A scaled experiment to study energy dissipation process during longitudinal compression of charged particle beams

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Abstract. Beam behavior during longitudinal bunch compression of charged particles was investigated using a compact simulator device based on electron beams. Beam current waveforms and bunch compression ratios were measured as a function of the initial beam current. We found that the current waveform became blunt and the compression ratio degraded at higher beam currents. These results indicate that space-charge fields dissipate the kinetic energy of beam particles.

1. Introduction

In heavy-ion fusion (HIF), the beam power must be increased to TW level. To achieve such an extremely high beam power, longitudinal beam compression has been adopted in the final stage of the drivers[1][2]. However, this bunching process is disturbed by strong space-charge fields. In particular, abrupt beam compression with a large velocity tilt may cause beam instabilities through the collective motions of beam particles and may substantially dissipate beam kinetic energy into thermal energy (random motion of particles), thereby degrading beam quality.

In general, a nonstationary beam mismatched to the external focusing field has free energy [3]. Thermodynamically, a nonstationary beam relaxes to its final equilibrium state as defined by the Maxwell-Boltzmann velocity distribution while dissipating free energy by long-time particle interactions through intrabeam scattering and/or space-charge fields. The quality and profile of resulting beam can be predicted on the basis of external focusing potential and beam self-potential [4][5]. However, the HIF final bunching stage employs an abrupt one-pass beam manipulation with linac, and beams have no time to completely dissipate any free energy induced by the strong velocity tilt. Thus, it is very hard to predict the final beam quality and profile, both which strongly depend on energy dissipation processes governed by collective effects [6].

To investigate the dissipation processes during longitudinal beam compression, we propose a scaled-down experiment using a compact and flexible simulator based on electron beams. Because of the small inertia and large specific charge of electrons, GeV-kA heavy-ion beams (typical in HIF) can be scaled down to keV-mA electron beams. In fact, a beam velocity β and a longitudinal perveance K_L equivalent to HIF beam parameters are readily available with electron beams (see Table 1). Moreover, electron motions can be restricted in the longitudinal direction by applying a longitudinal magnetic field. If beam compression is performed one-dimensionally,

Table 1. Typical beam parameters for heavy ion and electron beams. To obtain these values we assumed a bunch duration of 100 ns and a geometry factor g of 5.7 are assumed.

Beam species	q/m [C/kg]	Voltage [V]	Current [A]	β (v_z/c)	K_L [mm]
HIB (Pb$^+$)	4.67×10^5	$1{\sim}10 \times 10^6$	$0.1{\sim}10 \times 10^3$	$0.10{\sim}0.32$	$0.038{\sim}38$
Electron	1.75×10^{11}	$2.7{\sim}27 \times 10^3$	$0.27{\sim}27 \times 10^{-3}$	$0.10{\sim}0.32$	$0.038{\sim}38$

the current waveform of the bunched beam directly reveal the distribution of beam particles in longitudinal phase space. Thus, we have the prospect of discussing the particle dynamics by comparing the time evolution of beam current waveforms with those obtained from numerical simulations.

So far, we have constructed a compact electron-beam-based simulator for longitudinal compression experiments and investigated the effects of the initial velocity spread on the longitudinal focusing ability in a parameter region dominated by emittance [7]. This paper presents recent progress in our on-going study.

2. Experimental configuration and beam parameters
2.1. Experimental setup
Figure 1 shows a schematic diagram of the simulator device. The device consists of a hot-cathode electron gun, an induction voltage adder, a solenoidal transport line, and a current probe. In the experiment, first, a continuos electron beam is injected into the induction cavity. Next, the voltage adder, composed of five units, applies a time-varying voltage to the beam in order to induce a head-to-tail velocity tilt. Then, the beam is compressed quasi-one-dimensionally in the longitudinal direction as it drifts toward a focal point through the transport line with a solenoidal magnetic field of 5.7 mT.

As a modulation voltage (longitudinal focusing potential) for drift compression, we define an ideal voltage waveform by,

$$V_{mod}(t) = \frac{m_e}{2e} \frac{1}{(\sqrt{\frac{m_e}{2eV_o}} + \frac{T-t}{L_f})^2} - V_0, \tag{1}$$

here $V_0 = 2.8$ kV is the extracting voltage of the electron gun, $T = 80$ ns and $L_f = 1.92$ m are the initial pulse duration of the modulated beam, and the focal length from the endpoint of the modulation gap, respectively. With this ideal waveform, we can apply a linear focusing force in the longitudinal direction; that is, all electrons in the bunch are gathered at the focal point. Figure 2 shows the ideal and experimental voltage waveforms. To generate the ideal modulation voltage waveform, the voltage adder was carefully tuned [8].
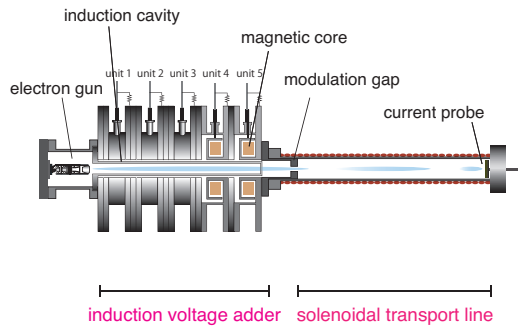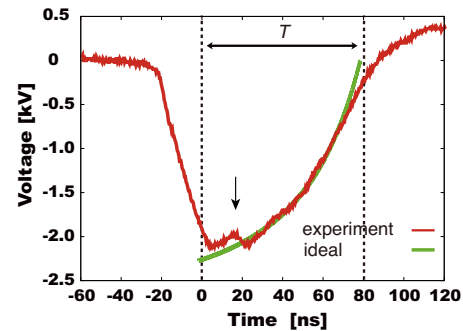

Figure 1. Schematic diagram of the simulator device.

Figure 2. Ideal and experimental modulation voltage waveforms.

Table 2. Relevant parameters for longitudinal beam dynamics in this experiment. Here, bracket denotes the index of the space-charge effect for the 20-times compressed case.

I_0 [mA]	g-factor	$\epsilon_{zz'_0}$ [m-rad]	K_L [mm]	$K_L Z_m/\epsilon_{zz'_0}^2$	$(K_L Z_m/\epsilon_{zz'_0}^2)$
0.1∼1	5.7	2.37×10^{-2}	0.109∼1.09	0.49∼4.9	9.8∼98

2.2. Analytical estimation of beam parameters

Longitudinal envelope equation [9] can provide a general description for the longitudinal behavior of the beam, so we used that equation to estimate beam parameters in our simulator [8].

For this study, the beam was extracted from the 2.8-kV electron gun with currents from $100\,\mu$A to $1\,$mA. Assuming the beam longitudinal temperature, T_L, is equivalent to the cathode temperature, we can use $k_b T_L = 0.1$ eV. Values for the major beam parameters are listed in Table 2. Regarding the value for $K_L Z_m/\epsilon_{zz'}^2$, which is an index of the strength of the space-charge force on beam dynamics, the bunched beam in our simulator covers a wide parameter space from emittance-dominated to space-charge-dominated regions; $K_L Z_m/\epsilon_{zz'}^2 \gg 1$, where $\epsilon_{zz'_0}$ is the initial emittance. Detailed descriptions are available in [8] and [10].
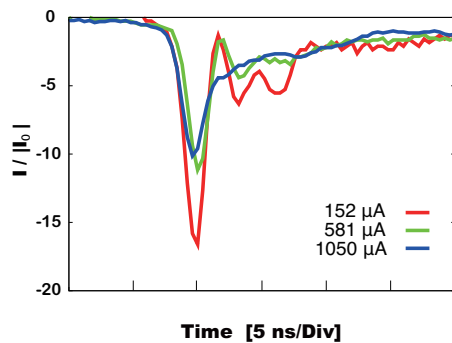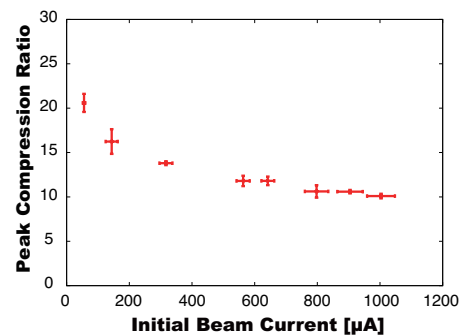
2.3. Estimation of beam dynamics by numerical simulation

In this study, a simplified one-dimensional electrostatic particle-in-cell simulation was carried out to examine the particle dynamics. In the calculation, we used the experimental modulation voltage shown in Fig. 2. We assumed that the space-charge field can be calculated with the g-factor model [9][10] and adopted it instead of the usual Poisson solver.

3. Results and discussions

Figure 3 shows typical current waveforms of compressed beams normalized by initial beam currents $I_0 = 152$, 581, or 1050 μA, respectively. In this experiment, the beam current was measured at $L = 1.95$ m, which was 3 cm downstream from the nominal focal point at $L_f = 1.92$ m. For $I_0 = 152\,\mu$A, the figure shows two peaks in addition to the first main peak. These peaks correspond to locally compressed components caused by the error in the modulation voltage shown with the arrow in Fig. 2. However, by increasing the initial beam current, these peaks were gradually smoothed; they completely disappeared at $I_0 = 1050\,\mu$A. In addition, the main peak heights decreased with increasing I_0. Figure 4 shows the dependence of the peak compression ratio on the initial beam current. Here the compression ratio is defined by the main peak height of the normalized current waveforme. As shown in Fig. 4, the ratio monotonically decreased with increasing beam current.

Figures 5(a) and 5(b) show numerical simulation results for the time evolution of beam particles in longitudinal phase space for $I_0 = 152$ and 1050 μA, respectively. In Fig. 5(a) and

Figure 3. Normalized compressed beam current waveforms.

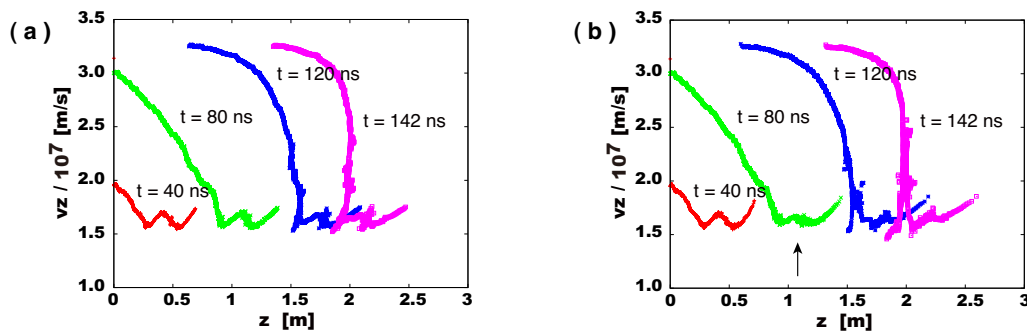**Figure 4.** Effect of initial beam current on peak compression ratio.

Figure 5. Numerically simulated particle dynamics in phase space (a) for $I_0 = 152$ μA and (b) for $I_0 = 1050$ μA.

5(b), $t = 0$ ns marks the time when the beam modulation started and $t = 142$ ns is the time of maximum bunch compression predicted for the ideal case. Figures. 5(a) and 5(b) both show that a twisted structure in the head of the beam bunch. This structure is due to the fluctuations in the longitudinal focusing force induced by the modulation voltage (see Fig. 2), which correspond to the two peaks observed in the experiment. In Fig. 5(a), the distribution gradually rotates with time and becomes spatially focused while closely maintaining the initial velocity tilts. Interestingly, at the higher beam current in Fig. 5(b), the distributions contain additional modulations. These modulations seem to be localized at reflection points of the distributions (arrow in the figure), which correspond to nonlinearly focused beam components. This phenomenon indicates that nonlinearly focused components induce additional perturbations in the beam that accelerate relaxation of the velocity distribution. As shown in Figs. 3 and 4, the current waveform and compression ratio obviously depend on the initial beam current. To discuss details of dissipation processes occurring in our bunching experiments, the g-factor model may not be most suitable because it assumes a uniform charge density in an ellipsoidal beam bunch. Thus, in our future study, two-dimensional electrostatic PIC code will be used instead.

4. Conclusions
A compact electron-beam-based simulator was used to conduct bunch compression experiments in parameter space ranging from emittance-dominated to space-charge-dominated. We found that the current waveforms of bunched beams depend on the initial beam current. In addition, beam particle dynamics were numerically simulated, and the results also supported the particle diffusion in the phase space. These results indicate that relaxation of the free energy affects the longitudinal focusing dynamics.

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