COMPACT SCALING FFAGS FOR MEDIUM ENERGY HADRON APPLICATIONS

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OUTLINES

- Introduction
- Lattice considerations
- Issues on magnet design

Applications:
- 700 MeV proton ring for ADSR application
- 400 MeV/u C$^{6+}$ ring for carbon ion therapy
INTRODUCTION

Applications of medium energy hadron beams (~ 1GeV proton):
- Accelerator driven subcritical reactor (ADSR)
- Proton driver for secondary beams
- Carbon ion therapy

Features of scaling FFAGs:
- Strong focusing
- Zero chromaticity
- Compact in footprint vs. synchrotrons and linacs
- Fast acceleration for high intensity pulse beam (1kHz repetition rate)
- Potential advanced features (cw beam with serpentine acceleration, straight section FFAG)
INTRODUCTION

Spiral type scaling FFAGs are re-considered

- Compact size due to smaller circumference factor \((R/\rho)\)
- Variable pole gap, free from distributed trim coils which are required in parallel gap magnets
- Field optimization to minimize vertical tune shift
- Use of ‘modified-scaling’ field with variable local spiral angle

2 Applications:
- 700 MeV proton ring for ADSR purpose
- 400 MeV/u carbon ring for hadron therapy, high field with novel super-ferric scheme
LATTICE CONSIDERATIONS

Parameter search

- Linear matrix method (SAD), for determination of the cell number N and approximate range of field index k.
- Ray-tracing using Enge models (Zgoubi), for investigation on tune shift and acceptances

Constraints:

- Small radius excursion for specific momentum ratio;
- The operational betatron tunes should be far away from low-order normal structural resonances;
- For practical factor, a reasonable spiral angle (<60deg.) and enough space for installation of RF cavities and kicker / septum magnets
TYPE OF POLE GAPS IN SPIRAL SECTOR FFAGS

Original flat pole type:  MURA 120 keV electron spiral FFAG / KURRI-IonBeta 2.5 MeV proton spiral FFAG

- Flat gap (Kai=0, for scaling fringe field, requires gap scaled with radius)
- Independent control pole face winding coils
  (eg. KURRI ion-beta used 32 coils)

Features:

- Good control of fringe field variation;
- Possible for change of working point
- But, complex design and construction for coil conductors

Variable gap shaping: RACCAM magnet

- \( g = g_0/(r/r_0)^k \);
- no trim coils required, pole shaping is necessary during magnet designs;
- Requires careful designs before construction, since working point is fixed.
‘MODIFIED-SCALING’ FIELD WITH VARIABLE SPIRAL ANGLE

Sufficient but not necessary condition of zero chromaticity in scaling FFAGs requires perfect scaling magnetic field (geometrical scaling):

\[ B_z(r, \theta) = B_0 \cdot \left( \frac{r}{r_0} \right)^k \cdot \mathcal{F}(\theta) \]

\( k = \frac{r}{B_0} \cdot \frac{\partial B}{\partial r} : \) constant local geometrical field index

\( \mathcal{F}(\theta) : \) azimuthal field distribution function independent of \( r \), has a shift \( \tan \zeta \cdot \ln \left( \frac{r}{r_0} \right) \) in spiral sectors.

Not realistic in variable gap dipoles, because of the changed fringe field especially in high field cases.
Linear model approximation

\[
\nu_x^2 \approx 1 + k, \quad \nu_z^2 \approx -k + F \cdot (1 + 2 \tan^2 \zeta)
\]

field flutter, a terminology in cyclotrons

\( F = R / \rho - 1 \), in hard-edge model;
affected by fringe field shape in realistic field

\[
F = \frac{B^2 - \overline{B}^2}{\overline{B}^2}
\]

\( k \) should be kept constant to keep \( \nu_x \) unchanged. To make compensation on tune shift \( \Delta \nu_z \) caused by the change of field flutter \( F \), a minute change of the local spiral angle \( -\Delta \zeta \) can be estimated and performed:

\[
\frac{d\nu_z}{d\zeta} = \frac{2F \cdot \tan \zeta}{\sqrt{-k + F(1 + 2 \tan^2 \zeta) \cdot \cos^2 \zeta}}
\]

'Modified-scaling' field: constant effective \( k \) (by field integrals), variable spiral angle as a function of \( r \).

- Not perfect scaling field;
- Applied for minimization of the tune shift.

From R. Baartman, Isochronous and scaling FFAGs, FFAG workshop 2003.
2 cases: normal field & high field
vertical tune shift vs. flutter change

\( \Delta F = 0.03 \rightarrow \Delta \nu_{z,\text{pred.}} = 0.06, \Delta \nu_z = 0.1 \)

\( \Delta F = 0.35 \rightarrow \Delta \nu_{z,\text{pred.}} = 0.35, \Delta \nu_z = 0.6 \)
MAGNET DESIGN ISSUES

Experiences from RACCAM magnets [1]
Studies on high field magnet design [2]

1) Not necessary if dQz is neglectable, such in normal field case;
2) Required in high field case, in general a minute linear modification is enough (cf. 0.04deg./cm, accumulated change < 3deg.)

Configuration of yoke size, total current, minimum gap size, pole chamfer, field clamps

\[
\begin{align*}
&BL = \int B_z \cdot dl \\
&BL_{theo} = B L_0 \cdot (R/R_0)^{k+1}
\end{align*}
\]

Compare with

\[
\begin{align*}
&L_{\text{entrance|exit}}^{\text{effective}} = (\int B_z \cdot dl)_{\text{entrance|exit}} / B_{\text{center}}^2 \\
&L_{\text{theory}} = (\pi/N) \cdot R \cdot p f
\end{align*}
\]

Compare with

Align local spiral angle as well.

For generation of high intensity neutron source, proton drive in ADSR system demands:

- **High beam energy.** Normally requires 0.2-1GeV protons, for 700MeV proton beam, the neutron multiplication rate per proton is about 10

- **High beam intensity.** Fast acceleration (~1kHz repetition rate) for beam output in MW level.
PARAMETER SEARCH FOR CELL TUNE AND TRANSVERSE ACCEPTANCES ($N=14$)

- Black-edge working points are calculated using Zgoubi code with fitted Enge models.
- Circle area scaled to the horizontal acceptance, and gray level scaled to the vertical acceptance.
- Red-edge points are samples calculated from TOSCA field maps.
- Normal sextupoles / octupoles resonances and the value of $k$ have significant influence on transverse acceptances.
- Working point A ($k=6.2$, zeta=58deg.) was selected for the proton ring, with acceptances: $\epsilon_x = 12000 / \epsilon_z = 450 (\pi \text{ mm} \cdot \text{mrad})$
- Working point B ($k=8.4$, zeta=58.5deg.) is an option for 700 MeV upgrade ring in KURRI, with $R_0>8m$ to match the present main ring. $\epsilon_x = 8000 / \epsilon_z = 400 (\pi \text{ mm} \cdot \text{mrad})$

**Figure 1:** Parameters search for cell tune and correspondences ($N=14$)

**Figure 2:** Variation of the ring tune

**Figure 3:** Difference between Enge models and tosca field maps
PARAMETERS DETAILS

<table>
<thead>
<tr>
<th>Parameters of the 700MeV proton ring</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell number</td>
<td>14</td>
</tr>
<tr>
<td>Injection / Extraction energy</td>
<td>150 / 700 MeV</td>
</tr>
<tr>
<td>Momentum ratio</td>
<td>2.43</td>
</tr>
<tr>
<td>Spiral index</td>
<td>6.2</td>
</tr>
<tr>
<td>Average angle</td>
<td>58.0 degree</td>
</tr>
<tr>
<td>Packing factor</td>
<td>0.38</td>
</tr>
<tr>
<td>Average orbit radius</td>
<td>6.85-7.75 m</td>
</tr>
<tr>
<td>$B_{max}$ @ extraction</td>
<td>1.45T</td>
</tr>
<tr>
<td>$\nu_x / \nu_z$ per cell</td>
<td>0.20 / 0.13</td>
</tr>
<tr>
<td>$\beta_x / \beta_z$ @ inj.</td>
<td>1.6 - 4.0m / 2.9 - 6.5m</td>
</tr>
<tr>
<td>Dispersion @ inj.</td>
<td>0.3 - 0.85 m</td>
</tr>
</tbody>
</table>

| Repetition rate                      | 1kHz |
| RF frequency                         | 3.5MHz - 5.1MHz |
| Number of cavities                   | 9 |
| Harmonic number                     | 1 |
| RF peak voltage                     | 20kV |
| $\phi_x$                            | 40° |
| $\gamma_t$                          | 2.68 |
| $Q$                                 | 2.7 |

Footprint of the 700 MeV proton ring

Lattice function @ injection / extraction energy
- **Field clamps** and **pole chamfer with variable width** are used to limit the fringe field and decrease the change of field flutter along radius.
- Iterative corrections on the pole gap and field boundary are performed to control the transverse **tune shift per cell within +/-0.005**

Tosca model of the spiral sector magnet

Footprint of the ring tune, calculated from tosca field map
Horizontal & vertical stability limit, Zgoubi result using TOSCA 2D maps.

\[ \epsilon_x = 10000 \, / \, \epsilon_z = 420 \, (\pi \, \text{mm} \cdot \text{mrad}) \] @ injection

Transmission is investigated using initial water-bag distribution beam with

\[ \epsilon_x = 500 \, / \, \epsilon_z = 120 \, (\pi \, \text{mm} \cdot \text{mrad}) \], 200\,\text{keV/turn}, 1000\,\text{turns}, \sim 2\% \, \text{beam loss}
Larger biological effect compared with protons/X ray, more efficient against hypoxic and radio-resistant tumors

- Carbon ion therapy has been transformed from research oriented to clinically oriented.
- 4 centers for carbon ion therapy constructed, 3 in Japan, 1 in Germany
- Present medical centers for carbon therapy employ synchrotrons with diameters larger than 20 m.
- Existing FFAG & ns-FFAG designs for hadron therapy

Advantage of FFAGs for carbon therapy:

- Variable energy (vs. cyclotron)
- Strong focusing, avoid beam loss (vs. cyclotron)
- High repetition pulse beam, suitable for spot scanning (vs. synchrotron)
- Simplesness and easy for operation (vs. synchrotron)
- Smaller excursion due to high field gradient (vs. cyclotron)
HIGH FIELD SPIRAL C\textsuperscript{6+} FFAG RING USING SUPER-FERRIC SUPERCONDUCTING MAGNET

![Schematic plan of the spiral FFAG ring for carbon therapy](image)

**Parameters of the 400MeV/u carbon ring**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle species</td>
<td>C\textsuperscript{6+}</td>
</tr>
<tr>
<td>Injector</td>
<td>superconducting cyclotron, or linac</td>
</tr>
<tr>
<td>Injection/extraction energy</td>
<td>40 MeV/u, 400MeV/u</td>
</tr>
<tr>
<td>Momentum ratio</td>
<td>3.45</td>
</tr>
<tr>
<td>Cell number</td>
<td>10</td>
</tr>
<tr>
<td>Field index</td>
<td>3.6</td>
</tr>
<tr>
<td>Spiral angle</td>
<td>51.0°</td>
</tr>
<tr>
<td>Packing factor</td>
<td>0.35</td>
</tr>
<tr>
<td>$\nu_x / \nu_z$ per cell</td>
<td>0.24 / 0.18</td>
</tr>
<tr>
<td>$\beta_x / \beta_z$ @ inj.</td>
<td>0.7 - 2.3m / 0.9 - 2.6m</td>
</tr>
<tr>
<td>Dispersion @ inj.</td>
<td>0.2 - 0.7 m</td>
</tr>
<tr>
<td>Average orbit radius</td>
<td>2.6-3.45 m</td>
</tr>
<tr>
<td>Ring diameter</td>
<td>9m</td>
</tr>
<tr>
<td>$B_{max}$ @ extraction</td>
<td>5.3T</td>
</tr>
</tbody>
</table>
Exotic rare-earth metal such as holmium (Ho) or gadolinium (Gd) are considered for their higher permeability in high magnetic field.

Ho, applied in some high gradient superconducting quadrupoles [1,2]

Features of Ho/Gd:
- almost linear relative permeability
- At normal field \( B < 2T \), \( \mu_r \ll \mu_{r,iron} \); At high fields \( B > 2T \), larger than saturated \( \mu_{r,iron} \)
- Saturated field > 8T
- Curie temperature:
  - Holmium: 20K;
  - Gadolinium: 290K

BH Data of Holmium@4.2K, taken from W. Schauer and F. Arendt, Cryogenics, 23 (1983) 562.

Multi-layer super-ferric magnet with exotic materials (2)

- Multi-layer pole combining Ho and iron is used to achieve high gradient. Configurations of the layer height and superconducting coils position are important because of non-neglectable reluctance in Ho/saturated iron layers and dominant $H$ field.

- In general, at higher field, the height of Ho layer should be larger.

$$L^{Gd}(r) = d_0 + d_1/g(r)^m$$

- Normal magnet with non-saturated poles

- High field case

Figure 5: Flow chart for procedures of magnet modelling and optimization
Design with GD Material

- First we considered Gd, for its declared higher $\mu_r$ (>10 @ B=5T);
- $k$ can be 4.6, lead to 80cm excursion for 20MeV/u to 400MeV/u (momentum ratio 5)

However, experiment results didn’t support this data. ($\mu_r \sim 1$)
- We have to go back to Holmium, similar design routines, but a lower field index $k \sim 4$. 
Multi-layer super-ferric magnet with exotic materials (3)

TOSCA model of multi-layer super-ferric magnet

Field integrals along the radius

Effective field index (from field integrals)
The field flutter $F$ has a large difference along the radius, that causes significant vertical tune shift. **A minute modification on the local spiral angle is required.**

**Multi-layer super-ferric magnet with exotic materials (4)**

- Minimization of tune shift in the ring during optimization procedures

![Fringe field represented by field flutter](image1)

![Model after correction on $k$ and field boundary](image2)

![Model after local $\zeta$ modification](image3)
RF, MAGNET PARAMETERS

### Basic rf parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate</td>
<td>200Hz</td>
</tr>
<tr>
<td>RF frequency</td>
<td>5.1MHz - 9.8MHz</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>4</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>1</td>
</tr>
<tr>
<td>RF peak voltage</td>
<td>5.5 kV</td>
</tr>
<tr>
<td>Synchronous phase</td>
<td>30 deg.</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>2.14</td>
</tr>
<tr>
<td>Field gradient</td>
<td>27.5kV/m</td>
</tr>
<tr>
<td>Radial aperture</td>
<td>90cm</td>
</tr>
<tr>
<td>Q</td>
<td>1.6</td>
</tr>
</tbody>
</table>

### Parameters of the magnet model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field index</td>
<td>3.6</td>
</tr>
<tr>
<td>Spiral angle</td>
<td>51 degree</td>
</tr>
<tr>
<td>Packing factor</td>
<td>0.35</td>
</tr>
<tr>
<td>Open angle</td>
<td>12.6 degree</td>
</tr>
<tr>
<td>Pole expand</td>
<td>2.4m-3.6m</td>
</tr>
<tr>
<td>Good field region</td>
<td>2.55m-3.45m (k error: +/-5%)</td>
</tr>
<tr>
<td>Total current of the coil</td>
<td>350kA · T</td>
</tr>
</tbody>
</table>

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**Figure 6**: TOSCA model of multi-layer superferric spiral sector

Iterative procedures on the sector pole geometry described in section 3.2 are performed. To demonstrate the comparative results, three models are picked up. model2 is the initial model, model7 is the model after correction of the central field and the effective boundary with 5 iterations, and the final model7-v4 is the model after modification on the local spiral angle. The corrections are performed in good field region (2.5-3.4m) on radial dimension, which covers the pole radius from injection 2.51m to extraction 3.37m. As shown in Fig. 3.4 and Fig. 8, by comparing model7 with model2, errors of effective field boundary are controlled within $\pm 0.5\%$, and both local field index and central magnetic fields are well aligned to the design value.

RF sweep mode, 4ms time of flight

Twiss parameters, calculated at injection and extraction momentum.
Horizontal & vertical stability limit, Zgoubi result using TOSCA 2D maps.

\[ \epsilon_x = 3000 / \epsilon_z = 400 (\pi \text{ mm} \cdot \text{mrad}) \quad @ \text{injection} \]

Transmission is investigated using initial water-bag distribution beam with

\[ \epsilon_x = 400 / \epsilon_z = 100 (\pi \text{ mm} \cdot \text{mrad}) \quad , \ 20\text{keV/turn}, 1000\text{turns}, \text{no beam loss} \]
Methods for design of variable pole gap spiral FFAGs are studied

- Working points search
- Control of tune shift due to fringe field

So far, from simulation, it is possible to employ high field in spiral scaling FFAGs (B_{max} \sim 5T, k \sim 4)

- Very small gap size @ extraction, \sim 1cm half size
- Realistic consideration on magnet construction, super-conducting coils, dose control & energy variability in hadron therapy scheme.
- Difficulties on fast extraction, high rigidity (6.4T.m) in small drift space (\sim 1m); resonance extraction, mass-less septum magnet?

For carbon therapy purpose, another arrangement is to split one main ring into two rings. The first ring covers energy from 5MeV/u to 65MeV/u, can be used for proton therapy (20MeV to 240MeV) as well; the second ring covers energy from 65MeV/u to 400MeV/u.