RF capture of
KURRI FFAG Main Ring

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=== Introduction ===
Charge-exchange multi-turn injection without Bump-magnets

The injected beams escape from the foil by rf acceleration:

\[ N_{\text{turn}} = \frac{dE}{dR} \times \frac{\Delta R_{\text{foil}}}{V \sin \phi_s} \]

\[ = \frac{1}{24 \text{ mm/MeV}} \times \frac{10 \text{ mm}}{4 \text{ kV} \sin \phi_s} \]

(\sim \text{ several 100 turns })

Circulating beams hit the foil many times.

(Offset inj)
What is problem?

Energy loss
\[ \Delta E_{\text{loss}} = 760 \text{ eV/turn} \]

Synchronous phase shift
\[ V \sin \phi_s = V \sin \phi_a + \Delta E_{\text{loss}} \]

Multiple scattering (neglected in this study)

Transverse emittance growth (neglected in this study)

Overheating of the stripping foil
This can give the intensity limit in future

Maximum capture efficiency with Minimum foil-hitting turn no.
Condition of charge-stripping inj scheme in KURRI-FFAG MR

* See K. Okabe in this workshop

Injected beam
- Peak intensity: < 5 mA
- Pulse length: < 100 us

Stripping foil
- Thickness: 20 ug/cm$^2$ (10 ug/cm$^2$ is under consideration)
- Energy loss: 760 eV/turn (From Bethe’s formula)
- Width: 25 mm

RF system
- Maximum voltage: 4 kV
Schematic diagram

Acceleration at constant PHI_a

Bucket areas are plotted here
Choosing acceleration phase

**Low $\phi_a$**
- 2581 turn
- $\phi_s = 05.0^\circ$
- 1202 turn

**High $\phi_a$**
- 658 turn
- $\phi_s = 20.0^\circ$
- 306 turn
- 350 turn
- 163 turn
- $\phi_s = 40.0^\circ$
- $\phi_s = 56.4^\circ$
Choosing acceleration phase

Low $\phi_a$
- Large bucket area
  - high capture efficiency
- Slow acceleration speed
  - long duration at $E_{\text{inj}}$
  - many foil-hits by particles
  - strong ‘boundary-effect’

High $\phi_a$
- Small bucket area
  - low capture efficiency
- Fast acceleration speed
  - short duration at $E_{\text{inj}}$
  - few foil-hits by particles
  - weak ‘boundary-effect’

trade-off

--> Simulation studies are necessary !!
Stimulation studies
Simulation model

- Simple kick-drift algorithm
- Particles are injected during first 100us.
- Uniform energy loss 760 eV each turn, for particles whose energy is less than threshold.
- The threshold corresponds to the foil edge.
- Transverse motions are neglected. Offset injection is not adopted.
Example (1) Fast acceleration

$\phi_a = 40^\circ$

$222 \mu s$

9.6 percent

$99 \mu s$

$\phi_a = 40^\circ$
Example (2) Present operation

$\phi_a = 30^\circ$

$\phi_a = 30^\circ$

$285\mu s$

$127\mu s$

$0\mu s$
Example (3) etc...
Example (4) Large bucket

$\phi_a = 5^o$
Capture efficiency depending on $\phi_a$.

Efficiency takes maximum around

$$\phi_a = 10^\circ \sim 20^\circ$$

But, how about the number-of-foil-hit? -->
Number of foil-hit depending on $\phi_a$.

The number of foil hits is very high.

However, the number foil-hits at high $\phi_a$ is dominated by the particles which has dropped from the bucket!

In order to decrease the Number of hits, ---->
Chopper?

Number of foil-hits is expected to decrease --->

Ion source → Chopper → C foil

100us

High-freq. chopper, synchronized with MR- rf.

Beam is injected only at given rf-phase region

1/Frf
Example of chopper work

Without chopper (again)

With chopper (0-130deg)

Accelerated particles; 35.1%  26.4%
Number of foil-hits;  679  190
SUMMARY

• Longitudinal simulation studies were done with energy-loss at stripping-foil.
• Capture efficiency took maximum when $\text{PHI}_a = 10-20\text{deg}$.
• Number of foil-hits by particles can be problem.
• Number foil-hits can be reduced when we use a chopper at injection beam-line.
RF of KURRI FFAG Main Ring

And Proposal of Combined-Cut-Core experiments

2011.09.15

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Y. Ito and T. Minamikawa (Fukui Univ.)
et al.
=== Existing RF system ===
Systems

- No tuning-loop (low Q)
- No feed-back

signal generator
Tektronics AWG430

solid-state amp
Thamway, 3kW

final amplifier
Tetrode, 55kW

MA loaded cavity

4kV at 1.5 - 5.0 MHz
Cavity photo
Magnetic alloy cores

Magnetic-alloy (FT-3M) x 2 pieces,
1700mm x 1000mm x 30mm
Impedance

\[ V \approx 4 \text{ kV} \quad (1500-4500 \text{ kHz}) \]
=== 2nd RF cavity ===
Motivation of Installing a new RF cavity

• Increase voltage
  
  ---> (1) fast acceleration, 
  for (1A) higher repetition, and/or 
  (1B) larger turn separation at inj. 

  (2) wide bucket area

• Suppress harmonic field components excited by RF cavity
## Requirements

<table>
<thead>
<tr>
<th>Kinetic energy</th>
<th>Orbit radius at straight-section</th>
<th>Revolution frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.0 MeV (linac output)</td>
<td>4398 mm</td>
<td>1557. kHz</td>
</tr>
<tr>
<td>11.57 MeV (booster output)</td>
<td>4414 mm</td>
<td>1591.84 kHz</td>
</tr>
<tr>
<td>100 MeV</td>
<td>5024 mm</td>
<td>3845. kHz</td>
</tr>
<tr>
<td>150 MeV *1</td>
<td>5154 mm</td>
<td>4435. kHz</td>
</tr>
</tbody>
</table>

Frequency: 1500-4500 kHz (Q<1)
Aperture: >~ 750 mm  ---> Very wide!
One candidate; Mitsubishi-cavity

Compared to the existing cavity,

Thickness is twice
.. larger COD source
Impedance is half
.. lower voltage

We (I) want to try another
Combined Cut Core (CCC)
Components of New RF System (planned)

Cavity  
    ---> newly made

Magnetic cores  
    ---> used cores of JPARC-RCS  ---> main topic

Amplifier  
    ---> 200 kW, tetrode (sleeping in KEK-PS)

Cooling System  
    ---> direct-cooling, with oil?
Used MA Cores of JPARC-RCS

- MA (FT-3M) core x 4 pieces (at least),
- Which was used in the JPARC-RCS RF
- Partially damaged by heat
- 850mm(OD)-375mm(ID)-35mm(Th)

Can we reuse them in our main-ring?
   Horizontal aperture is not enough
   --> Combined cut-core (???)
Combined cut-core --- basic idea ---

Combining cut-cores in order to **enlarge the aperture** to fit the MR

This technique enables to make a large aperture core piece by piece, without a large oven.
CCC(1) Flower type

Degree of freedom: 2

H/V aperture independently

Angular discontinuity at the boundary

\[ a=100_{\text{mm}} \quad \text{th}^*\ln(\text{OC/IC})=92.7882_{\text{mm}} \]
\[ b=0_{\text{mm}} \quad V=77351.3_{\text{cc}} \]
\[ 2r_1=375_{\text{mm}} \quad S=552509_{\text{mm}^2} \]
\[ 2r_2=850_{\text{mm}} \]
\[ \text{th}=140_{\text{mm}} \]
\[ L_1=1583_{\text{mm}} \quad \phi_1=30.932^\circ \]
\[ L_2=3071.28_{\text{mm}} \quad \phi_2=13.5126^\circ \]
\[ x_1=50_{\text{mm}} \]
\[ y_1=180.71_{\text{mm}} \]
CCC(2) Ribbon type

Smoothly connect at the boundary

Degree of freedom: 1

H/V apertures are trade-off

\[ a = 150_{\text{mm}} \]
\[ b = 593.849_{\text{mm}} \]
\[ 2r_1 = 375_{\text{mm}} \]
\[ 2r_2 = 850_{\text{mm}} \]
\[ \theta_h = 140_{\text{mm}} \]
\[ L_1 = 1784.27_{\text{mm}} \]
\[ L_2 = 3276.52_{\text{mm}} \]
\[ \theta_\text{ln} \left( OC/IC \right) = 85.0881_{\text{mm}} \]
\[ V = 84135.7_{\text{cc}} \]
\[ S = 600969_{\text{mm}^2} \]
\[ 2x_{ap} = 675_{\text{mm}} \]
\[ 2y_{ap} = 337.698_{\text{mm}} \]
\[ \theta_1 = 75.8241^\circ \]
\[ \theta_2 = 14.1759^\circ \]

\[ (x_1, y_1) = (104.081, 181.79)_{\text{mm}} \]
\[ (x_2, y_2) = (45.9176, 412.058)_{\text{mm}} \]
Potential problems (?)

1. Simple Combined-cut-core technique has been established by J-PARC RF group.
   Quality factor was controlled by changing gap-width.
   cf. Q=0.6(without cut), 2.0(gap 0.5mm), 10(10mm)

2. In our case, the two pieces coming from different cores are connected. --> Discontinuity of MA layers.
   . angular mismatch (flower type)
   . layers offset
   . number of layers

3. Boundary treatments
   . mechanical strength
   . gap width control (--> larger gap increases Q)
   . flatness

Experiments with sample cores are necessary!!
Purposes of the experiment

- Is it possible to combine cut-cores?
- to keep it rigid?
- $R \propto (\text{th})\log(L_2/L_1)$, even for those strange configuration?
- Does the layers discontinuity make problem? such as heat concentration?
- $Q$ reduction?
How to fix?

Binding method, for example

Or, pushing-screw from outside? Glue?
Choosing shape

We choose ribbon-type CCC with $a=240 \text{mm}$.

0.82 \( \leftrightarrow \) 200 ohm/core
Summary

1. We need to install another rf cavity.

2. One candidate is Mitsubishi-cavity already built, but its impedance is relatively low.

3. Instead, we will try a combined cut core configuration. It needs basic experiments.

4. CCC may bring a strong advantage, such as reuse of damaged core, or fabricating of large-aperture core without large oven.
How to make CCC

Thank you to Yoshii-sama

1. Core resin impregnation
2. Core WJ cutting
3. WJ cutting of low density resin impregnation
4. Cutting surface polishing
5. Surface coating

1 + (2) + (3)
East: Cutting cost for each core 160,000 yen (consuming)
(2) Other cases,
Mori Co. (株): Cutting 1 core / 500,000 yen
(4)
Takachiho (株): 2 cores / 4 cores / 500,000 yen
(5)
Art Science (株) + Ikeda (代理店): Cutting 2 cores / 4 cores / 500,000 yen

*WJ: water jet

New cutting process for core manufacturing:
1. Core low density resin impregnation: East
2. Core surface coating (cross 50 micros): East
3. WJ Cutting: East
4. Cutting surface low density resin impregnation: East
5. Diamond grinding: Takachiho
6. Portable silicon rubber polishing: Art Science
7. FRP booster and RTV silicon rubber coating: J-PARC RFG

WJ is necessary for 1, 2. KEK is also possible.

Diamond grinding is necessary for 4.

If the core is not stable, Takachiho can be used for polishing.
J-PARC-RFG FRP booster and RTV silicon rubber coating

Thank you.

1. KEK core cutting
2. Takachiho core cutting and polishing:
3. Core cutting and polishing as required
4. J-PARC-RFG FRP booster and RTV silicon rubber coating

Thank you.

For future projects, we will also need to consider safety measures.
Impedance of ‘Ribbon-Type’ core

\[
\frac{LI^2}{2} = \frac{1}{2\mu} \int B^2 dV = \frac{1}{2\mu} \left( \frac{\mu I}{\ell(r)} \right)^2 dV
\]

Assumption: Flux runs along the MA layers

\[
L = \frac{\mu \times (\text{Thick.})}{2\pi} \ln \left( \frac{\text{Outer circum.}}{\text{Inner circum.}} \right)
\]

\[
R = Q \times \omega L
\]