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MULTIPASS SIMULATIONS OF SPACE CHARGE COMPENSATION USING AN ELECTRON COLUMN AT IOTA *.

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Abstract

Defocusing repulsive forces due to self space charge fields lead to degradation of high-intensity particle beams. Being of particular concern for low- and medium-energy proton beams, they result in emittance growth, beam halo formation, and beam loss. They set stringent limits on the intensity of frontier accelerators; therefore, the mitigation of space charge effects is a crucial challenge to improve proton beam intensity. The space charge effects in a positively charged proton beam can be effectively compensated using negatively charged electron columns. In this paper, we present the results of simulations using Synergia of the Electron Column lattice for IOTA. Beam loss due to space charge effects and aperture restrictions have been studied, as well as bunch formation and matching using an adiabatic ramp of the RF cavity. The results show the need for space charge compensation, and provide the basis for integration of the Synergia and Warp codes in order to form a complete simulation of space charge compensation using an Electron Column in IOTA.

INTRODUCTION

Space charge compensation is commonly used in H^+ or H^- sources and linacs. It has been implemented with varying degrees of success in circular machines at the Institute of Nuclear Physics [1] and Fermilab [2, 3]. The Integrable Optics Test Accelerator (IOTA) at Fermilab's Accelerator Science and Technology (FAST) Facility aims to study the impact of space charge compensation implemented through both an Electron Lens and Electron Column on an intense, low energy proton beam [4, 5].

The Electron Column concept relies on building negative charge to counter the space charge force of the beam through ionization of hydrogen gas confined to a short section of the ring. Electric and magnetic fields will be used to match the profile of the ionization electrons to that of the beam, while the gas density will be tuned to prevent under- or over-compensation.

Simulations of the Electron Column over two beam passes have been done using the particle-in-cell (PIC) code, Warp, in order to demonstrate some initial space charge compensation, and provide the basis for studying the long term evolution of the plasma [6]. A more complete understanding of the beam evolution is needed, so the work reported here was done to include the rest of the IOTA ring and lay the foundation for a complete simulation of both the beam and plasma over relatively long periods of time.

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SIMULATION PARAMETERS

IOTA will reuse Fermilab's High Intensity Neutrino Source (HINS) RFQ for its proton injector [4]. The HINS RFQ operates at 325 MHz, 1 Hz maximum repetition rate, and can deliver up to 8 mA beam current. The revolution period for the 2.5 MeV protons in the 40 m circumference IOTA ring is 1.83 μs. At injection, the single RF cavity in IOTA will not be operated, allowing the beam exiting the RFQ with a dp/p of 0.1% to coast until it completely fills the ring. A single RF cavity, operated with a harmonic number of 4 (2.18 MHz), will be used to bunch the beam in IOTA. Table 1 lists relevant beam and ring parameters.

Table 1: Beam and IOTA ring parameters

Parameter	Value	Units
Beam Energy	2.5	MeV
Relativistic β	0.0728	
dp/p after RFQ	10^{-3}	
Circumference	39.968	m
Revolution period	1.83	μs
Maximum beam current	8	mA
RF cavity frequency (harmonic)	2.18 (4)	MHz
Number of particles per bunch	2.21×10^{10}	
Transverse RMS emittance	10	μm
RMS beam size, x, y	5.10, 3.72	mm

Synergia

The work reported here was done using the PIC code Synergia [7, 8]. The lattice for the Electron Lens implemented in MAD-X [9] was used with sextupoles turned off. For simulations involving space charge, at 2.5D Poisson solver with open boundary conditions was used [10, 11]. This solver works by finding the total beam charge and then applying the appropriate transverse momentum kick in each grid cell based on the electromagnetic field within that cell.

A 32x32x64 grid was used, with 131,072 macroparticles, representing 1 or 2 mA beam current when space charge

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was turned on. For some cases, a circular aperture with a 2.54 cm radius, corresponding to the radius of the beam pipe in IOTA, was implemented throughout the lattice. Periodic boundary conditions were used longitudinally to represent particles moving from one RF bucket to another, particularly during the ramp of the RF cavity. The simulations were run for 10,000 turns.

Beam Generation and Matching

A single bunch out of four will be considered here. The beam is generated to be matched to the lattice transversely, with a Gaussian distribution. The longitudinal distribution is generated randomly and the momentum spread is given a normal distribution based on the value listed in Table 1. The initial longitudinal distribution is shown in Fig.1.

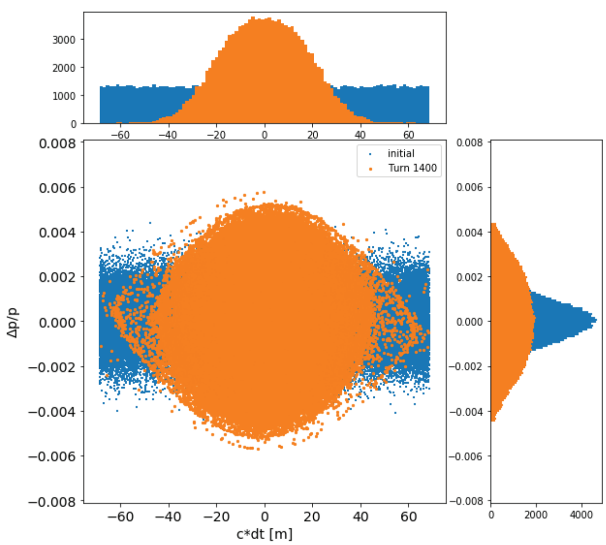

Figure 1: Longitudinal phase space of the beam initially (blue), and after the RF ramp is complete (orange).

Beam Bunching

The RF cavity will be adiabatically ramped according to the method described in Ref. [12]. The voltage as a function of time is given by

$$V(t) = \frac{V_0}{\left[1-\left(1-\sqrt{\frac{V_0}{V_1}}\right)\frac{t}{t_1}\right]^2} \qquad t < t_1 \tag{1}$$

$$= V_1 \qquad t \geq t_1 \tag{2}$$

where V_0 and V_1 are the initial and final ramp voltages, and t_1 is the capture time, which can be expressed by

$$t_1 = \left(1 - \sqrt{\frac{V_0}{V_1}}\right)\frac{n_{ad}}{\omega_{s0}} \tag{3}$$

where n_{ad} is the adiabiticity number, which for this work has been chosed to be 10, and ω_{s0} is the angular synchrotron frequency. For an initial voltage of 10 V, a slip factor of -0.9142, and a harmonic number of 4, the synchrotron tune is 1.08×10^{-3}. For a final voltage of 1 kV, the RF ramp time is 1,326 turns.

Figure 1 shows the longitudinal beam phase space initially and shortly after 1,400 turns, when the RF ramp is complete.

SIMULATION RESULTS

It should be noted that the Electron Column was not activated for any of the results reported here.

No Aperture, No Space Charge

A simulation was run without the aperture or space charge turned on to provide a baseline and establish the quality of bunch produced by the RF cavity ramp. The longitudinal phase space at the end of the ramp is shown in Fig.1, and the bunch quality improves only slightly over the next 8,600 turns. There is minimal emittance growth observed vertically, however 7-10% growth in the horizontal RMS emittance was seen, most likely the result of the beam becoming fully matched to the lattice.

Aperture, No Space Charge

With an aperture in place, 16.8% of particles are lost over the 10,000 turns. Almost one quarter of the loss occurs within the first 50 turns, and the rest occurring with a peak when RF cavity reaches its peak voltage and then tapering off over the next 2,000 turns. Locations around the ring where losses occur correspond to peaks in the beta functions. This leads to a reduction in RMS emittance of almost 10% vertically and 25% horizontally.

Aperture, Space Charge

With space charge and the aperture, only 6.7% of particles survive 10,000 turns for a 1 mA bunch current. Figure 2 shows the number of particles lost per turn. A large number of particles are lost initially due to space charge, followed by a steady increase until the RF cavity reaches its peak voltage, at which point the losses die away.

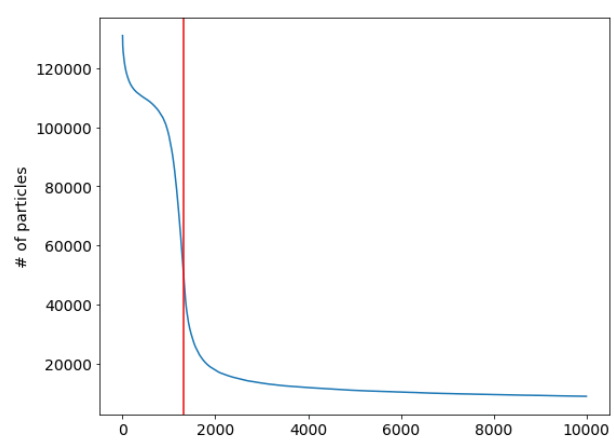

Figure 2: Number of particles vs turn with an aperture and space charge. The red vertical line corresponds to the turn at which the RF cavity reaches its peak voltage.

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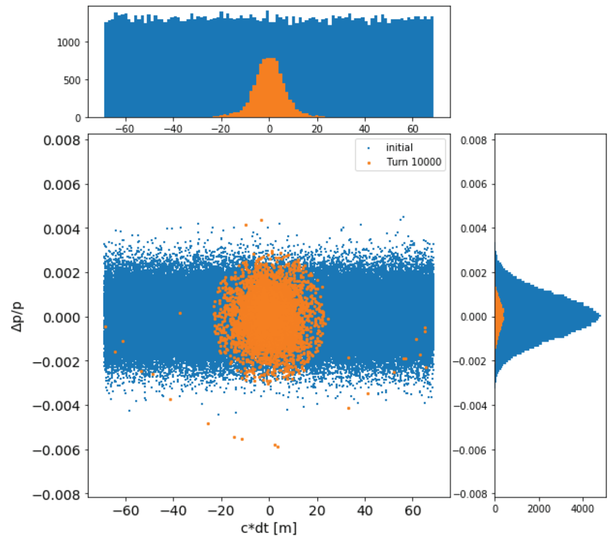

Figure 3: Δp/p-c dt distribution for the beam initially (blue) and after 10,000 turns (orange) with an aperture and space charge.

Figure 3 shows the longitudinal phase space for the initial beam distribution, and that at the end of the simulation. Figure 4 shows the emittance growth over the simulation. An initial blow up in both planes is observed due to space charge, followed by a steady increase during the RF cavity ramp. Following the RF cavity reaching its peak voltage, the emittance falls to some unreached equilibrium. Figure 5 shows the fractional tune diagram for the last 512 turns for a subset of 10,000 macroparticles. The bare lattice fractional tune (0.0557, 0.557) is very close to the fourth order resonance, which leads to the large losses observed.

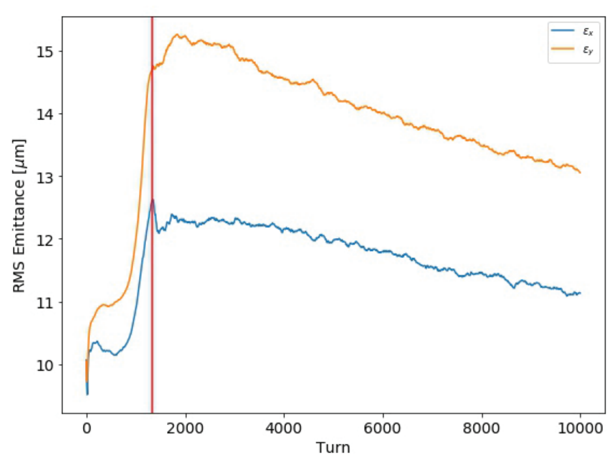

Figure 4: RMS emittance in x (blue) and y (orange) vs turn with an aperture and space charge. The red vertical line corresponds to the turn at which the RF cavity reaches its peak voltage.

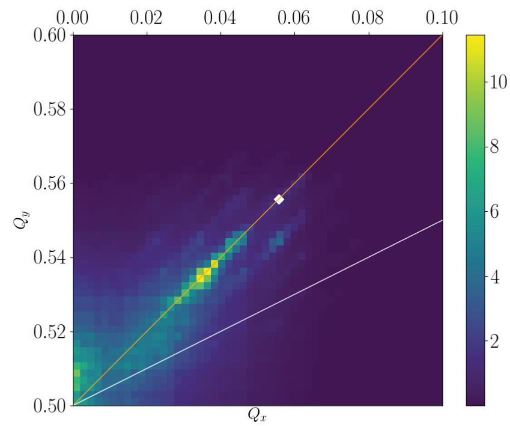

Figure 5: Fractional tune diagram showing the bare lattice tune (white diamond) and space charge tune spread.

COMMENTS

It has been shown that the coasting proton beam in IOTA can effectively be bunched using an adiabatic ramp of the RF cavity to 1 kV. The introduction of an aperture restriction led to almost 17% particle loss for the beam size expected out of the RFQ. A bunch current of 1 mA produced significant beam loss, which is to be expected based on a space charge tune shift of -0.20 and the resulting tune spread illustrated in Fig.5. It is clear, unsurprisingly, that space charge compensation is needed to reduce beam loss in IOTA. The effectiveness of the Electron Column will be tested under this space charge dominated regime.

The simulation framework, consisting of Synergia for modelling the IOTA ring and beam creation, and Warp for modelling the Electron Column, is now in place to provide an end-to-end simulation of the Electron Column experiment at IOTA.

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