INJECTION AND BROADBAND MATCHING FOR THE PRISM MUON FFAG*

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Abstract

The next generation of lepton flavour violation experiments requires high intensity and high quality muon beams. Such conditions can be met using phase rotation of short muon pulses in an FFAG ring, as was proposed for the PRISM project. The very large initial momentum spread and transverse emittance of the muon beam poses a significant challenge for the injection system into the PRISM FFAG. Also, the matching optics between the solenoidal transfer channel and the ring needs to create a specific orbit excursion in the horizontal plane, suppress any vertical dispersion and produce good betatron conditions in both planes. Candidate geometry for the matching and injection system is presented and its performance is tested in tracking studies.

INTRODUCTION

The PRISM (Phase Rotated Intense Source of Muons) has been proposed as a next generation muon to electron conversion experiment, which equipped with the dedicated detector PRIME aims for reaching a great single event sensitivity of $<10^{-18}$. The high sensitivity of PRISM can be achieved thanks to the superior properties of the muon beam it can deliver to the stopping target. Those advanced beam properties come from the use of an FFAG ring, which substantially purifies the beam from any unwanted composition. By passing the beam several turns in the ring the pion background can be reduced, 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. The substantial progress on the development of the PRISM system was achieved at Osaka University with the prototype scaling FFAG ring constructed at RCNP [1].

The PRISM system requires a proton driver capable of delivering short bunches (~10 ns) at the high power (~MW) to the pion production target. 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 PRIME. The essential requirement for the successful operation of the PRISM experiment is to deliver a high intensity muon beam with the required properties with respect to beam purity and momentum spread. A superconducting solenoidal channel is used as an efficient pion decay channel for the PRISM system and has quite distinctive properties with respect to the beam size, betatron frequency and momentum dispersion compared to the FFAG ring. An addition challenge is that the entire momentum spread of the beam needs to be injected into the FFAG ring simultaneously with very large emittances. This paper reports briefly on the progress obtained on the design of the broad band transport channel and injection into the PRISM FFAG ring, studied in the framework of the PRISM task force [2].

MUON FRONT END FOR PRISM

The role of the muon front end for PRISM is firstly to allow the muon beam to be formed from pion decay, which happens in the high magnetic field downstream of the pion production target. Secondly the beam needs to be injected into the FFAG ring maximising the beam intensity transfer in 6D phase space. One of the essential points is to perform dispersion matching: the beam with dispersion close to zero in the solenoidal channel needs to be adjusted to the horizontal orbit excursion in the FFAG ring. Since injection is foreseen in the vertical direction, the unavoidable vertical dispersion created by vertical dipoles also needs to be cancelled downstream of the injection septum.

The first goal of the study was to establish the configuration of the bent solenoidal channel and the corresponding muon beam conditions as a starting point for the design of the downstream alternating gradient (AG) channel using G4Beamline [3] to perform tracking simulations. 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 modelled using G4BeamLine.

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. This configuration was assumed as a starting point for the design of the AG channel.

At the end of the S-shaped bent solenoidal channel the dispersion in both planes are very close to zero and the

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betatron functions are very small and almost identical in both transverse planes. An adiabatic switch is used to slowly increase the betatron functions to the range of values acceptable by the AG channel. An additional solenoid matching lens is necessary downstream of the adiabatic switch, which is used to match both α parameters to zero. This allows, as seen in the tracking studies, the reduction of geometrical aberrations in the AG section.

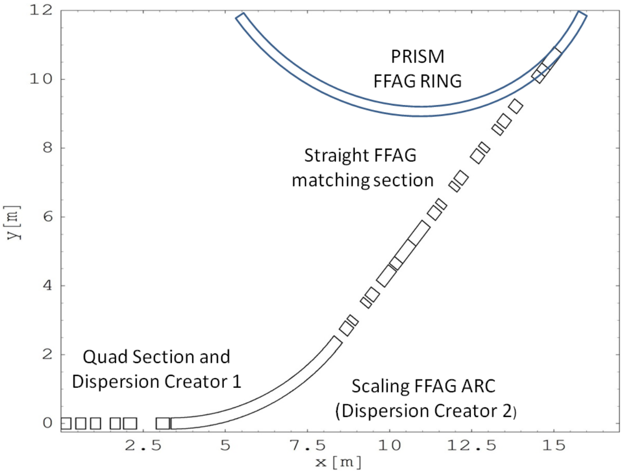

Figure 1: The approximate layout of the AG part of the PRISM muon front end

Following the solenoidal matching the AG channel would be used exclusively as the transport solution all the way to the FFAG injection point. The AG channel consists of the multiple modules each of which plays an important role in adjusting the beam parameters :

- The quadrupole matching section (currently five quadrupoles) breaks the approximate symmetry between transverse planes and controls the betatron function in dispersion creator 1, whilst maintaining zero dispersion in both transverse planes .
- Dispersion creator 1 consists of a pair of equal but opposite strength rectangular dipole magnets. The only variable parameters are the length of the dipoles, their strength and the distance between them. This system adjusts about 30% of the horizontal dispersion starting at zero with respect to the final value in the ring. The D' remains zero at the end of the second dipole as soon as the total field integral vanishes. The goal of this module is to create the initial part of the orbit excursion without any intrinsic nonlinear magnetic field components that could create geometrical aberrations and limit the transmission. In order to match the beam parameters to the entrance of the next dispersion creator 2, the upstream quads are used.
- Dispersion creator 2 consists of a pair of circular FFAG cells with total π horizontal phase advance, where the final dispersion adjustment to the value in the ring is performed. As the initial dispersion was already created in dispersion creator 1, the necessary increase of the field index k in the dispersion creator 2 is smaller than in the case of matching the dispersion directly from zero in an FFAG like system [4]. This helps to keep the dynamical acceptance large.
- Two vertical deflection sections (one incorporating the injection septum), which independently match the vertical dispersion and adjusts the direction of the incoming beam line.
- Two straight FFAG [5] betatron matching sections: one before and one between the vertical deflection systems to perform the final matching to the FFAG ring.

Fig.1 presents the approximate layout of the AG part of the current design for the PRISM muon front end. As can be seen in Fig. 1, the betatron functions on momentum are relatively well matched from the symmetric values in the solenoidal channel to the FFAG., although some mismatch at the very end 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.

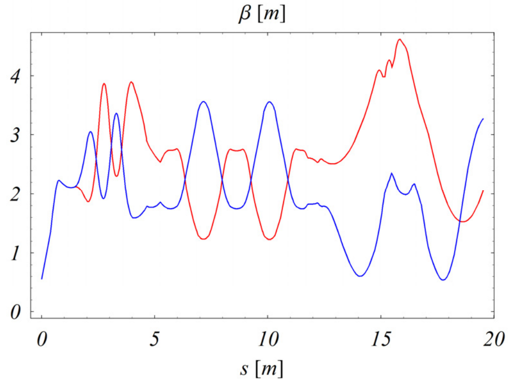

Figure 2: Horizontal (red) and vertical (blue) betatron functions in the PRISM front end. The starting point corresponds to the end of the adiabatic solenoidal switch.

TRACKING

The distribution of parameters corresponding to the beam coming from the solenoidal channel at the end of the adiabatic transition was generated using a truncated Gaussian distribution. The beam was then tracked using BeamOptics [6] for selected parts of the PRISM muon front end. The tracking model used included effects originating from large amplitudes and momentum spread but not fringe fields. Figure 3 shows initial transverse phase spaces, Figure 4 shows the phase space portraits after the quadrupole channel and Fig. 5 after the dispersion creator 2. The current studies show a transmission efficiency of 97 % in the AG part within the FFAG transverse physical total acceptances (3.8 and 0.57

π.cm.rad in the horizontal and the vertical plane respectively), which is an encouraging result. Tracking downstream of dispersion creator 2 will be addressed in future studies.

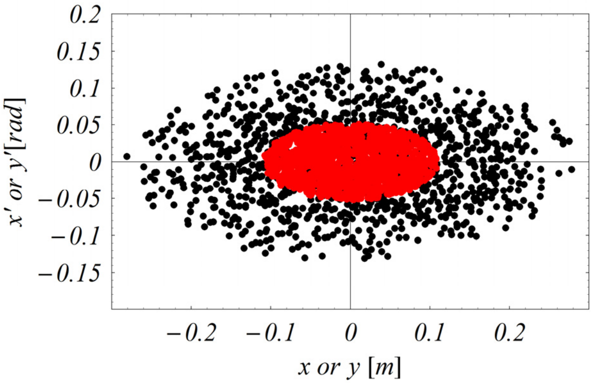

Figure 3: Horizontal (black) and vertical (red) phase spaces at the input to the AG part of the PRISM muon front end.

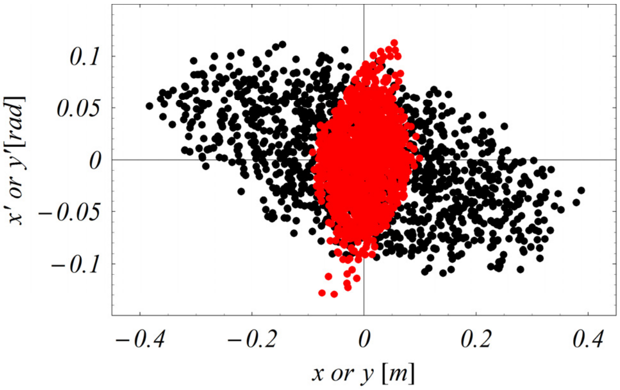

Figure 4: Horizontal (black) and vertical (red) phase spaces at the end of the quadrupole section.

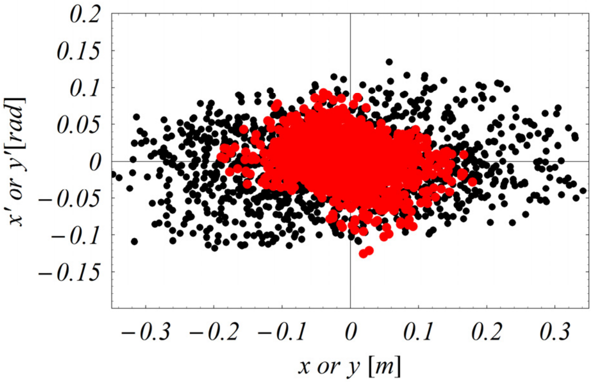

Figure 5: Horizontal (black) and vertical (red) phase spaces at the end of the FFAG-type dispersion creator 2. Some beam aberrations are visible.

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 one vertical septum followed by either one or preferentially two 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.

SUMMARY AND FUTURE PLANS

Substantial progress has been achieved in the design of the muon front end for PRISM. This includes a detailed study of beam properties in various configurations of the bent solenoidal channel; matching between the solenoidal channel and the AG section; and design of the dispersion creator and the vertical deflectors defining the geometry of the injection line. Preliminary tracking studies have been performed from the solenoidal channel till the end of the horizontal dispersion creator producing encouraging results. Further studies of the PRISM task force will continue the design and optimisation of the muon front end for PRISM. In particular the effects of fringe fields will be included and the final performance of the system will be evaluated. These results have direct application for the PRISM project itself and may also be applied to other systems that require beam transport from solenoidal channels to AG systems with large emittances and momentum spread.

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