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A scaled experiment to study dynamics during longitudinal compression of intense charged particle beams

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ABSTRACT

In order to investigate the beam dynamics during longitudinal compression in high power ion accelerator, we constructed a compact bunching simulator device based on electron beams with an induction voltage adder configuration. The compression ratio and the evolution of the beam current were compared with numerical simulations using a particle code. From the results, we confirmed that the space-charge force affects the beam dynamics and the compression ratio around the focal point.

1. Introduction

Heavy ion beams are expected to be potential drivers for high-energy density science and heavy ion inertial fusion [1,2]. In these researches and applications, the technology to compress a beam bunch in longitudinal direction is crucially important. For the heavy ion inertial fusion, we need to increase the beam power up to TW level. Processes of both longitudinal and transverse beam compressions are essential to increase the beam power density [3]. At the final stage of the accelerator, particularly, we have to increase the beam current about 10 times with abrupt longitudinal drift compression [2] of beam bunch [3,4]. However, in this compression stage, a non-adiabatic process may be induced through space-charge field [5]. When the beam bunch is modulated quasi-statically, emittance growth can be suppressed at a minimum level. However, it is not the case when an intense beam is manipulated rapidly in the final buncher [6]. In the final bunching stage, dynamic space-charge effects induce the beam coupling between transverse and longitudinal beam motions [7], which may result in unpredictable emittance dilution and decrease in the bunch compression ratio.

As discussed in Refs. [8] and [9], a decrease in the beam compression can have four causes: (1) accuracy of the modulation voltage waveform, (2) initial beam emittance, (3) quasi-static space-charge effects, and (4) collective effects, i.e., dynamic and nonlinear space-charge effects induced by a non-stationary beam density disturbance.

The collective effects may induce unexpected emittance growth and energy dissipation of the intense beam [10], so it is important to investigate the effects. To understand the mechanism of the emittance growth due to the collective motion, some groups are investigating the beam dynamics by using Paul trap and a circular electron accelerator. These researches experimentally confirmed emittance growth both due to rapid non-adiabatic compression in the transverse direction [11,12] and to the excitation of space-charge waves by longitudinally mismatched bunch confinement [13]. To investigate the beam dynamics and emittance dilution during the rapid longitudinal compression, we made a compact and flexible bunching simulator device based on electron beams. Until now, we have investigated the effects of initial beam energy spread on the beam dynamics [8].

In this paper, our recent progress in longitudinal beam-dynamics experiments is presented. The experimental results are compared with numerical simulations based on a particle code. We discuss the influence of initial beam current on the compression process.

2. Experimental setup and analytical estimation

A schematic diagram of the setup for the bunching experiment is shown in Fig. 1. The experimental device consists of a hot cathode electron gun, an induction voltage adder, a transport line with solenoidal magnetic field, and a Faraday cup (FC). An electron beam is injected continuously to the modulation gap of the induction adder from the electron gun. Next, a modulation voltage across the gap produces head-to-tail velocity variation in a section of beam, referred to here as a “velocity tilt”. Then, the beam is longitudinally compressed during the transport through the solenoidal field and the beam bunching is completed around 2 m downstream of the modulation gap. Finally, the bunched beam is measured with the FC.

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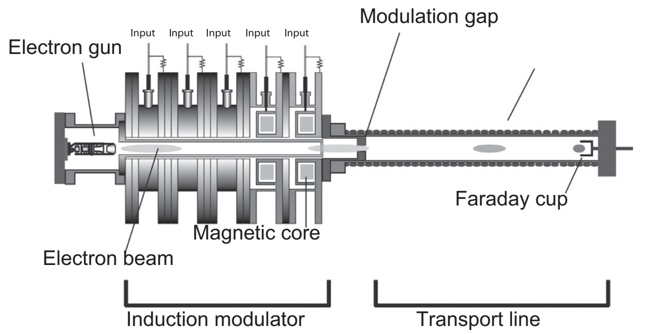

Fig. 1. Schematic diagram of the device for bunching experiment. Injected electrons are manipulated by modulation voltage and longitudinally compressed in the transport line.

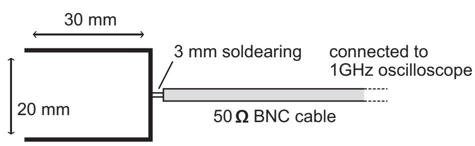

Fig. 2. Configuration of Faraday cup. Beams are mainly captured at the bottom of the FC.

Fig. 2 shows the configuration of the FC, which consists of cylindrical cup with 20 mm in inner-diameter and 30 mm in depth. The beam radius was estimated to be 2 mm by a fluorescent witness plate. Since that is smaller than FC radius and the beam is substantially restricted by the magnetic field, beams are captured with the bottom of the FC. This means there is no time difference of flight times for beam longitudinal slices. The FC is connected to a 50 Ω BNC cable with 3 mm length soldering, and the BNC cable is connected to 1 GHz oscilloscope. Considering this, the time resolution of the detector can be considered to be nsec.

As mentioned earlier, transverse and longitudinal motions of intense beam are predicted to be coupled in the final stage of bunch compression, so the evolution of emittance needs to be discussed in a 6-dimensional phase space that the beam particles occupy. Evaluation of the phase volume in the multi-dimensional space is not an easy task. To study the emittance evolution in our experiments, the beam bunch is one-dimensionally compressed in the transport line in which the transverse motion is suppressed by the longitudinal magnetic field. Then we expect that all of the dissipation processes (in longitudinal and transverse directions) can be reflected in the current waveforms and compression ratios of the beam current.

2.1. Modulation voltage waveform and induction voltage adder

In order to achieve beam compression in longitudinal direction, we use a drift-compression scheme [2,14]. By assuming all particles in the beam bunch has no velocity dispersion and no space-charge effects, the modulation voltage to compress the beam bunch into one point at the destination can be mathematically derived and written with SI unit by the following expression

$$V_{mod}(t) = \frac{m_e}{2q_e}\frac{1}{\left(\sqrt{\frac{m_e}{2q_eV_o}}+\frac{T-t}{L_f}\right)^2}-V_0, \tag{1}$$

where V_0 is the extracting voltage of the electron gun, T and L_f are, respectively, the initial pulse duration of the modulated beam and focus length from the endpoint of the modulation gap. In this experiment, we compress a beam with pulse length of 100 ns from

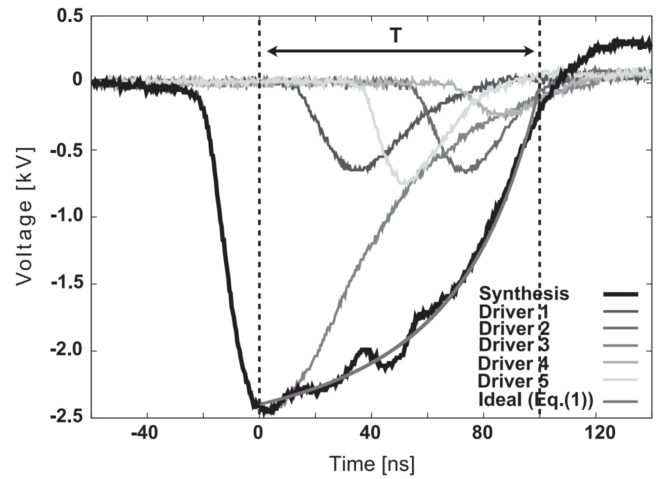

Fig. 3. Modulation voltage for longitudinal compression. Sharp gray line shows ideal waveform defined by Eq. (1) for L_f=1.942 m, and bold black line denotes synthesized waveform with induction adder.

continuously extracted with an energy of 2.8 keV. In this experiment, the modulation voltage is applied with an induction voltage adder consisting of five driver units (see Fig. 1). Each unit makes a sinusoidal waveform independently and they are synthesized at the modulation gap. By the induction adder configuration, we can apply arbitrarily controlled waveforms for bunch compression.

We used the modulation voltage defined by Eq. (1) for the bunching experiment, by which the tail of the beam bunch are modulated slightly and the particles composing the bunch tail move to the focal point with higher longitudinal velocity. This means that the compression ratio is more sensitive to the accuracy of the latter half of modulation waveform. By improving the accuracy of the tail of the waveform (corresponding to t=80–120 ns in Fig. 3), the compression ratio increased almost twice in comparison with the previous result [8].

Fig. 3 shows typical modulation voltage waveforms applied in this experiment. As shown in Fig. 3, we drove five independent pulsed sinusoidal like voltage (Driver 1–5) with the induction units and synthesized the waveforms into one modulation waveform (black bold line). The designed waveform defined by Eq. (1) (sharp black line) is also shown in the figure. The jitters of the waveform components were estimated to be 0.5% in time and 2% in voltage.

2.2. Criterion of space-charge-dominated beams

As mentioned earlier, longitudinally modulated intense beams are predicted to be strongly coupled in longitudinal and transverse dynamics due to the space-charge field. In order to investigate space-charge and/or collective effects on the emittance growth, the beam dynamics must be dominated by space-charge rather than initial beam emittance. The condition of space-charge-effective beam parameter can be estimated by using a beam envelope equation [5]. In longitudinal direction, the equation can be written by,

$$\frac{d^2Z_b}{ds^2}-\frac{K_L}{Z_b^2}-\frac{\epsilon_{zz'}^2}{Z_b^3}=0, \tag{2}$$

where $2Z_m$ is the bunch length, $K_L = 3gNr_c/2\beta_0^2\gamma_0^5$ is a longitudinal beam perveance, and $\epsilon_{zz'} = \sqrt{5}Z_m(\gamma_0^3k_bT_L/mc^2)^{1/2}/\beta_0\gamma_0$ is an unnormalized longitudinal emittance. $g = 2\ln b/a$ is the geometry factor [5], here a and b are radius of the beam and conducting transport line respectively, $r_c = q^2/4\pi\epsilon_0 mc^2$ is the classical particle radius, and N is the total particle number in the beam bunch. γ_0 is the Lorenz factor and here $\gamma_0 = 1$.