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Spectrometer Design Options for E160 P. Bosted

Abstract

This document outlines general design consideration for the E160 spectrometer, and examines several possible solutions. The final proposal for E160 is presented in a separate TN.

1 Some general considerations

We take as guidance the physics requirements outlined in TN 7. We assume $J/\psi$and ψ'will be detected by the decay to two leptons. The difficult requirements are to obtain mass resolution in the few percent range (not to exceed 4% in any case), ψ energy resolution in the few percent range (not to exceed 7%), p_t resolution on each muon of 0.1 GeV or better, and sufficient luminosity to obtain the desired statistics.

1.1 Electrons or Muons

The basic experimental strategy, given the poor duty cycle at SLAC, is to maximize the signal from decay leptons compared to the enormous backgrounds from hadronic interactions in the target. For a 1.6 gm/cm^2, there is about 1 hadronic interaction for every 10,000 photons, but about 10^9 photons are needed to produce a J/ψdecaying to two leptons. If electrons are used, it is essential that the spectrometer act as a p_t filter, and only detect particles above about $p_t = 1$ GeV, where the pion to electron rate becomes manageable (note the typical lepton from the decay of a heavy particle has $p_t = M/2$, or 1.5 GeV for the J/ψ). This necessarily means the particles have to bend around a corner, ensuring a relatively small solid angle (such as the 8 GeV and 20 GeV spectrometers originally used at SLAC). On the other hand, muons have the advantage of being relatively rare, and are possible to completely isolate from other particles with the use of a hadron filter. The main source of muons is from pion and kaon decays, so the filter must be very close to the target, and have a high density.

The hadron filter necessarily makes for worse resolution that is possible using electrons. However, the next sections show that mass resolutions in the 3 to 4 percent range are possible with a hadron filter, which according to TN7 means an increase in luminosity/acceptance of about a factor of two compared to the resolution of 1% or so that in principle is possible with electrons. Since the di-lepton acceptance for a muon spectrometer can reasonably be an order-of-magnitude higher than for electrons, there is clearly a bias towards using muons. This will be assumed for the rest of this report.

1.2 Absorber thickness

For a detector to be able to do reliable tracking in the environment of few hundred nsec beam spills, the rate of penetrating particles into the detector is a limiting factor. In the absence of other backgrounds, this limit will be determined by the number of charged particles from hadronic interactions that effectively penetrate (through secondary interactions) the absorber. Another consideration is the density of the absorber: lower density allows more distance for pions and kaons to decay over. Figure 1 shows the number of secondary charged particles emerging from alumina as a function of the thickness. The input distribution was generated using a coherent bremsstrahlung spectrum similar in shape to the 48.3 GeV endpoint setting shown in the proposal, but with ten times higher flux (in detail: the endpoint energy was 48.3 GeV, primary coherent peak at 35 GeV, diamond thickness 0.015 r.l., 3E10 incident electrons, and a 1 mm radius collimator at 78 m, leading to a total of 25,000 hadronic interactions/spill above 2.5 GeV). The PYTHIA Monte Carlo was used to generate hadronic interactions with this spectrum. The rate actually increases at first, as the hadronic shower develops, then decreases exponentially, then finally begins to flatten out as only penetrating muons are left. Since the mass resolution increases approximately linearly with absorber thickness (due to multiple scattering) in a typical spectrometer design, and the luminosity factor f increases roughly proportionally to the mass resolution, until the "brick wall" of the J/ψtail is reached, it is clear that in the absence of other backgrounds, it is best to choose the absorber thickness as close to the "knee" as possible.

Table 1 shows the thickness of the "knew" in meters and radiation lengths (r.l.) for several materials, as well as the number of emerging muons from decays. This was calculated by Piotr Decowski using GEANT. It can be seen that the "knee" r.l. increases slowly with Z, so that the best resolution is
will be obtained for a low Z absorber. This is also illustrated in the Table, which shows the mass resolution that can be obtained with three different types of spectrometer design, as discussed in more detail below. On the other hand, the length of the absorber increases for low Z materials, limiting the useful acceptance if a fixed aperture magnet is used for tracking. The muon rate is also higher as the density of the material decreases. Therefore a moderate Z material with high density is the optimum compromise. Alumina (density 3.6 gm/cm^2) is a very good material for this purpose, with graphite (density 2.2 gm/cm^2 assumed) being second best, and aluminum is also pretty good.

1.3 Angular Resolution with Absorber

To examine the effect of angular resolution for different absorbers, the relative invariant mass resolution was calculated in the idealized case where the angle of a muon is determined by the transverse position after an absorber, (i.e. $\theta = x/d$, where x is the transverse distance to the beam line, and d is the absorber thickness. The momentum is assumed to measured perfectly after the absorber, with the resolution on the original momentum at the target determined by fluctuations in energy loss about the mean. [See bosted/jpsi/oldspect.f with lasscode=1]. The results are shown in Table 1 as Res (a). The mass resolution is acceptable

Table 1: *For various materials, the length in meters and r.l. of the material that matches the "knee" condition, marking the transition from a steep slope of emerging particles, to a much flatter slope where mostly muons emerge. The input was the particles from about 25,000 nuclear interactions. Also listed is the number of emerging charged particles, assuming no drift between target and start of absorber. In reality, there must be a drift due to the beam pipe, which increases inversely with scattering angle, so the particle rate for copper is probably underestimated by a factor of three or so. Also shown are the invariant mass resolutions that would be obtained from: a) θ resolution from absorber alone (no magnetic field), and perfect momentum resolution after absorber; b) same as a) but momentum resolution from an iron range telescope; c) same as a) but momentum resolution from tracking in large dipole (Case II spectrometer); d) absorber immersed in constant 23 kG magnet field.*

Material	density	Knee (m)	Knee (r.l.)	Part.	Res (a)	Res (b)	Res (c)	Res (d)
Be	1.87 gm/cm^2	10	28	100	2.6%	4.3%	4.0%	2.3%
C	2.20 gm/cm^2	6	32	60	2.6%	4.4%	4.0%	2.2%
Al_2O_3	3.60 gm/cm^2	3.5	48	50	3.1%	4.9%	4.0%	3.2%
Al	2.70 gm/cm^2	5	56	80	3.6%	5.0%	4.4%	2.9%
Cu	8.96 gm/cm^2	2.0	140	10	5.7%	6.5%	6.0%	11%

for all materials except copper. It is best for C or Be, but a price in the size of the absorber would have to be paid. Alumina is clearly the best material from this point of view.

1.4 Momentum Measurement by Range

One way to measure momentum is by the range of a muon. In TN8, the range of 10 GeV muons in iron is shown, calculated using FLUKA. The distribution in z where the muons stop is not Gaussian: there is a long tail on the low z side, due to bremsstrahlung, pair production, nuclear interactions, and Landau fluctuations. This would lead to an asymmetry in the reconstructed J/ψmass peak, fortunately on the low energy side. The effective relative momentum resolution from a range telescope appears to be in the 5% to 7% range, which may be acceptable because the acceptance of a range telescope could be quite large. The relative mass resolution of a range telescope for various front absorber materials is shown as Res (b) in the Table, assuming 5% momentum resolution (this what actually achieved for muons up to 10 GeV in a rare kaon decay experiment). Except for a copper absorber, the resolutions are (just barely) adequate. [See bosted/jpsi/oldspect.f with lasscode=3]

The main drawback to this technique is the large size needed. To have good acceptance for ψ'decays (average $p_t = 1.85$ GeV), we would like good acceptance out to $p_t = 2.5$ GeV. Using an average energy loss of 1.4 GeV/m in iron, the radius of the telescope must be about 1.8 m, and the length must be about 18 m. The actual length and radius would have to be about 20% larger to allow for layers of detector to be placed between the iron slabs. The volume of iron needed turns out to be about 200 cubic meters, or 3 million pounds. A typical price for iron is \$0.50/pound, so this turns out to be prohibitively expensive. Another problem is the large number of detector layers that would be needed for a 5% momentum measurement, on the order of 40. With an active area of 10 m^2 per plane, this amounts to 400 m^2 of detector area, which could be expensive, even if very coarse granularity were used.

Another consideration with a range telescope is that there must be a reasonably large hole for the beam pipe. Since the average multiple scattering angle is approximately 0.3 of the original muon angle for fixed $p_t = 1.5$ GeV, there is a significant amount of deflection of the muons from their original trajectory, and some of them will scatter into the beam pipe region, where they can travel long distance, then re-emerge into the iron. This is very dangerous, as low momentum muons can be misidentified as high momentum muons, thus populating the high mass, low rate region. Detailed simulations are needed to determine if a range telescope is really practical.

1.5 Momentum Measurements using Dipole Fields: Case I

The use of a dipole magnetic field to measure momentum has several advantages compared to a range telescope: in principle much better momentum resolution can be achieved; and the overall length scale will be much smaller, potentially reducing costs to a manageable level. A nice feature of ψ decays is that the two muons are always of opposite sign, and therefore bend in opposite directions. We can distinguish two cases: one where the magnetic field encompasses the absorber, which all tracking detectors located beyond the magnetic field (Case I, as in the proposal); and a second case where an absorber is followed by a first detector, then magnetic field, and finally more tracking (Case II).

Lets first look at case I, absorber in a constant magnetic field, followed by tracking. In this case, both bending and multiple scattering scale inversely with momentum, which is slowly decreasing throughout the medium to energy loss. The particle momentum is basically determined by assuming it originated at the target, and made an effective bend angle $d\theta$ in the middle of the magnet. The ratio of multiple scattering ($0.016\sqrt{z/X_0}/P$, where X_0 is the r.l. of the material in meters) to bending ($Bz/33.356P$, where B is in kG) determines the momentum resolution, given by $\delta P/P = 0.53/B\sqrt{zX_0}$. To meet the physics goals, the momentum resolution should be no worse than 6%, which leads to the conclusion that the z length required for a fully saturated B field of 22 kG is given by $z = 0.11/X_0$ meters, as shown for some materials in Table 2. What the table shows is that adequate momentum resolution can be obtained for materials lighter than about calcium, when enough material is used to reach the "knee" condition. Unfortunately, in the case of iron, at least 7 m is needed, far more than is necessary to act as a hadronic filter. When fluctuations in energy loss are taken into account, if turns out more like 8 m is needed, which ranges out muons below 12 GeV. Since we need to detect muons down to 5 GeV for the decays of 15 GeV J/ψparticles, it is clear that the inexpensive option of using magnetized iron is ruled out.

Table 2: *For various materials, the amount needed in a uniform 23 kG field to obtain 6% momentum resolution (D).*

Material	r.l.	D
Beryllium	0.35 m	0.4 m
Carbon	0.27 m	0.4 m
Aluminum	0.089 m	1.3 m
Alumina	0.073 m	1.5 m
Iron	0.0176 m	7 m

We can now look at the case where the center of gravity of the absorber and magnet are different. If we call d_1 the target to center of absorber distance, d_2, the target to magnet center distance, and d_3 the target to front detector distance, and assume the detector makes a perfect measurement of x and θ, then solving for two equations in two unknowns yields:

$$Bz/33P = \theta(d_3/d_2) - x/d_2 + \theta_{ms}(d_1/d_2).$$

This shows that is better to have the absorber closer to the target than the magnet, all else being equal (for example by having higher Z material followed by lower Z material). The solution for the muon angle at the target is

$$\theta_0 = x/d_2 - \theta(d_3/d_2 - 1) + \theta_{ms}(d_1 - d_2)/d_2$$

which shows that the θ_0 resolution is optimized by having the absorber centered in the magnet. Since this solution also maximizes the acceptance for a given magnet, we will assume this criteria in the Case I design. What is clear is that there is little advantage in putting an absorber $after$ the magnetic field: instead the material should be chosen so that the "knee" length matches the physical length of the magnet system. The longer the volume of the magnet field, the better the resolution will be, at a cost of acceptance for fixed magnet sizes, or power bill if a very large magnet is used.

The last column in Table 1 shows the resolution of of a Case I spectrometer with uniform 23 kG field of the same length as the absorber, in the case where tracking granularity does not contribute significantly to momentum resolution. [See bosted/jpsi/oldspect.f with lass-code=0]. What is interesting is that the resolution is better than the case where the muon angle is measured after an absorber, and there is near-perfect momentum resolution! This can readily be seen from the above equations. Adequate mass resolution can be obtained for all materials shown except copper. Assuming that acceptance will be determined by the length of the system, but that worse resolution corresponds roughly linearly to increase running time, the optimal absorber material is alumina. This is very convenient, as it happens to match the length of the large B81/B82 dipoles.

We have examined in considerable detail the option of using B81 filled with alumina, running at the maximum integrated field of 78 kG-m. For sufficiently fine-grained hodoscopes (2 mm resolution in x, 1 cm resolution in y), and assuming the muons to originate from the target with realistic beam size and target length uncertainties, we find a mass resolution of about 3.5%. [see bosted/jpsi/d3spect.f and d3spect.inp]. As discussed in more detail in T.N. 14, this design can accommodate a high enough beam intensity to meet the statistical goals of the proposal, and so has been chosen as the E160 spectrometer design.

1.6 The Original Proposal Design

The proposal design is an example of a Case I design, with tracking after a magnetic field provided by the 29D43 and LASS dipoles. The proposal has 2 m of alumina, which is well below the optimal value of 3.5 m, and this limits the usable luminosity. From Fig. 1, we see that the charged particle rate hitting detectors would be about 100/spill using the proposal luminosity (10 times lower than that used to make the figure). This is close to the limit of the a scintillator hodoscope detector system, and higher than in the proposal due to improved simulations with less approximations. The design meets (just barely) all the resolution requirements outlined in TN 7, although this design does have rather uniform acceptance in R_e, so that the mass resolution of 4% means that the acceptance would be to be cut about a factor of two to about 0.25 at 35 GeV, to avoid large BH subtractions. The problem comes in meeting the goal of 200 clean ψ'counts per setting. Taking the proposal goal of 8000 J/ψ/day and scaling by 0.02, we find only 160 ψ'/day. But if we take into account the loss of statistics from the BH subtraction, we should divide this by the f factor of about 7. Another factor of $f = 1.5$ comes from the p_t resolution. So effectively, we are left with only about 16 clean ψ'counts per target, or over a factor of 10 below the physics goal.

How can the design be improved? It seems unlikely that a detector system could be designed to handle 2000 charged particles per 200 nsec beam spill, and to cleanly identify muons when they are only 2% of the tracks. It is not possible to increase the alumina thickness much, because the mass resolution quickly hits the "brick wall" of the J/ψtail. For a fixed limit of 100 charged particles per spill hitting the detectors, and assuming the photon beam intensity can be increased as much as we like, we find the optimal absorber thickness to actually be 3.25 m, optimizing only the statistical error on the ψ'cross section. Unfortunately, this corresponds to a mass resolution of 6%, for which the systematic error on the BH and J/ψtail becomes unacceptably large. And even if it were not a problem, there is only a gain of a factor of four in effective acceptance, so we are still a factor of three below the proposal goal for statistics.

The use of other absorber materials doesn't help, because alumina is already the optimal material (I tried 6 m of carbon and the performance was significantly worse because of increased material after the magnet field). Improving the acceptance is not possible, because the design already has over 50% acceptance at 35 GeV.

One possible solution is to increase the integrated magnetic field, allowing the alumina thickness to be increased while maintaining adequate resolution. The problem encountered with this solution are the huge coils of the LASS dipole, which extend in the beam direction by 85 cm from the yoke. Averaged over the physical length of the magnet (2.8 m), the average B field is only about 10 kG, or 45% of what can ideally be obtained from saturated

Table 3: *For various absorbers, the acceptance, luminosity for 100 particles/spill, and clean ψ'rate for 4 days of running.*

Material	L (m)	Acceptance	Photons/spill	dilution	ψ'/4 day
C	6.0	0.05	1.6E7	5.4	60
Al	5.0	0.09	1.2E7	6.6	60
Al_2O_3	3.5	0.14	2.0E7	5.4	200

iron (23 kG).

I conclude that the only way the proposal design can be modified, assuming the LASS dipole as the main magnet, is to change into a Case II design, with absorber followed by tracking before and after the LASS dipole. This option is studied in the next section.

1.7 Momentum Measurements using Dipole Fields: Case II

We now consider the Case II spectrometer, one where angle is mainly measured by position after an absorber, and momentum is measured in a dipole by the bending radius in vacuum (or helium to be practical). There is really only one dipole large enough at SLAC to be placed after an absorber, and still retain reasonable acceptance: the LASS dipole. Using bosted/jpsi/oldspect.f with lasstest=2, I have calculated the mass resolutions for various absorbers shown as Res (c) in Table 1. I assumed a momentum resolution of $\delta P/P = 0.002P$, corresponding to about 1.5 mm detector granularity in a detector array. To minimize the detector size, it is crucial to put the 29D36 magnet around the front part of the absorber. I assumed it can running at maximum field. To get even better acceptance, I assume a small 50 cm long dipole is place in front of the 29D36 magnet. To maintain reasonable acceptance, I assume there is only one detector before the dipole (hence only a position measurement, no angle), and two after the dipole (measure both position and angle). A front detector is placed a the beginning of the LASS dipole coil, another just after the coil, and another 2 m further down-beam. What can be seen in the Table is that the resolutions are fairly constant at about 4%, and somewhat worse than for the case I design; this is because the angular resolution is worse. A more detailed Monte Carlo simulation of the tracking (see bosted/jspi/spect.f) gives a slightly better resolution of 3.8%. In any case, the resolutions for all materials are (just barely) acceptable, except for copper. The best overall performance comes with the alumina absorber, as can be seen in Table 3, which for various absorbers shows the resolution, acceptance for ψ'at 35 GeV, effective dilution factor, and number approximate number of clean ψ'events in 4 ideal days of running. The luminosity was determined such that there should 100 charged particles/spill hitting the detectors. With the alumina absorber, the $\psi'$is very close to the physics goal, and gives essentially the same performance as the B81 solution. However, many more detector channels are needed for the LASS design, and they must work in a high magnetic field. Thus from a practical point of view, the B81 solution is much easier and less expensive.

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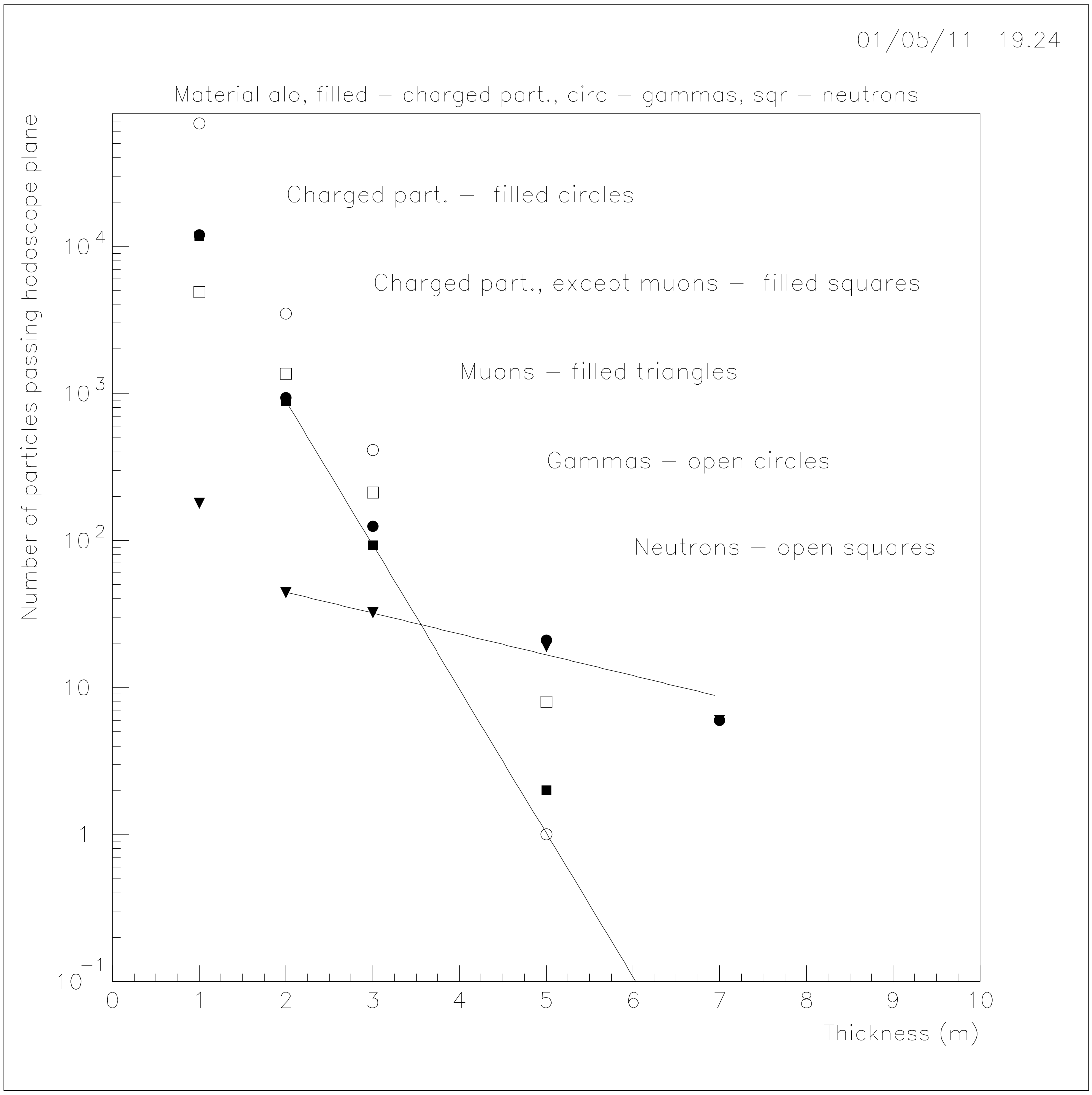

Figure 1: Number of particles of various types emerging from alumina as a function of distance. The input particles come from about 25,000 nuclear interactions with a typical 48.3 GeV endpoint coherent bremsstrahlung spectrum. This figure was made by Piotr Decowski using GEANT.