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DIPOLE BACKGROUND AND COLLIMATOR DESIGN IN LEP

Very important point page 10
(radial collimators)

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ABSTRACT

The background in a drift chamber in a LEP experiment caused by the dipole synchrotron radiation is calculated using analytic and Monte Carlo techniques. A collimator configuration is proposed that shields the experiment at 50 GeV without requiring collimators nearer than 100 meters to the experiment. The same collimator configuration may also suffice at 85 GeV. At higher energies the dipole background becomes critical but change of material of the collimator should reduce it to acceptable values. *

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* This LEP note is a shortened version of an ISR/ES Technical note available from K. Potter.

INTRODUCTION

When moving from proton accelerators/storage rings to electron-positron storage rings, new problems appear because of the very intense synchroton radiation produced by bending the electrons in a magnetic field (due to the much higher e/m for electrons than protons). Futhermore the higher the energy of the electrons, the harder is the synchrotron spectrum. At LEP beam energies of 50, 85 and 125 GeV the critical energies of the synchrotron spectra are 95 KeV, 441 KeV and 1.49 MeV respectively. There is therefore a large fraction of source photons above the high photo-electric absorption region of all but the most heavy materials. The photons may therefore reasonably easily transport by Compton scattering.

This produces problems of radiation dose to materials in and outside the bending magnets, energy deposition in air and consequent toxic gas production, and background radiation in the experiments. In this report we look at the background in the experiments from photons born in the dipole (bending) magnets. It should be born in mind that there are other sources of background which may be higher, viz. the quadrupole magnet radiation, off-momentum beam particles etc. However the dipole background may serve to define possible collimator configurations along the long straight section (LSS), which then have a role in shielding the quadrupole radiation, produced in the quadrupoles along the LSS

Although the nearest dipole magnet (the 10% one) is 250 meters away from the experiment, the background requirement is so low compared with the intensity of the source that care has to be taken to shield the experiment from radiation from this dipole magnet, and from radiation from the full strength dipoles that are even farther away.

In conjunction with simple analytic techniques for calculating the uncollided photon flux, the Monte Carlo code MORSE (ref. 1) is used for the transport of photons. This code is used in reactor core and shielding calculations. It normally follows neutrons (from some MeV down to thermal energies) and only calculates photon transport as a result of neutron interactions (the gamma photons are produced by inelastic scattering of neutrons or neutron absorption). It may however be used equally for photon transport on its own although the energy binning of the photon cross-section sets used by MORSE is suitable for gamma rays rather than a synchrotron spectrum.

In the problem of shielding the experiment from the dipole radiation, it turns out that a reasonable estimate of the background may usually be obtained from one or two photon collisions. In this case Monte Carlo is not necessary. It is however very convenient for the calculation of the transport, and of the number of mean free paths between collision point and experiment, in the rather complicated geometry of the problem.

GENERAL CONSIDERATIONS OF THE PROBLEM

The problem is to calculate the photon transport along a 250 meters tube of about 100 cm^2 cross section. From the 10% magnet there are about 3.7×10^{15} photons per second and from each 100% magnet about 2.2×10^{17} photons per second (at 50 GeV for 2 beams of 5 mA each). The tolerance of the photon background in the experiment is between 10^7 and 10^8 photons per second (or between 10^2 and 10^3 per bunch crossing). An attenuation of at least 10^8 for the 10% radiation and at least 10^{10} for the 100% magnet radiation is thus required. A complete analogue Monte Carlo calculation would therefore be impossible.

In practice the photons follow a restricted set of paths from the source to the detector. These paths involve a few collisions near the source or first collision point, streaming all the way along the vacuum tube to the experiment and some collisions near the experiment. As this is a 6 - 10 meters long surface of the vacuum chamber wall inside the experiment, collisions near the detector are usually unimportant - unless a collimator is near the detector. MORSE incorporating the "next-event" estimator is appropriate for this problem (see Appendix 1). The large attenuations required are accounted for by distance of detector from collision point and by the large number of mean free paths in the aluminium wall of the vacuum chamber that a photon has to traverse so as to travel directly from a collision far along the vacuum chamber straight to the experiment. There are however cases when the photon has a much smaller distance to travel in material before streaming to the detector:

- when the collision is very close to the detector.
- when the photon collides in an intrusion in the vacuum chamber such as a collimator.
- when the collision is in the wall of the vacuum chamber in the curved part of the LEP ring just before the LSS where the 10% and 100% magnets are situated.

It is a general characteristic of streaming of neutrons and photons in straight ducts that the farther along the duct from the source the more anisotropic is the particle flux. Also the smaller the cross-section of the duct the sooner the high anisotropy is achieved. Where there is high anisotropy the particles are streaming straight along the duct with few collisions with the walls which do not then contribute to the flux farther along the duct. The Monte Carlo simulation need only follow the particle until collisions become unimportant compared with streaming. In such a long duct with small cross-section only a few collisions need to be considered. (Furthermore for relatively low energy synchrotron photons which lose energy at each scattering and are absorbed with high probability at low energy, the number of collisions which contribute and the region of space in which particles need to be followed is made even smaller).

An important feature of this problem is that the source photons are hitting the vacuum chamber wall at a very small angle to the surface. The first collision is then close to the surface and the number of mean free paths that the scattered photons must traverse without a further collision before emerging and streaming to the experiment is not too large. If the photon scatters in some other direction which it in practice will do, its next collision is likely to be some way below the surface of the vacuum chamber wall on the same side or on the other side of the vacuum chamber. In this case the number of mean free paths between the next collision and the detector becomes much larger and the probability of reaching the experiment without further collision (having scattered in the direction of the experiment) becomes very small indeed.

As already mentioned there are instances when these arguments may not hold. When collisions occur near the experiment, for example when collimators are placed near the experiment, there is a much larger range of paths by which photons can arrive at the experiment. When first collisions occur in a collimator farther away from the experiment or in the wall of the vacuum chamber in the curved part of the LEP ring, the contribution to the background from subsequent collisions can be comparable to that from the first collision, although the absorption probability makes subsequent collisions rarer. (In practice in the calculation particles were never absorbed but their weight reduced at each collision according to the non-absorption probability. An elimination/survival game (Russian Roulette) was then played below a chosen weight).

DETAILS OF THE CALCULATION

MORSE contains the general combinatorial package which allows the real situation to be accurately modelled. A detailed account of the geometry mock-up is given in an ISR-ES Technical note. Figures 1 and 2 show the general lay-out, whilst Figure 3 shows which parts of the vacuum chamber wall are illuminated by photons from the different magnets. Each dipole magnet was taken as 23.16 metres long with 3 metres straight sections separating them. We note that because of the curvature of the LEP ring, we must also take into account its illuminated vacuum chamber wall well below the line of the inner wall of the long straight section.

The response function of each detector (ref. 2) was the inverse of the maximum permissible number of photons allowed in a typical multi-wire drift chamber per bunch crossing for each energy group (see Table 1). The response was then a measure of the number of photons impinging on the vacuum chamber wall at the drift chamber compared with the maximum number permissible integrated over all photon energies. If the response was greater than unity, the number of photons entering the experiment would be above the tolerance, and vice versa if less than unity. However bearing in mind the errors involved in the calculation plus the other sources of background, unity response is in fact not tolerable - we require approximately one order of magnitude below unity or less for the dipole background. Note that the photons only need to score by impinging on the vacuum chamber wall in the experiment, the response function already including absorption and backscattering in the vacuum chamber wall inside the experiment.

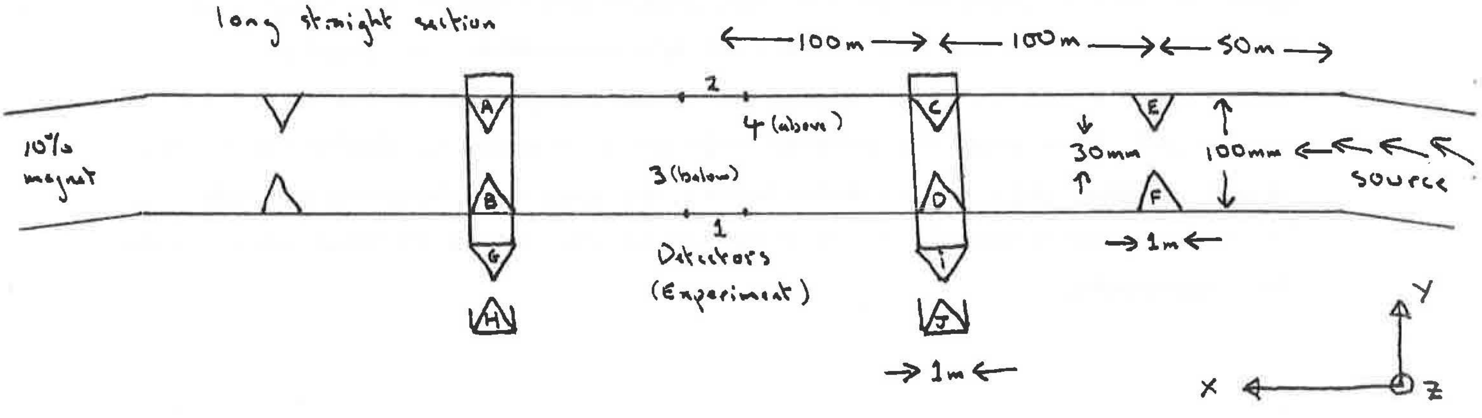
The appropriate synchrotron spectra were used for the 10% and 100% magnets for a 50, 85 and 125 GeV electron/positron beam, (see Tables 2A and 2B). The synchrotron source was sampled with energy, either according to the actual intensity, or evenly over all the energy groups (and then compensating with the weight). Its direction was on a tangent to the arc of the circle followed by the beam in each magnet, the starting position being found by sampling evenly over the arc of the circle. For the 10% magnet this circle had a radius of 35.456 km and for each 100% magnet a radius of 3.5456 km. This requires a bending angle over the 10% magnet of 0.03743 degrees, and over each 100% magnet of 0.3743 degrees.

The collimators used at the horizontal foci of the beam were wedge-shaped, either 3 metres or 1 metre long, and intruded into the vacuum so as to leave a gap of 30 x 30 mm^2 for the beam. Those used near the experiment were 30 cm long, annular, and left a gap of 80 mm diameter for the beam.

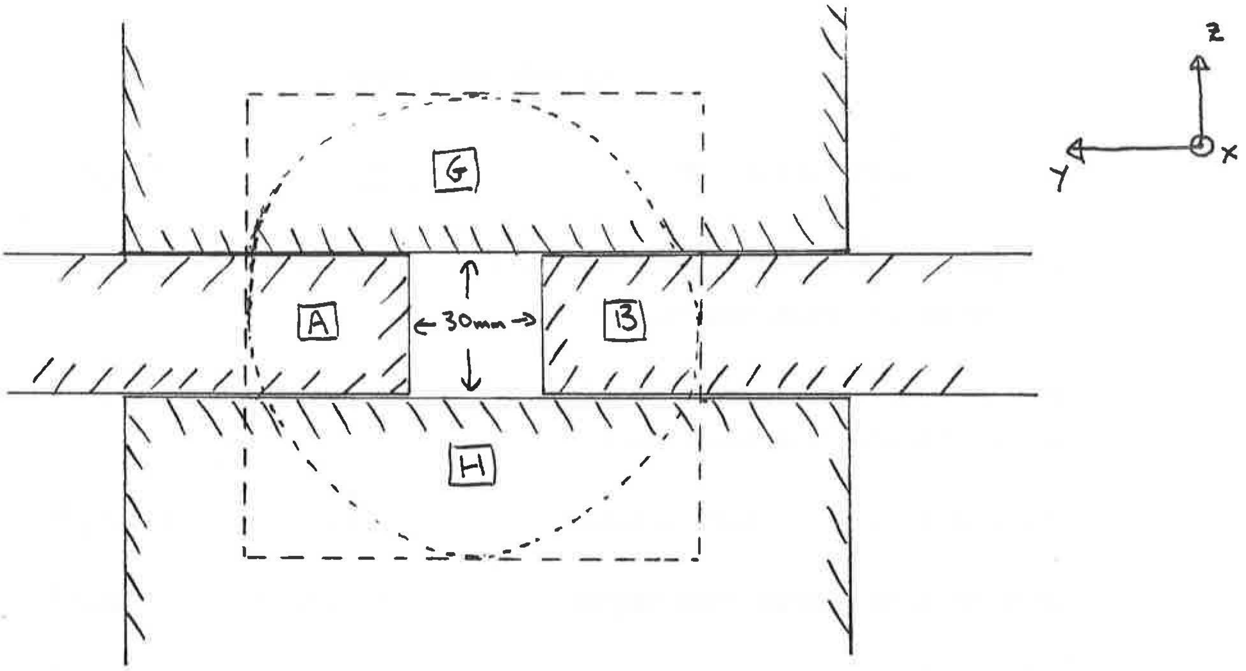
RESULTS

We wish to insert collimators in the vacuum chamber in the long straight section to reduce the background response in the experiment to well below unity. At the same time we wish to keep the vacuum chamber inside the experiment as narrow as the rest of the vacuum chamber in the long straight section, if possible, and also to try to avoid putting collimators too near the experiment when they might mask off small angle detectors.

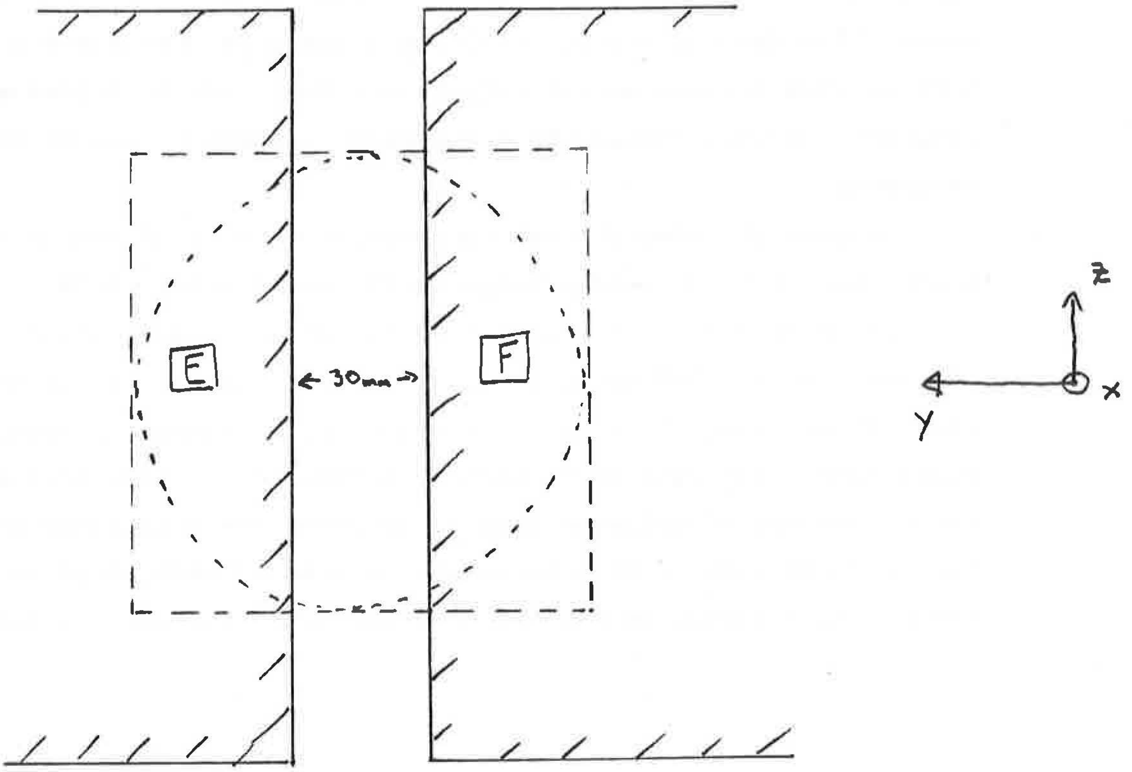
The following collimator configuration was designed to satisfy these conditions for a 50 GeV beam.



At 100 metres, on each side of the experiment, there are two pairs of wedge-shaped copper collimators one metre long, one pair in the plane of the paper, the other pair in the vertical plane. The cross-section at this point would be :



At 200 metres, on each side of the experiment, there is one pair of collimators in the plane of the paper. The cross-section at this point would be :



As these are horizontal foci, the collimators approach to within 15 mm of the beam axis. ($\gtrsim 7\sigma$)

The background responses from the different dipole magnets for all three beam energies are as follows (assuming 5 mA per beam for all beam energies) :

Background response

Beam Energy →	50 GeV	85 GeV	125 GeV
10% photons hitting far collimator A : at 100 metres from experiment	$2.2\text{x}10^{-3}$	$1.2\text{x}10^{-1}$	$7.5\text{x}10^{-1}$
10% photons hitting near collimator C : at 100 metres from experiment	$1.2\text{x}10^{-6}$	$6.5\text{x}10^{-3}$	$1.1\text{x}10^{-1}$
Photons from first 100% magnet :	$3.0\text{x}10^{-5}$	$1.9\text{x}10^{-5}$	$5.1\text{x}10^{-3}$
Photons from second 100% magnet :	$1.9\text{x}10^{-3}$	$2.2\text{x}10^{-2}$	$4.6\text{x}10^{-2}$
All dipole photons (total) :	$4.1\text{x}10^{-3}$	$1.5\text{x}10^{-1}$	$9.1\text{x}10^{-1}$

We see that the predominant background is from 10% photons that travel past the experiment and are reflected back from the collimator at 100 metres from the experiment. In Table 3 are shown the spectra of these photons as they impinge on the experiment. These may be folded with another response function should the background in another kind of detector be required.

Because of calculational approximations such as energy binning and truncation of the Legendre Polynominal series description of the angular scattering as well as neglection of the strong polarization of the source photons, the 125 GeV and possibly the 85 GeV background as well are unacceptably high (bearing in mind also the presence of other sources of background). The main contribution is from 10% photons hitting far collimator A. One way of reducing this is to place the collimator at 150 metres from the experiment. This particular source of background would then be reduced by a factor of only about a third. Furthermore, a number of extra difficulties are introduced when these collimators are at 150 metres from the experiment :

- for wedge-shaped collimators placed at 150 metres rather than 100 metres from the experiment, there is less attenuation of the 10% photons that would otherwise directly enter the experiment. For a 125 GeV beam, 3 metres long collimators are required at 150 metres. This is considering photons that may directly impinge on the vacuum wall in the experiment. If small collimators are placed near the experiment because of some other requirements such as shielding from quadrupole radiation, than the collimator at 150 metres must be 3 metres long and made of lead for a 125 GeV beam, whilst for an 85 GeV beam they may be 1 metre long only if they are made of lead. If at 100 metres from the experiment, the collimators may be 1 metre long and made of copper for all beam energies.

- collimator F fulfills the function of shielding the part of the vacuum wall inside the experiment on the outer side of the LEP ring (detector 2) from photons that have impinged on the vacuum chamber wall at the end nearest the long straight section of the second 100% magnet. These photons are actually born at the other end of the second 100% magnet. (If the vacuum chamber in the long straight section has a slightly larger radius than 10 cm, then also photons born at the beginning of the third 100% magnet are shielded by collimator F). When collimators A, B, C and D are moved out to 150 metres from the experiment, this leaves a clear path for these once-scattered photons to enter the experiment by passing above the tip of collimator F and below the tip of collimator C (even when collimator F is at 250 metres from the expriment right at the beginning of the long straight section). At 50 GeV this source of background would be tolerable but at 85 and 125 GeV might not be.

- collimators at 100 metres from the experiment also play a part in shielding the R.F. quadrupole radiation.

Another way to reduce the 10% background is to change the material of collimators A and C. A study of reflection coefficients of synchrotron radiation from various materials is being made. We may state here that changing the material of the collimators from copper to tantalum reduces the reflection coefficients of 85 GeV and 125 GeV 10% photons by 0.22 and

0.15. In fact because the radiation impinges at a small angle to the structure of the collimator and backscatters at roughly 180 degrees, only a thin layer of tantalum (roughly 0.02 cm) need be used. This modification should reduce the dipole background at 85 and 125 GeV to acceptable levels.

We now examine the function of each collimator by removing it and observing the increase in background. We do this for 50 GeV and extrapolate the results to 85 and 125 GeV using the ratios of the albedos at 50, 85 and 125 GeV of small angle scattering of 100% radiation from the aluminium walls of the vacuum chamber, 0.14, 0.21 and 0.23 respectively, and of 180 degrees backscattering of 10% radiation from copper collimators 0.0015, 0.013 and 0.044, respectively.

Collimators A and C protect the experiment from the direct 10% radiation. Their presence is strictly required. All other collimators could be removed and small annular collimators that intrude to within 40 mm of the beam axis, placed at 5 metres or so from the centre of the experiment. As has been seen A and C provide the highest dipole background from 10% photons that pass through the experiment and are reflected back. Their absence would produce an overwhelming background at all beam energies.

near
Q56
(between
Q55
& Q56)

Collimators B and D are required to shield detector 1 from photons from the first 100% magnet that are scattered from the vacuum chamber wall in the 10% magnet. Their other function would be to shield the experiment from photons scattered from the tip of a collimator placed on the outside of the LEP ring right at the beginning of the long straight section. This collimator, not in the diagram, would be in place for the purpose of shielding the first 38 metres or so of the vacuum chamber wall in the long straight section from direct photons from the first 100% magnet to reduce doses outside the vacuum chamber in the tunnel (see ref. 3). This source of background is however relatively small.

Collimator E is required to shield the experiment from photons from the first 100% magnet that directly impinge on the vacuum chamber wall in the first 38 metres of the long straight section and are scattered straight into detector 1. It is required even when a collimator is inserted right at the beginning of the long straight section to reduce the dose in the tunnel. If removed, the background response is raised by 2.4 for a 50 GeV beam and by 5.4 and 7.1 for 85 and 125 GeV beams respectively.

Collimators G, H,I and J shield detectors 3 and 4 (below and above the plane of the paper) from photons from the second 100% magnet that scatter from the vacuum chamber wall inside the first 100% magnet and stream directly to the experiment. Their absence would increase the background response by 1.2 at 50 GeV and by 2.7 and 3.6 at 85 and 125 GeV respectively.

Collimator F as already discussed shields detector 2 from photons born at the far end of the second 100% magnet (and the near end of the third 100% magnet if the vacuum tube is slightly wider in the long straight section). These photons scatter from the vacuum chamber wall at the near end of the second 100% magnet. In the absence of this collimator, the background response would be higher by 0.08 for a 50 GeV beam, and by 0.18 and 0.24 for a 85 and 125 GeV beam respectively.

As previously stated, collimators A and C must be retained. Instead of the other collimators, small annular collimators 1 cm deep (intruding to within 4 cm of the beam axis) and 30 cm long may be placed at 5 metres either side of the experiment. The total background response in the experiment from dipole radiation would then be of the following order (for copper annular collimators) :

50 GeV	85 GeV	125 GeV
2.6×10^{-3}	2.5×10^{-2}	4.7×10^{-2}

In this situation, most of the background comes from photons from the 100% magnets that are scattered once in the vacuum chamber wall in the beginning of the long straight section, in the 10%, first 100%, and near end of the second 100% magnets. This spectrum is harder than the source dipole spectrum and can reflect from or transmit past the small collimators near the experiment more easily than can the reflected 10% spectrum. Furthermore, in this case, there is no time delay between signal and dipole background, the path length of the 100% photons being similar to that of the beam electrons.

Finally, a number of points concerning the results can be noted :

- the calculation took account of the fact that the collimators at 100 and 200 metres from the experiment were wedge-shaped leaving a square aperture for the beam, the cross-section of the vacuum tube being circular. However, in the second option, the small collimators placed near the experiment must be annular;

- an estimated angular spread of 0.06 mrad of the 10% synchrotron radiation caused by orbit error and betatron motion is about half the angular spread required for 10% photons to start hitting directly the tip of the above-mentioned small annular collimators at 45° to the horizontal (i.e. to the plane of the LEP ring).

CONCLUSION

We must bear in mind the approximations that we have made to obtain the results:

- the binning of the synchrotron source spectrum into quite wide energy groups.
- the approximation of the angular scattering formulation which underestimates forward scattering.
- the neglection of the strong polarization of the source photons.

We wish therefore for a dipole background well below the tolerance because of these approximations and because other background sources are present. We wish also to try to avoid using small collimators near the experiment to leave room for the detection of particles at small angles. We would also like to try to keep the vacuum chamber as narrow as possible inside the experiment (if possible the same cross-section as the rest of the long straight section).

At 50 GeV, a collimator configuration has been reached that satisfies the above conditions, and gives a background level so far below tolerance that the approximations become unimportant.

This same collimator configuration gives backgrounds that may be acceptable at 85 GeV but are definitely too high at 125 GeV. However, coating the copper collimators with tantalum reduces the background to acceptable levels for all beam energies.

The photons that provide nearly all the dipole background are those from the 10% magnet passing through the experiment and reflected back from the collimator 100 meters away. They therefore arrive in the experiment some 670 nanoseconds after the signal.

Table 1

The Response Function.

Energy Group	Maximum number of photons permissible per bunch crossing	Response Function
21 (10- 20 KeV)	200	0.005
20 (20- 30 KeV)	100	0.01
19 (30- 45 KeV)	100	0.01
18 (45- 70 KeV)	300	0.0033
17 (70-100 KeV)	300	0.0033
16 (100-150 KeV)	300	0.0033
15 (150-300 KeV)	1000	0.001
14 (300-450 KeV)	1000	0.001

(In all the other energy groups 13 - 1, the response function is 0.001)

The numbers of photons permissible in each energy group are not mutually exclusive. If 150 photons in group 21 and 250 photons in group 17 entered the detector the total response would be 1.575. There would thus be about 60% too many photons entering the experiment, taking into account the importance of each group contributing to the backgound.

Table 2 A

The 10% magnet source.

(The number of photons per second from 2 beams of 5 mA each from a length of 10% magnet of 23.16 meters).

Group	Energy Bounds	Electron Energy Magnetic Field (Tesla)		
		50 GeV	85 GeV	125 GeV
		0.005373	0.009134	0.013433
8	2.5-3 MeV			4.0×10^{8}
9	2-2.5 MeV			8.8×10^{9}
10	1.5-2 MeV			3.2×10^{11}
11	1-1.5 MeV			1.4×10^{13}
12	700-1000 keV		1.3×10^{10}	1.3×10^{14}
13	450-700 keV		3.4×10^{11}	7.0×10^{14}
14	300-450 keV		1.3×10^{13}	2.0×10^{15}
15	150-300 keV	3.8×10^{8}	4.6×10^{14}	9.8×10^{15}
16	100-150 keV	1.0×10^{11}	1.3×10^{15}	7.4×10^{15}
17	70-100 keV	2.8×10^{12}	2.0×10^{15}	7.0×10^{15}
18	45-70 keV	5.1×10^{13}	4.2×10^{15}	8.6×10^{15}
19	30-45 keV	2.2×10^{14}	4.8×10^{15}	9.0×10^{15}
20	20-30 keV	3.5×10^{14}	6.4×10^{15}	8.8×10^{15}
21	10-20 keV	3.0×10^{15}	1.1×10^{16}	1.4×10^{16}
	Total	3.6×10^{15}	3.0×10^{16}	6.7×10^{16}

Table 2 B

The 100% magnet source.

(The number of photons per second from 2 beams of 5 mA each from a 100% magnet of length 23.16 meters).

		Electron Energy (Magnetic Field Strength)		
Group	Energy Bounds	50 GeV (0.005373T)	85 GeV (0.009134T)	125 GeV (0.013433T)
1	14-10 MeV			1.2×10^{14}
2	10-8 MeV			5.1×10^{14}
3	8-7 MeV			6.9×10^{14}
4	7-6 MeV			1.3×10^{15}
5	6-5 MeV		1.2×10^{12}	3.0×10^{15}
6	5-4 MeV		1.2×10^{13}	6.8×10^{15}
7	4-3 MeV		1.4×10^{14}	1.7×10^{16}
8	3-2.5 MeV		3.5×10^{14}	1.6×10^{16}
9	2.5-2 MeV		1.1×10^{15}	2.3×10^{16}
10	2-1.5 MeV		3.6×10^{15}	3.7×10^{16}
11	1.5-1 MeV	7.9×10^{11}	1.3×10^{16}	6.9×10^{16}
12	1000-700 KeV	2.8×10^{13}	2.2×10^{16}	6.9×10^{16}
13	700-450 KeV	4.6×10^{14}	4.1×10^{16}	9.3×10^{16}
14	450-300 KeV	2.6×10^{15}	5.1×10^{16}	8.9×10^{16}
15	300-150 KeV	1.7×10^{16}	1.0×10^{17}	1.5×10^{17}
16	150-100 KeV	2.1×10^{16}	5.8×10^{16}	7.4×10^{16}
17	100-70 KeV	2.4×10^{16}	5.1×10^{16}	6.0×10^{16}
18	70-45 KeV	3.4×10^{16}	5.8×10^{16}	6.9×10^{16}
19	45-30 KeV	3.3×10^{16}	5.1×10^{16}	5.6×10^{16}
20	30-20 KeV	3.5×10^{16}	4.5×10^{16}	4.8×10^{16}
21	20-10 KeV	6.0×10^{16}	6.9×10^{16}	7.4×10^{16}
Total		2.27×10^{17}	5.64×10^{17}	9.56×10^{17}

Table 3

10% magnet photons that enter the experiment (in the absence of collimators beside the experiment) having scattered from the far collimator at 100 meters from the experiment. (Divide by 4.5×10^4 to obtain the number of photons per bunch crossing, which may be then integrated with the response function to obtain a background that can be compared with unity).

Energy		Number of 10% photons entering experiment per second		
Group	Range	50 GeV	85 GeV	125 GeV
8	2.5-3 MeV			
9	2-2.5 MeV			
10	1.5-2 MeV			
11	1-1.5 MeV			5.9×10^{-1}
12	700-1000 KeV			3.2×10^{2}
13	450-700 KeV		2.0×10^{0}	3.3×10^{4}
14	300-450 KeV		9.5×10^{2}	2.2×10^{5}
15	150-300 KeV	1.3×10^{-2}	2.5×10^{4}	1.8×10^{6}
16	100-150 KeV	8.6×10^{-1}	2.3×10^{5}	4.1×10^{6}
17	70-100 KeV	1.2×10^{2}	3.0×10^{5}	3.6×10^{6}
18	45-70 KeV	2.8×10^{3}	4.1×10^{5}	9.0×10^{5}
19	30-45 KeV	5.0×10^{3}	1.6×10^{5}	3.0×10^{5}
20	20-30 KeV	2.7×10^{3}	3.9×10^{4}	4.1×10^{4}
21	10-20 KeV	2.4×10^{3}	7.2×10^{3}	7.7×10^{3}

References

1. M.B. Emmett, 'The MORSE Monte Carlo Radiation Transport Code System', ORNL-4972 (February 1975).
2. H.F. Hoffmann, Private Communication.
3. K. Burn et al., 'Dose Estimations for the LEP Main Ring', HS-RP/071 and LEP Note 248 (12.81).
4. D.E. Bartine et al., 'Production and Testing of the DNA Few-Group coupled Neutron Gamma Cross Section Library', ORNL/TM-4840 (March 1977).

APPENDIX 1

MORSE (ref. 1) uses the Monte Carlo Method to calculate the transport of neutrons and photons. Important features of the code for the particular problem of streaming of synchrotron photons down a long tube are:

- a division of the energy variable into groups, and the use of numerical cross-sections in this group structure. The cross-sections used were from the FEWG 1 data library (ref. 4), and used 21 photon groups from 14 MeV to 10 KeV. The group structure is as follows:

Group	Energy Range	
1	14-10	MeV
2	10-8	
3	8-7	
4	7-6	
5	6-5	
6	5-4	
7	4-3	
8	3-2.5	
9	2.5-2	
10	2-1.5	
11	1.5-1	
12	1-700	KeV
13	700-450	
14	450-300	
15	300-150	
16	150-100	
17	100-70	
18	70-45	
19	45-30	
20	30-20	
21	20-10	

The lower energy limit is adequate because of the very high absorption probability in all materials at low energy. Errors are however introduced when averaging the synchrotron spectrum over an energy group in energy regions where the spectrum has a high gradient. The averaging was made so as to deliberately overestimate the source, and the response may be too high by a factor of 2 for the 50 GeV 10% and 100% cases.

- the description of the angular scattering is in terms of a Legendre polynomial expansion in the cosine of the polar angle (note - the photons were assumed unpolarized so that the scattering was not a function of the azimuthal angle). The FEWG 1 cross-sections only contain an expansion up to P3 (i.e. the first four coefficients). Forward scattering at a small angle may therefore be somewhat underestimated (although a P8 run gave similar results). MORSE integrates up the angular scattering function into a number of angle bins using a generalised gauss quadrature. The number of bins depends on the order of Legendre polynomial used - for P3 it is recommended to use only 2 angular bins (for the polar angle - the azimuthal is sampled continuously). This is for "real" scattering - a continuous function for the variation of scattering probability with polar angle is used to compute the probability of scoring at each collision.

- the next-event estimator was used for scoring, which is the method in the standard "SAMBO" package available with MORSE. This estimator scores at each collision the probability of the photon emerging from the collision in the direction of the detector (the experiment) multiplied by the probability that the photon then reaches the detector without further collision. Thus very high attenuations may be accounted for by large distance from collision point to detector and large number of mean free paths between collision and detector. This means that a result is always obtained even if particles never arrive at the detector. For the result to be similar to the real result one must have a good sample of "last collision" events, i.e. of the collisions that are providing the important contributions to the result. In the case of the long vacuum tube the last collision events are clustered close to the first collision, apart from when there is a collimator close to the experiment. Then collisions in this collimator contribute to the response. In this case some other estimator, such as boundary crossing, must be used to score the number of photons entering the experiment.

- MORSE uses the combinatorial package which allows most geometries to be accurately simulated by using the unions and intersections of up to 9 different geometrical shapes.

- to improve statistics, particles are never absorbed in MORSE but their weight is reduced at each collision according to the non-absorption probability. Russian roulette is then played below a chosen weight. (This means below this weight particles are killed with a certain probability and if they survive their weight is increased so that overall weight is not lost. Further variance reduction schemes used were source biasing (equal source sampling with energy group was sometimes used), and non-leakage (where the variation of collision probability with distance travelled is modified to make leakage from the system impossible, and the particle's weight is modified to correct for sampling from the modified distribution).

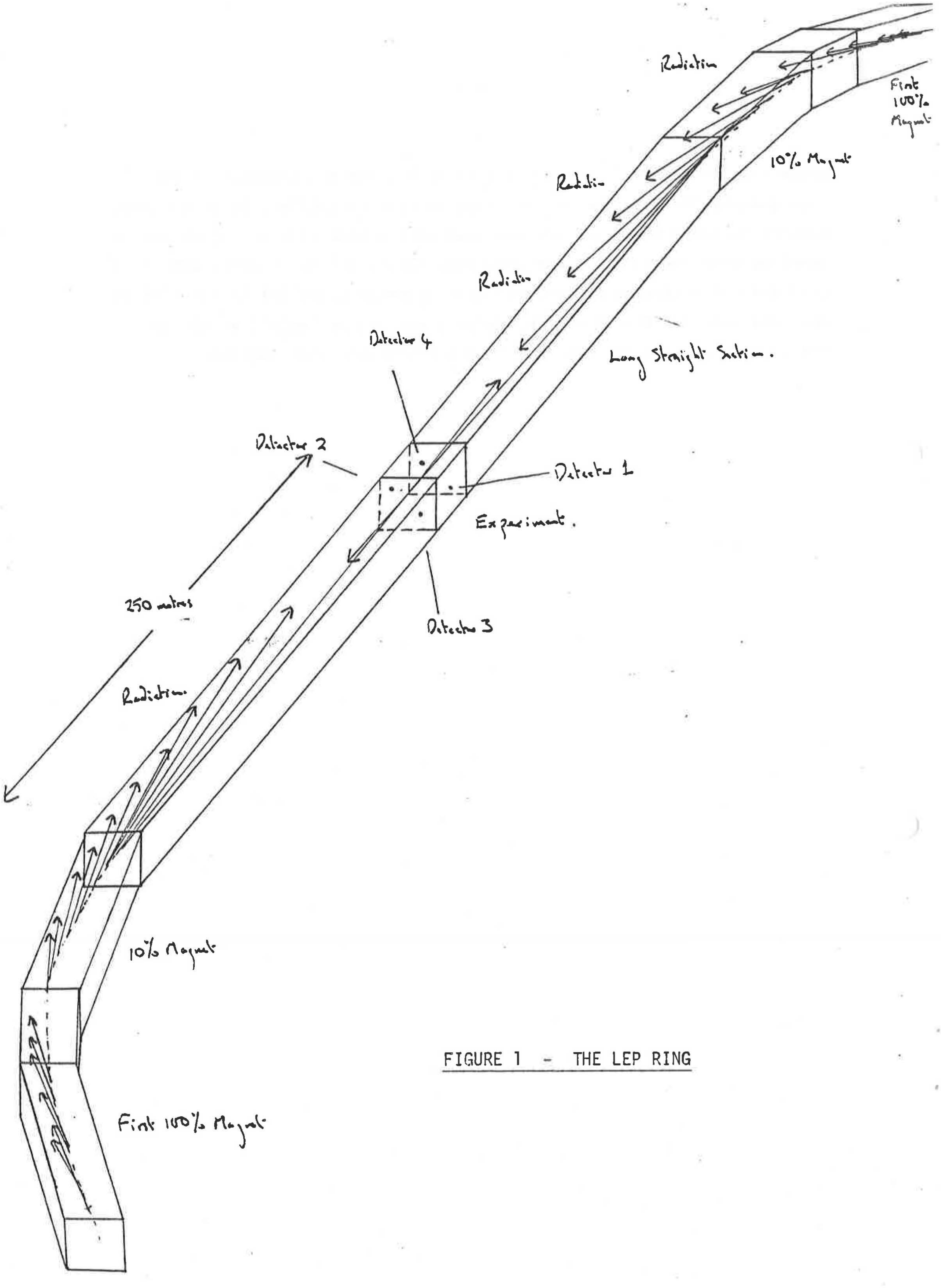


FIGURE 1 - THE LEP RING

FIGURE 2 - GEOMETRY OF THE LAST BENDING MAGNETS BEFORE THE LONG STRAIGHT SECTION (LSS)

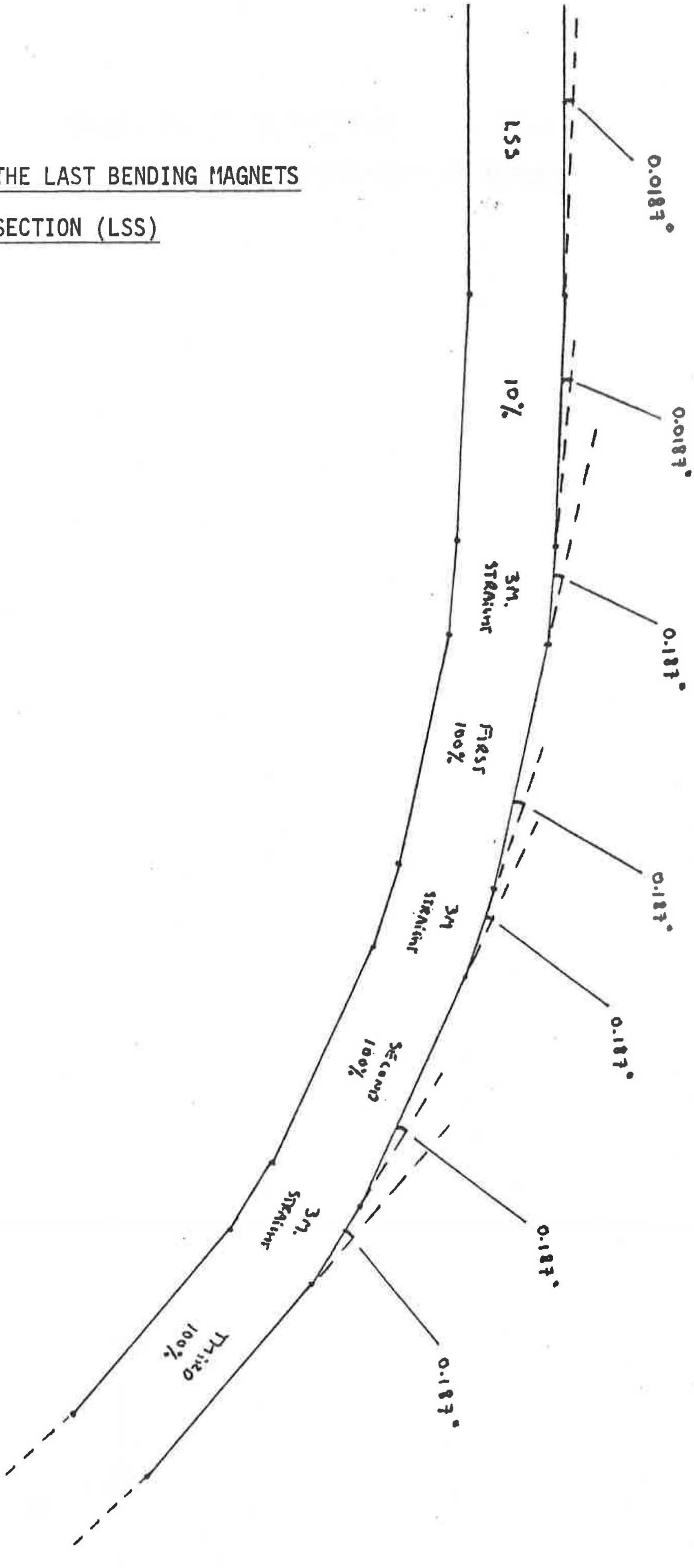


FIGURE 3 - ILLUMINATION OF THE VACUUM CHAMBER BY SYNCHROTRON RADIATION