# Use of the PiE3 beam at PSI for $\mu$LAN

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**Abstract**

This report is only intelligible in conjunction with a long e-mail. The e-mail gives TRANSPORT input and output for tunes with final triplets or doublets. Then follow the results of various Monte Carlo calculations with REVMOC( like TURTLE) for the separation and for the final beam spot.

It is possible to obtain a 20 MHz intensity. The kicking away of the muon beam is preferably done in the bend plane. The kicker will work with a full vertical gap of 15 cm, and a useable width of 20 cm. An electric field of 1.5 kV/cm is just sufficient, but 2 kV/cm would be better. Second order chromatic aberrations cause an asymmetry in the bend plane between the positive and the negative side. Therefore, there is a preferred direction for the kicking. Namely, the muon beam should be kicked to the positive side. Since the bend plane is vertical, the beam should be kicked upwards.

A 6 cm long production target gives a 40 percent higher rate than a 4 cm target at the exit of the doublet following bending magnet B2. This higher rate can be traded in for a better final beam spot through the operation of slits, until the rate gets below 20 MHz. These slits operate at the separation focus SLXY, and immediately following the last quadrupole in the beam line.

The source size in the bend plane does not have a significant influence on the possibility of kicking in the bend plane. A 6 mm full source size is assumed, but calculations with a 10 mm size give almost the same good kicking performance. The source size only affects the transmission of rate between Q9 and the final focus. For the 10 mm source it is 10 percent less than for the 6 mm source.

## 1 Introduction

The purpose of this report is an investigation of the possibility of kicking the muon beam away. Section 2 gives the optimum TRANSPORT tune, using triplets after the separator and kicker to optimize the transmission. Section 3 describes the setup for the Monte Carlo calculations in second order with REVMOC. Results for the separation are given in sections 4 to 6. Section 7 deals with the final beam spot, for which the results are summarized in table 1. Finally, there are some remarks with respect to the upcoming July tuning run in section 8.

# 2 TRANSPORT TUNE

First and second order beam sizes and angles are given for the central momentum and a ±4 percent momentum bite. Also shown are the first order transfer matrix elements. The input beam is ±3 mm bend plane size and ±150 mr bend plane angle. The non-bend plane size is ±2 cm and the angle is ±30 mr. The momentum bite is ±4 percent $\Delta$P/P.

The tune is almost the same up to B2 as the doornbos tune which was used during the tuning run last year. Now, the doublet Q8 and Q9 is used to steer the beam through the separator stage. It turned out that, from an optics point of view, separation in the bend plane gives better results than separation in the non-bend plane. The separation stage consists of a 1 m long crossed field separator to separate positrons and muons, and a 1 m long kicker to kick the muons away. They are represented in the input by the drift spaces SEPA and KICK. It is best to place the kicker after the separator. At first, point to parallel focussing was chosen between target and separators, or alternatively a waist in the separator space, but this gave a large difference in first and second order bend plane angle in the separators. Fortunately, it was possible to change Q9 from those settings by a modest amount to diminish the difference. Now, the first order angle is 8.2 mr and the second order angle is 10.2 mr, a small difference. The separation stage is followed by a triplet that focusses the beam in both planes at SLXY, 80 cm from the triplet, where the separation will take place. An other triplet refocusses the beam at the experimental target. Symmetric triplets were chosen to optimize the transmission. They reduce both the first order beam size and the second order beam size along the beam line, compared to the situation that doublets are used.

The final focus is 1 m from the last quad Q15. The distance from B2 to the final focus is 12.1 m. The total beam length from the production target is 22.05 m. The section with the separators, from Q9 to Q10 is 3.94 m long. The beam line length can be reduced by 1 m if two doublets instead of two triplets are used after the separator section. More length reduction is possible if the separator section can be shortened. Furthermore, it could be investigated whether Q8 and Q9 can be placed closer to B2, and whether the large distance between Q8 and Q9 can be reduced.

The curvatures on the faces of the bending magnets have not been included, since their effect on the beam is marginal. The TRANSPORT output shows that chromatic second order aberrations are important, while the non-chromatic aberrations are small. The sextupoles have some effect on the chromatic aberrations, but also introduce large non-chromatic aberrations. Therefore, they have been turned off. In the TRANSPORT file they are represented by drifts.

## 3 General REVMOC Monte Carlo results

REVMOC is a Monte Carlo program similarly to TURTLE, that was developed at TRIUMF over the years. The program gives results that agree with second order TURTLE, and is based on the same assumptions. The input file with the same magnet settings as the TRANSPORT file is given. The poletip radii on the magnet cards are only used to characterize the magnetic fields. They do not act like apertures. The physical apertures are given on the drift cards by one number for the radius of circular apertures, and by four numbers for rectangular apertures, namely bend plane followed by non-bend plane. The apertures are applied only at the end of the drift and not for the full length. It can be seen that the apertures on the separator( here labelled POSI, compared to SEPA in the TRANSPORT file) and the kicker KICK are 15 cm full aperture in the bend plane and 20 cm full aperture in the non-bend plane. The keyword SEP indicates a crossed field separator, and is used both for the separator and for the kicker. After the separators is the drift labelled ANSP, where output is given. The separation takes place at the end of the drift SLXY. A collimator can be placed immediately after Q15, at the thin drift labelled AQ15. The final focus is called F.

At the start 100,000 muons are generated in a large uniformly filled rectangular phase space, namely 400 mr by 0.6 cm in the bend plane, and 100 mr by 4 cm in the non-bend plane, whereas the total input momentum bite is 15 percent $\Delta P/P$. This gives a total of 23,768 counts at F.

The input file is followed by all kinds of output which give information about the behaviour of the beam along the beam line. The only column of importance here is the last column, which gives the percentage of muons left in the beam after the last preceding aperture. Especially important is the 35.5 percent left after Q9. Here the beam intensity was measured in last year's tuning run at PSI. It was 45 MHz for a 6 cm long production target. According to Monte Carlo calculations it will be 32 MHz for a 4 cm target. At the final focus 23.7 percent is left. This corresponds to 21.4 MHz. All slits are fully open.

Distributions at the production target show for those muons that make it to the final focus the acceptance as a function of the starting conditions. All distributions have 20 bins. The momentum acceptance is 9 percent FWHM, and 10.5 percent FWQ(uarter)M. The 6 mm bend plane source is fairly uniformly accepted, as is the 4 cm non-bend plane source. The angle distribution in the bend plane is 260 mr FWHM and 300 mr FWQM. In the non-bend plane the width of the angle distribution is 65 mr FWHM and 75 mr FWQM.

## 4 The bend plane phase space in the separators

This section deals with plots 1 to 4. All plots are for those muons that reach the final focus.

Plot 1 shows, after the separators at the entrance of Q10, at ANSP, the bend plane phase space for zero momentum spread for a 6 mm source. It is reminiscent of a slanted ellipse from which parts have been cut off due to the succeeding beam apertures. It is not a waist. The angle distribution is sharply defined without tails, between $\pm 10$ mr. The effective muon source size is not known. Therefore, it is worthwhile to show in plot 2 the same distribution for a 10 mm source. The phase space is indeed larger, and does not look so much like a slanted ellipse. The angle distribution is very similar and only slightly wider. Plots 3 and 4 show the same distributions for the full momentum bite. Any structure is mainly averaged out in both cases. The angle distribution is the same. The conclusion is that it is not more difficult to separate for a large source size as for a smaller source size. However, further calculations show that the transmission from Q9 to the final focus is 10 to 15 percent smaller for a 10 mm source than for a 6 mm source.

## 5 The kicked beam at the separator slit

This section deals with plots 5 to 7. The bend plane source size is 6 mm. The non-bend plane source size is 4 cm.

### 5.1 The unkicked beam

The plots 5a to 5c are for the separators off. Plot 5a gives the bend plane x in cm versus the non-bend plane y in cm at SLXY, where the separation slit will be placed. The x width is up to 3 cm, the y width is up to 6 cm. An x slit of $\pm 1.0$ cm will let more than 90 percent of the beam pass. Since the momentum width plays a large role due to the chromatic aberrations, it is wortwhile to show in plot 5b the bend plan angle distribution after the separators, at ANSP, at the entrance of Q10, versus the momentum. For the off-center momenta the angles are mostly positive, while for the central momentum the angle distribution is more balanced. This asymmetry in the projected angle distribution is partly the result of the second order angle term $T_{266}\delta^2$, which gives a positive slant to the angle for both positive as negative $\delta$. This is a typical feature of the bend plane. Both sides of the bend plane are not the same, as is the case in the non-bend plane.

Figure 5c shows the bend plane position x in cm versus the momentum at SLXY. It is a complicated picture, which is difficult to explain.

Apart from the usual second order chromatic terms having to do with the angle and position spread of the initial beam, there is also the aberration $T_{166}\delta^2$, where $\delta$ is the momentum deviation in percent. This term is positive for negative as well as positive $\delta$. It is balanced by a third order term in $\delta$ which arises because in REVMOC( and TURTLE) each beam line element acts on the coordinates at its entrance. Therefore, the second order terms implicit in the old coordinates are multiplied by the second order terms introduced by the element, and this gives rise to implicit third order terms. These are different from the explicit third order terms which may be generated by fringe fields, and can only be taken into account in a higher than second order program. This third order term has opposite signs for positive and negative $\delta$. It is also necessary to fold in the transmission through the rest of the beam which is different for positive and negative momenta, leading to different truncations of the distributions.

An important aspect of the projected x distribution is that the tail on the positive side is longer than on the negative side.

### 5.2 The kicked beam

The beam is kicked down by the kicker by -1.5 kV/cm, which results in a kick of 21 mr, compared to a divergence in the beam of $\pm 10$ mr. Plot 6a shows the resulting x-y distribution at SLXY. A $\pm 1$ cm slit would let 1.3 percent of the beam pass. The reason is that the positive tail of plot 5a is not sufficiently kicked down. Figure 7a shows what happens if the beam is kicked up instead with +1.5 kV/cm. The negative tail of plot 5a is kicked completely out of the range of the $\pm 1$ cm slit. Therefore, it is important to make sure that the kicking will be done in the right direction. This will ensure that the needed kick voltage is as small as possible. Plots 6b and 6c, and plots 7b and 7c., show again the angle distribution at ANSP and the position distribution at SLXY as function of momentum.

## 6 Positron rejection

Positrons can be separated by a 1 m long crossed field separator which precedes the kicker. It was checked with Monte Carlo calculations, but no distributions are given, since the results are very similar to the kicker results. Again, the direction of the positron deflection is important, namely deflecting up is the best. If E is +2 kV/cm, then B is +26 Gauss will let the muons go through, while deflecting the positrons down by 21 mr. This is not enough. 3 kV/cm and 39 Gauss, giving a defection of 31 are needed. But for deflection upwards -2kV/cm and -26 Gauss , giving 21 mr, is sufficient.

## 7 The beam spot at the stopping target

The final beam spot F is taken to be 1 m from the last quadrupole. The beam spot was determined for a number of cases. The SLXY slit was closed to $\pm 1$ cm in the bend plane to eliminate the kicked beam. This slit can also be closed in the non-bend plane. A collimator is assumed at the exit of the last quadrupole, at AQ15. The non-bend plane aperture of the SLXY slit and the aperture of the collimator were chosen to give a rate of 20 MHz in all cases. The source size in the non-bend plane was 4 cm or 6 cm. In the latter case the higher initial rate allows more manipulation of the apertures to minimize the beam spot tails. The polarities of the final symmetrically tuned triplet can be chosen. If it is bend plane focussing followed by non-bend plane focussing and then again bend plane focussing, then this minimizes the chromatic aberrations in the bend plane introduced by the final triplet. In that case there is a strong correlation between the bend plane position at SLXY and the bend plane position at F, and a weak correlation in the non-bend plane. The non-bend plane beam spot can then be influenced to some extent by the collimator at AQ15.

Plot 8a is for 4 cm and the triplet starting with bend plane focussing. The non-bend plane beam spot has a long tail, which can not be reduced

Table 1: Summary of beam spot sizes

| | bend plane | | | non-bend plane | | | |
|---|---|---|---|---|---|---|---|
| case | FWHM (cm) | FWQM (cm) | FWTM (cm) | FWHM (cm) | FWQM (cm) | FWTM (cm) | source (cm) |
| 8a | 1.8 | 2.4 | 3.3 | 3.0 | 4.5 | 6.6 | 4 |
| 8b | 1.8 | 2.4 | 3.3 | 3.3 | 4.5 | 5.1 | 6 |
| 9a | 2.1 | 3.0 | 4.8 | 3.0 | 4.5 | 6.0 | 4 |
| 9b | 1.8 | 2.4 | 3.0 | 3.3 | 4.5 | 5.1 | 6 |
| 10 | 1.2 | 1.8 | 2.1 | 3.6 | 4.2 | 4.8 | 6 |

by using the collimator without reducing the rate in an unacceptable way. Plot 8b is for a 6 cm source. Both the slit and the collimator are used in the non-bend plane, resulting in a drastically reduced tail.

Plot 9a and 9b are for opposite polarities of the triplet. Now the bend plane beam spot has long tails. In the case of 6 cm, the collimator is used to reduce the tails.

## 7.1 The beam spot for a tune with doublets

It is not clear whether it is possible to construct a beam line with two triplets after the separators. The advantage of triplets is a good transmission which makes a high rate possible. Even for a 4 cm source 20 MHz is possible. It has, however, been shown that it is advantageous to use a 6 cm source, which makes a smaller final beam spot possible with shorter tails. If a 6 cm source is indeed available during the real experiment, then it is worthwhile to also consider a tune with two doublets after the separators. A 4 cm source would give a far too small rate. The doublets are tuned such that there is a bend plane focus at SLXY, but a large size in the non-bend plane. Plot 10 shows the final spot. The spot is smaller than for the tune with triplets. Table 1 summarizes the FWHM, FWQ(uarter)M and FWT(enth)M for plots 8 to 10.

The beamline with doublets is 1 m shorter than the beamline with triplets. Depending on available space and equipment the doublet tune may be a better option not only during the experiment, but also during the tuning run in July.

## 8 Remarks about the July tuning run

The purpose of the July run is to determine how to separate positrons, how to kick away the muon beam, what is the beam spot at the stopping target, and what is the intensity.

Separation and kicking take both place in the bend plane. Therefore, it is not necessary to use two separators during the tuning run. One normal crossed field separator can be set to separate positrons with high field. Changing the electric field by up to 2 kV/cm will then kick away the muon beam, without affecting the positrons very much. It is important to check, using collimators, whether an aperture of the separator of 15 cm gap by 20 cm width is sufficient. Furthermore, the distance between Q9 and Q10 should be as in the above tunes, even though that means a large drift after the separator. However, it is worthwhile to study the effect of a shorter distance.

It is not sufficient to just measure the situation after the first triplet or doublet after the separator, at SLXY. There are losses in the succeeding triplet or doublet, which influence the results. These losses have to be taken into account. Without studying the beam at the final focus, it may be difficult to draw conclusions for the design of the detection system in the real experiment.

Before the July run it has to be decided to use either triplets or doublets, and whether to use a 4 cm or 6 cm long production target. The 6 cm target is preferred, since it gives a higher rate and abetter beam spot.

The calculations in this report are all in second order. Higher orders may play a role. Higher order calculations with a more sophisticated raytracing program for a previous tune show that the influence of higher order optics may not be as severe as originally feared. Therefore, the present calculations can, for the moment, serve as a good guidance for the tuning run and the possibilities during the experiment.

The next step is now to determine what kind of beam line configuration is possible at PSI during the July run. Then the theoretical tune has to be adjusted, and the sensisivities of the quadrupoles with respect to purity and final beam spot have to be studied. Finally, this may lead to a useful tuning strategy.