PRESENT STATUS OF FFAG PROTON ACCELERATORS AT KURRI*

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Abstract

In Research Reactor Institute of Kyoto University (KURRI), developments of FFAG accelerators for the basic study of Accelerator Driven Sub-critical Reactor (ADSR) system and various applications such as muon acceleration, hadron therapy have been in progress. Present status and developments of FFAG accelerators at KURRI are presented.

INTRODUCTION

Various scientific projects based on FFAG accelerators have been carried out in KURRI. Basic experimental studies on accelerator-driven subcritical reactor (ADSR) with spallation neutrons generated by 150MeV proton FFAG accelerator complex are major ones. Project of ADSR study using a small nuclear reactor(KUCA) where the output power is less than 100W has been started since 2006 and the world first ADSR experiment with spallation neutrons was carried out in March of 2009 [1].

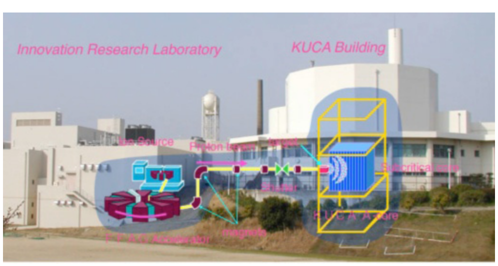

Figure 1: Schematic layout of ADSR experiment with 150MeV proton FFAG accelerator complex at KURRI.

Figure 1 shows a schematic layout of the FFAG-KUCA system for ADSR experiment. The 150MeV proton FFAG is installed at the newly constructed building called Innovation Research Laboratory and it is connected to KUCA with a long beam transport line which is located just 1m below from the office ordinary people is living. The FFAG accelerator complex is composed of three FFAG rings as shown in Fig. 2. Recently, in order to increase the beam intensity of the 150MeV proton FFAG, charge-exchange injection with negative hydrogen ion beams has been developed. A new H^- injector composed of H^- ion source and 11MeV RF linac (RFQ+DTL) has been installed.

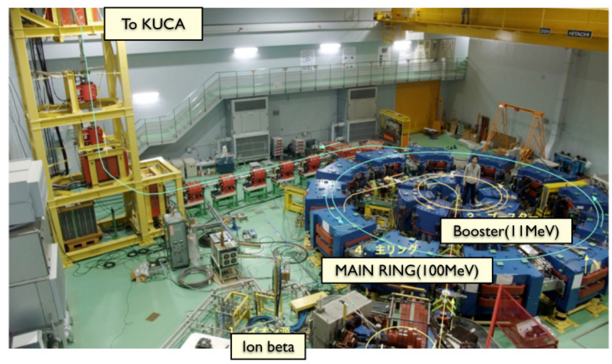

Figure 2: FFAG proton accelerator complex for ADSR study.

Various other projects and studies have also been carried out:(1) Beam power(intensity and energy) upgrade of FFAG proton accelerator (2) Development of compact neutron source with FFAG-ERIT scheme (3) Study of FFAG hadron accelerator with super conducting magnet with high temperature super conducting coil (HTSC) (4)Development of advanced FFAG accelerators for various applications such as muon acceleration and proton driver.

ADSR STUDY

The first experimental result with the uranium fuel cores at KUCA implying the thermal neutron yield as a function of time is shown in Fig.3. As clearly seen from this figure, the thermal neutron yield in the reactor core are multiplied by chain nuclear fission reactions following after very short (10nsec) pulsed proton beams from the FFAG accelerator are injected.

A thorium loaded ADSR is one of the most interesting schemes for future safe nuclear energy production from the viewpoint of fuel resource and physical protection of nuclear materials. Recently, we have tried an ADSR experiment with thorium loaded nuclear cores in KUCA. The beam intensity of the FFAG proton accelerator was in-

* This work was supported by MEXT(the Ministry of Education, Culture, Sports, Science and Technology) of Japan in the framework of a task entitled "Research and Development for an Accelerator-Driven Sub-critical System Using an FFAG Accelerator", NEDO (new Energy Development Organization in Japan), and JST s-innovation project
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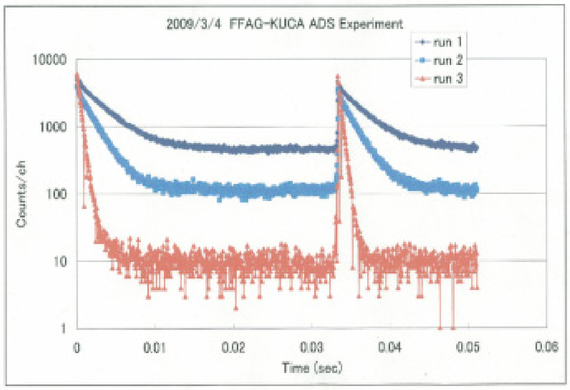

Figure 3: First ADSR experimental result with uranium fuel cores in KUCA.

creased up to about 1nA in the averaged beam current with a new H⁻ injector (described below), which was measured at the beam transport line to the front of the KUCA core, which reached almost the beam intensity limit claimed by radiation safety.

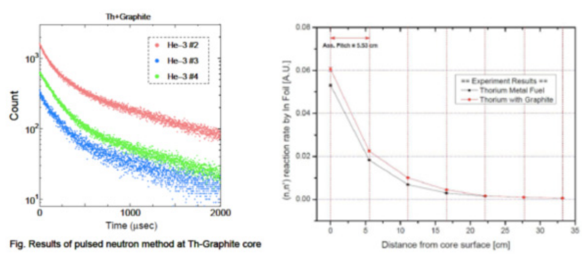

Figure 4: First experimental result with Th-Graphite core in KUCA.

Figure 4 shows some preliminary experimental results at Th-Graphite core in KUCA. It looks obvious that more intensive and detail studies are necessary in future. The accelerator control system was totally renewed with EPICS based accelerator control system under collaboration with the KEK control group [2]. The previously used control system was based on LabVIEW, which was sometimes very unstable, especially under heavy network traffic condition and seems to be not so adequate for time-varying accelerator such as synchrotron and FFAG accelerators. Using the EPICS based control system, the operation of FFAG accelerator becomes stable and reliable.

BEAM POWER UPGRADE

Higher beam power operation in the 150MeV proton FFAG accelerator is strongly demanded for various applications with intense spallation neutrons such as advanced study for ADSR , material sciences, solid state physics, nuclear data and so on in future, although the beam intensity for the present ADSR basic experiment with KUCA has almost reached to the level of radiation safety limit. The beam intensity for proton FFAG accelerator can be increased with the charge exchanged multi-turn injection with H⁻ ion beam just as that for proton synchrotron. Fortunately in KURRI, a H⁻ ion linac was constructed for the neutron source with ERIT-FFAG scheme(described below) and now is operational at the next room of the 150MeV proton FFAG accelerator. This linac has a capability to operate with the large beam duty factor where the maximum repetition and duration of the beam are 100Hz and 70 μsec, respectively. The beam energy of the linac is 11MeV which allows to inject the beam into the main ring of the proton FFAG accelerator. In 2010, a new beam line to transport the H⁻ ion beam from the linac to the main ring of FFAG accelerator shown in Fig. 5 was constructed [3]. Since the magnetic field of the FFAG accelerator is static, the H⁻ ion beam can be injected into the ring from outside passing through a couple of ring magnets where the careful beam optics designs are necessary. The charge stripping carbon foil is located almost at the center of the main ring magnet.

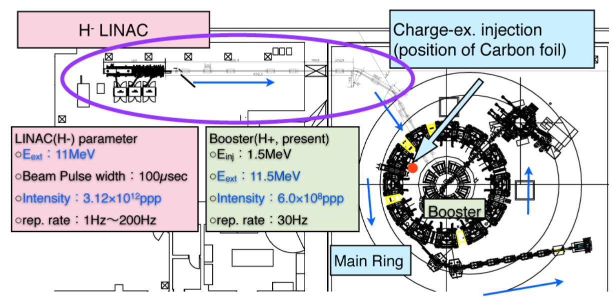

Figure 5: Schematic layout the H⁻ ion injection system.

Different from the conventional way of H⁻ injection used at ordinary proton synchrotron, no specific pulsed magnet such as pulsed bumper was needed. Since beam orbit moves to outside during the beam acceleration, there is, in principle, no need to have an injection bump orbit to minimize the multiple scattering effects caused by the carbon foil. In the preliminary experiment, we have succeeded in injecting and accelerating the beam at the main ring of FFAG accelerator and obtained an order of magnitude large beam current in the main ring.

ADVANCEMENT OF FFAG

Study for the beam optics and dynamics of FFAG accelerator has been advanced in our group. The scaling law of the FFAG accelerator to satisfy the zero chromaticity is applied to circular accelerator and each cell provides a total bending angle of a ring. If a scaling FFAG unit cell with straight section where a overall bending angle is zero is created, insertion/matching optics with straight sections can be cooperated to the ordinary FFAG ring. The scaling condition for the straight section unit cell, i.e. a same phase advance per cell at every energy, leads to a different field law. Applying the scaling field law to the FFAG straight section, insertion/matching optics adding to the ordinary scaling FFAG rings have been examined for various applications [7, 9]. Figure 6 shows an example of the race-track shape of scaling FFAG ring with straight sections and the dispersion suppressing insertion for low energy muon ring [7].

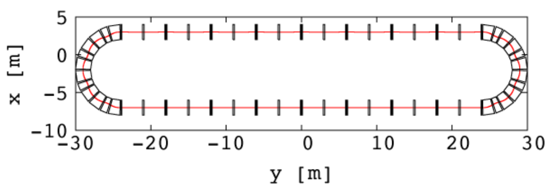

Figure 6: Schematic layout of muon FFAG storage ring with zero-chromatic straight sections.

Compared with ordinary strong focusing synchrotrons, very fast acceleration is possible in FFAG accelerator because the magnetic field is static. Accordingly, various new RF acceleration schemes with fixed-frequency RF system have been proposed and studied in our group aiming for fast beam acceleration.

In longitudinal phase space, the RF bucket of the scaling type of FFAG accelerator for relativistic particles such as high energy muons is not distorted for large momentum range because the momentum compaction keeps constant and has no momentum dependence. If the RF voltage is large enough, the particles can be accelerated in a stationary RF bucket after a half period of synchrotron oscillation. Applying this scheme, the muon accelerator for neutrino factory has been designed [9], which can accelerator muons from 3.6GeV to 12.6GeV with very large 6-D acceptance.

In the scaling FFAG accelerator, a serpentine acceleration scheme with a fixed frequency RF is possible where the beam is accelerated passing through the transition energy where the time-of-flight per turn is a minimum. The longitudinal Hamiltonian in the case of scaling FFAG accelerator is analytically obtained [8]. A serpentine path through the transition energy exists and beam acceleration for non-relativistic particles can be possible with this scheme in the scaling FFAG accelerator.

Various research and development studies on the scientific applications of FFAG accelerators have been also carried out in our group. A compact neutron source with ERIT-FFAG scheme as shown in Fig. 6 using ionization cooling has been developed [4, 5] and it was experimentally clarified to obtain the neutron yield of more than $5 \times 10^{8}\, \mathrm{n\, cm^{-2} sec^{-1}}$.

Design study of compact FFAG accelerators using super conducting magnets with high temperature super conducting(HTSC) coils has been carried out for future ADSR study and also for hadron therapy. Figure 7 shows an example of design of the compact FFAG accelerator for carbon therapy using super conducting magnets with HTSC coils [6].

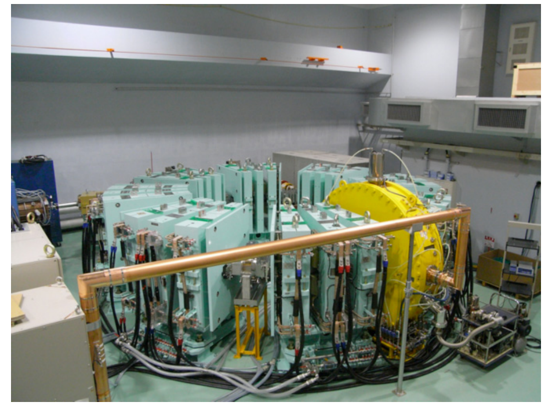

Figure 7: Photo of FFAG-ERIT compact neutron source.

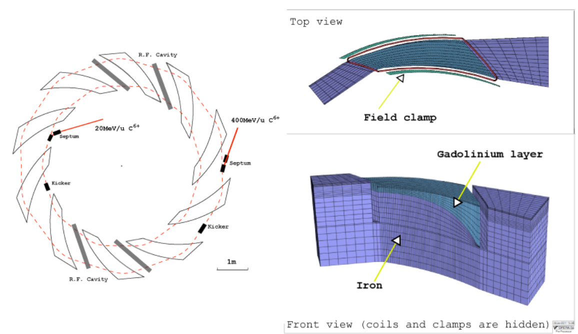

Figure 8: Schematic layout and magnet configuration of super conducting FFAG accelerator for carbon therapy.

SUMMARY

Present status of FFAG accelerators and some developments for various applications at KURRI have been described. The authors would appreciate the FFAG accelerator and KUCA groups of KURRI for their cooperations.

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