Memoirs of the Faculty of Engineering, Kyushu University, Vol.77, No.1, September 2017

Intense Muon Source with Energy Recovery Internal Target (ERIT) Ring Using Deuterium Gas Target

by

Yoshiharu MORI[*], Hidefumi OKITA[†],Yoshihiro ISHI[**] , Yujiro YONEMURA[***]
and Hidehiko ARIMA[***]

(Received September 13, 2017)

Abstract

An intense muon source for muon nuclear transformation, in particular, to mitigate the long lived fission products of nuclear reactor wastes is presented. The scheme is based on ERIT(energy recovery internal target) ring with gaseous deuterium target. Negative muon production of more than $10^{16}\mu^-$/s seems to be possible with this scheme.

Keywords: Muon, Nuclear Transmutation, ERIT, LLFP, Accelerator, FFAG

1. Introduction

Reduction of nuclear wastes, especially long-lived radioactive species whose half-lives exceed more than thousand years such as long-lived fission products (LLFPs), is one of the biggest issues concerning energy production for society based on nuclear power plants. One of the possible ways to mitigate LLFPs is to apply a nuclear transformation process induced by hadronic or leptonic interactions. In muonic atom, which is formed by trapping a negative muon, the atomic nucleus absorbs a negative muon with large probability (>95%), if the atomic number (Z) is more than 30. It transforms to a stable nucleus by beta decay and the emission of several neutrons[1), 2)].

In the case of cesium, for example, long-lived cesium isotope, ^{135}Cs ($\tau_{1/2}$=2.3Myear), which is about 13% of total cesium isotopes produced from the nuclear power plant in burning out one ton of enriched the nuclear fuel including 3% ^{235}U can be transformed to stable (non-radioactive) xenon isotopes such as ^{131}Xe, ^{129}Xe, ^{128}Xe and ^{127}Xe within five years, if the yield of negative muon is

* Professor, Research Reactor Institute, Kyoto Univ., Invited Professor, Department of Energy Engineering
† Graduate Student, Department of Nuclear Engineering, Kyoto Univ.
** Associate Professor, Research Reactor Institute, Kyoto Univ.
*** Assistant Professor, Department of Applied Quantum Physics and Nuclear Engineering

This work was funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan)

$1\text{x}10^{16}$ μ^-/s, as shown in **Fig. 1**.

Negative muons decayed from negative pions are efficiently produced by the nucleon-nucleon interactions with NΔ resonances with high energy proton or deuteron beams colliding with the target nucleus containing neutrons[3]. A beam energy of 500-600MeV/u or more is necessary to produce negative pions effectively.

There are a couple of problems for negative pion production with this energy range. The projectile particles lose their energy by ionization of target atoms while they pass through a thick target for negative pion production. The efficiency of negative pion production, conversely, becomes smaller because the cross section of pion production drops abruptly until reaching the threshold energy of pion production at about 250MeV/u. The absorption of negative pions in the solid target is another problem. The absorption cross section of negative pions with the target nucleus is so large that a thinner target must be inevitably used to eliminate the effect.

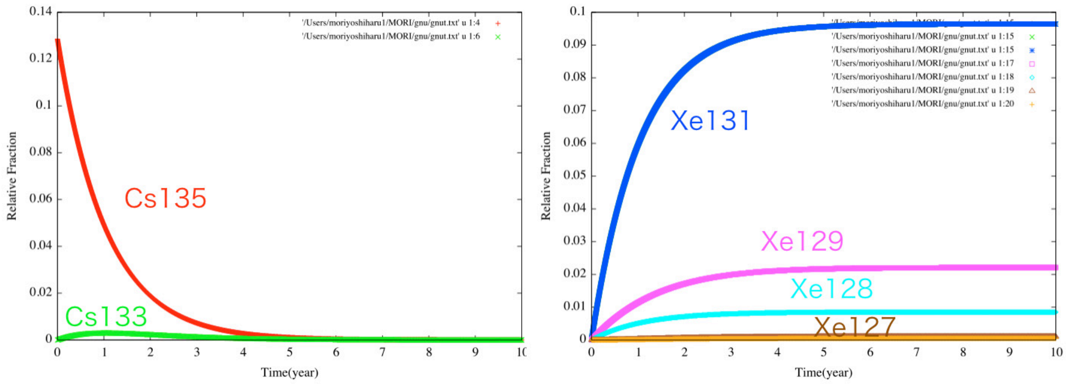


Fig. 1 Muon nuclear transformation for ^{135}Cs isotope included in the one ton spent fuel of nuclear power plant as a function of time. Horizontal axis shows time (year) and vertical shows the relative portions Cs and Xe isotopes.

In order to avoid these problems and to increase the negative pion production efficiency, use of a thinner target and recovery of the beam energy loss by re-acceleration, the so called energy recovery internal target (ERIT) scheme, is useful and convenient. The ERIT scheme was proposed at first for the efficient production of secondary particles such as neutrons and unstable nuclei [4), 5)]. The first ring of ERIT scheme was constructed at the research reactor institute of Kyoto University[6)].

This paper presents a possibility of applying the ERIT principle for intense negative pion/muon production of more than $10^{16}\pi^-(\mu^-)$/s for treating (mitigating) the particular long-lived radioactive fission products such as ^{135}Cs ($\tau_{1/2}$=2.3Myear) generated as nuclear wastes of nuclear power plants.

2. Negative Muon Production with ERIT

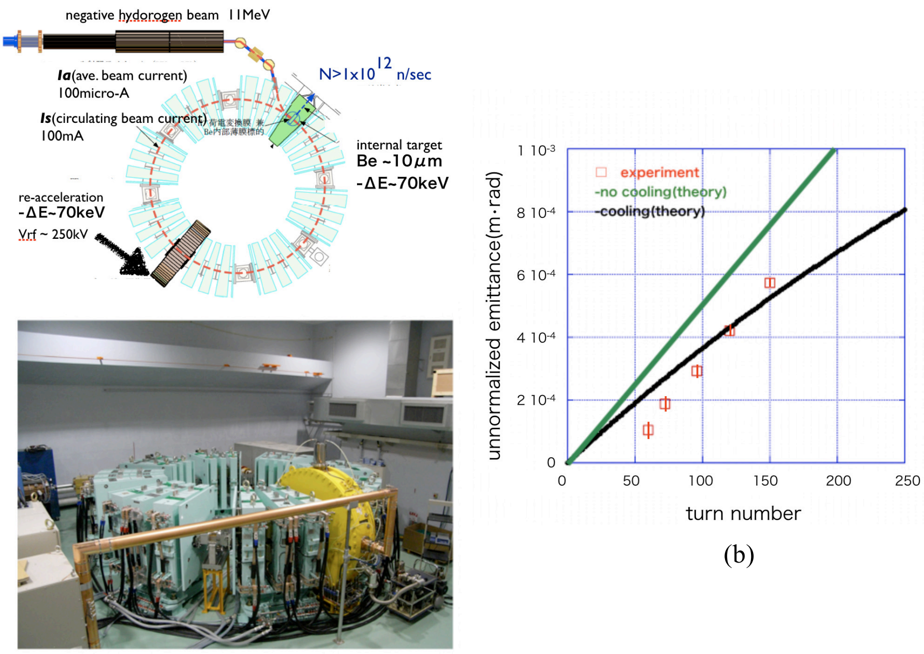
2.1 Principle of ERIT

In the ERIT scheme, projectile particles circulate and pass through a thin target placed in the ring and generate the secondary particles such as neutrons, pions, etc. Particles lose energy through ionization interactions (electronic stopping power) and are succeeded by re-acceleration in rf cavities. Beam emittance growth caused by multiple scattering (Rutherford scattering and straggling) at the target can be counteracted by ionization cooling. Re-acceleration imposes only longitudinal momentum transfer, while the energy losses occur in parallel to the particle momentum including transverse and longitudinal momentum; thus, the beam emittance does not increase. Ionization beam cooling has been proposed by Skrinsky[7] and Neuffer[8]. Longitudinal cooling occurs if,

$$\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E} > 0. \tag{1}$$

Here, dE/ds is the stopping power. Therefore, if a wedge-shaped target is placed in the ring at the particular position causing orbit dispersion, longitudinal emittance can be cooled.

The ERIT scheme was demonstrated at the research reactor institute of Kyoto University as a low energy neutron source. **Figure 2(a)** shows a schematic layout and a photograph of the world-first ERIT neutron source with ionization cooling at Kyoto University. The beam optics of the ERIT ring are based on fixed field alternating gradient(FFAG) focusing to hold large transverse and longitudinal acceptances. The 11MeV H^- ion beam is injected from a linear accelerator (linac) into the FFAG ring. The diameter of the ring at the central orbit is about 4.5m. A beryllium foil, a few μm in thickness, is placed at the straight section of the ring, where H^- ions from the linac are charge-stripped to protons and merged with the circulating proton beam. The energy loss at the beryllium target was recovered by the rf cavity, whose frequency was 18.1MHz and rf voltage was 250kV. The Be(p,n)B reaction is used for neutron production in this scheme. In this design, neutron production of more than 1×10^{12} n/s is expected with an average beam current of 100μA injected from the linac and beam circulation of more than 500turns in the ring.



(a)

Fig.2 (a) A schematic layout of the ERIT neutron source (upper) and a picture of the apparatus built at KURRI. (b) The beam emittance growth as a function of number of the beam circulating turns in the ERIT neutron ring which was measured by the beam scraping method. The error bars in the figure show the systematics errors come from the beam scraper positions, which was 0.5mm in accuracy. The theoretical values estimated with the rate equations of ionization cooling are also shown in the figure.

The emittance growth rate in the vertical direction as a function of turn numbers was measured with a beam scraper and an electrostatic bunch monitor. The bunch monitor permits a turn-by-turn measurements of the beam intensity during beam accumulation since the maximum amplitude of its signals was proportional to the number of charged particles per bunch. The position of the beam scraper was moved stepwise along a vertical axis and scraped the beam, and the output signals of the bunch monitor were measured. Since the beam accumulation is stopped when the beam hits the scraper and no increase of the beam intensity occurs after it, thus by looking at the accumulation time from the beginning of beam injection, the number of turns required for taking the emittance growth determined by the scraper position can be obtained.

The experimental results showed that these design configurations and requirements were successfully satisfied. By measuring the transverse emittance growth as a function of beam turn number, which was estimated by measuring the beam size with a beam scraper, we found that ionization cooling worked well as shown in **Fig.2(b)**.

2.2 Production of negative muon

Long-lived radioactive nuclear wastes from nuclear power plants are one of the biggest issues in present society. Muon nuclear transformation with intense negative muons may be worthwhile, if efficient production of a large number of negative muons is possible. For this, the application of ERIT for negative muons has been already proposed [9), 10)]. In this proposal, the projectile particles are protons which are injected at the relatively low energy of 400MeV and accelerated up to about 800MeV by an FFAG ring accelerator with fixed frequency rf acceleration.

After acceleration to the top energy, the beam is stored with the help of a wedge shaped liquid lithium target which is placed in the maximum energy orbit. If the target becomes thicker towards the outside of ring, then the beam stays around the maximum energy orbit where beam acceleration and energy loss at the target are well balanced. Also, the ionization beam cooling helps to suppress the emittance growth transversely and longitudinally, and the beam circulates until the requisite number of turns generates enough negative pions/muons. The details have been reported previously [11)].

One of the difficulties in this scheme is how to collect and transport negative pions and muons produced at the lithium target to the treatment position of nuclear wastes. In the present design, negative pions and muons generated at the liquid lithium target are swept away from the ring by the bending magnetic field, and captured and transported by wide aperture and high field solenoid magnets. The overall capture efficiency is estimated to be about 50% or less. None the less the production yield of negative muons in this system can satisfy the requirement.

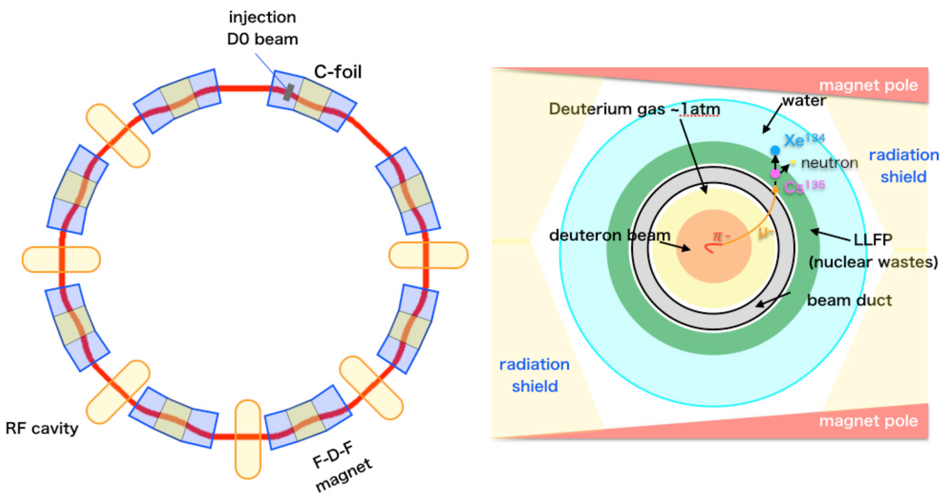


Fig. 3 (a) Schematic layout of the ERIT ring for negative muon production. (b) Cross sectional view of the ring pipe.

A deuterium gas target filling up the beam pipe of the ERIT ring instead of a liquid lithium thin target may improve the pion/muon capture efficiency and make muon nuclear transformation of long-lived nuclear wastes more manageable and uncomplicated. Pions are generated everywhere in the beam pipe around the ring. Negative muons decayed from negative pions are swept away to the outside of the beam pipe by the magnetic field and finally trapped as muonic atoms by LLFPs which cover the beam pipe, as shown in **Fig.3(a)** and **(b)**. In this scheme, therefore, almost all negative muons could be efficiently utilized to mitigate the long-lived fission products using muon nuclear transformation. Other energetic particles produced at the deuterium gas target such as neutrons, protons, positive and neutral pions and gamma rays could be thermalized by a water cell surrounding the beam pipe.

In this design, contrary to the previous one, the deuteron is chosen as the projectile particle instead of the proton. The cross section of negative pion production is almost five times larger than that of the proton for a beam energy of about 600MeV/u, although the beam loss caused by the break-up reaction to a proton and a neutron is large. The negative pion production cross section for a 600MeV/u deuteron is about 20mb [12]. Therefore, the negative pion yield Y attained with this system is presented as follows.

$$Y = L\sigma_{\pi} \,. \tag{2}$$

Here, σ_π is the negative pion production cross section and L is the luminosity ($cm^{-2}\cdot s^{-1}$) which can be expressed as follows.

$$L = N_d v_d n_T \,. \tag{3}$$

Here, N_d is the number of projectile particle(deuteron) per ring, v_d (cm/s) the projectile particle velocity and n_T (cm^{-3}) is the target particle density. A negative muon yield of 1×10^{16} μ^-/s can be accomplished when the luminosity is 5×10^{41} ($cm^{-2}\cdot s^{-1}$). When the pressure of deuterium gas target is 1atm, N_d becomes 7.9 $\times10^{11}$deuterons per ring.

The total beam loss cross section, σ_l, including deuteron break-up and pion generation estimated by Geant4:G4BL [13], is approximately 120mb, which is 6 times larger than the negative pion production cross section. Thus, a deuteron beam current of about 10mA should be continuously supplied to the system to attain the negative muon yield of 1×10^{16}(s^{-1}). On the other hand, the mean free path of the projectile particle, l_{mfp}, is about l_{mfp}=$1/\sigma_l n_T$~3000m, which is equivalent to a path length of about 90turns circumference of the ring whose diameter is about 11m. Thus, the ring acceptance should be large enough to accept the beam whose emittance is grown by multiple scattering and straggling after 90 turns. On the other hand, the system is under the circumstances of ionization cooling, thus, the beam energy loss by ionization is recovered by rf re-acceleration and the emittance blow up is suppressed. The emittance growth as a function of beam path can be estimated by ionization cooling rate equations [8].

Figure 4 shows the transverse beam emittance behavior estimated by the rate equation for the deuteron beam and deuterium target described above as a function of number of turns. Here, a beta function of 4m averaged over the ring is assumed. As can be seen from the figure, since the normalized rms emittance is about 6×10^{-5} m·rad after 100 turns, a ring acceptance(unnormalized) of more than 5×10^{-4} m·rad, which is almost ten times the rms emittance, seems to be enough.

The stopping power of 600MeV/u deuteron in deuterium gas is about 3MeV/g·cm^{-2} and the energy loss per turn in the ring filled with 1atm deuterium gas becomes approximately 1MeV. Therefore, the total rf voltage of more than 10MV, when the rf harmonic is one, seems to be enough for compensating the energy loss per turn.

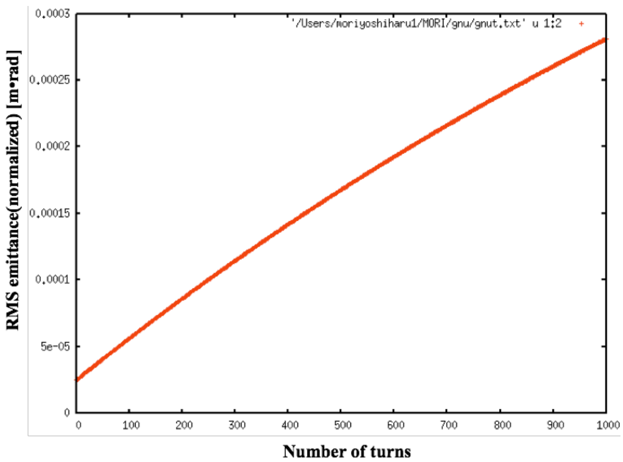


Fig.4 Transverse emittance growth as a function of number of beam circulating turns estimated with the rate equations of ionization cooling.

2.3 ERIT ring design

A preliminary ERIT ring design for negative muon production with a deuteron beam has been carried out. **Table 1** is a list of basic parameters of the ring. The ring is composed of an eight fold symmetry FDF scaling FFAG lattice and superconducting(SC) magnets are assumed to be used because of less consumption of the operational electric powers and the compactness of the ring size. The average ring radius of 5.5m is chosen at the central orbit so that the maximum magnetic field strength of SC magnet can be modest.

Table 1 Ring parameters.

Energy	1200MeV(600MeV/u)
Magnetic rigidity	8.126Tm
Lattice	FDF
Average radius	5.5m
Magnetic field(F)	4.016T
Magnetic field(D)	3.509T
Number of cell	8
Packing factor	0.7
Opening angle	
Focusing magnet	0.2032rad
Defocusing magnet	0.1432rad
Gap	0.01732rad
Geometrical field index	2.4
F/D ratio	1.1
Betatron tune(H):Q_H	0.2188/cell
Betatron tune(V) :Q_V	0.1797/cell
Curvature(F): ρ_f	2.023m
Curvature(D): ρ_d	2.316m

The betatron tunes per cell are 0.22 and 0.18 in horizontal and vertical directions, respectively. The averaged beta functions over the ring are about 3.1m and 3.8m in horizontal and vertical directions, respectively. The dynamic aperture of the ring is greater than 2×10^{-2}m·rad for both horizontal and vertical directions as shown in **Fig.5**, which is large enough for the requirement described above.

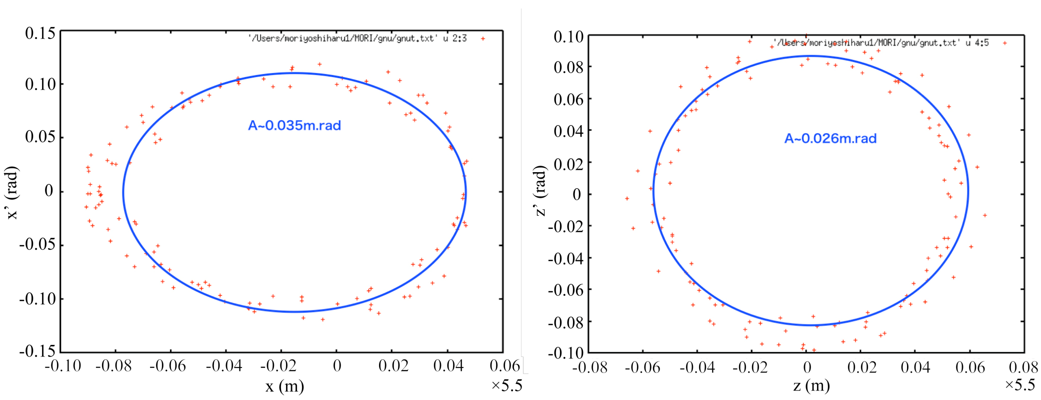


Fig.5 Beam acceptances of the pion/muon production ERIT ring. The left one is for the horizontal direction and the right one for the vertical one.

The maximum beam intensity limited by the space charge effect can be estimated by the following Laslett tune shift formula [14].

$$N = -\frac{2\pi\varepsilon\beta^2\gamma^3 B_f \Delta Q}{r_d F}. \tag{4}$$

Here, ΔQ is the betatron tune shift caused by the space charge effect, N the number of particles per ring, ε the beam emittance(m·rad), r_d the classical deuteron radius(m), F the form factor and B_f the bunching factor, β the relativistic velocity, γ the Lorentz factor, respectively. Assuming ΔQ=-0.25, ε=6x10^{-5} m·rad, F=1, B_f=0.3, r_d=7.7×10^{-19} m, β=0.79 and γ=1.64, then N becomes,

$$N = 1.0 \times 10^{14}. \tag{5}$$

This is well above the beam intensity of 7.9×10^{11} deuterons per ring which is requested for the production of negative muons with 1×10^{16} μ^-/s in this ring.

The multi rf cavities for recovering the energy lost in the deuterium gas target are placed in each straight section and the total rf voltage should be more than 20MV when the rf harmonic number is two. The frequency of the rf cavity is 13.8MHz.

Beam injection is one of the issues in this scheme. It is favorable to have an injection scheme with continuous beam to avoid the sacrifices of beam duty factor. Continuous beam injection could be possible with a charge exchanged injection scheme using a thin foil. In this case, however, the injected particle should not be the negative deuterium ion but rather the neutral deuterium atom contrary to the ordinary way, because the ring is fully occupied by a high pressure deuterium gas which would strip the electrons from negative ions. Neutral deuterium atoms can be stripped to deuterons with relatively higher deuterium gas pressure. However, the beam injection area allocated to the stripping foil should be evacuated to 0.1atm or less to avoid electron stripping before the foil. In this scheme, efficient differential gas pumping system at the injection region is essential to prevent the injected neutral deuterium beam from gas stripping and scattering. Obviously, a more detailed design for the beam injection is definitely necessary including new ideas.

3. Summary

A new scheme for efficient production of negative muons has been proposed to mitigate the long lived fission products in the nuclear wastes from the nuclear power plant with muon nuclear transformation. A negative muon source with 1×10^{16}μ^-/s could convert almost all ^{135}Cs included in 1ton spent fuel within five years to stable Xe isotopes. The scheme consists of the ERIT (energy recovery internal target) ring with a deuteron beam and deuterium gas target. In this scheme, it is expected that a muon yield of 1×10^{16}μ^-/s can be obtained with a 600MeV/u and 10mA deuteron beam, and a 1atm deuterium gas target filling the beam pipe of the ring.

Acknowledgements

The authors would like to express their sincere appreciations to the members of the ImPACT project.

References

1) S. Devons and I. Duerdoth; Muonic Atoms, Advances in Nuclear Physics (edited by M.Baranger and E.Vogt), pp.295-423(1969).

2) C. Piller, et al.; Nuclear Charge Radii of the Thin Isotopes from Muonic Atoms, Phys. Rev. C, Vol. 42, No.1, pp.182-189(1990).

3) K. Niita, et al.; Analysis of the Proton-Induced Reactions at 150MeV~24GeV by High Energy Nuclear Reaction Code JAM(in Japanese), JAERI-Tech, Vol.99-065(1999).

4) Y. Mori; Development of FFAG Accelerators and Their Applications for Intense Secondary Particle Production, Nucl. Instr. Meth., PRS, Vol. A562, pp.591-595 (2006).

5) Y. Mori; Secondary Particle Source with FFAG-ERIT Scheme, Proc. of. International Workshop on FFAG Accelerators (FFAG'05), KURRI, Osaka, pp15-20(2005).

6) Y. Mori et al. ; Neutron source with emittance recovery internal target, Proc. of Particle Accelerator Conference(PAC09),Vancouver, pp.3145-3149(2009).

7) A.N. Skrinsky and V.V. Parkhomechuk; Methods of Cooling Beams of Charged Particle, Sov. J. Part. Nucl., Vol.12, pp.223-247(1981).

8) D. Neuffer ; Principles and Applications of Muon Cooling, Particle Accelerators, Vol. 14, pp.75-90(1983).

9) Y. Mori; Muon Nuclear Transmutaion Project, International Workshop on FFAG Accelerators (FFAG'16), Imperial College London, UK, Sept.12(2016).

10) Y.Mori; FFAGs at Intensity Frontier, Special ISIS Seminar, Rutherford Appleton Laboratory, UK, Sept. 14(2016).

11) Y. Mori; Design and Beam Dynamics Issues of MERIT muon production ring, International Workshop on FFAG Accelerators (FFAG'16), Imperial College London, UK, Sept.12(2016).

12) A. Baldni, V. Flaminio, W.G. Moorhead, D.R.O. Morrison; Total Cross Sections for Reaction of High Energy Particles, Vol. 12a and Vol. 12b, Springer-Verlag Berlin 1988.

13) T. Roberts; G4beamline User's Guide, Ver.2.16 Dec. (2013).

14) L.J.Laslett; On Intensity Limitations Imposed by Transverse Space Charge Effects in Circular Particle Accelerators, BNL Report, Vol.7534, pp.324-367 (1963).