Induction Sector Cyclotron for Cluster Ions

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Outline of Talk

1. A brief history of induction acceleration in circular rings
2. Example of Induction acceleration
   - KEK Induction Synchrotron
     - Schematic features
     - Key hardwares
3. Outline of Induction Sector Cyclotron (ISC)
4. Acceleration and confinement in the longitudinal direction
5. Induction cell
6. Capability of ISC
7. Parameters of a typical ISC for C-60 ions
8. Summary
From Betatron to Induction Synchrotron / Cyclotron

\[ V = \int E \cdot dl = -\frac{d\Psi}{dt} \left( \Psi = \int B \cdot ds \right) \]

Betatron

Iron yolk

Vacuum chamber

Top view

Excitation coil

Fiducial density

Excitation coil (primary)

Synchrotron (KEK, 2006)

Linear induction accelerator

MURA 50-MeV FFAG (1964)

Initial Accel. in FFAG

Topological modification

Cyclotron

f < 1 - 3 MHz

f < 1 Hz (burst ~ 1 kHz)

for more history

K.Takayama and R.Briggs (Eds.)
“Induction Accelerators”
(Springer, 2010 October)
Characteristics of Circular Induction Accelerator (Synchrotron)

- RF Synchrotron
  - Transformer (Induction cell)
  - Induction Synchrotron
  - Ion bunch
  - Switching Power supply
  - Bunch monitor
  - Digital trigger controller

- Cascade type of accelerator complex
  - Ion source
  - Linac
  - Booster
  - Main accelerator
  - RF Synchrotron
  - Cavity and RF amp. with a limited bandwidth

- Single stage accelerator
  - Main accelerator
  - Ion source

- Functionally combined acceleration/confinedment ->
  - Increase in the local density ->
  - Limit on a beam current

- Functionally separated acceleration/confinedment
  - Increasing a freedom of beam handling
  - Pulse voltage for acceleration

- Time
  - RF voltage
  - Ion bunch
  - Acceleration phase
  - Deceleration phase
  - Diffusion phase

4
Equivalent Circuit of Induction Acceleration System and Individual Instruments

Switching power supply

DC Power Supply

Transmission line (40m long)

Induction accel. cell

Primary loop

Switching arm S1 (7 MOSFETs in series)

MOSFET board

Finemet (nano-structure crystalline, Hitachi Metal)

2.5kV, 20A, 1MHz, 500nsec

Development by KEK Nichicon

Gate drive power

MOSFET (rear)

Cooling water

Stacked induction cells output 2 kV/cell

Gate trigger light signal

Gate driver IC (rear)

Copper heat sink
ion $H^+$
500 MeV → 6 GeV
$N=2.5 \times 10^{11}$

Switching Power Supply
$40\text{kW} \quad \text{Max} f_{\text{rep}}=1\text{MHz}$

Induction cell
10 cells
$V_{\text{out}}=2kV/\text{cell}$

KEK 12GeV Proton Synchrotron
$C_0=340m$

500MeV Booster
$C_0=37m$

$40\text{MeV}$ H-Linac
$750\text{keV}$ Cockloft

Induction cells are located between adjacent sector magnets. Two type cells will be used. Cell A/B for acceleration, Cell C for confinement.

Horizontally wide aperture induction cells are required. In order to realize this shape, a nanocrystalline thin tape as a magnetic material will be wound in a race-track shape.
An ion beam is bunched by barrier voltages generated in Cell C. The beam pulse occupies less than half of the orbit length.

Cell A/B are set and reset every turn of the ion bunch to avoid saturation of the core material.

The primary coil of Cell A/B is connected in series with 8-figure, being driven by a common PS. Set-voltage in Cell A and reset voltage in Cell B contribute to the induction acceleration.

This series connection is helpful to duplicate the core inductance, resulting in mitigation of the droop voltage.
Achievable energy is simply dependent on the magnetic rigidity of sector magnet as well as in other cyclotrons.

Equivalent voltage, which can be easily compared with the acceleration voltage of electro-static accelerator, is shown as a function of the ratio of charge state “Q” to mass number “A”.
### Machine Parameters of a Typical ISC for C-60

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Numerical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass number/Charge state</td>
<td>$A/Q$</td>
<td>720/7</td>
</tr>
<tr>
<td>Number of sector magnets</td>
<td>$N$</td>
<td>4</td>
</tr>
<tr>
<td>Sector angle/edge angle</td>
<td>$\eta_0/\kappa$</td>
<td>$(\pi/4)/(\pi/8)$</td>
</tr>
<tr>
<td>Averaged radius at inj/ext</td>
<td>$r_1/r_2$</td>
<td>1.85/3.7 m</td>
</tr>
<tr>
<td>Bending radius at inj/ext</td>
<td>$\rho_1/\rho_2$</td>
<td>0.974/1.948m</td>
</tr>
<tr>
<td>Flux density at inj/ext</td>
<td>$B (r_1)/B (r_2)$</td>
<td>0.67/1.34 Tesla</td>
</tr>
<tr>
<td>Magnetic rigidity</td>
<td>$B\rho$</td>
<td>0.653/2.61 Tm</td>
</tr>
<tr>
<td>Period length at inj/ext</td>
<td>$L_1+L_2$</td>
<td>2.9/5.8 m</td>
</tr>
<tr>
<td>Length of straight section</td>
<td></td>
<td>1.38/2.75 m</td>
</tr>
<tr>
<td>Acceleration voltage per turn</td>
<td>$V_{acc}$</td>
<td>30 kV (2 × 15 kV)</td>
</tr>
<tr>
<td>Number of turns</td>
<td>$N_{turn}$</td>
<td>100</td>
</tr>
<tr>
<td>Inj./Integrated voltage</td>
<td>$V_1/V_2 (V_{acc} \times N_{turn})$</td>
<td>200 kV/3.0 MV</td>
</tr>
<tr>
<td>Rev. frequency at inj/ext</td>
<td>$f_1/f_2$</td>
<td>52.8/105 kHz</td>
</tr>
<tr>
<td>Betatron tune (tracking)</td>
<td>$\nu_x/\nu_y$</td>
<td>1.889/0.229</td>
</tr>
</tbody>
</table>

**Hard edge model**

![Diagram of a hard edge model showing parameters such as $\beta_x$ and $\beta_y$.](image)
An induction circular accelerator with fixed guiding fields, Induction Sector Cyclotron, has been proposed.

Its properties of turn-by-turn induction acceleration, barrier bucket confinement, have been presented.

Machine parameters of a typical ISC, which could be useful for acceleration of cluster-ions, such as C-60, has been given.
We are planning to construct a prototype.

Your comment, suggestion, criticism, and advice are really welcome through this conference.

$\beta_x$ and $\beta_y$
**Motivation**

Acceleration of cluster ions, Q/A of which is extremely small (< 1/10-100).
Its acceleration frequency falls out of that of RF.
So far a unique solution has been an electrostatic accelerator.
A single-end electrostatic accelerator has a limitation of achievable charge-state.

**Why**

Energy density of swift cluster ions is extremely high in space.

Deep damage on a target material is unpredictable because of nonlinear effects.

- Unique driver for development of functionally noble materials
- Unique driver for studying Material Science or Warm Dense Matter Science

*by Y. Oguri, in Proceedings of RPIA 2006*