Experimental Demonstration of the Induction Synchrotron

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We report an experimental demonstration of the induction synchrotron, the concept of which has been proposed as a future accelerator for the second generation of neutrino factory or hadron collider. The induction synchrotron supports a superbunch and a superbunch permits more charge to be accelerated while observing the constraints of the transverse space-charge limit. By using a newly developed induction acceleration system instead of radio-wave acceleration devices, a single proton bunch injected from the 500 MeV booster ring and captured by the barrier bucket created by the induction step voltages was accelerated to 6 GeV in the KEK proton synchrotron.

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As is well known, the first-generation induction accelerator is the betatron, which was realized by Kerst in 1940 [1] and has been used for various applications since its invention. An electron driver in the early history of nuclear physics and an x-ray driver for medical use and material science are among them. From the late 1950s to the present, linear induction accelerators (LIA), which are a kind of topological modification of the circular induction accelerator, have been constructed as accelerators for low- or medium-energy and high-intensity electron beams [2–5]. Demonstrations of high-power electromagnetic wave amplifiers, such as a free-electron laser [6–9], driven by electron LIAs, were notable highlights in the mid 1980s and early 1990s. Now, a newly developed electron LIA is being dedicated to the radiography facility at Los Alamos National Laboratory [10]. Meanwhile, ion linear induction accelerators have been continuously developed at Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory (LLNL) as a heavy-ion inertial fusion driver [11] since the mid-1970s. A concept of a recirculating accelerator of heavy ions employing an induction acceleration device, called a recirculator [12], was proposed in 1988, which was regarded as a natural extension of the LIA, but its R&D work at LLNL [13] was terminated before the mid-1990s without any notable experimental demonstration. The concept of the induction synchrotron (IS) was proposed by Takayama and Kishiro in 2000 [14] for the purpose of overcoming the shortcomings, such as a limitation of the longitudinal phase space available for the acceleration of charged particles in a rf synchrotron, which has been one of the indispensable instruments for nuclear physics and high-energy physics since its invention by McMillan [15] and Veksler [16]. Accelerating devices in a conventional synchrotron, such as an rf cavity, were replaced by induction devices in the IS. The acceleration and longitudinal confinement of charged particles are independently achieved with induction step-voltages in the IS, as schematically shown in Fig. 1. A long step-voltage generated in the induction acceleration cells gives the acceleration energy. Pulse voltages at both edges of some time period with the opposite sign, which are generated in other induction accelerating cells, are capable of providing longitudinal focusing forces. These pulse voltages are generated by the master trigger signal made from the bunch signal, which fires the switching power supply (SPS) to drive the induction acceleration cell. Consequently, acceleration and confinement are synchronized with the beam revolution. After the IS was proposed, the superbunch hadron collider [17] and all-ion accelerator [18,19] were under consideration as attractive applications. An extremely long superbunch is estimated to substantially diminish a serious problem of electron-proton instability and increase their luminosity, when the superbunch scheme is employed in colliders [20]. It is believed that any ion with any possible charge state including cluster ions can be accelerated from the sonic speed to high speed in a single all-ion accelerator because of a specific property that the induction acceleration devices are energized by the switching power supply synchronized with the ion-bunch circulation.

Under this background situation, the IS has been eagerly developed at KEK since 2000. After accomplishing the key devices, such as the SPS and the induction acceleration cell, to realize induction acceleration in a circular ring, an induction acceleration experiment was carried out step-by-step using the existing KEK 12 GeV proton synchrotron (12 GeV-PS), which is shown in Fig. 2. For the first time, induction acceleration in a high-energy circular ring was demonstrated in 2004 [21], in which a single proton bunch injected from the 500 MeV booster ring and captured in the rf bucket, was accelerated from 500 MeV to 8 GeV. This means that a hybrid synchrotron with functional separation

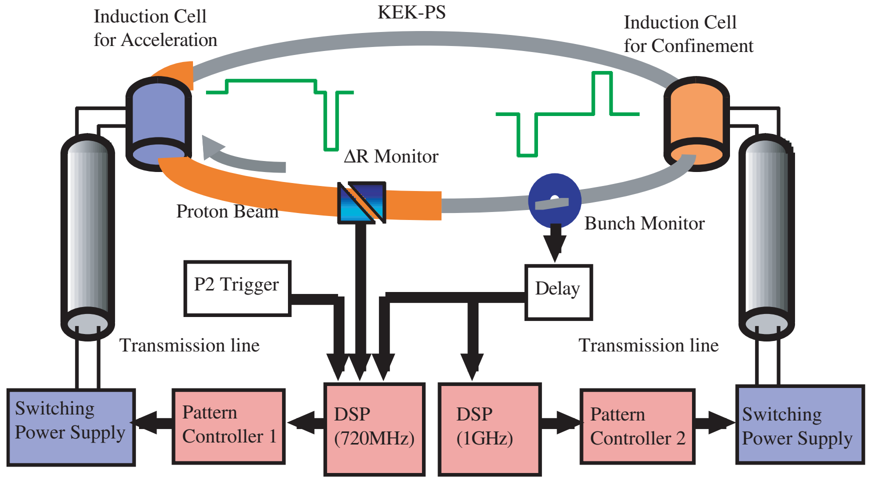

FIG. 1 (color). Schematic view of the induction synchrotron with the gate control system. The induction systems for the acceleration and confinement are of the same type except for the gate control, which can generate different voltage patterns, as shown. P2 means the start of acceleration. The signal monitored at the bunch monitor is employed as a master gate trigger signal for the switching power supplies.

in the longitudinal direction has been realized. In a succeeding experiment, the proton bunch was captured by the induction barrier voltages at an injection energy of 500 MeV and survived for more than 450 msec [22]. Furthermore, it turned out that the functional separation in the longitudinal direction in the hybrid synchrotron made a novel technique of transition-energy crossing, called quasiadiabatic nonfocusing transition-energy crossing, possible [23]. By this technique the desired bunch length at the transition-energy crossing is realized, substantially reducing any awkward beam behavior, such as microwave instabilities. Since then, a full demonstration of the IS, where a proton bunch captured in the induction barrier voltages is accelerated by the induction voltage, has been strongly expected by the high-energy accelerator society [24].

The key devices required to realize the IS are an induction accelerating cell [25], a SPS to drive the cell, and a gate control system to fire the SPS. The SPS is a kind of power modulator [26], which is capable of generating bipolar rectangular shaped voltage pulses at a repetition rate of 1 MHz. The full-bridge type SPS consists of four identical switching arms. Each switching arm is composed of power MOS-FETs arranged in series to carry an arm current of 20 A. The gate signals used to turn on the MOS-FETs are generated by manipulating both signals monitored at the fast bunch monitor and the beam position monitors in the gate control system, which consists of a digital signal processor and active delay modules, as shown in Fig. 1. The beam-orbit control was the most important issue in a full demonstration of the IS reported here, as well as in any synchrotron. Without this function, charged particles are not efficiently accelerated in a vacuum chamber. The so-called ΔR-feedback system is equipped to meet this requirement in a conventional rf synchrotron, where the rf phase seen by the bunch center is automatically adjusted in real time so as to compensate any surplus or shortage of acceleration. A similar feedback system [27], where the gate pulse generation was determined by integrating the digital gate pulse generator with the orbit information proportional to the momentum error, $\Delta p/p$, was introduced in the present IS. The position monitor directly gives $\Delta R = D(s)\Delta p/p$, where $D(s)$ is the momentum dispersion function at the location of the position monitor. When the signal amplitude exceeds a preset threshold value, the gate trigger signal is blocked in the DSP. Accordingly, the acceleration voltage pulse is not generated at the next turn and the momentum approaches the correct value, which is uniquely determined by the bending field. In this experiment, a sufficiently large ac-

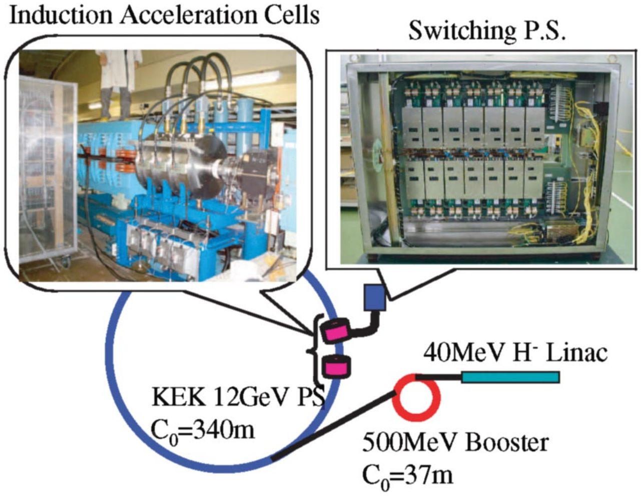

FIG. 2 (color). KEK-PS accelerator complex with the induction acceleration system, which consists of the 750 keV preinjector, 40 MeV H- drift-tube linac, 500 MeV booster synchrotron, and 12 GeV proton synchrotron. The ramping ratio of the bending magnets in the KEK-PS is 0.377 Tesla/ sec in the linear acceleration region. The upper right shows the SPS used to handle a maximum 35 kW of output power at a repetition rate of 1 MHz. The upper left shows three induction cells with an inductance of $L = 110$ mH, capacitance of $C = 260$ pF, and resistance of $R = 330\ \Omega$ in the equivalent parallel circuit model. Each induction cell is connected to an individual SPS through a transmission cable having an impedance of 120 Ω and to a matching resistance of 210 Ω.

celeration voltage was prepared as mentioned above. As a result, the gate trigger pulse was generated with a duty of less than 50%.

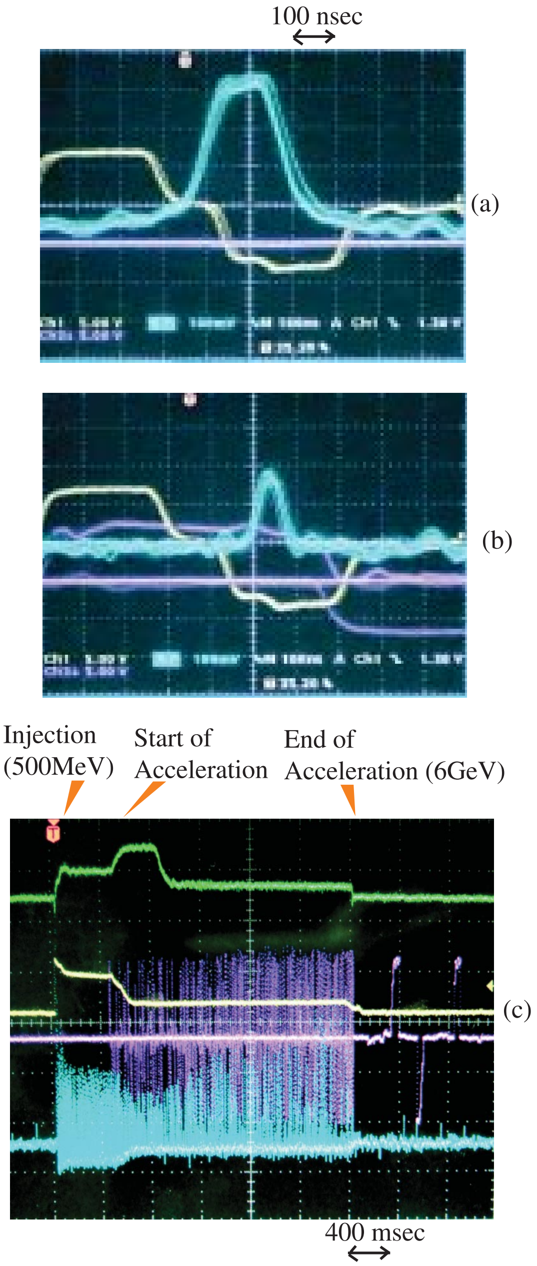

FIG. 3 (color). (a) Proton bunch trapped by step barrier voltages before acceleration. Sky blue, bunch signal; yellow, step barrier voltage (b) Proton bunch in the middle of acceleration. Sky blue, bunch signal; yellow, step barrier voltage; purple, induction acceleration voltage (c). Ch1(yellow), beam current (10^{12}/div); Ch2(sky blue), bunch monitor signal (the amplitude is inversely proportional to the bunching factor); Ch3(purple), gate pulse density vs time; Ch4(green), central beam position (ΔR) (10 mm/div).

A single 100 nsec-long bunch injected from the KEK 500 MeV booster ring into the KEK-PS was trapped in the barrier voltages shown in Figs. 3(a) and 3(b). A momentum spread of the injected beam was determined by measuring a debunching time of the injected beam in the KEK-PS. Its half-maximum $(\Delta p/p)_{\rm max}$ was 0.3%. The barrier voltages create a barrier bucket, the height of which is given by

$$\left(\frac{\Delta p}{p}\right)_{\rm height} = \sqrt{\frac{2eV_{bb}\tau}{\beta^2 ET|\eta|}},$$

where V_{bb} is the barrier voltage, τ the pulse width of the barrier voltage, and η the slippage factor; β, E, and T are the relativistic beta, total energy, and revolution period of the synchronous particle, respectively. The net V_{bb} magnitude of $1.8\ \text{kV} \times 6 = 10.8$ kV was sufficiently to accommodate the injected bunch. However, the injected bunch that had been captured by the rf bucket in the booster ring did not match the barrier-bucket shape. By way of the transient filamentation process in the longitudinal phase space, resulting in a bunch length of 400 nsec, the bunch was trapped by the barrier bucket during the injection field period of 450 msec. The trapped bunch was then accelerated to 6 GeV, which was determined by the ramping pattern of the guiding magnets. Since the KEK-PS is operated as a slow-cycle synchrotron, the ramping pattern is divided into three regions comprising two transient regions corresponding to acceleration start and end and the linear ramping region. The required accelerating voltage to follow this ramping pattern is described by $V_{\rm acc} = \rho C_0 dB/dt$, where ρ is the bending radius, C_0 is the circumference of the accelerator, and B is the bending magnetic flux as a function of time. Four induction acceleration cells of an output voltage of 1.6 kV per cell were employed for acceleration. A total magnitude of 6.4 kV, provided by the induction acceleration cells, was much larger than the acceleration voltage of 3.12 kV required in the linear ramping region. A substantial beam loss at the early stage of acceleration is apparent in Fig. 3(c), and beyond that the beam intensity was maintained to be constant without any beam loss. The beam loss just after the injection and at the beginning of acceleration are notable. From a previous experiment [22], it is known that the mismatching between the bunch shape and the barrier bucket creates a fine structure in the beam profile in time, yielding a signal from the bunch monitor with the same structure. This sometimes causes a timing error of the gate signal for the confinement barrier voltages, leading to a kind of bucket shaking, because the gate trigger signal is generated when the bunch signal exceeds the preset value in the present gate control system and a local peak isolated from the bunch center happens to exceed this preset threshold. The mechanism is a current speculation of the beam loss just after injection. The other beam loss at the beginning of acceleration seems to be caused by an insufficient ΔR feedback in the transient region approaching the linear ramping region, where the outer edge of the beam in the horizontal direction may hit the vacuum chamber. The bunch length gradually decreased with acceleration. Eventually it arrived at an order of 100 nsec near the transition energy close to 6 GeV. This is a naturally adiabatic behavior in the longitudinal motion, which was confirmed by a computer simulation assuming realistic barrier voltage parameters. Throughout the entire acceleration, the central orbit of the bunch was kept at a constant value, as expected. The result is shown in Fig. 3(c).

As mentioned earlier, various applications have been considered since the first proposal of the IS. The superbunch hadron collider [17], or a proton driver for the second generation of neutrino oscillation experiments are among them. These applications rely on the realization of a superbunch, the line density of which is just under the space-charge limit in the transverse direction. For this purpose, a long pulse duration between the barrier voltages and a long acceleration induction voltage is required. The induction acceleration device should be of low impedance to mitigate any serious beam-loading effects due to a large increase in the stored beam current. The SPS used to drive such a low-impedance device must be capable of carrying a larger arm current. The arm current is limited by the capability of the employed switching element. Research and development work on a high-current switching supply employing newly developed solid-state switching elements, such as a mold-type SI thyristor or a SiC MOSFET, is being conducted in collaboration between KEK, Nagaoka University of Technology, a solid-state material company, and a pulsed-power company [28]. Modifying the existing rf synchrotrons to the IS is rather easy, because it is just a matter of replacing the rf devices by the induction devices. In addition, the hybrid synchrotron seems to be very attractive.

The IS concept has been demonstrated in a complete form, although there are still unexplained features. We conclude that the principle of the induction synchrotron has been confirmed and the acceleration technology of charged particles has entered into a new era. Assuming further developments in the key devices, novel applications never realized in a conventional rf synchrotron will be expected in the near future.

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