Development of Superbunch Acceleration and its application to FNAL/LHC

Makoto Sakuda (KEK)
18 March 2003 @ Physics at HEP Frontiers

Outline
1. Introduction
2. Principle of Induction Synchrotron (SuperBunch)
3. R&D status and Milestone
4. Application to FNAL
5. Summary
1. Introduction

Superbunch Acceleration was proposed by Takayama in 1999 to increase the KEK-PS intensity by a factor 2 (“Intensity Doubler”) mainly for K2K neutrino oscillation experiment (PAC2001). R&D work of Superbunch Acceleration has continued through support from Grant-In-Aid and KEK Accelerator Laboratory.

Fortunately to all of us, JHF (J-PARC) project was approved in 2000, with the designed intensity being 50-100 times more than KEK-PS. The construction of JHF began in 2001. It is natural that such a proposal is forgotten.

Takayama et al. PRL88,144801,2002 showed realistic application of this scheme to Hadron Colliders and any existing hadron facility (Snowmass01). Sometimes, intensity increase by a factor 3-4 makes a big difference.
RPIA2002 Workshop  
(Recent Progress in Induction Accelerator, KEK, October 2002)  

→ CERN Courier, April 2003.

Snowmass2001 & RPIA2002:  
Idea and theory/simulation are ok. It need verification.
Upgrade of Proton Driver is the key in future HEP. See talks at US HEP Facility Committee Meeting (Pittsburg, Feb. 2003)

Upgrade of BNL/FNAL (x5-10) for future neutrino physics was one of the main discussions.

R&D: 3 years
Construction: 5 years
Budget: 200M-400M US$
## Current and Future Design Parameters of Proton Source

<table>
<thead>
<tr>
<th>Vital Statistic</th>
<th>NOW</th>
<th>Synchrotron</th>
<th>SC LINAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Energy (MeV)</td>
<td>400</td>
<td>600</td>
<td>2.5</td>
</tr>
<tr>
<td>Final Energy (GeV)</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Active length (m)</td>
<td>475</td>
<td>474</td>
<td>671</td>
</tr>
<tr>
<td>Rep Rate (Hz)</td>
<td>15</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Pulse Length (sec)</td>
<td>25</td>
<td>90</td>
<td>1000</td>
</tr>
<tr>
<td>per Pulse (sec)</td>
<td>0.5</td>
<td>2.5</td>
<td>15</td>
</tr>
<tr>
<td>Beam Power (MW)</td>
<td>0.05</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>MI Cycle (sec)</td>
<td>1.89</td>
<td>1.5</td>
<td>1.17</td>
</tr>
</tbody>
</table>

### Main Injector Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Present</th>
<th>Upgraded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Kinetic Energy (GeV)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Extraction Kinetic Energy (GeV)</td>
<td>120</td>
<td>8-120</td>
</tr>
<tr>
<td>Protons per cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protons per year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle Time at 120GeV (s)</td>
<td>1.867</td>
<td>1.533</td>
</tr>
<tr>
<td>Average beam current (sec)</td>
<td>2.6</td>
<td>16</td>
</tr>
<tr>
<td>Beam Power (MW)</td>
<td>0.3</td>
<td>2</td>
</tr>
</tbody>
</table>

2. Principle of Superbunch Acceleration (Induction Synchrotron)

- SuperBunch Acceleration or Induction Synchrotron is a new concept in the synchrotron. While it keeps the same momentum spread and the local intensity of the beam, it fills the beam longitudinally and makes a long bunch. It can co-exist with RF acceleration scheme and increase the intensity without re-building a new ring or LINAC.

Conventional Synchrotron – RF cavity, combined function
Induction Synchrotron – Induction Cell, Separated function

- Induction Acceleration is not new and the application already exists in LINAC. What is new is the application to the synchrotron. This idea has become possible due to the development of a fast and high power switching device and new Ferite (FineMet) in the industry.
## Concept of Induction Synchrotron

**Principle**

<table>
<thead>
<tr>
<th>RF Synchrotron</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Voltage</td>
</tr>
<tr>
<td>Proton bunch</td>
</tr>
<tr>
<td>Voltage with Gradient</td>
</tr>
<tr>
<td>Combined function: Accel.+Confinement</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Induction Synchrotron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Voltage</td>
</tr>
<tr>
<td>Acceleration</td>
</tr>
<tr>
<td>(Separated function)</td>
</tr>
</tbody>
</table>

**Ring Image**

- **Acceleration Gap for Confinement**
- **Acceleration Gap for Accelerating**

- Super-bunch
- Vbb(t)
- Vac(t)

**Modulator Circuit**

- Excite
- Reset
- 4 FETs SW1
- 4 FETs SW2
- 4 FETs SW3
- 4 FETs SW4
- Core loss
- Beam

### References

Difference between RF-synchrotron and Induction Synchrotron seen in the Phase-space

- Confined and accelerated beam bunch
- RF-bunch
- Super-bunch
- Maximum energy spread
Principle of Induction Acceleration

Faraday’s Law

\[ \oint E \cdot dS = - \oint \frac{dB}{dt} \cdot dS \]
3. Status of R&D: Accelerating device

**Actual load test**
- Rep. rate: 200 kHz
- Output voltage: 3 kV
- Switching element: SIThyristor

**Magnetic materials**
- Magnetic core stack
- Coaxial cable
- DC P.S.
- Power modulator
- Induction cell
- Magnetic material (nanocrystalline)
- Radiator panel

**Output voltage**

![Graph of induced voltage with time](image)
Status of R&D: 450 ohm load test

- Rep. rate: 1 MHz (CW)
- Output voltage: 1.5 kV

- Rep. rate: 1 MHz (burst)
- Output voltage: 2.2 kV

Switching element: MOSFET

Switching board
Milestone of SuperBunch R&D

**Step 1 (JFY2003)**
Acceleration: Induction (500MeV -> 12GeV)
Confinement: RF

**Step 2 (JFY2004)**
Super-bunch generation at 500MeV

diffusion in the phase space

**Step 3 (JFY2005-2007)**
Acceleration: Induction (500MeV -> 12GeV)
Stacking/confinement: Induction

Cost: 4.5M US$ or 500M Yen
Creative Basic Research nominated

NB. KEK-PS may shut down in 2005.
4. Application of Superbunch Scheme to FNAL

Takayama @Snowmass2001

Proton Beam Formation in the Collider Operation Mode

Boosters

<table>
<thead>
<tr>
<th>Booster</th>
<th>Main Injector</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h=588(53MHz)</td>
<td>h=1113(53MHz)</td>
</tr>
</tbody>
</table>

**RF-bunch scheme**

**Super-bunch scheme**

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>h=28 (2.5MHz)</th>
</tr>
</thead>
</table>

**Road map**

<table>
<thead>
<tr>
<th></th>
<th>‘03</th>
<th>‘04</th>
<th>‘05</th>
<th>‘06</th>
<th>‘07</th>
<th>‘08</th>
<th>beyond</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK</td>
<td>1st</td>
<td>2nd</td>
<td>3rd</td>
<td></td>
<td></td>
<td></td>
<td>LHC upgrade/ VLHC</td>
</tr>
<tr>
<td>FNAL</td>
<td>Assemble</td>
<td>Install test in Main Injector</td>
<td>Tevatron Run</td>
<td></td>
<td></td>
<td></td>
<td>VLHC</td>
</tr>
</tbody>
</table>

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If Design Value of Superbunch Scheme is Plotted, … (↑)

Note that the event rate is the same. You fill the beam uniformly.

If it is successfully introduced at Tevatron, the intensity increase of a factor 3-4 may be possible in 2007-2008. It will enlarge Higgs discovery limit. $3\sigma \rightarrow 5\sigma$
Higgs Search at Tevatron and LHC

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Proton Beam for MINOS Experiment

**RF-bunch scheme**

1. **Booster (400MeV → 8GeV)**
   - $N_B = 6 \times 10^{10}$/bunch
   - $N_{BR} = 82 \times N_B = 5 \times 10^{12}$/cycle
   - $h = 84$
   - 1 cycle = 1.9 sec

2. **Main Injector (8GeV → 120GeV)**
   - $N_M = 6 \times N_{BR} = 3 \times 10^{13}$/cycle
   - $h = 588$

**Superbunch scheme**

1. **Booster ($C_0 = 474.2$ m, $f = 15$ Hz)**
   - Injection ($400$ MeV)
   - $V_{acc} = 400$ kV
   - $t = 632$ kHz
   - $N_{sb} = 10^{13}$

2. **Main Injector ($C_0 = 3.32$ km, $\tau = 11$ $\mu$sec)**
   - Injection ($8$ GeV)
   - $V_{acc} = 750$ kV
   - $t = 545$ kHz
   - $N_{sb} = 1.2 \times 10^{14}$
5. Summary

1. The proof-of-principle experiment of Superbunch Acceleration which is planned at KEK-PS this year will be most important. A basic unit IC and a modulator have already been tested.

2. Then, the application of this scheme to Tevatron in 2007-2008 would be realistic and is most attractive. Event rate is unchanged if the beam is filled uniformly over one long bunch. It will enlarge the discovery limit of Higgs particles. LHC has already considered this option (Ruggiero et al. @ RPI A02) even though LHC likes more energy, not more intensity.

3. Application of this method to other hadron facilities will have a big effect on future neutrino experiments. This scheme can co-exist with RF acceleration scheme. It does not need to build a new proton driver to upgrade the intensity, but to add induction cells to accommodate this scheme.
K. Takayama, J. Kishiro, M. Sakuda, Y. Shimosaki, M. Wake

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# Plan of Superbunch Acceleration R&D

<table>
<thead>
<tr>
<th></th>
<th>‘03</th>
<th>‘04</th>
<th>‘05</th>
<th>‘06</th>
<th>‘07</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B</strong></td>
<td>Super-bunch Acceleration test</td>
<td>Step 1 First acceleration experiment V_{acc}=10kV/turn</td>
<td>Step 2 Pseud super-bunch handling test V_{acc}=25kV/turn</td>
<td>Step 3 Super-bunch acceleration test V_{acc}=22.5kV V_{conf}=55kV</td>
<td></td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>Super-bunch beam Physics</td>
<td>Coherent instability Strong-strong Beam-beam effects</td>
<td>Beam-halo formation</td>
<td>Lattice design for inclined crossing</td>
<td></td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>Detector for SHC</td>
<td>Assesments of required detector for SHC</td>
<td>R&amp;D works</td>
<td></td>
<td></td>
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<tr>
<td><strong>others</strong></td>
<td></td>
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</table>
Beam physics issues in the SHC

- e-p Instability (at CERN)
- Intrabeam Scattering (at KEK/CERN)
- Beam-halo formation (at KEK/CERN)
- Parasitic beam-beam effects

Luminosity & Crossing Scheme

A. Hybrid crossing to avoid the serious Beam-beam effects

B. More advanced crossing scheme: Inclined crossing

Design Value of LHC

Φ(μrad)
Proton Driver Plan
W. Chou (PAC2001)