Joe Nakano
- KEK FFAG group -

FFAGの開発とその応用について

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『中間エネルギービームによる物理』＠ RCNP
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  – The first proton FFAG Accelerator

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• PRISM
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• Summary
The characteristics of FFAG …

- **Fixed Field** (cf. Cyclotron)
  
  \[ B = B_0 \left( \frac{r_0}{r} \right)^k \quad k > 1 \]
  
  *Satisfying the cardinal condition, “zero-chromaticity”*

  - High repetition rate
  - Various acceleration patterns are possible
    
    *large beam current, flexibility, low power consumption*

- **Alternating Gradient Accelerator** (cf. Synchrotron)
  
  *strong focusing*

- **Large Horizontal acceptance**
  
  *wide aperture*

... Strong focusing accelerator

  *with high duty factor*
Introduction - Applications of FFAG

**FFAG’s catchphrase…**

*“High current, High repetition rate and High efficiency”*

- **Medical** - Cancer therapy
  - 3dimensional spot scan method
- **Atomic Energy** - Accelerator Driven System
  - High current and efficiency beam, low power consumption and low beam loss
- **Physics** – Accumulator of secondary beam
  - Manipulation of the short-lived secondary beam
    - ex.) PRISM, Neutrino-Factory and Unstable Nuclei
- **Environmental Hygienics** – Sterilizer
  - Electron beam or X-ray source for the sanitizing and the sterilizing.

..., etc.
A brief history of FFAG Accelerator - ‘PoP FFAG’

~50’s  FFAG was proposed by Ohkawa, Symon and Kolomensky.
    a electron FFAG at MURA project.
    “Proton FFAG was difficult.”
    • Difficulties of designing and manufacturing the large magnet gives
      the complex magnetic field
    • No RF cavity has the large aperture and gives the high gradient
      field over a wide-frequency

… Great advancement of technologies in 80’s ~ 90’s
    • large CPU power to do the calculation and the simulation easily
    • the invention of a Magnetic Alloy for FFAG RF cavity

1998    PoP (proof of principle) FFAG project, to construct the
        world first proton FFAG, was started.
PoP FFAG - *The first proton FFAG Accelerator in the world*

1. Basic performance
2. Studies of beam dynamics
   - Acceptance survey
   - Measurement of betatron tune with RF knockout
   - A study of resonance crossing with fast acceleration
PoP FFAG

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Top View of PoP-FFAG Accelerator

PoP-FFAG parameter table

- **Particle**: proton
- **Type of magnet**: radial sector type
- **No. of sector**: 8
- **Field index**: $k=2.5$
- **Energy**: 50keV => 500keV
- **Repetition rate**: 1kHz
- **Magnetic field**:
  - Focus-mag.: 0.14 - 0.32 T
  - Defocus-mag.: 0.04 - 0.13 T
  - Radial of closed orbit: 0.81 - 1.14m
- **Betatron tune**:
  - horizontal: 2.17 - 2.22
  - vertical: 1.24 - 1.26
- **RF frequency**: 0.61 - 1.38MHz
- **RF voltage**: 1.3 - 3.0kVp
Beam Position Monitor (BPM)

In FFAG, beam orbit shifts during the acceleration. => BPM must have large horizontal aperture.
Basic Performance of PoP FFAG

- Betatron tune
- Fast acceleration within 1msec
- Synchrotron oscillation
- Multi turn Injection
Betatron Tune (1)

PoP FFAG

Horizontal beam signal

Vertical beam signal

fractional part of betatron tune

\[ \mu_h = 0.199 \]

\[ \mu_v = 0.289 \]
Betatron Tune (2)

PoP FFAG

betatron tune vs F/D ratio

The vertical betatron tune is adjustable changing F/D ratio!

Betatron tune shift as a function of F/D ratio:

- vertical
  => shift !!

- horizontal
  => almost constant !!
Beam Acceleration

The beam is accelerated from 50keV to 500keV within 1msec.

=> The beam orbit shifts from 765mm to 1050mm.
The observed synchrotron frequency agreed with those expected by the beam simulation.
RF pattern

<table>
<thead>
<tr>
<th>magnetic field</th>
<th>RF pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>ordinary synchrotron</td>
<td>changing with regarding the magnet</td>
</tr>
<tr>
<td>FFAG synchrotron</td>
<td>constant without regarding the magnet</td>
</tr>
</tbody>
</table>

=> RF pattern can be flexibly designed in FFAG synchrotron!

\[
V_{rf} = \text{const.}, \quad \dot{q}_s = \text{const.}
\]

\[
\frac{dr}{dt} = \text{const.}, \quad \dot{q}_s = \text{const.}
\]

The various acceleration pattern is possible in PoP-FFAG.
The slow decay operation makes the multi-turn injection in possible.
Multi-turn Injection

The beam intensity can be increased with multi-turn injection.
The Studies of the beam dynamics in the PoP-FFAG.

Large horizontal acceptance
Measurement of betatron tune with RF knockout
A study of resonance crossing with fast acceleration
Horizontal Acceptance

PoP FFAG

horizontal acceptance @ injection energy

from tracking simulation

FFAG synchrotron has a large horizontal acceptance.
At the fast decay operation, the bump works as a fast kicker.

The fast decay time of bump voltage (decay time ~ revolution period) works as a fast kicker.

2.5 µsec/Div

bunched beam

bump
Horizontal acceptance survey (1)

PoP FFAG
The beam oscillations with various betatron motion

(a) Vbump=3kV
(b) Vbump=6kV
(c) Vbump=9kV
(d) Vbump=12kV
(e) Vbump=15kV

(at the 2kV no signal !!)

(at the 3kV the maximum amplitude)

(at the 12kV the optimum)

(obtained with BPM)
**Horizontal acceptance survey (2)**

PoP FFAG

**Horizontal acceptance is about 4000L mm.mrad !**
(The limit can be explained by the septum electrode.)
RF Knockout Resonance & Betatron tune

RF knockout resonance:

\[ p\xi_h + q\xi_V = \pm m \pm \frac{f_{RF}}{f_{rev}} \]

(\( p, q, m = \text{integer} \))

250keV flat top

250keV flat top after RF knockout

circulating beam signal
 revolution freq.
 side-bands
 for synchrotron

FFT spectrum

circulating beam signal
 revolution freq.
 side-bands
 for synchrotron
 side-bands
 for betatron

fractional part of betatron tune

\[ \xi_h = 0.195 \quad (0.199@E_{\text{inj}}) \]
Resonance & Fast Acceleration (1)

In FFAG synchrotron....... the fast acceleration => the beam can be accelerated even if the betatron tune crosses the resonance line during the acceleration!

In PoP-FFAG

Pole

\[
\frac{\partial \varphi}{\partial r} = 0, \quad \text{resonance crossing}
\]

radius

fractional part of tune

\[\varphi = \text{const.} \quad \xi = \text{const.}\]

\[50\text{keV} \quad 500\text{keV}\]

\[710\text{keV} \Rightarrow 630\text{keV} \Rightarrow \text{wall}\]

second accelerating start time

\[0 \quad 1 \quad 2 \quad \text{[msec]}\]

\[1 \quad 1.2 \quad 1.4 \quad \text{[MHz]}\]

\[0 \quad 1 \quad 2 \quad \text{[msec]}\]

\[1 \quad 1.2 \quad 1.4 \quad \text{[MHz]}\]

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\[1 \quad 1.2 \quad 1.4 \quad \text{[MHz]}\]

\[0 \quad 1 \quad 2 \quad \text{[msec]}\]
the beam was accelerated from 650keV to 710keV in various accelerating speed!

- $q_s = 20$ Deg
- $q_s = 10$ Deg
- $q_s = 4$ Deg
- $q_s = 2$ Deg

accelerating speed:
slow => doesn’t cross the resonance line
fast => can cross the resonance line
Resonance & Fast Acceleration (3)

- @700keV
- @705keV
- @708keV
- @710keV

Accelerated up to around the resonance!
Summary

PoP FFAG

*the measurements of the machine parameters:

- The PoP-FFAG works as designed.
- The proton can be accelerated within 1msec.
- It was ascertained that
  
  tune is adjustable as a function of F/D ratio,
  
  various acceleration pattern is possible,
  
  and the beam intensity increased with multi-turn injection.

*the studies of the beam dynamics:

- Horizontal acceptance at injection energy is at least 4000L mm-mrad.
- Betatron tunes almost didn’t change between 50keV and 250keV.
- The beam was accelerated even if the betatron tune crosses the resonance.