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Studies for the PRISM FFAG Ring for the Next Generation Muon to Electron Conversion Experiment

STUDIES FOR THE PRISM FFAG RING FOR THE NEXT GENERATION MUON TO ELECTRON CONVERSION EXPERIMENT*

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Abstract

High intensity and high quality muon beams are needed for next generation lepton flavour violation experiments. Such beams can be produced by sending a short proton pulse to a pion production target, capturing the pions and performing RF phase rotation on the resulting muon beam in an FFAG ring. Such a solution was proposed for the PRISM project and this paper summarizes its current status. In particular the PRISM task force was created to address the accelerator and detector issues that need to be solved in order to realise the PRISM experiment. Alternative designs for the PRISM FFAG ring are discussed and their performance compared. The injection/extraction systems and matching to the solenoid channels upstream and downstream of the FFAG ring are presented. The future direction for the study will be outlined.

INTRODUCTION

The current years area very exciting time for particle physics with the Large Hadron Collider (LHC) breaking new luminosity limits, new results from neutrino experiments and other precision measurements. These will provide new limits on physics beyond the current Standard Model (SM), which has proven to be extremely successful since it was first developed nearly 50 years ago. Charged lepton flavour violation processes, such as muon to electron conversion, are expected to be a fruitful area to search for physics beyond the SM. The COMET and Mu2e experiments aim to measure muon to electron conversion with a sensitivity of $<10^{-16}$. Even greatersensitivity of $<10^{-18}$ was proposed to be achieved by PRISM (Phase Rotated Intense Source of Muons)by using an FFAG ring for longitudinal phase-space rotation. This will allow the creation of a high purity muon beam and will reduce its momentum spread. The reference design of the PRISM ring has been produced using a scaling FFAG with 10 identical cells. Full size large aperture FFAG magnets and an RF system with Magnetic Alloy (MA) cores were successfully developed in Osaka, reaching their designed performance. A ring accelerator with six magnets was assembledat RCNP in Osaka and phase rotation was demonstrated with alpha particles [1]. However, there are a number of technological challenges that need to be addressed before a design for the experiment can be realized. The PRISM task force was set up to address these issues and utilise synergies with other muon accelerator projects such as the Neutrino Factory and the Muon Collider, increasing the international collaboration in these domains.The task force focuses on the detailed design of the injection and extraction system and the transfer line from the solenoidal pion decay channel into the FFAG ring. Alternative studies have been conducted in order to find competitive FFAG ring designs, which could be superior to the current solution. The task forcealso continues the studies on the necessary hardware, for example kicker and septum magnets and the RF system. This paper reports briefly on the progress obtained since IPAC'10 [2].

THE PRISM/PRIME SYSTEM

The PRISM/PRIME system (where PRIME denotes the dedicated detector system to be used with the PRISM muon beam) requires ashort proton bunch length (~10ns)for production of pions. This dictates constraints on the proton driver, but several options based on the Main Ring at J-PARC, the Booster at Fermilab or other future facilities have been proposed.

The pions would be backward captured in the high field solenoid and sent into the solenoidal transport channel, where the muon beam would be formed in the pion decay. The muon beam would then be injected into the FFAG ring, which would be used to reduce the energy spread (by a factor of ~10) using RF phase rotation and also to clean the muon beam from any contamination in several turns. The high quality muon beam would be extracted and sent to the stopping target, followed by the detector system (PRIME) searching for the electron signal from muon to electron conversion events. The schematic layout of the PRISM/PRIME system is shown in Fig. 1 and some of the main accelerator parameters are collected in Table 1.

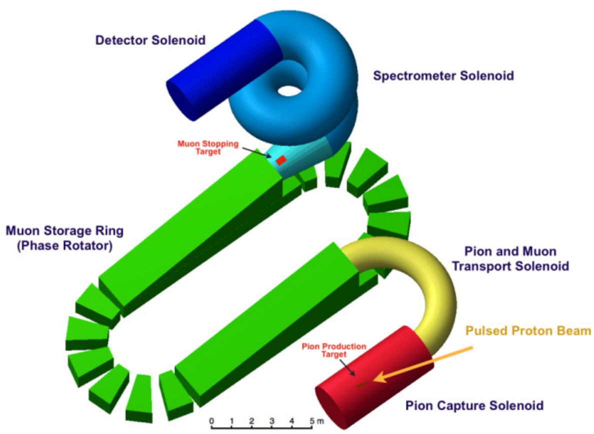

Figure 1: Conceptual layout of the PRISM/PRIME.

RECENT TASK FORCE STUDIES

The recent progress obtained in studies undertaken with the PRISM task force is presented in the paragraphs below.

Front End

The beam in the superconducting solenoidal channel and the FFAG has quite distinctive properties with respect to the beam size, betatron frequency and momentum dispersion. In addition the entire momentum spread needs to be injected into the FFAG ring simultaneously having very large emittances. The necessary dispersion matching needs to be performed: as injection is foreseen in the vertical direction, the unavoidable vertical dispersion createdby the septum needs to be corrected to zero and the horizontal dispersion (small or zero in the solenoidal channel) needs to be adjusted to the value in the ring.

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

The front end system has been designed consisting of the following modules:

- Solenoidal adiabatic matching to increase the beta function to the values in the alternating gradient (AG) part and the FFAG ring.
- Quadrupole matching section (currently quadruplet, but more can be added).
- Dispersion creator 1: consisting of apair of equal, but opposite strength rectangular magnets. This system adjusts about 30% of the dispersion (from zero to the value in the ring).
- Dispersion creator 2: Consisting of apair of circular FFAG cells with total π horizontal phase advance, where the final dispersion adjustment is performed.
- Two straight FFAG [4] betatronmatching sections.
- Two vertical deflection sections (one incorporating the injection septum), which independently match the dispersion and adjust the direction of the incoming beam line.

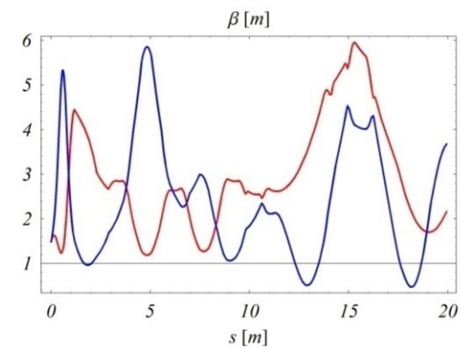

Figure 2: Betatron functions in the AG front end. The red (blue) line corresponds to horizontal (vertical) plane.

As can be seen in Fig. 2 the betatron functions on momentum are matched from the symmetric values in the solenoidal channel to the FFAG. Some mismatch between modules still exists due to the non-ideal solution in the straight FFAG parts. The matching condition off momentum needs to be addressed as the system contains non-zero chromatic components at the start and in the vertical deflectors.Figs. 3 and 4 show the vertical and horizontal layout of the front end. The injected beam is well separated with the ring both being on different levels.

Injection

The injection geometry was studied using several geometries. The initial design was based on the assumption that both injection and extraction employ the same kickers. The current solution assumes a separate injection system using 1 vertical septum followed by either 1 or preferentially 2 kickers each located in consecutive cells. Having a second kicker would decrease the required kicker strength, but the disadvantage is that the beam excursion becomes too large for the reference magnets and new large gap ones would be needed in the injection/extraction regions. The actual kicker design has been brought to the conclusion that the design is in principle possible with the current pulsed magnet technology, but the main goals (high repetition rate and short rise time) require dedicated prototyping.

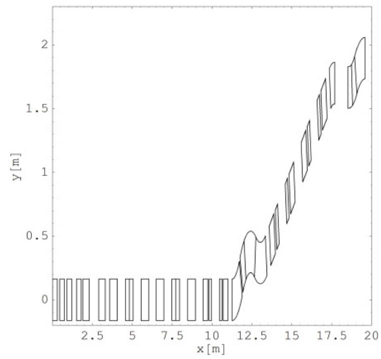

Figure 3: Vertical layout of the AG part of the PRISM front end. The beam from the solenoid enters on the left and the FFAG injection septum is on the right.

RF Studies

Substantial progress has been achieved in the design of MA cavities [5]. Recently, large-size MA cores have been successfully fabricated using a new FT3L material at J-PARC. Those cores have two times higher impedance than ordinary FT3M MA cores. These developments may be used for the PRISM RF system in order to either reduce the core volume cutting the cost by a factor of 3 or to increase the field gradient. Both options should be considered.

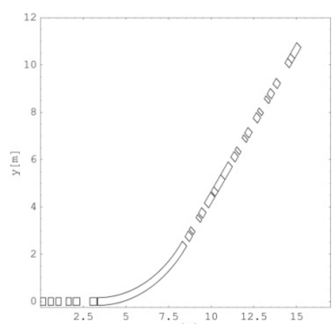

Figure 4: Horizontal layout of the AG part of the PRISM front end. The big curved section represents the FFAG dispersion suppressor.

Alternative Ring Designs

Several alternative ring designs have been produced using both scaling and non-scaling options. In generalthose studies try either to maximise the acceptance or incorporate asuperperiodic structure to facilitate injection/extraction. In particular there has been an interesting activity on rings based on advanced scaling FFAGs [3] incorporating arc sections with different radii ("egg-shaped", see Fig. 5) or the straight FFAG sections(racetrack). The acceptance studies for rings are under way and first results look promising.

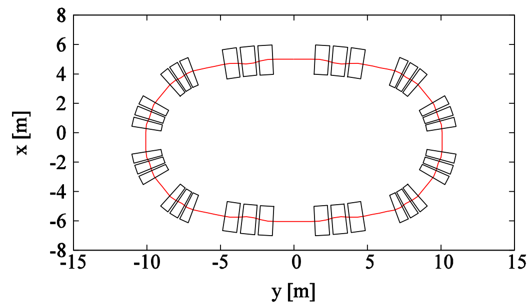

Figure 5: Layout of the advanced FFAG based on the arcs with different radii ("the egg-shaped ring").

SUMMARY AND FUTURE PLANS

High intensity and purity muon beams are needed for HEP experiments. This can be achieved using FFAG rings, which have superior properties such as a very large acceptance. The PRISM Task Force is working towards realizing the PRISM system for a muon to electron conversion experiment. Progress has been achieved in the definitions of the required muon front end, which couples the solenoidal pion production and muon transport channel with an FFAG ring, in definitions of the injection system and in RF hardware studies.Also several alternative ring designshave been proposed. Future studies will include further optimisation of the front end and injection system, systematic comparison of the performance achieved by alternative ring designsand continuation of the hardware studies. The muon phase rotation may also be tested using the MuSIC muon beam at RCNP in Osaka[6], which opens a possibility for experimental verifications of the designs studied by the PRISM task force.

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