FFAG Accelerators

Experimental Results

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Y. Mori (Kyoto Univ.)
Operational FFAGs

- **PoP FFAG (KEK):** world first proton FFAG
  scaling, radial sector (DFD), $E=0.5(1)\text{MeV}$, comm’d 2000

- **150 MeV FFAG (KEK)**
  scaling, radial sector (DFD), $E=100(150)\text{MeV}$, 2003

- **Injector of KURRI FFAG chains**
  scaling, spiral sector, $E=2.5\text{MeV}$, 2006, Jan. 1st.
PoP-FFAG

PoP-FFAG parameter table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>proton</td>
</tr>
<tr>
<td>Type of magnet</td>
<td>radial sector type</td>
</tr>
<tr>
<td>No.of sector</td>
<td>8</td>
</tr>
<tr>
<td>Field index</td>
<td>k=2.5</td>
</tr>
<tr>
<td>Energy</td>
<td>50keV =&gt; 500keV</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>1kHz</td>
</tr>
<tr>
<td>Magnetic field</td>
<td></td>
</tr>
<tr>
<td>Focus-mag.</td>
<td>0.14 - 0.32 T</td>
</tr>
<tr>
<td>Defocus-mag.</td>
<td>0.04 - 0.13 T</td>
</tr>
<tr>
<td>Radial of closed orbit</td>
<td>0.81 - 1.14m</td>
</tr>
<tr>
<td>betatron tune</td>
<td></td>
</tr>
<tr>
<td>horizontal</td>
<td>2.17 - 2.22</td>
</tr>
<tr>
<td>vertical</td>
<td>1.24 - 1.26</td>
</tr>
<tr>
<td>RF frequency</td>
<td>0.61 - 1.38MHz</td>
</tr>
<tr>
<td>RF voltage</td>
<td>1.3 - 3.0kVp</td>
</tr>
</tbody>
</table>
World First Proton FFAG Accelerator

- PoP(proof-of-principle) FFAG : KEK 2000
Fundamental Parameters as experimental evidences

• Transverse
  chromaticity: $Q_x$ ($Q_z$) vs. energy
  tunability: $Q_x$, $Q_z$ vs. F/D ratio

• Longitudinal
  synchrotron osc.: $fs$ vs. energy

• Closed orbit change
Field Optimization

Scaling

\[ B \propto r^k \]
including length

\[ Bl \propto r^{k+1} \]
Tune Measurement

- RF knock-out

\[ pQ_h + qQ_v = \pm m \pm \frac{f_{rf}}{f_{rev}} \]
Betatron Tunes
-design vs. measurement-

agreement: so good!
Betatron Tunes for various F/D ratio at injection energy of PoP FFAG

@ Injection Energy

![Graph showing energy of PoP FFAG](attachment:graph.png)

- measurement
- smooth approximation
- linear approximation:
  - with constant k
  - with effective k
- tracking-simulation:
  - with hard edge
  - with tosca
Synchrotron Frequency

![Graph showing synchrotron frequency vs. E_kin (keV)]
Closed Orbit Change

energy gain/turn=const.

\[ \frac{dr}{dt} = \text{const.} \]
Beam Intensity

- **Injected beam**
  
  \[ I_p = 0.5 \text{mA}, \quad \Delta T = 3 \mu \text{sec} \text{ (4-turn injection)} \]

  \[ N_p = I_p \times \Delta T / e = 1 \times 10^{10} \text{ppp} \]

- **Accelerated Beam ; \( N_p \sim 2-3 \times 10^9 \text{ppp} \)**

  No adiabatic capture process

  Neutralization \((H^+ \rightarrow H^0)\) at injection energy

  Looks no beam loss after rf capture.
150-MeV FFAG

• Unexpected difficulties
• Lower Injection beam energy - reduced field
- Operating tunes are drastic changed.

Need field correctors to avoid dangerous resonances

• Large magnetic field at straight section.
- Large COD by magnetic devices (rf cavity, kicker etc.)
  which break periodicity and excite unwilling non-structure resonances.

Need non-ferromagnetic kicer, bumper and COD corrector for rf cavity.
- Shunt impedance drop of rf cavity.

Need large rf power and cooling for cavity
150-MeV FFAG beam intensity

- **Injected beam**
  - Energy: 10 MeV (not 12 MeV)
  - Repetition rate: 100Hz
  - Intensity: \( I_p = 10 \mu A \) at injection septum
  - Turn number: 3\( \Delta T = 2.5 \mu \text{sec} \)
  - \( N_p = 1.6 \times 10^8 \text{ppp}, \ I_p = 2.5 \text{nA} \)

- **Extraced beam after acceleration**
  - Energy: 100MeV
  - Intensity: \( I_p = 1.5 \text{nA after beam extraction} \), Efficiency: \( \sim 60\% \)
  - Adiabatic capture effective but not perfect.
  - Looks small beam loss after rf capture.
FFAGs for ADS project

Kyoto University Research Reactor Institute (KURRI)
## Parameters of the Accelerator Complex

<table>
<thead>
<tr>
<th></th>
<th>Injector</th>
<th>Booster</th>
<th>Main ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Einj</td>
<td>100keV</td>
<td>2.5MeV</td>
<td>20MeV</td>
</tr>
<tr>
<td>Eext</td>
<td>2.5MeV</td>
<td>20MeV</td>
<td>150MeV</td>
</tr>
<tr>
<td>Lattice type</td>
<td>Spiral</td>
<td>Radial</td>
<td>Radial</td>
</tr>
<tr>
<td>Acc. scheme</td>
<td>Induction</td>
<td>rf</td>
<td>rf</td>
</tr>
<tr>
<td># of cells</td>
<td>8</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>k value</td>
<td>0-2.5</td>
<td>4.5</td>
<td>7.6</td>
</tr>
<tr>
<td>coil/pole</td>
<td>coil</td>
<td>coil</td>
<td>pole</td>
</tr>
<tr>
<td>Pext/Pinj</td>
<td>5.00</td>
<td>2.84</td>
<td>2.83</td>
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<tr>
<td>Rinj</td>
<td>0.60m</td>
<td>1.42m</td>
<td>4.54m</td>
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<tr>
<td>Rext</td>
<td>0.99m</td>
<td>1.71m</td>
<td>5.12m</td>
</tr>
</tbody>
</table>
Injector - spiral

- Features
  - Spiral sector  8-fold symmetry
  - Field index changeable  k=0 - 2.5
  - Energy variable  E=0.25 -2.5 MeV

- Commissioning was successfully completed. Jan. 17, 2006.
スパイラル磁石形状（モデル1:48分割）
FFAGイオンベータからビーム出射に成功

2005年6月14日（月）16時00分
入射エネルギー100keV、加速エネルギー250keV、加速ビーム電流0.25mA、出射ビーム電流0.12mA

加速電圧: 入射時(7μs) 2.6kV、加速時(120μs) 0.9kV、出射時(7μs) 2.6kV
Extracted beam from injector (ion-beta), Jan. 15th, 2006
イオンβ（トリムなし）コミッションングの軌道解析

三菱電機・先端総研・田中
2005-3-26

①100keV入射で
250keV程度までビーム加速可能

②165keVで水平方向
線形共鳴を通過する