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Beam behavior under a non-stationary state in high-current heavy ion beams

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ABSTRACT

Three-dimensional beam dynamics in a space-charge-dominated regime during a longitudinal pulse compression is investigated numerically using a multi-particle code developed. Results are compared with those of a two-dimensional particle simulation including a longitudinal current increase model. The rms transverse emittance additionally increases along the drift distance due to the longitudinal motion of the beam particles. The three-dimensional beam behavior can be also compared with a longitudinal one-dimensional calculation under a condition of a constant geometry factor for the transverse direction. Results indicate that the longitudinal beam dynamics are not affected by the transverse motions in the parameter regime.

1. Introduction

Heavy ion inertial fusion (HIF), ion-beam-driven warm dense matter (WDM) and high energy density physics (HEDP) require the generation of a high-current heavy ion beam (HIB) [1–4]. The intense HIB is in the space-charge-dominated state, and the beam parameters are far from those of conventional particle accelerators. Therefore, the beam dynamics and its control in the space-charge-dominated regime are important research issues in these fields.

At the final stage of the driver, the beam pulse must be longitudinally compressed into the range of 10–100 ns. We should transport and compress the bunch of HIB with a small emittance growth. For this reason, the final pulse compression and the final focusing are key technologies in the driver systems.

Recently, a neutralized pulse compression scheme was proposed, and was experimentally demonstrated [5,6] and also was theoretically and/or numerically investigated [7–10]. On the other hand, pulse compression scenarios without the charge and current neutralization mechanisms were proposed and have been studied by theoretical and numerical approaches in many years [11–17].

In our previous studies [18–20], the beam dynamics was investigated by using a two-dimensional (2D) multi-particle code including the longitudinal pulse compression model [12,18]. In this study we carry out numerical simulations by using a three-dimensional (3D) particle code during the drift compression in the linear transport line. The longitudinal and transverse beam parameter changes are discussed by the numerical simulation results during the pulse compression.

2. Simulation model and beam parameters

We use a two-dimensional calculation code in the transverse cross-section with the current increase model for the longitudinal bunch compression [12,18], and a three-dimensional one. The code used for the 3D calculation, which is based on a particle-in-cell (PIC) method [21], takes into account of a self-electrostatic and an external applied magnetic fields, and can be described in 3D Cartesian coordinates. The particle motions are calculated in the fully 3D space with gamma-factor corrections as the effect of a self-magnetic field [22,23].

2.1. Particle motions

The horizontal, vertical and longitudinal particle positions x, y and z as a function of time t are obtained by [24,25]

$$\frac{dx}{dt}=\frac{p_x}{m\gamma_0} \quad (1)$$

$$\frac{dy}{dt}=\frac{p_y}{m\gamma_0} \quad (2)$$

$$\frac{dz}{dt}=\frac{p_z}{m\gamma_0} \quad (3)$$

where p_x and p_y are the momentum of the beam particles in the horizontal and vertical directions, p_z is the momentum of the beam particles in the longitudinal direction, γ_0 is the relativistic factor of the beam center, and m is the mass of the beam particles.

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The equations of motion for the beam particles are calculated by

$$\frac{dp_x}{dt} = \frac{qE_x}{\gamma_0^2} - \frac{qp_z}{m\gamma_0} B_0' x \quad (4)$$

$$\frac{dp_y}{dt} = \frac{qE_y}{\gamma_0^2} - \frac{qp_z}{m\gamma_0} B_0' y \quad (5)$$

$$\frac{dp_z}{dt} = qE_z \quad (6)$$

where q is the charge of the beam particles, E_x and E_y are the self-electric fields in the transverse direction, E_z is in the longitudinal direction, and the magnetic field gradient B_0' is described by

$$B_0' = \frac{k_{\beta 0}^2 mc\beta\gamma_0}{q} \quad (7)$$

where $k_{\beta 0}$ is the betatron wavenumber due to the transverse focusing force, and β is the particle velocity divided by light speed c.

Using a leapfrog algorithm [21], the above equations for the particle motion are discretized by

$$x^{n+1} = x^n + \Delta t \frac{p_x^{n+1/2}}{m\gamma_0} \quad (8)$$

$$y^{n+1} = y^n + \Delta t \frac{p_y^{n+1/2}}{m\gamma_0} \quad (9)$$

$$z^{n+1} = z^n + \Delta t \frac{p_z^{n+1/2}}{m\gamma_0} \quad (10)$$

and for the momentum changes in the longitudinal direction,

$$p_z^{n+1/2} = p_z^{n-1/2} + q\Delta t E_z^n \quad (11)$$

and for the transverse momentum,

$$p_x^{n+1/2} = p_x^{n-1/2} + q\Delta t \left(\frac{E_x^n}{\gamma_0^2} - \frac{B_0'}{m\gamma_0} p_z^n x^n \right) \quad (12)$$

$$p_y^{n+1/2} = p_y^{n-1/2} + q\Delta t \left(\frac{E_y^n}{\gamma_0^2} - \frac{B_0'}{m\gamma_0} p_z^n y^n \right) \quad (13)$$

where n indicates the time step. The longitudinal momentum at n time step can be averaged as $p_z^n = (p_z^{n+1/2} + p_z^{n-1/2})/2$.

2.2. Field solver

According to the Poisson equation, the space-charge-induced electric field is calculated by

$$\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = -\frac{\rho}{\varepsilon_0} \quad (14)$$

where ϕ is the electrostatic potential, ρ is the charge density, and ε_0 is the permittivity of free space. By solving Eq. (14), the electric field can be completely determined by $\vec{E} = -\vec{\nabla}\phi$, however, in case of a direct 3D scheme, the higher computational cost is unaffordable for a lot of parameter studies.

Vorobiev and York proposed a sub-3D PIC method [26], and the approach is as follows. In their approach, the 3D Poisson equation (14) is replaced as

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = -\tilde{\rho} \quad (15)$$

where

$$\tilde{\rho} = \frac{\rho}{\varepsilon_0} - \frac{\partial E_z}{\partial z}. \quad (16)$$

If Eq. (16) can be solved including the transverse information, we can obtain the transverse electric field by solving the 2D Poisson equation as shown in Eq. (15).

Assuming the large aspect ratio to longitudinal and transverse directions for the beam bunch, we employ a simplified model for the longitudinal electric field in this study. The transverse electric fields are normally calculated by

$$E_x = -\frac{\partial \phi}{\partial x} \quad (17)$$

$$E_y = -\frac{\partial \phi}{\partial y} \quad (18)$$

while by assuming the long wave approximation the longitudinal electric field can be given as [25]

$$E_z = -\frac{g}{4\pi\varepsilon_0\gamma_0^2} \frac{d\lambda}{dz} \quad (19)$$

where λ is the line charge density. For a space-charge-dominated regime, g is the geometry factor defined by [25]

$$g = \log \frac{r_p^2}{r_x r_y} \quad (20)$$

where r_p is the outer boundary pipe radius, r_x and r_y are effective beam radii estimated as

$$r_x = 2\sqrt{\langle (x - \langle x \rangle)^2 \rangle} \quad (21)$$

$$r_y = 2\sqrt{\langle (y - \langle y \rangle)^2 \rangle}. \quad (22)$$

To reduce the computational cost and to calculate the transverse and longitudinal electric fields, the beam bunch is longitudinally sliced and separated as shown in Fig. 1. At each time-step the bunches sliced are identified by using the index b. The transverse electric fields are calculated at each slice. For this reason, the horizontal and vertical electric fields are rewritten as

$$E_{xb} = -\frac{\partial \phi_b}{\partial x} \quad (23)$$

$$E_{yb} = -\frac{\partial \phi_b}{\partial y} \quad (24)$$

at each slice. Here the subscript b indicates the sliced bunch index. Using Eqs. (15) and (16), the electrostatic potential at each slice can be calculated by

$$\frac{\partial^2 \phi_b}{\partial x^2} + \frac{\partial^2 \phi_b}{\partial y^2} = -\tilde{\rho}_b \quad (25)$$

where

$$\tilde{\rho}_b = \frac{\rho_b}{\varepsilon_0} - \frac{dE_{zb}}{dz}. \quad (26)$$

Here

$$\frac{dE_{zb}}{dz} = -\frac{1}{4\pi\varepsilon_0\gamma_0^2} \frac{d}{dz}\left(g_b \frac{d\lambda_b}{dz} \right). \quad (27)$$

The 2D Poisson equation at each slice can be numerically solved by using a multigrid and SOR methods [27].

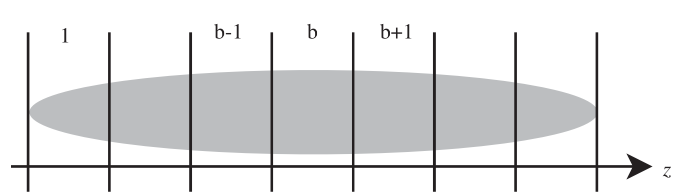

Fig. 1. Sliced bunch model for the self-electric field calculations.