All-ion accelerators: An injector-free synchrotron

Ken Takayama,[a] Yoshio Arakida, Taiki Iwashita, and Yoshito Shimosaki
High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Tanuja Dixit
The Graduate University for Advanced Studies, Hayama, Miura, Kanagawa 240-0193, Japan

Kota Torikai
National Institute of Radiological Science, 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan

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A medium-energy synchrotron capable of accelerating all-ion species is proposed. The accelerator employs a strong focusing lattice for ion-beam guiding and induction acceleration for acceleration and longitudinal capture, which is driven by a switching power supply. All ions, including cluster ions in their possible and arbitrary charge state, are accelerated in a single accelerator. Since the switching power supply employing solid-state switching elements is energized by a trigger signal, which is generated from a bunch monitor signal produced by a circulating ion bunch, the induction acceleration always synchronizes with the bunch circulation. This feature enables the realization of an almost injector-free synchrotron. © *2007 American Institute of Physics*.
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I. INTRODUCTION

For more than 70 years since the work conducted by Lawrence, Livingston, and other researchers in the 1930s,[1] the cyclotron, which has evolved into various forms, has been commonly used for the acceleration of most ion species in a medium-energy range of several hundreds of MeV/au. Any ions that have the same Z/A, where A is the mass number and Z is the charge state, can in principle be accelerated by the same cyclotron. For the acceleration of particular ions far beyond the medium-energy region, rf synchrotrons have been used. In the early 1970s, heavy ions, such as those of N, Xe, and U, were accelerated in the Princeton Particle Accelerator[2] and the Bevatron of Lawrence Berkeley National Laboratory.[3] The experiments then demonstrated the significance of the vacuum pressure in low- and medium-energy accelerators, where beam losses due to charge-state changing of partially stripped ions are serious. Nowadays, heavy ions, such as those of gold and copper, are accelerated in the Alternative Gradient Synchrotron and the Relativistic Heavy Ion Collider of Brookhaven National Laboratory, which are dedicated to collider experiments.[4] Lead ions are to be accelerated in the Large Hadron Collider of CERN for a similar purpose.[5] The heavy-ion medical accelerator of the National Institute of Radiological Science in Japan accelerates carbon ions to 400 MeV/au, which are delivered for cancer therapy;[6] in addition, He, N, O, Ne, Si, Ar, and Fe are provided for other purposes, such as radiation-damage tests on biological cells or investigating beam-plasma interactions. The SIS-18 synchrotron[7] of GSI is devoted to material science[8] or warm dense matter science,[9] providing H, D, C, N, O, Ne, Ar, Ni, Kr, Xe, Au, Bi, and U.

The accelerators mentioned above are classified as resonant accelerators employing radio-frequency waves for acceleration. Electric fields varying in time give the required energy per turn and provide the focusing forces in the direction of motion. This characteristic in a circular ring has been recognized to be an enormous figure of merit and is a major reason why the rf acceleration technique has quite a relatively long lifetime since its establishment. Once a synchrotron is determined to work on protons, a rf acceleration system consisting of a rf cavity and a rf power source is fixed. In a typical medium-energy synchrotron, the rf frequency sweeps over one order of magnitude throughout its entire acceleration, which takes place the increase in revolution frequency, where the relativistic beta changes from 0.1 to some value close to unity. The kinetic energy of an ion is expressed as $Amc^2(\gamma-1)$, where γ is the relativistic gamma of the ion and m is the proton mass; in the nonrelativistic region, it is approximated by $(1/2)Amc^2\beta^2$, where β is the relativistic beta. This formula suggests that the injection energy must be above $4.69A$ MeV to meet the rf frequency minimum limit. In other words, the integrated acceleration voltage in an upstream injector must be $V=4.69(A/Z)$ MeV. So far, this required voltage has been provided by a gigantic static accelerator, such as a Van de Graff generator, or by a drift-tube linac. An electrostatic accelerator of energy larger than several tens of MeV is not practical because of the technical limit of high-voltage breakdown and its huge cost. Note that the A/Z of an ion being accelerated in the drift-tune linac is limited by its rf frequency.

In principle, the acceleration of ions with a velocity far lower than $\beta=0.1$ in the rf synchrotron can be achieved by introducing higher-harmonic acceleration. The rf frequency f_{rf} is maintained at hf_0 throughout the entire acceleration, where f_0 ($=C_0/c\beta$, C_0: circumference of the ring) is the revolution frequency. In this higher-harmonic acceleration, the accelerated beam is segmented into h pieces of the rf bunch. The harmonic number h depends on the initial velocity of the ion, that is, $\sim 1/(10\beta)$. In higher-harmonic acceleration, se-

[a]Electronic mail: takayama@post.kek.jp

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rious beam loss at extraction is inevitable without additional beam handling of adiabatic recapturing by using lower-harmonic rf, after adiabatic debunching, because rf bunches are uniformly distributed along the entire ring right after acceleration by using the higher-harmonic rf, and extraction magnets excited for a finite time period kick a substantial fraction of these higher-harmonic rf bunches out of the extraction orbit. The additional rf system requires more space in the accelerator ring, and the complicated beam handling is time consuming. We can say that the higher-harmonic acceleration of a low-energy ion beam is not impossible but undesired.[10]

In this article, the concept of injector-free synchrotron, which allows the acceleration of all species of ions in a single ring, is proposed. To overcome the above limit of the existing rf acceleration, a developed acceleration technology is employed. Such a synchrotron is called an all-ion accelerator (AIA);[11] its characteristics and key issues are discussed below. So far, the irradiation of various ions on metals, magnetic materials, ceramics, semiconducting materials, and polymers has been discussed to develop materials such as nanowires, nanotransistors, quantumdots, and conducting ion tracks in diamondlike carbon.[8] Deep implantation of moderate-energy heavy ions may serve to create an alloy of bulk size. Meanwhile, energy deposition caused by the electroexcitation associated with the passing of swift ions through the material is known to markedly modify its structure.[12] Warm dense matter science is going to drastically evolve with the aid of high-power lasers and heavy-ion beams.[9,13] The irradiation of moderate-energy heavy-ion beams on metal in a small physical space of less than a mm in diameter and in a short time period of less than 100 ns is known to create a particularly interesting material state, where the temperature is 0.1–10 eV and the mass density is 1 g/cc. This state of matter is far beyond the playing grounds of solid-state physics and plasma science, where the equation of state has not yet been established, electric conductivity is not known, and the effects of the interactions between atoms are not confirmed. An AIA capable of delivering various heavy ions may be quite an interesting device that can drive the exploration of these paradigms.

II. FROM INDUCTION SYNCHROTRON TO ALL-ION ACCELERATOR

Recently, the concept of an induction synchrotron[14] has been demonstrated by the KEK 12 GeV proton synchrotron (KEK-PS),[15] where induction acceleration cells instead of rf cavities in a conventional synchrotron are employed. In the *induction synchrotron*, the acceleration and longitudinal confinement of charged particles are independently achieved with induction step voltages. A long step voltage generated in the induction acceleration cell gives acceleration energy, and a pair of pulse voltages, which are generated at both edges of some time period with opposite signs, are capable of providing longitudinal focusing forces, as shown in Fig. 1. In an experiment of the induction synchrotron, a single proton bunch was trapped in a barrier bucket created with the barrier voltages after injection from the 500 MeV booster ring, and it was accelerated up to

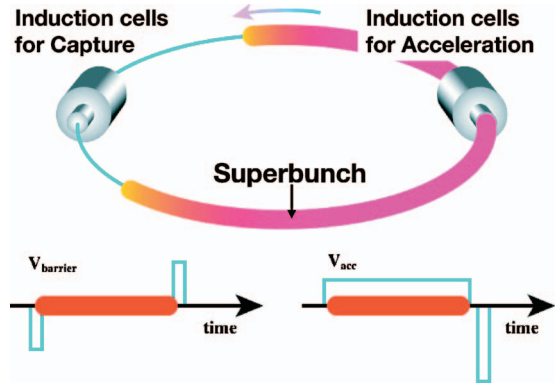

FIG. 1. (Color) Schematic view of the induction synchrotron. $V_{barrier}$ and V_{acc} are the barrier and acceleration voltages, respectively.

6 GeV in 2 s. Some results are shown in Fig. 2, which indicate the induction pulse shapes synchronizing with the proton bunch and the temporal evolution of the beam intensity. In addition to synchronization, ΔR feedback to keep the circulating orbit on the designed position in the vacuum chamber is an important issue, as in conventional rf synchrotrons. A sufficient acceleration efficiency is not expected without this function. In the induction synchrotron, the ΔR feedback is performed by blocking a trigger signal for the acceleration voltage when the position-monitor signal exceeds some preset value.[16] The acceleration voltage is not generated at the next turn. A typical example is shown in Figs. 2(a) and 2(b), where the preset value is 2 mm beyond the start of acceleration. Details of the experiment are given in other literature.[17]

The key devices required to realize an induction synchrotron are an induction acceleration cell and a switching power supply to drive the cell. The latter is a kind of pulse modulator,[18] which is capable of generating bipolar rectangular voltage pulses. The full-bridge-type switching power supply consists of four identical switching arms. Each switching arm is composed of solid-state power devices, such as metal-oxide-semiconductor field-effect transistors (MOS-FETs) arranged in series and parallel. Their gates are driven in their own gate-driving circuits. The gate signals are generated by converting light signals provided from the pulse controller, which is a part of the accelerator control system, to electronic signals. It is an essential point in the present proposal that these gate signals can definitely trigger the required accelerating and confining voltages at the desired timing. If a master signal for these gate signals is generated from a circulating ion-bunch signal, induction pulse voltages for acceleration and confinement should be automatically synchronized with the revolution of the bunch.[19] This fact suggests that the allowable revolution frequency is not limited if a sufficiently fast switching device is available. This differs markedly from a conventional rf synchrotron or cyclotron, where the range of the acceleration energy or ion mass is limited, since installed rf devices usually have a finite bandwidth, as mentioned earlier. An accelerator that can accelerate all species of ions of every possible charge state from the lightest to the heaviest, the AIA, can be realized when acceleration devices driven by the switching power

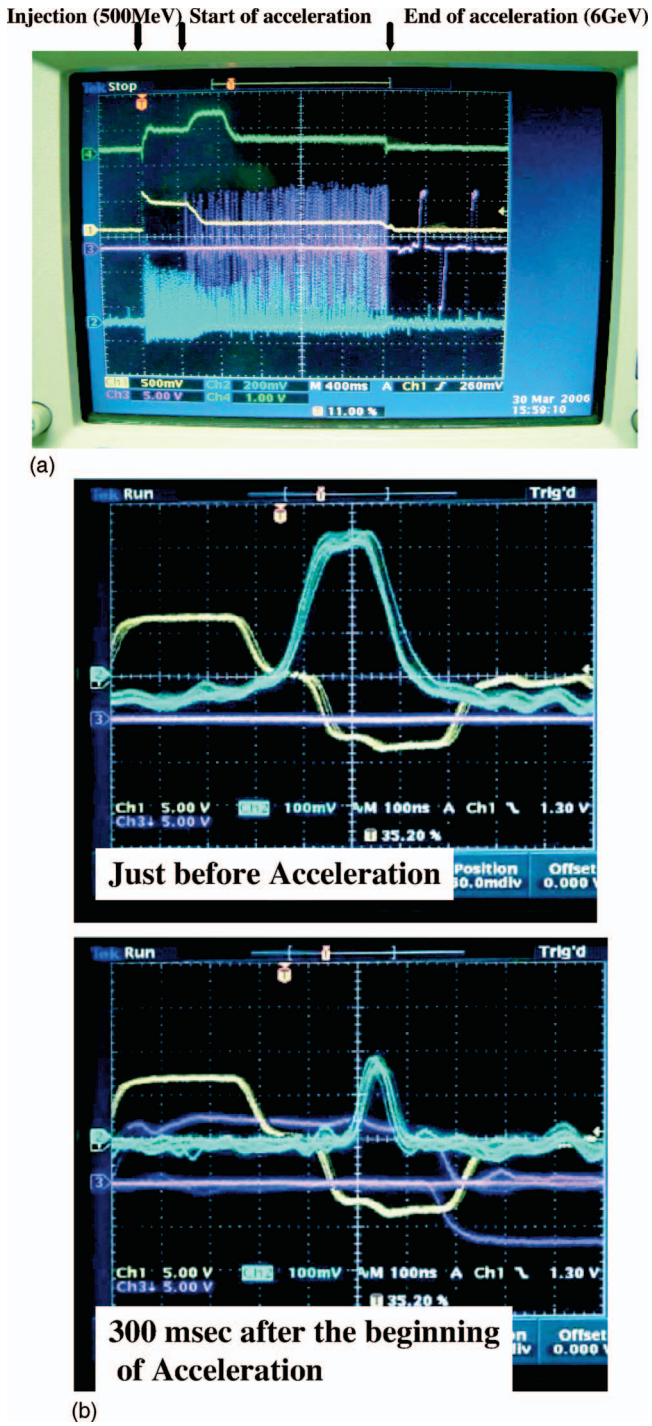

FIG. 2. (Color) (a)Experimental results using the induction synchrotron. From top to bottom, position of beam centroid, ΔR, (cm/div), beam intensity (10^{12}/div), acceleration voltage pulse, and bunch monitor signal as functions of time (400 msec/div). (b) Experimental results using the induction synchrotron. Induction acceleration voltage (purple), barrier voltage (yellow), and proton bunch trapped by barrier voltages (blue).

supply are employed. A schematic view of the AIA is depicted in Fig. 3, and the gate control system maneuvering the induction acceleration system, which is similar to the system developed for the demonstration of the induction synchrotron, is shown in Fig. 4. In this article, the essential characteristics of the AIA are discussed, and its typical composition and numerical parameters are given, assuming that the KEK

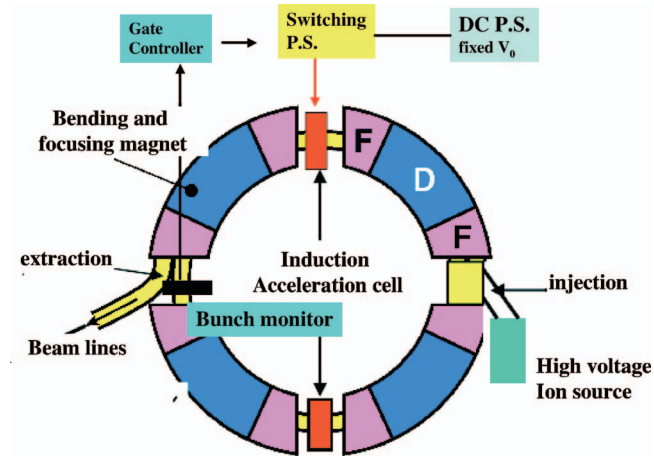

FIG. 3. (Color) Schematic view of the all-ion accelerator. The ion-bunch signals monitored by the bunch monitor are processed using the gate controller, and a gate signal for the switching power supply is generated.

500 MeV Booster Synchrotron (a rapid-cycle proton synchrotron), the beam, and machine parameters of which are listed in Table I, is modified to be an AIA.

III. ACCELERATION AND A LIMIT OF THE SWITCHING FREQUENCY

We can easily obtain the acceleration equation for an arbitrary ion with mass $M=Am$ and charge $Q=Ze$, where m and e are the mass of a proton and the unit charge, respectively. We have a force-balance equation in the accelerator with the magnetic flux density B,

$$M\gamma\frac{(c\beta)^2}{\rho} = Q(c\beta)B \Rightarrow Am\gamma\frac{c\beta}{\rho} = ZeB, \tag{1}$$

where ρ is the bending radius and C_0 is the circumference of the accelerator ring. Meanwhile, the averaged temporal change in ion energy is given by

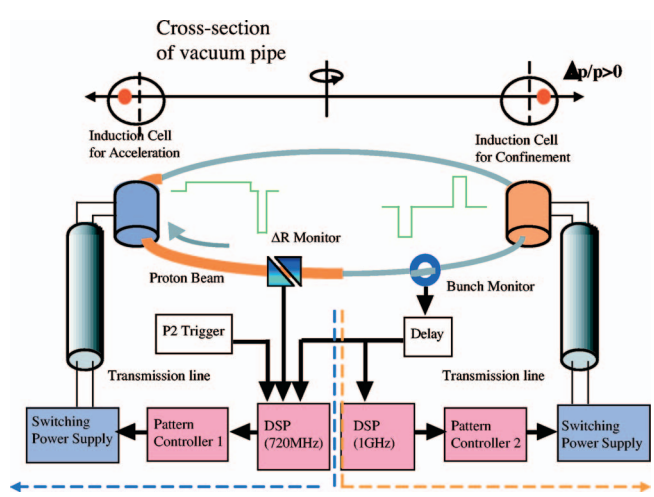

FIG. 4. (Color) Schematic view of the gate control system. The induction systems for the acceleration and confinement are of the same type, except for the gate control, which can generate different voltage patterns, as shown. P2 stands for the start of acceleration. The signal monitored at the bunch monitor is employed as a master gate trigger signal for the switching power supply.

TABLE I. AIA machine and beam specifications.

Circumference (m)	C_0	37
Curvature (m)	ρ	3.3
Minimum field (T) for Ar^{+18}	B_{min}	0.029
Maximum field (T) for $^{+18}$	B_{max}	0.8583
Acceleration voltage (kV) from (3)	V_{acc}	6.36
Operation cycle (Hz)	f	20

$$Amc^2(d\gamma/dt) = \frac{Zec\beta}{C_0}V_{acc}(t), \tag{2}$$

assuming that an induction voltage of $V_{acc}(t)$ is localized at a specific point on the accelerator ring. The ramping pattern of the bending field and the accelerating-voltage pattern must satisfy the following relation for the orbit of an ion to stay at the center of the accelerator ring:

$$V_{acc}(t) = \rho C_0 \frac{dB}{dt}. \tag{3}$$

Equation (3) gives the required accelerating voltage, since the ramping pattern of the magnetic field is determined first. There are two typical ramping patterns for $B(t)$: (1) excitation by the resonant circuit, which is commonly employed in a rapid-cycle synchrotron and (2) excitation with a pattern-controlled power supply, which is employed in a slow-cycle synchrotron. Since the former is typical for a medium-energy synchrotron, this case is considered here. $B(t)$ is expressed as

$$B(t) = \frac{1}{2}[(B_{max} + B_{min}) - (B_{max} - B_{min})\cos(\omega t)],$$

$$(dB/dt)_{max} = \frac{\omega}{2}(B_{max} - B_{min}),$$

where B_{min} and B_{max} are the injection field and the extraction field, respectively, and ω is the ramping cycle. From Eq. (1), the relativistic $\beta\gamma$ of an ion is straightforwardly written in terms of $B(t)$ as

$$\beta\gamma = \left(\frac{Z}{A}\right)\left(\frac{e\rho}{mc}\right)B. \tag{4}$$

The revolution frequency $f = c\beta/C_0$, is given by

$$f = \frac{c}{C_0}\sqrt{\frac{D}{1+D}}, \tag{5}$$

where

$$D \equiv (\beta\gamma)^2 = \left[\left(\frac{Z}{A}\right)\left(\frac{e\rho}{mc}\right)\right]^2 B^2(t).$$

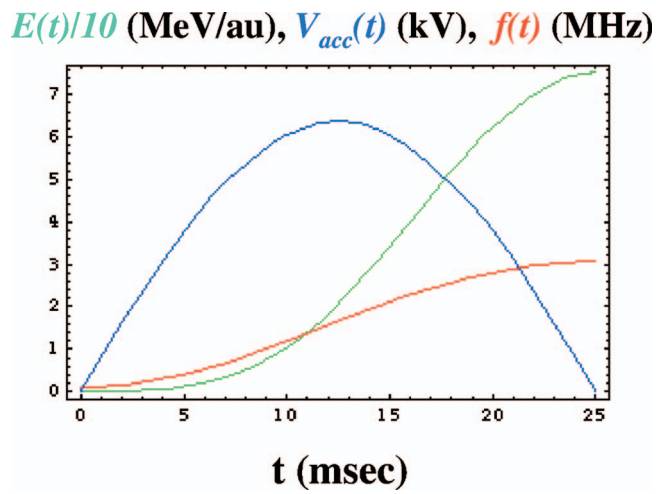

FIG. 5. (Color) Energy gain (green), required acceleration voltage (blue), and revolution frequency (red) vs time.

Similarly, the achieved kinetic energy of the ion is represented by

$$T = Mc^2(\gamma - 1) = Amc^2\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$$
$$= Amc^2\left(\frac{1}{\sqrt{1-(fC_0/c)^2}} - 1\right). \tag{6}$$

Since dB/dt is not constant for the rapid-cycle synchrotron, the accelerating voltage $V_{acc}(t)$ must change in time. Due to the one-to-one transformer nature of the induction acceleration system, the output voltage at the induction cell is the same as the output voltage of the dc power supply energizing the switching power supply. Therefore, it is difficult in a practical sense to change the acceleration voltage within one acceleration period on the order of several tens of milliseconds. Fortunately, a demanded energy gain per unit time Δt, $\Delta E = ZeV_{acc}(t)f(t)\Delta t$ is provided with a constant accelerating voltage V_0 and a modified switching frequency $g(t) = V_{acc}(t)f(t)/V_0$. In other words, the pulse density for acceleration is controlled. Namely, the gate trigger signal is intermittently generated. Usually, multiple induction acceleration cells are ready for acceleration. It is also possible to control in real time the number of dedicated acceleration cells. We use a combination of these two ways to generate the required accelerating voltage described by Eq. (3).

IV. LONGITUDINAL CONFINEMENT

Here, it should be noted that the switching capability of the commercially available switching element is limited to 1 MHz operation because of heat deposited on the switching element itself.[18] In the latter region of the acceleration period in the medium-energy AIA, the revolution frequency will exceed 1 MHz, as shown in Fig. 5. Superimposing intermittently triggered pulse voltages is a realistic technique for overcoming the limited repetition rate. For instance, every induction cell devoted to confinement is simultaneously triggered every three turns in the acceleration region with a

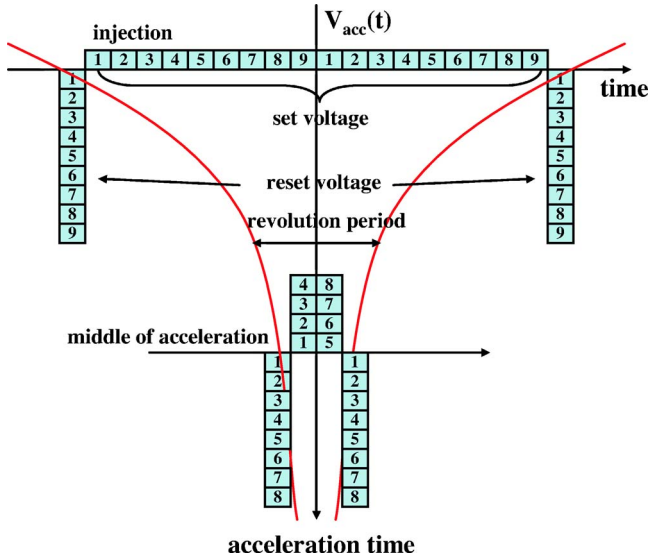

FIG. 6. (Color online) Acceleration voltage pattern. The numbers are identification numbers of the induction acceleration cells. The set voltage is generated with an accompanying reset voltage within a single revolution period if the revolution period is larger than 1 μs. Otherwise, the acceleration cells are intermittently triggered.

revolution frequency of 3 MHz, as can be seen in a typical example. The ion beam receives a confinement voltage that is three times larger than that required in the case that the induction cells are triggered every turn.

V. STACKING AND BEAM HANDLING DURING THE ACCELERATION

Injection into the AIA is done by the well-known multi-turn injection technique. The ion beam is injected until it builds up to its own space-charge limited intensity. Afterwards, the barrier step voltages are generated to capture the coasting beam. From the practical limit of current technology, the maximum pulse length for the induction acceleration voltage and its amplitude are on the order of 500 ns and 2 kV, respectively. The required long accelerating voltage is generated by superimposing induction-voltage pulses with a finite pulse width, a finite amplitude, and a limited repetition rate in time. Its schematic is shown in Fig. 6, where multiple acceleration cells are driven by individual switching-power-supply entries from the beginning of acceleration and the superimposed acceleration voltage-pulse length, as well as the time duration between the barrier voltage pulses, is deduced as the acceleration proceeds and the revolution period decreases. The entire acceleration process, as obtained by computer simulation, is depicted in Fig. 7.

VI. TRANSVERSE FOCUSING

Transverse focusing of an ion beam in a circular ring is also important. In a strong focusing lattice, the transverse motion of an ion is governed by the following equation:

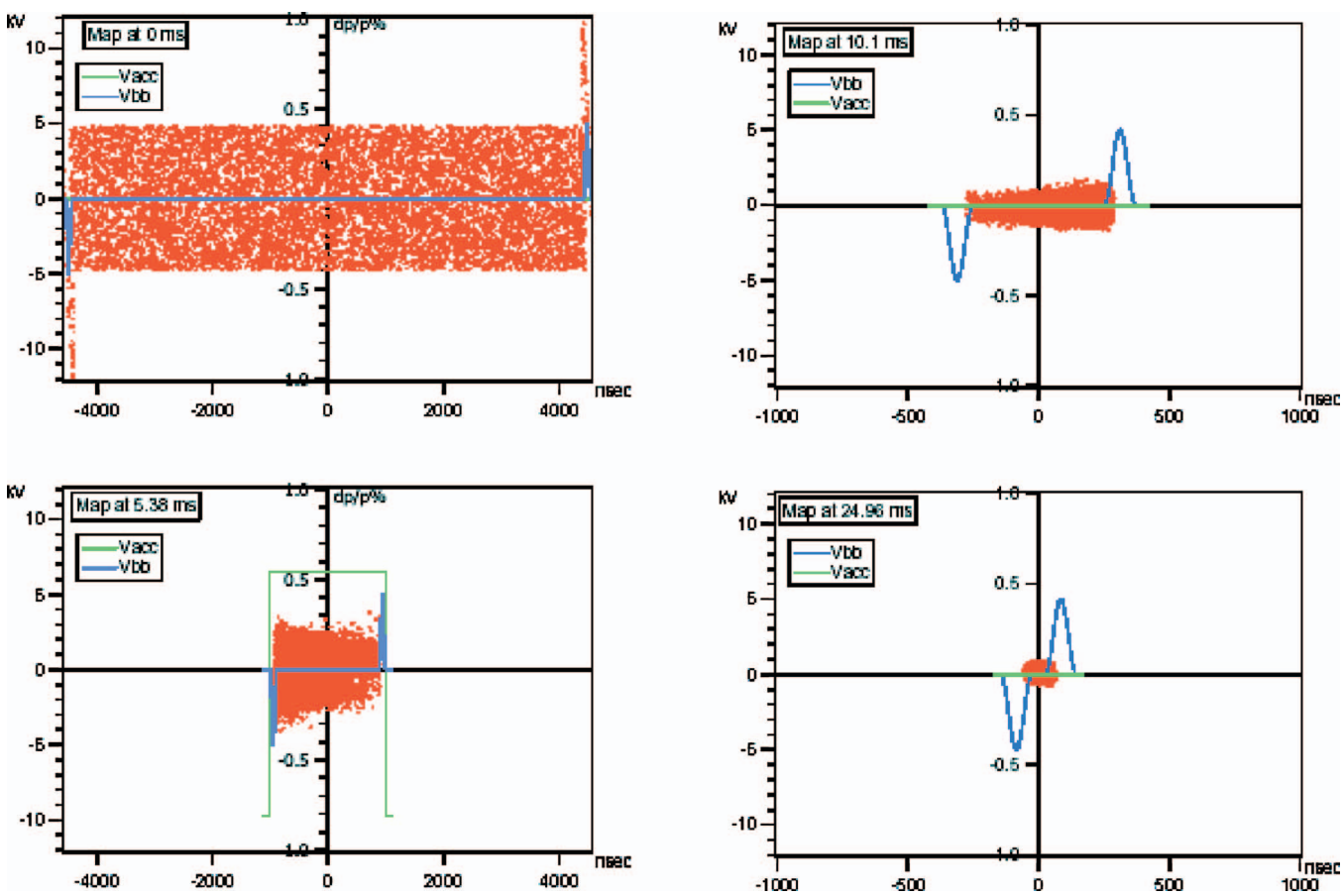

FIG. 7. (Color) Temporal evolution of an Ar^{+16} bunch in the longitudinal phase space. Phase plots from top to bottom show the ion bunch right after injection, at 5 ms, at 10 ms, and at the end of the acceleration, respectively. The output voltage per cell is 1.08 kV for acceleration, and the integrated barrier voltage (blue) is 5 kV.

$$Am\frac{d}{dt}(\gamma v_{\perp}) = -Zev_{\parallel}B'x, \tag{7}$$

where

$$B' \equiv \frac{\partial B_y}{\partial x}.$$

Using the orbit coordinates instead of the time derivative, Eq. (7) is rewritten in the well-known form of the betatron equation. Assuming that the changes in γ and β per turn are small, we have an approximated betatron equation,

$$\gamma c\beta_{\parallel}\frac{d}{ds}\left(\frac{dx}{ds}\right) = -\frac{Z}{A}\left(\frac{e}{m}\right)B'x \Rightarrow \frac{d^2x}{ds^2} + K(s)x = 0, \tag{8}$$

where

$$K(s) = \left(\frac{Z}{A}\right)\frac{(e/m)}{c\beta\gamma}\frac{\partial B_y}{\partial x}. \tag{9}$$

Substitution of Eq. (4) into Eq. (9) yields

$$K(s) = \frac{\partial B_y/\partial x}{B\rho}. \tag{10}$$

The k value does not depend on the ion mass nor its charge state; the betatron tune for any ion or any charge state is always the same. Once any ion is injected into the AIA with an appropriate momentum, as discussed later, the transverse beam dynamics throughout the entire acceleration is the same for all ions.

VII. TRANSEVERSE SPACE-CHARGE EFFECTS AND ION BEAM INTENSITY

Some ions subject to acceleration in the AIA are restricted by space-charge effects at injection because of an extremely low β. Its magnitude can be estimated by the term of the Laslett tune shift,

$$\Delta Q = \Gamma\frac{Z^2N}{AB_f\beta\gamma^2}, \tag{11}$$

where N is the number of charged particles per bunch, Γ is a function of the transverse emittance, and B_f is the bunching factor. It is believed that ΔQ is 0.25 in the space-charge limit. Thus, the allowed magnitude of N is known from Eq. (11). This number has been experimentally known for the proton in the KEK 500 MeV Booster.

The space-charge limited number of ions per bunch, N_i, is straightforwardly obtained using N_p, as shown in the following equation:

$$\frac{N_i}{N_p} = \left(\frac{A}{Z^2}\right)\left(\frac{\beta_i\gamma_i^2}{\beta_p\gamma_p^2}\right)\frac{(B_f)_{\mathrm{AIA}}}{(B_f)_{\mathrm{rf}}} \cong \sqrt{\frac{A}{Z^3}}\sqrt{\frac{V_i}{V_p}}\frac{(B_f)_{\mathrm{AIA}}}{(B_f)_{\mathrm{rf}}}, \tag{12}$$

where the subscripts i and p denote the parameters for an ion and proton, respectively. Here, $(B_f)_{\mathrm{AIA}}$ is a bunching factor in the AIA, which has been estimated to be 0.7–0.8 from extensive simulation work.[14] From the long experience of operating the KEK Booster for protons in the space-charge limited operation mode, where the injection voltage is V_p=40 MV, we know that $N_p=3\times10^{12}$ and $(B_f)_{\mathrm{rf}}$=0.3. Substituting these numerical parameters and the injection voltage V_i=200 kV into Eq. (12), we can evaluate the expected space-charge limited current for typical ions. For three cases of $^{12}C^{+6}$, $^{40}Ar^{+18}$, and $^{197}Au^{+79}$, we obtain $N_i=1.3\times10^{11}$, 4.7×10^{10}, and 1.1×10^{10} per bunch, or 2.6×10^{12}, 9.4×10^{11}, and 2.2×10^{11} per second, respectively. For simplicity, the same transverse emittance as that of a proton is assumed here.

The beam intensity suggested here is not very high but sufficiently attractive for material science. If the extracted ion beams are focused through a kind of mini-beta-focusing system commonly used in colliders, the beam size can be extremely minimized on a metal target, creating a higher-intensity beam. Bunch rotation in the longitudinal phase space is known to compress the ion bunch in time. Accordingly, a limited region in the three-dimensional (3D) physical space, where an ion beam manipulated in such a way loses most of its kinetic energy, will be useful for warm dense matter science.

VIII. SUMMARY

A scheme for realizing a medium-energy all-ion accelerator has been proposed. It simply involves a modification of an existing proton synchrotron by introducing induction acceleration, which has been experimentally demonstrated using the KEK 12 GeV proton synchrotron. Key features of the AIA, which are distinguished from a rf synchrotron, have been discussed. The KEK Booster synchrotron has been quantitatively evaluated as an example. The achievable beam energy and beam intensity have been given with the required parameters for the induction acceleration system. Various heavy ions of medium energy delivered from the AIA should be quite attractive for developing warm dense matter science. If a short acceleration gap in the induction acceleration cell and good vacuum are realized, even cluster ions, such as albumin of $A=5\times10^4$ and $Z<50$, may be accelerated in the AIA.[20] Heavy ions will be useful for deep ion implantation in various bulk materials, which is presently attracting the attention of material scientists.[21] Finally, it is emphasized that the idea of the AIA can be employed in existing rf synchrotrons and the modification is expected to be straightforward.

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T. Kono and K. Okazaki conditioned all induction acceleration systems to work stably. E. Nakamura and S. Inagaki have conducted ion-source R&D. M. Wake has been developing a reliable switching power supply. D. Arakawa provided useful information related to beam monitor signals, which are used as a master gate signal for the switching power supply. H. Sato examined the possibility of the slow-cycle operation of the KEK Booster magnets. T. Adachi investigated the closed orbit distortion (COD) in the KEK Booster, which should be induced due to remnant fields associated with the low injection-field operation. One of the authors (K.T.) thanks Y. Oguri for essential discussions about the possibility of accelerating cluster ions in the AIA. The present research has been supported by a Grant-In-Aid for Creative Scientific Research (KAKENHI 15GS0217).

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