RFFAG DECAY RING FOR NUSTORM

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Abstract

The nuSTORM facility aims to deliver neutrino beams produced from the decay of muons stored in a racetrack ring. Design of racetrack FFAG (Fixed Field Alternating Gradient) decay ring for nuSTORM project is presented in this paper.

INTRODUCTION

The idea of using a muon decay to produce a neutrino beam with the perfectly known spectrum and the flux composition was invented long time ago, but obtained a higher attention only when the neutrino oscillation phenomenon was discovered. This concept was developed further into the Neutrino Factory facility proposal, which was then addressed in several dedicated R&D studies culminating recently with the International Design Study for the Neutrino Factory (IDS-NF) [1]. The Neutrino Factory will consist of the high power proton driver, which output beam is directed towards the pion production target, followed by the decay channel, where muon beam is forming, the muon front end, where the beam is being prepared for the acceleration and the muon accelerator boosting the energy to the required value. Once the muon beam is accelerated to the final value it will be injected into the ring with long straight sections pointing towards the neutrino near and far detectors addressing the neutrino oscillation and interaction physics. Although it has been proven that such facility will be superior in its discovery potentials with respect to the conventional neutrino beam facilities based on the pion decay, it requires the construction of many new accelerator components, which does not exist at present and require further R&D studies to be realized.

In order to allow for a start of the neutrino physics experiments based on the muon decay using conventional accelerator technology, the neutrinos from STORed Muon beam (nuSTORM) project was proposed [2]. In nuSTORM high energy pions produced at the target will be directed into the ring after passing a short transfer line equipped with a proton absorber to reduce proton beam contamination. Once in the ring decaying pions will form the muon beam. A large fraction of the muon beam with energy lower than the injected parent pions will be stored in the ring and a fraction with similar or larger energy, will be extracted at the end of the long straight section to avoid activation in the arc and may also be used for the accelerator R&D studies for future muon accelerators. nuSTORM is recognized as the only facility, which can measure precisely neutrino cross sections including the ones for the electron neutrino for which almost no data exists. This is of high importance for all long baseline neutrino experiments as the uncertainties in the knowledge of neutrino interactions are a major source of systematic errors. In addition nuSTORM is capable to contribute to the search for sterile neutrinos, in particular by resolving the long standing LSND-MiniBooNE anomaly. nuSTORM, if approved will be equipped with near detectors for neutrino interaction physics and flux measurement, and far detector with ~2km baseline length for sterile neutrino searches. As required pion momentum is currently set at 5 GeV/c with large momentum spread of 10% to achieve circulating muon momentum of 3.8 GeV/c, relatively high proton energy at the target is required, which could be obtained from existing proton drivers like the Main Injector at FNAL or SPS at CERN.

As the flux intensity is one of key elements for a successful neutrino experiment, it is proposed to push the momentum acceptance of the ring to ±10% or even ±16%. Although the design based on the standard accelerator lattice with separated function magnets has been proposed [3], the design based on scaling FFAG lattice is being developed in parallel. The scaling FFAG technology allows to have zero chromaticity with large dynamical acceptance, which enables large momentum spread of the beam with low losses by avoiding the dangerous resonances. This paper describes the racetrack FFAG (RFFAG) ring design for nuSTORM.

RING DESIGN PRINCIPLES

The RFFAG ring design consists of long straight sections pointing towards neutrino detectors, where the majority of the pions will decay into muons and along which the neutrino beam will be formed firstly from the pion decay and secondly from the muon decay. Both signals can be separated by the detector timing information. The ring contains also very compact arcs in order to achieve a large neutrino beam production efficiency minimizing the size of the ring and the associated cost.

The ring consists of several distinct cell types:

- Straight scaling FFAG cells in the neutrino production straight sections equipped with room temperature magnets, in which the vertical magnetic field on the median plane follows the exponential law given by: $B=B_0Exp[m(x-x_0)]$, where m is a constant parameter, x is the transverse horizontal coordinate and B_0 is the field at the reference point x_0. The betatron function is set at high values in order to maximise the neutrino beam production efficiency. The muon orbit follows a scallop pattern with the zero net deflection angle, which is believed to have a negligible effect on the neutrino flux generation. The dispersion is kept at low values to obtain high muon storage efficiency.

- The matching cells based on straight FFAG room temperature magnets performing the betatron matching between the production straights and the arcs.
- Regular scaling FFAG arc cells equipped with the superconducting combined function FFAG-type magnets, in which the vertical magnetic field on the median plane follows the well know scaling FFAG law: $B=B_0(R/R_0)^k$, where k is the so called field index, R is the radius and B_0 is the field at the reference radius R_0.
- The matching cells based on scaling FFAG superconducting magnets to perform the dispersion matching between the arc and the production straight. It is also the place where the injection will be performed, as the orbit separation between the incoming 5GeV/c ±10% momentum spread pions and circulating muons with 3.8GeV/c ±16% momentum spread will be sufficient to allow for placement of a septum magnet.

The principle parameters of the ring are summarized in the Table 1. The betaron functions, dispersion function and the magnetic field seen by the muon circulating with maximum momentum are shown in Fig, 1, 2 and 3, respectively.

Table 1: The principle parameters of the design of the racetrack FFAG ring for nuSTORM

Parameter	**Value**
Total circumference	500m
Length of the single straight section	175m
Straight section to the total circumference ratio	35%
Max scallop angle in the straight section	12mrad
Number of cells in the ring:	
Regular straight cells	66
Straight matching cells	4
Arc matching cells	8
Regular arc cells	8
m-value in the straight FFAG cells	5.5 m^{-1}
Magnet packing factor in the production straight	0.16
Dispersion in the production straight	0.18m
R_0 in the regular arc cells	17.6m
k in the regular arc cells	6.043
Magnet packing factor in the regular arc cells	0.92
Dispersion in regular arc cells	2.5m
R_0 in the matching arc cells	36.2m
k in the matching arc cells	25.929
Magnet packing factor in the matching arc cells	0.57
Ring tune (H, V)	(7.07, 4.15)

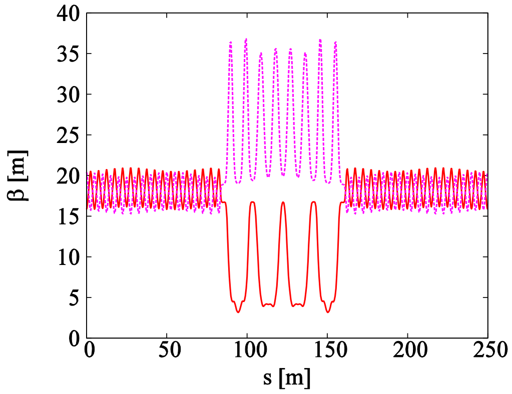

Figure 1: Horizonatl (red line) and vertical (pink one) betatron fuctions in the half of nuSTORM RFFAG ring .

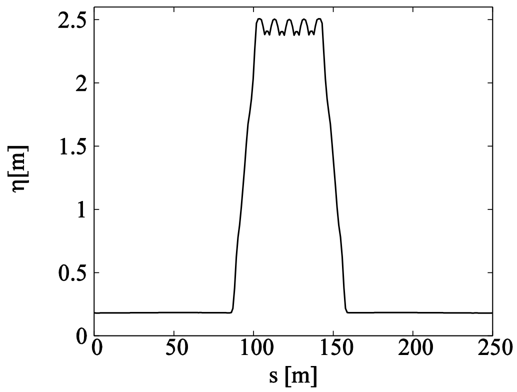

Figure 2: Dispersion fuctions in the half of nuSTORM RFFAG ring.

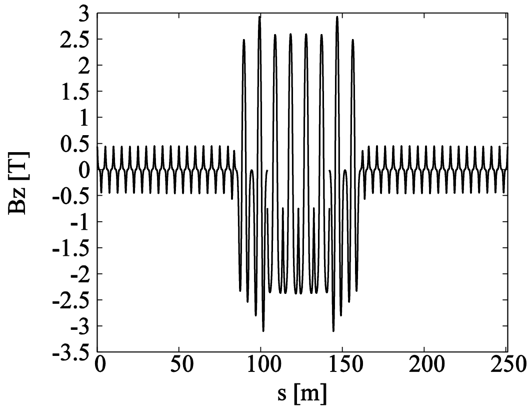

Figure 3: Vertical magnetic field on the median plane for the max momentum muon in the nuSTORM RFFAG ring.

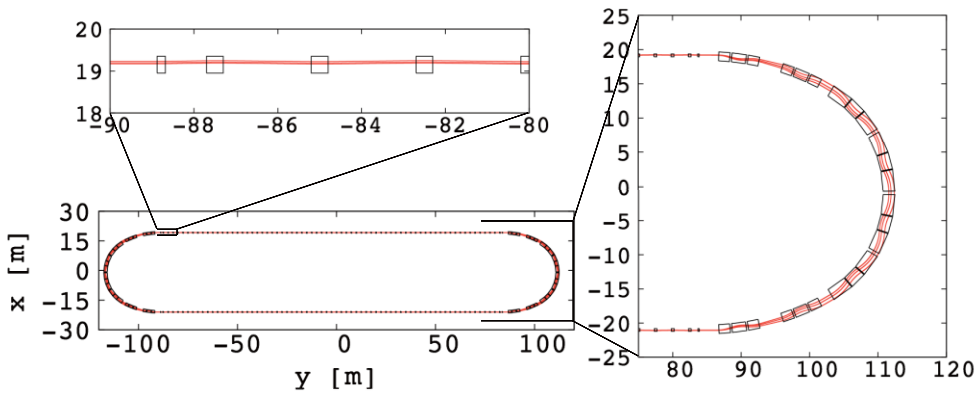

Figure 4:Layout of the ring with magnified cells in the production straight and in the arc together with muon closed orbits. The racetrack shape of the ring is dictated by the need of a high neutrino production efficiency.

OPTICS CONSIDERATIONS

The design effort was focused to ensure that the magnetic field is consistent with room temperature magnet technology in the production straight magnets and that the superconducting magnets (SM) in arc sections are below 3T in the good field region in order to minimize the necessary cost and to make their specification as close as possible to existing magnets, however the aperture requirement still remains very demanding. Currently large effort is focused on minimizing the SC magnets apertures

The matching of the dispersion between the arc and the production straight was achieved by using the dedicated circular matching section with the total of 180° horizontal phase advance, which in addition has a carefully chosen radius and k value to not only to allow for the dispersion matching, but also to facilitate pion "stochastic" injection by providing a sufficient space between the magnets. Although the injection in the current design is consistent with using SC septum magnet of ~1.8T field, another approach in the design of the circular matching cell may allow to substantially reduce this value facilitating the pion injection.

The horizontal matching between the arc and the straight section is realised by choosing a total phase advance in the arc including matching sections to be close to a integer multiple of π. The vertical matching is realised by carefully adjusting the phase advance both in the regular cells and in the matching cells. In addition the straight FFAG matching sections at both ends of each production straight is facilitating the matching in both planes by avoiding large beta beatings. Optimisation of these systems is still to be addressed.

The optics calculations presented in this paper assumes the Enge fringe field model for the magnetic field in all magnets.

CONCLUSION

nuSTORM project allows to address essential questions in the neutrino physics, in particular by offering the best possible way to measure precisely neutrino cross sections and by allowing to search for sterile neutrinos. It would also serve as a proof of principle for the Neutrino Factory and can contribute to the R&D for future muon accelerators.

A great amount of work remains to optimise the design with respect to the dynamical acceptance [4], magnet requirements, to facilitate the injection and evaluating the machine performance.

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REFERENCES

[1] IDS-NF website: http://ids-nf.org/
[2] D. Adey et al., “nuSTORM - Neutrinos from STORed Muons: Proposal to the Fermilab PAC”, arXiv:1308.6822 [physics.acc-ph]
[3] A. Liu et al., “Decay Ring Design Update for nuSTORM”, TUPRI006, IPAC’14, to be published
[4] S. Tygier et al., “DYNAMIC APERTURE STUDIES OF THE nuSTORM FFAG RING”, TUPRI013, IPAC’14, to be published