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Neutrino Factory design based on FFAG

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For the NufactJ Working Group

Abstract

An overview of a neutrino factory design in Japan is presented. Our design goal is to obtain 1×10^{20} muon decays per straight section per year with the muon energy of 20 GeV/c. It will be about four times more if the proton driver is upgraded. Upgrade path to higher muon energy is also considered.

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Keywords: FFAG (Fixed Field Alternating Gradient); Muon acceleration

1. Introduction

We propose a neutrino factory based on Fixed Field Alternating Gradient (FFAG) accelerators to accelerate muons [1]. Before going into details of our scheme, let us first examine another more conventional scenario, sometimes called as the PJK scenario, from our point of view. The PJK scenario consists of a couple of recirculators to accelerate muons up to 20 GeV/c or more. The accelerating gradient of the recirculating linac has to be more than 5 MV/m because quick acceleration is necessary against muon lifetime. Another reason to prefer high field is the accelerator size and complexity. If the field gradient is low, the accelerator becomes either long linear accelerating structures or many recirculating arcs, which make the footprint of the facility unrealistically large or the switching section between linac and arc complicated.

In order to achieve the high field gradient such as 5 MV/m, high-frequency RF system, say a few 100 MHz, has to be utilized. As a result, the aperture of the linac becomes small. Therefore, cooling in both transverse and longitudinal planes is necessary to fit beams into the small acceptance. Moreover, cooling has to be done at low-energy region because the cooling efficiency drops as the energy goes up. Emittance is, however, large and decay rate is fast at low energy. Therefore, muon yields cannot be high. In conclusion, we think the combination of secondary beams with large emittance in both transverse and longitudinal planes and recircular linacs does not make much sense.

There must be a historical background behind the PJK scenario. If a muon collider is the ultimate goal, small emittance is essential to obtain reasonable luminosity. Cooling of a beam should be

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considered at the front end and then the beam to be quickly accelerated to high energy. The neutrino factory demands somewhat different beam requirements. Only thing we care is the number of muons circulating in a final storage ring, no matter what the emittance is, as long as it fit in the acceptance.

An FFAG based scenario is considered as an alternative. There are several advantages. First, the demand for high field gradient and total RF power is relaxed because of multiple traverse in RF gaps, which is true in any ring accelerators. Although lower field gradient immediately means more loss of muons due to lifetime, which we will discuss later, the survival rate is not miserable if the gradient is more than 1 MV/m. Once we relax the requirement of field gradient down to the level of 1 MV/m, low-frequency RF system, say a few MHz, becomes a potential candidate. The low-frequency RF system is preferable because of large acceptance in both transverse and longitudinal phase space.

Fig. 1 shows the survival rate of muon as a function of muon energy taking the average field gradient as a parameter. When the field gradient is 5 MV/m, almost 90% of muons survives. If it is 1 MV/m, the value goes down to around 50%. However, we should say that the loss due to the lower gradient is only 50% which should be well compensated with other advantages of the FFAG scheme.

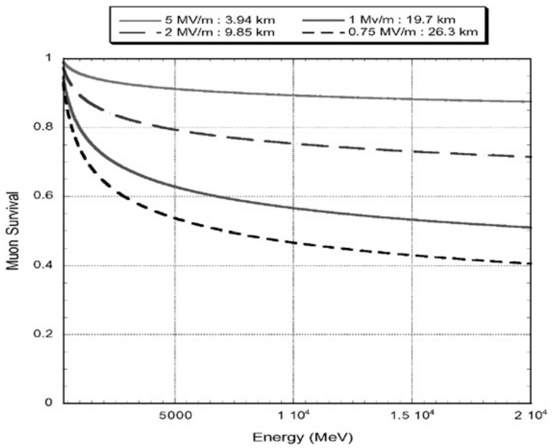

Fig. 1. Muon survival rate during acceleration. Field gradient is taken as a parameter.

2. FFAG

FFAG synchrotron was first proposed in late 1950s by T. Ohkawa in Japan and independently in US and in Russia, right after the invention of the Alternating Gradient focusing [2]. Two tiny size models and one machine, which was later used as an injector of an electron synchrotron, were constructed to accelerate electron beams.

FFAG has large transverse as well as longitudinal acceptance. Also quick acceleration is possible because of no need to ramp magnetic guiding and focusing field. Other advantages of FFAG-based scenario are simplicity of accelerator complex because of no phase rotation or no cooling. Earlier readiness of technology necessary and less R&D are expected. The last and most important reason is the lower cost of the facility.

3. Components

3.1. Proton driver

Construction of a high-intensity proton synchrotron (JHF project) is just started in April 2001. It will be completed by 2007 at JAERI Tokai site and eventually 1 MW proton beam power is expected. There are eight bunches circulating in the ring and those are extracted in one turn. The length of each bunch is 6 ns in rms and no extra effort to shorten a bunch is needed. Fig. 2 shows the accelerator complex with FFAG rings inside the proton driver.

3.2. Muon yield

The muon yield is estimated with fixed momentum acceptance of $dp/p = +/-50\%$. Fig. 3 shows the change of muon yield as a function of central muon momentum. Here, the transverse phase space cut was applied at 10,000 π mm-mrad and un-normalized emittance was employed for the transverse cut. With the emittance cut, the

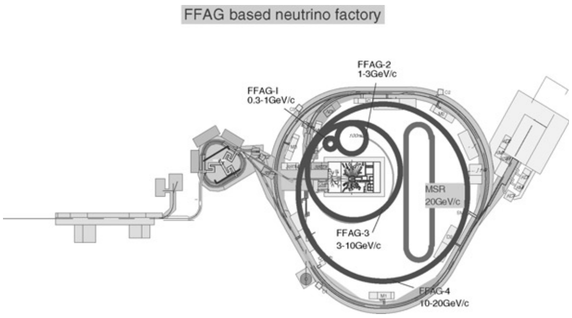

Fig. 2. Footprint of JHF accelerator complex with proposed FFAG rings inside.

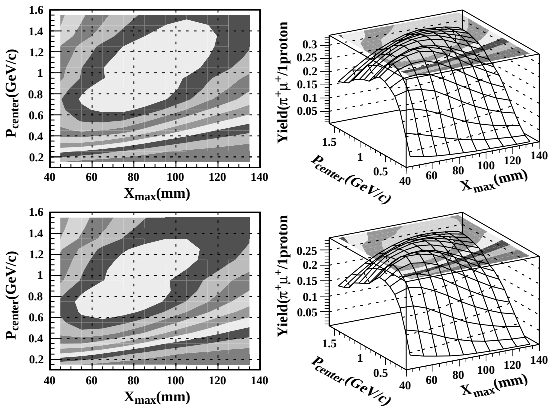

Fig. 3. Muon yield as a function of central muon momentum.

horizontal space was varied to find out the optimum point. In this figure, the muon yield reaches its maximum around the central energy of 0.9 GeV/c. The optimum energy tends to get lower, as the emittance cut point gets larger.

In the setup used in the study, the muon yields per one 50 GeV proton incident are around 0.3 and 0.5 for the case of emittance cut of 10,000 π and 20,000 π mm-mrad, respectively.

3.3. Muon acceleration

Since the magnetic field of the FFAG is fixed, the cycling time is only determined by the sweep of RF frequency and available RF voltage. The proof of principle FFAG model developed at KEK in 2000 shows in fact acceleration from 50 to 500 keV can be achieved in 1 ms (or equivalent repetition rate of 1 kHz), whereas an ordinary synchrotron such as ISIS at RAL with magnet ramping has the maximum repetition rate of only 50 Hz. For the acceleration of muon with finite lifetime, the very rapid acceleration is a must and only FFAG among ring accelerators will satisfy the requirement.

Like other type of accelerators, there is some limit of the ratio of injection and extraction momentum. An accelerator complex consists of cascade rings sounds feasible. The maximum ratio of FFAG is mainly limited by the field quality which must satisfy zero chromaticity and by the maximum available orbit excursion. In a type of FFAG whose field strength is varied with the shaped gap height, like the PoP FFAG, the ratio of 3 or 3.3 in momentum is the reasonable number. When the field variation in radial direction is made with coil distribution, the larger ratio such as 4 or 5 may be possible.

Our baseline scenario consists of four FFAG accelerators to accelerate muons from 0.3 to 20 GeV/c. The first one accelerates muons from 0.3 to 1 GeV/c, following with the one of 1 to 3 GeV/c, 3 to 10 GeV/c, and 10 to 20 GeV/c. The main parameters of the four rings are listed in Table 1. The footprint of the first ring and its lattice functions are shown in Figs. 4 and 5, respectively.

The alternative design consists of two FFAGs starting from 1 GeV/c. The first FFAG accelerates muons from 1 to 4.5 GeV/c and the second FFAG accelerates muons from 4.5 to 20 GeV/c. That momentum range is not achieved yet in practice, but we feel it is not difficult. The reason to have higher starting momentum is to capture more number of muons in smaller phase space. If the RF voltage of the first ring is adequate, the muon yield within the momentum deviation of $+/-20\%$ centered at 1 GeV/c is larger than the one at 0.3 GeV/c. Further increase of the phase space density can be achieved by adding lower ring with a cooling device in the second phase of construction.

3.4. Muon storage ring

A muon storage ring has a racetrack shape with two very long 300 m straight sections.[1] The lattice

[1] The storage ring lattice is designed by C. Johnstone at Fermilab.

Table 1
Main parameters of FFAG accelerator complex. For the first two rings, there are two lattice options with normal and superconducting magnet

Momentum (GeV/c)	0.3 to 1 (Normal)	0.3 to 1 (Super)	1 to 3 (Normal)	1 to 3 (Super)	3 to 10	10 to 20
Average radius (m)	21	10	80	30	90	200
Number of sector	32	16	64	32	64	120
k Value	50	15	190	63	220	280
Beam size at extraction (mm)	170 × 55	143 × 55	146 × 41	115 × 25	93 × 17	104 × 34

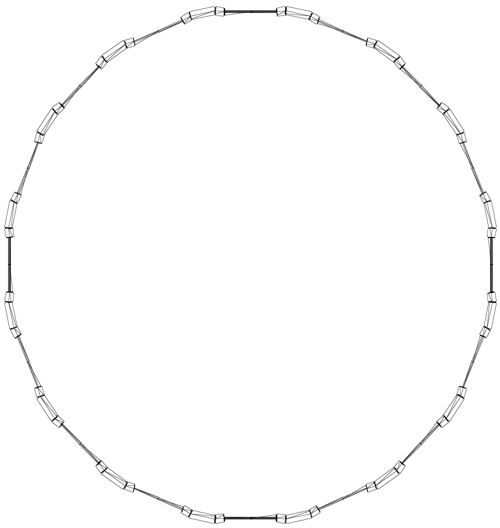
Fig. 4. Footprint of first FFAG ring.

function is enlarged so that the rms divergence of the beams is 0.92, that satisfies the condition of

$$D_{\text{beam}} \leqslant \frac{1}{5\gamma}. \quad (1)$$

It accommodates the 100% emittance of 30,000 π mm-mrad and the momentum spread of 1%. Fig. 6 shows the footprint of the storage ring and Fig. 7 lattice functions.

3.5. Muon cooling

In the FFAG-based neutrino factory, the muon cooling is not necessary because of large transverse as well as longitudinal acceptance. Nevertheless, relatively easy and simple cooling is proposed by H. Schonauer, that employs absorber with pressurized gas filling the beam pipe.

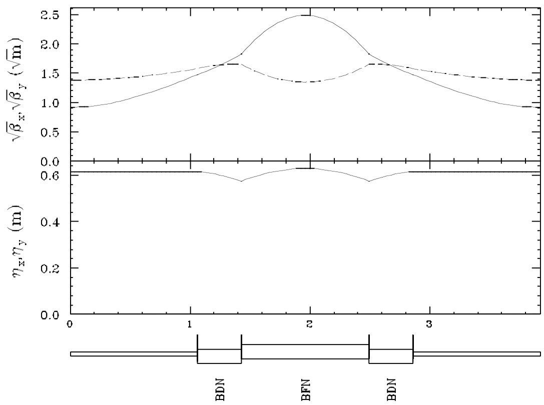

Fig. 5. Lattice functions of first FFAG ring.

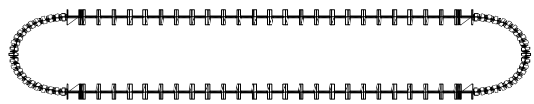
Fig. 6. Muon storage ring with race track shape.

The cooling effects depend on the transverse beta function. The heating caused by multiple scattering becomes dominant at lower energy for large beta function. A simple calculation shows that the reduction of the emittance is 0.57 with the transmission of 83% when the H_2 gas of 25 bar is filled in the 0.3 to 1 GeV/c ring whose beta function at the absorber is 2m (Fig. 8).

4. Hardware R&D

4.1. 150 MeV proton FFAG

Right after the success of the proton PoP FFAG, we started design and construction of

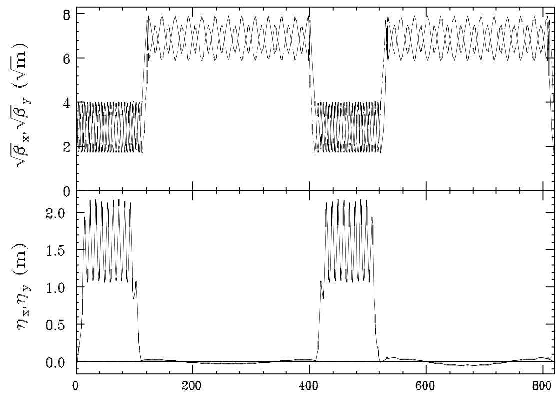

Fig. 7. Lattice function of muon storage ring.

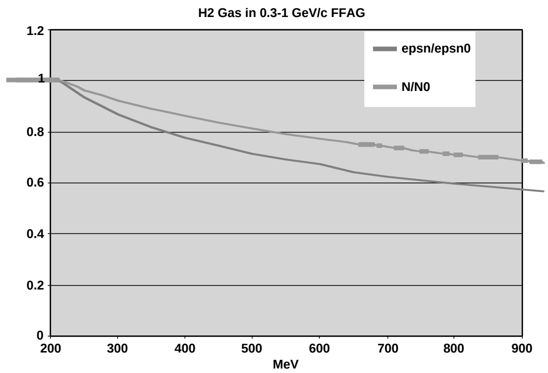

Fig. 8. Cooling factor and transmission as a function of muon energy for 0.3–1 GeV/c FFAG.

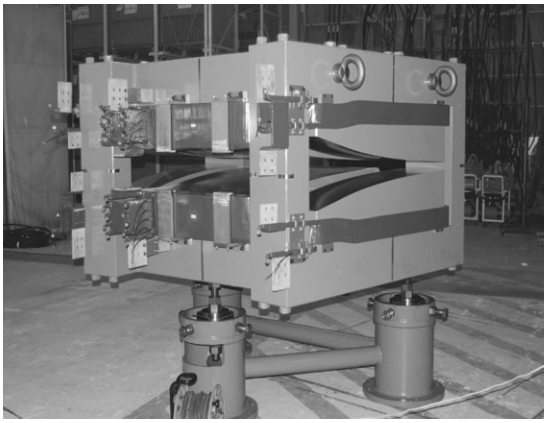

Fig. 9. Magnet of 150 MeV FFAG.

150 MeV proton FFAG. Its main goal is a construction of a prototype machine for medical use. It is further expected that any possible problems of FFAG for any applications will be revealed, studied, and fixed. It consists of 12 sectors of a triplet focusing unit and will be set at the experimental hall of the KEK 12 GeV PS. All of the magnet (Fig. 9) are ready and the first beam is expected in early 2003.

4.2. Low-frequency RF cavity

As a low-frequency RF cavity, we have several designs. Among them, one is the ferrite (SY25) loaded cavity (Fig. 10) and another is the so called air core cavity. The shunt impedance of the ferrite is measured and it turns out to be 1 or 2 order higher shunt impedance than the normal ferrite as shown in Fig. 11.

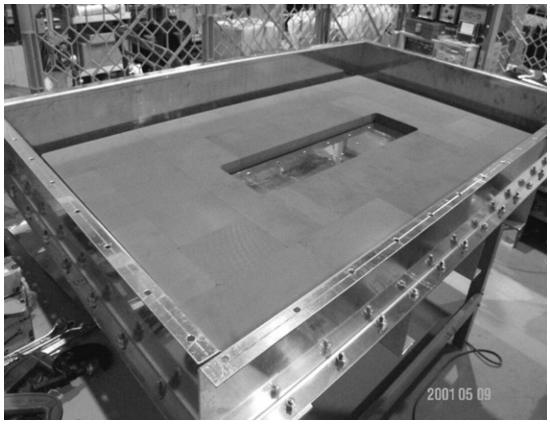

Fig. 10. Test bench of ferrite core for high-gradient RF cavity.

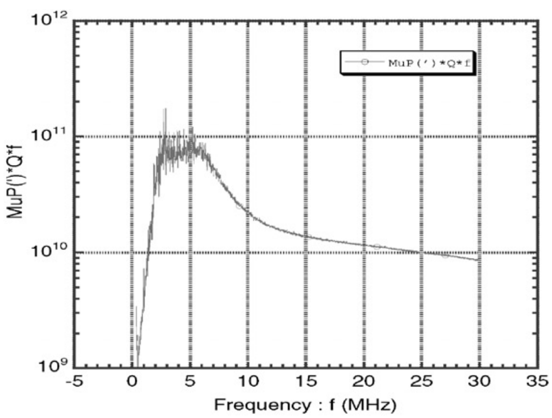

Fig. 11. Shunt impedance of the ferrite core.

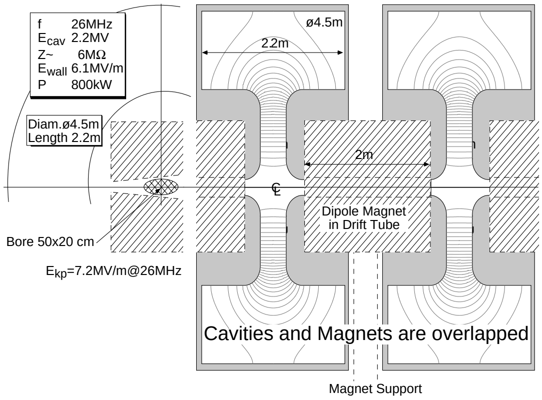

Fig. 12. Design of air core cavity.

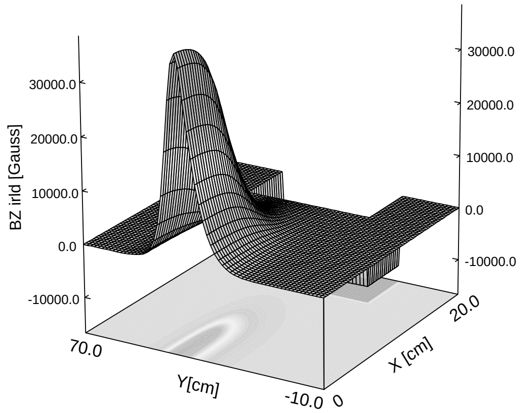

Fig. 14. Vertical field strength on the mid plane.

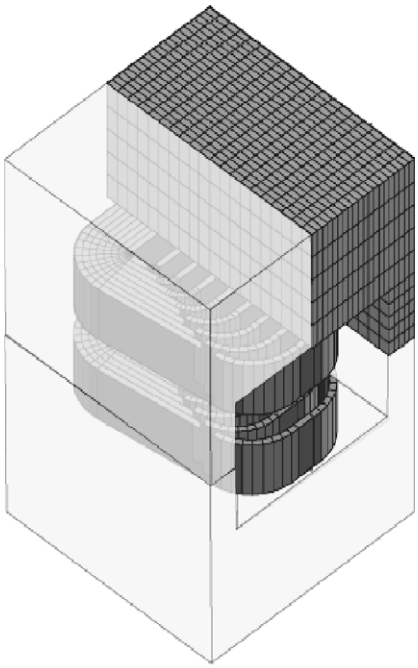

Fig. 13. 3D modeling of FFAG superconducting magnet.

Air core cavity is still at the calculation stage. The shape of the nose cone is optimized to reduce the ratio of the peak field and the field on the beam axis keeping high shunt impedance. Since the size of the cavity is huge, the cavity with magnet inside like drift tube linac is also investigated as shown in Fig. 12.

4.3. *Superconducting magnet*

Field gradient of FFAG magnet can be made either by the shape of pole face or the current density distributed on the parallel pole face. FFAG we have constructed so far uses the shape of pole face. The superconducting magnets are supposed to be used for the final and the one next to final rings and the distributed coils will make the field gradient. Fig. 13 shows the geometry of the pole face and coils and the field strength are depicted in Fig. 14. Here, we assume singlet focusing (FODO) lattice and only one of the magnets are calculated, which shows the smooth field distribution proportional to the kth power of radius.

References

[1] Complete design of the neutrino factory based on the FFAG may be found on http://www-prism.kek.jp/nufactj/index.html.
[2] T. Ohkawa, Bulletin of Physical Society of Japan, 1953.