BEAM DYNAMICS AND PULSE DURATION CONTROL DURING FINAL BEAM BUNCHING IN DRIVER SYSTEM FOR HEAVY ION INERTIAL FUSION

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Abstract

In accelerator system for heavy ion inertial fusion, beam dynamics is investigated by particle-in-cell simulations during final beam bunching. The calculation results show that the emittance growth during the longitudinal bunch compression for various particle distributions at the initial conditions and with two types of transverse focusing model, which are a continuous focusing and an alternating gradient focusing lattice configurations. Dependence in the pulse duration of heavy ion beam is investigated for effective pellet implosion, and the voltage accuracy requirement at the beam velocity modulator is also estimated for the final beam bunching.

INTRODUCTION

Physics of space-charge-dominated beams is crucial in heavy ion inertial fusion (HIF) [1]. In the HIF, energy of several MJ should be injected as a short time pulse to a fuel pellet. The pellet implosion can cause a high energy density state at the center of the pellet, and thermonuclear reactions can produce the high-temperature dense plasma. The intense heavy-ion beam (HIB) is one influential candidate as the energy driver.

Required parameter values of HIB are several GeV particle energy, $\sim$100 kA total current, and $\sim$10 ns short pulse duration [1], and the beam parameters are far from those of conventional particle accelerator system. Therefore the beam dynamics and control are important research issues in HIF. At the final stage, the beam pulse must be longitudinally compressed from $\sim$100 to $\sim$10 ns as shown in Fig. 1.

Induction voltage modulators, which have a precise waveform controllability, are useful devices for this purpose [2]. For an effective pellet implosion, we should transport and compress the bunch of HIB with a low emittance growth. A final focus and beam illumination are crucial, but a large emittance interferes the focusing to the small fuel pellet [3]. For this reason, the final beam bunching and the final focusing are a key technology in the HIF driver system. In these regions, the intense HIB is in the space-charge-dominated state, and beam instabilities occur during the beam transport.

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Not only the spatial nonuniformity of the beam illumination, but also the beam illumination error in time cannot be ignored. When the beam pulse duration is changed from the designed value, the void close time and implosion dynamics are also changed. As a result, the fusion output energy is decreased from the optimal value.

In our previous study [4], the beam instability excited by the strong space charge effect was observed using multiparticle numerical simulations during the final beam bunching. The particle-in-cell (PIC) [5] simulation with a longitudinal bunch compression model [6] is carried out to investigate transverse particle behaviors. The transverse rms emittance is shown in the beam transport with the continuous and the alternating gradient focusing lattice models. The allowable region of the HIB pulse duration is obtained from the simulation results [7] in the HIB pulse duration dependence of output energy. The voltage accuracy requirement for the beam buncher is also estimated by the tolerance of the HIB pulse duration.

BEAM DYNAMICS DURING LONGITUDINAL COMPRESSION

The high-energy particle beam is transported by using a magnetic quadrupole focusing channel as a unit of focus-drift-defocus-drift (FODO) lattice. The beam transport by the FODO lattice causes a non-axisymmetric behavior in the beam cross-section. We are interested in such beam dynamics with a longitudinal bunch compression. For the above reasons, the fully three-dimensional numerical scheme is essentially required by the beam dynamics sim-

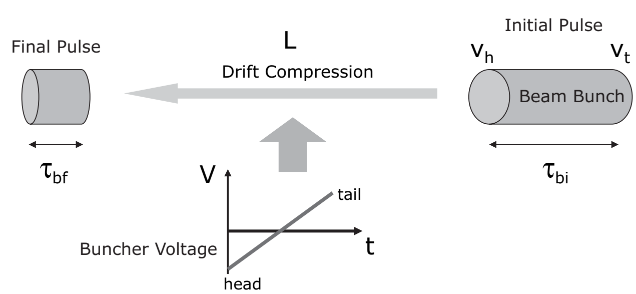

Figure 1: Drift bunch compression by bunching voltage applied at beam buncher at the final stage of HIF driver system.

ulation. From the viewpoint of the computational cost, the full calculations are difficult. While the longitudinal bunch length is of the order of meter, the scale of the transverse cross section is only a few cm in the stage of final beam bunching. Consequently, the small-scale phenomena by the space charge structure will be dominated by the transverse beam dynamics.

We deal with the particle dynamics in the transverse cross section of the beam by multi-particle simulations, and the effect of longitudinal compression is introduced as the beam current increases. The linear current increase model causes the most serious influence in the particle dilution in the phase space. From the viewpoint of the beam physics study, the history of linear current increase is assumed as model of the longitudinal bunch compression. We use the PIC method for descriptions of the transverse behavior with the longitudinal compression, the effect of which was evaluated by assuming linear increase in the beam current. The charge and mass of the super particles are re-weighted with the beam transport [6]. The quadrupole occupancy is fixed at 0.5, and the one lattice period is 3 m.

The beam parameters are assumed as Table 1 [1]. The

Table 1: Beam parameters for final beam bunching in HIF.

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

initial generalized perveance is assumed to 3.58×10^{-6}. The initial undepressed and depressed phase advances are $\sigma_0 = 72$ deg and $\sigma = 65.2$ deg. The transverse calculation region is fixed at the square of 10 cm $\times$ 10 cm, and the outer boundary condition is given as a conductor wall. The initially rms matched Kapchinskij-Vladimirskij (KV), waterbag (WB), Gaussian (GA), Parabolic (PA) [8], and semi-Gaussian (SG) [6] beams are chosen as the initial particle (non-stationary) distribution.

The ratio Δ/λ_D of the grid zone length Δ to the Debye length λ_D is evaluated by rms emittance ϵ_f after the final beam bunching. Since the behavior likes a quasi-neutral plasma, the Debye shielding is important issue in this region. The grid size of $0.23\lambda_D$ is used to satisfy the Debye shielding effect and the calculation cost [5]. For the validation of the numerical convergence, we also tried to check the calculation results using the different numbers of grids and super particles. The mesh number is varied from 64×64 to 1024×1024, and the super particle number is changed from 1×10^5 to 3×10^6. As mentioned earlier, we tried to check the many test calculations to change the numbers of particles and cells used. Consequently, we use the mesh number of 512 × 512 for the accurate calculation in this study. We study the emittance growth mechanism with two types of the transverse focusing lattice system, i.e. an alternating gradient (AG) focusing and a continuous focusing (CF) configurations.

We simulate numerically the beam dynamics during the final beam bunching with the CF and AG focusing models. The beam radius is extended with the beam current increase due to the longitudinal bunch compression. We use the average of unnormalized transverse rms emittance ϵ [4]. 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 to the initial one at each lattice period, is shown in Fig. 2. The beam instability is observed in case for the KV beam transport with the CF and AG focusing lattice configurations. However the instability contributes hardly the rms emittance growth in the KV beam transport with the CF lattice. Although the beam instability with the abrupt emittance growth can be induced for the WB beam transport with the AG focusing model, the rms emittance growth without the beam instability is caused in the WB beam transport with the CF lattice system. On the other hand, the initial GA, PA, and SG beams cause the gradual emittance growth in the transport with the CF and AG focusing lattices. Also the emittance growth histories are almost same in the GA and PA beam transport with the CF and AG focusing lattice models.

REQUIREMENT OF VOLTAGE ACCURACY FOR BEAM BUNCHER

The beam pulse can be longitudinally compressed by the bipolar voltage waveforms as shown in Fig. 1. Appling the voltage waveforms to the beam bunch, the beam head is decelerated and the beam tail can be accelerated. As a result, the beam bunch becomes short during the beam transport with the head-to-tail velocity tilt.

The relation between the pulse duration at final state and the head-to-tail voltage applied by the beam buncher is estimated by

$$\tau_{bf} = \tau_{bi} + \left(\frac{1}{v_t} - \frac{1}{v_h}\right) L, \tag{1}$$

$$v_h = c\sqrt{1 - \frac{1}{\left(1 + \frac{E_i - qV}{m_0 c^2}\right)^2}}, \tag{2}$$

$$v_t = c\sqrt{1 - \frac{1}{\left(1 + \frac{E_i + qV}{m_0 c^2}\right)^2}}, \tag{3}$$

where τ_{bi} is the initial pulse duration, v_t and v_h are the beam velocity at the tail and at the head of the bunch, L is the transport distance for the beam bunching, c is the speed of light, E_i is the initial kinetic energy of the beam, q and m_0 are the charge state and rest mass of the beam ion, and V is the total voltage applied by the beam buncher, respectively.

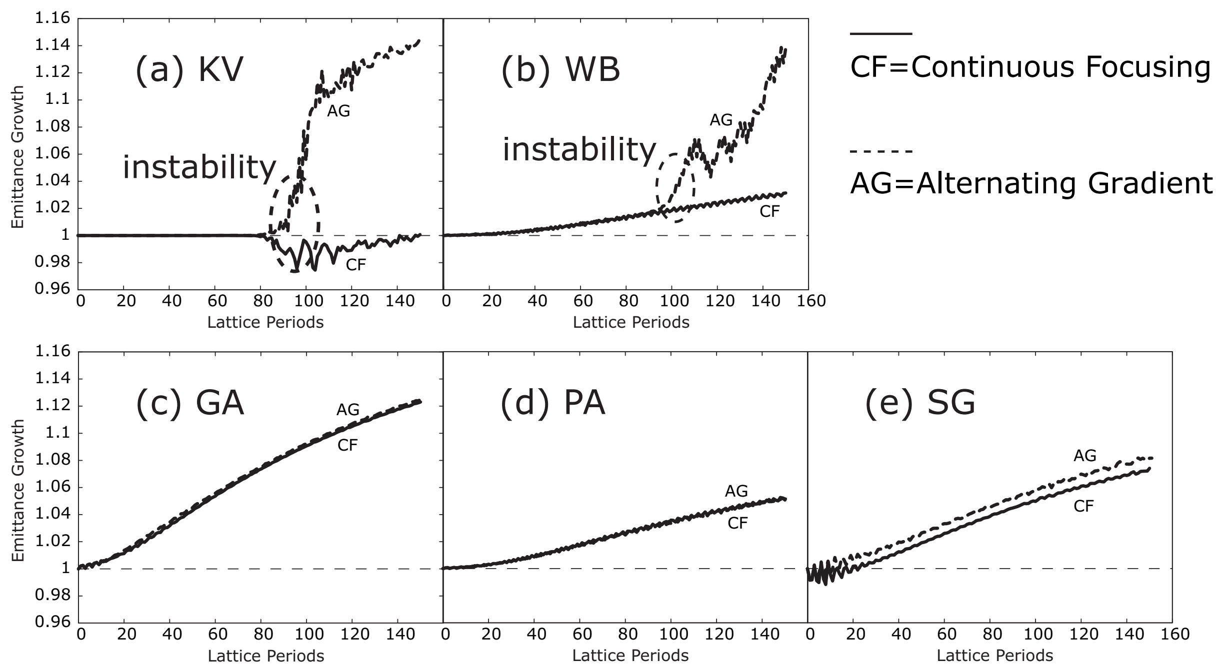

Figure 2: Evolution of the rms emittance during the final beam bunching, (a) for KV, (b) for WB, (c) for GA, (d) for PA, and (e) for SG beams, respectively. Solid curve shows the emittance growth for CF lattice, and the dashed line indicates one with AG focusing lattice.

The beam transport distance is assumed as $L = 500$ m. If at Pb^+ ion beam with 10 GeV particle energy the initial pulse duration is 250 ns, the allowable voltage range is required from 444 to 464 MV for the range of the beam pulse duration from 18 to 28 ns. From our previous study [7], the HIB pulse duration from 18 to 28 ns is estimated as the tolerance range for the HIF output energy. As a result, the relativistic error of the integrated buncher voltage $\Delta V/V$ is estimated as $-2.6 \sim 1.8$ % for the optimal point of 22 ns as indicated by Ref. [7].

CONCLUSION

The transverse beam dynamics and the voltage accuracy requirement for HIB pulse duration were investigated during the final beam bunching in the HIF driver system.

The PIC simulation with the beam current increase, as a model of the longitudinal bunch compression, was carried out for the study of beam transport under the strong effect of space charge oscillations. For the KV beam transport with the CF and AG focusing lattice configurations the beam instability was observed, however the beam transport was carried out without the emittance growth in the CF lattice model. The beam instability was caused in the WB beam transport with the AG focusing lattice, while could not be induced in case with the CF lattice. In the cases of GA, SG, and PA beams, it is expected that the instability induced by the space charge effect did not contribute to the emittance growth.

The HIB pulse duration dependence for effective pellet implosion in HIF was investigated. The requirements of the voltage applied by the beam buncher in the final region were estimated. The accuracy of the integrated voltage should be a few percent for the effective pellet implosion.

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