Generation of strong time compressed light ion beams


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Positive light ions (He\(^+\)) are extracted from a pulsed plasma source and accelerated in two stages, first at constant potential and subsequently by a time varying voltage which is programmed to generate a time compressed beam bunch, downstream at a defined distance from the accelerator. Time compression of a 1-\(\mu\)s extracted ion beam pulse into an 8-ns bunched pulse at a distance of 66 cm from the source has been achieved. The technique provides useful applications for concentrated energy deposition on targets and is part of a proposed Light Ion Fusion Experiment (LIFE) accelerator system where 20:1 axial pulse compression would be programmed to occur during the ballistically focused and neutralized transport of intense ion beams.

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I. INTRODUCTION

In the past few years the Inertial Confinement Fusion (ICF) program has expanded to include intense ion beams along with lasers as drivers for the implosion of ICF targets and fusion research. Both light ion (p, He) and heavy ion (Xe, U) intense beams are driver candidates. In the case of heavy ions, 5–10 GeV and 1–2 kA ballistically focused beams would be required so that in a multi-beam system, in excess of 2-MJ implosion energy can be imparted on targets in about 20-ns pulses. In the case of light ions, 3–10 MeV and 0.5–1-MA beams would be required. In both cases, beams should be prepared to propagate distances of 5–10 m and focus onto spot radii of 0.2–0.6 mm, delivering 150–300-TW beam power on targets at ~100 TW/cm\(^2\) focused power with energy density of 25–50 MJ/g. For the ballistically focused propagation of these neutralized ion beams a stringent emission requirement is imposed, with normalized transverse emittance \(\epsilon_{\text{VT}} = \beta \sigma_{\text{VT}} = (1 - 3 \times 10^5) \text{ m-rad} \). Light ion diodes with or without separate function ion sources are capable of accelerating MA currents to several MeV in ~40-ns pulses, however, beam divergence being large (~20 mrad) such beams are limited in power focusing range, propagation is restricted to the case of injecting beams into preformed high-current plasma channels, control in beam steering and focusing is difficult to achieve, and axial pulse compression is severely constrained so that high power technology is needed to energize the diodes. Consequently, the design\(^1\) of a multi-aperture, strong channel focused, multi-stage low \(\beta\) electrostatic accelerator was motivated to produce light ion ICF drivers with beams capable of propagating in 10-m standoff distance in 10\(^{-4}\)-Torr ambient gas, in the actively neutralized and ballistically focused manner,\(^2\) where also strong beam pulse axial compression is one of the key features. In the proposed\(^3\) Light Ion Fusion Experimental (LIFE) accelerator system, 25-kA beams need be accelerated in 400-ns pulses, where 20:1 axial pulse compression would be programmed to occur during propagation, delivering 0.5-MA currents at ICF targets in 20 ns and thus requiring a relatively low power technology to energize the multi-stage accelerator.

In this paper we discuss the production of a pulse of light ions and demonstrate the feature of strong beam compression in time by a suitably varying acceleration voltage. This approach provides advantages in that beam current densities at the source and accelerator need not be very large ((\(\sqrt{\text{source}}/\sqrt{\text{beam}}\)) \(\sim 10^6\)), the temporal waveform of the beam at the focus can be highly controlled and the beam power profile at the focus could also be programmed.

To date experiments with intense ion beams have been made with high-voltage diodes. Beams of hundreds of kiloamperes in current and ~1-MeV energy have been produced and a comprehensive review of this approach is prepared.\(^4\) Although these numbers are impressive, diode sources are not without drawbacks. So far in tests, the anode is usually a thin foil and is destroyed in every shot which necessitates breaking the vacuum for replacements; shot repetition rates are low (time of minutes) and reproducibility is a problem; the temporal shape of the pulse is not highly controllable; and for beam propagation a preformed high current plasma channel is required.

Here we wish to report the initiation of a different approach involving the production of a longer (~\(\mu\)s) pulse of ions from a pulsed rf induced plasma ion source.\(^5\) The ions are accelerated from the source through a multi-grid structure in which voltage waveform varies temporally such that \(v(t) = V_0 (t_0/t_0 - t)^n - 1\), where \(t < t_0\) and \(t_0\) is a constant. In addition to the temporal voltage, for convenience of monitoring a steady instead of pulsed voltage \(V_0\) is applied to the grids at \(t = 0\); but in intended applications \(V_0\) must be pulsed for a duration \(t_0\). This is illustrated schematically in Fig. 1. The axis on the left indicates the expected current to a collector, situated at one of three axial positions \(z\). At \(z = 0\) one would see a small steady current at all times due to the constant extraction voltage \(V_0\). The shaped acceleration voltage which is pulsed on for a time \(t_0\) causes some current amplification at \(z = z_0/2\) and a delta

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function current peak at \( z = z_0 \). Particles in the beam pulse tail are gradually accelerated to meet those in the beam front at \( z = z_0 \), the time focus drift position, where \( t_f \) is the flight time of the slowest particles at the beam front. The trajectories indicated by the arrows move apart after the time focus as particles which have left at the end of pulse \( t = t_f \) overtake those that were extracted at \( t = 0 \). In practice the ion beam is not cold when it leaves the source; its thermal spread augmented by space charge effects results in a temporal spread \( \Delta t \) of the beam around \( t = t_f \). One may then define the beam current amplification to be \( CA = t_f / \Delta t \).

This paper will first discuss the ion source, extraction, acceleration, and bunching system which includes the waveform generator. Since the beam is ultimately narrow in space and time at \( (z_0, t_f) \), a specialized probe was constructed and is described as well. Section III presents the results of the measurements, the beam compression ratio and divergence, and conclusions are made in Sec. IV.

II. EXPERIMENTAL SETUP

As shown in Fig. 2, the ion beam is extracted from a quasi-steady-state plasma source consisting of an rf discharge in Helium at low neutral pressures \( (p \approx 5 \times 10^{-4} \text{ Torr}) \). The discharge is produced by rf breakdown using a pulsed (1 ms on time, 16 ms repetition time) rf power oscillator (5-kW peak power, 300 kHz) with inductive coupling \((L \approx 4 \mu \text{H})\) to the parallel plasma load \((R \approx 30 \Omega)\). The plasma \((n_e \approx 1 \times 10^{11} \text{ cm}^{-3}, T_e \approx 4 \text{ eV}, \text{He}^+)\) is confined in a multi-dipole magnet cage \((25 \text{ cm diam}, 40 \text{ cm long})\) which is open on one side for the purpose of beam extraction. The plasma source chamber is electrically insulated from the grounded vacuum chamber. \( \text{rf} \) transmission lines, probe diagnostics, and gas input into the source chamber are high-voltage insulated.

Since the source plasma exhibits large potential variations in the presence of the rf pulse, beam extraction is performed in the early afterglow \((t \approx 50 \mu \text{s})\) where the plasma has become quiescent. The extracted pulse width \((t_f \approx 1 \mu \text{s})\) is short compared with the characteristic decay times \((\tau_e \approx 500 \mu \text{s}, \tau_n \approx 100 \mu \text{s})\) so that plasma parameters can be considered constant. Density and temperature are determined from Langmuir probe traces sampled at various times during the discharge and in the afterglow.

The ion beam is formed with a multi-stage accelerator system shown in Fig. 3. The first three grids operate as a conventional accel-decel system at a constant extractor voltage \( V_0 \) \((1 \text{ kV} \leq V_0 < 10 \text{ kV})\). The first grid, attached to the plasma source is biased at \(+ V_0\) with respect to the third grid. The second grid has a small negative bias voltage \((-300 \text{ V})\) so as to prevent possible back-streaming of secondary electrons. The first extractor system, presenting constant potentials to the plasma source, acts as a buffer stage to the second acceleration system with time varying potentials. If the latter were directly applied in a single stage the beam properties (divergence, perveance) would greatly vary in time, resulting in poor compression. The time
Figs. 4. (a) Block diagram of the circuit to generate the time varying acceleration voltage; (b) low-voltage input waveform generated by adding delayed pulses of adjustable amplitudes; (c) high-voltage output waveform amplified and applied to the accelerator grids. Only the progressively rising portion of the waveform is used for time compression; the remainder of the waveform is not relevant to this experiment.

voltage, \( V(t) \), \( 0 < V(t) < 10 \text{ kV}, \ t_p = 1 \mu\text{s} \) is applied between the third and fifth grid, the latter being at ground potential. The fourth grid biased negatively at \( V_4 = -300 \text{ V} \) serves again as an electron reflector. Since the first extractor stage was referenced with respect to the third grid, it is following the time varying waveform \( V(t) \) such that the total beam acceleration occurs with the potential \( V = V_4 + V(t) \). A blocking capacitor was used to stabilize the constant part of the applied potential.

Physically, the extractor grid consists of 1-mm stainless-steel plates spaced 1-mm apart (2 mm between electrodes No. 1 and No. 2). The circular electrodes (5-cm diam) were designed to accommodate an array of holes but in the present initial experiments only a single central hole was used with diameter 2 mm (2.8 mm in electrode No. 1). The holes in the five electrodes are coaxially aligned.

While the steady-state bias voltages are readily produced with floating charged high-voltage capacitors, the time varying waveform is generated in a special circuit sketched schematically in Fig. 4. In order to achieve optimum time compression a voltage waveform \( V(t) \propto (t_0 - t)^2 \) for \( 0 < t < t_0 \) needs to be generated accurately. This is accomplished by synthesizing the waveform with a sequence of 25 delayed pulses of adjustable amplitudes, generated with integrated circuit flip-flops. The low-voltage waveform is smoothed with an RC filter and subsequently amplified in several linear amplifier stages. The final stage is a high power tetrode (10 kV, 10 A) which, via transformer coupling yields the acceleration and beam compression voltage \( V(t) \). The final stage supplies not only the beam current but also the capacitive currents flowing from plasma source and associated power supplies to ground. Due to nonlinearities in the amplifier chain the output waveform differs somewhat from the input low-voltage shape. However, the distortions can be readily compensated by adjusting the synthesized input waveform. Examples of the characteristic input and output waveforms are shown in Figs. 4(b) and 4(c). The progressively rising waveform of the output voltage \( (0 < t < 1.1 \mu\text{s}) \) is closely matched to the theoretically required time dependence; the remaining trailing portion of the waveform does not contribute to the time compression of the beam.

After extraction and acceleration, the ion beam propagates along the axis of the vacuum chamber for distances of up to 1.5 m. It is detected by a shielded Faraday cup consisting of a fine mesh grid, biased negatively to reflect electrons and a 1-cm-diam grounded ion collector. In order to provide for a fast time response, a miniature broadband preamplifier \( (0.1-100 \text{ MHz}, 20 \text{ dB}) \) is mounted at the probe tip and connected via a coaxial cable to the external equipment. The probe can be positioned with motor drives to different axial and radial positions.

III. MEASUREMENT RESULTS

A. Beam pulse compression

Figures 5 and 6 are a collection of measurements showing the temporal behavior of the detected beam cur-

FIG. 5. A set of measurements of the temporal waveform of the ion current as a function of distance from the accelerator. At \( z < 30 \text{ cm} \) the signal is immeasurably small. The temporal width at the focus is 8 ns (measured profile shown in Fig. 6) and is represented here by a line shape.
rent as a function of axial position from the accelerator. Data are assembled from oscilloscope traces, as the one shown in the insert of Fig. 6. The behavior in the focal region which is outlined by the circle in Fig. 6 is temporally too narrow to be displayed on a microsecond time scale. The leading edge of the pulse at \( t = 0 \) corresponds to particles with energy 1.47 kV which is just above the dc accelerating voltage \( V_d \) of 1.2 kV. The time profile of the beam current is seen to have small ripples. One may consider the beam current density to be superposition of beamlets of various velocities: \( J = \sum_i n_i v_i \). Optimally the density of the \((i)\)th beamlet should equal that of the \((i+1)\), small amplitude kinks in the time varying acceleration voltage (which is generated by a superposition of flat pulses as discussed in Sec. II) are reflected in the measured current. As one approaches the position of the time focus, these inhomogeneities merge to form a sharp waveform which is measured to be 8 ns in duration at the focus. The actual duration at focus could be shorter, since the detected pulse is near the limit of the 100-MHz amplifier in the probe. The beam time compression ratio \( t_i / t_f \) is 125; the initial pulse being 1-\( \mu \)s duration. To our knowledge this is the largest ion beam time compression achieved in such a short distance.

B. Beam spatial compression

The spatial properties of the beam near focus have been measured. These are needed to evaluate the current-density compression ratio in the presence of space charge and uncorrected accelerator optical effects causing beam divergence. Consider the temporal waveform at three radial positions at \( z = 58.5 \) cm from the accelerator [see Fig. 7(a)]. The focal position in this case is at \( z = 66.0 \) cm, the initial and final peaks are from beamlets of 5.87 and 2.79 kV, respectively. The maximum beam voltage is 7 kV. By plotting the amplitude of the detected signal for each observed beamlet, it is possible to calculate the spatial profile and divergence angle of the beam as shown in Fig. 7(b). The faster beamlet \( V_2 \) (3.5 \( \times 10^5 \) cm/s) diverges less rapidly \( \theta_{\text{FW}}(V_2) = 1.37^\circ \) while the slower beamlet \( V_1 \) (2.1 \( \times 10^5 \) cm/s) is more divergent, \( \theta_{\text{FW}}(V_1) = 2.80^\circ \). This change in divergence can be explained by the time dependent focusing action between the last two grids given by \( \Delta \theta = \rexc\Delta E / (4V) \), where \( R_e \) is the aperture radius, \( \Delta E \) is the electric field difference on both sides of grid 3, and \( V \) is the potential of the beam in crossing this grid. Here \( \theta_{\text{FW}} \) is the half width at half maximum of the angular distribution. The divergence of the constant voltage beam was measured to be 3.5° with a different movable collector. There was no effort made to design an accelerator geometry which minimizes the beam divergence. Moreover, the space charge of the beam was not neutralized in an externally prepared manner.

At the focus of the beam the detector collected 1.8 \( \times 10^{-4} \) A over a spatial full width at half maximum of 2 cm, averaged over all velocity components. The detector is not sensitive to the dc component of the beam current. The beam density at the focus was 3.75 \( \times 10^5 \) cm\(^{-2}\). The ratio of focal area to the hole area of the accelerator is 100. The current density at \( z = z_0/2 \) is \( \sim 2 \times 10^{-3} \) A/cm\(^2\) and at \( z = z_0 \) is \( \sim 3 \times 10^{-4} \) A/cm\(^2\). By taking into account the space charge and accelerator uncorrected optics caused beam expansion, a current den-
sity amplification figure of 100 is derived which is consistent with the beam time compression ratio of 125.

IV. CONCLUSIONS

In the present experiment the effective compression of streaming ions accelerated in time to higher velocities has been demonstrated, starting with 1-μs duration pulses. Time compression of beam pulses by two orders of magnitude have been achieved, producing ion bursts of 8-ns duration after a propagation distance of 66 cm. If the beam would have no spatial divergence, the time compression would imply a corresponding enhancement in the beam density or flux. However, due to space-charge effects and unoptimized accelerator geometry the beam diverges. At the focal distance the beam density decrease due to beam divergence is approximately equal to the enhancement by time compression. Thus, although the total current has been increased by two orders of magnitude, no appreciable current density increase has been measured. However, in the present experiment attention was given to the time compression issue and no attempts were made to space-charge neutralize the beam or design an optimized accelerator. The beam divergence can be greatly reduced by providing a free-electron source in the target chamber, to produce conditions of co-moving and co-located ion-electron beams.\(^1\) One can also improve the accelerator electrode design by known techniques, so as to minimize the initial beam divergence and by using many extractor apertures spatially focused beamlets can be produced pointing to a common focus,\(^2\) thereby obtaining a further density enhancement. By combining strong time compression with spatial compression, \(10^6-10^7\) enhancement can be achieved in beam densities at a combined spatial/time focus.

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