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The Status of Diamond Detectors and a Proposal for R & D for CDF Beyond Run II

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Introduction

Enormous progress has been made in hadron collider physics over the last decade especially in the area of heavy quark studies. Much of this has been due to the superb performance of the CDF silicon vertex detectors. Future Tevatron runs offer unique physics opportunities but will present a number of experimental challenges. Plans to install a more radiation hard, double sided silicon vertex detector for Run II are already well advanced. However even the Run II delivered luminosity goal of 2 fb^{-1} may expose the innermost layer of SVX-II to a lethal radiation dose. For Run III, with a delivered luminosity goal of 30 fb^{-1}, alternatives to double sided silicon strips must be considered for at least the two innermost layers of the SVX-II.

Detectors based on chemical vapor deposition (CVD) diamond have been shown to survive up to 100 MRad doses of ionizing radiation far exceeding the anticipated dose near the CDF interaction region in Run III. The quality of presently manufactured CVD diamond is at the threshold for allowing high signal-to-noise detectors to be constructed, given currently available low noise readout electronics. Assuming that the occupancy rates in the inner detectors of SVX-II, with the present L0 and L1 geometry, remain acceptable up to luminosities of 10^{33} cm^{-2}s^{-1} then diamond-based detectors should be considered as a radiation hard alternative for these layers. The diamond detectors will have double-sided strip patterns and radiation length identical to SVX-II with low noise SVX3-compatible front-end chips, Such a system would, as a major benefit, retain the advantages and investment in the silicon vertex trigger (SVT). The diamond vertex layers would be functional equivalents of the silicon layers they would replace. The program described within also would allow for a diamond pixel alternative for the inner SVX layers, should CDF choose to move in this direction.

This document reviews the use and operation of diamond-based microstrip and pixel detectors, discusses the present status of their development, and describes a proposal for a development effort aimed at a CVD diamond prototype for the inner layers of the present SVX. Most of the results shown here are courtesy of the RD42 collaboration.

1 Introduction

In Fig. 1, we show the basic principle behind the use of diamond as a charged particle detector. A DC voltage of several hundred volts (~ 1 V/μm) is applied across a layer of diamond a few hundred microns thick. When a charged particle traverses the diamond, atoms in the crystal lattice sites are ionized, promoting electrons into the conduction band and leaving holes in the valence band. On average, 3600 electron-hole pairs are created per 100 μm of diamond traversed. These charges drift across the diamond in response to the applied electric field producing a signal that can be amplified and processed.

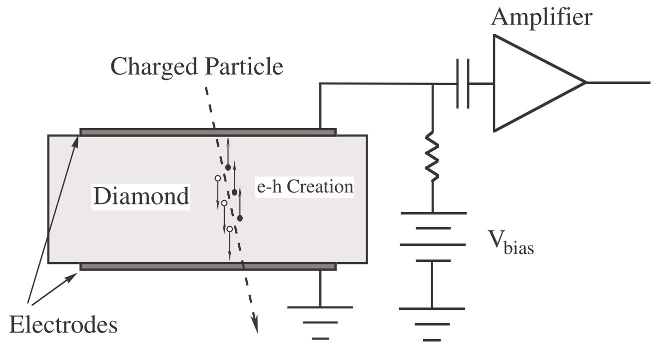

Figure 1: A schematic view of a diamond detector.

1.1 General Properties of Diamond

In Table 1 [1], we summarize the properties of diamond (and for comparison silicon and gallium arsenide) that are of interest when considering this material for use as a particle detector. Since diamond has a large band gap, 5.5 eV, it is an excellent electrical insulator. The electrical conductivity of diamond material is dominated by the presence of defects and impurities. Nevertheless, the resistivity of high-purity diamond is typically $> 10^{12}$ Ω-cm. Because of this large resistivity, a large electric field can be applied across the diamond layer without producing significant leakage current. Thus there is no need for a reversed biased *pn*-junction to prevent large leakage currents whose fluctuations would introduce noise.

The electron mobility in diamond is large and the hole mobility is approximately two-thirds that of the electrons. This in combination with the large breakdown field means diamond detectors are able to operate at or near the saturated drift velocity of $\sim$200 μm/ns. Thus, in a diamond detector with thickness of a few hundred microns, the charge collection time is a few nanoseconds.

Although diamond is an electrical insulator, it is also an excellent thermal conductor. At room temperatures, the thermal conductivity of diamond exceeds that of pure copper by a factor of five. A common problem with large strip detector systems is the management of the thermal load generated by the large number of electronic channels used in the detector readout. The handling of this thermal load will be greatly simplified if the detectors are constructed from diamond.

Diamond has two additional properties which play important roles. Its small dielectric constant means that the components of capacitance in detector configurations which depend on the dielectric properties of the material will be reduced. In addition, since diamond detectors do

Property	Diamond	Si	Ga As
Band Gap [eV]	5.5	1.12	1.43
Breakdown field [V/cm]	10^7	3×10^5	4×10^5
Resistivity [Ω-cm]	$> 10^{11}$	2.3×10^5	10^8
Intrinsic Carrier Density [cm^{-3}]	$< 10^3$	1.5×10^{10}	$\sim 10^8$
Electron Mobility [$cm^2V^{-1}s^{-1}$]	1800	1350	8500
Hole Mobility [$cm^2V^{-1}s^{-1}$]	1200	480	400
Saturation Velocity [km/s]	220	82	80
Mass Density [g cm^{-3}]	3.5	2.33	5.32
Atomic Charge	6	14	31, 33
Dielectric Constant	5.7	11.9	13.1
Thermal Expansion Coefficient [K^{-1}]	0.8×10^{-6}	2.6×10^{-6}	6.9×10^{-6}
Thermal Conductivity [W m^{-1} K^{-1}]	1000-2000	150	45
Cohesive Energy [eV/atom]	7.37	4.63	
Energy to create e-h pair [eV]	13	3.6	4.2
Radiation Length [cm]	12.0	9.4	2.3
Spec. Ionization Loss [MeV/cm]	4.69	3.21	5.6
Ave. Signal Created/100 μm [e]	3600	8900	13000
Ave. Signal Created/0.1% X_0 [e]	4500	8400	3000

Table 1: The physical properties of diamond, silicon and gallium arsenide at 293K.

not require diodic structures, this material is immune to many of the plagues of high radiation environments including type inversion.

Diamond appears ideal in many applications but it does have limitations: the large band gap which produces many of its outstanding properties also means that its signal size is not large, *i.e.*, approximately half that of silicon for equivalent thicknesses in radiation lengths. This effect may be compensated for, in certain configurations, by diamond's smaller dielectric constant, hence smaller capacitance and its almost non-existent leakage current.

1.2 Chemical Vapor Deposition Diamond

The research effort described in this document makes use of artificial diamond manufactured using the Chemical Vapor Deposition (CVD) process. In this 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, a hot filament, or some other energy source. The resulting reactive gas mixture is brought into contact with a substrate, typically silicon, where carbon based radicals are reduced and the carbon atoms link together with single bonds (sp^3 hybridized orbitals) forming a diamond lattice. Raman spectroscopy and X-ray diffraction unambiguously show that the CVD films are diamond and polycrystalline in structure.

CVD diamond typically grows in a polycrystalline columnar structure along the growth direction. The substrate side begins with small grains (~ 1 μm) which grow with material thickness. As the material grows it develops the texture of the fastest growing crystal orientation. It has recently been shown [2, 3] that the electrical properties of CVD diamond vary with the thickness of the material: the carrier lifetimes are small on the substrate side and large on the growth side. As a result, the raw diamond material can be "improved" by removing material from the substrate side. This procedure has been used to increase the signal size by 40% over the as-grown sample. Figure 2 shows the improvement of the quality of diamond as measured by the increase in signal size as a function of the fraction of material removed. The solid line is the result of a

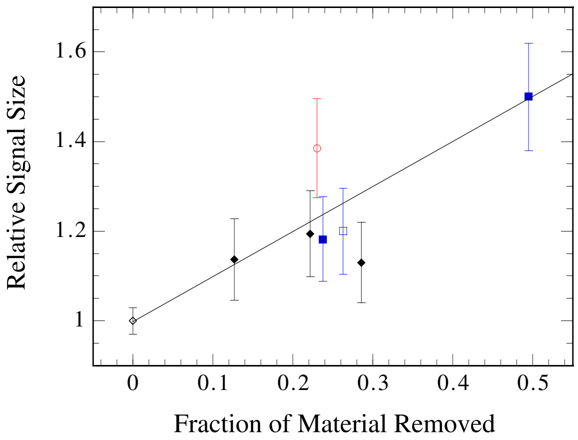

Figure 2: Improvement in the quality of a CVD diamond as a function of the amount of material removed. The different symbols represent different samples which have been studied.

model which predicts the quality of the material with thickness.

The growth of CVD diamond can be achieved through several processes and many companies including Crystallume, DeBeers, Diamonex, Kobe Steel, St.Gobain/Norton and Sumitomo are producing polycrystalline films. Nevertheless, this is still a developing field and there are a large number of parameters which must be optimized for the production of the quality diamond necessary for charged particle detectors. These include: type of excitation energy source, relative concentration of hydrocarbons, substrate temperature, gas pressure. Because of the large number of variables, systematic correlations between growth parameters and diamond quality are only now being completed. During past years, research has helped produce CVD diamonds which are now, as far as electrical properties are concerned, much better than natural IIa diamond.

1.3 History of Diamond R&D

Seven years ago a research program (originally named DIAMAS [4] and more recently RD42 [5] an on-going LHC R&D project) began to develop diamond technology to solve the high radiation, high rate, thermal problems and high cost associated with SSC and LHC detectors. During the first two years of this program it was demonstrated that diamond material could be used as the active element in a detector by constructing small diamond devices which observed single minimum ionizing particles [6]. During the third year of the program the first calorimeter-quality diamond wafers were produced and a diamond-tungsten calorimeter was constructed along with its readout electronics [7]. This device performed with the same energy resolution as a similar silicon-tungsten calorimeter.

During the fourth year the first diamond strip detector was constructed with 100 μm pitch and attained 25 μm spatial resolution, 90% efficiency, and a 6:1 signal to noise using a 1.5 μs shaping time in a 50 GeV pion beam at CERN [8]. During the next few years diamond strip trackers were constructed with 50 μm pitch. These detectors attained 12 μm spatial resolution, 98 % efficiency and 22:1 signal to noise with a 1.5 μs shaping time in a 100 GeV pion beam [9, 10]. This past year the signal to noise with 50 μm pitch trackers using 1.5 μs shaping time reached 50:1 [11], the first diamond pixel detector was constructed, achieving 22:1 signal to noise, and the first diamond tracker (50 μm pitch) was operated with 22 ns peaking time and attained 7:1

signal to noise.

These successes demonstrate the soundness of the idea of using diamond as the active material in a tracker. However, work must still be performed to increase the diamond signal size by producing better material so that we can achieve a minimum of 10:1 signal to noise at the short shaping times of the Tevatron. During the past few years, radiation damage studies using neutrons, photons, pions, and protons were also begun on CVD diamond devices to establish their radiation hardness [11]. As expected, no deterioration in the diamond devices has been observed at doses comparable to ten years of Tevatron operation. These tests must now be extended to the highest quality diamond.

2 Signal Size and Test Beam Results

We usually characterise the signal size observed from a diamond sample in terms of a *collection distance*, d, defined as the average distance electrons and holes separate before being stopped by defects or impurities in the diamond. The collection distance is a measure of the basic material properties such as carrier mobility and lifetime. The collection distance is also related to the average charge observed, Q, by $Q = d(\mu\mathrm{m})\times 36\ \mathrm{e}/\mu\mathrm{m}$. The collection distance of the best samples available today exceeds 200 μm. This means that for thin samples most of the charge is actually able to fully traverse the diamond detector – as is the case for the charge in mono-crystalline silicon.

One interesting effect that has been observed is that if a diamond is continually exposed to a radioactive source or other ionizing radiation, the average or most probable pulse height "pumps" up to a value $\sim$1.6 times its initial value after about 10 kRad exposure. Thereafter the pulse height is observed to remain constant. Though not proven, the current hypothesis is that charge liberated by the radiation diffuses through the bulk, filling trapping sites. Once filled, the traps cannot stop the passage of subsequent electrons or holes. Thus the collection distance increases with initial exposure to ionizing radiation. Diamond in the "pumped" state can be "depumped" by illumination with visible light. This effect gives an indication of what the energy levels of the trapping sites might be, and supports this explanation for the pump-up effect.

2.1 Bench Source Tests

Upon receipt of new samples from manufacturers bench tests are performed to evaluate the quality of the diamond. To quickly characterize diamond samples, each surface is metallized with a single circular electrode a few millimeters in diameter. Using this electrode structure tests can be performed using electrons from a ^{90}Sr source (2.3-MeV endpoint), triggering on those particles which pass through the detector via a scintillator. Typically these electrons deposit 1.08 times minimum ionizing energy [1]. This method provides a simple and quick way to perform basic measurements of diamond performance (the results of these tests have been fed-back to manufacturers as well). However, care must be taken using source measurements since the electrons are slow and so rate- and time-dependent effects may occur.

To illustrate the points described above we present the results from two of the better and more recent samples, D39 and D73. The former initially had an as-grown thickness of over 1600 μm and was measured to have a collection distance of 105 μm at 0.5 V/μm, in the pumped state. It was then "lapped" successively to thinner values and the collection distance was measured at each stage. These results form the basis for some of the data points in Fig. 2. In Fig. 3 we show the measured collection distance and average charge collected as a function of electric field for the final incarnation of D39. At a thickness of 675 μm, and an electric field of 1.0 V/μm, this diamond shows a pumped collection distance of 210 μm. The shape of the curve in Fig. 3 is typical of CVD diamond. After this data were taken this sample was re-metallized as a 50-μm-pitch microstrip tracker and tested in a high energy pion beam; these results are discussed in the next section.

The other sample, D73, has a thickness of 920 μm, and a measured collection distance of 180 μm at 1.0 V/μm. Its measured pulse height distribution is shown in Fig. 4. This diamond is presently being processed, to remove about 400 μm of material, for a July test and should, after processing, have a collection distance in excess of 240 μm.

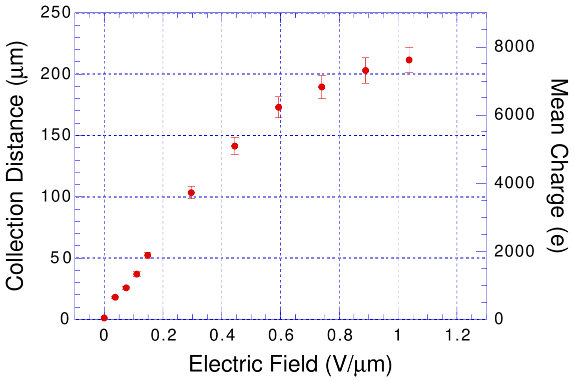

Figure 3: Signal size versus applied electric field for sample D39, measured with a ^{90}Sr source.

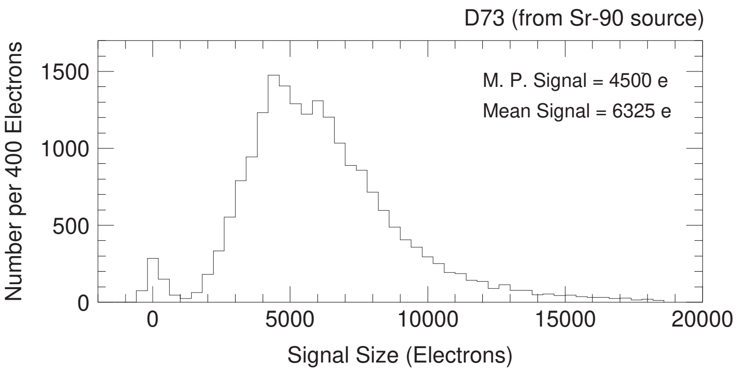

Figure 4: Pulse height distribution for sample D73, measured with a ^{90}Sr source. The small pedestal at zero pulse height is due to a 3 % false trigger rate.

2.2 Beam Tests

Tests of microstrip detectors in a charged particle beam provide another measurement of the amount of charge measured on the bench, as well as a detailed study of their performance as tracking detectors. In these tests, a 100-GeV π^- beam passes through a telescope consisting of eight planes of 50 μm pitch silicon microstrip detectors equipped with VA-2 readout chips [12], the diamond detectors under study, and scintillation trigger counters. The resolution of the track, using only the silicon planes, projected to the diamond plane is 2-3 μm. Figure 5 shows the pulse height distribution and position resolution obtained with the D39 sample. The measured mean charge (using the sum of the pulse heights in the three strips nearest the track) of 7450 e^- agrees well with that measured in the ^{90}Sr source tests (7500 e^- for a collection distance of 210 μm). The resolution of 16.7 μm is obtained by comparing the hit cluster position recorded on the diamond (using a three-hit pulse-height-weighted centroid) with the extrapolated track from the silicon reference planes. Thinner detectors (400-500 μm), with smaller charge, show somewhat better position resolution.

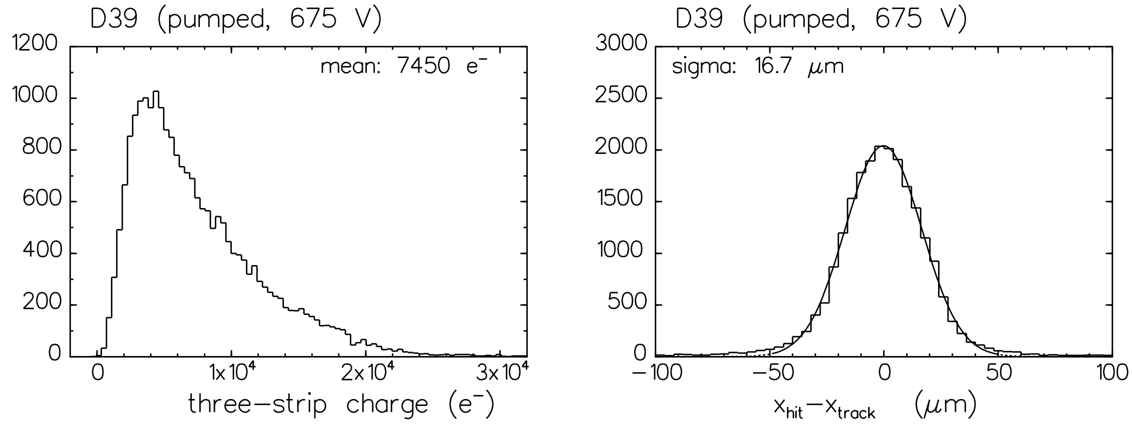

Figure 5: Pulse height distribution and position resolution of the D39 detector, measured with a 100 GeV pion beam. The fit superimposed on the second figure has a sigma of 16.7 μm.

3 Radiation Hardness of CVD Diamond

Determination of radiation hardness is a standard requirement for new particle detectors in high-rate environments. In particular, solid state tracking detectors must be able to operate in high particle fluences while keeping the signal to noise ratio as high as possible. Damage in solid state detectors can manifest itself in two ways: (1) an increase in leakage current and therefore an increase in noise, and/or (2) a reduction in the amount of collected charge. The signal to noise ratio in damaged detectors decreases as a result of either effect. The potential advantage of diamond compared to silicon is that it takes a much larger dose to cause degradation of diamond pulse height. In addition, no increase in the leakage current of diamond due to irradiation has been observed.

The expected doses at the radius of the innermost layer of the SVX-II detector, for 30 fb^{-1} are several 10^{14} pions per cm^2 and 30 MRad. Current tests of CVD diamond by RD42, for applications at the LHC, already exceed these doses and show no degradation in performance. It remains to be seen whether the highest quality material is similarly resistant. These studies are currently underway.

Diamond samples have, in the past, been exposed to doses of 10 MRad of photons [13] and 100 MRad of electrons [14] without any observed decrease in charge collection distance. Here we outline some of the more recent studies with pions and neutrons.

3.1 Pions

CVD diamond detector samples were irradiated with pions in three separate exposures in 1994 [15], 1995 and 1996. All irradiations were performed at the PSI, Villingen, Switzerland. The pions had a momentum of 300 MeV/c. The maximum available pion flux onto the samples was $\mathcal{O}(1.5\times10^9)$ $\pi/\mathrm{cm}^2/\mathrm{s}$. During irradiation the samples were biased with a voltage of > 100 V.

In Fig. 6a) the charge collection distance relative to its initial value as a function of pion fluence is shown. The open circles were measured before the pion irradiation using a ^{90}Sr source and show the "pump-up" effect. The closed circles were measured after each pion irradiation also with a ^{90}Sr source. The results of this study show that the samples remain in their pumped state after irradiation and show no decrease in signal size up to total pion fluences of 5.6×10^{14} π/cm^2.

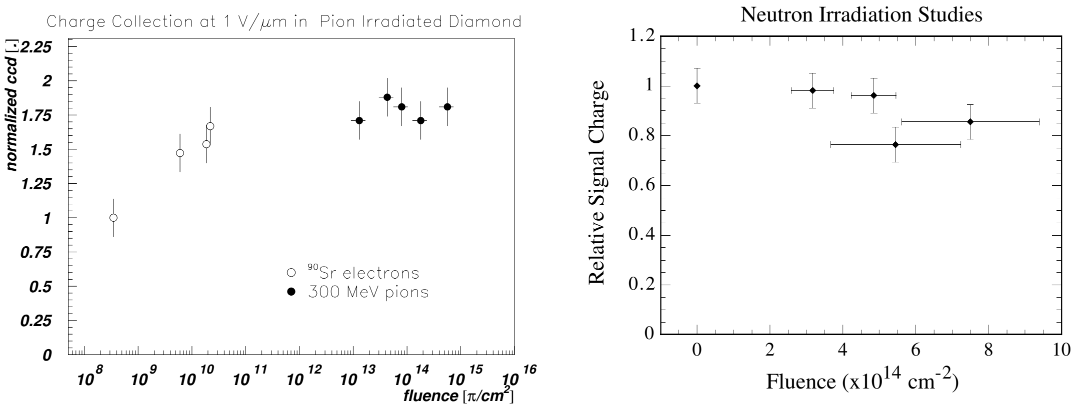

Figure 6: Normalized charge collection distance (ccd) in diamond samples as a function of a) pion and b) neutron fluence.

3.2 Neutrons

CVD diamond samples and silicon diodes were irradiated with neutrons in four exposures (1/95, 10/95, 12/95 and 11/96) at the ISIS facility at the Rutherford Appleton Laboratory, England. Neutrons with energies peaking at 1 MeV were used [16]. The mean n-flux above 10 keV was about $(1.7\pm0.6)\times10^8$ $n/\mathrm{cm}^2/\mathrm{s}$. The diamond samples were irradiated at room temperature biased at 100 V.

After irradiation of doses up to 5.0×10^{14} n/cm^2 the charge collection distance in the pumped state is comparable to its un-irradiated value (see Fig. 6b). A drop in signal size of at most 15% is observed at 8×10^{14} n/cm^2. This study has been extended to higher fluences with other samples and similar behaviour, to fluences slightly above 10×10^{14} n/cm^2. No significant fall off in signal size is observed. Measurements of several neutron irradiated samples were redone six months and one year after the irradiation and showed no change compared to the measurements immediately after the irradiation. Thus no annealing or anti-annealing effects are observed. The dark current was measured before and after neutron irradiation between -1 V/μm and +1 V/μm on depumped samples. No change in dark current was observed on samples irradiated up to 1.9×10^{15} n/cm^2.

During the most recent irradiation the beam induced currents in the diamond detectors and the silicon diodes were recorded every five minutes. Figure 7 shows the currents from a silicon diode and a diamond sample, with the same electrode size, as a function of time during the irradiation. The behaviour of the diamond, which is flat in time and clearly delineates beam on and beam off periods, is nicely contrasted by the current in the silicon diode which shows a linear increase from 100 pA to 30 μA after 120 hours.

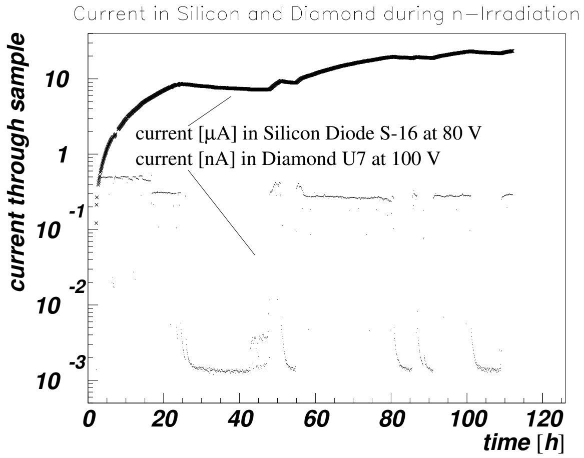

Figure 7: Currents in a silicon diode and a diamond sample during neutron irradiation. The drop in diamond current to the 1 pA level indicates that the neutron beam was off.

3.3 Summary of Radiation Damage Studies

CVD diamond samples were exposed to electrons, photons, pions and neutrons in several irradiations over the last two years. After pion irradiation up to 5.6×10^{14} π/cm^2 no degradation in signal size is observed. The leakage current after pion irradiation is the same as before irradiation. After neutron irradiation up to 5.0×10^{14} n/cm^2 no degradation in signal size is observed. The signal size may decrease by no more than 15% at 8.0×10^{14} n/cm^2. The leakage current remains unchanged even after 1.9×10^{15} n/cm^2. We conclude that diamond is a radiation hard detector material which is able to withstand the conditions which will be encountered in the operation of the SVX-II detector during Run III.

4 Proposed Upgrades to CDF

4.1 SVX-II Inner Layer Replacement

The inner two layers of the SVX-II detector could be upgraded with diamond sensors with exactly the same geometry. They would be double-sided detectors with the same readout pattern as the SVX-II silicon detectors so that no modification would be necessary to the SVT. The thickness will be, at most, 400 μm which is equivalent to 300 μm of silicon in radiation length. The only difference is that individual pieces will be about 4 cm long and therefore eight sensors will be needed to cover the z length of a single barrel. The crack between sensors may be smaller than for silicon because diamond sensors do not need a guard ring around the edge. The readout of the second side would be achieved by the same process used in silicon detectors, namely a double metal layer. Longer pieces may naturally be more cost-effective in the future. If CDF chooses a pixel geometry the R&D proposed below is also directly applicable to such a detector. The same diamond described for a barrel layer would be used with a different metallization pattern.

4.2 Luminosity Monitor

Another application where a radiation-hard sensor technology could be exploited is the luminosity monitor in the small angle region. Such a luminosity monitor could consist of three or four layers of half-split disks, in the same angular region as the present gas Cerenkov counters, in the 3^o hole of the end-plug planned for Run II. A possible geometry is shown in Fig. 8. Since the signal formation time in diamond is fast, on the order of 1-2 ns, an east and west coincidence can provide clear separation of up/down-stream interactions. The major improvement over the gas Cerenkov counter is the possibility of using double-sided strips, with radial and phi segmentation. With reasonable strip pitches, an excellent measurement of the z-coordinate of the event vertex can be made in higher trigger levels. Three or four layer coincidences could be used to eliminate albedo splash signals from the wall of the 3^o hole so that the fast signal is proportional to the true hard scattering luminosity. A detailed simulation will be necessary to optimize the geometry and segmentation.

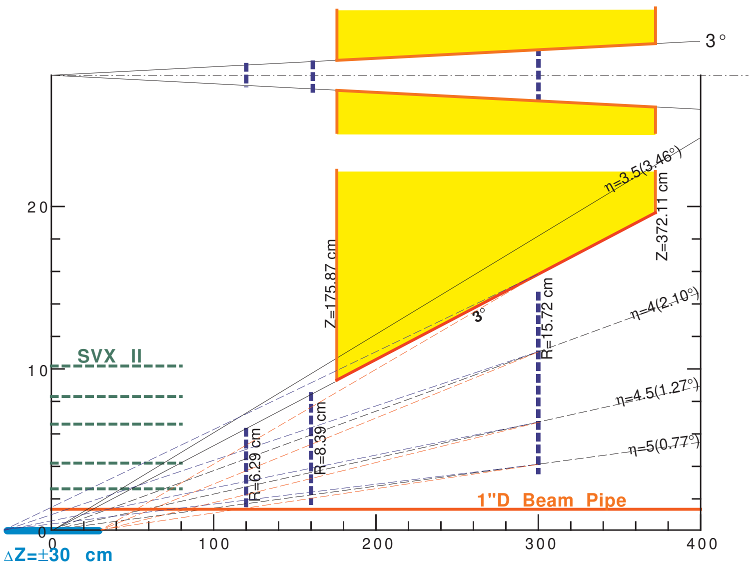

Figure 8: A schematic view of the proposed diamond luminometer layout. The three diamond planes would be positioned perpendicular to the beam at ~1.2, 1.6 and 3.0 m from the nominal interaction point, in both the forward and backward directions.

4.3 Requirements for Readout Electronics

Given that diamond sensors with 200 μm collection distances are now available and the process of scaling up the sizes of these detectors is underway, we are in a position to specify the electronics performance that would be necessary to operate a detector based on such a sensor.

It should be borne in mind that several of the material properties of diamond aid in obtaining suitably low noise electronics to match the somewhat reduced signal. That diamond detectors exhibit no leakage current, even after exposure to radiation doses far in excess of anything that will be seen in CDF, means that the leakage current noise in the front-end will always be negligible. Further the dielectric constant of diamond is about half that of silicon. Thus for a similar detector geometry, say with 60 μm readout pitch, a diamond device will have a smaller load capacitance than a silicon device. Both of these observations argue that an optimisation of the front-end electronics of a solid-state tracker readout chip could achieve substantial gains over the performance of the SVX-3 system.

We consider two possible scenarios. If we plan to implement a strip detector readout geometry then the noise in the front end should be no more than 700-800 electrons ENC. With a most probable signal of 8000 electrons this would produce a signal to noise ratio in excess of 10:1. If it becomes necessary to implement pixel detectors to combat high multiplicities at very high luminosities then we could use the diamond sensors in a pixel geometry. In this case the relevant benchmark for the readout electronics is the sparsification threshold. In order to be fully efficient with a diamond sensor having a most probable signal of 8000 electrons we require a threshold cut of no more than 1500 electrons. To keep the number of channels read out small this should represent a 4-5σ cut. This could be achieved with electronics with rms noise width dominated by threshold variations of no more than 350 electrons. For a diamond such as the one shown in Fig. 4 this would result in 99 % of all thresholds being less than 1500 electrons.

It is anticipated that the current front-end of the SVX-3 chip will not be suitable for use with even the highest quality diamond we foresee producing (of thickness up to 400 μm). Some optimisation could be performed, as outlined above, to match to the absence of leakage current and much reduced load capacitances (4-8 pF for layers 0 and 1 in diamond versus up to 30 pF for layer 4 in silicon) that must be accommodated by the current SVX-3 front-end design. An SVX-3 front-end, optimized for use with diamond would represent the most economical approach to developing a drop-in replacement of the inner two layers of the SVX-II detector.

Should it not be possible to adequately modify the SVX-3 front-end then other possibilities exist. The CLEO-3 silicon vertex detector is using a modified SVX-2 back-end readout with a front-end based on a CR-RC shaped single sample front-end (similar to the VA chip used in the diamond testbeams described above). This chip has operated with less than 250 electrons ENC at 700 ns shaping times [17]. It should be possible to reduce the shaping times to match the 132 ns bunch crossing and maintain noises of less than 700 electrons ENC. Further afield, there already exist silicon readout chips [18] with 25 ns peaking times (suitable for operation at the LHC) with noise performance of 700 electrons ENC. However this approach would require considerable modification to the SVX DAQ and hence would only be undertaken as a last resort.

5 Diamond Production Cost Estimates

One of the primary milestones for the current year of RD42 research is to better establish the cost of material based on sensors 2 cm $\times$ 4 cm in size. The companies involved in the project are in the middle of transferring the technology perfected on research reactors to their commercial growth machines. It is expected that by the end of the year we will have a preliminary quotation for the price of relatively large numbers of this size detector.

At the same time we have discussed with manufacturers the potential market for CVD diamond sensors in high energy physics experiments. We have indicated to them that diamond can be no more than three times as expensive as the silicon it would replace to make it an attractive alternative compared to silicon. When the cost, in terms of manpower and lost data-taking time, from removing the damaged silicon is included, we believe this sort of price range would make it extremely attractive to any experiment. That the manufacturers have continued to do diamond sensor development R&D leads us to believe that costs below \$300 per cm^2 are feasible.

Thus the replacement sensors for layers 0 and 1 of the SVX-II (4000 cm^2 of sensor surface area) should cost less than \$1.2M while the luminometer material (about 1000 cm^2) would cost less than \$300k. As mentioned above, better estimates and, hopefully, vendor quotes will be available by the end of the year.

6 Proposed R&D Organization

As discussed above an intensive R&D effort is already underway to make CVD diamond detectors a reality. This effort is now spreading into the various experiments that would benefit most from the implementation of such detectors. While many of the proponents on this proposal are already members of RD42 (several jointly with CDF) this proposal represents the synthesis of a group of individuals who are committed to doing the "experiment specific" job of ensuring that the diamond detectors which become available are suitable for use in CDF. The material itself has reached a sufficiently mature stage where one has to begin to worry about all the details that will turn the raw sensor material into a suitable detector system. While many members of this proposal will continue to invest some of their efforts in generic sensor R&D the focus will gradually shift to designing an entire readout system suitable for use in CDF.

It is anticipated that similar expressions of interest will start to emerge not only for the FNAL environment, but also from the ATLAS and CMS communities along with other high energy physics experiments, such as HERA-B. Clearly the time-scale at Fermilab is such that the Run III experiments stand a very good chance of being the first beneficiaries of the effort aimed at making CVD diamond a viable sensor material.

6.1 Specific Topics for further R&D

As mentioned above, work is already underway to scale up production of CVD diamond substrates to surface areas suitable for making full size detector prototypes. It is anticipated that by early 1998 a number of 2 cm $\times$ 4 cm size diamonds will have been delivered from mass production CVD reactors. This will yield a first glimpse of the issues associated with full scale production for a final detector. However there remain a number of issues – some of them experiment specific – to address before one can confidently place orders for large numbers of CVD diamond sensors. These include further refinement of the production reactor recipes. Although the production of diamond with 200 μm collection distances is now routine in research reactors, it may take a few rounds of sensor delivery to understand the reproducibility of large area high quality sensors. It may also prove cost effective to further scale up the production areas (beyond the currently envisaged 10 cm diameter wafers) to be able to make larger single sensors (2 cm $\times$ 8 cm or 3 cm $\times$ 8 cm). A number of post-growth processing steps need further refinement. Although many of these have also been perfected with high yield for small sensors it remains to be seen whether these techniques will have similar yields for larger area sensors. Finally we will need to establish final sensor acceptance and screening techniques, similar to the strip leakage current

Milestone	Date
Acquire four 2 cm × 4 cm sensors	June 1998
Assemble testbeam telescope	March 1999
Beam test	As soon as feasible
Assemble L0 prototype ladder	April 1999
Acquire four 3 cm × 4 cm sensors	December 1999
Beamtest of irradiated L0 prototype	May 2000

Table 2: Milestones for CDF-specific diamond sensor R&D.

and inter-strip capacitance tests currently performed on the SVX-II silicon sensors. To date all of this quality control has been on relatively small numbers of readout electrodes (typically 128 per detector and two or three detectors per beam test cycle).

We will want to perform radiation hardness studies of the final sensors. While tests of the hardness of the most recently delivered, high quality, material are underway we will want to further test all aspects of the post-growth processing to make sure that none of these steps degrade the radiation hardness in the underlying material.

We also propose to build a prototype multilayer telescope made completely out of CVD diamond sensors. This will serve two purposes. They will allow us to thoroughly test large areas (several times 2 cm × 2 cm) of CVD material and will allow us to better understand the tracking resolution which can be achieved with such sensors. Once we have a diamond test telescope we then propose to build a series of ladder prototypes – first for layer 0 and eventually for layer 1. The telescope could also be used to test the performance of prototype luminometer detectors, including the pointing accuracy achievable in the final geometry. Finally we will need to address the question of optimising the front-end of the readout chip chosen for operation with reduced capacitance loads and, essentially, zero leakage currents.

6.2 Schedule and Milestones

We foresee a three-year CDF-specific R&D program in which to achieve the goals set out in the previous section. Table 2 shows the intermediate steps we feel are reasonable.

7 Summary

The possibility of continued operation of the SVX-II at the existing radii and rapidities at much higher luminosities offers new physics potential. Given the hostile physical conditions near the interaction region, detector material with extraordinary properties is required. Diamond's physical hardness, electronic speed, radiation hardness, thermal properties and long radiation length, make it an attractive option. CERN has realized this potential and is supporting our European colleagues in their effort to get up to speed in this technology. CDF should also realize this potential and support the development of a small prototype detector to compare with silicon. The members of this proposal have the unique expertise of having developed and tested the best diamond material and detectors to date and represent an ideal group to perform this work.

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