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PROGRESS ON THE DESIGN OF THE RACETRACK FFAG DECAY RING FOR NUSTORM

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Abstract

The neutrino beam produced from muons decaying in a storage ring would be an ideal tool for precise neutrino cross section measurements and search for sterile neutrinos due to its precisely known flavour content and spectrum. In the proposed nuSTORM facility pions would be directly injected into a storage ring, where circulating muon beam would be captured. The racetrack FFAG (Fixed Field Alternating Gradient) option for nuSTORM decay ring offers a very good performance due to a large dynamic and momentum acceptance. Machine parameters, linear optics design, beam dynamics and injection system for nuSTORM FFAG ring are discussed in this paper.

INTRODUCTION

Using a muon decay to produce a neutrino beam with a defined spectrum and flux composition is a well-established idea. This concept was developed into the Neutrino Factory facility proposal, which was then addressed in several dedicated research and development studies culminating in the International Design Study for the Neutrino Factory (IDS-NF) [1]. The Neutrino Factory consists of a high power proton driver, the output of which is directed towards a pion production target; a decay channel, where the muon beam is formed; the muon front end, where the beam is prepared for the acceleration and the muon accelerator to boost the energy to the required value. The muon beam is then injected into the decay ring, one of the straight sections pointing towards near and far detectors and producing ν beams for both interaction and oscillation physics. Although it has been shown that such a facility will be superior in its discovery potential with respect to a conventional neutrino beam facility based on pion decay, it requires the construction of many new accelerator components, which do not exist at present.

In order to allow for the start of neutrino physics experiments based on 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 are directly injected into the ring after passing through a short transfer line equipped with a chicane to select charge of the beam. Once in the ring, decaying pions will form the muon beam. A 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 with a mirror system of the injection at the end of the long straight section to avoid activation in the arc. They may also be used for accelerator research and development studies for future muon accelerators.

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 ±8% 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 update of the racetrack FFAG (RFFAG) ring design for nuSTORM.

RING DESIGN

Triplet Cell in the Straight Section

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 compact arcs in order to achieve a large neutrino beam production efficiency minimizing the size of the ring and the associated cost. An RFFAG design was proposed previously [4], but further study of neutrino production from pion decays presented interest in long baseline scenarios. This scenario is incompatible with any scallop of the beam in the production straight. In the previous design, the long straight part of the ring was made of doublet cells, where the beam had a scallop of ±12 mrad for more than 90% of the production straight. This solution can thus no longer be used if long baseline scenario are to be considered. Doublet cells were used in order to minimize the magnet packing factor to limit the cost, and to limit the betatron function beating in the arc. However, a careful choice of straight FFAG triplet can be used to have a similar betatron function beating in the arc, while keeping a low packing factor. A triplet with long drift space has the advantage to allow the beam to be guided without any scallop for most of the production straight, giving possibility to long baseline studies.

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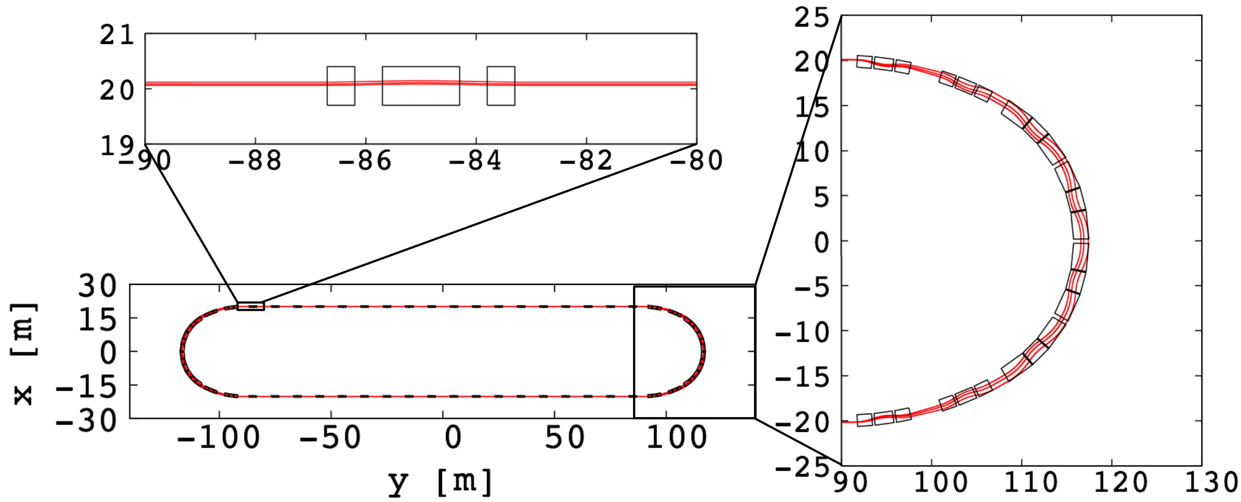

Figure 1: Top view of the racetrack FFAG lattice (bottom left scheme). The top left scheme shows a zoom on the straight section and the right scheme a zoom on the arc section. Matched, minimum and maximum momenta muon closed orbits are shown in red. Effective field boundaries with collimators are shown in black.

Lattice Design and Tracking in Field Model

The ring consists of several distinct cell types:

- Straight scaling FFAG cells in the neutrino production straight sections with room temperature magnets, in which the vertical magnetic field on the median plane follows the exponential law given by:

$$B_z = B_0 e^{m(x-x_0)}, \quad (1)$$

with x and s the horizontal and longitudinal coordinates, respectively, $B_0 = B_z(x_0)$, and m the constant normalized field gradient [5].

- 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 circular scaling FFAG law:

$$B_z = B_{0z}\left(\frac{r}{r_0}\right)^k, \quad (2)$$

with r the radius, k the constant geometrical field index, and $B_{0z} = B_z(r_0)$ [6]. The horizontal phase advance is chosen so that the arc is transparent to minimize beta beating, while FD ratio is chosen to adjust the vertical beta function.

- The matching arc cells are based on superconducting FFAG, with transparent horizontal phase advance, while the radius of the cells are chosen carefully to adjust the dispersion between straight section and arc part. At this place, 1.34 meter dispersion gives sufficient beam separation between circulating maximum muon momentum (4.4 GeV/c) and minimum momentum injected pion (4.5 GeV/c). A 2.6 meter-long drift space is then allowed to put a septum magnet for injection.

Ring parameters are summarized in Table 1. Stepwise tracking using Runge Kutta integration in field model with Enge-type fringe fields has been realized. Closed orbits of matching momentum, minimum momentum and maximum momentum are shown in Fig. 1. Dispersion and beta-functions at matching momentum are shown in Fig. 2. Magnetic field for maximum momentum muon closed orbit is presented in Fig. 3. Stability of the ring tune has been studied over ±16% momentum range. The tune shift is presented in Fig. 4.

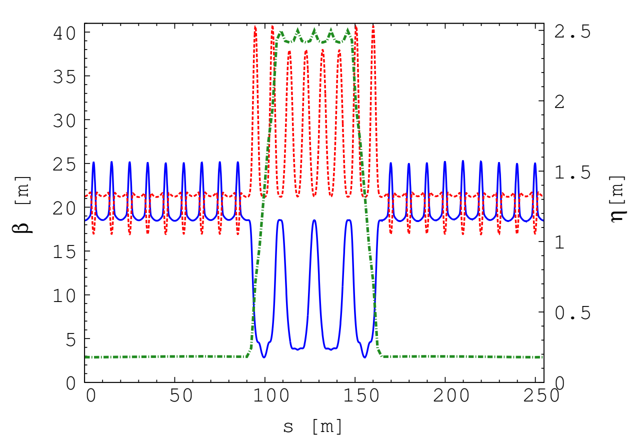

Figure 2: Horizontal (plain blue), vertical (dotted red) periodic betatron functions (left scale) and dispersion (mixed green line, right scale) of half of the ring for matching momentum. The plot is centered on the arc part.

Acceptance study at fixed energy has been done. Maximum amplitudes with a stable motion at the matching mo-

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Table 1: Lattice Parameters

Parameter	**Value**
Total circumference	510 m
Length of one straight section	180 m
One straight section/circumference ratio	35%
Maximum scallop angle	24 mrad
Momentum acceptance	3.8 GeV/c ±16%
Ring tune (H, V)	(6.91, 3.69)
Number of cells in the ring:	
Straight cells	36
Arc matching cells	8
Regular arc cells	8
m-value in straight cells	5.5 m^{-1}
Packing factor in straight cells	0.24
k-value in regular arc cells	6.057
R_0 in regular arc cells	17.6 m
Packing factor in regular arc cells	0.92
k-value in matching cells	26.0
R_0 in matching cells	36.2 m
Packing factor in matching cells	0.57

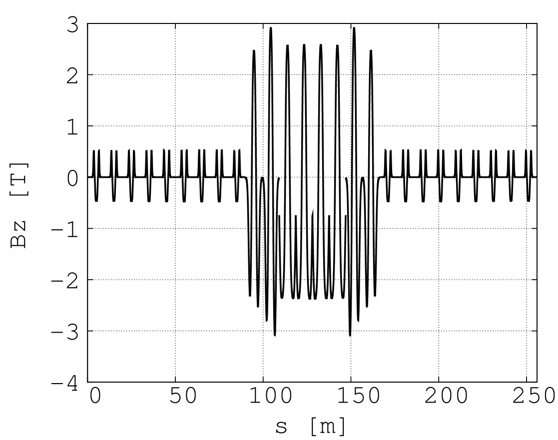

Figure 3: Vertical magnetic field on the median plane for the maximum circulating muon momentum of half of the ring. The plot is centered on the arc part.

mentum over 100 turns show a dynamical acceptance of about 1000 π mm.mrad unnormalized both in horizontal and vertical planes.

SUMMARY

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 light 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.

Optimizing the design with respect to the dynamical acceptance and magnet requirements remains to be done, and

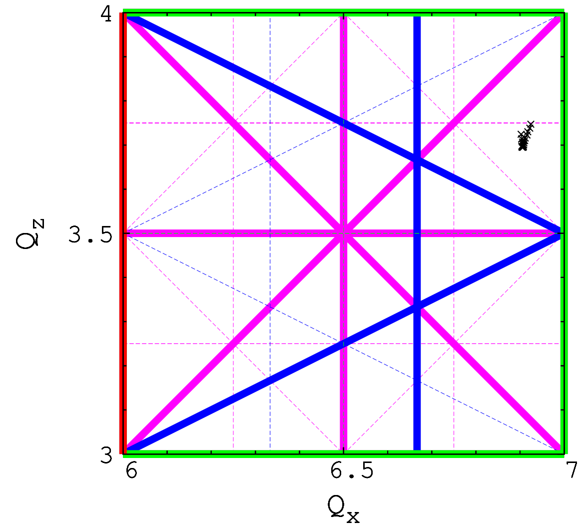

Figure 4: Tune diagram for momenta ±16% around 3.8 GeV/c. Integer (red), half-integer (green), third integer (blue) and fourth integer (purple) normal resonances are plotted. Structural resonances are in bold.

an automated procedure to change the tune point of the lattice is being written. A full comparison between separated function lattice and RFFAG regarding neutrino flux performance is also planned.

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