requires that the proton complex operate with beam bunch intensities four times larger than is currently handled. At these intensities space charge nonlinear defocussing effects cause unacceptable particle losses especially in the low energy rapid-cycling-synchrotron (RCS) Booster. Focusing electron lens elements may offer a solution by providing partial space charge compensation but there is a need for detailed simulations as this technique has not been demonstrated. We report on high fidelity numerical 6D space charge simulations in a model accelerator lattice with a record high space charge tune shift approaching unity.

INTRODUCTION

The Fermilab accelerator complex produces the beams for the accelerator-based experimental high energy physics program in the US. The 2014 Particle Physics Project Prioritization Panel (P5) report [1] identified the neutrino program centered at Fermilab as the top priority for domestic investment in experimental particle physics for the next 20–30 years. Neutrino experiments rely on an intense primary proton beam to produce neutrino beams that are directed towards detectors hundreds of kilometers distant. The next generation neutrino experiment, the Deep Underground Neutrino Experiment [2] will be located 1300 km from Fermilab at the Sanford Underground Research Facility (SURF) in Lead, South Dakota and will measure neutrinos produced at the end of a new beamline which will be constructed as part of the Long Baseline Neutrino Facility (LBNF) [3]. To achieve a useful neutrino event rate the primary beam must be extremely intense. Fermilab is pursuing a multi-stage program of accelerator upgrades [4] to boost the beam power for neutrino production from its current value of 700 KW. The PIP-I+ campaign will bring power levels to 900 KW while the proposed PIP-II project [5] will reach 1200 KW. The power increase will be achieved by boosting the throughput at all stages of acceleration by both increasing the protons per bunch and the accelerator cycle rate.

Space charge effects are most problematic in the low energy Booster machine. These effects scale inversely [6] with $\beta\gamma^2$. There is currently [4] about a 5% particle loss during the Booster ramp. To allow routine access to the machine components and comply with regulatory guidelines, beam loss must remain below 1 W m^{-1} which is about where it is currently. Plans call for increasing the beam energy and

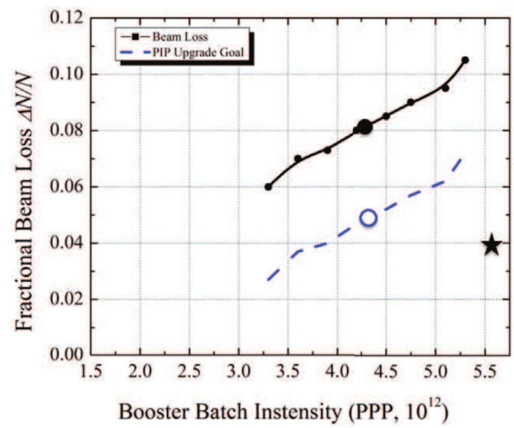

Figure 1: Fractional beam losses in Fermilab's 8 GeV proton Booster synchrotron vs. the total intensity of the batch of 84 bunches in the accelerator. The dashed blue curve shows the level at the recently reached 700 kW level while the star shows the anticipated level at the end of the PIP-I+ upgrade.

rep rate (see Fig. 1), forcing a reduction in the fractional loss rate and a solution to space charge effects.

Use of an electron lens element [7] has been suggested as a potential method to compensate the space charge force. An electrons lens introduces a region in the beampipe where a matched electron beam co-propagates with the proton beam. The electron beam profile may be adjusted in time and space to provide an attractive force that counterbalances the repulsive space charge force. The construction and deployment of electron lens elements is well understood. Electron lenses have been successfully used [7] in colliders for beam-beam compensation.

Compensation occurs locally within the lens region while space charge effects are distributed along the ring. Ref. [8] finds partial compensation even with incomplete coverage of the machine, but their simulations were in 2D, assumed the lens distribution changed dynamically to match the proton distribution, and neglected synchrotron motion. We are therefore undertaking a study with the 6D self-consistent code Synergia to understand the capabilities and limitations of electron lenses for space charge compensation.

SYNERGIA

Synergia is a particle-in-cell (PIC) based framework for self-consistent, high fidelity modeling of charged particle beam transport in accelerators or storage rings in the presence of collective effects such as space charge and wake fields. Synergia tracks macro-particles contained within one

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or more beam bunches through the accelerator. For purposes of calculating collective effects, each macro-particle represents the charge of 100–10000 real beam particles, but responds to fields as a single particle.

Synergia tracks one or more bunches of macro-particles through the same set of common magnetic elements and RF cavities as are supported by MAD-X [9]. Collective effects are combined with particle tracking using the split-operator method [10] and are applied at locations along the ring. Synergia includes several models of space charge; the 3D Poisson solver with open boundary conditions [11] was used in this study. At locations where space charge is applied, the Poisson solver calculates the electromagnetic field on a grid using the distribution of macro-particles. The resulting field produces a momentum kick on each particle. For ease of interpretation of results, the longitudinal effects of space charge were neglected.

For this study, an electron lens element was added. The lens is assumed to be a rigid round radially Gaussian transverse charge distribution. Passage through the lens imparts a transverse momentum impulse to the macro-particle based on its position within the charge distribution. The momentum kick strength of the lens may optionally be modulated longitudinally with a Gaussian profile to match the bunch charge profile.

Table 1: Parameters of the Model Lattice

Parameter	**Value**	**unit**
length	288.0	m
beam kinetic energy	0.8	GeV
RF frequency	43.814	MHz
slip factor	-0.291186	
x, y chromaticity	-5.68, -5.97	
total RF voltage	6.287	MV
bunch charge	2×10^{11}	e
RMS bunch length	0.5	m
RMS bunch $\Delta p/p$ spread	0.00288	
x, y emittance	1.0005×10^{-6}	m rad
β_x, β_y at lens	17.28, 17.27	m
x, y tunes	3.72, 3.84	
synchrotron tune	1/13	

SIMULATIONS

Simulations were performed of high intensity bunches propagating in a perfectly periodic model lattice comprised of 12 identical FODO cells. The electron lenses have not yet been energized. For ease of interpretation of the results, there were no bends in the lattice which was considered to be periodic. The parameters of the lattice are detailed in Table 1. The beta functions are shown in Fig. 2. There were 12 RF cavities to keep the beam bunched longitudinally and 24 electron lens elements placed at the locations where β_x and β_y are equal. The slight difference between the two planes is due to the different x and y tunes.

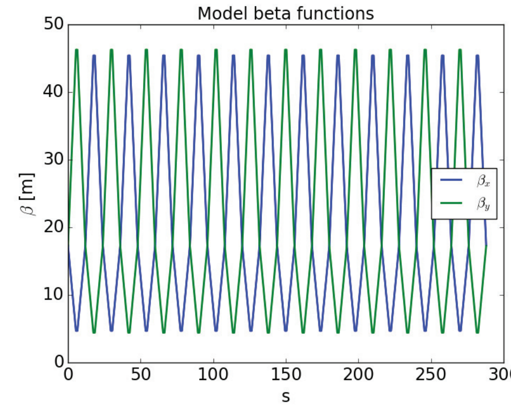

Figure 2: The x and y β functions for the model lattice.

In an RCS machine, the space charge effects in the first 1000 turns the acceleration cycle are most important because the energy increase after 1000 turns is enough so that further space charge effects are negligible. The simulations did not include increase, but the 1000 turns at the initial energy will be representative of the largest possible space charge effects. Simulations were performed for 1000 turns with 1 million macro-particles.

It was determined that observed emittance growth is unchanged with 72 or more space kicks per turn. The phase space coordinates of a 10 000 particle sample of the bunch was saved every turn for computation of tunes and the entire beam bunch was saved every 25 turns.

In assessing the simulations, we looked at emittance growth and the tune footprint of the particles. In terms of accelerator operations, the important figure of merit is particle losses. As a proxy for assessing particle losses, we computed the growth in RMS emittance and 99.9% emittance of the bunch bunch. The actions of all particles was computed using the known lattice functions. The action larger than 99.9% of the other actions is denoted the 99.9% emittance. Particles with large actions are those that are likely be lost in apertures.

The RMS and 99.9% emittance growth for the reference simulation base simulation with no electron lens is shown in Fig. 3. The emittance grows rapidly for the first 80 turns and levels off. This can be understood by looking at the space charge tune shift calculated from

$$\Delta Q_{SC} = \frac{1}{4\pi} \oint k_{\mathrm{SC}} \beta_x(s) ds$$

where k_{SC} is the normalized defocussing gradiant produced by the derivative of the bunch electric field analogous to a quadrupole magnet gradiant, β_x is the lattice function. The evolution of the tune shift is shown in Fig. 4. The tune shift begins close to unity and drops rapidly. As the tune drops, the rate of emittance increase slows down. Looking at the tune footprint (Fig. 5),we see that the particles have been pushed across the half-integer line at 3.5.

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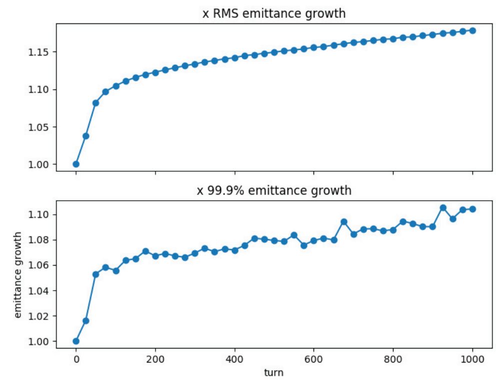

Figure 3: RMS and 99.9% emittance growth during the first 1000 turns of the of the perfectly periodic lattice with initial space charge tune shift of about 0.9 with no electron lenses.

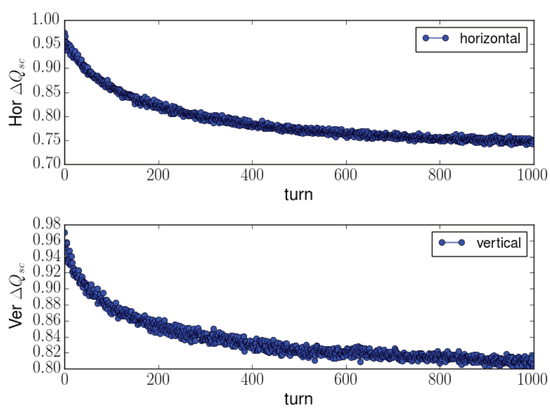

Figure 4: Evolution of the space charge tune shift during the first 1000 turns of the perfectly periodic lattice.

CONCLUSION

We have started systematic studies of space charge effects at record high proton beam brightnesses corresponding to $dQ_{\rm sc} = -1$. Our Synergia PIC modeling tool reveals detailed effects in situations with complicated dynamics. We plan to reveal effects one by one starting with an ideal lattice using the RMS and 99.9% emittance to evaluate the efficacy of compensation. Longitudinal dynamics, lattice imperfections and optimal tune settings will be studied next. Electron lenses will be introduced and the effects of the number and distribution of lenses and mismatch between the longitudinal and transverse lens profile will be studied.

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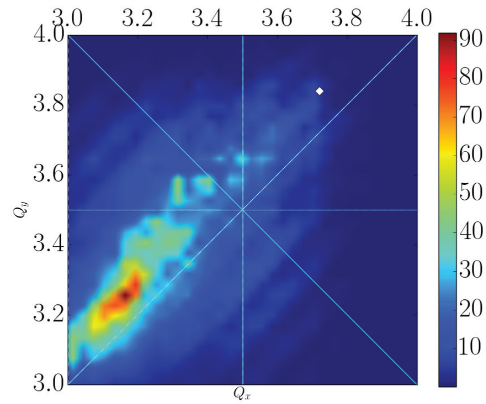

Figure 5: Tune power density in the first 200 turns of the perfectly periodic lattice. Each point on the plot represents the tune power spectrum present in all the particles. The diamond at (3.72,3.84) is the bare lattice tune without space charge. The faint lines parallel to the diagonal separated from the main population by twice the synchrotron tune are caused by the modulation of space charge by synchrotron motion.

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