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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

Over the past 14 months the RD42 collaboration continued the improvement of CVD diamond detectors for high luminosity experiments at the LHC. We have made extensive progress on the diamond quality, on the development of diamond trackers and on radiation hardness studies. Transforming the technology to the LHC specific requirements is now underway. In this report we present the progress made and the requirements specific to the programme.

1 The RD42 2001 Research Program and Milestones

Vertex detection in LHC detectors requires precise tracking radially close to the interaction regions and in the very forward regions. The integral fluences over the life time of the experiments will exceed substantially 10^{15} particles/cm^2 in these regions. The detector components installed in these regions, both sensor material and front-end electronics, will have to be extremely radiation hard. At present both the CMS and the ATLAS experiment plan to install pixel devices in the innermost layers of their tracking detector. The RD42 collaboration is developing tracking detectors, in particular pixel devices, using CVD diamond material. This material promises to be very radiation hard. The radiation hardness of CVD diamond has been investigated by RD42 up to fluences of 5×10^{15} particles/cm^2. Present results indicate that diamond pixel detectors can be operated with sufficiently high efficiency and spatial resolution close to the interaction region for many years of LHC operation at design luminosity. The availability of very radiation hard detector material and electronics will be of great importance in view of possible future luminosity upgrades for the LHC [1].

1.1 The LHCC Milestones

At the LHCC meeting on the 1 Feb. 2001 the RD42 project was approved for continuation with the goal of reaching two main objectives [2]:

- increasing the charge collection distance in a dedicated programme with an industrial partner to more than 250 μm from the then current 200 μm and
- testing diamond detectors with the latest radiation hard front-end chips from the ATLAS and CMS collaborations.

The research programme proposed by RD42 for 2001 included these objectives along with two additional goals:

- testing the performance of large detectors,
- finalization of the geometry and metallization of LHC pixel sensors.

Although highly attractive, CVD diamond has three properties that need to be addressed before diamond pixel detectors are viable. Foremost is to understand the effect of the signal size which with full charge collection is approximately half that of silicon. Second is to understand the effects of the material being polycrystalline. Finally the material must be reproducible in its electronic properties, especially charge yield, from production reactors before any orders or realistic pricing can be obtained.

1.2 Summary of Milestone Progress

The development of new diamond material came about as a result of a series of material studies. The primary result of this work showed that our understanding of the growth processes is correct and a clear path to higher quality diamond can be pursued. A decision to pursue such a research program was made and work on it has begun. The first results of this work produced a diamond with 250 μm collection distance. Fig. 1 shows the pulse height distribution of this diamond when irradiated by a ^{90}Sr source. The second diamond produced had a collection distance of 270 μm. The third diamond produced had a collection distance of 230 μm. All three of the new diamonds are better than previous ones which leads us to conclude the new process is a success. Our industrial partner has hinted that diamonds with a collection distance above 300 μm collection distance diamonds are reachable and now in sight. For this diamond to be generally available, this new process still must be transferred from the research reactors to the production facility. We expect this transition to begin at the end of this year. Very recently De Beers has delivered completely new material, following a new growth approach, which has the potential to go beyond 400 μm collection distance. Tests of this new material are underway.

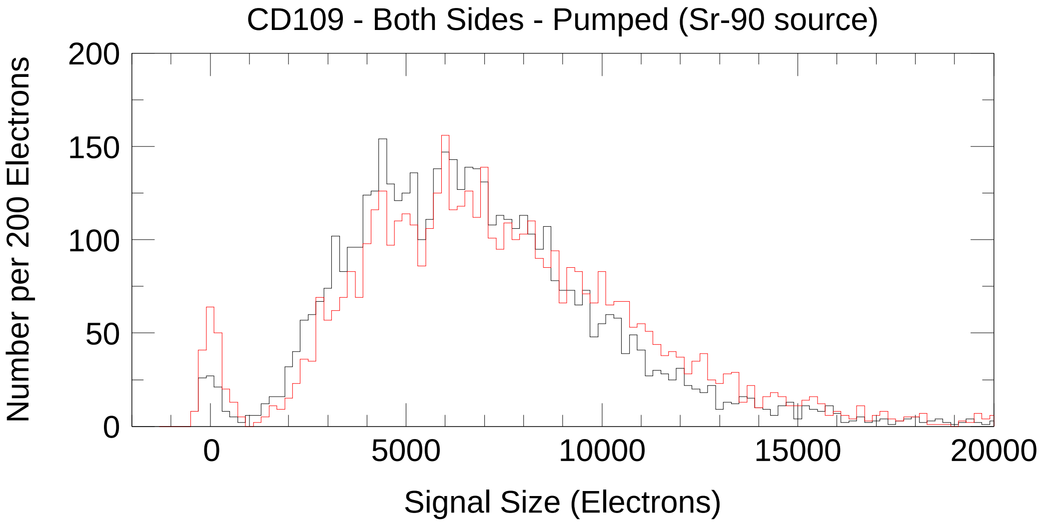

Figure 1: Pulse height distribution of the first diamond produced by a new process.

Using CVD diamond samples from production reactors our work has proceeded on the development of diamond pixel sensors. As reported last year rad-soft electronics with suitable noise and suitable threshold performance were available to us from both ATLAS and CMS. This coupled with the development of a number of large collection distance samples has allowed us to vigorously pursue the development of bump-bonded diamond pixel sensors. This work has been performed in collaboration with the groups developing front end electronics for both ATLAS and CMS. This past year however neither ATLAS nor CMS produced any version of their respective rad-hard electronics and so the test of diamond pixel detectors with the latest LHC electronics has been deferred to 2002. ATLAS recently received its IBM 0.25 micron pixel chip and CMS will receive a new pixel chip shortly.

With the previous generation of diamond pixel detectors, pixel efficiencies above $\sim$95 % have been achieved. Fig. 2 shows the efficiency distribution in a CERN beam test of a diamond pixel detector. The mean efficiency observed with this detector using a 1600 e threshold was 94%. The next generation of pixel detectors will use the newly available larger collection distance material (charge collection distance of about 250 μm) and should yield a pixel detector suitable for applications at the LHC.

During the last year a number of diamonds were tested in beams at CERN. One outstanding results was the production and testing of a full diamond beam telescope. Fig. 3 shows a side view of a 2 cm × 2 cm diamond telescope module fully equipped with readout electronics. Four such modules were fabricated and used to find the systemic effects of operating multiplanes of diamond together. The telescope reached a projection resolution of 10 μm using planes with 50 μm pitch.

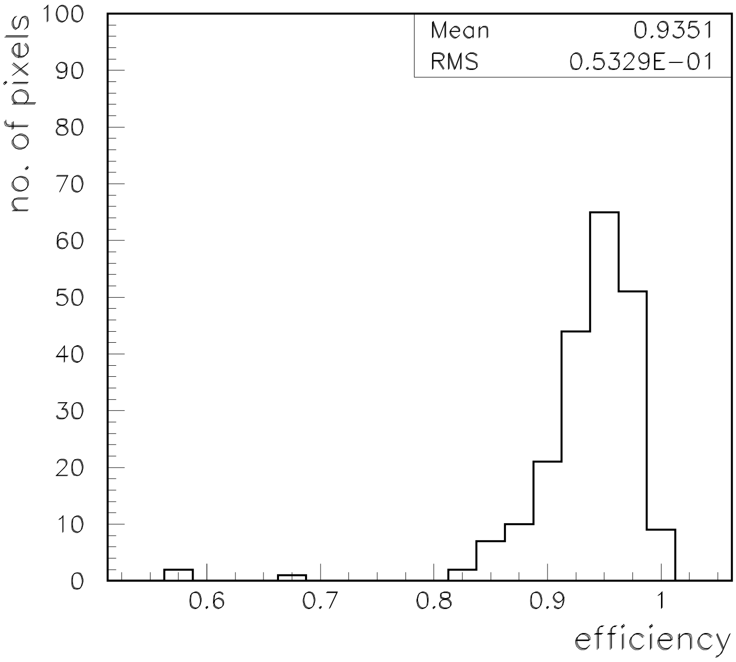

Figure 2: Efficiency distribution of a diamond pixel detector operated at 1400 e threshold.

Finally, we continued our irradiation studies of CVD diamond. The performance of diamond strip detectors after irradiation was evaluated in beam tests. A strip detector equipped with a fully radiation hard readout chip (SCTA) produced in the DMILL technology was constructed and tested with a source. Fig. 4 shows the source test result. We observe a charge distribution cleanly separated from the noise tail, indicating that a very high efficiency can be obtained with this device in a testbeam. The beam test of this device is planned for 2002. A more detailed description of the progress in 2001 is presented in the following sections.

2 Progress on the Improvement of CVD Diamond

Over the last few years, we have worked closely with the De Beers Industrial Diamond Division [3] to achieve major improvements in the charge collection distance and uniformity of CVD diamond.

- CVD diamond purchased from production reactors now regularly exceed 220 μm charge collection distance.
- New ‘avenues’ of research are being pursued by De Beers for greater than 250 μm charge collection distance. This research is being carried out with RD42 in 2001 and 2002.
- Research continued on lapping and uniformity in order to gain understanding and improvement in electronic quality.

This past year marked the production of approximately 20 new samples from production reactors aimed at testing the reliability of the production process for high quality diamond and the beginning of a research programme aimed at producing diamonds with $> 250\mu$m charge

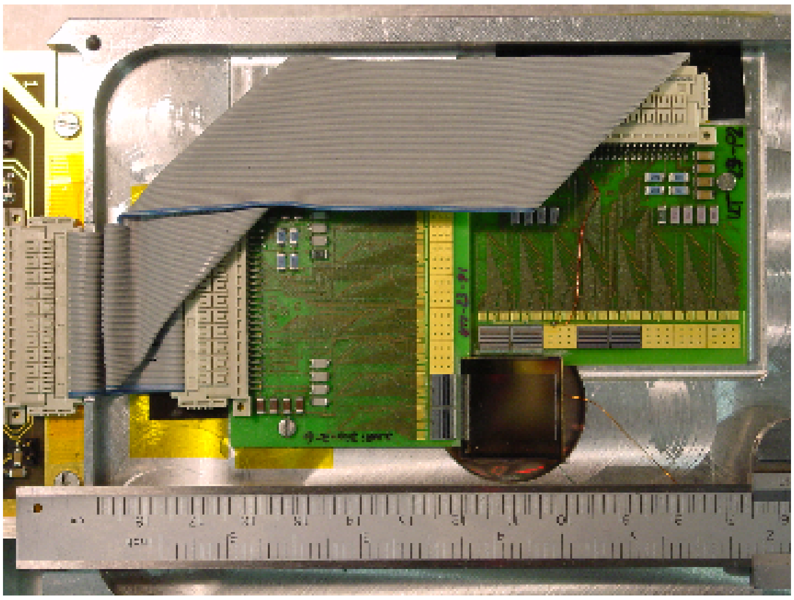

Figure 3: Photograph of the front view of two planes in a diamond telescope module.

collection distance. The production samples were all of excellent quality. The measured pulse height distribution, using a ^{90}Sr source, of a typical sample as-received from the manufacturer is shown in Fig. 5. To obtain this distribution we metallized the diamond with circular electrodes on each side. Operating at an electric field of 1 V/μm we observe a Landau distribution well separated from zero. We also observe that the charge collection is symmetric with applied voltage. The most probable charge is $\approx$ 5500 e and 99 % of the distribution is above 2000 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 charge collection distance of 210 μm in CDS-85 corresponds to a mean charge of 7560 e.

In the course of our work with De Beers the charge collection distance improved from several 10 μm to over 220 μm in production reactors. The research programme should allow us to reach close to 300 μm. Part of the work which enabled the research programme was understanding of the carrier drift length across the diamond bulk. Fig. 6 shows the charge collection distance measured in two CVD diamond samples as a function of the thickness after thinning on the growth side and on the nucleation side. We find that material removal from the growth side decreases the charge collection distance. The measurements from successive material removals on the growth side can be fit by a straight line indicating that the carrier drift length increases linearly from the nucleation side to the growth side. The intersection at zero gives the carrier drift length on the nucleation side of the diamond. We also find that material removal from the nucleation side improves the charge collection distance. However, charge collection distance must decrease again after a certain amount of material has been removed from the nucleation side. Hence there must be a thickness where the charge collection distance reaches a maximum.

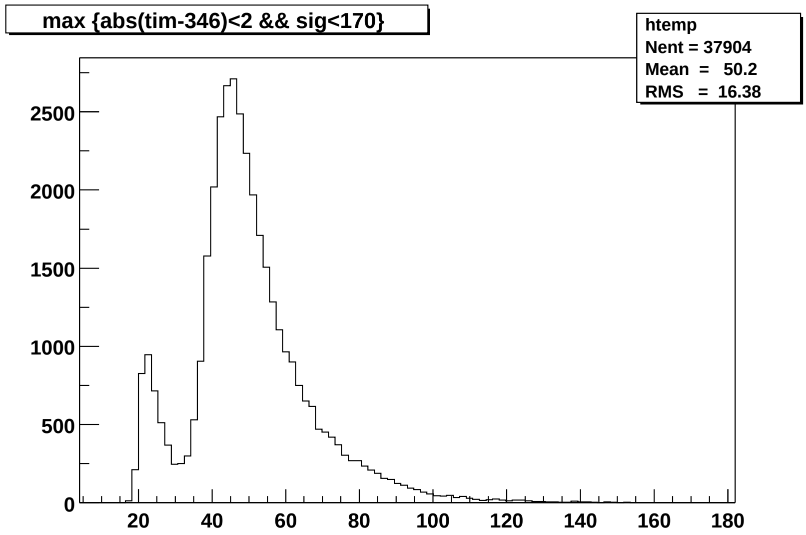

Figure 4: Pulse height distribution obtained with radhard SCT128A frontend electronics operating at 40 MHz.

3 Results from Diamond Strip Detectors

After characterization of diamond samples using the ^{90}Sr in the lab, the electrical contacts are removed and selected samples are patterned with strips or pixels in order to test them as trackers in particle beams. Tests with strips are essential on new materials to understand charge collection, charge sharing and material uniformity. Detailed work on the diamond material is easier achieved on strip- than on pixel detectors. The tests on strips were normally done using 'easy-to-use', low noise VA readout electronics [4]. VA readout was chosen since it allows one to focus on the diamond detector material.

Normally beam tests are performed using a silicon beam reference telescope consisting of 8 planes of silicon strip detectors. However, this past year a diamond telescope was constructed using seven planes of 2 cm × 2 cm diamond [5]. Fig. 7 shows the organization of the diamond planes. Silicon strip, diamond strip or pixel detectors were mounted inside the telescope. The silicon strip detectors were used to help calibrate the diamond telescope. The telescope allowed one to measure the intersection of the track with the test detector with a precision shown in Fig. 8.

3.1 Beam Test Results from the Diamond Beam Telescope

Extensive beam tests have been carried out in the year 2001 using the setup and experience from previous tests. All diamond strip sensors tested in 2001 had a 50 μm strip pitch at 25 μm strip width. The strips were made of a new metalisation with Al as the overmetal. This new metalisation process has increased the amount of charge collected by about 20%. All strips were readout from each plane using low noise VA electronics were the channel noise was about 100 e ENC.

Fig. 9 shows the charge signal distribution measured from a one diamond plane in the beam test. It can be seen that the signal distribution is very uniform across the diamond and separated from zero with more than 99 % of the entries above 2200 e. We attribute this uniformity to a large extent to the new metalisation process. This was the best diamond

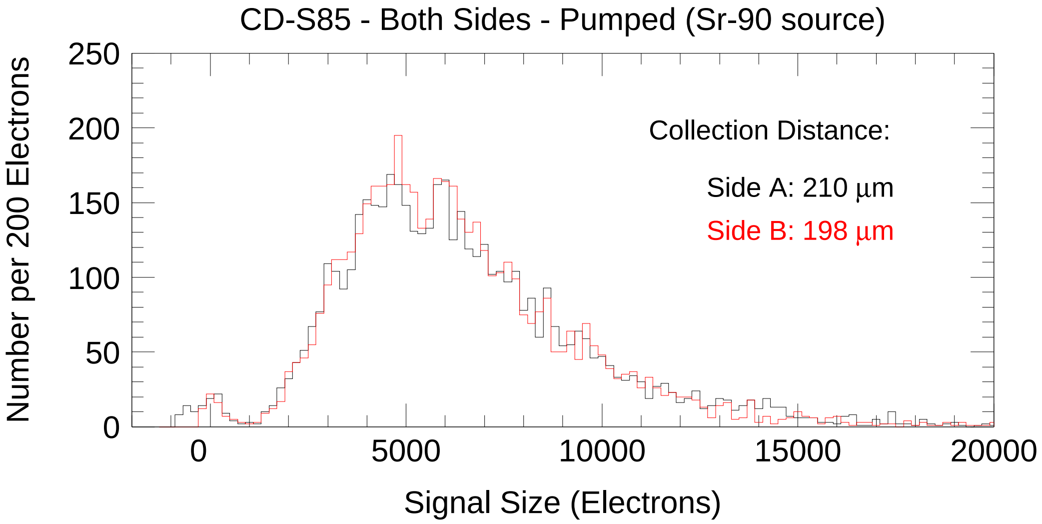

Figure 5: Charge signal from a recent production reactor diamond sample measured using a ^{90}Sr source in the laboratory. No cuts to the data have been applied.

tested with a mean charge of 8400 e and a collection distance of $\approx 230\mu$m.

Fig. 10 shows the signal distribution for single and double strips measured in the beam. The signal was obtained by adding the charge measured on strips nearest to the intersection of the track given by the diamond telescope (transparent analysis method). This result agrees with the measured charge distribution on the same diamond using the ^{90}Sr source.

Fig. 11 shows the residual distribution of two silicon detectors measured by the diamond telescope. The residual is the difference between the position of the track as measured by the telescope and the position of the hit as measured by the detector. The residuals are normal distributed around zero. The extrapolated position resolutions are 18.7 μm (H) and 20.7 μm (V) respectively. The expected resolutions were 13.5 μm and 17.0 μm. This resolution is slightly worse than what was expected but very reasonable giving that all the data is used without corrections. The projected resolution will improve on future detectors by implementing floating intermediate strips. This improvement is planned for 2002.

3.2 Performance after Proton Irradiation

While results on proton irradiated diamond samples with large circular contacts were reported previously [6] we continued our study of the performance of proton and pion irradiated diamond strip sensors. The irradiations were performed using 24 GeV/c protons from the Proton Synchrotron at CERN where details of the irradiation can be found in reference [7, 8].

The diamond which was irradiated was one of the best grown in a research reactor. Fig. 12 shows the transparent 2-strip signal-to-noise distributions measured on a diamond sensor in beam tests before and after irradiation with fluences of 1×10^{15} p/cm^2 and 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. 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-metallization we observe essentially the same signal-to-noise distribution as at 1×10^{15} p/cm^2 indicating that very little further damage occured 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

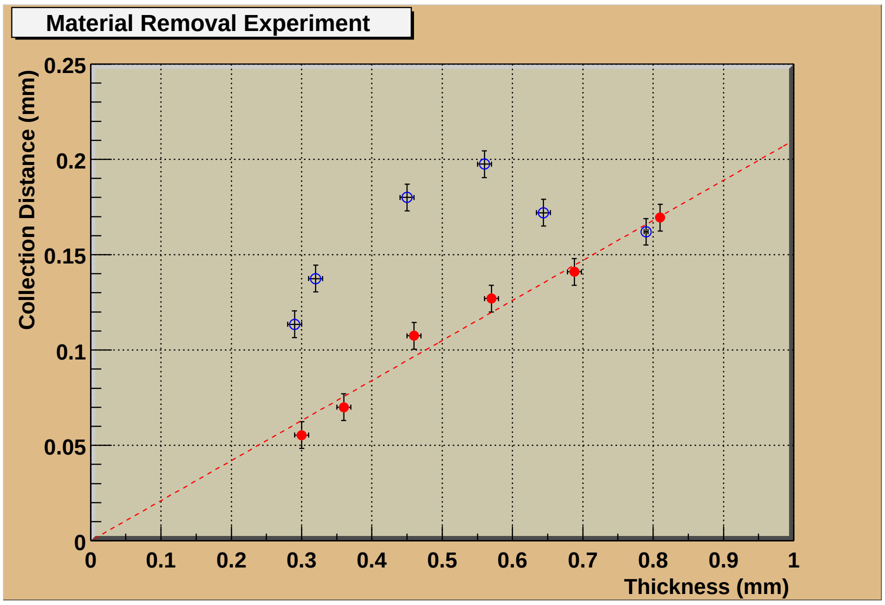

Figure 6: Thinning of two CVD diamond samples (DB91 and DB92). The charge collection distance measured as a function of the thickness after thinning on the growth side of DB91 and on the nucleation side of DB92.

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. This work has spurred research in the development of radiation hard diamond contacts. Diamond strip detectors with such contacts will be irradiated with neutrons and protons in 2002.

Fig. 13 shows residual distributions before and after irradiation at 1×10^{15} p/cm^2 and 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 landau distribution is narrower. The spatial resolution of nearly 7 μm with a detector of 50 μm strip pitch is comparable to results obtained with silicon detectors.

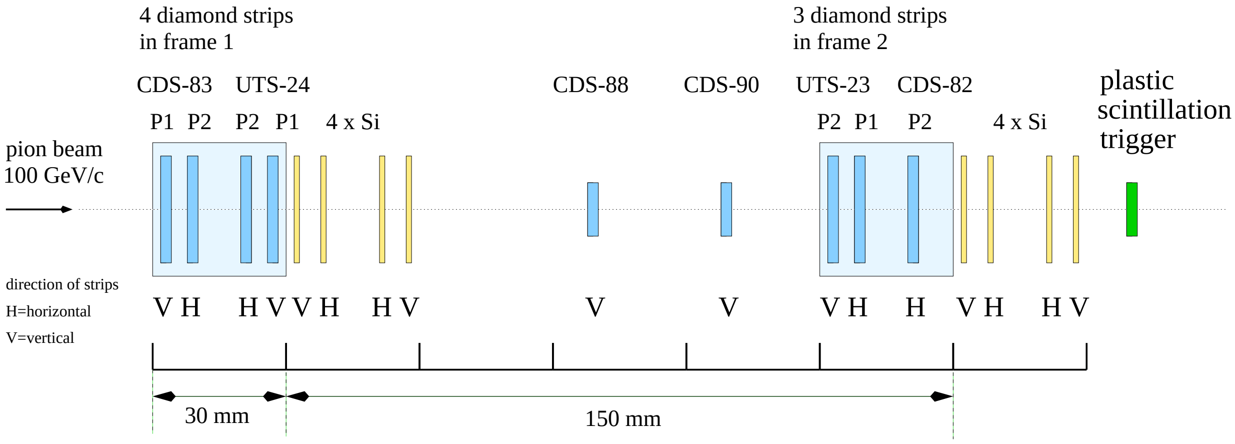

Figure 7: Schematic view of the diamond beam reference telescope.

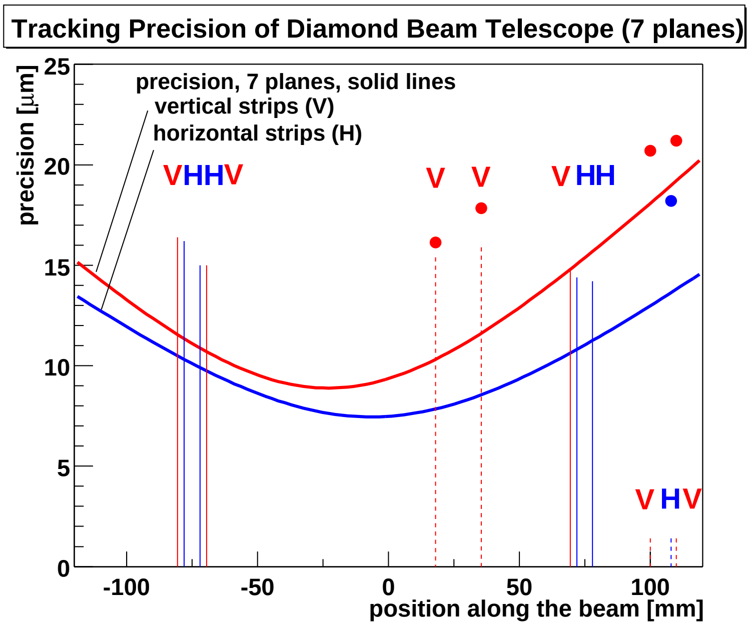

Figure 8: Predicted extrapolation precision with the diamond telescope.

3.3 Performance after Pion Irradiation

The results on pion irradiated diamond samples were reported previously [6] we include a short summary here for completeness. The irradiations were performed using 300 MeV/c pion from PSI. The details of the irradiation can be found in reference [8].

The diamond which was irradiated was one of the best grown in a research reactor approximately 5 years ago so it has approximately half the collection distance of the best present day diamonds. Fig. 14 shows the transparent 2-strip signal-to-noise distributions measured on the diamond tracker in beam tests before and after irradiation with fluences of 2.9×10^{15} π/cm^2. The contacts were replaced after the fluence of 2.9×10^{15} π/cm^2 and then characterized in the test beam. At 2.9×10^{15} π/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 have moved closer to the most probable signal. We find a reduction of 50 % in the most probable signal-to-noise after irradiation with 2.9×10^{15} π/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 2.9×10^{15} π/cm^2 used new contacts the observed decrease of 50 % is attributed to damage in the diamond bulk. Diamond strip detectors with the new rad hard contacts will be irradiated in 2002.

Fig. 15 shows residual distributions before and after irradiation at 2.9×10^{15} π/cm^2. As with the proton irradiation we observe that the spatial resolution improves from (13.7 ± 0.3) μm before irradiation to (10.6 ± 0.3) μm 2.9×10^{15} π/cm^2.

4 Diamond Pixel Detectors

4.1 Diamond Pixel Sensors for ATLAS

Four years ago, we have initiated test beam studies to determine both the hit efficiency and spatial resolution of diamond pixel detectors configured in both the ATLAS and CMS geometries and readout with the current ATLAS and CMS prototype readout chips.

Our first bump-bonded diamond pixel prototype was assembled with an early version of

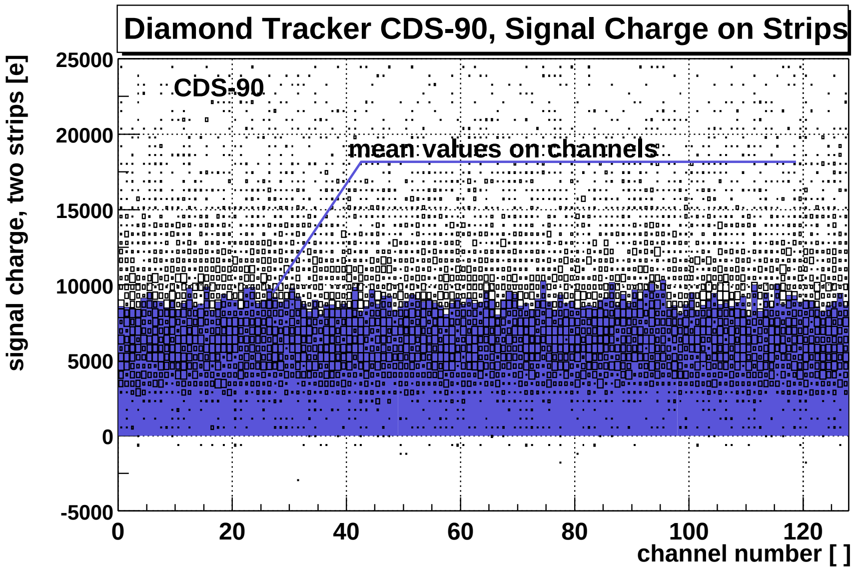

Figure 9: Charge signal distribution of each strip in CVD diamond CDS-90 measured at 1 V/μm in the test beam.

the ATLAS readout chip in 1998. The results from this indium bump-bonded detector were published in a NIM article in 1999 [9]. Since that time we have pursued bump-bonding at IZM and various readout chip options in an attempt to improve the overall efficiency of our devices. Bonding yields of close to 100%have been achieved.

The latest diamond material together with the new ATLAS rad hard pixel chip are a very attractive combination. First results of the chip indicate a functional circuit with reasonable threshold dispersion but a rather low yield. We are presently planning to produce two 1 cm × 1 cm pixel detectors with the new rad hard metalization which will be bump bonded at IZM and one large 2 cm × 6cm ATLAS module which will also be bump bonded at IZM. IZM has shown that they have solved the problem they had of bump bonding small individual detectors. These devices will be tested during 2002.

4.2 Diamond Pixel Sensors for CMS

In a series of tests this past year at the CERN SPS and PS, six CVD diamonds bump-bonded to CMS prototype readout electronics were tested. The diamonds were from a recent set of samples delivered by De Beers with comparable quality to the original CMS pixel detector. Diamond sensors were prepared with the 125 micron × 125 micron pitch to match the available chips. (The current CMS design calls for 150 micron × 150 micron pixels.) In the test beam measurements, a noise of 110 electrons and a threshold setting of 1400 to 1600 electrons were achieved. This is slightly worse than in the original tests.

The pulse height distribution for the pixel, to which a charge track extrapolated, is shown in Fig. 16. For events with tracks that passed through the active area the pulse height is comparable to that measured in the original tests.

The efficiency of individual pixels is slightly worse than that shown in Fig. 2 due to the higher threshold that was required to operate the electronics. This result confirms the previous measurements indicating that diamond pixel detectors are viable. By using higher quality diamond and optimizing the thickness of the diamond, the efficiency should be further improved to a level fulfilling the requirements for LHC experiments.

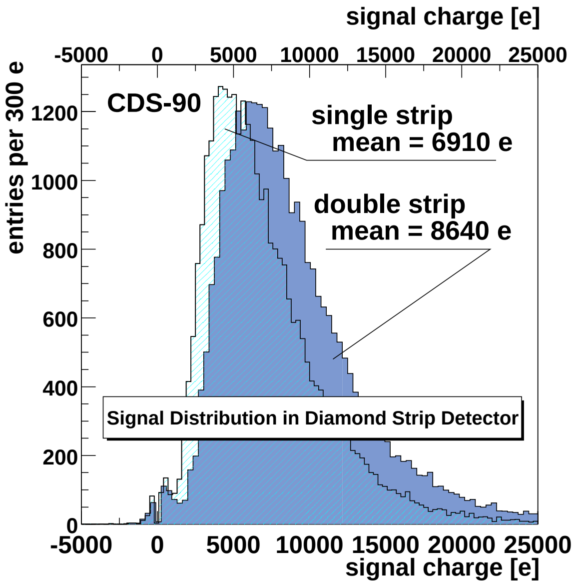

Figure 10: Charge signal distribution in CVD diamond CDS-90 measured at 1 V/μm in the test beam.

In the coming year, we will have higher quality diamond and we will optimize the thickness of the diamond. Together these should lead to further significant improvement in the efficiency approaching that achievable with silicon pixels.

5 Proposed Research Program for 2002

The goal of the RD42 research program is to develop best 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 De Beers Industrial Diamonds and continuous feed back of results to the manufacturer.
- Irradiation of samples with π, p and n to fluences up to 5×10^{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. This is partly due to the fact that more critical problems have been encountered than originally foreseen, but even more because there have been delays not under the control of RD42. Some of the major topics which could not be fully treated are the following:

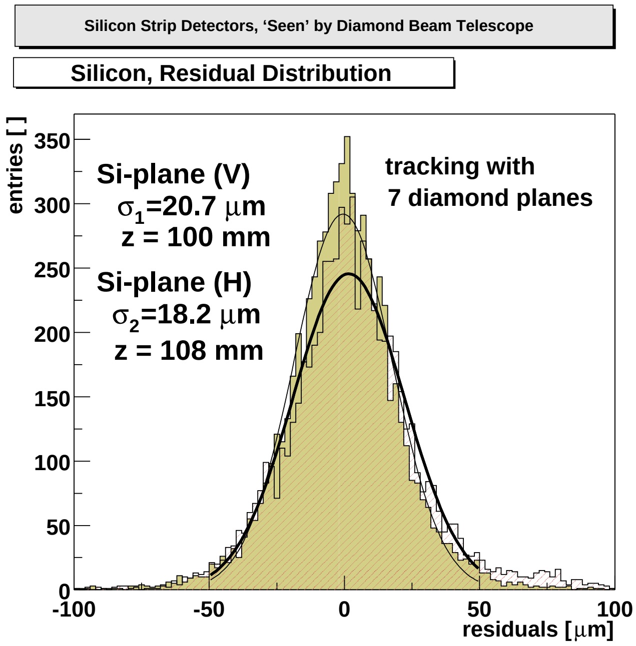

Figure 11: Residual distribution in Silicon measured by projecting the diamond telescope tracks in the test beam.

- RD42 has achieved in collaboration with De Beers to have material produced which shows on a regular basis charge collection distances between 200 μm and 220 μm. It has however been recognized that it could be advantageous and possible to produce material with charge collection distances in excess of 250 μm. A special program in form of a research contract - 100 % financed by the US part of RD42 - has been started with De Beers in 2000 to attempt to produce such material. This work will not conclude until early 2003.

- While there have been many promising results from irradiation studies with pions, protons, neutrons, electrons and photons with material of increasing quality, there are more measurements needed for the latest, highest quality CVD diamond samples.

- Material science studies have been pursued in a number of RD42 institutes. New methods and techniques had to be developed specific to CVD diamond. These are now in place, in particular in Florence, and need to be employed to study microscopic effects of the best quality materials. This will be very important in view of producing reliably high quality CVD diamond radiation sensors.

- The fast, radiation-hard SCTA128 readout chip developed for diamond strip detectors, in DMILL technology, was submitted into the ATMEL foundry in May 2000 and was delivered in August 2000 (failed run) and finally in August 2001 too late for the 2001 test beams. This first rad hard device will be tested in a beam in 2002. Several more SCTA128 assemblies, using the highest quality diamond strip detectors, will be constructed, tested and irradiated during 2002 and 2003.

In summary, RD42 proposes to concentrate its efforts in 2002 to the following topics

- Pixel detectors, using the top quality CVD material available: implementation of rad hard contacts and reliable, efficient bump bonding, construction and test of modules

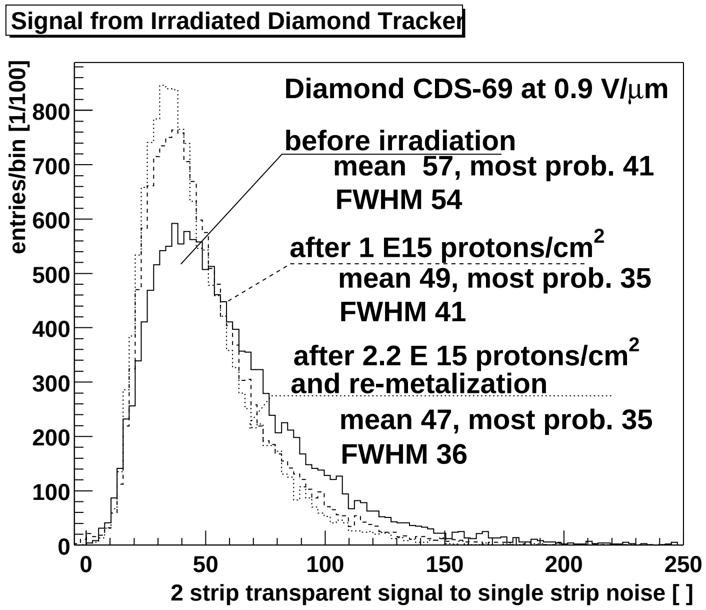

Figure 12: Transparent 2-strip charge signal-to-noise distributions before (solid line), after proton irradiations with 1×10^{15} p/cm^2 (dashed line) and after 2.2×10^{15} p/cm^2 (dotted line).

with the latest radiation hard ATLAS and CMS front-end chips, and beam test with these modules.

- Characterization of the new, highest quality CVD diamond material produced by De Beers under the existing research contract.

- Proton, neutron and pion irradiations with the highest quality material.

- Test of strip detectors with 2×4 cm^2 area with the radiation hard SCTA chip from ATMEL (DMILL technology). Eventually also tests with a DSM technology full CMOS front-end chip, implemented in TSMC technology, at present under development at CERN.

More details on the planned work program for the pixel test and defect characterization are described in the next paragraphs.

5.1 Plans for Future ATLAS Pixel Prototype Tests

A high priority is to improve on the ATLAS pixel prototypes we have been able to assemble so far. IZM has found a reliable way of achieving high quality bump-bonding across the whole face of a prototype sensor as well as a pixel module with sizes approaching 2×6 cm^2. With radiation hard pixel readout chips from ATLAS we will be able to “pump-up” the diamond sensors before operating them. With the extra factor of 1.6 in collected charge we expect diamond pixel prototypes with efficiency very close to 100 %. In particular a larger pulse height will reduce the loss of efficiency due to the time walk effect.

We plan to continue this program in the coming year including tests of improved diamond and comparisons of the hit efficiency and spatial resolution with identically configured silicon sensor pixels both before and after irradiations.

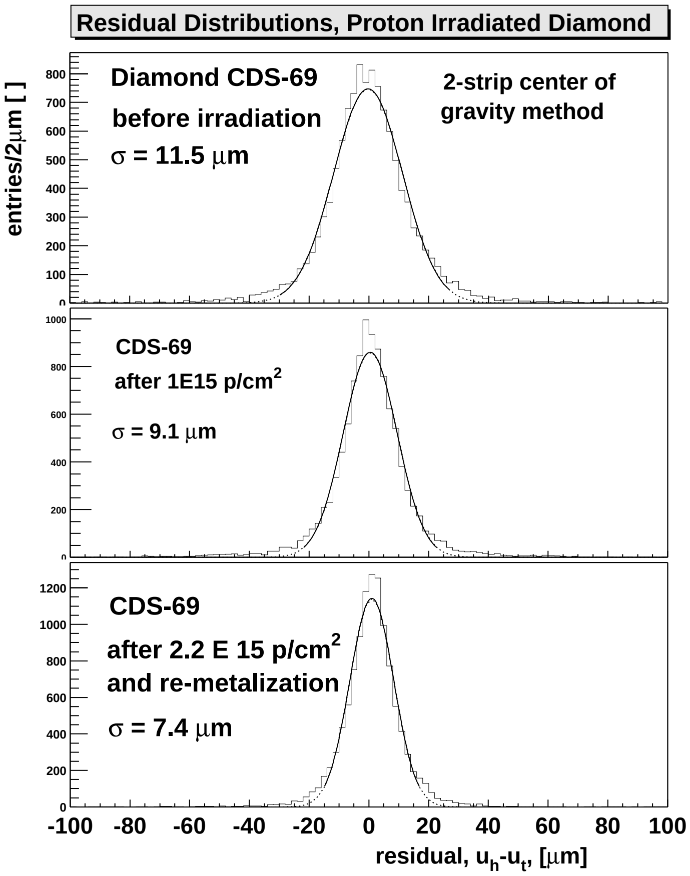

Figure 13: Residual distributions measure before and after proton irradiations.

5.2 Plans for Future CMS Pixel Prototype Tests

Substantial progress and significant breakthroughs have been made in test beam studies of CMS pixels. This year we plan to build on this momentum. The motivations and milestones for our test beam program in the current year are the following.

- Use higher quality diamond resulting from the De Beers R&D effort to improve efficiency and spatial resolution.
- Optimize the thickness of the diamond to improve efficiency and spatial resolution.
- Compare the performance of the diamond pixels before and after irradiation to several years of LHC pixel operation. (Note that the spatial resolution of diamond strip trackers significantly improves after Mrad of irradiation. Is the same true for the spatial resolution of pixel detectors?)

Ideally, the diamond results should be compared side-by-side with results from identically configured silicon detectors. This is planned for this year silicon sensors bonded to the latest version of the CMS readout chip will be available.

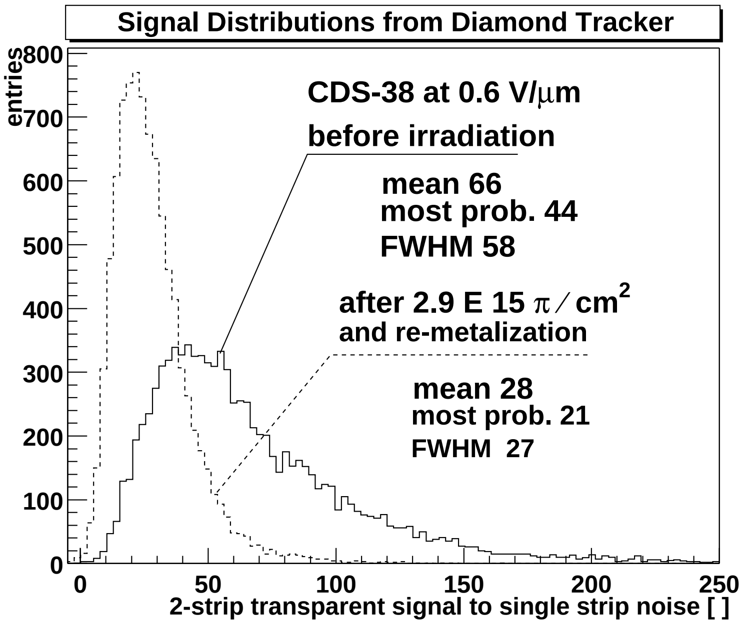

Figure 14: Transparent 2-strip charge signal-to-noise distributions before (solid line), after pion irradiations with 2.9×10^{15} π/cm^2 (dashed line).

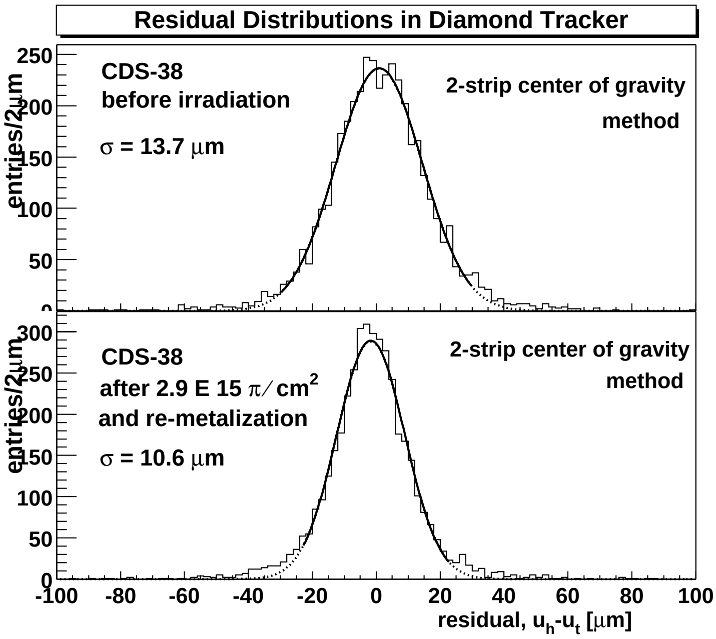

Figure 15: Residual distributions measure before and after pion irradiations.

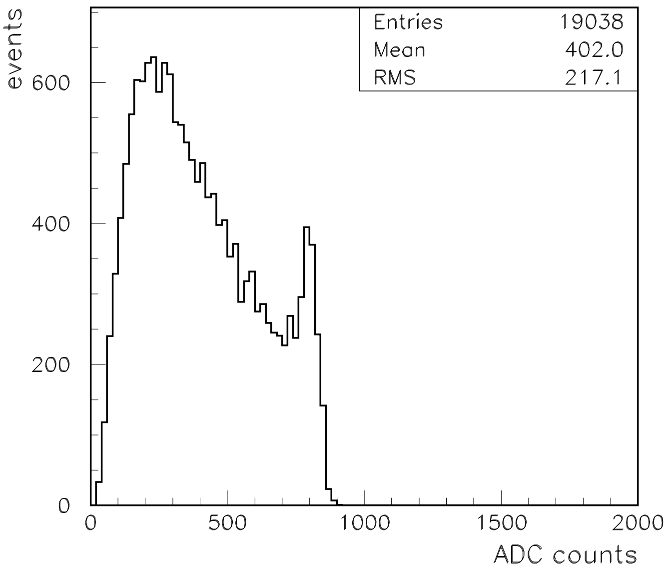

Figure 16: Single pixel pulse height distribution.

6 Funding and Requests for 2002

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 2002 is foreseen to be 250 kCHF. 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 5 we request 60 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 luminosity upgrades of the LHC, which is at present implemented [1]. We estimate that with the presently available manpower a conclusive completion of this program will need further 18 months. It will be very important for the proposed RD42 program to have access to beam tests. It is foreseen that a minimal infra-structure for sample characterization and beam test preparation is maintained at CERN. This will be a part of an EP division common project. The facility will be mainly used by external RD42 collaborators. We therefore request

- Three 7-day testbeam running periods per year for the duration of the project, of which one could be parasitic to other users.
- Maintain the present 20 m^2 of laboratory space for test setups, detector preparation and electronics development.
- Maintain the present minimal office space for full time residents and visiting members of our collaboration.

References

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[6] W. Adam *et al.* (RD42 Collaboration). "Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC". Status Report/RD42, CERN/LHCC 2000-011, CERN/LHCC 2000-015.

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