Transverse Particle Distributions of Intense Beams after Final Bunching for Heavy Ion Inertial Fusion

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Transverse particle distributions inside an intense ion beam in a final buncher of heavy ion fusion are discussed using particle simulations. In order to evaluate the uniformity of the particle distribution in one beam, evolutions of the nonlinear field energy factor in the buncher are investigated as a function of presumed initial particle distributions. The results indicate that regardless of the initial conditions, the beam particle distributions come close to a unified one in real space at the final stage.

Keywords:

final beam bunching, particle distribution, heavy ion beam, inertial confinement fusion

In the scheme of heavy ion inertial fusion (HIF), intense heavy-ion beam generation and transport are major research issues [1]. The intense heavy-ion beam is produced by a particle accelerator system, and in the final stage the beam bunch should be compressed longitudinally for the formation of short pulse width. The beam current has an extraordinary value in comparison with the conventional one, thus the beam dynamics is expected to involve many unclarified physical problems. Especially, the dynamics of the space-charge-dominated beam in the final buncher is a critical issue in HIF driver concepts [2,3].

On the other hand, the transverse focusings onto a fuel pellet after the final beam bunching is also an important issue [4]. Multiple beams of 10 to 100 are overlapped on the fuel target for uniform irradiation. In addition to the overlapping configuration, the particle distribution inside the beam is considerably important for the uniformity of beam irradiation in a low-number beam system [4]. Thus the particle distribution in one beam should be accurately estimated in order to define the initial condition of the final focus investigation.

Using particle simulation, we discuss the particle distribution on the cross section of one beam bunch after the final bunching. The beam is transported by the periodic lattice of the magnetic quadrupole lens, which produces a linear external force in the radial direction for the transverse confinement [5]. Space-charge-dominated beams behave as "nonneutral plasma", so that the external force for the beam confinement is shielded by the space-charge field. The space-charge field is enhanced by increasing the beam current during the longitudinal bunch compression. Consequently, it is expected that after the final beam bunching the charge distribution is rearranged in a cross section along the confinement force.

As a figure of merit for the uniformity of charge distribution in real space, the nonlinear field energy factor is defined by U/w_0 [5,6]. The field energy difference U is given by $U = w_n - w_u$, 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 $w_0 = I^2 / 16\pi\varepsilon_0 v_z^2$ [5,6], 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 $U/w_0 = 0$.

The non-uniform field energy is calculated by particle simulation, and w_u is given as the calculation using the envelope ellipse filled by uniform density. The beam envelope ellipse is assumed by effective horizontal and vertical radii [5], which are twice the rms beam radii given by particle simulation. As part of the simulation of beam dynamics, a particle-in-cell method is used in the transverse cross section of the beam by employing the simplified longitudinal bunch

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compression model [2,3]. The parameters for the calculation are assumed as those in the final bunching region of HIF [1-3]. The major parameters are as follows: the current of the Pb^{+1} beam increases linearly from 400 A to 10 kA, $v_z = 9.299 \times 10^7$ m/s, and the unit length of the focusing lattice with focus-drift-defocus-drift (FODO) configuration [5] is 3 m.

Figure 1 shows the nonlinear field energy factor during the final beam bunching. The initial particle distributions are assumed as Kapchinskij-Vladimirskij (KV), waterbag (WB), Gaussian (GA), semi-Gaussian (SG), and parabolic (PA) distributions [5]. Each initial U/w_0 corresponds to the value of Ref. [5], i.e. $U/w_0 = 0$ for KV, 0.0224 for WB, 0.1544 for GA, and 0.0563 for PA distribution [5] before the bunching process. In the case of KV and WB beams, since the space charge oscillation is induced due to the instability during the bunch compression [3], the factors slightly increased around 100 lattice periods as shown in Fig. 1. The SG distribution has uniform charge distribution in real space as well as in the KV beam, so that $U/w_0 = 0$ at the initial state. However, the SG beam is not in an equilibrium state, and the nonlinear field energy factor oscillates due to the conversion between kinetic and self-potential energy in the initial phase [5]. Although each of the distributed beams has various U/w_0 values at the initial condition, the factors approach zero at the final state as shown in Fig. 1, even if the instability during the beam bunching occurs and the distribution is under a non-equilibrium state. This means that the particle distribution in real space approaches uniform density during the final beam bunching, even though the initial distribution is different.

The particle simulations were carried out for the study of the beam dynamics during the final beam bunching of HIF, and the final state of the particle distribution inside one beam was discussed in this paper, using the nonlinear field energy factor. As a result, it is found that regardless of the initial state, the particle distribution approaches the same level of uniformity in real space after the final bunching. This result provides useful information for studies of final focus, beam transport in the reactor chamber, and target irradiation schemes in HIF.

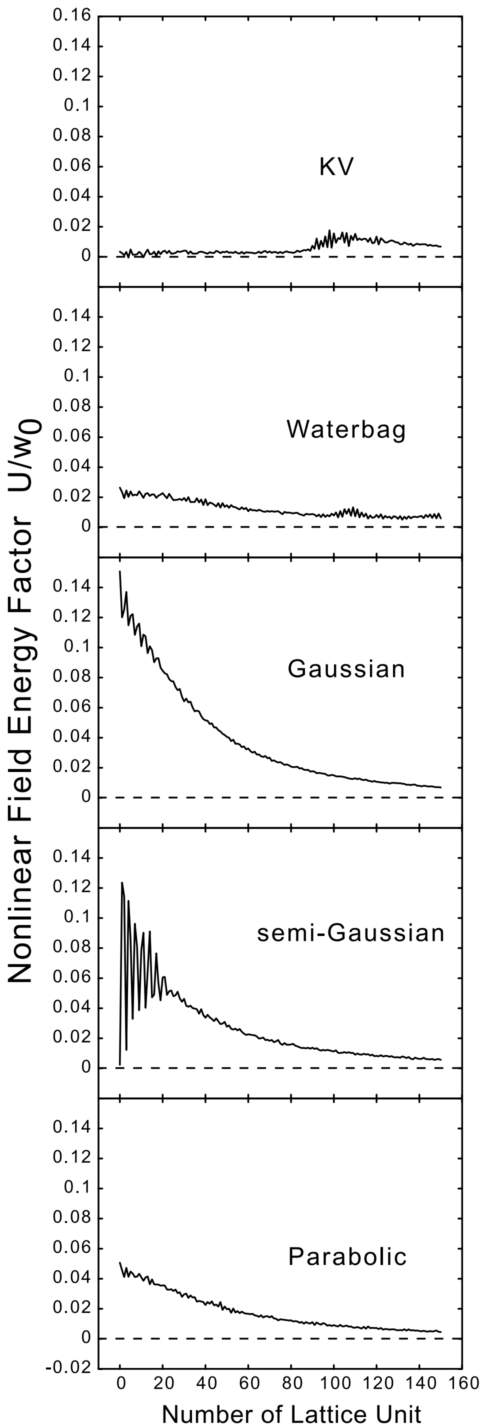

Fig. 1 Evolutions of nonlinear field energy factor along the transport line of final buncher for beams with various initial distribution.

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