FIRST RESULT OF INDUCTION ACCELERATION IN THE KEK PROTON SYNCHROTRON

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Abstract

Induction acceleration of a single RF bunch was confirmed in the KEK PS.

INTRODUCTION

Four years ago, the concept of an *induction synchrotron* employing induction accelerating devices was proposed by Takayama and Kishiro [1] for the purpose to overcome the shortcomings, such as a limitation of the longitudinal phase-space available for acceleration of charged particles, in an RF synchrotron, which has been one of indispensable instruments for nuclear physics and high energy physics since the invention by McMillan [2] and Veksler [3]. Accelerating devices in a conventional synchrotron, such as an RF cavity, are replaced with induction devices in the *induction synchrotron*. A gradient focusing force, seen in the RF waves, is not indispensable for the longitudinal confinement of particles. Pulse voltages, which are generated at both edges of some time-period with opposite sign, as shown in Figure 1, are capable of providing longitudinal focusing forces. A pair of barrier-voltage pulses work in a similar way to the RF barrier, which has been demonstrated at FNAL and BNL [4]. The acceleration and longitudinal confinement of charged particles are independently achieved with induction step-voltages in the *induction synchrotron*. This notable property of the separated-function in the longitudinal direction brings about a significant freedom of beam handling never seen in a conventional RF synchrotron, in which radio-frequency waves in a resonant cavity simultaneously take both roles of acceleration and longitudinal confinement. A big difference in the phase space between an RF synchrotron and the induction synchrotron is schematically shown in Figure 2.

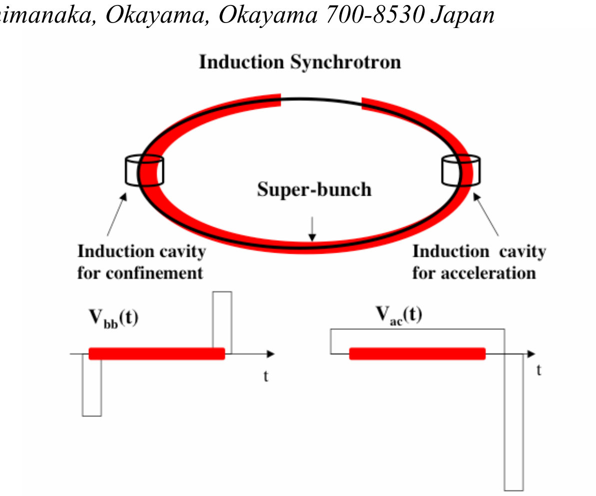

FIGURE 1. Conceptual view of the induction synchrotron and super-bunch with barrier voltages and acceleration voltage

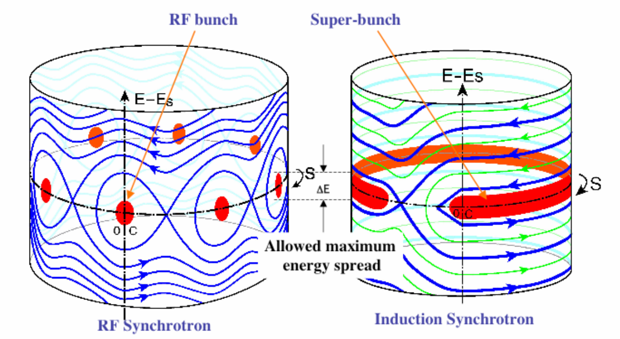

FIGURE 2. RF bunches and Super-bunch in the phase space

Associated with the separated-function, various figure of merits are expected. The formation of a *super-bunch*, which is an extremely long-bunch with a uniform line-density, and the use of which is considered in a proton driver for the second-generation of neutrino physics and a future hadron collider [5], is most attractive. In addition, transition crossing without any longitudinal focusing seems to be feasible [1], which could substantially mitigate undesired phenomena, such as bunch shortening due to non-adiabatic motion and microwave instabilities [6].

In April 2003, we started a new project to demonstrate an *induction synchrotron* using the KEK PS, where a *super-bunch* will be accelerated with the induction devices. The project consists of three stages [7]: at the first stage a single bunch captured in the RF bucket is accelerated up to 8GeV with the induction accelerating system, at the second stage multi RF bunches injected from the 500MeV Booster are captured in the barrier bucket to merge into a single *super-bunch*, and the last stage this *super-bunch* will be accelerated up to the flat-top energy. Here the current status of the first stage is presented.

The time-duration between barrier-voltage pulses determines a size of the *super-bunch*. For acceleration of the *super-bunch*, a long accelerating step voltage with a pulse length of the order of μ-sec is required. The voltage has to be generated at the revolution frequency of the beam in a ring. In the case of a ring-circumference of 300 m, a repetition rate of 1 MHz is required. So far, there has been no induction accelerating system capable of meeting these parameters. Recently, the prototype devices, which can generate a 250nsec flat-top voltage at a repetition rate of cw 1 MHz, have been assembled at KEK after the 3 years R&D stage and combined with the existing RF accelerating system.

A single proton bunch trapped in an RF bucket was accelerated with the induction accelerating system from 500MeV to about 1.5 GeV. In this paper, we report on the first experimental result of induction acceleration of a single RF bunch in the KEK proton synchrotron (KEK-PS) as well as a brief description of the induction accelerating system.

INDUCTION ACCELERATION SYSTEM

The key devices required to realize an *induction synchrotron* are an induction accelerating cavity [8] and a pulse modulator driving the cavity [9]. These devices are notably different from similar devices employed in modern linear induction accelerators [10]. Remarkable properties are its switching characteristics, repetition ratio, and duty factor. Another different feature is that the pulse modulator has to be kept far from the induction cavity placed in the accelerator tunnel, because the solid-state power switching elements obtainable at present can't survive an extremely high radiation dose. Thus, the pulse modulator is connected with the accelerating cavity through a long transmission cable. In order to reduce reflection from the load, a matching resistance has been installed at the end of the transmission cable. The induction accelerating system consists of an induction cavity with a matching load, a transmission cable, a pulse modulator, and a DC power supply. A typical system capable of generating a step-pulse of 2 kV output voltage and 18 A output peak current at 1 MHz with 50% duty has been demonstrated at KEK. An equivalent circuit for the induction accelerating system is shown in Fig.ure 3.

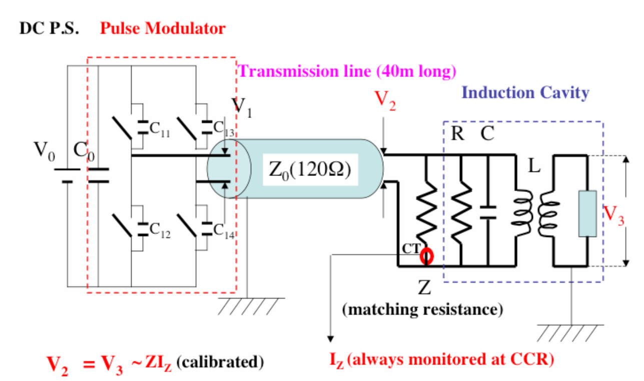

FIGURE 3. Equivalent circuit for the induction acceleration system

A core material of the induction cavity employed for the first acceleration experiment is a nanocrystalline alloy, called Finemet (Hitachi Metal). Heat generated due to core loss is cooled down by insulation oil. The electrical parameters of each unit-cell, such as capacitance, inductance, and resistance, which determine the property of pulse rising and falling are listed in Table 1. Three unit-cells with a 2 kV output voltage per unit are mechanically combined into a single module for the convenience of installation. Since the inner conductor with three ceramic gaps is common to three unit-cells, but both sides of each gap are electrically connected to the outer edges of each cell, a particle is accelerated with the same voltage passing these gaps. An engineering drawing is depicted in Figure 4.

Table 1

Capacitance	pF	260
Resistance	Ω	330
Inductance	H	110

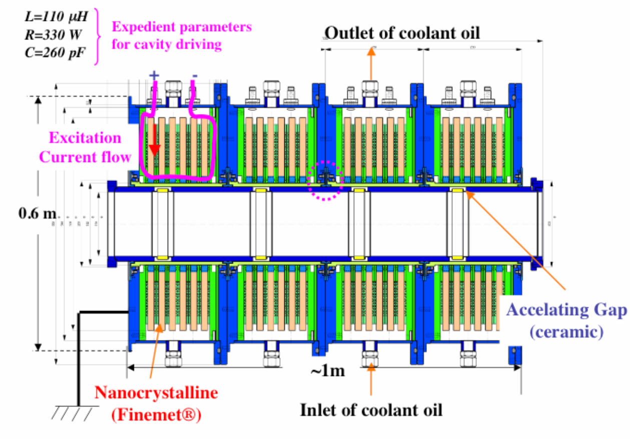

FIGURE 4. Induction cavity

A full-bridge switching circuit in the pulse-modulator, which is depicted in Figure 5, was employed because of its simplicity. The pulse modulator is capable of generating bipolar rectangular shaped voltage pulses. The full-bridge type pulse-modulator consists of four identical switching arms. Each switching arm is composed of 7 MOS-FETs, which are arranged in series. Their gates are driven by 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. Its details will be presented elsewhere [10]. The inside figure is given in Figure 6.

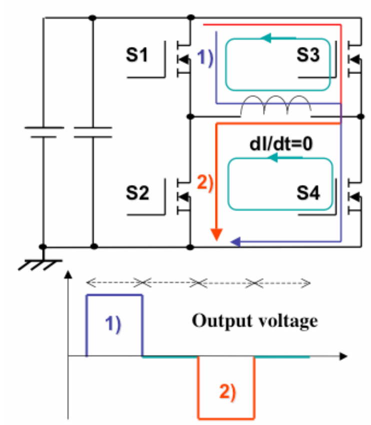

FIGURE 5. Architecture of the power modulator and switching sequence (top), typical pulse pattern (bottom)

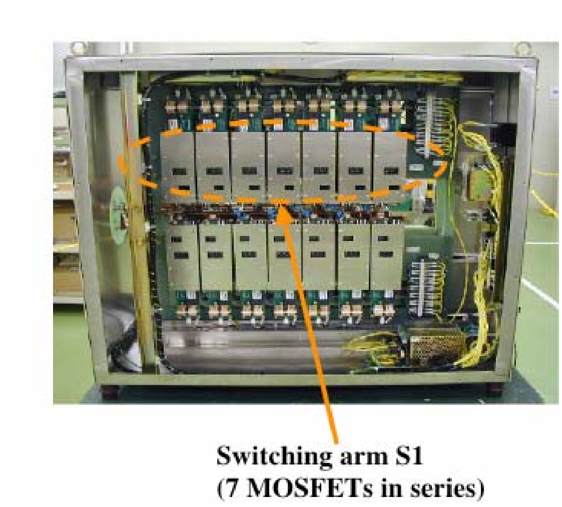

FIGURE 6. Photo of the pulse modulator

HYBRID ACCELERATION

The entire system employed for the current experiment is schematically shown in Figure 7. The generation of a 2 kV voltage pulse is directly controlled by trigger pulses for the switching elements of the pulse modulator, a master signal of which is created in the digital signal processor (DSP) synchronizing with ramping of bending magnets, and the gate-driving signal patterns initiated by this master trigger-signal are generated by the following signal-pattern generator to be sent to the gate controller of the pulse modulators through a long coaxial cable. The DSP counts the B-clock signal, and achieves the desired revolution frequency. Any delay between the accelerating pulse and a bunch monitor signal is always corrected by the DSP. The system is connected to the existing RF system through the RF signal, which shares the B-clock signal. As a result, synchronized induction acceleration is guaranteed. Here, the RF does not contribute to acceleration of the beam bunch but gives the focusing force in the longitudinal direction; the beam bunch is in principle trapped around the phase of zero. The machine parameters of the KEK PS employed for the experiment are listed in Table 2.

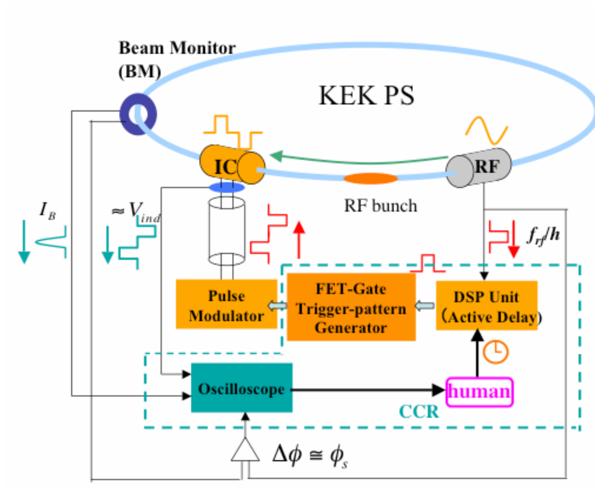

FIGURE 7. Schematic view of the hybrid accelerating system of the KEK PS

Table 2

Circumference	C_0	339 m
Transition energy	γ_t	6.63
Injection/extraction energy		500MeV/8 GeV
Revolution frequency	f_0	668 – 877 kHz
Ramping time (transient for start/stop)		1.9 sec (100 msec)
RF voltage	V_{rf}	48 kV
Harmonic number	h	9
Induction voltage per turn	V_{ind}	5.2 kV

EXPERIMENTAL RESULTS

In the experiment, the signals of the bunch monitor and three current transformers (CT), which always observed the current flow through the matching resistances, were monitored on the digital oscilloscope located at the central accelerator control room (CCR). Before the experiment, an actual induced voltage at the ceramic gap, an output voltage of the transmission cable, and the CT signal were simultaneously measured and the correspondence between each other was well calibrated. In addition, a delayed timing of the master gate signal triggering the pulse modulator is adjusted by the DSP so that the bunch signal would stay around the center of the induction voltage pulse through the entire accelerating period. Typical wave-forms of the CT signals are shown in Figure 8 together with the bunch signal.

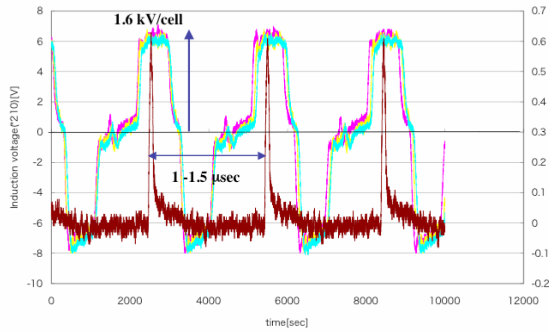

FIGURE 8. Induction pulse wave-forms (pink, yellow, blue) and a bunch signal (brown)

THEORETICAL BACKGROUND

Under coexistence with the RF voltage and the induction voltage, a charged particle receives an energy gain per turn,

$$eV_{acc}(t) = e\left[V_{rf}\sin\phi(t) + V_{ind}\right], \qquad (1)$$

where V_{rf} and V_{ind} are the RF voltage and the induction voltage, respectively, and $\phi(t)$ is the position of the particle in the RF phase, $\omega_{rf}t$. The orbit and energy of a particle are dominated by the following equations: for the force balance in the radial direction

$$m\gamma \cdot \frac{(c\beta)^2}{\rho} = ec\beta \cdot B(t), \qquad (2)$$

where $B(t)$ is the bending field and ρ is the bending radius, and for the change in energy

$$mc^2 \cdot \frac{d\gamma}{dt} = \frac{ec\beta}{C_0} \cdot V_{acc}(t), \qquad (3)$$

From (2) and (3), the accelerating voltage must satisfy the relationship, $V_{acc}(t) = \rho \cdot C_0 \cdot dB/dt$, so that the particle is synchronously accelerated with ramping of the bending field. The bending field is linearly ramped over 1.7 sec. In this linear ramping region, V_{acc} of 4.7 kV is required. For the simplicity, the induction voltage was fixed to be close to 5.1kV.

EXPERIMENTAL OBSERVATION

In order to confirm the induction acceleration, the phase signal, which shows the relative position of the bunch center to the RF, was measured through an accelerating region of concern. Particularly, we focused on three cases:

(1) with an RF voltage alone, (2) with an RF voltage and a positive induction voltage, and (3) with an RF voltage and a negative induction voltage. From Eq.(1), a theoretical prediction is $\phi_s=\sin^{-1}(V_{acc}/V_{rf})\sim V_{acc}/V_{rf}$ =5.7 degrees for case (1), ϕ_s=-0.66 degree for case (2), $\phi_s=\sin^{-1}(2V_{acc}/V_{rf})\sim 2V_{acc}/V_{rf}$ =12.4 degrees for case (3), where ϕ_s represents the position of the bunch center in the RF phase. Since the induction voltage is devoted to the acceleration for case (2), the RF does not serve for the acceleration, but takes a role of capturing alone; thus, the phase must be zero. In case (3), the RF has to give a two-times larger energy to the bunch than case (1) from the energy-conservation law; the phase should increase by a factor of two. Actually, the time-evolution of the phases through acceleration has been observed, as seen in Figure 9. At a first glance, we can find the qualitative agreement with the theoretical prediction. For both side of the transition, the evolution in the phase difference is clearly understandable.

This result was obtained at the very preliminary stage of the experiment. More recent results and their better understanding are available in the paper [11].

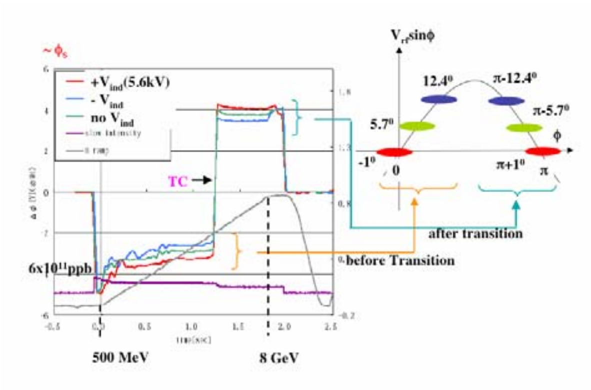

FIGURE 9. Temporal evolution of the phase

SUMMARY

It is emphasized that for the first time charged particles in the high-energy accelerator ring were accelerated with the induction accelerating system. The experimental fact of the induction acceleration in a circular ring and the reality that the key devices developed for this purpose, such as a pulse modulator as a switching driver, are on our hands are big mile-stones for us to achieve an *induction synchrotron* in near future and a *super-bunch hadron collider* in no so far future. Last it is emphasized that the induction system worked well through the entire operating period of 24 hours without any trouble. We will conclude that a typical demonstration will be performed for actual applications.

ACKNOWLEDGEMENT

The present research has been supported by the KEK PS division. The authors acknowledge S.Ninomiya for providing a lot of information on the KEK-PS RF system and helpful comments on the experimental result, and D.Arakawa for an advice on the bunch monitor. The present research has been financially supported by a Grant-In-Aid for Scientific Research for Creative Scientific Research (KAKENHI 15GS0217), and its early stage was partially supported by a Grant-In-Aid for Scientific Research on Priority Area (KAKENHI 140646221).

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