SIMULATION STUDIES OF SPACE-CHARGE EFFECTS IN THE LENS NONLINEAR TRANSPORT LINES*

M. Hess, A. Bogdanov, IUCF, Bloomington, IN 47408, U.S.A.

Abstract

The upgraded IUCF LENS beamline is designed to deliver a square shaped 13 MeV proton beam at 25 mA with a relatively uniform density using two octupole magnets for nonlinear focusing in both transverse directions. The space-charge effects in the LENS beamline (without nonlinear focusing) can vary the beam profile by roughly 8%-13% compared to a zero current beam. In this paper, we show the results of simulation studies of the LENS beamline which incorporate the effects of space-charge, as well as, nonlinear focusing from the octupole magnets. The simulations utilize self-consistent methods for computing the space-charge fields, since the beam density distribution can be nonlinear. We also show simulation results for beam currents in excess of 25 mA, which may be useful for future upgrades of LENS.

INTRODUCTION

The Low Energy Neutron Source (LENS) facility at the Indiana University Cyclotron Facility utilizes a high-intensity 13 MeV, 25 mA proton beam to irradiate a beryllium target for the production of neutrons [1]. One of the important features of the LENS beamline is the inclusion of two octupole magnets for the production of a uniform transverse beam distribution. Uniform distributions are essential for high-intensity neutron sources, since it is necessary to prevent any excessive heating of the target which could be caused by a non-uniform distribution, such as a Gaussian. It is well-known [2], that octupoles can be used for "spreading the beam" to produce a nearly a uniform distribution. In order to minimize the nonlinear coupling in both transverse directions due to the octupoles, a common beamline design strategy involves placing the first octupole, which is intended to spread in the x-direction, near the beam waist point in the y-direction. A focusing quadrupole is then placed shortly after the first octupole, and then the second octupole, which spreads in the y-direction, is placed near the waist point of the x-direction. Figure 1 shows a plot of the LENS beam envelope from the code TRANSPORT [3], and the locations of the two octupoles and target.

At 25 mA, space-charge forces in the LENS beamline can have about a 10% effect on the overall envelope at the target compared to a zero space-charge beam. However, future upgrade plans for LENS have been discussed which would increase the beam current to over 50 mA. The combination of increased current, as well as, a modification of the current density due to space-charge implies the need for a design study of the octupole spreading method which includes space-charge.

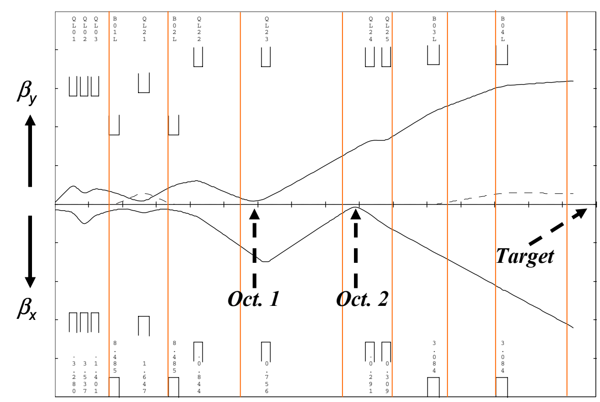

Figure 1: Plot of the beam envelopes of the LENS beamline assuming zero space-charge with the locations of both octupoles and target.

SIMULATION STUDIES

In order to simplify our beam spreading simulations, we only focus our attention on the two octupoles, intermediate quadrupole, and target. In the LENS beamline, the quarupoles and bending magnets that are after the second octupole provide relatively small focusing and do not change the overall distribution in the LENS beam spreading system.

The space-charge simulations utilize an initial bigaussian distribution at the first octupole, which was generated with a zero space-charge tracking simulation of the LENS beamline using the code TURTLE [4]. Fig. 2 shows plots of the initial beam phase space. We assume that the beam has zero initial energy spread and that the beam bunch is uniform in the longitudinal direction with an initial bunch length of 1.5 cm. In our simulations, the distance between: 1) the first octupole and the quad is 0.12 m, 2) the quad and the second octupole is 2.4 m, and 3) the second octupole and the target is 7.0 m.

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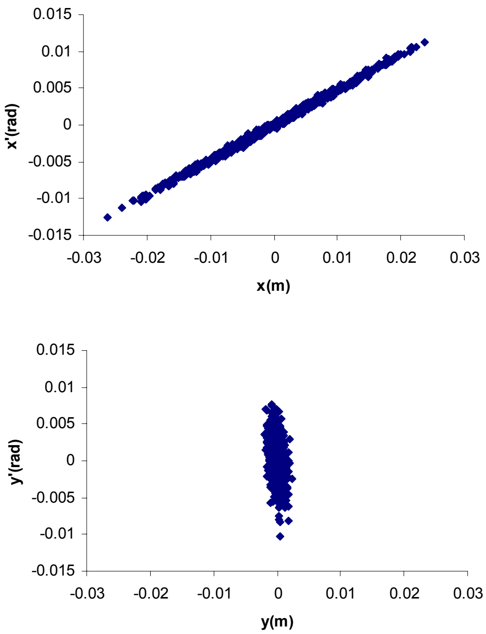

Figure 2: Plots of the initial transverse phase space immediately before the first octupole.

The simulation tracks the trajectories of M=1000 macroparticles, which each have a mass $m = Nm_p$ and a charge $q = Ne$, and where $Q = NMe$ is the total charge per bunch. The space-charge forces on the i^{th} simulation macroparticle are computed using a free-space interaction and are given by:

$$\vec{F}_{\perp i} = \frac{e^2 N^2}{4\pi\varepsilon_0 \gamma} \sum_{i \neq j} \frac{\vec{r}_{\perp i} - \vec{r}_{\perp j}}{\left[\left(\vec{r}_{\perp i} - \vec{r}_{\perp j}\right)^2 + \gamma^2 \left(z_i - z_j\right)^2\right]^{3/2}} \quad (1)$$

$$\vec{F}_{zi} = \frac{e^2 N^2}{4\pi\varepsilon_0} \sum_{i \neq j} \frac{\gamma\left(z_i - z_j\right)}{\left[\left(\vec{r}_{\perp i} - \vec{r}_{\perp j}\right)^2 + \gamma^2 \left(z_i - z_j\right)^2\right]^{3/2}} \ . \quad (2)$$

Equations (1) and (2) include both the self-electric and self-magnetic field components of the beam. These expressions can be readily derived by calculating the self-electric field in the beam rest frame and then Lorentz transforming back to the lab frame. We should note that in deriving the above force expressions, we have assumed that the beam energy spread is small. In the LENS experiment, the beam energy spread is a few percent. In our simulations, we focused our attention on the following beam current values: 25 mA (present LENS value) and 100 mA. Figure 3 shows plots of the beam phase space immediately after the first octupole and the quadrupole, respectively, for the case of the 25 mA beam. The phase space plots for the 100 mA case, look nearly the same as the 25 mA case due to the fact that these two elements are sufficiently close in distance such that the space-charge force has not had time to show a significant difference.

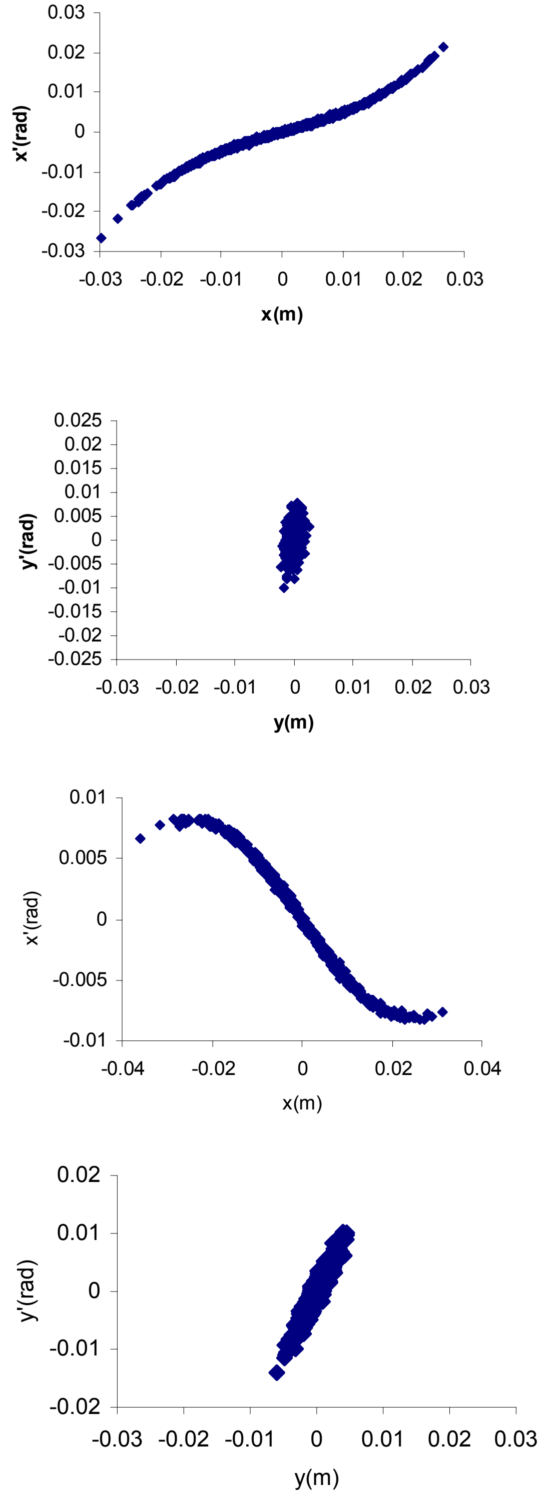

Figure 3: Plots of the transverse phase space immediately after the first octupole and quadrupole, respectively, for 25 mA.

However, at points after the second octupole, one does begin to see important differences in the phase space plots due to space-charge forces. In particular, the phase space plots display a focusing effect in the x-direction and a very slight defocusing effect in the y-direction. Figure 4 illustrates this for the 25 mA (blue) and 100 mA (red) cases.

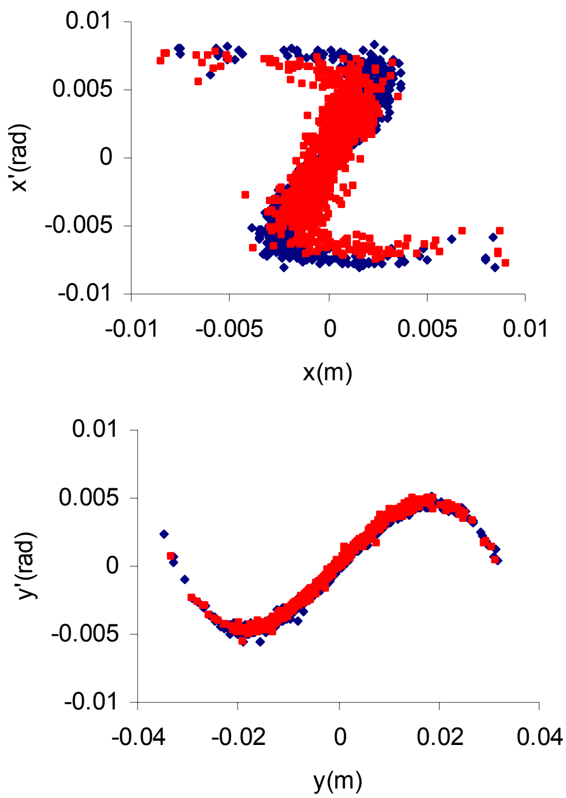

Figure 4: Phase space plots in the x-direction for the 25mA (blue) and 100 mA cases.

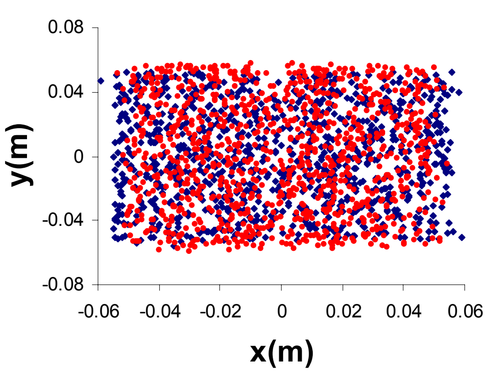

Figure 5: Final distribution at the target for 25 mA (blue) and 100 mA (red).

We find that the final distributions of protons at the target in the presence of space-charge for beam currents in the range of 25 mA-100mA have a noticeable compression (approximately 14%) in the x-direction and an even smaller expansion in the y-direction (approximately 9%). This implies that the beam current density will be slightly increased at the target at 100 mA compared to the 25 mA case which may be important for future LENS beamline designs and/or target design. Figure 5 shows a plot of the beam for 25 mA (blue) and 100 mA (red) at the target and the beam is clearly seen to have additional focusing in x-direction.

The additional focusing in the x-direction for the 100 mA case is largely an effect of the shift in the minimum x-envelope waist. For this particular range of currents, the space-charge force acts to reduce the slope of the x-envelope after the quadrupole. This implies that the minimum of the x-envelope, which is placed near to the second octupole, is not as small with space-charge at 100 mA as compared to without space-charge or at 25mA. And, hence, the divergence of the beam after the minimum in the x-direction will not be as large as without space-charge.

Our simulations do not show much of a difference in the amount of uniformity of the beam across the target. This may in part be due to the number of macroparticles (M=1000) in our simulations. Since we are using a Green's function type algorithm for computing the space-charge forces in equations (1) and (2), our simulation times are proportional to M^2, and hence, this parameter is limited.

For future LENS high-current proton beams which could operate at 100 mA, the combined increase in current, as well as, current density due to focusing in the x-direction may be important. Hence, future space-charge studies of the LENS beamline will be necessary.

REFERENCES

[1] A. Bogdanov, et al. "Commissioning of the New 13 MeV DTL for the Low Energy Neutron Source, EPAC'08 Genoa, June 2008, THPP018, (2008).

[2] P.F. Meads, IEEE Tr ansactions on Nuclear Science, Vol. NS-30, No. 4, p. 2838, 1983.

[3] K.L. Brown, D.C. Carey, Ch. Iselin and F. Rothacker, CERN Report No. 80-4 (1980).

[4] TURTLE, *Trace Unlimited Rays Through Lumped Elements*, D. C. Carey, Fermilab report NAL-64, 1971.