BEAM DYNAMICS AND INSTABILITY IN FINAL BEAM BUNCHING FOR HEAVY ION INERTIAL FUSION

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Abstract

Emittance growth and beam dynamics are investigated by a particle simulation for longitudinal bunch compression in an accelerator system of heavy ion inertial fusion. Rapid bunch compression in final stage of the driver system causes the emittance growth. Particle simulations are carried out at various initial particle distributions, and the emittance growths during the final beam bunching are considered.

INTRODUCTION

Studies on space-charge-dominated beam are crucial issue in inertial confinement fusion (ICF) [1] by using an intense-heavy-ion beam, i.e. heavy ion inertial fusion (HIF) [2,3]. In the ICF, energy of several MJ must be injected for a short time to a fuel pellet. The target pellet irradiated by the energy driver is rapidly imploded. The implosion can cause high energy density state at the center of the pellet, and a lot of thermonuclear reactions are expected by the high temperature and dense plasma of the fuel. The intense heavy-ion beam is one of the influential candidates as the energy driver for ICF system.

However, the required parameters of heavy ion beam are several GeV particle energy, 100 kA total current, and around 10 ns short pulse duration, so that the beam parameters are far from those of conventional particle accelerator. To this end, the beam dynamics and control are important research issue. In the final stage of HIF driver system, the beam pulse must be longitudinally compressed from 100 to 10 ns. For this purpose, induction voltage modulators, which have precise waveform controllability, are useful device [4]. For the effective pellet implosion, we should transport and compress the bunch of heavy ion beam without emittance growth as possible. A final focus and beam irradiation are crucial [5], but large emittance interferes the focusing to the small fuel pellet. For this reason, the final beam bunching is key technology in the HIF driver system.

There is beam instability caused by space charge oscillation [6-8]. The instability has threshold on strength of the space charge effect. When the tune depression is lower than 0.4, the beam transport may be unstable due to the instability induced by the space charge effect. In the region of the final beam bunching, the intense heavy-ion beam just becomes the space-charge-dominated beam, and passes through the threshold.

In this study, we investigate the beam dynamics during the longitudinal bunch compression in the final beam bunching. Numerical simulation using particle-in-cell (PIC) method is carried out for the consideration of particle behaviour. The emittance growth is calculated and is compared with various types of initial particle distribution.

TRANSVERSE PARTICLE BEHAVIOUR

In this study, the beam dynamics simulation requires fully three-dimensional numerical scheme. From the viewpoint of the computational cost, such full calculations are difficult. While the longitudinal bunch length is of the order of meter, the scale of the transverse cross section is only a few cm in the regime of final beam bunching [9]. As a result, the small-scale phenomena will be dominated by the transverse beam dynamics. We deal with the particle dynamics in the transverse cross section of the beam by multi-particle simulation, and the effect of longitudinal compression is introduced as the beam current increase [10].

The PIC method is used for descriptions of the

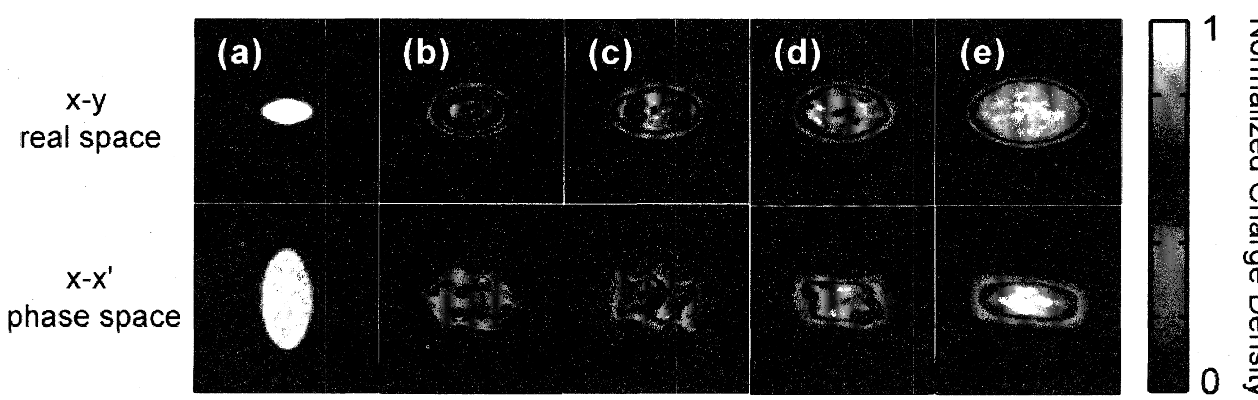

Figure 1: Normalized charge density in initial KV beam on real (top) and phase (bottom) spaces, (a) at initial condition, (b) at 87 l.p., (c) at 96 l.p., (d) at 108 l.p., and (e) at last (150 l.p.), respectively.

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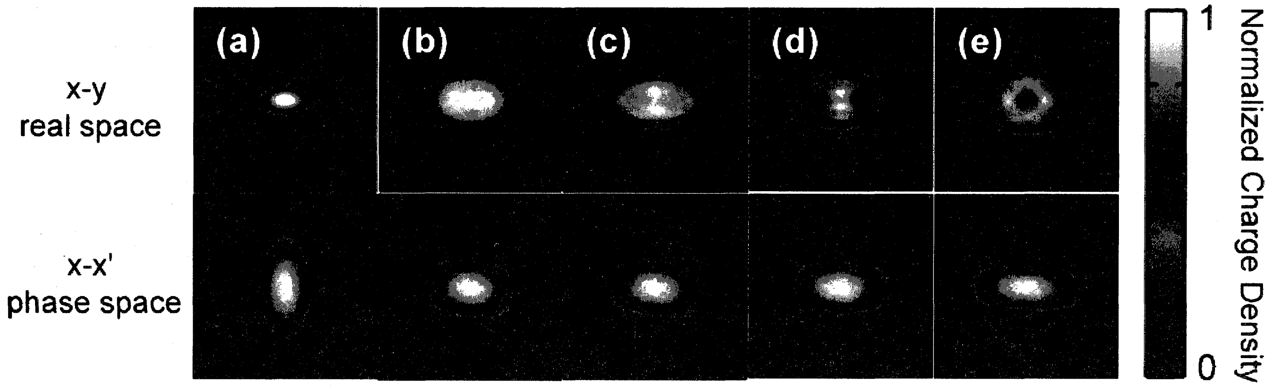

Figure 2: Normalized charge density in initial WB beam on real (top) and phase (bottom) spaces, (a) at initial condition, (b) at 87 l.p., (c) at 96 l.p., (d) at 108 l.p., and (e) at last (150 l.p.), respectively.

transverse behaviour with the longitudinal compression, the effect of which was evaluated by assuming linear increase of the beam current. The charge and mass of the super particles are increased and the ratio performs the reweighting of the super particle with the beam transport [10].

The beam parameters were assumed as Ref. [3], and the final bunch compression ratio is 25. The FODO magnetic quadrupole lattice is used for the beam transport. From the estimation by the longitudinal envelope equation, the total induction buncher length is assumed as 450 m with FODO unit of 3 m [9]. The transverse calculation region is fixed at 10 cm x 10 cm, and the boundary condition is given as a conductor wall. The Kapchinskij-Vladimirskij (KV) [11], waterbag (WB) [12], Gaussian (GA) [12], and semi-Gaussian (SG) [13] distributions are given as the initial condition.

Figure 1 shows the charge density maps of the beam ions in physical and phase spaces at each lattice period (l.p.) for initially KV distributed beam. In the real space maps, the horizontal and vertical scales correspond to the full calculation region. The charge density is normalized by the maximum value at each map. The beam radius is extended with the beam current increase due to the longitudinal bunch compression. As shown in Fig. 1, localized charge distribution in real space and the dilution of the beam particle in phase space are indicated during the final beam bunching. Also, qualitatively similar behaviours with KV beam are observed in WB distribution as shown in Fig. 2. On the other hand, as shown in Fig. 3, the localized charge density is not formed in the initial GA beam. Figure 4 shows the normalized charge density with initial SG beam. In the case of SG beam, the behaviours are almost the same as GA case.

EMITTANCE GROWTH

We define the average of unnormalized transverse rms emittance as $\varepsilon=(\varepsilon_{x,rms}+\varepsilon_{y,rms})/2$. The initial emittance is assumed at $\varepsilon_i=\varepsilon_{x,rms}=\varepsilon_{y,rms}=10$ mm mrad. At each initial distribution, the evolution of the emittance ratio $\varepsilon/\varepsilon_i$, which indicates the ratio of the average emittance and initial one at each lattice period, is shown in Fig. 5. As shown in Fig. 5, the emittance abruptly increases after 80 l.p. in the case of initial KV beam. As similar to the result of KV distribution, the emittance at initial WB beam is steeply increased over 90 l.p. The initial GA and SG beam cases cause the gradual increase of the emittance without abrupt growth. The final emittance ratios at 150 l.p. are around 1.23, 1.15, 1.12, and 1.08 in the initially KV, WB, GA, and SG distributed beams, respectively.

The space-charge-dominated beam plays as nonneutral plasma, and the collective behaviour causes the

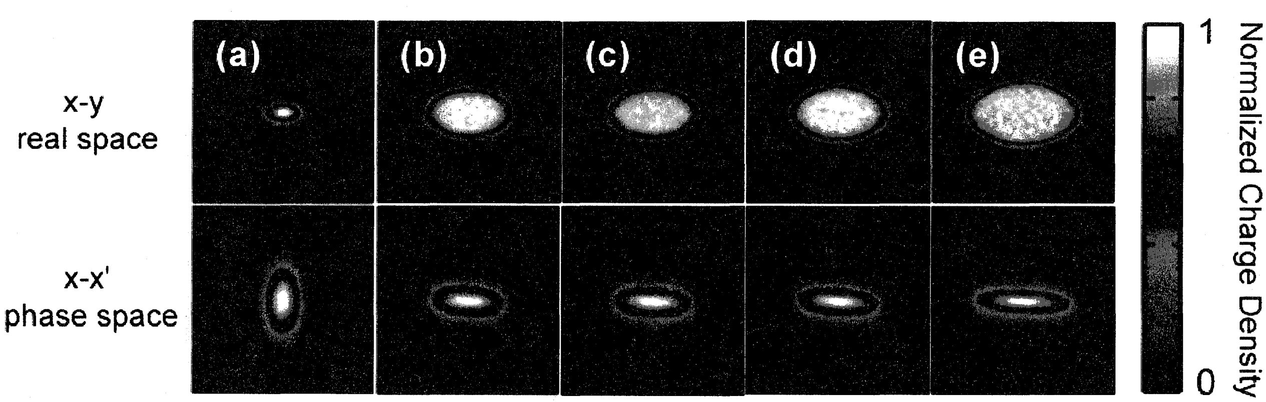

Figure 3: Normalized charge density in initial GA beam on real (top) and phase (bottom) spaces, (a) at initial condition, (b) at 87 l.p., (c) at 96 l.p., (d) at 108 l.p., and (e) at last (150 l.p.), respectively.

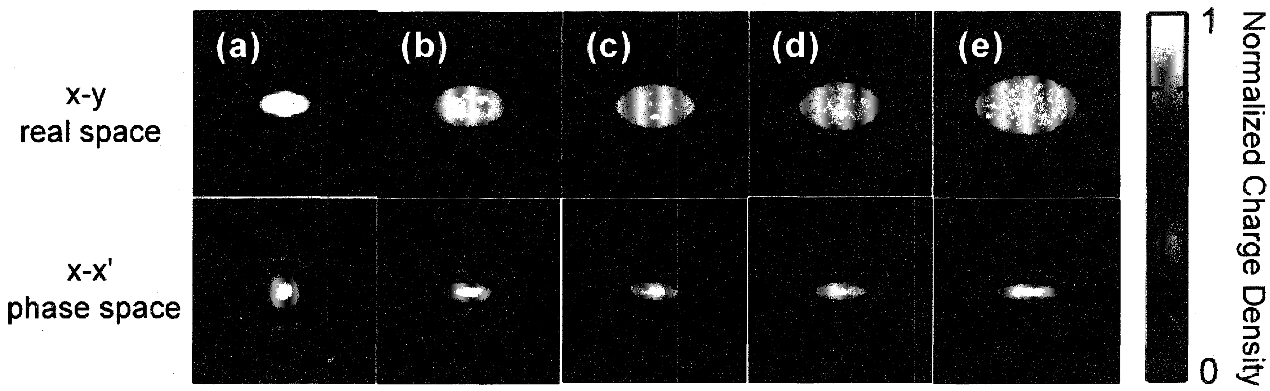

Figure 4: Normalized charge density in initial SG beam on real (top) and phase (bottom) spaces, (a) at initial condition, (b) at 87 l.p., (c) at 96 l.p., (d) at 108 l.p., and (e) at last (150 l.p.), respectively.

restructuring of the space charge distribution. The localized particle distribution in the beam interior is observed in Figs. 1 and 2, and the abrupt increase of emittance is also confirmed as shown in Fig. 5. Unstable beam transport caused by azimuthally symmetric flute perturbation is known as one of instabilities due to the space charge effect [7,8]. At each mode number of the flute perturbation, the dispersion relation in KV distribution can give growth rate of the instability. These analytical considerations suggested that the emittance growths observed by the particle simulations in the case of KV and WB beams are attributed to the instability due to the collective behaviour of space-charge-dominated beam during the final beam bunching [14].

CONCLUSION

In HIF driver system, the transverse beam dynamics was investigated during the final beam bunching. The transverse PIC simulation with the increase of the beam current, as a model of the longitudinal bunch compression, was carried out for the study of the beam transport.

As a result, the numerical simulations indicated that the beam is bunched accompanied by the restructuring of charge density distribution and emittance growth during the final beam bunching. The initially KV and WB distributed beams caused abrupt emittance growth due to the instability induced by the space charge effect. On the other hand, it is expected that initial GA and SG beams may pass through the final beam-bunching region without instability excited by space charge oscillation.

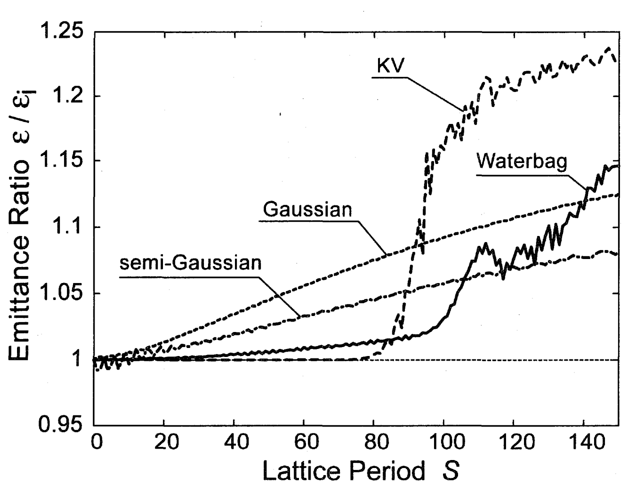

Figure 5: Emittance ratio at each initial particle distribution as a function of lattice period.

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