

# PHASE ROTATION EXPERIMENT AT EMMA FOR TESTING APPLICABILITY OF A NON-SCALING FFAG FOR PRISM SYSTEM

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## Abstract

EMMA is the world's first non-scaling FFAG, based at Daresbury Laboratory. EMMA has a very large acceptance and has demonstrated acceleration in the serpentine channel. PRISM (Phase Rotated Intense Slow Muon source) is a next generation muon to electron conversion experiment aiming to obtain intense quasi-monochromatic low energy muon beams by performing RF phase rotation in an FFAG ring. Current baseline design for PRISM applies the scaling FFAG ring, but an alternative machine could be based on a ns-FFAG principle. As the transverse-longitudinal coupling is present in ns-FFAGs due to a natural chromaticity, its effect on the final energy spread and beam quality needs to be tested. In order to gauge the expected results, an experiment was designed to be performed on EMMA. We report here the details of this experiment and the results gathered from EMMA operation.

## INTRODUCTION

The Large Hadron Collider (LHC) at CERN enables us to look at physics beyond the current Standard Model (SM), however, new results from current neutrino oscillation experiments looking at the physics of flavour changing in the neutral leptonic sector, have shown that quantities, like  $\theta_{13}$ , are 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 are a very important area to search for physics beyond the SM, with important implications for our understanding of particle physics. Therefore, muon to electron conversion searches are rapidly gaining interest 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 JPARC. Both experiments are expected to reach a single event sensitivity of  $< 10^{-16}$ . PRISM (Phase Rotated Intense Source of Muons) [1] constitutes an upgrade of COMET experiment and should give access to the higher sensitivity of  $< 10^{-18}$ . This high sensitivity of PRISM is based on the quality of the muon beam delivered to the stopping target. This quality is due

to an FFAG ring, used to reduce the pion background and to manipulate the beam in longitudinal phase-space. The pion background is reduced as the beam circulates for several turns in the FFAG ring and because pions decay faster than muons. At the same time as the beam is circulating, RF cavities inside the FFAG ring allow for the longitudinal phase-space rotation to reduce the final momentum spread.

The baseline for PRISM is to use a normal FFAG, however, a non-scaling FFAG is also being considered and several designs have already been looked at. In order to better understand the applicability of a ns-FFAG to PRISM, an experiment was carried out on EMMA [2]. EMMA is the world's first ns-FFAG which has recently [3] demonstrated acceleration. A brief description of the experiment is given in the next section, together with a discussion of the observations and results achieved so far in the remainder of the paper.

## DESCRIPTION OF THE EXPERIMENT

In order to test the non-scaling optics for PRISM on EMMA, one must first take into account of their difference in geometry and layout. This means that  $\frac{1}{4}$  of a synchrotron oscillation in EMMA takes approximately three turns, whereas it requires six in PRISM. Subsequently, there are two ways to proceed with the experiment. The first is to inject into EMMA with a fixed energy with different starting conditions, namely RF phase and transverse amplitude, with the RF on with the voltage and phase set so as to have a stationary RF bucket. It is then possible to extract the beam down the EMMA extraction line shown in Fig. 1. The difference between bucket and serpentine acceleration is illustrated below in Fig. 2 with the red line representing the middle of the serpentine channel and the blue line representing the boundary of the bucket. The extraction point is constrained by where the septum is positioned in the EMMA ring, but the idea is to extract the beam after  $\frac{1}{4}$  of a synchrotron oscillation,  $\frac{1}{2}$ ,  $\frac{3}{4}$  and so on, thereby showing that the bunch indeed rotates in longitudinal phase space as shown in Fig. 3 below. The rotation is identified by measuring both the energy and the time of flight.

The second possibility of performing the PRISM experiment on EMMA is to inject at different energies with disif-

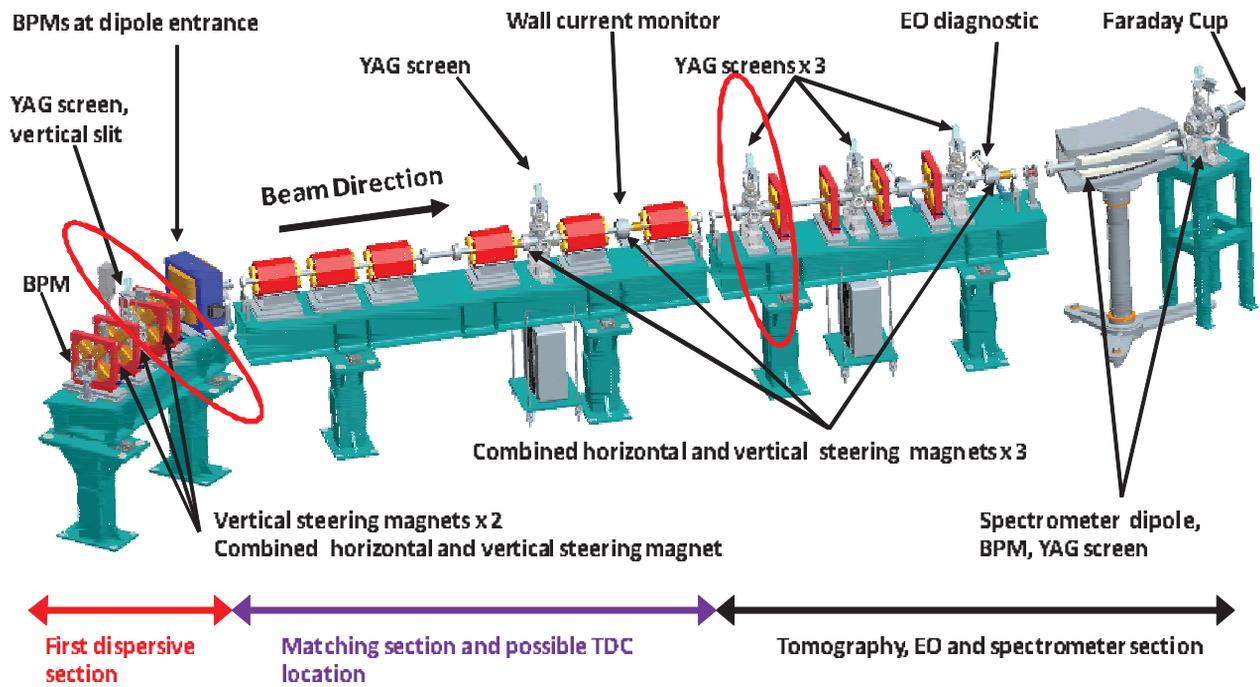


Figure 1: EMMA extraction and diagnostics line (YAG screens 01 and 03, used later for Figs. 4 and 5 are circled in red).

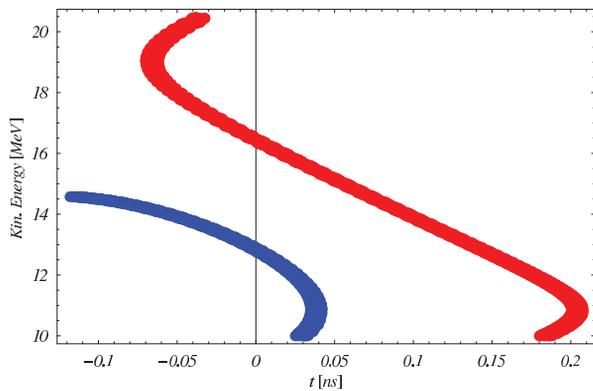


Figure 2: Difference between bucket and serpentine acceleration.

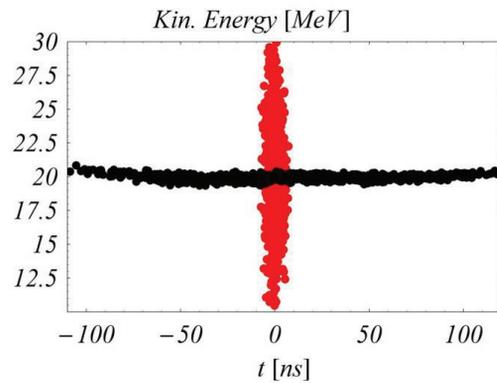


Figure 3: Longitudinal phase space rotation as required by the PRISM project (red before rotation, black after).

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ferent transverse amplitudes and with the RF on with the voltage and phase set to the stationary bucket. Subsequent measurements are the same as in the first case with energy and time of flight all being recorded.

Because the inverse process of longitudinal phase rotation is being simulated, instead of rotating a short bunch with a large  $\frac{dp}{p}$  to a long bunch with small  $\frac{dp}{p}$ , the opposite is done. The way to represent this in the EMMA ring is through three or more “beamlets”. The first represents the head of the muon bunch, the second the middle and the third the tail. Clearly, more beamlets can be introduced but the minimum required is three. To aid with the set-up of the extraction line when the energy of the beamlet in EMMA has increased, a script was developed so as to scale the entire line with energy. This does not give an exact recipe

for extraction but gives a good indication as to what the desired settings (quadrupole strengths etc.) should be. The reason the script only gives a good approximation is that, things like the pulsed extraction septum has to deal with energy dependent trajectories which start at different locations within the EMMA ring.

Together with extracting the beam whilst conducting the experiment, BPM readings inside the EMMA ring were also taken to show the synchrotron oscillation in greater detail.

## RESULTS OF THE PRISM EXPERIMENT ON EMMA SO FAR

Several results were obtained so far and are summarised below. The first set of results entailed a simple extraction of the beam together with a scaling of the magnets in the extraction line and stationary bucket acceleration. Figures 4 and 5 show the extracted beam on YAG-01 and YAG-03 of the extraction line (Fig. 1) after  $\frac{1}{2}$  a turn,  $\frac{3}{2}$  and  $\frac{5}{2}$  of a turn respectively. The images are all in the same location because of the scaling program used which scales the entirety of the extraction line according to energy. The energy gain per turn in the EMMA ring varied roughly between 0 Mev and 1 MeV as the phase of the cavities was scanned.

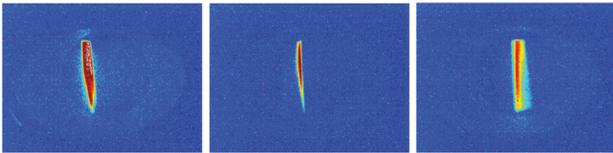


Figure 4: Extracted beam on YAG-01 after (from left)  $\frac{1}{2}$  a turn,  $\frac{3}{2}$  and  $\frac{5}{2}$  of a turn respectively and with the RF on.

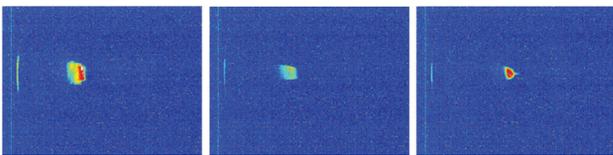


Figure 5: Extracted beam on YAG-03 after (from left)  $\frac{1}{2}$  a turn,  $\frac{3}{2}$  and  $\frac{5}{2}$  of a turn respectively and with the RF on.

If the beam is not extracted after just a few turns, synchrotron oscillations can also be observed via the BPMs. The BPMs are precise enough to be able to record the beam passing at every turn where one turn is the equivalent of around 55 ns. These synchrotron oscillations were indeed seen and an example is given in Fig. 6 below.

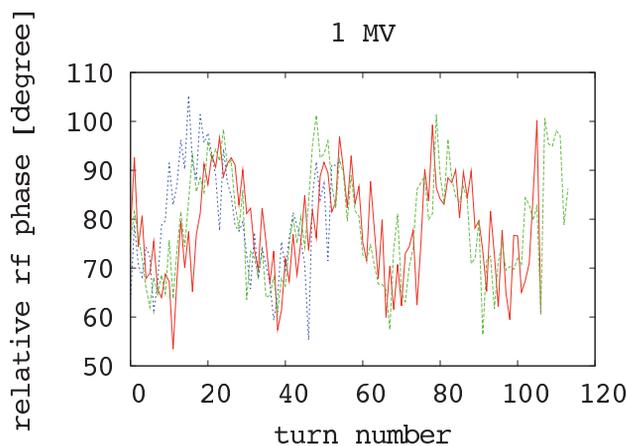


Figure 6: Synchrotron oscillations in EMMA.

## COMMENTS AND FUTURE MODELLING

Systematic studies of the aperture, both longitudinal and transverse, need to be done and, together with the measurements of the time of flight. Unfortunately, the best condition for this experiment would have been to capture the beam in the RF bucket but this was not achieved. The experiment so far also only involved extraction after  $\frac{1}{2}$  or  $\frac{3}{2}$  and  $\frac{5}{2}$ . Ideally, one should be able to extract the beam after a full synchrotron oscillation has occurred which means 12 turns. The beam should also be extracted down the entirety of the extraction line 1 so that the charge may be measured at the end of it. The more centred the beam is down the extraction line, the more precise the results can be. This can sometimes be a challenge because, in order for extraction to work, everything prior to it must also be working.

## CONCLUSIONS

Preliminary modelling for the PRISM experiment on EMMA was presented, together with initial results. Unfortunately, it was not possible to dedicate enough time to this experiment due to the availability of ALICE for EMMA. The intention is to complete this in the near future and to do a full transverse and longitudinal aperture scan on EMMA in order to fully determine whether a ns-FFAG would be suitable for all the PRIMS requirements. All the indications so far suggest that this is indeed possible but the details need to be worked out.

## REFERENCES

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