SIMULATION STUDY OF EMITTANCE GROWTH FROM COULOMB EXPLOSION IN A CHARGE SEPARATOR SYSTEM AFTER STRIPPING*

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Abstract

A computer 3D particle-in-cell (PIC) simulation is used to examine the emittance growth of an intense heavy ion beam after a charge stripper. Multi-species dynamics of the bunched uranium beam with various charge states and including compensation electrons will be presented. The rms-emittance growth shows different behaviour in the horizontal, vertical and longitudinal planes, dependent on initial conditions, like a bunch size, beam current and phase space ellipse orientation. An optimization of initial parameters is therefore crucial for a successful and efficient post-acceleration. The role of the separation system and of co-moving electrons will be discussed for the example of the GSI-Unilac.

INTRODUCTION

The increase of the beam intensity in heavy ion accelerators involves substantial challenges in design and development along the whole accelerator chain. Especially, in sections of high charge densities, as behind stripping sections, it is possible to expect the space charge dominated emittance growth. Such a growth and a variation in all spatial dimensions is crucial and limiting for the design of the post-stripper accelerating sections.

In this work, we concentrate on space charge effects in a single heavy ion bunch, just after stripping, and do not considering the stripping process in a detail. Fig.1 shows the situation schematically. Arriving heavy ions of charge Z (e.g. U^{4+}) and velocity v_i increase charge state in average to Z+N after stripping. However, stripping process produces more side charge states with different efficiency too. The particle velocity stays constant in our model, therefore all charge species are co-moving and contributing to the space charge. Depending on initial bunch conditions and external forces, the electrostatic field energy of multi species transforms into the kinetic energy in various ways.

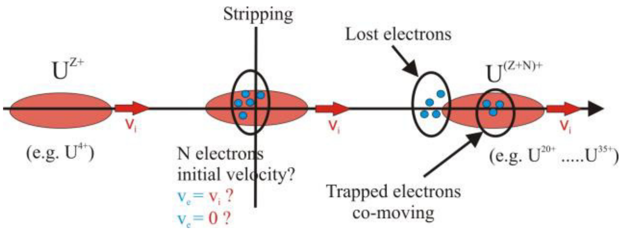

Figure 1: Schematic view on a studied Coulomb explosion of the heavy ion bunch.

For further species selection, a charge state separator consisting of an achromatic system of dipole magnets and a selection slit is used. A critical part, with respect to the space charge and the emittance growth, is located immediately after stripping, where the bunch potential reaches the maximum value. Such a strong repulsion, called also Coulomb explosion, was studied in a case of uniformly charged spheroids and zero initial emittances in works [1-2]. Here, we present results for a more particular case of initial conditions (multi species, non-zero initial emittances), for the example of the GSI-Unilac charge state separator (Fig. 2).

We focus an additional attention on secondary electrons produced at a stripping process, which helps to compensate the space charge repulsion fractionally. After separation from the moving bunch, momentum exchange between electrons and ions species take a part. This has influence on a beam quality and is therefore important for the next accelerating section.

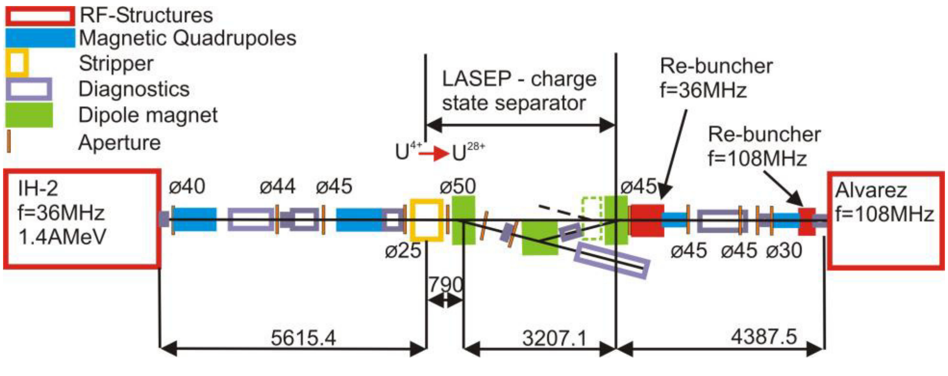

Figure 2: Example of a stripping section and charge state separator of the GSI-Unilac used for the simulation study.

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SIMULATION

Numerical simulations were completed using two PIC codes, the LORASR code [3] and the LASIN code [4]. First half of the single species U^{4+} bunch transport (W = 1.4 AMeV, I = 15 emA), from IH-2 to the gas-stripper position (Fig. 2), has been performed using the LORASR code. The simulation showed no significant emittance growth in this part. The resulting phase space distribution is shown in the Figure 3. The LASIN reads the output distribution of the LORASR and generates the new, multi-species, multi-charge states distribution with same emittances. The gas-stripper itself is considered as a black box. Due to the oversampling of the original data, the code adds a small Gaussian noise to the 6D coordinates, thus no macro-particles with identical coordinate exists.

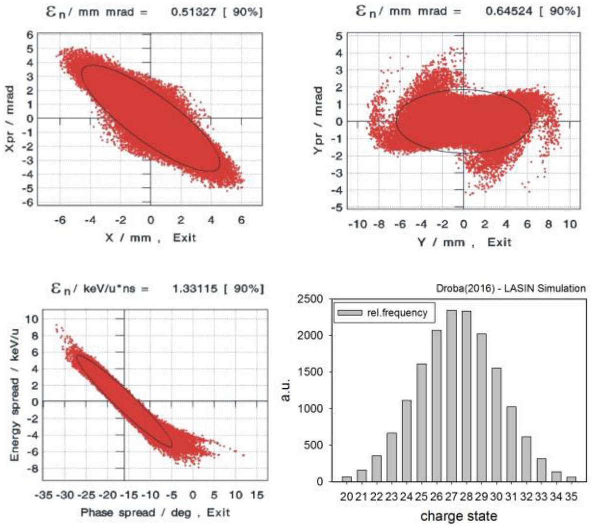

Figure 3: Phase space distribution at the position of the gas-stripper. The corresponding frequency is f=36MHz Numerically generated charge states are shown on the bottom right.

LASIN completed the further multi-species bunch transport, from the gas-stripper position to the separation slit, which is located after the first 15° bending magnet. In this part, major space charge effects with strong emittance growth occurred.

The following parameters were used: the time step $\Delta t = 6 \cdot 10^{-11}$ s, cylindrical mesh dimensions $\Delta r = 1$ mm, $\Delta z = 2$ mm and $\Delta\varphi = 0.21$ rad, the simulated distance L = 1 m electric current I = 15 emA for U^{28+}. The numerical simulations were performed on 42 computer nodes of the FUCHS cluster (Center for Scientific Computing) at the Frankfurt University.

ELECTRONS

Secondary electrons are produced physically by a stripping process from uranium ions and by impact ionization in a gas jet.

Electrons tracking starts in our study at the gas-stripper position. Two models use different starting average velocities, the static electron distribution with $\overline{v_e} = 0$ and the co-moving electron distribution with $\overline{v_e} = \overline{v_\iota}$. The overall charge density remains constant before and after a stripper, thus the charge density for a U^{4+} bunch before stripping is equal to the charge density after a stripping process – here we consider all uranium charge states and electrons together.

RESULTS

First, we performed study without space charge, to evaluate dispersion effects of the intrinsic energy spread of the incoming bunch from the IH-2 structure. We use these results in a comparison and as a reference for the studies with space charge. Figure 4. , the graph on the left, shows the energy spread of about ±0.5% in the kinetic energy.

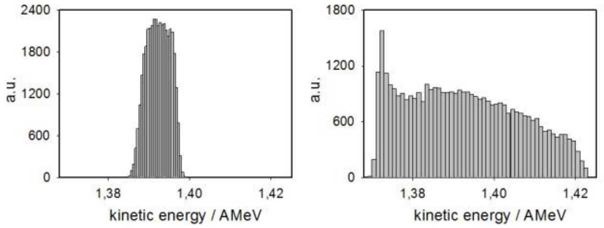

Figure 4: Energy distribution of the U^{28+} charge state located at a position behind the first dipole magnet without space charge (on the left) and with full space charge without compensation electrons (on the right).

In contrast, the simulation data with full space charge and without electrons show a maximum value of about ±1.9%. This is a large change, which is caused by electrostatic field energy stored in the bunch after the stripping process. The electric potential reaches 5kV in the maximum, just behind the gas-stripper, and this value is enough, to trap and to drag secondary electrons within the moving bunch. The co-moving electrons reduce the self-repulsion forces in the section between the gas-stripper and the first dipole magnet. Finally, electrons are stopped in their co-moving in a fringing field of the dipole magnet. The energy spread is partially reduced (Fig. 5).

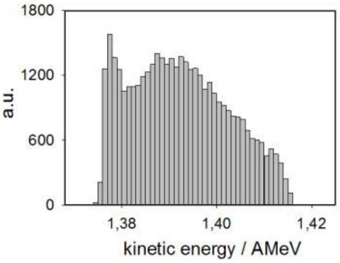

Figure 5: Energy spread at a position behind the first dipole magnet in the simulation with space charge and co-moving electrons.

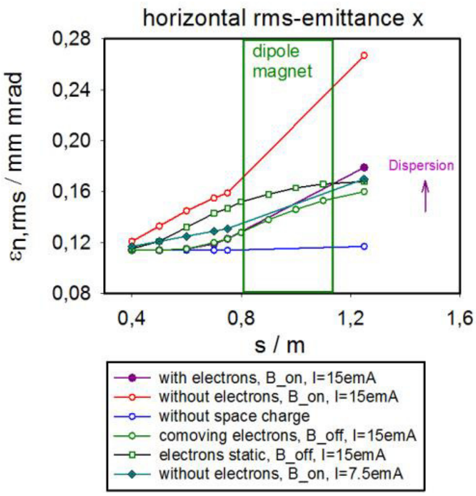

Figure 6: Emittance growth in the horizontal plane. Gas-stripper is located at s = 0.3 m.

The next evaluated parameter is the emittance of the desired species U^{28+} along the beam line. The strongest emittance growth appears in all planes in the case with full space charge (Fig. 6 – 8, red curve). The results show largest growth factor of about 4 in the longitudinal plane, while the factor in other planes is two times smaller. This effect is caused by initial bunch dimensions (in this work we have used a cigar-shaped bunch with dimension ratio *z/r ~ 2*) and they can be adjust by the focusing strength.

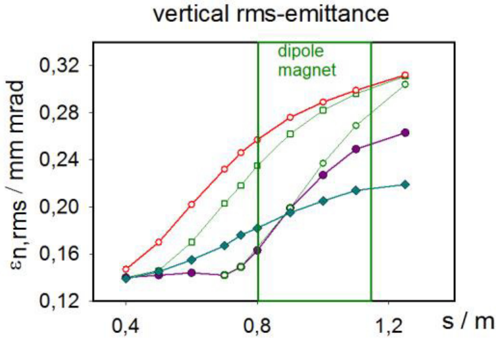

Figure 7: Emittance growth in the vertical plane. (Legend – see Fig. 6).

Coulomb explosion with secondary electrons was simulated without disturbing magnetic field as a next step (Fig. 6 – 8, green curves). Two models of secondary electrons show different growth rates from the start position, but almost the same emittance at the end. There is also clear difference to the case with a bending magnet switched on (Fig. 6 – 8, purple curve). The emittance growth is less in the vertical and longitudinal planes, while it is higher in the horizontal plane.

CONCLUSION

We have performed studies on the emittance growth of an intense heavy ion beam in a first part of the charge separator system. The growth is not negligible small and is strong dependent on the starting conditions. Electrostatic field energy, produced by a stripping process, gives basic limitations on a system. Influence of the initial aspect ratio of the bunch dimensions were discussed and seems to be important for the emittance ratio control.

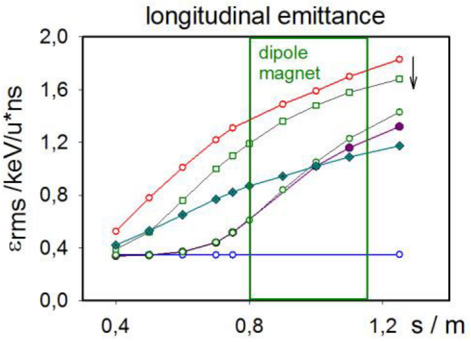

Figure 8: Emittance growth in the longitudinal plane (Legend – see Fig. 6).

The space charge compensation with secondary electrons improve the beam dynamics, however magnetic dipole field inhibits the efficiency. Thus, new and active strategies for the space charge compensation in dipole magnets seems to be necessary [5].

Further studies are planned to complete the beam transport through the whole system. The goal is to study the violation of the achromatic properties of the system and to find the optimum parameters for the minimum emittance growth.

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