Induction Synchrotron Experiment in the KEK PS

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on behalf of
Super-bunch Group which consists of staffs of KEK, TIT, NAT, and Nagaoka Tech. Univ.

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Contents

- Brief history of the *Induction Synchrotron* R&D at KEK
- Outline of the *Induction Synchrotron* (IS)
- Experimental results using the KEK 12GeV PS
- Perspective: beyond the POP experiment
- Summary
## History of Induction Synchrotron Research at KEK

<table>
<thead>
<tr>
<th>Year</th>
<th>Major topics &amp; outputs</th>
<th>Events</th>
</tr>
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<tbody>
<tr>
<td>2000</td>
<td>R&amp;D works on the 1MHz switching power supply started.</td>
<td>EPAC2000</td>
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<tr>
<td>2001</td>
<td>R&amp;D works on the 2.5kV, 1MHz induction acceleration cell started. Proposal of a Super-bunch Hadron Collider</td>
<td>PAC2001, Snowmass2001</td>
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<td>2003</td>
<td>5 years term Project using the KEK-PS officially started with a budget of 5M$.</td>
<td>PAC2003, ICFA-HB2003</td>
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<tr>
<td>2004</td>
<td>●The first engineering model of the switching P.S. was established. 3 induction acceleration cells (2 kVx3=6 kV) were installed. (May)●First experimental demonstration of induction acceleration in the KEK-PS (Oct. - Nov.)●Barrier trapping at the injection energy of 500MeV and a 500 nsec-long bunch was achieved. (Dec.)</td>
<td>APAC2004, EPAC2004, ICFA-HB2004, CARE HHH2004</td>
</tr>
<tr>
<td>2005</td>
<td>Proposal of All-ion Accelerators Another 3 induction acceleration cells (2 kVx3=6kV) were installed (Sept).●Quasi-adiabatic non-focusing transition crossing was demonstrated in the hybrid synchrotron (RF capture + induction acceleration), (Dec.)</td>
<td>PAC2005</td>
</tr>
<tr>
<td>2006</td>
<td>Another 4 induction acceleration cells (2 kVx4=8 kV) were installed.(Jan.)●Full demonstration of the IS concept (March)●All-ion Accelerator was awarded a patent. (November)</td>
<td>RPIA2006, HB2006, EPAC2006, HIF06</td>
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</table>
The first Synchrotron and newest one

$E=340\,\text{MeV}$
Week focusing
by courtesy of LBNL

Large Hadron Collider
$E=7\,\text{TeV}$
Circumference= 27km
Beam commissioning in 2007 fall
Concept of Induction Synchrotron


<table>
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<tr>
<th>Principle</th>
<th>Image of Accelerator</th>
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<tr>
<td><strong>RF Synchrotron</strong></td>
<td>![Induction Synchrotron Image]</td>
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<tr>
<td>RF voltage</td>
<td>Voltage with gradient of accel./confinement</td>
</tr>
<tr>
<td>RF bunch</td>
<td>Combined function of accel./confinement</td>
</tr>
<tr>
<td><strong>Pulse voltage</strong></td>
<td>Induction cells for Capture</td>
</tr>
<tr>
<td>for acceleration</td>
<td>for confinement</td>
</tr>
<tr>
<td>Separate function</td>
<td>Induction cells for Acceleration</td>
</tr>
<tr>
<td>introducing a big freedom of beam handling</td>
<td></td>
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<tr>
<td><strong>Induction Synchrotron</strong></td>
<td>Superbunch</td>
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</table>

*Faraday’s law*

\[
\oint E \cdot d\mathbf{A} = \int_S \frac{d\mathbf{B}}{dt} \cdot d\mathbf{S}
\]
Difference between RF and Induction Synchrotron seen in Phase-space

RF bunch
Super-bunch

allowed maximum energy spread

peak density: $\lambda(0) < \lambda_{\text{limit}}$

This space is not available for acceleration.
Equivalent Circuit for 2.5kV Induction Accelerating System

DC P.S.  Switching P.S.

Transmission line (60m long)  Induction Cell

\[ V_0 \sim V_2 = V_3 \sim ZI_z \text{ (calibrated)} \]

I_z (always monitored)

More information on key devices:  http://conference.kek.jp/rpia2006/
Switching Power Supply: switching sequence, output pulse

1) Gate pulse
2) $\frac{dl}{dt} = 0$

MOSFET board

Heat sink for MOSFET & drive IC

Gate drive power

Driver IC (rear side)

MOSFET (rear side)

2.5kV, 20A, 1MHz, 500nsec

M.Wake et al. MOPAN042
Set-up of the induction synchrotron using the KEK 12GeV PS

Induction acceleration cells
(total 10 cells)

KEK 12GeV Proton Synchrotron
C₀=340m

500MeV Booster
C₀=37m

Switching power supply
(1 MHz operation at maximum)

60m-long Transmission line

40MeV H⁻ Linac
750keV Cockcroft-Walton

Finemet

1st loop

Y. Shimosaki et al., Poster TUPAN044
Scenario of the POP Experiment

The scenario has been divided into three steps.

1st Step:
RF trapping + induction accel.
(Hybrid Synchrotron)
500 MeV -> 8 GeV for 6x10^{11} ppb
2004/10-2005/3

2nd Step:
Barrier trapping by induction step-voltages
at 500 MeV
through 2005

3rd Step:
Barrier trapping + induction accel.
(Induction Synchrotron)
500 MeV -> 6 GeV for 2-3x10^{11} ppb
2006/1-3
Monitored signals of induction voltage and an RF bunch signal in the step 1 experiment.

1.6 kV/cell

1 (8Gev)-1.5(500MeV) msec

- Synchronization between two signals has been confirmed through an entire acceleration.
Proof of the induction acceleration in the Hybrid Synchrotron:
Position of the bunch centroid in the RF phase

\[ V = V_{\text{rf}} \cdot \sin \phi_s + V_{\text{ind}} \]


Step 1
Hybrid Synchrotron
Focusing-free Transition Crossing (FFTC) in the Hybrid Synchrotron

RF Synchrotron
- RF voltage: always on around $\gamma_T$
- Induction voltage: continuously triggered for acceleration.

Hybrid Synchrotron
- RF voltage: off around Transition energy.
- Induction voltage: continuously triggered for acceleration.

Specific features in TC:
- Non-adiabatic motion
- Sync. motion frozen
- Stretched in $\Delta p/p$
- Compressed in phase
- Reach momentum aperture
- Jonsen effects: serious
  - $\phi_{n+1} = \phi_n + 2\pi n(\Delta p/p)_{n+1} + k(\Delta p/p)^2_{n+1}$
- Instabilities:
  - Microwave instability @ (KEK-PS)
  - e-p instability (RHIC)

$\gamma < \gamma_T$

$\gamma \sim \gamma_T$

$\gamma > \gamma_T$
Experimental Results for QNTC

Beam Intensity measured by Slow Intensity Monitor (2x10^{11}ppb/div) and Wall current measured by Wall Current Monitor (a) NTC and (b) QNTC.


Simulation Results

Polynomial reduction

\[ V_{rf}(t) = a|t^n\sin[\omega_{rf}t] \]


\[ V_{\text{rf}}(t) = a|t^n\sin[\omega_{\text{rf}}t] \]

Bunch length measured by Wall Current Monitor.
Step 2: Confinement by Induction Step-barriers
Formation of a 600nsec-long bunch

6 kV barrier-voltage

Shallow notch potential

Injected proton bunch

100nsec

t=0 msec after injection

t=100 msec after injection

600nsec

Trapped protons

**Induction Cell for Acceleration**

**Induction Cell for Confinement**

**KEK-PS Switching Power Supply**

**Bunch Monitor**

**Switching Power Supply DSP (1GHz)**

**Switching Power Supply DSP (720MHz)**

**Transmission line**

**ΔR Monitor**

**Proton Beam Pattern Controller 1**

**P2 Trigger Delay**

**Transmission line**

**Switching Power Supply**

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**Accelerator parameters & control system**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_0 )</td>
<td>339 m</td>
</tr>
<tr>
<td>Inj/Ext Energy</td>
<td>0.5/6 GeV</td>
</tr>
<tr>
<td>Revolu fre.</td>
<td>667-876 kHz</td>
</tr>
<tr>
<td>Accel. time period</td>
<td>2.0 sec</td>
</tr>
<tr>
<td>( dB/dt )</td>
<td>0.377 T/sec</td>
</tr>
</tbody>
</table>

**Induction acceleration voltage:**
- Acceleration: 6.4 kV (4 sets)
- Confinement: 10.8 kV (6 sets)

**Cross-section of vacuum pipe**

**Δp/p>0**

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**Step 3-1 Induction Synchrotron**

**T. Iwashita et al., TUPAN044 in this PAC**
Step 3-2
Induction
Synchrotron

P2 (just start of accel.)
Start of acceleration
Injection (500MeV)

P2+400 msec
End of acceleration (6GeV)

near end of accel. (6GeV)

beam position (10 mm/div)
Beam current ($10^{12}$/div)
acceleration voltage pulse (1kV/div)
bunch signal

Movie show of the full demonstration

Temporal Evolution of the Bunch Length: Adiabatic dumping in the Induction Synchrotron

Step 3-3
Induction Synchrotron

Theory: A WKB-like solution of the amplitude-dependent oscillation system (synchrotron oscillation in the barrier bucket)

Technical Issues and further R&D Works

Noise Problems (TUPAN050)
Essentially pulse devices with reflection
- potential noise sources
  -> pulse leak currents through the earth or EM waves propagate in air
  -> shielding or protection by optimized cabling

Importance of Trigger Control and Beam Physics Issues
How to get the macroscopic center of bunch correctly
- incorrect gate timing
  - acceleration or deceleration by the barrier voltage
    - Over-focusing and defocusing due to the droop voltage
    - Chaotic diffusion caused by the discrete barrier voltages
    - beam loss due to adiabatic motion of barrier voltage-pulses

Next Generation of Switching Power Supply (MOPAN042)
Requirement of high intensity beam acceleration
- beam loading effects
  - low impedance acceleration cell at 1 MHz
  - high driving current keeping the same accelerating voltage
    -> large switching arm current
    -> novel solid-state switching elements, such as SIThy or SiC
from the Induction Synchrotron to All-ion Accelerators

from the experimental demonstration of induction acceleration in the KEK-PS

- Stable performance of the switching power supply from ~0Hz to 1MHz
- Master trigger signal for the switching P.S. can be generated from a circulating beam signal

Allow to accelerate even quite slow particles

Betatron motion doesn’t depend on ion mass and charge state, once the magnetic guide fields are fixed.

A single circular strong-focusing machine can accelerate from proton to uranium.

All-ion accelerators

almost injector-free for a low intensity beam

B. Material Science and selective breeding: Irradiation on bulk materials

- High-energy ions
- B-1 Implant
- B-2 Electro-excitation

C. Warm Dense Matter Science

- Bulk target or Plant seeds (mutation)
- Pb tamper
- Explore “Equation of State” inside Jupiter and Brown Dwarf
Outline of the KEK All-ion Accelerator

Combined function mag.

Induction acceleration cells

Irradiation area for material science

200kV Ion source

E. Nakamura et al., TUPAN046 in this PAC

Present KEK 500 MeV Booster

Beam lines

High vol. terminal
Summary

- A reliable full module for the induction accelerating system consisting of 50kW DC P.S., Pulse Modulator, Transmission Cable, Matching Resistance, Induction Cell, which is capable of operating at 1 MHz, has been confirmed to run over 100 hours without fatal troubles.
- The digital gate control system with a function of beam feed-back has been developed.
- A 400 nsec-long proton bunch captured in the barrier bucket was accelerated up to 6 GeV with the induction acceleration voltage.

This is a full demonstration of the Induction Synchrotron Concept.

- Novel beam handling (Qusi-adiabatic non-focusing TC method) in the hybrid synchrotron (functionally separated synchrotron) has been demonstrated.

One of possible and unique applications of IS in a low/medium energy region may be an All-ion Accelerator (AIA): the injector-free induction synchrotron.

- A modification plan of the KEK Booster Ring to the AIA was briefly introduced. Hopefully, available heavy ion beams will be provided for WDM Science, bulk material science, and cancer therapy.
Shimosaki’s idea:
Linear change in RF amplitude  $n=1$

\[
\begin{align*}
J_2\left(\frac{b}{2} \cdot t^2\right) &= \frac{2}{\sqrt{n} \pi b} \sin\left(\frac{b}{2} \cdot t^2\right), \\
N_2\left(\frac{b}{2} \cdot t^2\right) &= -J_{-2}\left(\frac{b}{2} \cdot t^2\right) = -\frac{2}{\sqrt{n} \pi b} \cos\left(\frac{b}{2} \cdot t^2\right)
\end{align*}
\]

Amplitude $C$ never changed.

(a) $\Delta t$ and (b) $\Delta E$ size depend on $n$. (c) Bunch length control by QNTC($n=1$). (sim)
Example of Ar\textsuperscript{+18} Acceleration Simulation

D. Iwashita, T. Dixit et al., Poster TUPAN044
Low energy injection and space-charge limited current

**Low energy injection -> low Space-charge limit -> restrict high intensity operation**

$v$: injection velocity into the all-ion accelerator

\[
\frac{1}{2} A \cdot m v^2 = e \cdot Z \cdot V
\]

\[
v = \sqrt{\frac{Z}{A}} \cdot \frac{2e}{m} \cdot V
\]

\[
\beta \propto \sqrt{\frac{Z}{A}} \cdot V
\]

**Laslett tune-shift:** \(\Delta Q\)

\[
0.25 \geq \Delta Q \propto \frac{Z^2 \cdot N}{A \cdot B_f \cdot \beta \cdot \gamma^2} \propto \frac{Z^2 \cdot N}{A} \sqrt{\frac{A}{Z \cdot V}} = N \cdot \sqrt{\frac{Z^3}{A \cdot V}}
\]

**Space-charge limit particle number:**

\[
N_i = \left( \frac{A}{Z^2} \right) \left( \frac{\beta_p \cdot \gamma_p^2}{\beta_f \cdot \gamma_f^2} \right) \left( \frac{B_f}{B_f}_{AIA} \right) = \sqrt{\frac{A}{Z^3}} \cdot \sqrt{\frac{V_i}{V_p}} \cdot \left( \frac{B_f}{B_f}_{AIA} \right)
\]

**Scaled from the data for Proton our experience:**

in the 500MeV Booster

\[
N_{limit} = 3 \times 10^{12} \text{ /bunch, } V_p = 40 \text{ MV}
\]

\[
B_f = 0.3, \ f = 20\text{Hz}
\]

**Other assumptions in AIA:**

same transverse emittance

\[
V_i = 200 \text{ kV}
\]

\[
B_f = 0.7, \ f = 10\text{Hz}
\]

We will try at first.

<table>
<thead>
<tr>
<th>(12^\text{C}+6)</th>
<th>(40^{\text{Ar}}+18)</th>
<th>(197^{\text{Au}}+79)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/Z</td>
<td>12/6</td>
<td>40/18</td>
</tr>
<tr>
<td>(N_{limit}(=N_p))</td>
<td>1.3x10^{11}</td>
<td>4.7x10^{10}</td>
</tr>
<tr>
<td>N/sec</td>
<td>1.3x10^{12}</td>
<td>4.7x10^{11}</td>
</tr>
<tr>
<td>extract. E (MeV/au)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>depo.energy (J/cc)</td>
<td></td>
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</tr>
</tbody>
</table>
Beam-line for the WDM Science

a. Transverse dir. (half-mini beta)

\[ K \text{-value} = k_0^2 \]

RF or Induction cells

Calculation by Kikuchi (Utsunomiya U.)

b. Compression in the longitudinal direction (Phase-rotation)

F D

K-value=k_0^2

Calculation by Kikuchi (Utsunomiya U.)

Beam line for Bulk Materials

Wobbler mags.

31 m

Modification region with beam dump

T.Kikuchi et al., Poster TUPAN066

Δp/p

100 nsec