BEAM OPTICS STUDY ON FFA-MERIT RING*

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Abstract

An intense negative muon source MERIT (Multiplex Energy Recovery Internal Target) for the nuclear transformation to mitigate the long-lived fission products from nuclear plants has been proposed. For the purpose of proof-of-principle of MERIT scheme, a FFA(Fixed Field Alternating focusing) ring has been developed. The beam optics of the FFA-MERIT ring has been studied.

INTRODUCTION

Recently, nuclear transmutation with negative muons has been conceived as one of the ways to mitigate the radioactive nuclear wastes such as long lived fission products (LLFPs)[1].In muonic atom, which is formed by trapping negative muon, the atomic nucleus absorbs a negative muon with large probability (95 per cent) [2], if the atomic number Z is more than 30 and then, it transforms to stable nucleus by beta decay and the emission of several neutrons. For example, long lived cesium isotope ^{135}Cs ($\tau_{1/2}$ = 2.3 million years) which is produced from the nuclear power plant in burning out one ton of enriched the nuclear fuel including 3 per cent ^{235}U can be transformed to non-radioactive Xe isotopes within about five years, if the yield of negative muon is 10^{16} μ^-/s.

Negative muons decayed from negative pions are efficiently produced by the nucleon-nucleon interactions with high energy hadron beam using the target nucleus containing neutrons.

In order to generate negative muons effectively, MERIT (Multiplex Energy Recovery Internal Target) scheme has been proposed. The principle of the MERIT scheme is shown in Fig.1. Contrary to the original ERIT-scheme [3,4], the transverse emittance growth caused by multiple scattering is rather modest since a primary hadron beam energy is relatively high. On the other hand, the longitudinal emittance growth rate becomes large. The wedge-shaped target placed at the dispersive orbit could reduce this effect and also the injection beam energy becomes lower, which could cure the load of the injector.

The characteristics of the MERIT scheme are shown as follows.

- Energy recovery and ionization cooling
- CW operation with fixed RF frequency beam acceleration and storage
- Negative pion production using internal thin target

There are a couple of difficulties in negative pion production. One is the energy loss of the projectile proton by ionization of target. The efficiency of negative pion production drops until the particle energy reaches the threshold energy of pion production at about 250MeV/u. Another problem is the absorption of negative pions in the solid target. The absorption cross section of negative pions with the target nucleus is so large that a thinner target must be used. Thus, a high beam current and a thin target are both essential to improve the efficiency in negative muon production.

In MERIT scheme, the fixed RF frequency acceleration makes a cw beam operation with low energy beam injection. Negative pion production using a thin target has advantages for reducing the negative pion loss in the target and keeping high reaction rate with energy recovering and cooling by RF re-acceleration.

In order to prove a principle of MERIT scheme, in particular, on the fixed RF frequency beam acceleration and storage with a wedge type of thin internal target, a scaling type of FFA ring(PoP-MERIT) has been developed with re-modelling the FFA-ERIT proton ring [3,4] which was built at the institute for radiation and nuclear science in Kyoto University (KURNS).A charge-exchange injection with negative hydrogen beam is used for the FFA-ERIT proton ring.

This paper describes the beam optics study on COD (closed orbit distortion) correction and betatron motion in PoP-MERIT ring.
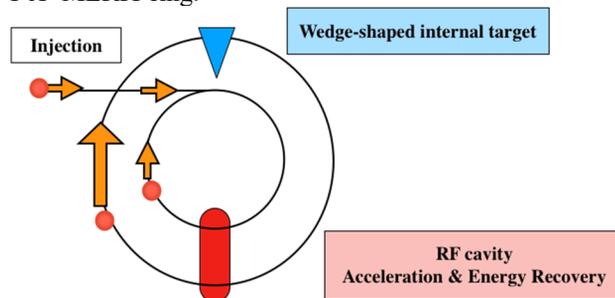
Figure 1: Schematic diagram of MERIT scheme.

POP-MERIT RING

PoP-MERIT has been developed with several modifications of existing FFA-ERIT proton ring, however, a charge-exchange injection with negative hydrogen beam is still used for the FFA-ERIT proton ring.

MC4: Hadron Accelerators

A12 Fixed-Field Alternating Gradient Accelerators

A semi-isochronous acceleration in scaling FFA is useful for the fixed RF frequency acceleration [5], where it is essential to keep a slippage factor(η) close to zero. In case of the scaling FFA, η depends only on the field index k and Lorentz factor γ as shown in Eq.1.The injection beam energy of FFA-ERIT proton ring is about 10MeV.Thus, the field index k was changed from the original value of 1.92 to about 0.07 by modifying the magnetic field shape, which led the slippage factor of -0.044.

$$\eta = \frac{1}{k+1} - \frac{1}{\gamma^2} \qquad (1)$$

The difference of the longitudinal beam motions before and after modifying field index k are shown in Fig. 2.With this modification, the energy range of the ring was extended to accelerate the proton beam from 9.5 MeV to 12.5 MeV.
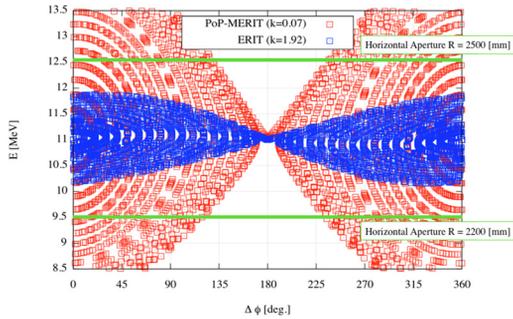
Figure 2: The longitudinal beam motions of fixed RF frequency acceleration for two different field indexes. The blue and red points show the beam motions for two different cases; one is for the field index of $k = 1.92$ and the other for $k = 0.07$, respectively.

In the scaling FFA, the horizontal tune can be obtained approximately from Eq. (2).The horizontal tune of PoP-MERIT ring becomes $\nu_H \sim 1.03$.

$$\nu_H \sim \sqrt{1+k} \qquad (2)$$

Table 1: Parameters of ERIT and PoP-MERIT Ring

Parameters	ERIT	PoP-MERIT
Particle	proton	proton
Lattice	FDF-triplet	FDF-triplet
Cell	8	8
Field Index k	1.92	0.07
Slippage Factor η	-0.63	-0.044
Proton Energy [MeV]	11.0	9.5 ~ 12.5
Orbit Radius [mm]	2350	2200 ~2500
Tune (H/V)	1.76 / 2.22	1.03 / 1.25
RF Voltage [kV]	75~225	75~225
Harmonic Number	6	6
RF Frequency [MHz]	18.12	18.12

COD CORRECTION AND INJECTION ORBIT MATCHING

In the MERIT scheme, a relatively large horizontal aperture is essential for beam acceleration and storage. Since the horizontal tune of the PoP-MERIT ring is about 1.03, which is close to integer, a large horizontal COD could be induced with small dipole field errors. Thus, the COD correction in the PoP-MERIT ring is especially at the beam injection point is essential and important.

The amplitude of horizontal COD can be estimated with Eq. (3). In this equation, $\delta(Bl)$ is a strength of dipole field error at $s = s_0$, and $\beta(s)$ and $\psi(s)$ present the beta function and betatron phase, respectively.As shown in Eq.(3),when the horizontal tune is close to an integer number, the amplitude of COD becomes large.

$$x(s) = \left[\frac{\sqrt{\beta(s)\beta(s_0)}}{2sin(\pi\nu_H)} \frac{\delta(Bl)}{B\rho}\right] cos(\pi\nu_H \qquad (3)$$
$$ - |\psi(s) - \psi(s_0)|)$$

One of the strong dipole field errors in the PoP-MERIT ring is field clamps at the RF cavity section. Because of the size of the RF cavity, the field clamps at the RF section is thin and short compared with other sections.The fringing field at the RF section behaves differently from those at other sections and localized dipole field errors are induced.

The dipole magnetic field error at the RF cavity section was evaluated with a 3D magnetic field simulation code(Opera3D/TOSCA) [6]. The field error integral (BL: error field strength times effective length) as a function of the ring radius at the RF section is shown with a black line in Fig. 3. As can be seen from this figure, the error field integral is slightly increased but almost constant as a function of the ring radius, which is about 0.004Tm around the beam radius of 2350 mm. The maximum COD caused by the error field is about 60 mm, which could reduce the horizontal aperture to less than 50%.

In order to correct the field error, a pair of back-leg coils were wound around the magnet yokes beside the RF cavity. The turn number of back-leg coil is 32 and the maximum current was 100 A, which corresponds to about 7% of the field strength of main magnet. The calculation shows that the field error could be corrected by adjusting the coil current of both coils properly, as shown in Fig. 3.When the coil current of back-leg is 50 A, the field error at design orbit decreases to almost zero and the COD amplitude could be well suppressed.

The trajectories of the closed orbit for different back-leg coil currents at the beam injection energy were calculated with beam tracking simulation and the results are shown in Fig. 4. Apparently, the injection orbit distortion can be corrected by the back-leg coils. When the coil current is 70 A, the injection beam orbit overlaps the position of the charge-exchange foil so that the injection matching can be achieved.
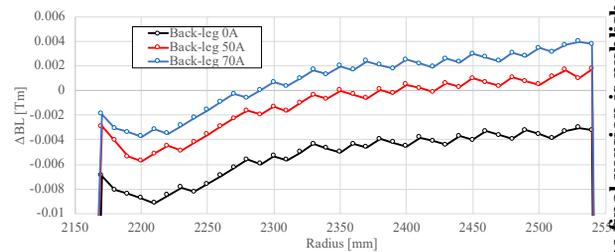
Figure 3: Magnetic field error at the RF cavity section. The vertical axis shows the field errors estimated from the difference of BL integrations with and without RF cavity.

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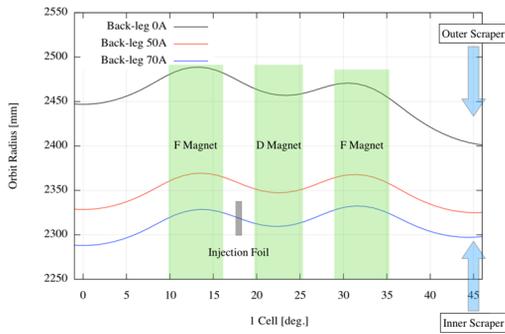
Figure 4: Closed orbit profiles for various back-leg coil currents at the injection point. The positions of the charge-exchange injection foil and scrapers are also shown in the figure.

The effect of back-leg coil currents to the closed orbits was experimentally examined by measuring the horizontal beam size and position of the circulating beam at the injection energy. The beam size and position were measured using a pair of beam scrapers (inner and outer) placed at the straight section next after the beam injection point.

Figure 5 shows the variation of output signal from the beam bunch monitor for different positions of the beam scrapers. The measurements were taken after a sufficient time (>50turns) from beam injection enough to smear the beam in the horizontal phase space. As can be seen from this figure, the closed orbit moved towards the design injection orbit and the beam size became smaller when the back-leg coil current was 70 A, which was expected from Fig. 4.
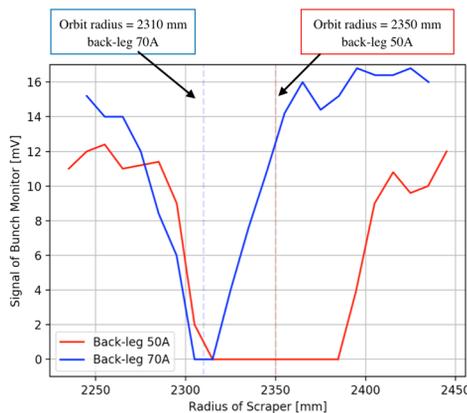
Figure 5: Beam size and orbit position measured by the beam scrapers.

BETATRON TUNE

The field index is important in PoP-MERIT as described above, therefore, the horizontal and vertical betatron tunes of the PoP-MERIT ring were measured. The measurements have been carried out with processing the sampled and digitized difference signals from the electro-static beam position monitors for the beam circulating around the ring at the beam energy of about 10.5 MeV. The measured horizontal and vertical tunes are plotted with the red open squares in the tune diagram shown in Fig. 6. The horizontal and vertical tunes are slightly varied in the scaling FFA ring

by changing the ratio of the focusing and defocusing magnetic field strength (F/D ratio). Each point in Fig. 6 shows for the different F/D ratio (2.2 ~ 2.6). Also in this figure, the calculated betatron tunes are plotted with the blue open squares, which are estimated by beam tracking simulations using the 3D magnetic field maps obtained from Opera3D/TOSCA. As it can be seen from this figure, the measured betatron tunes are in good agreement with those obtained from the beam tracking simulations.
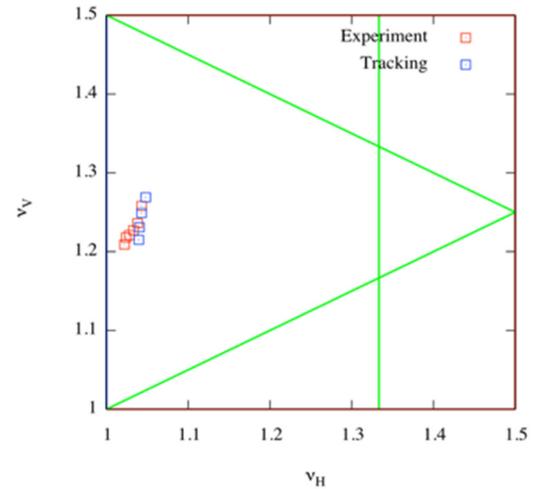
Figure 6: Betatron tunes. The red open squares show the betatron tunes obtained from the measurement and the blue ones from the beam tracking one, respectively.

SUMMARY

Beam optics study on the COD correction and betatron motion of the PoP-MERIT ring has been carried out for the preparation of proof of principle beam experiment of MERIT scheme. From confirmation of validation of the COD correction method using back-leg and tune measurement, the beam experiment on MERIT scheme have been ready. The proof-of-principle beam experiment of MERIT scheme with an internal target in the PoP-MERIT ring is in progress.

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