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

The RD42 Collaboration

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◇ Spokespersons

Abstract

During 2005 detectors based on pCVD material have been produced which are candidates for use in LHC experiments. The first full size diamond pixel module with full Atlas specifications was built using a 2×6 cm^2 pCVD sample and tests were carried out during 2005 in a DESY test beam. Both ATLAS and CMS have tested and are planning to use diamond for their beam conditions monitoring systems. Construction of the BCM system for ATLAS began at the end of 2005. A similar device is under study for the CMS experiment. Single crystal CVD samples were produced and made available to RD42 institutes. Characterization of a number of samples has been carried out using the Transient Current and other techniques. In this report we present the progress and work done by the RD42 collaboration on the development of CVD diamond material for radiation detectors.

1 Introduction

Progress in experimental particle physics in the coming decade depends crucially upon the ability to carry out experiments in high radiation areas [1]. In order to perform these complex and expensive experiments new radiation hard technologies must be developed. Chemical Vapor Deposition (CVD) diamond has been discussed extensively as an alternate sensor material for use very close to the interaction region of the LHC where extreme radiation conditions exist.

Over the past year the RD42 collaboration continued to work on CVD diamond detectors for high luminosity experiments at the LHC. The Collaboration has grown with ITEP Moscow and the Josef Stefan Institute in Ljubljana joining the effort. This R&D effort is growing as first attempts from the LHC community try to understand the radiation environment at the upgraded LHC, the Super-LHC(SLHC), and its consequences for detector design and implementation. In SLHC scenarios the total expected fluence at radii of about 5 cm will exceed 10^{16}particles/cm^2. Many studies are now being performed to find solutions for detectors which have to operate in these radiation environments. For silicon detectors material engineering, device engineering and change of detector operational conditions are envisaged. Other materials, 4H-SiC, GaN, CZT, *etc.* are also being examined. So far it is found that at such high fluencies the operational conditions especially for silicon are extreme. The availability of a very radiation hard detector material and electronics will be of great importance in view of possible future luminosity upgrades for the LHC [1]. Thus there is considerable interest to continue investigations into CVD diamond material and optimization of CVD diamond for these radiation environments.

2 The RD42 2004 Research Program and Milestones

During the last year we have made great progress with diamond quality. Material with charge collection distance (ccd) of 300 μm has been grown in wafer sizes with very good reproducibility. Transforming this technology to specific requirements of the LHC is ongoing. The first ATLAS diamond pixel module (which uses diamond from such a wafer) was constructed with the same bump-bonding and electronics that the present ATLAS silicon pixel modules use. Atlas has, during the last year, completed the design of a Beam Conditioning Monitor (BCM) based on polycrystalline CVD (pCVD) diamonds. The first modules have been built and tested. The CMS experiment is also working on a BCM based on pCVD diamond material. Material studies of single-crystal CVD diamond (scCVD) samples have been carried out.

2.1 The LHCC Milestones

The RD42 project was approved by the LHCC for continuation (CERN/LHCC 2005-004 LHC 74) with the following objectives:

- to construct and test diamond pixel detector modules with ATLAS/CMS front-end electronics,
- to pursue the development of single crystal CVD (scCVD) diamond material,
- to test the radiation hardness of the highest quality pCVD and scCVD diamond and,
- to continue the development of systems for beam monitoring for the LHC.

2.2 Summary of Milestone Progress

New polycrystalline diamond material has recently become available, in the form of wafers, by our industrial partner, Element Six Ltd [2]. The collection distance of material from these wafers routinely exceeds 300 μm. Fig. 1 shows two such diamond wafers with as-grown collection distances of 315 μm and 310 μm respectively. During the year, some difficulties were encountered in the processing the samples at Element Six. In some cases, a loss of charge collection was observed after the final processing depending on the details of the processing technique. Element Six has addressed this problem and so far it has not re-appeared.

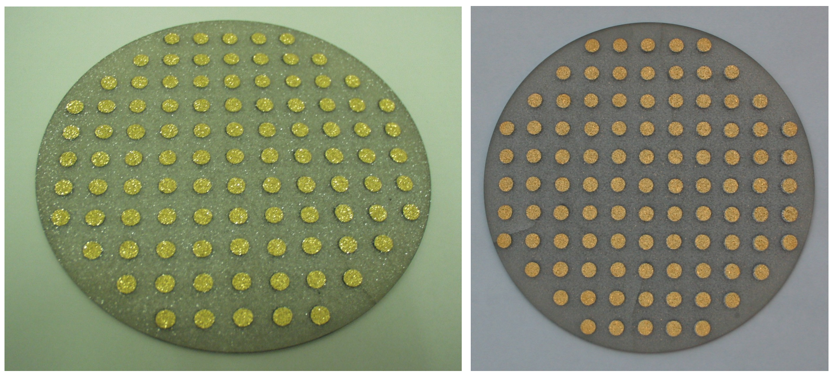

Figure 1: Photograph of the growth side of two full 12 cm wafers metalized with dots contacts 1cm apart for testing. The charge collected was measured at each dot on the wafer using a ^{90}Sr source in the laboratory. The largest collection distances on these wafers is 315 μm and 310 μm.

The production of high quality pCVD material has allowed RD42 to develop applications of diamond to high energy physics experiments. In collaboration with the groups developing front end electronics for both ATLAS and CMS, RD42 has constructed new pixel detectors. This past year we constructed the first full diamond ATLAS pixel module (~46,000 channels) using diamond from one of the wafers described above, with the final ATLAS IBM 0.25 micron rad-hard electronics, and tested it in the stand-alone ATLAS test beam at CERN. During this test we found that all 16 chips work, observed hits in over 90% of the pixels and mapped out the beam profile. Unfortunately the test was cut short before the complete module was tested. The module was then transported to DESY and tested in their 6 GeV electron beam. This module performed quite well with a noise of 136e, threshold of 1450e and efficiency of >97%.

Two years ago RD42 began a three year research program to develop single crystal CVD (scCVD) diamond. This type of CVD diamond has the potential to solve many if not all of the issues associated with pCVD material. This past year both the thickness and size of the scCVD diamonds was increased. The thickest part produced with full charge collection was 770 μm. The largest area part produced was just over 1.4cm^2. Material studies on the scCVD samples have been continued. On the first sample investigated with the TCT method we had found that this diamond had a positive space charge throughout the bulk, as reported last year. Many of the newer samples have been investigated in the same way and those samples did not exhibit any significant space charge. All samples again showed high low-field mobilities around 2300 cm^2/Vs, with holes always having higher mobilities than electrons. Charge collection showed saturation at electric field values above 0.4 V/μm. Carrier lifetimes in excess of the charge transit time through the whole thickness of the detector have been measured. This indicates that full charge collection is possible for detector thicknesses up to 800 μm operating at electric fields above 0.5 V/μm. Some interesting results from measurements with α sources show very promising spectroscopy performance of scCVD samples.

As part of the radiation hardness program, RD42 irradiated the highest quality pCVD and scCVD diamond. We have reached a fluence of 20×10^{15} p/cm^2 with pCVD diamond and 6×10^{15} p/cm^2 with scCVD diamond. After these fluences the diamonds were still working and tested in test beams.. We observed that after 20×10^{15} p/cm^2 the diamonds still function well with 25% of the un-irradiated charge. These studies will be repeated on additional samples and extended during the coming year as the CERN irradiation facilities become available.

RD42 together with BaBar, Belle, CDF, ATLAS, and CMS are developing diamond detectors to provide radiation monitoring and abort protection for the various experiments. BaBar has taken the lead here and installed two pCVD samples in the IR between the beam-pipe and silicon vertex detector. Belle has installed two equivalent devices, CDF has installed five devices and ATLAS and CMS have just completed radiation tests and beam tests of pCVD diamonds. As a result of these tests a proposal was presented to the ATLAS community to build a diamond Beam Conditioning Monitor (BCM) in the heart of the ATLAS detector for on-line monitoring of the circulating proton beams, to provide early signals of beam instabilities and give a beam abort message to the Main Control Room. Construction of this detector was approved and began at the end of 2005.

3 Progress on the Improvement of CVD Diamond

Over the last few years, we have worked closely with the Element Six [2] to achieve major improvements in the charge collection distance and uniformity of CVD diamond.

- CVD diamond produced from production reactors now regularly reaches 300 μm charge collection distance.

The pCVD diamond research recipes have been migrated to production reactors. Production wafer diamonds are now planned for use in various experiments. The measured collection distance and pulse height distribution, using a ^{90}Sr source, of a typical point on an as-grown wafer is shown in Fig. 2. To obtain this distribution we metalized the diamond with circular electrodes on each side. The mean charge is 11,340e and the most probable charge is $\approx$ 8000 e and 99 % of the distribution is above 4000 e. From the mean value, $\langle Q \rangle$, of the signal spectrum one derives the charge collection distance

$$\bar{d} = \frac{\langle Q \rangle \ \ [e]}{36 \ e/\mu\mathrm{m}} \tag{1}$$

where 36 e/μm is the mean number of electron-hole pairs generated by a minimum ionizing particle along 1 μm in diamond. The mean charge of 11340 e corresponds to a charge collection distance of 315 μm.

Fig. 3 shows a photograph of a sample from a recent 12 cm wafer produced in a production reactor. The sample has not been processed after production. Also shown is a micrograph from a small region of this sample indicating the as-grown surface morphology.

In Fig. 4 the leakage current versus electric field is shown for a sample, which had the standard mechanical surface processing before contacts were applied. The contacts on both sides were dots with guard rings around them. The leakage current is of the order of tenth of a pA up to $\pm$1.5V/μm and nearly symmetric for positive and negative voltages.

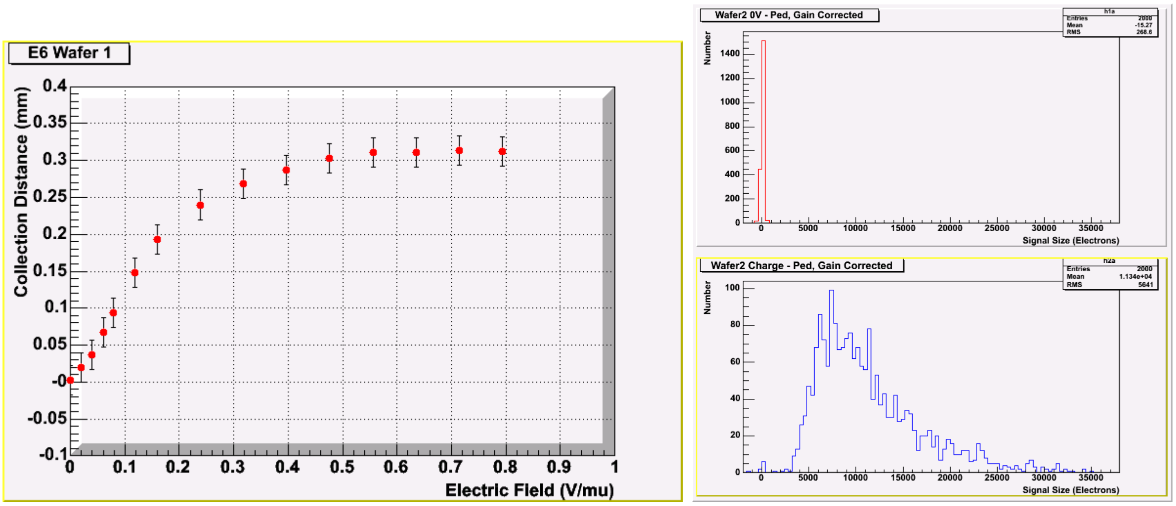

Figure 2: (a) Charge collection distance as a function of electric field and (b) Landau distribution measured with a ^{90}Sr source in the laboratory. The histogram is taken for each scintillator trigger. The upper histogram is the observed pulse height with 0V applied to the diamond. The lower histogram is the observed pulse height at an electric field of 0.7V/μm.

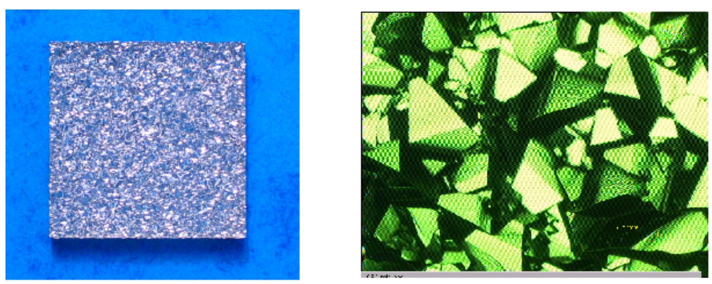

Figure 3: Photograph of an unprocessed sample cut from a 12 cm diamond wafer and micrograph of the surface morphology.

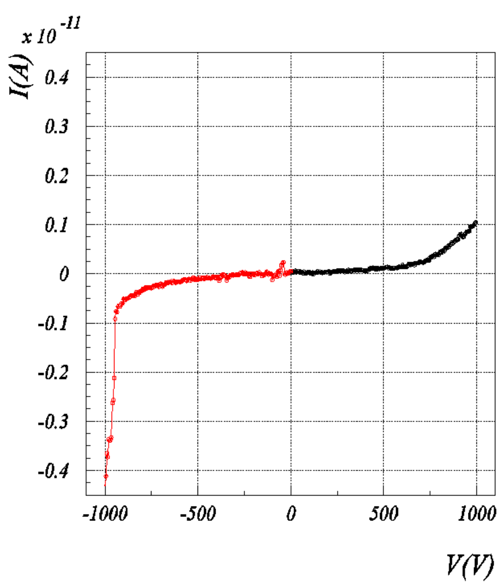

Figure 4: I-V curve for a surface processed pCVD sample.

4 Progress with scCVD Diamond

In late fall 2002 we received the first single crystal diamonds grown by a chemical vapor deposition process [3]. The samples they produced were synthesized with a microwave plasma-assisted CVD reactor using a specially prepared $\langle 100 \rangle$ oriented single crystal synthetic diamond substrate. The RD42 group has entered into a three year research contract with Element Six to develop this material.

In the framework of the on-going research contract with Element Six to develop high electronic quality scCVD diamond samples with sizes exceeding 1cm^2 many more samples have become available in several RD42 institutes. Single-crystal CVD samples can be grown at present to sizes up to and exceeding 1 cm^2. In Fig. 5 a photograph of a typical sample is shown.

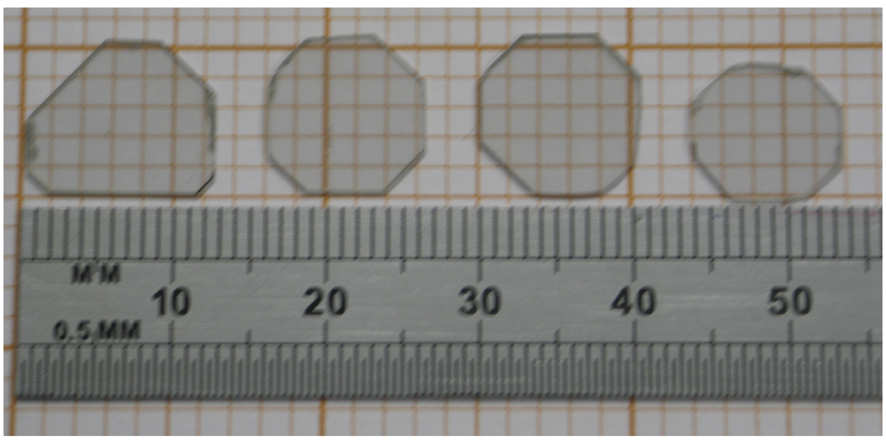

Figure 5: Photograph of four scCVD samples from the research contract.

In Fig. 6 we show the pulse height spectrum observed from four single crystal CVD diamonds. The diamonds are 210, 330, 435, and 685 μm thick. We observe collection distances consistent with full charge collection; most probable charges of 5,500e, 9,500e, 13,400e and 21000e; FWHM's of 3000e, 3000e, 4000e, and 47000e; and more than 4,000e, 7,000e, 10,000e and 15,000e separation between the pedestal and the beginning of the charge distribution. The cutoff on the lower side of the Landau distribution occurs at about 75% of the charge at the Landau peak, which is more favorable than in silicon. The FWHM/MP for these single crystal CVD diamonds is approximately 0.3-0.5, about one third that of polycrystalline CVD diamond and about two thirds that of correspondingly thick silicon.

In Fig. 7 we show the most probable charge for scCVD diamond versus thickness of the material. A clear linear relationship is evident out to thicknesses of 770 μm. In order to understand the basic properties of this new material we began a program to measure the carrier lifetime and mobility by observing the transient current pulse when a particle penetrates a diamond and stops near the entrance electrode. The α particles only penetrate about 14 μm into the diamond bulk before they deposit all their energy. A fast current amplifier (rise time below 1 ns) is used to record the current pulses. Depending on the polarity of the electric field current pulses from holes or electrons are recorded separately, since the respective other charge carrier is instantly absorbed on the close electrode. The parameters we are able to extract from the data include transit time, velocity, lifetime, space charge independently for electrons and holes. Our first results [4] shown last year indicate that the carrier lifetimes in scCVD diamond are of the order of 35ns and that this particular

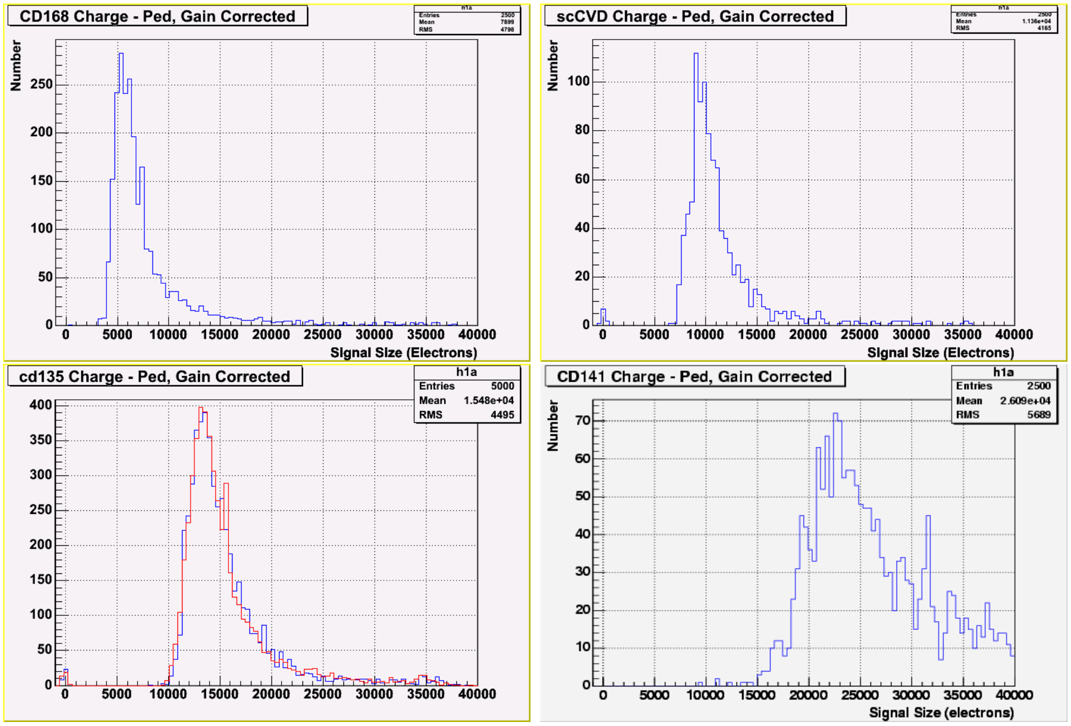

Figure 6: The pulse height distribution of various scCVD diamonds. The thicknesses of the diamonds are, from top left to to bottom right 210, 330, 435, 685 μm. When there are two curves they are the results for positive and negative applied voltage.

diamond has a positive space charge in the bulk of the material.

These measurements were repeated on several samples in 2005 with obtained from Element Six. In Fig. 8 we show the current pulses created by alpha particles injected on one surface of the scCVD diamond 480 μm thick as a function of time. This data allows the extraction of low field mobility and lifetime of charge carriers. Fig. 9 shows measured drift velocities and extracted mobilities for the sample with space charge measured previously and a new sample under study. The data from both samples is similar. It can be observed that the saturation velocities in both samples are about one order of magnitude higher than drift velocities at normal operation conditions. From this data we have extracted values for electron and hole carrier lifetimes. The lifetimes calculated are significantly longer than the transit times of the charge carriers throughout the thickness of the detector in both samples. This means that scCVD diamonds have full charge collection. The effective mobilities at normal operating conditions for both samples are on the order of 1000 cm^2/Vs for electrons and about 1250 cm^2/Vs for holes. Thus the carrier mobilities of both charge carriers in CVD diamond are very high, which is a substantial advantage over silicon for certain applications where very fast signals are required.

Results such as this should help in our understanding of the CVD process and in the manufacturing of still better material. Based on our test results, this new material seems extraordinary: single-crystal CVD diamond may resolve many if not all of the issues associated with polycrystalline material. We are looking forward to measuring more samples of this material as the research contract proceeds.

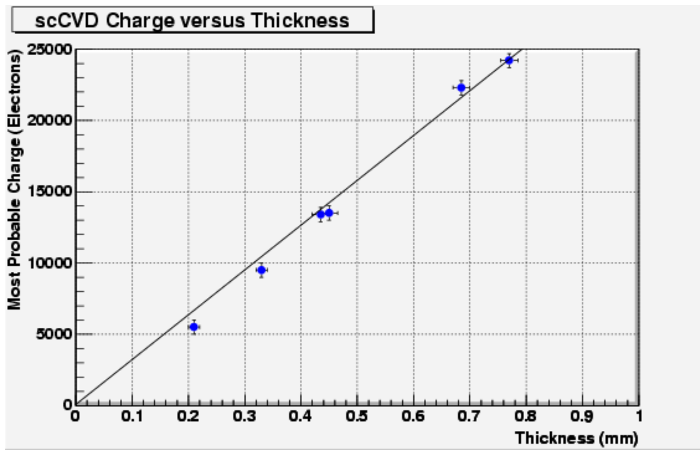

Figure 7: The most probable pulse height versus thickness for scCVD diamonds.

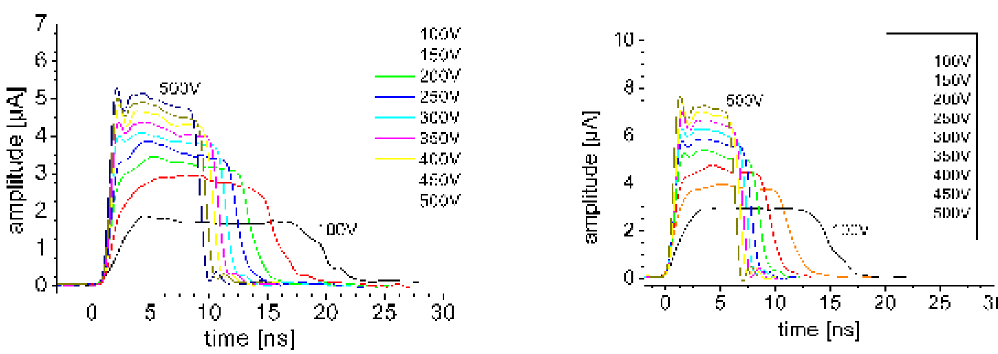

Figure 8: The observed current pulses created by alpha particles injected on one surface of the sCVD diamond as a function of time.

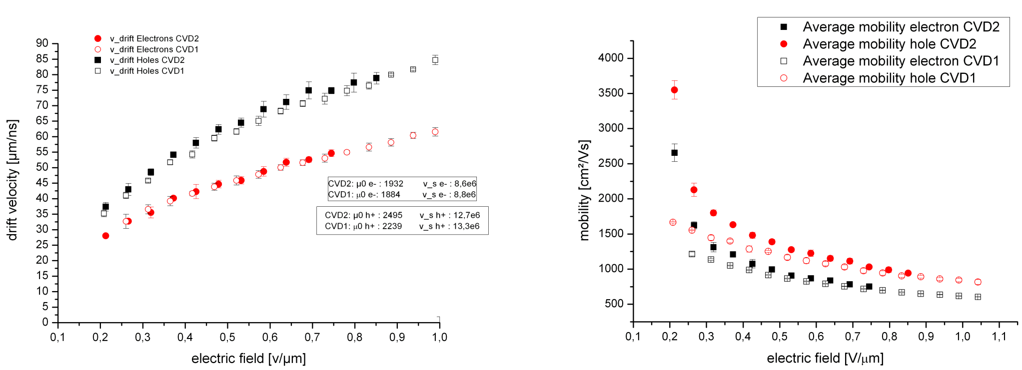

Figure 9: The observed drift velocities and extracted mobilities of sCVD diamond samples.

5 ATLAS Pixel Module

The production of high quality polycrystalline CVD material [2] with charge collection distance larger than 250μm allowed us to develop applications of diamond to high energy physics experiments. In collaboration with the groups developing front end electronics for ATLAS and the Fraunhofer Institute for Reliability and Microintegration (IZM) [5] for bump-bonding we constructed a range of diamond pixel detectors. Using the procedures developed for ATLAS, tests performed on 1cm^2 diamond pixel detectors based on older diamond samples showed resolutions with a 1cm^2 ATLAS pixel detector of 12μm in the x-view (where the pixels have 50μm pitch) and a characteristic 'top-hat' distribution in y where the pixels are 400μm long. The efficiency for finding hits in this pixel detector that correspond to tracks reconstructed in the reference telescope was above 98%. Encouraged by the success of the 1cm^2 pixel detectors and the availability of the new high collection distance diamond we decided to try to produce a full 2cm $\times$ 6cm diamond ATLAS pixel module. This past year, using high quality diamond, we constructed the first full diamond ATLAS pixel module, bump-bonded it to the final ATLAS IBM 0.25μm rad-hard electronics, and tested the assembly at CERN and DESY.

In the normal production of an ATLAS module, a silicon wafer is laser cut after bump-bonding. However, laser cutting a diamond wafer after bump-bonding graphitizes the surface. Thus we decided to first remove the 2cm $\times$ 6cm diamond part from the wafer, perform the photolithography and then install the diamond in a carrier for bump-bonding. In Fig. 10 we show the diamond after photolithography has been performed mounted in the carrier wafer ready for bump-bonding. We also show a close-up view of the metal pixel pattern on the diamond after the under-bump metal has been applied.

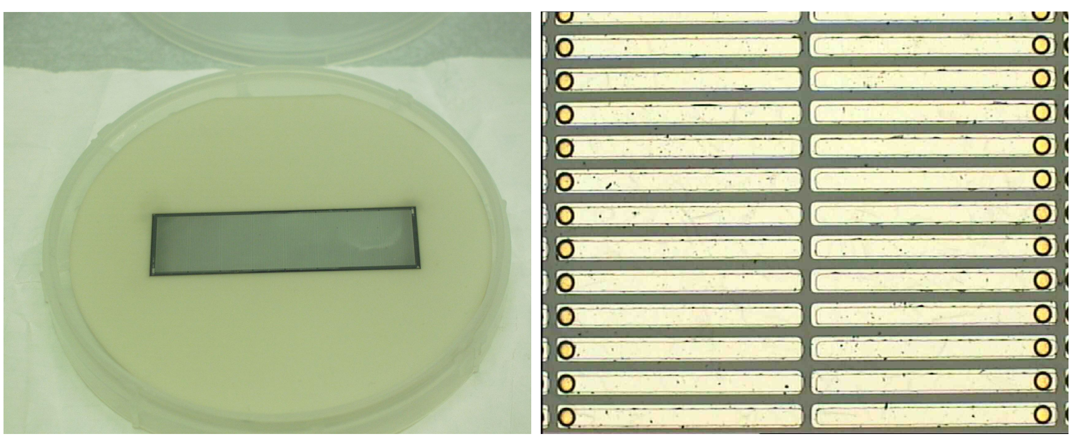

Figure 10: (a)Photograph of the ATLAS pixel diamond mounted in the carrier ready for bump bonding. (b)Zoom view of the pixel pattern after the under-bump metal is deposited.

In Fig. 11 we show the final diamond pixel module with 16 pixel integrated circuit readout chips ready for external cables and testing. This module was tested at CERN using the ATLAS telescope for external tracking. However there were complications during this test and the diamond pixel module only received a small amount of beam time and then was removed, while the module was still working perfectly well.

During that data taking period the beam was not centered in the ATLAS beam telescope yielding very poor tracking results. Even with these hardships we were able to obtain an image of the beam in the ATLAS diamond pixel module. In Fig. 12 we show the hit map in

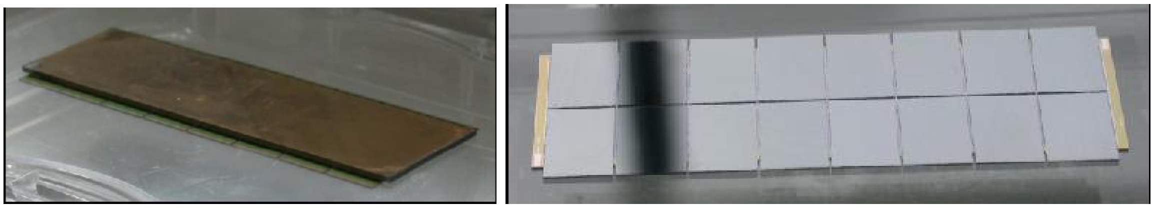

Figure 11: Photograph of the detector side (a) and electronics side (b) of the final ATLAS pixel module

the diamond pixel module for events which triggered the pixel module. A clear beam image is evident indicating that all 16 chips work and that a substantial fraction of the detector was operating as expected. The missing stripe in the CERN data is in the ganged pixel region where tracking information is required to unravel the pixel ambiguity introduced by the ganging of multiple pixels to a single electronics channel. During this test the tracking telescope was misaligned and no tracking information was available. In this plot ambiguous hits are not displayed. To continue these tests the diamond module and ATLAS telescope were moved to DESY.

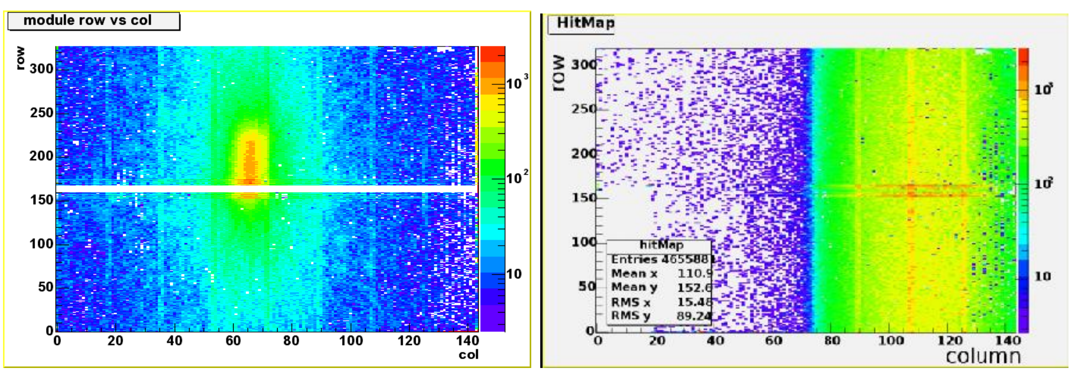

Figure 12: ATLAS pixel module hitmaps in the 180 GeV pion beam at CERN (a) and the 4-6 GeV electron beam at DESY (b). At DESY, with telescope tracking, one observes the edge of the scintillator trigger and that the ganged pixel region has been resolved.

Fig. 13 shows the module noise and threshold obtained in the laboratory before moving to DESY. Fig. 14 and Fig. 15 show the tracking results obtained at DESY. Compared to a silicon module the diamond module exhibits smaller noise ($136e$), can be operated at lower threshold ($1450e$) and attains a similar efficiency (>97%). The spatial resolution observed is 23μm in the x-view where the pixels have 50μm pitch and a characteristic 'top-hat' distribution in y where the pixels are 400 and 600μm long. In the low energy 4-6 GeV beam at DESY the spatial resolution is dominated by multiple scattering. For example the silicon detectors in the telescope have an observed resolution of roughly 7μm per plane at CERN and 37μm per plane at DESY. It seems evident that this generation of pixel detectors using the newly available larger collection distance diamond are suitable for applications at the LHC.

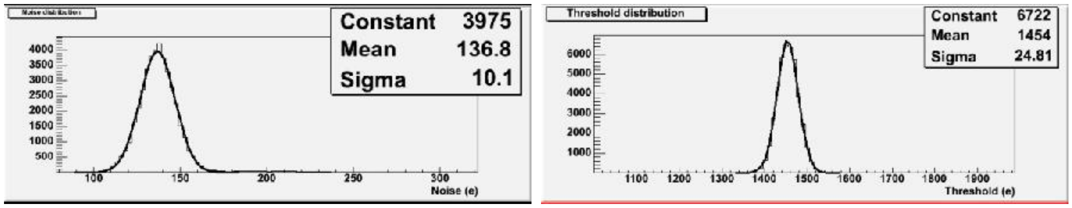

Figure 13: ATLAS pixel module results for noise and threshold at DESY.

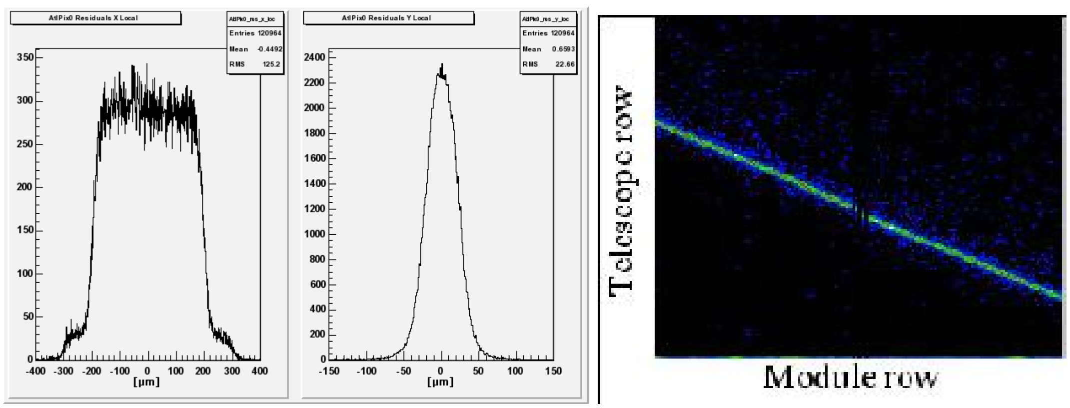

Figure 14: (a)Pixel module spatial resolution in the testbeam at DESY. The contribution from multiple scattering dominates the resolution and has not been unfolded. (b)ATLAS pixel module correlation with the tracking telescope.

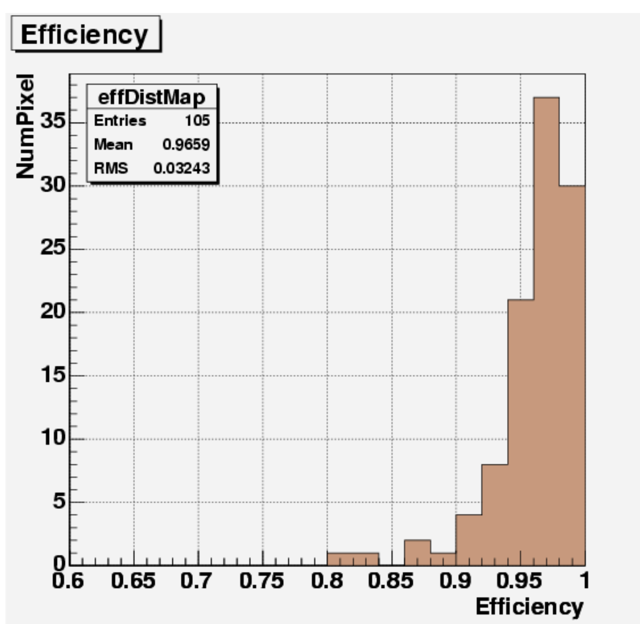

Figure 15: ATLAS pixel module preliminary efficiency.

6 Radiation Hardness

During the year 2005 the irradiation facility at the CERN PS was not in operation and thus no diamond sample irradiations could be carried out. For completeness the summary of results on radiation hardness of diamond samples which was shown previously is repeated here.

The results from previous irradiations [7], [8] show that up to 2.2×10^{15} p/cm^2 pCVD diamonds lose at most 15% of the most probable charge and improve their resolution by roughly 40%. In Fig. 16, we show the previous results for the collected charge from a poly-crystalline diamond strip detector after irradiation with a fluence of 24 GeV protons of 1×10^{15} p/cm^2 and after 2.2×10^{15} p/cm^2. While the strip contacts before and after irradiation with fluences of 1×10^{15} p/cm^2 were unchanged the contacts were replaced after a fluence of 2.2×10^{15} p/cm^2 and then characterized in the test beam. This step was necessary since the wire bond pads were only usable twice. At 1×10^{15} p/cm^2 we observe that the shape of the signal-to-noise distribution is narrower than before irradiation and entries in the tail of the distribution appear closer to the most probable signal. At 2.2×10^{15} p/cm^2 and after re-metalization we observe essentially the same signal-to-noise distribution (measured with a low noise VA chip amplifier) as at 1×10^{15} p/cm^2 indicating that very little further damage occurred to the diamond bulk. The most probable signal-to-noise was 41 before irradiation and 35 at 1×10^{15} p/cm^2 and also at 2.2×10^{15} p/cm^2. We find a reduction of maximum 15% in the most probable signal-to-noise after irradiation with 2.2×10^{15} p/cm^2. The noise was measured to remain constant at each beam test. Since the beam test with the detector irradiated with a fluence of 2.2×10^{15} p/cm^2 used new contacts the observed decrease of 15% is attributed to damage in the diamond bulk.

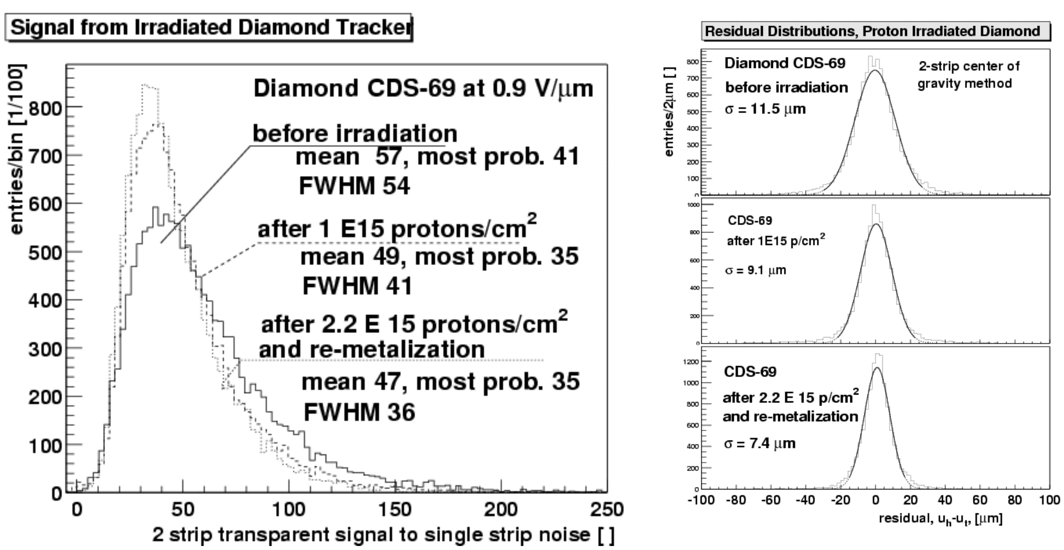

Figure 16: (a)Transparent 2-strip charge signal-to-noise distributions before (solid line), after proton irradiations with 1×10^{15} p/cm^2 (dashed line) and after 2.2×10^{15} p/cm^2 (dotted line). (b)Residual distributions before and after proton irradiation.

Fig. 16 also shows residual distributions before irradiation, after 1×10^{15} p/cm^2 and after 2.2×10^{15} p/cm^2. We observe that the spatial resolution improves from (11.5 ± 0.3) μm before irradiation to (9.1 ± 0.3) μm at 1×10^{15} p/cm^2 and to (7.4 ± 0.2) μm at 2.2×10^{15} p/cm^2. At present the explanation for this effect is that the irradiated material is more uniform in the sense that the probability of large landau fluctuations has been reduced by the irradiation. The spatial resolution of nearly 7μm with a detector of 50μm strip pitch is comparable to results obtained with silicon detectors.

The RD42 group has now extended these irradiations to fluences up to 20×10^{15} p/cm^2 for pCVD material. This figure corresponds to a dose of roughly 500Mrad. In Fig. 17 we show the pulse height distribution before and after the irradiation to 20×10^{15} p/cm^2. At this fluence the pCVD diamond retains 25% of its original pulse height.

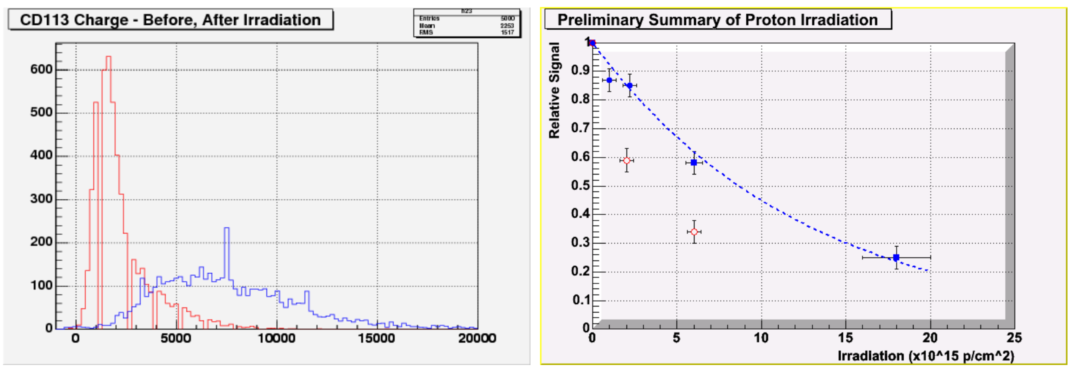

Figure 17: (a)Pulse height distributions before (blue curve) and after (red curve) the irradiation to 18×10^{15} p/cm^2. (b)Summary of proton irradiation results for pCVD material up to a fluence of 20×10^{15} p/cm^2 (filled data points). The blue curve is an exponential with exponent -0.08$\times$fluence. Also shown are the results of the irradiation of the first scCVD diamond (open data points).

In Fig. 17 we show a summary of the proton irradiation results described above. We find that all of the irradiations fall along an exponential curve. The diamond signal is down by 1/e at 12.5×10^{15} p/cm^2. In Fig. 17 we also show the results of the first irradiation of any scCVD diamond. Our preliminary data indicates that scCVD diamond is damaged more easily than pCVD material. These results are in the process of being checked.

7 Beam Monitors

Radiation monitoring plays a crucial role in any experiment which operates a high precision tracking system close to the interaction region. Experience has shown that to protect the inner tracking devices systems must be provided which can abort the beams on large current spikes. In addition, radiation monitoring allows for the measurement of the daily dose and integrated dose which the tracking systems receive and thus allow the prediction of device lifetimes, etc.

Presently BaBar and Belle use silicon PIN diodes for radiation monitoring inside of their silicon vertex detectors. After 100fb^{-1} the signal size for stable beams is approximately 10nA while the leakage current in the PIN diodes is approximately 2μA. Thus in these systems radiation monitoring is already becoming very difficult. Couple this with the fact that the PIN diodes must be temperature corrected continuously and one quickly finds that the radiation monitoring systems are a large effort to keep working. As a result both BaBar and Belle have installed diamond replacements for the silicon PIN diodes. The main advantages of CVD diamond over silicon for this application is its small leakage currents, radiation hardness and temperature independent operation.

Recently ATLAS, CMS and CDF have studied possible beam losses and their implication for the inner detectors. Such simulations have led groups being formed in each experiment to investigate diamond for their applications as well. For ATLAS, for example, an international working group has already designed and tested a nearly final system.

7.1 CDF Studies

5 abort is due to a smaller but longer lived increase in the dose During the Fall 2004 shutdown CDF installed one diamond to test as a radiation monitor. The CDF experiment has already had many beam incidents that have caused failures in its silicon detector. During the last year of data taking alone CDF reports it lost or damaged 2.5% of all SVXII chips due to beam incidents. As this is the closest environment to the LHC it was decided to install five diamond detectors to see how they perform.

In Fig. 18 we show the diamond response to the first beams at CDF. The beam monitoring in this case relies on the measurement of changes of the dc current of the diamond detector. In this application the very low leakage currents of diamonds even after strong irradiations is essential. One observes that the diamond current is very small (pA) with no beams in the Tevatron (before 19:54) and generally follows the structure of the proton beam. The diamond monitor should be more correlated with the anti-proton beam but that data was not available. The instantaneous peaks of the order of 65 nA are easy to follow. CDF estimates that their signal to noise is between 100:1 and 1000:1. They are so pleased with the operation of the diamond that they have asked RD42 for additional diamonds.

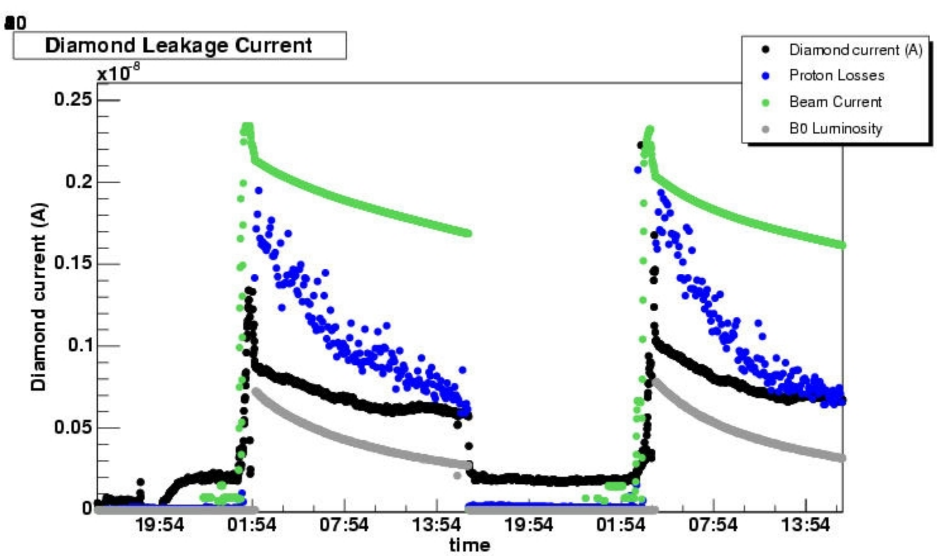

Figure 18: The operation of the CDF diamond beam monitor. The proton beam current is the upper trace (green); the measured proton beam loss is the second curve (blue); the diamond current is the third curve (black); the luminosity is the bottom curve (gray). One can see the turn on of the Tevatron at 19:54 and the residual beam current between fills.

In Fig. 19 we show the diamond during injection, p-bar transfers, ramping, scraping and colliding beams. One observes that the diamond sees each of these events with a very large signal to noise.

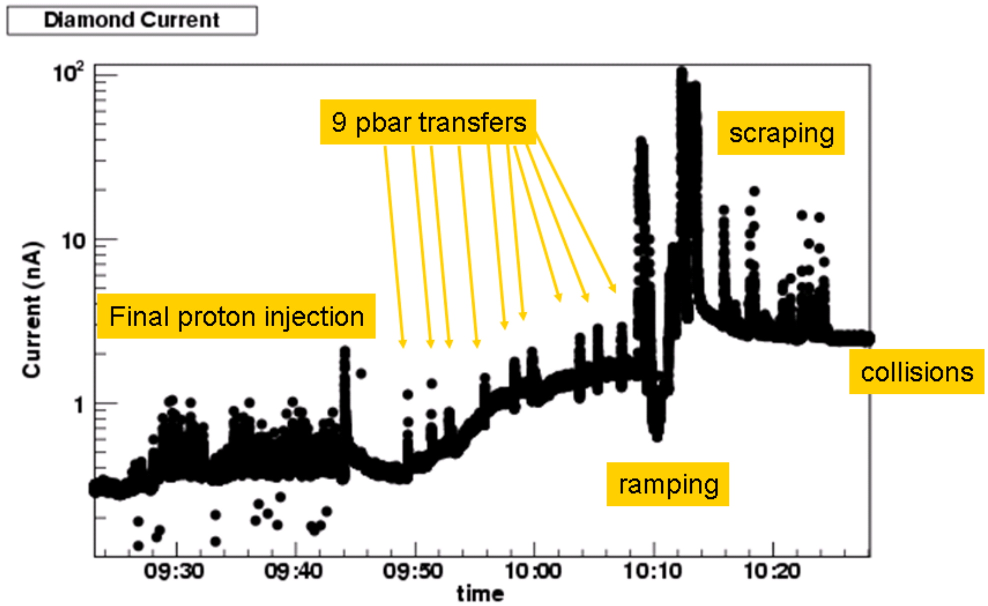

Figure 19: Operation of the CDF diamond beam monitor during a variety of beam conditions.

7.2 ATLAS/CMS Studies

ATLAS and CMS have a similar application to BaBar/Belle/CDF. Fig. 20 shows a photograph of one of the devices tested by ATLAS in a pion beam.

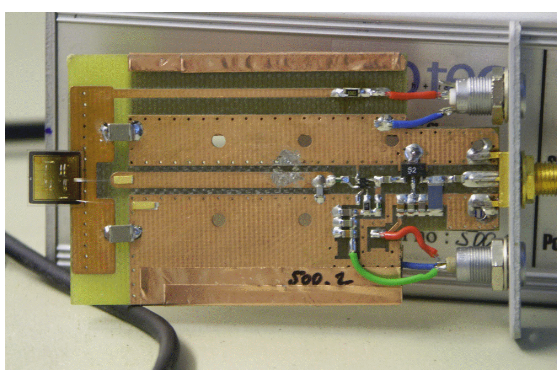

Figure 20: A photograph of the prototype devices tested by ATLAS in the pion beam.

In Fig. 21 we show the current signal observed for a single MIP (5 GeV/c pions) in an ATLAS BCM prototype module (see Fig. 20). The detector was read out through a 2-stage 500MHz current amplifier as envisaged for the BCM and a 16m long analog signal cable. The signal rises in under 1 ns and the average pulse width is 2.1ns

After these successful tests ATLAS has a schematic plan for its diamond Beam Conditions Monitoring system. The ATLAS experiment decided in 2005 to pursue a proposal to build

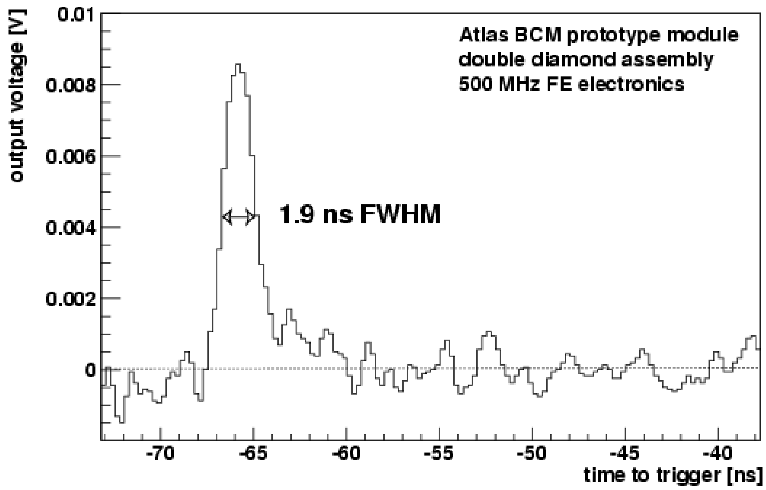

Figure 21: A scope trace of a MIP pulse observed in two diamond detectors in the ATLAS/CMS beam test.

a BCM detector, based on pCVD diamond sensors. The aim is to detect minimum ionizing particles with good signal over noise ratio and a time resolution of ∼1 ns. The choice of diamond sensors was motivated by the radiation hardness of diamonds, the high charge carrier velocity leading to very fast and short current signal, very narrow pulses due to short charge carrier lifetime and very low leakage currents even after extreme irradiations. No detector cooling is needed.

In Fig. 22 we show a schematic view of the ATLAS BCM plan where the diamond monitors are placed in modules on the forward disks of the pixel detector. A module consists of a box housing two pCVD diamonds of 1cm × 1cm area with square contacts 8mm × 8mm mounted back to back. The signals from two sensors are fed in parallel into one channel of very high bandwidth current amplifiers. The design of a module aims at a S/N ratio of ∼10:1 in order to detect with high efficiency minimum ionizing particles.

Two stations will be installed symmetrically around the interaction region with 4 BCM modules mounted on each station. The stations will be installed at z= ± 183.8 cm (corresponding to 12.5 ns travel time of particles coming from the beam crossing) and r = 7 cm and mounted on the pixel detector support structure. This structure will allow distinction between true bunch crossing interactions and beam interaction upstream and downstream of the interaction region in the beam pipe or in collimators by assigning very precisely a time stamp to each signal. Signals with relative time stamps of 0ns, 25ns, 50 ns *etc.* come from the interaction region whereas signals with a time stamp difference in station one and station two come from other interactions due to beam instabilities. This system will monitor the stability of the proton beams on a bunch to bunch timescale. A very fast beam abort signal can be generated by this detector. In addition being positioned at a pseudo-rapidity of ∼4, this detector can also be used to measure the instant luminosity in the LHC in addition to the ATLAS main luminosity detector LUCID. The system of 10 modules is now being constructed. Fig. 22 shows a finished module. The full system should be installed in the Fall 2006.

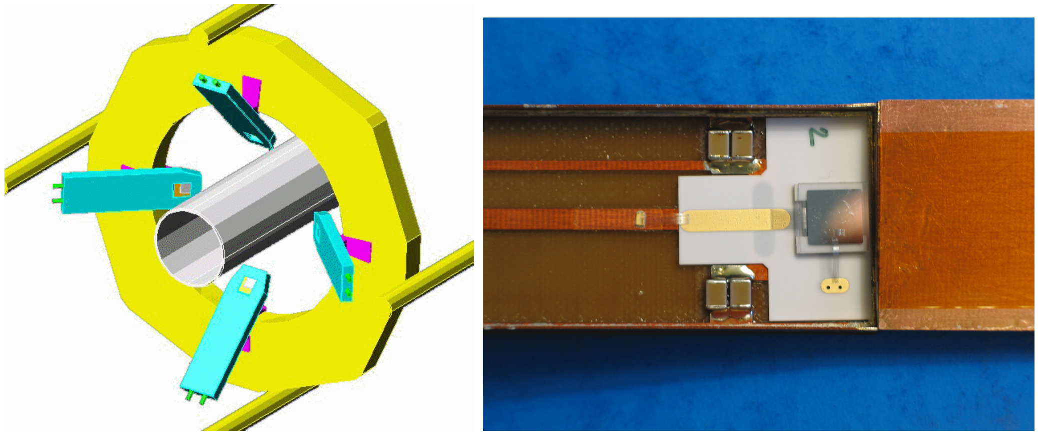

Figure 22: (a)A schematic view of the ATLAS BCM system. (b)A photograph of the final module used by ATLAS for its BCM system.

8 Proposed Research Program for 2006

The overall goal of the RD42 research program is to develop electronic grade CVD diamond and to demonstrate the usefulness and performance of CVD diamond as a radiation sensor material capable of detecting minimum ionizing particles in extremely high radiation environments. In order to achieve this goal the following main program steps had to be performed:

- Characterization of the electrical performance of specific CVD diamond samples grown by Element Six and continuous feed back of results to the manufacturer.
- Irradiation of samples up to fluences of 20×10^{15} particles/cm^2.
- Material science studies on these CVD diamond samples for defect characterization.
- Test of CVD diamond tracking devices with tailor made radiation hard front-end electronics for strip detectors and pixel detectors, including beam tests.

A large part of this program has been successfully achieved over the last years. There are however a number of important and decisive measurements still to be performed in this research program.

- A systematic study of pCVD samples from the latest production runs from as "grown" to "fully processed". Details of the processing after growth, both done at Element Six and RD42 institutes, have still to be investigated in detail.
- A complete irradiation program for scCVD material and further irradiation studies with pCVD material have to be performed. Of particular importance are irradiations with protons up to and beyond 10^{16} protons/cm^2 and with pions to the highest possible fluencies.
- Continued material characterization of pCVD and scCVD samples and extended material science studies including TCT measurements. Material science studies have been pursued in a number of RD42 institutes. This will be very important in producing reliably high quality CVD diamond radiation sensors.

- Beam tests with new tracking devices; double-sided strips and pixel modules.
- Collaboration on future applications like FP420 proposition.

In summary, RD42 proposes to concentrate its efforts in 2005 to the following topics

- Pixel detectors, using the top quality CVD material available: construction of a second pixel module with rad hard contacts and reliable, efficient bump bonding, test of modules with the latest radiation hard ATLAS and CMS front-end chips, and test these modules at CERN. Transfer the technology for constructing a diamond module to industry.
- Test of CVD diamond tracking devices with tailor made radiation hard front-end electronics for single-sided and double-sided strip detectors and pixel detectors, including beam tests.
- Characterization of the new, highest quality scCVD diamond material produced by Element Six under the research contract including a systematic study of pCVD samples from as-grown to fully processed. Material science studies on these pCVD and scCVD diamond samples for defect characterization.
- Irradiation of pCVD and scCVD samples up to fluences of 20×10^{15} particles/cm^2 with protons, neutrons and pion beams using the highest quality diamond material.
- Tests of beam monitors for use in BaBar, Belle, ATLAS and CMS.

9 Funding and Requests for 2006

As a result of the ongoing progress the RD42 project is supported by many national agencies and the total anticipated funding from sources outside CERN in 2005 is foreseen to be 250 kCHF. The majority of this funding is now through our North America colleagues who are funding the ongoing scCVD Research Program with Element Six. One reason why our collaborating institutes obtain national funding is that the RD42 project is officially recognized by CERN within the LHC R&D program. Official recognition of RD42 by CERN with the LHC R&D program has helped in the past to obtain funding from national agencies. For the continuation of the RD42 program as described in section 8 we request 25 kCHF of direct funds from CERN and that the LHCC officially approve the continuation of the program. This is essential to ensure future funding from national agencies. Furthermore a continuation of the RD42 program will be the basis of future diamond sensor development in the framework of R&D for future very high luminosity upgrades of the LHC, which is at present implemented [1]. It is foreseen that a minimal infra-structure for sample characterization and test preparation is maintained at CERN. The facility will be mainly used by external RD42 collaborators specifically ATLAS and CMS. We therefore request

- Maintain the present 20 m^2 of laboratory space in Bat.161 for test setups, detector preparation and electronics development.
- Maintain the present minimal office space for full time residents and visiting members of our collaboration.
- Three SPS test beam periods in 2006.
- Several irradiations in PS beam facility in 2006.

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