EFFECTS OF ERRORS OF VELOCITY TILT ON MAXIMUM LONGITUDINAL COMPRESSION DURING NEUTRALIZED DRIFT COMPRESSION OF INTENSE BEAM PULSES*

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Abstract

Neutralized drift compression offers an effective means for particle beam focusing and current amplification. In neutralized drift compression, a linear longitudinal velocity tilt is applied to the beam pulse, so that the beam pulse compresses as it drifts in the focusing section. The beam intensity can increase more than a factor of 100 in the longitudinal direction. We have performed an analytical study of how errors in the velocity tilt acquired by the beam in the induction bunching module limits the maximum longitudinal compression. It is found in general that the compression ratio is determined by the relative errors in the velocity tilt. That is, one-percent errors may limit the compression to a factor of one hundred. However, part of pulse where the errors are small may compress to much higher values determined by the initial thermal spread of the beam pulse.

INTRODUCTION

Longitudinal compression during neutralized drift is achieved by accelerating the tail of the beam pulse relative to the head. This is accomplished experimentally by passing the beam pulse through a time-dependent bunching module. For the Neutralized Drift Compression eXperiment-I (NDCX-I) [1-3], the accelerating module is the induction bunching module. In the case of an ideal velocity tilt, all beam ions arrive at the same location at the target plane. The bunching module operates with some errors in voltage, which results in errors in the velocity tilt. Due to errors in the velocity tilt, the beam ions arrive at the target plane at different times. We have performed an analytical study of how errors in the velocity tilt acquired by the beam in the induction bunching module can limit the maximum longitudinal compression. Due to errors in the velocity, δv_b, the beam pulse width at the target plane, l_f, is of order $\delta v_b t_f$, where t_f is the time to reach the target plane. Correspondingly, the width of the beam pulse is decreased from the initial pulse width, $v_{b0} t_p = l_p$, to $\delta v_b t_f$. Here, v_{b0} and t_p are the initial beam velocity and pulse duration, respectively. This gives a compression ratio of order

$$C \sim \frac{l_p}{l_f} = \frac{v_{b0} t_p}{\delta v_b t_f}. \quad (1)$$

The time to reach the target plane is related to the applied velocity tilt Δv_b by $\Delta v_b t_f = l_p$, so that the beam ions from the tail overtake the beam ions at the head at the target plane after drifting in the compression section. Typically, the pulse duration is much shorter than the focusing time, $t_p << t_f$, and the velocity modulation is small compared with the initial beam velocity, $|\Delta v_b| < v_{b0}$, with the fractional velocity tilt, $Max(\Delta v_b) / v_{b0}$, of order 5-30%. Substituting $\Delta v_b t_f = l_p$ into Eq. (1) gives

$$C \sim \frac{\Delta v_b}{\delta v_b} = \frac{\Delta U}{\delta U}. \quad (2)$$

Therefore, the compression ratio is limited by the relative errors in the applied velocity tilt in the induction bunching module, compared with the ideal velocity tilt [4], and are related to the voltage errors in the induction bunching module. Here, $\Delta U = M v_b \Delta v_b$ is the amplitude of the voltage, and $\delta U = M v_b \delta v_b$ is a typical value of the voltage error. Similarly, the minimum compressed pulse duration is $\delta t_p \sim \delta v_b t_f / v_b = \delta v_b t_p / \Delta v_b$, and is also determined by the voltage errors according to

$$\delta t_p \sim t_p \frac{\delta U}{\Delta U}. \quad (3)$$

Typical values of the relative error in the voltage of the induction bunching module are about 1-2%. Equation (2) then gives a compression ratio C in the range C~50-100. This estimate agrees well with the reported values of longitudinal compression obtained in experiments [1-3, 5]. If there were no errors in the velocity tilt, then the effects associated with a small thermal velocity v_T ($v_T = \sqrt{2T_{bz} / M}$ and $T_{bz} \sim 0.2cV$) would limit the compression ratio in Eq. (2) to a value of order $C_T \sim \Delta v_b / v_T$. For example, for the 300keV potassium beam in NDCX-I, $v_{b0} / v_T \sim 1000$ and $C_T \sim 300$ for a velocity tilt $\Delta v_b / v_{b0} \sim 1/3$ [3]. However, this would require a very precise design of the induction bunching module with an error of order 0.1%; and, similarly, the control of the beam velocity in the ion source should be realized with a precision within 0.1%.

If the value of the error $\delta v_b / \Delta v_b$ is much smaller for a part of the beam pulse, then this part of the beam pulse compresses to high values, whereas the rest of the pulse does not compress well. For important practical cases, the analysis of compression is more complicated because both the thermal spread and errors in the velocity tilt should be considered simultaneously. This requires a kinetic treatment of the longitudinal compression. Analytical formulas for the beam profile dynamics have

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been derived and can be used for practical calculations of the longitudinal compression [6].

ANALYSIS OF EFFECTS OF VOLTAGE ERRORS ON LONGITUDINAL COMPRESSION FOR THE NDCX-I EXPERIMENT

The NDCX-I experimental configuration is well described in several publications [1-3, 5]. In these experiments, a potassium ion beam with energy of about 300keV passes through an induction bunching module and then drifts through a neutralized drift section of several meters length. As a result, part of the beam (several 100ns) is compressed to a few ns. Experimentally-achieved compression ratios range from 50 to 90 depending on the beam energy and the target location. We have performed a detailed analysis of the longitudinal compression for a drift section of length 286.8cm, and the voltage pulse waveform shown in Figure 1. The data is from Ref. [7]. We have also analyzed other data sets (the results are similar to the data shown in Figure 1), and found that the maximum compression ratio can increase from 60 to 90 for optimal beam energy in agreement with the experimental data.

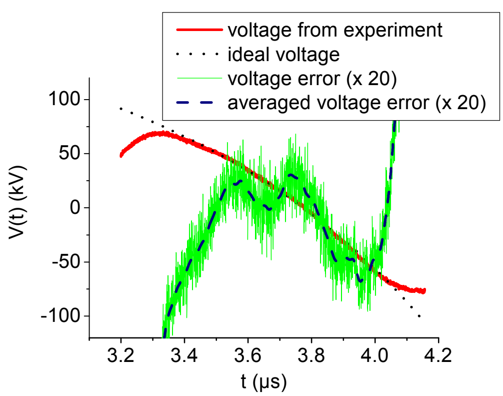

Figure 1: Plots of experimental voltage waveform of the NDCX-I induction bunching module [7] as a function of time and an ideal voltage waveform needed to compress the beam pulse at the target plane for beam energy 270keV (dotted curve). Also shown is the error in the experimental voltage as compared with the ideal voltage pulse.

As evident from Figure 1, the experimental voltage waveform is close to the ideal voltage waveform pulse starting at t_0 = 3.48μs and ending at t_1 = 4.07μs for the total duration of t_p=0.59μs. Therefore, this part of the beam pulse is expected to compress. At the beginning of the pulse, the beam head is decelerated from 270kV to 210kV at t_0 = 3.48μs and accelerated from 270kV to 348kV at the end of the pulse at t_1 = 4.07μs. Note that the voltage polarity shown in Figure 1 is such that a positive voltage corresponds to the beam deceleration.

The ideal voltage waveform is given by

$$U(t) = \frac{M}{2}\left\{\left[v_b^i(t)\right]^2 - v_b^2(t_0)\right\},$$

where $v_b^i(\tau) = v_{b0}t_f / \left(t_f - \tau\right)$ and $\tau = (t - t_0)$. The time to reach the target for the head of the beam is t_f = 2.81μs. Voltage errors are at the level of several percent.

Therefore, the ideal voltage waveform parameters (t_f and v_{b0}, or beam energy at the start of the beam pulse, E_{b0}) can be also chosen within several percent accuracy. For example, the choice of t_f = 2.83μs and E_{b0} = 210keV corresponds to a beam pulse compressed at $v_{b0}t_f$ = 288.3cm in the limit of ideal compression without any errors; this is slightly behind the target positioned at 286.8cm. Choosing t_f = 2.679 μs and E_{b0}=217keV corresponds to the ideal beam pulse compressed at the target location, $v_{b0}t_f$ = 286.8cm. Similarly, the choice of t_f = 2.77 μs and E_{b0}=208keV corresponds to a compression plane located at $v_{b0}t_f$ = 281cm, just before the target plane. The compressed beam profiles at different locations are shown in Figure 2.

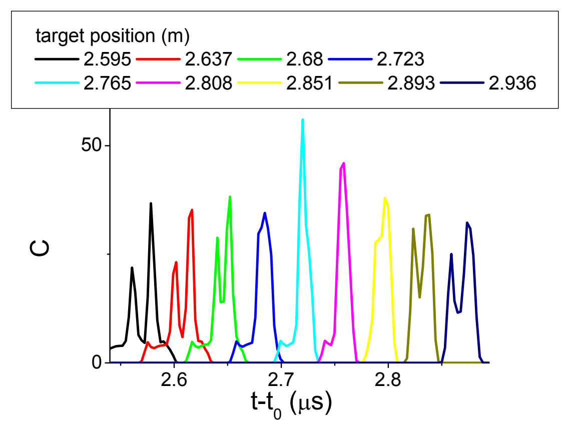

Figure 2: Simulated compressed pulse waveform at ten different target locations from z= 259.5 cm to 293.6 cm as a function of drift time after the beam pulse passes through the induction bunching module for the voltage waveform shown in Figure 1. The beam energy is 270keV and the longitudinal temperature is Tz is 0.27eV.

From Figure 2 it is evident that the beam pulse compresses significantly at different positions, which are spread over large distances relative to the target plane. Because the compression time when neighboring slices of the beam arrive at the same position depends on time derivative of the voltage waveform, small but fast changing errors result in large variations of the compression time of different parts of the beam pulse. That is, one percent errors in the beam velocity tilt can result in 10-20 percent variations of the compression time. A zoomed-in plot of the compression ratio is shown in Figure 2. It is evident from Figure 2 that the compressed pulse foot width is of order 10ns due to the errors, but the compressed pulse full-width at half-maximum can be reduced to a few ns for optimum beam energy. Indeed, if there is an error in the beam velocity, δv_b, due to voltage errors, the beam pulse width at the target plane is $\delta v_b t_f$. Correspondingly, the beam pulse duration at the target plane due to voltage errors of 1kV for a 300 keV beam is $\delta v_b t_f / v_{b0} \sim 2.8\mu s/300 \approx 10ns$.

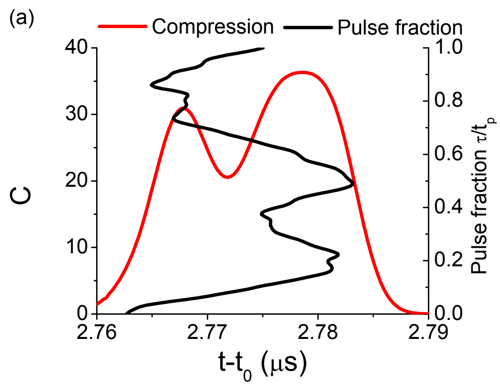

Figure 2: The simulated compressed pulse waveform at the target location z= 286.8 cm is plotted as a function of drift time for the voltage waveform shown in Figure 1. The beam energy is (a) 270keV, (b) 276keV, and the longitudinal temperature is T_z=0.27eV.

For the optimum beam energy or target location, the voltage errors are a factor of 3 smaller for this part of beam pulse [see Figure 2], and the corresponding compressed pulse width is reduced from 10ns to 3ns [compare Figure 2, for z_t= 2.85m and z_t =2.765m]. If the voltage errors are reduced, the compressed beam pulse width is also reduced and the compression ratio is increased. The effect of reduced errors is shown in Figure 4. Reducing the errors by a factor of five increases the compression ratio only by a factor of two (compare black and magenta curves in Figure 4).

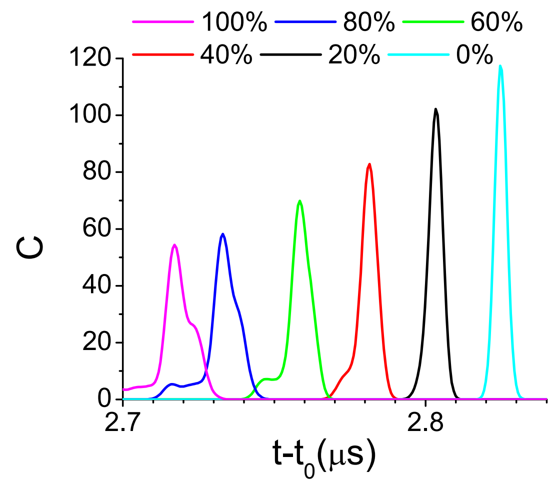

Figure 4: Simulated compressed pulse waveform at optimal target locations (100% error at z= 276cm; 80% at 278cm; 60% at 280cm; 40% at 283; 20% at 286cm; 0% at 288cm) is plotted for reduced voltage errors as a function of drift time for the voltage waveform shown in Figure 1. The beam energy is 270keV and the longitudinal temperature is Tz=0.27eV.

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