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DIAGNOSTIC BEAM LINE FOR A THIRD GENERATION STORAGE RING*

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Diagnostic Beam Line for a Third Generation Storage Ring*

by

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Abstract

A knowledge of the position, size, and stability of the source and the angle of emission of synchrotron radiation (SR) from the storage ring are essential for optimizing the operation of storage ring, insertion devices and monochromators. Berkeley's Advanced Light Source (ALS) has a natural emittance of 3.4×10^{-9} m-rad , and has beam sizes σ_h and σ_v (assuming a 10% emittance ratio into the vertical direction) in bending magnet 1 (BM1) of 44 μm and 83 μm respectively.

Simple diffractive optical calculations show that imaging this beam using visible light optics is not feasible and imaging must be performed using photon energies greater than 50 eV. This will be the same for all third generation low emittance storage rings.

The synchrotron radiation diagnostics at ALS will consist of an imaging system for 200 eV photons and a "white beam" port with a streak camera to obtain the timing information. The imaging system will employ two crossed spherical mirrors in a Kirkpatrick-Baez configuration, to eliminate astigmatism. Use of 1:1 imaging will eliminate coma, resulting in an image of the source which is only limited by the residual aberrations of the optics. Real time imaging of the beam is deemed feasible by the use of a high resolution CCD, and the associated electronics necessary to read the CCD. The design of the imaging system of the diagnostic beam line for ALS and the detection system will be discussed with a view toward applications in other third generation SR sources.

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1. Introduction

Precision imaging of the electron beam using synchrotron radiation, is planned as a means of measuring the transverse dimensions of the electron beam in the ALS storage ring[1]. Additional information will be obtained from this diagnostic device about the positional stability and length of the bunch. These measurements are essential for optimizing the operation of storage ring, insertion devices and monochromators.

The diagnostic beamline will be installed at the first bend magnet following the RF straight. It will use radiation delivered to a restricted space on the experimental floor, an area least suitable for user beamlines. The vertical electron beam size is at its largest at all bend magnet 1 (BM 1) and BM 3 positions in the storage ring lattice.

The bend magnet field is B = 1.069 T. The critical energy is given by:

$$\varepsilon_c(\mathrm{keV}) = 0.665\ E^2\ (\mathrm{GeV})\ B(\mathrm{T}) = 1.60\ \mathrm{keV}$$

For the ALS, when operating at 1.5 GeV, the approximate opening half-angle of the radiation at the critical energy is ,

$$1/\gamma = m_e c^2 / E = 0.34\ \mathrm{mrad}$$

The ALS has a natural rms horizontal emittance [1] of 3.4×10^{-9} m rad. Assuming a 10% emittance ratio into the vertical direction, the beam emittances are:

$$\varepsilon_h = 3.4 \times 10^{-9}\ \mathrm{m\ rad}$$

and

$$\varepsilon_v = 3.4 \times 10^{-10}\ \mathrm{m\ rad}$$

In bend magnet 1 the horizontal and vertical beta functions (β_h and β_v) take the values 0.394 m and 20.3387 m respectively[1] and the horizontal dispersion, D_h is 0.0301. The relative momentum spread, $\Delta p/p$, is 8×10^{-4}. Therefore, the rms beam sizes are:

$$\sigma_h = (\varepsilon_h \beta_h + D_h\ \Delta p/p)^{1/2} = 43.8\ \mu\mathrm{m}$$

and

$$\sigma_v = (\varepsilon_v \beta_v)^{1/2} = 83.2\ \mu\mathrm{m}$$

2. Optical Design

The rms beam sizes σ_h and σ_v in ALS bend magnet 1 are 44 μm and 83 μm, respectively. The numerical aperture (N.A.) which specify the "light-gathering power" of the imaging system is defined as the sine of the angular semi-aperture multiplied by the refractive index of the medium. The (rectangular) N.A. required by an imaging system utilizing photons of wavelength λ is:

$$N.A = \lambda/2d$$

where d is the image resolution .

If the resolution of the proposed imaging system is to be $\sigma/4$, resulting in a broadening of the image due to diffraction by about 3%, then the vertical numerical aperture must be:

$$N.A._v \geq 2.4 \times 10^{-6}\ \lambda(\text{Å})$$

We propose to use a vertical focussing mirror collecting 1 vertical milliradian ($N.A._v = 5 \times 10^{-4}$), which means:

$$\lambda \leq 207\ \text{Å}$$

As the wavelength becomes shorter, the divergence is less. Figure 1 shows the spectral and angular distribution of bend magnet radiation. At about 400 eV the radiation no longer fills this mirror, but the required $N.A._v$ has also become smaller and is filled for this and all shorter wavelengths.

Since the horizontal beam size is smaller than the vertical size, the horizontal numerical aperture must satisfy the following condition:

$$N.A._h \geq 4.5 \times 10^{-6}\ \lambda(\text{Å})$$

This corresponds to a mirror subtending 1.9 horizontal milliradians at 207 Å. We propose to collect 2 horizontal milliradians.

We now consider the depth of focus $\approx \lambda/N.A^2$. The local radius of the electron orbit is 4.8 m, so that by collecting 2 horizontal milliradians we are creating a source 9.6 mm deep. If the middle of the source is in focus, the ends will be defocussed with a horizontal ray deviation at the image equal to:

$$N.A._h \times 4.8\ \text{mm} = 4.8\ \mu\text{m}$$

Since this is less than the desired horizontal resolution, the aperture is sufficiently small.

I. Kirkpatrick-Baez imaging system.

In 1948, Kirkpatrick and Baez[2] devised a simpler method to eliminate the astigmatism of a single mirror used at glancing incidence. Their optical system uses two crossed spherical mirrors, so that the tangential rays, strongly focused by the first mirror, become the sagittal rays for the second mirror and are weakly focused. Similarly, the sagittal rays of the first mirror become tangential rays for the second mirror. Since the mirrors focus the corresponding sagittal rays so weakly, the spherical mirrors could equally well be cylindrical mirrors. This method essentially eliminates the astigmatism, and a use of 1:1 focusing system will eliminate coma. Hence resolution is limited only by the residual aberrations.

A schematic diagram of the proposed imaging system is shown in Figure 2. A vertically deflecting mirror (M_1) located at 5.70 m from the source, will focus the beam (vertically) at 12.20 m and the second mirror (M_2) located at 6.10 m from the source focus the beam horizontally at the same position. Mirrors are positioned such that the glancing incidence angle for the principal ray, for M1 and M2 are 1.5 and 2.0 degrees respectively. The focussing properties of these two mirrors must satisfy the Coddington's equation

$$\frac{1}{u}+\frac{1}{v}=\frac{2}{R\sin\theta}$$

Where u and v are object and image distances and R the radius of curvature of the mirror. The calculated spherical radii for the two mirrors M_1 and M_2 are 232.03 m and 174.79 m, respectively.

II. Ray tracing the beam line

The x-ray optics ray tracing program[3] SHADOW, based on the geometrical optics tracings of the rays propagating through an optical system formed by sequential surfaces was used. ALS BM1 source was modeled assuming random (Monte Carlo) distributions in both real and momentum space. The parameters used in generating the BM source using SHADOW are presented in Table 1 and cross-section of the synchrotron radiation source at the waist of the BM1 is shown in Figure 3. Ray tracing of the imaging system was performed. Figure 4 shows the image plane computed by ray tracing program, neglecting the figure errors of the two mirrors. Comparing Figs. 3 and 4, the resulting aberrations are small and the image quality is better than the resolution of the proposed imaging system and the detector.

3. Detector

For imaging of the beam, shape as opposed to position and determining beam dynamics, an image size of 10σ (σ_v=830 μm, σ_h=440 μm) would be considered useful. In order to visibly observe changes in the beam dynamics, it will be necessary to have spatial resolution of the electron beam better than $\sigma/2$. The limiting dimension of the beam in the first bend magnet is in the horizontal plane which is 44 μm.

Current CCD's now have resolutions better than 25 μm and the CCD that we are currently evaluating has a pixel size and spatial resolution of 6.8 μm, while the total number of pixels per CCD is on the order of 10^6. The frame rate of reading such a CCD at 5 x 10^5 pixels per second is on the order of 2 seconds. This would present a problem of producing a real time image which is usually associated with time scales on the order of television frame rates which are 1/30 sec. Fortunately the size of the beam is small enough that we can divide the CCD into subsets, and read only the pixels that are basically illuminated by the synchrotron radiation. Unfortunately the number of pixels required to see the image at 1/30 sec has an area approximately equal to 10 σ of the beam. This does not allow for any gross beam motions which would allow the beam to wander off of the subset region, and therefore become lost on the CCD.

This problem can be solved by allowing the pixels of the CCD to be binned[4] Binning is a process which reads the data from more than 1 set of pixels at a time. In other words, if the data collection area were originally a 1 x 1 pixel, then by binning, one could increase the data collection area to 2 x 2 pixels, or 3 x 3 pixels, etc. This reduces the resolution of the image, but brings the integration time of the data back down to a real time display rate. Thus for viewing dynamic oscillations of the electron beam in a stable or motionless orbit, the CCD can be put into a high resolution mode. If the beam should wander, software limits can note the motion, and switch the CCD into a lower resolution binning mode, which can then keep track of movements of the beam. Even with 4 or 9 pixel bins, the CCD image will still have a resolution of better than 25 μm.

Another problem associated with the use of the CCD is the saturation limit of the pixels. The CCD under consideration has a saturation limit of 45,000 electrons. For simplicity if we assumed a 0.01% conversion efficiency of photons to electrons, then for the ALS BM 1 at about 200 eV, the photon flux would be on the order of approximately 10^{13} photons per second and would therefore provide more than 10^{10} electrons per second to the detector. This would constantly saturate the CCD and prevent any type of imaging of the beam. In addition deposition of 10^{13} photons per second on the CCD in such a small spot size would cause thermal loading on the CCD which would have deleterious effects. Also because the light is not monochromatic, lower energy photons (visible light) will reach the detector, and provide additional signal and broadening of the image due to diffraction. Two methods can be applied together that will help to alleviate these problem.

The first method is to build a filter box which will produce a notch in the spectrum that will restrict the photons that reach the detector to a small region around the 200 eV range. This is far less expensive and both optically and mechanically simpler than building a monochromator which passes only 200 eV photons. A 10 μm thick carbon foil will be utilized to filter the low energy photons and two carbon-coated mirrors will filter out the high energy photons. Computed[5] flux through the gold-coated M_1 and M_2 mirrors and the filter/mirror combination in the filter box is shown in the figure 5 along with the spectral flux from the BM 1 within a 2-mr horizontal angle and all vertical angles. As seen from Fig. 5 about 40 eV wide band of radiation peaked at about 220 eV will reach the imaging detector. By incorporating carbon-coated mirrors in the filter box, we can also adjust and always maintain a maximum image signal to the detector by increasing or decreasing the incidence angle of the beam to the mirror as seen from net flux curves in Fig. 5. This will always provide an optimal signal to noise ratio for the detector, regardless of the current stored in the storage ring.

The second method which will aid in reducing the photon flux to the detector, is the conversion efficiency of the phosphor that will be required to convert the 200 eV photons to a wavelength that the CCD will be sensitive to. For 450 nm photons, the CCD under consideration has a quantum efficiency of 10%. Thus by choosing the right phosphor, with the appropriate conversion efficiency, and resolution requirements, we should be able to bring the signal level of the CCD to well within its maximum saturation limit of 45,000 electrons.

4. Conclusion.

We have designed a simple beamline based on a Kirkpatrick-Baez mirror configuration for precision imaging of the electron beam at the ALS. This beamline will allow the accelerator physicist to measure the transverse dimensions of the beam in real time. The quality of the image is extremely sensitive to thermal loading and residual aberrations. With proper design and detailed analysis, we believe these problems to be solvable[6]. Real time imaging of the beam is deemed feasible by the use of the appropriate phosphor, a high resolution CCD, and the associated electronics necessary to read the CCD. This beamline is scheduled to be in operation by April of 1992 to facilitate the commissioning of the ALS storage ring.

REFERENCES

1. ALS Handbook, Lawrence Berkeley Laboratory, Berkeley, CA. PUB-643 Rev. (1989).
2. P. Kirkpatrick and A. V. Baez, J. Opt. Soc. Am. **39**, 766 (1948).
3. B. Lai and F. Cerrina , Nucl. Inst. Meth. **A246**, 337 (1986).
4. S. Gruner, Rev of Sci. Inst. **60**, 1545, (1989)
5. M. M. Thomas, J. C. Davis, C. J. Jacobsen, and R. C. C. Perera, Nucl. Inst. Meth. **A291**, 107 (1990).
6. A. Warwick and S. Sharma, (to be published).

TABLE 1: Source Description of ALS Bend Magnet 1.

```
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

Random Source.
Generated total        2000 rays.
Source assumed TRIDIMENSIONAL.
Source Spatial Characteristics: GAUSSIAN
                  Sigma X :  0.37 E-02  cm    Sigma Z :  0.83 E-02 cm
Depth:  SYNCHROTRON SOURCE.
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

Source Emission Characteristics
Distribution Type: SYNCHROTRON
Distribution Limits.                X :  2.0 mrad
                                    Z :  1.0 mrad
Magnetic Radius =    4.81 m.      Beam Energy =   1.5 GeV.
Beam Emittancies. EPSI_X:  0.9189 E-04  rad EPSI_Z:   0.4096 E-05 rad
Distance from Waist.    X:  0                       Z:  0
Polarization Used: SR TOTAL

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

Source Photon Energy Distribution: SINGLE LINE
Photon Energy:  200 eV, or   61.99 Å.
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FIGURE CAPTIONS

1. Angular and spectral distribution of photons from an ALS bend magnet operating at 400 mA and 1.5 GeV.

2.. A schematic diagram of the diagnostic bend magnet beam line at ALS. The visible light beam line for timing measurements will be developed later.

3. The cross-section of the synchrotron radiation source at the waist of the ALS BM1 modeled by the ray-tracing program SHADOW.

4. The image at the detector computed by SHADOW

5. Computed flux through the M_1 and M_2 mirrors and a 10 μm thick carbon foil plus two carbon mirrors (at 5 degrees and 8 degrees) in the filter box along with the spectral flux from the BM 1 within a 2-mr horizontal angle and all vertical angles. As seen from calculated flux curves about 40 eV wide band of radiation peaked at about 220 eV will reach the imaging detector.

Beamline Flux
vs.
Energy and Angle

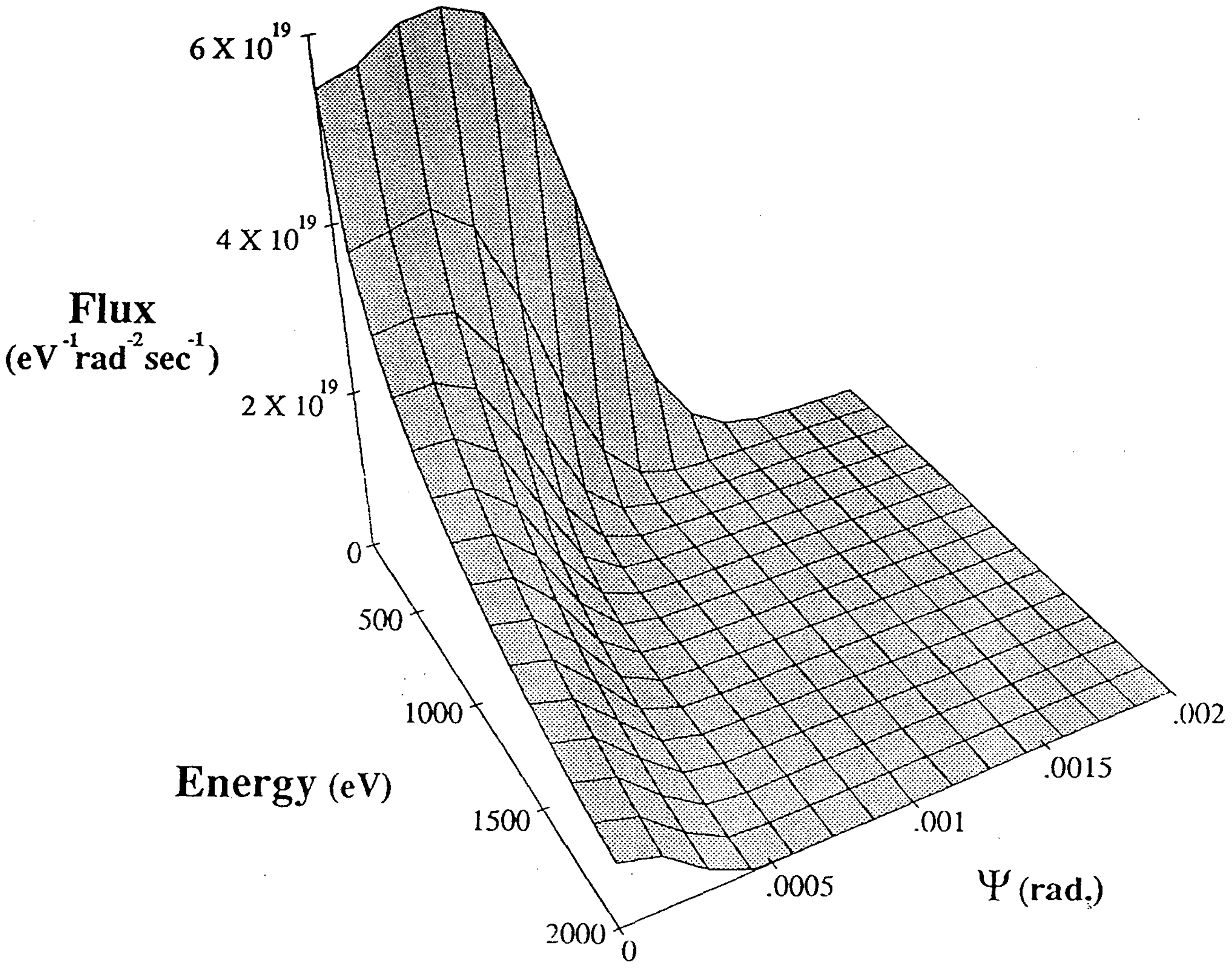


Figure 1

Diagnostic Bend Magnet Beamline

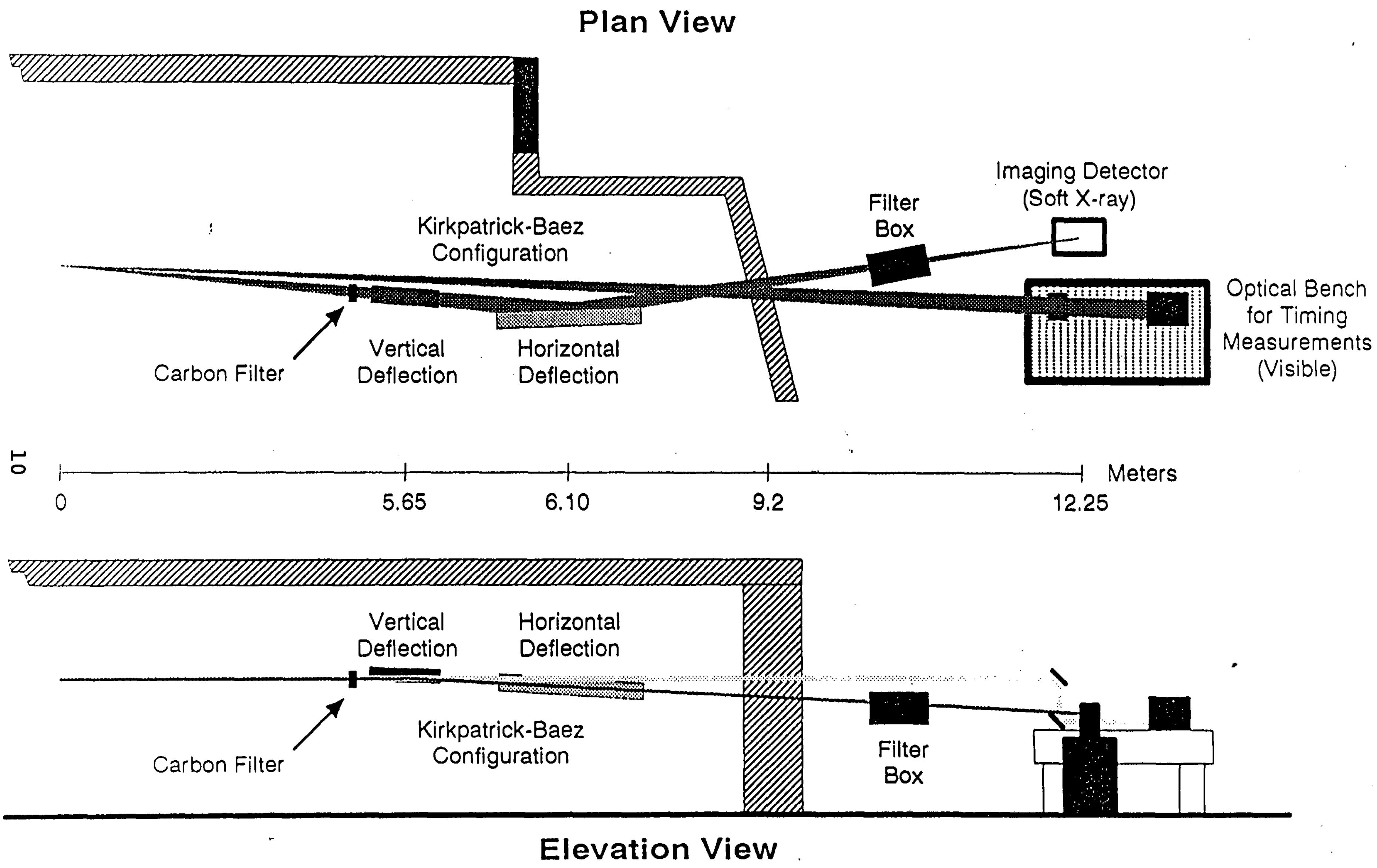
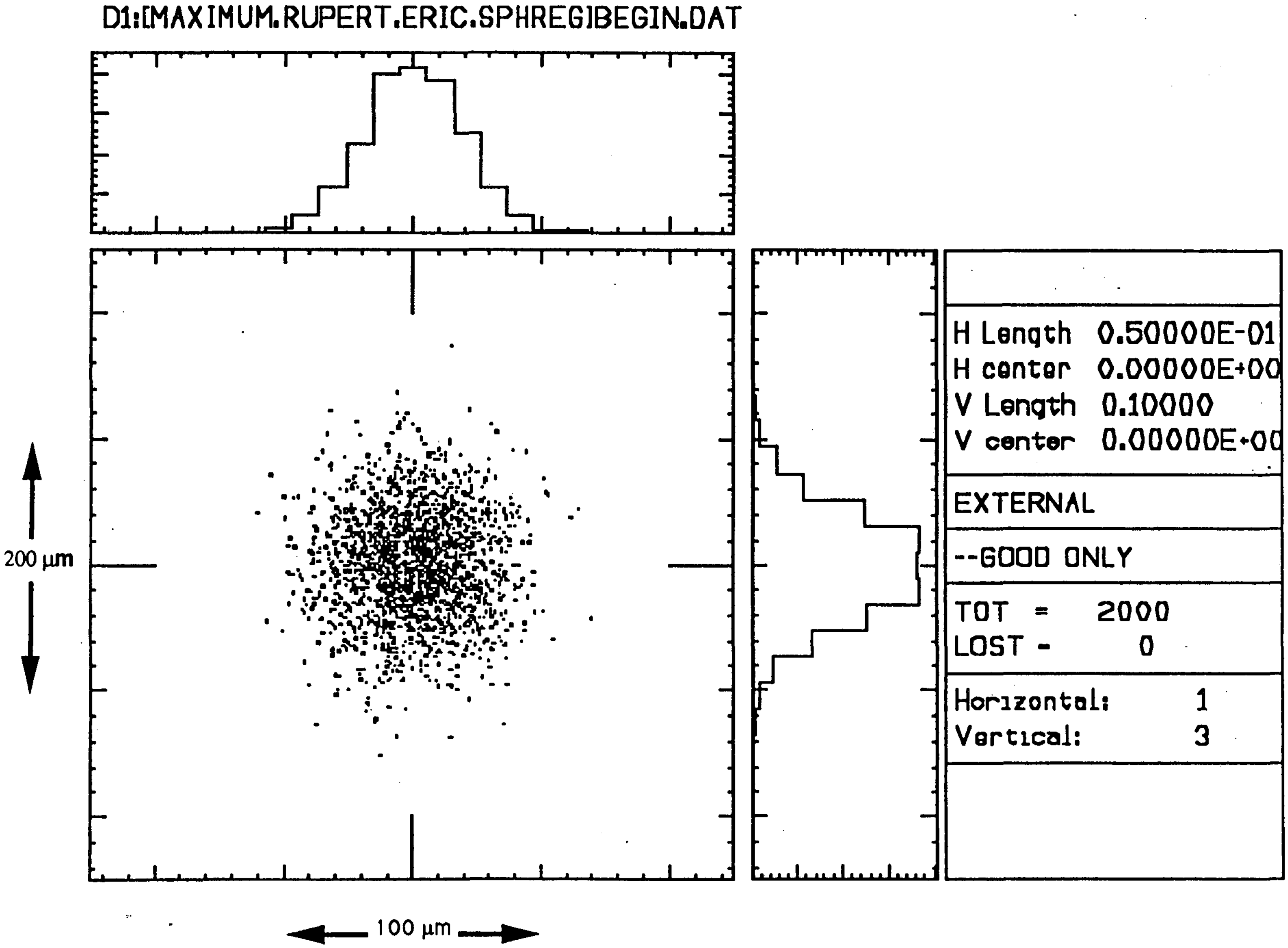


Figure 2



```
D1:[MAXIMUM.RUPERT.ERIC.SPHREG]BEGIN.DAT

H Length  0.50000E-01
H center  0.00000E+00
V Length  0.10000
V center  0.00000E+0

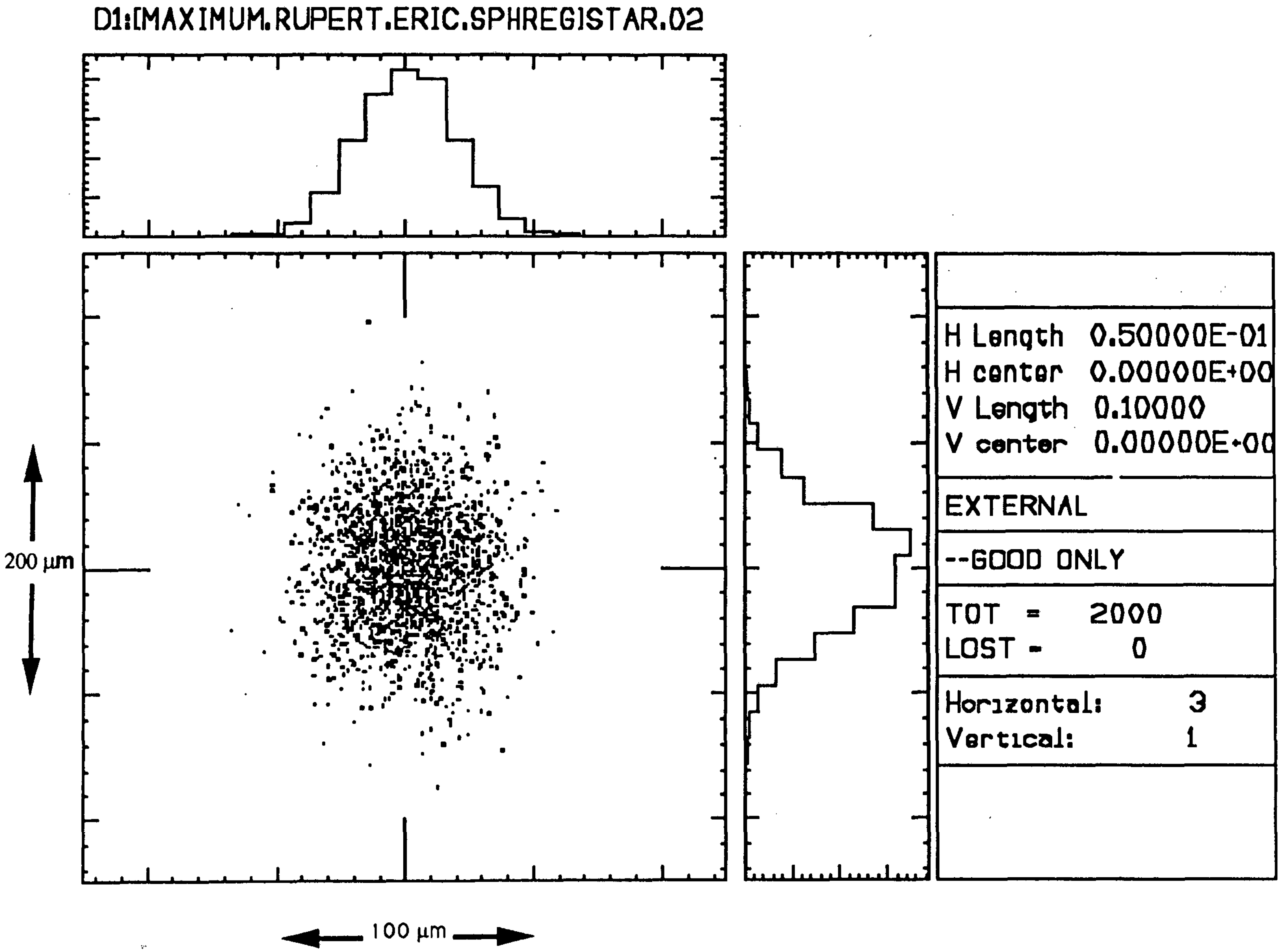
EXTERNAL

--GOOD ONLY

TOT  =    2000
LOST -       0

Horizontal:      1
Vertical:        3
```

Figure 3



```
H Length  0.50000E-01
H center  0.00000E+00
V Length  0.10000
V center  0.00000E+0

EXTERNAL

--GOOD ONLY

TOT  =    2000
LOST -       0

Horizontal:      3
Vertical:        1
```

Figure 4

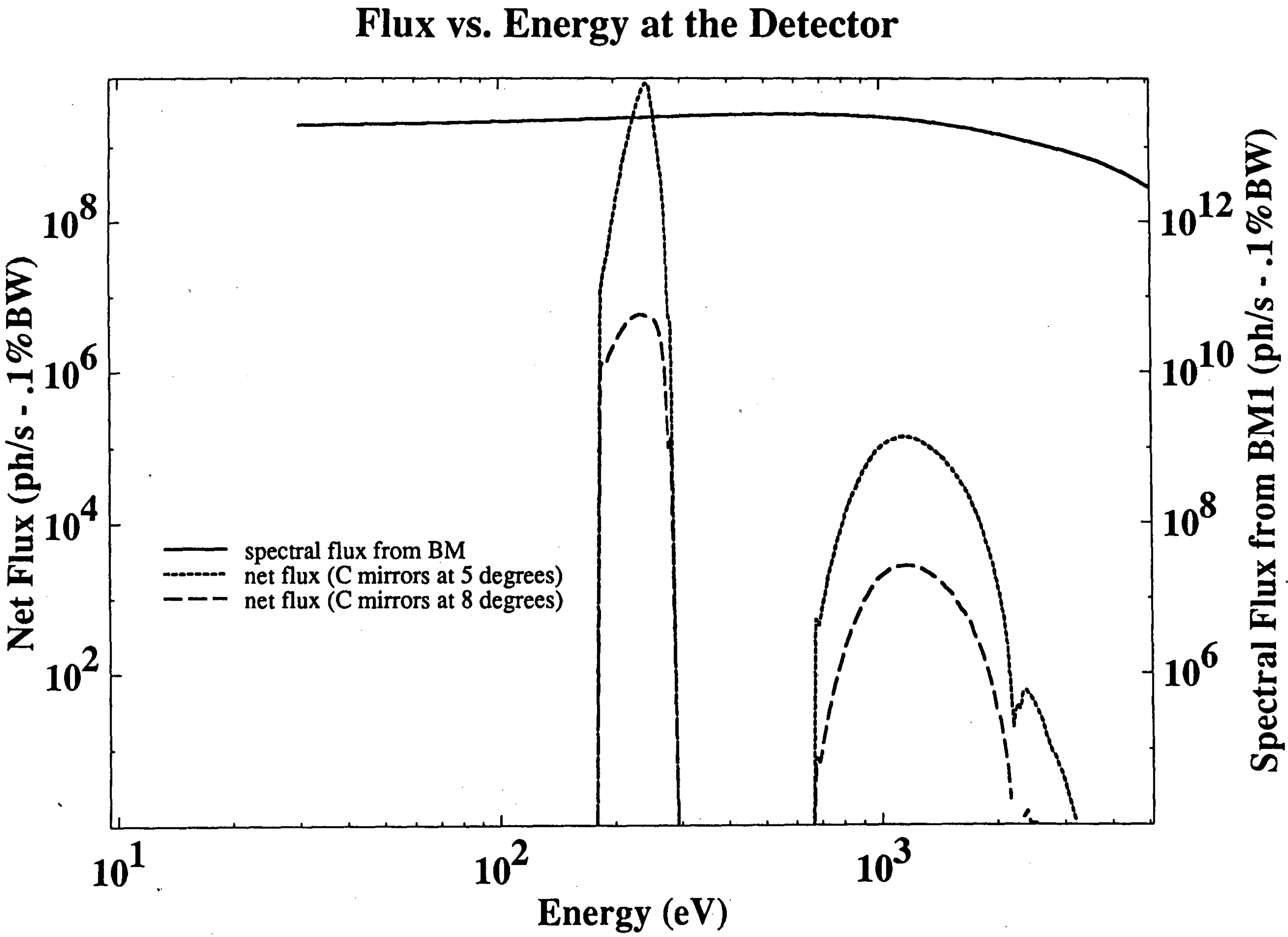

Flux vs. Energy at the Detector
Net Flux (ph/s - .1%BW)
10^8
10^6
10^4
10^2
Spectral Flux from BM1 (ph/s - .1%BW)
10^{12}
10^{10}
10^8
10^6
Energy (eV)
10^1
10^2
10^3
spectral flux from BM
net flux (C mirrors at 5 degrees)
net flux (C mirrors at 8 degrees)

Figure 5