STUDY OF FFAG-ERIT NEUTRON SOURCE

K.Okabe, Fukui University, Fukui, Japan
Y.Mori, Y. Ishi, T. Uesugi, Kyoto University Research Reactor Institute, Osaka, Japan

Abstract

As for BNCT (boron neutron capture therapy) medical applications, an accelerator-based intense thermal or epithermal neutron source has been strongly requested recently. A scaling type of FFAG accelerator with ERIT (energy/emittance recovery internal target) scheme has been developed for this purpose. In this scheme, the beam emittance degradation caused by the neutron production target are cured by ionization cooling method. In this paper, recent beam study of FFAG-ERIT neutron and magnetic field correction in FFAG ring are described..

INTRODUCTION

In recent years, accelerator-based neutron sources for Boron neutron capture therapy (BNCT) has been strongly requested. Reactions such as ^{7}Li(p,n)^{7}Be, ^{9}Be(p,n)^{9}B with low-energy protons (~10MeV) are currently being investigated as accelerator-based neutron sources. As an intense neutron source for the BNCT system, a FFAG storage ring with ERIT has been developed in the KURRI. The ERIT scheme uses the primary beam efficiently since circulating particles hit the thin target many times, until they make a neutron production reaction or drop out of the ring acceptance. 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 ring has an rf system that recovers the energy loss every turn in the target. In ERIT scheme, the average accelerating beam current can be relatively small, if long time duration of beam storage is realized.

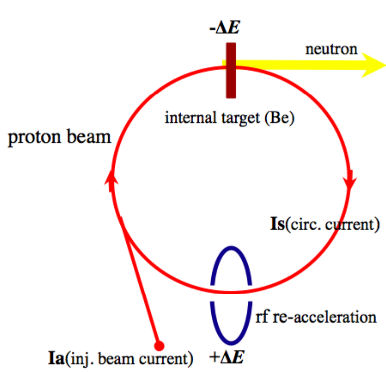

Figure 1: Schematic diagram of ERIT.

However, the proton beam can be lost from the ring very quickly because the beam emittance in transverse and longitudinal directions blow up by effects of multiple scatterings and energy straggling in the target. However these deleterious effects can be cured by ionization cooling [1]. The ionization cooling suppresses transverse and longitudinal emittance blow up in ERIT scheme. The differential equation for transverse ionization cooling of a proton beam is

$$\frac{d\varepsilon}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon + \frac{\beta_\perp E_s^2}{2\beta^3 mc^2 L_R E}, \qquad (1)$$

in which the first term is the cooling term and the second is the multiple-scattering heating term. The ε is the normalized rms emittance, E is beam energy, β and γ are the Lorentz factors, dE/ds is the energy loss rate, L_R is the material radiation length(Be 35.28 cm), E_s is the scattering energy, $\beta_\perp$ is the betatron function at the neutron production target, and the rms beam size is given by $\sigma = (\varepsilon\beta_\perp/\beta\gamma)^{1/2}$. The lifetime of protons in a storage ring with target foil (that is also the neutron-producing interaction source) is extended by ionization cooling and this enables large neutron production.

The detailed beam simulations have been carried out with ICOOL and the results are shown in Figure 2. For a 11 MeV proton beam with a 5 μm beryllium target, an analytical solution calculated from Equation 1 and the simulation results are corresponding well while beam loss is few(~200 turns) in transverse direction.

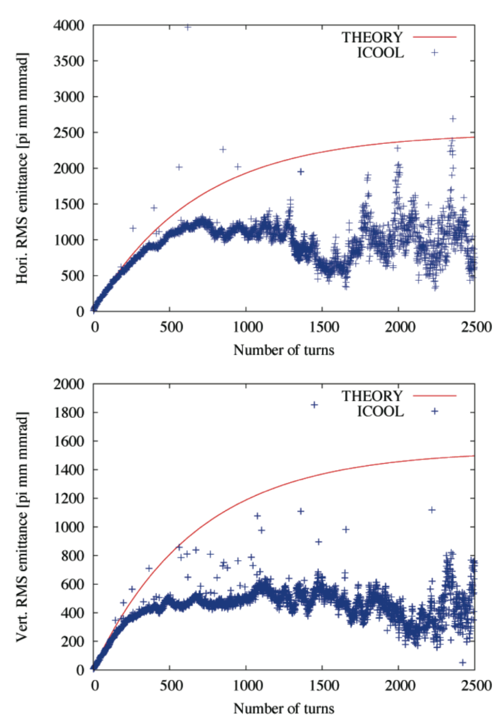

Figure 2: Transverse emittance growth in ERIT.

For a proton storage ring with ERIT scheme, huge momentum and transverse acceptance of FFAG [3] is a big advantage to circulate a beam whose emittance and momentum spread gradually increase.

APPERATUSES FOR ERIT SCHEME

Fabrication and installation of FFAG-ERIT system at KURRI have been completed in 2008 [5]. Figure 3 shows a picture of the ERIT system installed in the experimental room of KURRI.

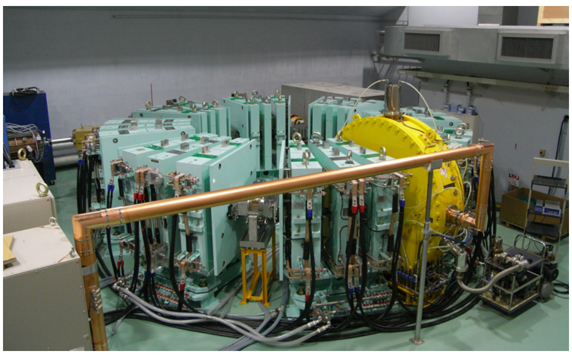

Figure 3: Photograph of FFAG-ERIT accelerator

In this FFAG-ERIT system, the H^- ions are accelerated by the linac 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.

The H^- ion source is a volume type of H^- ion source. The available H^- beam current(peak) is about 5 mA. And the injector for FFAG-ERIT is a linac which composes a 425 MHz RFQ and DTLs. A linac accelerates H^- ions up to 11 MeV and the maximum beam duty factor is about 1.8% where the beam repetition is 200 Hz.

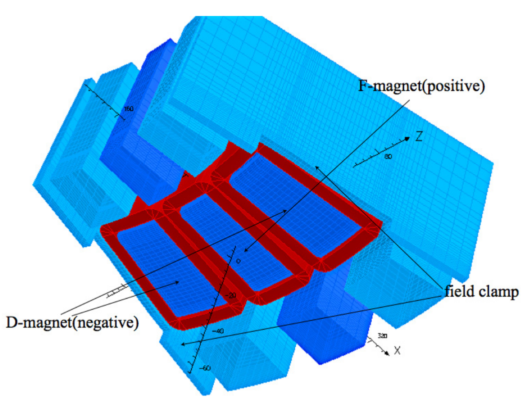

Figure 4: A 3D model of FDF radial sector magnet in TOSCA.

The ERIT ring is a radial focusing type of FFAG proton storage ring where an 8-cell FDF triplet lattice is adopted. The design of the ring magnet was carried out with 3-dimensional magnetic field calculation by TOSCA code. Figure 4 shows one example of 3D model, which used in TOSCA.

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 T and 073 T, respectively. The acceptance of the FFAG ring as mentioned above is important to increase an efficiency of neutron production in this scheme. The horizontal and vertical acceptance of the ring are 7000 mm.mrad and 3000 mm.mrad. And full gap height of ring magnet is about 35 cm.

The RF cavity to re-accelerate the proton beam is basically TM010 mode and made of cupper-plated iron. The rf frequency is about 18.1 MHz and a large capacitive plate is placed inside of the cavity to reduce a size of the cavity less than 2m in diameter. The thickness of cavity with iron shields is about 60cm. The measured quality factor was about 9000 and the maximum RF voltage of 230kV which is enough for requirement has been obtained with the input RF power of 100kW.

MAGNETIC FIELD CORRECTION AT CAVITY SECTION

Large gap to realize magnetic field gradient leads a few hundred Gauss of fringing field at straight section. In order to suppress the fringing field effects, two field clamps are installed at both magnet end(Fig. 4). However, there was no field clamp in cavity section, because the length of straight section is narrow compared to the thickness of rf cavity(Fig. 5).

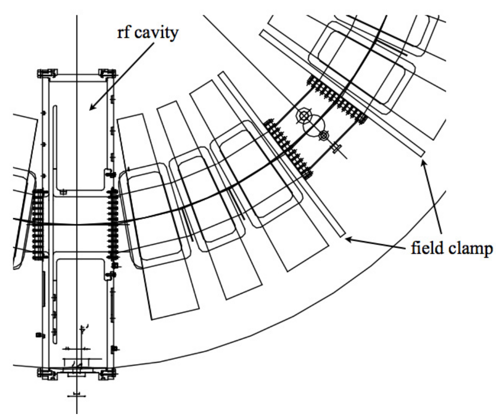

Figure 5: Top view of FFAG-ERIT ring

Figure 6 shows results of magnetic field measurement in azimuthal direction and calculated magnetic field at the median plane. The strength of fringing field suppressed by field clamp is consistent with TOSCA calculation and that is under 10 G at the center of straight section. Wile on the other hand, magnetic field strength at cavity section is about 1000 G higher than other section with field clamp.

This fringing field affects beam orbit and causes closed orbit distortion. In the ERIT scheme, the acceptance of the FFAG ring is important to an efficiency of neutron production. However, if COD exists in the ERIT ring, effective acceptance of the ring is reduced by COD. In order to compensate COD, two additional field clamp are installed at both side of rf cavity. Figure 7 shows installed field clamps at cavity section. These field clamps suppressed fringing field at cavity section(Fig. 6).

Figure 8 shows observed beam positions with or without COD correction. In Fig. 8, red line is a design orbit from tracking simulation and green line is a result of tracking simulation assumed magnetic field error in cavity section. After additional field clamp was installed, beam position at BPM was near than before one. However, residual COD was not corrected exactly. In order to compensate residual COD, more detailed beam study is undergoing.

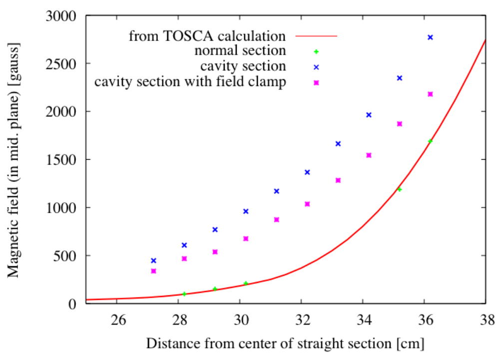

Figure 6: Azimuthal variations of magnetic field at straight section. The radial position is 2525mm.

Figure 7: Installed additional field clamp at cavity section.

SUMMARY

Fabrication and installation of FFAG-ERIT system at KURRI have been completed in 2008. And the beam commissioning of FFAG-ERIT is well in progress. The major source of COD has been identified, that is fringing field at cavity section where field clamps ware not installed. The additional field clamps have been installed at both side of rf cavity, and these clamps suppressed fringing field. More detailed study to compensate COD and basic study for neutron generation is done.

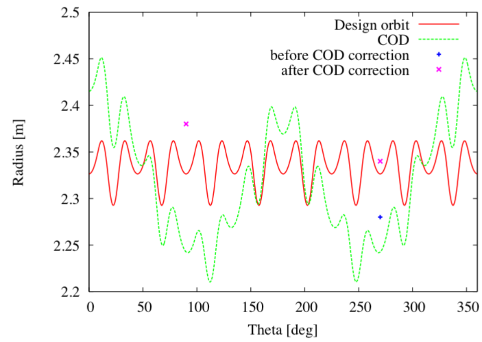

Figure 5: Beam position measurement.

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