First Tracking Studies of Phase Rotation Using a Scaling FFAG

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Abstract. This paper presents first tracking studies of longitudinal phase-rotation using a scaling FFAG ring for a future neutrino factory. These simulations were done using the tracking code ICOOL and a field map produced from a TOSCA simulation of the PRISM FFAG magnet.

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INTRODUCTION

In a future neutrino factory, where a multi-megawatt proton beam is used to create spallation pions, the muon beam produced from the decay of the pions will have a very large momentum spread. This means that very few mouns will fit within the acceptance of an ionisation cooling channel. It is therefore necessary to rotate the longitudinal phase-space of the muon beam, i.e. exchange the large spread in momentum and short spread in time for a large spread in time and a short spread in momentum. One way of doing this is to use a scaling FFAG.

TRACKING METHOD USING ICOOL

The tracking code ICOOL [1] was used to perform these simulations. The analytic fields in ICOOL suitable for the simulation of an FFAG currently only include hard edge models, which would not provide a realistic simulation. It was decided to use the the field map from the magneto-static simulation of an FFAG magnet. The PRISM project aims to use a scaling FFAG for longitudinal phase rotation and simulations based on an engineering design of the magnet have been done [3]. This PRISM magnet is a radial-sector scaling DFD type magnet with a field index of 4.6. The ring is made up of 10 sectors with an average radius of 6.5m and has 5MHz cavities that aim to produce 150-200 kV/m between 8 of the sectors. The results of the TOSCA simulation of the PRISM FFAG magnet were obtained from A. Sato. This field map was too detailed to input into ICOOL without recompiling the source and more importantly, the simulation time would be increased. It was therefore decided to do the first simulations by averaging the field map points to give a coarser field map.

VERIFYING THE TRACKING METHOD

To verify that the simulation method was working correctly, phase-rotation in the PRISM scenario, i.e. for muons with a average momentum of 68 MeV/c, was simulated. The first step was to determine the closed orbit particle. The dynamic aperture was then estimated using a beam evenly distributed in transverse phase space for different values of total momentum. The beam was then tracked through 10 turns of the ring (i.e. 100 sectors), without including the rf cavities, and the dynamic aperture was estimated from the distribution of the particles that survived, as shown in Figure 1.

A gaussian beam was then generated using $\sigma_{px} = 0.001$ GeV/c, $\sigma_x = 0.05$ m, $\sigma_{py} = 0.001$ GeV/c, $\sigma_y = 0.025$ m, $\sigma_{pz} = 0.034$ GeV/c and $\sigma_z = 0.0001$ m. This beam was the tracked through 7 turns of the ring which included rf cavities between 8 sectors that were pulsed with the saw-tooth waveform show in Figure 2. The distribution of the momentum spread and spread in time relative to the closed orbit particle was then calculated after each turn of the ring, see Figure 3. This shows that the beam has its minimum momentum spread after 6 turns of the ring. This is

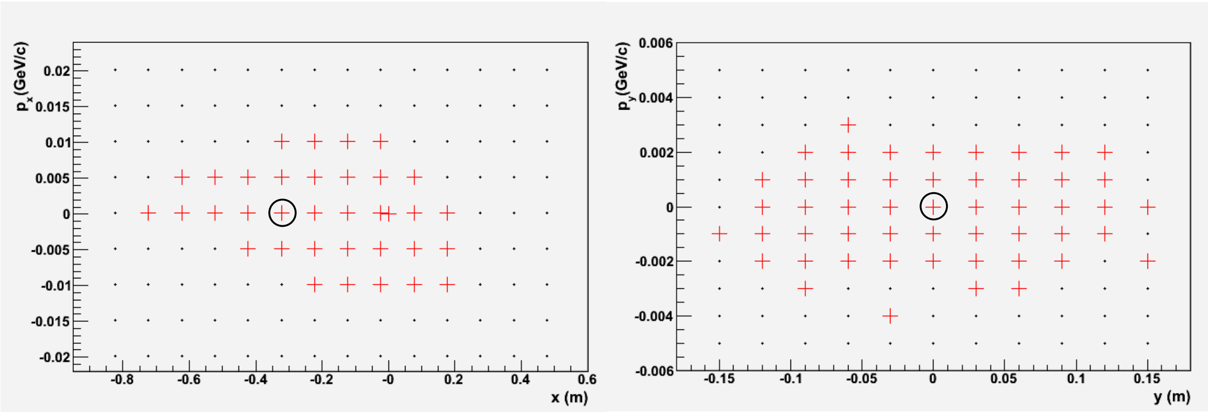

FIGURE 1. Plots showing the transverse phase-space distribution of particles that survive 10 turns of the ring. The circle indicates the closed orbit particle.

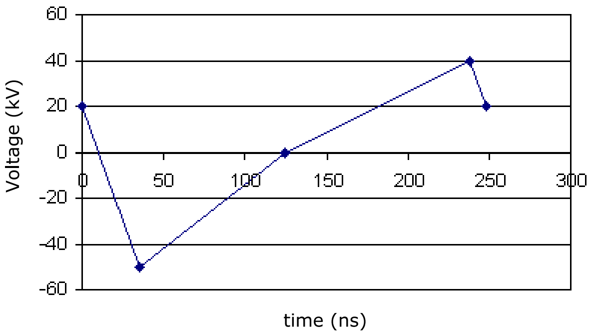

FIGURE 2. Sawtooth waveform used to pulse the cavities in the simulation.

consistent with the results produced by other simulations of the PRISM ring [4].

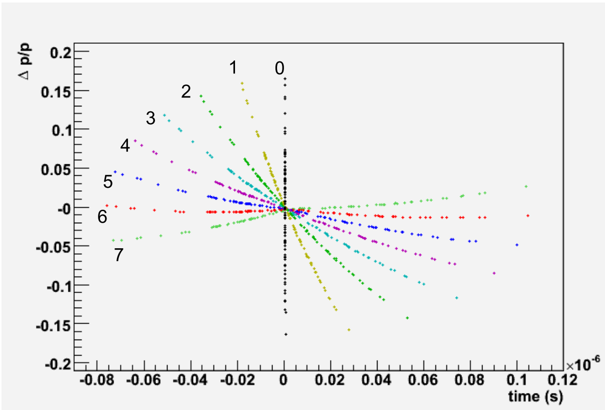

FIGURE 3. Distribution of the momentum spread and spread in time relative to the closed orbit particle after each turn for 7 turns of the ring.

PHASE ROTATION IN A NEUTRINO FACTORY SCENARIO

The main aim of this study is to investigate longitudinal phase rotation at a future neutrino factory where the average momentum of the muons will be 200 MeV/c. The simulations shown above have been for muon beams with an average momentum of 68 MeV/c. To study the neutrino factory scenario the field map was scaled by the ratio 200/68. Figure 4 shows the estimate of the dynamic aperture, which was determined using the method described above. A gaussian

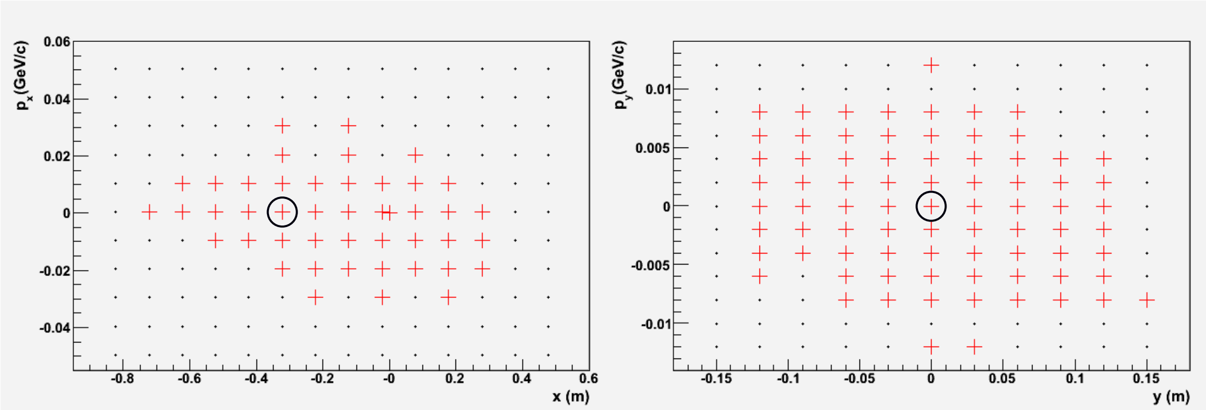

FIGURE 4. Plots showing the transverse phase-space distribution of particles that survive 10 turns of the ring. The circle indicates the closed orbit particle.

beam was then generated using $\sigma_{px} = 0.01$ GeV/c, $\sigma_x = 0.05$ m, $\sigma_{py} = 0.005$ GeV/c, $\sigma_y = 0.025$ m, $\sigma_{pz} = 0.1$ GeV/c and $\sigma_z = 0.0001$ m. This beam was the tracked through 7 turns of the ring, which included rf cavities pulsed with the same saw-tooth waveform show in Figure 2. Figure 5 shows the distribution of the momentum spread and spread in time relative to the closed orbit particle. It can be seen from this figure that the beam is not rotated and appears to only

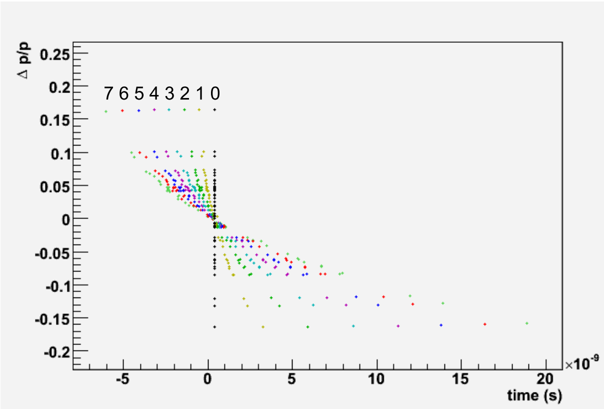

FIGURE 5. Distribution of the momentum spread and spread in time relative to the closed orbit particle after each turn for 7 turns of the ring.

drift. The rf gradient was then increased by a factor of 10 and Figure 6 shows that the beam now begins to rotate.

So far the simulations have been done using an idealistic beam that fits within the dynamic aperture of the FFAG ring. As a first step towards performing a more realistic simulation, a beam distribution from a 10 GeV/c protons on a mercury target simulation was used as input into the FFAG ring. It was found that only 1 muon out of the 978 muons in the input file lie within the dynamic aperture of the FFAG ring. However, this input file does not include the full length of the decay solenoid nor has any attempt been made to match the beam into the FFAG ring, which would improve this situation.

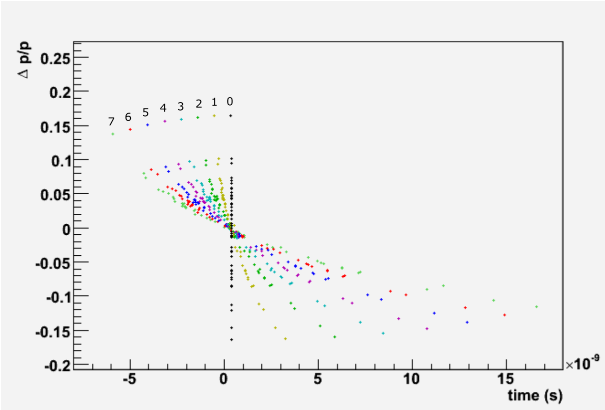

FIGURE 6. Distribution of the momentum spread and spread in time relative to the closed orbit particle after each turn for 7 turns of the ring now with an effective rf gradient 10 times higher.

CONCLUSIONS AND FURTHER WORK

First tracking studies of a phase rotation ring for a future neutrino factory, based on the PRISM magnet design, have been done. The simulation method was verified by obtaining comparable results for phase rotation in the PRISM experiment. The acceptance of the PRISM ring was estimated by calculating the value of the input emittance of the beam that survives 10 turns of the ring, as in Figure 1. An unnormalised, rms calculation of the emittance gave values of $\varepsilon_x = 7800\ \pi$ mm mrad and $\varepsilon_y = 985\ \pi$ mm mrad, for the horizontal and vertical acceptances, respectively. This needs to be multiplied by a factor of four to compare it with the emittance ellipse. An estimate of the acceptance by fitting ellipses by eye to the distributions in Figure 1 gave $\varepsilon_x = 60000\ \pi$ mm mrad and $\varepsilon_y = 5500\ \pi$ mm mrad, which is similar to the values quoted in [4].

After scaling the magnet field map to study phase rotation in the neutrino factory scenario it was found that the rf gradient would need to be increased by more than a factor of 10 to obtain the minimum momentum spread after 6 turns of the ring. This may not be as bad as it first appears since the frequency of the rf cavities can be increased due to the smaller time spread of the bunch in a neutrino factory. It is also possible to wait longer than 6 turns to obtain the minimum momentum spread. However, the use of the mecury target simulation input beam file indicates that the acceptance of the ring would need to be increased.

The PRISM magnet design only rotates a beam with a momentum spread of $\pm$ 20% but the aim for a neutrino factory would be to rotate a beam with a momentum spread of $\pm$ 50%. It is therefore necessary to investigate magnets with a different value for the field index. An analytic field model, including fringe fields, for a radial sector type FFAG magnet is being implemented in ICOOL for this purpose.

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