ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB062

nuSTORM DECAY RING

J.-B. Lagrange*, STFC/RAL, UK
J. Pasternak STFC/RAL, UK and Imperial College, UK,
R.B. Appleby, S.C. Tygier, University of Manchester, UK

Abstract

Precise neutrino cross section measurements and search for sterile neutrinos can be done with neutrino beams produced from muons decaying in a storage ring due to its precisely known flavour content and spectrum. In the proposed nuSTORM facility pions would be directly injected into a racetrack storage ring, where circulating muon beam would be captured. The storage ring has three options: a FODO solution with large aperture quadrupoles, a racetrack FFA (Fixed Field Alternating gradient) using the recent developments in FFAs and a hybrid solution of the two previous options. Machine parameters, linear optics design and beam dynamics of the hybrid solution are discussed in this paper.

INTRODUCTION

The production of a neutrino beam with a defined spectrum and flux composition using a muon decay is a well-established idea. This concept was developed in the International Design Study for the Neutrino Factory (IDS-NF) [1]. The simplest implementation of a neutrino factory was proposed [2] with the neutrinos from STORed Muon beam (nuSTORM) project. The main goal of nuSTORM is to precisely study neutrino interactions for electron and muon neutrinos and their antiparticles, but the facility could also contribute to sterile neutrino searches, and serve as a proof of principle for the Neutrino Factory concept.

In nuSTORM high energy pions produced at the target are first focused with a magnetic horn [3], and directly injected into the ring after passing through a short transfer line equipped with a chicane to select the charge of the beam. Once in the ring, decaying pions will form the muon beam. A fraction of the muon beam with momentum lower than the injected parent pions will be stored in the ring and a fraction with similar or larger momentum will be extracted with a mirror system of the injection at the end of the long straight section to reduce beam loss, and to avoid activation in the arc. The intrinsic design challenges of the decay ring arise from the large range of beam momenta in the ring. There are currently three options under study for the design of the decay ring. The first one is the FODO solution with large bore conventional quadrupoles with alternating gradients [4] in the long straight sections and with lattice based on separate function magnets in the arcs. This solution provides excellent performance with respect to the transverse acceptance, but it has very limited longitudinal acceptance, resulting directly from alternating gradient conventional magnet approach. The second solution is the use of recent developments in Fixed Field Alternating gradient (FFA) accelerators. In these machines, which come in scaling and non-scaling flavours, large aperture non-linear magnets allow the beam to move through the aperture at varying momenta, with a constant betatron tune in the case of a scaling FFA. The advantage of such a lattice is the large momentum acceptance together with a possible large transverse acceptance by choosing a ring tune far from dangerous resonances, thus increasing the number of stored muons in the ring. The design is realised by keeping the ring zero-chromatic over the whole momentum range, and choosing the tune point far from harmful resonances. Furthermore, to maximise the portion of the ring pointing towards the detector, an FFA racetrack shape is now possible [5], while keeping the ring zero-chromatic for a large momentum range, thanks to use of straight scaling FFAG cells [6]. The constant betatron tune with momentum provides a strong constraint on the fields in a scaling FFA cell. In the arcs, the vertical magnetic field B_{az} in the median plane produced by the combined-function magnets follows the circular scaling law [7], while in the straight sections, the vertical magnetic field B_{sz} in the median plane produced by the combined-function magnets follows the straight scaling law [6]. The beam orbit oscillations through scaling magnets in this type of straight produce a characteristic periodic beam angle oscillation known as a scallop angle, which ultimately limits the achievable neutrino flux. Since the central momentum of the injected pion is different from the central momentum of the circulating beam, the horizontal position of the reference trajectories for the two of them limits the captured muons produced from pion decay to the area within the acceptance of the circulating beam. The third option is a combination of the FODO and the FFA solution, called the hybrid option. It features a production straight section with conventional quadrupoles like in the FODO solution, and FFA magnets in the rest of the ring, like in the FFA solution. This paper gives preliminary results about the hybrid option.

HYBRID SOLUTION

Although estimations promise better performances with the FFA lattice than with the FODO lattice with respect to the neutrino flux production [8, 9], a lattice combining the advantages of the FODO and the FFA solutions would give an optimal performance. A production straight made of conventional quadrupoles would remove the problem of the scallop angle, while optimising the muon capture efficiency. The chromaticity of the ring can be greatly reduced if the rest of the ring is made zero-chromatic like in the FFA solution. Furthermore, a large beta function is desirable in the production straight to minimise the momentum angle for a given emittance, limiting the phase advance of the section, and thus its natural chromaticity. Such a lattice can

* jean-baptiste.lagrange@stfc.ac.uk

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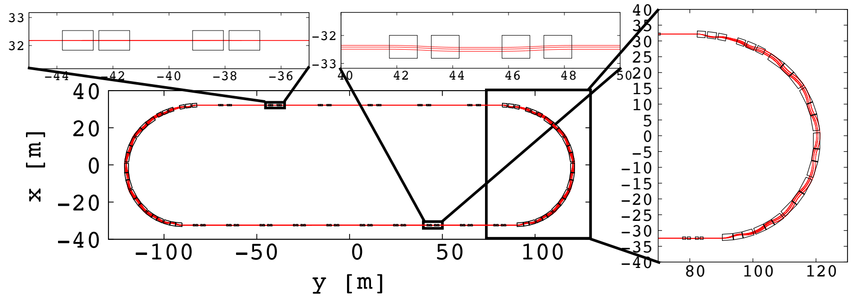

Figure 1: Top view of the racetrack hybrid lattice (bottom left scheme). The top left scheme shows a zoom on the production straight section, the top middle scheme the FFA straight part, and the right scheme a zoom on the arc section. Matched, minimum and maximum momenta muon closed orbits are shown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

keep the tune excursion of a large momentum range confined between half-integer resonances, which allows a large transverse acceptance for a large momentum range. Since the dispersion is different in the two straight sections, i.e. null in the quadrupole section and constant non-null in the straight FFA section, two different dispersion matching sections have to be design around the straight sections. A new interest in higher energy up to 6 GeV/c has been pushed recently, and has been taken into account in the new design.

Preliminary design parameters are presented in Table 1. 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 ±15% momentum range. The tune shift is presented in Fig. 4. The transverse acceptance in both planes is studied by tracking over 100 turns a particle with a displacement off the closed orbit and a small deviation in the other transverse direction (1 mm). This lattice gives a maximum emittance of more than 1 mm in both horizontal and vertical, as shown in Fig. 5 and in Fig. 6, respectively.

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. The FFA solution for the decay ring gives good performance regarding transverse and momentum acceptance, but a hybrid solution would give an optimal result. An optimised version of the hybrid lattice and a full comparison in terms of neutrino flux for the three solutions remains to be done.

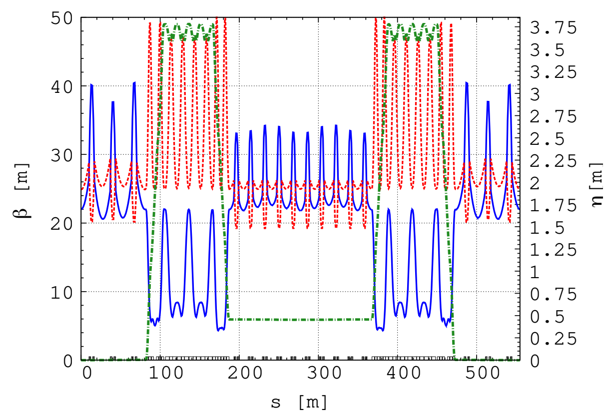

Figure 2: Horizontal (plain blue), vertical (dotted red) periodic betatron functions (left scale) and dispersion (mixed green line, right scale) in the ring for matching momentum. The plot is centered on the straight FFA part.

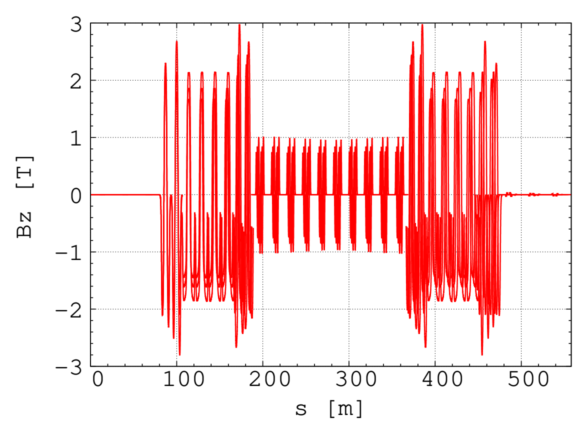

Figure 3: Vertical magnetic field on the median plane for the maximum circulating muon momentum in the ring (6.1 GeV/c). The plot is centered on the straight FFA part.

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Table 1: Lattice Parameters

Parameter	Value
Total circumference	533 m
Production straight section length	161 m
straight section/circumf. ratio	30%
Momentum acceptance	5.3 GeV/c ±15%
Ring tune (H, V) at 5.2 GeV/c	(6.20, 3.26)
Number of cells in the ring:	
Quadrupoles straight cells	6
Straight FFA cells	10
Arc first matching FFA cells	4
Arc second matching FFA cells	4
Regular arc cells	8
Field gradient in quadrupoles	-2.34, 2.31 T/m
Packing factor in quadrupole cell	0.16
m-value in straight FFA cell	2.2 m^{-1}
Packing factor in straight FFA cell	0.24
k-value in regular arc FFA cell	7.252
R_0 in regular arc FFA cell	31.2 m
k-value in first matching FFA cell	24.969
R_0 in first matching FFA cell	49.08 m
k-value in second matching FFA cell	13.369
R_0 in second matching FFA cell	30.42 m

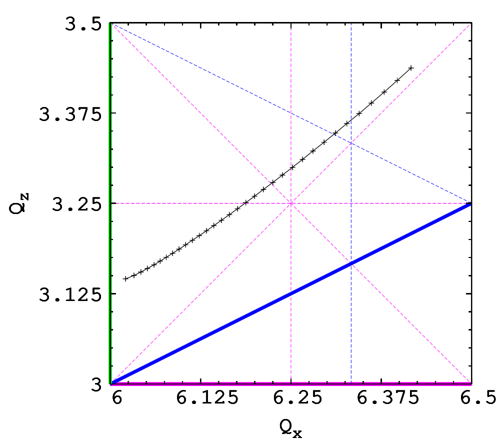

Figure 4: Tune diagram for momenta ±15% around 5.3 GeV/c. Integer (red), half-integer (green), third integer (blue) and fourth integer (purple) normal resonances are plotted.

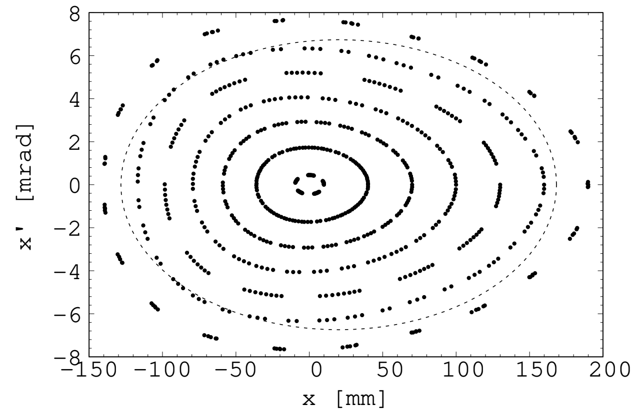

Figure 5: Stable motion in the horizontal Poincare map for maximum initial amplitude over 100 turns for p_0. The ellipse shows a 1 mm.rad unnormalized emittance.

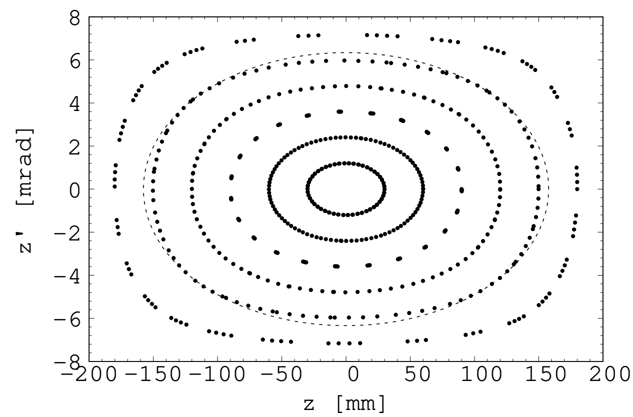

Figure 6: Stable motion in the vertical Poincare map for maximum initial amplitude over 100 turns for p_0. The ellipse shows a 1 mm.rad unnormalized emittance.

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