FEASIBILITY OF INJECTION/EXTRACTION SYSTEMS FOR MUON FFAG RINGS IN THE NEUTRINO FACTORY*

J. Pasternak[†#], M. Aslaninejad[†], J. Scott Berg[◊], D. Kelliher[#], S. Machida[#]
[†] Imperial College of Science and Technology, London,
[#]STFC/RAL, HSIC, Didcot, UK,
[◊]BNL, Upton, Long Island, New York

Abstract

Non-scaling FFAG rings have been proposed for muon acceleration in a neutrino factory. In order to achieve small orbit excursion and small time of flight variation, lattices with a very compact cell structure and short straight sections are required. The resulting geometry places very challenging constraints on the injection/extraction systems. The feasibility of injection/extraction is discussed and various implementations focusing on minimization of kicker/septum strength are presented.

INTRODUCTION

In order to perform experiments in precision neutrino oscillation physics and in particular to address the existence of the leptonic CP violation, a neutrino factory based on muon deacy is being studied in the framework of the IDS [1] (International Design Study). Muon acceleration is a significant fraction of the total cost of a neutrino factory facility and should be optimised carefully. The reference design for the muon acceleration chain consists of the following subsystems:

- A linac, accelerating from 0.2 to 0.9 GeV.
- Two RLAs, accelerating from 0.9 to 3.6 GeV and from 3.6 to 12.6 GeV.
- A nonscaling (NS) FFAG ring (12.6 – 25 GeV).

The use of a nonscaling FFAG ring is motivated by higher efficiency of acceleration, as the beam can pass through the RF cavities as many as 12-16 times in FFAG whereas is can only make 4-5 passes in an RLA. The nonscaling FFAGs are very strong focusing rings with very small dispersion, which allows for small aperture magnets. In addition, the nonscaling design allows for a quasi-isochronous design where γ_T is close to γ of the beam, which allows the use of a relatively high constant RF frequency (201 MHz). The use of only linear magnetic field components in the NS FFAG results in a very high dynamical acceptance, which is needed for muon acceleration. Although muon acceleration in NS FFAGs is looking very promising several important issues need to be addressed:

- Beam loading in superconducting RF cavities.
- Dependence of time of flight on transverse amplitude and its relation to longitudinal emittance blow-up.
- Muon beam injection and extraction.

[◊]Work Supported by the United States Department of Energy, Contract No. DE-AC02-98CH10886.

In this paper we address the problem of beam injection and extraction in a muon NS FFAG.

MUON BEAM DYNAMICS IN NS FFAG

The present IDS reference design of NS FFAG for muon acceleration [2] has been adopted from the previous one realized in the framework of ISS (International Scoping Study) [3], taking into account the change of the baseline final energy from 20 to 25 GeV. Actually there exist several ring designs, which differ mainly in the cell structure and total number RF cavities per ring [2]. In particular, there are designs based on FODO, triplet and doublet cell geometries. Table 1 shows the parameters of a muon machine with the FODO cell geometry.

Table 1: Parameters of NS FFAG Based on FODO

Number of cells	62
Circumference	462 m
RF voltage	1.526 GV
Magnetic field in F magnet	3.4 T
Magnetic field in D magnet	7.6 T
Beam radius in F magnet	20.7 cm
Beam radius in D magnet	9.5 cm
Muon decay loss in FFAG	3.5 %
Injection energy	12.6 GeV
Extraction energy	25 GeV

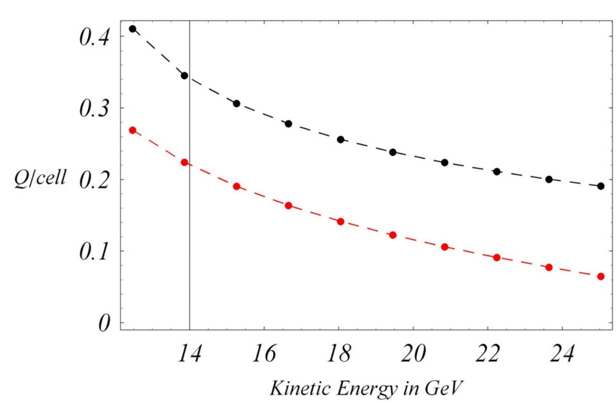

Figure 1: Tunes as a function of energy in the FODO FFAG ring. Dots correspond to Zgoubi [4] results and dashed lines to BeamOptics [5] ones (black is horizontal tune and red is the vertical one).

INJECTION

The nonscaling FFAG lattices for muon acceleration at the Neutrino Factory have very strong focusing optics in order to squeeze the orbit excursion and accordingly the size of the superconducting magnets. The strong focusing is achieved by designing a ring with a large number of cells, which leads to relatively short drift lengths and strong quadrupole magnets, resulting in small beta functions and dispersions. This strategy, which is introduced in order to limit the cost of the machine, almost unavoidably makes injection and extraction more difficult.

In this paper we study injection and extraction in the FODO lattice, which was chosen in favor of the triplet solution due to economical reasons as it contains only 2 magnets per cell and in favor of the doublet as it in principle allows a symmetric injection/extraction schemes for both signs of muons. Injection at 12.6 GeV in the horizontal plane turns out to be very difficult. The strong focusing, reflected in the high horizontal tune per cell of 0.4 at injection energy, leads to low beta functions. The beam off-set x_O at the observation point after passing through the kicker magnet with deflection θ_K can be approximated by the following formula:

$$x_O = \theta_K \sqrt{\beta_K \beta_O} \sin \Delta\mu ,$$

where β_K and β_O are the beta functions at the kicker and observation points respectively, and $\Delta\mu$ is the difference in phase advance between the two points. As the beta function is small, sufficient orbit separation, for the large normalized emittance of 3 π cm rad, can be obtained only with unrealistically high kicker strength. In addition the large tune per cell translates into a rapid beam oscillation after application of the kick, which makes it difficult to build a coherent superposition of distributed kicks. Secondly, beam injection in the vertical plane was studied. The tune per cell is 0.25 at injection energy, which is much lower than in the horizontal plane and allows a more feasible injection scheme involving distributed kickers.

A vertical injection scheme applying 6 kickers (with 3 positive and 3 negative deflections) is shown in Fig.2. The beam undergoes $3\pi/2$ betatron oscillations before reaching the septum (2.5 T). In order to maximize the kicker strength a 1.4 m long magnet is placed in the middle of a 2 m long straight section with 0.12 T peak field. An advantage of this solution is the possibility to reuse the kickers for both signs of muons as the kicker distribution is symmetric with respect to mirror reflection.

Another scheme, where the beam undergoes $5\pi/2$ betatron oscillations is shown in Fig. 3. In this scheme 10 kickers were used, which allows a reduction in the kicker strength to 0.08 T. The disadvantage of this solution is the need for special magnets with large aperture in order to allow for large beam oscillations caused by the distributed kickers. The special magnets will break the symmetry of the ring as larger aperture magnets will have a different fringe field effect, which can cause a beam ellipse mismatch and closed orbit distortion. Table 2 summarizes the parameters of the studied vertical injection schemes.

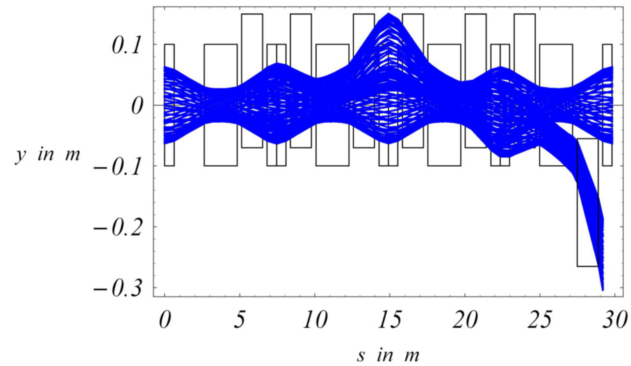

Figure 2: Vertical injection scheme into the FODO FFAG ring using 6 kicker magnets ($3\pi/2$ betatron oscillations).

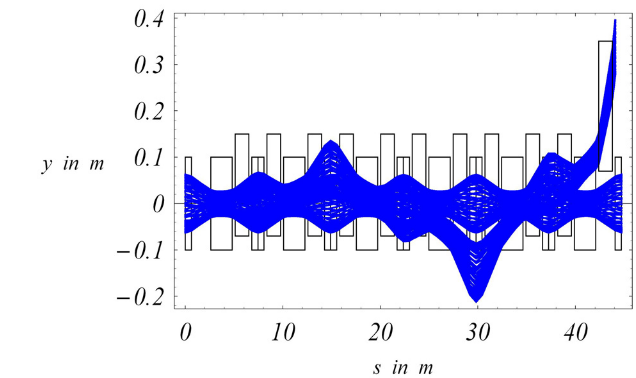

Figure 3: Vertical injection scheme into the FODO FFAG ring using 10 kicker magnets ($5\pi/2$ betatron oscillations).

Table 2: Parameter of Injection and Extraction Schemes for the FODO FFAG Ring

Scheme	Injection I	Injection II	Extraction
Plane	vertical	vertical	vertical
Number of kickers	6	10	6
Kicker top magnetic field	0.12 T	0.08 T	0.1 T
Septum field	2.5 T	2.5 T	4T
Kicker/septum length	1.4 m	1.4 m	1.4 m
Mirror symmetry	Yes	Yes	Yes

EXTRACTION

Subsequently we studied beam extraction from the FODO machine. The discussion in the previous section concerning the effects of tune per cell and values of the betatron functions on the strength and distribution of the kickers apply equally for the extraction study. As can be seen in Fig. 1 the betatron tunes are 0.2 and 0.06 per cell in horizontal and vertical plane respectively. Horizontal extraction turns out to be difficult. As can be seen in Fig. 4, the beta function in the drift is much smaller in the horizontal plane than in the vertical one. A scheme involving 12 kickers at 0.12 T distributed over a phase advance of $5\pi/2$ between the first kicker and the septum was found. The vertical extraction scheme shown in Fig. 5 turned out to be much more satisfactory allowing a reduction of the kicker strength to 0.1 T and the number of kickers to 6. This scheme allows for symmetric extraction with both signs of muons reusing the kickers, but similarly to the case of vertical injection the beam aperture needs to be increased to hold the kicked beam, requiring special magnets with higher aperture to be placed in the extraction region. Another studied vertical extraction scheme consists of only 4 kickers but distributed over more cells. The table 2 summarizes the parameters of the first extraction scheme.

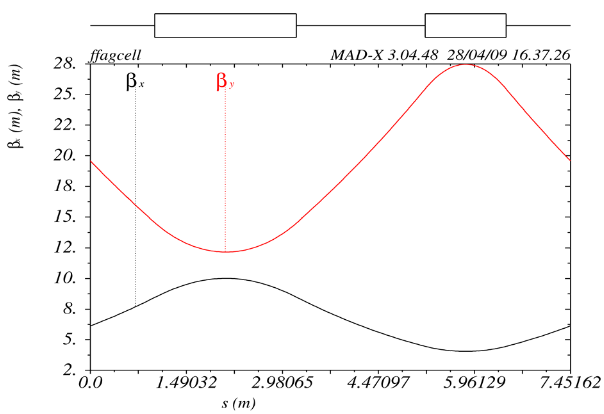

Figure 4: Betatron functions at extraction enery (25 GeV) in the FODO FFAG ring.

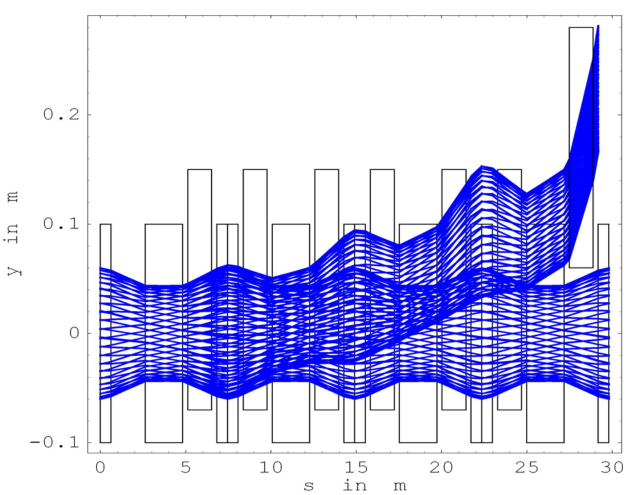

Figure 5: Vertical extraction scheme from the FODO FFAG ring using 6 kicker magnets.

EFFECTS OF SPECIAL MAGNETS ON BEAM DYNAMICS

Since vertical extraction from the FFAG results in large excursions in the magnets preceding the septum, large aperture magnets will be required in this region to accommodate the kicked beam. These 'special' magnets will have a longer fringe field extent and their introduction will break the symmetry of the FFAG. The long fringe field extent may cause orbit and optics distortion in the circulating beam.

In order to study these effects, it is first necessary to establish the aperture of both the normal and special magnets. Following Zgoubi tracking studies, it is found that the aperture increased from 31.7 cm to 41.6 cm in the case of the F magnet and from 14.4 cm to 39.1 cm in the case of the D magnet.

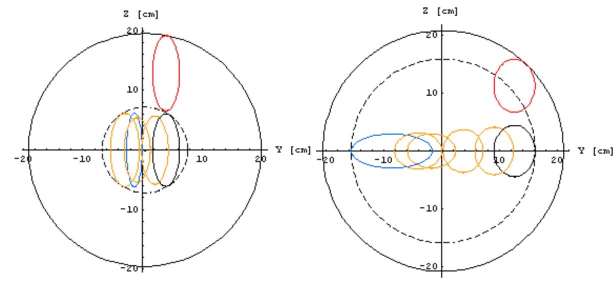

Figure 6: Aperture of normal (dashed circle) and special magnets (solid circle) defined by 3π cm beam ellipses over momentum range for both the D (left) and F (right) magnets. The red ellipse represents the kicked beam.

The accelerated orbit distortion is calculated by introducing cavities in every drift and tracking over the 12.6-25 GeV energy range. For simplicity, a constant acceleration rate is assumed. When the tracking is started at the phase space coordinates given by the closed orbit at the injection energy, a maximum accelerated orbit distortion of over 1 cm is calculated. This distortion can be reduced by optimizing the initial phase space coordinates – preliminary results show a reduction in maximum distortion from 1.7cm to 1.15 cm.

SUMMARY

The injection and extraction systems in the nonscaling FFAG for muon acceleration in a neutrino factory were studied in the ring based on FODO lattice. The vertical direction was found to be preferential for both injection and extraction, which allows for lower kicker strengths and facilitates the distribution of kickers due to a lower phase advance per cell in comparison with the horizontal plane. It is possible to design mirror-symmetric schemes in which the kickers can be reused for both signs of muons. The disadvantage of these solutions is a need for special magnets with large apperture in the injection/extraction region due to the large kicked beam oscillations. The strengths of the required kickers are still very challanging and the fields in the septum magnets dictates the need for a superconducting design.

REFERENCES

[1] http://www.ids-nf.org/
[2] J. Scott Berg, S. Machida, This Proceedings.
[3] J. Scott Berg *et al.*, RAL-TR-2007-23.
[4] F. Meot, Nucl. Instr. Meth. A, 427, p. 353 (1999).
[5] B. Autin *et al.*, CERN-98-06.