KURRI FFAG'S FUTURE PROJECT AS ADSR PROTON DRIVER

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Abstract

The accelerator complex using FFAG synchrotrons at KURRI has been operated for the ADSR experiments connecting the 100 MeV proton beam line with the research reactor facility so called KUCA since 2009. Fruitful results have been produced for the reactor physics using various configurations of the nuclear fuel core and variations of the neutron production target. Since higher energy beams such as 300 – 500 MeV are desired for the further study of the ADSR system, we are investigating the energy upgrade possibility of the accelerator complex. One of the candidates is to construct a new FFAG ring which adopts continuous acceleration with fixed frequency (serpentine acceleration) outside of the existing.These higher energy beams can be used for neutron or muon production experiments as well as ADSR study.

INTRODUCTION

An Accelerator Driven Sub-critical Reactor (ADSR[1]) is a hybrid system which is composed of a nuclear reactor facility and an accelerator facility.It sustains a nuclear fission chain reaction induced by a large amount of spallation neutron obtained by irradiation of a heavy metal target using high energy proton beams generated by accelerators. The nuclear reactor plays the role of neutron booster which amplifies the neutron flux from the target.

These days, especially after the severe nuclear accident in Fukushima Japan, the ADSR is paid attention not only as an energy production facility but as a device which transmutes long-lived radioactive materials such as the minor actinide (MA) to other materials whose lifetimes are much shorter than the original ones [1]. In the nuclear fuel cycle, MAs can be processed in a fast breeder. But in terms of the stability of the critical operation, the fraction of the MAs in the fuel system is limited as a few percent. On the other hand, in the ADSR, MA can be loaded up to some 30 % because the fuel system is operated as sub-critical.

At the Kyoto University Research Reactor Institute (KURRI), basic experimental studies about the ADSR have been started since 2009 using a one of research reactors Kyoto University Critical Assembly (KUCA) [2]. In these studies, the KUCA has been operated in the sub-critical mode and FFAG accelerators has been used as a proton driver. In this report, an overview of the FFAG accelerator complex, a current status of the usage of beams and discussion of possible upgrades of it will be presented.

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[1] Sometimes it is also referred as ADS which stands simply for Accelerator Driven System.

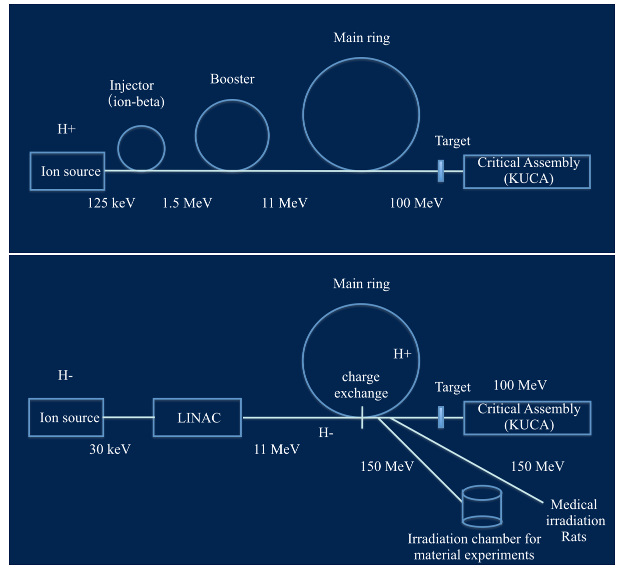

Figure 1: The schematic diagram of the FFAG Accelerator Complex. The upper is the original configuration, the lower is the upgraded one. The injector system composed of the Injector (ion-beta) and the Booster has been replaced by the H^- linac.

OVERVIEW OF THE FFAG ACCELERATOR COMPLEX AT KURRI

The schematic diagram of the KURRI-FFAG accelerator complex is shown in Fig. 1. The complex used to have 3 FFAG rings: the ion-beta, the booster and the main ring. All three rings adopt an FFAG focusing scheme [3]. However, the original injector system, which was composed of the ion-beta and the booster has been replaced by the 11 MeV H^- linac in order to increase the beam intensity. Table 1 shows the basic parameters of the complex. Figure 2 is an overview of the complex. The main ring has 2 extraction energies: 100 MeV for the ADSR experiments and 150MeV for other irradiation experiments.

The new injector system consists of 3 linacs RFQ, DTL1 and DTL2. It was adopted as an injector of the ERIT ring [4]. The injection beam line is shown in Fig. 3. The H^- beams are injected into the FFAG main ring through a charge stripping foil made of carbon. In this injection scheme, no pulse device is used. Even orbit merging magnets are not necessary because the H^- beams are merged into the circulating beam inside the main magnet of the main ring as shown in Fig. 4. The beam current extracted from the main ring has been increased by a factor of 10 because of this replacement.

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Table 1: The Basic Parameters of KURRI-FFAG Accelerator Complex

Linac	
Repetition rate	<200 Hz
Peak current	<5 mA
Pulse length	< 100 µs (uniform)
Energy	11 MeV
Main ring	
Field index k	7.5
Magnetic field	1.6 T (max.)
Energy	11 - 100 or 150 MeV
Revolution frequency	1.6 - 6.2 MHz
Rf voltage	4 kV

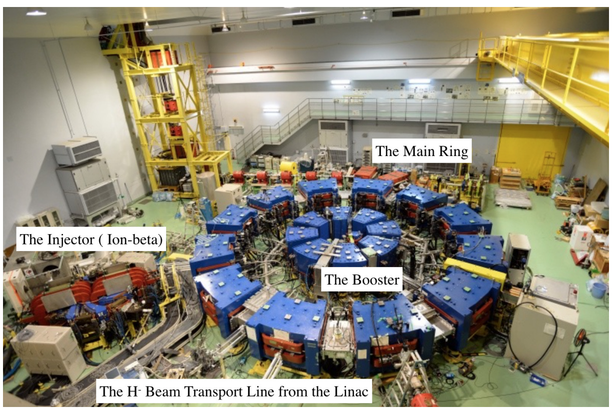

Figure 2: FFAG Accelerator Complex at KURRI.

USAGE OF BEAMS

The proton beams from the FFAG complex are delivered to users of various experiments: the ADSR experiments, the irradiation experiments for the materials and the biological experiments with irradiation to living animals (rats) for a basic study of BNCT [2]. Figure 5 shows the break down of the machine time for each user group. The machine time was measured as the integration of time when the beam was on.

[2] Stands for Boron Neutron Capture Therapy

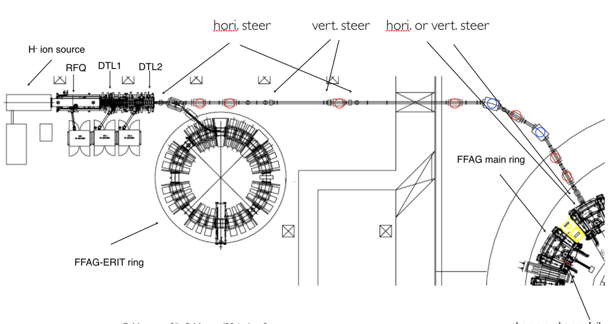

Figure 3: The H$^-$ beam transport line.

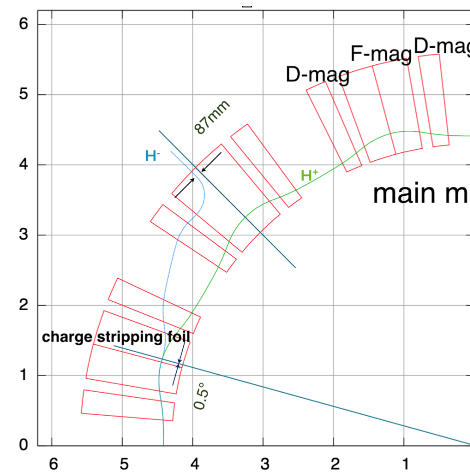

Figure 4: The H$^-$ beam injection using the charge stripping foil.

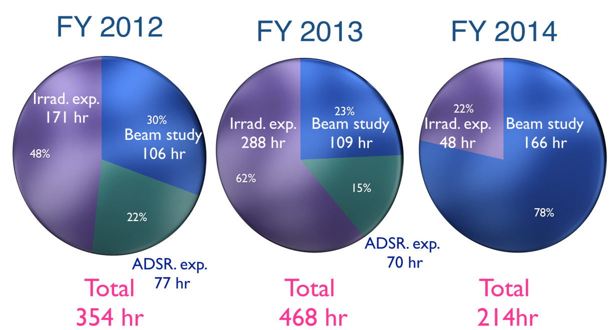

Figure 5: The machine time breakdown of KURRI-FFAG facility in recent 3 years.

For the ADSR experiments, the beam is transported from the accelerator facility to the sub-critical fuel system located at one of the core in the KUCA called "A-core" (Fig. 6). Two kinds of measurement are performed in the KUCA: dynamic characteristics measurements detecting prompt and delayed neutrons and static measurements of neutron energy spectrum or reaction rate distributions using radio-activation of the indium (In). The result of dynamic measurements from the first experiment in the world is shown in Fig. 7. There are 2 components in the neutron counting rate: the fast component decaying exponentially and the slow component caused by delayed neutrons almost constant in time. The presence of the delayed neutrons indicates that neutrons generated through nuclear fission chain reaction inside the fuel system. This series of ADSR experiments are ongoing since 2009 changing experimental conditions such as material of the neutron production target, configuration of the fuel system and beam intensity. The results from these experiments can be seen in the articles [5]- [9]

FUTURE PROJECT

In order to make the facility multi-capable, we are investigating two upgrade possibilities: (1) Increasing the beam

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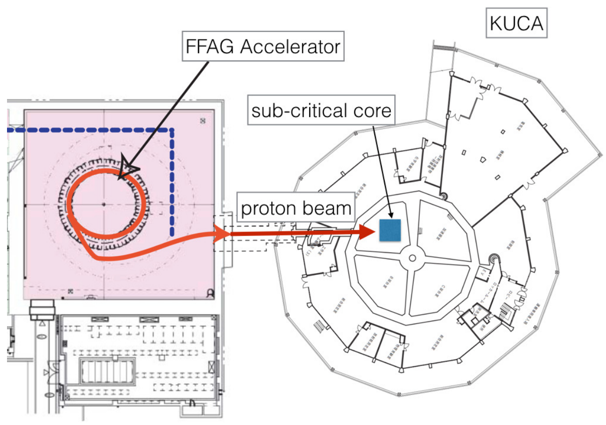

Figure 6: The connection between the FFAG accelerator complex and KUCA.

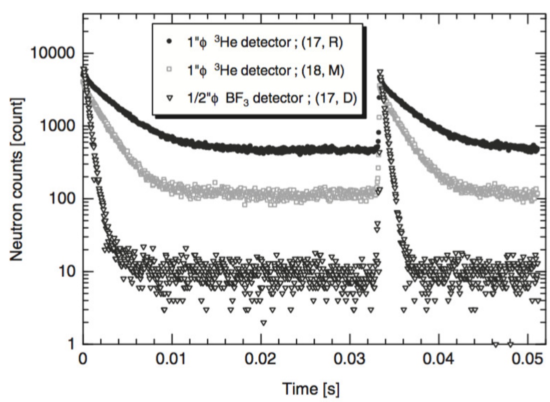

Figure 7: Measured prompt and delayed neutron behaviors obtained from different configurations of detectors.

current up to the order of μA by increasing the repetition rate at the order of 100 Hz. (2) Energy upgrade by adding a new ring outside the main ring.

Beam Stacking at High Energy Orbit

As a candidate of high intensity proton driver of spallation neutron source, potentially, an FFAG accelerator has advantage in terms of high repetition rate such as 100 - 1000 Hz. However, some users desire low spill rate (~10 Hz) for the experiments e. g. neutron radiography using TOF which needs to get rid of contamination from the pulse of different timing. FFAG rings can provide long interval pulse for users, while the machine operation itself is kept at high repetition rate by using rf stacking after acceleration [10]. This scheme reduces space charge effects at injection energy. For the machine, charge in each bunch can be reduced by high repetition rate. In the high energy region i. e. outer radius, accelerated beams are stacked and circulating around until necessary amount of charge is accumulated. For users, highly compressed beam with long time interval can be delivered.

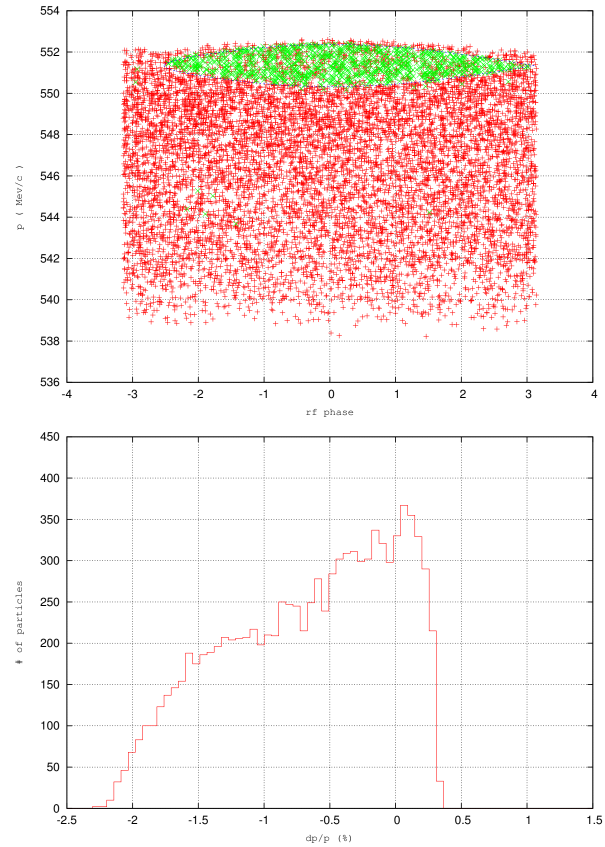

Figure 8: Results of the beam stacking simulation. The upper is the phase space plots from the stacking simulations with adiabatic landing and the lower is the momentum distribution after the beam stacking.

To confirm the feasibility of rf stacking at extraction energy, simulation studies have been carried out. Figure 8 shows the results from the stacking simulations. In the upper,a longitudinal phase space structure are shown. The vertical axis is the momentum and the horizontal one is the rf phase. The red points are stacked particle coasting around the extraction orbit, the green ones are accelerated particles landing on the extraction orbit and the blue lines are separatrices. In these simulations, the acceleration goes up to 150 MeV. While the landing process is going on, already stacked particles are slipping below the bucket in the phase space. Eventually, beams have been stacked below the extraction momentum. In the lower, momentum distribution is plotted. After first acceleration, full width of momentum spread is about 0.5%, the final momentum spread after 10 stacks is 2.5% of full width. This is much smaller then naive guess that is intrinsic momentum spread of each stacked beam multiplied by number of stacks i. e. 0.5 % ×10.

Although simulation studies showed that adiabatic landing, where the rf voltage is adiabatically reduced, is effective to suppress the momentum spread of the stacked beam, experimental study is necessary.

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Table 2: Parameters of the 400 MeV FFAG Ring

Lattice	16-cell
Field index k	0.672
Energy	150 - 400 MeV
Average orbit radii	6.6 - 9.3 m
Magnetic field	1.3 T
Tune	(1.356, 2.248)

An Additional Ring

Number of neutrons produced through the nuclear spallation process strongly depends on the beam energy of the primary protons. If the beam energy is increased from 100 MeV to 400 MeV, the number of neutrons corresponding to single primary proton is increased by a factor of 20. Therefore, the energy upgrade of the accelerator facility is desired by the reactor physicists.

Fortunately, there is an enough space to build an additional higher energy ring outside the main ring. A basic design of the additional ring is being carried out. The layout of the complex with a newly designed 400 MeV FFAG ring is shown in Fig. 9. Basic parameters of the new ring are shown in Table 2. The ring consists of 16 cells. Beta functions for one cell are shown in Fig. 10.

The k is set to a rather small value of 0.672. This value of k makes a *serpentine acceleration* [11] possible. The longitudinal phase space structure in this acceleration scheme is shown in Fig. 11. Generally, the profits of this scheme are follows

- Since a fixed frequency is used, high electric field of the acceleration cavity is easily obtained.
- This makes a fast and continuous acceleration possible.
- The ERIT mechanism [12] can be applied to make secondary particles such as pions and their decay muons.

In the ordinary ERIT system as shown in Fig. 12, the ring is operated in a storage mode. However, in the extended ERIT system, the ring is in an acceleration mode. In this operation mode, since the beam hits the target at the maximum energy, the production efficiency of the secondary particles becomes high compared with the case of the storage mode.

SUMMARY

An FFAG accelerator complex for the ADSR study has been constructed at KURRI. The first ADSR experiment in the world has been done successfully in KUCA by using 100 MeV proton beam from the complex in 2009. Since then, fruitful results have been produced from these experiments. In order to increase the beam current, the original injector system composed of the ion-beta and the booster has been replaced by the H$^-$ linac. The beam current from the main ring has been increased by a factor of 10 by this replacement. Now the proton beams from the FFAG complex are used by the experiment in various fields such as the material science

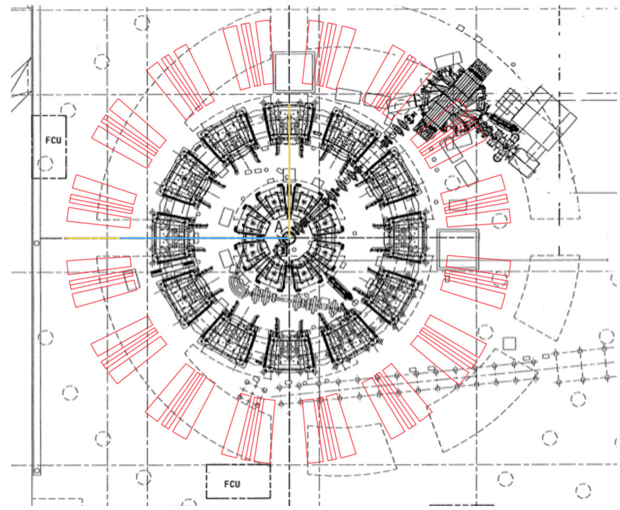

Figure 9: A layout of the complex with a newly designed 400 MeV FFAG ring, which surrounds the main ring.

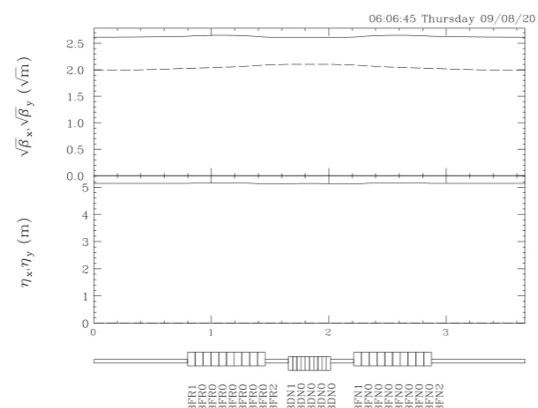

Figure 10: Beta functions for a basic cell of the 400 MeV FFAG ring.

or the biological science as well as the reactor physics in KUCA.

Not only for higher performance in the ADSR experiments, but for the extension to the pulsed neutron source, a beam stacking at the high energy orbit is considered. In addition to the existing FFAG accelerators, a new 400 MeV FFAG ring is now under consideration for the energy upgrade of the complex. It adopts the serpentine acceleration to realize the extended ERIT mechanism, which can produce secondary particles such as pions and their decay muons efficiently.

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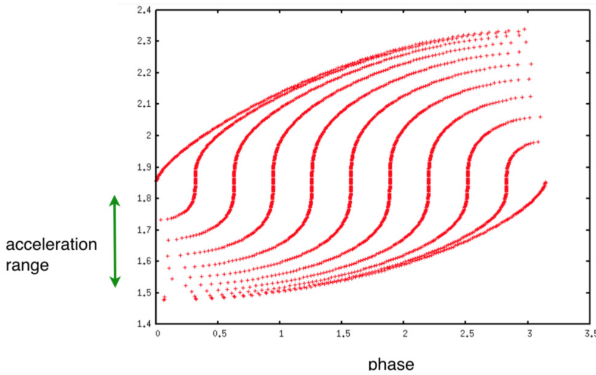

Figure 11: A phase space structure in the longitudinal direction for the serpentine acceleration.

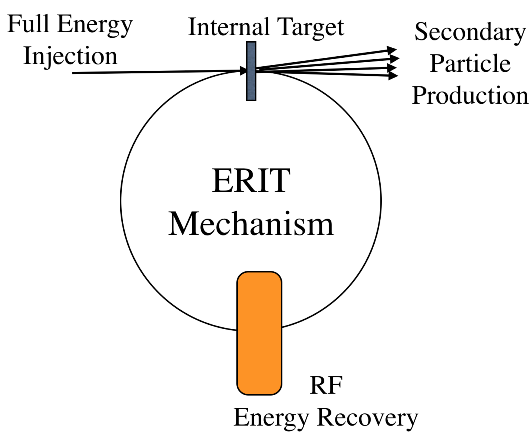

Figure 12: The ERIT mechanism to produce secondary particles.

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