

Designing and Optimizing JLEIC Booster Injection

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Abstract

Jefferson Lab personnel are designing a new Electron-Ion Collider facility (JLEIC). One major part of JLEIC is the ion Booster, a mid-range energy synchrotron that takes an H^- beam from the linac and accelerates it before transfer to the collider. During the long process of injection that takes the pulse of H^- beam 300+ times around the ion Booster, the beam will pass through a stripping foil, making the beam H^+ . Space charge, the tendency for like particles to push apart, can affect how the beam acts and needs to be accounted for. The goal of this project is to design an optimal injection process for the beam into the Booster at a kinetic energy of 280 MeV and simulate it using codes in pyORBIT, a code developed at Oak Ridge National Lab for the SNS. To do this, the ion Booster layout needed to be read into pyORBIT, which was used to determine optimal location for ion Booster injection and beam optics parameters. Phase space painting using an injection bump is designed to ameliorate space charge effects. Designing the injection bump involved exploring various parameters and the stripping foil to explore the injected beam quality. The final code will include the chosen and calculated optimal parameters needed for ion Booster injection, including the injection bump location, stripping foil, and injection location. The model can be used to investigate changing parameters of ion Booster injection and how the beam is affected by them. This code will be used for future design of JLEIC, including generating results for publication in the upcoming preconceptual design report.

INTRODUCTION : JLEIC AND THE JLEIC BOOSTER

JLEIC is a proposed accelerator that would be built to collide up to 10 GeV electrons with up to 100 GeV protons, or ions of equivalent rigidity, for nuclear physics experiments. The entire ion complex will be new construction. Ions will be produced in an ion source, accelerated through a superconducting linac, and enter a Booster synchrotron that will accelerate the beam from 280 MeV to 8 GeV proton kinetic energy. This beam is transferred to a collider ring that will bring the ion beam to its top energy [1]. A layout of this complex is shown in Figure 1.

The reference Booster design was updated in 2017-2018; this design and the motivation behind its optics design choices are described in [2]. The magnet layout of the Booster is shown in Figure 2, and relevant Booster parameters are listed in Table 1.

Table 1: JLEIC Booster Parameters for H- Beam

Parameter	Units	Value
Circumference	[m]	313.489
Beam energy (injection)	[MeV]	280
Beam velocity ($\beta=v/c$)	[--]	0.638
Revolution period	[us]	1.639
Linac pulse length	[us / turns]	500 / 305
Linac pulse current	[mA]	2.0

BACKGROUND : BOOSTER INJECTION

There are several parameters that need to be considered to design Booster injection from the linac. These include injection location, foil thickness, and bump design. To determine optimal injection location, the beam must have a reasonable emittance that is not too large or too small. There must also be space to build the injection location, meaning there must not be any magnets or obstacles in the way. The thickness of the foil will scatter the beam, and create a star-like structure as the particles repeatedly go through the foil. Space charge, the electromagnetic self-repulsion of the H^+ ions in the beam, will also affect how much the beam emittance grows. To limit this growth, we must design an injection bump that will re-

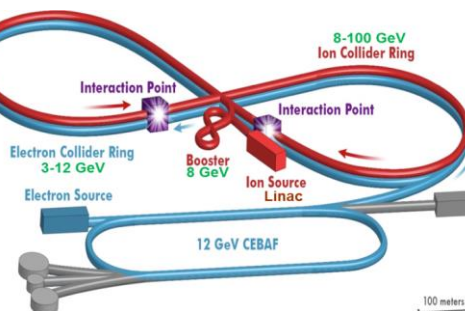


Figure 1: Schematic of the Jefferson Lab Electron-Ion Collider, showing the 8 GeV Booster near the center.

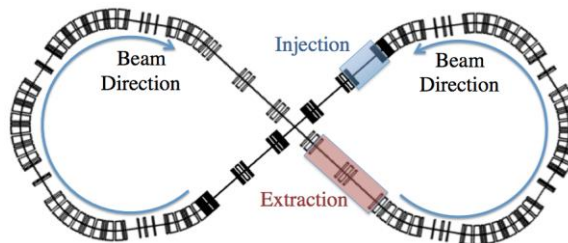


Figure 2: Layout of the JLEIC Booster. Larger boxes are dipole magnets which bend the beam; smaller boxes are quadrupole magnets that maintain the beam focus and optics. Beam direction and injection/extraction regions are also shown.

duce the number of times the beam goes through the foil; the dilution of the beam by the injection bump also reduces the effects of space charge. This bump includes three parameters that will affect the location of injection and how the foil affects the beam.

The process of injecting beam through a foil is typically called “charge-exchange” injection, and movement of the injection bump through the injection process that dilutes the beam is called “phase space painting” [3].

PYORBIT

pyORBIT is a package of python and C++ libraries that are designed to track particles and simulate beam dynamics in a synchrotron or linac [4]. It was developed by personnel at Oak Ridge National Laboratory in the course of designing the Spallation Neutron Source, and has since become a well-understood tool, used for simulations and design of high-intensity synchrotron injection at other facilities such as FAIR at GSI [5].

pyORBIT has several features that make it attractive for use in simulations of the JLEIC Booster injection design:

- Open source: all source code is freely available and user-modifiable.
- Can import mad and madx lattice descriptions of the accelerator directly from design lattice files
- Can include time-dependent parameters of any accelerator lattice parameter, including strengths of dipole magnets for injection bumps and phase space painting
- Can generate particle distributions from optics, or use user-specified particle distributions
- Can include several different models of space charge

pyORBIT includes no graphics packages; its output files are raw text. We use gnuplot [5] for generating relevant plots for the remainder of this paper.

INJECTION AND BUMP DESIGN

Injection Location and Bump Layout

Injection into the Booster is planned for one of the straight sections at the center of the figure 8. The injection region should have considerable downstream space in the straight for an injection dump and potential injection kickers. Injection should also have zero dispersion, and available space near quadrupoles for injection bump dipole magnets discussed in the next subsection. The injection region identified for this study is indicated in Figure 2, between the exit of the counter-clockwise arc and the first quadrupole triplet in the straight section.

Four dipole correctors were added to the Booster lattice, occurring in pairs around each of the quadrupole triplets at the start and end of the injection region for an overall bump length of 12.58m. The horizontal transport matrices between these four correctors as given by the design lattice are:

$$M_{12} = \begin{pmatrix} 1.00886 & 3.06217 \\ -0.13159 & 0.59181 \end{pmatrix}$$

$$M_{23} = \begin{pmatrix} 1.00000 & 6.97926 \\ 0 & 1 \end{pmatrix}$$

$$M_{34} = \begin{pmatrix} 0.87808 & 3.50135 \\ -0.12725 & 0.63143 \end{pmatrix}$$

These were used to construct closed local orbit bumps for independent control of the design orbit central trajectory position and angle at the injection point. These bumps then had to be calibrated in pyORBIT to produce orbit control necessary for injection simulations.

pyORBIT injection bump

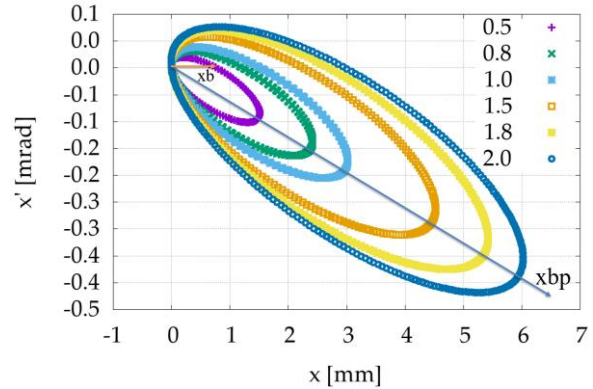


Figure 3: The three bump parameters are x_b , x_{bp} , and $x_{centerpos}$. This minimizes the amount of times the particles go through the foil, as well as where this is relative to the point of injection.

Bump Calibration in pyORBIT

There are three parameters that control injection bump amplitudes in our pyORBIT simulation:

- $x_{centerpos}$: the position relative to $x=0$ where beam is injected.
- x_b : the injection bump position.
- x_{bp} : the injection bump angle.

These parameters had to be calibrated properly within the pyORBIT simulation. Figure 4 shows a scan of the x_b injection bump position parameter; beam is injected at (0,

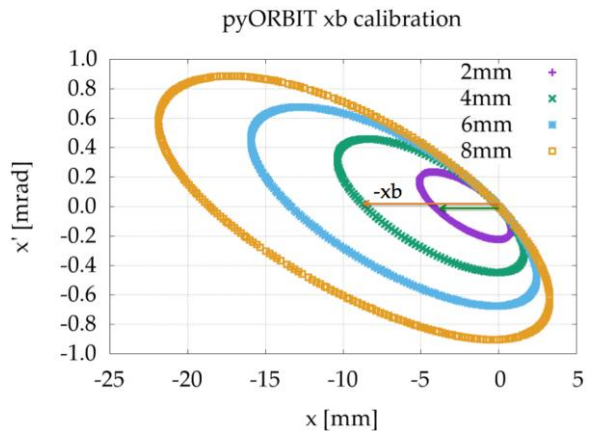


Figure 4: Calibration of the x_b injection bump position parameter.

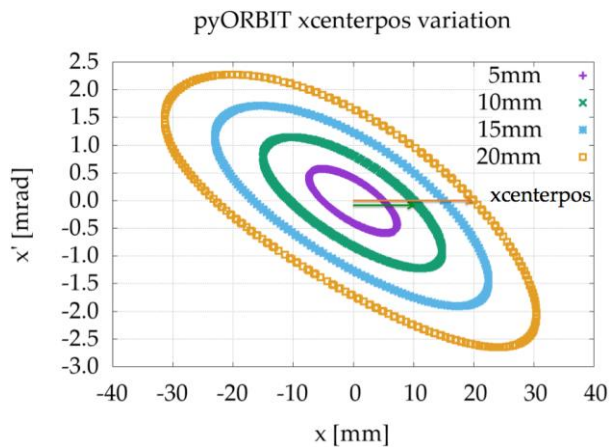


Figure 5: Calibration of the xcenterpos bump amplitude parameter, showing slope of horizontal phase space ellipse at the injection point.

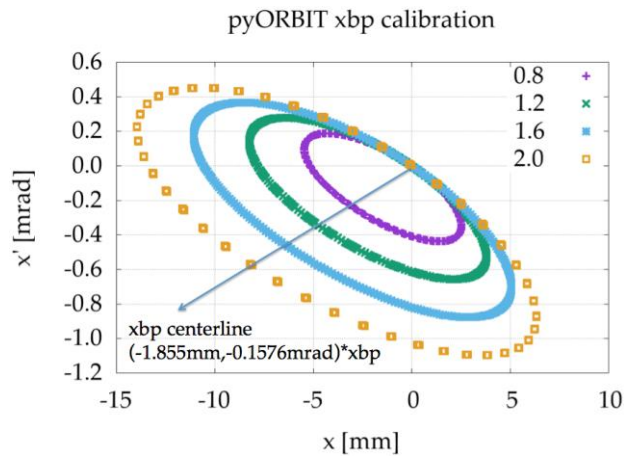


Figure 6: Calibration of the xbp injection bump angle parameter.

0) since xcenterpos=0, but the center of the phase space ellipses is effectively located at (xb,0).

Figure 5 shows a scan of xcenterpos, showing that the phase space ellipses are centered at (0,0), but particles are injected at successively larger horizontal positions (xcenterpos,0). Phase space ellipses here are clearly inclined. As will be discussed, the optimal injection bump is a combination of position and angle bumps that moves injection along the indicated diagonal line of slope -0.0586 mrad/mm.

Figure 5 shows a scan of xbp. Here it is apparent that the four-bump arrangement for adjusting the injection angle also adjusts the injection position, so we must fit this line and calculate new parameters to independently adjust injected beam position and angle for the injection bump.

Writing the ellipse center locations as functions of xb and xbp from data in Figures 3 and 5, and inverting this relationship, we can find:

$$\begin{pmatrix} x_{cent} \\ x'_{cent} \end{pmatrix} = \begin{pmatrix} -1 & -1.83 \\ 0 & -0.155 \end{pmatrix} \begin{pmatrix} xb \\ xbp \end{pmatrix}$$

$$\begin{pmatrix} xb \\ xbp \end{pmatrix} = \frac{1}{0.155} \begin{pmatrix} -0.155 & 1.83 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} x_{cent} \\ x'_{cent} \end{pmatrix} = \begin{pmatrix} -1 & 11.82 \\ 0 & -6.45 \end{pmatrix} \begin{pmatrix} x_{cent} \\ x'_{cent} \end{pmatrix}$$

The beam ellipse axis where we want to inject is along a line through $(x_{cent}, x'_{cent}) = (\text{bump scale}) \cdot (1\text{mm}, -0.0586\text{mrad})$ from Figure 4, so we can now find the correct scalings for our position and angle bumps:

$$\begin{pmatrix} xb \\ xbp \end{pmatrix} = (\text{bump scale}) \begin{pmatrix} -1 & 11.82 \\ 0 & -6.45 \end{pmatrix} \begin{pmatrix} 1\text{mm} \\ -0.0586\text{mrad} \end{pmatrix}$$

$$= (\text{bump scale}) \begin{pmatrix} -1.693\text{mm} \\ 0.378\text{mrad} \end{pmatrix}$$

Phase space ellipses for various bump scalings with these coefficients are shown in Figure 7, indicating that the simulated bump is now aligned properly with the phase space ellipse.

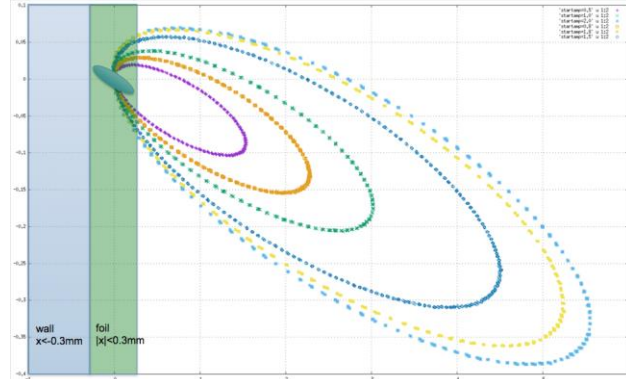


Figure 7: Variations of calibrated injection bump amplitude, showing alignment of bump with injection phase space ellipse. (replot with larger labels and exposition on foil and wall)

INJECTION WITHOUT SPACE CHARGE

Injection Setup

We first need to look at the pyORBIT code developed at Oakridge. A similar code must be written, but without the inclusion of space charge and foil. This will demonstrate what the beam will look like without any effects, and we will design injection based off this original beam shown in Figure 9. The SNS code from Oakridge is not entirely identical to what we need. There are certain parameters that are not needed for the Booster simulations and other parameters need to be added to the Booster simulation code. Now

To begin design without space charge, a location must be chosen for injection. This must be in a place where the beam is of a reasonable emittance such that there will be enough particles in the phase space, but not too many. This location must also be accessible and located in a drift of the Booster. At the top of Figure 8, there is a layout of the magnets inside the Booster. After observation, we can determine that the most optimal location for injection is in the drift located at 136.5 m into the Booster. At this point, both the x and y Beta functions are at a reasonable size for emittance.

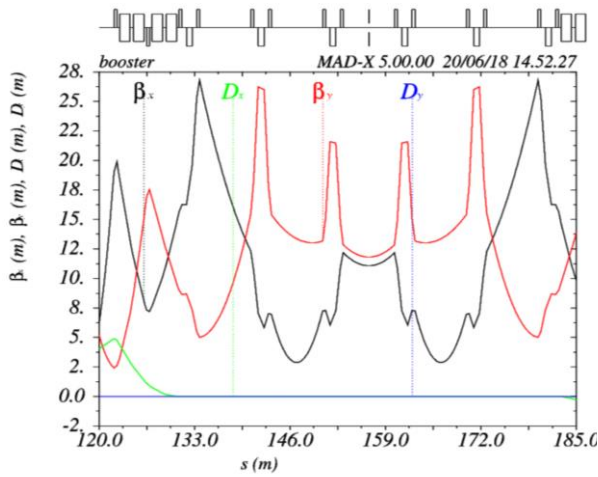


Figure 8: The Beta functions demonstrate how the beam changes as it passes through the magnets and drifts.

Injection Foil Effects

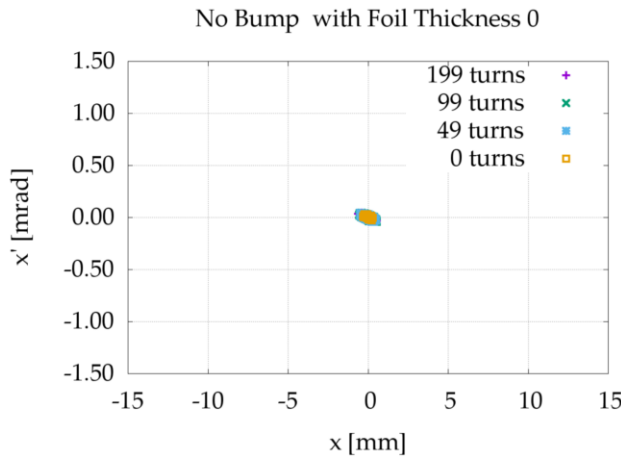


Figure 9: Original beam with no bump or foil included.

Figure 9 will be the comparison point for all phase space graphs to come. Figure 10 shows immediately how much the foil affects the beam as it has scattered across the xbp line by an exponential amount. One can also observe the star-like structure created by the foil.

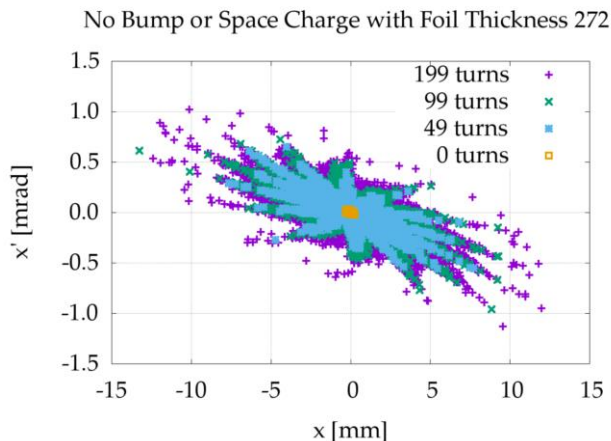


Figure 10: Phase space without a bump means that the particles pass through the foil on every turn.

Phase Space Painting

The spaces between the spikes of the star-like structure will need to be filled using the phase space painting bump. Figure 11 shows how the bump has slightly reduced the size of the beam, and filled in the space.

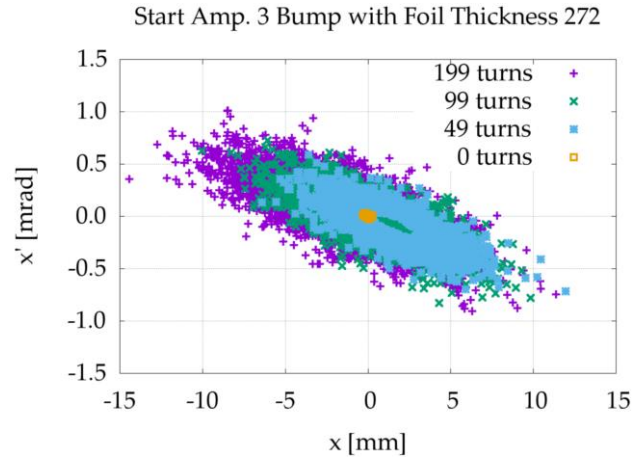


Figure 11: Beam with no space charge included, with bump of a starting amplitude of 3, and a full foil thickness of 272 $\mu\text{g}/\text{cm}^2$.

Injected Emittance

Beam emittance increases as foil thickness increases with a quadratic relationship with one another. This proves that the foil causes extreme scattering as thickness increases.

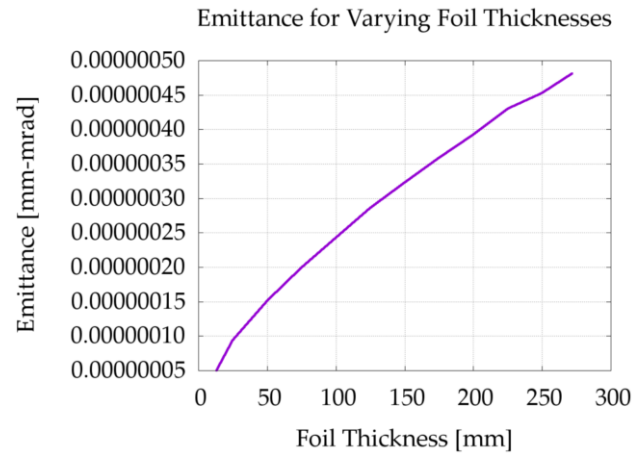


Figure 12

INJECTION WITH SPACE CHARGE

Injection Setup

Space charge is now added into the code lacking it. This space charge piece of code is also taken from the original SNS ring simulation developed at Oakridge. The space charge will make the beam scatter severely, even without a bump or foil [Figure 12]. The scattering of the beam increases as the number of particles injected increases as they make their way around each turn.

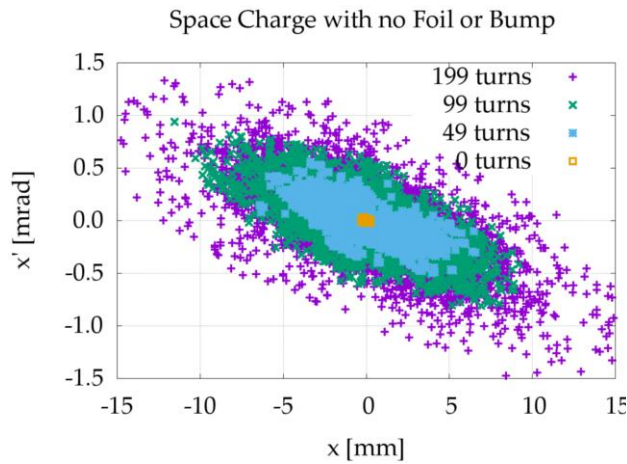


Figure 13: Beam scattering with space charge compared to without space charge in Figure 9.

Space Charge Effects

Figure 14 shows how the emittance increases exponentially more with space charge than it does without.

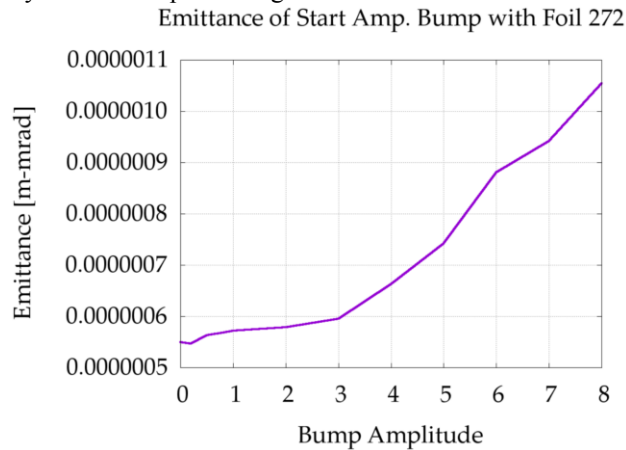


Figure 14: Exponential increase in emittance as bump amplitude increases.

After adding foil to the injection process that includes space charge, there will be more of a variance of charged particles, which means the effects of space charge will be reduced ever so slightly [Figure 15].

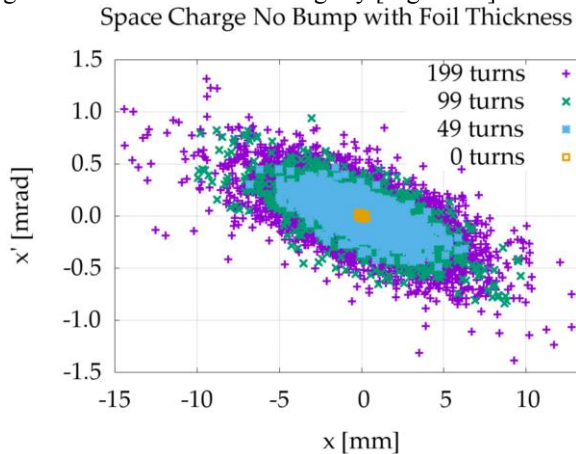


Figure 15: Addition of foil reduces the effects of space charge. Compare this to Figure 9.

After adding the injection bump, the effects will be similar to that of adding the bump without space charge. The beam phase space paints along the xbp line, as can be shown in Figure 16.

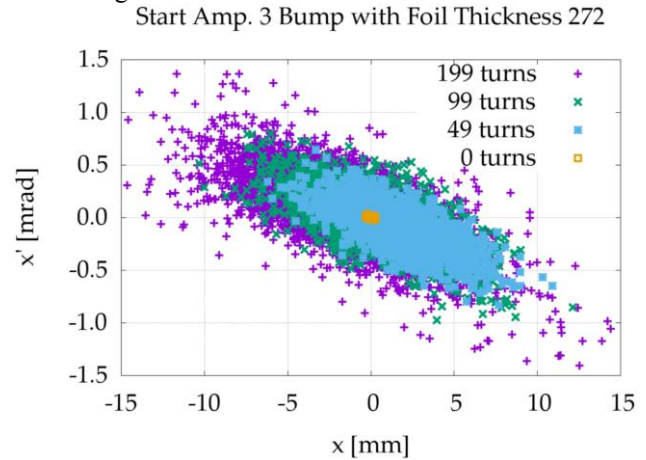


Figure 16: Adding injection bump and foil reduces the effects of space charge.

Comparison With and Without Space Charge

Viewing Figure 11 and Figure 16, one can see that space charge scatters the beam such that the largest x' value increases from approximately 1 mrad, to 1.5 mrad, and the largest x value increases from approximately 12 mm, to 15 mm. The outer edges of the ellipse in Figure 16 are scattered much more than they are in Figure 11, showing the difference in the beam after considering space charge.

CONCLUSION AND FUTURE WORK

Booster injection parameters have been decided. Injection will occur at 136.5 m, proper x_b and x_{bp} have been calibrated for the bump, foil thickness has been accounted for, and space charge has also been accounted for such that the phase space painting reaches optimal design.

The next steps of this project are to use design linac emittance. The vertical phase space painting bump parameters will need to be calibrated. These parameters will also need to be optimized with design Booster aperture.

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