

Answers to Diamond Pixel Modules Proposal for the ATLAS Inner Detector Upgrade Referee Questions/Comments

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December 2007

We have updated the Diamond Pixel Module R&D proposal for the ATLAS Inner Detector Upgrade subsequent to the discussions with our two referees (Nanni Darbo and Hartmut Sadrozinski) and Nigel Hessey in late September 2007. Several of the concerns raised by the referees are addressed here and not in the full public proposal. Much of the information contained in this document comes from the RD42 collaboration and has not been published or approved for public dissemination. Therefore we are uncomfortable including it in an ATLAS document.

From Nanni Darbo – prior to September 24 phone call:

Questions to be clarified

scCVD

- Is the R&D (and plan to use for the b-layer) only on pCVD or also are also sCVD considered?

Based on availability and size polycrystalline Chemical Vapour Deposition diamond has been chosen as the baseline solution. The use of single crystal Chemical Vapour Deposition diamond is reserved as a future option if the manufacturers can attain sizes in the range 16mm x 16mm.

- If scCVD are considered for the b-layer, are they compatible with the new FE chip design that will have a size of $\sim 1.6 \times 1.6 \text{ cm}^2$?

Conditionally, see above.

- if pCVD are the detectors for the b-layer, is spatial resolution as good as silicon pixels? ($\sim 10 \mu\text{m}$). This is a critical parameter for a b-layer.

The spatial resolution of pCVD sensors as with 3D silicon or ordinary silicon sensors depends only on the amount of charge sharing. The current module was designed to have the electrodes be 50% of the pitch. As a result there is little charge sharing. As a result the current spatial resolution is 14 microns before irradiation. With diamond strip trackers with the same 50 micron pitch and same 50% electrode of the pitch as the pixel module RD42 has seen this improve to better than 10 microns after irradiation. There is test-beam data with irradiated pixel module prototypes from this year, which needs to be analysed.

Changes or updates to the proposal:

Charge Collection:

- Update Fig. 14 and 15 with new data for the new sensors with CCD $\geq 300\mu\text{m}$ on charge collection vs. fluence. Show in a table and plot the actual charge collected in electrons vs. fluence with the initial charge collection distance CCD as a parameter. Include data taken with the proposed efficient diamond sensors with CCD ≥ 300 and larger, and scCVD.

The proposal has been updated to clearly indicate that the radiation hardness measurements shown are from samples with 190 to 215 micron collection distances. This collection distance falls within the distribution of diamonds received lately. We have started irradiations with higher quality samples (around 250 microns). Results from these irradiations should become available in 2008.

We measure the charge collected from the diamond sensors undergoing radiation hardness studies using MIP-tracks in a pion test-beam. In those studies we measure the ratio of the signal collected to the noise present on the same strips in test-beam events where no track is present. Due to the low capacitance the noise is much smaller than silicon based detectors. Thus the appropriate way to compare devices is the signal to noise. In addition calibrating the absolute noise on strip tracker detector is a difficult measurement during the test-beam. We use the standard technique of relying on the injection of MIP-like charges from a very small capacitor into spare front-ends of the readout channel. We do this in the lab not the test-beam. This calibration is itself subject to a 10-20% uncertainty. Moreover the noise may vary from run-to-run (i.e. from one irradiation state to the next) and from the test-beam to the lab. Thus neighboring points would be subject to independent 20-30% systematic uncertainties. Putting such a large point-to-point error into the irradiation plot is unnecessary and in the past overshadowed the physics we are trying to understand. Instead we can measure the S/N in successive test-beams with 5% uncertainties (or better) making the point-to-point uncertainties in Fig 14. (now Fig. 16) less than 10%.

We are in the process of irradiating and measuring ~ 250 micron collection distance samples. This data is not yet available.

- Plot the exponent of the exponential decay of the charge collected vs. fluence as a function of the initial charge collection distance.

The proposal has been updated to include a proper damage curve ($1/ccd = 1/ccd_0 + k\Phi$). The damage constant is roughly $k \sim 10^{-18} \text{ cm}^2/\text{micron}$.

- Extract the expected charge collected as a function of fluence for the new sensors with CCD ≥ 300

Recent diamonds measured by RD42 have shown damage consistent with a k of $k \sim 10^{-18}$. This now includes small 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 formula which describes the data is $1/ccd = 1/ccd_0 + k\Phi$, with k independent of the initial collection distance

ccd₀.

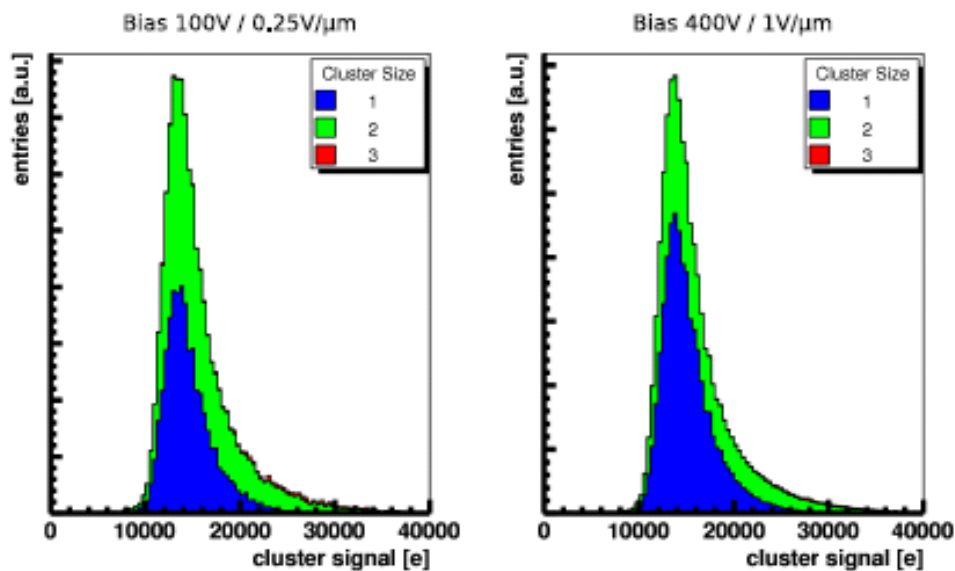
Accordingly to the proposal some more test and module should be made at today. If the following measurements are already available they maybe included in the updated version, otherwise we expect such measurements made and reported in a future review of the project.

Yes, these are underway and should start to become available in 2008.

Module Test Updates:

- Results from the full module tested at CERN in 2006. Provide operational threshold, efficiency, collected charge and time over threshold measurements. Are threshold and efficiency compatible with the expected collected charge?

This was in the original version of the proposal. The threshold was 1450 electrons, the threshold spread was 25 electrons, the efficiency is being measured however the BAT telescope was in very poor condition which makes the analysis problematic. We know from the on-line system the diamond was very efficient although the precision on this is one of the things we hope to nail down with further analysis. The calibration of absolute charge in the pixel readout system for small charges is less well understood than for our strip tracker electronics. For instance in the scCVD diamond single-chip module we “observe”, after using the standard pixel calibration, 20% more charge than is possible from the detector thickness and 20% more than measured in the lab. Our understanding from the Bonn group is that given these caveats the threshold and efficiency are compatible with the expected charge. Below we have attached a pulse height plot for the scCVD diamond single chip pixel module using a diamond which is 395 microns thick indicating a mean charge of 16,400e. However the largest mean charge possible from this diamond is 14,400e which is just what we measure in the lab. We thus quote only the Signal/Noise rather than absolute Signal.



- Accordingly to the proposal a second module has been build. What is the performance? Is the October beam test still planned? If yes, can we expect at the Valencia meeting data on collected charge, efficiency and time over threshold measurements with the beam?

The second module is being fabricated. It was not ready for the fall 2007 beam-tests. We hope to have this in time for the first test-beams in 2008.

Questions/Comments from Nigel Hessey (October 23, 2007)

1. pCVD is the baseline, scCVD as fall forward, 16mm square not available yet in scCVD.

Done, in the abstract of the updated proposal.

2. Resolution: Si achieves 10 micron, better than 50 micron/ $\sqrt{12}$ ~ 14 micron. Add that diamond resolution is measured, needs to be better measured, and show the results.

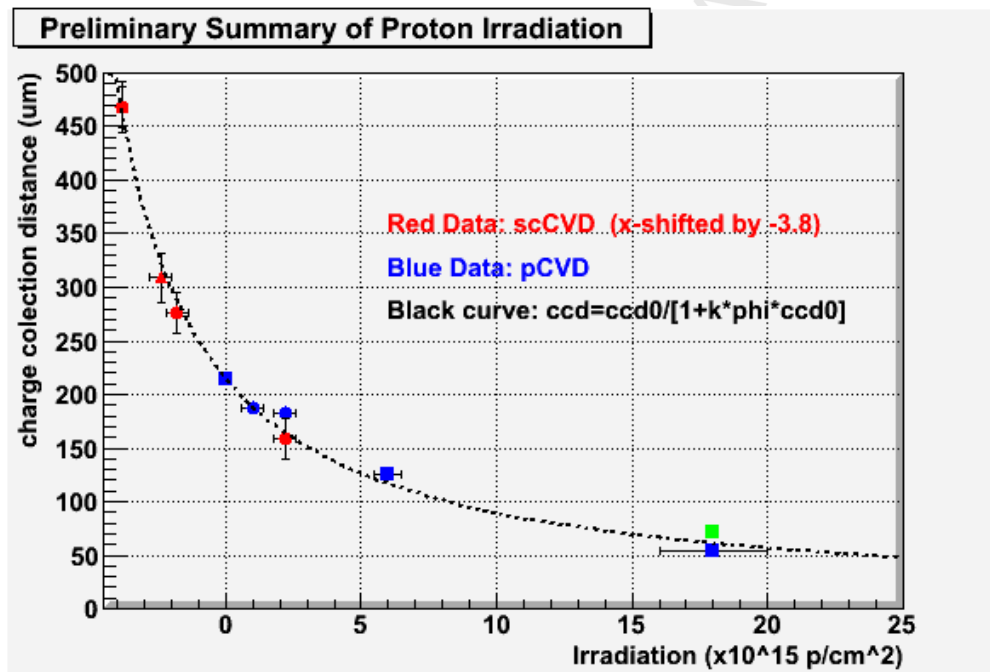
The proposal now includes a plot with 19.4 microns resolution and states that the telescope resolution was 11 microns leading to 16 micron position resolution in the diamond module. We are looking for a plot of the 'final' results on the pCVD module that indicated a sensor resolution of 14 microns. We expect that this will improve with the irradiation. The first test of the irradiated module was in October 2007. Results are expected over the winter.

3. Clarify charge collected with fluence (not scaled to 1.0). Explain what data is available. Explain RD42 will continue to improve on this, and this proposal is not aimed at single detector performance, which is left to RD42. (I think no data is available for 300 micron CCD. You therefore have to use data from sensors with 140-180 CCD. Clarify fig. 15 - use noise of 140.

See details in answer to Nanni's comments above. For our large dose irradiations we used 190 and 215 micron collection distance material. These diamonds were the best "research" diamonds available when the irradiations were performed and now correspond to the typical production diamond (as shown in Figure 4 of the proposal). To produce figures 14 and 15 (now figures 16 and 17) in the proposal the mean noise measured was 140 electrons.

In order to estimate the radiation damage effects on diamond as the collection distance increases 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 polycrystalline material. By comparing the effective damage constants (k) for the two different materials we can definitively answer the question whether high quality material is damaged more quickly than lower quality material. Figure 2 (next page) shows that a single damage constant describes our observations for both materials.

In Figure 2 we overlay the collection distances so that 0. on the x-axis corresponds to the un-irradiated collection distance of our pCVD material (215 microns). In addition the scCVD fluences are shifted by -3.8×10^{15} p per 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} protons/ cm^2 . The data indicate a single damage constant $k \sim 6.5 \times 10^{-19} \text{cm}^2/\text{micron}$ for both materials indicating that the next generation of material should follow similar curve.



3b. Summarise the results of CERN 2006 testbeam.

The proposal is updated with these.

4. Add more details on where help is needed; generally make it easier for people to join.

We have added a paragraph after section 4.8 making it clearer which areas we think could use more help.

5. Clarify that the main work is towards 2016 sLHC upgrade, but b-layer replacement could be possible in 2012.

Yes. The abstract makes this clearer now.