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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 2007 RD42 continued making progress in diamond detector technology. Polycrystalline and single-crystal chemical vapor deposition (pCVD and scCVD) diamond detectors were constructed, irradiated and tested at CERN. Beam test results of irradiated diamond showed that both pCVD and scCVD diamond follow a single damage curve allowing one to extrapolate their performance as a function of dose. Two pixel modules were irradiated as integrated devices (electronics and diamond) and function quite well with >99% efficiency after 1×10^{15} p/cm^2. The pCVD diamond based ATLAS Beam Condition Monitor system was installed in 2007 and diamond Beam Loss Monitor systems were constructed for ATLAS and CMS. Two additional diamond manufacturers have been contacted and have supplied samples which are being characterized. The ATLAS experiment approved the diamond Inner Detector LHC upgrade R&D proposal. 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

With the commissioning of the LHC expected in 2008, and the LHC upgrades expected in 2012, ATLAS and CMS are planning for detector upgrades which require radiation hard technologies. Chemical Vapor Deposition (CVD) diamond has been used extensively in beam conditions monitors as the innermost detectors in the highest radiation areas of BaBar, Belle and CDF and is now planned for all LHC experiments. This material is now being discussed as an alternate sensor material for use very close to the interaction region of the super LHC where the most extreme radiation conditions will exist [1].

Over the past year the RD42 collaboration continued to work on CVD diamond detectors for high luminosity experiments at the LHC. The RD42 collaboration has grown with the University of Bristol joining the effort. This R&D effort is growing as the LHC community tries 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. The availability of a very radiation hard detector material and electronics will be of great importance in view of the now planned luminosity upgrades for the LHC [1]. The ATLAS experiment, for example, recently approved the diamond Inner Detector R&D Upgrade project entitled *Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade* for just this reason. Thus there is considerable interest to continue investigations into CVD diamond material and optimization of CVD diamond for these radiation environments.

2 The RD42 2007 Research Program and Milestones

During the last year we have made great progress with the production of high quality diamond material. Two new polycrystalline diamond wafers, from our industrial partner, Element Six Ltd [2] were characterized. Fig. 1 shows a photograph of the two diamond wafers tested.

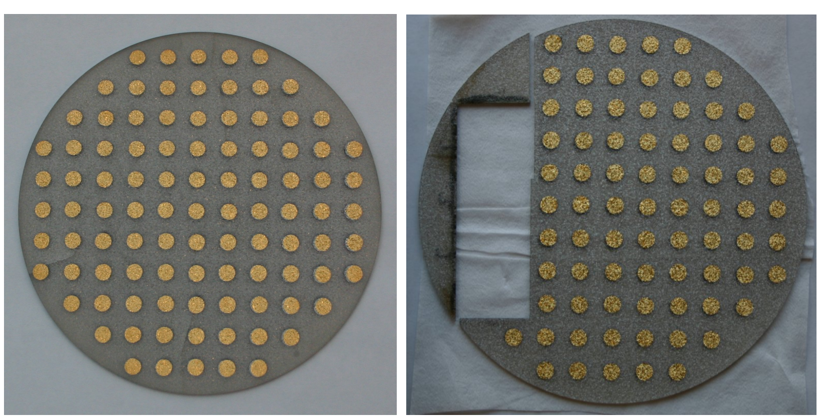

Figure 1: Photograph of the growth side of two full 12 cm wafers metalized with dot contacts 1cm apart for testing. The charge collected was measured at each dot on the wafer using a ^{90}Sr source in the laboratory. The largest collection distances on these wafers is 308 μm and 292 μm respectively.

Fig 2 shows the collection distances of these wafers as a function of position on the wafer indicating good consistent quality. The two wafers of material show charge collection distances (ccd) of $\sim 300\ \mu$m measured at an electric field of 0.66 V/μm indicating very good reproducibility. The usual operating electric field is 1 V/μm so these measurements indicate a lower limit to the actual collection distance. Transforming this technology to specific requirements of the LHC is ongoing.

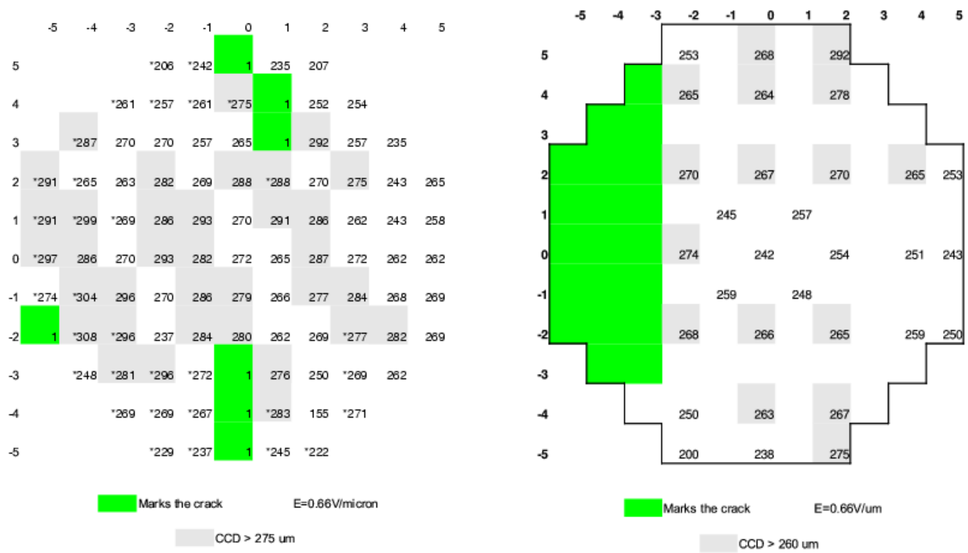

Figure 2: Charge collection distance measurements of the two 12 cm wafers in Fig. 1 measured at an electric field of 0.66 V/μm. The largest collection distances at this electric field on these wafers is 308 μm and 292 μm respectively. The usual operating electric field is 1 V/μm so these measurements indicate a lower limit to the actual collection distance.

The radiation hardness studies of polycrystalline and single-crystal CVD diamond strip detectors were extended. In addition, the first full ATLAS diamond pixel module (which uses high quality diamond and 16 FE-I3 integrated circuits) was irradiated as a unit and tested in the high energy proton beam at CERN and a single-crystal ATLAS diamond pixel module was also irradiated and tested in the proton beam at CERN. The result of these tests is that a single damage curve for diamond material was observed and can now be used to predict the effect of irradiation of diamond to almost any dose. As part of the program to find new diamond manufacturers two companies were identified as possible suppliers. Initial material from each company has been tested. The results indicate that the new manufacturers are not at the state-of-the-art yet but are getting close. ATLAS has, during the last year, completed the construction of their Beam Condition Monitor (BCM) based on polycrystalline CVD (pCVD) diamond. The full ATLAS BCM system is now installed. In order to provide some redundancy for the ATLAS BCM system, during the last year the ATLAS Beam Loss Monitor (BLM) system, also based on pCVD diamond, was designed and constructed. This system is presently being installed. The ALICE, CMS and LHCb experiments are also constructing BCM systems based on pCVD diamond material. Based on these successes the ATLAS experiment approved the Inner Detector R&D Upgrade project entitled *Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade* which is based on pCVD diamond.

2.1 The LHCC Milestones

The RD42 project was approved by the LHCC for continuation (CERN/LHCC 2007-019 LHC 88) with the following objectives:

- to test the radiation hardness of the highest quality pCVD and scCVD diamond,
- to pursue the development of pCVD and scCVD diamond material and develop additional suppliers for such material,
- to construct and test diamond pixel detector modules with ATLAS/CMS front-end electronics and
- to continue the development of systems for beam monitoring for the LHC.

3 Radiation Hardness

In order to obtain the most reliable irradiation results the RD42 irradiation program consists of testing each sample prepared as a strip detector in a CERN test beam before and after irradiation of the samples. During the last year RD42 performed three irradiations of diamond samples and correspondingly three test beams. Fig. 3 shows a photograph of four samples prepared as strip detectors and read-out with VA-2 electronics for characterization in the test-beam at CERN. Both pCVD and scCVD samples were prepared in this manner.

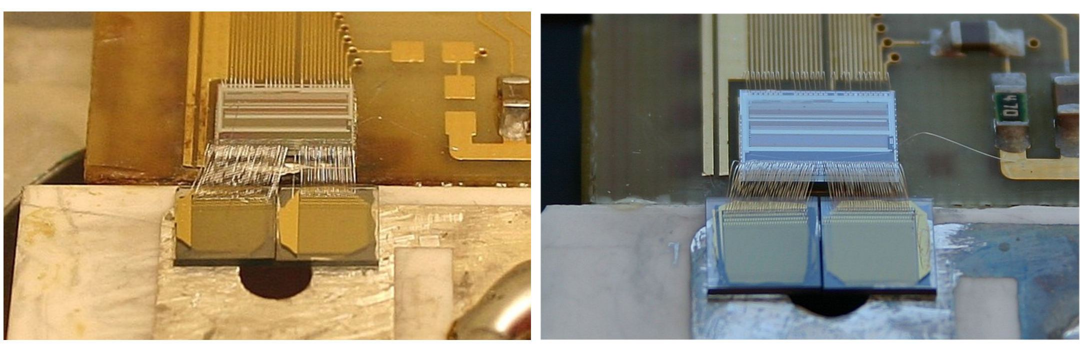

Figure 3: Photographs of the four samples characterized in the 120 GeV pion beam at CERN in Fall 2007.

Fig. 4 shows the results of the pulse height spectrum for a recent pCVD diamond after 1.4×10^{15} p/cm^2. A clear Landau distribution is observed in the data with the mean observed charge of 7300e and a most probable charge of 6000e. To set the scale, for use at the LHC as a pixel detector with ATLAS FE-I3 electronics it is estimated that a minimum charge of 2200e (1400e threshold plus 800e overdrive) corresponds to an efficiency of >99%. Fig. 5 shows the results of the pulse height spectrum for a recent scCVD diamond before and after 1.5×10^{15} p/cm^2. Clear Landau distributions are observed in the data with the mean ADC counts of 1393 before irradiation and 837 after irradiation.

This data has been added to the previous irradiation data to summarize the RD42 proton irradiation results. In order to estimate the radiation effects on the collection distance we have compared the collection distances for pCVD and scCVD samples before and after irradiation. The scCVD diamond is expected to be representative of the next generation high quality

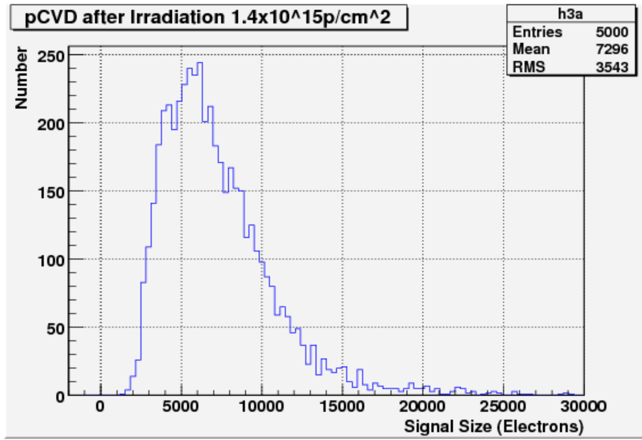

Figure 4: The pulse height spectrum from an irradiated pCVD strip detector after 1.4×10^{15}p/cm^2. A clear Landau distribution of pulse heights is observed.

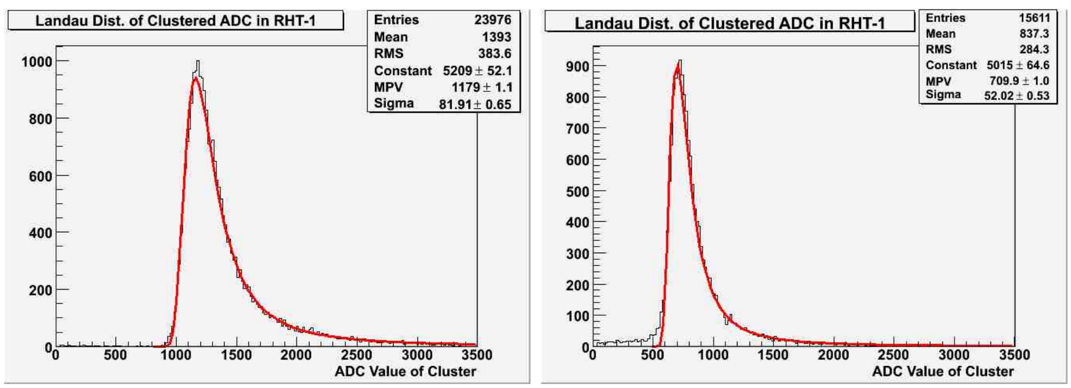

Figure 5: The pulse height spectrum from an irradiated scCVD strip detector before and after 1.5×10^{15} p/cm^2. Clear Landau distributions are observed.

polycrystalline material. By comparing the effective damage constants for the two different materials we can definitively find the relation between the two. In Fig. 6 we overlay the collection distance measurements of pCVD and scCVD samples before and after irradiation so that 0 on the x-axis corresponds to the un-irradiated collection distance of our pCVD material. In addition the scCVD fluences are shifted by -3.8$\times$ 10^{15} p/cm^2. In effect the scCVD material starts with a signal advantage that corresponds to a fluence of about 4×10^{15}. Another way of thinking of this is that our un-irradiated pCVD material has that same number of trapping centres as the scCVD material after a dose of 4×10^{15} p/cm^2.

Fig. 6 shows that all of the irradiations fall along a single damage curve given by the equation $1/\text{ccd} = 1/\text{ccd}_0 + k\phi$ where $1/\text{ccd}_0$ is the initial collection distance and k, the damage constant is independent of the initial collection distance. The diamonds measured by RD42 have shown damage consistent with a k of $\sim10^{-18}$. This result now includes scCVD samples that have initial collection distances in excess of 400 microns. We don't expect the higher quality pCVD material to be any different. The data indicate a single damage constant k for both materials indicating that the next generation of material should follow similar curve.

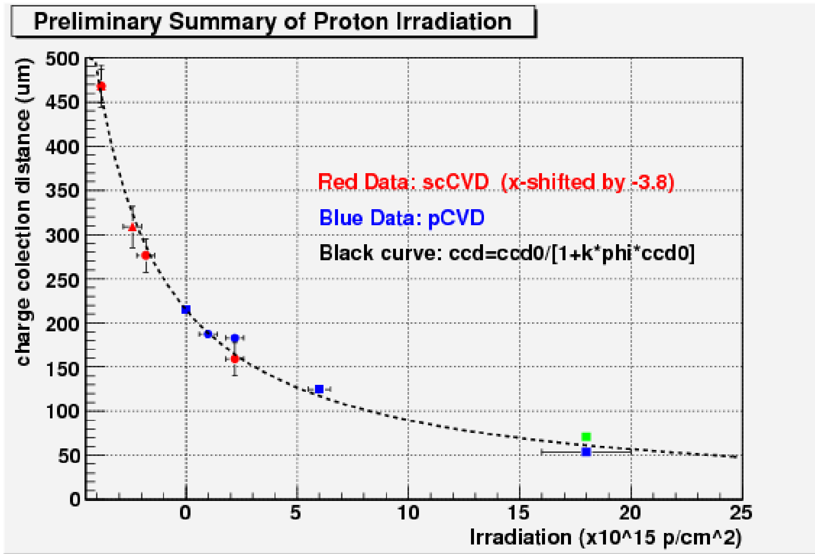

Figure 6: Summary of proton irradiation results for pCVD (blue points) and scCVD (red points) material at an electric field of 1 V/μm and 2 V/μm (solid green square point) to a fluence of 18×10^{15} p/cm^2. The black curve is a standard damage curve $1/\text{ccd} = 1/\text{ccd}_0 + \text{k}\phi$. The scCVD data has been shifted to the left by a fluence of 3.8×10^{15}. With this shift the pCVD and scCVD data fall on a single curve indicating the damage due to irradiation is common to both.

The Karlsruhe group of RD42 has continued it's theoretical analysis to see if the NIEL hypothesis works for diamond material. The work used the package SRIM (Stopping and Range of Ions in Matter) for Coulomb scattering together with an add-on package to calculate nuclear interactions and fragment energy spectrum. The results of this study indicate that at high energy radiation damage is dominated by the inelastic cross section while at low energy the radiation damage is dominated by the elastic cross section. Since silicon irradiation results fall on the silicon total cross section curve we conclude that in all cases we expect diamond to be more radiation hard than silicon.

As indicated in Sec. 5 the diamond pixel module, due to its low capacitance and low leakage current operates at a lower noise level than a comparable silicon detector. We can compare the noise in one of the diamond pixel modules with that of a standard silicon pixel module or a 3D silicon pixel module all operating with the same electronics. We find the noise levels are 140e for diamond, 180e for silicon and 220-310e for 3D silicon depending on the geometry. In Fig. 7 we show the expected signal to noise as a function fluence for diamond pixels. The signal data for the diamond is taken from this report from irradiated diamonds. We expect to observe a S/N $\sim$15 after 1.8×10^{16} p/cm^{-2}.

4 Progress on the Improvement of CVD Diamond Material

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. The pCVD diamond research recipes have been migrated to production reactors and the material is very reproducible. Production wafer diamonds are now planned for use in every LHC experiment. The measured collection distance and pulse height distribution, using a ^{90}Sr

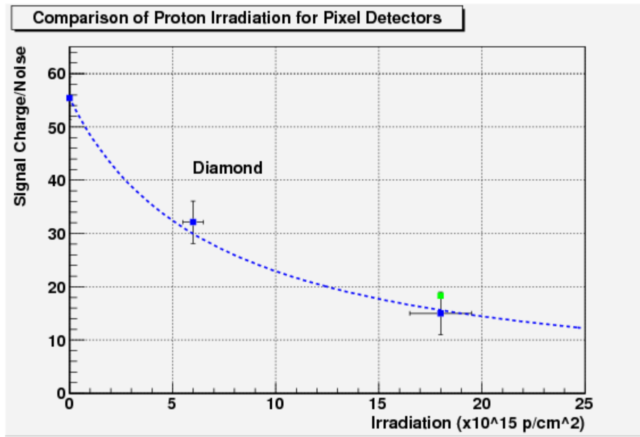

Figure 7: The expected Signal-to-Noise for irradiated diamond pixel modules.

source, of a typical point on an as-grown wafer is shown in Fig. 8. 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 $\approx$ 8000e and 99% of the distribution is above 4000e. 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 1μm in diamond. The mean charge of 11340e corresponds to a charge collection distance of 315 μm.

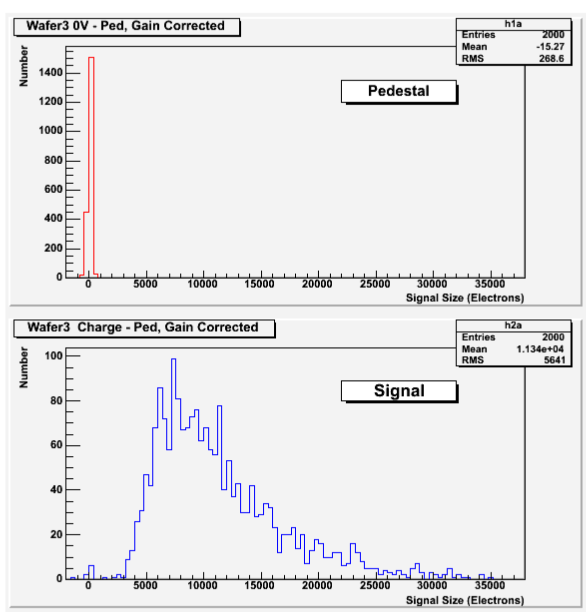

Figure 8: The Landau distribution obtained from the latest wafer measured with a ^{90}Sr source in the laboratory. The histogram shown is taken using every scintillator trigger. The upper histogram is the observed pulse height with 0V applied to the diamond. The lower histogram is the observed pulse height at an electric field of 0.66V/μm.

Element Six is apparently pleased enough with these results that they have spun-off a company, Diamond Detector Ltd., to market diamond detector material. A summary of where our work stands with Element Six/Diamond Detector Ltd is given below

- pCVD diamond is produced in production reactors in 12 cm wafers.
- pCVD diamond wafers now regularly reaches 250-300 μm charge collection distance.
- scCVD diamond has been produced in production reactors in sizes $\sim$ 1 cm^2.
- scCVD diamond produced from production reactors now regularly reaches full charge collection without any observable space charge.
- Diamond Detector Ltd. has been created to market detector grade diamond.

Recently two additional diamond manufacturers have contacted RD42 with the purpose of having RD42 characterize their diamond material to help them develop high-quality detector grade diamond. Samples from these companies are shown in Fig. 9. Each company is capable of growing wafers in the 5-14 cm diameter range. These first samples are quite good with reasonable collection distances given that the diamonds were not optimized for large collection distance. This is a very exciting development and is indicative that the CVD process for growing high quality diamond is reaching a new plane. Our expectation is to have at least two manufacturers of detector grade diamond within one or two years.

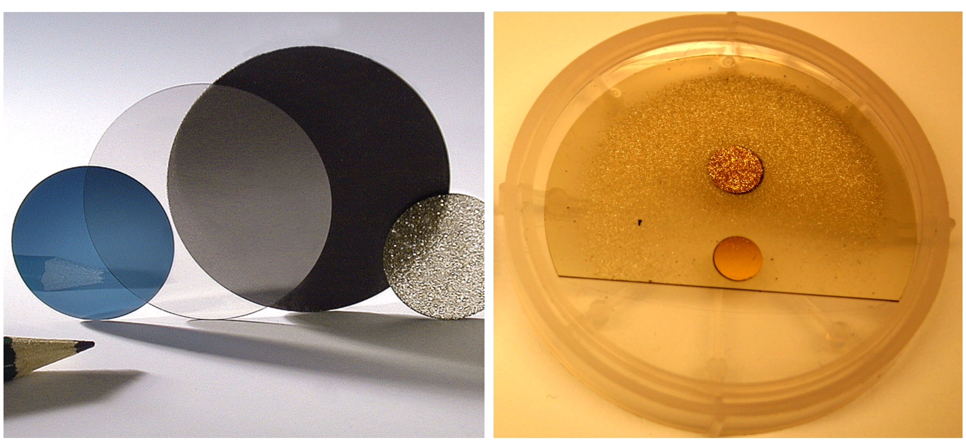

Figure 9: Photographs of the first samples from two new diamond manufacturers. The wafers in the left photograph range from 5 cm to 14 cm diameter. The wafer in the right photograph is 5 cm diameter.

5 ATLAS Pixel Modules

The production of high quality polycrystalline CVD material [2] with charge collection distance larger than 250μm allowed RD42 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) [3] for bump-bonding we constructed a range of diamond pixel detectors including a full 2cm $\times$ 6cm diamond ATLAS pixel module using pCVD diamond and a 1cm $\times$ 1cm single chip diamond

ATLAS pixel module using scCVD diamond, bump-bonded them to the final ATLAS FE-I3 IBM 0.25μm rad-hard electronics, irradiated them and tested the assemblies at CERN.

In Fig. 10 we show the final pCVD diamond pixel module with 16 pixel integrated circuit readout chips (46k channels) ready for external cables and testing and the scCVD diamond single-chip assembly (2880 channels) ready for testing. These modules were irradiated in 2007 and tested at CERN in 2007 using the Bonn-ATLAS telescope for external tracking.

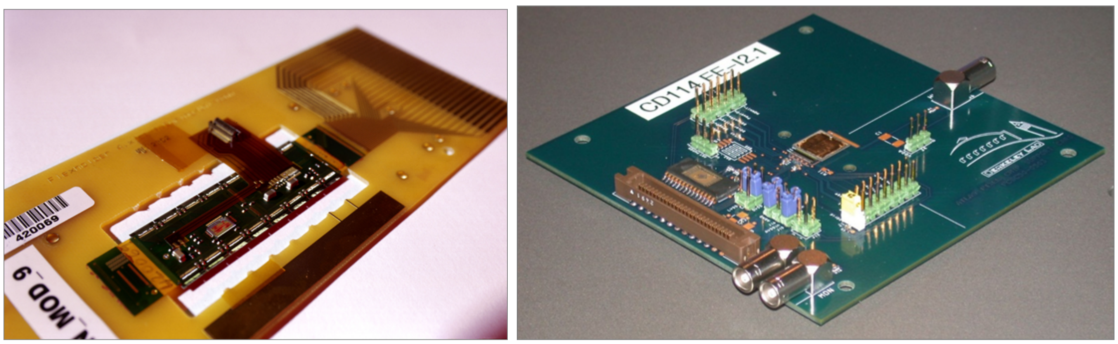

Figure 10: Photograph of the full ATLAS pCVD pixel module (left) and the single-chip ATLAS scCVD pixel module (right) ready for testing.

Fig. 11 shows the module noise and threshold obtained in the laboratory before attachment of the detector (i.e. the bare ATLAS pixel chip performance). Compared to a silicon module or 3D module the diamond module exhibits smaller noise (136e) and can be operated at lower threshold ($< 2000e$).

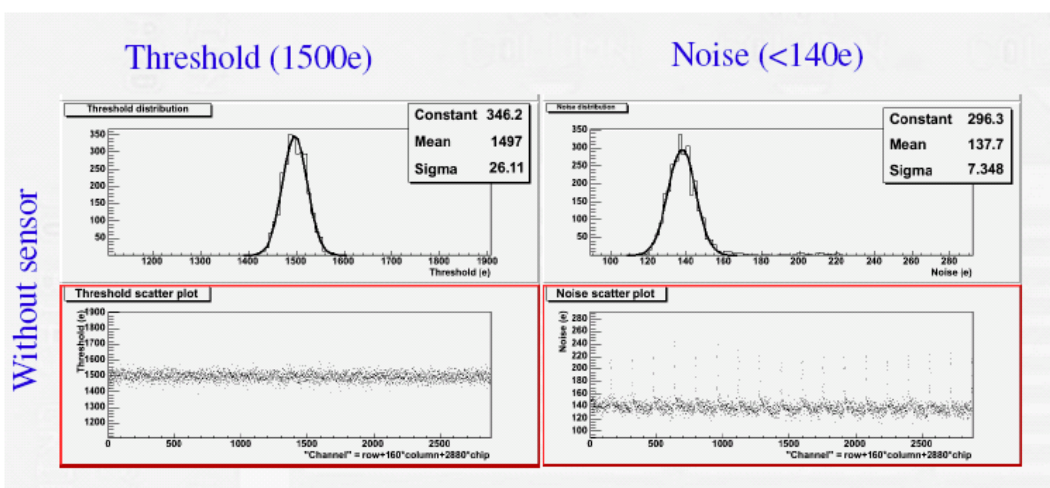

Figure 11: Bare (no detector) ATLAS pixel chip results for threshold and noise.

The full and single chip modules were irradiated in 2007 and tested in the Fall 2007 test beam at CERN. During these tests both irradiated modules exhibited noise of 140e and the irradiated modules were operated at thresholds of 1700e. The full module was irradiated to $\sim 1\times 10^{14}$ p/cm^2; the single-chip module was irradiated to $\sim 1\times 10^{15}$ p/cm^2. Fig. 12 shows the test-beam setup.

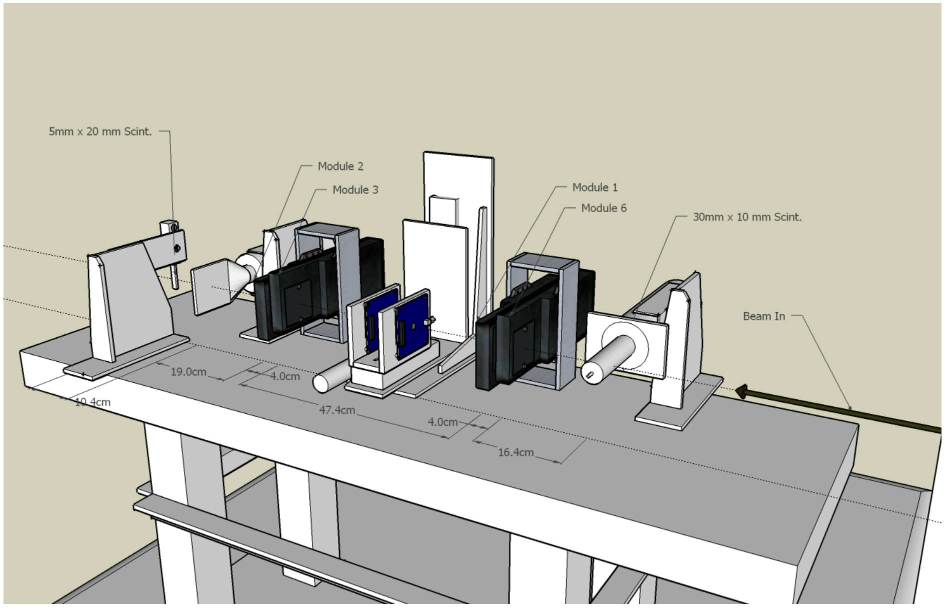

Figure 12: Schematic view of the Bonn ATLAS telescope.

In order to test the full 2cm×6cm irradiated module the test beam was scanned from pixel chip to pixel chip. Fig. 13 shows the number of pixels hit in the irradiated full pCVD diamond module and the single chip scCVD pixel module for each telescope trigger. All triggers in the data run are shown even though the telescope trigger is larger than a single pixel chip. In the pCVD irradiated module most of the events have a single pixel hit; in the scCVD irradiated module most of the triggers have two pixel hits. This is what is expected due to the larger pulse height in the scCVD module.

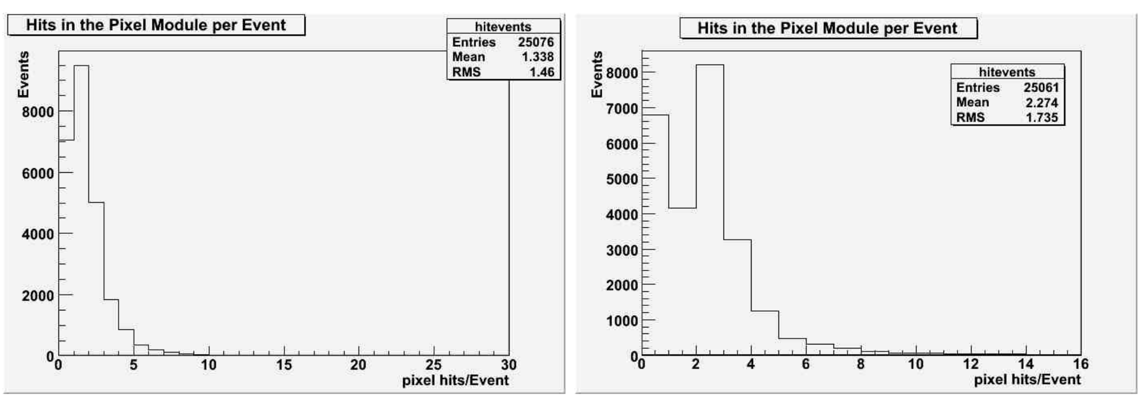

Figure 13: Distribution of hits in the irradiated full pCVD ATLAS pixel module (left) and the single-chip scCVD pixel module (right) during the CERN 2007 beam test.

Fig. 14 shows the reconstructed x and y distributions of the raw beam profile in one chip of the irradiated full module. Good correlations and clear beam profiles are observed between the module and the telescope tracks. The analysis of these data is underway with final results expected soon.

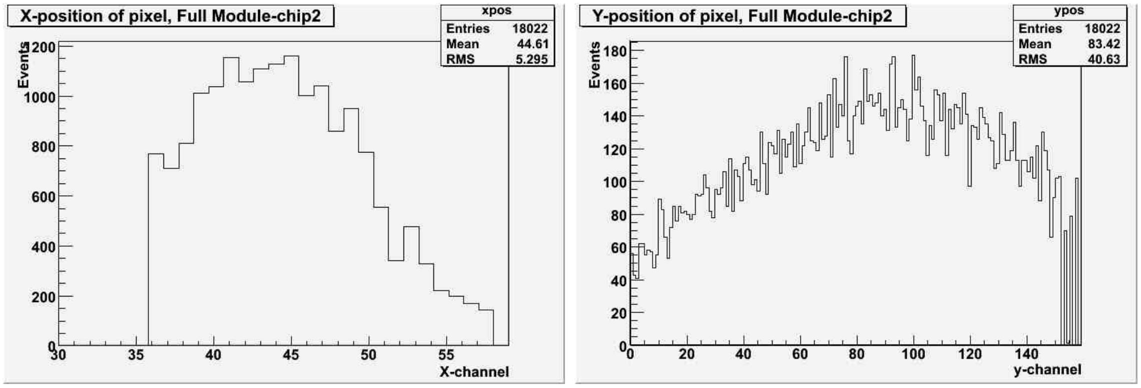

Figure 14: Hit distribution in x and y in the irradiated full ATLAS pixel module during the CERN 2007 beam test.

Fig. 15 shows the reconstructed x and y distributions of the raw beam profile in the irradiated single chip scCVD module. Good correlations and clear beam profiles are observed between the module and the telescope tracks. The analysis of these data is underway with final results expected soon.

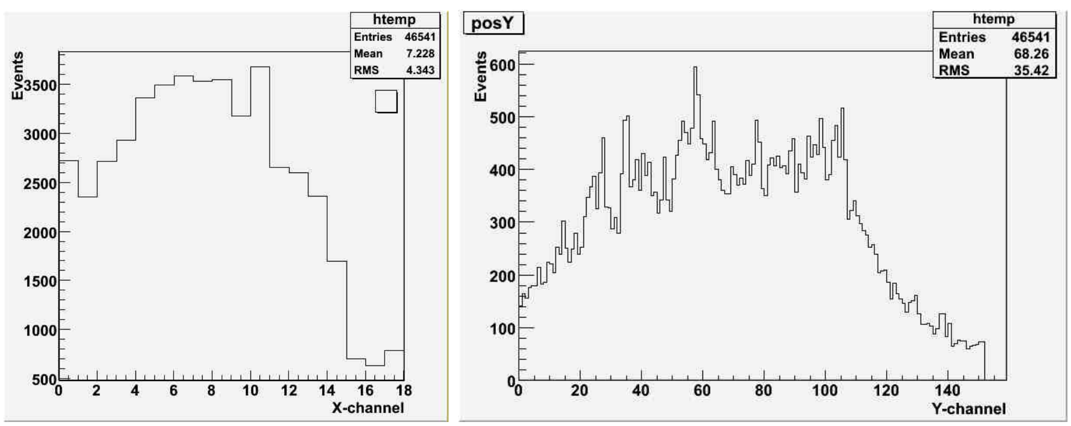

Figure 15: Hit distribution in x and y in the irradiated single chip ATLAS pixel module during the CERN 2007 beam test.

Given the number of triggers and the trigger efficiency we estimate the both modules are greater than 98% efficient.

6 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 [11], Belle and CDF [12] with the help of RD42 use CVD diamond for beam condition monitoring because of its small leakage currents, radiation hardness and temperature independent operation. Recently with the help of RD42 ATLAS and CMS has installed beam condition/loss monitoring (BCM/BLM) systems based on pCVD diamond. We describe these below.

6.1 ATLAS BCM Studies

ATLAS has a similar application to BaBar/Belle/CDF. The ATLAS experiment decided in 2005 to pursue a proposal to build 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. The ATLAS BCM is already installed. For a backup system ATLAS decided to build a second Beam Loss Monitor (BLM) system. This system was constructed during the last year and is presently being installed.

In Fig. 16 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 aim of a module is a S/N ratio of ∼10:1 in order to detect with high efficiency minimum ionizing particles.

The ATLAS system of consisting of 10 modules including spares is complete and installed. Fig. 16 shows a finished module. In Fig. 17 we show the test beam results for the timing of a final module.

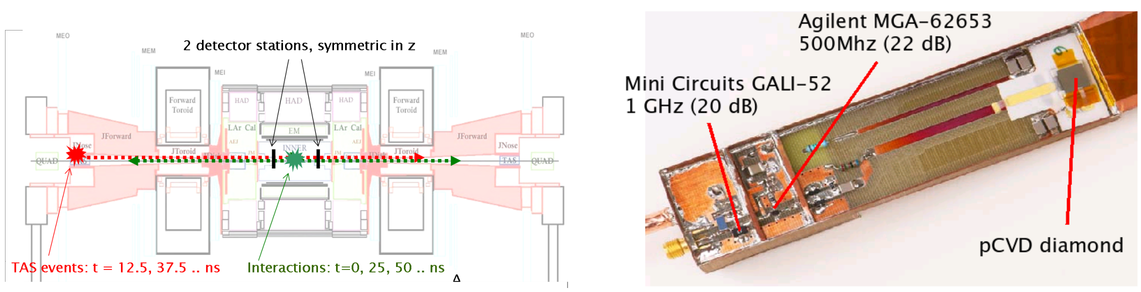

Figure 16: (a)A schematic view of the ATLAS BCM system. (b)A photograph of the final module used by ATLAS for its BCM system.

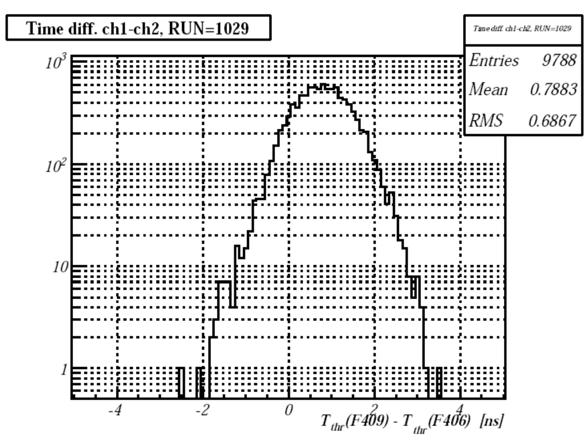

Figure 17: The timing difference distribution of two final ATLAS BCM modules.

In Fig. 18 we show the test beam results for the efficiency and noise rate scaled to a 25ns interval of a final module. At 99.5% efficiency the noise rate is 10^{-6}; at 97.5% efficiency the noise rate is 10^{-9}. The final modules meet all of the initial specifications. In Fig. 19 we show one half of the installed final BCM system.

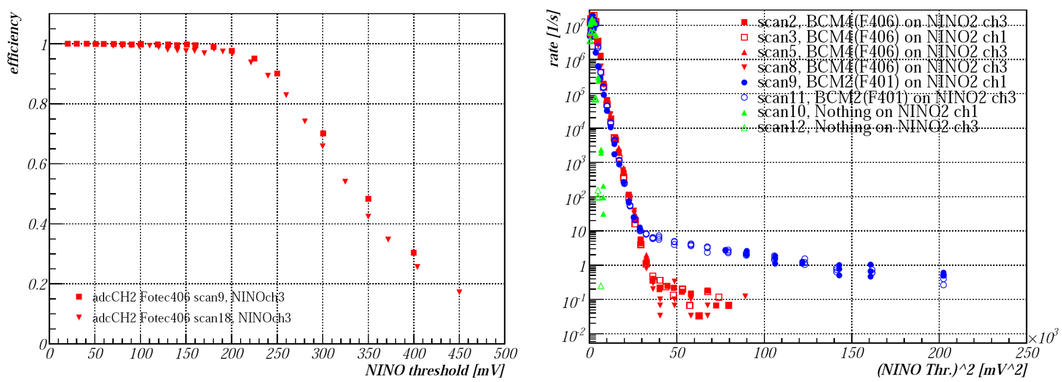

Figure 18: The efficiency (left) and noise-rate (right) as a function of threshold of a final ATLAS BCM module measured in a CERN test beam.

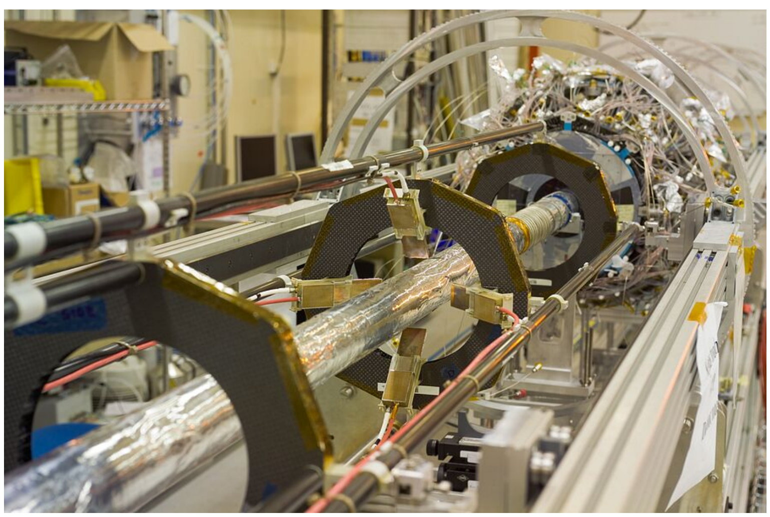

Figure 19: Photo of one half of the final ATLAS BCM system installed on the beam pipe.

6.2 CMS BLM Studies

CMS has a similar application to BaBar/Belle/CDF. The CMS experiment decided in 2006 to construct a Beam Loss Monitor (BLM) detector based on pCVD diamond sensors. The aim is to measure the background via a current measurement similar to CDF. The CMS BLM is presently being constructed.

In Fig. 20 we show a photograph of the final CMS BLM detector unit. In Fig. 21 we show the test results for the linearity of the CMS BLM current versus the number of incident particles. The system is linear over four decades of incident particles. The system is nearly complete and will shortly be installed.

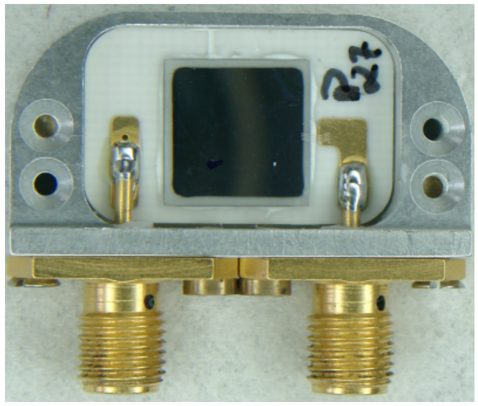

Figure 20: A photograph of the final module used by CMS for its BLM system.

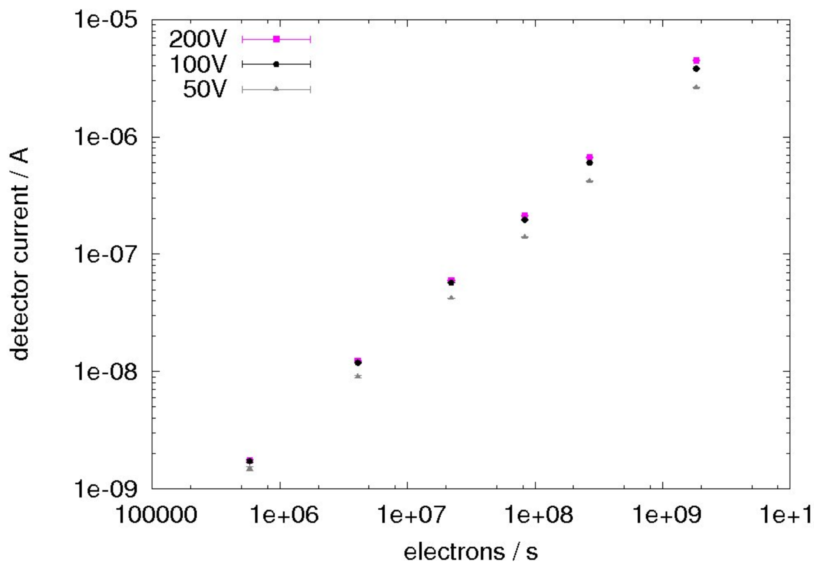

Figure 21: The measured current versus number of incident particles as a function of voltage for the final CMS BLM system.

7 Proposed Research Program for 2008

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:

- Irradiation of the latest samples up to fluences of 2×10^{16} particles/cm^2.
- Beam tests of irradiated samples as strip detectors and pixel detectors..
- Transfer the technology of making tracking devices to industry.
- Characterization of the electrical performance of specific CVD diamond samples grown

by Element Six and other suppliers with continuous feed back of results to the manufacturer.

- Material science studies on these pCVD and scCVD diamond samples for defect characterization and comparison to help make increase the collection distance of pCVD material.

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 complete irradiation program for scCVD material and further irradiation studies with pCVD material have to be performed. Of particular importance are irradiations 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; strip and pixel modules.
- Collaboration on future applications like the ATLAS Pixel Upgrade Proposal.

In summary, RD42 proposes to concentrate its efforts in 2008 in these areas.

- Irradiation of pCVD and scCVD samples up to fluences of 1×10^{16} particles/cm^2 with protons, neutrons and pion beams using the highest quality diamond material. To this end we have prepared pCVD and scCVD diamond samples and characterized them in test beams at CERN in 2007. The proton, pion and neutron irradiations are underway and will continue in 2008. In addition we propose to test the irradiated first diamond ATLAS pixel module and characterize it in test beams at CERN.
- Test of CVD diamond tracking devices with tailor made radiation hard front-end electronics for strip detectors and pixel detectors in test beams.
- Pixel detectors, using the top quality CVD material available. This year we expect to transfer the technology for constructing a diamond module to industry. To this end construction of a second and third ATLAS pixel module is in progress. For these modules the contacts will be produced in industry (IZM) as will reliable, efficient bump bonding. We propose to test these modules in beam-tests at CERN with the latest radiation hard ATLAS and CMS front-end chips.
- Characterization of the new, highest quality scCVD diamond material produced by Element Six under the research contract. Begin 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.

8 Funding and Requests for 2008

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 2008 is foreseen to be 150 kCHF. The majority of this funding is now through our North America colleagues who are funding the ongoing research programs. 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 7 we request 50 kCHF of direct funds from CERN and that the LHCC officially approve the continuation of the program. This will 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]. We expect 15-20kCHF of the CERN funds to be used to enter into a research contract with Diamond Materials of Freiburg, Germany to develop a second supplier of diamond material. It is also request that a minimal infra-structure for sample characterization and test preparation be maintained at CERN. The facility will be mainly used by external RD42 collaborators. We therefore request the following:

- 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 2008.
- Several irradiations in PS beam facility in 2008.

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