PRESENT STATUS AND FUTURE OF FFAGS AT KURRI AND THE FIRST ADSR EXPERIMENT *

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Abstract

World's first ADSR experiments which use spallation neutrons produced by high energy proton beams accelerated by the FFAG synchrotron has started since March 2009 at KURRI. In these experiments, the prompt and delayed neutrons which indicate neutron multiplication caused by external source have been detected. The accelerator complex for ADSR study in KURRI consists of three FFAG proton rings. It delivers the 100 MeV proton beam to the W target located in front of the sub-critical nuclear fuel system constructed in the reactor core of KUCA at 30 Hz repetition rate. Current status of the facility and the future plans of ADSR system and high intensity pulsed spallation neutron source which employ a newly added 700 MeV FFAG synchrotron to the existing FFAG complex in KURRI will be presented.

INTRODUCTION

Accelerator driven sub-critical reactor (ADSR) is a system which keeps 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 a role of neutron booster which amplifies the neutron flux from the target. The ADSR can be recognized as "safer system" because the chain reaction in the sub-critical core is stopped inevitably by stopping the beam from the accelerator.

Another feature of this system is that the output of the nuclear reactor can be controlled by changing the beam power from the accelerator. Output from the sub-critical reactor P is expressed as

$$P \sim \frac{S}{1-k_{eff}}, \tag{1}$$

where S is the intensity of the neutron source and k_{eff} is the effective multiplication factor of sub-critical nuclear fuel system. Factor k_{eff} can be adjusted with the control rod, and S can be adjusted by changing the beam energy and/or the beam current of the accelerator.

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ADSR PROJECT AT KURRI

ADSR studies have been carried out in Kyoto University Research Reactor Institute (KURRI) as the MEXT-supported program "Research and Development for an Accelerator-Driven Sub-critical System Using an FFAG Accelerator". The main purpose of this R&D is a basic feasibility evaluation of ADSR as an energy production device. It is also required to compare the nuclear design calculations with the experimental data concerning sub-critical reactor characteristics mainly on the neutron multiplication which depends on the energy of the neutrons. The experiment of ADSR driven by neutrons of the energy of 14 MeV had been already done by D-T reaction (a fusion reaction) using a Kockcroft-Walton accelerator in KUCA, but the experiment of ADSR driven by the spallation neutrons generated by protons of the energy of 100 MeV grade had not been yet done. Therefore, as for the ADSR experiment with the high energy proton accelerator, this study is a world's first trial.

The Kyoto University Critical Assembly (KUCA) is used as the sub-critical reactor for this experiment. Because KUCA is a small research reactor of the maximum output 100 W (1 kW for short term operation, 10 W or less for usual), it is easy to rearrange the reactor core. Fixed Field Alternating Gradient (FFAG) synchrotron which realizes high beam current and high beam energy simultaneously has been adopted as the accelerator which drives ADSR. The KURRI-FFAG accelerator complex has been connected to KUCA as shown in Fig. 1 in order to deliver the high energy proton beam. Because the magnetic field of FFAG is fixed, the repetition rate can be increased 10-100 times higher than that of an ordinary synchrotron; therefore the space charge limit of beam current is also increased. Table 1 shows the basic parameters of the ADSR experiment in KURRI.

Table 1: The basic parameters for ADSR experiment.

Reactor output power	$\sim$10 W
Neutron multiplication factor	$\leq$ 100
Beam power	$\leq$ 0.1 W
Beam energy	100 - 150 MeV
Beam current	$\leq$ 1 nA

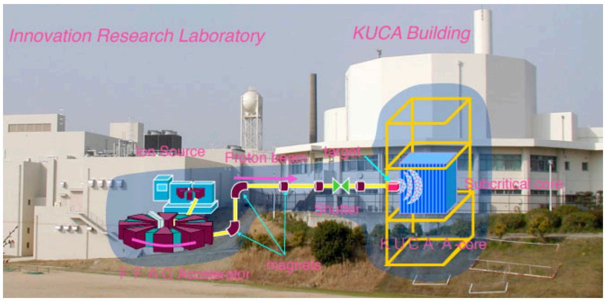

Figure 1: FFAG Accelerator Complex connected to KUCA for ADSR experiment.

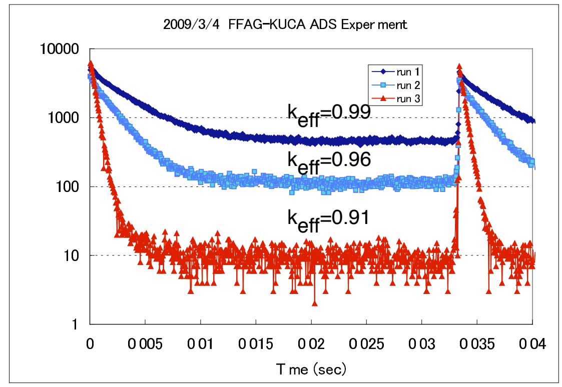

Figure 2: Number of neutrons detected as a function of time with different k_{eff}.

DESIGN AND PERFORMANCE OF FFAG ACCELERATORS

KURRI-FFAG accelerator complex consists of three circular accelerators: the injector, the booster ring and the main ring. All three rings adopt FFAG focusing scheme. Table 2 shows the basic parameters.

FFAG magnets are designed so that magnetic field $B(r)$ has the dependency of $B(r) = B_0 \left(\frac{r}{r_0}\right)^k$ in orbital radius r to realize zero chromaticity, where B_0 and r_0 are constants. The injector is composed of 8 spiral sector magnets which have parallel flat poles with 32 pole-face winding coils in addition to the main coil in order to make k variable, and the extraction energy out of the injector can be changed by varying the current distribution of the pole-face winding coils. On the other hand, in the booster and the main ring, the field distribution in the radial direction is shaped by curved magnetic poles. Another feature of the injector is the adoption of the induction acceleration using lamination core made of thin iron tape. Detailed description for the design is available in [1].

Three rings are operated at 30 Hz. The rf patterns for the booster and the main ring are generated independently but synchronized by a common clock in the multi-channel arbitrary function generator (Tektronix AWG430). Timing-critical devices such as bump magnets and kicker magnets are also controlled by the same function generator.

There is no remarkable beam loss observed in the booster, but in the main ring we still have some beam losses [3]. Even with such beam losses, the beam intensity right after the extraction reaches 0.1 nA which is the value limited by the regulation of radiation safety. However for further upgrade of beam intensity order of μA in near future, we are working on solving this problem.

ADSR EXPERIMENT

First ADSR experiment successfully started on March 4, 2009 [2]. A 100 MeV proton beam extracted from the main ring was delivered to the sub-critical fuel system constructed in KUCA. The proton beam was irradiated into the tungsten target installed at the end of vacuum pipe of the beam transport line from the main ring, and it was located in front of the fuel system. ^{3}He detectors are set up neighboring the reactor core. Figure 2 shows the neutron counting rate as a function of time measured with one of these detectors. This plot shows that there are two components in the response: 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 reaction inside the fuel system; it tends to have higher level with higher k_{eff} which means shallower subcriticalrity of the fuel system.

FUTURE PLANS

Recently in KURRI, a high intensity pulsed neutron source is desired not only for ADSR study but as a substitute for the 5 MW research reactor (KUR). Using FFAG system as a proton driver for the neutron source, two major upgrade paths are considered: (1) the intensity enhancement by changing the injector system; (2) the energy upgrade up to 700 MeV to enlarge the number of spallation neutrons from the heavy metal target.

H^- injection

In an ordinary multi-turn injection of positive charge beam, accumulated beam intensity is limited by the transverse acceptance at the inflector. However charge changing H^- injection scheme can get rid of such a limitation. The space charge limit of the accumulated proton beam is estimated 12 μA at a repetition rate of 100 Hz. For the injector of this scheme, ERIT [1] injector system composed of RFQ and DTL can be used; it is installed in the same building. The linac accelerates H^- beam up to 11 MeV which is about the same as the injection energy of the main ring. Figure 3 shows the layout of the linac, the beam transport line and the main ring. The beam line will be constructed

[1] ERIT stands for Energy/Emittance Recovery Internal Target [1].

Table 2: The basic parameters of KURRI-FFAG accelerator complex.

	Injector	Booster	Main Ring
Lattice	8-cell spiral	8-cell radial	12-cell radial
Acceleration	Induction	RF	RF
Field index k	2.5*	2.5	7.5
Energy (max)	1.5 (2.5) MeV	11 (20) MeV	100 (150) MeV
P_{ext}/P_{inj}	5.00 (Max)	2.84	2.83
Average orbit radii	0.60 - 0.99 m	1.42 - 1.71 m	4.54 - 5.12 m

* Output energy of the injector is variable

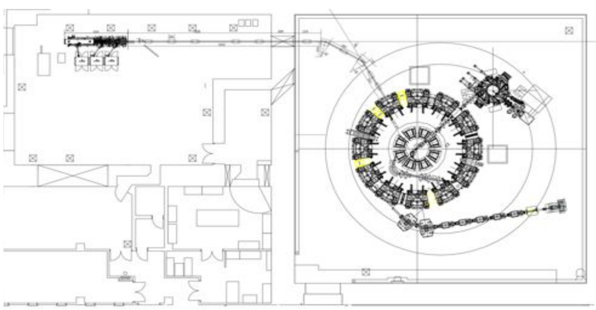

Figure 3: Layout of new beam line for H^- injection.

Table 3: Parameters of a 700MeV FFAG ring.

Lattice	16-cell spiral
Field index k	12
Energy	150 - 700 MeV
Average orbit radii	6.6 - 7.2 m
Magnetic field	1.5 T

in the summer of 2010, and the beam commissioning is planned to be done by the end of 2010. Detailed description about this scheme is available in these proceedings [4].

700 MeV spiral FFAG

Number of neutrons produced through the nuclear spallation process is strongly dependent on the beam energy of the primary protons. If the beam energy is increased from 100 MeV to 700 MeV, the number of neutrons corresponding to single primary proton is increased by a factor of 30. The specifications of a 700 MeV ring are shown in Tab. 3. Figure 4 shows the layout of the main ring and newly added 700 MeV ring.

SUMMARY

In KURRI, the FFAG accelerator complex for the ADSR study has been constructed; 100 MeV proton beam from the main ring has been delivered to the sub-critical core in KUCA. World's first ADSR experiment has been successfully started on March 4, 2009. In these experiments, we have obtained evidence for the chain reaction induced by the spallation neutrons produced by the high energy proton beam. Not only for higher performance for the ADSR experiments but for the pulsed neutron source, intensity upgrade program using H^- injection for present main ring has been started. In addition to the existing FFAG accelerator complex, a 700 MeV spiral FFAG ring is now under consideration.

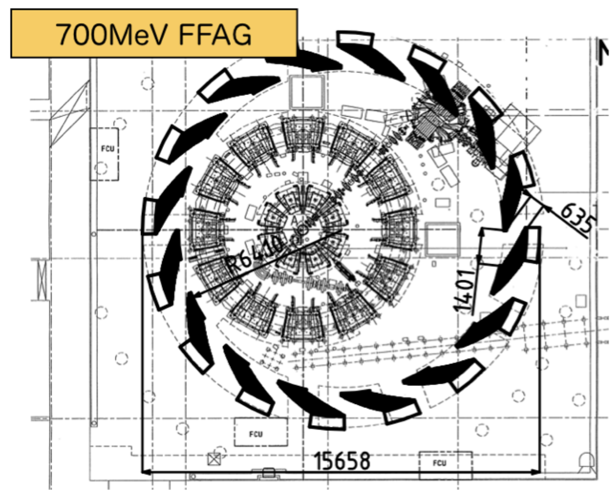

Figure 4: Layout of a newly added 700 MeV ring surrounding the main ring.

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