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Shielding the RadPhi Photon Beam Line

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Abstract

During the brief data-taking periods obtained by RadPhi in 1997 a high background rate was observed in the trigger counters that was not associated with events from the target. Subsequently it was shown that these rates are in good agreement with what is expected for the $e^{\pm}$ halo around an unshielded bremsstrahlung beam. In this report a series of Monte Carlo simulations are presented which test the effectiveness of a variety of shielding schemes for reducing this background. A solution is found which reduced background from the beam halo to a level consistent with running at the rates for which the experiment was designed. This solution fits into the immediate constraints on time and resources for 1998, and is currently being implemented. Possibilities for further improvements are discussed.

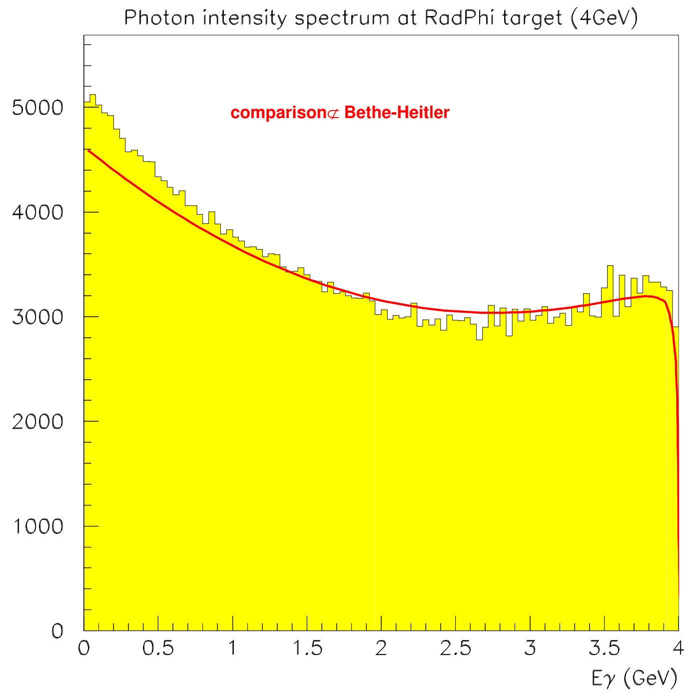

Figure 1: Monte Carlo bremsstrahlung intensity spectrum

Shielding the RadPhi photon beamline is of paramount importance in reducing the background rate in the RadPhi trigger, as was discovered during the brief running period during the summer of 1997. During that running period with no beamline shielding in place between CLAS and RadPhi, moving the target completely out of the beam had very little effect on the rates in the trigger counters. The experiment has been designed in view of total hadronic trigger rates expected to be of order 20kHz [1] at level 1 with $5 \cdot 10^7 s^{-1}$ in the tagger. Scaled according to tagger rates, the level 1 rate in 1997 was two orders of magnitude greater, which would prohibit running at design luminosity. In a previous study [2] presented at the RadPhi collaboration meeting in Sept. 1997, the background was accounted for in terms of electromagnetic halo ($e^{\pm}$ pairs) around the photon beam from conversions in the air and other material upstream of our apparatus. That study was based upon an analytic calculation of the electromagnetic preshower in air. As soon as collimation and shielding are introduced, the analytical problem becomes unwieldy, and Monte Carlo provides a more suitable method of solution. In this report I begin by reproducing the results of the analytic calculation with a GEANT-based Monte Carlo program. I then carry out a series of Monte Carlo experiments with this program, trying different collimation and shielding schemes and comparing the results in terms of background trigger rates. The report concludes with a proposal for a shielding scheme that is both simple and effective.

1 Comparison between Monte Carlo and analytic calculation

Before the two calculations can be compared, one must check that they are based upon the same physical input. In my analytical calculation I approximated the bremsstrahlung spectrum by the function N_0/k with N_0 fixed by the rate in the tagger. The simulation of electron bremsstrahlung in GEANT, based upon the parameterisation of Berger and Seltzer [3], is shown by the histogram in Fig. 1. Photon intensity is defined as the rate times the energy of the photon. Berger and Seltzer go beyond the simple Bethe-Heitler formula (red curve in Fig. 1) to include radiative, screening and Migdal corrections, but the comparison is not bad. The approximation used in the analytic approach would be a rectangular distribution in Fig. 1.

Another important input to the calculations is the bremsstrahlung angular distribution. GEANT uses a parameterisation of the Tsai's formula [4]. It is shown by the histogram in Fig. 2, compared with the simple

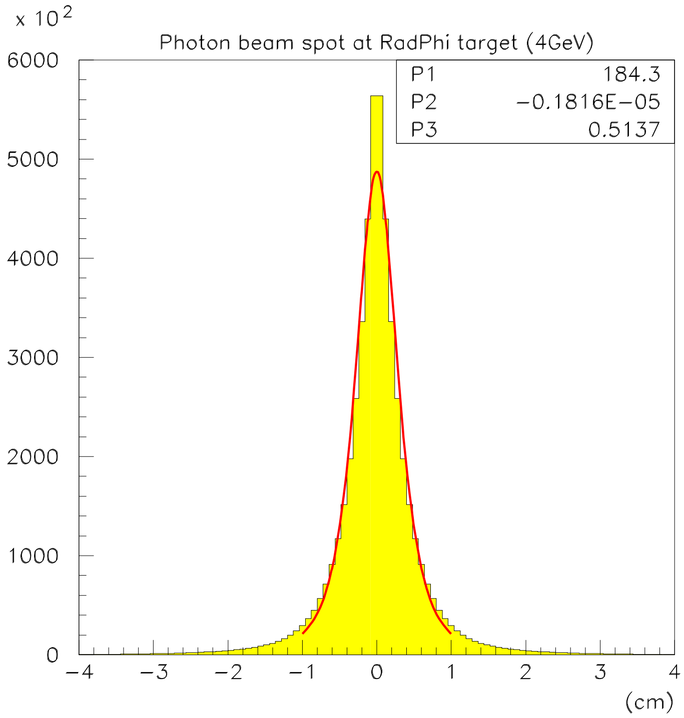

Figure 2: Monte Carlo bremsstrahlung angle distribution

dipole formula (red curve in Fig. 2) used in the analytical calculation.

Similar approximations were used for the pair production distributions in the analytic calculation, where again GEANT incorporates more precise descriptions taken from the literature. In spite of these minor differences, the two calculations can provide a check on each other and on the hypothesis that the background seen by RadPhi in 1997 was primarily due to electromagnetic halo around the beam. To compare the Monte Carlo with the simplified formula, I set up GEANT with a thin (10^{-4} radiation lengths) radiator 40m upstream of the RadPhi target. After travelling inside vacuum for 23.3m the simulated photon beam exited through a 100m mylar window into air, in which it travelled the rest of the way to the target. The $e^{\pm}$ flux in the halo around the photon beam at the RadPhi target position is plotted *vs* distance from the beam axis in Fig. 3. The histogram is the result from GEANT normalised to a tagged rate of 1MHz. The red curve is the analytical result.

There is a good agreement out to about 8cm from the beam axis. At large distances from the beam one would expect multiple scattering processes would begin to be important contribution, in addition to the tails of single-scattering distributions represented by the red curve. Hence it is not surprising that the analytic result is an underestimate at large radii, and we would expect Monte Carlo to give a more accurate description. Because most of the halo is concentrated in the region where the two calculations coincide, the results for the integrated rate for 4cm $< a <$ 50cm agree to within a few percent. One may then ask for the partial rate in the restricted region covered by a pair of RPD $\Delta E - E$ counters. This result can be compared with the data taken during the target-region scans. The most complete scan data set was taken at 1.4GeV during May, 1997. These data are shown in Fig. 4 (points), compared with the Monte Carlo prediction (histogram). Both sets of data are normalised to a tagger rate of 1MHz in Fig. 4.

I conclude that the Monte Carlo results are in good agreement with both the analytic calculation and the experimental data. These checks are important. Ideally one would prefer to check out shielding ideas "on the floor" with beam and high voltage on. Background in a big hall can depend on many factors, and can be notoriously difficult to predict. It would appear from these checks that our dominant backgrounds at present are unsubtle, and that we can rely on a simple beamline Monte Carlo to evaluate shielding schemes, at least for the first order of magnitude reduction in the background. Beyond that we will need more measurements.

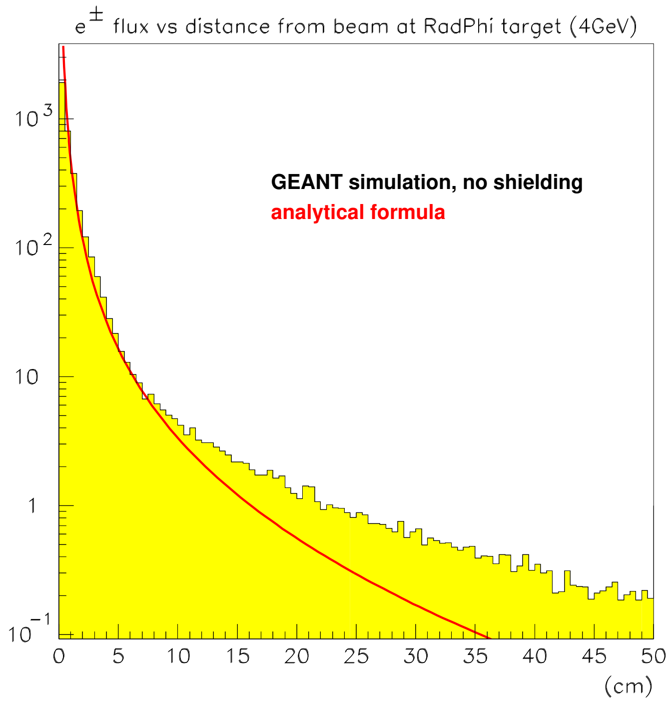

Figure 3: Comparison of charged flux in beam halo between Monte Carlo and analytic calculations

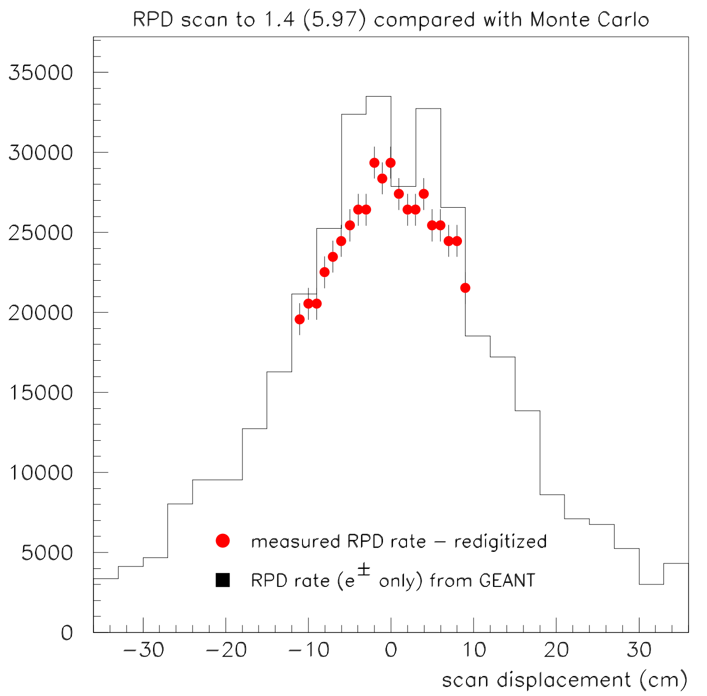

Figure 4: Monte Carlo RPD rate compared with measurement at 1.4GeV

2 Tests of shielding scenarios

In the above mentioned simulation, there was nothing between the bremsstrahlung radiator and RadPhi than a stretch of vacuum, a thin vacuum exit window, and air. As the first step in introducing some reality to the description, I introduce the photon beam collimator assembly and the CLAS magnet yoke, both of which play a role in defining the shape and composition of the beam. The CLAS target full of liquid hydrogen is added next. I then introduce sequentially a series of shielding or collimation ideas, accumulating the ones that are effective in reducing the charged particle rate in the RadPhi apparatus and discarding those which are not. The sequence of configurations is listed below.

1. **only air** (as in 1997, used as baseline for comparison)
   The CLAS magnet yoke is present in this simulation, but there is no CLAS target and no photon beam collimation.

2. **with collimators**
   The photon beam collimation assembly is introduced 7m downstream from the radiator, still in vacuum. A copper collimator 30cm long with a 8mm diameter hole is followed by a pair of sweeping magnets with a gap 4cm wide and 20cm long each. The field is a uniform 5kG between the poles. Following the magnets and 2m downstream from the primary collimator is a secondary one, also 30cm long and made of copper, with a 16mm bore. It serves to block the charged particles swept from the beam by the magnets. Although they do not do much to reduce background in the RadPhi apparatus (see Fig. 6 below), they will be in place during normal CLAS running, and so are retained in the following simulations.

3. **with CLAS target**
   22m downstream from the radiator and still inside vacuum the CLAS target is added. It is 15cm of hydrogen in this simulation and 2.54cm in diameter. The windows are neglected. Since this will normally be present for RadPhi running, it is included from now on.

4. **with helium tube**
   This is the first step to be taken to reduce backgrounds in RadPhi. Helium is present starting immediately after the vacuum exit window inside CLAS, through the CLAS magnet yoke, all the way downstream to the RadPhi target. To leave room for a shielding wall upstream of RadPhi (see next item) the helium tube stops 1.55m upstream of the RadPhi target. There is a 100m mylar window followed by air between the helium and the target. Between the exit from CLAS and RadPhi the helium tube is 25cm in diameter, made from 500μm mylar. The helium tube gives a significant reduction in background in RadPhi, and will be retained in the following simulations.

5. **with lead wall**
   The remaining charged particles in the beam halo must be stopped, either with sweeping magnets or a shielding wall (or both). First I try a shielding wall alone, consisting of 10cm of solid lead (18 radiation lengths). The inner aperture is defined by a circular hole 6cm in diameter. The wall extends out beyond the extent of the RadPhi apparatus in the simulation, but the inner 50cm are the most important for shielding. The lead wall gives a significant improvement in RadPhi backgrounds, and will be retained for the following simulations.

6. **with wall, 8cm hole**
   It is conceivable that some Hall B experiments might be adversely affected by a 6cm aperture in the photon beam at the RadPhi position. A safe number would be 8cm, the same as the diameter of the hole through the lead glass wall. The rates in this configuration are somewhat worse than with a 6cm hole, so this configuration is discarded for the following simulations.

7. **with sweeping magnet following CLAS**
   Part of the background problem is associated with charged particles inside the photon beam, created

inside the CLAS target and thereabouts, which can scatter into the RadPhi acceptance. With the lead wall in place, one does not need a very powerful magnet to deflect the charged particles of all energies far enough to be blocked by the wall. In this simulation I tried a magnet of 0.2T-m (a copy of the sweeps used in the photon beam collimator assembly) just downstream of CLAS. None of the charged particles passing through the magnet made it through the hole in the lead wall. The magnet was assumed to be contained inside the helium volume, without windows in the beam. No significant improvement was observed with the sweeping magnet in place, and so it is not retained in the following simulations.

8. **with extended helium tube**
   With some additional effort, it would be possible to extend the helium tube through the lead wall right up to the RadPhi target. In this simulation the helium tube is joined to the lead wall at both sides, and stops 10cm before the RadPhi target. The background reduction is significant, and is retained below.

9. **without wall, extended helium tube**
   Seeing the background reduction that is obtained simply by extending the helium tube, one might ask if the wall is now redundant. In this simulation the helium tube extends from the vacuum exit window inside CLAS down to 10cm short of the RadPhi target. There is no lead wall. This configuration is significantly worse than the previous one, and so it is discarded.

10. **with small-bore photon collimator**
    The 8mm bore of the smallest primary collimator presently available projects to a diameter of 4.6cm at the position of the RadPhi target. This corresponds to $4.5m/E$ at 4GeV (6.7 at 6GeV) and could be reduced by nearly a factor of 2 without shadowing the RadPhi target. This simulation is done with a 5mm-bore primary collimator to show its effect on the background at RadPhi. The small-bore collimator is retained below.

11. **the clean sweep solution**
    The above test of a sweeping magnet downstream of CLAS assumed the presence of the lead wall to catch the swept particles. If the magnet were sufficiently strong that no charged particles could get out of the magnet and the helium pipe were replaced with vacuum all the way down to RadPhi, one might not need the lead wall. The photon beam would be practically free of pairs. By filling the gap of the sweeping magnet with lead, apart from a 8cm hole for the beam, the pairs trapped in the magnetic field would be absorbed inside the magnet. What would the halo look like under these conditions? The magnet for this test is 2m long with a 12kG uniform field inside the 10cm gap. The helium tube is replaced with a vacuum pipe of the same dimensions all the way down to 10cm short of the RadPhi target. The lead wall is removed.

These simulations are all done with a 4GeV bremsstrahlung beam. The rate is normalised so that there is 1MHz of photons in the range [3.2,3.8]GeV hitting the RadPhi target. Note that this is somewhat lower than the "tagger-OR" rate because of various tagging inefficiencies, including the finite diameter of the RadPhi target (a 10% effect at 4GeV) and the presence of absorbers like the CLAS target in the beam between the tagger and the RadPhi target. The actual photon rate is used in this study because it is the bottom line that must be considered in optimising the performance of the setup. It should be kept in mind, however, that the ceiling of $5 \cdot 10^7$Hz (or thereabouts) applies to the "tagger OR"; the "tagged flux on target" used for normalisation in this study will be limited to a proportionately lower figure.

A view of the geometry description used by GEANT in these simulations is shown in Fig. 5. The figure is a planar slice containing the z axis (points to the right) and the y axis (points up). The horizontal scale has been compressed by a factor of 200 and the vertical scale by a factor of 2. The electron beam entering at the left strikes the radiator (red, far left). Tracking of the electron is abandoned when it exits the radiator, and the simulation carries on with any secondaries (eg. bremsstrahlung photons) generated.

In the event shown in Fig. 5, a single bremsstrahlung photon is produced in the radiator. GEANT draws gamma rays as dotted blue lines and $e^{\pm}$ tracks in red. The photon makes it through the photon beam collimators (two blue apertures inside the black vacuum pipe) but converts to a pair inside the CLAS

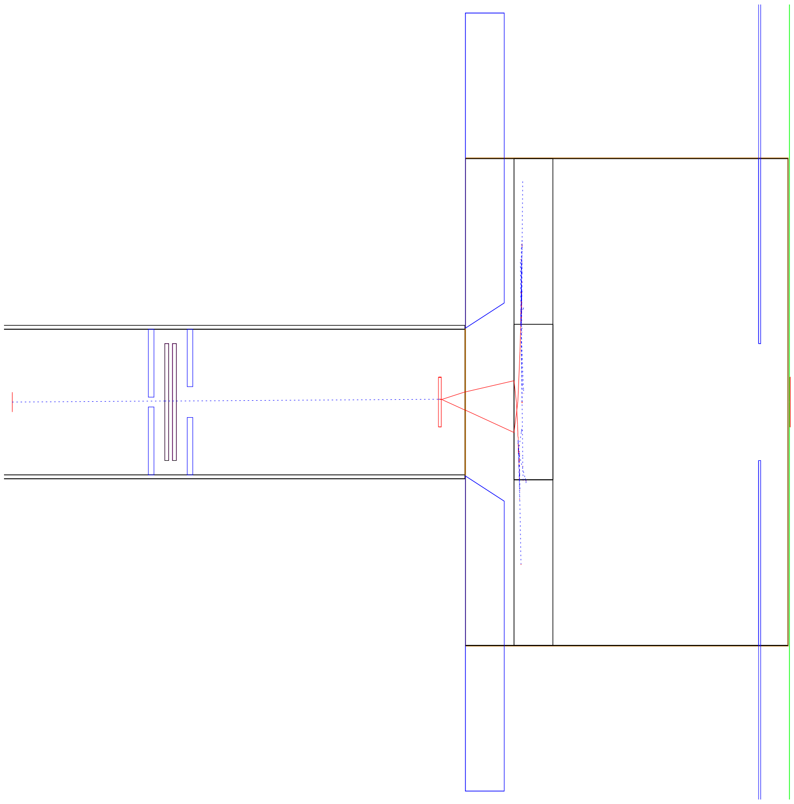

Figure 5: Cutaway view produced by GEANT of the geometry used for simulations (all configurations overlayed).

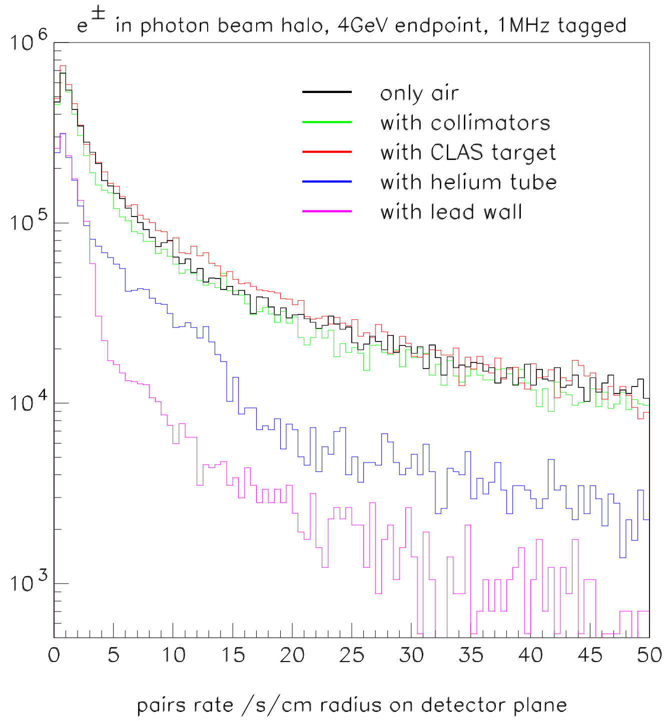

Figure 6: Beam halo profile from Monte Carlo, charged component

target. The opening angle of the pair is a typical value; it looks large in this drawing because of the 100:1 horizontal:vertical aspect ratio. After exiting the vacuum through the window (brown) the electrons pass through the hole in the CLAS magnet yoke (conical hole shown in blue) at which point they are already inside the helium volume. After coming out the back of CLAS they enter a sweeping magnet (2m of 1.2T field) where they are swept into a block of lead and absorbed. This is the **clean sweep** magnet described in item 11 above. If the photon had not converted in the CLAS target it would have continued down the helium pipe (rectangular region in black containing the magnet and appearing to penetrate through the CLAS yoke in this drawing) through the lead wall (heavy lines in blue) to enter the RadPhi apparatus. A few mm upstream of the RadPhi target (green in the figure) is a CPV plane which is used to monitor the halo around the beam. Charged particle and gamma rates are recorded on this plane as a function of energy and distance from the beam axis. Particle tracking (tracing for gammas) is abandoned at a 1MeV cutoff, and their remaining energy deposited at that point.

In the following figures is plotted the radial distribution of $e^{\pm}$ impacts on the CPV (essentially the plane of the target/RPD). Configurations 1-5 are shown in Fig. 6, and 6-9 in Fig. 7 with 1 and 5 included for reference. Configurations 10 and 11 are represented in Fig. 8.

These results are summarised in Tables 1-2. The first column of numbers is the integral of the above histograms over 4-50cm. The second column is the same integral for gammas. Notice that the two have quite different responses to shielding.

It is apparent that these collimation schemes are more effective at reducing the charged halo than the gamma component. While the level 1 trigger is relatively insensitive to gammas, they might have an adverse effect on the resolution and reconstruction efficiency of clusters in the lead-glass. To examine this question, I plot in Fig. 9 the energy spectrum of the gammas incident on the RadPhi target plane in simulation 8 between 4cm and 50cm from the beam axis (320KHz in Table 1).

In this spectrum over 95% of the photons are less than 25MeV, with about 100Hz over the lead-glass threshold of 100MeV. We do not have to be concerned about these photons. The gamma spectrum is harder, however, for configuration 11 shown in Fig. 10 (notice the horizontal scale has changed).

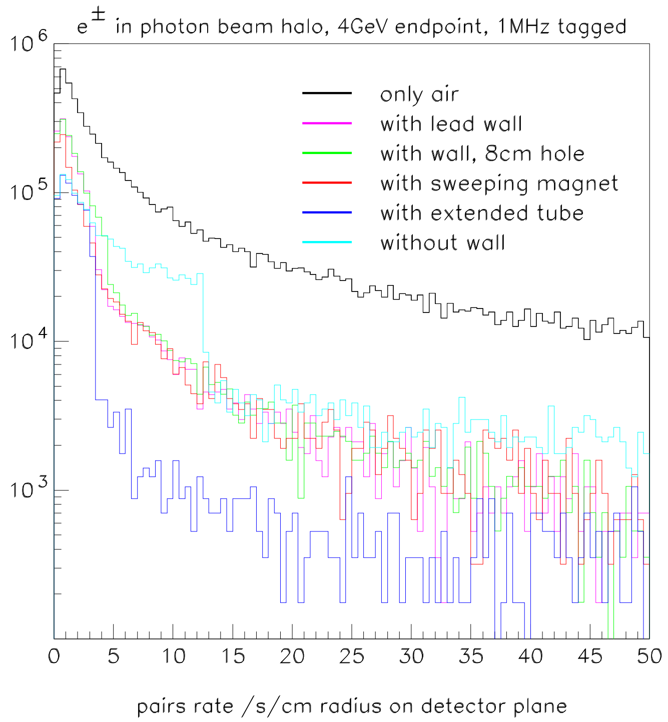

Figure 7: Beam halo profile from Monte Carlo, charged component

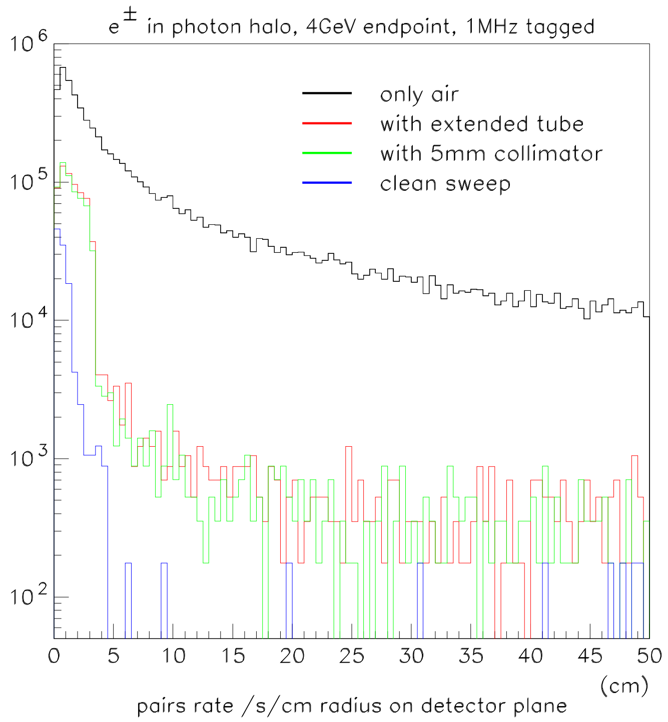

Figure 8: Beam halo profile from Monte Carlo, charged component

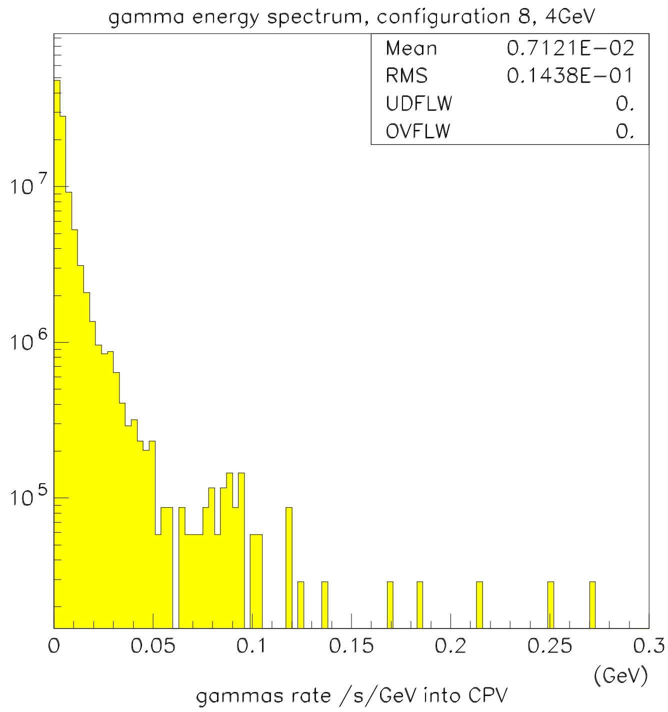

Figure 9: Gamma energy spectrum in halo for simulation 8.

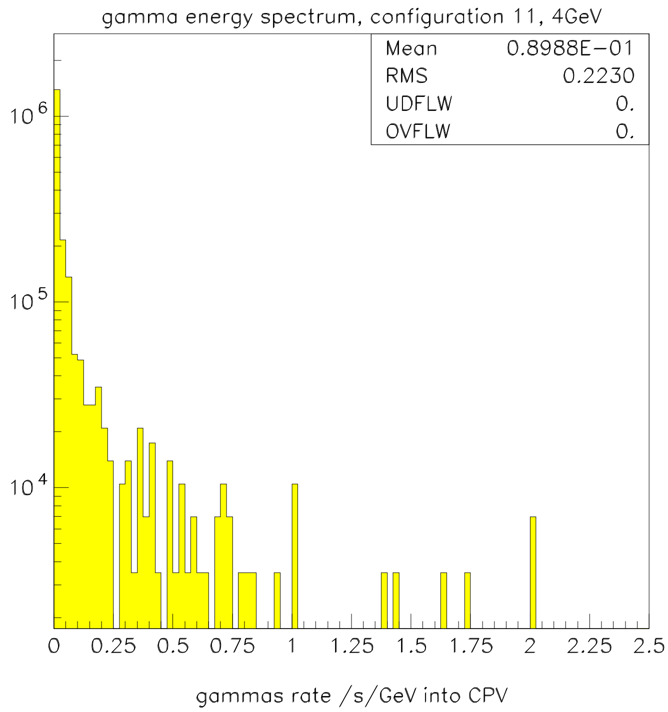

Figure 10: Gamma energy spectrum in halo for simulation 11.

Here the mean photon energy is around 90MeV and the rate above the 100MeV threshold is 9KHz. In this configuration the lead wall is absent and the sweeping magnet is doing the work of shielding. The lead inside the gap of the sweeping magnet is not sufficient to completely absorb the showers and some of the gammas are leaking out into the halo.

3 Conclusions

I discuss the options in decreasing order of lead-time and expense. The **clean sweep** solution comes first. This is a 2m magnet with a gap 10cm thick and 25cm wide running at the saturation field of iron. I have not played with the parameters to see if a smaller size or field would have a comparable effect, except to show that a small magnet of the type used in the collimator assembly is not effective (configuration 7). It is probable that the vacuum pipe diameter used in the **clean sweep** setup could be reduced to 8cm without significantly affecting the halo. It was left the same size as the helium tube to facilitate the comparison. Whatever the optimum arrangement might be, implementation would require (a) vacuum pipe and pump, (b) the magnet and (c) associated equipment such as power supply and plumbing, (d) a moulded piece of lead to fill the gap around the beam pipe, and (e) a mounting scheme that does not interfere with CLAS. The last item may include additional iron to shield CLAS phototubes from the fringe fields of the sweeper. A new source of funding would also need to be found. This is not going to be possible for 1998.

The next solution in decreasing order of lead-time and expense is configuration 10. The critical item here from the engineering point of view is the 5mm collimator. This collimator does produce some useful improvement over the 8mm one that currently exists (used in configuration 8) and is worth having. At 6GeV it will make even more sense, as the 8mm collimator becomes increasingly marginal in its effect. A smaller collimator (4mm for example) begins to cast a shadow on the outside of the RadPhi target, costing us tagged photon flux on target for a given *tagger-OR* rate, so 5mm would be the optimum size at 4 or 6GeV. This comment does not apply in the case that we opt for untagged coherent bremsstrahlung, which requires its own collimation arrangement. The 5mm collimator would enhance whatever shielding arrangement is installed downstream of CLAS, so the subsequent discussion is decoupled from the question of when and if the 5mm collimator becomes available. To a great extent this depends on its usefulness to other hall-B experiments with photons.

The immediate solution for 1998 is clearly configuration 8. Even if we decide later to install a **clean sweep** magnet for 1999 and beyond, the gamma ray background in RadPhi is still unpleasant (500KHz of gammas over 100MeV hit the lead-glass at a tagged flux of $5 \cdot 10^7$) unless the lead wall is in place. Configuration 8 achieves a reduction factor of 50 in the CPV rate from beam halo, relative to 1997 running conditions, a good deal more than the factor 10 which was the goal of this study.

At 1.4GeV in May,1997 the rate of the *RPD-OR* was about 17% of the *tagger-OR*. This number comes from the data shown in Fig. 4, taking into account that the only 1/6 of the RPD azimuth was enabled [5]. Later in the May,1997 run at 4GeV endpoint energy the ratio *RPD-OR / tagger-OR* was about the same, according to the scalers recorded for run 3014. Actually the ratio drifts upward during that run, starting near 15% and ending just under 20%, probably an indication of the instability of the beam during that run period [6]. Normalising the rates to the tagger at fixed momentum bite makes the low-energy beam flux independent of endpoint energy. However the halo is not necessarily invariant, being pulled inward with increased endpoint by the better focus of the beam and at the same time intensified by the increased energy flux in the beam; RadPhi backgrounds could go either way, depending on the details. In July,1997 we had a brief run, this time at 3.2GeV endpoint, where things were apparently more stable [7]. Here the *RPD-OR / tagger-OR* is level at 8% and the *CPV-OR / tagger-OR* is 1.2 and stable. The corresponding numbers from the **only air** simulation at 4GeV are 9% and 120% respectively, where a tagging efficiency (rate of tagged photons hitting the RadPhi target divided by the *tagger-OR*) of 75% has been applied (85% for the tagger itself, and additional 10% losses from photons that miss the target). The prediction for 1998 running at 4GeV endpoint in configuration 8 is 0.2% for *RPD-OR / tagger-OR* and 2.4% for *CPV-OR / tagger-OR* (target-out rates).

At the end of Ref. [2] I showed the evolution of the level 1 trigger rate from background as a function of the *tagger-OR*. In Fig. 11 is shown the same calculation compared with the rates under 1998 (configuration 8) conditions. The level 1 trigger is defined by Eq. 3

$$[RPD\text{-}OR] \cdot NOT[CPV\text{-}OR] \cdot [tagger\text{-}OR]$$

with the coincidence timing parameters given in Table 3. These are actually quite tight given the intrinsic spread in the signals, and represents in my judgement an optimistic projection for 1998. Under these

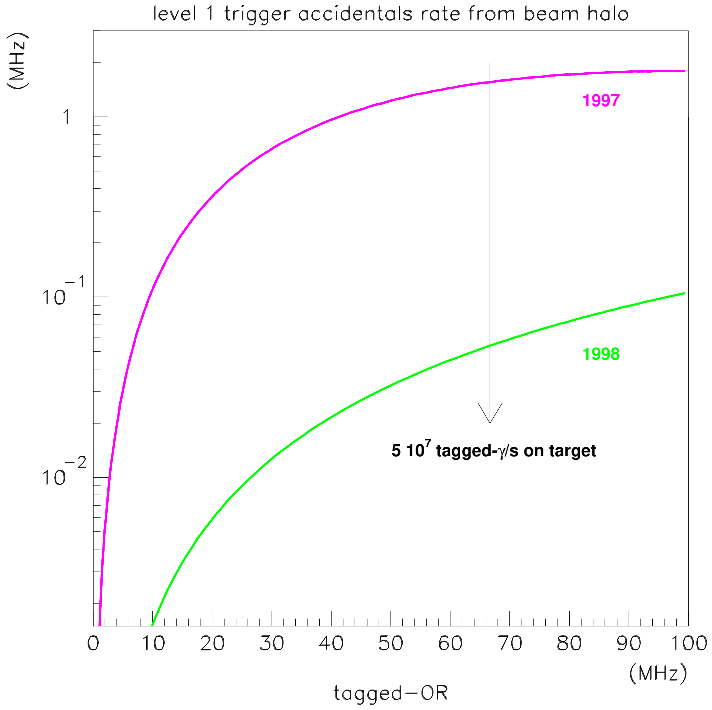

Figure 11: Level 1 accidentals rate vs *tagger-OR*.

conditions the level 1 trigger rate from accidental coincidences is given by Eq. 3

$$\text{accidentals(level 1)} = [RPD\text{-}OR] \cdot e^{-0.015[CPV\text{-}OR]} \cdot \left(1 - e^{-0.008[tagger\text{-}OR]}\right)$$

with all rates in MHz. This function is plotted in Fig. 11, the purple curve for 1997 and the green curve for 1998.

References

[1] "A Pre-Trigger Rate Estimate for E94-016", D.R. Rust, Feb. 29, 1996.

[2] "A Second Look at Rates in the RadPhi Detector", R.T. Jones, presented to the RadPhi collaboration Sept. 28, 1997.

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[4] Y-S. Tsai, Rev. Mod. Phys., **49** p.421 1977.

[5] RadPhi logbook **3.2.97-17.5.97** p.88, bottom table.

[6] RadPhi logbook **17.5.97-28.7.97** p.9ff.

[7] RadPhi logbook **17.5.97-28.7.97** p.67.

Table 1: Summary of halo rates from Monte Carlo

Test #	Setup $E_{beam} = 4\text{GeV}$, $N_{tag} = 10^6/\text{s}$	Charged $E_e > 1\text{MeV}$ $4\text{cm} < R < 50\text{cm}$	Photons $E_\gamma > 1\text{MeV}$ $4\text{cm} < R < 50\text{cm}$
1.	1997: no collimation No CLAS target No helium tube No shield wall	1.7 MHz	1.7 MHz
2.	With collimation (8mm + 16mm) No CLAS target No helium tube No shield wall	1.5 MHz	350 KHz
3.	1998: Collimation (8mm + 16mm) With CLAS target No helium tube No shield wall	1.8 MHz	520 KHz
4.	Collimation (8mm + 16mm) CLAS target With helium tube (25cm diameter) No shield wall	550 KHz	260 KHz
5.	Collimation (8mm + 16mm) CLAS target Helium tube (25cm diameter) With shield wall (6cm hole 10cm thick) No sweeping magnet	160 KHz	380 KHz
6.	Collimation (8mm + 16mm) CLAS target Helium tube (25cm diameter) Shield wall (8cm hole, 10cm thick) No sweeping magnet	190 KHz	290 KHz
7.	Collimation (8mm + 16mm) CLAS target Helium tube (25cm diameter) Shield wall (6cm hole 10cm thick) Sweeping magnet after CLAS	170 KHz	690 KHz
8.	Collimation (8mm + 16mm) CLAS target Helium tube (25cm diameter) Shield wall (6cm hole 10cm thick) (with helium tube extended through the wall to 10cm from target) No sweeping magnet after CLAS	32 KHz	320 KHz

Table 2: Summary of halo rates from Monte Carlo, part II

Test #	Setup $E_{beam} = 4\text{GeV}$, $N_{tag} = 10^6/\text{s}$	Charged $E_e > 1\text{MeV}$ $4\text{cm} < R < 50\text{cm}$	Photons $E_\gamma > 1\text{MeV}$ $4\text{cm} < R < 50\text{cm}$
9.	Collimation (8mm + 16mm) CLAS target Helium tube (25cm diameter, extended to 10cm from target) No shield wall No sweeping magnet after CLAS	400 KHz	230 KHz
10.	Collimation (5mm + 16mm) CLAS target Helium tube (25cm diameter, extended to 10cm from target) Shield wall (6cm hole 10cm thick) No sweeping magnet after CLAS	25 KHz	320 KHz
11.	Collimation (5mm + 16mm) CLAS target Helium tube (25cm diameter, extended to 10cm from target) No shield wall Heavy duty sweeping magnet after CLAS (2m long 12kG field, lead-filled gap)	2.2 KHz	55 KHz

Table 3: Coincidence timing parameters

logic signal	width
RPD-OR	5 ns
CPV-OR	15 ns
tagger-OR	5 ns
minimum overlap	2 ns