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# REMODELING OF 150 MeV FFAG MAIN RING AT KURNS TO PION PRODUCTION RING

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*Abstract*

A possibility of remodeling main ring of 150 MeV FFAG accelerator at Kyoto University, Institute for Integrated Radiation and Nuclear Science (KURNS) to Pion Production Ring (PPR) for muon transmutation study has been discussed. Design was made on the assumption that 400 MeV proton beams circulate and hit a target in the ring to generate pions. Optimizations of lattice parameters and 3D magnet modeling are reported.

## INTRODUCTION

In order to reduce and recycle high-level radioactive waste generated from nuclear reactors, studies have been conducted to transmute long-lived fission products into stable or short-lived nuclei. As one of the methods of transmutation, muon transmutation has begun to be considered. It has been discussed that main ring of 150 MeV FFAG accelerator at KURNS, shown in Fig. 1, is remodeled to PPR for muon transmutation study. The study requires a high intensity and high efficiency muon beam source. As existing muon beam sources, there are MuSIC at the Research Center for Nuclear Physics (RCNP) and MUSE at J-PARC Center [1, 2]. In these systems, muon beams are generated using a method in which proton beams accelerated by a cyclotron or synchrotron are extracted and hit a target placed outside the ring to generate pions. The pions decay during transport to muons. On the other hand, PPR uses the ERIT or MERIT method [3, 4]. In this method, a target is placed inside the ring, and proton beams circulating in the ring repeat the generation of pions by passing the target and the recovery of the lost beam energy in the RF cavity. The pions are extracted from PPR and decay to muons. By using this method, it is expected that high intensity and high efficiency muon beams will be generated. PPR will be a proof-of-principle machine of this new muon beam generation method. The design of PPR was made on the assumption that 400 MeV proton beams circulate and hit a target in the ring to generate pions.

Figure 1: Photograph of main ring of 150 MeV FFAG accelerator at KURNS.

## PION PRODUCTION RING DESIGN

### *Optical Design*

To determine basic design parameters of PPR, optical design was performed like the synchrotron design. Table 1 shows the design parameters before and after remodeling [5]. In order to increase the energy of the beam that circulates in the ring, the maximum magnetic field was increased and only the focusing (F) magnet that bends the beam in the forward direction was used, and the defocusing (D) magnet that bends it in the reverse direction was not used. Horizontal focusing was obtained by F magnet and vertical focusing was obtained by edge focus. The similar focusing scheme is discussed in [6]. Because of the combination of strong and weak focusing, this machine can be called an FFAG accelerator or a cyclotron. The field index $k$ was determined in consideration of the stability of the beam. The electromagnets of PPR were arranged as shown in Fig. 2, and the beta function and the Z-direction magnetic field is as shown in Fig. 3.

Table 1: Basic Design Parameters Before and After Remodeling

| | Beam Species | Beam Energy [MeV] | Field Index $k$ | Reference Radius [m] | Maximum Magnetic Field [T] | Horizontal Tune | Vertical Tune | Number of Cells | Basic Cell |
|---|---|---|---|---|---|---|---|---|---|
| 150 MeV FFAG Main Ring | proton | 11 - 150 | 7.8 | 5.4 | 1.6 | 3.85 | 1.2 | 12 | DFD Triplet |
| PPR | proton | 300 - 400 | 1 | 5.3 | 1.76 | 1.44 | 0.98 | 12 | F Singlet |

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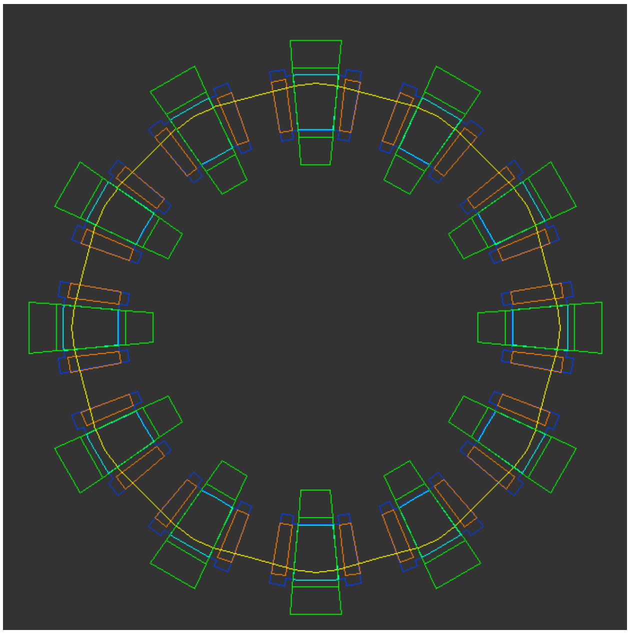

Figure 2: Arrangement of the electromagnets of PPR.

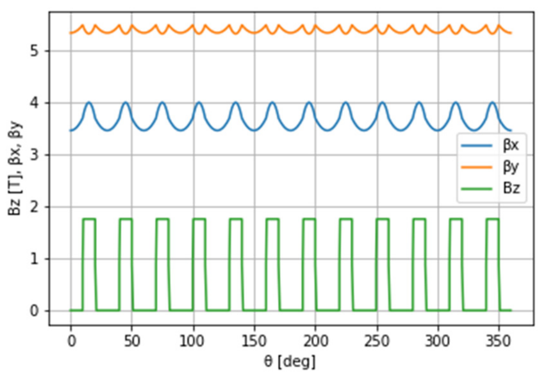


Figure 3: Beta functions and $B_z$ of PPR.

## 2D Magnetic Field Calculation

The electromagnet shape of PPR was determined by POISSON which is a two-dimensional magnetic field analysis code. In the case of PPR, the field index $k$ is small, so the shape of the pole face is approximated by a straight line, and the pole tip is cut at 45 ° by applying the Rogowski cut principle. The slope of the straight line and the cut width were selected such that the deviation of the two-dimensional local magnetic field gradient $k_{local\_2D}$ from the field index $k$ determined by the optical design was small as shown in Fig. 4 [7], even though the influence by the magnetic saturation was large. The two-dimensional local magnetic field gradient $k_{local\_2D}$ is expressed as Eq. (1) where $r$ [cm] is a radius.

$$k_{local\_2D}(r) = \frac{\left(B_z(r+dr) - B_z(r)\right)}{dr}\frac{r}{B_z(r)} \tag{1}$$

The pole gap $g$ [cm] was as shown in Eq. (2).

$$g(r) = -0.0224(r-480) + 10.4 \tag{2}$$

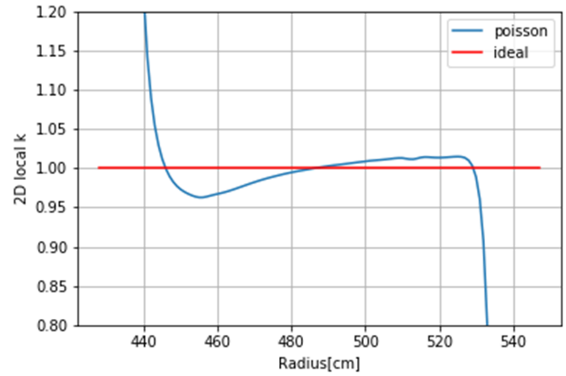


Figure 4: Two-dimensional local magnetic field gradient $k_{local\_2D}$ as a function of radius.

## 3D Magnetic Field Calculation

Based on the electromagnet shape determined by two-dimensional magnetic field calculation, a three-dimensional model of the electromagnet was created as shown in Fig. 5.

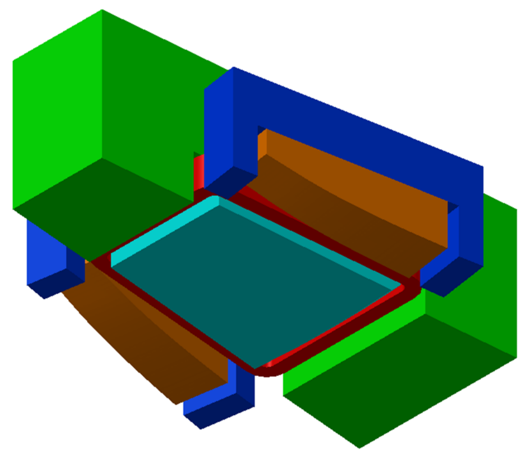

Figure 5: 3D model of the electromagnet of PPR.

The F pole was remade and the D pole was used as a field clamp. Also, a new yoke was added. Three-dimensional magnetic field calculation was performed using this model. OPERA-3D which is three-dimensional magnetic field analysis software was used for the calculation. Fig. 6 shows $k_{local\_2D}$ at the center of the F pole. Comparing Fig. 4 and Fig. 6, there is a slight difference between the two-dimensional magnetic field calculation and the three-dimensional magnetic field calculation. Fig. 7 shows the three-dimensional magnetic field gradient $k_{local\_3D}$ . It is smaller than the field index $k$ due to the influence of the magnetic field due to the D pole. The three-dimensional magnetic field gradient $k_{local\_3D}$ is expressed as Eq. (3) where $B_l$ is an integral value of $B_z$ in the circumferential direction of one cell, and is expressed as Eq. (4).

$$k_{local\_3D}(r) = \frac{r}{B_l(r)}\frac{dB_l(r)}{dr} - 1 \tag{3}$$

$$B_l(r) = \int_{cell} B_z(r,\theta) r d\theta \tag{4}$$

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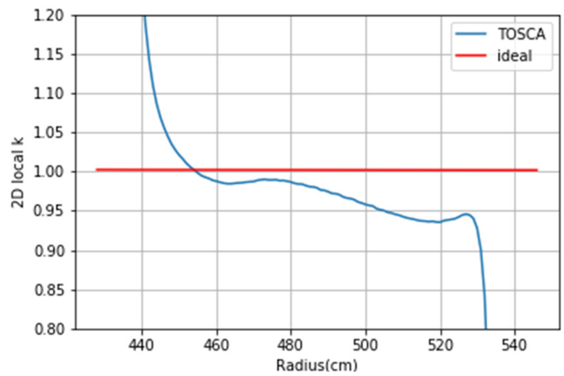

Figure 6: Two-dimensional local magnetic field gradient $k_{local\_2D}$ as a function of radius at the center of the F pole.

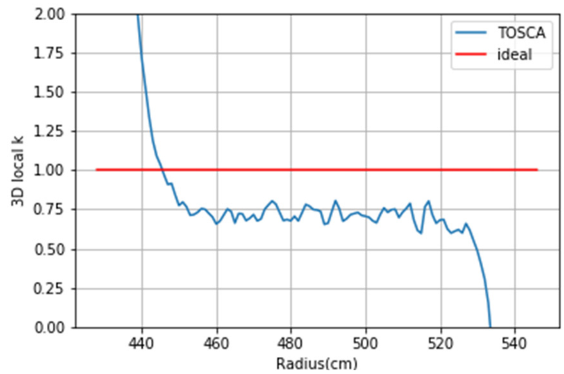

Figure 7: Three-dimensional local magnetic field gradient $k_{local\_3D}$ as a function of radius.

### *Orbit Calculation*

The orbit of the beam was simulated using the results of three-dimensional magnetic field calculation. The change in tune when accelerating from 300 MeV to 400 MeV is shown in Fig. 8. Horizontal tunes during acceleration are too close to the third resonance line. To avoid the resonance effect, these can be corrected by further optimization of $k$ and iron should be added to the four shunts to reduce the magnetic field due to the D pole.

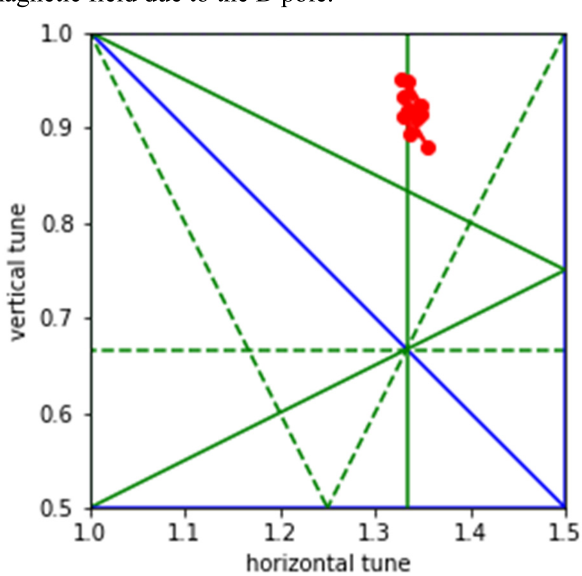

Figure 8: Tune diagram of PPR.

## SUMMARY

A design for remodeling main ring of 150 MeV FFAG accelerator at KURNS to Pion Production Ring was reported. It was performed in the order of optical design, two-dimensional magnetic field calculation, three-dimensional magnetic field calculation, and orbital calculation. One of the plans for remodeling was shown. Further optimization of lattice parameters and 3D magnet modeling is needed. In the future, it is also necessary to consider the energy spread of proton beams after interaction with the target and the pion generation efficiency.

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