DIGITAL ACCELERATION SCHEME OF THE KEK ALL-ION ACCELERATOR*

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Abstract

The novel digital acceleration (DA) scheme in the KEK All-ion Accelerator (AIA) is discussed. As an example, acceleration of Argon ions is explained along with the experimental results of the induction acceleration system, which has been developed for this purpose.

INTRODUCTION

The KEK-AIA is based on the induction synchrotron (IS) concept [1] which was demonstrated in 2006 [2]. KEK-AIA is a versatile accelerator which can accelerate all-ions from a very low energy because of its unique feature [3]. The transverse focussing requirement is same for any ions; therefore, the existing 500MeV KEK Booster Ring (BR) can be modified as AIA. BR is a rapid cycling synchrotron (RCS). The acceleration voltage in such a RCS must be dynamically changed. Our induction acceleration system has crucial limitations such as a maximum rep-rate of 1MHz, fixed output voltage of 2kV and finite pulse width of 500nsec. In order to overcome these limitations and to meet the acceleration requirement in the RCS, a novel DA scheme is developed, where the pulse width and voltage amplitude effectively seen by ions are varied in time by a method combining intermittent operation and sorting of a plural number of induction acceleration cells. At first, the DA concept is explained and then the acceleration scheme is described and in the end results of experiment are given.

DIGITAL ACCELERATION CONCEPT

In the induction synchrotron (IS), the function of confinement and acceleration is separated. Both functions are realized with independently operated induction acceleration systems. The key devices are induction cells, switching power supply (SPS) and a gate trigger control system [2]. The induction cell works as a 1:1 transformer. The output voltage of the induction cell is fixed and with same output voltage as DC power supply energizing the SPS. The SPS is basically a full bridge circuit consisting of MOS-FET's as switching elements. The gate trigger signals are manoeuvred according to bunch signal during acceleration.

The maximum switching frequency is limited to 1MHz due to heat deposition problem. The droop in the output voltage pulse of induction cell is ~15% in 250nsec.

Unlike an RF synchrotron, where the acceleration phase is automatically adjusted in time so as to allow the particles to follow the magnet ramping, in the IS the acceleration voltage pulse density in time is controlled so that the effective acceleration voltage received by the particles is of the desired value. This pulse density control is a digital technique also known as pulse density modulation. Pulse density control has been demonstrated in the proof of principle experiment of the IS [2].

For the KEK-AIA, a sophisticated scheme of staging and intermittent operation with dynamic sorting of induction acceleration cells during acceleration period is designed. This scheme overcomes the present limitations of the induction cells. But to obtain a 2μsec droop free acceleration voltage, a new 2 turn induction cell has been assembled [4].

500MeV KEK Booster to KEK-AIA

The KEK-AIA will be the refurbished BR for acceleration of ions. Some modifications are required in the present setup to make it an AIA [5]. Its schematic diagram and parameters are shown in Fig.1and in Table 1 respectively.

Table 1: KEK-AIA parameters

Machine parameters		Value
Bending radius, ρ	(m)	3.3
Circumference, C_0	(m)	37.71
Maximum acceleration voltage	(kV)	3.24
Injection voltage	(kV)	200
Magnetic flux density, B_{min}	(T)	0.02916
Magnetic flux density, B_{max}	(T)	0.8583
Frequency of magnet ramping, f	(Hz)	10

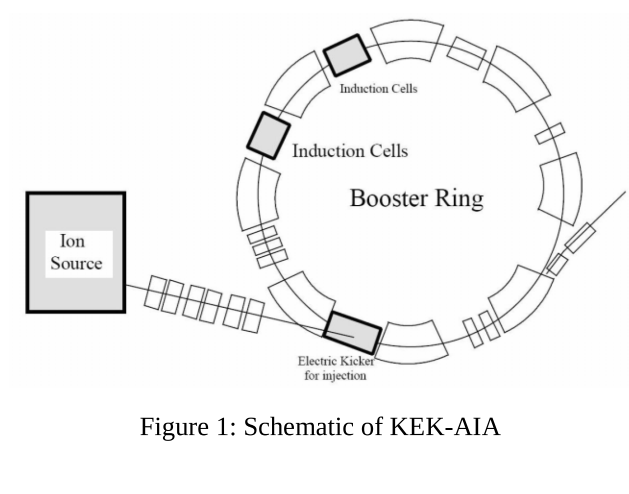

Figure 1: Schematic of KEK-AIA

$$V_{ac} = \rho C_0 \frac{dB(t)}{dt} \quad (1)$$

$$B(t) = \left(\frac{B_{\max} + B_{\min}}{2}\right) - \left(\frac{B_{\max} - B_{\min}}{2}\right)\cos\omega t \quad (2)$$

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For the proof of principle experiment, to accelerate heavy ions, an ECR ion source, which is embedded in the 200kV high voltage terminal, is under development [6]. The ions will be ejected with an initial kinetic energy of Zx200keV where, Z is the charge state and then injected through a low energy beam transport line into the BR and accelerated to the final energy. The acceleration and confinement of ions will be carried out with pulse voltage induced on independent induction cells. The required acceleration voltage is given by Eq.1 and the magnetic flux density variation is given by Eq.2 where, ρ is bending radius and C_0 is circumference. The various beam dynamical issues of the KEK-AIA are discussed in [7].

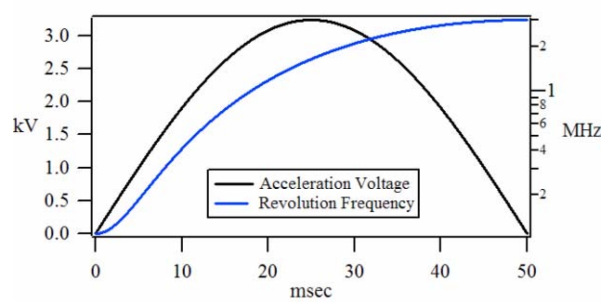

Figure 2: Variation of acceleration voltage and particle revolution frequency in the KEK-AIA

DIGITAL ACCELERATION SCHEME

For Argon ions with mass 40 and charge state +18 the variation of acceleration voltage and revolution frequency calculated using the KEK-AIA parameters is shown in Fig. 2. The acceleration voltage must be continuously changed from 0 V to 3.24 kV and again to 0V. However, the output voltage of the induction acceleration cell is fixed. Therefore, some technique is required to meet the present acceleration condition. Also, the revolution frequency of Argon ion changes with acceleration from ~100 kHz at injection to 3 MHz near extraction. Therefore, the pulse width of the acceleration voltage needs to be varied as a function of the revolution frequency. Hence a novel acceleration scheme to meet both the requirements has been developed. In this scheme, the acceleration period is divided into stages.

A chopped ion bunch of 4μsec duration is assumed as an injected bunch from the ECR ion source. The bunch (shown in red) is confined by two opposite polarity barrier voltage pulses (shown in pink and blue) and a long rectangular pulse for acceleration (shown in black) is generated overlapping with half confinement voltage pulse on each side of the bunch, shown in Fig. 3. In the stage I, a long acceleration voltage pulse is required. This can be generated by sequentially triggering two induction acceleration cells because only 2μsec long pulse can be generated by the present induction cell. In the figure for convenience, the cells are labelled as ID#1 and ID#2. The amplitude of cell ID#1 & ID#2 is assumed to be 2.2 kV and with maximum pulse width of 2μsec flat top.

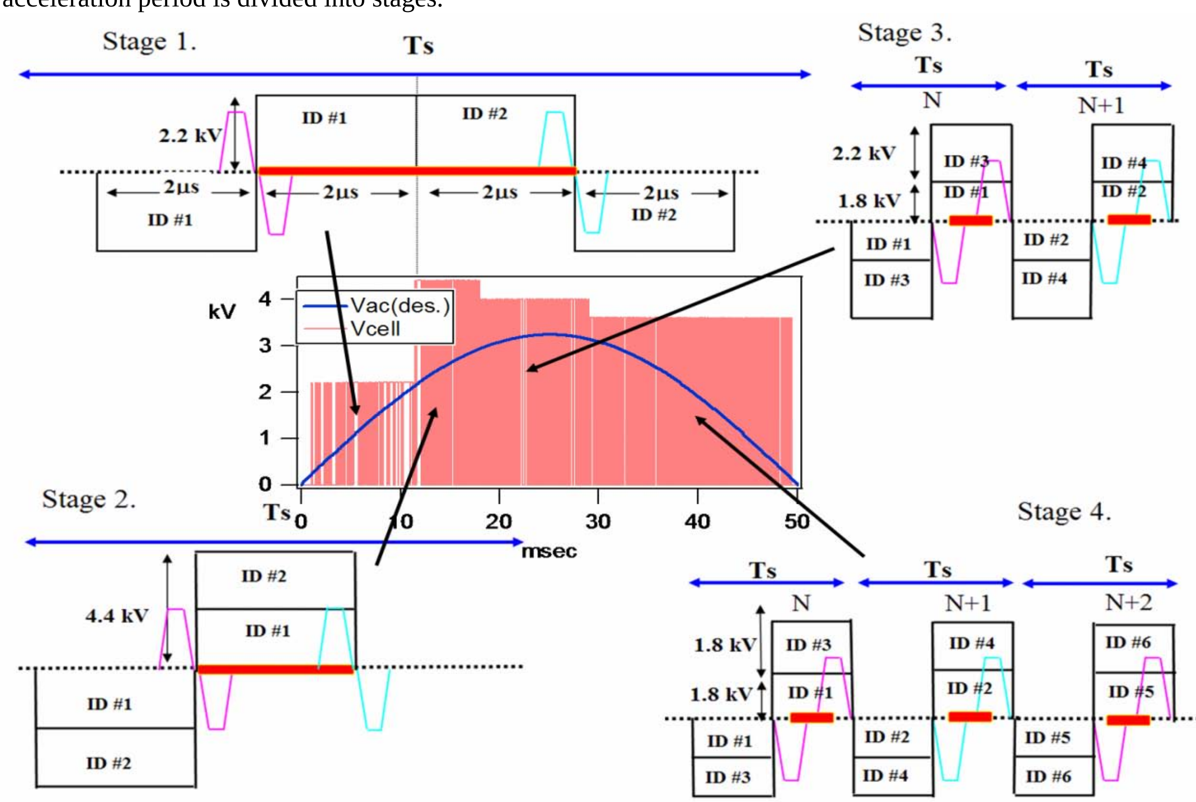

Figure 3: Digital acceleration scheme in the KEK-All ion accelerator

In the stage II, the acceleration voltage requirement exceeds 2.2 kV, therefore the cell ID#1 & ID#2 is triggered simultaneously to generate a superimposed voltage of 4.4 kV. In the stage III, the particle revolution frequency becomes greater than 1 MHz therefore two additional induction acceleration cells are required in the subsequent turn. The new cells are identified as ID#3 & ID#4. So a combination of ID#1 & ID#3 and ID#2 & ID#4 are triggered simultaneously to meet the designed acceleration voltage requirement. In this stage a single cell is used to generate confinement voltage pulse with the bunch located at its centre. Thus intermittent operation starts from this stage onwards. In the stage IV, the particle revolution frequency becomes greater than 2 MHz therefore two more induction cells ID#5 & ID#6 are required. This scheme was verified by a longitudinal particle tracking code which has been developed to understand the longitudinal motion in the IS.

EXPERIMENTAL RESULTS

The digital acceleration scheme has been experimentally verified using beam simulator signals obtained from the arbitrary function generator (AFG). The high voltage experimental setup is shown in Fig. 4. The AFG was triggered at 10 Hz frequency which is the frequency of magnet ramping of the KEK-AIA. In this experiment, DSP set1 and set2 (each consisting of 4 DSP's [7]) are used to generate gate trigger signals depending on the beam simulator signal. This signal is then given to the switching elements driving cell ID#1. The set and reset signal for cell ID#2 is generated by DSP set2. High voltage measurement is done across a wire connected between ends of two induction cells and CT signal connected to the matching resistance of each induction cell was observed during the experiment.

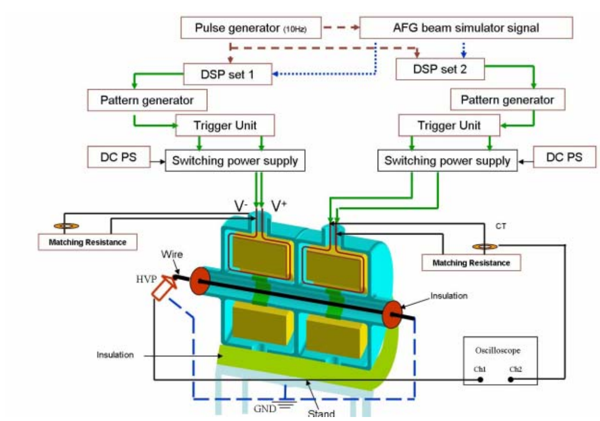

Figure 4: Experimental setup for digital acceleration scheme verification in stage 1 and stage 2

The sequential and parallel operation required in stage I and in stage II of acceleration has been demonstrated in this experiment. The waveform obtained during the experimental result is shown in Fig.5. The waveforms, yellow curve shows the high voltage output picked up on a wire. Pink and green signals are from CT connected to the matching resistance of each cells. Red shows the sum of two CT signals. It is clear from the Fig.4 the output voltage becomes double after 7msec from injection and this is the point of transition from sequential operation to parallel operation. There is no break during transition from stage I to stage II. This experiment was performed up to 10msec acceleration time. This limit comes from the AFG. Maximum number of points in an AFG is limited to 131000. Therefore to maintain an acceptable granularity in the beam simulator signal bunch signal up to 10msec is simulated.

CONCLUSION

Digital acceleration scheme is worked out for the acceleration of Argon ions in the KEK-AIA using induction acceleration devices. In this scheme variable pulse widths are achieved with acceleration. Using intermittent operation the induction cells can be used beyond its capability of 1 MHz. The scheme was verified experimentally using beam simulator signal in the stage I and the stage II of acceleration where induction cells are operated in sequential and parallel mode. The gate trigger signals can be generated successfully in DSP without a break during stage transition.

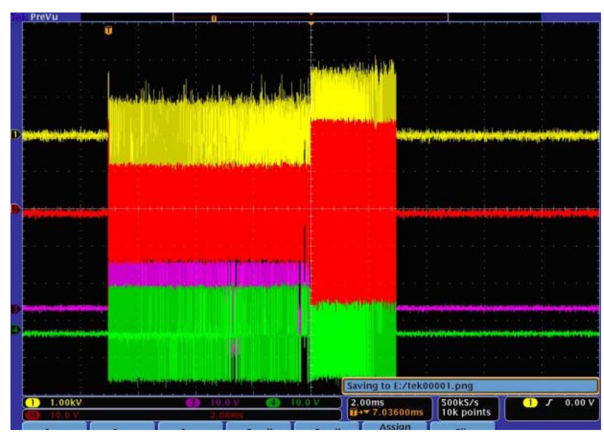

Figure 5: Experimental result of digital acceleration scheme in stage 1 and stage 2

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