Present Achievements of Induction Synchrotron and its Possibility for Super-Bunch

Yoshimoto, Takashi (KEK)

14 November 2016
Present achievements of induction synchrotron and its possibility for super-bunch acceleration

2014/11/14

Takashi Yoshimoto**

**KEK digital accelerator group/Tokyo institute of technology
Contents

◆ What is induction synchrotron?
◆ System of KEK digital accelerator
◆ Three induction acceleration technique
  • wide-band acceleration
  • novel beam handling
  • (super-bunch acceleration)
◆ Upgrade plan for super-bunch acceleration
◆ Problem of super-bunch acceleration in high intensity synchrotron
◆ Conclusion
What is Induction synchrotron?

KEK digital accelerator (Wide-band fast cycling induction synchrotron)\(^1\)

**Induction cells, not RF cavities!!**

200 keV beam is directly injected.

<table>
<thead>
<tr>
<th>Circumference</th>
<th>(C_0)</th>
<th>37.7 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep-rate</td>
<td>(f)</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Injec. Energy</td>
<td>(E_{inj})</td>
<td>200 keV</td>
</tr>
</tbody>
</table>

Three distinguished features of Induction synchrotron

Super-bunch acceleration\(^1\)

Wide-band acceleration\(^2\)

- **Advantages**
  - Rev. frequency: 0 ~ a few MHz
  - So many ion species can be provided in a broad energy range.

- **Disadvantages**
  - Space charge limit & residual gas interactions in low energy region
  - In small ring (~100 m), max. rev. frequency is limited by semiconductor switching of acc. volt.

RF acceleration & Induction synchrotron

**Conventional RF acceleration**

- Voltage
- Beam
- Time

Confinement & Acceleration function are combined.

**Induction acceleration**

- Voltage
- Beam
- Time

Hamiltonian contour plot

\[
\begin{array}{|c|c|c|}
\hline
\text{Phase} & \text{dp/p} \\
\hline
-0.02 & 0.00 \\
-0.01 & 0.01 \\
0.00 & 0.02 \\
0.01 & 0.01 \\
0.02 & 0.00 \\
\hline
\end{array}
\]
Conventional RF acceleration & Induction acceleration synchrotron

Confinement & Acceleration function are combined.

Separate function can creates a longer bucket ⇒ Diminishing space charge effect.
Switching Power Supply for Induction cells

One arm consists of 7-series MOSFETs.

Waveform generated by switching power supply (2.5kV, 20A, 1MHz)

Next generation of SPS: K.Okamura, et al., MOPME068 in IPAC’14
“SiC-JFET Switching Power Supply toward for Induction Ring Accelerators”
Fully programmed control of KEK digital accelerator

In advance, all information for acceleration timings is load to FPGA. Virtual $B(t)$ decides ideal revolution period and acc. timings.

Virtual $B_{control}(t) \rightarrow$ PC $\rightarrow$ FPGA

Input data (Revolution period, Acc. timings)

Switching power supply

Start trigger

Beam

Ion source

DC (V)

Induction cells (1 to 1 pulse transformer)

Bending magnet

Magnetic core

Virtual $B(t)$

How to generate confinement voltages

Reference signals: 12 μs → 1 μs (which generate every ideal rev. period of beam)

\[ T(t) = \frac{C_0}{c} \sqrt{1 + \frac{D}{D}} \]

\[ D = \left( \frac{Q}{A} \right) \left( \frac{e\rho}{m_0 c} \right)^2 B^2 \]

Here,
- ratio of charge to mass: \( Q/A \)
- charge element: \( e \)
- bending radius: \( r \)
- unit mass: \( m_0 \)
- ideal magnetic field: \( B(t) \)

Conf. voltages are generated every turn.
How to generate acceleration voltage

Reference signals (signals of ideal rev. period) :12 μs→1 μs

Required acc. voltage per turn $V(t)$:

$$V(t) = \rho C_0 \frac{dB(t)}{dt}$$

$\rho$ : bending radius
$C_0$ : circumference
$B(t)$: ideal magnetic field

Induction acc. voltages are generated discretely in order to give required acc. voltage spuriously.

Pulse density control
Result of beam acceleration

**Experimental conditions:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending magnetic flux density</td>
<td>0.039 → 0.51 [T]</td>
</tr>
<tr>
<td>Mass to charge ratio A/Q</td>
<td>4/1</td>
</tr>
<tr>
<td>Energy</td>
<td>0.05 → 8 [MeV/u]</td>
</tr>
<tr>
<td>Injection current</td>
<td>~100 μA</td>
</tr>
</tbody>
</table>

Wide-band acceleration (experiment)

Rev. period: 12 μs → 1 μs!!

Beam waveform (experiment)

Beam signal

Acceleration voltage $V_{acc}$ (±1.6 kV, experiment)

Cofinlement voltage $V_{bb}$ (±2 kV, experiment)

Beam bucket: 2 μs → 200 ns
Beam survival & discussion

Beam survival: ~ 10%

Reasons

- **Vacuum** (~ $10^{-6}$ Pa)
  
  Strong interaction with residual gas in low energy (200 keV ~)

- **Non-zero dispersion optics** (D = 1.4 m at Induction cell region)
  
  Unfortunately, present optics was designed for the PS booster ring 40 years ago.

- **Discrete acceleration**
  
  In our case, acc. voltages are constant because of DC power supply. Therefore we do not generate acc. voltage every turn.

*Solution:*

Time varying DC power supply to meet required voltage demand may be ideal, especially for super-bunch acceleration.
Development of FPGA code for novel beam handling

This FPGA code can generate arbitral pulse timings at each cell (Max.5) in each turn (Max.5000). Therefore everyone can program each arbitral pulse easily and flexibly.
Comparison of IS and RF beam handling

IS and RF beam handleings are qualitatively different.

1. It is easy to decide each beam length and quantity.
2. Timing control of acc. voltages is so simple.

The beam motion of the experiment is reproduced in the simulation macroscopically. Therefore it is easy to design the beam length and quantity.
How to realize super-bunch acceleration in the KEK digital accelerator?

1. Asymmetric pulse for super bunch acceleration

2. Time varying DC power supply

Discrete acceleration

Continuous acceleration at every turn
1. Asymmetric pulse for super bunch acceleration

Different voltages are applied to positive and negative pulses.
1. Asymmetric pulse (Result in low voltage experiment)

Asymmetric pulses can be generated with bridge circuits easily.
DCDC converter technique in itself is well used in industry.

- msec-control is not so difficult.
- Output voltage should be the same as the actual needed acceleration voltage.
- Super bunch acceleration is needed at injection because of space charge limit.
- Maximum voltage should be reduced because of difficulty of high-voltage and MHz switching.
Can super-bunch acceleration be applied to high-intensity machine such as RCS(300m~) @ J-PARC?

1. Difference of RF (MA cavity) and Induction cells
2. High acceleration voltage
3. Beam loading effect
What is the difference between MA cavity and Induction cell?

MA cavity @ JPARC-RCS

![Diagram of MA cavity]

Figure 1: The MA cavity for the RCS.

Induction cell @ KEK digital accelerator

![Diagram of Induction cell]

Fig. 5: $Q_x=2$ at 1.7MHz with parallel inductor

MA cavity with low $Q$ is the same of induction cavity.
Demand of acceleration voltage height

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RCS</th>
<th>MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [m]</td>
<td>348.3</td>
<td>1567.5</td>
</tr>
<tr>
<td>Bending radius [m]</td>
<td>11.65</td>
<td>89.381</td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>0.181–3</td>
<td>3–30</td>
</tr>
<tr>
<td>Max voltage [kV]</td>
<td>450 (400)</td>
<td>280 (160)</td>
</tr>
<tr>
<td>Period [s]</td>
<td>40 ×10^{-3}</td>
<td>3.52</td>
</tr>
<tr>
<td>No. of cavities</td>
<td>12 (11)</td>
<td>7+3 (5+0)</td>
</tr>
<tr>
<td>Q-value of cavity</td>
<td>2</td>
<td>26</td>
</tr>
</tbody>
</table>

\[400 \text{kV} \times \sin\left(\frac{\pi}{2}\right) = 280 \text{kV}\]

Needed acc. voltage: 280 kV (Max.)
Therefore,
Max. V = 280 kV/10 cavity(9)/3 gaps = 9.3(10.4) kV

Series is difficult !!
Parallel is easy !!

In many series of MOSFET switch, each voltage are imbalance.

Pulse transformer
(Primary :5kA, 33kV
Turn ratio:1:14)

M. Akemoto et al, "PULSE TRANSFORMER R&D FOR NLC KLYSTRON PULSE MODULATOR", SLAC–PUB–7583
Beam loading problem

- Beam distribution and acceleration waveform are interacted with each other.
- The inequality in area of positive and negative pulse generates inductance saturation.
- Low impedance system reduce beam loading effect but increase electric power loss.
Conclusion

• We demonstrated Wide-band acceleration and Novel beam handling.

• Asymmetric pulse generation and time varying DC power supply are concretely designed for super-bunch acceleration scheme.

• Problems in high-intensity super-bunch acceleration are clarified. Especially, beam loading effect is key problem.
Thank you for attention !!