DESIGN OF HIGH ENERGY HADRON FFAGS FOR ADSR AND OTHER APPLICATIONS

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Abstract

Design study of high energy proton FFAG accelerator has been carried out at Kyoto University Research Reactor (KURRI) for the next generation ADSR experiment where the proton beam energy covers up to 700MeV. The scaling type of FFAG with spiral sectors was employed. Details of the design issue concerning about the operational working points, lattice parameters and 3D magnet modeling / optimization are described. Also, some possibilities to apply this design to carbon therapy accelerators are presented.

INTRODUCTION

In KURRI, the first Accelerator driven sub-critical reactor (ADSR) experiment has started from March 2009, using a FFAG proton accelerator complex as a spallation neutron driver. At current phase, the output of the main ring in FFAG complex is 100MeV / 0.1nA [1]. Since the output power of the sub-critical reactor is proportional to the intensity of the neutron source, which related to the beam energy and intensity from the accelerator driver, some upgrade plans for the existing FFAG complex have been proposed and carried out [2]. One is to increase the beam intensity by replacing the current injector (Ion-beta + Booster) with a 11MeV H^- Linac injector [3]. The other way is to enhance the extraction beam energy to about 700MeV by adding a new ring. Since the number of neutrons during the nuclear spallation process has a strong dependency on the beam energy of the primary proton, the neutron multiplication rate can be increased by a factor of 30 when the proton beam energy is increased from 150MeV to 700MeV [2].

BASIC PARAMETERS FOR THE 700MEV FFAG RING

The present FFAG complex for ADSR experiment consists of one spiral injector (Ion-beta) with the extraction energy 1.5MeV, one 8-cell radial type booster and one 12-cell radial type main ring to accelerate beam energy covering 1.5MeV$\sim$11MeV and 11MeV$\sim$100MeV. The maximum energy of the main ring can be increased to 150MeV by changing the output energy of the injector.

The 700MeV upgrade ring will adopt the scaling type of FFAG with spiral sectors. For high energy scaling FFAG accelerators, the spiral sector is not so commonly used compared with the DFD triplets, due to the difficulty of controlling vertical tune shift. However, with the aid of 3D magnet modeling and optimization, it is possible to control the tune shift and maintain zero chromaticity. Meanwhile the compactness of the spiral sector makes it attractive.

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For a given momentum ratio p_{ext}/p_{inj}, the radius excursion ΔR is related to the injection radius R_0 and field index k by the scaling law $B = B_0 \cdot (R/R_0)^k$, as Eq. 1. In case of the 700MeV ring, $p_{ext}/p_{inj} = 2.44$, when taking $R_0 = 6.9m$, ΔR is in range of 0.8m$\sim$0.5m when changing k from 7.0 to 12.0.

$$\Delta R = ((P_{ext}/P_{inj})^{\frac{1}{1+k}} - 1) \cdot R_0 \tag{1}$$

The stable region for (k, ζ) parameter set is searched with first order matrix method, at different cell number $N = 8 \sim 16$. The main design constraints are the following: (1) Field index should be larger than 6.0, to keep a compact magnet dimension; (2) Spiral angle should be smaller than 60 degrees, for considerations on rf cavity installation etc. (3) The working point should be far away from low order normal structural resonances.

For the case of cell number $N = 14$ with the packing factor 0.4 , the working point $(\nu_x = 0.22, \nu_z = 0.14)$ is selected around parameters $(k = 7.0, \zeta = 58°)$ (see Fig. 1). The main parameters are listed in Table 1.

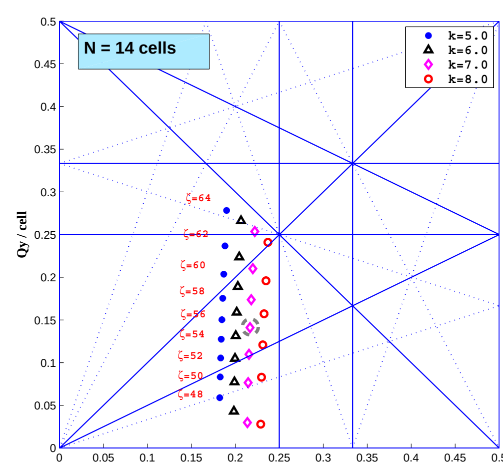

Figure 1: Working point search for $N = 14$. k is the field index, ζ is the spiral angle

The lattice was validated using Zgoubi code with FFAG-SPI procedure [4]. This procedure uses the soft enge model

Table 1: Parameters of the 700MeV ring

Lattice type	spiral sector, scaling FFAG
Cell number	14
Injection / Extraction energy	150 / 700 MeV
Field index	7.0
Spiral angle	58.0 degree
Packing factor	0.4
Average orbit radius	6.9-7.7 m
B_{max}@$700MeV$	1.45T
ν_x/ν_z per cell	0.22 / 0.14
$\beta_x \quad min/max$	1.4 / 4.0 m
$D_x \quad min/max$	0.65 / 1.0 m

to simulate the realistic fringe field effect, and overall there exist a decrease for vertical tune. In realistic model, the packing factor need be decreased to compensate this vertical tune drop while keeping the same k and ζ

STUDY OF 3D TOSCA MODEL

For spiral sector FFAG, generally there exists two gap geometry formation. One is the flat pole gap, the field gradient is generated by distributed trim coils. An example is the Ion-beta in KURRI FFAG complex. The other type uses the natural variable gap shape with only main coil. Since the magnetic field flux $B(r) \propto 1/g(r)$, then the gap size $g(r)$ can be determined by $g(r) = g_0 \cdot (r_0/r)^k$, where g_0 is the gap size corresponds to r_0.

For the latter case, the coil configuration is more simple. But the vertical tune shift will be enlarged due to the decreasing fringe extend caused by the smaller gap size at higher beam energy. Some experiences such as the RACCAM prototype magnet has shown the possibility to modulate this tune shift by model optimization [5].

In general, three main methods are employed to reduce the vertical tune shift and keep zero chromaticity feature addressed by the scaling FFAGs.

1. *Introducing pole chamfer with variable width and field clamp*
2. *Effective magnetic field boundary correction based on the calculation of the field integrals $\int B_z \cdot dl$*
3. *Minute modification on local spiral angle, to compensate the vertical tune shift caused by fringe extent.*

The first magnet sector model of 700MeV spiral ring was built with OPERA/TOSCA [6], shown in Fig. 2. The chamfer width is set to be proportional to $1/g(r)$, which means larger chamfer width at larger radii. Field clamps with constant gap size is adopt to limit fringe field. The packing factor in this magnet model is reduced to 0.37 to keep the same working point in linear model.

In Fig. 4 it can be observed there exist significant vertical tune shift with $\Delta\nu_{z,cell} > 0.07$ in the initial model (model-3). The sources come from errors of the local field index,

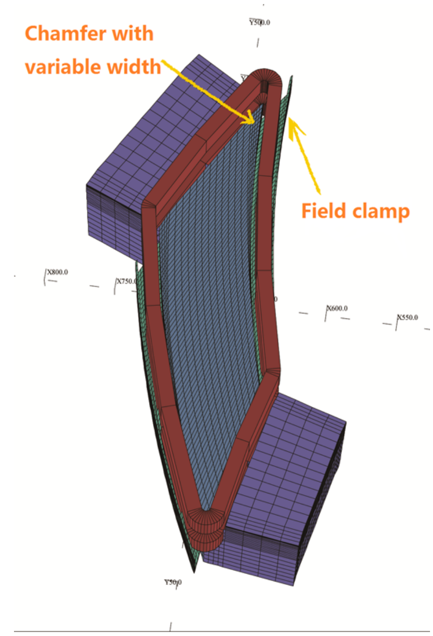

Figure 2: TOSCA magnet model with variable gap

local spiral angle and fringe field extent. The first stage to optimize the magnet model is to align the effective magnetic field boundary along the radius, using a procedure described in [5]. This is proved to be an efficient method to correct both local k and local ζ.

After some iterations, errors of the effective boundary and local spiral angle is well controlled within negligible value limited by 3D TOSCA calculations, as shown in Fig. 3. And the vertical tune shift is abbreviated especially in high energy region (blue line in Fig. 4, model-14). But obvious tune deviation still exists at lower energy (150-350MeV). Because the source of the local field index and local spiral angle have been eliminated, then the only reason is the fringe field extent, or in terms of the field flutter defined by $F = \frac{1}{N} \cdot \Sigma \frac{(B(\theta)-\bar{B})^2}{\bar{B}^2}$. The relation between ν_z and k, ζ, F can be approximately expressed by:

$$\begin{aligned} \nu_z^2 &= -k + \tfrac{N^2}{N^2-1} \cdot F \cdot (1 + 2\tan^2\zeta) \\ &\approx -k + F \cdot (1 + 2\tan^2\zeta) \qquad if\ N \gg 1 \end{aligned} \tag{2}$$

The flutter is mainly determined by magnet pole geometry and will not change when the effective field boundary is fixed. The field index k should be kept constant to ensure a stable ν_x. Then the last free parameter is the local ζ. By using the derived Equ. 3 and observed $\delta\nu_z$, the minute change of local spiral angle $\delta\zeta$ can be estimated from known numerical information.

$$\frac{d\nu_z}{d\zeta} = \frac{2F \cdot \tan\zeta}{\sqrt{-k + F(1 + 2\tan^2\zeta)} \cdot \cos^2\zeta} \tag{3}$$

This modification was applied on model-14 in range of $r < 730cm$, with $\delta\zeta < 0.03°/cm$ and max pole edge modification $\delta\theta_{max} < 0.4°$. The vertical tune of the final optimized model (model-18) is shown in Fig. 5, with a small shift about 0.01 per cell.

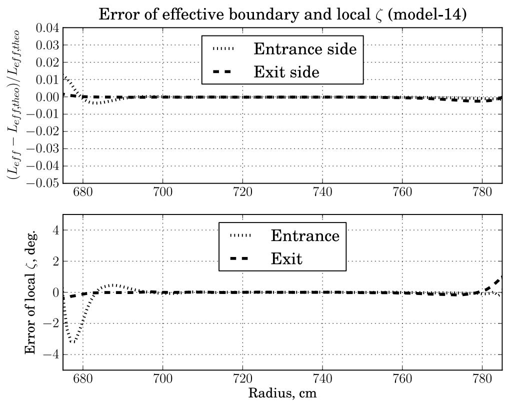

Figure 3: Errors of effective boundary and local spiral angle error after model optimization (model-14)

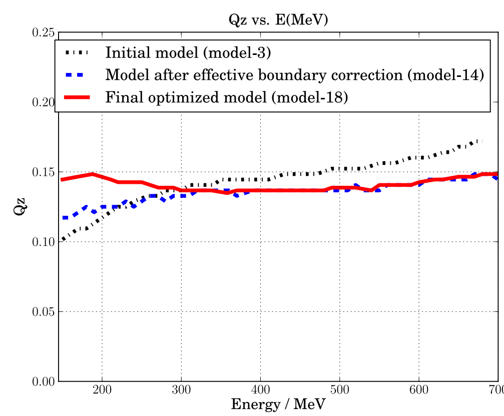

Figure 4: Evolution of the vertical tune shift, using 3D TOSCA maps. Blue:model-14 after correction of effective boundary; Red:model-18 with modification on local ζ

APPLICATION TO CARBON THERAPY

Fig. 6 shows there exists possibility to use a working point with horizontal phase advance larger than 90° and high field index, for instance $(k = 10.0, \zeta = 57°)$. For applications that does not demand large acceptance, such as carbon therapy accelerators, this is an attractive scheme because the high field index makes the magnet more compact. For a scaling superconducting FFAG ring accelerates carbon ions from 12MeV/u to 400MeV/u (momentum ratio=6.35), the radius excursion can be achieved at about 0.45m with $R_0 = 2.5m$, packing factor 0.5 and maximum magnetic field 4.3T.

SUMMARY

To increase the number of neutrons during the spallation process in KURRI ADSR experiment, an energy upgrade plan is proposed to boost the beam energy of the FFAG complex to 700MeV. The scheme using spiral sector scaling FFAG was discussed. A magnet model with variable

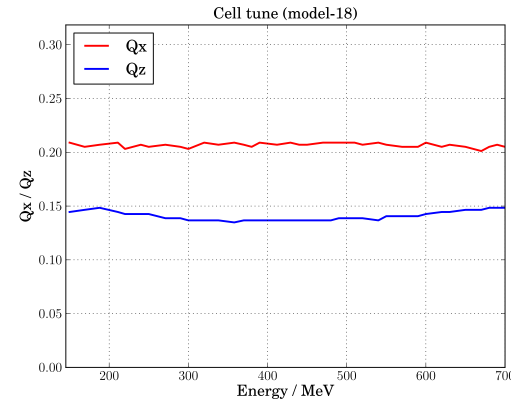

Figure 5: Horizontal and vertical tune per cell of model-18

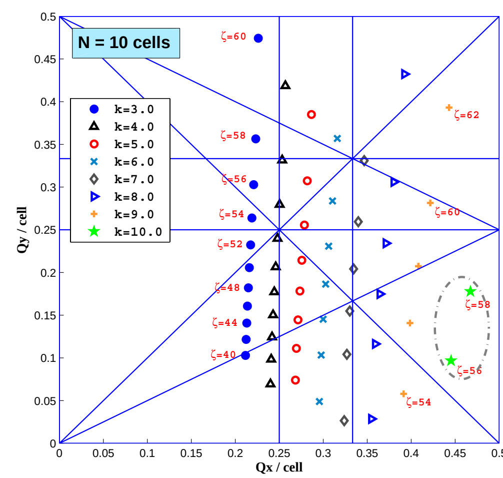

Figure 6: N=10 case, for possibilities to use high horizontal phase advance with higher k

gap shape was studied with TOSCA code, and methods were employed to optimize the vertical tune shift. The possible application on carbon therapy accelerators using higher k was also discussed.

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