ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK034

PRACTICAL BETATRON TUNE BEHAVIOR DURING ACCELERATION IN SCALING FFAG RINGS AT KURNS*

Y. Ishi†, Y. Fuwa, Y. Kuriyama, H. Okita, T. Uesugi, Y. Mori
Institue for Integrated Radiation and Nuclear Science, Kyoto University, Kumatori, Osaka, Japan
J-B. Lagrange
Science and Technology Facilities Council, Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK

Abstract

In scaling FFAG accelerators, ideally, betatron tunes are the same for all closed orbits concerned with the certain beam energy. Therefore, they should not vary during acceleration. However, it is not the case since practical implementations of the magnetic field can not provide perfect scaling conditions. In this report, we discuss the tune behavior in scaling FFAGs in both measurements and simulations, using data of BOOSTER and MAIN RING in the FFAG complex at KURNS as examples of real machines.

INTRODUCTION

A scaling FFAG accelerator has zero-chromatic characteristics *i.e.* betatron tunes are fixed while acceleration. This nature can be realized by orbit similarity for the different energy beams and the magnetic field distribution so that

$$B(r,\theta) = B_0(\theta)\left(\frac{r}{r_0}\right)^k, \qquad (1)$$

where θ is the azimuthal angle, r is the radius from the machine center and k is a constant number. If these scaling conditions are fulfilled, zero-chromatic operations can be carried out. However, in a practical machine, it is impossible to guarantee the perfect zero-chromatic field configuration. One of major reasons for breaking the conditions is leakage magnetic field from the main body region to the straight section. If the leakage field distribution was scaled in the same manner as the main body field, zero chromaticity would be conserved. However, it is not the case for real machines. Since the gap of the FFAG magnet becomes wider toward the inside, the influence of the leakage field becomes stronger in the inside without adjusted field clamps.

There are 2 similar radial sector scaling FFAG synchrotrons at KURNS [1] : BOOSTER and MAIN RING. These rings adopt different types of magnets: one has no return yokes so called 'yoke free type' adopted by MAIN RING which has a large tune variations causing non negligible beam losses; the other has return yokes and field clamps adopted by BOOSTER which has smaller tune variations compared with MAIN RING. We report the tune measurements and calculations based on 3-d magnetic field calculations about these two types of ring and discuss the scaling conditions in FFAG accelerators.

FFAG COMPLEX AT KURNS

At KURNS, basic experimental studies on ADS have been performed since 2009, using a research reactor KUCA which stands for Kyoto University Critical Assembly [1] connected with the FFAG accelerator complex. In these studies, KUCA is operated in a sub-critical mode and FFAG MAIN RING is used as a proton driver.

Although the maximum energy of MAIN RING is 150 MeV, The energy of the beam used for the ADS experiments is limited up to 100 MeV by the radiation safety.

The machine complex is composed of an H^- ion source, an 11 MeV injector LINAC and MAIN RING. This configuration has been used since 2011. Before that, the different combination of machines was used as the original complex, which was composed of an H^+ ion source, an injector IONBETA, BOOSTER and MAIN RING [2]. Latter 2 rings are both FFAG synchrotrons, of which specifications are shown in Tab. 1. MAIN RING can be operated in 2 different energy modes *i.e.* 100 MeV and 150 MeV modes, which are used for the ADS experiments and various irradiation experiments, respectively.

Table 1: The Basic Parameters of FFAG Synchrotrons at KURNS

	BOOSTER	MAIN RING
Beam species	proton	proton
Injection energy	1.5 MeV	11 MeV
Extraction energy	11 MeV	150(100) MeV
Lattice structure	8-cell DFD	12-cell DFD
Field index k	2.5	7.5
Average orbit radii	1.42 - 1.71 m	4.52 - 5.12 m

DESIGN PARAMETERS OF THE MAIN MAGNETS

Lattice structures of BOOSTER and MAIN RING are almost the same. These are both DFD triplet. However, the basic design concept of the main magnet is totally different. Regarding MAIN RING, the different energy beam extraction is realized by changing the position of the extraction kicker and septum magnets. In this scheme, the beams with

* The name of the institute has been changed since April 2018. It was Kyoto University Research Reactor Institute(KURRI) .
† ishi@rri.kyoto-u.ac.jp
[1] KURNS stands for Institue for Integrated Radiation and Nuclear Science, Kyoto University.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK034

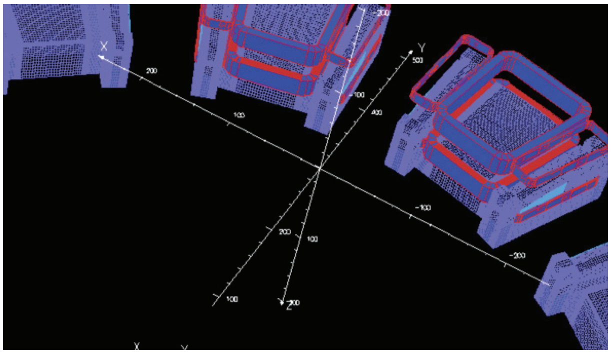

Figure 1: The input model of the main magnet in MAIN RING for the magnetic field calculation by TOSCA. Return yokes are not installed to make energy variable beam extractions easy. No field clamps are adopted.

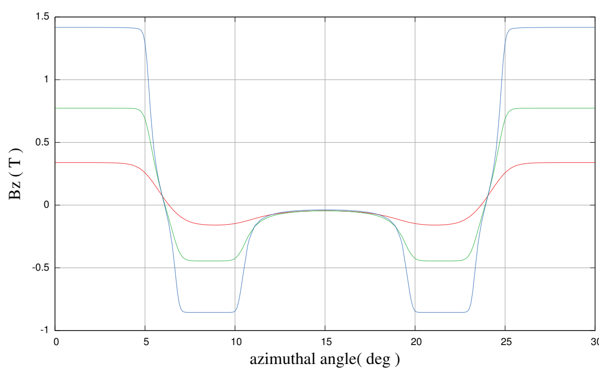

Figure 2: B_z vs θ along different radii for the unit cell in MAIN RING. Red, green and blue lines correspond to radius of 4.4 m, 4.9 m and 5.3 m, respectively.

different energies are extracted through different trajectories. Therefore, we needed to expand the extraction channel which located at the space for the return yoke. It is difficult to provide a wide channel inside the return yoke iron, getting rid of the leakage field inside the channel. A novel idea to get around this difficulty is to get rid of return yokes. The input model of the main magnet in MAIN RING for the magnetic field calculation by TOSCA is shown in Fig. 1. Flux generated by the coil of the F pole returns through D poles, making the use of field clamps unpractical. At the cost of an increase in leakage field in the straight section, we got a solution to the variable energy beam extraction. As shown in Fig. 2, there is leakage magnetic field more than a few 100 gauss at the center of the straight section.

Figure 3 shows the TOSCA input model of the BOOSTER main magnet, which has return yokes and field clamps to minimize the leakage field at the straight sections. As seen in Fig. 4, the leakage field at the center of the straight section is almost zero. In addition, the shape of $B_z(\theta)$ including leakage field scales with radius, which is desirable for the zero chromaticity.

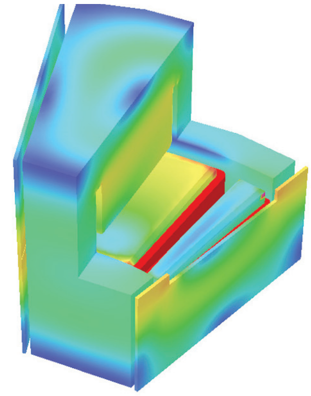

Figure 3: The input model of the main magnet in BOOSTER for the magnetic field calculation by TOSCA. Return yokes and field clamps are adopted.

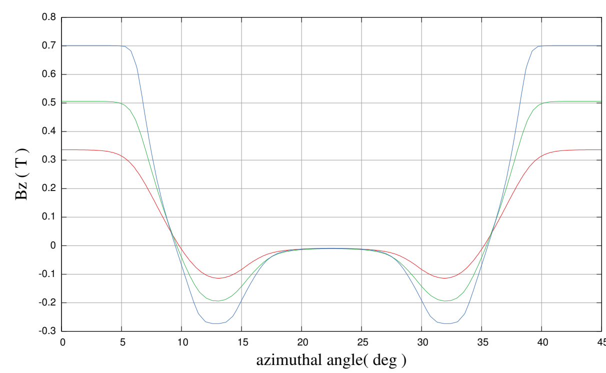

Figure 4: B_z vs θ along different radii for the unit cell in BOOSTER. Red, green and blue lines correspond to radius of 1.2 m, 1.4 m and 1.6 m, respectively.

TUNE SPREAD, RESONANCE CROSSING AND BEAM LOSSES

Betatron tunes for different energies have been measured in MAIN RING and BOOSTER. The measurements were performed at the flat top after acceleration for different energies. The tune footprint during acceleration in MAIN RING is shown in Fig. 5. Tunes from the simulations based on 3-d magnetic field map are also shown in this figure. These are calculated from the transfer matrix determined in a small segment along the scalloped closed orbit which is obtained by using 4th order Runge-Kutta solver. A simulation code named EARLIETIMES [3] has been used to calculate closed orbits, tunes and others.

The tune spread during acceleration in MAIN RING is too large to avoid crossing the resonance lines. Figure 6 shows the output signal from the bunch monitor. One can see some non negligible beam losses around 1.0 ms, 2.7 ms, 4.3 ms and 20.1 ms from the start of acceleration. These loss timings could be regarded the same timings as resonance crossing indicated in Fig. 5. In this case, the harmful resonance seems to be $Q_x - 2Q_y = 1$.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK034

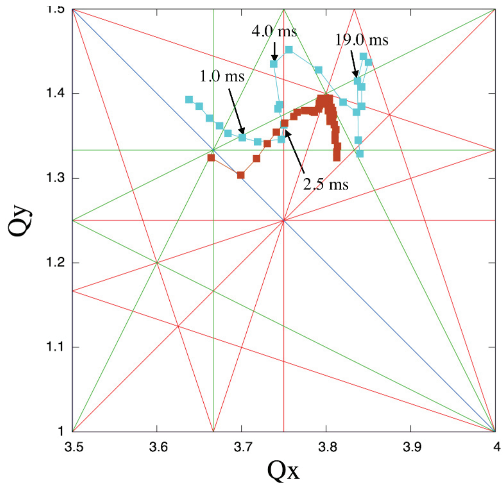

Figure 5: MAIN RING betatron tune footprints. Blue and brown squares indicate measurements and simulations, respectively.

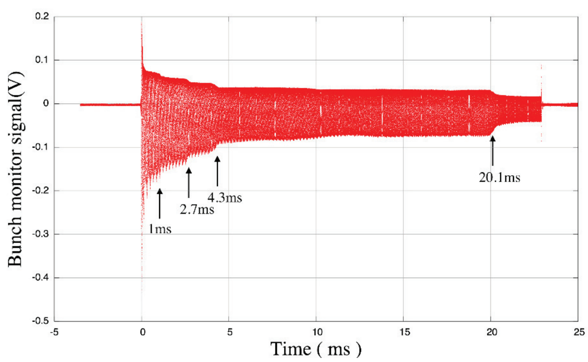

Figure 6: The output signal from the bunch monitor. There are some remarkable beam losses during acceleration.

The tune footprint during acceleration in BOOSTER is shown in Fig. 7. The tune spread is small compared with MAIN RING. It is small enough to avoid crossing the resonances. We should only be concerned with $Q_x + 2Q_y = 5$. But no remarkable beam loss can be seen as shown in Fig. 8.

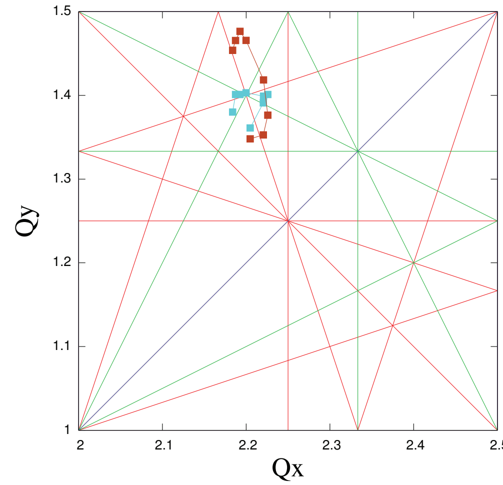

Figure 7: BOOSTER betatron tune footprints. Blue and brown squares indicate measurements and simulations, respectively.

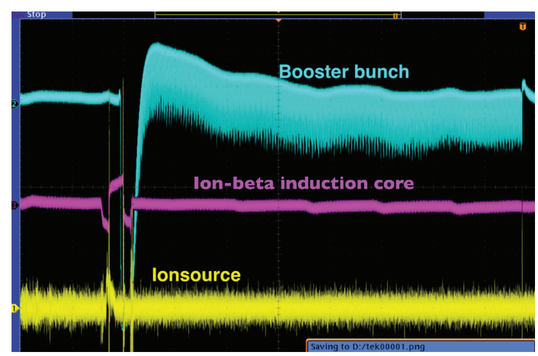

Figure 8: The output signal from the bunch monitor indicated by a blue line. There is no remarkable beam loss during acceleration.

CONCLUDING REMARKS

Like BOOSTER at KURNS, a scaling FFAG accelerator with magnets adopting the flux return yokes and field clamps to suppress the leakage magnetic field at the straight section considerably reduce the tune excursion during acceleration. In other words, it is scaled.

AKNOWLIGEMENTS

We wish to thak Mr. Hiromitsu Inoue, Mitsubishi Electric Corporation and his colleagues for giving detailed information on the design and production of the magnets adopted in BOOSETR and MAIN RING.

REFERENCES

[1] C. H. Pyeon *et al.*, "First Injection of Spallation Neutrons Generated by High-Energy Protons into the Kyoto University Critical Assembly" *J. Nucl. Sci. Technol.*, vol. 46, no. 12, p. 1091(2009).

[2] Y. Ishi *et al.*, "Present Status and Future of FFAGs at KURRI and the First ADSR Experiment", in *Proc. 1st International Particle Accelerator Conference (IPAC'10)*, Kyoto, Japan, May 23 2010, paper TUOCRA03, p. 1327–1329.

[3] S.L. Sheehy *et al.*, "Progress on Simulation of Fixed Field Alternating Gradient Accelerators", in *Proc. 6th International Particle Accelerator Conference (IPAC'15)*, Richmond, VA, USA, May 3-5 2015, paper MOPJE077, p. 495–498.