Inductive Postacceleration of a Charge- and Current-Neutralized, Intense Pulsed Ion Beam

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An induction accelerator system has been successfully operated to postaccelerate an intense pulsed ion beam that is highly space-charge and current neutralized. An annular ion beam (energy 90 keV, current 5.7 kA, pulse width 750 nsec) extracted from an applied-B_r magnetically insulated diode is injected into the induction accelerator, where a short pulse (210 kV, 50 nsec) is applied. Measurements of beam energy by a Thomson-parabola spectrometer before and after the postacceleration have confirmed the increase in beam energy of H^+ up to ~ 240 keV after being postaccelerated.

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An intense pulsed light-ion beam (LIB) such as H^+ with an energy of ~ 10 MeV is considered to be a promising candidate as an energy driver for an inertial-confinement fusion since it is relatively easy to obtain high-power beams at a considerably low cost.[1] Nevertheless, there is a serious problem to be solved: The divergence angle is large; hence it yields poor focusing.[2]

On the other hand, the use of a medium-mass ion beam (MIB) such as B^+ with higher energy, greater than several tens of megaelectronvolts, seems to be an alternative candidate instead of the use of protons.[2–6] To obtain such a high-energy MIB, we use a multistage induction accelerator.[7,8] The basic idea is to postaccelerate a space-charge- and current-neutralized ion beam by use of many accelerating gaps that are insulated magnetically. The features can be summarized as follows: (1) Since the energy is high [higher than LIB but much lower than the heavy-ion beam (HIB)] and the current is low (lower than LIB but much higher than HIB), beam divergence due to the space-charge effect can be reduced.[4–6] (2) Since the energy density dissipated in accelerating gaps becomes low, damage in the gaps decreases, and hence the reliability of the pulse-power source is improved, being able to be highly repetitive. (3) The influence of anode-source plasma that strongly affects beam divergence is reduced in such a multigap system.

As a first step of the multistage acceleration of a space-charge- and current-neutralized ion beam, we have constructed an induction accelerator system, MALIA-I (which stands for Medium-mass Atom Linear Induction Accelerator[4,5]), and made the first observation of the postacceleration of the space-charge- and current-neutralized LIB and MIB, which will be described in this paper.

Figure 1 illustrates the schematic of the experimental apparatus MALIA-I. As seen from Fig. 1, it consists of two sections: ion diode and postaccelerator.

The ion diode is an applied-B_r magnetically insulated diode,[9,10] which is directly connected to a Marx generator (200 kV, 5 kJ). The anode (aluminum) is annular, and equipped with a flashboard of polyethylene sheet (outer diameter, 170 mm; inner diameter, 100 mm; effective area, 148 mm^2; thickness, 1.5 mm), on which approximately 1500 holes (1-mm diam each) are drilled. The cathode comprises two coaxial cylinders, the diameters of which are 180 and 90 mm. The gap length between anode and cathode is 15 mm. The insulating magnetic field is produced by coaxial coils, which are fired by a slow capacitor bank (5 kV, 400 μF). The numbers of turns are five and eighteen for the outer and inner coils, respectively. The magnetic flux density is typically ~ 0.15 T at the center of the anode, $r = 67.5$ mm, if charged at 1 kV. From a

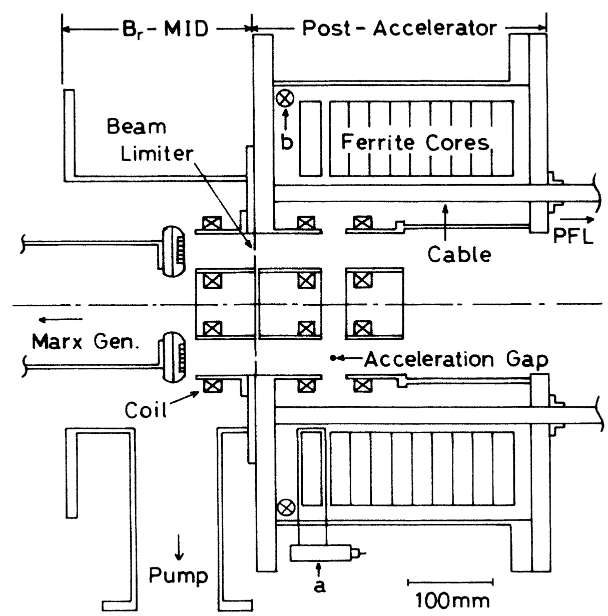

FIG. 1. Schematic of induction-accelerator system, MALIA-I, where *a* and *b* denote the voltage divider ($CuSO_4$) and the Rogowski coil, respectively.

computational calculation using a finite-element method, the magnetic lines of force are expected to be nearly parallel to the anode surface.

The postaccelerator is driven by a Blumlein pulse-forming line (PFL) with switching reversed, where a four-channel switch is located between the outer and intermediate conductors. Design parameters of the PFL are 300 kV, 50 nsec, and 15 Ω. The PFL is charged by a Marx generator with a stored energy of 900 J. The center conductor of the PFL is directly connected to the postaccelerator through three 50-Ω cables (diameter of inner conductor, 6 mm; diameter of outer conductor, 33 mm), where neither the prepulse switch nor the charging inductor is present. In the charging phase of the PFL, therefore, the reversed current (prepulse) flows through the vacuum chamber inside of which ten pieces of ferrite cores are installed, by which the ferrite cores are ready to reset to full swing. The ferrite cores used in the postaccelerator are made of Ni-Cu-Zn ferrite,[11] which is characterized by ΔB (flux swing) ~ 0.63 T, μ_i (initial relative permeability) ~ 300, and ρ (specific resistivity) $\sim 10^4\ \Omega\cdot$m. The dimensions of the ferrite cores are as follows: outer diameter, 508 mm; inner diameter, 308 mm; thickness, 25 mm each, hence giving the effective cross section $S = 250\ \text{cm}^2$. By use of a simple relation,

$$V\tau = S\Delta B,$$

where τ is the pulse width and V is the induced voltage, we thus calculate

$$V\tau = 1.57\times 10^{-2}\ \text{V}\cdot\text{sec}. \qquad (1)$$

The postaccelerating gap, with a separation of 20 mm, is provided by a pair of two coaxial cylinders (outer diameter, 180 mm; inner diameter, 90 mm). To avoid bombardment of the ion beam onto electrodes at the acceleration gap, a beam limiter (0.1-mm-thick copper) has been placed 94 mm upstream from the gap. The beam limiter has a slit of 138 mm outer diameter and 122 mm inner diameter, hence yielding an annular beam with a thickness of 8 mm.

The output voltage (V_{PFL}) and current (I_{PFL}) of the PFL are measured by a voltage divider ($CuSO_4$) and a Rogowski coil, respectively. The one-turn voltage (V_{ot}) induced in one ferrite core is measured by a voltage divider ($CuSO_4$) (see *a* in Fig. 1). The excitation current of the ferrite cores (I_{ex}) is measured by a Rogowski coil placed in the outer side of the current feeders [see *b* in Fig. 1].

Figure 2 shows the equivalent circuit of MALIA-I. In Fig. 2, L_f (~ 330 nH) is the inductance of the current feeders, L_{FC} ($\sim 7.6\ \mu$H) the inductance of ferrite cores, L_{gap} (~ 20 nH) the inductance in the duct that forms the accelerating gap, and V_{ind} the induction voltage through the ferrite cores. From simple circuit theory, we easily find the relations

$$I_{\text{PFL}} = I_{\text{ex}} + I_{\text{gap}},$$
$$V_{\text{ind}} = 10V_{\text{ot}} = V_{\text{PFL}} - L_f\, dI_{\text{PFL}}/dt, \qquad (2)$$
$$V_{\text{gap}} = V_{\text{ind}} - L_{\text{gap}}\, dI_{\text{gap}}/dt.$$

Figure 3 shows the wave forms of the B_r magnetically insulated diode (MID): diode voltage (V_d), diode current (I_d), and ion-current density (J_i) measured by a biased ion collector placed at $z = 171$ mm (at the accelerating gap). As seen from Fig. 3(a), the diode voltage is kept at $V_d \sim 90$ kV for 500 nsec, decreases gradually, and finally tends to diminish at t (time after the start of V_d) $\sim 1.4\ \mu$sec. From Fig. 3(b), the peak ion-current density is found to be $J_i \sim 20\ \text{A/cm}^2$, and the pulse width is ~ 750 nsec (FWHM). Integrating

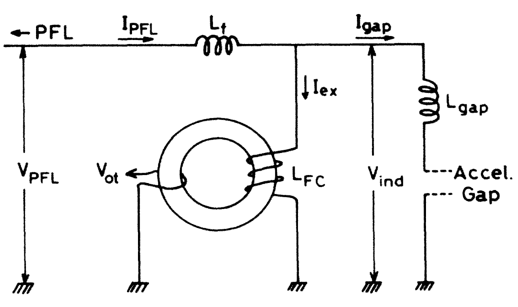

FIG. 2. Equivalent circuit of MALIA-I.

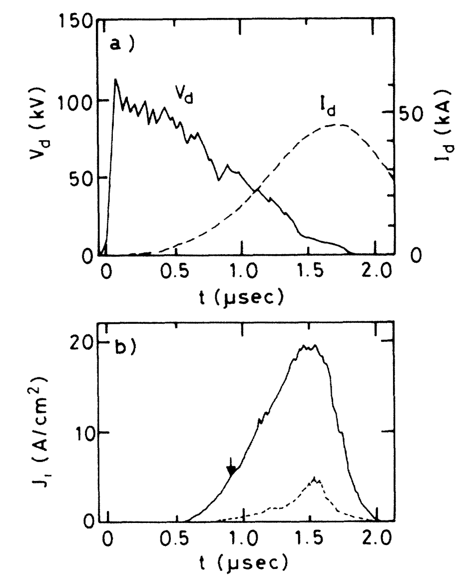

FIG. 3. Wave forms of incident B_r MID: (a) V_d and I_d, and (b) J_i. Broken and solid lines in (b) show those without and with bias voltage (−90 V), respectively. The arrow at $t \sim 0.9\ \mu$sec in (b) indicates timing where V_{ind} begins to rise.

the radial distribution of $J_i(r)$, we have estimated the total ion current to be $I_i \sim 5.7$ kA. From the measurement by the biased ion collector with and without the bias voltage [see Fig. 3(b)], we have calculated the current-neutralization factor to be $f_c \sim 0.8$ at $z = 171$ mm. Furthermore, the beam is considered to be highly charge neutralized.[12]

Figure 4 shows wave forms of V_{PFL}, V_{ind}, and I_{ex}, where broken and solid lines represent those without and with beam, respectively. From Fig. 4(a), we see that the peak voltage of V_{PFL} (without beam) ~ 390 kV and V_{PFL} (with beam) ~ 320 kV. From Fig. 4(b), in the absence of the beam, we find V_{ind} (peak) ~ 285 kV, $\tau \sim 60$ nsec, and hence $V_{ind}\tau \sim 1.7\times10^{-2}$ V·sec, which is in a good agreement with that designed [cf. Eq. (1)]. In the presence of the beam, on the other hand, the induction voltage decreases to V_{ind} (peak) ~ 210 kV, which seems to be due to the decrease in V_{PFL} and the increase in the voltage drop due to L_f with increasing I_{gap} [cf. Fig. 2 and Eq. (2)]. From Fig. 4(c), in the charging phase of the PFL, a reversed current is seen to flow, I_{ex} (without beam) ~ 7.5 kA and I_{ex} (with beam) ~ 5.8 kA, by which the ferrite cores are ready to reset to full swing as mentioned previously. In the above experiment, we have applied V_{PFL} at $t \sim 0.9$ μsec. If we change the timing of V_{PFL}, wave forms of the postaccelerator change drastically. In fact, when we apply V_{PFL} at $t = 0.9$ to 1.2 μsec, we have found V_{ind} (with beam) $= 210$ to 100 kV, respectively. Furthermore, if we fire V_{PFL} near the peak of ion current, $t \sim 1.4$ μsec, we have observed $V_{ind} \sim 50$ kV, hence yielding little acceleration.

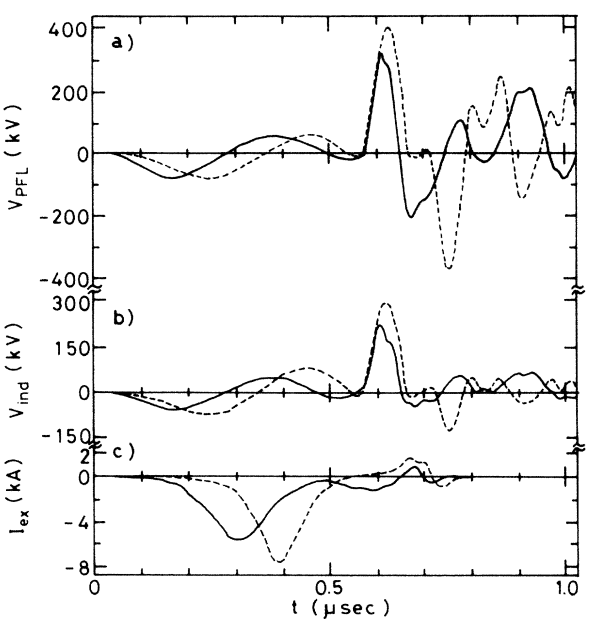

FIG. 4. Wave forms of (a) V_{PFL}, (b) V_{ind}, and (c) I_{ex} without (broken lines) and with (solid lines) beam.

Figure 5 shows the results of the Thomson-parabola spectrometer before and after the postacceleration. As the recording medium of the detector, we have used a cellulose nitrate film (CN-85). The distance between anode surface and first pinhole of the spectrometer is $z = 388$ mm. From Fig. 5(a), we find the presence of H^+, $H_2{}^+$, C^+, and C^{2+}. The peak energies of H^+, $H_2{}^+$, and C^{2+} are $\sim (90\ \text{keV})/Z$. The track density corresponding to the energy of $(80\text{–}90\ \text{keV})/Z$ is relatively high, which is comparable to the peak diode voltage as shown in Fig. 3(b). For C^+ ions, on the other hand, the peak energy is ~ 170 keV, which seems to be due to charge exchange with C^{2+} ions.

Applying $V_{ind} \sim 210$ kV at $t \sim 0.9$ μsec [see the arrow in Fig. 3(b)], we have carried out the postacceleration experiment. As seen from Fig. 5(b), we evidently find the peak energy to be ~ 240 keV for H^+, which is ~ 150 keV higher than that before the postacceleration.

In summary, by use of an inductive postaccelerator, MALIA-I, we have carried out an experiment on beam production and its postacceleration. The conclusions obtained are summarized as follows:

(1) By use of an applied-B_r MID, we have produced an ion beam with $V_d \sim 90$ kV, $J_i \sim 20$ A/cm^2, $I_i \sim 5.7$ kA, and $\tau \sim 750$ nsec (FWHM), which is highly charge and current neutralized.

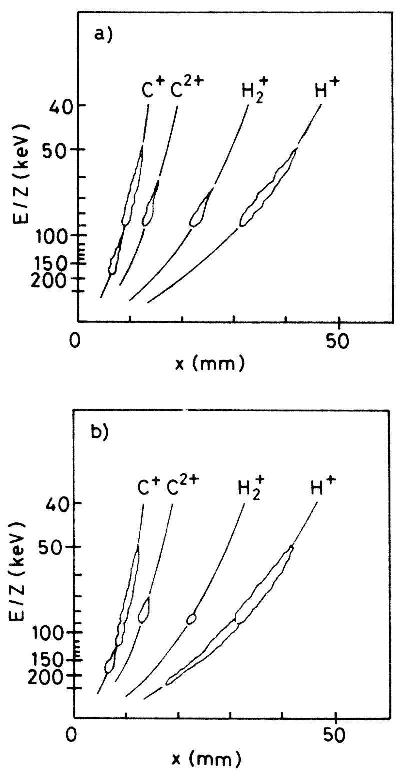

FIG. 5. Thomson-parabola spectrometer data (a) before and (b) after postacceleration.

(2) The low-energy H^+ beam extracted above is then injected into the postacceleration gap, where a short pulse (210 kV, 50 nsec) is applied at $t \sim 0.9$ μsec, and we have confirmed the increase in the beam energy of H^+ up to ~ 240 keV after being postaccelerated.

Although the above experiment has clearly shown the inductive postacceleration of H^+ that is charge and current neutralized, we have not evaluated the propagation efficiency of particles or energy spectra of postaccelerated beams. These will be clarified in a more suitable machine where a short-pulsed ion source is utilized with an accurately controlled postaccelerator.

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[12]The space-charge neutralization factor (f_s) has not been determined in this experiment. However, if we assume $f_s \leq 99\%$, a simple estimate gives us that a radial electric field due to space charge will be produced with $E_r \geq 17$ kV/cm at the outer edge of the beam ($r = 90$ mm). Such a strong electric field will make the beam diverge more than twice as wide as at the diode, and hence the beam cannot be transported up to the postacceleration gap ($z = 171$ mm downstream from the diode). Therefore, we can suppose $f_s > 99\%$ at least, hence almost full charge neutralization. In regard to space-charge neutrality of the ion beam in more detail, see K. Yatsui, K. Masugata, and M. Matsui, Phys. Rev. A **26**, 3044 (1982).

If such a highly charge- and current-neutralized ion beam (e.g., energy of protons ~ 90 keV) is injected into the postacceleration gap, neutralizing electrons will be returned back to the anode even in the absence of a transverse magnetic field since the energy of electrons (~ 50 eV for this case) is sufficiently low compared to the gap voltage (e.g., $V_{ind} \sim 210$ kV), and hence only ions can be accelerated in the gap.