NEUTRON SOURCE WITH EMITTANCE RECOVERY INTERNAL TARGET*

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Abstract

Accelerator based neutron source for BNCT (boron neutron capture therapy), which is based on ionization cooling with emittance recovery internal target (ERIT) placed into the FFAG proton storage ring has been developed at KURRI. The system has been constructed and worked successfully. In this paper, the characteristics and performance of FFAG-ERIT are presented.

INTRODUCTION

An accelerator-based intense thermal or epithermal neutron source (ABNS) has been strongly requested for BNCT aiming a hospital size apparatus. In the ABNS for BNCT, thermal/epithermal neutron flux of more than 10^9 n cm^{-2}sec^{-1} is requested. In order to satisfy the requirement, neutron production reactions induced by low energy (3–10 MeV) proton or deuteron with lithium or beryllium target can be used and the maximum proton energy should be less than 15 MeV which is a threshold energy of spallation reaction of tritium production by fast neutrons to avoid radiation hazard in hospital use. In ordinary scheme of ABNS with an external target, the requested proton beam current should become quite large such as about 10 mA for 10 MeV and 50 mA for 3 MeV proton beams, respectively. For such large beam power around 100kW, serious problems concerning the heat load and radiation damage of the neutron production target can also be eliminated.

In order to overcome these difficulties of ABNS with an external target, an ERIT (energy/emittance recovery internal target) concept with a scaling type of FFAG proton storage ring has been proposed for this purpose [1, 2, 3]. Figure 1 shows a schematic diagram of ERIT. This scheme may also be used to produce intense beams of other secondary particles such as unstable nuclei, muons etc. The circulating current of the beam inside a strong focusing ring accelerator, such as an FFAG, is fairly large because the bunch orbits the ring many times with large revolution frequency. For example, in the case of neutron production, when 10^{11} protons at 10 MeV orbit a ring of circumference 10 m, the circulating beam current reaches 70 mA. 10^{11} protons per bunch is a relatively modest number for such strong focusing proton accelerators of this energy. If a neutron production internal target such as a beryllium thin foil is inserted into the ring and the beam hits the target efficiently, the neutron yield should become comparable with that from a nuclear reactor.

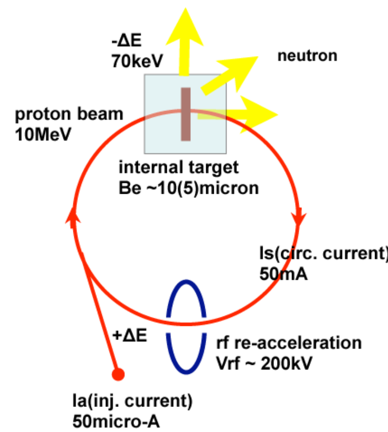

Figure 1: Schematic diagram of FFAG-ERIT.

IONIZATION COOLING

In this scheme, however, the incident proton beam will be lost from the ring very quickly because the beam energy of the incident protons is lost to ionization of the target atoms turn by turn, and also because the beam emittances, in transverse and longitudinal directions, are blown up by multiple scatterings with the target electrons. These deleterious effects can, however, be cured by ionization cooling [4, 5]. The transverse emittance reaches equilibrium in this energy recovery internal target scheme. The transverse unnormalized rms emittance reaches about 1500 $\pi\times$mm$\times$mrad after 2,500 turns for a 11 MeV proton beam with a 5 μm beryllium target which is placed at the position of beta-minimum of about $\beta = 0.9$ m. No cooling effect, however, can be expected in the longitudinal direction and large energy spread is inevitable. The rms energy spread of the 11 MeV proton beam increases up to about ± 5 MeV after 1000 turns. In order to circulate such a large emittance beam in the ring, the FFAG looks the most suitable one because of strong focusing and zero chromaticity and can be applied for generating not only neutrons but other particles such as pions and unstable nuclei.

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Figure 2: Photograph of FFAG-ERIT ring.

FFAG-ERIT

The FFAG-ERIT consists of the injector and the proton storage ring in which a thin Be target for generating neutrons is placed. The H^- ions are accelerated by the injector and injected into the ring by charge exchange injection with a thin Be target. The beam emittance and energy distorted by the Be target are cured by reacceleration with a RF cavity placed in the ring.

Injector

The injector consists of an ion source and a proton linac which composes a 425 MHz RFQ and DTLs and accelerates H^- ions up to 11 MeV. The ion source is a volume type of H^- ion source operated in pulsed mode and the peak current reaches about 5mA at the entrance of the RFQ linac. The maximum beam duty factor is about 1.8 percent where the beam repetition is 200 Hz. The available H^- beam current (peak) is about 5 mA.

Ring

The ring is a radial focusing type of FFAG proton storage ring where an 8-cell FDF triplet lattice is adopted. Figure 2 shows a photograph of the ERIT ring installed at the experimental room of KURRI. The mean radius of the ring is 2.35 m and the packing factor of the magnets occupied in the ring is about 60. The magnetic fields for F and D magnets at the mean radius are 0.83 and 073 T, respectively. The beam acceptance of the FFAG ring as mentioned above is important to increase an efficiency of neutron production in this scheme. The horizontal and vertical rms acceptance of the ring are 1500 mm×mrad and 600 mm×mrad, respectively.

The RF cavity to re-accelerate the proton beam is basically TM010 mode and made of copper-plated iron and the thickness of the cupper is approximately 100 µm. The rf frequency is about 18 MHz and a large capacitive plate is placed inside of the cavity to reduce a size of the cavity less than 2 m in diameter even at such relatively low frequency. The measured quality factor was about 9000 which was about 75 of that obtained from 3-D field calculation. The RF cavity is operated in cw mode and the maximum RF voltage of 230 kV which is enough for requirement has been obtained with the input RF power of 100 kW.

The neutron production target is a beryllium foil of 5–10 µm in thickness, which is also used for charge stripping at beam injection. Surrounding the neutron production target, a neutron moderator for generating thermal or epithermal neutrons is placed. The moderator is composed of three layers made of iron, aluminum and aluminum fluoride (ALF3) as shown in Fig. 3. Graphite and lithium fluoride (LiF) composite polyethylene are used for neutron reflectors and surrounding them, lead and bismuth gamma ray shield are used. The shape and thickness of each layer are determined by optimizing the neutron yield and energy spectrum with MCNP and PHITS [6] codes, respectively and the results obtained by MCNP are shown in Fig. 4. The initial energy spectrum and angular distributions at the neutron source point of the beryllium target were obtained experimentally using cyclotron [7].

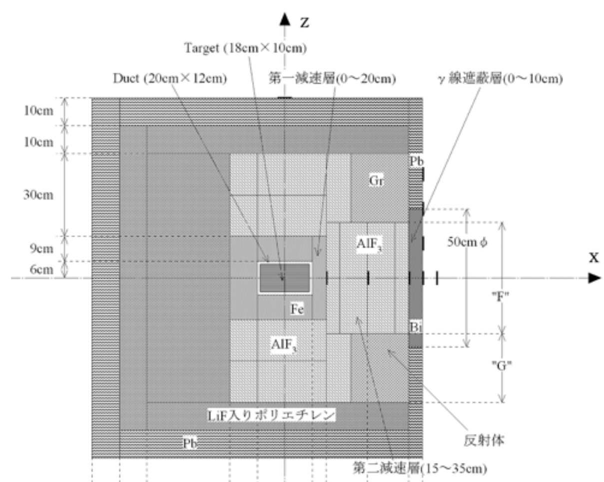

Figure 3: Schematic configuration of neutron moderator.

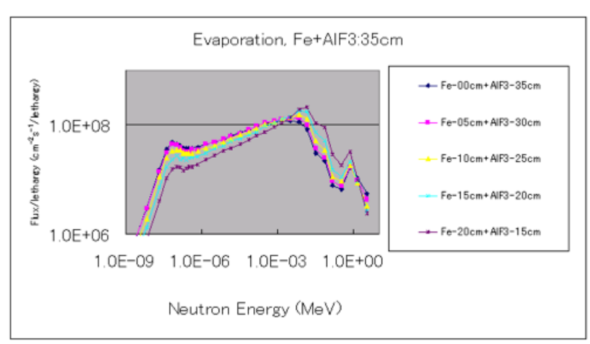

Figure 4: Neutron yield and spectrum simulated by MCNP/PHITS.

BEAM EXPERIMENT

The beam experiment has been carried out to check the principle in the scheme. Especially on the beam accumulation based on ionization cooling. The beam behaviour in the ring was mostly measured by an electrostatic bunch monitor which was placed at the straight section and it has been observed that the beam accumulation and survival (500–1000 turns) were well enhanced by emittance and energy recovery with RF voltage as expected. We have measured and compared the emittance growth rate in transverse (vertical) direction as a function of turn numbers using a beam scraper placed at one of the straight sections in the ring where the beam scraper positions were varied. 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. Figure 5 shows the emittance growth in the vertical direction measured with this procedure as a function of beam turn numbers. Also in this figure, a theoretical emittance growth estimated by ionization cooling model [2] is presented with a solid line. Neutrons generated at the beryllium target were moderated and detected successfully by a neutron detector in the preliminary experiment.

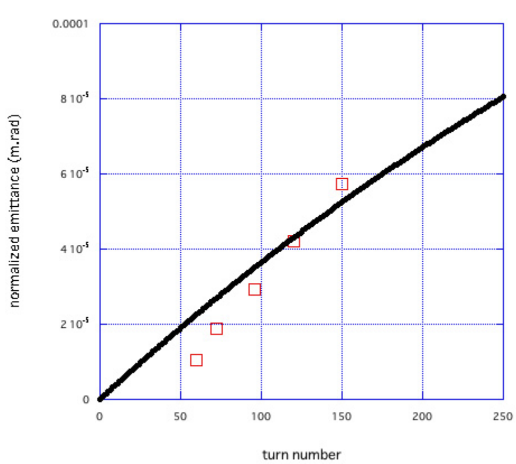

Figure 5: Emittance growth in the vertical direction as a function of turn numbers. Vertical axis in this figure shows a normalized emittance. Open squares show the experimental results and a solid line shows the theoretical estimation based on the ionization cooling model.

SUMMARY

An accelerator based neutron source for BNCT using FFAG-ERIT scheme was constructed and the performance was almost what we expected. The beam behaviors shown in the experiment were expected of ionization cooling model and it was found that beam accumulation and survival in the FFAG-ERIT ring were cured by emittance and energy recovery with ionization cooling scheme with RF acceleration. Using this apparatus, biological effects caused by neutrons are going to be examined experimentally.

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