Muon Transport Considerations for E614

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Work on the delivery of muons to E614 has been done using the beam optics codes Transport and Revmoc. Studies related to the pion production target have been done using Geant. In addition, the surface muon beam characteristics have been studied in the M13 beam line.

This report summarizes some of the work done in the following areas:

1 - Surface Muon Selection

M13 should provide a surface muon with high polarization.

2 - Effective polarization - beam divergence

Placement of the solenoid near a traditional focus should result in a low divergence beam.

3 - Muon depolarization - slit scattering

Simulations show that none of the muons scattered from slits upstream of the second dipole are transported to E614. This will need some type of online monitoring.

4 - Muon contamination - muon TOF

Space permitting, we should be able to adjust the total TOF to tune the spacing between the pion and muon peaks. This may improve our live time. Other sources of background will be studied using Geant.

5 - π production target - geometrical considerations

The size of the 1AT1 image was studied by feeding Geant output into Revmoc for the purpose of studying the sensitivity to possible wander of the proton beam spot. These studies did not show an "image" of the proton spot, in apparent contradiction to the data. In any case, it is expected that the proton wander can be made small. There is no argument at present for redesigning 1AT1.

1 - Surface Muon Selection

The muons produced at some depth within the pion production target will suffer multiple scattering and energy loss as they emerge into our beam line. Dave Gill has done Geant simulations which indicate the amount of depolarization for a given depth. His calculations show that for a momentum acceptance of 1%, we accept muons produced within approximately 30 μ of the surface, with a consequent mean depolarization of 0.55 X 10^{-4}. These results are summarized in the attached figures 1 - 4.

Proposal: We may be able to study the polarization dependence of the result by looking at E614 data produced from non-surface muons. This would be done by tuning for a lower momentum beam, thereby selecting muons produced at some depth within the pion production target. This would give us a useful check on polarization dependent systematics. We may be able to study this in M11 during the summer beam tests.

2 - Effective polarization - beam divergence

The effective polarization which is available to us is $(P)(\cos\theta)$, where P is the muon polarization relative to the muon momentum direction, and θ is the angle of the momentum within the holding field relative to the spectrometer axis.

It has been suggested that we use the fringe field as the muons enter the solenoid as a final defocusing element in the beam line, for the purpose of delivering a low divergence beam to the E614 target.

The solenoidal fringe field "mixes" the spatial coordinate of a particle (x,y) with the divergences (dy, dx). Therefore, the introduction of divergence by the solenoid is minimized when the beam is focused at the entrance to the solenoid.

I have worked with a senior undergraduate student (Lance Doherty) in Physics Engineering through this past semester to verify that there is an optimal placement of the E614 solenoid relative to the last quad in M13. The conclusions of this study are:

- there is an optimal placement which results in a low divergence beam at the midpoint of the solenoid.
- both Revmoc and Transport deal with idealized fringe fields. There is no means of introducing a field map. I believe that this is because the codes deal with integrals of the field.

Lance's study will be listed as a technical note. The results will need to be tested with a "real" fringe field.

Conclusion: It is reasonable that we can use a somewhat traditional tune of M13 to produce a low divergence beam at the midpoint of the E614 solenoid. The expected muon distribution would have $\langle\cos(\theta)\rangle > 0.9999$.

3 - Muon depolarization - slit scattering

It has been shown through Revmoc that the muons depolarize when scattering on the slits, and that the depolarization is accompanied - as expected - by a degradation of the muon momentum.

The two dipole design of M13 effectively eliminates muons degraded on the slits - as long as there are no slits downstream of the second bend.

The plots in Figure 5 show that while degraded muons appear after the first slits, these are eliminated and no more "bad" muons are introduced prior to the end of the beam line.

Proposal: One thing that bothers me is the fact that it will not be feasible to do complete simulations at the 0.01 percent level. Hopefully beam profiles will give us a handle on the shape of the momentum distribution - and any possible low momentum tail - in the actual data. This could be related to a bound on the slit edge scattering and consequently to a limit on the depolarization through multiple scattering.

4 - Muon contamination - muon TOF

One of the considerations is the RF frequency. The decay-in-flight of pions results in a muon signal at the detector which has a time fixed to the cyclotron RF. The pions at the detector are also timed to the RF. If the experiment is inhibited during the arrival of these two pulses, the time remaining is useful for looking for surface muons. These are out of phase with the beam RF, since the pions have decayed at rest.

Figure 6 shows two overlayed distributions. That highlighted in yellow shows the flux (in arbitrary units) with the momentum tuned for surface muons (roughly 29.7 MeV/c). The pion half-life is clearly visible between the spikes.

The underlying distribution was obtained at a slightly higher momentum. In this case, pions decaying at rest cannot give muons enough momentum to make it through the channel. The peaks which are observed are muons from pion in-flight decay, and pions. The wider region between the peaks is that which is usable for collecting surface muons.

A simple (classical) calculation shows that the time difference between the muon peak and the pion peak is

$$\Delta t = \left[\frac{L}{c}\right]\left[\frac{1}{pc}\right]\Delta mc^2$$

where L is the length of the beam line, and p is the momentum tune of the channel. In the figure shown, the time difference is actually (roughly) 27 ns. With an RF period of (roughly) 34 ns, this results in a separation of 7 ns between the two peaks. This separation makes it look like the beam line was roughly 7.1m in length - somewhat shorter than a typical M13 setup of 9.5 m.

The interesting point is that we may be able to (slightly) alter the total length of the beam line to optimize the timing of the muon (in-flight) and pion peaks. Furthermore, the question has arisen as to whether M11 will be suitable from this point of view. The separation (for a 29.7 MeV/c channel tune) walks at 3.7 ns / meter. The following table summarizes some interesting lengths of beam lines:

Length	muon-pion separation (ns)	comment
7.1 m	7.0 ns	timing difference on figure 1
7.9	-4.	
8.95	0.0	
9.5	2.1	length of M13
10.0	4.0	
13.4	17.0	worst possible time difference
15.5	-9.0	length of M11
16.8	-4.0	
17.8	0.0	
18.9	4.	

If we choose to resolve the muon and pion peaks, we may wish to have a separation of 4 ns. If we don't care to resolve the two peaks, 0 separation is preferable (to minimize the inhibit time).

Conclusions: It has been agreed that a full Geant Monte Carlo will be developed for the purpose of studying in detail the beam contaminants, including the slits as sources of surface muons (out of time with the RF), and $e^{\pm}$ beams. It would be interesting to measure the "walk" between the pion and muon peaks this summer by using detectors positioned at more than one distance along the beam line. I conclude that from the point of view of the pion/muon separation, the use of M11 is likely feasible. The total flight path will need to be chosen, with consequences for the beam tune.

5 - π production target - geometrical considerations

Ever since a surface muon beam profile was obtained (by members of our collaboration at TRIUMF) which showed evidence of a hot spot associated with the proton beam position[1] , there has been concern that we may be sensitive to "wander" in the distribution in the spectrometer associated with a wander in the proton beam position.

[1] This was also seen at PSI. See figure 7.

For quite some time, we considered the possibility of modifying 1AT1 for the purpose of screening our view of the proton entrance into the pion production target. This could be a complex problem due to the heat dissipation requirements in the target. An alternative which was proposed some time ago was that a beam control feedback system - perhaps borrowed from parity - could be used to fix the position of the proton beam spot. This is likely the better solution.

Meanwhile, we have developed a Geant simulation (Peter Gumplinger, in particular) which models the pion production within 1AT1. In addition, Dennis Wright is working on an improved version of the Geant generator which incorporates parameterizations of measured pion production cross sections.

The simulations done by Peter Gumplinger have been used to generate surface muons which have been used as input into the M13 beam line, as modeled by Revmoc. The Geant simulations rely on pion production distributions generated by Fluka and Geisha. Discrepancies between these two distributions are shown in figures 8 and 9.

Two simple targets were studied. One is similar to that presently installed at 1AT1. This has the protons entering from the "end" of the target. Both this end and the side of the target are viewed at 45° (see figure 10). Muons emerging from the surface of this target are tracked through M13 (using Revmoc). The distributions are created for muons which are transported to the focus, at which the spectrometer will be placed. For example, the beam profile at the focus is shown (for the "existing" target) in figure 11.

The second target geometry is one for which the proton enters a face inclined at 45°. In this case, the target itself screens this face from view by the M13 channel, as shown in Figure 12. The beam profile at the muon focus is shown in figure 13.

These simulations fail to predict the observed hot spot associated with the proton entrance position. This may well be due to the known shortcomings in the pion production cross sections. For example, Geisha and Fluka predict significantly different rates for back angle pion production (Figure 8/9). Therefore, the existing simulations are not able to address target geometry, in particular with respect to sensitivity to the proton beam spot.

Conclusion: It will be important to pursue simulations with realistic pion production cross sections. At the same time, even assuming that a "hot spot" exists (as shown in the data, Figure 7), it is certainly easier to control the position of the proton beam than to modify 1AT1. We should force the beam line simulation to assume a source distribution in agreement with Fig. 7, and look at the sensitivity of the whole experiment to the amount of wander in the proton beam.