KEK Digital Accelerator
and
Recent Beam Commissioning Result

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on behalf of KEK Digital Accelerator Group

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Tokyo Institute of Technology

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Contents

1. Concept of Induction Synchrotron(*)
2. Outline of KEK Digital Accelerator
   (A fast cycle induction synchrotron)
   Key components
3. Beam commissioning results
4. Summary

* References
K. Takayama et al., “Experimental Demonstration of the Induction Synchrotron”,

Companion paper (Poster Session of this afternoon, PO13):
X. Liu et al., “Longitudinal Beam Motion in the KEK Digital Accelerator:
   Tracking Simulation and Experimental Results”
Characteristics of Induction Synchrotron (Digital Accelerator)

Functionally combined acceleration/confinement -> increase in the local density -> limit on a beam current

Functionally separated acceleration/confinement -> increasing a freedom of beam handling

Cascade type of accelerator complex

Single stage accelerator

1945 E.M.McMillan, V.Veksler

2000 Takayama/Kishiro

Resonant cavity

RF Synchrotron

Induction Synchrotron

Transformer

Switching Power supply

Ion bunch

Digital trigger controller

Cavity and RF amp. with a limited bandwidth

Ion bunch

Linac

Booster

Ion source

Digitally triggered controller

SW1

SW2

SW3

SW4

Ion bunch

Pulse voltage for acceleration

Pulse voltage for confinement
Equivalent Circuit for Induction Acceleration System

Switching Power Supply

- Capacitance: $C = 260 \text{ pF}$
- Resistance: $R = 330 \text{ } \Omega$
- Inductance: $L = 110 \mu\text{H}$

Induction Cell

- $V_0$
- $Z_0(120\Omega)$
- Trasmi. line (40m long)
- Matching resistor

Capacitance: $C = 260 \text{ pF}$
Resistance: $R = 330 \text{ } \Omega$
Inductance: $L = 110 \mu\text{H}$

ECRIS & 200 kV HVT
Einzel Lens Longitudinal Chopper: Idea, Device, Performance

Why we need a Chopper?

- 1 turn injection < 10 μsec
- A long pulse from ECRIS ~ 2 - 5 msec

What type is desired?

- Low energy operation
- Low cost (~ $2,500)
- Low energy x-ray
- Reduced out-gassing
- Reduced secondary e⁻

Einzel lens longitudinal chopper

FET switch driven 4 stages Marx generator

Longitudinal gate study by IGUN

Pulsed beam from ECRIS

Chopped beam

Beam Profile on the Screen Monitor placed upstream in LEBT

Beam profile plotted from the result from “Screen Monitor

<table>
<thead>
<tr>
<th></th>
<th>Horizontal rms emittance $\varepsilon_x[\mu\text{mrad}]$</th>
<th>Vertical rms emittance, $\varepsilon_y[\mu\text{mrad}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement by Pepper pot device</td>
<td>~100</td>
<td>~75</td>
</tr>
</tbody>
</table>

200 keV
H1+
100 $\mu$A
Electrostatic Injection Kicker

Driving circuit of the injection ES kicker

- Electrode (+)
- Injected Beam
- Interim Electrode
- High voltage electrode
- Vacuum Chamber
- Ground Electrode

Injection timing

Kicker Voltage (kV)

for interim electrodes

Coaxial Cable (20Ω: R=50Ω)

Injection Kicker

Switch

HV P.S.

Thyratron Switch

Matching Resistor (R=50Ω)
### Combined-function type magnet (lower half)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending radius</td>
<td>$\rho$ 3.3 m</td>
</tr>
<tr>
<td>Ring circumference</td>
<td>$C_0$ 37.7 m</td>
</tr>
<tr>
<td>Maximum flux density</td>
<td>$B_{\text{max}}$ 0.84 T (1.1 T)</td>
</tr>
<tr>
<td>Accel. voltage/turn</td>
<td>$V$ 3.24 kV</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$f$ 10 Hz</td>
</tr>
<tr>
<td>Betatron tune</td>
<td>$\nu_x/\nu_y$ 2.17/2.3</td>
</tr>
</tbody>
</table>

### Resonant LCR Circuit Power Supply

![Resonant LCR Circuit Power Supply Diagram]
Scenario of induction acceleration/capture of He\(^{2+}\) and C\(^{6+}\)

- **B(t)**
- **Injection**: 0.84 T
- **Acceleration region**: 100 msec
- **Extraction**: 0.84 T

**Note Dynamic range**

- 50-80 kHz
- ~ 3 MHz

**Acceleration voltage**

\[ V_{acc} = \rho C(dB/dt) \]

**Barrier voltage**

- 20 msec
- 5 msec
- 30 msec
- 10 msec
- 40 msec
- 15 msec
- 50 msec

by T. Dixit et al., N.I.M. 602, 326 (2009).
**Technical Limitation of Induction Acceleration Cell**

1. **Fixed output voltage** \( V_{\text{out}} \approx 1 - 2 \text{kV/cell} \)
   - Primary voltage is not easily changed.

2. **Maximum pulse length** \( \sim 0.5 - 2 \mu\text{sec/pulse} \)
   - Voltage pulse length is determined by droop.

3. **Maximum rep-rate** \( \sim 1 \text{ MHz} \)
   - Heat deposit is serious beyond 1 MHz.

**Induction Acceleration Scenario**

1. **Pulse density control**
2. **Superimpose of pulses in time**
3. **Sequential trigger in time**
4. **Intermittent operation**

*If magnet ramping is slow*
- When requirement exceeds its capability of rep-rate and pulse-width,
  - \( V_{\text{out}} > V_{\text{req}} \)

*If larger acceleration voltage is required*
- \( V_{\text{acc}} \)

*If longer pulse width is required*
- \( \text{Cell A} \) \( \text{Cell B} \)

*If higher rep-rate is required*
- \( \text{Cell A} \) \( \text{Cell B} \) \( \text{Cell A} \)
KEK Digital Accelerator (Rapid Cycle Induction Synchrotron)


Equivalent Circuit for Induction Acceleration System

Switching Power Supply

Induction Cell

Trasmi. line (40m long)

Capacitance: $C = 260 \text{ pF}$
Resistance: $R = 330 \Omega$
Inductance: $L = 110 \mu\text{H}$

Equivalent Circuit for Induction Acceleration System
Induction Acceleration Control System using FPGA/DSP

In Accelerator tunnel
- Ion Beam
- Induction acceleration cell
- v(t)
- Bunch monitor

Matching resistor
- Ion source

Induction Acceleration Control System using FPGA/DSP

Main Control Room
- PC for FPGA control
- JTAG
- SCI
- Virtual beam signal
- Beam signal PDC
- DSP TMS3206416T DSK
- Induction voltage
- Bunch signal

Matching resistor
- Ion source

Optical converter
- Switching power supply
- Optical signal
- NIM Divider Fan-out
- FPGA (Field Programmable Gate Array)
- Xilinx Vertex5 MOF 300MHz
- Trigger signal Active delay
- Beam signal PDC Vac on/off control
- Beam signal PDC Vac on/off control
- MOF 1GHz

In Accelerator tunnel
- Induction acceleration cell
- v(t)
- Bunch monitor

Guiding magnet

Optical signal converter

Switching power supply

In Accelerator tunnel
- Induction acceleration cell
- v(t)
- Bunch monitor

Guiding magnet
Closed Orbit Distortion
originated from residual flux density in the main magnets

$5 \text{ Gauss} < B_{\text{remnant}} < 10 \text{ Gauss}$

$B_{\text{inj}} \approx 200 - 400 \text{ Gauss}$

It is significant at the injection energy.

**COD correction method:**

Limitation: limited number of position monitor (5)

- **1st and 2nd harmonic correction**
  
  $Q_x = 2.17 \rightarrow N=1, 2$ dominant

- **8 figure correction coil winding**
  
  Between every other magnets to avoid induced voltage on P.S.

**Results:**

- Practically its size is acceptable.
- Current correction is still not enough; 3rd harmonic seems to appear in residual COD.

**Emittance blow-up**

originated from

**Synchro-beta Coupling**

**No dispersion-free lattice**

$$
\begin{align*}
\begin{bmatrix}
  x_i (n+1) \\
  \dot{x}_i (n+1)
\end{bmatrix}
&= 
\begin{bmatrix}
  \cos (2 \pi Q_x (n)) & \beta \cdot \sin (2 \pi Q_x (n)) \\
  -\frac{1}{\beta} \cdot \sin (2 \pi Q_x (n)) & \cos (2 \pi Q_x (n))
\end{bmatrix}
\begin{bmatrix}
  x_i (n) \\
  \dot{x}_i (n)
\end{bmatrix}
\end{align*}
\times
\begin{bmatrix}
  x_i (n) - D \left( \frac{\Delta p}{p} \right)_r
\end{bmatrix}
$$

Introduction of a combination of low/high voltage pulses
Beam Commissioning (1): Free Circulation at $E_{\text{inj}}$ under $B_{\text{min}}$

Notable facts in LEBT:
- Modulation in the momentum space caused by the transient fields of the chopper
- Drift compression

Notable facts:
- Some spread in the momentum space
- Diffusion and further compression depends on beam intensity

Notable facts in LEBT:

\[ \Delta p/p \]

\[ t \]

Time, t [s]

\[ \eta = \frac{1}{\gamma^2} - \frac{1}{\gamma^2} < 0 \]

\[ \Delta t \propto \eta \cdot \frac{\Delta p}{p} \]

Turn from injection (msec)

- $I_B=22 \ \mu A$
- $I_B=38 \ \mu A$
- $I_B=50 \ \mu A$

$T_0=12 \mu s$

In the DA ring

Simulation

Projection of Bunch Signal Mountain view (3D)

Entrance of LEBT (Entrance of Ring)

Exit of LEBT

Measurement at 1 turn in the ring

In Ring

Diffusion and further compression depends on beam intensity
Beam Commissioning (2): Barrier Volt. Confinement at $E_{inj}$ under $B_{min}$

Case A

- Trapping region
- Time after injection (msec)
- $V_{bb} t$

Case B

- Trapping region
- Time after injection (msec)
- $V_{bb} t$

Case C

- Trapping region
- 45 msec

Beam loss is obvious.
Possible reasons:
- low $\beta \sim 10^{-2}$
- No orbit correction
- $e^{-}$ capture/ $e^{-}$ stripping
- Scattering by residual atoms or molecules
Beam Commissioning (3): Bunch Squeezing Experiment

8 nsec/turn

$\Delta p/p$

0 – 7 msec

$\Delta p/p$

> 7 msec

fixed

Note: Polarity of barrier voltage signal is opposite.
Beam Commissioning (4): Demonstration of He1+ Acceleration (Preliminary)

<table>
<thead>
<tr>
<th>Ion source</th>
<th>ion</th>
<th>energy</th>
<th>Particle number/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECR Ion Source</td>
<td>H, He, C, N, O, Ne, Ar</td>
<td>&lt; 140 MeV/au, 200MeV</td>
<td>&lt;10^{10}</td>
</tr>
<tr>
<td>Laser Ablation Ion Source</td>
<td>Xe, Fe, Cu, Ag, Au</td>
<td>&lt; 70 MeV/au</td>
<td>&lt; 10^9</td>
</tr>
</tbody>
</table>
Coming half year and Future Plans

**Confirmation of Induction Acceleration toward the last stage in the KEK-DA**

1. by Completely programmed control based on B-clock trigger
2. by Beam feedback control

**Deliver of p, He, C, N, Ar to applications**

- Laboratory
- Space Science
- Experiment using virtual cosmic rays

In collaboration with JAXA-ISAS/NAO/Yokohama Nat. Univ.

**Introduction of LAIS for Metal ions (Fe, Cu, Ag, Au)**

- Replacement by S.P.S. employing SiC-JFETs
  - 1.2/2.4 kV SiC-JFET Package developed by KEK/SunA
  - Present S.P.S. (7 MOSFETs in series)

In collaboration with RIKEN-BNL Research Center

In collaboration with SunA and JPPL
Summary

- Noble device such as Einzel lens longitudinal chopper has been developed. Its capability is excellent.

- Beam Commissioning of KEK Digital Accelerator
  - Induction acceleration was confirmed (but not complete yet).
  - Beam handling using barrier voltage pulses was demonstrated with increasing freedom of beam handling in the longitudinal direction.

Consequently,
- it turned out that Induction Synchrotron Concept can work both as
  - Slow Cycle Synchrotron (2 sec, KEK 12 GeV PS, 2006)
  - Rapid Cycle Synchrotron (50 msec, KEK-DA, 2011)

- Plan/possibility of applications utilizing heavy ions (virtual cosmic-rays)
  - *Laboratory Space Science*: Systematic development of electric circuits to work in space (single ion phenomena), confirmation of “origin of life” (authorized)
  - *Industrial use*: Deep implantation of RI particle into materials
    - Use of high energy ion track through materials
  - *Medical use*: The next generation of hadron cancer therapy with option of C-11 cancer therapy