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STUDY OF MERIT RING FOR INTENSE SECONDARY PARTICLE PRODUCTION

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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 have been proposed. For the purpose of proof-of-principle of MERIT scheme, a FFA (Fixed Field Alternating focusing) ring has been developed. In this paper, the results of study for proof-of-principle experiment on MERIT scheme will be reported.

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%) [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% of ^{235}U can be transformed to non-radioactive Xe isotopes within about five years, if the yield of negative muon is $10^{16} \mu^-/s$.

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 250 MeV/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.

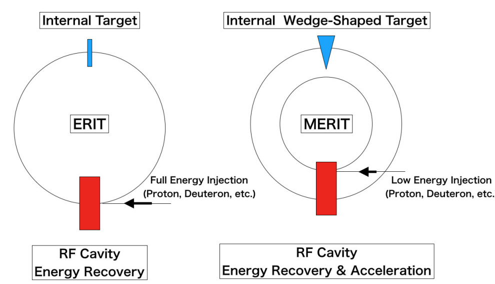

Figure 1: Schematic diagram of ERIT and MERIT scheme.

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.

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, the name is MERIT-PoP (Proof-of-Principle) ring has been developed with remodeling the FFA-ERIT ring [3,4], which was built at the Institute for Integrated Radiation and Nuclear Science in Kyoto University (KURNS). As preparation for the experimental study on MERIT scheme, beam study on the closed orbit distortion (COD) correction and measurement of betatron tune of the MERIT-PoP ring was carried out [5]. In this paper, study for the PoP experiment on MERIT scheme using the MERIT-PoP ring is reported.

MERIT-POP RING

The MERIT-PoP ring has been developed with several modifications of existing the FFA-ERIT proton ring. A semi-isochronous acceleration in the scaling FFA is useful for the fixed RF frequency acceleration [6], 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

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γ as shown in Eq. (1).

$$\eta = \frac{1}{k+1} - \frac{1}{\gamma^2} \tag{1}$$

The injection beam energy of the MERIT-PoP ring is about 10.0 MeV. Thus, the field index k was changed from the original value of 1.92 to about 0.07 by changing the magnetic pole shape as shown in Fig. 2, which led the slippage factor of −0.044. With this modification, the energy range of

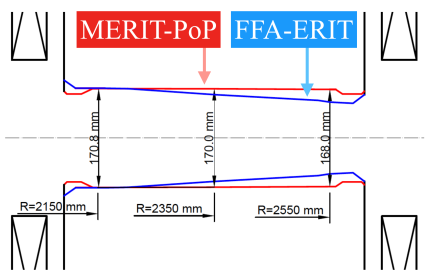

Figure 2: Schematic view on modification of magnetic pole shape. This figure shows the pole shape of focusing magnet of the FFA-ERIT ring and the MERIT-PoP ring, respectively.

the MERIT-PoP ring was extended to accelerate the proton beam from approximately 9.5 to 12.0 MeV. All parameters are shown in Table 1.

Table 1: Parameters of MERIT-PoP Ring

Ring Paramters		
Particle		Proton
Number of Cells		8
Lattice		FDF-triplet
Field Index	k	0.07
Energy Range	[MeV]	9.5 – 12.0
Orbit Radius	[mm]	2250 – 2500
Slippage Factor	η	-0.044
Betatron Tune	H/V	1.03 / 1.25
Magnetic Field F/D	[T]	0.59 / 0.14
Opening Angle of F/D magnet	[deg.]	6.4 / 5.1
Minimum Half Gap of F/D magnet	[mm]	84.0 / 85.2
RF Voltage	[kV]	75–225
Harmonic Number		6
RF Frequency	[MHz]	18.12

In the scaling FFA, the horizontal tune can be obtained approximately from Eq. (2). The horizontal tune of MERIT-PoP ring becomes $\nu_H \sim 1.03$. In Fig. 3, the betatron tune of the MERIT-PoP ring plotted in the tune diagram is shown.

$$\nu_H \sim \sqrt{k+1} \tag{2}$$

INTERNAL TARGET

In order to show the beam acceleration and storage in MERIT scheme experimentally, a semi-wedge type of internal target was designed and made. The design of the internal

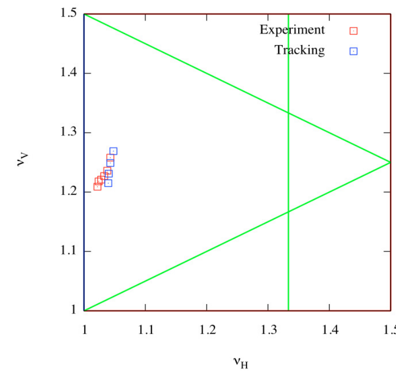

Figure 3: Betatron tune of the MERIT-PoP ring. Red and blue plots show the results of measurement and tracking simulation, respectively. Betatron tunes were measured and calculated by changing the focusing and defocusing magnetic field strength.

target is shown in the Fig. 4. The target material is carbon, which is composed of two stages in thickness. The thickness of the inner stage is 720 µg/cm^2 and the outer stage is 980 µg/cm^2, respectively. The width and height of the target are 140 and 115 mm, which corresponds to approximately 40% and 80% of the region of the vacuum chamber in horizontal and vertical direction, respectively. The energy loss at each stage for 11 MeV proton beam is about 27 and 37 keV, respectively. Also, the scattering at each stage for 11 MeV proton beam is about 1.9 and 2.2 mrad, respectively.

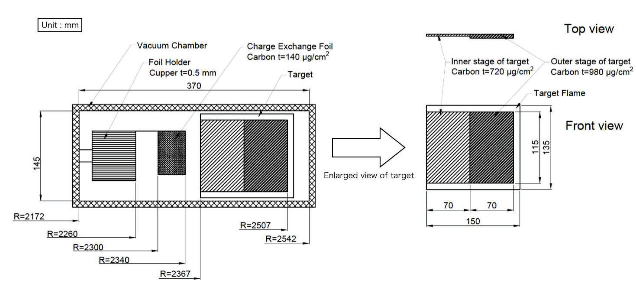

Figure 4: Design of the internal target.

TRACKING SIMULATION WITH G4beamline

In order to evaluate the particle motions in detail, the particle tracking simulation code, G4beamline (G4BL), was used. The G4BL code is basically a single particle tracking and simulation code based on the Geant4 toolkit, which enable to estimate the particle interactions and tracking in collision with the materials [7]. The three dimensional field distribution of the ring magnet, which is required for the beam tracking, were calculated with the OPERA3D/TOSCA code [8].

The result of G4BL beam tracking in longitudinal direction for two different cases are shown in Fig. 5. Figure 5 shows the results when RF voltage is 75 kV. Upper and lower graph in Fig. 5 show the result in case without and with the internal target, respectively. As can be seen from Fig. 5, the

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beam is lost until about 50 turn in case without the internal target because the beam hit the radial outside of physical aperture located around the 12.0 MeV. In contrast, in case with the internal target, the beam starts to hit the internal target after about 20 turns, and reaches maximum energy of 11.5 MeV after 40 turns. After that, beam circulates more than 100 turns with acceleration and storage although the beam intensity decreases gradually because of the emittance growth.

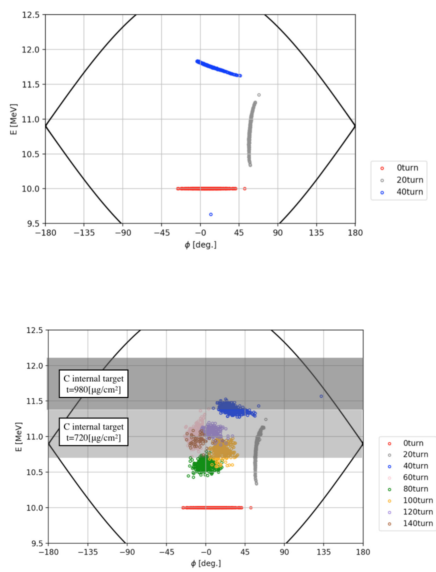

Figure 5: Results of G4BL tracking in longitudinal direction for all 20 turns for MERIT-PoP ring for two different cases; upper and lower graph show the result without and with the internal target, respectively. The two grey regions in the lower graph indicate the position of each stage of the internal target.

SUMMARY

This paper presents study for the PoP experiment on MERIT scheme, which has been proposed as an intense negative muon source. The MERIT-PoP ring was formulated by remodelling the existing ring for neutron source with energy recovering internal target with ionization cooling [3, 4]. To evaluate the particle motion for the PoP experiment on MERIT scheme using the MERIT-PoP ring in detail, tracking simulation using the G4BL was performed. The results showed beam circulation more than 100 turns with acceleration and storage with the internal target.

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