INDUCTION SECTOR CYCLOTRON FOR CLUSTER IONS*

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Abstract

A sector cyclotron aiming to acceleration of extremely heavy cluster ions has been proposed [1]. We call such a cyclotron as "Induction Sector Cyclotron (ISC)". Its key feature is repeated induction acceleration of a barrier trapped ion bunch. The induction cell (one-to-one 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. Such a control scheme assures the acceleration synchronizing with the revolution of any ion beam. A conceptual design of an induction cell for the ISC is described here.

INTRODUCTION

An "Induction Sector Cyclotron (ISC)" is a sector cyclotron aiming to acceleration of extremely heavy cluster ions by using induction acceleration cells instead of a conventional rf acceleration cavity. The induction cell is a one-to-one transformer. 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 of its acceleration, as described later.

An induction acceleration cell (IC) was first introduced to the FFAG [2] and soon linear accelerators [3], where a repetition of cell excitation was 1 Hz at most. On the other hand, the induction synchrotron (IS) was proposed in 2000 by introducing induction cells capable of excitation at a repetition rate up to 1 MHz. Principle of the IS was fully demonstrated using the KEK 12 GeV PS in 2006 [4]. Protons in the IS were accelerated and captured with pulse voltages generated by the ICs. They were energized through the corresponding switching power supply (SPS), in which solid-state power devices such as a MOSFET are employed as switching elements. A gate pulse determining their on/off timing is generated by using the signal of a circulating ion beam. The ICs were set and reset within a single revolution of the proton bunch in the 12 GeV PS. In this demonstration the SPS was operated with maximum switching repetition of 1 MHz. This feature can be distinguished from any induction acceleration demonstrated previously by using circular rings in the world. Consequently, the acceleration synchronized with the revolution of 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. The first "all-ion-accelerator (AIA)", called the KEK digital accelerator [5], was constructed at KEK and its beam commissioning is underway [6].

A similar induction acceleration of barrier trapped ions can be utilized in cyclotrons operated in a pulse mode [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.

INDUCTION ACCELERATION OF A BARRIER TRAPPED ION BUNCH

Induction Acceleration

Fig. 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).

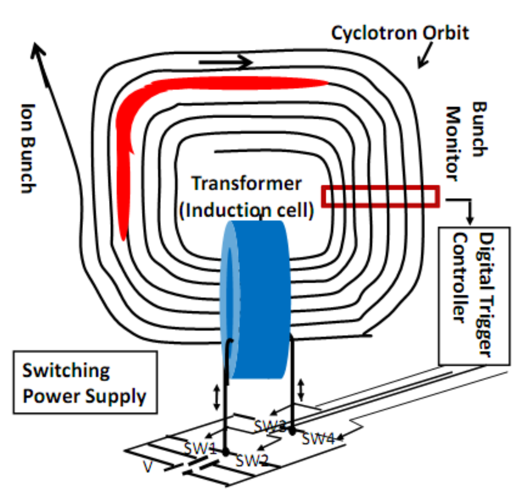

Figure 1: Principle of the ISC

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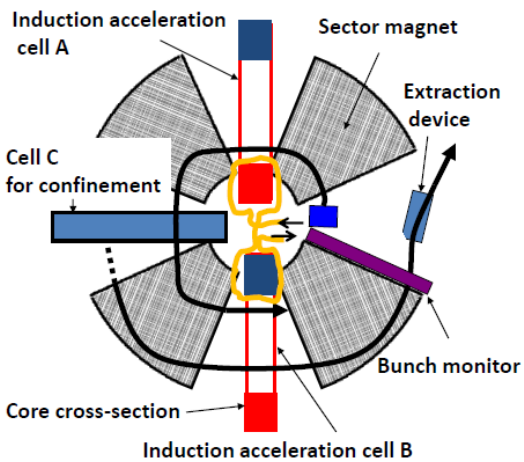

Figure 2: Concept of the ISC. Brown line indicates the exciting coil.

The concept underlying operation of an ISC is fairly simple, as shown in Fig. 2. 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), and the other (Cell C) is used for confinement of ions. The induction acceleration system consists of the ICs, SPS that drives the ICs, 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 (KEK-DA)") [5]. Cells A and B are placed symmetrically in the drift spaces between adjacent sector magnets, as shown in Fig. 2.

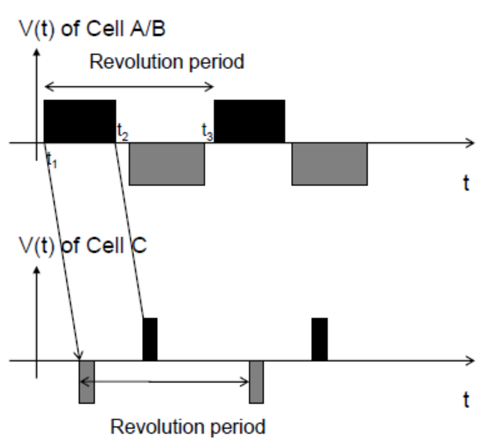

Figure 3: Induced voltage pulse profiles.

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 Fig. 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.

Induction Cells

The induced voltage through the IC is described as $V\tau = -B_{max} S$, where V is the induced voltage, τ is the pulse width, B_{max} is the maximal magnetic flux density inside the 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 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.

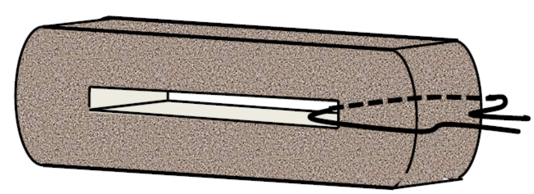

Figure 4a: Core of the induction cell.

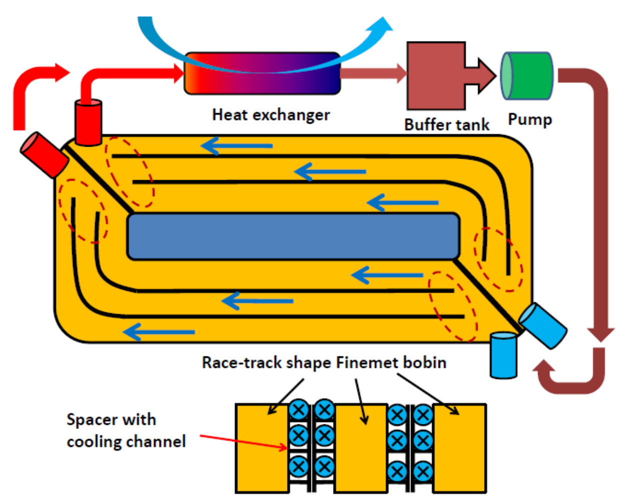

Figure 4b: Cooling system of the induction cell.

DESIGN OF THE RING AND AN IC DRIVING SYSTEM

We have already proposed a small-scale ISC aiming to acceleration of C_{60} cluster ion [1]. Machine parameters are listed in Table 1.

Table 1: Machine Parameters

Item	Value
Mass/Charge state	720/7
No. of sector magnets	4
Sector angle/Edge angle	$(\pi/4)/(\pi/8)$
Averaged radius at Inj/Ext	1.85/3.7 m
Bending radius at Inj/Ext	0.97/1.95 m
Flux density at Inj/Ext	0.67/1.34 Tm
Length of short straight sections	1.38/2.75 m
Acceleration voltage/turn	30 kV
Horizontal/Vertical tunes	1.89/0.23
Revolution frequency at Inj/Ext	52.8/105 kHz

Design of the induction cell and power supply system for this ISC is now in progress. Dimensions of a basic unit of the IC are shown in Fig. 5. FINEMET FT-3M of Hitachi Metals, Ltd. is used as a core material. Main characteristics are listed in Table 2 (according to manufacturer's datasheet).

Table 2: Main Characteristics of FT-3M

Item	Value
Thickness	18 μm
Density	$7.3\text{x}10^3$ kg/m^3
Resistivity	1.2 μΩm
Saturation flux density B_s	1.23 T
Relative permeability μ_r at 100 kHz	$1.5\text{x}10^4$
Power loss P_{CV} at 100 kHz, 0.2 T	300 kW/m^3

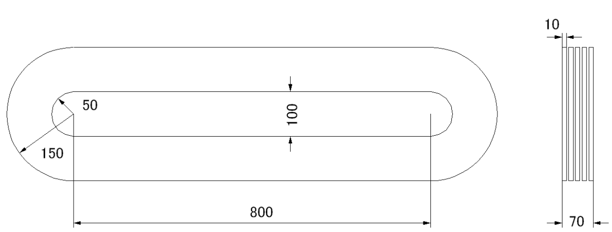

Figure 5: Dimensions of the IC.

There is a trade-off in determining the flux-density swing (ΔB) of the magnetic core, because it affects both the value of V×Δt and the power loss in the core. In case of ΔB = 0.2 T, which is about 17 % of the saturated flux-density, and an acceleration time of Δt = 200 ns, the acceleration voltage calculated from the dimensions given in Fig. 5 yields V = 10 kV.

Therefore, the electrical parameters of the IC are estimated, supposing the following operation conditions:

- Maximal flux density 0.2 T
- Repetition rate 100 kHz
- Acceleration voltage 10 kV
- Pulse duration 200 ns

The results are summarized in Table 3, where the overall load impedance has been assumed to be 200 Ω.

Table 3: Electrical parameters of the IC

Item	Value
Peak voltage	10 kV
Load current	50 A
Peak power	500 kW
Average power	10 kW

It is noted that the real impedance of IC decreases in time due to the increase of the excitation current during the pulse. Calculations based on the parameters given above show that the IC primary current has to increase from 8.4 A to 32.1 A during the acceleration time of 200 ns, in order to keep a constant acceleration voltage of 10 kV, raising a challenging issue for electrical coupling between SPS and IC. The same problem had occurred in IS, although the impedance variation of IC had been much small, and had been solved by using a dummy-load connected in parallel to IC which dominated the load impedance.

SUMMARY

Design of a sector cyclotron aiming to acceleration of C_{60} cluster ion is now in progress. The IC is a key feature for this accelerator. Presently, dimensions of a basic unit of the IC have been fixed, and power loss and the peak current are estimated. A cooling system for the IC must be designed in the next step. Then, feasibility tests will be performed.

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