INDUCTION ACCELERATION OF A SINGLE RF BUNCH IN THE KEK PS

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Abstract

Results of the induction acceleration of a single RF bunch in the KEK PS are reported.

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. 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 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. 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 realized in a conventional RF synchrotron.

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 [2], is most attractive. In addition, transition crossing without any longitudinal focusing seems to be feasible [1,3], which could substantially mitigate undesired phenomena, such as bunch shortening due to non-adiabatic motion and microwave instabilities.

In April 2003, we started this project to demonstrate an *induction synchrotron* using the KEK PS. The project consists of three stages: 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. Recently the induction acceleration of a single RF bunch was demonstrated in the KEK-PS [4]. This stage is a kind of hybrid system employing the RF and induction accelerating system. Here the current status of the first stage is presented. A part of the second stage will be discussed in the companion paper [5].

Last year, the prototype devices, which can generate a 250nsec flat-top voltage at a repetition rate of about 1 MHz, have been installed in KEK-PS with a ring-circumference of 340 m and be combined with the existing RF accelerating system.

INDUCTION ACCELERATION SYSTEM

The key devices required to realize an *induction synchrotron* are an induction accelerating cell capable of generating an output voltage of 2kV and a switching power supply (SPS) driving the cell with a duty factor of 50%. The SPS has to be kept far from the induction cell placed in the accelerator tunnel, because the solid-state power switching elements can't survive an extremely high radiation dose. Thus, the SPS is connected with the accelerating cell through a long transmission cable of 120Ω. In order to reduce reflection from the load, a matching resistance has been installed at the end of the transmission cable. An equivalent circuit for the induction accelerating system is shown in Fig.1.

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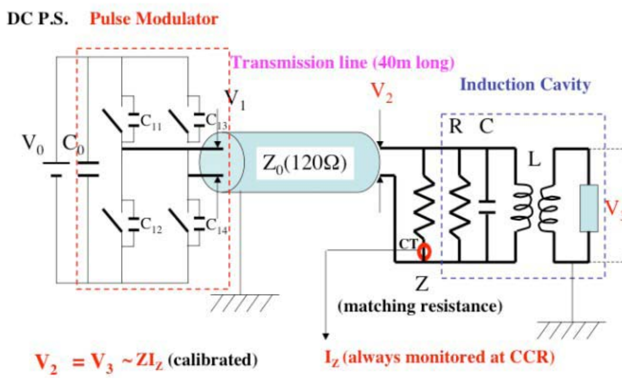

Figure 1. Equivalent circuit for the induction acceleration system

A core material of the induction cavity employed for the first acceleration experiment is a nanocrystalline alloy, called Finemet (Hitachi Metal). Each cell has a capacitance of 260pF, an inductance of 110μH, and a resistance of 330Ω, which determine the property of pulse rising and falling. Three cells are mechanically combined into a single module for the convenience of installation. Its details are described in the companion paper [5].

A full-bridge switching circuit in the SPS, which is depicted in Fig.1 but described in detail elsewhere [6], was employed because of its simplicity. The SPS is capable of generating bipolar rectangular shaped voltage pulses. The SPS 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 the pulse controller, which is a part of the accelerator control system. The inside photograph is given in Fig.2.

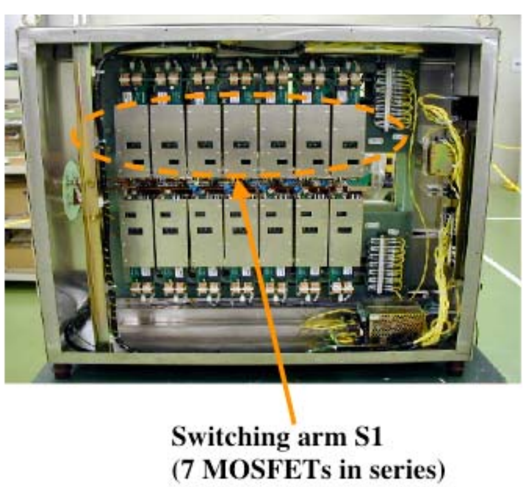

Figure 2. Photo of the pulse modulator

HYBRID ACCELERATION

The entire system employed for the current experiment is schematically shown in Fig.3. 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) handling both of a bunch monitor signal and the RF signal. As a result, the synchronized induction acceleration is guaranteed. The RF does not contribute to acceleration of the beam bunch but gives the focusing force in the longitudinal direction. The machine parameters of the KEK PS employed for the experiment are listed in Table 1.

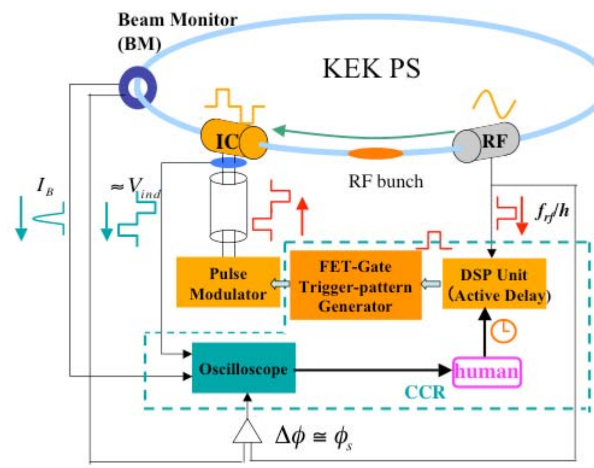

Figure 3. Schematic view of the hybrid accelerating system of the KEK PS

Table 1

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 CCR. 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 Fig.3 together with the bunch signal.

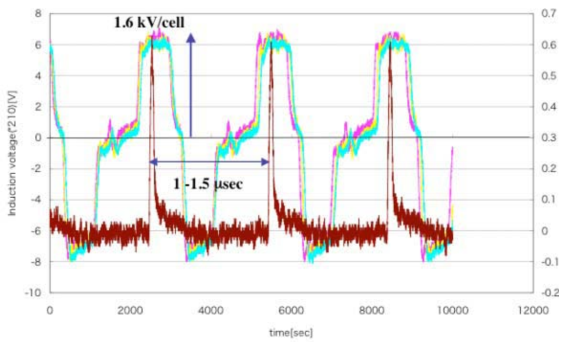

Figure 3. Induction pulse wave-forms (pink, yellow, blue) and a bunch signal (brown)

THEORETICAL BACKGROUND

Under the coexistence with 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 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, where, V_{acc} of 4.7 kV is required.

EXPERIMENTAL OBSERVATION

In order to confirm the induction acceleration, the phase signal of the bunch center was measured through an accelerating region. 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), $\phi_s=-0.66$ 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 Fig.4. 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. The more quantitative discussion on the time-evolution of the phase is given in the companion paper [5].

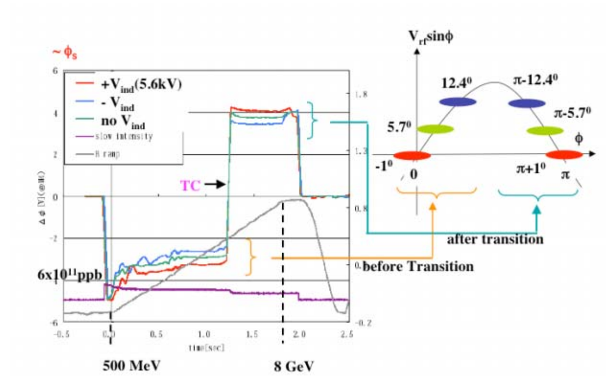

Figure 4. Temporal evolution of the phase

SUMMARY

For the first time charged particles in the high-energy accelerator ring were accelerated with the induction accelerating system. The induction system worked well through the entire operating period of 24 hours without any trouble.

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