R&D Activities on FFAG Accelerator

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Kyoto University
(KEK)
FFAG R&D Activities in Japan

On-going project
- 150-MeV proton FFAG R&D : KEK
  - Prototype for various applications
- FFAG for ADS : Kyoto Univ.
  - FFAG + Sub Critical Reactor
- Muon phase rotation  PRISM : Osaka Univ.
  - Muon Rare Decay (Mu-e conversion)

Future project
- Hadron therapy @ Ibaraki Prefecture
- Electron source for sterilization
- Neutron source for BNCT
- Neutrino factory (muon accelerator )
FFAG project

Mori moved from KEK to Kyoto University

- Kyoto University Research Reactor Institute
- ADS, Neutron Source, Particle Therapy

KEK : FFAG project office (officially organized)

- Particle Therapy, Muon
**150MeV Proton FFAG**

![Diagram of 150MeV Proton FFAG](image)

**Design parameter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet</td>
<td>radial sector type</td>
</tr>
<tr>
<td></td>
<td>(DFD triplet)</td>
</tr>
<tr>
<td>Num. of cell</td>
<td>12</td>
</tr>
<tr>
<td>k-value</td>
<td>7.6</td>
</tr>
<tr>
<td>$E_k$</td>
<td>$12 \Rightarrow 150\text{MeV}$ (10 $\Rightarrow 125\text{MeV}$)</td>
</tr>
<tr>
<td>Av. radius</td>
<td>$4.47 \Rightarrow 5.20\text{m}$</td>
</tr>
<tr>
<td>betatron tune</td>
<td>hor. : $3.69 \sim 3.80$</td>
</tr>
<tr>
<td></td>
<td>ver. : $1.14 \sim 1.30$</td>
</tr>
<tr>
<td>Peak Field</td>
<td>F-mag. : $1.63\text{T}$</td>
</tr>
<tr>
<td></td>
<td>D-mag. : $0.78\text{T}$</td>
</tr>
<tr>
<td>revolution</td>
<td>$1.55 \sim 4.56\text{MHz}$</td>
</tr>
<tr>
<td>repetition</td>
<td>250Hz</td>
</tr>
</tbody>
</table>
12-150MeV mode operation

criterion
1) $\Delta \nu < 0.1$
2) avoid structure & linear resonances
9-100MeV mode operation (B~80%)
Betatron Tunes

![Graph showing horizontal and vertical tunes for different radius values at a straight section. The graph plots fractional part of tune against radius at a straight section in meters. The horizontal tune is marked with green triangles, and the vertical tune is marked with red circles. The measured data is shown with green triangles, and the calculated data is shown with red circles.]
Resonance Crossing

$3n_x = 11$: lowest order and normal Crossing right after injection

Direction of crossing

Particle Trapping
Emittance Growth
Resonance Crossing

direction of crossing

\[ \xi \propto \frac{1}{3} p - \nu \]

(a) \( \xi = 0.01 \)
(b) \( \xi = 0.00281 \)
(c) \( \xi = 0.0026 \)
(d) \( \xi = 0 \)
(e) \( \xi = -0.02 \)

(a)\(\rightarrow\)(e): particle trapping
(e)\(\rightarrow\)(a): emittance growth
“Particle trapping”

“Emittance growth”

エミッタンス増大は有限

※変化を分かりやすくするため 150MeVと無関係なパラメータ
Resonance Crossing:
Emittance Growth

Max. Emittance Growth Rate

\[
\frac{R + A/\pi}{R} = 1 + \frac{\pi}{\sqrt{2}} \kappa^{-1/2} R^{-1/4}
\]

\(a_s: \text{relative emittance at island}

\[A \approx \frac{\pi^2}{\kappa^{1/2} \alpha_s^3} \text{ area of island}\]

\(\epsilon: \text{Crossing speed}

\(B_0 = \frac{<\beta>}{16 \pi \nu} \int_0^{2\pi} O(\theta) d\theta\)

Driving term:

\[A_p = \frac{<\beta>}{8 \pi \nu} \int_0^{2\pi} e^{-ip\theta} S(\theta) d\theta\]

Linear tune shift:

\[\Delta_L = \frac{1}{3} p - \nu\]

Nonlinear tune shift:

\[\Delta_{NL} = -12 B_0 a_0\]

Excitation width:

\[\Delta_e = -3 A_p a_0^{1/2}\]

\[\kappa = 3 \Delta_{NL} 4\Delta_e, \quad \xi = 3 \Delta_L 2\Delta_e\]
Crossing Speed

\[ G(\alpha) = 1 + G_m \exp(-\alpha / \tau) \]

\[ \alpha_1 = \left( \frac{\varepsilon}{4\pi \Delta_{NL} \Delta_e} \right)^{\frac{2}{3}} : \text{Adiabatic parameter} \]

Crossing speed: \( \varepsilon \)
Nonlinear tune shift: \( \Delta_{NL} = -12 B_0 a_0 \)
Excitation width: \( \Delta_e = -3 A_p a_0^{\frac{1}{4}} \)

Error: -5 mrad., 300 p mm-mrad.

Emittance Growth: 300 p \( \Rightarrow \) 420 p
Experiment

黒：COD corrected
赤：COD uncorrected
〜30%

COD corrected ➔ No Beam Loss!
Error source of COD: dipole kick

〇<5mrad: possible

Error: 5mrad.

Error: 10mrad.

Error: 25mrad.
Beam Intensity

![Graph showing beam intensity over time with error bars and a trend line. The y-axis represents beam intensity in mV*msec, and the x-axis represents time in msec. The graph includes a linear trend line.]
rf voltage
FFAG for ADS

ADSR in Kyoto University Research Reactor Institute (KURRI)

Feasibility study of ADSR
Five-year program 2002 – 2006

Subject
Accelerator technology
- variable energy FFAG
Reactor technology
- basic experiments for energy dependence of the reactor physics
FFAG for ADS
ADSR in Kyoto University Research Reactor Institute (KURRI)

Feasibility study of ADSR
Five-year program 2002 – 2006

Subject

• Accelerator technology
  -variable energy FFAG

• Reactor technology
  -basic experiments for energy dependence of the reactor physics
What is ADSR?

• Accelerator Driven Sub-critical Reactor charged particle

Beam off @ chain reaction stops
Safer system!
FFAG – KUCA ADSR system schematic diagram

- Ion source
- Injector
- Booster
- Main ring
- 100keV
- 2.5MeV
- 20MeV
- 150MeV
- KUCA subcritical reactor
## 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><strong>Einj</strong></td>
<td>100keV</td>
<td>2.5MeV</td>
<td>20MeV</td>
</tr>
<tr>
<td><strong>Eext</strong></td>
<td>2.5MeV</td>
<td>20MeV</td>
<td>150MeV</td>
</tr>
<tr>
<td><strong>Lattice type</strong></td>
<td>Spiral</td>
<td>Radial DFD</td>
<td>Radial DFD</td>
</tr>
<tr>
<td><strong>Acc. scheme</strong></td>
<td>Induction</td>
<td>rf</td>
<td>rf</td>
</tr>
<tr>
<td><strong># of cells</strong></td>
<td>8</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td><strong>k value</strong></td>
<td>2.5</td>
<td>4.5</td>
<td>7.6</td>
</tr>
<tr>
<td><strong>coil/pole</strong></td>
<td>coil</td>
<td>coil</td>
<td>pole</td>
</tr>
<tr>
<td><strong>Pext/Pinj</strong></td>
<td>5.00</td>
<td>2.84</td>
<td>2.83</td>
</tr>
<tr>
<td><strong>Rinj</strong></td>
<td>0.60m</td>
<td>1.42m</td>
<td>4.54m</td>
</tr>
<tr>
<td><strong>Rext</strong></td>
<td>0.99m</td>
<td>1.71m</td>
<td>5.12m</td>
</tr>
</tbody>
</table>
Layout of the complex
Model of injector magnet
Particle Beam Therapy
Requirements
To extend the use of Proton Therapy widely in (Japanese)society

- Efficient treatment
  - >500 patients/year
- High dose rate
  - >5 Gy/min.
- Flexibility (various types of cancer)
  - Respiration mode
  - Spot scanning
- Easy operation
- High maintenance ability
  - Small residual radio activities
- Small cost
  - Construction and operation
# Features

proton therapy accelerator

<table>
<thead>
<tr>
<th>Feature</th>
<th>Synchrotron</th>
<th>Cyclotron</th>
<th>FFAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>Low</td>
<td>Enough</td>
<td>Enough</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Normal</td>
<td>Hard</td>
<td>Normal</td>
</tr>
<tr>
<td>Operation</td>
<td>Not easy</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td>Multi-extraction</td>
<td>Difficult</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Accelerator for Hadron(proton) Therapy

• Requirements
  • Proton energy 230MeV (variable)
  • Intensity >100nA: 5Gy/min
  • Beam extraction efficiency >90%
  • Synchrotron I ~16nA, not enough
  • Cyclotron Extraction efficiency ~<70%

FFAG I > 100nA (100Hz), Extraction >95%
Proton Beam Therapy
FFAG Accelerator

FFAG magnet
spiral sector
#sector:8
k:2
hybrid magnet

RF cavity
extraction(>20Hz)
injector(Linac or Cyclotron)

10m
Injector
16m
16m
Neutron Source for Boron Captured Neutron Therapy (BNCT)
**Boron Neutron Capture Therapy (BNCT)**

Borocaptate sodium (BSH)

L-p-Boronophenyl alanine (BPA)

\[ _1n + 10B \rightarrow 4He (\alpha) + 7Li + 2.8 \text{ MeV} \]
Neutron source

- Large neutron flux
  - $> 1 \times 10^{10} \text{n/cm}^2/\text{sec}$ at patient for 30 min. treatment.
  - Nuclear reactor only can provide.

- Low energy spectrum: thermal/epi-thermal neutron

Limited to extend the use of BNCT widely in society.
Kyoto University Research Reactor (KUR)
The rough sketch of D2O-neutron facility in KUR
Accelerator-based neutron source

- Neutron production reaction
  - $^9$Be(p,n)B, $^8$Li(p,n)Be
- Proton energy 3-10 MeV
  - (Coulomb barrier ~2 MeV)
  - Low gamma-ray background
- Beam current >20 mA (cw)
Difficulties

• Beam current : >20mA (CW)

• Very high duty factor
  
  • ex. Linac (RFQ, IH, DTL)

• cw operation : technically not easy & expensive

• Heat load for the target : Beam power ~100kW

• Stopping power ~100MeV/g/cm², Range <1mm
Proton beam power is mostly consumed by ionization in the target, not by neutron production.

- Neutron production/Ionization(energy loss) Efficiency $\sim <1/1000$
- If the beam energy lost in the target is recovered by re-acceleration, the efficiency of neutron production can be improved.
ERIT

Energy Recovering Internal Target

- $\Delta E$

neutron production target

proton beam

rf re-acceleration:

+ $\Delta E$
ERIT for neutron production with FFAG

- Energy loss
  - recovered by rf re-acceleration
- Emittance growth due to scattering
  - cured by “Ionization Cooling”
- Beam current
  - Required accelerating averaged beam current can be reduced because the circulating current in the ring is large.
Energy loss

• Proton energy  10 MeV  dE/dx  ~30MeV/g/cm²

• Target : Be 5microns

Energy loss/turn  ~ 30keV
Power loss in the target  ~1.2kW
Heat load becomes modest.
Beam current

\[ I_p = \frac{eN_p f_{rev} T_{st}}{(T_{acc} + T_{st})} \]
\[ \frac{I_p}{I_{ave}} = f_{rev} T_{st} \]

- Revolution frequency \( \sim 5 \text{MHz} \)
- Storage time \( \sim 0.5 \text{msec} \)
- Number of turns \( n = f_{rev} T_{st} = 2500 \)
- Accelerating time \( 0.5 \text{msec} \)
- \( N_p \) \( \sim 5 \times 10^{10} \)
- \( I_p \sim 40 \text{mA} \), \( I_{ave} \sim 16 \text{micro-A} = I_p / 2500 \)
Emittance growth

• Using an internal target, the beam emittance could be increased by the effects of multiple scattering and straggling.

• In ERIT, however, “Ionization Cooling” should help to cure the emittance growth.

ERIT = Ring Ionization Cooling
Ionization Cooling

Only muon!
How about proton?
\[ \tau_{\mu} = 2.2 \gamma \mu s \text{ or } L_{\mu} = 660 \beta \gamma m \]
Ionization cooling

\[
\frac{d\varepsilon}{ds} = A\varepsilon + B
\]

- Transverse
  \[
  A = -\frac{1}{\beta^2 E} \left\{ \frac{dE}{ds} \right\} \quad B = \frac{\beta \gamma}{2} \frac{\beta_r}{(\beta c p)^2} L_s \]

- Longitudinal
  \[
  A = 2 \frac{\partial \left( \frac{dE}{ds} \right)}{\partial E} \quad B = 4\pi \left( r_m c^2 \right)^2 n_e \gamma \left[ 1 - \frac{\beta^2}{2} \right]
  \]

cf. p:10MeV, Be target

Transverse: Cooling
Longitudinal: Heating without coupling.

\[\sum_{i=1}^{3} g_i > 0\]
In all of directions (trans. & long.), the beam can be cooled.
1.6 < D \frac{\rho'}{\rho_0} < 2

\sum_{i=1}^{3} g_i \sim 0.4 \ (E_p \sim 10\text{MeV})

for 3D cooling
Tran x Long

$\Delta E < 0$

$\Delta E = 0$

$\Delta E > 0$

wedge target

need hor.&ver. coupling?
縦方向運動のシミュレーション

シミュレーションの条件

<table>
<thead>
<tr>
<th>ビームエネルギー：T0 [MeV]</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>加速器平均半径：r0 [m]</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>周回周波数：Frev [MHz]</td>
<td>4.46</td>
<td>4.61</td>
</tr>
<tr>
<td>Dispersion: D [cm/%]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>ターゲット厚 @ r0：G0 [mm]</td>
<td>5, 8</td>
<td>5, 8</td>
</tr>
<tr>
<td>ターゲット厚の傾き：r'/r0 [1/cm]</td>
<td>0.03~0.07</td>
<td>0.03~0.07</td>
</tr>
<tr>
<td>RF加速電圧: Vrf [kV]</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>ハーモニックナンバー: h</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>エネルギーロス @r0：dEt [keV]</td>
<td>63, 101</td>
<td>36, 57</td>
</tr>
<tr>
<td>ストラグリング(s): dEs [keV]</td>
<td>8.1, 10.2</td>
<td>8.1, 10.2</td>
</tr>
<tr>
<td>Dr'/r0</td>
<td>0.75~1.75</td>
<td>0.75~1.75</td>
</tr>
</tbody>
</table>

RF cavity
Be Target

$r_0$ 5mm
$p_0$
$p>p_0$
$r<r_0$
$r/r_0=0.05$の場合

$r_0$ 2.5mm

$r_0$ 10cm
シミュレーションの結果

$T_0 = 5$ MeV  
Be 5mm の場合

$T_0 = 10$ MeV  
No wedge  
$D\rho'/\rho_0 = 0.75$  
$D\rho'/\rho_0 = 1.5$

運動量アクセプタンス  
$\sim 10\%$

Phase rel. to RF [deg]
シミュレーションのまとめ

アパーチャー ±10 cm
粒子数 100 個の平均

イオン化冷却により 2~3000 turn 程度可能
Heat Load

- Advantages of ERIT
  - $\frac{dE}{dx} \sim$ smallest at maximum beam energy
- Power loss at target
- $P = I_c \times \Delta E$  
  cf. $50\text{mA} \times 30\text{keV} = 1.5\text{kW}$
Requirements for ERIT Ring

• Beam intensity
  • $5 \times 10^{10}$ ppp

• Acceptance
  • $\text{trans.}: 1000\text{mm.mrad}, \text{long.}: \Delta p/p \pm 10\%$

• Repetition rate
  • $\sim 1\text{kHz}$

FFAG looks the best choice.
熱中性子源 FFAG

磁石の形式 : Radial sector type
セクター数 : 8
k 値 : 4
ビームエネルギー : 100keV
～4.7MeV
加速時間 : 4 ms 以下
平均磁場強度 : 0.35 ～ 1.63 Tesla
軌道半径 : 0.8 ～ 1.2 m
rf 周波数 : 0.87 ～ 4 MHz
rf 電圧 : 4 kVp
イオン源 : H+, 100keV, 10mA

BNCT 治療患者
FFAG neutron source
with ERIT

Be target
5 microns

rf cavity for ERIT

D$_2$O moderator

Bi