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Features of the E-144 CCD Spectrometer, III
Shielding Against Synchrotron Radiation

Abstract

We present calculations of background hits in the CCD spectrometer due to synchrotron radiation x-rays for various configurations of shielding. The calculations reproduce the results of the May 1994 test to reasonable accuracy.

We propose to place two W/Cu collimators, each 25-30 X_0 long, between Clive's monitor and the 5D36 magnet. The (fixed) apertures for these collimators are given in Table 2.

The Compton γ's will be converted by a carbon wire located either next to the first collimator or just downstream of IP2. An in-vacuum motion stage for this will be provided by Princeton.

For the September 1994 run the CCD's will be mounted in air, but backgrounds from x-ray scattering in the air close to the CCD's are predicted to be overwhelming. We therefore propose to extend the vacuum line through the CCD spectrometer with a 1-cm-diameter tube.

1 Estimate of Synchrotron Radiation Flux

We have used the formulae of sec. 5.1 of SLAC-121 by M. Sands to estimate the flux of synchrotron radiation from various FFTB magnets relevant to E-144. The magnet parameters are listed in Table 1 and the results are shown in Fig. 1 for a bunch of 10^{10} electrons. In calculating the radiation from the final focus quadrupoles, we supposed that the electron beam was round and had $\sigma_x = \sigma_y = 1$ mm.

Table 1: Parameters of FFTB magnets considered in the synchrotron radiation calculations.

Magnet	B (Gauss)	L (m)	E_{critical} (keV)
Alnico dump magnet	4500	1	662
Soft bends	500	2	74
Very soft bends	60	2	8.9
Earth's magnetic field	0.33	50	0.049
Final Focus quadrupoles	9500 G/26 mm	2	≈ 75

The alnico dump magnet has the hardest spectrum, but since all of this radiation is at angles of at least 0.5 mrad to the E-144 γ-beam this should be maskable. All of the other magnets listed yield some radiation within 50 μrad of the γ-beam, which radiation cannot be masked, but must be survived. The Final Focus quadrupoles appear to be the biggest source of this class of radiation.

We have also included the effect of the earth's magnetic field, although this is not a problem for the CCD spectrometer. Rather, the earth's field appears to be the source of the radiation detected in the optical synchrotron radiation monitor!

2 Estimate of Synchrotron Radiation Backgrounds in the May 1994 CCD Test

In this test we found that when the CCD's were out of the γ-beam but within the aperture of the lead house (so-called position 2) there were still hundreds of hits in the CCD's when the 7 X_0 of Pb associated with Clive's monitor was in place, and thousands of hits when that lead was out of the beamline.

It is easy to see that the large fluxes summarized in Fig. 1 are troublesome. The desired signal of a high-energy electron in the CCD is about 1600 electron-hole pairs (80 pairs/μm

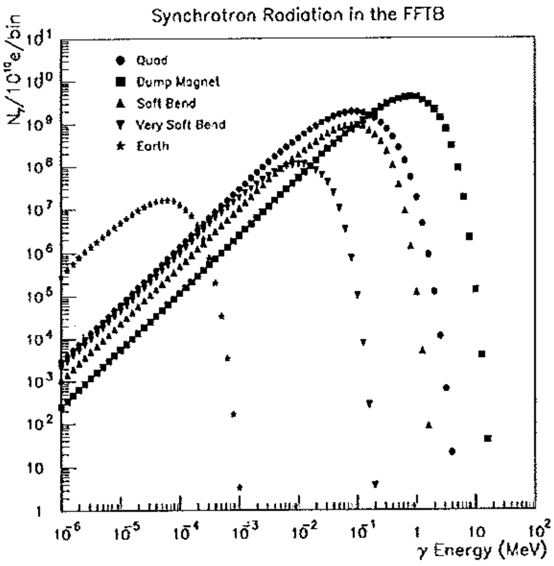

Figure 1: Calculated flux of synchrotron radiation from various FFTB magnets for 10^{10} electrons. Each point represents the sum over a bin in energy where $E_{\max} = 1.26 E_{\min}$.

$\times$ 20 μm effective collection thickness). Since it takes 3.6 eV to create each electron-hole pair on average, the desired signal corresponds to a deposited energy of about 6 keV in the CCD. Hence any synchrotron radiation photon with energy greater than 6 keV is a potential background.

In general, a synchrotron radiation photon can hit a CCD that is not in line with the beam only if the photon has scattered. Scattering (rather than absorption) of the synchrotron radiation photons is just Compton scattering (or Thomson scattering at energies below $\sim$ 100 keV) off atomic electrons. The scattering cross section at 6 keV is just $8\pi r_0^2/3 \sim 7 \times 10^{-25}$ cm^2. In most materials there are about 0.5 electrons per nucleon, which implies 6×10^{23} electrons in 2 gm. Hence the Compton scattering length is about 4 gm/cm^2.

The γ-line vacuum tube ended in a $1''$-thick aluminum plate, corresponding to about 7 gm/cm^2 or 1.75 scattering lengths. Hence that plate acted as an excellent diffuser, much the the detriment of the CCD's.

We have made an estimate of the number of hits in the CCD's due to scattered x-rays by convoluting the following ingredients:

1. The synchrotron radiation flux from Fig. 1.
2. The differential cross section, $d\sigma(E)/d\Omega$, for Compton scattering of the x-rays in the Al window, Clive's 7 X_0 of Pb, and the air along the latter part of the γ-line.

3. The absorption of x-rays between the scattering point and the CCD's, in air or in the packaging of the CCD's.
4. The absorption of X-rays in the active volume of the CCD's ($\approx 5 \times 10^{-3}$ gm/cm^2 to give a background hit.

The x-ray absorption length *vs.* energy for various elements was taken from a computer program we have at Princeton. Results for a few representative elements are shown in Fig. 2. We infer that the active layer of the CCD's is one absorption length thick for x-rays of energy about 6 keV, exactly the energy that mimics a minimum-ionizing particle.

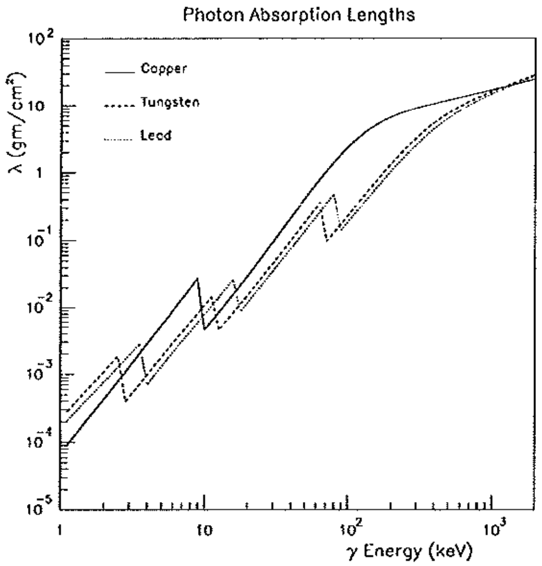

Figure 2: X-ray absorption lengths for various elements.

The results of the calculation are shown in Figs. 3 and 4, corresponding to Clive's 7 X_0 of pb being out, and in, respectively. The predicted rate of hits in the CCD's is similar to that observed, although perhaps somewhat on the low side. The qualitative agreement is good enough that we believe we can use our calculation to draw valid insights about synchrotron radiation backgrounds in other configurations, as considered in the following sections.

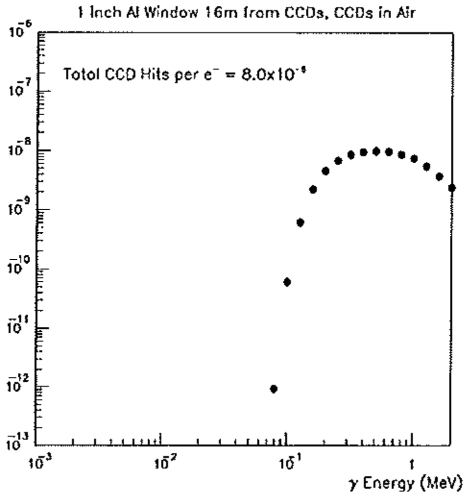

Figure 3: Calculated number of hits in a CCD 16 m downstream of a 1″-thick aluminum plate in the γ-beam.

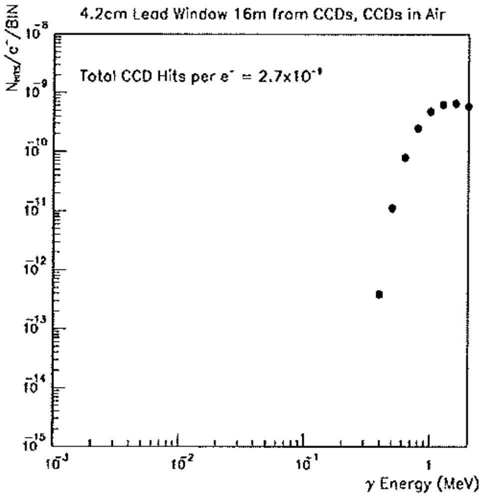

Figure 4: Calculated number of hits in a CCD 16 m downstream of 7 X_0 of lead associated with Clive's monitor in the γ-beam.

3 Proposed γ-Line Configuration for CCD's in Vacuum

We believe the x-ray backgrounds will be best reduced in a configuration of the γ-line in which the CCD spectrometer is in vacuum, with two W/Cu collimators upstream. In this section we suppose the CCD's are in vacuum and considered the needed arrangement of collimators. In the next section we consider an interim solution for the September 1994 run with the CCD's in air.

3.1 Collimator Thickness

Figure 4 shows that 7 X_0 of lead is not sufficient to attenuate synchrotron radiation with energy near 1 MeV. This is also apparent from the x-ray absorption lengths summarized in Fig. 2, which shows that the absorption length for 2-MeV x-rays is about 25 g/cm^2 $\approx 4\ X_0$.

The 20-μm-thick active layer of the CCD's corresponds to 5×10^{-3} gm/cm^2, so the probability of absorbing a 2-MeV photon is about 2.5×10^{-4}. Figure 1 shows that a bunch of 10^{10} electrons emits about 10^{10} such x-rays when passing through a single dump magnet. If we desire to shield this until only 1 x-ray per pulse is absorbed in a CCD, the attenuation factor must be 2.5×10^6, corresponding to 15 absorption lengths or 60 radiation lengths. We distribute this material between two collimator/absorbers, which should thus be 30 X_0 each.

For reasons of vacuum compatibility, the collimator material must be tungsten rather than lead.

3.2 Collimator Apertures and Spectrometer Acceptance

The first collimator should be located in just downstream of Clive's monitor, about 11.5 m downstream of IP2. The vacuum pipe is 4$''$ in diameter in this region. The second collimator should be located just upstream of the 5D36 magnet, about 24.5 m downstream of IP2. As discussed further below, we no longer propose to have the Compton convertor near the 5D36 magnet.

The scenario that determines the horizontal apertures of the two collimators is sketched in Fig. 5. The freedom to chose two apertures allows us to satisfy two conditions. After some thought we have taken these to be:

1. Photons emanating from the vicinity of IP1 that pass through the aperture of collimator 1 should not hit collimator 2. The stay-clear distance at collimator 2 was taken to be 0.5 mm for a ray emanating from the south edge of the beam at IP1 and grazing the north edge of collimator 1.

2. Photons that scatter off collimator 1 should be intercepted by collimator 2 before they strike the CCD's. Again, the stay-clear distance at collimator 2 was taken to be 0.5 mm for a photon scattering off the south edge of collimator 1 and pointing to the inner edge of the north CCD.

That is, the CCD's are protected against direct illumination by synchrotron radiation and against singly scattered x-rays. Protection against doubly scattered x-rays would require a third collimator.

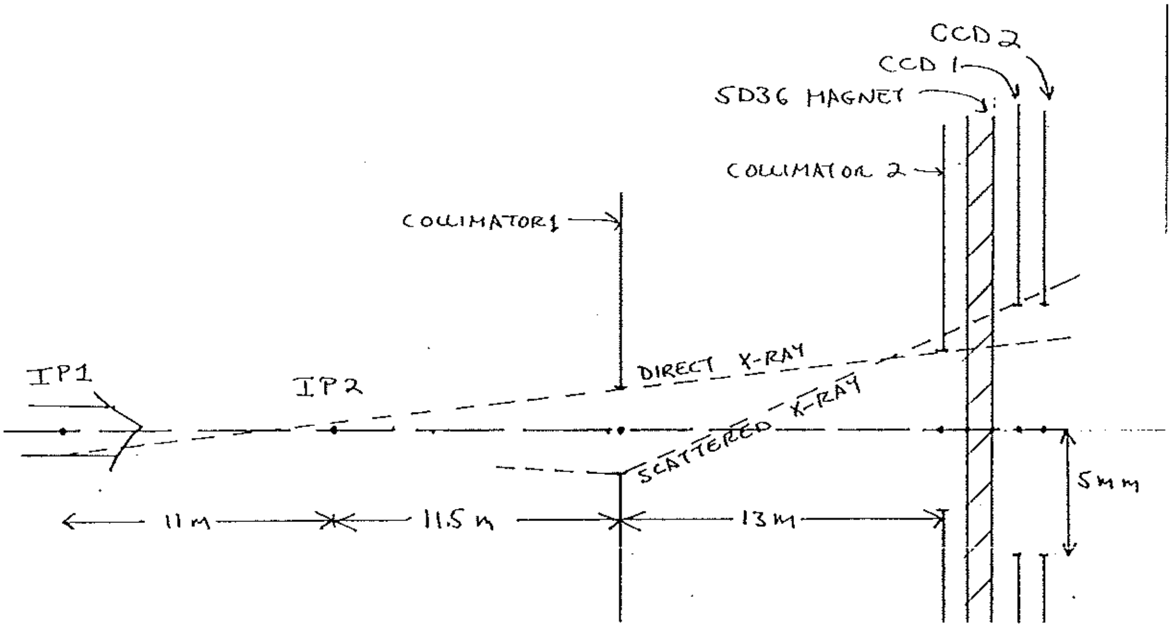

Figure 5: Top view of the γ-line showing proposed collimator apertures, and the scenarios that determine those apertures.

We then used a Monte Carlo simulation to study the effect of various strengths of the 5D36 magnet and various transverse positions of the CCD's. For each location of the CCD's, the corresponding apertures of the collimators were calculated according to the above criteria. A reasonable optimum was found using a kick of 125 MeV/c in the 5D36, and separation of 1 cm between the inner edges of the 2 CCD arms. The resulting acceptance for e^+e^- pairs produced by γ-laser interactions at IP2 is shown in Fig. 6.

The expected mass resolution for the reconstructed pairs is shown in Fig. 7. The position resolution for hits in the CCD was assumed to be 6 μm. The first CCD was 1 m downstream from the center of the 5D36 magnet, and the second CCD was 1 m downstream of the first. The mass resolution is better than 10 keV for all pair mass below 3 MeV/c^2, which has been our design goal.

The vertical apertures of the collimators were taken simply to lie along the line of sight from IP2 to the upper and lower edges of the CCD's. Table 2 summarizes various parameters regarding the collimators.

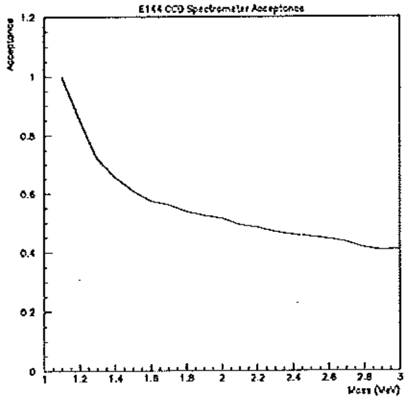

Figure 6: Calculated acceptance for the E-144 CCD pair spectrometer when located inside the FFTB tunnel 25 m downstream of IP2. The analysis magnet is a 5D36 with a kick of 125 MeV/c. The first CCD is 1 m downstream of the center of the magnet, and the second CCD is 1 m downstream of the first. The CCD's have active area 26 mm (H) × 17 mm (V), and their inner edges are 5.0 mm from the beamline.

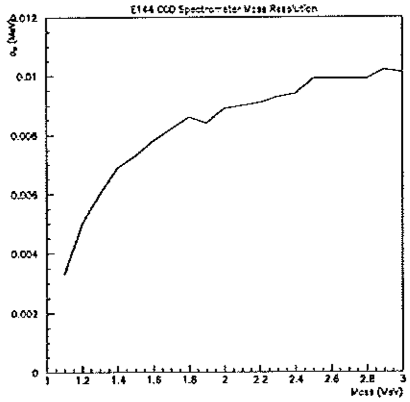

Figure 7: Calculated mass resolution for the E-144 CCD pair spectrometer in the conditions of Fig. 6. The CCD's are mounted via their edges so particles pass through only 300 μm of silicon in each detector plane. The detectors are assumed to be in vacuum for this calculation.

Table 2: Parameters of the proposed E-144 γ-line.

Device	Distance from IP2 (m)	x edge (mm)	y edge (mm)	Kick (MeV/c)
Final Focus	23.3			
IP1	11.0			
Collimator 1	11.5	±1.70	±5.46	
Collimator 2	24.5	±3.21	±8.54	
5D36 magnet	25.6			125
CCD1	26.6	±5-31	±8.6	
CCD1	27.6	±5-31	±8.6	

3.3 Compton Convertor

For the CCD pair spectrometer to analyze nonlinear Compton scattering, the Compton γ's must be converted upstream of the 5D36 magnet. Because the number of Compton γ's should approach 10^6 we desire to convert only a small fraction of these. We now propose to do this with a 10-μm diameter carbon wire, corresponding to about 5×10^{-5} X_0.

However, this wire presents about 2×10^{-3} grams to the synchrotron radiation, and could be a major source of scattered x-ray backgrounds. As the wire must intercept the γ-beam, the collimators will not serve to eliminate all of the scattered x-rays. Rather, we must place the carbon wire far enough upstream of the CCD's that their solid angle for scattered x-rays is sufficiently small.

The farthest upstream that the wire could be is about 4 m downstream of IP2, where there is presently a 6″ vacuum pipe. We made a calculation of the rate of x-ray hits in the CCD's supposing the wire is at this location, with results shown in Fig. 8.

It seems reasonably safe to place the wire 4 m downstream of IP2, some 22 m upstream of the CCD's. However, the mechanics of placing the wire there are complicated by the requirement that no material can be within 3 inches of the beam during FFTB beam studies (so Clive's monitor has a clear view of the Final Focus). To accomplish this we could use the large 5-way cross and air cylinder now in use with the optical synchrotron monitor, along with the precision stage sketched in Fig. 9. We do not have a detailed drawing of the whole assembly at present.

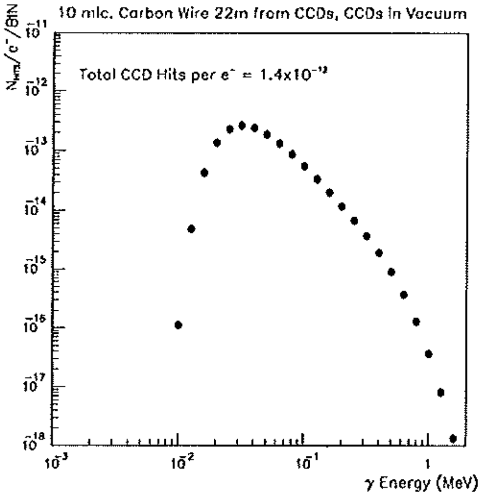

Figure 8: The calculated rate of synchrotron radiation photons scattered by the Compton-convertor carbon wire that subsequently cause background hits in the CCD's.

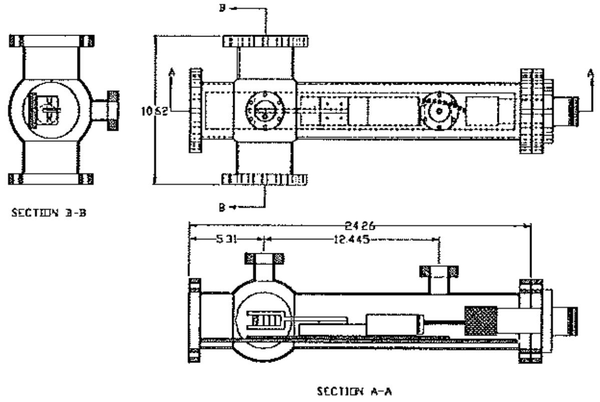

Figure 9: Sketch of an assembly to hold the carbon wires that convert Compton γ's if located in a 4″ vacuum pipe near collimator 1.

We could also place the carbon wire next to collimator 1, 11 m downstream of IP2 and 14 m upstream of the CCD's. In this position the solid angle of the CCD's is about double that just considered, and so the x-ray rates would double. This is also likely acceptable. Figure 9 sketches an assembly to accomplish this. A custom cross of 4″ tubing houses the Aerotech stage recently used in the CCD tests. An electrical feedthrough on a Conflat flange permits in-vacuum use of the stage. A fork contains three carbon wires of various diameters and a

1-cm-wide foil to study Compton conversions in several conditions.

If the carbon wire were placed near collimator 2, only 2 m upstream of the CCD's the rate of scattered x-rays would be two orders of magnitude higher than that predicted in Fig. 8. This is likely unacceptable, and we no longer consider locating the convertor here.

The final decision on placing the convertor wire upstream or downstream of Clive's monitor remains to be made. If the wire is upstream of Clive's monitor, collimator 1 will shield the CCD's from much of the scattered x-rays, but the mechanics are more complicated.

4 Proposed γ-Line Configuration for CCD's in Air

For the September 1994 run will not be able to mount the CCD spectrometer in a vacuum box, but we can have a setup with the CCD's in air. However, the May 1994 test showed that x-ray backgrounds are too severe for track reconstruction unless proper shielding is added.

We propose to install the collimators discussed in the previous section, and extend the vacuum line through the CCD spectrometer for the September 1994 run.

An important issue is where the vacuum line ends. Any window, and the air beyond that window, are major sources of scattered x-rays. We now believe the only viable solution is to have the vacuum window downstream of the CCD's. This presumes a special section of vacuum pipe downstream of the 5D36 magnet, sketched in Fig. 10, that would only be used in the September 1994 run. This pipe has an outer diameter of 1 cm, and should be at least 3 m long.

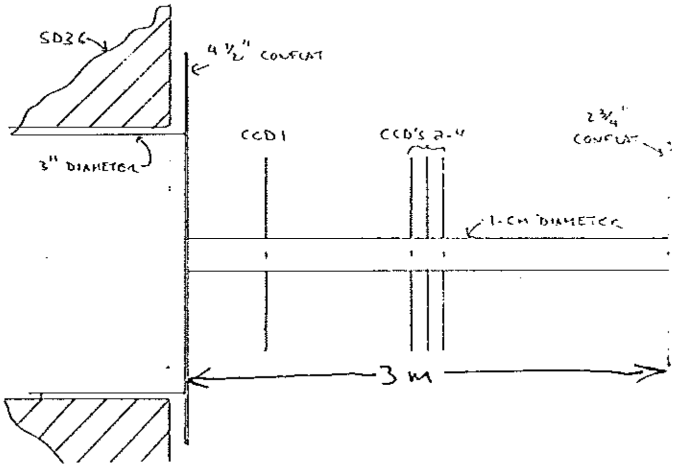

Figure 10: Proposed vacuum line extension through the CCD spectrometer for the September 1994 run.

To see the need for such a pipe, we have calculated the number of scattered x-ray hits in the CCD's supposing the vacuum pipe ends just after the 5D36 magnet, 50 cm upstream of the first CCD. Results are shown in Fig. 11, and seem quite unacceptable. Very similar results were obtained if the vacuum pipe ends just upstream of the 5D36 magnet. The problem is scattering in the air very close to the CCD, which can only be solved by having the γ-beam in vacuum in the vicinity of the CCD's.

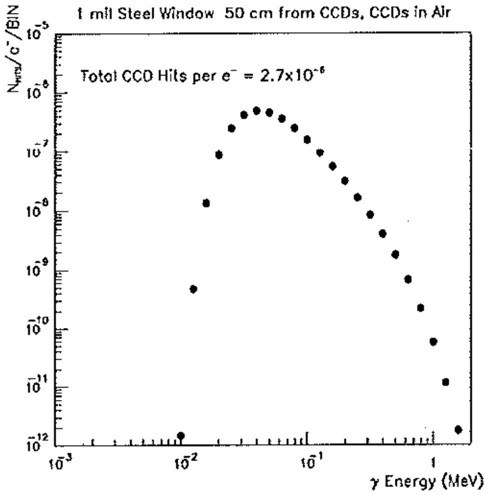

Figure 11: The calculated rate of synchrotron radiation photons scattered by the air downstream of the 5D36 magnet that subsequently cause background hits in the CCD's.