ACCELERATION SCHEME OF THE AIA AND ITS CONTROL SYSTEM*

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Abstract

Acceleration scheme of All Ion Accelerator (AIA), one of the active applications of Induction Synchrotron (IS) is proposed with its beam simulation analysis. The KEK 500 MeV booster is going to be modified to KEK-AIA. Trigger system of the accelerator is described. A new type of acceleration cell for KEK-AIA is described.

INTRODUCTION

An AIA [1], an injector-free IS [2], has been proposed as a heavy ion driver for material science or cancer therapy. Works to modify the KEK 500 MeV booster into the all-ion accelerator are going on [3]. The Booster is a rapid cycle synchrotron operating at a repetition rate of 20 Hz. The AIA based on the booster requires more flexible trigger generation for the acceleration and confinement system than the one used for the IS POP experiment [4]. Assuming Ar+18 injected from a 200 kV ion source, the revolution period changes from 9.08 μsec to 333 nsec at the end, and the required acceleration voltage changes from zero volt to 3.24 kV at the middle of acceleration.

Since a number of available acceleration cells is finite, and their maximum pulse width and output voltage are limited to 500 nsec and 2 kV/cell, respectively, we have developed a new type of acceleration cell which can generate a 2 μsec long induction voltage.

CONCEPT OF AIA

The main components of acceleration devices of an IS are a DC Power Supply (DCPS), a Switching Power Supply (SPS) [5], and an induction cell [6]. The acceleration pulse voltage is generated by the SPS and transmitted to the induction cell. In the IS, the acceleration voltage is triggered by the gate signal, which is generated from a signal of the beam-bunch monitor.

This feature introduces a larger freedom in beam handling than in the normal RF synchrotron. In the RF synchrotron, the band width of the RF is limited by the design of cavity structure and its power amplifier. This restricts the effective range of accelerating energy and Z/A of an accelerated particle. On the other hand, generation of the induction acceleration voltage pulse can be controlled by the signals from a bunch monitor. In other words, the AIA can accelerate any kind of particles including heavy ions, from hydrogen to uranium, any charge state and mass numbers. The accelerator is injector-free in principle; ion source and the magnetic fields at injection are switched as the need arises. This is the concept of AIA. Figure 1 shows a schematic view of the KEK-AIA with the ion source and induction acceleration cell.

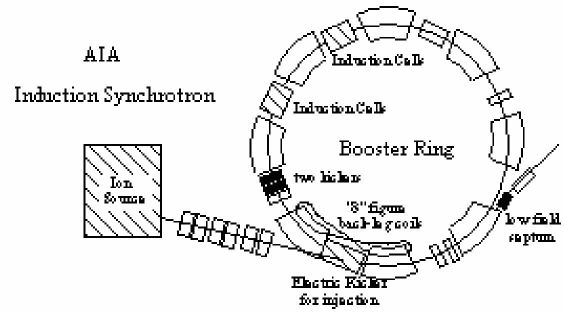

Figure 1: Schematic view of the KEK-AIA with the ion-source and induction acceleration cells.

ACCELERATION SCHEME

The acceleration parameters of the KEK-AIA using the existing booster are shown in Table 1. In the first stage of the POP experiment, argon 18+ is the choice of the ion species.

Table 1: Parameters of AIA (Argon case)

Parameters	Value
Atomic mass A	39.948
Charge state Z	+18
Injection voltage	200 kV
Revolution period at injection	9.08 μsec
Magnetic filed at injection	0.02916 T
Magnetic filed at extraction	0.8583 T
Frequency of magnet ramping	10 Hz
Bending radius	3.30 m
Circumference	37.71 m
Maximum acc. voltage	3.24 kV

The booster is a rapid cycle synchrotron operated at 20 Hz. We are planning to modify the power source of the main magnets; the ramping frequency will be 10 Hz. The maximum acceleration voltage required is 3.24 kV in the middle of acceleration period.

A beam from the ECR ion source will be continuous right after the injection. To capture and accelerate the beam, barrier and long acceleration voltages are required. At beginning a long acceleration voltage pulse of 4 μsec is generated using two cells (A/B), where the pulse voltage of cell A is generated 2 μsec after that of cell B, as seen in Figure 2. Development of the induction cell for the 2 μsec pulse is described later. The number of induction cells for acceleration is uniquely decided by the

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revolution frequency of 3 MHz at the end of acceleration and the required maximum acceleration voltage. At this moment, the maximum switching frequency of the SPS is limited to 1 MHz; therefore alternative firing of 3 cells is required at frequency greater than 2 MHz.

The acceleration voltage that has to match the ramping pattern of the magnets also changes from zero volts to 3.24 kV. Since the DC voltage of the DCPS is fixed (1.8 kV in current devices), the acceleration voltage is effectively varied in the manner of pulse density control. This voltage control can be pre-programmed using digital signal processors (DSP).

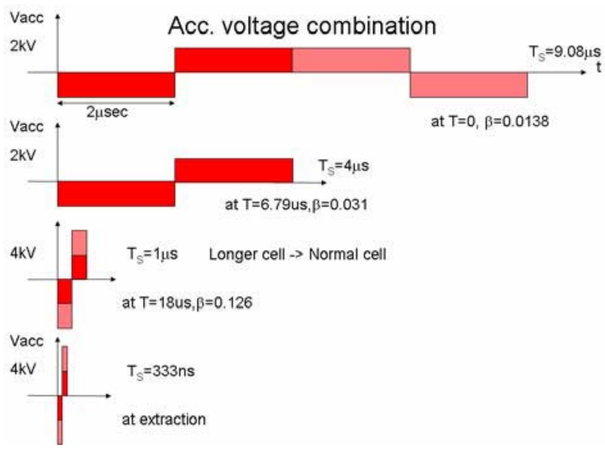

Figure 2: Acceleration scheme of the KEK-AIA from the injection to the extraction. A set of positive and negative pulse voltage is required for the magnetic core not to saturate. The pulse width must be changed during acceleration because the revolution frequency increases.

Beam simulation

Beam simulation for the KEK-AIA in a case of Ar+18 was carried out using a particle tracking code [7]. Simulations were done with 10,000 particles. Since the maximum momentum aperture is +/- 1 %, an injected continuous beam with a momentum spread of +/- 0.4 % was assumed. The longitudinal phase space plots are shown in Figure 3-a and b, at injection and near extraction. Confinement voltage pulses shown in blue are short pulses of 150 nsec width with opposite polarity. The ideal acceleration voltage profile shown in green is assumed. A width and height of the acceleration voltage pulse vary as a function of revolution time.

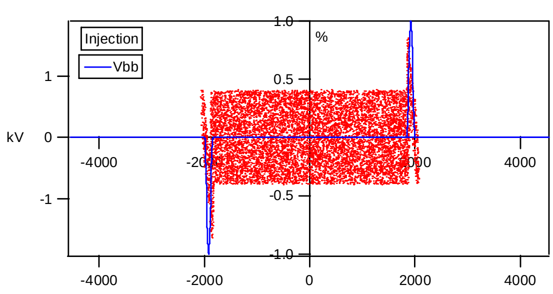

Figure 3-a: Phase plots at injection.

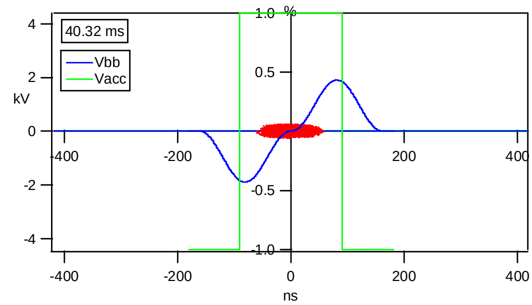

Figure 3-b: Phase plots at extraction.

TRIGGER SYSTEM

Requirements for the AIA gate trigger system are:
1. Synchronize with 100 kHz ~ 3 MHz revolution frequency
2. Make active delays which depends on particle velocity
3. Control relative timing of each acceleration cells
4. Turn on/off each acceleration cells
5. Control of the acceleration voltage in the ΔR feedback system [8]

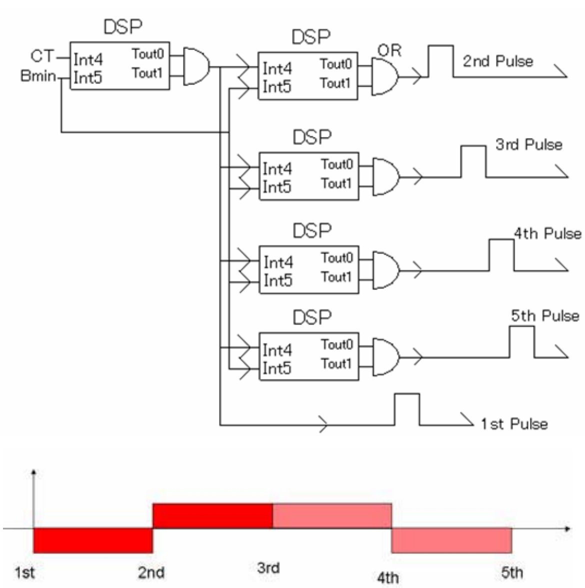

Figure 4: Trigger system of the KEK-AIA just right after the injection. Serial DSP array generates the timing signals to trigger the pulse voltages. The 1^{st}~5^{th} signals maneuver start/stop of positive/negative pulse.

From requirement 1, the positive/negative pulse width is changed during the acceleration period of 50 msec. Four independent timing control systems are needed for each start/end of positive/negative pulses. Requirement 2 and 5 have been basically achieved in the IS experiment with the DSP [4]. Requirement 3 and 4 are related to the combination of acceleration cells. At the start of acceleration we need long (several μsec) pulses, so sequential operation of induction cells are indispensable. In the middle of acceleration, we need a short (less than 1 μsec) and higher acceleration voltage pulse, so simultaneous triggering of cells is needed. This acrobatic cell control is carried out by changing relative trigger timing for each cell.

Figure 4 shows a proposed trigger system of the KEK-AIA. The trigger signal of each positive/negative pulse is controlled by DSPs. Since all trigger signals are made from the bunch monitor signal and have fixed delays, the pulse width of acceleration voltage can be changed during acceleration.

NEW TYPE CELL FOR A LONG PULSE

The acceleration cell developed for the IS experiment at the KEK PS is designed to provide a ~300 nsec long pulse voltage to confine/accelerate a proton beam bunch. In the coming AIA experiment, it is required to generate much longer pulses to accelerate the beam directly injected from the ECR ion source. If the pulse voltage is not flat enough, the beam cannot be accelerated uniformly. Usually, the induction pulse voltage have negative slope (droop) which is approximately $exp(-Zt/L)$, where Z is the impedance of the induction accelerating system and L is the core inductance. It is most simple to increase L for the purpose of reducing the droop. Winding of the excitation coil of the existing induction cell was increased from one turn to two turns. The modified cell is expected to have 4 times larger inductance.

Impedance measurement of the two turns cell was carried out using a vector network analyser (VNA), where the VNA impedance measurement is based on a parallel circuit model and small amplitude CW excitation. Complex impedance can be directly read from the Smith chart. Measurement results (solid) and theoretical predictions (dash) are shown in Figure 5, where we obtained the cell capacitance of 180 pF so as to fit the impedance curve to the measurement results. In addition, we have obtained 4 times larger impedance as expected.

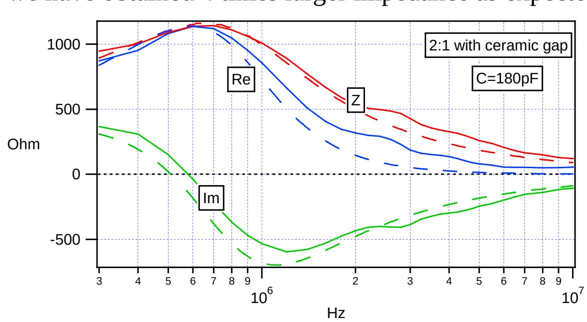

Figure 5: Impedance measurements and theoretical prediction assuming $L(\omega)=[\mu'+(\mu'')^2/\mu']L_0$ and $R(\omega)=\omega[\mu''+(\mu')^2/\mu'']L_0$, where the complex permeability, $\mu=\mu' - j\mu''$, of Finemet ® is known as a function of ω and L_0 is the core inductance in air, with packing factor and constant C of 180 pF.

In the actual operation, the cell is excited with high voltage of kV and in pulse mode. Pulse profile in the realistic situation is shown in Figure 6 where the induced voltage is proportional to the current flowing through the matching resistance and the droop is reduced beyond our expectation. In order to analyse this single pulse, we introduce constant values of the core inductance L of 440 μH and core resistance R of 1290 Ω for SPICE simulations. These numbers are consistent with VNA measurements. Reduced droop and reflection and undershoot after the pulse are notable in the SPICE simulation results. We understand that the reflection takes place between the induction cell and the SPS. The reflection wave might have cancelled the droop effect. The undershoot is originated from the change of boundary condition upstream after switching. The SPICE simulation considering reflection well reproduces the pulse shape.

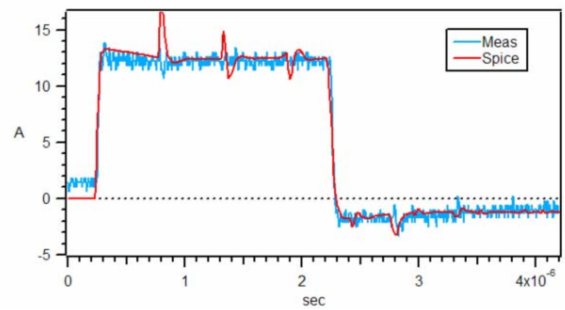

Figure 6: Matching resistance current (I in ampere) profile. Induced voltage V_{ind} is written by $Z_M I/2$, where Z_M (134Ω) is the matching resistance.

SUMMARY

The acceleration scheme of the KEK-AIA was described with simulation results. A trigger system to make this acceleration scheme possible is discussed. We have developed a new type of acceleration cell capable of generating 2 μsec long induction voltage pulses Its impedance characteristics were reported in details. Experimentally obtained pulse voltage was shown. Other aspects of the KEK-AIA are described in the companion paper [3].

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