Project Description

Development of Diamond Tracking Detectors

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1 Introduction

In the coming decade, the frontier research program of experimental particle physics will be centered at the Tevatron Collider at Fermilab and the Large Hadron Collider (LHC) at CERN. Research at these facilities is likely to provide information on the generation of mass, supersymmetry between bosons and fermions, and CP violation. Most of this program requires that the colliders provide the highest possible luminosity. For the Tevatron, this will be an order of magnitude more than at present colliders and, for the LHC, two orders of magnitude more. While it seems certain that the machines will provide this luminosity, it is much less certain that the detectors will be able to cope with it. The issue of radiation damage to vertex trackers near the interaction region is particularly severe. These detector components are among the most crucial for extracting the physics mentioned above. Searches for Higgs particles, measurements of decays of supersymmetric particles, studies of top decays and searches for CP violation are crucially dependent on the ability to identify b-quark jets by distinguishing the secondary vertices from the primary collision vertex. If the vertex detectors in future collider experiments function inadequately, or cease to function entirely, the physics program will be seriously jeopardized.

Existing vertex trackers are based on silicon sensors. This is a mature technology and silicon trackers have functioned admirably in the relatively low radiation environments of present day colliders. Silicon is, however, by its nature not radiation hard and great efforts are being made at "engineering in" the necessary hardness. There are two failure modes of silicon that must be overcome. First, as the silicon is exposed to radiation it undergoes type inversion. In order to maintain an appropriate thickness of the depletion layer, the bias voltage must be increased. Current plans for LHC pixel detectors are to bias the silicon to 500 V or more. Under this situation, in order to maintain sufficiently low leakage current from surface conduction, complicated guard ring structures must be engineered. Second, silicon suffers from reverse annealing whereby the signal size decreases over a period of time after the silicon has been exposed to radiation. A possible means of preventing or slowing this reverse annealing process is to cool the sensors to about -10^o C. This temperature must be maintained both during the running of the experiment and after exposure. The silicon must not be allowed to warm up to room temperature for more than about one day per year after exposure or it will be irrevocably damaged.

Even with a large concerted effort involving complicated operational procedures, vertex silicon sensors are unlikely to survive for long at the highest luminosities. A different and far simpler alternative is to base the vertex trackers on a fundamentally radiation hard sensor material. Diamond is such a material. Its large band-gap of 5.5 eV leads to an intrinsic radiation hardness that, as detailed below, has been shown to be sufficient for survival in the LHC environment for the lifetime of the planned experiments.

Several years ago, members of this proposal pioneered research and development on detectors based on chemical-vapor-deposited (CVD) diamond. Since then, the quality of CVD diamond detectors has improved to the point where trackers with a large signal-to-noise ratio can now be constructed. For the last four years, the work on CVD diamond detector development has been carried out by the RD42 collaboration based at CERN of which we are founding members. The work of this collaboration is one of the efforts funded by CERN to promote innovative R&D in support of new technology for the LHC. The collaboration is composed of eighteen institutions of which twelve are European and six are North American. With relatively little North American funding during this time, the North American contingent of RD42, consisting of members of this proposal, have, nevertheless, played major leadership roles. This situation is no longer viable. Without increased investment of North American resources, this effort will have to be relinquished to Europe. Conversely, with the support requested in this proposal North American groups can continue to provide leadership in diamond detector development, experiment-specific applications led by North American groups can be implemented and North American manufacturers can be encouraged to return to production of detector-quality diamond.

2 Research Activities

The instrument that we are proposing to develop is a diamond tracking detector. It will be used in experiments at the Fermilab Tevatron and the LHC to make precise tracking measurements close to the interaction point and, thereby, to identify displaced vertices associated with the decay of heavy quarks. This technique identifies b-quarks and is essential for studying the decays and properties of the top quark, searching for the Higgs boson and measuring CP violation in the b-quark system. As an example, the ability to identify b-quarks was crucial in the first observation of the top quark announced in 1994 by the Collider Detector at Fermilab (CDF) collaboration at Fermilab.[1] Vertex detecting was also essential in isolating $B \to J/\psi K_S$ decays which are needed for a measurement of CP violation in the b-quark system.[2] In short, the operation of a high quality vertex detector is essential for extracting much of the important physics in future high intensity hadron colliders.

For the next eight years, the Tevatron at Fermilab will continue to be the highest energy collider in the world. CDF has amassed a large sample of data from collisions at 1.8 TeV center-of-mass energy at the Tevatron. These data have led to major discoveries and measurements in high energy physics, including

- discovery of the long-sought top quark and a measurement of its mass,
- a precise measurement of the W boson mass,
- searches for numerous new particles, predicted by extensions to the standard model such as supersymmetry,
- studies of quantum chromodynamics (QCD),
- studies of the b quark and B meson systems.

In 2000, the upgraded Tevatron collider will be capable of delivering an order of magnitude more luminosity than in the previous Run I period. In Run II, the collider will deliver roughly 4 fb^{-1} of integrated luminosity. The copious production of $b\bar{b}$ events will allow searches for and measurements of rare B meson decays, and may allow tests of CP violation in the B system. Perhaps most interestingly, the 4 fb^{-1} sample will greatly extend the discovery limits on numerous processes beyond the standard model. Beyond Run II, a higher luminosity Run III accumulating 40 fb^{-1} is planned for before turn on of the LHC.

The experiments that will be employed at both the Tevatron and LHC colliders consist of large detector systems (e.g., CDF, D0, ATLAS and CMS) that are built and operated by large international collaborations. The number of physicists working in any one of these collaborations ranges from four hundred to well over one thousand. These numbers divide approximately equally among senior physicists, postdoctoral associates and graduate students. The operational lifetime of the detectors will be five to ten years. The cost of constructing, installing and operating the diamond detectors will be borne by the funding agencies, both US and foreign, supporting the large collaborations.

3 Description of the Research Instrumentation and Needs

3.1 Principles of Diamond Detectors

In Table 1, we summarize the properties of diamond and, for comparison, those of silicon that are of interest when considering the material for use as a particle detector. The most distinctive feature of diamond is its large band gap, 5.5 eV. This large band gap along with the associated large cohesive energy are responsible for much of the radiation hardness of diamond. The large band gap also makes diamond an excellent electrical insulator. As a result, a large electric field can be applied without producing significant leakage current. Thus, there is no need for a reverse biased *pn*-junction and the diamond detector functions much like a "solid-state" ionization chamber. Diamond has two additional properties that are favorable compared to silicon. Its smaller dielectric constant yields a smaller detector capacitance and, thereby, better noise performance of the associated front-end electronics. In addition, even though diamond is an electrical insulator, it is an excellent thermal conductor with a thermal conductivity exceeding that of 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 would be simplified if the detectors are constructed from diamond.

Diamond appears ideal in many respects but it does have a limitation: the large band gap which produces many of its outstanding properties also means that its signal size is at most

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

Table 1: The physical properties of diamond and silicon at 293K. [3]

approximately half that of silicon for a given detector thickness in radiation lengths. This may be compensated by lower front-end electronic noise due to diamond's nearly non-existent leakage current and, for strip detectors, diamond's lower capacitive load.

In Fig. 1, we show the basic principle behind the use of diamond as a charged particle detector. Several hundred volts ($\sim$ 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, 3,600 electron-hole pairs are created per 100 μm of diamond traversed by a minimum ionizing track. These charges drift across the diamond in response to the applied electric field producing a signal that can be measured.

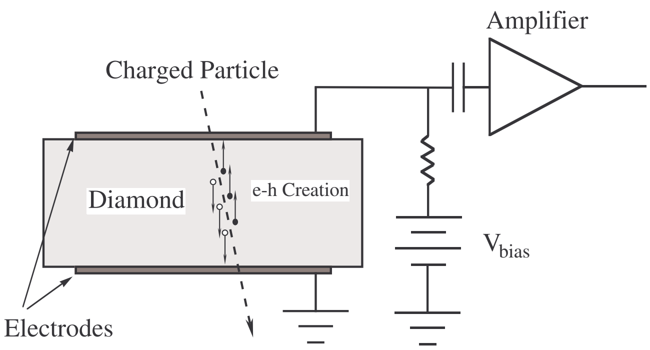

Figure 1: A schematic view of a diamond detector.

An interesting feature of diamond sensors is that they improve with exposure to radiation for exposures up to about 1 kRad. This "pump-up" effect is due to an increase of carrier lifetime caused by passivation of deep traps. Because diamond has such a large band gap there may exist traps more than 1 eV from the valence or conduction bands. Exposure to radiation fills these traps with electrons (holes) produced by the radiation. If the traps are far enough from the conduction (valence) bands, the rate of thermal ionization of these traps will be slow and they will remain passivated for long times. We have found that diamonds kept in the dark remained pumped for at least three months. Exposure to room light rapidly ionizes the traps and depumps the diamond.

3.2 CVD Diamond

The discovery of the growth of diamond using the Chemical Vapor Deposition (CVD) process allows the consideration of large scale use of diamond detectors. 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. The electrical properties of CVD diamond vary with the thickness of the material [4, 5]: the carrier lifetimes are small on the substrate side and large on the growth side. As a result, the mean charge-collection signal can be increased by removing material from the substrate side.

The growth of CVD diamond can be achieved through several processes and many companies are producing polycrystalline films. A large number of parameters must be optimized for the production of the quality diamond necessary for charged particle detectors. These include: type of gas-excitation energy source, relative concentration of hydrocarbons, substrate temperature and gas pressure. Because of the large number of variables, systematic correlations between growth parameters and diamond quality need to be studied.

3.3 Diamond Detector R&D

3.3.1 History

The collaborating institutions on this proposal bring with them an extensive and unique set of capabilities in diamond detector research. The groups from Rutgers and Ohio State pioneered the work on CVD diamond detectors in the DIAMAS proposal [6] to the SSC in 1989. Since 1994, these two groups have continued to play major roles in diamond detector research as founders and leaders of the RD42 collaboration [7] at CERN. In addition,

From 1989 to 1993, the DIAMAS collaboration pioneered the field of CVD diamond detectors. This collaboration was the first to observe single minimum ionizing particles in CVD diamond [8]. In 1993, the first calorimeter-quality diamond wafers were produced and a diamond-tungsten calorimeter was constructed along with its readout electronics [9]. This device achieved the same energy resolution as a similar silicon-tungsten calorimeter demonstrating that diamond calorimetry works. This was also the first demonstration of large-scale production of CVD diamond detector material with 200 cm^2 of diamond produced in six months.

3.3.2 Diamond trackers

Since 1994, the RD42 collaboration has worked on continuing to improve the quality of CVD diamond material, constructing and testing diamond microstrip and pixels detectors and testing the radiation hardness of the diamond detectors. The first diamond microstrip detector was constructed and tested in 1994. This detector had a 100 μm strip-pitch and yielded a 25 μm spatial resolution, 90% efficiency, and a peak signal-to-noise ratio of 6:1 with 1.5 μs shaping-time electronics in a high energy pion beam [10]. Since then, diamond trackers constructed with 50 μm strip-pitch have yielded 12 μm spatial resolution, 98% efficiency and 50:1 peak signal-to-noise ratio with 1.5 μs shaping-time electronics [11, 12, 13]. In the past year, the first diamond pixel detector was constructed, attaining a 22:1 peak signal-to-noise ratio, and the first diamond tracker (50 μm pitch) was operated with 22 ns peaking-time electronics attaining a peak signal-to-noise ratio of 5:1.

Figure 2 shows the pulse height distribution and position resolution obtained with one of the better diamond trackers. This sample had an as-grown thickness of 1,600 μm. Material was then lapped from the substrate side until a final thickness of 675 μm was attained. This procedure improved the signal size of the diamond by 40%. The 675 μm thick sample was then metallized as a 50-μm-pitch microstrip tracker and tested in a high energy pion beam. The measured most-probable charge (based on the sum of the pulse heights in the three strips nearest the track) is 4,200 electrons. A spatial resolution of 16 μm is obtained by comparing the hit cluster position recorded on the diamond with the extrapolated track from silicon reference planes.

3.3.3 Radiation hardness

Over the past three years, the RD42 collaboration has studied the radiation hardness of CVD diamond detectors to various types of radiation.

Electrons and γ's. Irradiations up to 10 MRad of ^{60}Co gamma rays and 100 MRad of 2.2 MeV electrons showed no decrease in signal nor any increase in leakage current.

Pions. CVD diamond detectors were irradiated with 300 MeV/c pions [14]. Fig. 3 shows the normalized signal size relative to the unirradiated value as a function of pion fluence. The open circles were measured before the pion irradiation using a ^{90}Sr source. They show the "pump-up" effect described above. The closed circles were measured with a ^{90}Sr source after each pion irradiation. 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}.

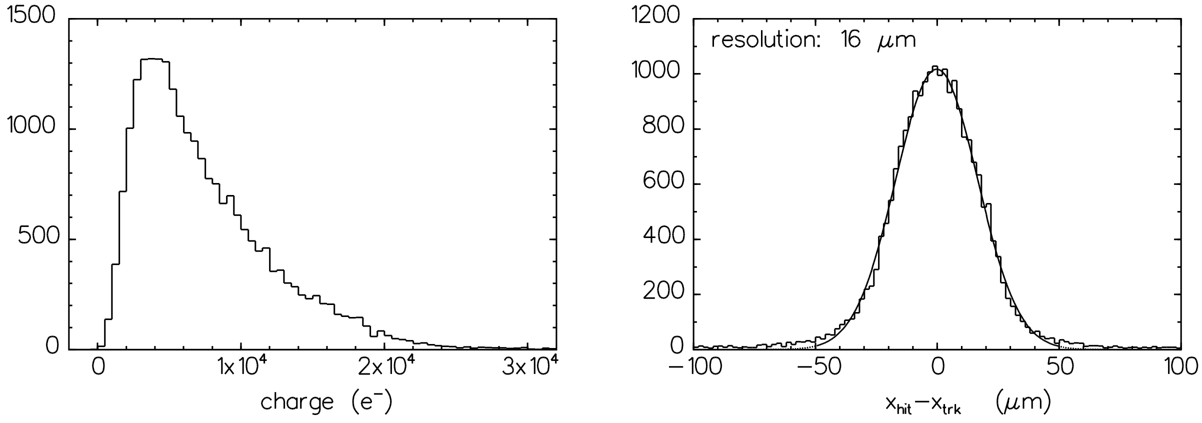

Figure 2: Pulse height distribution and position resolution measured with a 100 GeV pion beam.

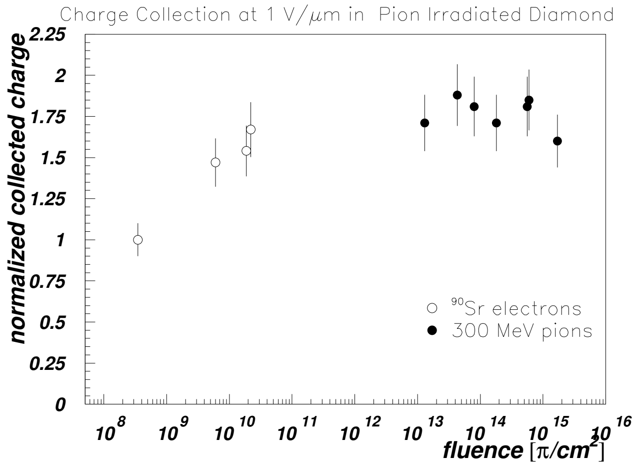

Figure 3: Normalized collected charge in diamond samples as a function of pion fluence.

Neutrons. CVD diamond samples were irradiated with neutrons at the ISIS facility at Rutherford Laboratory. The neutron spectrum peaked at 1 MeV [15]. For fluences up to 5.0×10^{14} n cm^{-2}, the signal size in the pumped state is comparable to the unirradiated pumped value as shown in Fig. 4a. A possible drop in signal size of about 15% is observed at 8×10^{14} n cm^{-2}. The significance of this drop is presently uncertain with more recent preliminary results at fluences above 10×10^{14} n cm^{-2} showing no measurable decrease in signal size. Measurements of several neutron irradiated samples were redone six months and also one year after the irradiation and showed no change compared to the measurements immediately after the irradiation.

Protons. Recently, RD42 completed analysis of diamonds irradiated with 24 GeV protons to fluences up to 5×10^{15} cm^{-2}. The results are shown in Fig. 4b. No damage is seen for

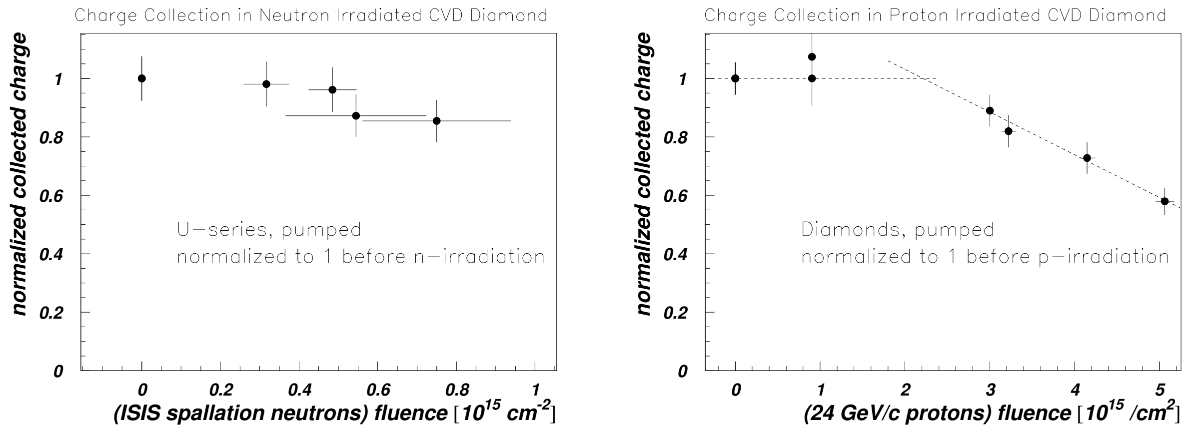

Figure 4: Normalized collected charge in diamond samples as a function of neutron and proton fluence.

	1 LHC Year [16] $r = 7.5$ cm	Dose Required to Damage Diamond
Neutrons	5×10^{13} cm^{-2}	$> \ 5 \times 10^{14}$ cm^{-2}
Charged Hadrons	2×10^{14} cm^{-2}	$> \ 5 \times 10^{14}$ cm^{-2} π $> \ 2 \times 10^{15}$ cm^{-2} p
Total Ionizing Dose	10 MRad	$>$ 10 MRad γ $>$ 100 MRad e

Table 2: Summary of of diamond irradiations.

fluences of 1×10^{15} cm^{-2}. A linear decrease in pulse height is seen for exposure of more than 3×10^{15} cm^{-2} indicating a possible onset of damage at about 2×10^{15} p cm^{-2}.

The leakage currents of the diamond samples were measured before and after irradiation for both the pion and neutron irradiations. The leakage current, typically 0.5 pA/mm^2 at a field of 1 V/μm remained unchanged up to the maximum fluences of 8×10^{14} n cm^{-2} and 5.6×10^{14} π cm^{-2}.

The results of the above irradiations are summarized in Table 2. For comparison, the expected dose at a radial distance of 7.5 cm from the beam line for one year of LHC running at design luminosity is also given. These results indicate that diamond detectors will survive the radiation exposures expected for LHC pixel detectors for at least ten years of LHC running.

3.3.4 Remaining issues

The technology of CVD diamond detectors has made great strides in the past eight years. Their radiation hardness has been clearly demonstrated and detector material capable of providing a peak signal-to-noise ratio of 5:1 with fast-shaping electronics has been produced and tested. It is now time to plan for use of diamond detectors in physics experiments.

There are, though, some remaining issues. The signal size should be increased by about 70% in order to achieve a most-probable collected charge of 7,000 electrons for a minimum ionizing track. This combined with an optimization of the front-end electronics will give a peak signal-to-noise ratio of 10:1 with fast-peaking electronics. A realistic cost estimate for the production of several thousand cm^2 of detector-quality diamond needs to be obtained from the manufacturers. Prototypes of unit cells and ladders of planned detectors need to be constructed and tested.

3.4 Proposed Program

Due in large part to our pioneering work and continued leadership, CVD diamond detector technology has developed from a revolutionary concept to the point of being poised to play a major role in particle physics experiments. Having come so far, we must now ask whether North American groups will continue to be leaders or whether this technology will necessarily be ceded to Europe. We propose here a program that should guarantee continued North American leadership. There are three aspects to this program. First, we must maintain a dynamic effort in generic diamond detector R&D. This must include a full North American participation in RD42 to address those remaining issues mentioned above. In addition, we should develop a North American test beam facility and a center for material characterization that will complement those available to RD42 European groups. Second, we must begin examining experiment-specific applications of CVD diamond detectors. We propose to work on developments for a diamond microstrip vertex detector for Collider Detector at Fermilab (CDF) in Run II and beyond and for the forward pixel detectors for the Compact Muon Solenoid (CMS) detector at the LHC. Third, for the vitality of both the North American and global diamond efforts we must encourage and aid North American manufacturers of CVD diamond to develop the capability to grow diamond-detector material. We detail the three prongs of this program below.

3.4.1 Generic diamond detector R&D Program

Collaboration with RD42

The central point of our proposal is to maintain a vigorous effort on the study and improvement of detector-quality diamond in collaboration with our RD42 colleagues. As explained above, this has been a highly productive effort over the past four years. We hope to continue it. In the next two years, we expect to concentrate on the following tasks which will be carried out jointly with RD42.

- **Improvement of signal size**. The signal size of CVD diamond has improved enormously over the past eight years. As the quality of the diamond has approached that required for use as particle detectors, the rate of improvement as shown in Fig. 5 has continued. Based on our experience, we believe that another 70% improvement in collection distance can be attained.

- **Estimation and reduction of cost**. One of the primary goals of the coming year is to establish an estimate of the cost of diamond detector material. Associated with this will be an effort to achieve cost reduction. Currently, there is only one company that is manufacturing high detector-quality diamond. A key component of our program is to encourage additional manufacturers, thereby, facilitating cost reduction.
- **Study of radiation hardness of the highest quality diamonds**. The current measurements on radiation hardness are for diamond samples with modest signal size. We need to conduct radiation hardness tests of the highest quality diamond.

North American test beam facility

For the past four years, we have made extensive use of test beams at CERN for testing diamond sensors. We believe it is essential for the North American groups to have access to an independent and more conveniently located test facility. This will allow us to undertake tests more related to our particular interests, provide rapid feedback on diamond supplied by North American manufacturers and test the experiment-specific prototypes discussed below. Fermilab, particularly with the advent of the Main Injector, is a natural location for this test facility. At the request of Fermilab's Director, John Peoples, we intend to submit proposals for detector performance studies in a Main Injector test beam and for detector radiation-hardness assessment at the Booster radiation facility.

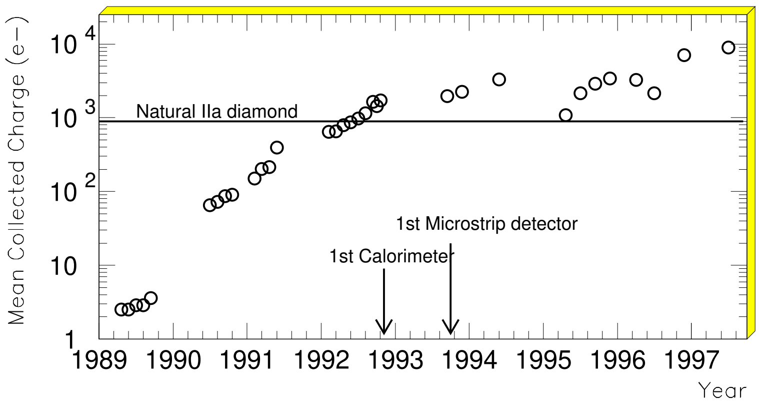

Figure 5: Pulse height of diamond detector for minimum ionizing track versus date.

3.4.2 Purchase of Diamond and Promotion of Manufacturers

Currently, DeBeers is the only manufacturer that produces detector-quality CVD diamond. This was not formerly the case. In the past, several North American companies, most notably Norton, were able to produce diamond of the highest quality. These companies discouraged by the lack of American support for CVD diamond detectors are presently not developing their technology further. This situation needs to be reversed. It is our experience that maintaining the interest of a company requires an annual purchase of diamond of order \$100K. With this level of purchase, companies seem willing to commit a multi-fold match of internal funds to support and maintain their in-house research on detector diamond material.

3.5 Experiment-specific Diamond Detectors

In addition to the generic program described above, we propose to initiate two experiment-specific efforts: diamond microstrip detectors for CDF and diamond pixel detectors for CMS. We will fabricate and test diamond-based prototypes of these detector components to demonstrate that diamond is the preferred material for these applications. Since diamond sensors are not currently part of the approved CDF and CMS programs, this development work cannot be supported presently by them. If, due to our work, diamond were to be selected as the material of choice in either of these experiments, the funding of further prototyping and construction of the actual detector components would be through the respective collaboration.

We also intend to work with the BTeV group at Fermilab. BTeV is an experiment being proposed for the Tevatron collider at Fermilab whose purpose is to measure CP violation and rare decays of the b and c quarks. The BTeV group is exploring the possible use of diamond for the inner most segments of their pixel detector.

The CDF Vertex Detector

The CDF collaboration has embarked on a major upgrade program for Run II, including new endcap calorimetry and a completely new charged particle tracking system. The inner portion of the tracking system, the SVX-II, is comprised of five double-sided silicon microstrip layers. The innermost layer of the SVX-II is about 2.5 cm from the beam line. It provides the most crucial information about secondary vertices and suffers the largest radiation exposure. It is likely that the Run II delivered luminosity goal of 4 fb^{-1} will expose the innermost layer of silicon to a lethal radiation dose. For Run III, the two innermost silicon layers of the SVX-II will not survive. CVD diamond detectors, on the other hand, have been shown to survive doses of radiation far exceeding those anticipated for Run III as described above.

We propose to develop diamond detectors as a radiation hard alternative for the innermost layers. The diamond layers would be functional equivalents of the silicon layers they would replace. The thickness of the diamond layers would be, at most, 400 μm which is equivalent to 300 μm of silicon in radiation length. The readout of the second side would be achieved by the same process used in the silicon layers, namely a double metal layer.

We will undertake a program leading to construction and testing of a full diamond prototype of the SVX-II inner layer readout with the actual electronics to be used in the experiment. The identified tasks that are needed to carry out this effort are given below.

- **Sensors of large area.** In the innermost layer of the SVX-II the unit sensor cell is approximately 2 cm $\times$ 8 cm. In order to be compatible, the diamond units should be of the same area. It is anticipated that in 1998 a number of 2 cm $\times$ 4 cm size diamonds will have been delivered from mass production CVD reactors. The diamond unit cell could be made by wire-bonding two of these pieces end-to-end. Based on our experience, it will likely require several 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 to be able to grow 2 cm $\times$ 8 cm single sensors.
- **Radiation hardness of final sensors.** We will need to perform radiation hardness studies of the final sensors.
- **Post-growth processing.** 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. We will need 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.
- **Final sensor acceptance and screening.** We will need to establish final sensor acceptance and screening techniques, similar to the strip leakage current and inter-strip capacitance tests currently performed on the SVX-II silicon sensors.
- **Development of front-end electronics.** Because of the inherently smaller signal size of diamond compared with silicon, the noise performance of the front-end electronics should be improved if possible. Fortunately, optimization of the electronics for the absence of leakage current and the reduced load capacitance of diamond should allow for this improvement. This front-end will need to be compatible with the existing SVX back-end electronics. An example of such a front-end, is the one designed by OSU for the CLEO experiment at Cornell.
- **Testing of assembled prototypes.** We will design and construct a prototype module of the same size, fiducial characteristics and strip specifications as one of the 72 inner-layer modules of the SVX-II detector. The module would consist of two diamond unit cells each 400 μm thick and 7.2 cm x 1.5 cm in area. They will have microstrip electrodes deposited on each side. The 7.2 cm long ϕ-strips on one side will be orthogonal to 1.5 cm z-strips on the opposite side.

The CMS pixel detectors

Beginning in the year 2005, the Large Hadron Collider at CERN will be the forefront machine in both energy and luminosity. The detectors being constructed for the LHC will place far greater demands on radiation hardness than those for the Tevatron. In particular, the pixel detectors located nearest to the interaction region will have severe radiation hardness requirements.

For the Compact Muon Solenoid (CMS) experiment, the pixel detectors will be arranged in a central barrel and in forward disks. The barrel pixel detector is the responsibility of a group from PSI in Zurich while the forward pixel disks are the responsibility of a group of American institutions.

We propose to undertake a program leading to construction and testing of a full diamond prototype of a CMS forward pixel sensor cell that is readout with the actual electronics to be used in the experiment. We would implement a development and prototyping program parallel to that for silicon pixel sensors. Taking advantage of our existing association with the forward pixel project, we would use the same test beam time with the same electronics as those for silicon tests. The identified tasks that are needed to carry out this effort are the following.

- **Fabrication of diamond pixels.** Pixel electrode patterns will be etched on diamond and a passivation layer applied. Such a detector has recently been fabricated by OSU and is awaiting test of bump bonding at PSI.
- **Bump-bonding to front-end electronics.** The CMS pixel group at PSI is developing bump-bonding capability. They will soon test their ability to bond to the diamond pixel detector that has been delivered. In the future, we would hope to continue a working relationship with this group to further develop bonding capability.
- **Full scale beam test of diamond sensors with CMS pixel electronics.** We will mount a program of beam test of diamond sensors parallel with the effort on silicon presently underway in the CMS forward pixel group. The goal will be demonstration of a working diamond pixel meeting the specification of the forward pixel detectors.
- **Optimization of electronics.** As for the case of strip readout mentioned above, the pixel electronics may be able to be optimized for the low leakage current and the smaller capacitance of diamond. We plan to coordinate with Fermilab's efforts to develop front-end electronics both to take advantage of their successes and to keep them aware of the diamond pixel developments.
- **Test of radiation hardness.** As noted above, the radiation hardness of sensors for the LHC detectors is the most challenging of any application currently foreseen in particle physics experiments. Tests with the full-scale prototypes simulating these exposures will need to be made.

4 Milestones

The current proposal is a three year program. The decision on the CMS pixel sensor material is expected at the end of the second funding year while the decision on material for the CDF vertex detector is expected somewhat later toward the end of the third funding year.

We set the following milestones that must be met in order to meet these decision schedules. Our effort will be weighted toward generic R&D in the first year, CMS prototyping and CDF development in the second year and CDF final prototyping in the third year.

4.1 End of first year

- Acquire, characterize and optimize large area 2 cm $\times$ 4 cm diamond pieces
- Confirm radiation hardness of highest quality diamonds
- Obtain initial cost estimate of production-mode diamond
- Set up facility for beam tests of diamond in North America
- Construct and test trackers on 2 cm $\times$ 4 cm pieces
- Fabricate diamond detector with 125 μm $\times$ 125 μm pixels
- Develop the process of bump-bonding to diamond pixels
- Initiate test of diamond pixel with CMS electronics

4.2 End of second year

- Achieve 10:1 peak signal-to-noise ratio using fast electronics
- Refine cost estimates of production diamond and initiate any necessary cost reductions
- Finalize process for bump-bonding to diamond
- Complete tests of diamond pixels with CMS electronics
- Complete full scale test of CMS pixel prototypes
- Confirm radiation hardness of CMS pixel diamond

4.3 End of third year

- Develop process for final acceptance and screening of diamond sensors for CDF
- Determine radiation hardness of final sensors for CDF
- Complete optimization of front-end electronics for diamond
- Construct and test prototypes of the CDF SVX inner layers
- Establish cost of produced diamond

5 Impact of Infrastructure Projects

As stated above, development of diamond tracking vertex detectors will ensure that the full physics potential of the high intensity Fermilab Tevatron collider will be realized. The Tevatron is the premier high energy physics facility in the US and, at least through the middle of the next decade, will be the premier high energy facility in the world. Diamond vertex detectors will likewise be of great importance in the program at the LHC when it commences around the year 2005.

At both facilities, there will be a large number of US graduate students participating in the experimental program and sharing in the data from the installed diamond vertex detectors. Installation of a diamond tracking vertex detector will provide future CDF (and LHC) students with access to state of the art experimental instrumentation.

We have employed several Rutgers undergraduates as research assistants during the past five years in our work on the development of diamond detectors. Among these are David Fish, one of the best undergraduates to come through the Rutgers Physics Department in many years, and Adam Pietz who is currently working with us. Work on diamond detectors has provided excellent training for these undergraduates and an excellent introduction to experimental particle physics. The diamond detectors are table-top devices unlike most of the large experimental facilities used in high energy physics. At the same time, they are state of the art devices at the forefront of instrumentation. The work allows the students to become intimately involved with apparatus design, electronics, materials science, and data acquisition and analysis. With this proposal, we intend to continue this tradition of training undergraduate students.

Because the diamond detectors are small but state of the art, they also can provide an excellent introduction to high energy and materials physics for high school students and their teachers. We intend to devote a few percent of the resources in this project to an outreach program to area high schools. In the summer months we will employ one or more local area high school teachers in the diamond detector lab. They will then be encouraged to send us their students who will then be able to get first-hand experience of their own working with the detectors. The best students may be able to work with us for us on a regular basis and make useful contributions to our work. We will also devote resources from this proposal to maintaining a web page on diamond detectors so that the general public can be informed of the development of this state-of-the-art instrumentation and its many interesting uses.

6 Project and Management Plans

Our proposal is to develop a new class of research instrumentation, diamond tracking detectors. After these instruments are developed, they will find wide application in high energy physics experiments and elsewhere as described above. As a result, many individual instruments will result from our proposed development. The maintenance, operation technical support of these instruments will be provided by the collaborations constituting the large experiments of which these instruments will be a part. In the case of the CDF experiment at Fermilab and the CMS experiment at the LHC, our group will be closely involved.