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STATUS REPORT OF THE RD-8 COLLABORATION

Presented by K.M.Smith,
(University of Glasgow),
for

The GaAs Collaboration

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1 Introduction

The main objectives of the collaboration during the last year have been: -

- testing of microstrip detectors of close to LHC specifications, fabricated 'in-house' and commercially
- understanding of the properties and limitations of these detectors
- continued investigation of alternative wafer materials and detector fabrication technologies
- evaluation of the radiation-hardness of GaAs detectors to charged particles as well as to neutrons
- continued efforts to develop a detailed understanding of the costs of commercial detectors
- evaluation of GaAs pixel detectors, fabricated 'in-house' and commercially

GaAs microstrip detectors are now very close to achieving the performance goals for operation at the Large Hadron Collider in terms of low temperature operation, signal to noise ratio, speed and spatial resolution. Optimisation of the detector strip geometry is now possible, using data obtained from a range of prototypes. Operation at low temperatures, compatible with the requirements of silicon microstrip detectors, has been shown to present no problems. Pixel detectors have also been successfully tested. Recent results indicate a greater sensitivity to radiation damage by pions and protons than expected, however. Further investigation of this sensitivity is now in progress.

2 Material and Processing Issues

The incomplete collection of the charge released by ionising radiation in GaAs Schottky diode detectors has been studied using a variety of experimental techniques. The results are all consistent with an approximately linear growth in the sensitive thickness with increasing reverse bias [1, 2]. This behaviour has been successfully simulated in a Monte Carlo model [3] based on the effect of deep traps close to the Fermi Level in the middle of the bandgap. Band bending at the metal-semiconductor boundary leaves these traps ionised and the resulting space charge creates an electric field distribution which differs from that found in silicon junction devices. The measured signal from a detector is then due to the efficient collection of charge released in the 'high-field' region next to the Schottky contact, with relatively poor collection from the remaining 'low-field' region.

Efforts continue, however, to try to improve our understanding of the charge collection process using simple, pad detectors. The Prague and Freiburg groups have utilised Van de Graaf accelerators as sources of variable energy protons and deuterons with which to probe the variation with depth of the charge collection efficiency (c.c.e.). Systematic studies have also been carried out aimed at identifying the optimum substrate material, based on measured correlations between detector performance and material characteristics. Figure 1 from the Sheffield group, for example, shows the measured correlation between wafer resistivity and the c.c.e. for illumination of a simple, pad detector by an alpha particle source.

Detailed investigation of the nature of the charge trapping centres in the substrate have been carried out within the collaboration and elsewhere,[4, 5, 6]. Models have also been developed of the charge collection inefficiency, involving $EL2-EL2^{+}$ transitions within the high electric field region of the reverse-biased diode detector[6, 7]. As yet, no outstanding feature has been found which would unambiguously identify the optimum material, although the last year has revealed more encouraging signs of some correlations between detector performance and certain material properties.

The Freiburg group has also tested detectors fabricated on liquid-phase epitaxial (LPE), high purity layers with charge carrier concentrations of $< 10^{14}/cm^3$. It is difficult to reach this quality in the layer thicknesses of $100\mu m$ or more desirable for high energy physics applications, however, and the high quality of surface finish required for good detectors has also proved difficult to achieve in a consistent way.

Improved fabrication technology of GaAs detector electrodes has been demonstrated by the Modena group with Alenia SpA, Rome, using ion implantation and also non-alloyed ohmic contacts [8]. The

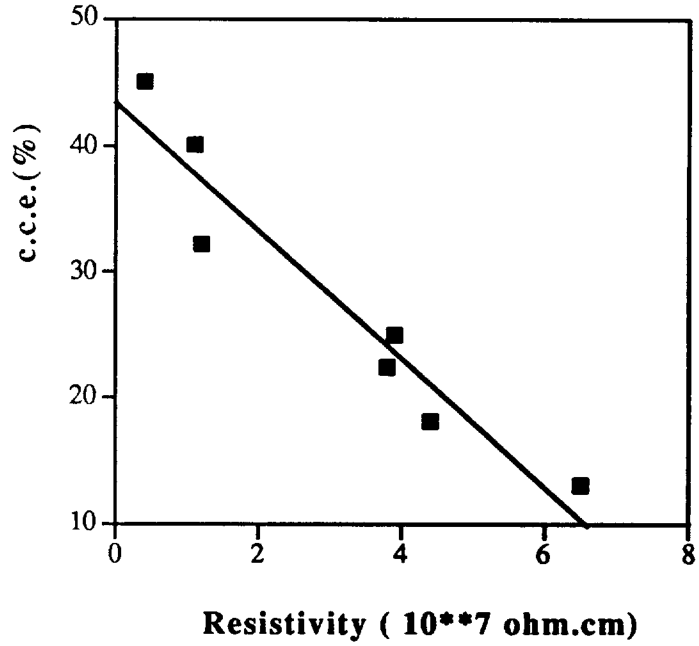


Figure 1: Variation of c.c.e. with GaAs substrate resistivity

reverse bias operating range has been substantially extended thereby, and maximum charge collection efficiency achieved more reliably.

3 Charge Transport and Collection in Simple Pad Detectors

As shown in Figure 2, it is now possible to achieve 100% charge collection efficiency in simple Schottky barrier detectors on standard semi-insulating, undoped (SIU) GaAs wafers even with standard electrode metallisation, although more reliably with the methods referred to in the preceding paragraph.

In Russia, the Tomsk group has continued to develop the fabrication technology which creates a so-called $\pi - \nu$ region inside the wafer thickness by in-diffusion of deep-level dopants of iron or chromium[9]. Early versions of these detectors were shown to possess excellent radiation hardness against neutron irradiation, but were not sensitive through the full thickness of the wafer. More recent samples have 'dead' layers which are less than 10% of the total thickness and also provide a good c.c.e., as shown in Figure 3.

4 Microstrip Detectors

Our aims in test beam running this year were firstly to investigate commercially produced microstrip detectors and secondly to continue studies of microstrip detectors fabricated in our own laboratories. Our studies focused in particular on defining the optimum strip pitch and aspect ratio, position resolution achievable and the effects of wafer and processing variations in detector fabrication.

Microstrip detectors, typically 25mm wide and 25 or 52mm long were made 'in-house' in the Universities of Glasgow, (Department of Electrical and Electronic Engineering), Sheffield, Aachen and Freiburg. Commercial prototypes were produced by EEV (Chelmsford), Alenia SpA (Rome) and the SPTI (Tomsk).

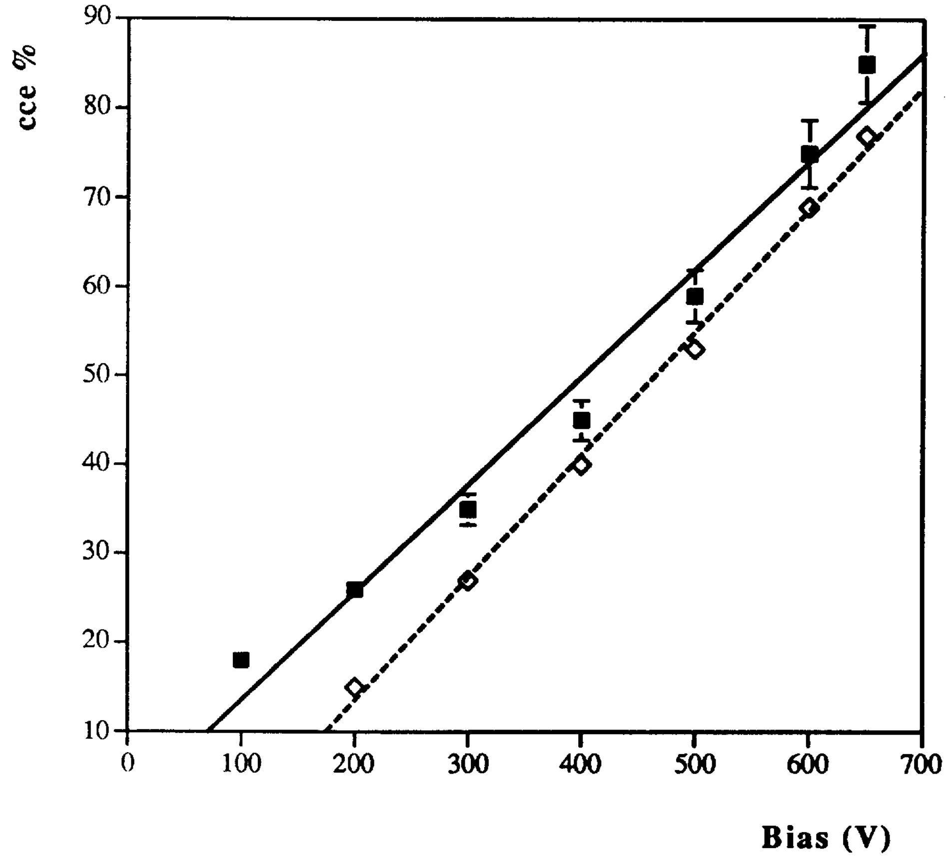


Figure 2: C.c.e. vs. reverse bias for a 510μm thick Glasgow pad detector, at 20^oC (solid squares) and -10^oC (diamonds)

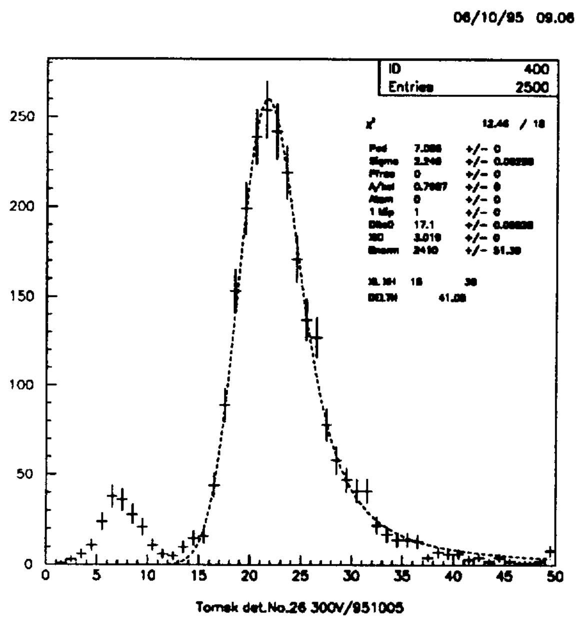


Figure 3: Pulse height distribution from mips in a recent Tomsk pad detector, measured with a NICON fast preamplifier. The most probable charge signal is around 17000 electrons for 300V bias

The Freiburg detectors were the first GaAs microstrip devices to be tested in the H8 test beam with LHC-compatible electronics, using the Premux 128 front end chip with a shaping time of 45 nsec to read out the charge signals. One EEV detector with 11mm long strips, tested by the Melbourne group, was read out by a DHARP chip. The other microstrip devices tested were all read out using Viking VA2 read-out electronics [10]. These had strip lengths of 25mm or 52mm and a $50\mu m$ pitch, apart from the Aachen detectors which were tested with 50GeV/c electrons in the X3 beam and used $200\mu m$ pitch microstrips with $100\mu m$ wide electrodes.

The Glasgow, EEV and Alenia detectors used a 'punch-through' bias strip, placed close to the detector strips. One short strip version was A.C.-coupled to the VA2 read-out electronics using a silicon nitride dielectric layer between the two layers of strip metallisation. The semi-insulating substrates were thinned and carefully polished to 200 μm thickness. The strip electrodes were 30 μm wide on a 50 μm pitch. The other detectors were biased using R-C decoupling chips between the strip electrodes and the preamplifiers. Tests were also made with $50\mu m$ pitch detectors having $10\mu m$, $25\mu m$ and $40\mu m$ metallic strip widths, to study the influence of the interstrip capacitance on detector performance.

The detectors were operated in high energy particle beams at bias voltages close to breakdown, chosen to optimise the charge collection efficiency. The beam was defined by a silicon microstrip detector telescope with a spatial resolution of around 3 μm [11].

Figure 4 shows the signal to noise ratio and cluster size obtained with the Aachen detector as a function of the angle of incidence of the test beam electrons on the microstrips and of the (metal/pitch) aspect ratio of the electrodes.

Eta distributions and cluster pulse height information obtained with the $50\mu m$ pitch Freiburg detectors with Premux128 read-out are shown in Figure 5.

Similar results were also obtained with Alenia, EEV and Glasgow detectors using the slower peaking time read-out with VA2. In each case, the spatial precision achieved was at least as good as $(pitch/\sqrt(12)$. The signal-to-noise ratios varied with the strip length, but it is difficult to make a detailed comparison among the different detectors because of the differences in beam particle type, read-out shaping time and system noise associated with the different test beam environments. Figure 6 shows one example of the

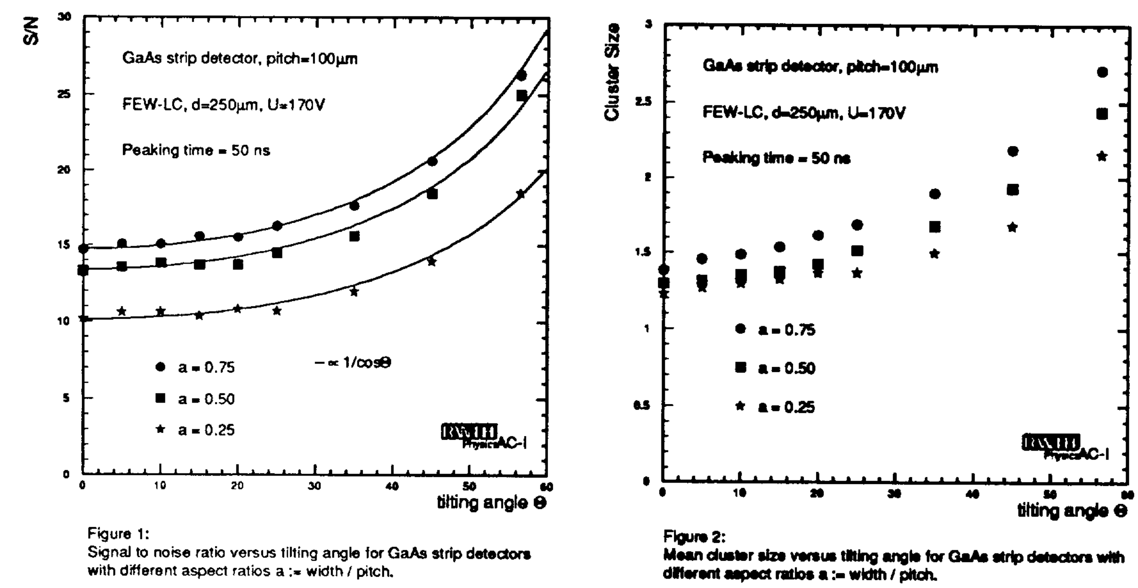
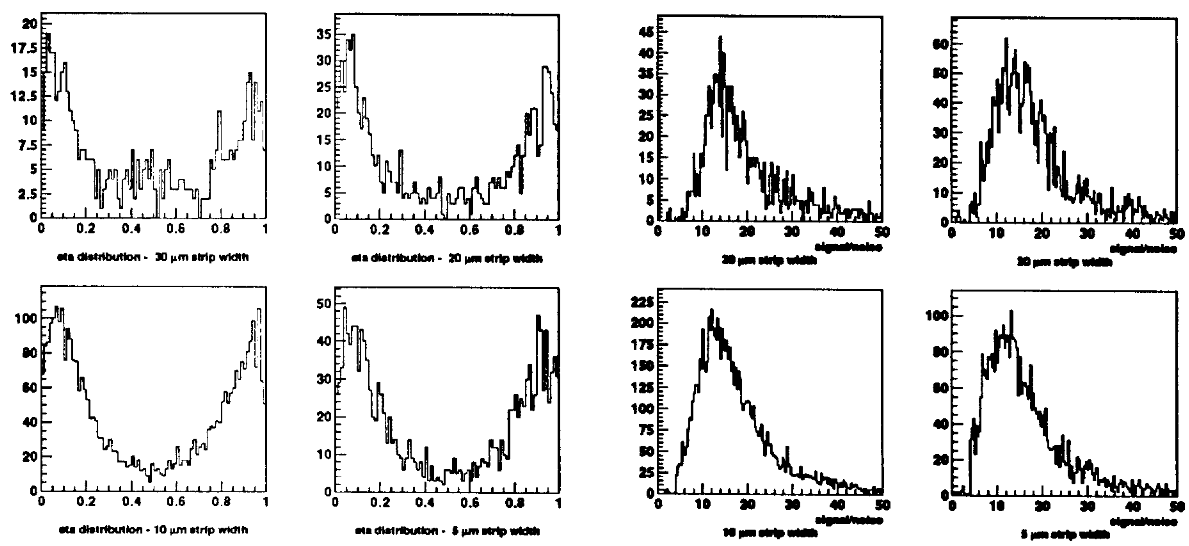


Figure 4: Signal-to-noise and cluster size versus angle of incidence and metal/pitch ratio for Aachen 200μm pitch detector in 50GeV/c electron beam



(a) η distributions

(b) Pulse height distributions

Figure 5: Distributions from Freiburg 50μm pitch detector with Premux128 read-out

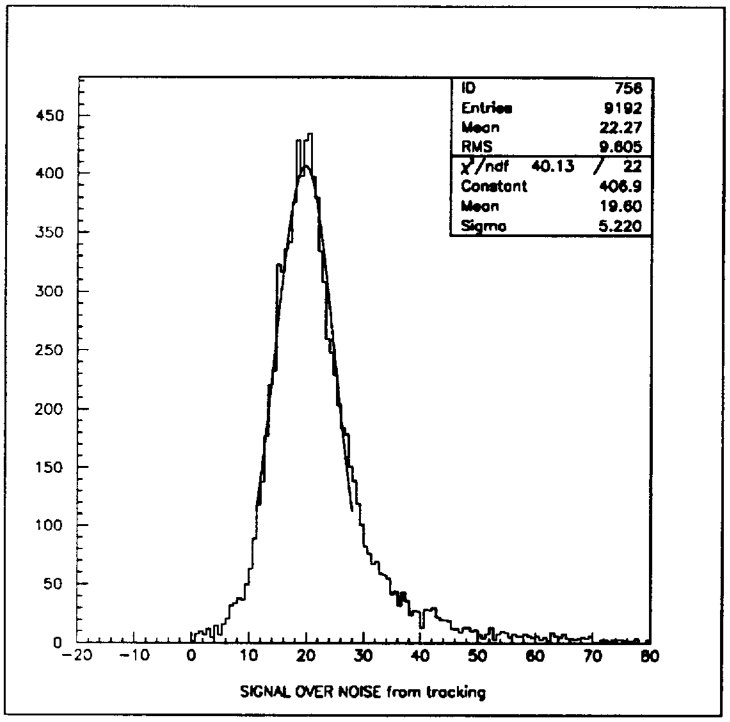


Figure 6: Measured signal to noise from 12mm long strips of the EEV prototype detector

Microstrip Detector Performance					
Bias Method	Detector	Strip length(mm)	$\tau(nsec)$	S/N	$\sigma(\mu m)$
Punchthrough	A.C. Alenia	25	300	15.5	9
Punchthrough	Long Alenia	52	400	8.0	12
Punchthrough	Glasgow (G114)	25	300	18	14
R-C	EEV	12	1400	20	13
R-C	Freiburg (premux128)	25	50	19	n.a.
R-C	Tomsk-Protvino	25	1400	(>6)	n.a.
R-C	EEV (DHARP)	12	45	n.a.	n.a.

Table 1: Summary of preliminary analysis of microstrip detector performance

measured signal-to-noise obtained with the 12mm long strips of the EEV detector in the H8 pion beam.

Preliminary analyses of the test beam data are summarised in Table 1. (Results are all preliminary - n.a. indicates that even the preliminary analysis is not yet complete.) Optimisation of the biasing geometry will continue with the production of further commercial prototype detectors incorporating a range of test structures.

5 Pixel detector tests

16×64 GaAs pixel detector arrays with pixel size 75 $\mu m \times 500$ μm were fabricated on a polished 200 μm thick semi-insulating substrate and bump-bonded to CERN Omega 2 read-out chips [12] at GECMMT, Caswell Labs. Figure 7 shows the measured beam profiles and a single event obtained from this first, three layer GaAs pixel detector telescope in a high energy test beam. An innovation in these tests was the use of the charge signals from the back ohmic contact of the pixel detector for triggering purposes. This has potential advantages in the use of GaAs pixel detectors for medical X-ray imaging [13]. The spatial resolution of the GaAs pixel detectors measured by the Genoa group in the RD19 test beam is illustrated in Figure 8. The variation of track-finding efficiency across the array, also shown in this Figure, illustrates the uniformity of the response [14].

6 Radiation Hardness Studies

Simple Schottky barrier pad detectors have been exposed to $\sim$ 1MeV neutron fluences of up to $10^{15} cm^{-2}$ at the ISIS irradiation facility, RAL [15]. The variation with neutron fluence of the most probable signal from minimum ionising particles (mips) is shown in Figure 9.

The signal from GaAs detectors operated for ten years of LHC running is likely to fall by roughly a factor of two from its initial value, with no change in bias voltage. Evidence from the Sheffield group that the loss in signal charge is associated with a large drop in the hole component is shown in Figure 10, where the signal from alpha particles illuminating the back, ohmic contact is shown as a function of reverse bias. Since the alpha particle range is only around 20 μm in GaAs, almost all of the observed signal is due to holes in this case.

The increase in reverse bias leakage current, around a factor of three, is much less than the corresponding change in silicon detectors. Figure 11(a) shows the reverse bias current-voltage (I-V) characteristic and the c.c.e. of a neutron-irradiated pad detector. The c.c.e. plateau begins at a bias voltage close to the onset of 'soft' breakdown of the detector. As seen in Figure 11(b), the $1/C^2 - V$ characteristic, where C is the capacitance measured at 120 Hz, shows the same trend.

Samples of Schottky barrier pad detectors were exposed to 24 GeV protons from the CERN PS at the level of $\sim 10^{14} cm^{-2}$. The degradation in charge signal with dose, also shown in Figure 9, is significantly worse than that observed for comparable neutron fluences. In Figure 12(a), which shows the reverse bias I-V curves for $160 \mu m$ and $500 \mu m$ thick GaAs detectors, there is little difference between the curves up to the onset of 'soft' breakdown in the thinner detector, suggesting that surface, rather than bulk effects may be more significant in the damage process. It is also worth noting that there is a noticeable increase in reverse bias leakage current after only $\sim 10^{13} p/cm^2$, after which the leakage current appears to stabilise, as shown in Figure 12(b). Such an effect is not observed in typical silicon detectors.

The sensitivity of the c.c.e. in GaAs to high energy protons has also been observed by the Aachen, Freiburg, Protvino and Sheffield groups, as illustrated for example in Figure 13. This sensitivity is also in marked contrast with the behaviour in silicon detectors [16].

Measurements of the extent of pion-induced damage in GaAs at PSI, Zurich, have shown similar sensitivity, as illustrated in Figure 14(a) in which the charge signal from pion- irradiated detectors appears to reach a limit after irradiation which is independent of the physical thickness of the detector. The corresponding mean free path for charge carriers is shown in Figure 14(b). The electron and hole mean free path after irradiation may also be obtained from comparisons of the measured response to alpha particles with predictions of the Monte Carlo model of charge transport and trapping referred to above. The predicted evolution with pion dose of the signal due to minimum ionising particles is shown in Figure 15. A summary of the range of substrate materials and detector thicknesses tested by the Aachen group is given in Figure 16.

Characterisation of irradiated detectors using techniques such as PICTS, CTS and TSC is also in progress, together with an evaluation of the potential benefits of various annealing treatments.

Investigations of the trapping centres in neutron-irradiated Schottky diode detectors have recently been reported [4, 6, 17]. No single trap has yet been unambiguously identified as responsible for the degradation in detector performance. Nevertheless, there is some evidence of the influence of the $EL2^+$ level on detector performance,[6, 7, 17].

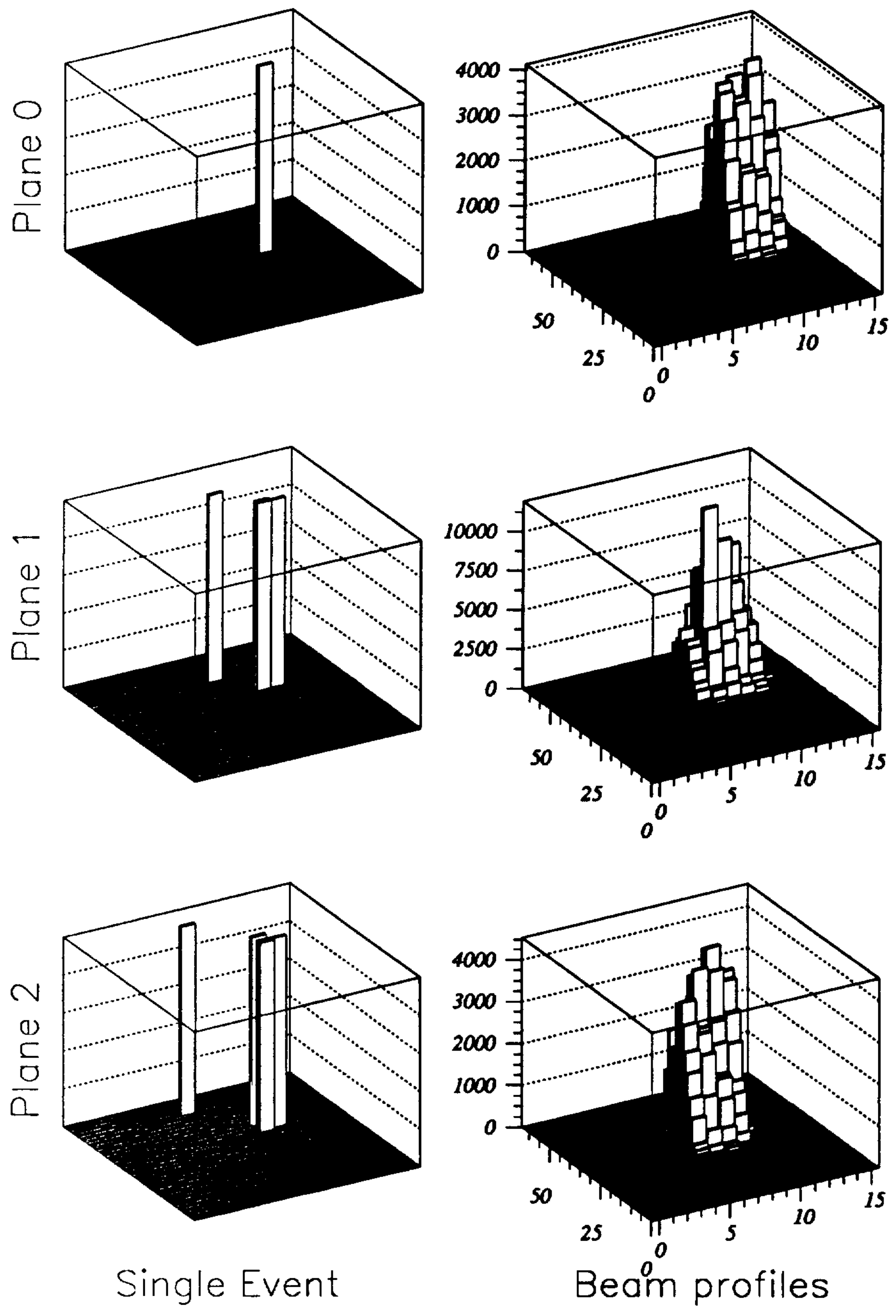


Figure 7: Beam profile obtained from a telescope of three GaAs pixel detector arrays coupled to Omega 2 read-out chips

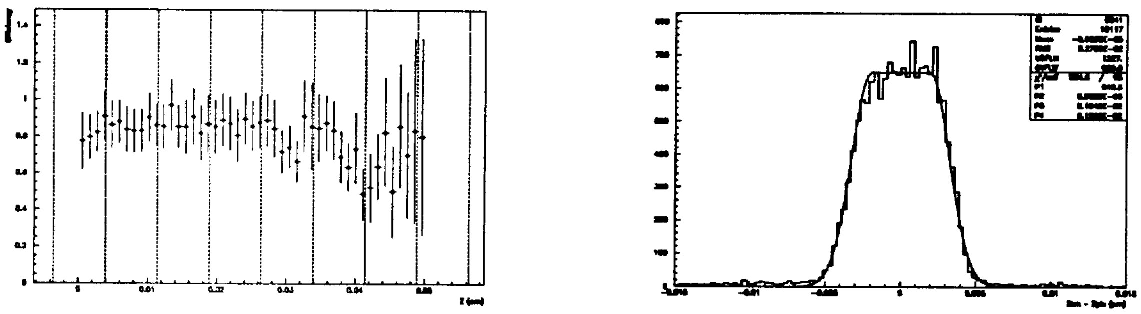


Figure 8: Performance of GaAs pixel array in the RD19 test beam run; uniformity of efficiency across the pixel and distribution of track residuals

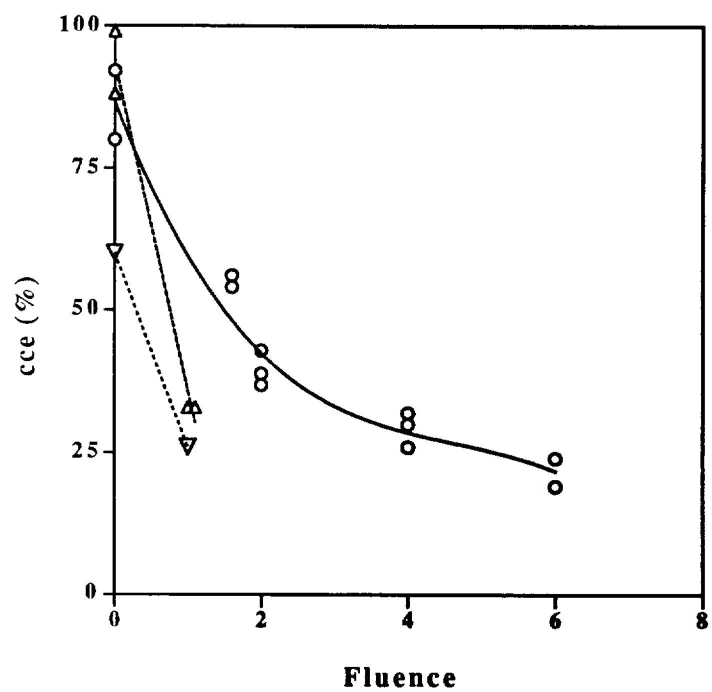


Figure 9: C.c.e. vs. fluence ($\times 10^{14}/cm^2$) for 24GeV proton ($\Delta and \nabla$) and $\sim$ 1MeV neutron ($\circ$) irradiations

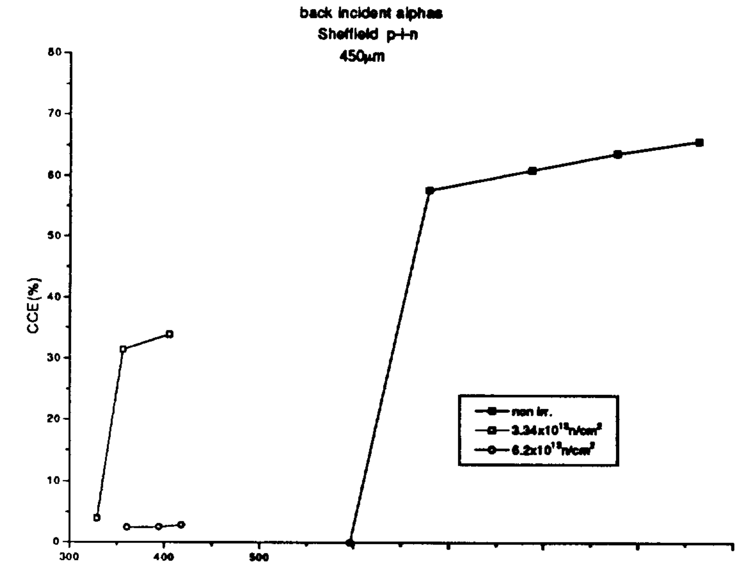
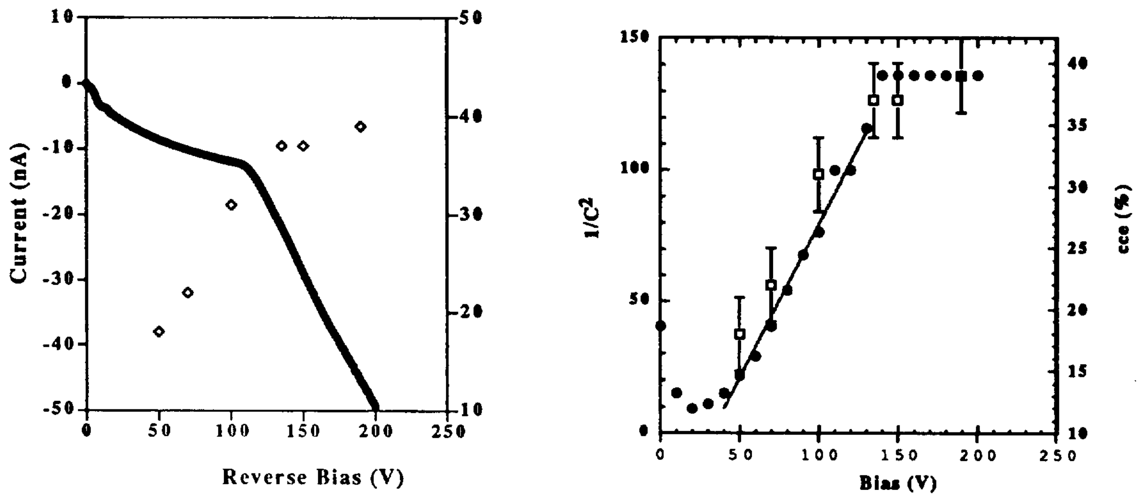


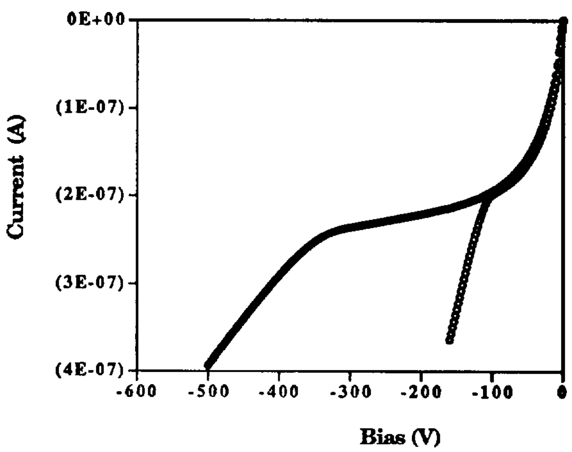
Figure 10: Charge signal with b



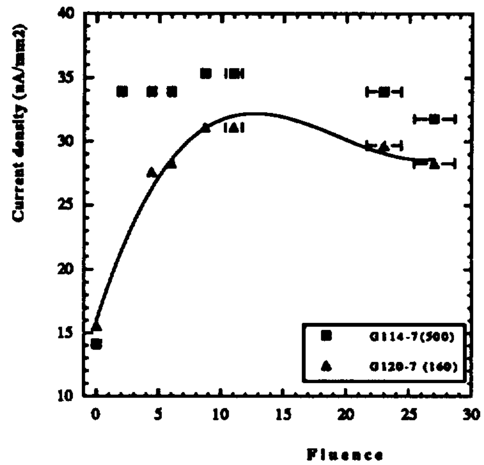
(a) I-V (•) and c.c.e.(◇)

(b) $1/C^2$ (•) ($\times 10^6 cm^4/pF^2$) at 120 Hz and c.c.e.(□)

Figure 11: Detector characteristics vs. bias after $2 \times 10^{14} n/cm^2$



(a) reverse bias I-V characteristics



(b) Leakage current density vs. 24 GeV proton fluence ($\times 10^{13}/cm^2$)

Figure 12: Comparison of $7mm^2$ $150\mu m$ and $500\mu m$ thick detectors after irradiation with 6.0 $10^{13}p/cm^2$

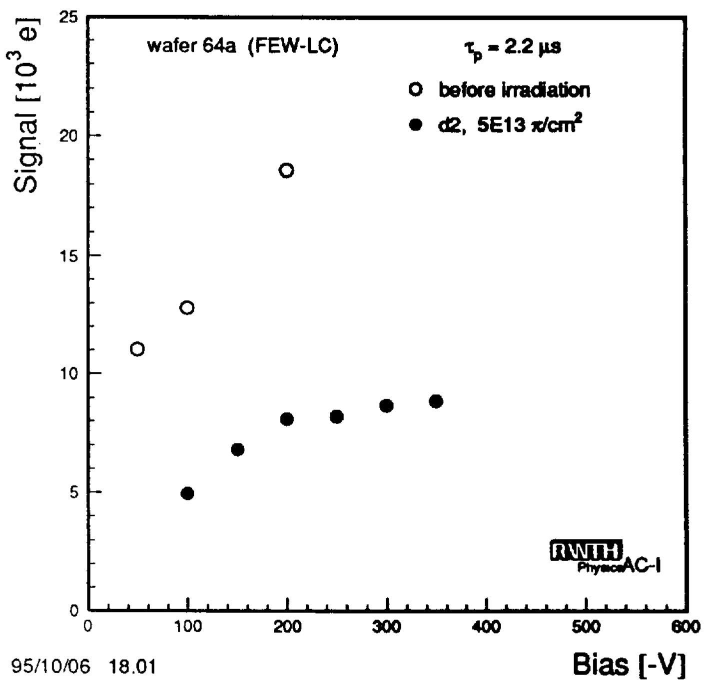
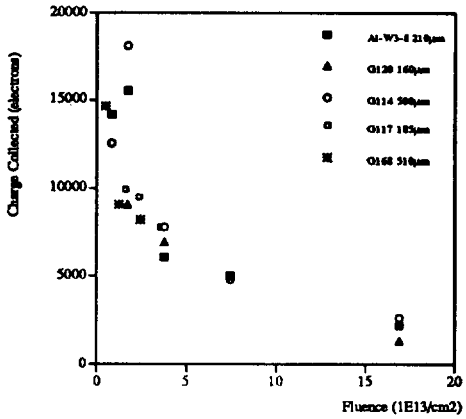
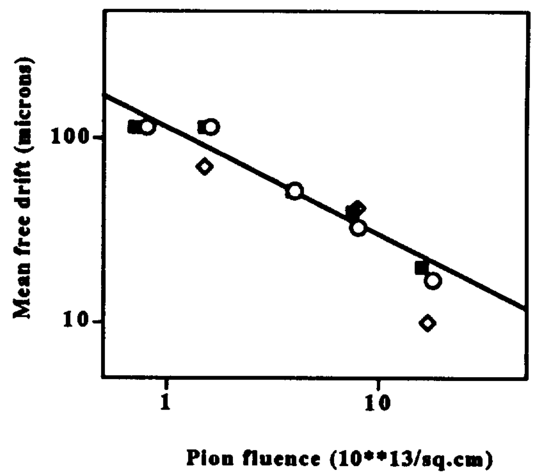


Figure 13: Charge signal versus bias before and after irradiation with 24GeV/c protons



(a) Charge signal



(b) Mean free path for carriers

Figure 14: Charge signal from mips and mean free path of charge carriers versus pion fluence

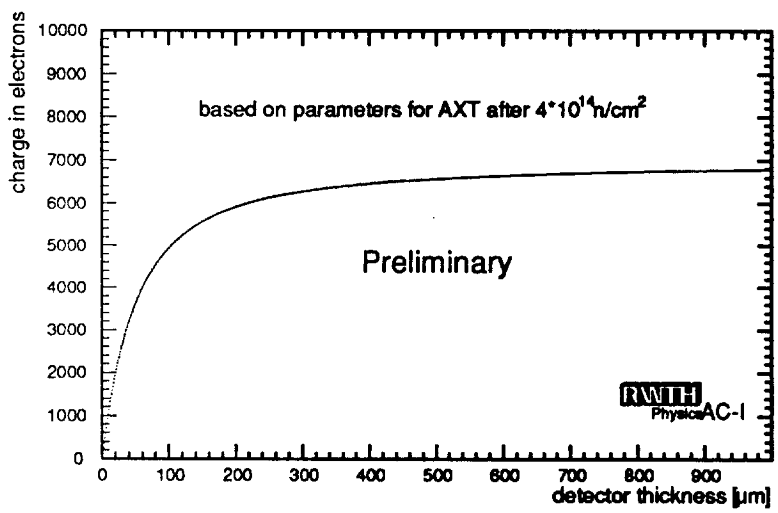


Figure 15: Signal charge from mips versus irradiated detector thickness from Monte Carlo simulation

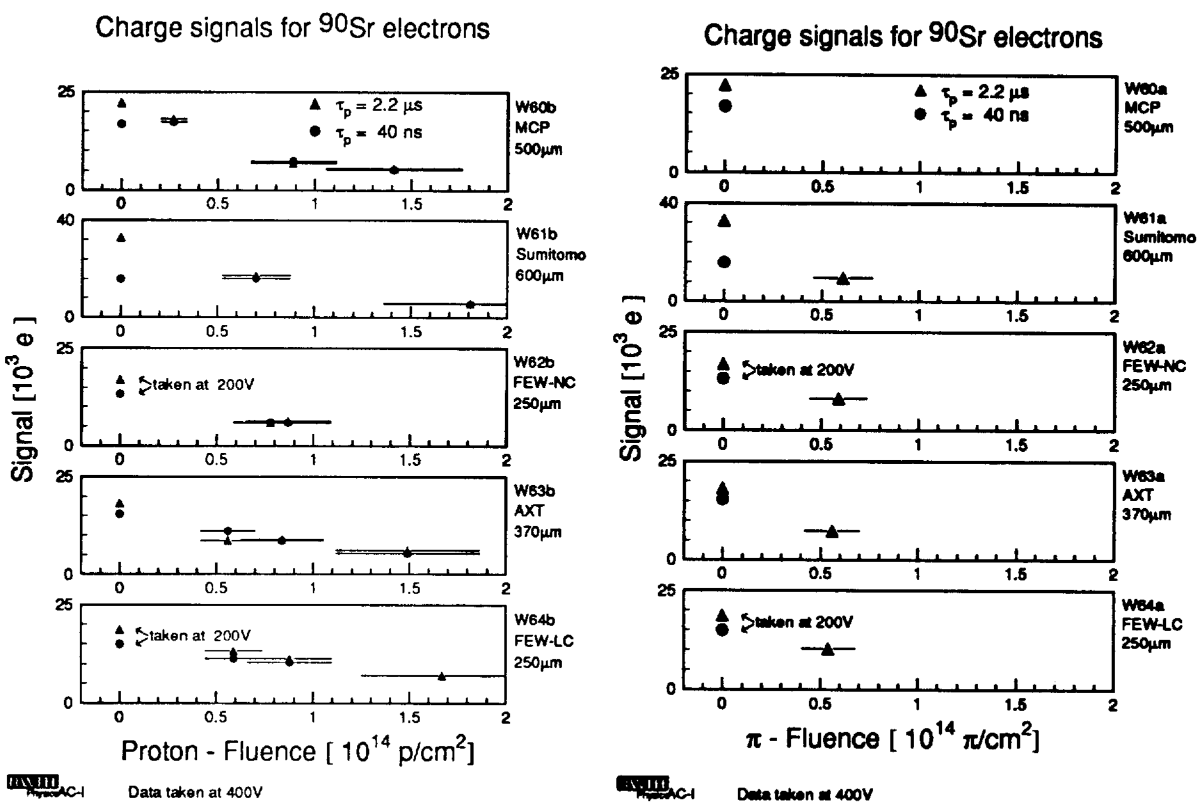


Figure 16: Measured charge signals from irradiated detectors tested by the Aachen group

7 Requests to LDRB

Commercial production of GaAs microstrip and pixel detectors by more than one source has been successfully achieved this year. Discussions with some manufacturers concerning the probable costs of large scale production of these detectors lead to optimism that the final costs can be competitive with those for silicon detectors. The resources allocated to RD8 for further purchases this year of commercial prototype detectors have not yet been used, because of our desire to extract as much information as possible from the first generation of commercial detectors and also because of the unexpected sensitivity to charged particle irradiation which was discovered early this summer. When a thorough review of the latter measurements has been made, we plan to place orders for at least one production run of microstrip detectors during this year, to allow continued development of commercial production of these detectors. Detailed tests of these detectors would entail test beam running, which we plan to incorporate in ATLAS, CMS and RD19 test beam periods. In addition, we propose to carry out further proton irradiation tests with 24 GeV protons at the PS and pion irradiation at the P.S.I., Zurich. We bid in addition for consumables costs, associated with the 'generic' part of our activity in pixel detector development and extended radiation hardness studies. These costs are associated with wafer and mask purchase and processing in our own labs. and particularly for development of double-sided detectors using the Tomsk fabrication technology and commercial bump-bonding of a further sample of 10 pixel detectors to the new Omega3 read-out chips.

We bid also for a modest allocation of computing time on central CERN computers, to allow the partial analysis of our test beam data.

Summary of requests		
Consumables, (Wafers,Masks,Bump-bonding etc.)		10kSfr
Total		**10kSfr**
Computing time	VXCERN	10hrs
	CERNVM	10hrs
PS irradiation test beam time		10 days

8 Conclusions

GaAs microstrip and pad particle detectors are now close to achieving the performance specifications required for LHC operation. Microstrip detectors of an area close to that needed for the ATLAS forward tracker wheels, for example, are now available commercially. Further developments are required to optmise the detector geometry and fabrication technology. Choices of single- versus double-sided detectors, A.C.- versus D.C.-coupling and simple Schottky versus 'Tomsk' technology have still to be resolved on the basis of continuing detailed evaluation of more refined prototypes. It has been demonstrated experimentally that the read-out electronics for GaAs detectors can be identical to that used for silicon and that operation at the lower temperatures required for silicon presents no real difficulties. A test beam telescope made up of GaAs pixel detectors has been successfully used for the first time. The X-ray imaging potential of GaAs has also been demonstrated.

The radiation damage induced by high energy protons and pions in GaAs has been shown to be more serious than that due to 1MeV neutrons and represents our major cause for concern at present, since pions represent the main source of irradiation damage at the LHC. Our priority in the next few months is to carry out a more comprehensive, quantitative evaluation of the magnitude of this problem and to examine possible explanations for the sensitivity and potential methods for alleviating the problem. Microscopic characterisation of the damaged substrate material may provide clues to the detailed nature of the damage and suggestions for improving the response.

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