INDUCTION SYNCHROTRON EXPERIMENT IN THE KEK PS*

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Abstract

Recent progress in the KEK induction synchrotron is presented. A single proton bunch, which was injected from the 500 MeV Booster ring and captured by the barrier bucket created by the induction step-voltages, was successfully accelerated to 6 GeV in the KEK proton synchrotron, by using a newly developed induction acceleration system instead of RF devices.

INTRODUCTION

The concept of the induction synchrotron (IS) was proposed by Takayama and Kishiro in 2000 [1] 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 and Veksler. 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.

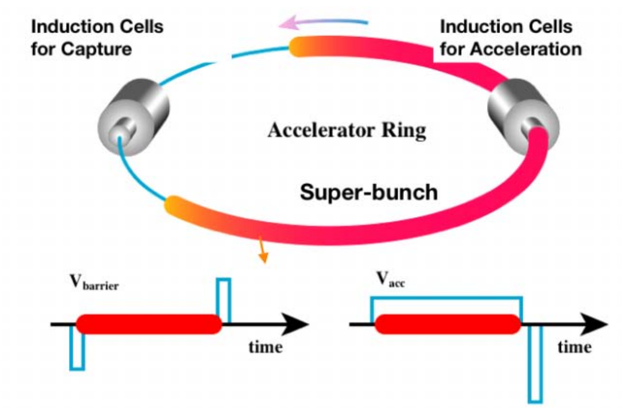

Figure 1: Schematic view of the induction synchrotron*

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, the acceleration and confinement are synchronized with the beam revolution. The experimental demonstration was divided into three stages as briefly described in Fig.2: (1) induction acceleration of a single bunch captured by the RF bucket, (2) trapping of an injected bunch by the barrier voltages, and (3) induction acceleration of the barrier bucket trapped bunch. Each of them will be discussed in a somewhat compact manner.

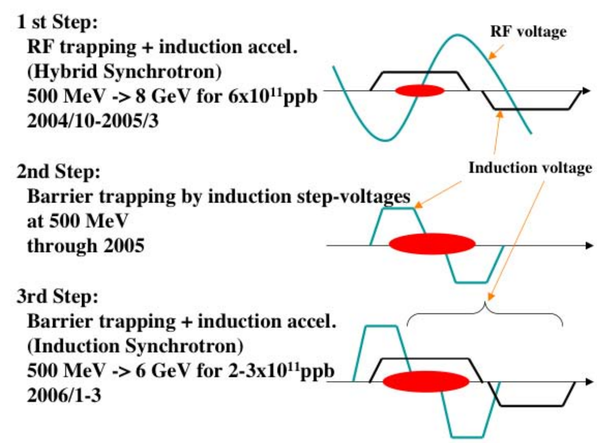

Figure 2: Scenario of the proof of principle experiment for the IS concept

EXPERIMENTAL SET-UP

Introducing of the Induction Acceleration System into the KEK-PS

The KEK PS is a slow cycle proton synchrotron, which had dedicated to the K2K experiment, the first accelerator driven long base-line neutrino oscillation experiment, until February 2004. In a regular RF synchrotron operation, 9 bunches delivered from the 500 MeV Booster are accelerated by four RF cavities generating an RF voltage of 23 kV/each up to 12 GeV in 0.8 sec. Since 2004 summer, induction cells, which took 3 years for R&D to achieve required specifications, have been installed together with other components of the system every summer and winter shutdown. Eventually 10 induction cells were installed and used for the full demonstration of the IS.

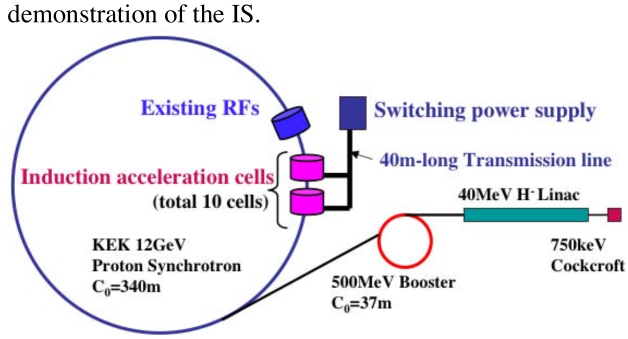

Figure 3: Outline of the KEK 12 GeV-PS with the induction acceleration system

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Induction Acceleration System (IAS)

One induction acceleration system consists of the acceleration cell of 2.5 kV, matching register of 210 Ω to minimize a reflection from the load, SPS to drive the load, 40 m-long transmission line connecting between the load and SPS, and DC power supply to charge the SPS. The system is written in an equivalent circuit model, as shown in Fig.4. Before the installation, the induced voltage V_3 was confirmed at the test bench to almost equal to V_2, V_1, and V_0. In the operation, the current flowing through the matching regiter was monitored by the CT. The SPS was placed away from the accelerator ring, because the MOSFETs employed as a switching element can't survive serious radiation damages.

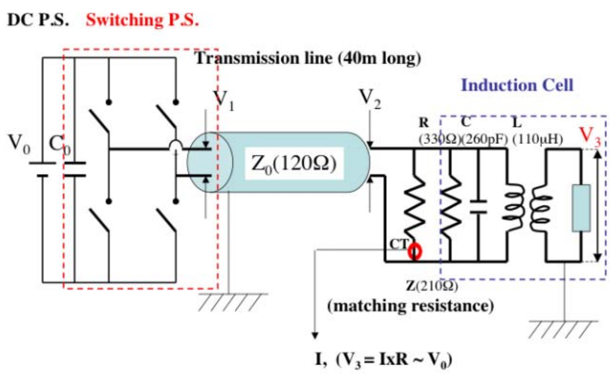

Figure 4: Equivalent circuit of the 2.5 kV IAS

Induction Acceleration Cell (IAC)

A compact IAC with a large inductance was designed and assembled at KEK. As a core material, we selected Finemet of Hitachi Metal (FT-3M), because it has the characteristics of a large permeability and relatively small core-loss. One cell consists of 6 Finemet bobbins, the size of which is 220mm in inner diameter, 500 mm in outer diameter, 15 mm in width, and 13-18 μm in thickness. All bobbins are encircled by a single current bar, which takes a role of the primary winding. Heat deposit in the cell at 1 MHz operation is more than 10 kW. The heat is removed by circulating silicon-oil. Each bobbin fixed by glass-epoxi plates with cooling channels is embedded in the cage. The inner chamber of stainless steel with ceramic acceleration gaps are completely free from contact with oil and both sides of each gap are electrically connected with the outer cage. Eventually the acceleration voltages generated at 4 gaps are superimposed when protons pass through the chamber.

In order to determine the IAC impedance, specifically the cell inductance L, resistance R representing the magnetization loss and eddy loss, and capacitance C, three methods were tried: (1) the network-analyzer measurement assuming a LCR parallel circuit model and CW small amplitude excitation, (2) the induced voltage measurement in a single pulse excitation, and (3) the measurements of voltage induced between the input terminals by a circulating beam. Using $L(\omega)=[\mu'+(\mu'')^2/\mu']L_0$ and $R(\omega)=\omega[\mu''+(\mu')^2/\mu'']L_0$, where the complex permeability, $\mu = \mu' - j\mu''$, of Finemet is known as a function of ω and L_0 is the core inductance in air, we obtained the cell capacitance of 260 pF so as to fit the impedance curve to the result of (1). Considering L and R in the AC mode and the pulse profile in a single pulse mode, which were obtained for (2) and (3), we have determined L=110 μF and R=330 Ω.

The matching register consisting of 10 units of 21 Ω/each (Tokai Konetsu,WD-6-7515) is arranged so as to minimize stray inductance and water cooled. Details of the IAC are shown in Fig.5.

Switching Power Supply (SPS)

For simplicity, a full-bridge type circuit architecture depicted in Fig. 4 was employed both for the acceleration and barrier voltages. As a high rep-rate performance of CW MHz and a fast rising/falling speed of 10-20 nsec were required, the power MOSFET was a unique solution as a switching element at that moment. The full-bridge SPS consists of four switching arms. Each arm is composed of 7 MOSFETs (IXYS Co.,DE-475-102N20A) arranged in series. Their gates are driven by their own gate driving circuits, which are electrically isolated with extremely lower capacitive DC-DC converters from their primary power source connecting to the ground, because each MOSFET must work with an individual voltage separation [3]. The gate signals are generated by converting light signals provided from the pulse controller described below.

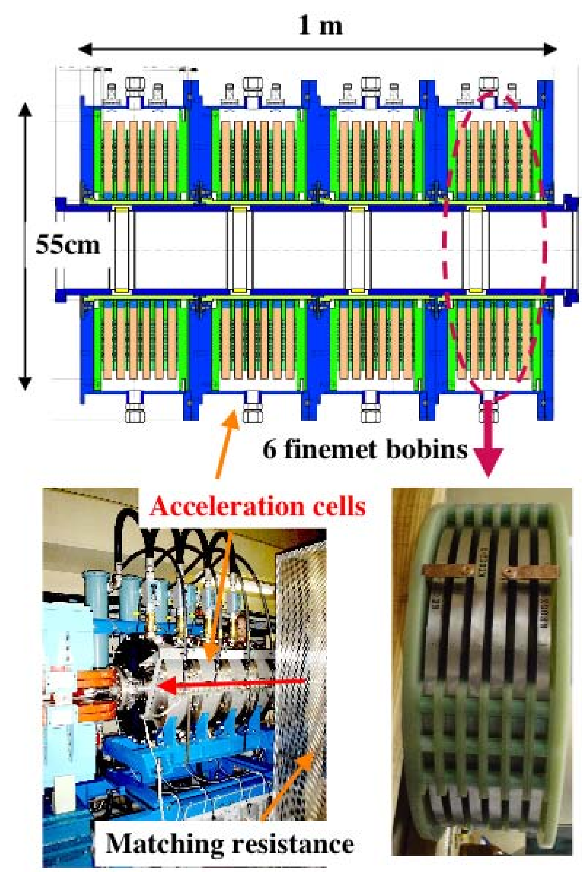

Figure 5: Induction acceleration cells (2 kV/cell). top: engineering drawing of 4 cells, bottom-left: photo of the

installed cells with transmission cables and oil cooling systems, bottom-right: photo of the inductance core.

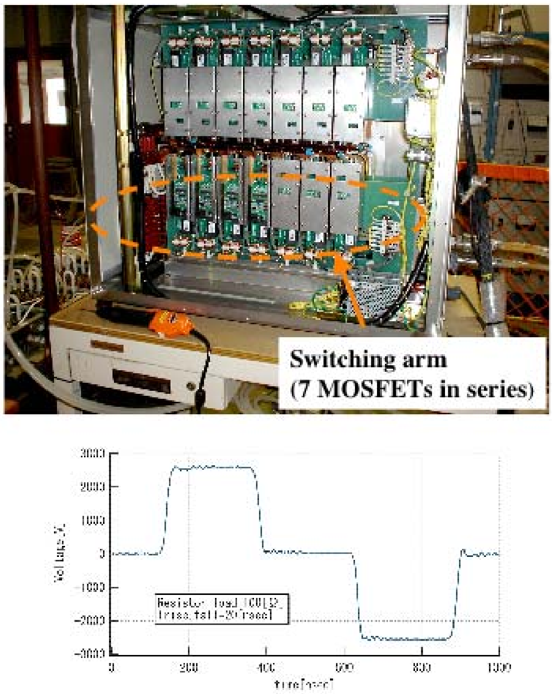

Figure 6: top: Photo of the switching power supply capable of generating pulse voltages of 2.5 kV and 500 nsec long at 1 MHz (made in Nichicon Kusatsu Co. LTD), bottom: output voltage with 100 Ω pure resistance.

Gate Trigger Control System

The generation of voltage pulses is directly controlled by trigger pulses for the switching elements of the SPS to drive the IAC. The gate signals used to turn on the MOSFETs 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. 7. 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, 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 IS [2,4]. 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 acceleration voltage was prepared as mentioned above. As a result, the gate trigger pulse was generated with a duty of less than 50%.

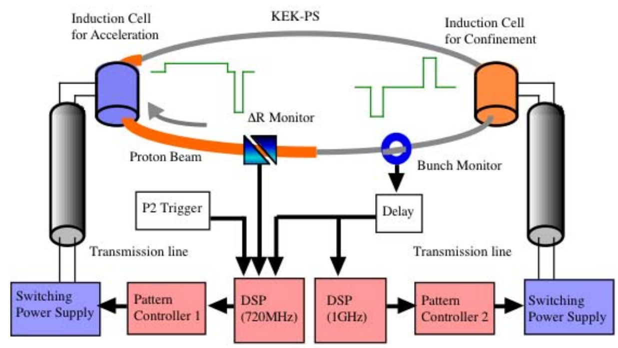

Figure 7: Schematic view of the IS with the gate control system. The induction systems for the acceleration and confinement are of the same type except for the gate control, which can generate different voltage-patterns, as shown. P2 means the start of acceleration. The signal monitored at the bunch monitor is employed as a master gate trigger signal for the SPSs.

EXPERIMENTAL RESULTS

Step1: Induction acceleration in the hybrid scheme

Soon after accomplishing the key devices, such as the SPS and the IAS, an induction acceleration experiment was carried out. For the first time, induction acceleration in a high-energy circular ring was demonstrated in 2004 [5], in which a single proton bunch injected from the Booster ring and captured in the RF bucket, was accelerated up to 8 GeV. This means that a hybrid synchrotron with functional separation in the longitudinal direction had been realized. Fig.8 shows its experimental result. The relative position of the bunch to the RF in phase was monitored through the entire acceleration period including the transition crossing, for three cases with induction acceleration (red), induction deceleration (blue), and without induction acceleration (green). The temporal evolution of the phase and its magnitude were in agreement with the theoretical prediction.

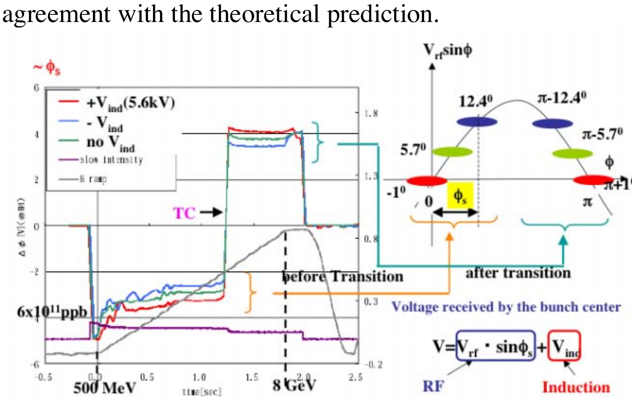

Figure 8: Proof of the induction acceleration of an RF bunch. Left, the phase monitor signals, ramping pattern, and temporal change in the beam intensity; Right, schematic views of the RF bunch and the sinusoidal RF voltage

Step 2: Formation of a superbunch in the barrier bucket

In a succeeding experiment [2] the proton bunch captured by the induction barrier voltages survived for more than 450 msec at the injection-energy. The induction step-barrier voltages created a shallow notch potential, where the injected bunch was trapped. The injected RF bunch was not matched to the barrier bucket in the phase-space. After a large filamentation in the bucket, the bunch achieved its 600 nsec-long size, as seen in Fig.9. In this experiment, the barrier-voltage amplitude for confinement was not enough for a lack of induction acceleration cells. Instead of the voltage amplitude, a long barrier-voltage pulse-length was ensured so as to fully capture the injected bunch with a momentum spread of 0.4%.

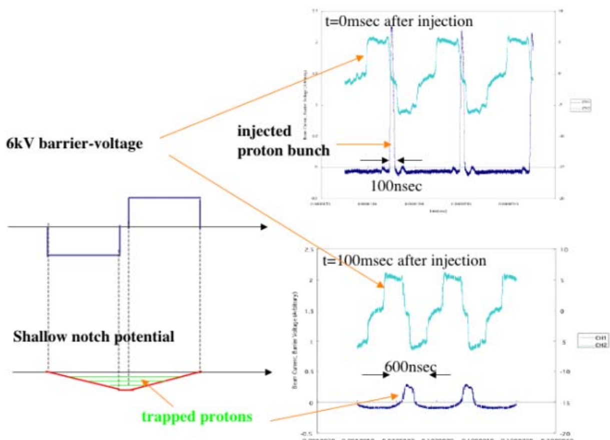

Figure 9: Left, Schematic view of the shallow notch potential; Right, the injected bunch and captured super-bunch with the barrier voltages.

Step 3: Full demonstration of the induction synchrotron

In this step, the injected single bunch was trapped in the barrier bucket and accelerated up to 6 GeV in 2 sec with the induction step voltages. Fig.10 shows the temporal evolution in the bunch length together with the barrier voltage pulses and step acceleration voltage pulses. Other experimental results were shown in Fig.11. The top line in the Fig.11 is the ΔR signal, which is kept to be 2 mm after the starting of acceleration. While a fraction of the injected particles was lost just after injection because of mismatching of the injected bunch-shape to the barrier bucket, most of the beam loss took place in the transient region from the injection stage to the parabolic ramping region of the bending field; beyond that the intensity was held to be constant. It is speculated that the ΔR feedback was not accurate in this transient region. Details of the experimental result and their theoretical analysis are given elsewhere [6,7].

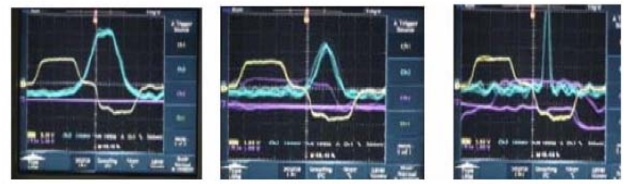

Figure 10: Typical pulses (yellow: barrier pulses, purple: accelerating voltage pulses, sky blue: beam pulses). From left to right: just at the beginning of acceleration, 400 msec, and 2 sec (end of the acceleration).

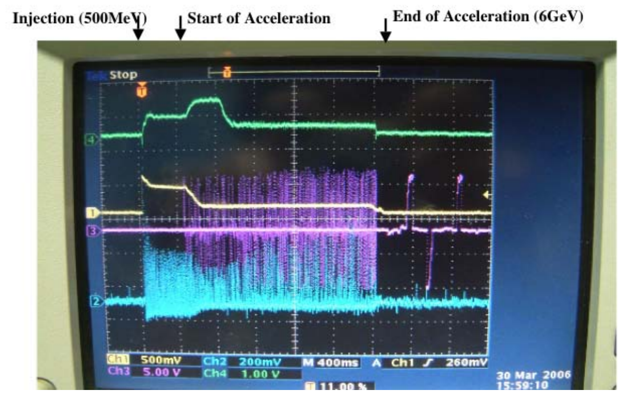

Figure 11: Typical experimental results green: Beam position (10 mm/div), yellow: beam current (10^{12}/div), purple: Acceleration voltage pulses (1 kV/div), blue: Bunch signal

BEYOND THE POP EXPERIMENT

At the next step just after the demonstration of the IS concept, the quality of acceleration, such as the stability of the system itself and perturbations on other accelerator components, is demanded, because the SPS is a pulse device to manipulate a large current.

Improvement of the Induction Acceleration System

To test the system for endurance, we have continuously run the induction acceleration system without beam over 100 hours. Any fatal problems have not been found. Details are reported in one of the companion papers [8]. We are expecting to accelerate a super-bunch of high current in near future. In high intensity operation, beam loading effects in the induction acceleration cell are not ignored as well as in a conventional RF cavity. A lower impedance cell is indispensable, requiring a low impedance transmission cable and SPS capable of carrying a higher arm current. To realize such SPS, we are trying to assemble the SPS employing powerful solid-state switching elements, such as SIThyristor and SiC-MOSFET [3,9].

Long Pulse Induction Acceleration Cell

Super-bunch acceleration should demand accelerating voltage pulses of 1-10 μsec long. The available pulse length is limited by a droop in the accelerating voltage, a size of which is inversely proportional to the cell inductance. It is best to introduce a large volume core with the high permeability to satisfy the demand. However, such magnetic core is bulky and expensive. Instead, we have modified the original 1 to 1 induction cell into the 2 to 1 induction cell, which has a primary coil of 2 turns, and tested it. We have obtained a satisfactory result at expense of a reduction in the output voltage by a factor of two, as described in the companion paper [10].

APPLICATIONS

Various applications have been considered since the first proposal of the IS. The super-bunch hadron collider [11], or a proton driver for the second generation of neutrino oscillation experiments are among them. These applications rely on the realization of a super-bunch, the line density of which is just under the space-charge limit in the transverse direction.

Hybrid Synchrotron

Modifying an existing RF synchrotron 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. As a matter of fact, a novel transition crossing method [12], which is called "quasi-adiabatic no-focusing transition crossing", has been developed in the KEK-PS. According to this method, where the RF voltage is linearly reduced to zero at the transition energy and increased to a nominal value, the bunch size is controlled with a desired value. This allows us to avoid any serious problems, such as microwave instability, Johnsen effects, and electron cloud instability, associated with transition crossing in a conventional RF synchrotron.

Injector-free All-ion Accelerators

An all-ion accelerator [13] is under consideration as one of attractive applications of the IS. 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 SPS synchronized with the ion-bunch circulation. Since the SPS is fired at an arbitrary timing or desired timing, extremely low-energy particles can be accelerated up to the energy, which the guiding magnetic fields allow. As a matter of fact, the KEK Booster, which is a 500 MeV rapid-cycle proton synchrotron, is going to be modified into the first all-ion accelerator. Of course, the lower energy injection reduces the space-charge limited beam current in inversely proportion to relativistic β. In this sense, this sort of accelerator may be not suitable for applications that demands only the beam intensity. In addition, the low energy injection requires a wide range of guiding magnetic fields. In the KEK all-ion accelerator, the minimum bending field is about 250 Gauss, where a dispersion of remnant field is not ignored. The careful COD correction or tune correction at the low field region must be performed. The present status of the modification work is presented in the companion papers [10,14,15].

Superbunch Hadron Colliders

Extremely long bunches, referred to as super-bunches, are generated by a multi-bunch stacking method employing barrier buckets at the injection into the collider and are accelerated with an induction step voltage. Super-bunches intersect with each other, yielding a luminosity of more than 10^{35} cm^{-2}sec^{-1}. A combination of vertical and horizontal crossing is employed in order to avoid any significant beam-beam tune shift. However, we still need a long step to realize the super-bunch collider, because an accidental beam loss in a large stored-intensity ring is hazardous and present high-energy physics detectors are unable to accommodate a pileup of junk events associated with the super-bunch collision.

SUMMARY

The IS concept has been demonstrated in a complete form. We conclude that the principle of the IS 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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