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Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC

(The RD42 Collaboration)

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Abstract

The LHC offers unique physics opportunities in an extremely difficult operating environment. In order for tracking detectors to play an important role in the physics discoveries they must survive the harsh environment of the LHC. As a result, the tracking devices of the LHC need to have special properties. They must be radiation hard, provide fast collection of charge, be as thin as possible and remove heat from readout electronics. The unique properties of diamond allow it to fulfill these requirements.

The RD42 research program aims to further improve the charge collection properties of CVD diamond, to study the radiation hardness of the material and to develop low noise radiation hard readout electronics suitable for use with diamond trackers. Our work combines the forces of universities and (inter)national laboratories, as well as researchers from disciplines not traditionally associated with high energy physics. In this report we describe the progress made in the last year by the RD42 collaboration and outline the research program we intend to pursue to finish this work.

Contents

1 The RD42 Research Program and Milestones

High precision solid state microstrip detectors have become an important tool in charged particle track reconstruction and the study of long lived particle decays in high energy physics experiments. While it is hoped that silicon can continue to be used in these applications it is becoming apparent that silicon detectors will only survive the intense radiation environment in limited regions of the experiments currently being planned for the LHC and elsewhere. In order to perform experiments at future high energy and high luminosity hadron colliders it is essential to develop detector technologies which are capable of withstanding high rates and particularly severe environments.

1.1 Why Diamond Trackers in an LHC Experiment?

Detectors based on diamond as the active element could have advantages over present day technologies because of their radiation hardness, fast charge collection and low cost. The practical use of diamond as a detector material has been made possible by advances in the chemical vapor deposition (CVD) growth process. This process allows diamond to be produced economically over a large area and with high purity. The use of CVD diamond as a charge collection material has been demonstrated by measurements using diamond as the active material in a sampling calorimeter [1] and as the sensor material in a charged particle tracker [2]. A vertex detector at the heart of a hadron collider experiment is an ideal application for diamond in high energy physics.

Two approaches have been taken to solve the problems faced when trying to build a vertex detector for an LHC experiment. One is to modify existing detector technologies to adapt them to the task at hand – silicon is a clear example [3]. Another approach is to take a material which has the inherent properties required to survive at the LHC and use it to produce detectors. Our group pursues the second approach and the material we have chosen is diamond. The properties of diamond which attract us to this approach are:

- Diamond is radiation hard, essential in the environment of the LHC;
- Diamond is an excellent insulator with a high breakdown voltage, allowing the application of a large electric field to attain a saturated drift velocity while maintaining a very low leakage current;
- Diamond detectors can operate at high temperatures. The large band gap insures small leakage currents and that detectors will not be driven into thermal runaway by the typical doses at the LHC;
- Diamond is extremely fast to read out. We can collect all of the charge within one nanosecond [4] – diamond is one of the few materials in which all the charge can be collected faster than the LHC repetition rate;
- Diamond has low Z. With low Z the multiple scattering and photon conversion rate in diamond will be small;
- Diamond has half the dielectric constant of silicon. Thus the components of detector noise which depend on the dielectric properties of the material will be minimised;
- Diamond is physically robust. It does not need a supporting substrate like glass, again minimizing multiple scattering;
- Diamond requires relatively simple processing. Its present total cost is similar to that of silicon, however, unlike silicon this cost is mainly in the production of the diamond wafer itself and not in the post-processing to fabricate detectors.

1.2 The RD42 Research Program

In our first year of operation we were encouraged to concentrate on the improvement of diamond material in order to maximise the signals produced by charged particles. At the same time we were expected to continue studies of the radiation hardness of the material that were already underway at the time of approval. Since the ultimate goal of our project is to build a charged particle tracker for use at the LHC we have also studied possible designs of strip trackers in order to better understand the issues involved in patterning electrodes on diamond material as well as in the use of low-noise readout electronics. In what follows we will highlight the progress made towards satisfying the milestones set out by the DRDC when the project was approved.

The first milestone was to obtain a material which gave approximately 8000 electron signal when traversed by a minimum ionising charged particle. We believe that we are well on the way to satisfying this goal. When the project began we had charged particle trackers which gave signals of 1400 electrons. We now have trackers which give signals of 2500 electrons – almost a factor of two improvement has been observed. In getting to this stage we have identified a number of further improvements in the production of the material which should allow us to achieve the remaining factor of three which separates us from our goal. Furthermore when we started we were working exclusively with one diamond manufacturer. During our first year of operation we have established a working relationship with a second manufacturer which has also demonstrated the potential to produce detector grade diamond material. Having more than one company involved in the effort to improve the quality of detector grade CVD diamond is the best insurance that one or both of them will eventually be able to meet our specifications of signal size.

The second milestone was to demonstrate that the CVD diamond material was sufficiently radiation hard to survive operation in the highest dose and rate environments at the LHC. Having studied photon doses up to 10 MRad and 5 MeV alpha fluences in excess of 10^{15} per cm^2 [5] we turned our attention during our first year of operation to pions, protons and neutrons. A first pion irradiation was performed up to fluences of almost 10^{14} per cm^2 at PSI in June of 1994. These measurements are being followed up to fluences of a few $\times 10^{14}$ per cm^2 during a run in September of 1995. Proton irradiations of CVD diamond were performed at TRIUMF in the fall of 1994 and again in the spring of 1995 up to fluences of 10^{14} per cm^2. Both of these irradiations provide insight into the radiation hardness expected in CVD diamond. We have further studied electron irradiations at a facility near Strasbourg in France up to doses of 100 MRad. Finally we have exposed CVD diamond samples to neutron fluences up to 10^{15} per cm^2 at the ISIS facility in early 1995. These neutron irradiations will be repeated in the fall of 1995 in order to better understand the influence of the low energy neutrons present at ISIS on the diamond material and on the electrode contacts.

Preliminary comparisons of the thermal performance of CVD diamond, silicon and beryllia (BeO) substrate materials were made in 1995 [6] with power densities between 0,1 and 1.2 Watts cm^{-2} applied. The study illustrated the value of CVD diamond as a heat spreader: thermal gradients a factor 4-5 (5-6) less than those in beryllia (silicon) substrates were observed consistent with expectations of CVD diamond [7]. Further thermal studies are planned with CVD diamond samples having dimensions similar to those of a full sized semiconductor inner tracker module for a collider experiment.

2 Progress on the Improvement of CVD Diamond

Two important developments occurred in the improvement of detector grade CVD diamond during the first year of RD42. The first development was a breakthrough in the diamond production process. For the last few years the St. Gobain/Norton company has produced the highest quality CVD diamond available [8]. When RD42 began, the best available CVD diamond had a collection distance of 40 μm. Tracking detectors constructed with this material had an average signal of 1400 electrons. As stated in the DRDC milestones, one of the highest priorities of this year was to improve the quality of diamond. After approval, the spokespersons of RD42 met with representatives of the company to discuss how to achieve the initial milestones. As a result of that meeting, St. Gobain/Norton agreed to proceed with a matrix of chemistry experiments to determine the effect of the various growth parameters (plasma temperature, plasma pressure, gas flow rate, gas percentage, substrate temperature, etc) on the electronic properties of the diamond grown. In Fig. 1 we show the collection distance at an electric field of 10 kV/cm for a 700 μm thick diamond for twelve sequential runs from this matrix study. The results of this study are:

- a stable process for producing CVD diamond with a 125 μm collection distance (4500 e^- signal) designated as run 10 in Fig. 1;
- a recipe for post processing the as-grown diamond to enhance the collection distance to 150 μm (5400 e^- signal) shown by the solid square in Fig. 1;
- an understanding of how to modify the growth reactor to reach a new portion of the growth parameter space which will yield 200 μm collection distance diamond (7200 e^- signal) as grown.

Presently RD42 has accepted one 10 cm diameter wafer; a second 10 cm wafer growth is in progress. Trackers made from the first growth have been tested and results are reported later in this document. Trackers from the second growth will be tested with a source initially and then in our September testbeam at CERN. After the present growth run is complete, one reactor will be modified. This process will take approximately one month at which time two additional growths for RD42 will commence. All expectations are to reach a collection distance of 200 μm by the end of 1995.

The second important development involves an additional manufacturer. The De Beers Co. has now produced CVD diamond with a reasonable collection distance (40 μm) [9]. We have tested several small samples of diamond and we are now giving De Beers the appropriate feedback they need to improve the performance of their diamonds. We have constructed a tracker on a sample of their diamond and attained a 1000 electron signal, approximately what we expected.

2.1 How We Plan to Increase Charge Collection Distances

The basic method we have endorsed with each company to increase the charge collection distances involves three parts: A serious chemistry study to understand the operating parameters of the different growth machines and their effect on the collection distance. For this part of the program we provide instantaneous feedback of the collection distance to the manufacturers. The advantages of using this property are:(1) the collection distance appears to be one of the most sensitive diagnostic parameters (we are easily able to detect changes in the growth machine in a blind test) and (2) the growth process is tuned and correlated to the final parameter we are interested in. The second part of the program involves the manufacturers making a thick, ~ 700 μm full wafer run to understand the stability of the process and the thickness scaling laws since the collection distance grows with material thickness [10]. The final part of the process involves post-growth treatment: manufacturers are asked to remove 35% of the material from the substrate side where the collection distance is nearly zero.

We are well into this program with St. Gobain/Norton and have just started this program with De Beers. The program as outlined above takes 1-2 years for the manufacturer to reach the full potential of their individual process.

2.2 The Status of St. Gobain/Norton Growths

During the past year we entered into contracts with St. Gobain/Norton to produce 5 wafers of diamond, each 10 cm in diameter. From each diamond wafer, we will produce tracking detectors and measure the radiation hardness properties. Since the first half of this year was devoted to chemistry, to date Norton has delivered one run. Presently, one run is in progress and the remaining runs are planned for September, November and December.

2.3 The Status of De Beers' Growths

During this year De Beers will supply us with 10 small samples (1 cm $\times$ 1 cm) of CVD diamond as they proceed with their optimization study. Recently, they have requested that we measure an additional twenty diamonds for them. We have agreed to provide the additional feedback and they appear enthusiastic about what they have learned from us.

2.4 What We Can Reasonably Expect in 1996

The program outlined above will lead to signal sizes of approximately 7000 e^-. A small amount of tuning will be required to reach signal sizes of 8000 e^-. This will take place in 1996. Also during 1996 we propose to order 6 wafers of diamond (split between two manufacturers). This will provide enough of the new higher quality material to produce reasonably sized trackers and to complete the radiation hardness studies we have begun. Finally, in 1996 we will begin working with the manufacturers to determine how to reduce the production costs of the raw material. This stage will require additional chemistry experiments to assess the consequences, if any, for the collection distance as we change the growth conditions. Overall, at the end of 1996 we hope to have a working prototype of an LHC tracking element and realistic indications of the final cost of such a tracking element.

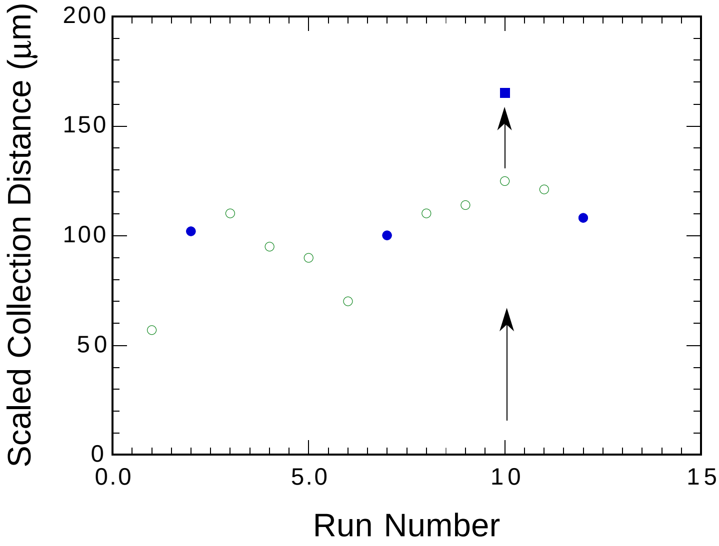

Figure 1: The scaled collection distances of twelve, chemistry testing growths. Runs 2, 7 and 12 (solid points) are re-growths of the same chemistry. We are now working to grow a full thickness wafer of run 10 (lower arrow). By removing 35% of the material from the substrate side of this thick growth we should achieve a collection distance in excess of 150 μm (solid box).

3 Radiation Hardness of CVD Diamond

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. The tightly bound lattice structure of diamond suggests that it will be insensitive to large doses of radiation.

The radiation damage induced increase of leakage currents in solid state detectors is caused by the creation of states that lie in the middle of the bandgap region. The existence of such states in the middle of the bandgap allows excitation of electrons from the valence to the conduction band to proceed via a two step process, each step involving an excitation energy of only 1/2 the bandgap energy. Since the excitation probability to a state of energy E is proportional to the exponential of (-E/kT) where k is the Boltzmann constant and T is the temperature in Kelvin, a factor of 1/2 in the exponent has a very large effect. Given the small size of the bandgap in silicon, there exists a small, but non-negligible probability for electrons to be excited to the conduction band by a two step thermal excitation process. Once in the conduction band, those electrons are then swept out by the applied detector bias voltage giving rise to the leakage current. The same process occurs in diamond, but given its much larger bandgap energy, the leakage current remains essentially zero. Using bandgap energies of 5.5 eV and 1.12 eV for diamond and silicon respectively and a temperature of 300°K, one finds excitation probabilities for reaching a level in the middle of the bandgap which are at least 10^{-30} times smaller in diamond than in silicon. Hence, compared with silicon, there is no bulk leakage current in diamond.

The other effect of radiation damage in silicon detectors is a decrease in the observed pulse height. This is due to the production of trapping/recombination centers which results in a decrease in mean carrier lifetime. These centers can be produced by charged particles or neutrons through atomic displacements in the lattice. Diamond with its large cohesive energy and tight lattice structure appear also be resistant to this type of damage, as our studies (see below) show.

3.1 Current Studies of Radiation Damage in CVD Diamond

During the last year we have undertaken several studies of radiation damage to CVD diamond detectors. These were tests which were designed primarily to look for evidence of radiation damage rather than to understand the underlying damage mechanism. One study looked for damage due to electrons. A second study investigated the damage caused by charged pions. The third study looked for damage caused by protons.

3.1.1 Electron Irradiations

We have shown through a study started in 1993, using a ^{60}Co gamma (1.2 and 1.3 MeV) source at Argonne National Laboratory, that radiation doses up to and including 10 MRad showed *no evidence* of degradation of electronic properties in CVD diamond by measuring bulk collection distances before, d_0, and after, d, each irradiation [5]. These data showed a curious effect however: at low dose levels, of less than 10 kRad, the observed charge signal increased linearly with dose. Although not fully understood, the working hypothesis is that ionization from the irradiation fills trapping centers in the diamond, allowing electrons and holes to move farther, giving rise to an increase in the observed signal size.

In order to extend the range of the exposure with non-hadronic interacting particles, diamond detectors were exposed to a high intensity 2.2 MeV electron beam from a Van de Graaf accelerator at Strasbourg, France (Société AERIAL) in 1995 to a dose level of 100 MRad. The Gaussian-shaped electron beam with a current of 125A and a 6 cm diameter (FWHM) was rastered at a frequency of 20 Hz across 20 cm to achieve high degree of irradiation uniformity. The pass duration was 8 s and they were repeated every 3 minutes. The bulk collection distance was measured before and after the completion of successively higher doses. The relative collection distance (d/d_0) was measured as a function of dose (Fig. 2) at an applied electric field of 10 kV/cm. The data in Fig. 2 indicate that diamond detectors can withstand 100 MRad of radiation. This result confirms the lower dose photon result and extends it by an order of magnitude. Moreover, there appears to be *no evidence* of signal degradation up to this dose.

3.1.2 Pion Irradiation

Very near the interaction region in the LHC, at radii smaller than 15 cm, the predominant source of radiation is charged pions. Furthermore a large fraction of these pions will have very low momenta (coming from the hadronization of jets) and thus can excite nuclear resonances in the detector material.

The pion irradiation study [13] was performed using a 300 MeV/c high intensity pion beam at the Paul Scherrer Institute in Villigen, Switzerland. This pion momentum was chosen since it corresponds to the peak of the pion-nucleon cross section.

The diamond devices used in this test were characterized before, during and after the irradiation. In addition, two silicon photodiodes were exposed for comparison. The collection distance and leakage current were measured before and after the irradiation and the beam induced current was monitored during the irradiation.

The beam-induced currents for a diamond and a silicon detector are shown in Fig. 3. Two families of currents are apparent, those in the presence of beam (higher points) and those from the residual leakage current in the devices (lower points) measured when the beam was off. Furthermore, when the beam was on there were two discrete intensities, 100% and 85% of nominal current. The constancy of the beam induced current for the diamond is evidence that the samples' charge collection properties were unchanged during the exposure. In the case of silicon, there is clear evidence of the increase of leakage current with dose and of the annealing that occurs when the beams are off.

In Fig. 4, we show the collection distance for one of the diamond samples as a function of electric field before and after pion irradiation. The collection distance after the irradiation has increased over the pre-irradiation value by a factor of 1.5-1.8 depending on the electric field. In Fig. 5 we show the relative collection distance at an electric field of 10 kV/cm, normalized to the unirradiated value, as a function of fluence. The data below 10^{11} cm^{-2} were taken with electrons. These data confirm the rise in collection distance with small dose. As with the electron irradiation, *no evidence* for damage was observed for pion fluences up to 8×10^{13} pions cm^{-2}.

3.1.3 Proton Irradiation

During the life of an LHC tracker, the proton fluence is expected to be about an order of magnitude lower than the pion fluence but, the radiation damage from protons will be significant due to their mass. In order to determine the radiation hardness to protons, a study [14] was performed using a 500 MeV/c high intensity proton beam at TRIUMF in Vancouver, Canada.

Similar to the pion irradiation, bulk collection distance measurements were made on several diamond detectors before and after the irradiation with detectors receiving different levels of fluence. In addition, a silicon photodiode was also exposed for comparison. During the exposure, the beam-induced currents from the diamond detectors were monitored.

The results are similar to the pion irradiation results. The beam-induced currents for the diamond and silicon are shown in Figs. 6 and 7, respectively. The leakage current in the silicon detector increased dramatically over the course of the irradiation due to proton damage, but the diamond showed no change in the leakage current under the same conditions. In Fig. 8, the response of a diamond detector as a function of beam current is shown by examining the ratio (IPR) of the beam-induced current to the ion-chamber current (on-line beam-current monitor) which is constant up to a fluence level of 10^{14} protons per cm^2. This result clearly shows the radiation hardness of diamond. In Fig. 9 we plot the relative collection distance at an electric field of 10 kV/cm up to 10^{14} protons per cm^2. *No evidence* of degradation of electronic properties in CVD diamond is observed. Once again, the increase in collected charge with small dose is

Figure 2: Exposure of CVD diamonds to 2.2 MeV electrons. The relative collection distance, d/d_0, is measured as a function of radiation dose.

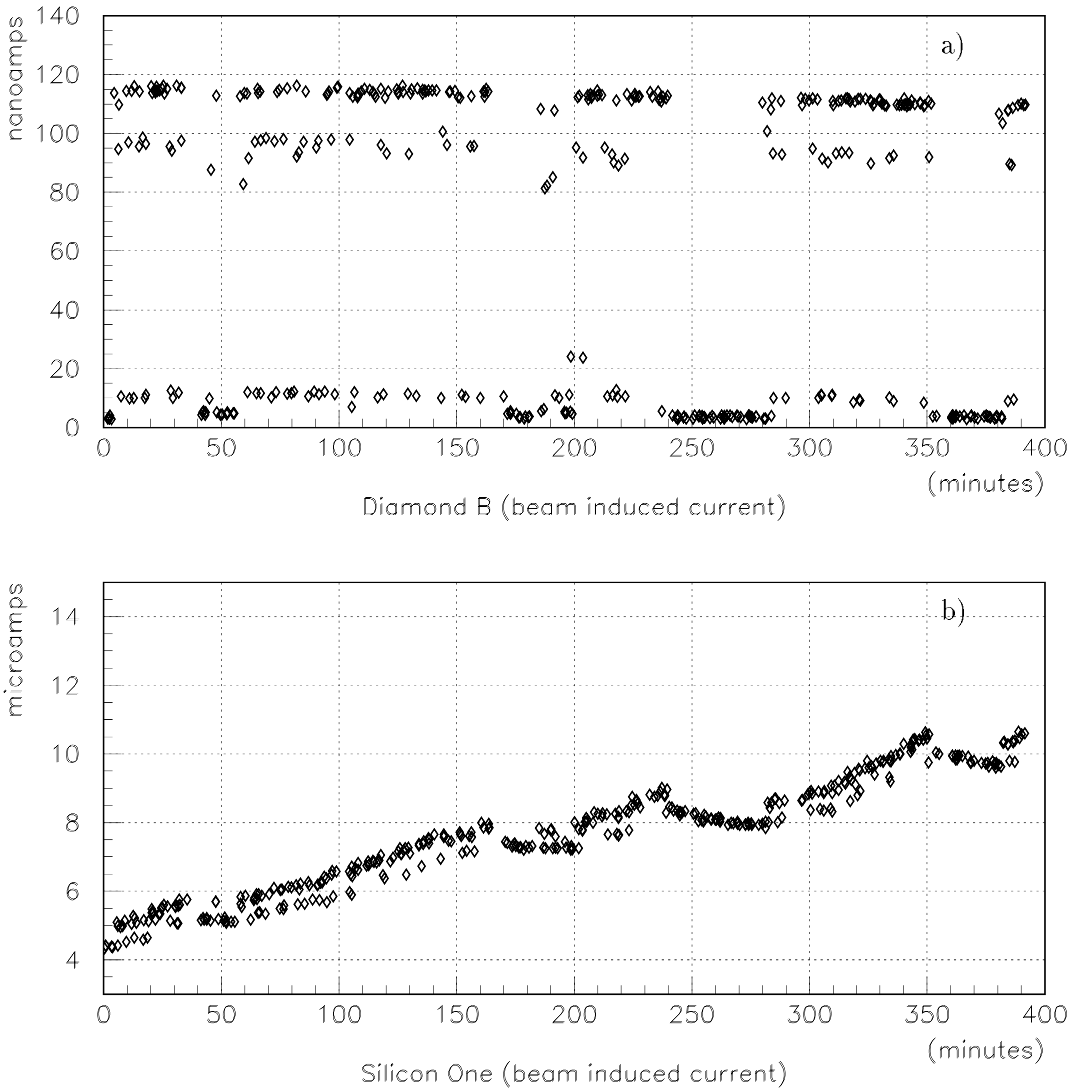

Figure 3: The beam-induced current in a diamond sample (a) and a silicon sample (b) in the high intensity region of the beam measured during the pion irradiation as a function of time. On the time axis (t=0) is 200 minutes after the beginning of the irradiation. The pion fluence increases from 1.4×10^{13} pions/cm^2 at t=0 to 4.3×10^{13} pions/cm^2 at t=400 minutes in both graphs. The two families of points in each figure correspond to times when the beam was on (upper points) and off (lower points). When the beam was "on" there were two different intensities, 100% of nominal and 85% of nominal. The dominant effect in (b) is the growth of the diode leakage current as the silicon is damaged.

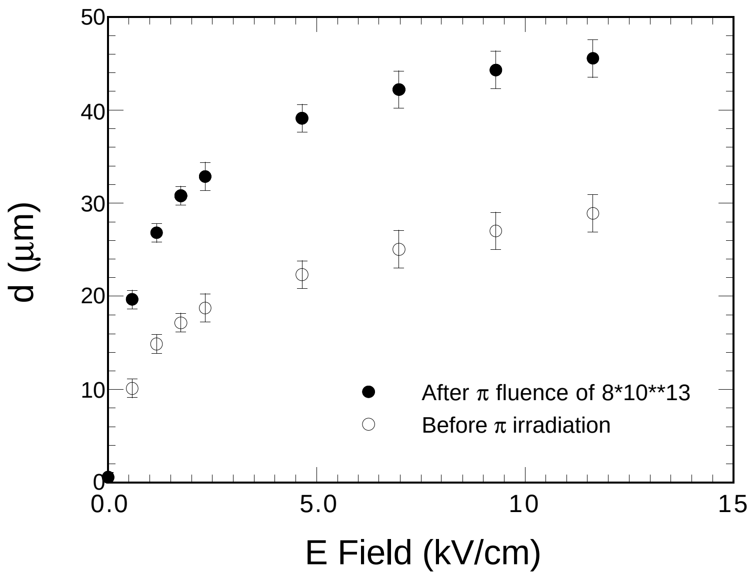

Figure 4: The collection distance, d, as a function of electric field, E, for a diamond sample measured before and after pion irradiation.

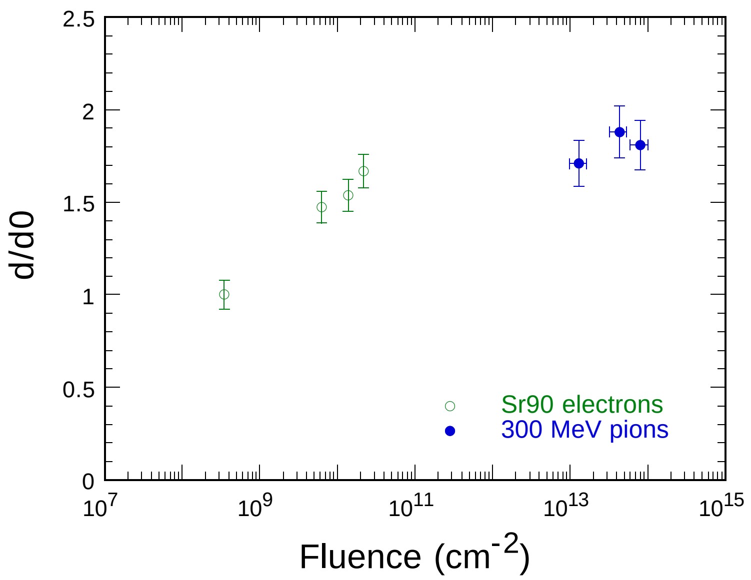

Figure 5: The relative collection distance, d/d_0, in diamond at an electric field of 10 kV/cm as a function of pion fluence normalized to the lowest fluence point.

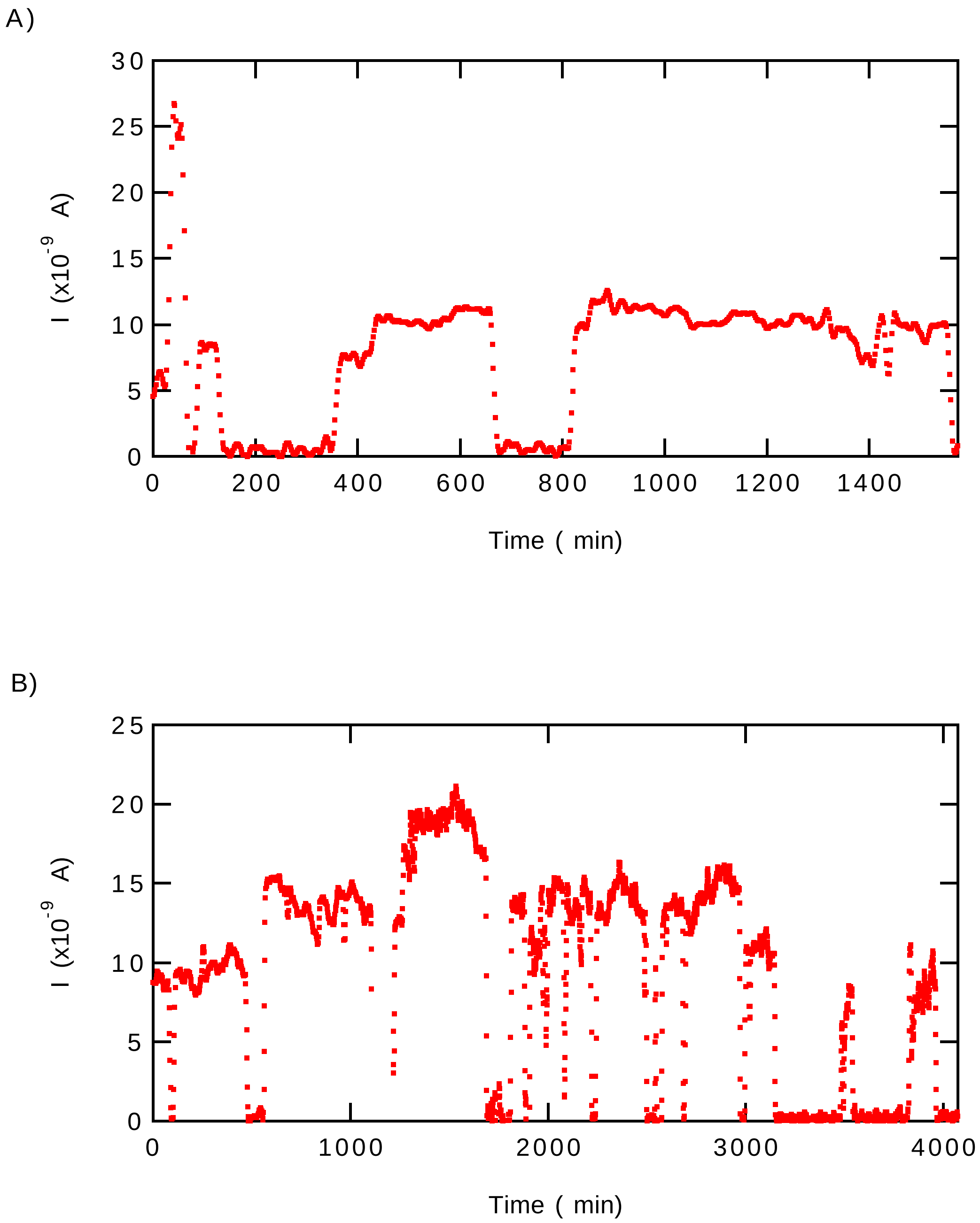

Figure 6: The proton-beam-induced currents in diamond detectors as a function of time during the irradiation: A) Diamond detector LANL4: B) Diamond detector LANL3. When the beam is off, the current from the detectors is zero but when the beam is on the current corresponds to the beam current.

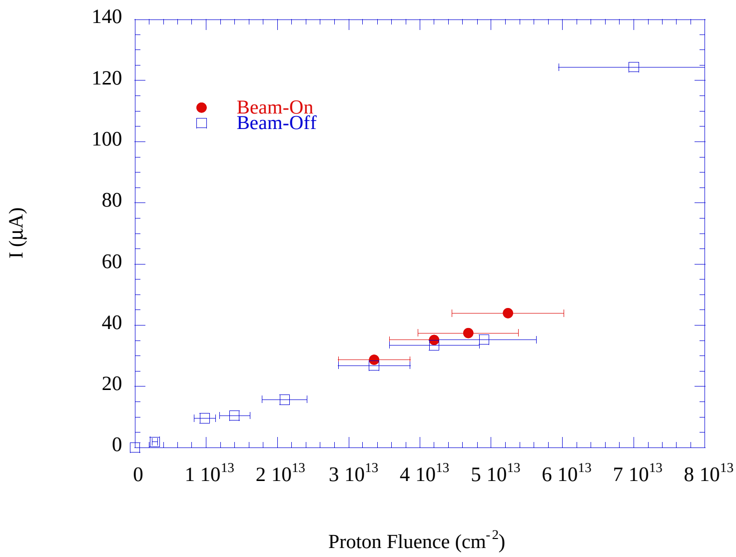

Figure 7: Leakage currents from the Si-photodiode as a function of 500 MeV/c proton fluence.

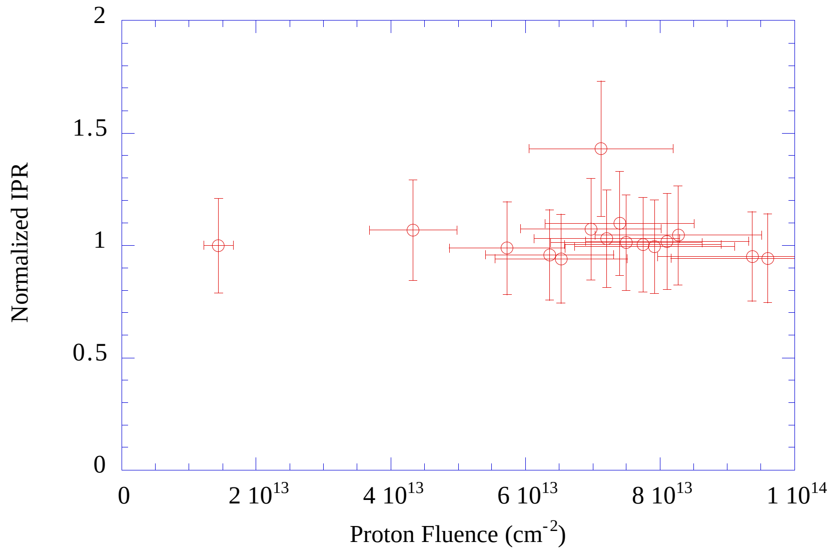

Figure 8: The ratio of the beam-induced current to the ionization chamber current (IPR) for diamond sample LANL3 as a function of fluence.

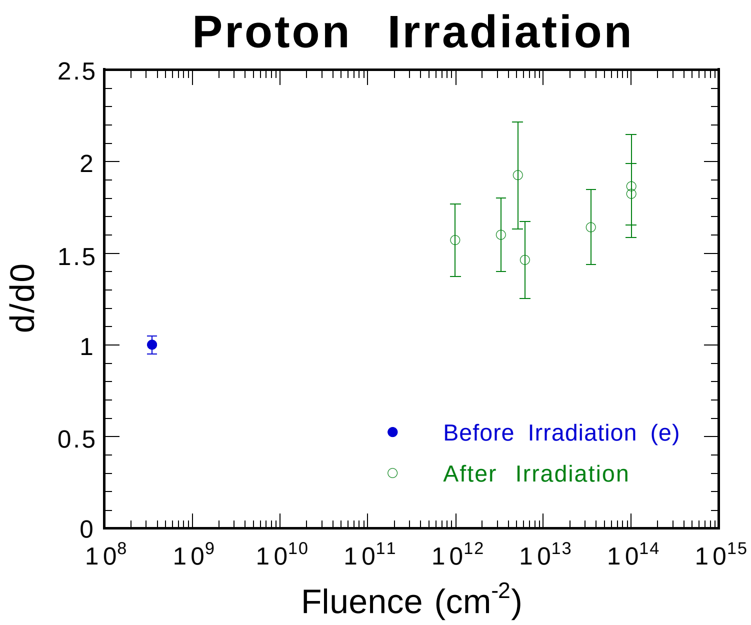

Figure 9: The relative collection distance at an electric field of 10 kV/cm as a function of proton fluence normalized to the lowest fluence point.

4 Results from Tracker Prototypes

The performance of diamond tracking detectors has been evaluated in several testbeams at CERN. The diamond trackers were produced on high quality CVD diamond material. Prior to the electrode deposition the surface was cleaned; no material was removed from the substrate side. Two different strip configurations were tested on several diamonds: In tests performed in late 1994 the diamond detectors had strips of 100 μm pitch, with an interstrip gap of 50 μm as with our original trackers [2, 15]. In the spring of 1995 new diamond material was metallized with strips of 50 μm pitch, with a 25 μm interstrip gap. In both configurations the strips were deposited on one side of the diamond only, a continuous contact on the other side is used to apply the drift voltage. The overall sensitive area was approximately 6.8$\times$6.8 mm in both configurations. Each tracker was read out by a single VA2 front-end chip with a 2 μs shaping time. The analog data were digitized by VME SIROCCO modules. In order to allow a precise determination of the diamond spatial resolution a telescope with high resolution silicon detectors was used. The diamond trackers were placed in a 100 GeV pion beam in line with eight silicon microstrip detectors to form a telescope with four "x" and four "y" measurements along a track, plus the measurement from the diamond detectors under study. The silicon detectors gave hit position resolution of 2-4 μm, and were aligned to an accuracy of better than one micron, taking into account all rotations and offsets.

4.1 Measured Signal Distributions in Diamond Tracking Detectors

For the analysis presented here the signal response of each diamond - amplifier system is calibrated by means of an external test capacitor at the input of one VA2 channel. Knowing the injected charge on the test capacitor the correlation between output signal in ADC counts and input charge can be derived. As a first step in the analysis chain the signal raw data are corrected for their individual DC-pedestals as well as for any DC shift common to all channels. The signal calculation additionally updates the pedestal and r.m.s. noise for each channel on an event-by-event basis.

Two different approaches were chosen to evaluate the signal response of the diamond trackers: In a first analysis a cluster finding algorithm searches the diamond for particle hits. This analysis considers the diamond signals only and uses no external information from the reference telescope, much as would be the case in a real tracker. For each diamond strip the ratio of its signal and its r.m.s. noise is calculated. A cluster is identified as a group of adjacent strips where each strip has a signal-to-noise ratio higher than 1.5. The signal-to-noise ratio for the entire cluster is then given by the sum of the single strip signal-to-noise ratios. In order to be accepted as a particle hit the total cluster signal-to-noise ratio has to exceed 6. The signal-to-noise distribution as measured on the diamond with 50 μm strip pitch is illustrated in Fig. 10. The most probable signal-to-noise on this diamond is measured to be 22. This high signal-to-noise value for the diamond influences both reconstruction efficiency and spatial resolution positively. In a second analysis the reference system is used to predict a track hit position on the diamond under test. The signals on diamond strips next to the prediction are used to determine the cluster signal. This analysis does not impose any direct threshold on the diamond to reconstruct the cluster and therefore yields an unbiased result for the diamond signal, which is comparable to results from the diamond characterization. Figure 11 shows the diamond signal distributions for a 50 μm pitch and a 100 μm pitch diamond detectors made from different CVD wafers (hence the different signal sizes). The signal is defined as the sum of the 3 single strip signals centered on the predicted hit position. An average signal on the 50 μm pitch diamond of 2500 electrons has been achieved.

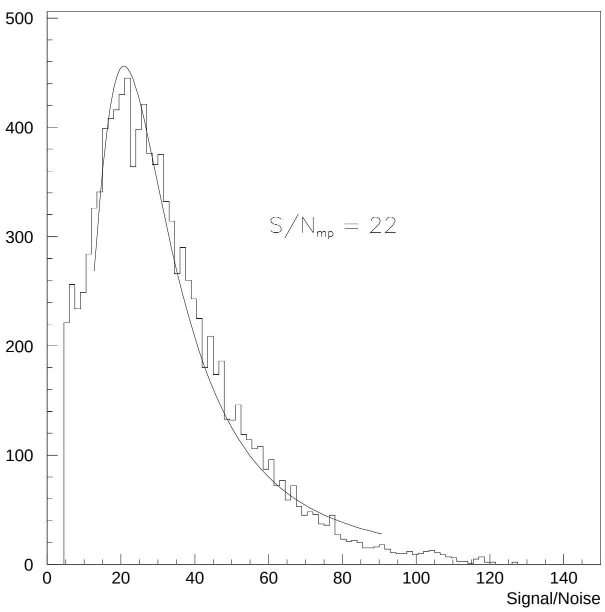

Figure 10: Signal to noise distribution as measured on the 50 μm pitch diamond tracker

4.2 Spatial Resolution and Hit Finding Efficiency

With a sufficiently large signal-to-noise ratio and charge sharing between neighboring strips, a CVD diamond microstrip tracking detector should attain a position resolution comparable to that of silicon detectors.

Figure 12 shows the hit residual distribution for the detector with 100 μm pitch. The r.m.s. of the distribution at 24 μm is slightly better than digital resolution (28.8 μm), the resolution expected if only the position of the strip with maximum pulse height is used.

With strips every 50 μm one would expect improvement both from the finer pitch and from the smaller interstrip gap, which decreases distortions in the electric field in the bulk of the detector. After all alignment corrections, and after restricting attention to the region of the detector well away from the strip ends and noisy strips, the best position resolution obtained with the 50 μm detector is 12.8 μm. This is illustrated in Fig. 13. The resolution comes from the standard deviation of a Gaussian fit to the residual distribution over the range $-50 < \delta u < +50$ μm, where δu is the difference between the coordinate measured by the detector and the track coordinate in that detector plane. In the case of the 50 μm pitch detector the position was determined from a simple two-strip linear interpolation.

With a signal-to-noise ratio of 22, one would expect excellent hit efficiency. The efficiency, defined here as the fraction of tracks which give rise to a cluster found independently of knowledge of the track position, depends on the details of the cluster finding algorithm, especially the thresholds. For the diamond clusters presented in Fig. 13 the cluster finding algorithm required only that a strip has at least 10 ADC counts (about 2.7 standard deviations above the noise). Such an algorithm is nearly 100% efficient in this case, but does not realistically represent the thresholds needed for actual running in a collider environment.

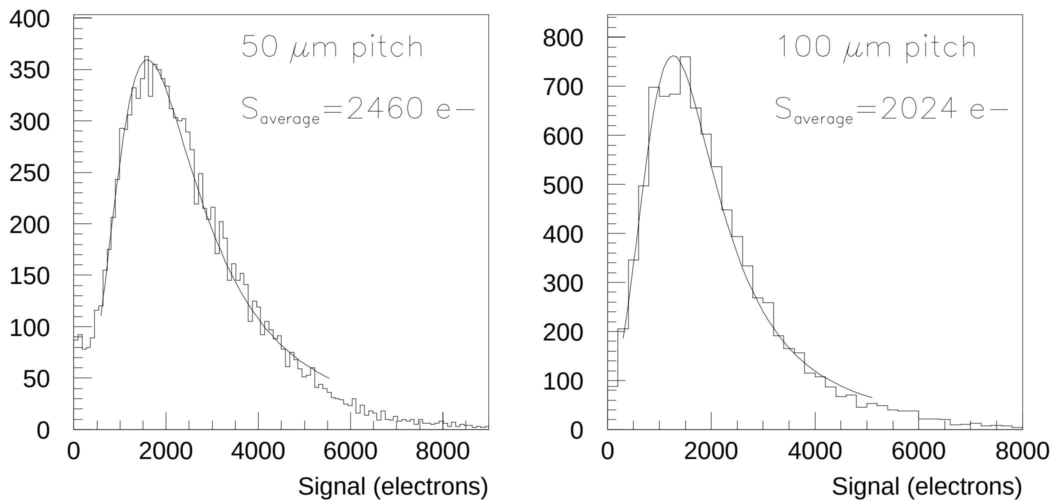

Figure 11: Signal distributions for a 50 μm pitch and a 100 μm pitch diamond tracker.

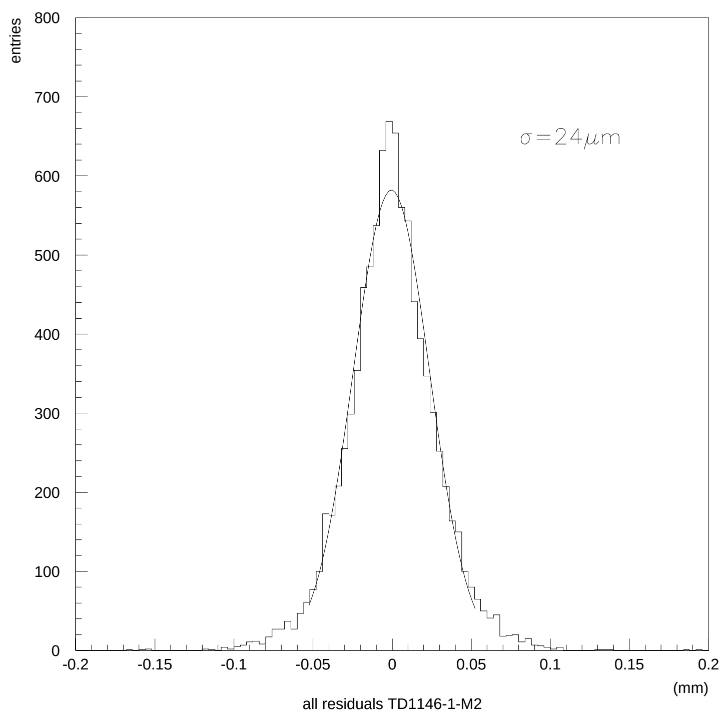

Figure 12: Distribution of track hit residuals in the 100 μm pitch diamond tracker.

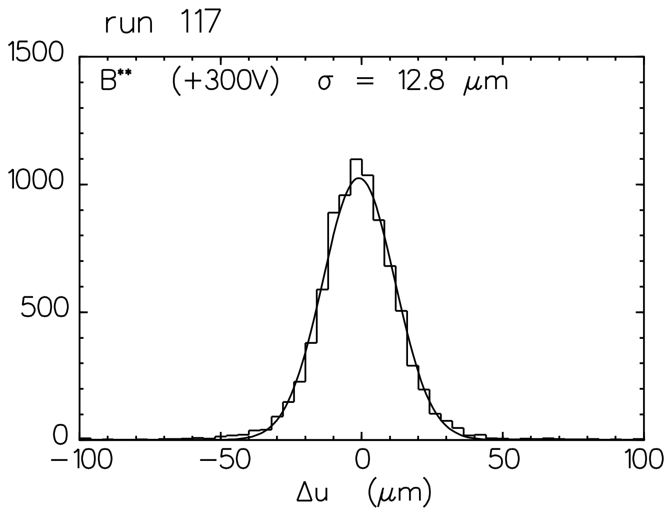

Figure 13: Distribution of track hit residuals in the 50 μm pitch diamond tracker after fiducial cuts.

5 Development of Front-End Electronics for Diamond Trackers

While one cannot ever expect to have available a charge exceeding about 10,000 electron-hole pairs from a 300 μm thick diamond detector, it will nevertheless be possible to read out diamond sensors, which are placed in areas with very high radiation levels, with acceptable signal over noise ratios at LHC speed.

To begin the development for a diamond sensor fast front-end readout chip, we assume that a charge yield of about 4000 - 6000 electron-hole pairs will be achieved within the next six months. At this point, it is useful to mention some advantages of diamond over silicon with respect to fast readout feasibility. These advantages can, to some extent, compensate for the shortcomings caused by the reduced charge obtainable from diamond sensors:

- Parallel Noise: In silicon detectors, the parallel noise caused by the increasing leakage current under irradiation (in a 10 year high luminosity scenario, one expects about 2 μA leakage current for detectors run at 0°C for a 12 cm long sensor with 50 μm strip pitch) will finally dominate the noise performance of the tracker system. For diamond sensors the leakage current is negligible for unirradiated sensors and does not change significantly under irradiation.

- Series Noise: The other essential difference with silicon is the lower dielectric constant of diamond ($\epsilon_{Si} = 11.7$, $\epsilon_{di} = 5.6$). This is important since this quantity determines the capacitance of one strip to all neighbouring strips and to the backplane. For diamond we estimate that the total load capacitance (all neighbours plus backplane) of a 1 cm long strip can be kept below 0.5 pF for 50 μm strip pitch.

Furthermore, it is assumed that diamond strip sensors will be 8 cm long which might be the maximum affordable length due to increased occupancy at small radii. A signal-over-noise ratio between 12:1 to 15:1 is considered to be sufficient to obtain adequate background rejection even for inclined tracks and to have high efficiency for finding tracks. It is assumed that due to the high carrier mobility in diamond the spatial resolution will be very close to the digital resolution of pitch/$\sqrt{12}$ for tracks with vertical incidence. However, the majority of tracks will traverse the detector under an angle and in this case a good signal over noise ratio will be important to get the best spatial resolution. From these requirements, one can derive a specification for the noise performance of the front-end. The total Equivalent Noise Charge (ENC) should be lower than 400 e^- for a 8 cm long detector.

Several possibilities will be discussed in the following. In a first attempt, it seems desirable to use existing front-end architectures for silicon readout and optimise them for use with diamond detectors. One of our groups is involved in the development of new devices like the HEMT, which will also be discussed below.

5.1 The RD20 CMOS Deconvolution Architecture

A 128-channel front-end chip with a CMOS preamplifier shaper input stage, a 40 MHz 84-cell long analog pipeline (ADB), a circuit which allows fast reshaping of the sampled signal from the shaper (APSP or deconvolution circuit) and an analog multiplexer which operates at 20 MHz is at present under test. A 32-channel version of this chip has been tested and shows full functionality [16]. Both these chips have been produced in standard non-radhard technology. First versions of this readout architecture in radhard CMOS technology are available and presently tested.

In order to optimise the 128-channel chip for the readout of diamond sensors, only small design modifications will be necessary:

- Adaptation of the input FET to the smaller load capacitance of about $C_L \approx 5$ pF.

- Increase of voltage gain in the input stage to adapt to the smaller signal.
- Choice of optimal peaking time, τ_P, for low noise peak amplitude.
- Modification of the weights used in the deconvolution circuit to have adequately fast double-pulse resolution.

The present 32-channel RD20 circuit has a noise performance of ENC = 370 e^- + 23 e^-/pF (see Fig. 14). The input FET is laid out with w/l = 3000 μm/1.4 μm. Extrapolating to w/l = 800 μm/1.4 μm, a noise slope of 40 e^- to 50 e^- and a baseline noise of 150 e^- to 200 e^- can be achieved with a shaping time of τ_P = 40 ns. This will give the required 400 e^- ENC for an 8 cm long detector. Fast reshaping, to 1/3 τ_P will provide optimal double-pulse resolution.

In a second phase, it will be necessary to implement this chip in a radhard technology (e.g. HARRIS). Transistors produced in HARRIS ALVSIRA technology have been tested and show good radiation hardness up to 10 MRad. It is expected that this technology can provide radiation hardness up to 100 MRad.

5.2 A Transresistance Amplifier with a PMOSFET Input Stage

A prototype front-end transresistance amplifier designed in radhard DMILL technology is presented here. A version with bi-polar, BJT, transistors on the input, a peaking time of 25 ns and a total power dissipation below mW has been obtained. The noise performance of this circuit is ENC = 616 e^- + 34 e^-/pF, when measured with a collector current of 220 μA in the input transistor. We have modelled the replacement of the input BJT transistor by a PMOS cascode stage, optimized for the low capacitance loads typical of diamond detectors. Preliminary simulations show a gain of 40 mV/fC at 25 ns peaking times for 6 pF loads on the input. Comparing the transconductances of the BJT and PMOS devices and extrapolating noise results from the bi-polar version a noise of 500 e^- for 5 pf loads should be obtainable.

A transimpedance amplifier stage based on a novel current mode feedback topology has been designed and tested [17]. The chip was fabricated using industrial 0.7 μm CMOS radsoft technology. The measured transimpedance gain is 10 mV/fC (obtained in a single stage) for a peaking time of 45 ns. Under these conditions a total noise of 360 e^- has been obtained for a 5 pF load at the input. Comparable designs using radiation hard CMOS and BiCMOS technologies are being developed.

5.3 Radiation Hard MESFET Amplifiers

Several technologies are currently being evaluated, in order to find the solution to the problems imposed on the front-end electronics by the LHC environment. Devices based on GaAs or GaAs-related compounds (as well as on other III-V compound semiconductors), such as HEMTs and MESFETs, by virtue of their large transition frequency, allow for very high speed performances and feature a low channel thermal noise. They also show good properties in terms of radiation hardness, especially to neutrons. More "established" monolithic silicon processes, such as CMOS rad-hard, are also being considered, in view of the design versatility and the functional density they offer. A mixed solution might prove to be the best one, combining a low-noise front-end chip based on GaAs devices and a rad-hard CMOS readout chip, implementing functions such as pipelining, sparsification, etc.

A CMOS rad-hard process with 0.8 μm minimum gate length is providing good results in the design of the front-end chip for the readout of silicon microstrip detectors [18]. The analog section of the chip implements preamplification and shaping, with a 100 ns peaking time. A study was carried out in order to evaluate the possibility of using this process to cope with the parameters of diamond trackers. This basically means a shorter signal peaking time (20 ns) and a reduced detector capacitance for the same geometry. The extrapolations carried out from the measured noise parameters of this process show that an ENC of about 550 e^- rms can be

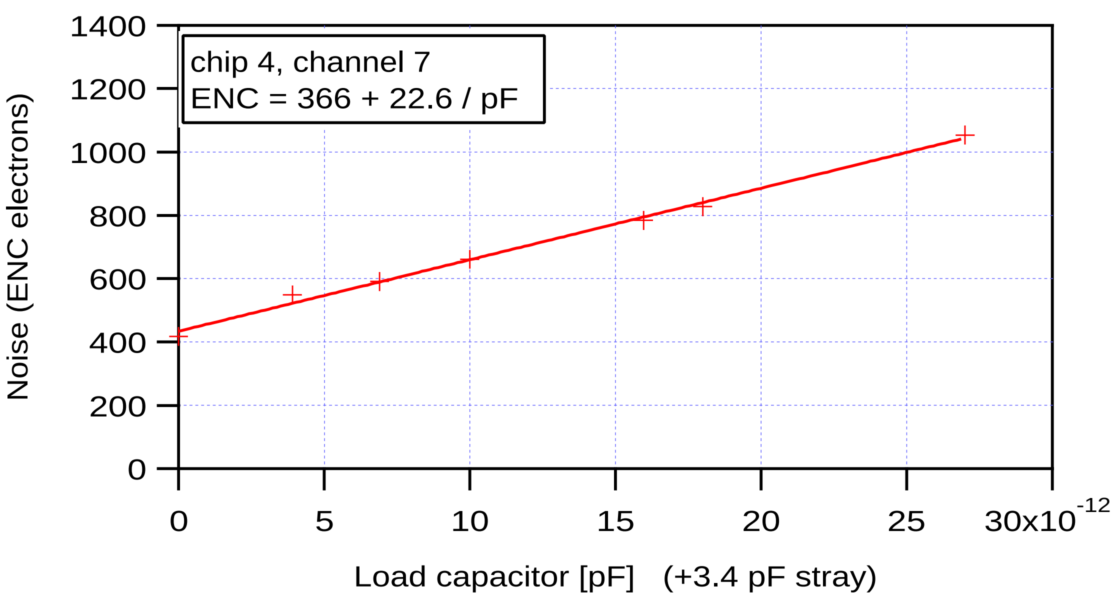

Figure 14: Noise characteristic for 32 channel RD20 front-end preamplifier shaper.

obtained, using a preamplifier input device matching a detector capacitance, C_D, of about 4 pF, at reasonable values of power dissipation. The possibility of designing a front-end chip tailored to the diamond specifications is currently being evaluated. Mixed technologies, such as DMILL, combining JFETs and MOSFETs on the same substrate, are also interesting possibilities. The use of the JFET may allow for an increased radiation hardness, as well as for better noise performances.

Heterojunction field effect-transistors, also called HEMTs (High Electron Mobility Transistors) feature very high cut-off frequencies, which is advantageous in applications requiring short shaping times. Compared to other field-effect devices, they allow for the same speed performances at a lower power dissipation. Monolithic charge-sensitive preamplifiers based on HEMTs were integrated [19] with good results. The analysis of the HEMTs noise properties show that a limitation arises from frequency-dependent noise sources, while the intrinsic limit set by white channel thermal noise is very low [20]. The HEMTs show a very large degree of radiation hardness; experimental studies demonstrate they are able to stand very high doses of ionizing radiation (up to 100 MRad photons) and high neutron fluences (up to 10^{15} n/cm^2) with negligible performance degradation [21]. Work is in progress, with the aim of optimizing the geometry and the bias conditions of the devices, as well as the integration process. GaAs MESFETs presently appear to give superior noise performances; as shown by experimental results on commercial devices (see Fig. 15) ENC values around 500 e$^-$ rms, at $C_D = 5$ pF and $\tau_P = 20$ ns are obtained at low values of power dissipation. Future work on the design of charge-sensitive preamplifiers based on HEMTs and MESFETs is foreseen, focusing on the requirements set by diamond trackers in the LHC.

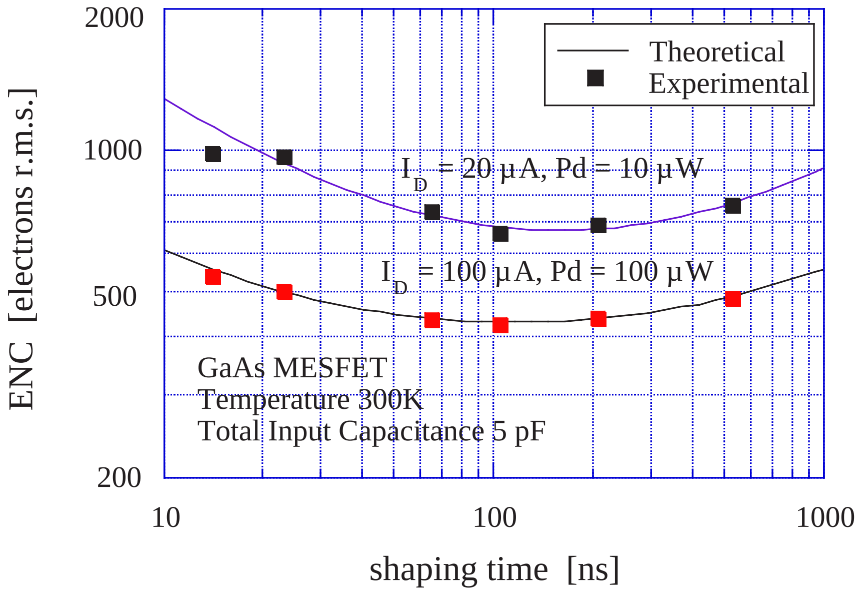

Figure 15: Equivalent Noise Charge (ENC) as a function of the shaping time of an RC-CR filter for a GaAs MESFET with W/L = 250/0.3, at drain currents of $I_D = 20\ \mu A$ and $I_D = 100\ \mu A$.

6 Proposed Research Program for 1996

We will continue to focus our research for the remainder of the project on working with manufacturers to improve the quality of the diamond material. We have demonstrated that collection distances on the order of 100 μm are possible in our first year of work. We intend to continue to work with companies to further improve the material. We believe that we now have the knowledge to obtain collection distances in excess of 200 μm. Satisfying this milestone should be possible by the end of our second year of research. Having produced various configurations of single sided detectors we intend to study the feasibility of double sided trackers in the coming year. Our studies also indicate that the strip coverage (50%) we have used up to now may not be optimal. Of particular interest is a study of the ratio of the strip width to pitch to optimize these devices.

The improvement in quality of CVD diamond for particle detectors has been achieved with a strong laboratory, university and industrial effort. Our collaboration is now fully up to speed and has the expertise to quantify the results of different diamond growth processes. We intend to exploit this expertise to provide rapid feedback to diamond manufacturers on the quality of their products thereby continuing the rapid increase in electrical properties we have recently attained.

In order to test the radiation hardness of the material produced we continue to expose samples of the newest CVD diamond material to pions, protons, neutrons, alpha and ^{60}Co sources as new generations of the material become available. To improve the understanding of the mechanisms at work in both un-irradiated and irradiated CVD diamond we have begun a program of exposures with low energy protons which have a limited range in the material. This allows us to study charge deposition near the two surfaces of the material. From these studies we expect to demonstrate whether variations in the production process affect radiation hardness and to work to optimise the growth of radiation-hard diamond.

In early 1996, we anticipate that we will be in a position to equip a tracker with readout electronics suitable for use at the LHC and demonstrate the ability to track charged particles in diamond at repetition rates of 40 MHz. Although the diamonds we have now will probably have S/N ratios of about 5:1 with the required shaping time, the anticipated improvements in the diamond material (see above) coupled with the proposed optimisations of the readout electronics for diamond should make it possible to achieve our ultimate goal of 15:1 signal to noise for LHC-type trackers. Such diamond material will also clearly be suitable for solid-state detectors in other configurations at the LHC and members of our collaboration are already starting to investigate such applications.

7 Responsibilities and Funding for 1996

What follows is a breakdown of the areas of research that will be pursued at the different institutes (table 1) involved in the project, a budget for the work to be carried out (table 2) and sources of funding expected for the project (table 3).

7.1 Requests from CERN Infrastructure

It is anticipated that in addition to funding to purchase diamond samples and develop radiation hard low noise electronics that the following requests will be made on the CERN infra-structure:

- four 5-day testbeam running periods per year for the duration of the project;
- computing time and disk space on the central CERN computers;
- 20 m^2 of laboratory space for test setups, detector preparation and electronics development;
- office space for 3 full time residents and 10 visiting members of our collaboration;

Institute	1	2	3	4	5	6	7	8	9	10	11	12	13
Diamond Characterisation	x			x		x	x	x			x	x	x
Radiation Hardness			x	x		x	x			x	x		x
Detector Design		x	x			x	x	x		x			x
Low Noise Electronics	x	x			x				x			x	
Rad.Hard Electronics		x			x				x				
Heat Sinks/Electronic Substrates			x					x					
Data Analysis	x	x			x					x		x	x

Table 1: Research Interests of groups involved (1=Bristol, 2=CERN, 3=CPPM, 4=LLNL, 5=LEPSI, 6=LANL, 7=MPI-Heidelberg, 8=OSU, 9=Pavia, 10=Rutgers, 11=Sandia, 12=Toronto, 13=Vienna).

Item Budget	(Year 2)	(Year 3)
Raw Diamond Material	220	400
Detector Fabrication	40	60
Fast Low Noise Electronics	90	-
Radiation Hard Electronics	40	100
Thermal Grade Diamond	20	20
Auxiliary Electronics	25	50
Offline Computing	20	-
Travel	60	60
Totals	515	690

Table 2: Estimated Budget (in kCHF).

Institute (Anticipated Funding)	(Year 2)
CERN	140
CPPM	20
LEPSI	30
Milan/Pavia	25
MPI-Heidelberg	20
Toronto	30
U.K.	10
U.S.A. (LANL,LLNL,OSU,Rutgers,SNL)	220
Vienna	20
Totals	515

Table 3: Funds (in kCHF) subject to approval of national funding agencies.

8 Publications and Talks given by RD42

8.1 Publications

1. M. H. Nazaré *et al.*, "Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC", CERN/DRDC 94-21, DRDC-P56, May 1994.
2. R. Stone *et al.*, "Test of a Diamond-Tungsten Sampling Calorimeter", Mat. Res. Soc. Symp. **Vol 339** (1994) 121.
3. C. White *et al.*, "Correlations Between Electrical and Material Properties of CVD Diamond", Mat. Res. Soc. Symp. **Vol 339** (1994) 589.
4. R.J. Tesarek *et al.*, "Performance of a Diamond-Tungsten Sampling Calorimeter", Nucl. Instr. and Meth. **A349** (1994) 96.
5. A. Rudge, "Investigation of a Fast Amplifier with a Diamond Detector", Submitted to the Elba meeting (May 1994).
6. W. Dulinski *et al.*, "Diamond Detectors for Future Particle Physics Experiments", CERN PPE/94-222, submitted to ICHEP94, Glasgow, Dec. 1994.
7. C. White *et al.*, "Diamond Detectors for High Energy Physics", Nucl. Instr. and Meth. **A351** (1995) 381.
8. F. Borchelt *et al.*, "First Measurements with a Diamond Microstrip Detector", Nucl. Instr. and Meth. **A354** (1995) 318.
9. H. Pernegger *et al.*, "Radiation Hardness of CVD Diamond Detectors", Proceedings of the 7th Wire Chamber Conference, Vienna 95, to be published in NIM A.
10. W. Dulinski *et al.*, "Recent Results from CVD Diamond Trackers", Proceedings of the 7th Wire Chamber Conference, Vienna 95, to be published in NIM A.
11. C. Bauer *et al.*, "Pion Irradiation Studies of CVD Diamond Detectors", to be submitted to Nucl. Instr. and Meth.
12. C. Bauer *et al.*, "Proton Irradiation Studies of CVD Diamond Detectors", in preparation.

8.2 Talks

1. Charm 2000
2. Indiana Vertex Detector Workshop 94 (2)
3. Beauty 94
4. International Conference on HEP (Glasgow) 94
5. Como 94 (3)
6. Diamond Films 94
7. Vienna Wire Chamber Conference 95 (2)
8. Semiconductor Detectors (Schloss Elmau) 95
9. Israel Vertex Detector Workshop 95
10. Beauty 95
11. European Physical Society (Brussels) 95

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[13] C. Bauer *et al.*, "Pion Irradiation Studies of CVD Diamond Detectors," to be submitted to NIM.

[14] C. Bauer *et al.*, "Proton Irradiation Studies of CVD Diamond Detectors", in preparation.

[15] W. Dulinski *et al.*, "Recent Results from CVD Diamond Trackers", in the Proceedings of the 1995 Vienna Wire Chamber Conference to appear in NIM.

[16] S. Gadomski and P. Weilhammer, "Fast and Low Noise Frontend Electronics for Silicon Detectors at the LHC", Nucl. Inst. and Meth. **A351** (1994) 201.

[17] F. Anghinolfi *et al.*, "A Transimpedance Amplifier Using a Novel Current Mode Feedback Loop", presented at the 7th European Symposium on Semiconductor Detectors, Schloss Elmau, May 7-10, 1995, CERN-ECP/95-10.

[18] P.F. Manfredi, V. Re *et al.*, "Signal Processing in the Front-end Electronics of the BaBar Vertex Detector", presented at 7th European Symposium on Semiconductor Detectors, Schloss Elmau, May 7-10 1995.

[19] G. Bertuccio *et al.*, "A Fully Integrated Low Noise HEMT Charge-sensitive Preamplifier", submitted to NIM.

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