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A COMPACT DIAMOND-BASED DETECTOR FOR THE SSC

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1 Introduction

The SSC provides a unique opportunity for investigating a new unexplored energy region. As such, experiments at the SSC must be capable of definitive searches for the Higgs, supersymmetry, technicolor, compositeness, etc., which so far have eluded experimental detection, as well as the ability to recognize unanticipated phenomena. The signatures for *new physics* include the production of high p_T leptons, jets and missing energy. For example, Higgs searches require lepton and jet reconstruction while supersymmetry and technicolor searches require finely segmented hermetic calorimetry to determine the missing energy. Further, since the scale of these new interactions is unknown, full exploitation of the physics potential of the SSC will require operation at the highest possible luminosity, in excess of 10^{34} cm^{-2}s^{-1}. A detector that can function at this luminosity will have to operate in a very high radiation environment and must be able to handle extremely high event rates. No existing detector technology completely fulfills these requirements. As a result, a generic detector based on present day technology will have unwanted compromises. We propose a detector based on the novel use of diamond technology to solve the high radiation, high rate problems associated with the SSC. Moreover this technology has the potential to allow for a compact detector with both uncompromised tracking and calorimetry inside the magnetic volume, at a fraction of the cost of a detector based on other technologies.

Although the detailed work on a final detector design is not complete, our studies indicate that it is possible for the key sections of tracking and calorimetry to be based on diamond technology. These include a diamond charged particle tracking chamber (diamond tracker), diamond electromagnetic calorimeter, and diamond-tungsten hadron calorimeter all of which will reside inside a 5 Tesla magnetic volume. Diamond was chosen as the radiation detector of both the tracker and the calorimeter because of its inherent radiation hardness and high speed, allowing operation at luminosities above 10^{34} cm^{-2}s^{-1}. Moreover, limiting the number of distinct elements in a compact detector should keep the final design simple and economical.

Although natural diamond has been used in radiation detectors for over 40 years[1] (the first solid state detector ever used was diamond), several shortcomings, primarily high cost and impurities, have prevented its widespread implementation. Within the past ten years, however, a new method of manufacturing diamond by chemical vapor deposition (CVD)[2] has been developed for commercial production of diamond. Recent advances show promise of yielding high quality diamond on an economically feasible scale for large area radiation detectors while solving the inherent problems associated with natural diamond.

We have formed a collaboration to pursue the idea of a compact magnetic spectrometer based on CVD diamond as a radiation detector. We propose to conduct a research program, over the next 3 years, to determine whether this technology can be applied to an SSC detector.

2 Physics Requirements

The physics motivation for experiments at the SSC has been addressed in a number of documents[3, 4, 5, 6, 7] and it is not necessary to reiterate them here. We instead concentrate on those measurements we consider to be of particular importance and discuss, in general, the requirements imposed on a detector. We assume a luminosity of 10^{34} $cm^{-2}s^{-1}$.

The standard Higgs search relies on tagging large p_T charged leptons from the decay mode $H \rightarrow ZZ$ followed by $Z \rightarrow e^+e^-, \mu^+\mu^-$. Higgs reconstruction using jet energies ($Z \rightarrow 2\ jet$) and missing energy ($Z \rightarrow \nu\bar{\nu}$) provide additional self consistency checks. This is of particular importance for a high mass Higgs where the cross section is small and its width is large. Therefore an SSC detector must have good lepton identification and energy resolution and be able to detect the presence of missing energy. Other searches have similar requirements. For example, the search for technicolor, which requires W and Z reconstruction through their leptonic and hadronic decay modes, and the search for new neutral gauge bosons which relies

on dilepton detection or dijet reconstruction. Further, calibration of the electron detector, measurement of the momentum and charge of a lepton, and the separation of e's from γ's and π^o's requires charged particle tracking situated inside a magnetic volume. Finally, heavy quark tagging through secondary vertex reconstruction and separation of multiple interactions within the same bunch crossing, require fast tracking with good resolution near the interaction region.

Our general detector design satisfies the constraints imposed by the various physics processes. The centerpiece of this detector is the diamond calorimeter and diamond tracker inside of a magnetic volume. These devices will reside in the high radiation area near the interaction region. The calorimeter is a diamond-tungsten, finely segmented, projective geometry detector while the proposed tracker is a high spatial resolution double sided strip detector. All active detector elements are inside the magnetic coil, eliminating cracks due to support structures, plumbing, etc. This allows us to optimize both the calorimetry and tracking and solves the hermeticity and uniformity problems associated with jet energy measurement and missing energy determination; the lepton detection and momentum measurement problem; and the multiple beam crossing problem (since the collection time in diamond is of the order of nanoseconds). Thus, a detector based on diamond technology need not compromise charged particle tracking at the expense of calorimetry and vice versa. In this sense, the diamond technology gives us the ability to produce a detector uniquely suited to the challenges of the SSC.

3 Characteristics of Diamond

In Fig. 1, we show the basic principle of the use of diamond as a radiation detector. A few hundred volts are applied across a layer of diamond a few hundred microns thick. When a charged particle traverses the diamond, atoms at the crystal lattice sites are ionized,

promoting electrons into the conduction band and leaving holes in the valence band. These charges are free to move about the crystal and drift across the layer in response to the applied electric field producing a signal pulse which can be preamplified and further processed.

Since diamond has a large band gap, 5.5 eV, it is a very good insulator. Diamond with no impurities or defects would have an effectively infinite resistivity. The conductivity of actual diamond material is, in fact, dominated by the effect of defects and impurities. Nevertheless, the resistivity of natural diamond is typically 10^{12} Ω-cm to 10^{16} Ω-cm. As a result, a high electric field can be applied across the diamond layer without producing significant leakage current. In contrast, for silicon, which has a much smaller band gap, 1.3 eV (and thus lower resistivity), a reversed biased *pn*-junction is needed to prevent a large leakage current whose fluctuations would dominate the signal.

3.1 High Speed

In Table 1, the characteristics of diamond and silicon are compared. The electron mobility is slightly higher in diamond than in silicon while the hole mobility in diamond is three times larger and is approximately equal to the electron mobility. Despite the similarity of mobilities, the collection time in diamond is an order of magnitude shorter than in silicon. For diamond, the breakdown electric field is about 10^7 V/cm. It is, therefore, possible to apply a field of a few times 10^4 V/cm to reach the saturation velocity of 2.7×10^7 cm/s, as shown in Fig. 2. With silicon, because of the *pn*-junction and associated depletion region, the maximum field that can be applied before avalanche breakdown is about 10^3 V/cm. As shown in Fig. 2, this limits the electron velocity to a few 10^6 cm/s and three times less for the holes. For either diamond or silicon the required detector thickness is a few hundred microns. The collection time for a 200 micron thick sample would be 1 ns for diamond compared to 20 ns and 60 ns for the electrons and holes, respectively, in silicon.

3.2 Radiation Hardness

There are two primary manifestations of radiation damage in solid state detectors. One is an increase in leakage current and the other is a decrease in pulse height. Several studies[8, 9] have shown that diamond detectors are very resistant to both types of damage for several reasons. For silicon detectors, the most serious effect of radiation damage is the increase in leakage current. This current arises from radiation-induced lattice dislocations that produce states with energies that are within the band gap. These sites act as current generation centers emitting electrons into the conduction band and holes into the valence band. These charges are then immediately swept out of the depletion region by the applied field. Since, in the depletion region, the carrier concentration is not in equilibrium (i.e., $pn < n_i^2$ where p, n, and n_i, are the hole, electron, and intrinsic carrier densities respectively), it can be shown[10] that the generation current is proportional to the intrinsic carrier concentration n_i. Since no pn-junction is required in a diamond detector, there is no depletion region and the carrier concentrations are in equilibrium, $pn = n_i^2$. The recombination rate is, therefore, equal to the generation rate and there is no net generation/recombination current. It is interesting to note that even if there were a pn-junction, the resulting generation current would be negligible compared to silicon since $n_i \propto e^{-E_g/2kT}$ is about 30 orders of magnitude smaller in diamond than in silicon. As a result, the amount of radiation induced leakage current should be negligible for diamond detectors. Schottky diodes made with silicon and with diamond were exposed to 1.5 MeV electrons at doses up to $10^{16}/\mathrm{cm}^2$, corresponding to about 1 gigarad[9]. The diamond diode showed no increase in leakage current while the silicon diode showed an increase of about a factor of 40 (see Fig. 3). Even before the exposure to radiation, the leakage current in the silicon diode was about 2 orders of magnitude larger than that of the diamond diode.

The other effect of radiation damage is a decrease in the observed pulse height due to decreased collection efficiency. This is due to the production of trapping centers which results

in a decrease in carrier lifetime. If the lifetime is small compared to the collection time, the collection efficiency will be low. Diamond is also stronger than silicon against this type of damage. For a given exposure of radiation, silicon is more sensitive to neutrons than to other types of radiation, as shown in Fig. 4. This may be due partially to the transmutation of the silicon by neutron induced reactions. Since the cross section of carbon for neutron transmutaton is 3.2 mb compared to 80.0 mb for silicon, diamond should be less sensitive to neutron damage. The other cause of trapping centers is lattice dislocations. Since the binding energy of carbon in the diamond lattice is much greater than the binding energy of silicon in its lattice, the number and the severity of lattice dislocations should be much smaller in diamond than in silicon. Lattice dislocation distance in diamond is, in fact, usually less than the lattice spacing. As a result, the dislocations that do occur anneal easily.

There are few systematic studies of radiation damage to diamond detectors and a part of our proposed program is to carry out these studies. However, there is a study by Kozlov et. al.[8] which shows that a diamond detector can survive up to a few times 10^{14} neutrons/cm^2 which is about two orders of magnitude higher than for silicon (see Fig. 5).

3.3 Limitation of Natural Diamond as a Radiation Detector

The use of diamond as a radiation detector is not new. Hofstader described diamond detectors in a 1949 issue of Nucleonics[11]. In fact, the first solid state detector used was diamond, presumably, because sizable crystals of diamond were more readily available than crystals of silicon or germanium. Despite its early development, diamond did not find wide spread use as a radiation detector due to several disadvantages associated with natural diamond. First, natural diamond is obviously prohibitively expensive in large quantities. Second, the large resistivity of natural diamond causes a build up of trapped charge when the diamond is exposed to ionizing radiation. The inevitable presence of impurities and crystal defects cause some amount of the ionized charge to be trapped. Since, in a large band

gap material like diamond, some of the trapping centers may be far below the conduction band, the trapping time is very long. Charge, therefore, builds up and causes a reduction in the effective collection field. Third, because natural diamond contains a large amount of impurities, particularly nitrogen, the carrier lifetime is short and the collection efficiency for a moderately thick detector is small. Fortunately, a new technology of manufacturing diamonds by chemical vapor deposition (CVD) has recently been discovered[2, 12] which has the potential of solving these problems while allowing diamond to be grown in large sheets at a reasonable cost.

4 CVD Diamond

4.1 The CVD Process

In the CVD process, a hydrocarbon gas, such as methane, is mixed with a large concentration of molecular hydrogen gas. The gas mixture is then excited by either microwaves, hot filament, or other energy source. The resulting reactive gas mixture is brought into contact with a substrate, typically silicon, where the carbon based radicals are reduced and link together with single bonds (sp^3 hybridized orbitals) forming a diamond lattice. A large concentration of atomic hydrogen is a crucial part of the process and is believed to play two separate roles in promoting diamond growth. It hydrogenates the surface of the film thus preventing the formation of graphitic double bonds, and it also serves to etch any graphite that happens to form since hydrogen reacts much more readily with graphite than with diamond. Raman spectroscopy and X-ray diffraction have unambiguously shown that the CVD grown films are crystalline diamond as distinguished from diamond-like carbon films.

The CVD growth of diamond can now be achieved through several processes. Many companies and universities in both the US and Japan are producing polycrystaline CVD diamond films. Nevertheless, this is still a developing field and there are a large number

of parameters which must be optimized for the growth process. These include: type of excitation energy source, relative concentration of hydrocarbons, substrate temperature, gas pressure, etc. Different parameters lead to different properties of the resulting film. Because of the large number of variables, systematic correlations between growth parameters and film quality is only now being developed and one of the main tasks of our program will be to determine which choices of the growth parameters lead to the highest detector quality film.

Despite the lack of a complete understanding of the growth process, the following general observations can be made.

- Films with thicknesses of up to several hundred microns have been grown.
- Growth rates of several hundred microns per hour have been acheived.
- The films grown on non-diamond substrates are polycrystaline.
- The lateral crystal size is of the order of 10 microns.
- The crystals tend to grow in columns in the direction of the layer growth. As the layer grows thicker, these columns become longer, extending from one side of the layer to the other. Columns up to 100 microns long have been observed.
- The purity of these films is very high, typically several orders of magnitude better than that of natural diamond.
- The defect density of the thin film crystals is somewhat high. This is an area where improvement is needed.
- P-type diamond can be easily made by doping with controlled amounts of boron introduced during the CVD growth process.
- Layers of single crystal diamond up to several tens of microns thick have been grown on diamond substrates (homoepitaxy).

Most importantly, the CVD process shows promise of solving the major problems limiting the use of natural diamond; high cost and large trapping center density which leads to a short carrier lifetime and charge buildup. In contrast to traditional high-pressure, high-temperature diamond synthesis methods, which produce crystals typically 1 mm in size, CVD production can be scaled efficiently to cover large areas.

4.2 Carrier Trapping

The major technical problems related to natural diamond arise from the large concentration of trapping centers which are mainly due to the presence of nitrogen impurities. Typically, the nitrogen concentration in natural diamond is greater than $10^{20}/cm^3$. Nitrogen impurities produce an energy state near the middle of the band gap which is a trapping site for electrons. Since it is a deep state, the trapping time is very long and the trapped charge does not contribute to the signal pulse. In the CVD process, if care is taken to prevent impurities from entering the reaction chamber, the grown diamond will be much purer than natural diamond. The density of trapping centers will, therefore, be lower, resulting in longer carrier lifetimes. In the case of natural diamond, the charge collection efficiency is limited by the short carrier lifetime which is < 1 ns. On the other hand, low-nitrogen, high-pressure synthetic diamond has a much longer carrier lifetime which may be as long as a few hundred nanoseconds[13]. The purity of CVD diamond has been shown to be higher than that of the low-nitrogen, high-pressure synthetic diamond which, in principle, should have an even longer carrier lifetime. However, the carrier lifetimes for CVD diamond measured so far have been comparable to those of natural diamond, a few hundred picoseconds. This is likely due to the fact that the CVD diamond is polycrystaline and the defect density, at present, is high. A major part of our effort will be to work with suppliers to produce higher quality CVD diamond with long carrier lifetimes.

Another problem related to carrier trapping is the reduction of the applied collecting field

due to build up of trapped charge. The CVD process also provides a means of greatly reducing this problem. During CVD deposition, the diamond can easily be doped with controlled amounts of boron by introducing boron into the reaction chamber. This is routinely done at present. Since boron is an acceptor, it makes the diamond p-type and increases its conductivity. By controlling the amount of boron doping, the conductivity can be selected to give a current sufficient to neutralize the trapped charge. The concentration of boron required would depend on the rate of ionization and on the density of trapping centers. For example, at 10° from the beamline at the SSC, there will be approximately 5×10^5 $GeV cm^{-2} sec^{-1}$ of neutral energy. At shower maximum in the electromagnetic part of the calorimeter, this will lead to about 10^8 tracks $cm^{-2} sec^{-1}$. Since each track produces 50 ion pairs/μm in the diamond, assuming that 10% of the produced charge were trapped, a 200-μm-layer would require a current of about 20 nA/cm^2 and, thus, a resistivity of about 10^{12} $\Omega - cm$. At 90° to the beamline, it would be an order of magnitude less.

5 Results of Present Work on CVD Diamond Detectors

Kozlov et al.[8] have extensively studied natural diamond as a radiation detector. They measured the response of natural diamond to alpha particles and determined the energy resolution. In addition, they found that the carrier lifetime is a function of the nitrogen impurity concentration. For diamonds with a nitrogen concentration less than 10^{19}/cm^3, the measured lifetimes were greater than 1 ns. As mentioned above, they also measured the resistance of the diamond detectors to radiation damage caused by neutrons.

Recently, members of our collaboration from Livermore National Laboratory and Stanford University have succeeded in measuring signals in CVD diamond exposed to a flux of synchrotron radiation X-rays from SPEAR[13, 14]. The diamond samples were uniformly

illuminated by a 350 ps pulse of X-rays. The carrier lifetimes were determined by measuring the decay time of the signal and the mobilities of the carriers were determined by measuring the amplitude of the signal which is proportional to the product of the mobility and the carrier lifetime. Two sets of samples, produced by two different CVD processes, were used in these measurements. In one sample, the layer thickness and grain sizes were 0.6 to 1.5 microns. Carrier lifetimes from 90 to 300 ps and mobilities from 0.01 to 1.0 cm^2/V-s were measured for these samples. In the second set of samples, the layer thickness and grain sizes were 4 to 20 microns. In these samples, carrier lifetimes from 150 to 200 ps and mobilities from 100 to 1000 cm^2/V-s were observed. This has demonstrated that process improvements can dramatically improve the electrical characteristics of the sample.

In order to attain detector quality diamond, carrier lifetimes of at least 1 to 10 ns and mobilities on the order of 1000 cm^2/V-s are required. The second sample already has mobilities that are within reach of the required value but improvement in the carrier lifetimes must still be made. The present low carrier lifetimes are likely due to defects within individual crystals.

Measurements by this group have also verified that there is a strong correlation between nitrogen concentration and carrier lifetime. A piece of natural diamond with a nitrogen concentration of $2 \times 10^{20}/\text{cm}^3$ had a carrier lifetime of 300 ps while a sample of synthetic high-pressure diamond with a nitrogen concentration less than $1 \times 10^{19}/\text{cm}^3$ had a carrier lifetime greater than 100 ns. It seems likely, therefore, that if the purity of the diamond is high, the carrier lifetime will be sufficiently long. The purity required to achieve high carrier lifetimes can be attained with the CVD process. The remaining problem is to reduce the the crystal defect density in CVD diamond.

In addition to carrier lifetime measurements, members of the collaboration from Ohio State University have demonstrated the feasibility of using surface-enhanced Raman spectroscopy (SERS) in detecting the initial phases of diamond CVD nucleation. The method

consists of exposing substrates for short times (≈15 min.) to a diamond CVD process. The exposed substrate is then vacuum coated with 30 Å of silver and studied with a Raman spectrometer. The resulting Raman spectrum is used to determine the characteristics of the first few layers of diamond, that is, the initial nucleation sites.

Further work by this group has involved diamond CVD deposition on substrates other than silicon and routine analysis of samples provided by manufacturers on bulk and surface properties of the samples. In order to attain consistently high quality diamond at low cost a reasonable substrate must be found and its properties measured.

In addition to the work described above, members of our collaboration from Rutgers University and Ohio State University have observed charged particle tracks from α and β sources using high-pressure synthetic single crystal diamond. This diamond had a large nitrogen concentration and, therefore, a short carrier lifetime. As a result, the observed pulse heights for both the α and β sources was about 5% of that expected from the calculated energy loss. Although this particular sample is unsatisfactory as a radiation detector, the work clearly demonstrates that we have the capability of detecting signals from a single charged particle traversing a layer of diamond a few hundred microns thick. In fact, for a diamond detector with high collection efficiency the signal size will be 20 times larger.

6 A Diamond-Based SSC Detector

Presently, our main goal is to determine whether detector quality CVD diamond can be produced at a reasonable cost. When the feasiblity of this has been demonstrated, we can then begin design of a complete SSC detector based on the diamond detector technology. Although at this stage it is not appropriate to begin detailed engineering studies, we have made a conceptual design of a powerful and relatively inexpensive detector as an example of what could be possible if the development of diamond detectors is successful.

Besides the advantages of high speed and radiation hardness which have already been discussed, diamond allows the design of a detector which is compact. Sampling calorimetry with 200 micron thick layers of diamond would be nearly as dense as the absorber material and the good spatial resolution provided by a diamond microstrip tracker would require only a short tracking length.

The detector that we envision is based on a high-field solenoid. The inner radius of the coil would be 200 cm with a 5 Tesla magnetic field. Although this is a large coil, the detector itself would be compact since all of the central part including the muon system would be inside of the coil. This would solve one of the problems of previous designs of high-field detectors in which part of the hadron calorimetry was located outside of the coil. Because a high-field coil must be fairly thick, greater than 0.5 interaction lengths, locating the calorimetry outside seriously compromises the electromagnetic/hadronic response. Having the calorimetry inside of the coil has the added advantage that the coil can be as thick as necessary to provide mechanical stability and quench protection. The characteristics of the proposed coil are listed here.

- Field strength = 5 Tesla
- Inner radius = 200 cm
- Length = 500 cm
- Stored Energy = 860 MJ

Inside of the coil, would be a central charged particle tracker extending from a radius of 10 cm to 50 cm. This would be followed by a 24 X_0 electromagnetic calorimeter extending radially from 55 cm to 65 cm and a hadron calorimeter from 70 cm to 150 cm. In the gap from 150 cm to 200 cm, we would place straw tubes for making a second momentum measurement of muons. In addition, a pre-radiator could be placed in front of the electromagnetic

calorimeter which could identify electrons through detection of the synchrotron gamma rays emitted in the 5 Tesla field. The overall layout of the detector is shown in Fig. 6. Below, we describe the relevant characteristics of each of the detector subsystems.

6.1 Diamond Tracker

The central tracker is a microstrip detector constructed on 200 μm thick diamond. It extends in radius from 10 cm to 50 cm from the interaction point and is made up of 4 superlayers. Figure 7 shows a side view of the detector. Each superlayer consists of 5 double-sided layers which have ϕ-strips on one side and z-strips on the other. The readout pitch is between 50 and 100 μm. The solid angle coverage extends to rapidities of $\eta = \pm 2.5$. Assuming a spatial resolution per layer of 10 μm in r-ϕ and 30 μm in z, the momentum resolution in a 5 Tesla field is shown in Fig. 8 with multiple scattering included. The resolution without a vertex constraint is $\sigma_{p_T}/p_T = 0.20 p_T(\text{TeV})$; with a 5 μm vertex constraint, the resolution is then $0.11 p_T(\text{TeV})$. Using similar techniques as those used in silicon today, it may be possible to attain a resolution of 5 μm or better per layer. If 5 μm resolution per layer can be achieved, the corresponding resolutions are $0.10 p_T(\text{TeV})$ and $0.07 p_T(\text{TeV})$. For particles in a jet, the first superlayer may not be able to resolve individual tracks since the average separation between tracks is approximately 50 microns at a radius of 10 cm. Without the first superlayer the resolutions (for 10, 5 μm resolution per layer) are $0.47 p_T(\text{TeV})$, $0.23 p_T(\text{TeV})$ without a vertex constraint and $0.12 p_T(\text{TeV})$, $0.08 p_T(\text{TeV})$ with 5 μm vertex constraint. These resolutions are quite adequate for sign determination of 1 TeV charged particles, and observation of heavy particle states (Z', Higgs) by mass reconstruction[15]. Further, the vertex resolution of this type of tracker is better than 20 μm in both the r-ϕ and z directions(Fig. 9). The high resolution thus allows for vertex tagging and outer detector track matching. Using the radiation levels of the SSC Central Design Group Task Force we estimate that at $\eta = 0$ and r = 10 cm, the detector would be illuminated with 4.0 MRad per year at a luminostiy of

10^{34} $cm^{-2}s^{-1}$ while at $\eta = 2.5$ and r = 40 cm, the radiation level would be 8.0 MRad per year.

The advantages of a diamond tracker over silicon and other trackers are the following:

- Diamond can survive several tens of MRads.
- The charge will be collected in 1 ns well before the next beam crossing.
- The capacitance will be a factor of 2 lower than for silicon because of the smaller dielectric constant of diamond.
- Using the CVD process, the area of each diamond piece and, therefore, the maximum length of the strips can be much longer than for silicon.
- The thickness in radiation lengths will be smaller than for silicon. The radiation length of diamond is 16 cm compared to 9 cm for silicon.

A disadvantage of diamond that should be noted is that the signal will be about a factor of 3 smaller than in silicon since it requires about 13 eV to produce an electron-hole pair in diamond.

6.2 Calorimetry

The calorimetry is based on tungsten absorber with diamond sampling. The electromagnetic calorimeter would have 24 X_0 with 30 layers of sampling. Each layer would consist of 2.8 mm (0.8 X_0) of tungsten, 200 μm of diamond, and an additional 400 μm of material for the readout lines. It would have a total thickness of 10 cm and extend in radius from 55 cm to 65 cm. The lateral segmentation would be 0.02 x 0.02 in $\Delta\phi$ x $\Delta\eta$ for $|\eta| < 1.5$ and 0.03 x 0.03 in $\Delta\phi$ x $\Delta\eta$ for $1.5 < |\eta| < 2.5$. There would be two longitudinal segmentations. The total area of diamond would be 300 m^2 and the total weight of tungsten would be 20

tons. There would be 136,000 channels of readout electronics. The energy resolution would be $\sigma_E/E = 15\%/\sqrt{E}$ (E in GeV). The radiation level for $\eta = 2.5$ and r = 140 cm would be 40 MRad per year. At $\eta = 1.6$, it would be 4 MRad per year.

The hadronic calorimeter would have 7.2 interaction lengths with 120 layers of sampling. Combined with the 0.8 interaction lengths of the electromagnetic calorimeter, the total thickness of the calorimetry would be 8 interaction lengths. A study has shown that a calorimeter depth of 8 interaction lengths is sufficient for detecting a quark compositeness signature[16]. Each layer would consist of 6 mm (0.06 λ) of tungsten, 200 μm of diamond, and an additional 400 μm of material for the readout lines. It would have a total thickness of 80 cm and would extend in radius from 70 cm to 150 cm. The lateral segmentation would be 0.06 x 0.06 in $\Delta\phi$ x $\Delta\eta$ for $|\eta| < 1.5$ and 0.09 x 0.09 in $\Delta\phi$ x $\Delta\eta$ for $1.5 < |\eta| < 2.5$. There would be 2 longitudinal segmentations. The total area of diamond would be 5000 m^2 and the total weight of tungsten would be 600 tons. There would be 15,000 channels of readout electronics. The energy resolution would be $\sigma_E/E = 50\%/\sqrt{E}$. The radiation level for $\eta = 2.5$ and r = 160 cm would be 4 x 10^{14} neutrons per year while, at $\eta = 1.6$, it would be 4 x 10^{13} neutrons per year.

A critical question to address is whether diamond sampling calorimetry can be made compensating. We are encouraged by the results of calculations by Wigmans[17] and independently by Brau and Gabriel[18] which show that silicon sampling calorimetry can be made compensating. An essential property of silicon which allows it to be compensating is the lack of saturation for dense ionization. We expect diamond to also exhibit little or no saturation, although this must be experimentaly confirmed. In fact, carbon might be expected to have better compensation ability because, being a lighter nucleus than silicon, the maximum energy transfer for a neutron interaction will be larger.

6.3 Lepton Identification

This detector will be well suited for lepton identification. In the radial space from 150 cm to 200 cm, a second momentum measurement of muons could be made in the 5 Tesla field. If straw tubes with spatial resolution of 80 μm were used, a momentum resolution of $0.7p_T$(TeV) could be achieved. This momentum could then be matched to the momentum of tracks measured in the central tracker to identify the muon track.

For electron identification, a pre-radiator in front of the electromagnetic calorimeter could be used[19]. The pre-radiator samples the shower every $0.1X_0$ over the first 3 X_0's. With a lateral segmentation of a few hundred microns, synchrotron radiation photons emitted by electrons bending in the 5 Tesla field could be detected. With a detection threshold of 5 MeV, electrons from 100 GeV to about 500 GeV could be identified as was suggested in the 1987 Berkeley Workshop[6]. This pre-radiator could be based on either scintillating fibers as now being developed by the SPACAL collaboration or, if the technolgy can be developed, on diamond drift cells in which the charge would be drifted along the diamond layer and collected by electrodes spaced every few hundred microns.

6.4 Summary of Detector Characteristics

The detector we have outlined here would be made possible by CVD diamond technology. It is a powerful and flexible detector which could be built at a reasonable cost. Some of its important features are:

- It will operate at a luminosity of 10^{34} $cm^{-2}s^{-1}$.
- It has unsurpassed momentum resolution, $\sigma_{p_T} = 0.1p_T$ with vertex constraint.
- It has hermetic calorimetry for $|\eta| < 2.5$. There are no cracks for cryostats or magnet plumbing.

- It is an order of magnitude lower in cost than some other detectors that are being discussed. In addition, about 50% of the cost is in electronics which become cheaper before SSC turn on.

- It will have unmatched lepton identification. A second momentum measurement of muons will be made in the 5 Tesla field. Electrons will be identified by their emitted synchrotron radiation as well as their shower properties.

- Because the detector is compact it will allow flexibility. As new technology is developed, the detector can be upgraded without substantial cost since each component is relatively very small.

- Finally, by taking advantage of the compactness of the detector, minimizing the number of different subsystems and emphasizing ease of construction in the design, we believe that the detector could be built in a relatively short period. If the CVD diamond technology can be demonstrated within the next three years and if we were then to receive approval for beginning detector construction in 1993, we believe that it could be ready for SSC turn on in 1998.

6.5 Preliminary Cost Estimate

We have made a preliminary estimate of the hardware cost for the proposed detector. We assume that the cost of the electronics will be the same as those for other multi-purpose detectors since the number and type of channels are similar. The tungsten and diamond material, the solenoidal coil, and the straw tubes for the muon system make up the dominant hardware expense. To estimate the cost of the coil, we take the cost of the AMY coil and scale by the volume of superconductor and the value of the field. For the tungsten, we use a value of \$45/lb which is the price quoted in the 1989 CRC. For diamond, we assume a cost of \$0.25/cm^2. We are presently able to acquire CVD diamond at \$2000 for a 4-inch wafer

which corresponds to $\$25/cm^2$. Thus, we are assuming that in the next 5 years the cost will fall by two orders of magnitude. Since the price of a wafer is essentially independent of thickness, the present cost is mostly in setup. It seems likely, therefore, that large scale production will give significant cost reduction. *Several manufactures agree with this outlook*, see Appendix A. Finally, for the muon system, we assume a cost of $50 per tube.

With the above assumptions, we arrive at the following estimates.

Coil	30.0 M
Tracker	0.3 M
EM Calorimeter	2.5 M
Hadron Calorimeter	56.5 M
Preradiator	1.0 M
Muon Tracking	1.8 M
Total Hardware Cost	92.1 M

This number represents hardware cost only. The total cost including electronics and construction should be less than $200 M.

7 Proposed Program of Research

We propose a three-fold research plan to develop the technology necessary for an SSC detector. The areas of research include diamond growth, diamond calorimeter, and charged particle tracking.

7.1 Diamond Research

Our research effort in diamond detectors will consist of parallel efforts in developing prototype trackers and calorimeters using the available state-of-the-art CVD diamond and undertaking the necessary materials studies leading to production of high-grade detector material. This effort is a collaboration among the various groups participating in this proposal, and will bring together a unique mix of expertise in the areas of materials characterization, high energy particle detector development, and the physics and chemistry of materials growth.

Our initial effort in the development of a prototype detector will employ the use of state-of-the-art CVD diamond films. In collaboration with materials fabricators (e.g., Crystallume, Advanced Technology Materials, Advanced Fuel Research), diamond films will be manufactured to our specifications on a best effort basis. The electrical, structural, and mechanical properties of these test samples will be characterized at OSU and LLNL. Transient photoconductivity measurements will be used to measure the carrier mobility and lifetime[13, 20]. In addition, SEM, TEM, X-ray diffraction, and Raman spectroscopy will be employed to further characterize the films. All of this information can be used to assist in improving the quality of the films and in motivating future materials development, as discussed later. Continued iteration with the vendors will help to optimize the diamond material for application to a prototype detector.

A systematic study of the effects of radiation damage on natural and CVD diamond can begin immediately using a variety of radiation sources. Our collaboration will have access to the Omega West Reactor at LASL and a cesium X-ray source at U.C. Berkeley. Irradiations will be made to simulate the effects of high luminosity operation of the SSC to establish the radiation hardness of diamond.

To establish the materials properties limits in thin film diamond, a parallel effort will pursue the fabrication and characterization of homoepitaxial diamond, i.e., single crystal

diamond grown on a diamond substrate. Several groups have grown homoepitaxial diamond using the CVD process. These diamond on diamond structures will be used to determine if detector quality material can be produced under the best possible nucleation conditions. As described above we will characterize these materials and attempt to relate their properties to the growth conditions. During this phase of our research, the understanding of the nucleation of single crystal diamond will be initiated. Raman surface scattering and gas phase spectroscopy during thin film growth will expand our understanding of the diamond nucleation process in preparation for the study of growth of detector quality material on suitable substrates at low cost.

The final stage of this cooperative effort will be to determine the fabrication process suitable for the growth of large quantities of detector quality material.

The ability to tailor the CVD process to generate heteroepitaxially grown diamond for large films (greater than $10cm^2$ and 200 μm thick) will require careful study of the growth mechanisms and their interaction with the substrate material. The study of the surface interactions must be correlated with the gas phase excitation chemistry of the hydrocarbon species and with the environmental operating parameters (pressure, temperature, etc.). This effort will determine the process for the large scale production of detector quality diamond for the SSC. The letters shown in Appendix A demonstrate interest from the diamond manufacturers in this program. Our collaboration has demonstrated expertise and capability in this area. Appendix B summarizes our measurement capabilities.

7.2 Calorimeter Prototype

The results of our work have shown that presently available CVD diamonds are applicable to the design and construction of a prototype calorimeter. In parallel with the program described of developing high quality CVD diamond, we will construct a series of calorimeter prototypes utilizing the highest quality diamond as it is developed. Since initially the dia-

mond will not be of high grade, we do not want to purchase sufficient quantities to construct a complete prototype. The first prototype will, therefore, simply be a single layer of diamond located behind 1 to 2 cm's of lead at shower maximum. We will test this simple prototype in an electron beam of several GeV. This should give a substatial and measurable signal even if the collection efficiency is not near 100%. From an EGS Monte Carlo simulation, we can calculate precisely the energy deposited in the diamond and compare to the measured signal. This measurement will complement the measurement of carrier lifetimes made by transient photoconductivity measurements and will help to characterize the quality of the sample.

When the quality of the CVD diamond has been sufficiently developed and satisfactory collection efficiency has been attained, we will construct a full prototype with 30 layers of sampling and with full shower containment. With this prototype, we will be able to determine the energy and postion resolution of a diamond sampling calorimeter.

At a later stage, after the characteristics of the electromagnetic calorimetry have been well established, we will construct a prototype hadron calorimeter. We will then determine the achievable energy resolution for hadrons and, very importantly, the ability of the hadron calorimeter to compensate.

7.3 Prototype Tracker

At present, the results of our work are not applicable to a high efficiency tracking device. As a result we will begin our tracking development on silicon and transfer the results to a diamond based system when detector grade diamond becomes available. In parallel with the program described on the development of high quality CVD diamond, and the construction of a prototype diamond calorimeter,we will construct a series of two-dimensional strip detector and drift detector prototypes utilizing presently available techniques. Our goal is twofold: to produce strip devices with transverse strips which are resistively voltage biased with capacitively coupled signal lines to avoid leakge current problems in the electronics; and to

produce two dimensional drift detectors. These prototype devices will be 1 cm $\times$ 1 cm. We plan to use existing electronics (CAMEX for the strip detectors and the LBL Kleinfelder waveform sampling chip for the drift detector) to readout the test devices. We will measure spatial resolution in two dimensions for each device. Since we plan to use the drift detectors to readout the pre-radiator for the electromagnetic calorimeter, we will construct a small prototype section of such a device and measure its properties in front of the calorimeter prototype.

7.4 Budget Request

Below we list the requested research budget for the first year of operation. We also identify the institutions responsible for the various detector elements:

Calorimeter Prototype Cost Estimate (1st yr)	
Materials and Supplies	
Diamond	50 K
Tungsten	5 K
Electronics	10 K
Computer	20 K
Personnel	
Research Associate	50 K
Students	20 K
Miscellaneous	
Shop Time	5 K
Travel	5 K
Test Beam	5 K
Total	170 K

Tracking Prototype Cost Estimate (1st yr)	
Materials and Supplies	
Silicon Strip Detectors (1cmx1cm)	30 K
Silicon Drift Detectors (1cmx1cm)	30 K
Electronics	10 K
Mechanical Support	5 K
Computer	20 K
Personnel	
Research Associate	50 K
Students	20 K
Miscellaneous	
Shop Time	5 K
Travel	5 K
Test Beam	5 K
Total	180 K

Diamond Research Cost Estimates (1st yr)	
Materials and Supplies	
Diamond CVD Samples	50 K
Diamond Single Crystal Samples	50 K
Diamond Single Crystal Substrates	30 K
Non-Diamond Crystal Substrates	10 K
Laser Operating Costs	15 K
Gas	20 K
Lab and Operating Supplies	15 K
Personnel	
Research Associate (2 @ 60 K)	120 K
Students	20 K
Miscellaneous	
Travel	5 K
Total	335 K

Total Program First Year Cost: 685 K

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A Letters of Manufactures' Interest

1. Crystallume – Laurie Conner, Vice President, Marketing and Sales
2. Advanced Fuel Research – Philip Morrison, Senior Chemical Engineer
3. Advanced Technology Materials, Inc. – Charles Beetz, Director, Thin Film Research and Development

Crystallume
Engineered Diamond Products

125 Constitution Drive • Menlo Park, California 94025 • (415) 324-9681
FAX (415) 324-2958

May 17, 1990

Dr. Steven Schnetzer
Department of Physics
Rutgers University
P.O. Box 849
Piscataway, NJ 08854

Dear Steve:

I would like to thank you for inviting us to attend your recent conference on CVD diamond for use in the SSC Detector. As I hope you learned from our talk, and others, CVD diamond technology has progressed significantly in a short time and applications development has begun. While the technology is not fully developed for use as a high energy detector, there are promising results which indicate that diamond films could make an important contribution to the SSC project.

As the leading commercial company in the CVD diamond world, we are very interested in participating in the development of diamond for the SSC. We would be pleased to work with you and your colleagues to devise a useful set of diamond substrates with which you can perform proof-of-concept experiments. We prefer working on a joint development basis, as opposed to being a vendor of diamond substrates, because it will require an iterative process to develop diamond suitable for this demanding application.

We look forward to working with you on this project. Thank you again for an informative meeting.

Sincerely,

Laurie C. Conner
Vice President
Marketing and Sales

cc John Herb
Maurice Landstrass

ADVANCED FUEL RESEARCH
P.O. Box 18043
East Hartford, Connecticut 06118
Telephone (203) 528-9808

May 22, 1990

Professor Stephen Schnetzer
Rutgers University
Physics Lab
Piscataway, NJ 08854

Dear Steve,

I want to express my interest in your proposal to employ diamond films in a calorimeter for the SSC. In my discussions with you, I feel that the technical requirements for the diamond calorimeter are not significantly beyond the state of the art and that with proper engineering, the large areas can be fabricated. I believe that proof of concept experiments are certainly justified.

My company, Advanced Fuel Research, is actively developing a deposition method to coat diamond films onto large areas using an acetylene flame. I think our flame method is well suited to deposit the films for the calorimeter. We would like to participate in the feasibility studies as well as the research, development, and manufacture of the films for the calorimeter.

I hope that your proposal is successful and that we will be working together in the future.

Sincerely,

Philip W. Morrison Jr.

Philip W. Morrison, Jr.
Senior Chemical Engineer

PWM/sb

Advanced Technology Materials, Inc.
520-B Danbury Rd., New Milford, CT 06776 (203) 355-2681 FAX (203) 355-9486

16 May 1990
Professor Steven Schnetzer
Department of Physics
Rutgers University
P.O. Box 849
Piscataway, NJ 08855-0849

Dear Prof. Schnetzer:

The meeting at Rutgers on May 9 regarding the design of a compact diamond based detector for the SSC was very interesting. Over the past two years at ATM, we have been persuing the application of diamond film technology for use as ultrafast optoelectronic switches for pulsed power. Many of the materials issues in switch design are common to detector designs in which the diamond is used as a solid state ionization chamber. We have been also working in this area with Professor David Winn at Fairfield University investigating the use of diamond films as x-ray detectors. At the present time I have four federally supported programs in this area with David as a subcontractor and a joint program with David supported by the state of Connecticut.

The development of a diamond based detector will require a multidiscipline effort and we are interested in working with you in the development of a detector for the SSC. We can supply you with diamond films, provide film analysis and characterization data as well as detector fabrication facilities.

We are enthusiastic about the prospects of the use of diamond films as detector materials for the SSC. We are confident that there are significant commercial markets that could develop around diamond detectors.

Sincerely

Dr. Charles P. Beetz, Jr.
Director, Thin Film Research and Development

B Research Facilities

Lawrence Livermore National Laboratory

- Picosecond UV laser
- Picosecond Laser Plasma X-ray Source
- Proton Accelerator/ Neutron Source
- Omega West Reactor (LANL)
- Radioactive Sources

Ohio State University

- High Resolution Pulsed Dye Lasers with UV Extension
- Raman Spectrometer with Microprobe
- Emission Spectrometers and Optical Multichannel Analyzer
- X-Ray Diffractometers
- Scanning Electron Microscopes (SEM)
- Tunneling Electron Microscope (TEM)
- Vacuum Film Deposition System
- Auger, EELS, and XPS Capability

Stanford University

- SPEAR Synchrotron (SSRL)
- IC Fabrication and Test Facilities
- UV Spectrophotometer

University of California at Berkeley

- Intense Cesium γ-Ray Source

C Diamond Diagnostics

Gas Phase Laser Spectroscopic Diagnostics

The characteristics of diamond materials produced by chemical vapor deposition (CVD) or by plasma-assisted CVD (PACVD) processes are strongly dependent upon gas phase reactive chemical species concentrations, chemical reaction kinetics, and the physical deposition environment. For PACVD there are additional complications due to the presence of energetic free electrons and ions, sustained radical production, plasma-surface interactions, and electric fields. Application of laser spectroscopic probe diagnostics can provide a detailed picture of these interactions; for diamond CVD, laser diagnostics for observing the majority of chemical species and their concentrations are well developed. Laser diagnostics have the capability to make in-situ, non-intrusive, spatial and temporal measurements of reactive species concentration profiles and gas phase parameters. The Ohio State University Laser Spectroscopy Facility (OSU LSF) has been a leader in laser spectroscopic diagnostics on gas phase reactive molecules. The use of laser-induced fluorescence (LIF) techniques on carbon-bearing molecules has been demonstrated at OSU LSF and elsewhere. Likewise, there is a wealth of information provided by the use of LIF on hydrogen and oxygen, where the observation of excited rovibronic states of these molecules gives information on molecular temperatures and chemical excitiation kinetics.

The measurement of ground state atomic concentrations generated in CVD/PACVD deposition can be measured by the technique of two photon allowed laser-induced fluorescence (TALIF). This capability has has been fully demonstrated at OSU LSF for both atomic hydrogen and oxygen. This technique has excellent spatial resolution (200 μm) and can be operated in a time-resolved mode with a nominal resolution of 50 nanoseconds. This development opens up a new capability to explore the excitation and production dynamics of atomic and molecular species in CVD processes.

The exact production mechanism of carbon allotropes from the gas phase on substrates

is uncertain. Applying TALIF to measuring atomic carbon concentrations in CVD/PACVD systems would determine the amount of available atomic carbon present during different processes. The production of either acetylene or methyl radicals from the gas phase chemistry have been proposed as major surface reactive species leading to diamond formation. Both species can be detected by LIF or by photodissociation and the subsequent TALIF detection of the hydrogen atom fragment which has a characteristic Doppler component due to the bond dissociation energy. Profiling of spatial distributions would indicate the relative importance of each species. In addition, radicals such as Cx, CHx, COx, and OH and their ions are present as directly ascertained by emission spectrometry or are indirectly indicated by mechanistic schemes. Many of these species are easily monitorable by LIF techniques or by in situ titration.

Laser spectroscopic probes also offer the capability to measure physical parameters in reactive gas media such as electric fields, Doppler velocities, and temperatures. Such parameters influence the excitation and production dynamics of atomic and molecular species. Certainly, the deposition of CVD diamond can be correlated with parameter and surface diagnostic results both in an empirical fashion and with low-temperature non-equilibrium CVD theoretical and computational models.

Laser Raman Surface Diagnostics

A key indication of the production of diamond crystalites formed from a CVD/PACVD process is the presence of a surface Raman scattering spectrum characteristic of diamond. The main feature of such a spectrum is a single sharp line located at 1332 cm^{-1} wavenumber shift. The linewidth of this feature has an inverse dependence on the average crystalite size. Present also to varying degrees are Raman features associated with glassy carbon, graphite, and the substrate material.

Raman and Surface-Enhanced Raman (SERS) spectra for CVD/PACVD diamond are obtained at the OSU LSF using a scanning Raman spectrometer with microprobe which al-

lows for broad survey scans over large areas of a substrate, or using the microprobe, confining the scan to smaller features of interest on the surface. The research group responsible for maintaining the Raman spectrometer has an active research interest in the Raman spectra of the allotropes of carbon and has contributed invaluable technical expertise and theoretical interpretation of the Raman spectra.

Surface Diagnostics for Diamond CVD

The microstructure of the CVD/PACVD materials can be characterized by OSU Department of Materials Science and Engineering and the OSU Physics Department Materials Research Laboratory. X-Ray diffraction and scanning electron microscopy (SEM) allow the internal structure and morphology to be characterized on a coarse scale. X-Ray diffractometry has several advantages: It is relatively fast, non-destructive, and gives information on the average structure over a CVD-deposited substrate. In each sample, diffraction peaks from the known crystalline substrates can serve as an internal calibration standard so that additional diffraction peaks from the film can be readily identified. Since the width of the diffraction peaks are inversely related to the average grain size, this can serve as an index of the relative grain size throughout a sample. Relative intensities of different peaks, e.g. (004) vs. (111), are useful for identifying preferred grain orientations (crystalline texture) developed during the CVD process. SEM is very useful for characterizing the effects of processing variables on the morphology of CVD processed materials. Film continuity, surface roughness, preferential grain orientation, size, and shape can be systematically correlated for fast screening and optimization for CVD growth procedures.

On a fine scale, microstructural features and chemical analysis can be achieved using transmission electron microscopy (TEM), Auger electron spectroscopy, electron energy loss spectroscopy (EELS), and X-Ray photoelectron spectroscopy (XPS). TEM speciemens can be prepared by mechanical thinning and subsequent ion milling. TEM investigations provide useful information on type and density of crystal defects in diamond films as well as size and

orientation of individual grains; both in plan-view and in cross-section.

Table 1: Properties of Diamond

Property	Diamond	Silicon
Neutron Cross Section (mb)	3.2	80.0
Resistivity (Ω-cm)	$> 10^{12}$	10^{5}
Electron Mobility ($m^2/V/s$)	0.18	0.15
Hole Mobility ($m^2/V/s$)	0.12	0.05
Band Gap (eV)	5.5	1.1

Figure Captions

- Fig. 1. Schematic of use of diamond as a radiation detector.
- Fig. 2. Electron drift velocity in various materials as a function of applied electric field.
- Fig. 3. Plot of leakage current for diamond and silicon diodes exposed to a flux of 1.5 MeV electrons. Figure is courtesy of M. Geis, MIT Lincoln Laboratory.
- Fig. 4. Induced leakage current in silicon from exposure to neutron, electron, and proton radiation.
- Fig. 5. Comparison of radiation resistance of diamond (solid curves) to silicon (dashed curves) based on measurements with an α-source after exposure to a flux of fast neutrons (maximum in spectrum of 0.5 MeV).
- Fig. 6. Outline of the proposed detector showing all of the detector subcomponents.
- Fig. 7. Outline of the proposed diamond tracker.
- Fig. 8. Momentum resolution of diamond tracker.
- Fig. 9. Vertex resolution of diamond tracker.

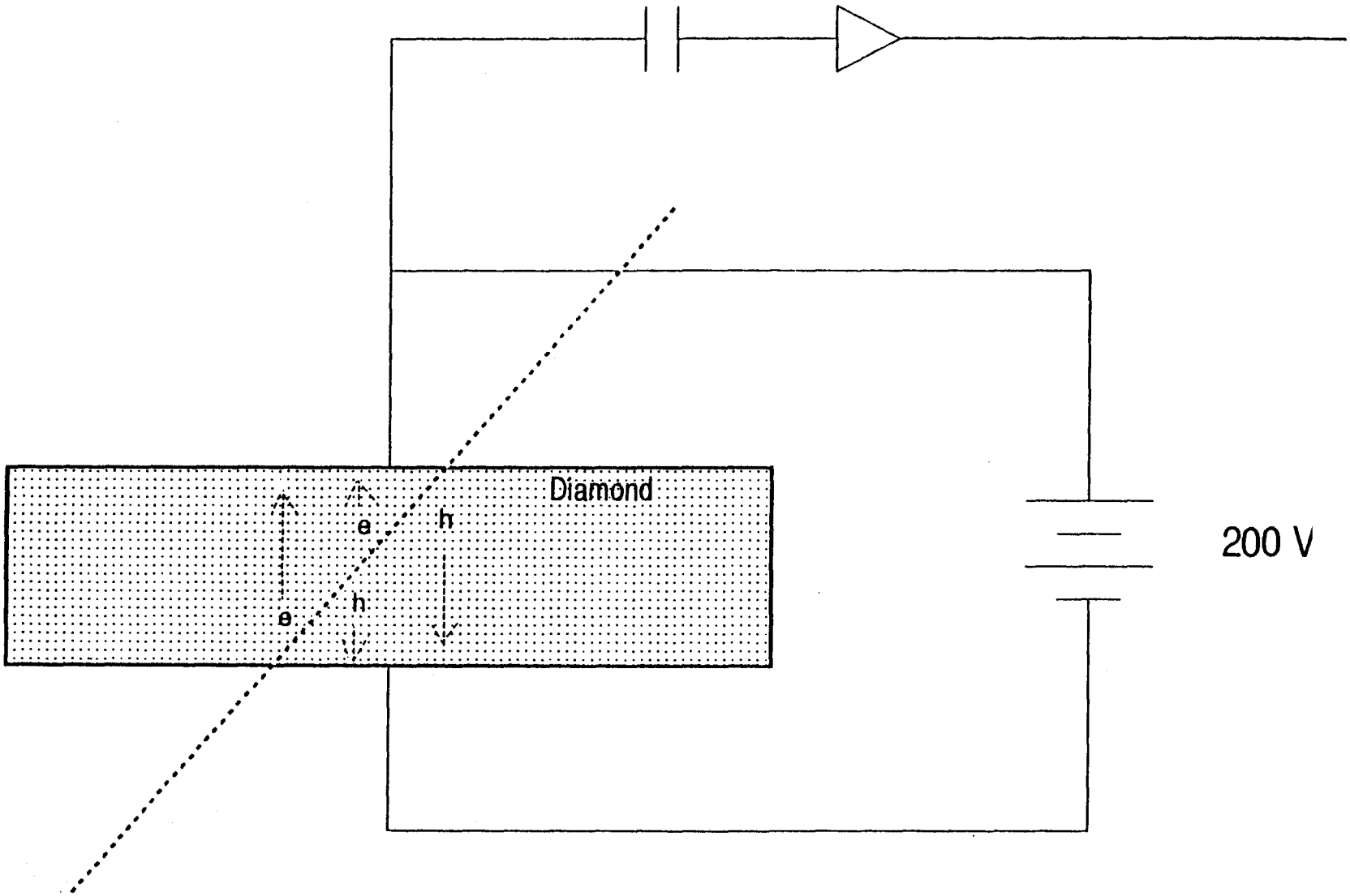


Figure 1

STEADY-STATE VELOCITY-FIELD CHARACTERISTICS

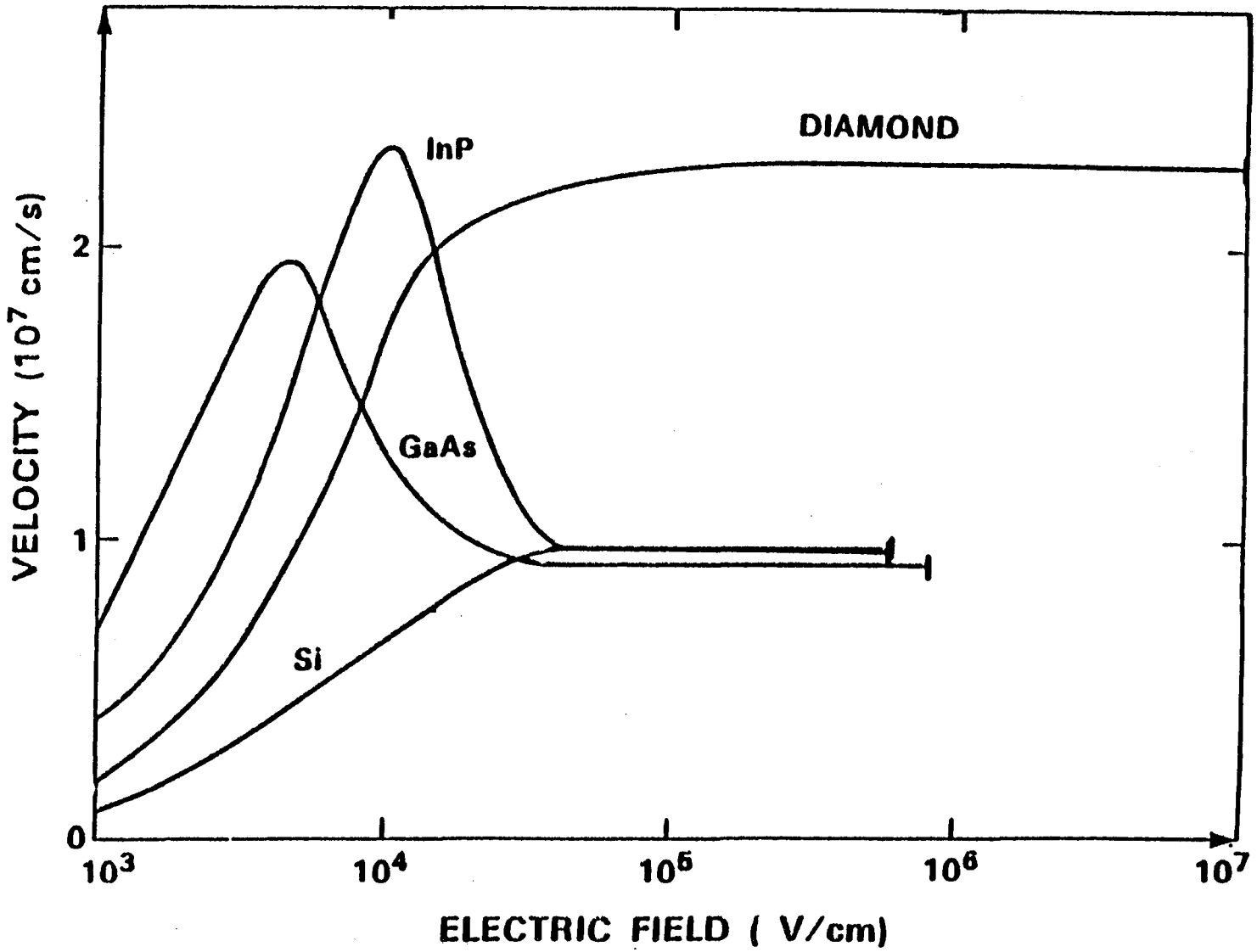
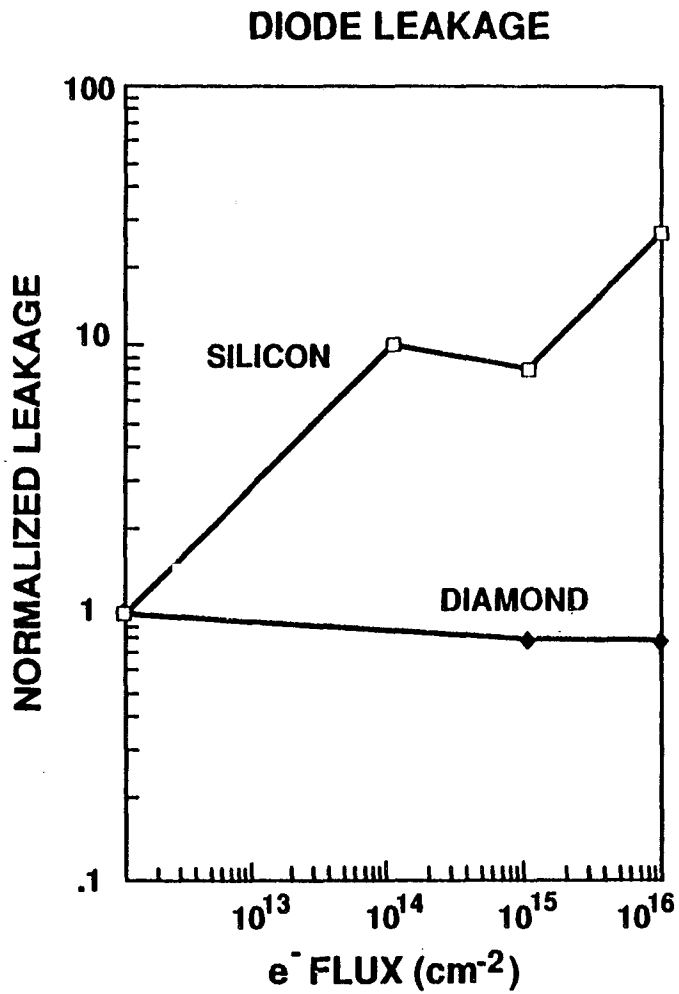


Figure 2

RADIATION DAMAGE BY 1.5 MeV ELECTRONS



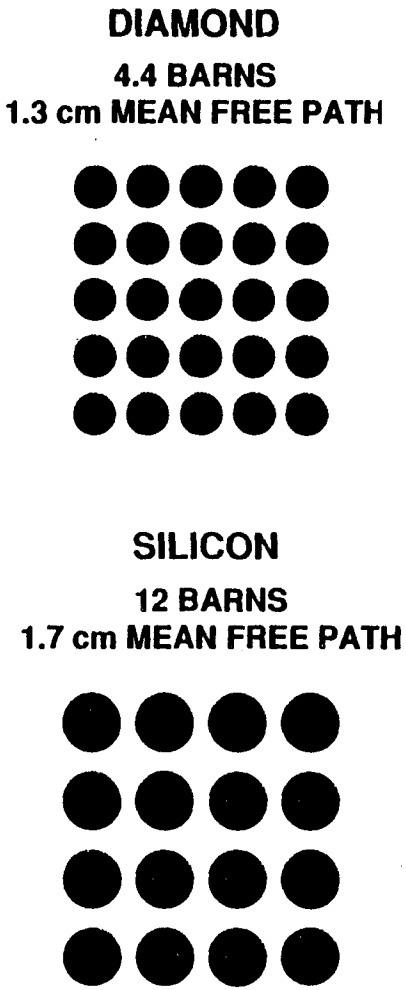


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Figure 3

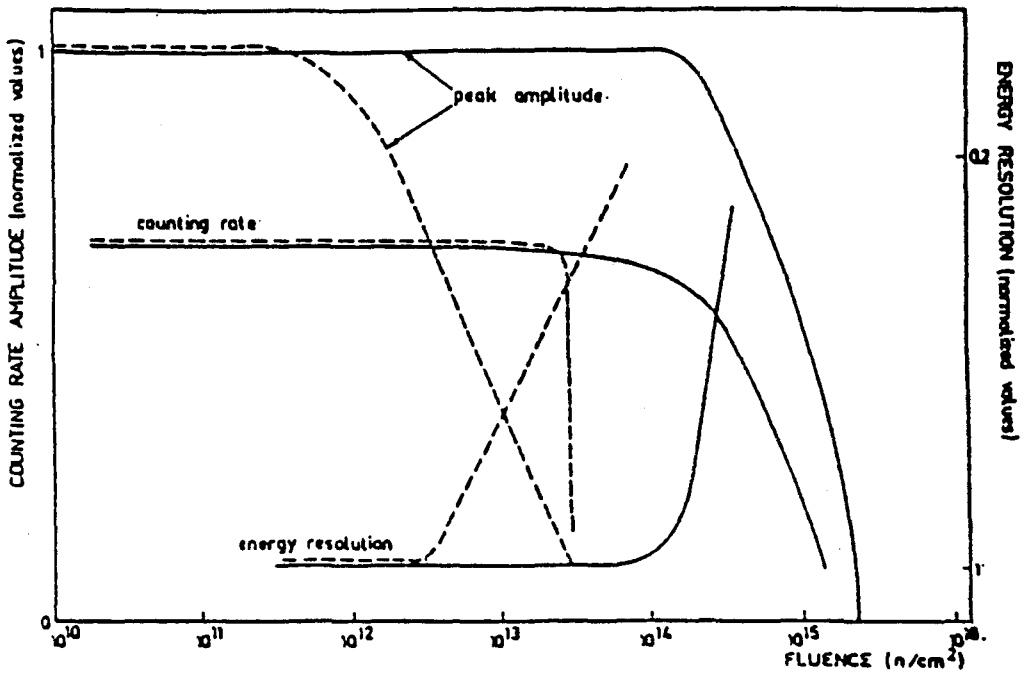


Figure 4

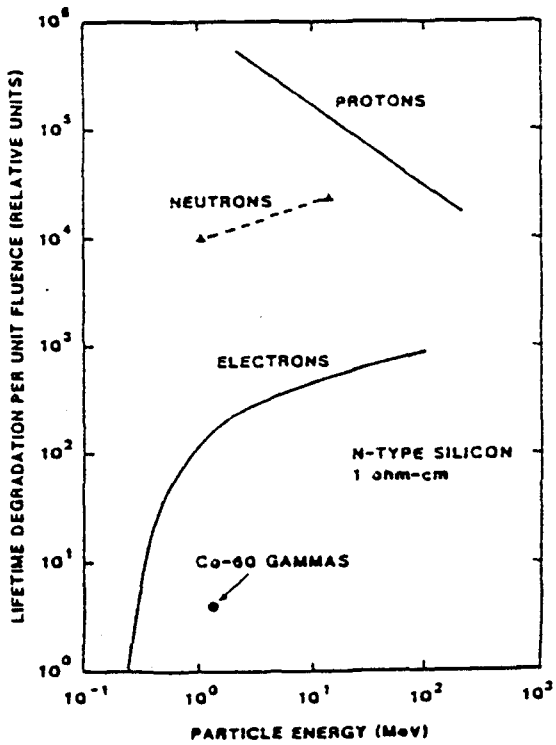
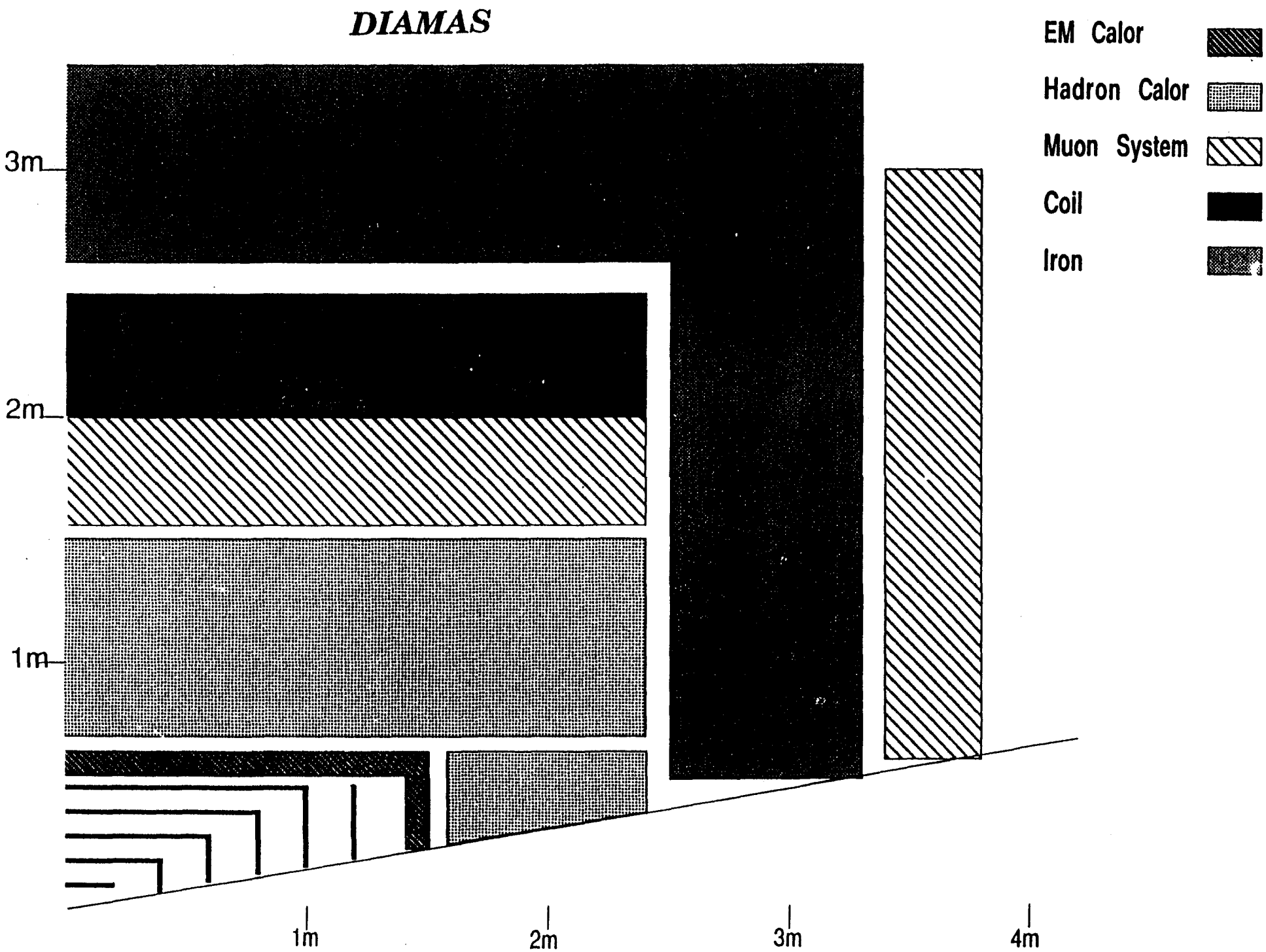


Figure 5


DIAMAS
EM Calor
Hadron Calor
Muon System
Coil
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3m
2m
1m
1m
2m
3m
4m

Figure 6

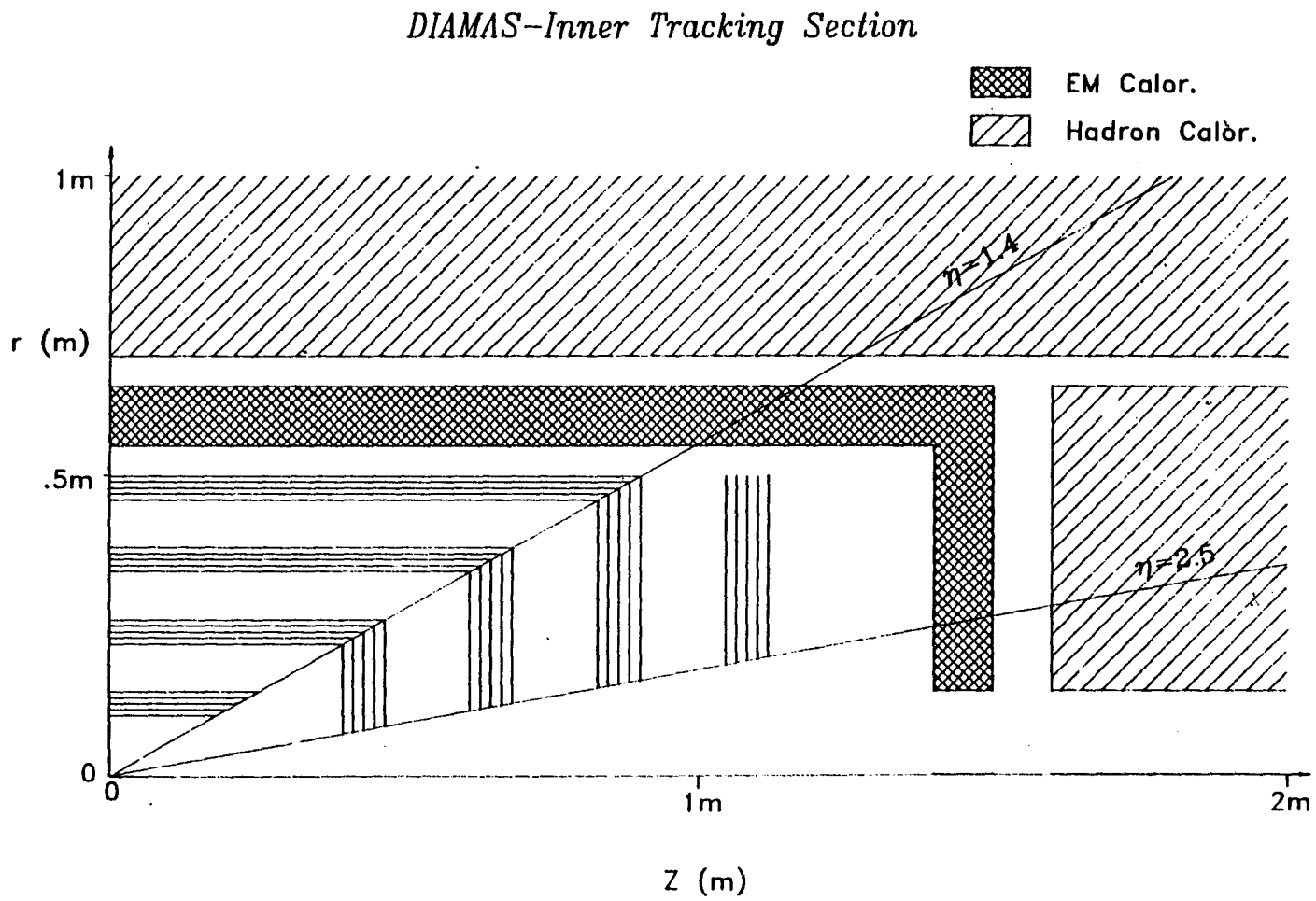
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Figure 7

Figure 8

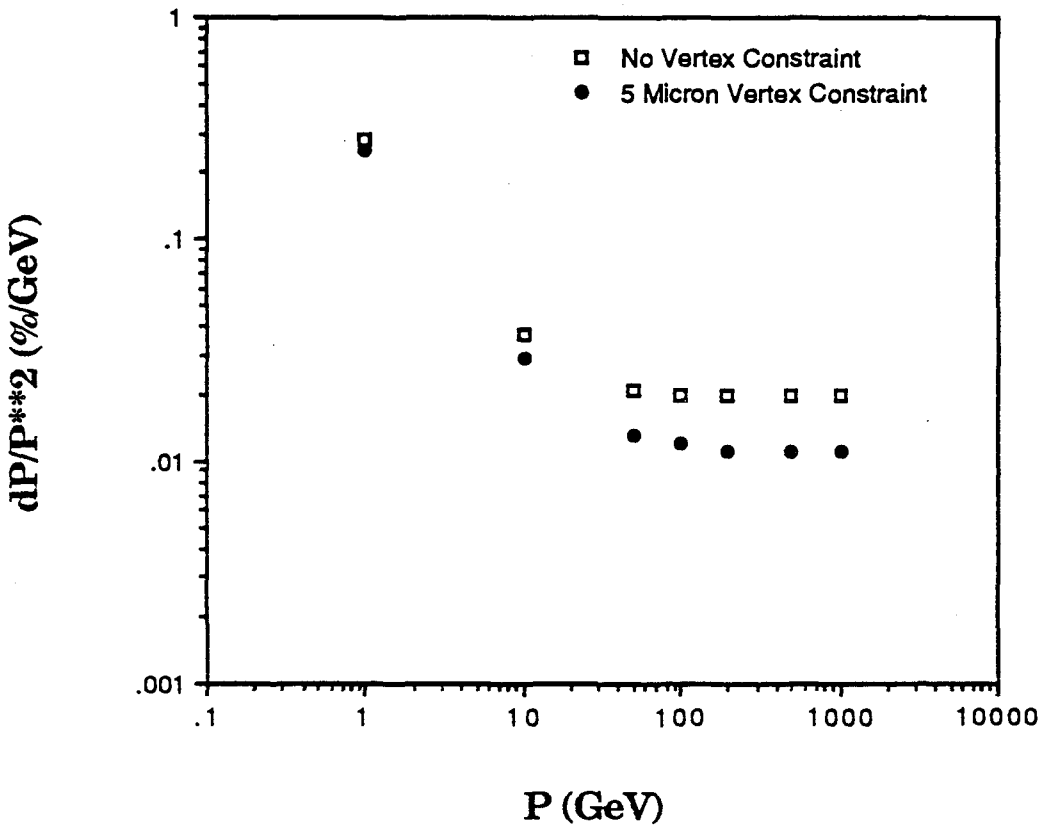
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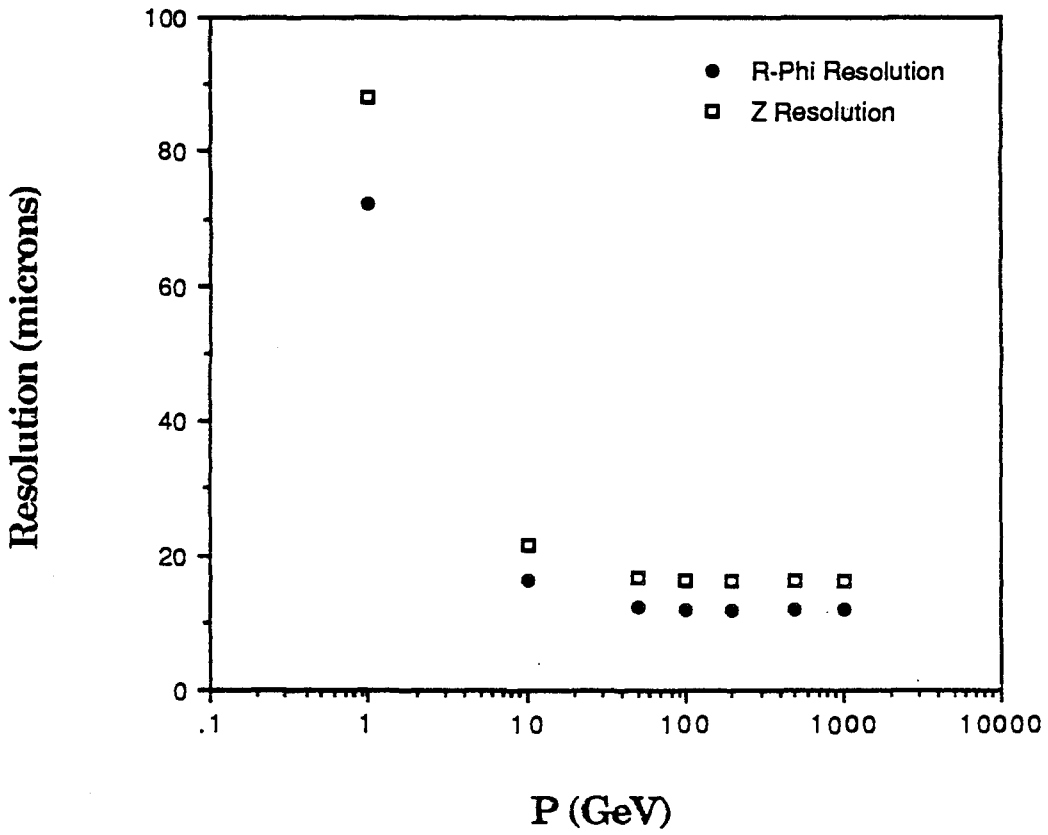
Figure 9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Resolution (microns)
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P (GeV)