BACKGROUND SOURCES AND MASKS FOR MARK II DETECTOR AT PEP*

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I. Introduction: Types of Backgrounds and Their General Character

The shielding masks currently at use in several of the current experiments at PEP are the result of an early (~ 1977) organized effort to understand the sources of particle background expected at PEP, followed by the evolution of the conceptual designs into actual hardware (~ 1978-1979). A designated group commissioned to study backgrounds consisted of: Bill Ash, Al Clark (chairman), John Kadyk, Ed Miller, Pier Oddone, and Ben Shen. The degree and kind of background particle loading which could be tolerated was expected to differ significantly among the different experiments, and several designs emerged from the common study. Qualitatively, the types of radiations studied were: Synchrotron Radiation (SR), Beam Gas Bremsstrahlung (BGB), and, to a limited extent others, e.g. Electroproduction (EP). Calculations will be given of predicted occupancies in the pipe counter and other sensitive elements at small radius, since these will be most susceptible to the SR and BGB backgrounds. The calculations presented in this note are specific to the Mark II detector. (During a one year interval when I was away, George Trilling consented to bear the responsibility for the Mark II masking, for which I am very grateful and indebted.)

Some general statements will be made first about the character of each of the various types of backgrounds considered, then some detailed calculations made for application to the Mark II detector. Figure 1 shows the layout of the PEP ring and straight sections near the Interaction Regions. (We will call the Interaction Regions, abbreviated as IR, the experimental area between the innermost insertion quadrupoles. The center of the luminous region of the colliding beams will be called the Interaction Point or IP). Below is a table giving some of the PEP design parameters. This will be referred to as the "standard" PEP design, or sometimes as "AC*."¹

TABLE I

Some PEP Design Parameters (AC*)

General Machine Parameters:

Beam Energy	E = 15 Gev
Beam Current (3 bunches)	I = 55 ma

MASTER

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$e^{\pm}$ per Bunch	$N = 0.83 \times 10^{12}$
Peak Luminosity	$\mathcal{L}_{\text{max}} = 1.0 \times 10^{32} \text{ sec}^{-1} \text{ cm}^{-2}$
Machine Circumference	$2\pi \langle R \rangle = 2200 \text{ m}$
Beam Collision Frequency	$f = 409 \text{ kHz}$
Synchrotron Radiation Power per Beam	$P_S = 1.46 \text{ MW}$
Installed R.F. Power	$P_{\text{RF}} = 6.0 \text{ MW}$
Transverse Damping Time	$\tau_d = 0.0082 \text{ s}$
Horizontal Tune	$\nu_x = 21.25$
Vertical Tune	$\nu_y = 18.75$
Maximum Tune Shift	$(\Delta\nu)_{\text{max}} = 0.06$
X - Y Coupling Coefficient	$K = 0.26$
Beam Energy Spread	$\delta = \frac{\Delta E}{E} = 0.10\% \text{ (rms)}$
Interaction Point Parameters:	
Horizontal Beta	$\beta_x^* = 2.6 \text{ m}$ Vertical Beta: $\beta_y^* = 0.11$
Horizontal Beam Size (betatron size only)	$\sigma_{x\beta} = 0.60 \text{ mm}$ Vertical: $\sigma_y = 0.030 \text{ mm}$
Momentum Dispersion	$\eta^* = -0.49 \text{ mm}$
Horizontal Beam Size (Total)	$\sigma_{x\text{tot}} = 0.75 \text{ mm}$

A. Synchrotron Radiation (SR) Background

This background results from bending of $e^{\pm}$ beam particles in the magnetic field of: (1) the last dipole magnets before the straight section (principally the lattice or high-field dipole), and (2) the insertion quadrupoles, Q1 and Q2. The background consists of a very large number of low energy photons: there are $\sim 10^{12}$ photons generated by the insertion quads alone, with an average energy of about 2 keV. Photons with energies above an absorptive cut-off value for a given beam pipe material ($\sim 20 \text{ keV}$ for aluminum, $\sim 5 \text{ keV}$ for beryllium) will penetrate the pipe and deposit energy in sensitive elements of the detector by photoelectric absorption and Compton scattering. Since very large numbers of photons are involved, the pulse-to-pulse variation of energy deposit is small, and this results in a relatively sharp turn-on/turn-off level for a detector with a fixed threshold, such as a scintillation counter, or a rather constant-amplitude analogue signal, such as current in a proportional counter. This is to be contrasted with beam-gas events, which occur with "poor statistics" and are characterized by large fluctuations in energy deposit. Some evidence for the characteristics are given in Appendix C.

To be quantitative, the power radiated per meter of path by one $e^{\pm}$ of energy E (GeV) in a field B (Tesla) is:

$$P_{\gamma} \left(\frac{\text{GeV}}{E - m} \right) = 380 E^2 B^2 = 4226 \frac{E^4}{\rho^2},$$

where ρ is the radius of curvature of the $e^{\pm}$ orbit in meters. The average photon energy, $\langle u \rangle$, is simply related to the critical energy, u_c :

$$\langle u \rangle = \frac{8}{15\sqrt{3}} u_c = 0.31 u_c,$$

$$\text{and: } u_c (\text{keV}) = 0.666 E^2 B = 2.22 E^3 / \rho$$

All SR spectra can be scaled from a normalized spectrum in terms of the variable (u/u_c) , u = photon energy (Fig. A-1). The rate of γ emission per unit bend angle is then given by the simple formula:

$$\frac{dN}{d\theta} = \frac{1}{c} P_{\gamma} / \langle u \rangle \approx 20 E (\text{GeV}) \text{ rad}^{-1}$$

The SR is emitted strongly forward along a line tangent to the $e^{\pm}$ trajectory, and inside a cone having the very small half angle $\theta \sim m_e/E$. The radiation so emitted from the last main bending magnet has a critical energy $u_c = 45 \text{ keV}$ ($B = 0.3 \text{ T}$), and a radiated flux of $\sim 1.5 \times 10^{12}$ photons/meter of radiating pathlength, inside a cone of $\sim 0.03 \text{ mrad}$ half angle. Most of this background strikes the walls of the vacuum pipe in the straight section, or is stopped at the 36m or 51m masks. However, there is some SR emitted from the last few centimeters of the orbit in this magnet which escapes past these two masks, and strikes the wall of the vacuum pipe in the vicinity of Q1, Q2 as can be seen in Fig. 2b. If not shielded at this point this becomes a serious source of background. Such a problem was anticipated by the background study group, and was felt to be tractable by shielding locally when and if it occurred 'it did!'. In actual experience with PEP, this background was encountered, and adequately suppressed with a few layers of thin ($\sim 1/E''$) lead sheet around the beam pipe, and over openings in Q1 and Q2. The problem affected only the outermost Mark II elements, the outer muon detector proportional tubes, the photon energies being too low to penetrate further in. The characteristic narrow distribution in energy deposit mentioned earlier was observed (see Appendix C). It was necessary to shield with lead sheet only as far in toward Mark II as the 8.7 m mask, where the SR was stopped. Softer SR from the low-field bend magnets ($u_c = 3 \text{ keV}$) strikes the beam pipe closer to the IP, but is of much lower intensity and is much less penetrating.

The only other sources of SR are the insertion quadrupoles. Because these radiation sources are relatively very close to the detector, shielding

is a much more difficult problem. In fact, this is the major source of potential SR background to the experiment, with nearly 10^{12} photons being radiated toward the detector per collision from these quads, which are located only 10-12 m from the IP.

B. Beam-Gas Bremsstrahlung (BGB)

Collisions between the circulating $e^\pm$ in the stored beams and the residual gas in the vacuum pipe are called beam-gas (BG) collisions. Inelastic BG collisions which result in sufficient energy loss that the scattered electron is no longer in the energy acceptance of PEP ($\Delta E/E \sim 0.5\%$) will be quickly lost. This is the dominant loss mechanism at higher machine energies, and since it usually occurs via a radiative collision, it is called beam-gas bremsstrahlung (BGB). The partial lifetime for this process scales as $\sim 1/P$, where P = residual pressure in the vacuum pipe. For an average pressure of $\sim 10^{-6}$ torr, the partial beam lifetime is a few hours. (See Ref. 2 for calculation of this and other beam loss mechanisms.) Such off-energy scattered beam particles are quickly swept out of the beam in the arcs of PEP, but when occurring in the straight sections (~ 120 m long), the scattered $e^\pm$ continues to travel nearly in its initial direction; i.e., straight along the beam direction, until reaching the insertion quadrupole doublets at $|Z| \sim 10-12$ m. At this point, many of these degraded electrons are "overfocused" and deflected into the beam pipe. In the absence of shielding, the showers resulting would create serious background problems in the Mark II resulting in spurious digitizations in a variety of detector components and intolerably high trigger rates. The γ 's emitted from the BGB collisions generally cause no problems since they continue straight along the beam axis through the detector and out on the opposite side without striking the wall of the vacuum system.

C. Coulomb Scattering (CS)

Elastic or quasi-elastic scattering of the beam by residual gas can result in beam particles having large betatron amplitudes, yet they can still pass through the bending arcs in PEP since they have the full beam energy and are still synchronous with the accelerating rf voltage. They may continue in orbit until their amplitude damps down to more nearly average values, or, if the amplitude is sufficiently large, these scattered $e^\pm$ may strike an aperture limit in the vacuum pipe system. If this happens close to the detector, severe electron shower background can result. Estimates indicate that CS is important in determining beam lifetimes at lower energies (it is comparable to BGB at 5 GeV),

but that it is not a large component of beam loss at high energies ($\tau_{CS} \sim 50$ hours at $E = 15$ GeV). The CS partial beam lifetime scales as $\sim E^2/P$. Although beam lifetime is not dominated by CS at PEP, there is evidence that background from electron showers caused by this mechanism can play a prominent role.^{3,4} At present, shower background is tolerable for the Mark II detector, being noticeable in only a few percent of the genuine events of interest and resulting in a trigger rate $\lesssim 2$ Hz.* However, it could increase to an unacceptable level if beam currents were increased substantially in achieving higher luminosities. If this were to occur, it is likely that the background from the CS mechanism can be controlled by installing movable beam scrapers at one or more positions around the PEP ring, the "halo" induced by CS being stopped by a scraper sufficiently far from the detectors.

D. Other Machine-Produced Backgrounds

Other mechanisms of various kinds also are potential causes of backgrounds: (1) Electroproduction near the IP: BG events near $\theta_Z = 0$ which create valid triggers from the large-angle charged secondary particles (usually hadrons) which result. (2) Beam "burps": simultaneous loss of a large number of beam particles, presumably due to some beam instability or power transient. (3) Electrical noise pickup: most often (?) due to ultra high frequency rf generated by the short (~ 4 cm) beam bunches passing by a discontinuity in beam pipe cross section. (1) is largely unavoidable once the pressure in the IR has been reduced as much as possible, and it usually can be eliminated in the analysis stage by appropriate cuts on the data (e.g., total energy). Normally this is not considered to be a serious problem, but one which must be reckoned with. (2) Beam burps cause a large fraction of the Mark II components to "light up," making these events easy to recognize and dispose of. Fortunately, they occur relatively rarely, and therefore are not a serious problem. (3) Electrical noise was a considerable problem at SPEAR, caused principally by rf noise induced by passage of beam bunches, and manifested by spurious signals in the drift chamber and liquid argon preamplifiers. Although design peak beam currents are ~ 10 times larger at PEP than at SPEAR, there has been no problem encountered due to this effect. This is perhaps because the preamplifier boxes were rebuilt and repositioned to help minimize rf pickup when Mark II was moved to PEP, and the central beam pipe was changed from the thin stainless steel corrugated tube, relatively transparent to rf radiation, to a pipe of aluminum with

*In essence, the present Mark II charged particle trigger requires at least four out of seven wire layers, distributed throughout the sixteen total drift chamber cylindrical layers, have a digitization, plus two tracks digitize at least through the 10th layer, subtending a minimum angle of 36° and be found by the secondary trigger logic. The neutral trigger rate is comparatively small ($\sim 0.1 - 0.2$ Hz).

2 mm wall thickness. Some electrical noise was experienced also from switching (SCR's) in dc power supplies at SPEAR, but no such problems have been seen at PEP.

These last three backgrounds will not be further discussed. The other mechanisms will now be examined in more detail.

II. BACKGROUND CALCULATIONS AND MASK DESIGN (AC*)

A. Philosophy of Mask Design

The principal backgrounds that must be suppressed by the masking system are SR and BG. These are fundamentally quite different types of backgrounds, but some common techniques may be used in the efforts to suppress them. First, the attenuation is typically quite large for each scatter or incidence of a SR photon or of a degraded BGB electron upon a surface. For example, reflectivities of a few percent are typical at the energies of the SR encountered. Thus, the larger the number of "bounces" or interactions which the background radiation must execute before entering the sensitive region, the larger the attenuation. The philosophy adopted was that at least two interactions should be required by the mask geometry. Second, the scatter or interaction generally results in more or less isotropic secondary radiation, so that minimizing the solid angle from the scattering source to the detector components can result in a great reduction in background. This suggests that the scattering or interaction sources, i.e., the masks, be kept as far from the sensitive components as possible. In this regard, some experience exists elsewhere wherein dense masks were placed well within one meter of the IP, and these turned out to be very serious background sources. Another principle should be adhered to with regard to electron showers: a small amount (~ few radiation lengths) of masking material can do far more harm than no mask at all, serving only to develop the shower from perhaps a single $e^\pm$ to a large cascade of many $e^\pm$. Therefore, masks for suppressing showers should be many (~ 30-40) radiation lengths thick to do an effective job, and should have the minimum physical thickness consistent with this, i.e., it should be made of dense and high-Z material. The reason for this latter advice is that most "leakage" from masks is due to "edge scattering," which is proportional to the mask thickness. Materials which are good in these respects are tungsten, uranium and tantalum, though only the latter is considered acceptable inside the PEP vacuum system. Lead, although having high Z, is somewhat lacking in density and is also not good in vacuo.

B. Geometry

The studies of the SR and BGB backgrounds resulted in conceptual scheme involving only two types of masks: (1) a mask near $|Z| = 9\text{ m}$ to stop the residual SR from the last lattice dipole, and (2) a mask near $|Z| = 3\text{ m}$ to stop degraded electrons from BGB and further collimate the SR. The 9 m mask need only be thin to stop SR, but since it intercepts a substantial flux of BG electrons, it should have adequate thickness (in X_0 's) to stop electron showers as well. The mask near $|Z| = 3\text{ m}$ is conceptually as shown schematically in Fig. 3 (the "Miller" design in the Mark II case). Here there is a "plug" of 30-40 X_0 of dense material with a circular aperture extending to small radius, 29 mm in the present instance (vertical beam-stay-clear). To this plug is attached a "snout" nearly a meter long, which is intended for shielding the detector against the "spray" of radiation off the inner edge of the plug. This scheme satisfies the criterion for two "bounces" before radiation can penetrate the beam pipe and enter the detector proper.

As might be expected, such an idealized design was not practical, given the engineering difficulties and the constraints of time, money and the vacuum system. It evolved into the actual design shown schematically in Fig. 4. Here, the plug has been approximated by a series of external lead and tungsten absorbers, narrowing finally to a throat of tantalum inside the vacuum pipe surrounded by tungsten outside. The snout was replaced by layers of lead sheet ($\sim 3/8$ " thick) wrapped around the "outer cone" (Figs. 4, 6). Most of the features of the conceptual design are kept in the practical design, including the criteria for at least two γ interactions, and adequate thickness of dense material.

The mask at $|Z| \sim 9\text{ m}$, shown in Fig. 7, has a rectangular aperture at beam-stay-clear both vertically and horizontally, and the walls are lined with tantalum plates (3 mm on sides, and 6 mm top and bottom). These Ta liners are 15 cm thick along Z, corresponding to about 38 X_0 , and they are in good thermal contact with the copper body which has provision for water cooling. This is insurance against the (remote) possibility that the higher-order-mode power generated by the tapering cross section of the mask should be all absorbed locally (~ 100 watts at design beam current). There is a 3 mm Cu wall containing the vacuum, and immediately outside in the horizontal plane are lead blocks extending outwards an additional 2" on each side. This mask is intended to stop both SR and degraded electrons, and shadows the 3 m mask in both vertical and horizontal planes from direct hits by beam electrons (see phase-space diagrams and discussion in Section IIE). In addition, the 3 m mask shadows the beam pipe inside the detector from a direct

path to 9m mask which is a "hot" shower source. Increasing somewhat the diameter of the 3m mask would allow background from the 9m mask to strike the 7" diameter Mark II beam pipe, while decreasing it would result in more SR backscattering from the opposite side mask (see next section), and would also violate beam-stay-clear. Thus, the 3m mask is approximately optimized. The 9m mask stops the SR from the last lattice dipole, and referring to Figs. 2, 4 and 5 the lead sheeting mentioned earlier wrapped around the beam pipe between the 9m mask and Q1 attenuated the SR striking the beam pipe upstream of this mask.

Given in Table II are the locations and aperture sizes of the masks, central beam pipe and some other important aperture limits. Also given are the energy depositions due to SR photons striking these apertures, as well as BGB electron hits per beam bunch. These quantities are determined as described in next two sections.

C. Calculations of Synchrotron Radiation from Q1,Q2

An estimate will be made in this section of the effect of SR generated by the insertion quadrupole magnets. The flux, average energy and direction of the radiation generated clearly depends sensitively on the PEP configuration (e.g., beam size, quad. strengths, etc.) and beam energy, while the amount of SR detected depends on the local geometry (masks, beam pipes, detector locations, and the relative solid angles between these) and the properties of the materials (reflectivity, transmittance for SR photons).

What has been done is to make use of a computer simulation⁵ of the SR process in Q1 and Q2, given the strengths of these elements and the beam phase space entering Q2 (going toward the IP). Moreover, the actual geometry of the vacuum and masking system is also used by this program to calculate both the number and energy distribution of SR photons striking the apertures (masks, beam pipes, etc.) in the vacuum pipe system in the IR. The next step is to calculate the scattered or reflected flux re-radiated toward sensitive detector components. The final step is to compute what flux actually is absorbed in an element, in our case the pipe counter or vertex detector, after scattering once more (or possibly penetrating) the beam pipe near $|Z| = 0$. These last two computations have been done by hand.

Since the field varies linearly with radius in the quads, and is zero on axis, the amount and energy of SR depends rather critically on the beam phase space, and the centering of the beam on the magnetic axis. The ratio of vertical

Table II. Masks: Locations, Apertures, and Incident Backgrounds ($K = 0.30$)

Mask or pipe	Z location	X-Aperture (mm)	Y-Aperture (mm)	SR energy (keV/bunch)	BGB hits/bunch
9 m mask	-8.685	± 33	± 74	1.505×10^5	304×10^{-3}
	-8.007	± 75	± 75	0	1.3 ↓
	-5.588	± 60	± 60	0	36.
	-4.635	± 48	± 48	5×10^{-4}	0
	-3.315	± 38	± 38	1.94×10^3	197.
3 m mask	-3.027	± 31	± 31	4.87×10^6	73.
	-2.904	± 30	± 30	5.03×10^6	16.
	-2.781	± 29	± 29	1.254×10^7	22.
	-2.600	± 29	± 29	2.08×10^6	6.2
	-1.600	± 149	± 149	0	0
Central	-0.780	± 85	± 85	0	0
bear	0	± 90	± 90	0	0
pipe	+0.780	± 85	± 85	0	0
	+1.600	± 149	± 149	0	0
	+2.600	± 29	± 29	8.98×10^6	231.
	+2.781	± 29	± 29	1.27×10^8	8.8
	+2.904	± 30	± 30	0	-
3 m mask	+3.027	± 31	± 31	0	-
	+3.315	± 38	± 38	0	-
	+4.635	± 48	± 48	0	-
	+5.588	± 60	± 60	0	-
	+8.007	± 75	± 75	0	-
9 m mask	+8.685	± 33	± 74	3.11×10^9	-

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and horizontal beam size is determined by the coupling parameter, $K = \frac{\sigma_y}{\sigma_x} \sqrt{\frac{\beta_x}{\beta_y}}$, where $\sigma_{x,y}$ are the beam sizes, and $\beta_{x,y}$ are the betatron values. Assuming the beam envelope to be gaussian and well-centered, most of the SR is due to beam particles of $\sim 1-2\sigma$ displacement. However these photons do not strike anything, since the maximum angular divergence corresponding to 1σ at Q1 in the vertical (y) plane is only 0.30 mrad for $K = 0.25$, approximately the design coupling. At the 3m mask on the other side of the IP from the Q1 source, a displacement of only 4.1mm of these photons occurs, compared with a mask radius of 29mm, which is the narrowest vacuum pipe restriction. Clearly only beam particles having many σ , and/or much larger coupling can result in SR photons scattering on this mask. It is, in fact, backscattering from the downstream 3m mask that contributes most of the SR background, as can be seen from Table II. The fact that much more SR strikes the downstream than the upstream mask is explained by the greater distance from the sources Q1 and Q2 in which spreading occurs. It is known that the coupling K effectively increases towards unity in the "tails" of the beam particle distribution (for $\approx 5\sigma$), implying that the population is non-gaussian (this may well be due to dominance in this halo region by Coulomb scatters). As an example of the sensitivity to K, the ratio of SR photons striking the downstream 3m mask for $K = 1.0$ and $r = 0.25$ is about 120, and this comes from the 3σ to 5σ beam population mostly. Since the beam size is $\sigma_x(Q2) \approx 1.3\text{mm}$ and $\sigma_y(Q1) \approx 2.7\text{mm}$ for $K = 0.25$, it is apparent that steering off the magnetic center by a few mm can lead to very large SR background increases.

The next step in the SR background estimate is to determine the "reflectivity" of the materials struck by the largest flux of SR. From Table II, this is flux striking the downstream 3m mask, and the thin (0.005" thick) aluminum high-order-mode (h.o.m.) screen (see Fig. 6). We will need the reflectivity of both aluminum and tantalum.* There are, in general, three processes contributing to photon backscattering: 1) Compton scattering, 2) Rayleigh scattering, and 3) fluorescence. Only the first two of these play a role in the case of Al, since the photoelectric absorption edges are at very low energies for this material (K edge is $\sim 1.5\text{ keV}$). Moreover, the photoelectric absorption cross section is such that the screen is nearly transparent to photons above 20 keV energy, but is opaque to photons below this energy; this is also true of the 2mm thick central beam pipe. The screen will be a very important scattering source when we consider (in a later note) the replacement of the Al by a beryllium beam

*Part of the 3m mask is tungsten ($Z = 74$), but tantalum ($Z = 73$) is taken for both parts as a sufficiently good approximation.

pipe, since Be transmits photons very well down to 5 keV. In Fig. 8 is shown the incident flux, reflectivity,* and reflected flux for the Al h.o.m. screen.

There is in the case of Ta the additional emission of fluorescence photons when above the K-edge (67 keV) or L-edge (9.9 keV). There is a 5-fold increase in cross section at the K edge, and about 80% of this is for re-radiated fluorescence photons, varying from 56 keV up to 67 keV. The K-L transitions leave the L shell vacant, and so subsequently 9-12 keV photons are emitted also due to L shell transitions. About 80% of the K level transitions are K-L. In Appendix A, Table A-II is summarized the various cross sections in Ta in barns/atom vs photon energy, and an explanation is given illustrating the calculations of reflectivity and reflected fluxes. The cross-section data was taken from tables compiled by Israel and Storm.⁶ The results are also summarized in Fig. 9.

The final calculational step is now to follow the backscattered radiation to the nearest detecting element of the Mark II, which is the pipe counter, a set of two concentric scintillation counters surrounding the beam pipe. Since the downstream 3m mask dominates the SR scattering, and this is only a first-order estimate, we will calculate only this contribution, and remember to double the final result, since we have so far calculated only one of the two colliding bunches. For this purpose the solid angle from the 3m masks to the central beam pipe is needed, as well as the result of transmission through or scattering in this 2mm Al pipe wall, and finally the amount of photon absorption in the pipe counter scintillators, all as a function of photon energy. The scattered radiation is essentially isotropic at these energies for all important processes, and background fluxes are proportional to the respective solid angles subtended.

Referring to Figs. 4 and 5, we calculate next the solid angle of the Al beam pipe adjacent to the pipe counter as seen from the face of the 3m mask, the backscattering source. For this purpose, the same length of beam pipe as pipe counter is taken, viz., 32". It will turn out that virtually no photons can penetrate the beam pipe without interacting; therefore it is the solid angle of this segment of the beam pipe, not that of the pipe counter itself, which is relevant. Within the precision of this estimate, this is computed simply as the solid angle subtended from a point on the beam axis at the distance of the front of the mask, $|z| = 2.60m$:

$$\frac{1}{4\pi}(\Delta\Omega) = \frac{1}{2}(\cos \theta_1 - \cos \theta_2) ,$$

*Reflectivity was calculated using Ref. 6 for σ_{Compton} , σ_{Rayleigh} , and $\sigma_{\text{photoelectric}}$, and $r = \frac{\sigma_{\text{Compton}} + \sigma_{\text{Rayleigh}} + \sigma_{\text{fluorescence}}}{2\sigma_{\text{total}}}$. See Appendix A.

where θ_1, θ_2 are the angles of the ends of the beam pipe segment at $Z = 2.60$ m. Since the pipe radius is $3.5" = 88.9$ mm:

$$\tan \theta_1 = \frac{0.0889}{2.60 + 0.405}, \quad \theta_1 = 1.69^\circ$$

$$\tan \theta_2 = \frac{0.0889}{2.60 - 0.405}, \quad \theta_2 = 2.32^\circ$$

$$\frac{1}{4\pi}(\Delta\Omega) = 1.91 \times 10^{-4} \text{ sr}$$

There are, of course, photons which scatter in this segment and miss the pipe counter, decreasing the occupancy in this counter. However, photons will also scatter in the pipe wall (or other materials such as flanges) outside this segment and find their way to the counter, increasing the occupancy. These effects tend to cancel; they are neglected for the present estimate.

In Table A-III is given the final calculation of energy deposit in the inner pipe counter, taking fluxes incident on the Al beam pipe from Tables A-I and A-II for the scattering from the h.o.m. screen and Ta mask, respectively. It should be noted that the screen reflects a considerably larger flux than the Ta mask, especially at lower energies. This is principally because of the much larger area struck, nearly 10 times larger for the screen. After integrations over the scatter point in the Al wall and the scatter angle, the transmission, T , for the Al wall is found. The rather complicated double integration reduces, because of the small slant angle (2°) and resulting large scatter probability of the incident γ , to*

$$T = \int_0^1 e^{-(\mu d/Z)} dZ, \quad ,$$

with $Z = \cos \varphi$, φ = angle of scattered γ with respect to the normal, d = wall thickness = 2 mm, and $\mu(E_\gamma)$ = attenuation coefficient for Al. This integral was evaluated numerically at each E_γ . Allowance was made for the γ scattering away from the adjacent scintillator, crossing the pipe diameter, and having a chance to penetrate through the pipe wall and enter the scintillator on the opposite side. However, this problem was approximated in two-dimensions, taking sets of planes of Al and scintillator rather than cylindrical geometry. This is expected to result in an upper limit on the energy deposited. Note that at low energies T is "zero"; because of the large attenuation, the scattering occurs very near the inside surface, and then cannot penetrate the 2 mm wall even at angles close to normal. Above 20 keV this attenuation drops rapidly. For the

*This is equivalent to π scatter on the inside surface of beam pipe.

scintillator, the average slant factor ($\frac{1}{(\cos \phi)} \approx 2$) was used; at energies where there is appreciable flux reaching the inner scintillator, the transmission through the scintillator is 70%-80%, so the outer scintillator receives nearly the full flux. The fraction of energies scattered out (via γ 's) or absorbed (via atomic electrons) as represented by f^S and f^A were obtained from Ref. 6, as were cross sections and attenuation coefficients, μ .

The final result for this AC* configuration is that about 150 keV per bunch or 300 keV per two colliding bunches is deposited in each scintillator. This is about 23% of the 1.3 MeV deposited by a minimum ionizing charged track traversing the scintillator normal to the surface. The discriminator threshold setting for a counter of this type is set low, so the counter may be at the verge of being turned "full-on" (100% occupancy) with a 200-keV signal. Since this results from many photons, the fluctuations are expected to be small, and the turn-on very abrupt. Although the calculations have emphasized energy deposit rather than numbers of photons it is clear from the illustration how the latter may be estimated, the only complication being in treating fluorescence where more than one photon can be emitted per photoabsorption event (this will be important for the Mark II Vertex Detector to be installed soon where each photon can digitize).

It should perhaps be mentioned that some but not all of the physical processes involved in these calculations exist in the EGS program,⁷ popularly used for shower calculations. An example of an important process not treated presently in EGS is the Rayleigh or coherent scattering, which is especially important for high Z materials at low energies. Here it dominates the reflectivity at energies below the K and L edges. This can be seen in Table A-II. Fluorescence is treated in EGS for K-shell absorption in an approximate way (see p. 2.15-3 of Ref. 7), and is not treated for other levels.

D. Calculations of Beam-Gas Bremsstrahlung

As in the case of SR background discussed in the previous section, an estimate is made here based on a computer model of the background production in PEP and the distribution of the background hits on various masks, followed by analysis of energy deposit in the pipe counter resulting from the electron showers which result in the masks. For the first step, Refs. 8 and 9 were used. W. Ash has summarized the essential procedures at this stage in his note PTM-108,⁸ which is agreement with the results from the DECAY TURTLE⁹ program used in the present estimate for matters of convenience and precise mask geometry definition. The next step involves the analysis of the showers created of the beam-gas degraded

$e^{\pm}$ which are swept into the masks by the overfocusing of quadrupoles Q1 and Q2. The objective here is to estimate the residual flux of photons and electrons which emanates from the 3m mask due to incomplete extinction of the showers: this is inevitable because of the "edge scattering" on a finite length of inner surface of the mask. For this purpose, a set of shower curves have been developed to parametrize showers in terms of the impact parameter of the electron from the inner edge of the mask. These curves are given and described in Appendix B, and are based on a set of computer runs using the EGS program.⁷ A thickness of about $30 X_0$ of tantalum was used for the mask, a length which is necessary to reduce the direct punch-through to a small amount (region 3 in curves). Then, since the backscattering is also small (region 1), the dominant contribution to this form of background is from partially attenuated showers which re-emerge on the inside surface (region 4), the so-called "edge scattering." This is perhaps best seen in Fig. B-4 where the total emitted radiation (energy or number of photon are separately plotted) is plotted vs the impact parameter of the incident (degraded beam) electron. Note here that the impact point must be ≈ 3.5 cm in from the edge before the edge scattering radiation is comparable with punch through and backscattering. Except for very small impact parameters, the residual radiation in all regions is essentially all low energy ($\sim 1-3$ MeV) photons (Fig. A-1), and the flux is not strongly directional (Fig. B-2). It was found that the fluxes all approximately scaled with the incident electron energy, and the curves have been so normalized.

The term "occupancy" is used to specify with what probability a region will receive a background radiation signal or $e^{\pm}$ hit per beam crossing, and this is estimated by the DECAY TURTLE program. The shower curves of Appendix B will then give an estimate of the photon flux emitted in the direction of the pipe counter, and with the known solid angle, the flux striking this counter. The average angle of incidence on the beam pipe is 2.6° for photons directed toward the pipe counter, and for the 1-3 MeV range of interest, the transmission probability is about 50%-60%. The average energy deposited subsequently in the scintillator is $\sim 1/3$ of the incident energy. A sample calculation is given here as an illustration. The center of the front face of the 3m mask is taken as the background source point on beam axis, and tables of Ref. 6 are used for cross sections:

$$\begin{aligned} \text{Inner pipe counter: } \theta_1 &= \tan^{-1} \frac{0.108 \text{ m}}{2.60 \text{ m} + 0.406 \text{ m}} = 2.06^{\circ} \text{ (far end)} \\ (32'' \text{ long } \times & \\ 8\frac{1}{2}'' \text{ diam.}) & \quad \theta_2 = \tan^{-1} \frac{0.108 \text{ m}}{2.60 \text{ m} - 0.406 \text{ m}} = 2.82^{\circ} \text{ (near end)} \\ & \quad (\Delta\Omega/4\pi) = 2.8 \times 10^{-4} \end{aligned}$$

Outer pipe counter: $\theta_1 = \tan^{-1} \frac{0.127 \text{ m}}{2.60 \text{ m} + 0.406 \text{ m}} = 2.42^\circ$ (far end)
 (32" long x
 10" diam.) $\theta_2 = \tan^{-1} \frac{0.127 \text{ m}}{2.60 \text{ m} - 0.406 \text{ m}} = 3.31^\circ$ (near end)
 $(\Delta\Omega/4\pi) = 3.9 \times 10^{-4}$

$\varphi_0 = \text{ave. } \gamma \text{ incident angle} = 2.65^\circ$

$d = \text{beam pipe wall thickness} = 2 \text{ mm}$

E_γ	$\mu(\text{Al}), \frac{\text{cm}^2}{\text{g}}$	$\exp[-\mu(\text{Al})d/\sin \varphi_0]$	$\sigma_{\text{tot}}(\text{CH}_{1.1}), \frac{\text{b}}{\text{at.}}$	$f^A(\text{CH}_{1.1})$	$\mu(\text{CH}_{1.1})/\sigma_{\text{tot}}$
1 MeV	0.061	0.49	1.48	0.44	0.070
3 MeV	0.036	0.66	0.82	0.59	0.033

E_γ	$1 - e^{-\mu_0/\sin \varphi_0}$	(Transmission in Al) x (Scatter in CH	Energy deposit
1 MeV	0.63	0.31	$0.347 \times 1 \text{ MeV}$
3 MeV	0.42	0.28	$0.333 \times 3 \text{ MeV}$

Here μ is the attenuation coefficient, and f^A is the energy fraction absorbed.

Next, let us find the occupancy and average incident particle energy. From Fig. 3 of Ref. 8 and Table II (or from DECAY TURTLE) we find the average energy of $e^\pm$ striking masks in the vicinity of the detector as $\langle P' \rangle/P \sim 0.4$, $\langle P' \rangle =$ degraded electron energy $\sim 6 \text{ GeV}$. In spite of the broad angular distribution of shower background flux, it is still much stronger ($10-20\times$) in the forward than backward directions, and only the former is used. Looking at Table II we see the numbers of upstream hits on various mask apertures for a fixed 20,000 BGB events generated between 80.2 m and 1.80 m from the IP, a total of 78.4 π . Of this distance, only the pathlength up to Q1 (center at 11 m) can contribute, so we should renormalize to 69.2 m, or 17,653 events. All hits in the upstream 3 m mask area are used, up to $Z = 5.6 \text{ m}$, since this entire length is visible to the pipe counter: there are 1078 hits, or 6.1% of the total events. To convert this to occupancy, we need to know the actual number of BGB events per beam crossing. The total number of BGB events per bunch crossing is:

$$N_{\text{BGB}} = N_b (69.2 \text{ m} / X_0(\text{m})) \ln \frac{E'_{\text{max}}}{E'_{\text{min}}}$$

The residual gas is usually thought to be mostly CO, which has $X_0 = 37.9 \text{ g/cm}^2$, or at a standardized pressure of $\sim 5 \times 10^{-9} \text{ torr}$, $X_0 = 4.61 \times 10^{13} \text{ m}$. N_b (Table I) = $0.83 \times 10^{12}/\text{bunch}$, and for the computer runs $E'_{\text{max}} = E$, $E'_{\text{min}} = 0.01 E$, and $N_{\text{BGB}} = 5.74$. Using the 6.1% of total BGB events which strike the upstream 3 m mask gives an occupancy per bunch of 0.35, or 0.70 per crossing because of the two bunches.

Next it is necessary to estimate the residual photon shower flux, given that, on the average, 6 GeV $e^{\pm}$ strike the mask. Here, as distinct from the SR background situation, we want the number of photons rather than total energy, since BGB is a case of low photon statistics, but relatively high trigger probability per photon. The number of hits (in the run with 1078 total hits) on each of six steps in the upstream 3m mask are tabulated, along with the average impact parameter (half of radial step size), and the scattered flux (region 4, edge scattering) taken from Fig. A-2. The last three entries are quite uncertain due to the small impact parameter.

$z(m)$	$\overline{\Delta r}(cm)$	N_{hits}	$\frac{1}{E} \frac{dN_Y}{d\Omega}$	$\left(\frac{dN}{4\pi}\right)$	N_Y
5.59	0.72	111	7	0.34×10^{-4}	2.0
3.32	1.12	607	2.4	1.6	17.6
3.03	0.34	225	20	2.1	71.2
2.90	0.05	48	~ 200	2.4	173.7
2.78	0.06	68	~ 200	2.7	276.3
2.60	0.02	19	~ 200	3.35	96.0
					<u>637.4</u>

The (attenuation in beam pipe wall) $\times$ (scatter probability in scintillator) ≈ 0.3 from above, so that the occupancy per scintillator layer per degraded electron hit is:

$$\frac{637.4}{1078}(0.3) = 0.18 ,$$

and the double coincidence occupancy is $\sim (0.18)^2(0.7) = 0.022$. Actually in the Mark II, each hemicylindrical half of the pipe counter is "AND-ed" with its adjacent partner, and the two such sets "OR-ed" together. This reduces the coincidence rate by a factor $\frac{1}{2}$, so that the final predicted occupancy is:

$$\text{pipe occupancy} \approx 0.011 = 1.1\%$$

The error on this can easily be 100%, since the most of the photon contribution is from the close-in mask segments where the impact parameter is small and $dN_Y/d\Omega$ is not well determined by Fig. B-2. However, the pressure bump test performed by R. Larsen in the IRL2 straight section⁴ gave results that, when scaled for the current and pressure were within a factor of three of the above estimate. The PEP configuration under which this test was run was not AC*, but gave essentially the same predicted background hits by TURTLE (about 10% less) as the AC* configuration, so that such a comparison is valid.

E. Phase Space Analysis of 3 and 9 m Masks

One geometric feature of the masking system which might be of some importance is illustrated in the phase space diagrams shown in Figs. 10 and 11. As is well known, the horizontal and vertical motions of the beam particles can be described independently, and the description of the beam profile in one plane, horizontal (x) for example, is given by (x, θ_x) plot which is the horizontal phase space plot, such as Fig. 10. Here the $\pm 10\sigma_x$ limits have been drawn in x (with no dispersion), and a dashed line delimits the $10\sigma_x, 10\sigma_{\theta_x}$ beam ellipse. The straight lines are the aperture limits of the 3 and 9 m masks, ± 2.9 cm and ± 3.3 cm, respectively, as transformed to $Z = 0$ by a simple drift distance transform: $\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$. At $Z = 0$, $\sigma_x \approx 0.60$ mm, and $\sigma_{\theta_x} \approx 0.22$ mm for $K = 0.25$. It is apparent that very large amplitudes are required to hit the 9 m mask, about $18\sigma_{\theta_x}$ ($x = 0$) or $55\sigma_x$ ($\theta_x = 0$), but more important, that this mask is struck before the 3 m mask aperture limit is reached. This should greatly reduce background by causing showers to develop far enough away from the detector to be relatively innocuous. That is, the 3 m mask is shadowed by the 9 m mask for large amplitudes, such as might be induced by Coulomb scattering or perhaps by transverse deflecting modes in the rf cavities ("noise"). For very large amplitudes, $\sim 44\sigma_x$, it is possible to hit the 3 m mask directly as can be seen from the intersection of aperture limits at 27 mm. For beam loss through processes where the "tails" or halo of the beam is a rapidly decreasing function of the deviation from the central region or "core" of the beam, this protection by phase space shadowing could be very significant. Although CS is one of these types of phenomena, it is possible to have scatters occur in the "unprotected" region, i.e., very large x and moderate to negative θ_x (or the reverse signs). A more sophisticated mask system conceivably might place a third mask with appropriate beam optics such that the aperture lines have opposite (positive) slope intersecting the 9 m mask aperture lines to form a closed area around the beam phase space that excludes the 3 m mask entirely! However, such is not the case here, and it would involve masks outside the IR region.*

A similar discussion applies to the phase space in the vertical (y plane, as plotted in Fig. 11. Here the beam size is only $\sigma_y \approx 30\mu$, while $\sigma_{\theta_y} \approx 0.27$ mrad (also $K = 0.25$). The dashed lines for the 9 m mask in Fig. 11 indicate the present y aperture limits (at BSCV) of ± 7.4 cm; the 3 m mask limits are the

*There are "masks" in the straight section made of lighter materials (e.g., Al). No analysis of their effect, if any, is made here.

same as in x plane (circular aperture): ± 2.9 cm. Here, $\sim 250 \sigma_y$ and $\sim 28 \sigma_{\theta_y}$ are required before the 3m mask is struck directly, and this appears to shadow even more effectively than in the x plane. These arguments are not substantially changed using our current most commonly used configuration ($\beta_y^* = "26$ cm", where the beam dimensions $\sigma_x \cong 0.72$ mm and $\sigma_y \cong 0.048$ mm are, respectively, 16% and 60% larger than the AC* values.

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(Thanks to Dikran Atreasyan for teaching me how to use his version of the program.)

APPENDIX A: SYNCHROTRON RADIATION BACKGROUND

(1) Reflectivity of SR From Al H.O.M. Screen

Effective (slant) Incident
distance in screen: 0° Photon
 180° Scattered photon

$$\frac{0.005''}{\sin 6.6^\circ} = 0.0435'' = 1.10 \text{ mm}$$

$$= 0.30 \text{ g/cm}^2 = l$$

Scattering is isotropic (except for attenuation). Assuming $(\frac{\Delta\Omega}{4\pi})$ is used to calculate backscatter flux, then equivalent reflectivity, $r(\text{Al})$, is:

$$r(\text{Al}) = \frac{1}{2}[(1 - e^{-2\mu l}) \frac{\sigma_C^S + \sigma_{Fe} + \sigma_R}{\sigma_{\text{tot}}}]$$

where: $\mu(E_\gamma) =$ attenuation coefficient (cm^2/g)

$\sigma_C^S =$ Compton cross section times fraction of energy re-radiated

$\sigma_{Fe} =$ fluorescent yield: photoelectric cross section times fraction of energy re-radiated

$\sigma_R =$ Rayleigh (coherent) cross section

The factor of $\frac{1}{2}$ is from attenuation of γ entering and exiting material, and comes from integrating: $\int_0^l e^{-\mu x} (\mu dx) e^{-\mu x}$

The values in the table below are calculated using these cross sections as tabulated by Israel and Storm⁶ (σ 's in barns/atom). (K edge = 1.56 keV)

Table A-I

E_γ (keV)	$\frac{dN}{dE_\gamma}$ Y inc	σ_C^S	σ_{Fe}	σ_R	σ_{tot}	$\mu(\frac{\text{cm}^2}{\text{g}})$	$r(\text{Al})$	$r(\text{Al}) \frac{dN}{dE_\gamma}$ Y inc
5	7.3×10^7	3.0	90.	50.	8510.	189.9	0.0084	61.2×10^4
6	5.7	3.4	40.	43.2	5070.	113.2	0.0085	48.4
8	3.9	4.1	10.	32.4	2210.	49.3	0.010	41.0
10	2.7	4.7	10.	24.7	1180	26.3	0.017	45.1
15	1.3	5.5	1.	14.1	349	7.79	0.023	38.0
20	7.3×10^6	5.9	0.	9.2	152	3.39	0.043	31.5
30	2.8	6.2	0.	4.9	49.7	1.11	0.054	15.2
40	1.1	6.2	0.	3.1	25.2	0.56	0.053	5.8
50	4.0×10^5	6.2	0.	2.1	16.4	0.37	0.050	2.0
60	1.9	6.0	0.	1.5	12.4	0.28	0.044	8890×10^0
80	4.0×10^4	5.7	0.	0.90	9.0	0.20	0.042	1660
100	8.1×10^3	5.4	0.	0.59	7.6	0.17	0.038	310

Here the photon flux $(\frac{dN}{dE})_{inc}$ incident on the H.O.M. screen has been calculated using the program QSRAD of A. Clark, the actual Mark II vacuum pipe geometry, and a coupling $K = 0.30$. These results are summarized in Fig. 8.

(2) Reflectivity of SR From Ta Mask (2.6 m)

As in Table A-I, cross section data is taken from Ref. 6, and values are in barns/atom. In this case the mask is thick and no SR penetrates, so:

$$r(Ta) = \frac{1}{2} \left[\frac{\sigma_C^S + \sigma_{Fl} + \sigma_R}{\sigma_{tot}} \right],$$

where σ 's are defined in Table A-I, as are other relevant details. A difference in this case is that the fluorescent yield is much more important, the K and L absorption edges both lying in the energy band of interest ($E_\gamma > 5$ keV): $E_K = 67.4$ keV, $E_{LII} = 9.9$ keV. The fluorescent contribution to reflectivity in the L shell (10-12 keV) region is computed from Ref. 6, as in Table A-I, as $\sigma_{Fl} = \sigma_{p.e.} - \sigma_{p.e.}^a$, where $\sigma_{p.e.}^a$ is $\sigma_{p.e.}$ weighted by fraction of energy given to atomic electron ejected. At energies > 67.4 keV, this fluorescent energy gotten from σ_{Fl} is composed of two parts: 80% transitions to the L-shell (2 transitions), and 20% to all other levels (8 transitions); only the former will be of interest because the subsequent β transitions are outside our energy band. This 80% of σ_{Fl} then de-excites from the L-shell with a second γ , with $\sim 80\%$ probability to a γ of ~ 9 keV (weighted average). In terms of numbers of photons, this then leads to an enhanced reflectivity if these photons can penetrate the beam pipe: this occurs for a beryllium pipe (Vertex Detector), but not for an aluminum pipe (present geometry). The second figure in parentheses is the incremental enhanced value, part of which represents lower energy photons, subject to different (energy-dependent) treatment subsequently in beam pipe penetration and energy deposit in scintillator. (There is $\sim 5\%$ error near K edge, which is neglected, in no. of photons, since $\sigma_{p.e.}^a$ assumes one photon re-radiated at incident energy, when in fact one is radiated at the K-L energy, 57.1 keV, and subsequently another, with 80% probability, at 9 keV, from L transitions.) "+" indicates values just above an absorption edge in the table below.

$$r = \frac{1}{2} \left[\frac{\sigma_C^S + \sigma_R + 0.8(+0.64)\sigma_{Fl}}{\sigma_{tot}} \right]$$

The final results of this table are shown in Fig. 9.

Table A-II

(Abs. Edge)	E_Y (keV)	$\frac{dN}{dE_Y}$ inc	σ_C^S	σ_{Ff}	σ_R	σ_{tot}	$x(+\Delta x)$	$x' \frac{dN}{dE_Y}$ inc
(L _{III})	5	10.3×10^6	8.2	0	2220	157,000	0.0071	7.3×10^4
	6	8.1	9.7	0	1990	101,000	0.0099	8.0
	8	5.3	12.2	0	1600	48,600	0.0166	8.8
	9.88	3.8	14.2	0	1330	28,600	0.0235	8.9
	+ ϵ	"	"	9700	"	75,000	0.0507	23.1
(L _{II})	10	3.7	14.3	9200	1320	72,500	0.0500	22.2
	11.14	3.2	15.4	6100	1180	53,600	0.0567	18.1
	+ ϵ	"	"	10400	"	74,900	0.0635	20.3
(L _I)	11.65	2.9	15.8	8600	1130	65,400	0.0614	17.8
	+ ϵ	"	"	10500	"	75,100	0.0636	18.4
	15	1.8	18.4	4300	852	39,800	0.0541	9.7
	20	9.6×10^5	21.3	1500	601	18,800	0.0485	4.7
	30	3.2	24.9	340	355	6,500	0.0502	1.61
(K)	40	2.1	26.8	120	232	3,060	0.0580	1.22
	50	5.4×10^4	27.6	50	163	1,630	0.0583	3699×10^0
	60	2.4	27.8	25	122	1,060	0.0601	1920
	67.42	1.4	27.8	16	101	790	0.0836	1250
	+ ϵ	"	"	2240	"	3,510	0.274(+0.204)	3840(+2860)
	80	5670×10^0	27.5	1214	74.5	2,280	0.235(+0.193)	1330(+1030)
	100	1215	26.7	537	49.4	1,280	0.098(+0.164)	240(+200)

(3) SR Penetration of Al Beam Pipe and Energy Deposit in Pipe Counter;

Calculated Occupancy From SR

Angle of incidence of SR radiation backscattered from 3m mask or H.O.M. screen is about 2° , resulting in a slant distance nearly 30 times the 2mm beam pipe wall thickness, or $l(\text{Al}) \approx 16 \text{ g/cm}^2$. This means that nearly every incident photon of any energy in the 5-100 keV range interacts in the pipe wall. Next, the γ scatters isotropically (ave. slant factor ≈ 2 , i.e., $\theta \approx 60^\circ$ to normal) carrying off a fraction $f^S(\text{Al})$ of its initial energy. Below about 15 keV, there still is little chance of escaping the beam pipe due to the large attenuation cross section and the small value of $f^S(\text{Al})$ in this range. Above 15 keV, the SR escapes relatively easily. Values of μ vs E_γ are given in Table A-I for Al. The fluxes incident are backscatter from the H.O.M. screen and Ta of the 3m mask, and are computed from QSRAD.⁵ These are shown in Tables A-I and A-II, and their sum is given in the table below. The solid angle of the segment of beam pipe adjacent to the pipe counters is $(\Delta\Omega/4\pi) = 1.9 \times 10^{-4} \text{ sr}$ (see Sec. IIC). Input information to Table A-III is from Tables A-I, A-II and Ref. 1. The combination CH was computed from using data from C and H separately, and multiplying the H data by 1.1 to achieve the C/H = 1/1.1 ratio in polyvinyl-toluene base scintillator (Pilot F, Y, B, NE102, etc.).

In the table below:

$l(\text{Al})$ = beam pipe wall slant distance

$f^S(\text{Al})$ = fraction of incident γ energy carried away after scatter

$f^A(\text{CH})$ = fraction of incident γ energy absorbed giving signal in scintillator

$\bar{l}(\text{CH})$ = ave. γ pathlength in 1/4" scintillator $\approx 0.50" = 1.27 \text{ cm} = 1.31 \text{ g/cm}^2$

$(dW/dE_\gamma) = \frac{T}{4\pi} (\Delta\Omega) (dN_\gamma/dE_\gamma)_{\text{tot}} f^S(\text{Al}) (1 - e^{-\mu \bar{l}(\text{CH})}) f^A(\text{CH}) E_\gamma$ = scintillator energy deposit per keV inc. energy

$(0.0470 \text{ g/b/atom}) = \mu(\text{cm}^2/\text{g})$ for $\text{CH}_{1.1}$

$\Delta W = (dW/dE_\gamma) \Delta E_\gamma$ = energy deposit per energy interval

Table A-III

E_γ (keV)	$\frac{dN}{dE_\gamma} \text{ tot}$	T (see text)	$f^S(\text{Al})$	$\sigma_{\text{tot}}(\text{CH})$	$f^A(\text{CH})$	$e^{-\mu \bar{L}}(\text{CH})$	$\left(\frac{dW}{dE_\gamma}\right)$	ΔW (keV)
5	68.5×10^4	0.	0.016	381.	0.974	1×10^{-10}	0.	0.
6	56.4	0.	0.018	217.	0.959	2×10^{-6}	0.	0.
8	49.8	0.	0.023	87.3	0.915	0.005	0.	0.
9.88	53.8	0.	0.033				0.	0.
+ ϵ	67.9	0.	0.033				0.	0.
10	67.3	0.	0.034	46.0	0.858	0.062	0.	0.
11.14	61.6	0.	0.040				0.	0.
+ ϵ	63.8	0.	0.040				0.	0.
11.68	60.5	0.	0.043				0.	0.
+ ϵ	61.2	0.	0.043				0.	0.
15	47.7	0.003	0.060	16.3	0.658	0.374	0.10	2.
20	36.2	0.055	0.099	9.30	0.460	0.572	1.40	29.0
30	16.8	0.30	0.23	5.73	0.228	0.708	4.41	41.5
40	7.0	0.55	0.37	4.77	0.144	0.750	3.90	29.7
50	2.37	0.67	0.50	4.34	0.118	0.770	2.04	15.1
60	10810×10^0	0.74	0.61	4.10	0.114	0.781	0.98	8.1
67.42	7460	0.77	0.65	4.00	0.117	0.787	1.20	
+ ϵ	9980(+2860)	0.77	0.65	4.00	0.117	0.787	1.60	14.3
80	2990(+1090)	0.81	0.73	3.78	0.123	0.796	0.67	8.5
100	550(+200)	0.83	0.78	3.55	0.140	0.807	0.183	

148.3 keV

The total energy deposit due to two bunches is thus ~ 300 keV. Since the energy deposited by a minimum ionizing track normal to the scintillator is 1.29 MeV, or ~ 4 times the SR signal, the pipe counter is on the verge of being turned on by the SR background, if the threshold is set low, as it normally would be to have high efficiency and good timing properties. For the expected running conditions $K \approx 0.25$, which results in $\sim 1/2$ the flux, and it is possible that the pipe occupancy could be $\sim 0\%$ due to SR under "ideal" conditions. However if the coupling is higher than assumed in these tables ($K = 0.3$), such as for a bad beam configuration leading to large beam sizes, or a beam steered off magnetic axis, or simply due to the "halo" population at large θ , the pipe counters would be expected to have full occupancy. From the table

we see that the transmission through the inner pipe counter is 70%-80%, and so nearly the same flux hits the outer counter, and roughly the same energy deposit occurs there. Since the energy deposits come from large numbers of photons incident, the transition should be sharp between zero and full occupancy when the threshold is exceeded, and, of course, the coincidence required between inner and outer counters will not reduce the occupancy in spite of the hits being uncorrelated.

Finally, the transmission, T , given in the table is calculated in two different ways, depending on the energy. Up to 30 keV, a two-dimensional problem was solved "exactly," assuming photons incident at 2° , scattering at an angle θ either into the pipe wall or out and toward the axis and other side of the pipe where it has another chance to penetrate (at angle θ). The integral was done over two variables: the interaction (scatter) point and the scattering angle. For > 40 keV, where the γ has a high probability to escape once it has scattered, the average escape distance was used, based on isotropic scattering ($\cos \theta = 1/2$, or twice the distance normal to surface).

APPENDIX B: ELECTRON SHOWER CURVES; PHOTON ATTENUATION CURVES

Figures B-1 through B-5 summarize the results of an analysis of electron showers resulting from energetic electrons incident upon a tantalum mask ($Z = 73$, $X_0 = 3.9$ mm) idealized as a rectangular block of $30 X_0$ thickness (see sketch on Fig. B-1). Such a large thickness is necessary to prevent appreciable shower punch through from region 1 to region 3. The results for energy and photon number are plotted as a function of the impact parameter, X , and in terms of the photon spectrum (Fig. B-1), angular distributions (Figs. B-2 and B-3), and the sum of energy or N_γ vs X (Fig. B-4) for the three regions: region 1, backscattering; region 3, punch through; region 4, edge scattering. Due to the scaling nature of the results, it was possible to normalize these distributions to the incident electron energy, which for most computer runs was 5 GeV. Figure B-5 gives the $\sum E_\gamma$ and $\sum N_\gamma$ distributions vs X as for Fig. B-4 except analyzed from runs with 15 GeV e^- incident, to show the level of validity of scaling. The prominent peak at ~ 0.5 MeV on Fig. B-1 results from positron annihilation. Indeed nearly all the endproducts are photons for impact parameters more than a few mm. In Fig. B-2 can be seen sharp forward peaking at small X , corresponding to partially developed showers leaking back into region 4; otherwise the angular distributions are reasonably

Outer pipe counter: $\theta_1 = \tan^{-1} \frac{0.127 \text{ m}}{2.60 \text{ m} + 0.406 \text{ m}} = 2.42^\circ$ (far end)
 (32" long x
 10" diam.) $\theta_2 = \tan^{-1} \frac{0.127 \text{ m}}{2.60 \text{ m} - 0.406 \text{ m}} = 3.31^\circ$ (near end)
 $(\Delta\theta/4\pi) = 3.9 \times 10^{-4}$

$\varphi_0 = \text{ave. } \gamma \text{ incident angle} = 2.65^\circ$

$d = \text{beam pipe wall thickness} = 2 \text{ mm}$

E_γ	$\mu(\text{Al}), \frac{\text{cm}^2}{\text{g}}$	$\exp[-\mu(\text{Al})d/\sin \varphi_0]$	$G_{\text{tot}}(\text{CH}_{1.1}), \frac{\text{b}}{\text{at.}}$	$f^A(\text{CH}_{1.1})$	$\mu(\text{CH}_{1.1})G_{\text{tot}}$
1 MeV	0.061	0.49	1.48	0.44	0.070
3 MeV	0.036	0.66	0.82	0.53	0.033

E_γ	$1 - e^{-\mu\sigma/\sin \varphi_0}$	(Transmission in Al) x (Scatter in CH)	Energy deposit
1 MeV	0.63	0.31	0.347 x 1 MeV
3 MeV	0.42	0.28	0.333 x 3 MeV

Here μ is the attenuation coefficient, and f^A is the energy fraction absorbed.

Next, let us find the occupancy and average incident particle energy. From Fig. 3 of Ref. 8 and Table II (or from DECAY TURTLE) we find the average energy of $e^\pm$ striking masks in the vicinity of the detector as $\langle P' \rangle/P \sim 0.4$, $\langle P' \rangle =$ degraded electron energy $\sim 6 \text{ GeV}$. In spite of the broad angular distribution of shower background flux, it is still much stronger (10-20x) in the forward than backward directions, and only the former is used. Looking at Table II we see the numbers of upstream hits on various mask apertures for a fixed 20,000 BGB events generated between 80.2m and 1.80m from the IP, a total of 78.4m. Of this distance, only the pathlength up to Q1 (center at 11m) can contribute, so we should renormalize to 69.2m, or 17,653 events. All hits in the upstream 3m mask area are used, up to $Z = 5.6\text{m}$, since this entire length is visible to the pipe counter: there are 1078 hits, or 6.1% of the total events. To convert this to occupancy, we need to know the actual number of BGB events per beam crossing. The total number of BGB events per bunch crossing is:

$$N_{\text{BGB}} = N_b (69.2 \text{ m} / X_0(\text{m})) \ln \frac{E'_{\text{max}}}{E'_{\text{min}}}$$

The residual gas is usually thought to be mostly CO, which has $X_0 = 37.0 \text{ g/cm}^2$, or at a standardized pressure of $\sim 5 \times 10^{-9} \text{ torr}$, $X_0 = 4.61 \times 10^{13} \text{ m}$. N_b (Table I) = $0.83 \times 10^{12}/\text{bunch}$, and for the computer runs $E'_{\text{max}} = E$, $E'_{\text{min}} = 0.01 E$, and $N_{\text{BGB}} = 5.74$. Using the 6.1% of total BGB events which strike the upstream 3m mask gives an occupancy per bunch of 0.35, or 0.70 per crossing because of the two bunches.

Next it is necessary to estimate the residual photon shower flux, given that, on the average, 6 GeV $e^{\pm}$ strike the mask. Here, as distinct from the SR background situation, we want the number of photons rather than total energy, since BGB is a case of low photon statistics, but relatively high trigger probability per photon. The number of hits (in the run with 1078 total hits) on each of six steps in the upstream 3m mask are tabulated, along with the average impact parameter (half of radial step size), and the scattered flux (region 4, edge scattering) taken from Fig. A-2. The last three entries are quite uncertain due to the small impact parameter.

$Z(m)$	$\overline{\Delta r}(cm)$	N_{hits}	$\frac{1}{E} \frac{dN_Y}{d\Omega}$	$\frac{(\frac{d\Omega}{4\pi})}{}$	N_Y
5.59	0.72	111	7	0.34×10^{-4}	2.0
3.32	1.12	607	2.4	1.6	17.6
3.03	0.34	225	20	2.1	71.2
2.90	0.05	48	~ 200	2.4	173.7
2.78	0.06	66	~ 200	2.7	276.3
2.60	0.02	19	~ 200	3.35	95.0
					<u>637.4</u>

The (attenuation in beam pipe wall) $\times$ (scatter probability in scintillator) ≈ 0.3 from above, so that the occupancy per scintillator layer per degraded electron hit is:

$$\frac{637.4}{1078}(0.3) = 0.18 ,$$

and the double coincidence occupancy is $\sim (0.18)^2(0.7) = 0.022$. Actually in the Mark II, each hemicylindrical half of the pipe counter is "AND-ed" with its adjacent partner, and the two such sets "OR-ed" together. This reduces the coincidence rate by a factor $\frac{1}{2}$, so that the final predicted occupancy is:

$$\text{pipe occupancy} \approx 0.011 = 1.1\%$$

The error on this can easily be 100%, since the most of the photon contribution is from the close-in mask segments where the impact parameter is small and $dN_Y/d\Omega$ is not well determined by Fig. B-2. However, the pressure bump test performed by R. Larsen in the IRL2 straight section⁴ gave results that, when scaled for the current and pressure were within a factor of three of the above estimate. The PEP configuration under which this test was run was not AC*, but gave essentially the same predicted background hits by TURTLE (about 10% less) as the AC* configuration, so that such a comparison is valid.

E. Phase Space Analysis of 3 and 9m Masks

One geometric feature of the masking system which might be of some importance is illustrated in the phase space diagrams shown in Figs. 10 and 11. As is well known, the horizontal and vertical motions of the beam particles can be described independently, and the description of the beam profile in one plane, horizontal (x) for example, is given by (x, θ_x) plot which is the horizontal phase space plot, such as Fig. 10. Here the $\pm 10\sigma_x$ limits have been drawn in x (with no dispersion), and a dashed line delimits the $10\sigma_x$, $10\sigma_{\theta_x}$ beam ellipse. The straight lines are the aperture limits of the 3 and 9m masks, ± 2.9 cm and ± 3.3 cm, respectively, as transformed to $Z = 0$ by a simple drift distance transform: $\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$. At $Z = 0$, $\sigma_x \approx 0.60$ mm, and $\sigma_{\theta_x} \approx 0.22$ mrad for $K = 0.25$. It is apparent that very large amplitudes are required to hit the 9m mask, about $18\sigma_{\theta_x}$ ($x = 0$) or $55\sigma_x$ ($\theta_x = 0$), but more important, that this mask is struck before the 3m mask aperture limit is reached. This should greatly reduce background by causing showers to develop far enough away from the detector to be relatively innocuous. That is, the 3m mask is shadowed by the 9m mask for large amplitudes, such as might be induced by Coulomb scattering or perhaps by transverse deflecting modes in the rf cavities ("noise"). For very large amplitudes, $\sim 4\sigma_x$, it is possible to hit the 3m mask directly as can be seen from the intersection of aperture limits at 27 mrad. For beam loss through processes where the "tails" or halo of the beam is a rapidly decreasing function of the deviation from the central region or "core" of the beam, this protection by phase space shadowing could be very significant. Although CS is one of these types of phenomena, it is possible to have scatters occur in the "unprotected" region, i.e., very large x and moderate to negative θ_x (or the reverse signs). A more sophisticated mask system conceivably might place a third mask with appropriate beam optics such that the aperture lines have opposite (positive) slope intersecting the 9m mask aperture lines to form a closed area around the beam phase space that excludes the 3m mask entirely! However, such is not the case here, and it would involve masks outside the IR region.*

A similar discussion applies to the phase space in the vertical (y plane, as plotted in Fig. 11. Here the beam size is only $\sigma_y \approx 30\mu$, while $\sigma_{\theta_y} \approx 0.27$ mrad (also $K = 0.25$). The dashed lines for the 9m mask in Fig. 11 indicate the present y aperture limits (at BSCY) of ± 7.4 cm; the 3m mask limits are the

*There are "masks" in the straight section made of lighter materials (e.g., Al). No analysis of their effect, if any, is made here.

same as in x plane (circular aperture): ± 2.9 cm. Here, $\sim 250 \sigma_y$ and $\sim 28 J_{\theta_y}$ are required before the 3m mask is struck directly, and this appears to shadow even more effectively than in the x plane. These arguments are not substantially changed using our current most commonly used configuration ($\beta_y^* = "26"$ cm), where the beam dimensions $\sigma_x \approx 0.72$ mm and $\sigma_y \approx 0.048$ mm are, respectively, 16% and 60% larger than the AC* values.

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(Thanks to Dikran Atreasyan for teaching me how to use his version of the program.)

APPENDIX A: SYNCHROTRON RADIATION BACKGROUND

(1) Reflectivity of SR From Al H.O.M. Screen

Effective (slant)
distance in screen:

Incident
0° Photon
180° Scattered photon

$$\frac{0.005''}{\sin 6.6^\circ} = 0.0435'' = 1.10 \text{ mm}$$

$$= 0.30 \text{ g/cm}^2 = l$$

Scattering is isotropic (except for attenuation). Assuming $(\frac{\Delta\Omega}{4\pi})$ is used to calculate backscatter flux, then equivalent reflectivity, $r(\text{Al})$, is:

$$r(\text{Al}) = \frac{1}{2}[(1 - e^{-2\mu l}) \frac{\sigma_C^S + \sigma_{Fl} + \sigma_R}{\sigma_{\text{tot}}}]$$

where: $\mu(E_\gamma) = \text{attenuation coefficient (cm}^2/\text{g)}$

$\sigma_C^S = \text{Compton cross section times fraction of energy re-radiated}$

$\sigma_{Fl} = \text{fluorescent yield: photoelectric cross section times fraction of energy re-radiated}$

$\sigma_R = \text{Rayleigh (coherent) cross section}$

The factor of $\frac{1}{2}$ is from attenuation of γ entering and exiting material, and comes from integrating: $\int_0^l e^{-\mu x} (\mu dx) e^{-\mu x}$

The values in the table below are calculated using these cross sections as tabulated by Israel and Storm⁶ (σ 's in barns/atom). (K edge = 1.56 keV)

Table A-I

E_γ (keV)	$\frac{dN}{dE_\gamma}$ γ inc	σ_C^S	σ_{Fl}	σ_R	σ_{tot}	$\mu(\frac{\text{cm}^2}{\text{g}})$	$r(\text{Al})$	$r(\text{Al}) \frac{dN}{dE_\gamma}$ γ inc
5	7.3×10^7	3.0	90.	50.	8510.	189.9	0.0084	61.2×10^4
6	5.7	3.4	40.	43.2	5070.	113.2	0.0085	48.4
8	3.9	4.1	10.	32.4	2210.	49.3	0.010	41.0
10	2.7	4.7	10.	21.7	1180	26.3	0.017	45.1
15	1.3	5.5	1.	14.1	349	7.79	0.023	38.0
20	7.3×10^6	5.9	0.	9.2	152	3.39	0.043	31.5
30	2.8	6.2	0.	4.9	49.7	1.11	0.054	15.2
40	1.1	6.2	0.	3.1	25.2	0.56	0.053	5.8
50	4.0×10^5	6.2	0.	2.1	16.4	0.37	0.050	2.0
60	1.9	6.0	0.	1.5	12.4	0.28	0.044	8670×10^0
80	4.0×10^4	5.7	0.	0.90	9.0	0.20	0.042	1660
100	8.1×10^3	5.4	0.	0.59	7.6	0.17	0.038	310

Here the photon flux $(\frac{dN}{dE})_{inc}$ incident on the H.O.M. screen has been calculated using the program QSRAD of A. Clark, the actual Mark II vacuum pipe geometry, and a coupling $K = 0.30$. These results are summarized in Fig. 8.

(2) Reflectivity of SR From Ta Mask (2.6 m)

As in Table A-I, cross section data is taken from Ref. 6, and values are in barns/atom. In this case the mask is thick and no SR penetrates, so:

$$r(Ta) = \frac{1}{2} \left[\frac{\sigma_C^S + \sigma_{Fl} + \sigma_R}{\sigma_{tot}} \right],$$

where σ 's are defined in Table A-I, as are other relevant details. A difference in this case is that the fluorescent yield is much more important, the K and L absorption edges both lying in the energy band of interest ($E_Y > 5$ keV): $E_K = 67.4$ keV, $E_{LII} = 9.9$ keV. The fluorescent contribution to reflectivity in the L shell (10-12 keV) region is computed from Ref. 6, as in Table A-I, as $\sigma_{Fl} = \sigma_{p.e.} - \sigma_{p.e.}^a$, where $\sigma_{p.e.}^a$ is $\sigma_{p.e.}$ weighted by fraction of energy given to atomic electron ejected. At energies > 67.4 keV, this fluorescent energy gotten from σ_{Fl} is composed of two parts: 80% transitions to the L-shell (α transitions), and 20% to all other levels (β transitions); only the former will be of interest because the subsequent β transitions are outside our energy band. This 80% of σ_{Fl} then de-excites from the L-shell with a second γ , with $\sim 80\%$ probability to a γ of ~ 9 keV (weighted average). In terms of numbers of photons, this then leads to an enhanced reflectivity if these photons can penetrate the beam pipe: this occurs for a beryllium pipe (Vertex Detector), but not for an aluminum pipe (present geometry). The second figure in parentheses is the incremental enhanced value, part of which represents lower energy photons, subject to different (energy-dependent) treatment subsequently in beam pipe penetration and energy deposit in scintillator. (There is $\sim 5\%$ error near K edge, which is neglected, in no. of photons, since $\sigma_{p.e.}^a$ assumes one photon re-radiated at incident energy, when in fact one is radiated at the K-L energy, 57.1 keV, and subsequently another, with 80% probability, at 9 keV, from L transitions.) "+" indicates values just above an absorption edge in the table below.

$$r = \frac{1}{2} \left[\frac{\sigma_C^S + \sigma_R + 0.8(+0.64)\sigma_{Fl}}{\sigma_{tot}} \right]$$

The final results of this table are shown in Fig. 9.

Table A-II

(Abs. Edge)	E_Y (keV)	$\frac{dN}{dE_Y} \text{ inc}$	σ_C^S	σ_{ff}	σ_R	σ_{tot}	$r(+\Delta x)$	$r' \frac{dN}{dE_Y} \text{ inc}$
	5	10.3×10^6	8.2	0	2220	157,000	0.0071	7.3×10^4
	6	8.1	9.7	0	1990	101,000	0.0099	8.0
	8	5.3	12.2	0	1600	48,600	0.0166	8.8
(L _{III})	9.88	3.8	14.2	0	1330	28,600	0.0235	8.9
	+ ϵ	"	"	9700	"	75,000	0.0607	23.1
	10	3.7	14.3	9200	1320	72,500	0.0600	22.2
(L _{II})	11.14	3.2	15.4	6100	1180	53,600	0.0567	18.1
	+ ϵ	"	"	10400	"	74,900	0.0635	20.3
(L _I)	11.68	2.9	15.8	8600	1130	65,400	0.0614	17.8
	+ ϵ	"	"	10500	"	75,100	0.0636	18.4
	15	1.8	18.4	4300	852	39,800	0.0541	9.7
	20	9.6×10^5	21.3	1500	601	18,800	0.0485	4.7
	30	3.2	24.9	340	355	6,500	0.0502	1.61
	40	2.1	26.8	120	232	3,060	0.0580	1.22
	50	5.4×10^4	27.6	50	163	1,630	0.0583	3699×10^0
	60	2.4	27.8	25	122	1,050	0.0801	19.0
(K)	67.42	1.4	27.8	16	101	790	0.0836	12.0
	+ ϵ	"	"	2240	"	3,510	0.274(+0.204)	3840(+2860)
	80	5670×10^0	27.5	1214	74.5	2,280	0.235(+0.193)	1330(+1030)
	100	1215	26.7	537	49.4	1,280	0.098(+0.164)	340(+200)

(3) SR Penetration of Al Beam Pipe and Energy Deposit in Pipe Counter;

Calculated Occupancy From SR

Angle of incidence of SR radiation backscattered from 3m mask or H.O.M. screen is about 2° , resulting in a slant distance nearly 30 times the 2mm beam pipe wall thickness, or $l(Al) = 16 \text{ g/cm}^2$. This means that nearly every incident photon of any energy in the 5-100 keV range interacts in the pipe wall. Next, the γ scatters isotropically (ave. slant factor ≈ 2 , i.e., $\theta \approx 60^\circ$ to normal) carrying off a fraction $f^S(Al)$ of its initial energy. Below about 15 keV, there still is little chance of escaping the beam pipe due to the large attenuation cross section and the small value of $f^S(Al)$ in this range. Above 15 keV, the SR escapes relatively easily. Values of μ vs E_γ are given in Table A-I for Al. The fluxes incident are backscatter from the H.O.M. screen and T_a of the 3r mask, and are computed from QSRAD.⁵ These are shown in Tables A-I and A-II, and their sum is given in the table below. The solid angle of the segment of beam pipe adjacent to the pipe counters is $(\Delta\Omega/4\pi) = 1.9 \times 10^{-4} \text{ sr}$ (see Sec. IIC). Input information to Table A-III is from Tables A-I, A-II and Ref. 1. The combination CH was computed from using data from C and H separately, and multiplying the H data by 1.1 to achieve the C/H = 1/1.1 ratio in polyvinyl-toluene base scintillator (Pilot F, Y, B, NE102, etc.).

In the table below:

$l(Al)$ = beam pipe wall slant distance

$f^S(Al)$ = fraction of incident γ energy carried away after scatter

$f^A(CH)$ = fraction of incident γ energy absorbed giving signal in scintillator

$\bar{l}(CH)$ = ave. γ pathlength in 1/4" scintillator $\approx 0.50" = 1.27 \text{ cm} = 1.31 \text{ g/cm}^2$

$(dW/dE_\gamma) = \frac{T}{4\pi} (\Delta\Omega) (dN_\gamma/dE_\gamma)_{\text{tot}} f^S(Al) (1 - e^{-\mu \bar{l}(CH)}) f^A(CH) E_\gamma$ = scintillator energy deposit per keV inc. energy

$(0.0420 \text{ cm}^2/\text{atom}) = \mu(\text{cm}^2/\text{g})$ for $CH_{1.1}$

$\Delta W = (dW/dE_\gamma) \Delta E_\gamma$ = energy deposit per energy interval

Table A-III

E_Y (keV)	$\left(\frac{dN}{dE}\right)_{\text{tot}}$	T (see text)	$f^S(\text{Al})$	$\sigma_{\text{tot}}(\text{CH})$	$f^A(\text{CH})$	$e^{-\mu l}(\text{CH})$	$\left(\frac{dW}{dE}\right)_Y$	ΔW (keV)
5	68.5×10^4	0.	0.016	381.	0.974	1×10^{-10}	0.	0.
6	56.4	0.	0.018	217.	0.959	2×10^{-6}	0.	0.
8	49.8	0.	0.023	87.3	0.915	0.005	0.	0.
9.88	53.8	0.	0.033				0.	0.
+ e	67.9	0.	0.033				0.	0.
10	67.3	0.	0.034	46.0	0.858	0.062	0.	0.
11.14	61.6	0.	0.040				0.	0.
+ e	63.8	0.	0.040				0.	0.
11.68	60.5	0.	0.043				0.	0.
+ e	61.2	0.	0.043				0.	0.
15	47.7	0.003	0.060	16.3	0.658	0.374	0.10	2.
20	36.2	0.055	0.099	9.30	0.460	0.572	1.40	29.0
30	16.8	0.30	0.23	5.73	0.228	0.708	4.41	41.6
40	7.0	0.55	0.37	4.77	0.144	0.750	3.90	29.7
50	2.37	0.67	0.50	4.34	0.118	0.770	2.04	15.1
60	10810×10^0	0.74	0.61	4.10	0.114	0.781	0.98	6.1
67.42	7460	0.77	0.65	4.00	0.117	0.787	1.20	
+ e	9980(+2860)	0.77	0.65	4.00	0.117	0.787	1.60	14.3
80	2990(+1090)	0.81	0.73	3.78	0.123	0.796	0.67	8.5
100	550(+200)	0.83	0.78	3.55	0.140	0.807	0.183	

148.3 keV

The total energy deposit due to two bunches is thus ~ 300 keV. Since the energy deposited by a minimum ionizing track normal to the scintillator is 1.29 MeV, or ~ 4 times the SR signal, the pipe counter is on the verge of being turned on by the SR background, if the threshold is set low, as it normally would be to have high efficiency and good timing properties. For the expected running conditions $K \approx 0.25$, which results in $\sim 1/2$ the flux, and it is possible that the pipe occupancy could be $\sim 0\%$ due to SR under "ideal" conditions. However if the coupling is higher than assumed in these tables ($K = 0.3$), such as for a bad beam configuration leading to large beam sizes, or a beam steered off magnetic axis, or simply due to the "halo" population at large σ , the pipe counters would be expected to have full occupancy. From the table

we see that the transmission through the inner pipe counter is 70%-80%, and so nearly the same flux hits the outer counter, and roughly the same energy deposit occurs there. Since the energy deposits come from large numbers of photons incident, the transition should be sharp between zero and full occupancy when the threshold is exceeded, and, of course, the coincidence required between inner and outer counters will not reduce the occupancy in spite of the hits being uncorrelated.

Finally, the transmission, T , given in the table is calculated in two different ways, depending on the energy. Up to 30 keV, a two-dimensional problem was solved "exactly," assuming photons incident at 2° , scattering at an angle θ either into the pipe wall or out and toward the axis and other side of the pipe where it has another chance to penetrate (at angle θ). The integral was done over two variables: the interaction (scatter) point and the scattering angle. For > 40 keV, where the γ has a high probability to escape once it has scattered, the average escape distance was used, based on isotropic scattering ($\cos \theta = 1/2$, or twice the distance normal to surface).

APPENDIX B: ELECTRON SHOWER CURVES; PHOTON ATTENUATION CURVES

Figures B-1 through B-5 summarize the results of an analysis of electron showers resulting from energetic electrons incident upon a tantalum mask ($Z = 73$, $X_0 = 3.9$ mm) idealized as a rectangular block of $30 X_0$ thickness (see sketch on Fig. B-1). Such a large thickness is necessary to prevent appreciable shower punch through from region 1 to region 3. The results for energy and photon number are plotted as a function of the impact parameter, X , and in terms of the photon spectrum (Fig. B-1), angular distributions (Figs. B-2 and B-3), and the sum of energy or N_γ vs X (Fig. B-4) for the three regions: region 1, backscattering; region 3, punch through; region 4, edge scattering. Due to the scaling nature of the results, it was possible to normalize these distributions to the incident electron energy, which for most computer runs was 5 GeV. Figure B-5 gives the $\sum E_\gamma$ and $\sum N_\gamma$ distributions vs X as for Fig. B-4 except analyzed from runs with 15 GeV e^- incident, to show the level of validity of scaling. The prominent peak at ~ 0.5 MeV on Fig. B-1 results from positron annihilation. Indeed nearly all the endproducts are photons for impact parameters more than a few $m.m.$ In Fig. B-2 can be seen sharp forward peaking at small X , corresponding to partially developed showers leaking back into region 4; otherwise the angular distributions are reasonably

smooth and broad, though a forward/backward flux ratio is usually $\gtrsim 10$ for X values more than a few mm. It is clear from these graphs that edge scattering (region 4) dominates the contributions to shower background in practical cases, and to minimize this the mask should be kept physically short, i.e., the Z (atomic number) and ρ (density) should be as high as possible, or more succinctly, the X_0 measured in cm should be as small as possible.

Figure B-6 shows a plot of photon attenuation and energy deposit (borrowed from LBL Particle Data Group tables), given as an orientation over a wide energy range to the behavior of some of the materials (or their neighbors) that are considered in this note.

APPENDIX C: DISTRIBUTIONS OF BACKGROUND TRIGGERS IN MUON AND TIME-OF-FLIGHT COUNTERS

Shown in Fig. C-1 are distributions of background triggers registered in two different sets of detection elements, which by their locations are expected to respond to different kinds of backgrounds: the muon tube (proportional counters on the outermost layers of the Mark II detector, and the time-of-flight (TOF) counters, just outside the central drift chamber, but inside the magnet coil, shower counter and muon detector. The muon chambers tend to respond to the background in the IR hall, especially the outer layer, while the TOF counters respond mainly to the background coming out of the beam pipe. Two different runs are analyzed: 6371 and 6598. The spread of the distributions relative to their means is clearly quite different for the two detector elements. In the earlier run, the mean is ~ 1.5 times higher for the number of muon triggers than for the TOF counters, yet the spread is much less for the muon tubes. In the later run the beam pipe was shielded by wrapping lead sheets around it, reducing the background in the IR hall, and the mean number muon triggers decreased accordingly, but still with a relatively narrow distribution.

The interpretation of these distributions is that the outer muon tubes were responding to intense SR flux originating at the last main bend magnet before the straight section ($Z \approx 66\text{ m}$) and scattering off the beam pipe around $Z = 10\text{--}12\text{ m}$. This scatter source was partially masked by the lead wrapping resulting in the observed improvement in the later run. SR flux consists of a very large number of low energy photons and, as has been said in the text, should result in background effects having narrow distributional spreads due to the high statistics nature of the source. On the other hand showers

originating from lost beam particles result in much smaller numbers of higher energy photons and would be expected to cause effects manifested by larger spreads, just what seems to be observed. However, the critical energy of SR from the last lattice dipole is ~ 45 keV, or about 30 times higher than from Q1 and Q2, so that the tail of this spectrum reaches into the MeV region, energies not unlike those of electron shower residuals, and also not completely attenuated by small layers ($\sim 1/8''$) of lead. Other observations of backgrounds near the beam pipe, such as distributions of hits in the trigger chamber (0.16-0.24 m in radius) substantiate the interpretation that the background in the interior of the Mark II is dominated by showers initiated by lost beam particles.

PHYSICS NOTES

TG-330

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SUBJECT

APPENDIX D:

AN INTERPRETATION OF BACKGROUND TESTS IN IR12

NAME

John Kadyk

DATE

December 4, 1980

On November 23, a series of background tests was run at PEP, coordinated by R. Larsen (and V. Lüth at IR12). This note is a summary of one of many tests done during that run period, viz., the pressure bump test in IR12, and an interpretation of the results. A comparison is made with an a priori calculation of background in the Mark II detector due to beam gas bremsstrahlung (BGB) including the masking. Further details on this estimate will be in a following note.

For this test PEP was run with configuration "21," and five runs were made (runs 15-19) on the same beam fill of a three-bunch beam of e^+ only, which had a lifetime of 8-9 hours. The total current only varied from about 13 to 12 mA. During the first and last "normalizing" runs the vacuum pumps were all operating, while during the intermediate runs 16, 17, 18 there were "pressure bumps" introduced by turning off pumps at one or both of two locations: (1) near the end of the 12B straight section close to the main bending magnet in arc 1, and (2) near the insertion doublet Q1-Q2. Figure 1 shows schematically the magnet locations in the straight section on one side of the IP, as well as half of one arc. The horizontal and vertical beam profiles are indicated, as are positions of several vacuum gauges to monitor the beam pipe pressure. The pressure profile in regions 12A and 12B are shown in Fig. 2 vs. z. The pressure integral $\int Pdz$ from 60m to 10m determines the BGB background. The relevant rates corresponding to the runs are:

Run Number	15	16	17	18	19
<u>Beam Conditions:</u>					
$\int_{60m}^{10m} Pdz$ (nT-m)	150.	465.	1471.	241.	124.
Current (mA)	13.2	13.0	12.6	12.2	12.0
Lifetime (hrs)	8.2	8.9	7.5	8.7	9.0
<u>Rates (kHz):</u>					
Pipe Counter	6.25	9.30	17.	6.90	5.41
SAT N Gross	8.20	13.3	26.8	9.77	7.32
SAT S Gross	1.26	1.70	2.81	1.29	1.12
TOF OUT	1.47	2.02	3.57	1.64	1.37
TOF IN	1.87	2.58	4.52	2.03	1.70
<u>Normalized Rate:</u>					
Pipe Ctr./ I_{DCCT} (kHz/mA)	0.472	0.717	1.347	0.567	0.457

The rate increase due to the largest pressure bump is about 3X for the pipe counter and somewhat higher for the N Gross Counter. This is explained as being

due to electron showers induced by energy-degraded beam e^+ resulting from BGB events in the residual gas. In the usual approximation, the degraded e^+ continues in nearly the incident beam direction with negligible angular spreading after the BG collision in the straight section ($\theta \approx m_e/E'$, where $E' =$ degraded energy). The off-energy e^+ are overfocused by the Q1-Q2 doublet, and driven into the beam pipe, shielding, etc. causing the showers, the end-product of which is mostly low-energy photons (~ 1 MeV) which convert (Compton scatter) in the counters.

In this model, only the region 60 m to 10 m contributes to BGB, since degraded e^+ originating in the arcs are swept out by the bending magnets, and those beyond 10 m go straight forward through the IR and detector without hitting anything. Therefore, the pressure integral, $\int_{60\text{ m}}^{10\text{ m}} (\text{Press}) dz$, has been calculated to make the following study of BGB. The values of the pipe counter rates, normalized to beam current, have been plotted vs. $\int P dz$ in the corner insert shown on Fig. 2 (other counters could have been plotted to give similar results). There is clearly a background rate component that responds linearly to the pressure integral, plus another constant background rate. If all background were due to BGB in IR12 straight section then the dashed line eyeball fit drawn would intersect the origin. The relative sizes of these two components can be estimated from the "normal" runs 15 and 19 compared to the zero-pressure intercept: only a $\sim 15\%$ decrease in background can be obtained by pumping a perfect vacuum in the straight section, implying another background component about 6 times larger than that induced by the pressure in the straight section. It is not now known with certainty the character of this other background source, although Coulomb scattering, as suggested in a note by Schwitters (August 18, 1980) seems to be a likely candidate. Such elastic e^+ collisions would induce large amplitude betatron oscillations, causing the population in the "tails" of the transverse beam profile to increase, but the energy of the scattered electron (or positron) is not degraded significantly, so that the scattered e^+ may remain within the acceptance region of the beam phase space and travel through many arcs before finding an aperture limit. Small amplitude oscillations do not seem to contribute as a background source, as has been demonstrated by inducing a short beam lifetime and high loss rate by lowering the cavity rf voltages. There resulted virtually no change in the Mark II background rate. The naive inference from these results is that the unknown, and by far the largest background mechanism (if only one exists), has the character of: (1) large betatron amplitude, (2) induced primarily not by the pressure in the straight section, and therefore presumably by the pressure around the ring.*

*Note added later: A persistently higher background occurs in IR12 from the e^- beam, by a factor of 2-3, relative to the e^+ beam used in the present test. Since the only important known asymmetry is that of the rf cavities in the straight section on the e^- side, it may be these introduce backgrounds by yet another mechanism.

An estimate of background in the Mark II pipe counter was made some time ago, based on PTM-108 by Bill Ash (6/30/77), and upon studies of EGS showers (summarized in graph form in an imminent note). This gave an estimated occupancy of $\approx 1-2\%$ for full beam (110 mA total) at 15 GeV/beam, a 5 nTorr pressure, and the present geometry. Scaling this latter result to the present current and pressure (e.g., run 15) predicts $0.07-0.14\%$, to be compared with measured 1.5% . However, the BGB on which the rate prediction is based appears to be only $\approx 15\%$ of the total, hence the comparison should be made with $15\% \times 1.5\% = 0.22\%$, close to the predicted value,* but an indication that the showering mechanisms of BGB and calculations thereof are reasonably well understood. However, it is by no means clear what is the other, larger background mechanism, and how to suppress it, if that is possible. If the mechanism can be identified, then the means to suppress it (if any) will probably require some significant lead time to fabricate and install, if it is judged desirable to do so.

*A piece of shielding has been inadvertently left out of the Mark II shielding in a location which could well reduce the measured rate further.

Pressures in IRI2 Straight-Section: Background Tests, 11/23/80

Fig. D-2

Schematic Layout of the Storage Ring

Fig. 1

F — FIXED MASKS, 30 R.L. To

M — MOVEABLE MASK, 30 R.L. To (does not exist; only a fixed mask, as F above, exists here)

Fig. 2b

Plan View of Interaction Region and Straight Section.

Fig. 3a

Mask II: Horizontal Plane Only: Hevimet. Side toward interaction region placed as for Mask I.

Mask III: Scale 5cm = 1 square (1/4"). Circular Hole. Materials: Lead
(symmetric about t)

Flare: See Figure 3a

Fig. 3b

Fig. 4

XRL 799-4215

Fig. 5

NHL 794 4216

11.122	167.25
107.12	26.677
107.12	1.160
107.12	75.00
107.12	16.752
107.12	16.378
106.25	16.616
105.38	16.764
104.51	16.912
103.64	17.060
102.77	17.208
101.90	17.356
101.03	17.504
100.16	17.652
99.29	17.800
98.42	17.948
97.55	18.096
96.68	18.244
95.81	18.392
94.94	18.540
94.07	18.688
93.20	18.836
92.33	18.984
91.46	19.132
90.59	19.280
89.72	19.428
88.85	19.576
87.98	19.724
87.11	19.872
86.24	20.020
85.37	20.168
84.50	20.316
83.63	20.464
82.76	20.612
81.89	20.760
81.02	20.908
80.15	21.056
79.28	21.204
78.41	21.352
77.54	21.500
76.67	21.648
75.80	21.796
74.93	21.944
74.06	22.092
73.19	22.240
72.32	22.388
71.45	22.536
70.58	22.684
69.71	22.832
68.84	22.980
67.97	23.128
67.10	23.276
66.23	23.424
65.36	23.572
64.49	23.720
63.62	23.868
62.75	24.016
61.88	24.164
61.01	24.312
60.14	24.460
59.27	24.608
58.40	24.756
57.53	24.904
56.66	25.052
55.79	25.200
54.92	25.348
54.05	25.496
53.18	25.644
52.31	25.792
51.44	25.940
50.57	26.088
49.70	26.236
48.83	26.384
47.96	26.532
47.09	26.680
46.22	26.828
45.35	26.976
44.48	27.124
43.61	27.272
42.74	27.420
41.87	27.568
41.00	27.716
40.13	27.864
39.26	28.012
38.39	28.160
37.52	28.308
36.65	28.456
35.78	28.604
34.91	28.752
34.04	28.900
33.17	29.048
32.30	29.196
31.43	29.344
30.56	29.492
29.69	29.640
28.82	29.788
27.95	29.936
27.08	30.084
26.21	30.232
25.34	30.380
24.47	30.528
23.60	30.676
22.73	30.824
21.86	30.972
20.99	31.120
20.12	31.268
19.25	31.416
18.38	31.564
17.51	31.712
16.64	31.860
15.77	32.008
14.90	32.156
14.03	32.304
13.16	32.452
12.29	32.600
11.42	32.748
10.55	32.896
9.68	33.044
8.81	33.192
7.94	33.340
7.07	33.488
6.20	33.636
5.33	33.784
4.46	33.932
3.59	34.080
2.72	34.228
1.85	34.376
0.98	34.524
0.11	34.672

Fig. 6: Outer Cone

Reflection of Synchrotron Radiation from Al H.O.M. Screen

JAK 6/15/81

Fig. 8

Fig. 9

Phase Space Plot (at I.P.)

Horizontal Plane

2.8m & 8.7m Masks

$K=0.25$

Fig. 21

Normalized Synchrotron Radiation Spectrum

J.A.K. (6/10/16)

Photon Number Distributions:

Defines E = photon energy, keV, ρ = radius of curvature, m,

$\gamma = (E_e/m_e c^2)$, u_r = energy radiated

Then: u_c = critical energy = $\frac{3}{2} \frac{h c \gamma^3}{\rho}$, $r = (E/E_c)$

$u_r = C_r \frac{N_e E_e^2 L}{2 \pi \rho^2}$, $C_r = 88.5 \text{ Wre.m/GeV}^2$

L = radiating path length, m

E_e = electron(s) energy, GeV

N_e = No. of electrons

1.0-

Integral Spectrum, F_n

Differential Spectrum, $10^{-2} f_n(r)$

Distribution Function:

$$\frac{du_r}{dE} = \left(\frac{u_r}{u_c^2} \right) F(r) \text{ : Defines } f(r)$$

$$F(r) = \int_r^\infty f(r) dr \text{ : Defines } F(r)$$

Normalized Distributions:

$$F_n(r) = \frac{F(r)}{F(0)}, F(0) = \frac{15 \sqrt{3}}{8} = 3.25$$

$$f_n(r) = \frac{f(r)}{F(0)}$$

$F_n(r), f_n(r)$

10^{-3}

10^{-4}

10^{-5}

0.01

0.1 $r = (E/E_c)$

1.0

10

Fig. A-1

(dN_γ/dE_γ(MeV))/E_{inc}(GeV)

E_γ distributions for photons
leaving mask into region ④,
vs. X (inc. e⁻ position)
(based on EGS computations)

- X = 0.1 cm
- X = 1.0 cm
- - - X = 3.0 cm
- - - X = 4.0 cm
- Δ X = 3.0 cm, 15 GeV e⁻

5 GeV e⁻

(dN_γ/dE_γ(MeV))/E_{inc}(GeV)

Fig. B-2

Fig. B-3

FIG. B-4

Fig. B-5

Photon Mass Attenuation Coefficients, Energy Deposition

Fig. B-6

$\frac{dN}{dN_L}$

$N_L = \text{No. of Latches/Event}$