Simulations of an Electron Lens

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Abstract

An electron lens is an element of a particle accelerator lattice which generates an electromagnetic field by creating a beam of low-energy electrons. This negatively charged beam should match the positively charged proton beam circulating the accelerator in an attempt to improve beam stability. We simulate the impacts of an electron lens using Synergia, a 6D particle accelerator simulator capable of simulating collective effects. We simulated an electron lens in the IOTA (Integrable Optics Test Accelerator), a storage ring under construction at Fermilab.

1 Introduction

1.1 Motivation

Eliminating the effects of space charge is crucial for a variety of applications. In one major example, Fermilab will be deploying the long baseline Neutrino Facility to produce neutrinos that will be detected at the Deep Underground Neutrino Experiment (DUNE). This neutrino experiment will surpass NOvA, the current state of the art, by a distance of nearly 300 miles (500 km) [3] [2]. As the distance between the accelerator and the target increases, fewer particles intercept the detector, and thus there are fewer neutrino events to study. The neutrino rate at the detector is proportional to $1/r^2$, where r is the distance of particle travel. To increase the number of neutrino events, the neutrino beam intensity is being increased by boosting protons delivered to the neutrino production target. As the proton beam intensity is increased, the losses increase proportionally, primarily due to space charge effects. Unfortunately, the losses are already at the regulatory mandated levels. To lower the corresponding constant of proportionality, space charge must be mitigated. Space charge is inherently defocussing with deleterious effects more pronounced at low energies as found in injectors and LINACs. Counteracting this collective effect is crucial for DUNE.

1.2 Electron Lens

An Electron Lens creates an electron beam that propagates along the channel alongside the proton beam. This electron beam can be varied in both its distribution and beam intensity. The theory behind space charge compensation with the electron lens is that the negative charge of the electrons should counteract the positive space charge of the protons. This will neutralize the total charge in the beam and eliminate space charge. Since the beams should match in both the horizontal and vertical directions, the kick of our electron lens should be radially symmetric and focusing. Only one electron lens in IOTA is being simulated, so the hope is to show a partial reduction in the impacts of space charge. If the technology works, more electron lens would be implemented to see bigger reductions.

1.3 Synergia

Synergia is perhaps the most complex software for particle accelerator simulations. It is 6D, self consistent; and most importantly, can account for collective effects such as space charge. The simulation uses the particle-in-cell technique of simulating particles. This means that there are macroparticles that can represent a large number of physical particles. The main calculations of Synergia are done with pre-compiled C++ functions, yet the simulations are driven by python code. With Synergia, you can import MADX files with preconstructed lattices. Furthermore, it is possible to create new and custom lattice elements, such as an electron lens. The electron lens in our simulation is done using a thin lens approximation.

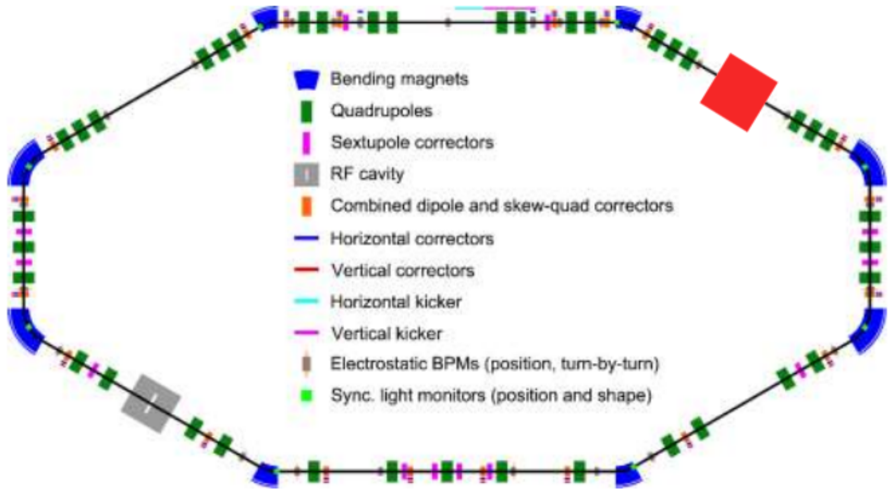

Figure 1: The IOTA lattice. The red box represents where the electron lens is placed in our simulations.

1.4 IOTA

The Integrable Optics Test Accelerator (IOTA) is an electron and proton storage ring in the process of being built at Fermilab. The parameters and uses of the synchrotron are outlined in Ref. [1]. IOTA is designed for researching experimental lattice elements, such as nonlinear integrable magnets or electron lens. The machine is designed so that the lattice functions match for a relatively lengthy period of time. The lens is intentionally placed in an area where the horizontal and vertical beta functions match, as the kick from the electron lens is radially symmetric and we want the beam to match horizontally and vertically where we place it.

2 Simulations

2.1 Overview

We began running simulations by using a MADX IOTA lattice created by Radiasoft. Their online tool, https://beta.sirepo.com/#/about, greatly aided the research process. We made our own simulation file and added an electron lens to the pre-existing IOTA lattice. The parameters in the simulation were based on those found in [1], and further modified until the results were found to be more reliable. Initially, we were experiencing heavy losses even within the first few hundred turns.

It is important to note that these simulations were done without implementing any RF cavities, integrable optics, or sextupoles as the IOTA lattice will contain. These were instead replaced with drifts. Neglecting these elements eliminates some confounding variables, allowing us to pinpoint the changes due to specifically the electron lens. Furthermore, all elements of the lattice were run with the chef_map property; forcing their impacts to be linear. The only non-linear element in the lattice was the electron lens.

2.2 Physical Parameters

Upon our first trials of the IOTA lattice, we found that we were having heavy losses in the first 1,000 turns. We implemented code to calculate the tuneshift of the lattice, using the Laslett tuneshift formula. We were surprised to see that our tuneshift was over 3 while using the parameters in [1], likely because those parameters assumed the presence of the other non-linear elements of our lattice. To solve this, we lowered our physical particles simulated by a factor of 4, and our RMS was increased by a factor of 4. After the manipulation, our tuneshift was reduced to 0.197 - a reasonable value. The simulation was no longer losing particles over a short 1,000 turn interval.

The electron lens parameters had to be calculated next. According to [1], the length was 0.7 m, and for practicality the current had to be within the range of 5 mA - 5 A. The RMS radius of the electron beam was calculated by using the formula $\sqrt{\epsilon * \beta_t}$, where ϵ is the emittance, and β_t is

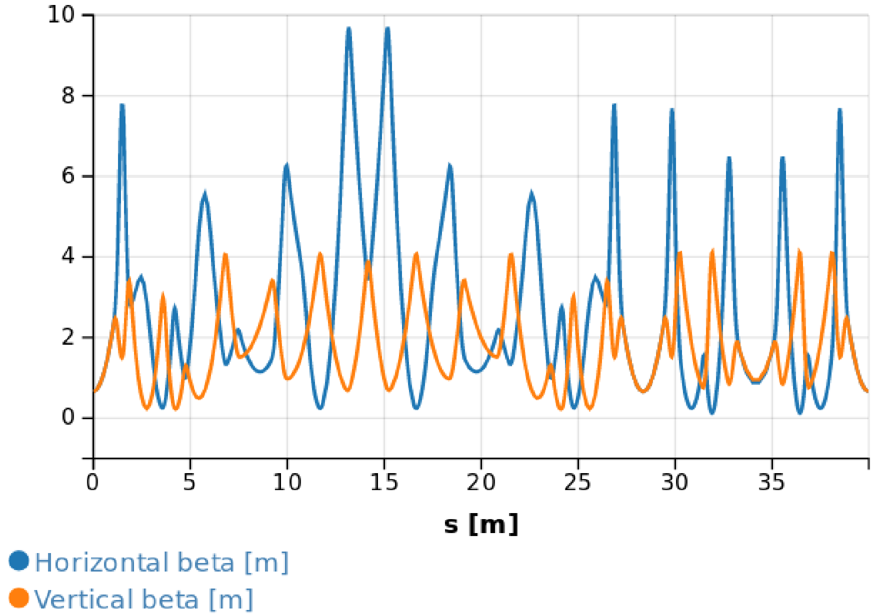

Figure 2: The IOTA lattice functions. Notice: There are a few locations where the beta functions match.

the value of the horizontal and vertical Twiss beta at the position of the electron lens. This meant that our electron lens distribution matched the distribution of the propagating protons.

2.3 Simulation Parameters

The simulation was ran over 2,000 turns with 100,000 macroparticles. Furthermore, we used 2D Open Hockney space charge. 2D, instead of 3D, should be sufficient for our horizontal and vertical space charge compensation, while saving on computational time. The rest of the parameters were as follows:

Parameter	**Definition**
Proton Kinetic Energy	2.5 MeV
Real Particles	2.25E9
Macro Particles	100,000
Emittance	1E-5
Electron Lens Current	0 - 0.5 Amps
Electron Lens RMS	$\sqrt{\epsilon * \beta}$

Table 1: Parameters used in our simulations.

Importantly, we ran the current of the electron lens in the range of 0 to 0.5 A because as we further increased the current, we saw our beam start to become instable and have extremely rapid emittance growth and proton losses. Furthermore, we matched the distribution of the electron lens to the distribution of our proton beam. This was done so that we had equal parts positive and negative charge. The distribution of the electron and proton beams were both gaussian.

2.4 Calculation of the Electron Lens Kick

Eric Stern, a coder of the electron lens in Synergia, in [4], walks through the calculations for the Electron Lens kick. He suggested that the force of the kick would be:

$$\frac{\Delta p_x}{p_b} = -\frac{2JLr_p(1+\beta_e\beta_p)}{e\beta_e\beta_p\beta_b\gamma_b c}(1-e^{-r^2/2\sigma^2})\frac{x}{r^2}$$
$$\frac{\Delta p_y}{p_b} = -\frac{2JLr_p(1+\beta_e\beta_p)}{e\beta_e\beta_p\beta_b\gamma_b c}(1-e^{-r^2/2\sigma^2})\frac{y}{r^2}$$

Furthermore, it is simplified near the origin:

$$\frac{\Delta p_x}{p_b} \approx -\frac{2JLr_p(1+\beta_e\beta_p)}{e\beta_e\beta_p\beta_b\gamma_b c}\frac{x}{2\sigma^2}$$
$$\frac{\Delta p_y}{p_b} \approx -\frac{2JLr_p(1+\beta_e\beta_p)}{e\beta_e\beta_p\beta_b\gamma_b c}\frac{y}{2\sigma^2}$$

And the tune shift for an electron lens kick $k\,x$, can be calculated as:

$$\Delta Q = -\frac{1}{4\pi}k\beta$$
$$k = \frac{\partial \Delta p/p}{\partial x}$$

If the same tune shift is observed in the results, this is one way of checking the reliability of the simulation.

Parameter	**Definition**
J	Electron current
L	Electron lens length
e	unit of electric charge
c	speed of light
m	proton mass
r_p	proton classical radius $e^2/4\pi\epsilon_0 mc^2$
σ	RMS radius of current distribution
β_e	electron velocity/c
β_p	proton velocity/c
γ_b	reference proton beam relativistic factor
Q	Tune of distribution
k	Momentum kick of the electron lens

Table 2: Parameters used to calculated the kick of the lens. From [4].

3 Results

3.1 Data

After justifying the parameters above, multiple simulations were ran. Data visualizations were then created by matplotlib. The datasets have all been run over 2,000 turns using space charge. The x-axis of the graphs is the distance in meters down the beam line.

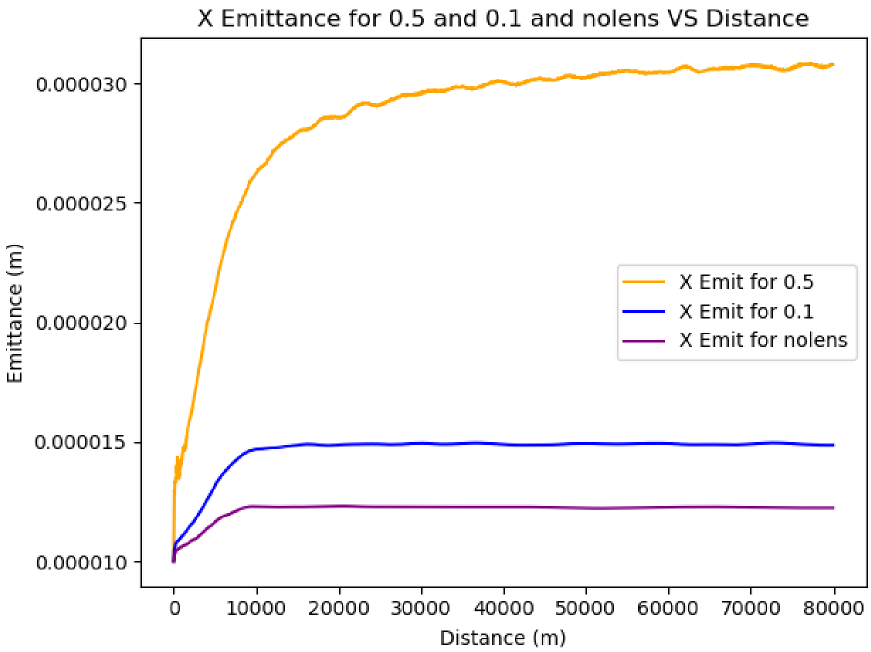

Figure 3: The x emittance for a lattice with no electron lens, compared to that of one with an electron lens a both 0.1 A and 0.5 A. This is over 2,000 turns.

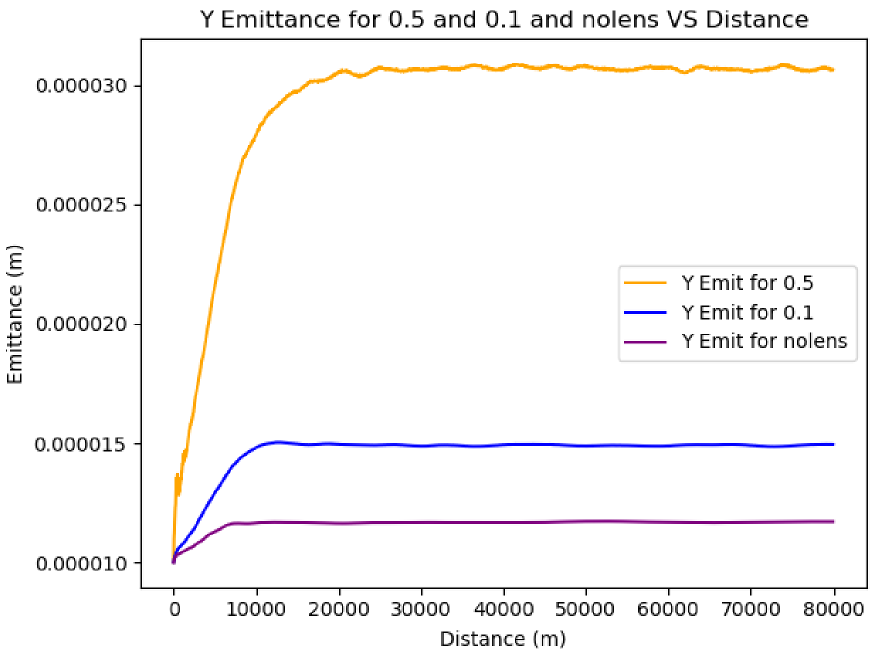

Figure 4: The y emittance for a lattice with no electron lens, compared to that of one with an electron lens a both 0.1 A and 0.5 A. This is over 2,000 turns.

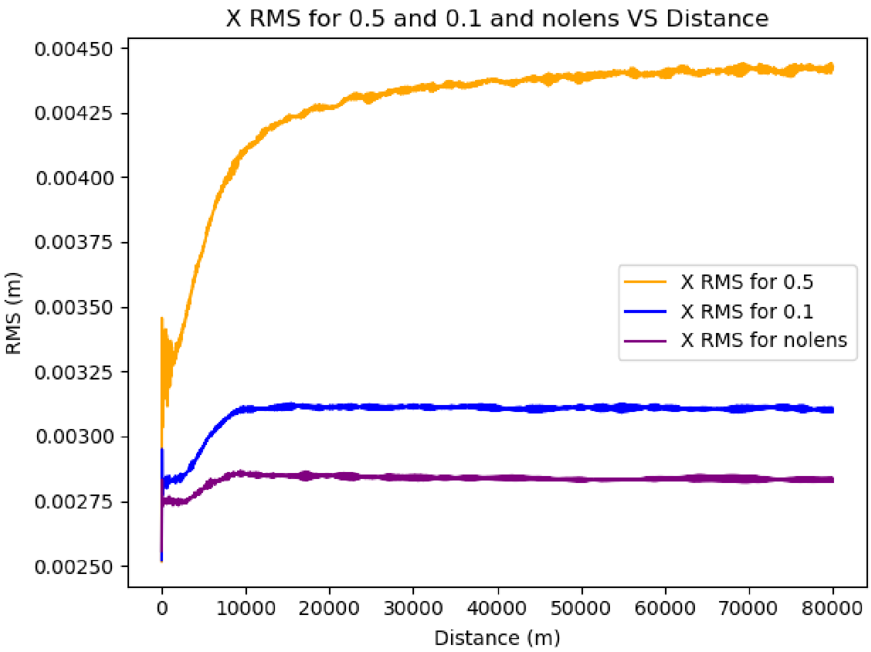

Figure 5: The x RMS for a lattice with no electron lens, compared to that of one with an electron lens a both 0.1 A and 0.5 A. This is over 2,000 turns.

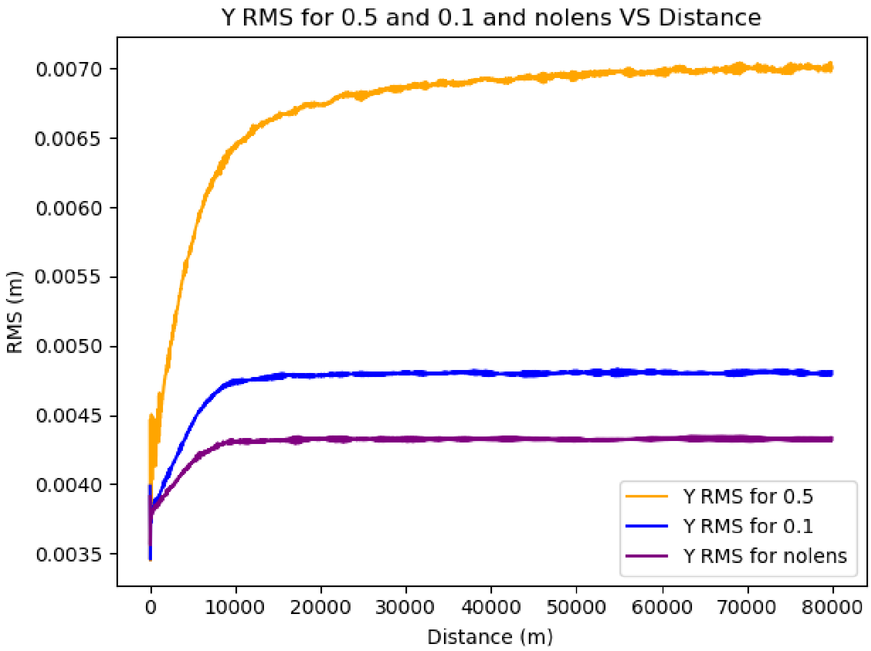

Figure 6: The y RMS for a lattice with no electron lens, compared to that of one with an electron lens a both 0.1 A and 0.5 A. This is over 2,000 turns.

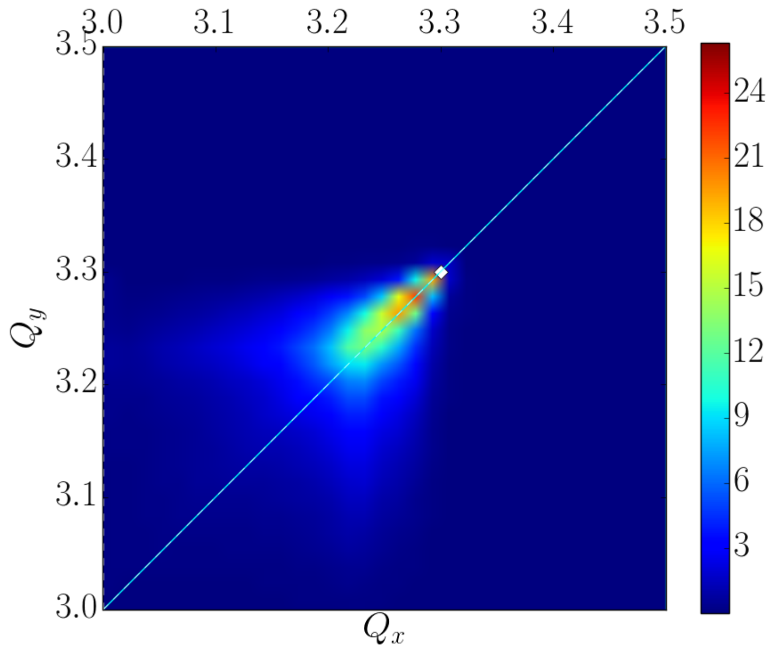

Figure 7: The tune density plot generated over 2,000 turns in IOTA. This is without an electron lens. The white dot at (3.3, 3.3) is the nominal tune of the lattice.

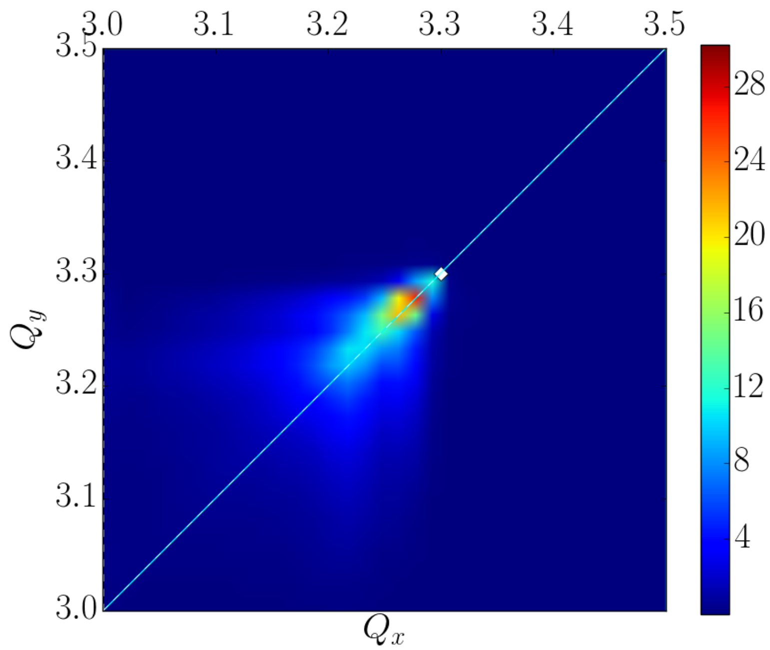

Figure 8: The tune density plot generated over 2,000 turns in IOTA. This is with an electron lens at 0.1 A.

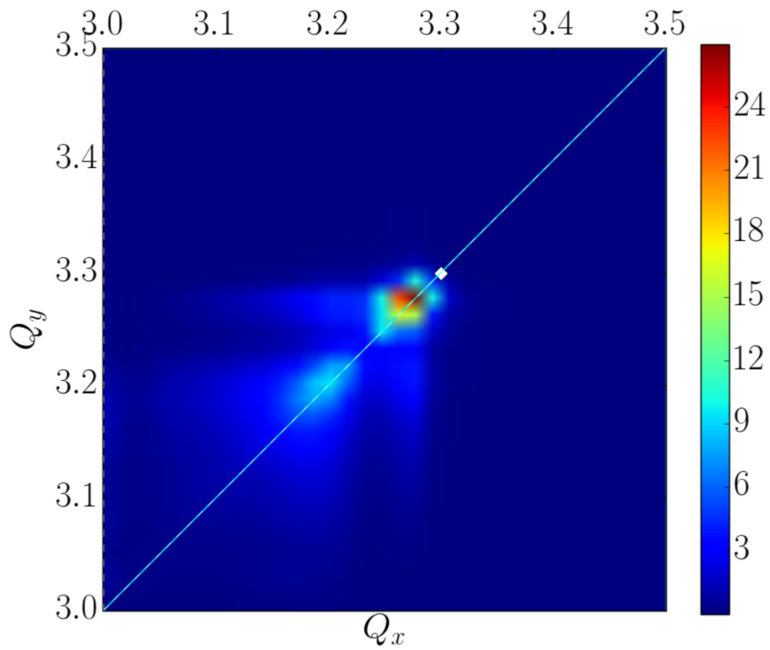

Figure 9: The tune density plot generated over 2,000 turns in IOTA. This is with an electron lens at 0.5 A.

3.2 Data Analysis

We have characterized our beam based on data we have plotted. The emittance graphs 3 and 4 show an increase in both horizontal and vertical emittance when we implement the electron lens. We can see that the increase also scales with the electron lens amplitude. Furthermore, we see a similar increase in horizontal and vertical RMS of the proton beam over time. Again, this scales with the strength of our electron lens. We were not able to find a current at which the emittance decreased from without the electron lens. Tests were also ran plotting emittance as a function of the electron lens RMS, but we were not able to find an improvement on beam stability doing that either.

The tune density plots which are figures 7, 8, and 9, show some interesting points. The downward spread shown by 7 is a result of space charge causing a tune shift. As we can see in 8, and even more in 9, our tune spread due to space charge has actually been decreased as we had initially anticipated. This means that our electron lens is compensating for space charge in some way, but the details of that compensation are not beneficial for our simple lattice. Furthermore, we are able to calculate the tune shift that the electron lens will cause and this is observable in our tune density plots.

4 Conclusion

In conclusion, the results of our simulations show a general decrease in beam stability caused by the electron lens. In our simplified IOTA simulations, we saw an increased emittance and RMS growth. Furthermore, we saw a compensation in the tune shift caused from space charge, however this did not prove to be beneficial to our beam stability.

References

[1] Sergei Antipov, Vladimir Shiltsev, et al. Iota (integrable optics test accelerator): Facility and experimental beam physics program. 2016.

[2] Fermilab. How does nova work?

[3] Fermilab. Long-baseline neutrino facility (lbnf).

[4] Eric G. Stern. Momentum kick to a proton traversing an electron lens.