EMITTANCE GROWTH AND PARTICLE DISTRIBUTIONS DURING FINAL BEAM BUNCHING IN HEAVY ION FUSION DRIVER

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Abstract

Emittance growth and particle distribution in transverse direction of the beam are investigated during final beam bunching in driver system for heavy ion inertial fusion. Multiparticle simulations for various particle distributions at initial condition predict the emittance growth during the longitudinal bunch compression. Particle distributions in the transverse cross section of the beam are changed with the emittance increases.

INTRODUCTION

Space-charge-dominated beam physics is crucial in heavy ion inertial fusion (HIF). In the HIF, energy of several MJ should be injected as a short time pulse 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. The intense heavy-ion beam is one influential candidate as the energy driver.

Although, the required parameters of heavy ion beam are several GeV particle energy, 100 kA total current, and around 10 ns short pulse duration [1], the beam parameters are far from those of conventional particle accelerator system. To this end, the beam dynamics and control are important research issues in HIF. In the final stage of HIF driver system, the beam pulse must be longitudinally compressed from 100 to 10 ns [1, 2]. Induction voltage modulators, which have precise waveform controllability, are useful device for this purpose [3]. For the effective pellet implosion, we should transport and compress the bunch of heavy ion beam without emittance growth as much as possible. A final focus and beam irradiation are crucial, but large emittance interferes the focusing to the small fuel pellet [4]. For this reason, the final beam bunching is key technology in the HIF driver system.

There is beam instability caused by space charge oscillation, and 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 [5]. In the region of final beam bunching, the intense heavy-ion beam just becomes the space-charge-dominated beam, and passes through the threshold [6]. Not only the instability, also dilution of particle distribution can cause the emittance growth [7]. Nonequilibrium particle distribution will approach to thermal equilibrium state during the final beam bunching.

In this study, we investigate the beam dynamics during the longitudinal bunch compression in the final beam bunching. Multiparticle simulation using particle-in-cell (PIC) method with the longitudinal bunch compression model is carried out for the consideration of transverse particle behaviors. The emittance growth is calculated and is compared with various types of initial particle distribution. The particle distributions during the final beam bunching are also discussed by nonlinear field energy factors.

CALCULATION MODEL AND BEAM PARAMETERS

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 estimated as only a few cm in the regime of final beam bunching [8]. 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 multiparticle simulation, and the effect of longitudinal compression is introduced as the beam current increase.

The PIC method is used for descriptions of the transverse behavior with the longitudinal compression, the effect of which was evaluated by assuming linear increase of the beam current in this study. The charge and mass of the super particles are increased and the ratio performs the reweighting of the super particle with the beam transport [9]. In this study, the number of total simulation particles is 3×10^6, and the meshes of 512×512 in the transverse plane are used for the resolution of Debye length scale [6].

The beam parameters were assumed as Table 1 [2], so that the final bunch compression ratio is 25. The magnetic quadrupole lattice of focusing-drift-defocusing-drift (FODO) configuration is used for the beam transport [10]. From the estimation by the longitudinal envelope equation, the total induction buncher length is assumed as 450 m with FODO unit of 3 m [8]. The transverse calculation region is fixed at 10 $\times$ 10 cm, and the boundary condition is given as a conductor wall. The Kapchinskij-Vladimirskij (KV), waterbag (WB), Gaussian (GA), semi-Gaussian (SG), and parabolic (PA) distributions [10] are given as the initial condition.

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Table 1: Beam parameters for final beam bunching in HIF [2]

Ion species	Pb^{1+}
Number of ions	6.25×10^{14}
Particle energy [GeV]	10
Initial beam current [A]	400
Final beam current [kA]	10
Initial pulse duration [ns]	250
Final pulse duration [ns]	10

EMITTANCE GROWTH DURING FINAL BEAM BUNCHING

The emittance value is used for the evaluations of beam transport quality. We define the average of unnormalized transverse rms emittance ϵ as

$$\epsilon = \frac{\epsilon_{x,rms} + \epsilon_{y,rms}}{2}, \tag{1}$$

where $\epsilon_{x,rms}$ and $\epsilon_{y,rms}$ are the unnormalized rms emittances for horizontal and vertical directions, respectively. The initial emittance is assumed at $\epsilon_i = \epsilon_{x,rms} = \epsilon_{y,rms} =$10 mm mrad. At each initial distribution, the evolution of the emittance growth ϵ/ϵ_i, which indicates the ratio of the average emittance and initial one at each lattice period, is shown in Fig. 1. As shown in Fig. 1, the emittance abruptly increases after 80 lattice periods 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 lattice periods. These rapid emittance increases are confirmed as result of the beam instability due to the strong space charge effect during the final beam bunching [6]. On the other hand, initial GA, SG, and PA beams cause the gradual increase of the emittance without abrupt growth. The final emittance growth ratios at 150 lattice periods are around 1.15, 1.14, 1.12, 1.08, and 1.05 in the initially KV, WB, GA, SG, and PA distributed beams, respectively.

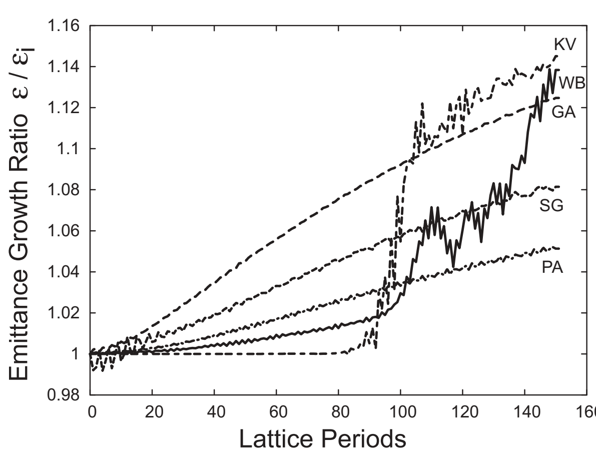

Figure 1: Emittance growth during the final beam bunching at each initial distribution.

PARTICLE DISTRIBUTIONS DURING FINAL BEAM BUNCHING

The particle distribution inside one beam is also important for the uniformity of beam irradiation in a low-number beam system [4]. As a figure of merit for the uniformity of charge distribution in real space inside one beam, the nonlinear field energy factor is defined by U/w_0 [10, 11]. The field energy difference U is given by

$$U = w_n - w_u, \tag{2}$$

where w_n and w_u are the field energies per unit length in the cases of nonuniform and uniform beams, respectively. The field energy per unit length within the actual beam volume is written as [10, 11]

$$w_0 = \frac{I^2}{16\,\pi\,\epsilon_0\,v_z^2}, \tag{3}$$

where I is the beam current, ϵ_0 is the permittivity of free space, and v_z is the longitudinal beam velocity, respectively. The nonlinear field energy factor expresses the degree of uniform charge distribution in real space, i.e., the charged particles are distributed uniformly if $U/w_0 = 0$. Figure 2 shows the nonlinear field energy factor given by PIC simulation during the longitudinal bunch compression [12]. Although each of the distributed beams has various nonlinear field energy factor at the initial condition, the factors approach zero after the final beam bunching as shown in Fig. 2. As a result, the transverse particle distribution in real space approaches uniform density during the final beam bunching [12].

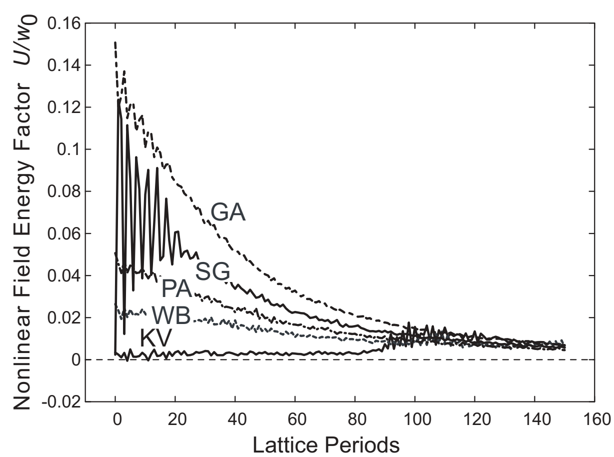

Figure 2: Nonlinear field energy factor during the final beam bunching at various initial distributions.

Also the ratio of emittance growth possibility can be estimated by the nonlinear field energy factor during the final beam bunching. The possible emittance growth ϵ_f/ϵ_i is given as [10, 11]

$$\frac{\epsilon_f}{\epsilon_i} = \left[1 + \frac{1}{2}\left(\frac{\sigma_0^2}{\sigma^2} - 1\right)\frac{U}{w_0}\right]^{\frac{1}{2}}, \tag{4}$$

where σ and σ_0 are the phase advance per lattice period with and without space charge effect. Figure 3 shows the possible emittance growth for initial KV and GA beams during final beam bunching. In this case, the depression

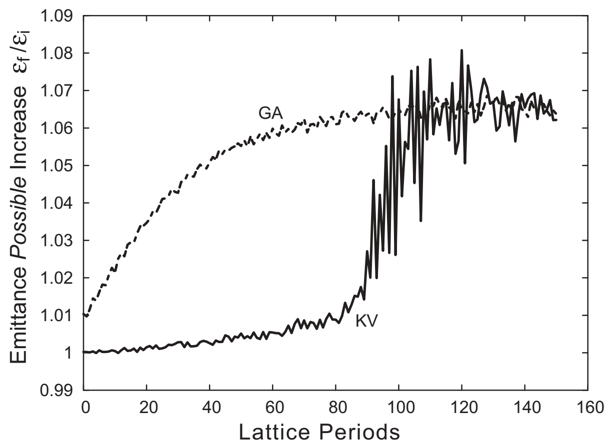

Figure 3: Possible emittance increase during the final beam bunching at initial KV and GA distributions.

of phase advance σ/σ_0 is assumed as the value of tune depression [6]. As shown in Fig. 3, the initial KV and GA beams have same value of the possible emittance increase. However the emittance growth for the initial KV beam is lager than the value for the initial GA beam as shown in Fig. 1. These results indicate that the beam instability due to the strong space charge effect may cause the additional emittance growth during the final beam bunching.

CONCLUSION

In this study, the transverse beam dynamics was investigated during the final beam bunching in HIF driver system. 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.

Although the initially KV and WB distributed beams caused abrupt emittance growth due to the instability induced by the space charge effect, it is expected that initial GA, SG, and PA beams may pass through the final bunching region without instability excited by space charge oscillation. The emittance growth can be estimated as 15% at the highest in this study.

The nonlinear field energy factors indicated that the transverse particle distribution inside one beam approaches uniform density after the final beam bunching. Also the possible emittance growth given by the nonlinear field energy factor may be able to predict that the additional emittance growth is caused by the beam instability due to the strong space charge effect.

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