ACCELERATOR AND PARTICLE PHYSICS RESEARCH FOR THE NEXT GENERATION MUON TO ELECTRON CONVERSION EXPERIMENT - THE PRISM TASK FORCE

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Abstract

The next generation of lepton flavour violation experiments will use high intensity and high quality muon beams. Such beams can be produced by sending a short proton pulse to the pion production target, capturing pions and performing RF phase rotation on the resulting muon beam in an FFAG ring, which was proposed for the PRISM project. A PRISM task force was created to address the accelerator and detector issues that need to be solved in order to realise the PRISM experiment. The parameters of the initial proton beam required and the PRISM experiment are reviewed. Alternative designs of the PRISM FFAG ring are presented and compared with the reference design. The ring injection/extraction system, matching with the solenoid channel and progress on the ring's main hardware systems like RF and kicker magnet are discussed. The progress and future directions of the study are presented in this paper.

INTRODUCTION

The next few years will be a very exciting time for particle physics with results from the Large Hadron Collider (LHC), neutrino experiments and other precision measurements. These will provide an insight into 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, promises 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 $<10^{-16}$. This sensitivity may be enough to observe this process, which would be a ground breaking discovery, but in order to get an understanding of the mechanism behind this process a sensitivity of $<10^{-18}$ is needed. PRISM aims to achieve this unprecedented sensitivity 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. 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 projects such as the Neutrino Factory and the Muon Collider.

PRISM FFAG RING

The PRISM (Phase Rotated Intense Slow Muon beam) project was proposed in order to realize a low-energy muon beam with a high-intensity, narrow energy spread and high purity. For this purpose, a scaling FFAG ring has been chosen as for this solution a large transverse and longitudinal acceptance is expected. The original design of the FFAG ring for PRISM is based on 10 identical DFD triplets. An R&D program to study its feasibility was performed during 2003 - 2009 in Osaka, Japan. In the program, full size large aperture FFAG magnets and an RF system with Magnetic Alloy cores were successfully developed with designed performance. Then a ring accelerator with the six magnets was assembled and the phase rotation was demonstrated with alpha particles [1]. The PRISM-FFAG ring would be tested in the MUSIC project at RCNP [2] using a muon beam.

PRISM Task Force Initiative

In order to continue the research towards the PRISM FFAG and strengthen the activity on muon accelerator physics, the PRISM Task Force was formed. The research programme 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. Alternatively studies have been conducted in order to find another FFAG ring design, which could be superior to the current solution. In particular the search aims on a ring with a very high transverse acceptance and on a machine with long straight sections in order to facilitate injection and extraction and allow a lot of space for RF cavities. Possible solutions include: advanced FFAG rings, which are formed from scaling FFAG arcs matched to FFAG-type straight sections; FFAG rings with superperiodicity; and non-scaling FFAG rings.

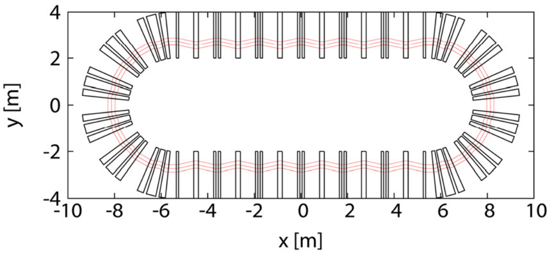

Figure 1: Layout of the advanced FFAG solution for the PRISM ring. Closed orbits of 55 MeV/c, 68 MeV/c and 82 MeV/c muons are shown.

INJECTION AND MATCHING FROM SOLENOIDAL CHANNEL

The solenoidal channel has been identified as the most efficient and cost effective pion decay channel, and is where the muon beam is formed. Its optical properties are characterised by small and equal betatron functions in both transverse planes. The FFAG ring on the other hand requires different betatron functions and a non-zero dispersion function. It is necessary to perform the matching of beam conditions for the broad momentum range of ± 20%. The injection into the PRISM ring was proposed to be in the vertical direction. This means the vertical dispersion needs to be matched to zero inside the ring. It was proposed to use the FFAG straight line as a dispersion suppressor, where a π phase advance is chosen in the lattice with half of the orbit excursion compared to the value in the FFAG ring, to match the horizontal dispersion function. An additional vertical bending magnet at a distance of 2π vertical phase advance is used to give zero net deflection in the vertical direction. Additional cells are required in order to match the betatron functions.

ALTERNATIVE PRISM FFAG RING DESIGNS

Advanced FFAG

The problem of injection and extraction remains to be the most important obstacle for realizing the PRISM system. To solve this problem, we consider the use of the advanced FFAG concept [3], in which straight FFAG cells [4] with zero net deflection and magnetic field on the median plane described by ~ e^{mx} are combined with the compact scaling FFAG arc. The layout of the new proposed design is shown in Fig. 1 and the lattice parameters are summarized in Table 1.

Particle tracking studies have been performed using the Runge-Kutta integration in soft edge fields with linear fringe field falloffs. Components of the field off the mid-plane are obtained from a first order Taylor expansion, satisfying Maxwell's equations.

Table 1. Parameters of the advanced FFAG lattice for PRISM

Circular section FDF triplet scaling FFAG cell	
k	2.55
Mean radius (at 68 MeV/c)	2.7 m
Horizontal phase advance	60 degrees
Vertical phase advance	90 degrees
Number of circular cells	12
Straight section FDF triplet scaling FFAG cell	
m	1.3 m^{-1}
Cell length	1.8 m
Horizontal phase advance	27 degrees
Vertical phase advance	97 degrees
Number of straight cells	12

The original PRISM design has a very large dispersion function (~1.2 m) that makes the injection and the extraction difficult. The new proposal starts from a smaller one (~0.8 m). A better matching of the periodic beta-functions of the different cells gives a less modulated beta-function, and helps to have a larger acceptance. The first step is thus to minimize the mismatch of the beta-functions, then the bending part of the ring is made transparent by imposing the modulo π phase advance, to limit the effect of the remaining mismatch on the amplitude of the betatron oscillations.. The following step is to choose the working point in the tune diagram so that it is far from the structural normal resonances.

The transverse acceptance in both planes is studied by tracking over 30 turns a particle with a displacement off the closed orbit and a small deviation in the other transverse direction (~1mm). Collimators (~1m in horizontal direction, ~30 cm in vertical one) are used to identify the lost particles. Horizontal (~24000 π.mm.mrad) and vertical (~6000 π.mm.mrad) acceptances have been estimated from the tracking studies.

Scaling FFAG with Superperiodic Structure

Another method to generate the long straight sections needed for injection and extraction is to introduce a superperiodicity. This can be done still keeping strictly to the scaling FFAG conditions. The field profile to satisfy the scaling conditions is

$$B_z = B_{z0}\left(\frac{r}{r_0}\right)^k F(\theta) \qquad \text{(X)}$$

where B_{z0} is the vertical field at the reference radius r_0 and F(θ) describes the azimuthal dependence of the fields. The scaling FFAG design so far assumed a simple repetitive function for F(θ), such as a FODO or triplet.

However, there is no reason why it cannot have a more complicated azimuthal dependence. In order to make enough space for injection, extraction and RF cavities, it is desirable to have a variety of drift space distances instead of many identical and rather short spaces.

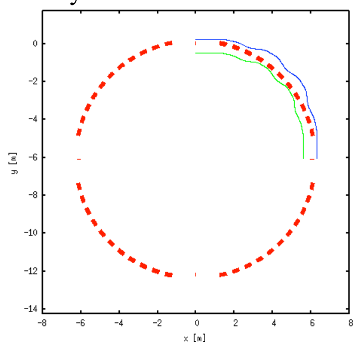

Figure 3: Scaling FFAG lattice with four fold symmetry. Red blocks indicate magnets. Green and blue lines are orbits whose momentum ratio is 2.6.

As an example, a four fold symmetry FFAG lattice for PRISM was designed as shown in Fig. 3. Each arc consists of three triplet focusing units and an extra focusing magnet at both ends. The resulting number of magnets is rather large compared to the original scaling PRISM lattice, but it could be reduced by further optimization. The design also needs the adjustment of each magnet strength to eliminate beating of beta functions due to long drifts. A fitting procedure is established and implemented as a design code [5].

Non scaling FFAG

Another approach for having a very large transverse acceptance is to use a non-scaling FFAG.. This kind of machine - EMMA is presently under construction at the Daresbury Laboratory in the UK and commissioning will start very soon [6]. The magnetic fields are linear in a non-scaling FFAG consisting of only a dipole and quadrupole field components. In this way, the only non-linearities that could limit the machine acceptance come from fringe fields and kinematics. A machine with 10 cells was designed and encouraging tracking results were obtained. It was also noted, that due to the intrinsic non-zero chromaticity in the non-scaling FFAG, the time-of-flight dependence of the transverse amplitude may limit the performance of the phase rotation.

STATUS OF HARDWARE R&D

MA Cavities R&D

An RF system has been constructed and tested [7]. The beam experiment using α beam has been performed to simulate the bunch rotation [1]. Very large (~1.7 m X 1.0 m) magnetic alloy cores were loaded in the cavity. To drive the cavity, a compact and high peak power amplifier was developed for very low duty operation.

Total RF voltage of 2-3 MV at 3.8 Mz is necessary and more than 40 RF systems are required. To reduce the cost, it is important to improve the performance of magnetic alloy. It is noteworthy that an independent work on development of a new material, FT3L, is undergoing [8].

Kicker R&D

The injection and extraction system for PRISM requires kicker magnets with very large apertures due to the large muon beam emittance. Also, the large orbit excursion pushes the horizontal aperture even further. Another important constraint comes from the rise and fall time, which needs to be about 80 ns. It is proposed to use a Pulse Forming Network (PFN) followed by a fast thyratron switch, connected to the kicker magnet by coaxial wires and terminated with a matching resistor. In order to suppress reflections, the impedance needs to be matched throughout the system. The kicker magnet may be subdivided into smaller kickers in order to meet the rise time requirement. Each section of the kicker magnet requires added capacitance in order to match the PFN impedance. In order to obtain a very high repetition rate (100 Hz - 1 KHz) hardware components tests are needed.

SUMMARY AND FUTURE PLANS

It is clear that physics needs high intensity and purity muon beams. FFAG rings are the best option to deliver these requirements as they have very large acceptances and give cost effective beam purification by beam recirculation. The PRISM Task Force is working towards realizing the PRISM system for a muon to electron conversion experiment. Several new ideas like the advanced FFAG or the superperiodic scaling FFAG have been proposed. They can be applied for a future PRISM system or for other FFAG applications like for the Neutrino Factory, the Muon Collider, cancer therapy, energy production and neutron sources.

REFERENCES

[1] A. Sato, "Demonstration of phase rotation using alpha particles in the six-sector PRISM-FFAG ", in this proceedings.

[2] M.Yoshida, AIP Conference Proceedings, Volume 1222, pp. 400-402 (2010) .

[3] JB. Lagrange et al.., "Applications for advanced FFAG accelerator", in this proceedings.

[4] JB. Lagrange et al.., "Zero-chromatic FFAG straight section", in proceedings of FFA'09, Chicago.

[5] S. Machida, "A Fixed Field Alternating Gradient Accelerator with Long Straight Sections", in this proceedings.

[6] R. Edgecock, "Commissioning of the EMMA Non-Scaling FFAG", in this proceedings.

[7] C. Ohmori et al. , HIGH FIELD GRADIENT RF SYSTEM FOR BUNCH ROTATION IN PRISM-FFAG, Proceedings of EPAC08, p796.

[8] C.Ohmori et al., DEVELOPMENTS OF MAGNETIC ALLOY CORES WITH HIGHER IMPEDANCE FOR J-PARC UPGRADE, in this proceedings.