Kinetic Energy Partitioning Between Longitudinal and Transverse Directions of Beam using Compact Electron Beam Simulator for Final Pulse Compression in Heavy–Ion Inertial Fusion

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ABSTRACT

Kinetic energy partitioning between longitudinal and transverse directions of beam bunch was studied for longitudinal pulse compression during final stage of energy driver in heavy–ion inertial fusion. Beam parameters were corresponded with experimental parameters of compact electron beam simulator. The kinetic energy equipartition was estimated by the multi–particle simulation results. It was expected that the equipartition in a theoretical approach is underestimated in comparison to the numerical simulation result.

Keywords

Heavy–Ion Inertial Fusion, Space–Charge–Dominated Beam, Space Charge Effect, Pulse Compression, Equipartitioning, Compact Beam Simulator

1 Introduction

In an energy driver of heavy ion inertial fusion, beam dynamics in a longitudinal pulse compression is an important issue for an effective implosion process of a fuel pellet [1]. A large scale of a particle accelerator complex is required to generate intense heavy–ion beams. However it is not suitable for the researches of the beam dynamics from the viewpoint of the cost. For this reason, theoretical and numerical approaches were carried out [2–8], moreover an experimental device by using electron beam was proposed for a scaled simulator [9–12]. It is easy to achieve the space–charge–dominated state in a small experimental device.

The equipartitioning of the longitudinal and the transverse temperatures of the beam is expected in the space–charge–dominated condition [13], and is important topic for the beam dynamics and transport [14, 15]. In this study, the kinetic energy partitioning between the longitudinal and the transverse directions of the beam is discussed with the evolution of the kinetic energies in the compact beam simulator.

2 Calculation Conditions

The numerical simulation is carried out using multi–particle tracking with space charge effect. The calculation box for the numerical simulation and the detail of the calculation conditions are described in Refs. [16–18]. The transverse confinement of the beam is carried out with the pulse solenoidal magnet. The magnetic flux density B_z for longitudinal direction z is given with 11 mT corresponding to the experimental condition. The velocity modulation pulse duration applied by the induction unit is 100 ns. The injected kinetic energy of electrons is 2.8 keV, and the initial pulse duration is 100 ns. After the initial setting, the beam bunch is injected into the modulation gap. The applied voltage $V_{\rm dec}$ is geven by

$$V_{\rm dec} = \frac{m_{\rm e}}{2e}\frac{1}{\left(\sqrt{\frac{m_{\rm e}}{2eV_0}} + \frac{\tau_{\rm p} - t}{L}\right)^2} - V_0, \qquad (1)$$

where $m_{\rm e}$ is the mass of electron, e is the charge of electron, V_0 =2.8 kV, $\tau_{\rm p}$ =100 ns is the pulse duration, t is the time, and L=1.93 m is the drift length for transport. To apply the modulation voltage into the gap, the longitudinal velocity distribution of injected electrons has the head-to-tail velocity tilt. For this reason, the pulse duration of electron bunch is compressed in order to the velocity tilt during the drift transport after the gap.

In the experimental condition, the electron gun emits the electrons, and the electrons accelerate longitudinally to 2.8 keV in quasi-DC mode after the electron emission from the thermal cathode surface. In this study, the initial transverse and longitudinal temperatures are assumed by $T_{\perp} = T_{||}$ = 1000 K, and the temperatures give the velocity spread to the initial particle distribution. For this reason, the longitudinal velocity of particle has the average velocity for injection kinetic energy of 2.8 keV with the thermal velocity spread of 1000 K. The condition is an ideal case starting with the equal temperatures. The initial beam current is -265 μA.

3 Simulation Result

It was found that the longitudinal kinetic energy of the beam particle was converted into the transverse kinetic energy due to the space charge effect [18]. The effective transverse and longitudinal temperatures are evaluated by

$$T_{\perp} = \frac{m_{\rm e}\langle v_{\perp}^2\rangle}{2} = m_{\rm e}\frac{\langle(v_{\rm x} - \langle v_{\rm x}\rangle)^2\rangle + \langle(v_{\rm y} - \langle v_{\rm y}\rangle)^2\rangle}{4}, \qquad (2)$$

and

$$T_{||} = \frac{m_{\rm e}\langle v_{||}^2\rangle}{2} = m_{\rm e}\frac{\langle(v_{\rm z} - \langle v_{\rm z}\rangle)^2\rangle}{2}. \qquad (3)$$

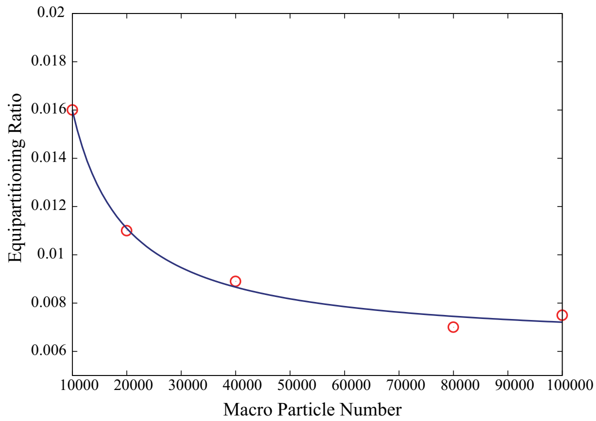

Figure 1: Equipartitioning ratio $T_{\perp}/T_{||}$ as a function of macro (super) particle number $N_{\rm sp}$. The red circle indicates the numerical simulation result, and the solid line indicates the fitting curve of $f(N_{\rm sp}) = 103.78\,N_{\rm sp}^{-1.00695} + 0.00625084$.

Here, $m_{\rm e}$ is the mass of electron, $v_{\perp}$ and $v_{||}$ are the transverse and longitudinal velocities of particle on the beam frame, and $v_{\rm x}$, $v_{\rm y}$, and $v_{\rm z}$ are the particle velocities in x, y, and z directions on the laboratory frame, respectively. The value $\langle X\rangle$ indicated with brackets means the average value of X. The equipartitioning ratio $T_{\perp}/T_{||}$ is obtained by the ratio of Eq.(2) to Eq.(3).

Figure 1 show the equipatitioning ratio at t = 160 nsec (i.e., the maximum compression time) as a function of the number of macro (super) particles used for the numerical simulation. By using the least–square approach, the numerical simulation results are fitted by

$$f(N_{\rm sp}) = 103.78\,N_{\rm sp}^{-1.00695} + 0.00625084, \qquad (4)$$

where $N_{\rm sp}$ is the macro (super) particle number. From Eq. (4), it is expected that the equipartitioning ratio converges on 0.00625084 for $N_{\rm sp} = \infty$.

On the other hand, the theoretical estimation for the equipartitioning ratio indicated as 0.00285 [18]. It is implied that the theoretical result underestimates the kinetic energy equipartition between the longitudinal and the transverse directions.

4 Conclusion

The kinetic energy partitioning between the longitudinal and the transverse directions of the beam was investigated numerically for the longitudinal pulse compression during the final stage of the energy driver in heavy–ion inertial fusion. The beam parameters were corresponded with the experimental parameters of the compact electron beam simulator. The equipartitioning ratio $T_{\perp}/T_{||}$ was estimated as 0.00625084 in the multi–particle simulation results. It was expected that the equipartitioning in the theoretical approach was underestimated in comparisons to one of the numerical simulation.

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