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STATUS OF THE PRISM FFAG DESIGN FOR THE NEXT GENERATION MUON-TO-ELECTRON CONVERSION EXPERIMENT*

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Abstract

The PRISM Task Force continues to study high intensity and high quality muon beams needed for next generation lepton flavour violation experiments. In the PRISM case such beams have been proposed to be produced by sending a short proton pulse to a pion production target, capturing pions and performing RF phase rotation on the resulting muon beam in an FFAG ring. This paper summarizes the current status of the PRISM design obtained by the Task Force. In particular various designs for the PRISM FFAG ring are discussed and their performance compared to the baseline one, the injection/extraction systems and matching to the solenoid channels upstream and downstream of the FFAG ring are presented. The feasibility of the construction of the PRISM system is discussed.

INTRODUCTION

While the Large Hadron Collider (LHC) at CERN sets new limits on physics beyond the current Standard Model (SM), new results from current neutrino oscillation experiments provide insights into the physics of flavour changing in the neutral leptonic sector; in particular θ_{13} has been proven to be non-zero. This opens the possibility to measure CP-violation and suggests that non-trivial physics may be coupled with the leptonic sector of the particle spectrum. Charged lepton flavour violation processes, although still not discovered experimentally, are a very important area to search for physics beyond the SM, with important implications for our understanding of particle physics. Muon to electron conversion searches are gaining more interest worldwide with two proposed experiments COMET and Mu2e. In particular, the COMET experiment will be built in two stages and the beam line for COMET stage 1 has been approved by J-PARC. Both experiments are expected to reach a single event sensitivity of $<10^{-16}$.

The PRISM (Phase Rotated Intense Source of Muons) has been proposed for even greater sensitivity of $<10^{-18}$. The high sensitivity of PRISM is based on the superior properties of the muon beam it can deliver to the stopping target. Those advanced beam properties come from an FFAG ring, which is used to purify the beam from any unwanted composition, mainly reducing the pion background by passing the beam several turns in the ring, since pions decay much faster than muons. In addition the muon beam in an FFAG ring can undergo longitudinal phase-space rotation by using RF cavities to reduce the final momentum spread, which allows for optimisation of the thickness of the stopping target. Substantial progress on the development of the PRISM system was achieved at Osaka University with the prototype scaling FFAG ring constructed at RCNP [1], which was equipped with an RF system based on Magnetic Alloy (MA) cavities. This allowed a proof of principle demonstration of phase rotation to be performed. The remaining technological challenges on the path to realising the PRISM experiment are being addressed by the PRISM task force. The task force aims are: to design the injection and extraction system and the transfer line from the solenoidal pion decay channel into the FFAG ring; provide alternative solutions to the baseline scaling FFAG ring; and address technological challenges, e.g. the design of the RF cavities and the kicker system. This paper reports briefly on the progress obtained since IPAC'11 [2].

THE PRISM/PRIME EXPERIMENT

In order to create the proton beam to feed the pion production target of the PRISM/PRIME experiment (PRIME denotes the detector optimised for using the muon beam from PRISM) a proton driver with a capability to create a short proton bunch length (~10ns) is needed. This type of driver has almost identical parameters to the one required for the Neutrino Factory or

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Muon Collider and is one of the synergies between those projects. It must be noted that although such a driver with the required power (i.e. a few MW) does not exists at present, several designs have been proposed mainly in the framework of the Neutrino Factory studies [3].

Following the pion production, the beam is captured in the opposite direction to the proton beam in a high field solenoid and transported to a bent solenoid channel. The bent solenoid channel allows charge and momentum selection and reduces pion contamination. The muon beam is then transported into an FFAG ring, which reduces the energy spread using RF phase rotation and further reduces the pion background. After extraction, the beam enters the stopping target region where a series of disks stops the muon beam. Electrons produced by muon decay or a conversion process undergo momentum selection using another bent solenoid channel and are then detected using a detector system (called PRIME). The main accelerator parameters of PRISM/PRIME are in Table 1.

Table 1: Principle accelerator parameters for PRISM

Parameter	Value
Target type	solid
Pion capture field	4-10 T
Momentum acceptance	±20 %
Reference μ^-momentum	40-68 MeV/c
Harmonic number	1
Minimal acceptance (H/V)	3.8/0.5 π cm rad
RF voltage per turn	3-5.5 MV
RF frequency	3-6 MHz
Final momentum spread	±2%
Repetition rate	100 Hz-1 kHz

LATEST TASK FORCE STUDIES

In this section the selected subjects of the studies undertaken by the PRISM task force are briefly presented.

Front end

The challenge of the front end for PRISM is to design a transport and an injection system maximising muon transmission from the superconducting bent solenoid channel to the FFAG ring for a beam with a very large emittance and momentum spread. The system previously designed [2] has been revised and preliminary tracking studies have been performed in selected parts of the system. Firstly efficiency and the beam conditions have been compared between various versions of the bent solenoid channel using G4Beamline [4]. Geometries based on S-shape and C-shape bent solenoid channels, consisting of two 90º bent solenoid sections which differ in the relative sign orientation, were studied. The correlation between x and y positions and momentum were calculated, as in Figure 1 for the y direction.

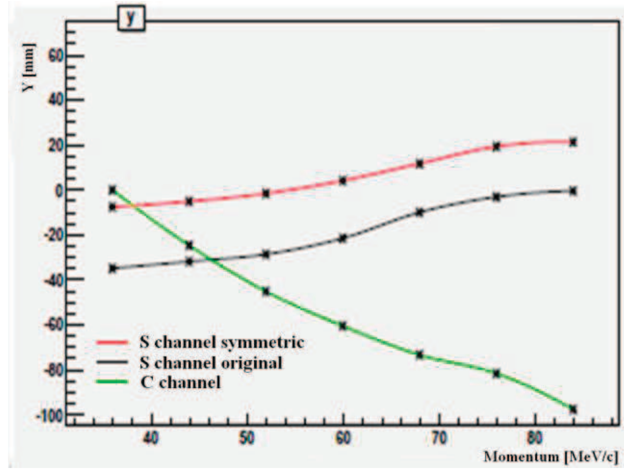

Figure 1: The mean position of the beam at the end of the bent solenoid channel in various configurations.

This study shows that the S-shape channel, with dipole fields of the same absolute value but opposite signs in both 90º sections, performs best with respect to transmission and also has the smallest dispersion. The S-channel is assumed to be followed by a matching solenoid followed by an adiabatic switch, where the solenoidal field is gradually reduced. An additional solenoidal matching lens is necessary downstream of the adiabatic switch, which modifies the beam conditions to the values necessary at the start of the alternating gradient (AG) section. The AG section consists of five quadrupole lenses followed by two horizontal dispersion creators, which adjust the orbit excursion to the value necessary in the FFAG ring. This is followed by vertical deflectors and FFAG matching sections, which aim to match the betatron functions and reduce the vertical dispersion to zero in the ring downstream of the vertical injection septum. The betatron functions in the AG section were readjusted with respect to earlier studies to reduce the maximum value of the beta function, since this causes large geometrical aberrations, as verified by simulations.

An interesting alternative for the front end based on the forward pion collection was studied using the G4MICE code [5]. In order to capture more pions a higher central momentum has been chosen. The beam is then injected into a muon decelerator containing 100 MHz RF cavities with the phase set to the stationary bucket used to keep the initial bunch length of 10 ns and Lithium Hydride absorbers used mainly to decelerate the muons as seen in Figure 2., but also to reduce the resulting beam emittance using ionization cooling. The actual geometry of the lattice used as a muon decelerator is very similar to the one proposed as a cooling lattice for the Neutrino Factory and is based on the so called Bucked Coils concept [6]. In this study the beam momentum was reduced by a factor of 1.6 with a transmission of 65%. Optimisation could allow further reduction of the beam momentum whilst maintaining satisfactory transmission.

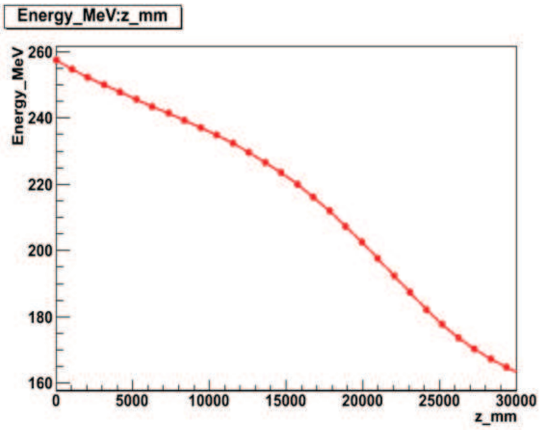

Figure 2: Mean muon energy as a function of distance in the PRISM front end based on forward capture and the muon decelerator concept.

Alternative ring designs

One of the important goals set by the task force is a search for an alternative ring, which could offer advantages with respect to the baseline solution. In particular, solutions facilitating the beam injection/extraction or having larger acceptance were aimed for. Various designs based on scaling and non-scaling FFAG principles have been produced including a new interesting solution using a scaling FDF triplet configuration. Recent tracking studies of this lattice, see Figure 3, have shown that it has a larger dynamical acceptance than the baseline ring and the length of the D magnet is longer, which should facilitate the optimisation of the fringe fields.

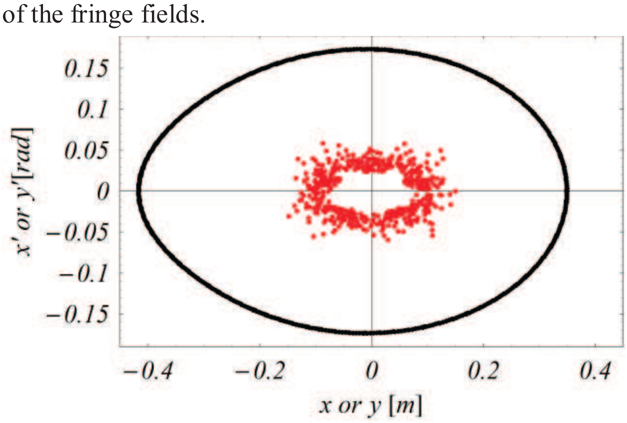

Figure 3: Dynamical acceptance of the new FDF scaling FFAG ring for PRISM in horizontal (black) and vertical (red) planes respectively. Horizontal position is presented subtracting the mean closed orbit.

In addition, the injection in the vertical plane seems to be facilitated with the presence of the D magnet, in contrary to the baseline case, increasing the beam clearance at the septum.

Table 2: Parameters of an alternative scaling FFAG

Parameter	Value
Number of cells	10
k	5.1
(Q_H, Q_V)	(2.62, 1.91)
Lattice type	Symmetric FDF triplet
R	6.5 m
Acceptance (H, V)	(5.55, 0.78) π cm rad
B_F/B_D at R	0.2397/-0.1745 T
$\Theta_F/\ \Theta_D/\ \Theta_S$	0.0607/0.0607/0.3394 rad

SUMMARY AND FUTURE PLANS

The PRISM Task Force continues to work towards realising the PRISM system for a next generation muon to electron conversion experiment. Substantial progress has been achieved in the studies of the muon front end, which includes detailed studies of beam properties in various configurations of the bent solenoid channel, matching between the solenoidal channel and the FFAG ring, and studies of an alternative front-end based on the capture of forward pions. Several alternative ring designs have been proposed and in particular a promising new scaling solution based on an FDF triplet may be a strong candidate to challenge the baseline. Further studies will be focused on demonstrating the feasibility of PRISM.

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