Neutrino factory in Japan

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Abstract. The Japanese scheme of a neutrino factory based on fixed-field alternating (FFAG) gradient accelerators is presented.

1. Introduction

One of the candidates of the next-generation particle physics facilities is a neutrino factory, which is capable of studying 3x3 neutrino MNS mixing matrix in lepton sector intensively. The number of muon decays in the muon storage ring is aimed to be more than $1x10^{20}$ muon decays/one straight section/year. The energy range of muons is 20-50 GeV. The accelerator complex of the neutrino factory considered in Japan consists of several sequential rings of the fixed-field alternating gradient (FFAG) accelerators, which is significantly different from the others in U.S. and Europe. [1] The schemes considered by them are based on the linear accelerators. A high accelerating gradient and small total length of the accelerator minimizes beam loss caused by muon decay, but requires that the rf frequency used in the linear accelerator system becomes relatively high. The typical RF frequency range utilized in this scheme is several 100MHz. Moreover, a small total length of the linear accelerator system also helps to reduce the cost of the accelerator. The disadvantage of the high frequency system is its small beam. Thus, in this case, muon beam phase rotation and cooling become essential. Ionization cooling consists of a number of energy degrading media between the rf accelerating cavities, and seems to be a possible solution. Since the initial pions, and the product muons have a large energy spread, phase rotation before cooling is also required to decrease the energy spread. Even with this, the muon beam intensity after cooling could drop substantially [2], and the total facility cost should become expensive.

If a circular accelerator can be adopted to muon acceleration, this limitation becomes modest. Many turns for acceleration in the same ring using the same accelerating system helps to reduce the total size of the accelerator and the total construction cost. Figure 1 shows the muon survival for different accelerating energy gains as a function of the muon energy from 0.3GeV/c to 20GeV/c. In case of the energy gain of 5MeV/m, the muon survival is almost 90%. Even when the accelerating gradient is only 1MeV/m, the muon survival during acceleration is still more than 50 %, which should not be so painful. This energy gain difference affects the total length of the accelerator very much. In the linear accelerator system, if the energy gain is 5 MeV/m the total length of the accelerator becomes almost 4km, which is acceptable. However, if the energy gain is 1 MeV/m, the total length exceeds more than 20 km and only a

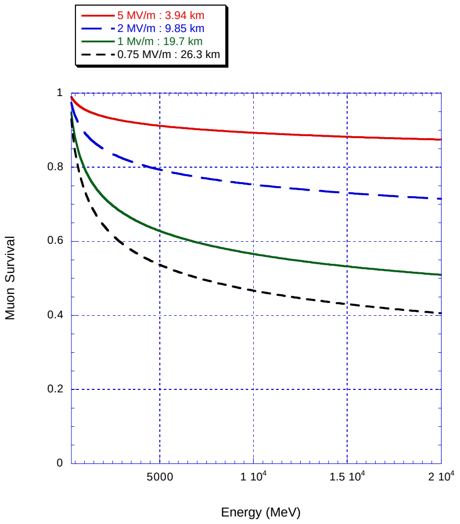


Fig.1 Muon survival

circular accelerator can be realistic. The ordinary synchrotron is obviously inadequate for accelerating muons. The magnetic field in an ordinary synchrotron must increase during acceleration and the ramping rate cannot be fast enough to compete with the muon lifetime.

The FFAG (fixed-field alternating gradient) accelerator seems to be adequate for accelerating muons to high energy. The idea of FFAG originated from a Japanese physicist, Ohkawa, in 1953.[3] Since then, except several electron models of FFAG built for MURA project in U.S. in the mid 60's, no attempt has been made by the most recent year when the KEK accelerator group constructed the small POP (proof of principle) proton model in 2000. This machine was successfully operated.[4]

A big advantage of the FFAG accelerator for accelerating short lived particles such as muons is that the beam guiding magnetic field is static. The acceleration time can be short enough to eliminate the particle decay if the rf voltage is large enough. Another advantage of the FFAG accelerator is that it has a large acceptance for both transverse and longitudinal directions. Thus, in the neutrino factory based on the FFAG accelerators does not need muon cooling and phase rotation, which would help a lot to reduce a total construction cost of the facility.

2. Neutrino factory based on FFAG accelerators

The FFAG has unique features such as 1) the fixed magnetic field 2) strong transv. focusing and 3) strong long. focusing. These features can realized the very large acceptance and very quick acceleration, which are very useful for muon acceleration. Figure 2 shows a conceptual scheme of the neutrino factory based on FFAG accelerators. In order to make a simple magnetic field configuration and avoid a phase slip problem during acceleration, the multistep acceleration seems to be realistic. At this moment, we are thinking to have at least 3 or 4 stages for accelerating muons from 0.3 GeV/c to 20 GeV/c. This multistep scheme may also be useful for providing various interesting physics in each stage such as muon rare decays.

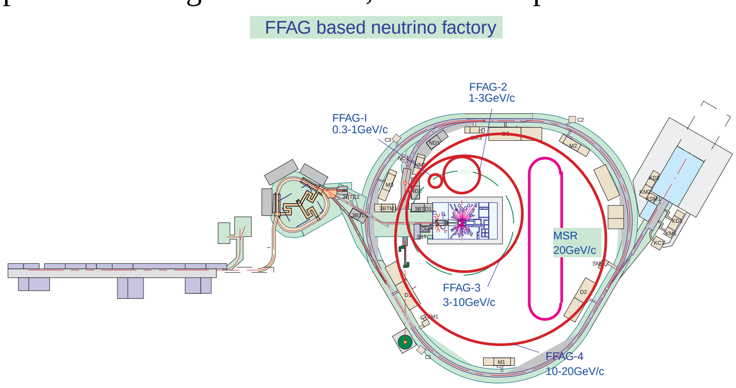


Fig. 2 Schematic layout of the FFAG based Neutrino Factory

In Fig. 2, a conceptual schematic layout of the

FFAG based neutrino factory with the 50 GeV proton driver at JAERI Tokai site is also presented. The neutrino factory based on the FFAG accelerators consists mainly of four parts: proton driver, target and capture region, FFAG accelerator chains and muon storage ring.

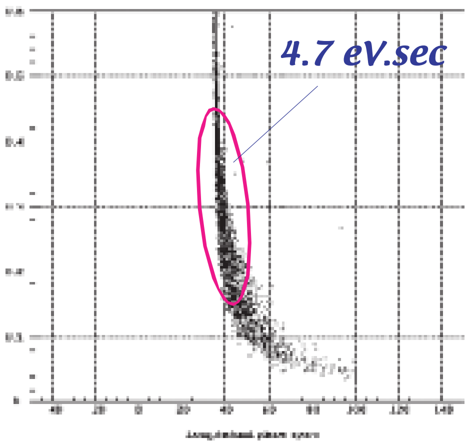


Fig.3 Longitudinal distribution of pions generated by the 50GeV PS.

2.1. Acceptance

How large acceptance is needed? We have made some calculations to examine how large transverse and longitudinal acceptance are needed to satisfy the requirements of the muon yields such as 1×10^{20} muon decays/one straight section/year in the muon storage ring. This number corresponds almost 0.3muons/proton when the beam intensity of the JHF 50GeV proton driver is assumed.

The longitudinal acceptance depends on its rf frequency. The particle distribution of the initial pions and the product muons in the longitudinal phase space after the captured solenoid when the 50 GeV proton driver described above is used were calculated. In this case, the bunch length of the proton beam from the 50 GeV proton driver is assumed to be 6 nsec in rms value. Figure 3 shows a longitudinal phase space distribution of the pions, which are produced by the 50GeV proton beam, at the distance of 6m away from the target position. According to these simulations, the particles having central momentum and momentum spread of 300MeV/c and +- 50%, respectively, are well within the area of 4.6 eV.sec.

This size of longitudinal acceptance can be realized by a low frequency rf accelerating system having an accelerating field gradient of 1MV/m. One of the advantages in using a low frequency rf system is its large longitudinal acceptance. The typical longitudinal acceptance with such a low frequency rf system would be several eV.sec or more. Such a low accelerating field gradient can be realized with a rather low frequency rf accelerating system. For example, in the antiproton decelerator (AD) at CERN, the 9MHz rf cavity has achieved a field gradient of about 0.8MV/m in burst mode operation. Thus, a ring accelerator is practically the only scheme possible for muon acceleration with a low frequency rf system.

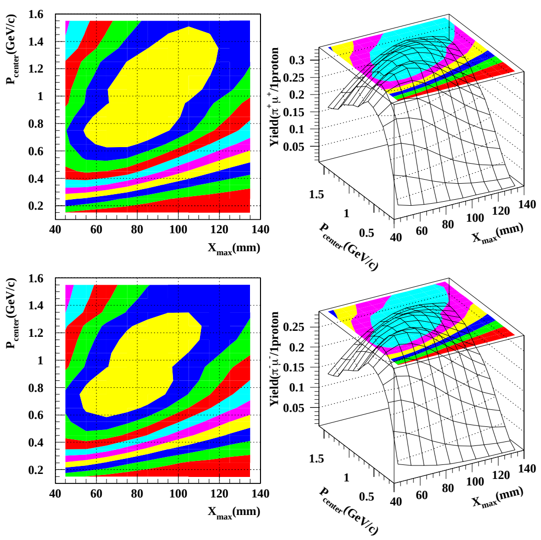


Fig.4 Number of pions(π+, π-)generated by 50GeV protons as a function of the pion beam momentum.

The horizontal acceptance of the FFAG accelerator is very large because of this feature and normally exceeds 0.03 m.rad in normalized acceptance. The momentum acceptance is also very large and a beam having a large momentum spread of more than +- 50% can be accelerated. Thus, both muon cooling and, accordingly, phase rotation should not be necessary. This may become a kind of "brute" force option for muon acceleration in the neutrino factory.

Figure 4 shows the number of pions(π+, π-)generated by 50GeV protons as a function of the pion beam momentum if the normalized transverse acceptance and the longitudinal momentum acceptance are assumed to be 0.03 m.rad and +-50%, respectively. As can be seen from this figure, the optimum pion energy range to satisfy the muon yield of 0.3 muons/proton is rather broad, which is 0.4-1.5GeV/c.

In the following sections, specifications of each part of the FFAG based neutrino factory are described.

2.2. proton driver

The 50 GeV proton synchrotron of the joint project between KEK and JAERI, which will begin construction April , 2001 as a 6-year term project, is considered to be the proton driver for the future neutrino factory. The planned 50-GeV proton synchrotron consist of a 400-MeV proton linear accelerator (400-MeV linac) as an injector, a 3-GeV rapid cycling synchrotron as a booster and a 50-GeV proton synchrotron (main ring).[5] The accelerators will be constructed at the south site of JAERI-Tokai, as shown in Fig.2.

The main ring is to accelerate protons from 3 GeV to 50 GeV. The expected beam intensity in the main ring is 3.3×10^{14} ppp and the repetition rate is about 0.3 Hz. The 50-GeV protons are extracted by slow and fast extraction schemes into two experimental areas: one is for experiments using secondary beams (K, antiproton, etc.) and primary beams by slow extraction, and the other is for the neutrino oscillation experiments by fast extraction. When operated in a slow extraction mode, the average current and duty factor, which is defined as the fraction of a cycle when a beam is available, are 15 μA and 0.20, respectively.

Four batches from the booster are injected into the main ring when the main ring stays at a low field. Then, 8 buckets out of 10 are filled with beams, and the main ring starts acceleration while three other facilities start to use 3-GeV beams directly from the booster. The average beam current of 15.6 μA for slow extraction and 19.6μA for fast extraction at the first stage will be increased in future. There are several upgrading options. Roughly speaking, two major paths should be taken: one is increase of repetition rate and the other is increase of particles per pulse. Although the repetition rate of the main ring at the beginning is 0.29 Hz for slow extraction mode and 0.37 Hz for fast extraction mode, the lattice magnets themselves are designed so that a higher repetition rate such as 0.51 Hz operation for slow extraction and 0.79 Hz for fast extraction will be possible. That pushes up the average current to roughly 26.8 μA and 41.6 μA, respectively. In this case, the electric power required for exciting the lattice magnets increases and becomes almost doubled. Although the main ring is not a space charge limited synchrotron at the design particles per pulse in terms of space charge tune shift, special care is necessary if we need to increase the number of particles. One of the options to increase the number of particles is to use barrier buckets at injection. Capturing with barrier buckets decreases the local line density at injection so that the tune shift becomes less. Another advantage of using barrier buckets for injection is that we can inject as many booster batches as we want in contrast with bunch to bucket transfer. If a higher repetition rate and barrier bucket injection with 10 beam batches are adopted simultaneously in future operation, the average current increases up to 59.4 μA for slow extraction mode and 86.9μA for fast extraction mode. In case of the neutrino factory, the duty factor, which means a portion of the flat-top time duration in one main-ring cycle, becomes roughly 33 %. In the FFAG based scenario, the requirement of the bunch length is much more modest compared with the linac based neutrino factory because the longitudinal acceptance of the FFAG using a low frequency rf system is relatively large. The expected bunch width from the proton beam should be even 6 ns or more in rms size for the FFAG based neutrino factory. The rms bunch length at 50 GeV is approximately 6 ns in ordinary operation, which is almost the same as required in the FFAG based neutrino factory. This means that no special treatment to the bunch shortening is necessary for the 50GeV proton driver in our FFAG based neutrino factory.

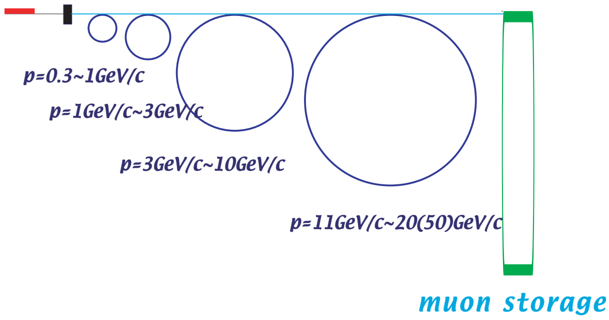
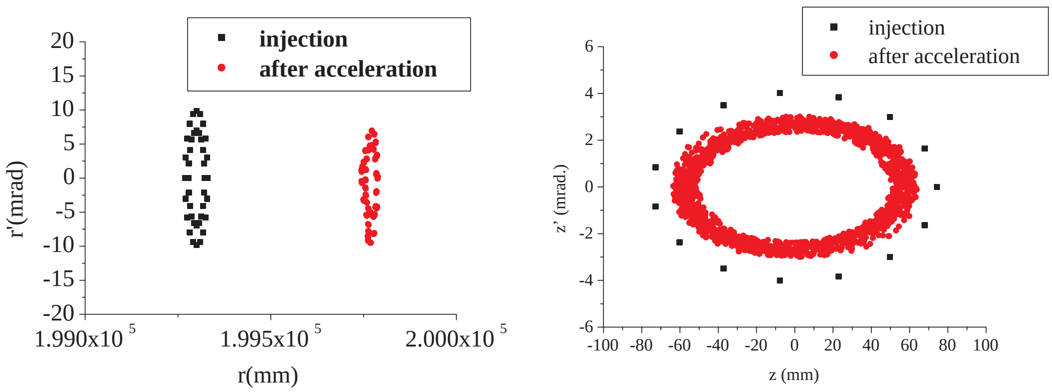


Fig. 5 FFAG chain.

2.3. FFAG chain

A conceptual scheme of the neutrino factory based on FFAG accelerators is shown in Fig.5. In order to make a simple magnetic field configuration and avoid a phase slip problem during acceleration, the multistep acceleration seems to be realistic. At this moment, we are thinking to have at least 3 or 4 stages for accelerating muons from 0.3 GeV/c to 20 GeV/c. This multistep scheme may also be useful for providing various



(a) Horizontal

(b) Vertical

Fig. 6 Beam simulations in the FFAG accelerator (10-20GeV/c).

interesting physics in each stage such as muon rare decays.

Since the practical momentum range from injection to extraction in the FFAG accelerator is about 3-4 times, there are four FFAG rings for acceleration of muons from the momentum of 0.3 GeV/c to 20 GeV/c in this scheme. The first ring accelerates muons from 0.3GeV/c to 1GeV/c, followed by the second one of 1GeV/c to 3GeV/c, the third one of 3GeV/c to 10GeV/c, and the final one of 10GeV/c to 20GeV/c. The momentum ratio of injection and extraction for each ring is less than 3, which is modest to give a small beam excursion of about 0.5m.

A scaled radial sector type of FFAG with a triplet focusing, which is same for the POP machine, is applied to each ring. There are several advantages in triplet configuration compared to the other radial and spiral types. One is field cramping which is expected between adjacent focusing and defocusing magnets. Second, the length of each straight section becomes large because one focusing and two half defocusing magnets are combined together to make one multi function magnet. Finally , the lattice functions has mirror symmetry at the center of a straight section.

2.4 Beam apertures

In the scaling type of FFAG, the larger ring should have a larger magnetic field index,k. Therefore, such large field index may suffer the dynamic aperture seriously because of its large nonlinear field. However, the reality is not such a situation. As can be shown in eq. (1), in case of the scaling type of FFAG, the high order of the magnetic field at the closed orbit does not scale with k but k/r, where r is a orbit radius. Therefore, we may have a large k-value for the large ring to keep the large beam dynamic apertures

$$B = B_0\left(\frac{r}{r_0}\right)^k \cong B_0\left\{1+\left(\frac{k}{r_0}x\right)+\frac{1}{2!}\left(\frac{k}{r_0}x\right)^2+\cdots\right\} \qquad (1)$$

Figure 6 shows the beam tracking results for the last FFAG ring (10-20GeV/c) . The normalized emittance of the beams for horizontal and vertical directions are both assumed to be 0.03 m.rad, respectively.

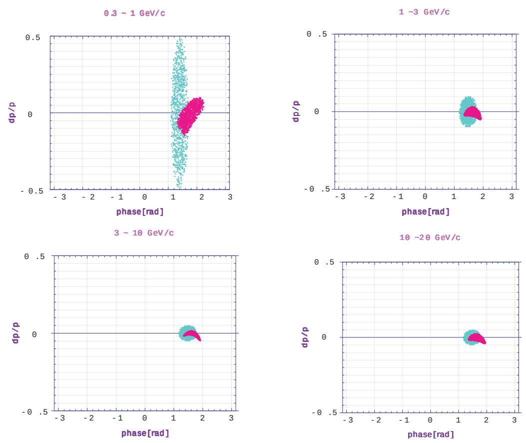


Fig.7 Longitudinal beam simulations from 0.3GeV/c to 20GeV/c

In order to examine the longitudinal particle motions in the beam acceleration through these four FFAG rings using superconducting magnets, particle tracking simulation has been carried out for. The assumed initial longitudinal emittance and the maximum momentum spread at injection

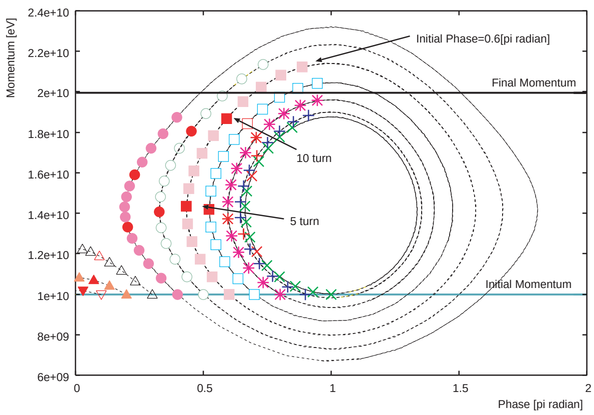


Fig. 8 Longitudinal rf bucket configuration of the scaling type of FFAG.

are 4.6 eV.sec and +-50%, respectively. In this simulation, the averaged rf accelerating field strength of about 1 MV/m is assumed for all of the rings. The simulation results are summarized in Fig 7. As can be seen from these results, the particles are accelerated up to the final energy without having serious problems and the momentum spread is reduced to less than +-5%.

In the scaling type of FFAG, the momentum compaction factor keeps constant for different beam energy.

$$\alpha = \frac{1}{k+1} \qquad (2)$$

Thus, almost no distortion in the rf bucket even at the very large momentum range. Figure 8 shows the rf bucket of the last FFAG ring where the accelerating field of 0.7MeV/m is assumed. As can be seen from this figure, the beam can be accelerated in the stationary rf bucket even when the rf frequency is fixed.

One of the key technologies to realize a FFAG based neutrino factory is a low frequency and high gradient rf cavity. There are several candidates for low frequency and high gradient rf cavitiesas showin Fig.9; (1)ferrite-loaded, (2) ceramic gap and (3) air gap. All of these R&D are proceeding under the US-Japan high energy collaborations.

2.5 Storage ring

A storage ring is designed and it has two of approximately 300m straight sections. At

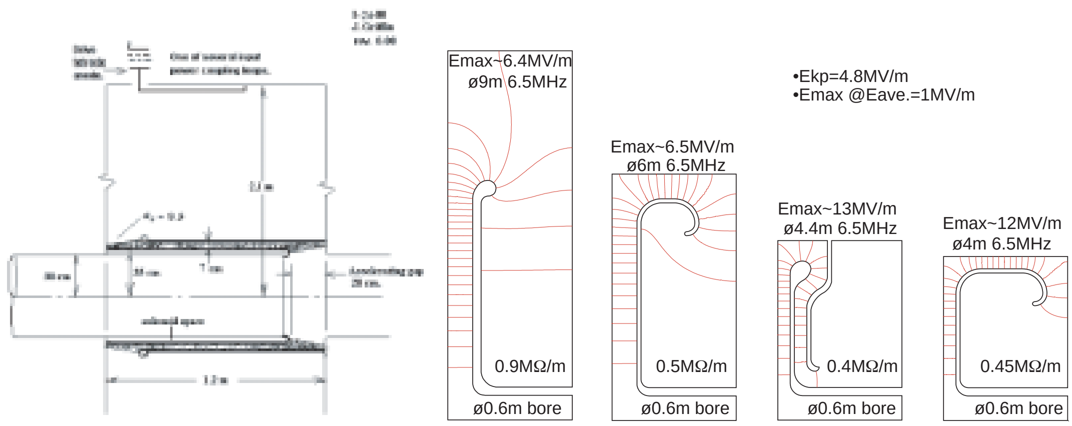


Fig. 9 Low frequency and high gradient rf cavities.

the straight section, beam size is enlarged and the rms divergence of beams becomes 0.92. That satisfies the condition of

$$D_{beam} < 1/5\gamma$$

where γ is a relativistic Lorentz factor.

3. Summary

In the FFAG based neutrino factory, the expected muon intensity after acceleration exceeds more than 6 $\times 10^{20}$ muons/year with the 50 GeV and 0.75MW proton driver and about 2 $\times 10^{20}$ muon decays/year in the muon storage ring can be realized. If the 50 GeV proton driver is upgraded to reach the beam power of 4 MW as described below, the more than 1 $\times 10^{21}$ muon decays/year becomes possible.

References

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