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Numerical Analysis of Beam Dynamics for Final Pulse Compression Simulated by Compact Electron Beam Device for Heavy Ion Inertial Fusion

小型電子ビーム装置を用いた重イオン慣性核融合の最終段パルス圧縮を模擬したビーム動力学数値解析

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In a final stage of an accelerator system for heavy ion inertial fusion (HIF), pulse shaping and beam current increase by bunch compression are required for effective pellet implosion. A compact simulator with an electron beam was constructed to understand the beam dynamics. In this study, we investigate theoretically and numerically the beam dynamics for the extreme bunch compression in the final stage of HIF accelerator complex. The results indicate that high current-low temperature condition in comparisons with current status of experimental compact simulator is necessary to create the space charge dominated beam.

1. Introduction

A compact simulator with an electron beam was constructed to understand beam dynamics during final pulse compression for inertial confinement fusion (ICF) driven by heavy ion beams [1]. It is important to clear the beam dynamics for the precise control of high-current charged particle beams due to effective fuel pellet implosion of ICF.

To investigate the limitation of longitudinal pulse compression, we study the space-charge dominated beam dynamics with theoretical and numerical simulation approaches [2].

2. Theoretical Estimation to Create Space Charge Dominated Beam Condition

Using a longitudinal beam envelope equation, the ratio between the repulsion forces due to the space charge and the emittance of the beam bunch are estimated. The envelope equation is written by [3]

$$z_m'' + k_z z_m - \frac{K_L}{z_m^2} - \frac{\varepsilon_{zz'}^2}{z_m^3} = 0 \qquad (1)$$

where z_m is the half bunch length, K_L is the longitudinal perveance, k_z is the longitudinal focusing force, $\varepsilon_{zz'}$ is the longitudinal emittance, respectively. From Eq.(1), the condition of the space charge dominated beam is obtained by

$$\frac{K_L z_m}{\varepsilon_{zz'}^2} = \frac{3egI_{b0}\tau_{b0}}{40\pi\varepsilon_0 z_m k_B T_L} \geq 1 \qquad (2)$$

where e is the elementary charge, g is the geometry factor, I_{b0} is the initial beam current, τ_{b0} is the initial pulse duration, ε_0 is the permittivity in vacuum, $k_B T_L$ is the longitudinal temperature, respectively.

The estimation result normalized by the initial bunch length z_{m0} is shown in Fig.1. The initial beam current I_{b0} is 100 μA and the initial pulse duration τ_{b0} is 100 ns. As a result, it is predicted that the compression ratio of 57.8 is required to demonstrate the space charge dominated beams in the apparatus for $k_B T_L$=1 eV.

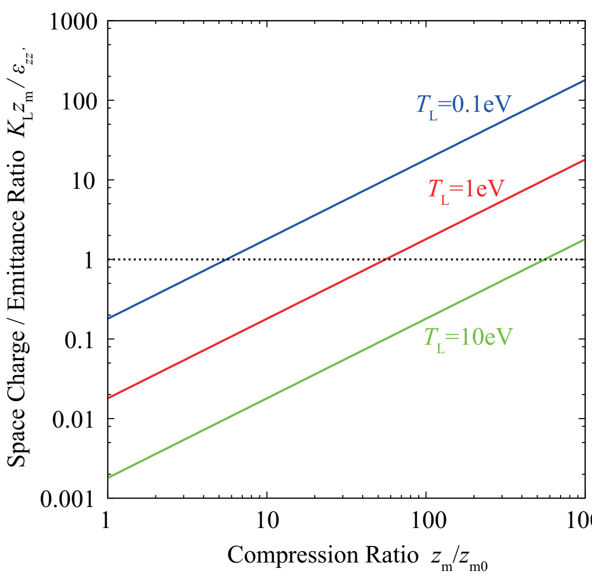

Fig.1. Ratio of longitudinal repulsion force due to space charge and emittance as a function of compression ratio

3. Numerical Simulation during Bunch Compression with Solenoid Transverse Confinement

Numerical simulations based on particle-in-cell (PIC) code [4] are carried out. The model is a one-dimensional electrostatic PIC code with the long wave approximation for the longitudinal space charge calculation [3]. The longitudinal self-electric field E_z is calculated by

$$E_z = -\frac{g}{4\pi\varepsilon_0}\frac{d\lambda}{dz} \tag{3}$$

where λ is the line-charge density. The electron bunch is extracted from an electron gun assisted by thermal emission. The electron bunch is modulated by the applied electric field in the gap. The voltage pulses produced at each module are overlapped at the gap using induction modulator technology [1]. The overlapped voltage pulse V_g at the gap is given by

$$V_g(t) = \frac{m_e}{2e\left(\sqrt{\frac{m_e}{2eV_0}} + \frac{T-t}{L}\right)^2} - V_0 \tag{4}$$

where m_e is the electron mass, V_0 is the extraction voltage of the electron beam at the electron gun, T is the pulse duration of the applied voltage, L is the beam transport distance with solenoid magnetic field, respectively. In this study, V_0=2.8 kV, T=100 ns, L=2 m are assumed in comparison with the experimental condition. By the applied voltage as given by Eq.(4), the head of the beam bunch is decelerated, while the tail of the beam bunch is not modulated. As a result, the beam pulse is compressed during the transport.

It is assumed that the extracted electrons are thermalized at the electron gun as

$$v_{th} = \sqrt{\frac{k_B T_L}{m_e}} \tag{5}$$

where v_{th} is the initial thermal velocity.

Figure 2 shows the calculation results of the ratio of the beam current to the initial one, i.e., the pulse compression ratio. As shown in Fig.2, the applied voltage for the pulse compression is good enough for the operation for the case without the space charge effect and in quite low temperature condition. However the space charge effect and the initial temperature of electron bunch interfere the extreme pulse compression. In this experimental condition, it is found that the initial temperature of electron bunch is main issue of interference for the extreme pulse compression.

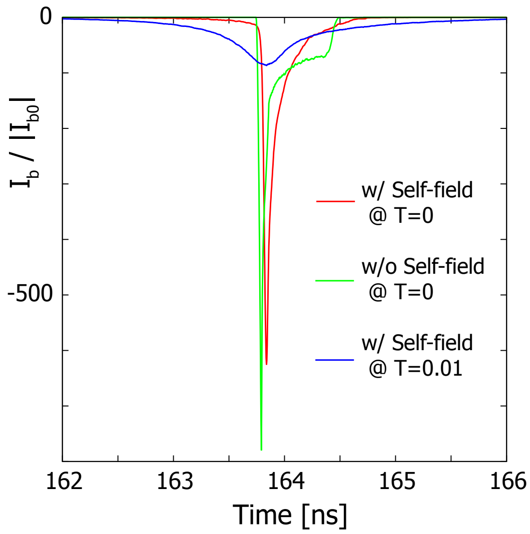

Fig.2. Pulse compression ratio during beam transport. The red curve indicates the result with space charge effect and $k_B T_L$=0, the green line shows the result without space charge effect and $k_B T_L$=0, and the blue curve shows the result with space charge effect and $k_B T_L$=0.01 eV, respectively.

4. Conclusions

To understand the beam dynamics during final beam compression for inertial fusion energy driven by heavy ion beams, the compact simulator with electron beam was constructed. We studied the beam dynamics with theoretical and numerical simulation approaches to investigate the limitation of longitudinal pulse compression.

Using longitudinal beam envelope equation, the ratio between the repulsion forces due to the space charge and the emittance of the beam bunch were estimated. Also numerical simulations are carried out. These theoretical and numerical approaches suggested that in the compact simulator the strong pulse compression and/or higher beam current are needed to observe the beam dynamics around the stagnation point at the unneutralized bunch compression.

References

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