FORMATION OF HIGH CHARGE STATE HEAVY ION BEAMS WITH INTENSE SPACE CHARGE

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Abstract

High charge-state heavy-ion beams are of interest and used for a number of accelerator applications. Some accelerators produce the beams downstream of the ion source by stripping bound electrons from the ions as they pass through a foil or gas. Heavy-ion inertial fusion (HIF) would benefit from low-emittance, high current ion beams with charge state >1. For these accelerators, the desired dimensionless perveance upon extraction from the emitter is $\sim 10^{-3}$, and the electrical current of the beam pulse is ~ 1 A. For accelerator applications where high charge state and very high current are desired, space charge effects present unique challenges. For example, in a stripper, the separation of charge states creates significant nonlinear space-charge forces that impact the beam brightness. We will report on the particle-in-cell simulation of the formation of such beams for HIF, using a thin stripper at low energy.

MOTIVATION

For accelerator applications where high charge state and very high current are desired, space charge effects present unique challenges. For example, in a stripper, the separation of charge states creates significant nonlinear space-charge forces, which impact the beam brightness.

A heavy ion accelerator driver for inertial fusion energy would have unusually high betatron tune depression [1] due to space charge. This is characterized by the ratio of the space-charge depressed phase advance per lattice period to the betatron phase advance, $\sigma/\sigma_o \approx 0.1\text{-}0.2$ through much of the accelerator. Prototype driver-scale injectors (I~ 0.5 A, $\varepsilon_n < 1$ mm•mrad, $\Delta t \approx 5$ μs) have produced single charge (q=1) heavy ions, because of their demonstrated relative charge state purity, low emittance and high current [2]. Thus, most of the related accelerator concepts and studies are for singly-ionized ions. For average accelerator gradients of a few MV/m, the total accelerator length is several km. Higher charge state ions with suitable beam parameters would enable shorter accelerators. Developing high charge state ion sources is one approach. In this paper, we explore the space charge, multiple scattering and straggling implications of stripping a singly ionized beam to a higher charge state shortly after injection.

We note that other accelerator stripper systems have observed some space charge effects [3].

500 MeV, $U^+ \rightarrow U^{12+}$

As a test case, we have chosen beam parameters similar to those that have recently been considered for a heavy-ion fusion driver. The beam stripping energy is 0.5 GeV, and the downstream charge state of interest is q=12, which could be further accelerated to tens of GeV in an accelerator that would be much shorter than an accelerator for q=1 (no stripping). The question is how much beam degradation occurs in the stripping process due to straggling, multiple scattering, and nonlinear space charge forces due to the other charge states created in the stripper, and the alternating dipole fields designed for charge state separation.

The initial current and transverse emittance of the q=1 beam are 11 Amperes and ε_{un} = 10 mm•mr (unnormalized), focused to a space-charge limited waist with a radius of r_i = 5 mm at the entrance of the vapor jet. The longitudinal energy spread is 35 keV, based on the estimated longitudinal emittance of the injected beam into the accelerator. The beam is simulated using the 3-dimensional Warp particle-in-cell [4] code. A 0.1 μs bunch is simulated, shorter than needed for the fusion application (~ 1 μs), but long enough to see space charge effects in a relatively short computation time. Electrons created in the stripping process are followed through the simulation, but they are mostly lost shortly downstream of the stripping target due to charge separation in dipoles. Electrons produced in beam gas interactions and from ions lost to the walls are not included.

We assume that the higher charge states are reached by a series of single-electron-loss interactions, that is $\sigma(q \rightarrow q+1) = 10^{-17}$ cm^2, for all q. For a 3-cm thick vapor jet of Li with density 10^{17} / cc, the charge state distribution leads to a binomial distribution with peak probability of ≈0.11 for charge state 12. The actual situation is more complicated, as shown in [5] for example, where multiple electron loss and electron pickup are considered. However, our simpler model is adequate for studying the magnitude of space charge effects during stripping.

The energy spread from straggling, Ω, will lead to an increase in the longitudinal emittance of the beam. There are experimental data [6] in that are a modest extrapolation from the beam parameters considered, and tabulated for a variety of beam-target combinations. The Bohr energy independent straggling model [7] shows the dominant atomic number and target thickness dependence:

$$\Omega_B^2 = 4\pi Z_1^2 Z_2 e^4 N \cdot \Delta x \qquad (1)$$

Z_1 and Z_2 are the ion charge of the projectile and target (stripper), N is the number density of the target, and Δx is the thickness of the target. Scaling the measurements [6] of straggling of ^{127}I on thin Au targets, (1.4 MeV/amu) to

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^{238}U on ^{7}Li (2.1 MeV/amu) yields Ω = 92 keV. Since this is greater than the injected energy spread, it is not negligible, and may limit the minimum bunch duration at the end of the accelerator.

Multiple scattering can degrade the transverse emittance. However, the projected rms angle, $<\theta^2>^{1/2}$ = 0.28 mrad due to small-angle Rutherford scattering [8] is smaller than the characteristic emittance angle, $\theta_e \approx (\varepsilon_{un}/r_i) = 2$ mrad.

We have modeled a simple chicane consisting of four idealized dipoles (d1, d2, d3, d4) with hard edge fields (L = 0.75 m, B=3.5 T). There are no gaps between the magnets. The dipole bends exert a strong kick on the beam to disperse the charge states, as illustrated in Fig. 1. Midway through the chicane the transverse displacement of the q=12 beam centroid is 0.7 m. An aperture is located after d2 to prevent transmission of most of the undesirable charge states.

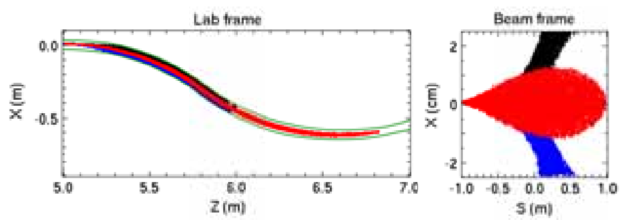

Figure 1: Particle distribution partway through the four-dipole chicane, and downstream of the stripper. Red: q=12, blue: q>12, black: q<12. The initial current of the beam was reduced by a factor 10^{-6} from the nominal case to 11 µA. At this low current, only the q=12 ions pass through the aperture downstream of d2 and all other charge states are rejected.

Emittance growth of the beam was followed through the stripper and in the downstream sequence of dipoles in the chicane. In a series of simulations, the input current was varied and the resulting emittance growth is greatest for the highest current, showing that space charge effects are dominating the phase space evolution (Fig. 2). Though the emittance growth is as much as 4x the initial emittance, it is significantly less than the simulated growth of a beam without charge state separation. In the case of I_o = 11 A, a few percent of unwanted charge states leak into the system through the aperture, and the transmission of the q=12 ions is only 0.5. This can probably be improved by optimization of the aperture dimensions, the dipole field strengths and dimensions.

SUMMARY

We have modeled the phase space evolution of a very high space charge beam passing through a stripper. Energy spread in the stripper will increase the longitudinal emittance. Transverse emittance growth due to space charge is significant, but magnetic separation of charge states after the stripper can lower the emittance growth.

Further studies are needed to clarify whether effects and considerations not included in the modeling described here are important. For example, the PIC simulations could eventually include realistic field models for the dipole magnets, more accurate stripping and charge exchange cross sections, and electron generation in the chicane from beam gas and beam wall interactions.

On the design of a realistic implementation in a heavy ion driver for inertial fusion, there are several challenges: gas load, heat load on stripping target, and implementation in a multiple beam linac where many beams are in close proximity to each other.

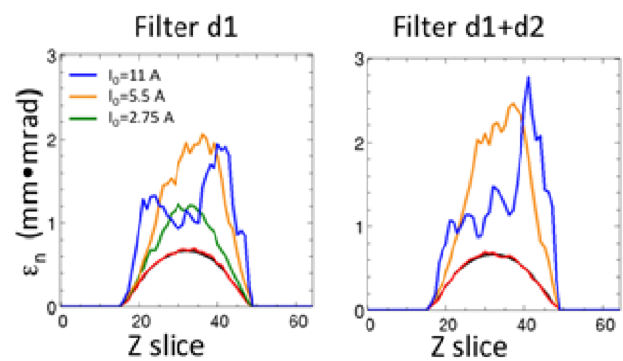

Figure 2: Emittance of the beam after the stripper, and partway through the four-dipole chicane. The left and right plots show the emittance after d1 and after d2 respectively. The green, orange and blue curves correspond to the downstream emittance for different initial currents, as indicated by the legend.

REFERENCES

[1] R. O. Bangerter, Il Nuovo Cimento **106 A** No. 11, 1445 (1993), and A. Friedman, Nucl. Inst. and Meth. **A544**, (2005) 160.
[2] F. M. Bieniosek et al., Phys. Rev. ST-AB **8**, 010101 (2005).
J. W. Kwan et al., Rev. Sci. Instrum. **77**, 03B503 (2006).
L.R. Prost et al., Phys. Rev. ST-AB **8**, 020101 (2005)
[3] W. Barth et al., (2010) Proc. LINAC10 http://silver.j-parc.jp/linac10/MOP044.PDF
[4] D. P. Grote et al., Nucl. Inst. Meth. **A464**, 563 (2001).
[5] L. Wu and G. H. Miley, J. Phys: Conf. **112** (2008) doi:10.1088/1742-6596/112/3/032030.
[6] S. Ouichaoui et al., Nucl. Instr. and Meth. **B164** (2000) 259.
[7] N. Bohr, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. **418** (1948) 8.
[8] J.D. Jackson, *Classical Electrodynamics*, Wiley, 3rd Ed., (1999) ch 13.