DEVELOPMENT OF FFAG-ERIT RING

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Abstract

Neutron source with Emittance–Energy Recovery Internal Target (ERIT) scheme enables large neutron production and this intense neutron source has possibilities of various applications such as Boron Neutron Capture Therapy. A Fixed Field Alternating Gradient (FFAG) ring is used as a low energy proton storage ring (~10MeV) with internal target. We are developing a compact FFAG accelerator with spiral sector magnet. The FFAG-ERIT project has been funded in Japan.

INTRODUCTION

Boron neutron capture therapy (BNCT) is radiation therapy which has a potential ability to selectively kill tumor cells embedded within normal tissue. It makes use of intense thermal or epithermal neutrons to irradiate tumours previously loaded with the stable isotope ^{10}Be. Many groups have investigated epithermal neutrons for BNCT with compact nuclear reactor. In the last years, accelerator-based neutron sources for BNCT, which is easier hospital accommodation than reactor, have aroused an increasing interest. 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. It is, however, very difficult to realize an accelerator-based neutron source because very high beam current is required as far as an external target is employed.

To overcome this difficulty, the scheme using an internal target placed in the circulating orbit of a ring accelerator has been proposed [1]. This scheme, ERIT, utilizes the primary beam efficiently since circulating beam particles hit a thin target many times until they make neutron production reaction or drop out the ring acceptance. The ring has an RF system that recovers the energy lost in the target for every turn. In ERIT scheme, the average accelerating beam current can be relatively small and modest, contrary to the case for the external target with extracted beam if long time duration of beam storage is realized.

However, the incident proton beam will be lost from the ring very quickly because the beam emittance in transverse and longitudinal directions are blown up by effects of multiple scatterings and energy straggling in target. At the same time, ionization beam cooling[2] could suppress the emittance growth of the beam. The ionization cooling method has been studied for muons at optimal cooling energies. The same methods can be applied to the proton-material interactions at low energies. The lifetime of protons in a low-energy storage ring with cooling foil (that is also the neutron-producing interaction source) is extended by ionization cooling and this enables large neutron production.

Figure 1 shows a typical layout of ERIT system having injector 10MeV H^- linac, a storage ring for protons, RF cavity for energy recovery, a Be foil target for neutron production, and an extraction line with moderator for medical use of the neutrons. The goal of the ERIT system is to achieve the production of neutrons (flax ~ 10^9 n/cm^2/s) with the reaction ^{9}Be(p,n)^{9}B, which has a cross-section of 500 mbarn at 10MeV. The baseline parameters of ERIT system are displayed in Table 1. Large transverse and momentum acceptance are necessary for ERIT system so that the ionization cooling works efficiently. FFAG will satisfy the requirements of large acceptance in both transverse and longitudinal directions since it satisfies zero chromaticity condition and has a constant momentum compaction factor.

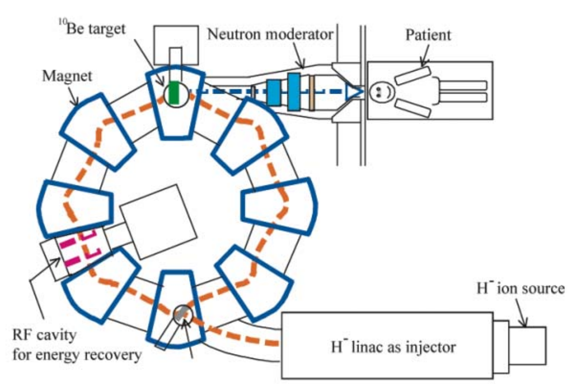

Figure 1: A schematic layout of ERIT system.

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Table 1: Main parameters of ERIT system

ERIT system	Expected turn number	> 1000 turns
	Be target thickness	~ 5 [μm]
Injector(linac)	Ion spices	H^-
	Kinetic energy	10 [MeV]
	Average beam current	~ 45 [μA]
FFAG storage ring	Injection scheme	H^- injection
	Average beam current	~ 45 [mA]
RF cavity	RF voltage	200 [kV]
	Harmonic number	5

DESIGN OF FFAG MAGNET FOR ERIT SCHEME

Since the world's first proton FFAG synchrotron (pop-FFAG) was successfully commissioned at KEK in 2000 [3], FFAG accelerator is prospective as a compact and versatile accelerator. To achieve the aimed performance in ERIT system, the following requirements should be fulfilled:

- Large momentum acceptance more than 5%
- Large transverse acceptance more than 1000 πmm mrad
- Long straight sections, about 0.6m, for RF cavities

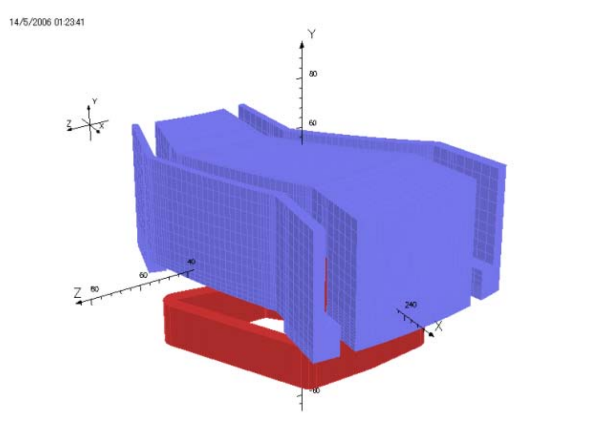

Figure 2: A 3D model of the FFAG-ERIT magnet.

Scaling FFAG accelerator are generally classified into

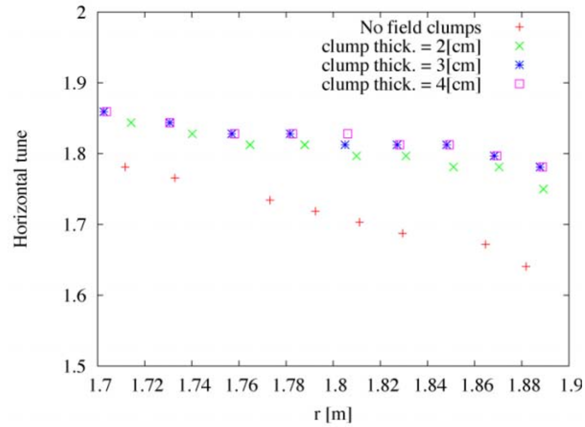

Figure 3: Distribution of horizontal tune, which is calculated with the tracking simulation, in a radius.

the following two types: radial sector and spiral sector. A spiral sector type FFAG[3] is better in compactness than a radial sector type because radial type has reverse bends. In order to design the machine, basic parameters has been determined with the linearized model. In spiral-sector lattice, our initially preferred design basic parameters are shown in Table 2.

Table 2: Initial parameters of FFAG-ERIT ring. These parameters are determined by linearized model.

Mean radius	1.8 [m]
Sector number	8
Opening angle	13.5 [deg]
Field index k value	2
Spiral angle	26 [deg]
Horizontal tune, Vertical tune	1.89, 1.34

The design of the ring magnet was carried out with 3-dimensional magnetic field calculation by TOSCA code. And to study the beam dynamics of FFAG, three-dimensional tracking simulation is adopted. Figure 2 shows one example of 3D model, which used in TOSCA. In order to achieve large transverse and longitudinal acceptance, we optimize the ring magnet through the two steps.

First, we install two field clamps at both magnet end, in order to suppress the fringing field effects. Figure 3 shows distribution of horizontal tune as a function of radius when any field clamp of different thickness is installed. It can be obviously seen that horizontal tune

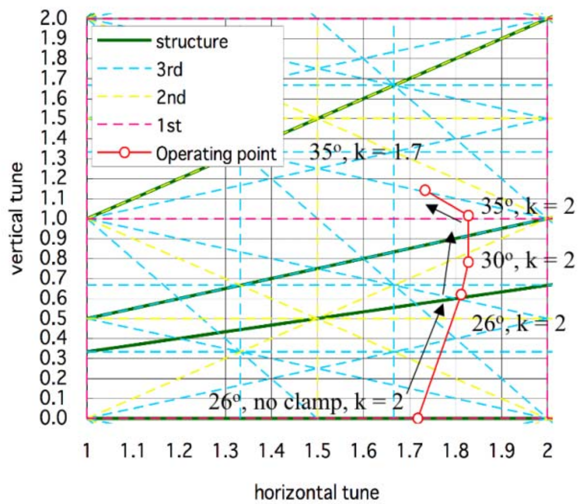

Figure 4: Betatron tunes optimization by varying k value and spiral angle.

shift in a radius is suppressed by effect of field clamps.

Second, we optimize k value and spiral angle from initial value. Figure 4 plots betatron tune shift of the operating point on the tune diagram. Because effective opening angle of magnet is broadened by effect of fringing field, vertical tune is very low value compared with the value calculated from linearized model. Optimized magnet parameters are shown in Table 3.

Table 3: Optimized parameters of FFAG-ERIT ring and magnet.

Mean radius	1.8 [m]
Sector number	8
Opening angle	13.5 [deg]
Field index k value	1.7
Spiral angle	35 [deg]
Half gap @ r = 1.8 [m]	7 [cm]
MMF	~ 42000 [A turn]
Horizontal tune, Vertical tune	1.73, 1.14

In Figure 5, the particles which can survive after 128 turns are plotted in a phase space. The top figure is the phase space projected to the horizontal-phase-space plane and the bottom one is that projected to vertical one. From this figures, it can be seen that the horizontal acceptance is 14,000 π mm mrad and the vertical one is 1,300 π mm mrad. This acceptance is much larger than the requirements acceptance from ERIT scheme.

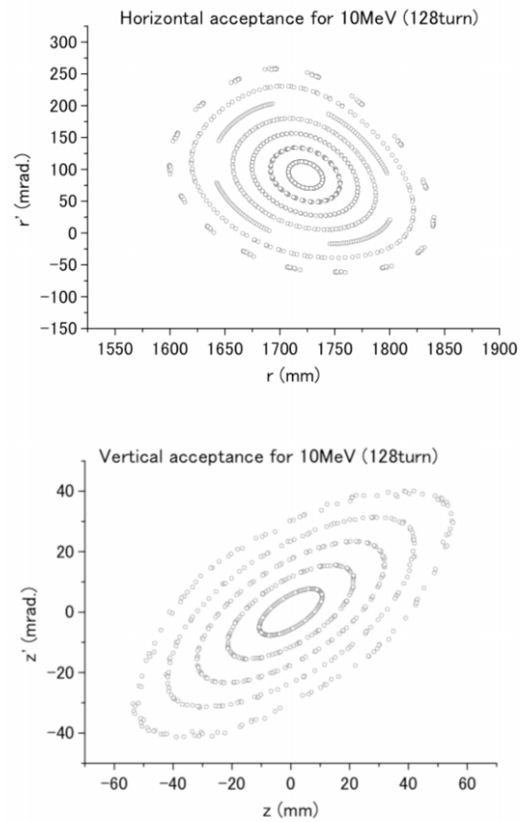

Figure 5: Phase space plot of tracking particle.

SUMMARY

The optics and magnet design of FFAG-ERIT storage ring has been almost completed. From tracking simulation, it have been confirmed that the transverse acceptance more than 1,000 πmm mrad can be achieved. This acceptance satisfies requirement of ERIT scheme. This machine is expected to be the prototype of next generation intense neutron source.

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