INDUCTION SECTOR CYCLOTRON FOR CLUSTER IONS*

K. Takayama, T. Adachi, KEK, Tsukuba, Ibaraki 305-0801 Japan
H. Tsutsui, Sumitomo Heavy Industries, Ltd., Nishitokyo, Tokyo 188-8585 Japan
W. Jiang, Nagaoka University of Technology, Nagaoka, Niigata 940-2188 Japan
Y. Oguri, Tokyo Institute of Technology, Ookayama, Tokyo 152-8550 Japan

Abstract

A novel scheme of a sector cyclotron to accelerate extremely heavy cluster ions, called "Induction Sector Cyclotron (ISC)", is described [1]. Its key feature is repeated induction acceleration of a barrier trapped ion bunch. The induction cell (transformer) is energized by the corresponding switching power supply, which is controlled by gate signals manipulated from the circulating beam signal of an ion bunch. The acceleration synchronizing with the revolution of any ion beam is always assured. A cluster ion beam such as C-60 [2] can be accelerated from an extremely low velocity to a nearly light velocity. Its fundamental concept including required key devices is described.

CONCEPT OF THE ISC

Definition

It is noted that a terminology "*sector cyclotron*" is used in the following broad sense:

- Sector magnets are employed as guiding magnets.
- A circulating orbit is varied in the radial direction in the fixed guiding fields, associated with acceleration.
- Revolution frequency of circulating ions changes in an acceleration cycle.
- Transverse focussing is resulted from edge focusing effects and field gradient in the sector magnet themselves.

In addition, the ISC is not operated in a CW mode but in a pulse mode due to an essential nature in its acceleration, as described later.

Historical Background

Historically the induction acceleration in a circular ring was invented in Europe and demonstrated in a complete manner as a betatron by Kerst. Topological modification of the betatron acceleration device was achieved. One of them was realized in a linear betatron accelerator (linear induction accelerator) and has been extensively developed [3]. Meanwhile, the concept of induction acceleration in a FFAG ring was proposed and actually demonstrated as an acceleration tool at the initial acceleration stage in the MURA 50 MeV electron FFAG [4]. This acceleration method was nothing but the original betatron acceleration, because the magnetic material cores used for the induction acceleration were excited at the acceleration cycle, yielding a small continuous induced voltage of few tens of volts. That was necessarily always less than 1 Hz; the induction device was ramped just one time during its acceleration cycle.

The induction synchrotron (IS) proposed in 2000 [5] was fully demonstrated using the KEK 12 GeV PS in 2006 [6]. Protons in the IS were accelerated and captured with pulse voltages generated by transformers known as "induction acceleration cells (IC)". The ICs were energized through the corresponding switching power supply (SPS), in which solid-state power devices such as a MOSFET are employed as switching elements and their tuning on/off state is operated through gate signals digitally manipulated from the circulating signal of an ion beam. The ICs were set and reset within a single revolution of the proton bunch in the 12 GeV PS. The ICs were operated at 1 MHz. This feature can be distinguished from any induction acceleration demonstrated in circular rings. Consequently, the acceleration synchronized with the revolution of the ion beam is always guaranteed, regardless of the type of ions and their possible charge state. In this scheme, any ions directly injected from an ion source embedded in a high voltage terminal can be accelerated from an extremely low speed almost to the speed of light. As a matter of fact, the construction of the first AIA through renovation of the existing KEK 500 MeV proton synchrotron is almost complete [7].

A similar induction acceleration of barrier trapped ions can be utilized in cyclotrons operated in a pulse mode. This idea has been proposed in the last year [1]. A sector cyclotron to accelerate cluster ions especially seems to be attractive among them, because there have been no actual methods to accelerate them to high energy in a circular accelerator so far.

Schematic View of the ISC

Figure 1 shows the principle of the ISC, where the varying cyclotron orbit is located in the inner aperture of the induction cell through the entire acceleration period. The induction cell and bunch monitor with a wide aperture are required. This feature is different from that of the induction synchrotron. An ion bunch is captured by the so-called barrier voltages, which are also generated by the other induction cell (see Fig. 2).

INDUCTION ACCELERATION OF A BARRIER TRAPPED ION BUNCH

Induction Acceleration

The concept underlying operation of an ISC is fairly simple. Conventional D-electrodes with a limited frequency bandwidth are replaced by two types of ICs, one of which is used only for acceleration (Cells A and B

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in Fig.2), and the other (Cell C in the same figure) is used for confinement of ions. The induction acceleration system consists of the IC, SPS that drives the IC, and an ion bunch monitor and intelligent gate control module, where the ion bunch signal is manipulated and gate trigger signals are created in order to fire the SPS. Their essential features are the same as in the first IS and the first AIA (named “KEK digital accelerator”) [8]. Cells A and B are placed symmetrically in the drift spaces between adjacent sector magnets, as shown in Fig. 2.

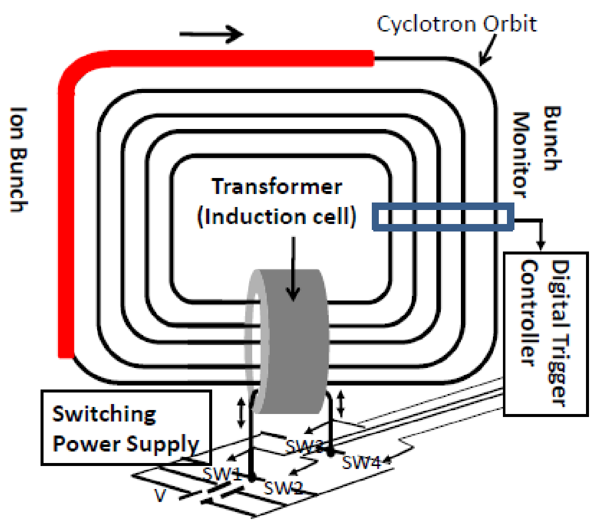

Figure 1: Principle of the ISC

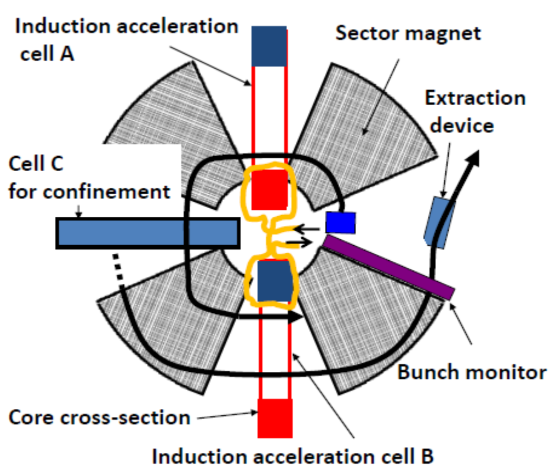

Figure 2: Concept of the ISC. Brown line indicates the exciting coil

Cells A and B are powered by a single SPS and are connected in series (primary) in such a way that the induced pulse voltages are cancelled out along the circular beam line (secondary) in Figs. 2 and 3 (top). Immediately after injection, Cell C is triggered to generate the barrier voltage, and two barrier voltage pulses are adiabatically removed in time, thus creating a long ion bunch. The length of the bunch is always maintained to be less than half a revolution period. The bunch monitor receives a passing signal from the ion bunch, based on which the respective SPSs driving Cells A/B and C are triggered through the gate trigger control module. The operational modes of Cells A/B and C are depicted with respect to time in Fig. 3 (bottom). Pulse voltages with dual polarity are generated within a single revolution period. This operation prevents the saturation of the magnetic cores in the ICs. This is a reason why the repeated acceleration is possible. The ion bunch on its circulation orbit is desirably accelerated at both acceleration gaps at every turn in accordance to the figure-8 primary winding of Cells A and B. This figure-8 winding reduces a droop in the accelerating voltage because of driving a duplicated large inductance.

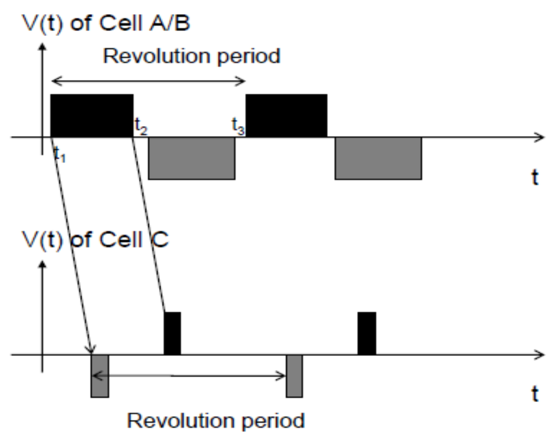

Figure 3: Induced voltage pulse profiles

Induction Cells

The induced voltage through theIC is described as $V\tau = -B_{max} S$, where V is the induced voltage, τ is the pulse width, B_{max} is the maximal flux of the swinging induction core, and S is its cross section. Here, B_{max} and S are optimized by minimizing both the heat deposited in the magnetic material and the total cost consistent with any constraints on the available space. The core is segmented into multiple bobbins. A possible core material is a nanocrystalline alloy, such as Finemet, where a thin tape 13 μm in thickness is wound in a shape resembling a race track, the inner size of which is sufficiently large to accommodate the rectangular vacuum chamber with the ceramic acceleration gap, as shown in Fig. 4a. Heat deposit inside the acceleration cell is not small. It must be removed in an efficient way similar to that in the KEK-DA. Its conceptual scheme is shown in Fig. 4b.

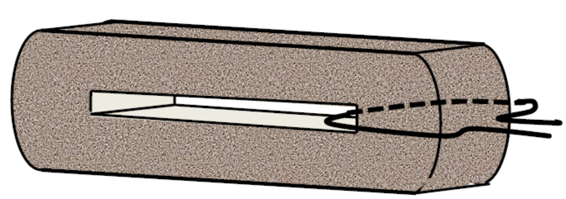

Figure 4a: Induction cell core

TRANSVERS FOCUSING

Characteristics of beam focusing in the ISC are summarized as below:

- Edge focusing of the sector magnet gives focusing in the radial direction and defocusing in the vertical direction.
- The field gradient in the F-type sector magnet takes opposite roles.
- Betatron tunes are determined by a drift length between adjacent sector magnets in addition to a balance of above focusing and defocusing effects.

Due to those properties, the present ISC may be different from a sector cyclotron in a narrow sense. A simple analysis has been given in the other paper [1] and its more details shall be given in a forthcoming full paper.

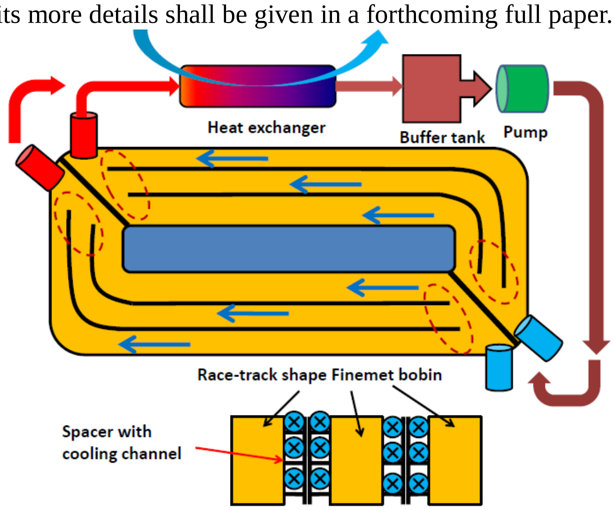

Figure 4b: Cooling system of the induction cell.

TYPICAL EXAMPLE OF THE ISC FOR C-60 LUSTER IONS

An achievable energy is given as a function of the ratio of charge state Q to mass number A of ion for different magnetic rigidity B of the sector magnet in Fig.5. Machine parameters of a typical example of the ISC for C-60, the magnetic rigidity of which is plotted with a black dot in Fig. 5, is given in Table 1.

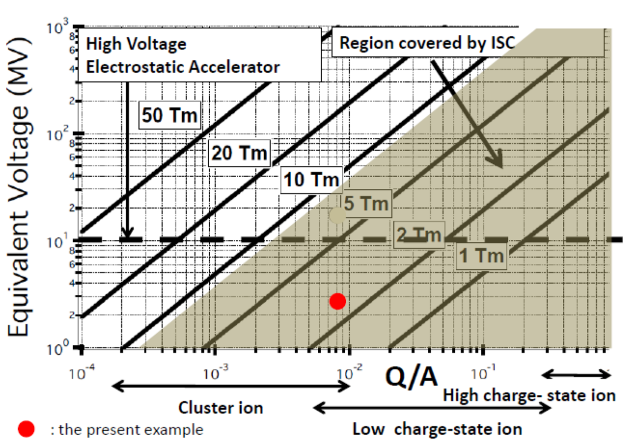

Figure 5: Achievable ion energy

SUMMARY

The present discussion is summarized as follows.

- Novel concept of induction acceleration in fixed field circular rings such as a sector cyclotron or FFAG has been proposed.
- An example of the induction sector cyclotron for C-60 has been introduced.

There are a lot of subjects remaining unsolved, such as a high charge-state cluster ion source and required good pressure and the stability of cluster ion itself under high magnetic fields. Experimental results on the life-time of cluster ions in the electro-static storage ring, which was reported by Tanabe [10], may give good suggestions to these issues.

Table 1: Machine parameters

Item	Symbol	Num. value
Mass/Charge state	A/Z	720/7
No. of sector magnets	N	4
Sector angle/Edge angle	η_0/κ[9]	(π/4)/(π/8)
Averaged radius at Inj/Ext	r_1/r_2	1.85/3.7 m
Bending radius at Inj/Ext	ρ_1/ρ_2	0.97/1.95 m
Flux density at Inj/Ext	$B(r_1)/B(r_2)$	0.67/1.34 Tm
Length of short straight		1.38/2.75 m
Acceleration voltage/turn	V_{acc}	30 kV
Turn number	N_{turn}	200
Rev. Freq. at inj/ext	f_1/f_2	52.8/105 kHz
Betatron tune	ν_x/ν_y	1.89/0.23

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