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FFA ACTIVITY IN JAPAN AND FUTURE PROJECTS

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Abstract

An FFA facility at KURNS(Institute for Integrated Radiation and Nuclear Science, Kyoto University) has been operating for the experiment of various fields such as ADS(accelerator driven system), material science, medical physics and radiation damage of the memory chips since 2009. As ADS experiment which is original aim of this facility has been completed, we are planning several upgrade modifications of the ring aiming secondary particle production using the ERIT which stands for energy recovery internal target. In this presentation, two options of ERIT for the muon production facility and nuclear experiment of super heavy elements.

INTRODUCTION

At the Kyoto University Research Reactor Institute (KURRI), basic experimental studies on the ADS, which stands for accelerator driven system, have been started since 2009 using a one of research reactors Kyoto University Critical Assembly (KUCA) [1]. In these studies, the KUCA has been operated in the sub-critical mode and FFA accelerators has been used as a proton driver. In this report, an overview of the FFA accelerator complex, a current status of the usage of beams generated by the complex and discussion of possible upgrades of it will be presented.

It has been 12 years since the main ring started operation. In early 2009, we demonstrated the feasibility of ADS in the Uranium loaded sub-critical core under thermal system, hitting the tungsten target with proton beams of which energy is 100 MeV to generate the spallation neutron) [2]. In the next year, ADS experiments with Thorium loaded core were performed. For the next decade, experiments were conducted at this facility with a variety of core configurations. Finally, in 2019, phenomena of transmutations of MAs such as 237Np and 241Am in the ADS was confirmed using this facility [3]. As almost all the originally planned ADS experiments have been completed, reuse plans of the main ring of FFA facility at KURNS is now under consideration. In this report, we present two major options. One is modifying the main ring to a pion production ring aiming for producing decay muons for various purposes such as muon transmutations and muon-catalyzed fusion. The other modification is for producing super heavy elements of which mass is 119 or more. Both options are aimed at producing secondary particles using an ERIT mechanism [4].

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CURRENT CONFIGURATION OF THE COMPLEX AT KURNS

The FFA accelerator complex at KURNS is shown in Fig. 1. It consists of an H^- ion source, a linac, an FFA synchrotron as a main ring and beam transport lines. The basic parameters of the KURNS FFA facility is shown in the Table 1. The output energy of the ion source is 30 keV

Table 1: Basic Parameters of KURNS FFA Accelerator Complex

LINAC	
Energy	11 MeV
Peak current	< 5 μA
Pulse length	< 100 μs (uniform)
Repetition rate	30 Hz
	200 Hz(max.)
MAIN RING	
Energy	11 - 100 (150) MeV
Field index k	7.5
Magnetic field	1.6 T (max.)
Revolution frequency	1.6 - 4.3 (5.0) MHz
Rf voltage	4 kV
Repetition rate	< 30 Hz

and the peak current is 2 mA with a duration of 100 μs. The linac is composed of 3 MeV RFQ, 7 MeV DTL and 11 MeV DTL. A charge stripping injection scheme is used in the main ring. The thickness of the stripping foil is 20 $\mu g/cm^2$ which is 2-fold of 10 $\mu g/cm^2$ thin carbon foil. It is located around the center of one of 12 main DFD triplet magnets to merge the injected beam to the circulating beam. Only one rf station is inserted in the straight section to accelerate the beam from 11 to 150 MeV with the peak rf voltage of 4 kV sweeping the frequency from 1.6 MHz to 6 MHz. As the turn separation in the FFA ring is much smaller than the beam size because of the high k value, the beam extraction needs kicker and septum magnets. The repetition rate is 30 Hz and the pulse length of the extracted beam is variable such as 10-100 ns using the bunch rotation scheme in the longitudinal phase space.

As the time structure of the beam from KURNS FFA synchrotron has very unique properties, it is very suitable for experiments such as nuclear data taking, flash radiotherapy, radiation damage on the memory chips and high energy physics detector development.

The H^- linac was built as an injector of the ERIT [1] ring which was a proof-of-principle ring of a neutron production ring with energy recovery internal target.The ERIT ring was

[1] stands for Energy Recovery Internal Target

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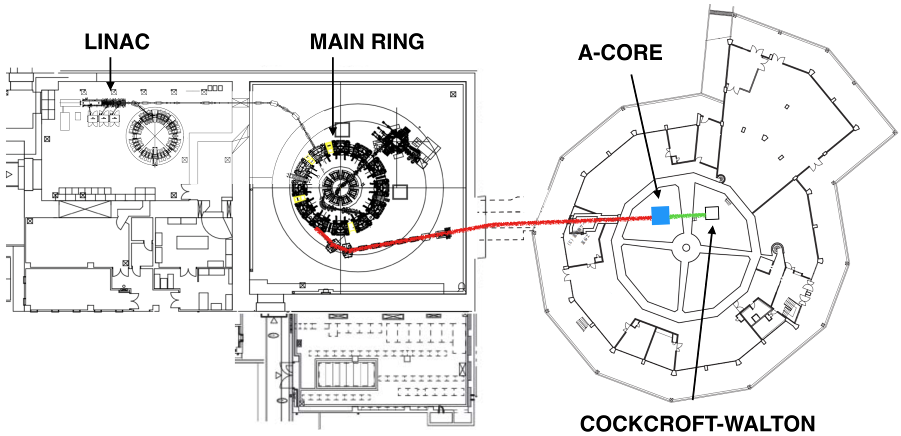

Figure 1: Layout of FFA accelerator complex and KUCA.

moved to Kyushu University in the spring of 2022 for use as a secondary particle production ring for nuclear physics experiments.

UPGRADE PLANS OF KURNS FFA SYNCHROTRON

The scaling FFA is the best ring to realize ERIT because of several unique characteristics as follows:

- A large acceptance in both horizontal and longitudinal directions.
- Zero chromaticity which guaranties constant tunes in both horizontal and vertical directions within wide range of momentum spread.

There are 2 major modification options of the FFA main ring at KURNS: a pion production ring to produce decay muons and a super heavy element production ring. Both use the ERIT mechanism.

Pion Production ERIT Ring

A basic design to convert the main ring at KURNS into a pion-producing ERIT ring (hereafter PiPER) is under consideration [5]. This plan is based on the assumption that the ring will be relocated to other facilities such as RIKEN, as it will require an injector capable of full energy injection of 300 MeV or higher.

The concepts and constraints are as follows:

- This ring is dedicated to pion production.
- It uses ERIT scheme that is no acceleration
- Injection beam is 330 MeV proton from the full energy injector e.g. AVF cyclotron at RIKEN
- It uses no reverse bending. That is, we use only F magnets with small k value for the horizontal focusing and the edge angle for vertical focusing.
- We aim for small tune variations and small CODs.

The structure of the magnets is shown in Fig. 2. It has thick return yoke only inside the ring in order to reduce the outer radius of the magnet. Using this structure, beam tracking simulations were performed with the 3-d magnetic field map obtained by using TOSCA. Finally, we got the sufficiently small tune variation and COD at most 1 mm as shown in Figs. 3 and 4, respectively.

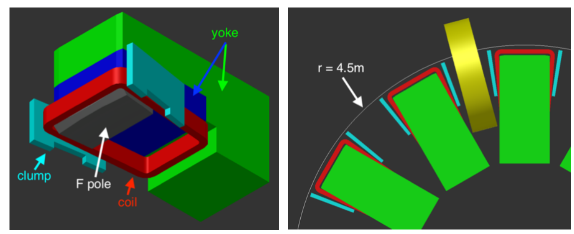

Figure 2: Remodeling of KURNS main ring to PiPER.

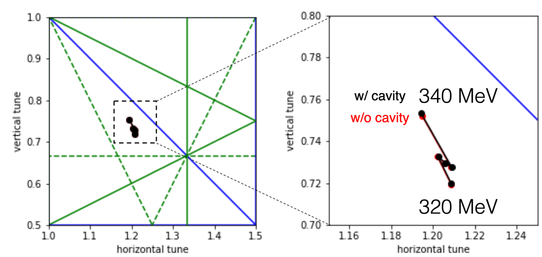

Figure 3: Tune variation in PiPER.

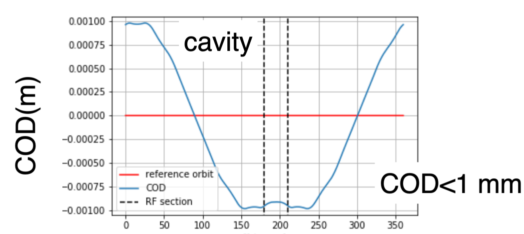

Figure 4: COD in PiPER with RF cavity as a COD source.

The main parameters of the PiPER are shown in Table 2.

Super Heavy Element Producing ERIT

Another option of reuse plan of the KURNS FFA main ring is modification into the ERIT ring aiming for producing super heavy elements of which mass number is 119 or more. Possible processes of producing super heavy elements are described by equations below.

$$^{51}_{23}\mathrm{V} + ^{248}_{96}\mathrm{Cm} \rightarrow {}_{119}\mathrm{Xx} \tag{1}$$

$$^{54}_{24}\mathrm{Cr} + ^{243}_{95}\mathrm{Am} \rightarrow {}_{119}\mathrm{Xx} \tag{2}$$

$$^{54}_{24}\mathrm{Cr} + ^{248}_{96}\mathrm{Cm} \rightarrow {}_{120}\mathrm{Xx} \tag{3}$$

$$^{55}_{25}\mathrm{Mn} + ^{243}_{95}\mathrm{Am} \rightarrow {}_{120}\mathrm{Xx} \tag{4}$$

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Table 2: Main Parameters of the PiPER

Beam species	proton
Beam energy	330 MeV
Radius of the central orbit	4.07 m
Tunes	(1.21,0.73)
$(\beta_x, \beta_y)_F$	(3.5 m,5.5 m
B at the central orbit	1.48 T
Beam current from the injector	1 pA
Target thickness	100 µm
Turns of survival	100
Pion production rate	200 π^-/s, 1000 π^+/s

Prior to these real super heavy element searches, it will be supposed to perform a test run such as

$$^{48}_{20}\mathrm{Ca} + ^{238}_{92}\mathrm{U} \rightarrow ^{286}_{112}\mathrm{Cn}. \tag{5}$$

For this process, we performed beam simulations to obtain over how many turns beam can survive (Fig. 5). We assume the production target is 200 µg/cm^2 thick UO_2 with the wedge factor $\eta > -0.5$. The wedge factor is defined as

$$\eta = \frac{D}{\rho}\frac{\partial\rho}{\partial R}, \tag{6}$$

where D is a dispersion function and ρ is the density of the target. The result of the growth of the horizontal emittance and the momentum spread are shown in Fig. 6. We expect over 100 turns can contribute to SHE producing process.

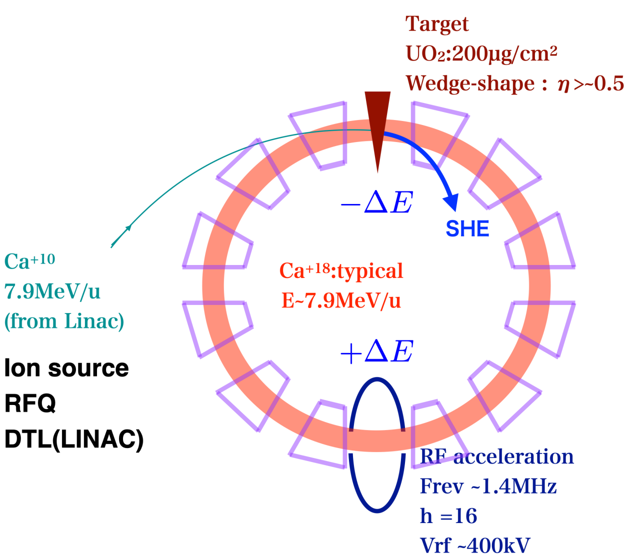

Figure 5: Schematic configuration of an ERIT system for producing super heavy elements.

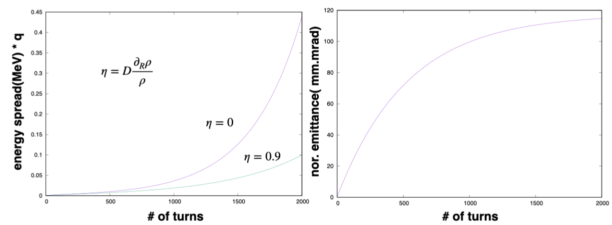

Figure 6: Beam simulation results of the growth of the horizontal emittance and the momentum spread.

SUMMARY

As almost all the originally planned ADS experiments have been completed, reuse plans of the main ring of FFA facility at KURNS is now under consideration. Two reuse options have been presented: modification of the main ring to a pion production ring aiming for producing decay muons for various purposes such as muon transmutations and muon-catalyzed fusion; and a super heavy element producing ring. Both options are aimed at producing secondary particles using an ERIT mechanism.

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