LONGITUDINAL DRIFT EXPANSION AND COMPRESSION OF ELECTRON BUNCHES IN A PERIODIC SOLENOID FOCUSING TRANSPORT CHANNEL*

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Abstract

A longitudinal beam drift expansion and compression experiment has been conducted in the electron beam transport facility at the University of Maryland to study the longitudinal beam physics of space-charge dominated beams. The experimental configuration and preliminary experimental results are presented in this paper.

Introduction

Space-charge dominated beams are used in many practical applications, such as heavy ion inertial fusion, FELs, nuclear waste transmutation, and microwave tubes. The physics of space-charge dominated beam is not yet fully understood. Our systematic study is aimed at a better understanding, comparison with simulation codes, and improvement of the design schemes.

The transverse dynamics of space-charge dominated beams has been studied extensively at U. of Md. Electron Beam Transport Experiment. Excellent agreement with theory, experiment and simulation has been achieved [1]. Longitudinal drift expansion and compression experiments of electron bunches have been initiated to study the longitudinal beam dynamics for space-charge dominated beams.

Longitudinal Beam Physics

The typical beam parameters in this experiment are 2.5 keV energy, 40 mA current and low intrinsic energy spread 0.1 eV, i.e. a relatively cold beam. In this regime a one-dimensional fluid model consisting of the continuity and force equations can be employed. Since the beam length is ten times larger than the tube diameter the "long wavelength" approximation [2] can be applied to calculate the space-charge forces.

For a parabolic line charge density with an initially uniform or linear velocity, the longitudinal beam dynamics can be described by a longitudinal envelope equation, which can be more generally derived from the Vlasov equation [3]. With the proper initial conditions, the linear velocity and parabolic density distributions are preserved in the expansion and compression processes. Since the longitudinal emittance is negligible compared with the space-charge force the envelope equation can be written as

$$\frac{d^2 Z_m}{ds^2} = \frac{2gI_p(0)}{\beta^3 I_0}\frac{Z_i}{Z_m^2} = \frac{\alpha^2 Z_i}{2Z_m^2}, \qquad (1)$$

where $2Z_m$ is the bunch length, s is the drift distance, $I_p(0)$ and $2Z_i$ are the initial peak current and bunch length, respectively, $I_0=17\times10^3$ Amps for electrons, and g is the geometry factor of order unity that depends on the transverse beam radius. With a linear initial velocity tilt the relation between the normalized parabolic bunch width and the drifting distance can be obtained by integrating Eq. (1) as

$$\sqrt{\theta}\sqrt{\theta-1} + \ln(\sqrt{\theta}+\sqrt{\theta-1}) - \sqrt{\theta\zeta}\sqrt{\theta\zeta-1} - \ln(\sqrt{\theta\xi}+\sqrt{\theta\xi-1}) = \alpha\theta^{3/2}\frac{s}{Z_i}, \qquad (2)$$

where $\theta = 1 + \frac{Z_i'^2}{\alpha^2}$, $\zeta = \frac{Z_m}{Z_i}$ with Z'_i being determined by the initial velocity tilt.

For an initial uniform velocity and line charge density the fluid equations can be solved analytically by the characteristic method [4]. The current at the beam edges can be expressed as

$$I \approx I_i\left(1-\frac{t}{\tau}\right)^2 \qquad 0 \le t \le \tau, \qquad (3)$$

where $\tau = \frac{v_0^2}{3c_s s}$, $c_s = \sqrt{\frac{egI_i}{4\pi\varepsilon_0 v_0 m_e}}$, I_i is the initial beam current, c_s is the wave velocity, and v_0 is the beam frame velocity.

However, this solution is not valid for a beam with an initial velocity tilt. The analysis of the rectangular drift compression must heavily rely on numerical simulations. A PIC code called SHIFT Z, developed by I. Haber of NRL will be run to simulate this experiment.

Experimental setup

The configuration of the experiment, shown in Fig. 1, includes an injector, a periodic focusing channel and a diagnostic system.

The electron beam injector consists of a variable-perveance electron gun, an induction acceleration module, and three matching lenses [5]. The beam parameters can be varied in the range of up to 10 keV in energy, a few hundred milliamperes in current, and 5-100 ns in pulse duration. The longitudinal beam profiles can be made either rectangular or parabolic by varying the grid pulse shape of the gun. An initial velocity tilt can be imparted to the beam by the time-varying induction acceleration field.

The channel is 5-meter long and consists of a periodic array of 36 solenoid lenses. Due to the variation of beam energy the phase advance will vary along the beam pulse, and the beam can only be matched radially at one position within the pulse (usually the center). To prevent transverse instability and beam

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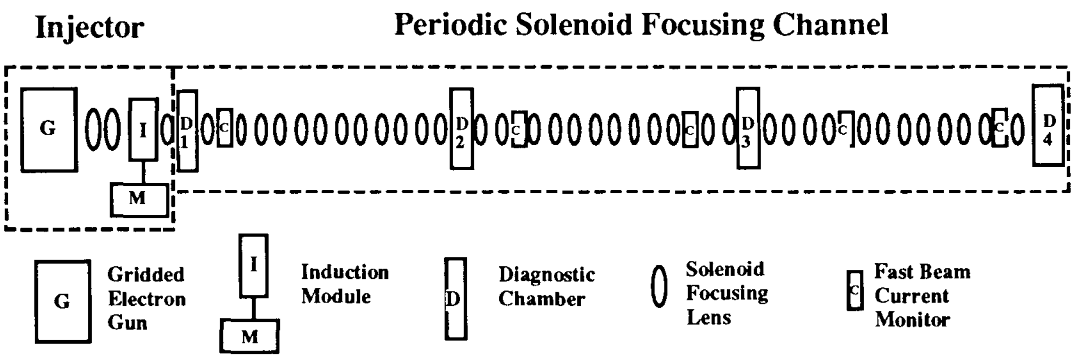

Fig. 1. Experimental configuration.

loss, we operate at a zero current phase advance per period of less than 90° for all electrons.

Five fast beam wall current monitors with a bandwidth up to 2 GHz are located along the channel. Three time-resolved beam energy analyzers are installed in the first, third and last diagnostic chambers. In addition, a beam image system is available, which includes a movable fluorescent screen, a CCD camera and a Macintosh II computer to investigate the average transverse behavior.

Measurement results

The current measurement for both expansion and compression experiments are made at five different locations along the channel and shown in Fig. 2 and 3, respectively. From the fitting of these waveforms the beam width, the peak current and the beam center can be obtained. This data gives the average beam velocity and energy. Matching it with the induction gap voltage one can calculate the initial velocity tilt imparted by the induction gap acceleration. The comparison of the experimental results to the results of Eq.(2) is plotted in Fig. 4. The g factor is determined from the K-V radial envelope calculations of the different beam currents and by averaging along the channel and along the beam as well. One obtains essentially the same picture as for transverse free expansion of a space-charge dominated beam.

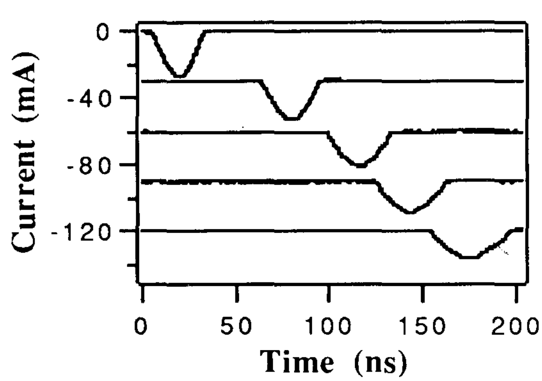

Fig. 2. Beam current waveforms for drift expansion.

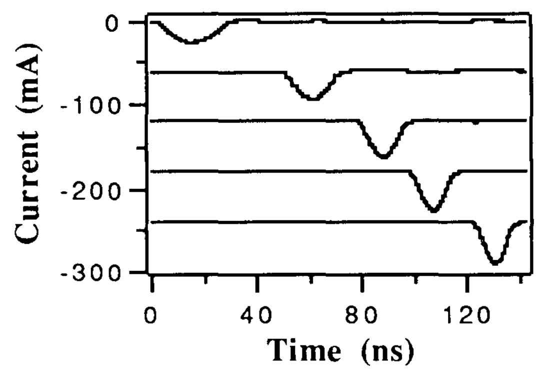

Fig. 3. Beam waveforms for drift compression.

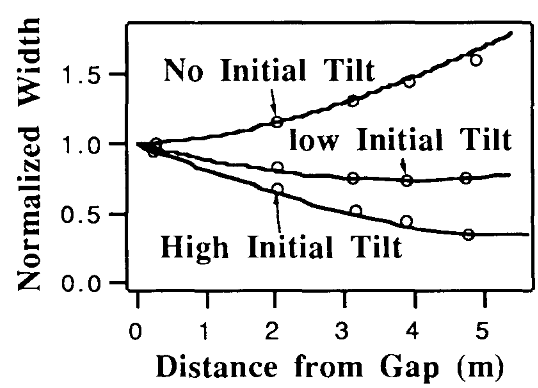

Fig. 4. Normalized bunch width vs. drift distance for parabolic bunches where the solid curves represant theory and the circles experiment.

The space-charge force tilts the velocity profile continually such that the front half electrons gain energy while the backhalf ones lose energy. Without the initial tilt the bunch width and the peak current continue to increase and decrease, respectively. With the initial tilt, bunch compression takes place. However, the repulsive space-charge force tends to resist

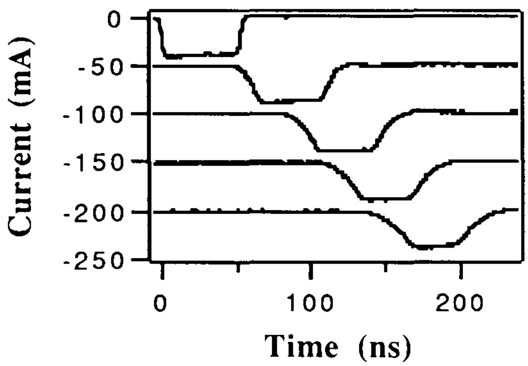

Fig. 5. Beam waveforms for drift expansion.

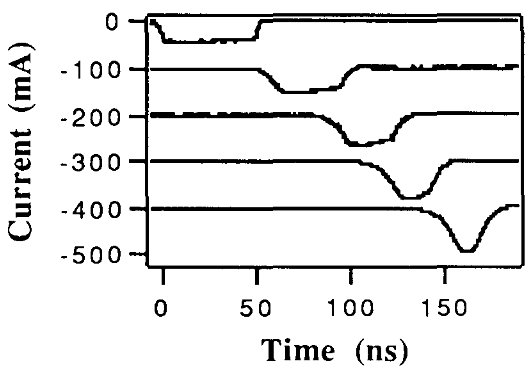

Fig. 6 Beam waveforms for drift compression.

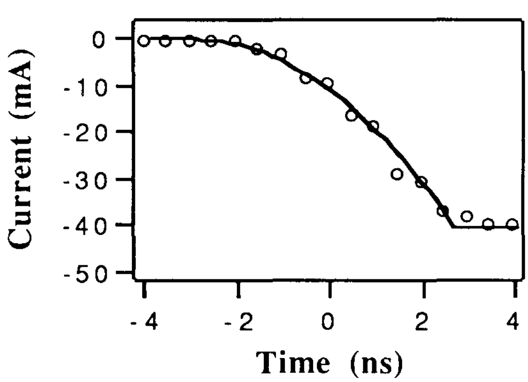

Fig. 7. Leading edge of first waveform in Fig. 5. the solid curve represants theory and the circles experiment.

it. Eventually, the waist is reached where the initial tilt is removed. After that the bunch starts to expand again.

The current waveforms for the expansion and compression rectangular pulses are shown in Fig. 5 and 6, respectively. In Fig. 7 and 8, the leading edges of the first and last waveforms in Fig. 5 are enlarged and fitted with the theoretical curves generated by Eq. (3).

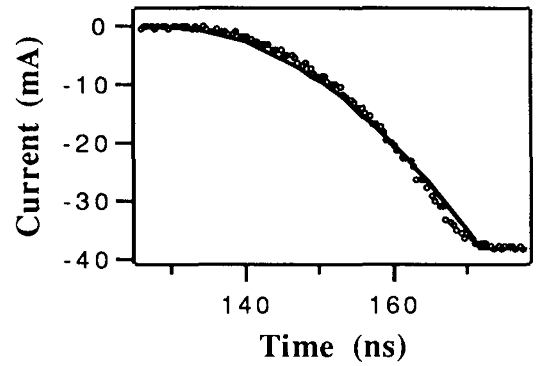

Fig. 8. Leading edge of last waveform in Fig. 5. the solid curve represants theory and the circles experiment.

It should be noted that the initial density at the leading edge is theoretically treated as a step function while the rise time at the gun is about 0.7 ns, which may cause these slight differences between the experiment and the calculation. Due to the extremely strong space charge forces at the edges a strong wave propagates at 2Cs speed inward and at Cs outward. As a result the edges significantly spread out. However the center region remains flat since the space-charge force is absent there. With an initial tilt the center is easily compressed and the edges spread out substantially .

Conclusions

The experimental results show the very good agreement with the envelope description for the parabolic profile and the wave explanation for the drift expansion of the rectangular one. It indicates that the "long wave" calculation of space-charge forces is a fairly good approximation and works well even at the beam edges. The beam energy will be measured soon to give a more complete picture of the longitudinal phase space. A detailed comparison will be made with PIC code simulation results.

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