# FFAG BASED NEUTRINO FACTORY

Takeichiro Yokoi, Shinji Machida, Yoshiharu Mori,KEK, Tsukuba, Ibaraki, Japan ,
Yoshihisa Iwashita, Kyoto univ., Kyoto, Japan,
Yoshitaka Kuno, Osaka univ. Osaka, Japan

*Abstract*

Fixed Field Alternating Gradient(FFAG) accelerators can accelerate a large emittance beam in a very short time. The feature is suitable for the acceleration of secondary particles. With the help of low frequency high gradient rf cavity, a FFAG-based neutrino factory becomes feasible. It can directly accelerate muon without phase rotation and muon cooling. As a result, the accelerator complex becomes simple and cost effective compared to that of the ordinal neutrino factory scenario. In the paper, the overview and conceptual design of the FFAG-based neutrino factory are presented.

## 1 INTRODUCTION

Neutrino oscillation is a highlight of particle physics. Up to now, the investigation has been led by so called 'conventional' neutrino beam generated by the neutrino horn. However, for the precision measurement of the oscillation parameters, a purer and higher intensity neutrino beam is demanded. The idea of the neutrino factory has risen with such a background and world wide R&D studies are undergoing[1, 2].

A neutrino factory usually consists of five stages: (1)pion capture, (2)phase rotation,(3)muon cooling,(4)muon acceleration, and (5)storage. The phase rotation and the muon cooling is indispensable for the possible upgrade to the muon collider. However, they require a lot of rf cavities and large and long solenoid channels before accelerating muon and result in a fairly large construction cost.

Other approaches without having phase rotation and muon cooling to the neutrino factory has been considered. The FFAG based neutrino factory is proposed as a dedicated neutrino factory.

## 2 FFAG RENAISSANCE

The idea of FFAG accelerator was originally proposed by T. Ohkawa in 1950s[8]. After the prototype developments lead by the MURA project [3], there was practically no activities in the field. After the long interruption of 30 years, the FFAG accelerator was re-developed by the KEK group to investigate its potential for a practical and modern accelerator[4]. The first machine, named PoP(**P**roof **o**f **P**rinciple) FFAG has been successfully constructed. This is the world first proton FFAG accelerator. Through the commissioning, interesting features of the FFAG accelerator were found[4, 5].

Typical results are as follows.

- It can accelerate a proton beam from 50keV to 500keV within 1ms.
- It has a huge horizontal acceptance of more than 5000$\pi$mm·mrad.
- The validity of the design scheme based on numerical calculation was verified.

  The observed machine parameters such as betatron tune were consistent with the design values.

With the success of the PoP FFAG, the construction of a new and large FFAG accelerator which can accelerate a proton beam up to 150MeV has started[6] and many ideas of application of the FFAG accelerator have been proposed. The FFAG based neutrino factory is one of such applications.

## 3 BASIC CONCEPT

The FFAG accelerator has two remarkable features for the beam handling of short-lived particle beam with large emittance. One is that it can accelerate a particle beam with short acceleration time, and the other is that it has huge horizontal and longitudinal acceptance. The first one, the short acceleration time comes from the characteristics of the fixed field. Since, unlike the ordinal synchrotron, it dose not need to modulate a magnetic field of the ring during beam acceleration, the acceleration time is only determined by the accelerating field gradient. As discussed in the later section. the accelerating field of 1MV/m can be achieved in a low frequency rf cavity. Figure 1 shows the muon survival rate during the acceleration.

The transverse acceptance is expected to be typically more than 10000$\pi$mm·mrad from the computer simulation and the momentum acceptance is typically about $\pm 50\%$, which is achieved with the high gradient low frequency rf cavity. Figure 2 shows a typical longitudinal phase space distribution of pion generated by a tungsten target. The longitudinal acceptance is typically $\sim$5eV·sec, which is reachable with low frequency rf cavities. Such huge acceptances make it possible to accelerate a muon beam directly without complicated beam handling schemes such as phase rotation and muon cooling, which are the major cost eater of the ordinal neutrino factory scenarios and are also the most difficult issues among R&D items.

The elimination of phase rotation and muon cooling sections offers another advantage. As shown in Figure 1, the decay loss of muon is dominated in the low momentum region. The phase rotation and muon cooling force muons

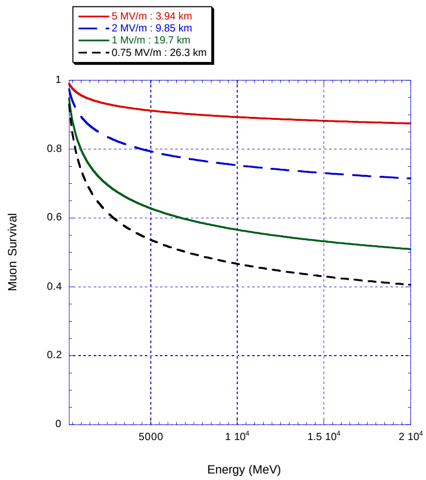


Figure 1: Muon survival rate during acceleration in various accelerating field gradient

to stay in the high loss region until cooling is completed. Thus, skipping these two stage results in suppressing the muon decay loss.

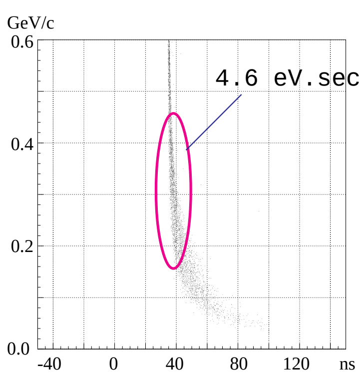


Figure 2: The particle distribution of the initial pions and the product muons generated by a short bunched 5 GeV proton beam in the longitudinal phase space. (Horizontal axis: time of flight(ns) Vertical axis:total momentum(GeV/c) )

These two are the key features of the FFAG based neutrino factory. The following sections give the overview.

## 4 PION CAPTURE

In ordinary neutrino factory scenario, the initial captured pions are momentum range of 100MeV/c $\sim$ 300MeV/c. This is requested from phase rotation and muon cooling. However, in the FFAG scenario, since the phase rotation and muon cooling channels are skipped, the initial momentum region must be re-optimized.

As the proton driver, JHF main ring is to be adopted in the study[1]. Figure 3 shows the pion and muon momentum spectrum and yield as a function of central captured momentum with fixed momentum acceptance of 50%. It shows that the optimum central momentum is around 700MeV/c. If the captured momentum is set to be relatively higher momentum, another advantage can be expected. Generally speaking, high energy pion are forwardly boosted at birth. Therefore, the initial emittance expected to be relatively small. In addition, the emittance blow up caused by pion decay is also small compared to that for low energy capture. These two advantages result in the reduction of transverse dimension of the apparatus.

[1]Proton energy: 50GeV, Beam power 1MW

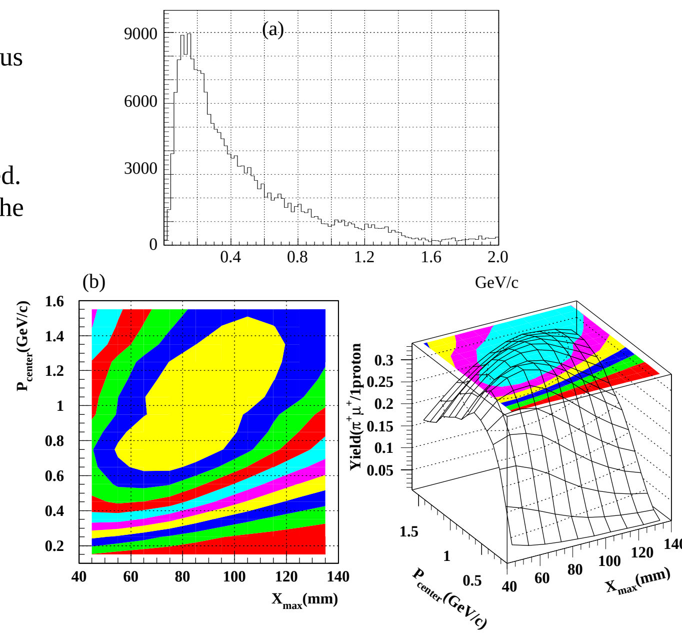


Figure 3: (a) Muon and pion distribution with fixed transverse acceptance(10000$\pi$mm·mrad), (a)Total Momentum distribution (b) particle yield in various central momentum and beam size with fixed horizontal(10000$\pi$mm·mrad) and momentum acceptance(dp/p=50%)

In the FFAG scenario, the reduction of the initial beam emittance is crucially important. For the issue, recently a promising idea has arisen. That is the concept of "Conducting target"[7]. The idea is as follows. Feeding a huge pulsed electric current in a target made of conducting materials such as graphite, a strong toroidal field is generated inside of the target. The generated pions are confined inside of the target by the field and finally go out from the downstream surface of the target. Unlike the conventional target of the neutrino factory, the source point is unique and the beam size at the source is the production target radius. As a result, the initial emittance is drastically reduced compared to the conventional target.

The idea has another interesting feature. Since the source point is the downstream edge of the target, it does not need free space around the target. It could solve the cooling and radiation problem of the primary target of the solenoid capture scheme.

## 5 MUON ACCELERATION

In a FFAG accelerator, the accelerating time is only limited by the accelerating field gradient of rf cavity. Thus, as shown in Figure 1, high gradient and low frequency rf cavity is crucially important to suppress the decay loss of muons. A field gradient of 1MV/m and frequency of about 5MHz is aimed to develop for rf cavities of a FFAG based neutrino factory. To realize such cavities, three candidates have been studied; (1)the inductive material loaded cavity using a new type of ferrite, (2)the capacitive material loaded rf cavity using high grain ceramic, and (3)the air gap rf cavity. The R&D study suggests the feasibility of the field gradient of 1MV/m[9].

In the FFAG scheme, the muon acceleration is carried out through cascaded FFAG rings. In the present study, it would employ four FFAG rings to accelerate muon up to 20GeV/c. Table 1 summarizes the main parameters of the rings, and Figure 4 shows a typical layout of FFAG based neutrino factory in the JHF Tokai site. Among these rings, the 3rd and the 4th ring will employ superconducting magnet to obtain high bending field, typically 5T. In order to increase the packing factor of rf cavities, a sufficiently long($>$2m) drift spaces are placed between the cell. The long drift space also makes the beam extraction easier with help of a high field kicker magnet[10]

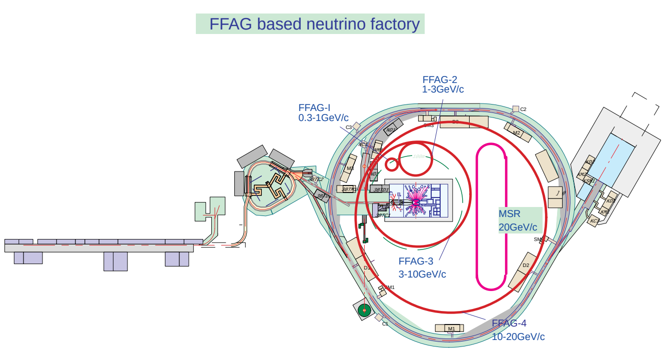


Figure 4: FFAG-based neutrino factory at the Tokai campus

## 6 SUMMARY

The neutrino factory is a key facility for the investigation of lepton sector physics of the next generation, and worldwide development is undergoing now.

In such a context, the FFAG based neutrino factory is proposed as a dedicated neutrino factory. The huge acceptance makes it possible to directly accelerate muons without the phase rotation and muon cooling channel, and in results the construction cost will be drastically reduced. In addition, the fast acceleration will suppress the muon decay loss during the low energy region.

With the help of high gradient cavity and the conducting target, the FFAG based neutrino factory will come to a realistic stage.

Table 1: Main parameters of FFAG rings of FFAG neutrino factory. P: Momentum, $R_{av}$: average radius,$N_{cl}$:number of cell, $L_{st}$: length of the straight section, $t_{rev}$: revolution time, SC(NC):Super(normal)conducting magnet

| P (GeV/c) | $R_{av}$ (m) | $N_{cl}$ | $L_{st}$ (m) | $t_{rev}$ (ns) | |
|---|---|---|---|---|---|
| (1) 0.3∼1.0 | 21 | 32 | 2.1 | 440 | NC |
| 0.3∼1.0 | 10 | 16 | 2.1 | 210 | SC |
| (2) 1.0∼3.0 | 80 | 64 | 4.3 | 1680 | NC |
| 1.0∼3.0 | 30 | 32 | 3.2 | 630 | SC |
| (3) 3.0∼10.0 | 90 | 64 | 5.0 | 1880 | SC |
| (4)10.0∼20.0 | 120 | 200 | 5.7 | 4190 | SC |

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