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A High Bandwidth Gamma Monochromator*

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1. INTRODUCTION

The purpose of this instrument is to distinguish the temporal variations on the order of nanoseconds of a faint gamma emitter in the energy range of 10 to 20 MeV despite a coincident gamma background of lower photon energy yet orders of magnitude greater power. The instrument itself is a combination of a Compton electron monochromator comprised of two dipole magnets, a dual lens total internal reflection Cherenkov optical system, and microchannel plate photomultiplier detectors. Two units were built, called H1 and H2, differing only in magnet strength and viewing the following energy bins:

H1 gamma energy bin:	15.7 to 17.7 MeV,
H2 gamma energy bin:	13.7 to 15.7 MeV.

The H1 design aims at a large signal-to-noise through-put and fast temporal response, and this limits the energy resolution. The H1 unit has a 671 MHz bandwidth (FWHM = 463 ps) for the energy bin shown above.

2. ELECTRON OPTICS

Figure 1 is a scaled drawing of the H1 unit. A 30-cm long Pb collimator with a 1-cm diameter bore defines an object spot on a 5-mm thick beryllium plate which acts as the Compton converter. A half-inch thick steel collimator defines a Compton spray of about 7.6° that expands to about 4 cm in diameter by the time it reaches the first dipole magnet. A mean electron kinetic energy of 15.5 MeV with a spread of ±1 MeV is expected within this cone from the interaction of gammas of 16.7 ± 1 MeV with the beryllium.

The dipole magnets of the H1 unit have a mean field of 5.33 kG (.533 T) and a 4-cm gap. The electron optics of the H1 unit were calculated by Prof. Harald Enge (Deuteron, Inc., of Winchester, MA.), and the dual-dipole magnet system was built to his specifications by Field Effects, Inc., of Acton, MA. Figure 1 shows the envelope of electron orbits at the midplane of the magnets when the total electron energy is 16 MeV, and the momentum spread is negligible (0%). The envelope in the vertical dimension (perpendicular to the pole faces) increases from 1 cm (-.5 cm to +.5 cm) at the object spot to 4 cm (-2 cm to +2 cm) at the magnet entrance, where it bends inward due to jxB forces induced by the rotated fringing field. Thereafter it remains within the 4 cm gap until it exits the second magnet and converges down to a 1-cm diameter image spot. Prof. Enge has calculated these optics for momenta spread as large as ±6%. This mirror image optical system was selected because aberrations induced in the beta rays by the first magnetic "lens" are cancelled by the second dipole magnet, resulting in a nearly isochronous system. This ensures both high bandwidth and an image that is similar to the object in small size, roundness and divergence (or convergence) of electron trajectories. Figure 2 shows an engineering drawing of the H1 unit magnets, vacuum chamber and optics can. Directly behind the primary H1 unit lies a second one that is in every respect identical, except that the magnetic field is reduced so that the electron energy band of the instrument is 13.5 ±1 MeV.

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3. LIGHT OPTICS

Upon transiting the image plane of the H1 unit the 15.5-MeV electrons burrow into a lucite lens which focuses the Cherenkov light they emit onto microchannel plate photomultiplier tubes. This system was chosen because of its speed and gain (10^2 to 10^4). Faraday cups are faster detectors, but 10 to 100 volt signals were desired from 1 ma electron currents. The light optics was designed by Mike Graser (of EG&G at Amador Valley Operations in Pleasanton, CA.), and the lenses were machined on the diamond turning lathe at LLNL.

The Cherenkov emission is at 45.2° with respect to the electron trajectory. As electrons range through the plastic their trajectories are deflected by multiple scattering so that an initially parallel electron beam expands with depth. As a result of this the Cherenkov emission will be increasingly spread out in angle about 45° with increasing depth. Figure 3 shows two models of e-beam and Cherenkov angle spread in lucite as well as a relative light intensity versus depth. The model theta, shown in Figure 3 with a solid line, uses a depth-dependent electron energy based on a linear range equation in the textbook formula of multiple scattering angle. The relative proportions of the elements comprising lucite are accounted for in this model. A fit to this model curve is given by theta = $3.67(x)^{1/2}$, where theta is in degrees and x is the depth in mm. For 15.5-MeV electrons in lucite the range is near 88 mm. This model predicts a net beta ray deflection of ±11.6° after 1 cm of penetration. Consequently, the Cherenkov emission observed from the 1-cm depth plane is estimated to be spread between 33.6° and 56.8°. Judy Kammeraad (of LLNL) studied this phenomena in a series of EGS4 calculations (a Monte Carlo code of electron-gamma showers developed at SLAC). I have plotted her results for theta with a dotted line in Figure 3. The similarities between these two theta models as to the magnitude of the depth effects was sufficient to permit the design of the lucite optical system.

Figure 4 shows rays in a meridional plane of the lucite optics from source points 1, 5 and 9 mm of depth and 0.5, 2.5 and 4.5 mm off-axis. Three rays are drawn from each site, one at 45° and one each at plus and minus deflections from 45° appropriate to that depth. A cross section of the resulting lenses is seen in Figure 1.

The Cherenkov emission is totally internally reflected from conical sides, projected in a parallel manner by toroidal lenses, and focused down to the detector photocathode by a converging conical internal reflector and an axicon refractor just in front of the detector. Three dimensional ray-trace calculations for the axisymmetric lens system were also performed, and the effects of the detector entrance window and the position of the photocathode were accounted for. The actual lens system was bench tested (by M. Graser at AVO) where the net transmission along the Cherenkov path length at 400 mm was determined to be 0.3. This light is observed by an ITT 4126, single microchannel plate photomultiplier tube in an EG&G (Las Vegas Operations) designed 50-ohm mount.

A second, low bandwidth channel is also coupled to this optical system. After a depth of 24.5 mm of lucite, a 2.5-cm diameter by 5-cm long suprasil (quartz-like) rod is embedded in the forward lucite lens. This rod has an MCP-PM mounted on its back end where this detector fits within the inner radius of the toroidal lens. The lucite side of the lucite-suprasil boundary is painted black, while the rod itself has a reflecting coating everywhere except on the end face by the detector. Thus, the first 28% of the electron range is in lucite and accessed by the high bandwidth channel, while the remaining 72% of the electron energy is ranged out in the suprasil so that its light is collected into the low bandwidth channel.

Figure 5 shows a schematic of the suprasil optics. A parallel, 1-cm diameter e-beam is shown expanding through lucite and sample meridional light rays are shown in the suprasil. Using the analytical theta model described above, the lateral extent of a beta ray, y in mm, is estimated to vary with depth, x in mm, by $y = .0427x^{3/2}$. This is deduced by integrating dy/dx = tan(theta) for the model theta(x). Figure 5 shows the resulting expansion. Typical Cherenkov rays at 24.5-mm depth in lucite are shown propagating through the suprasil, and their path lengths and propagation times are noted. By 27 mm in the suprasil, the electrons are ranged out, and this is denoted by the vertical dotted line. It is clear from this diagram that an impulse of electrons would smear out into a light pulse hundreds of picoseconds wide at the output end of the suprasil.

4. H-UNIT BANDWIDTH

The two "H units" built have 4x4-cm electron apertures between the dipole magnets and exhibit a net impulse response out of the high bandwidth channels of $\Delta t = 463$ ps FWHM, or equivalently a -3 db bandwidth of 671 MHz. The low bandwidth channels have an impulse width of 735 ps, or equivalently a -3 db bandwidth of 423 MHz. Figure 6 shows the measured impulse response of both the fast and slow channels. Note that the ITT 4126 photomultiplier alone has an impulse response of 318 ps (in the EG&G/LVO mount). These systems were extensively tested on the LINAC linear electron accelerator (at EG&G at Santa Barbara, CA.). Prof. Enge's calculations of the magnet system impulse response and energy dispersion at the aperture "mirror plane" were duplicated quite accurately. Figure 7 shows measured dispersion characteristics and electron energy bins of the magnets sets.

5. H-UNIT GAIN

The gain of the fast and slow detector channels was measured on the LINAC directly. The 15.5 MeV LINAC e-beam pulses were shot through a 1-cm diameter collimator into an assembled lucite-suprasil lens-detector system at various current levels. Here the gain is defined as the ratio of coulombs out of the MCP-PM for a given e-beam coulombs into the lucite. The fast channel gain is 1.22×10^4 while the slow channel gain is 1.29×10^4. This gain was found to be stable for pulses which are long in comparison to the MCP-PM impulse width (i.e., >300 ps), and these detectors were able to deliver a maximum of 15 nC of total charge while under a negative high voltage of over 3 kV. Generally, the detector gain is independent of pulse width for total output under 1 nC (verified with 50 ps pulses).

6. H-UNIT SUMMARY

For this particular experiment, the number of electrons expected through the H-unit magnets and into the lucite-per-incident gamma-ray is .004. As a result, this system can deliver 50 electrons out of the detector for each incident high energy gamma and with an impulse response of 463 ps. In an experimental situation these units were able to discern a high energy gamma source amidst a 0.5- to 2-MeV gamma "background" which was over 10^5x more intense and with a resulting signal-to-noise ratio of 25:1.

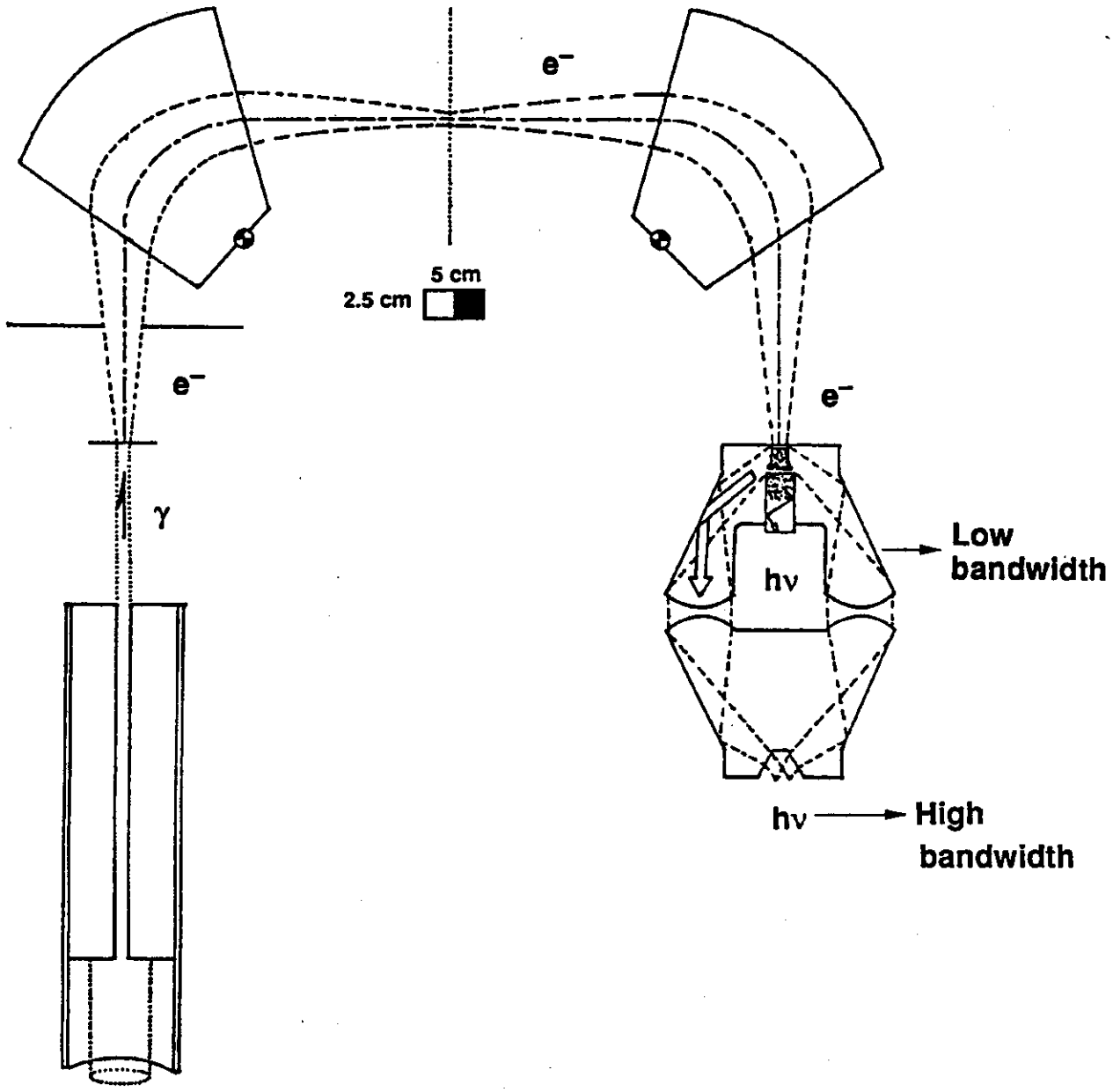

Figure 1. The High Bandwidth Gamma Monochromator.

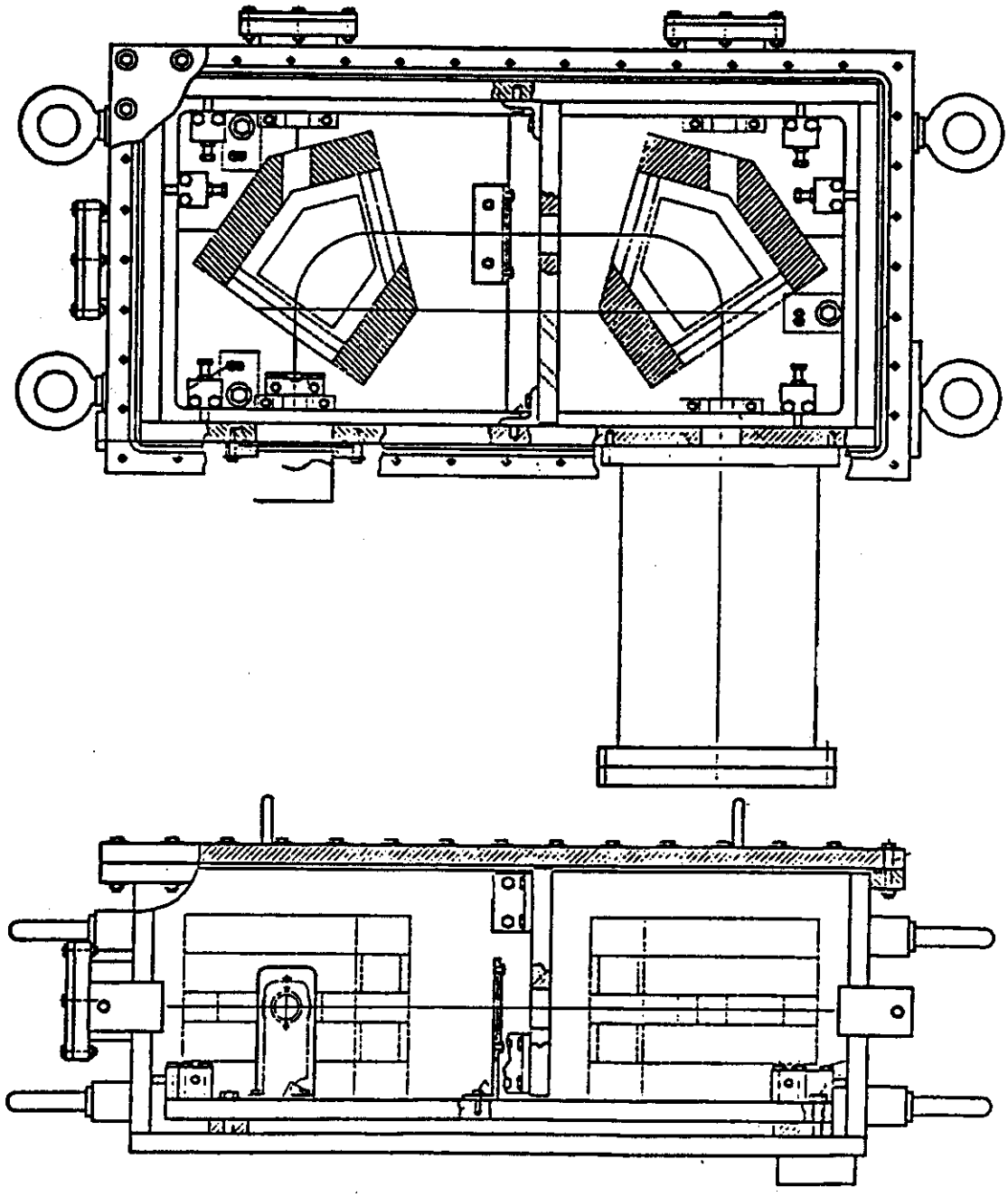

Figure 2 Engineering drawing of the HBGM.

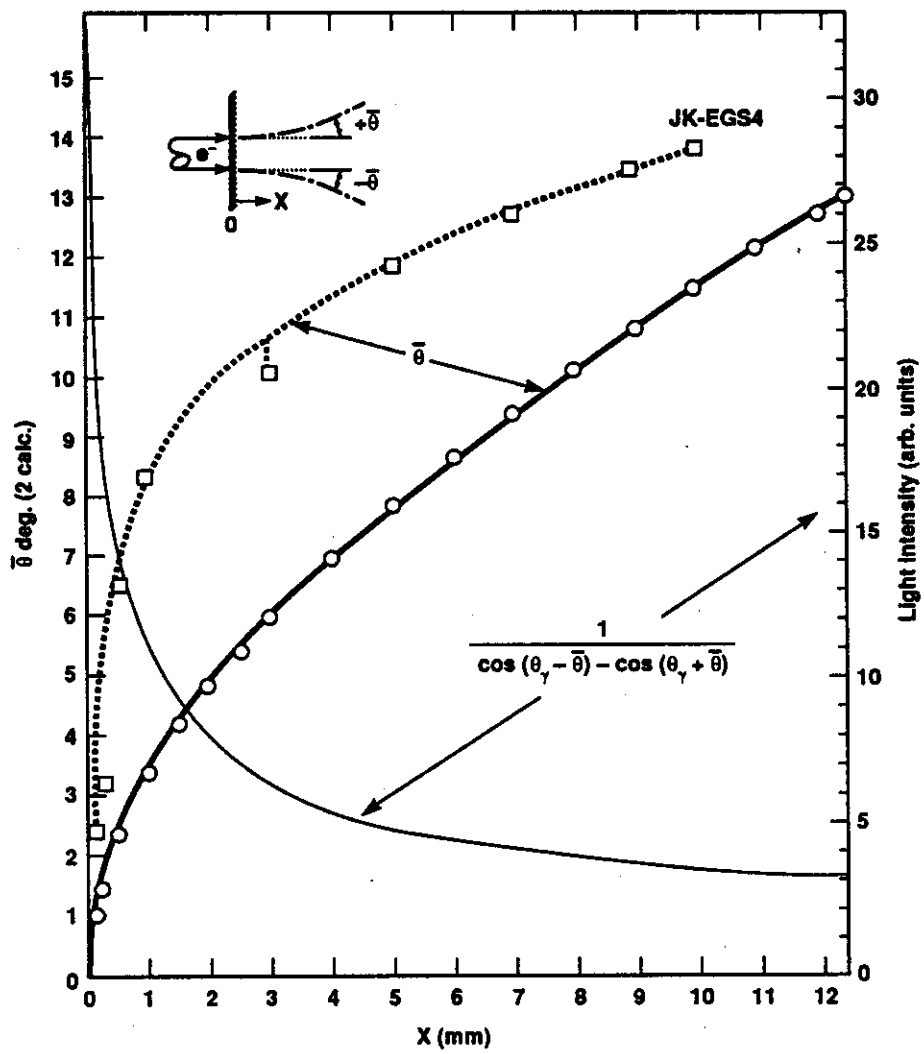

Figure 3. E-beam spread in lucite. E-beam spread θ and Cherenkov intensity.

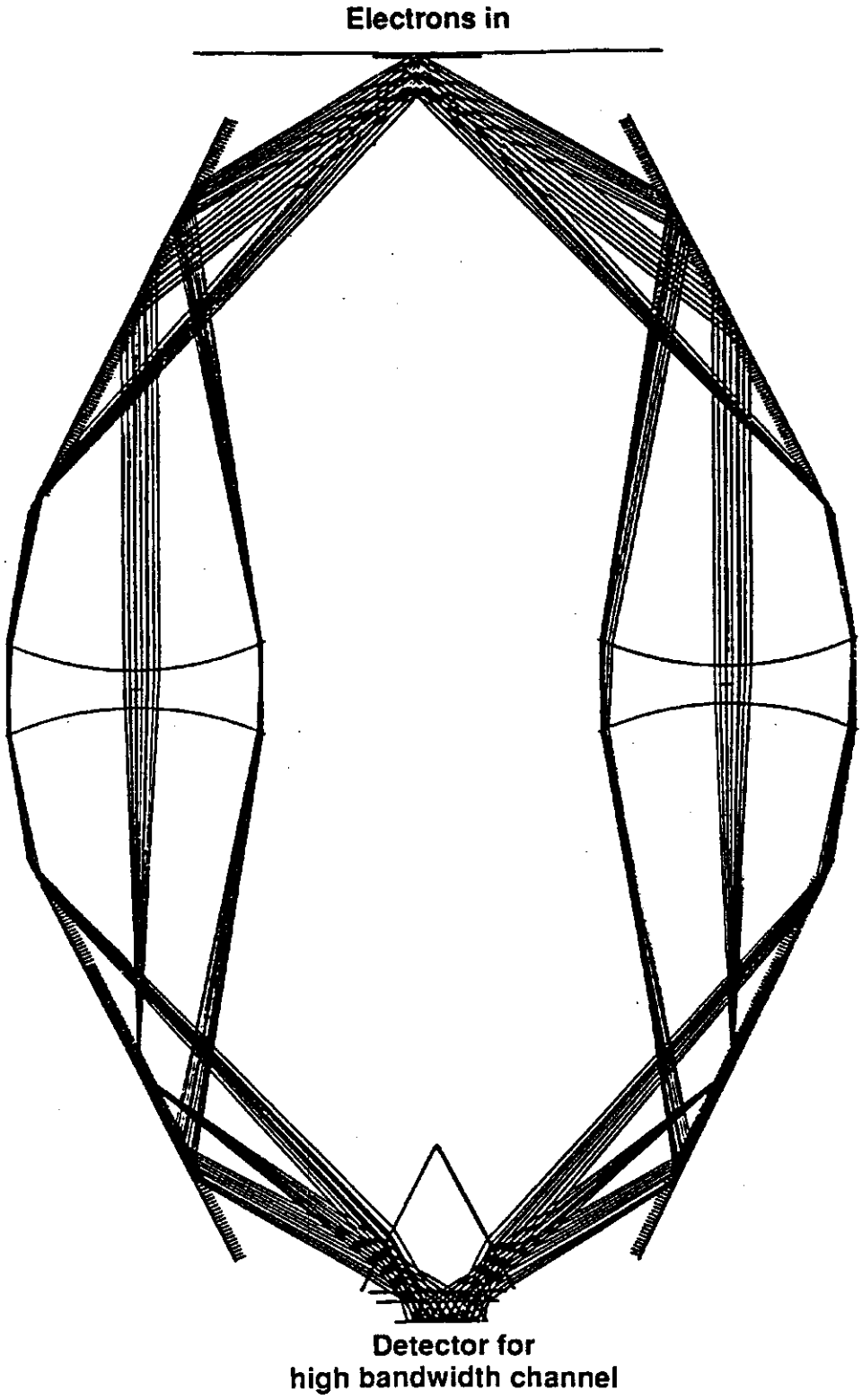

Figure 4. Total internal reflection Cherenkov optics.

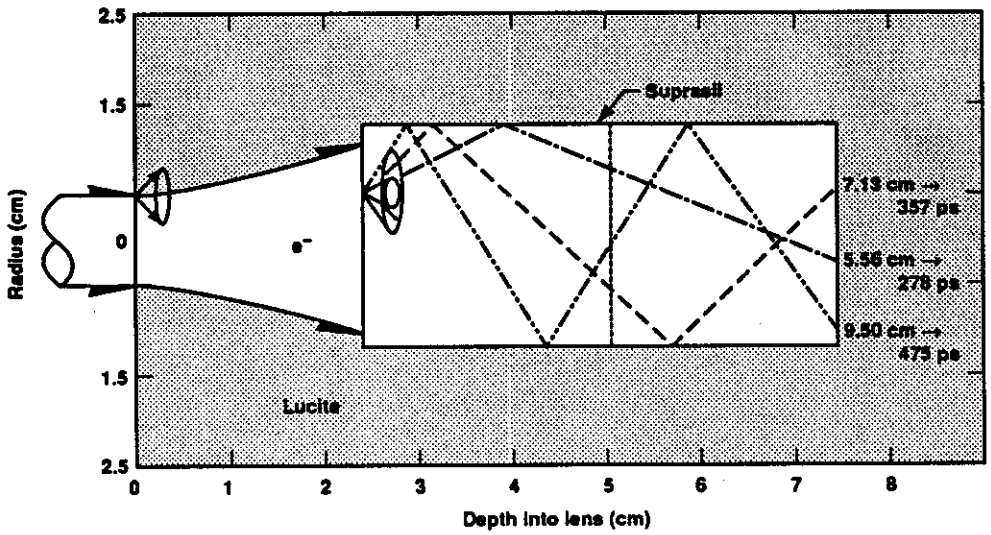

Figure 5. Suprasil optics.

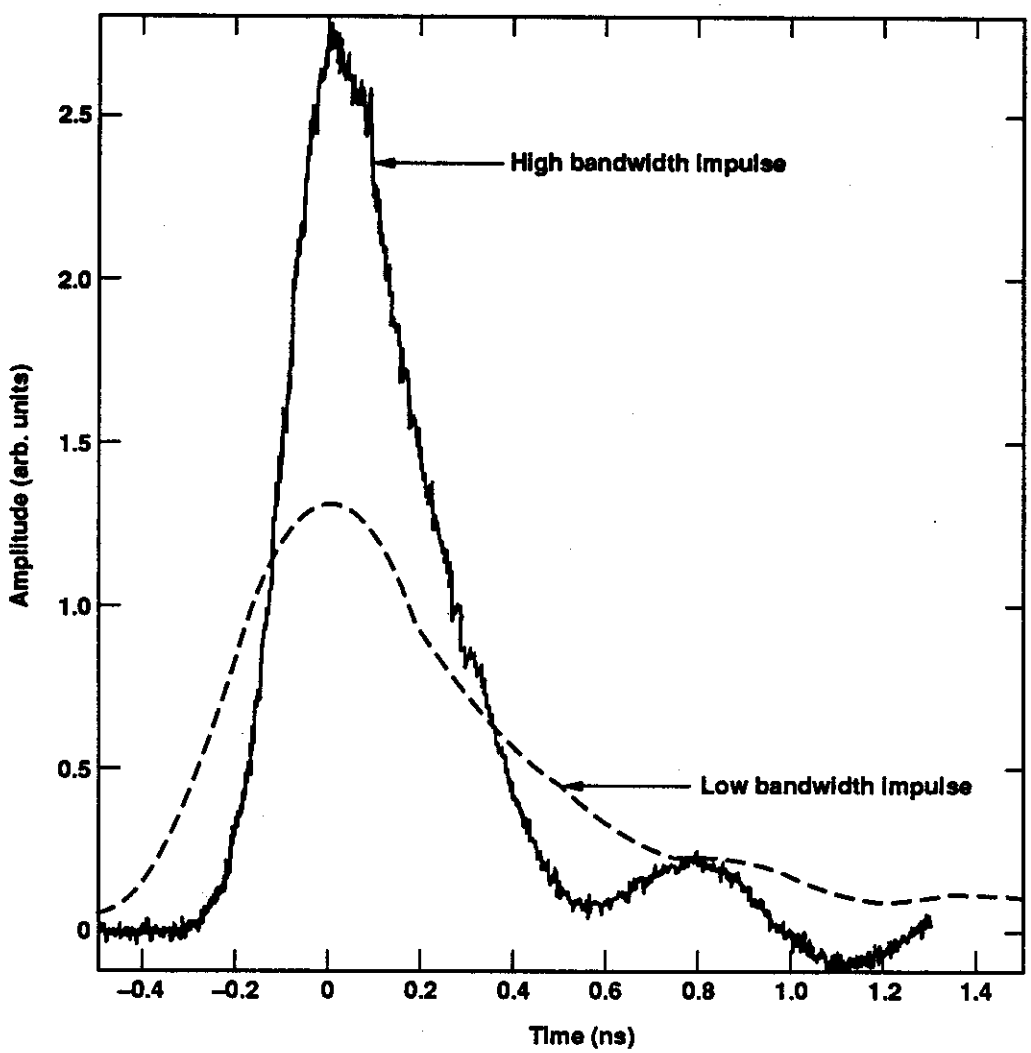

Figure 6. Fast and slow channel impulse responses.

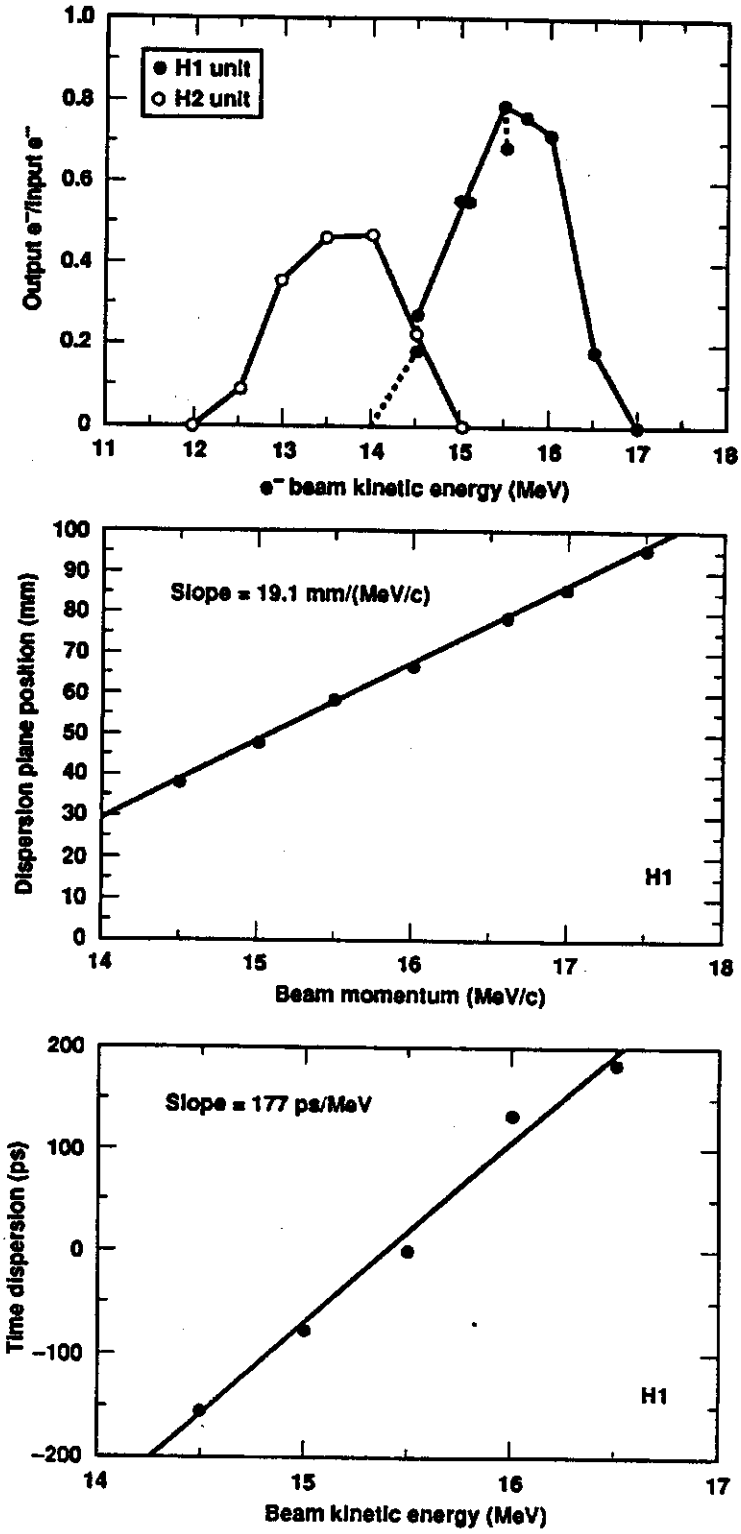

Figure 7. HBGM instrument functions measured at EG&G/SBO.