2 DOSIMETRY OF HEAVY IONS BY USE OF CCD DETECTORS

J.U. Schott

ABSTRACT

The design and the atomic composition of Charge Coupled Devices (CCDs) make them unique for investigations of single energetic particle events. As detector system for ionizing particles they detect single particles with local resolution and near real time particle tracking. In combination with its properties as optical sensor, particle transversals of single particles are to be correlated to any objects attached to the light sensitive surface of the sensor by simple imaging of their shadow and subsequent image analysis of both, optical image and particle effects, observed in affected pixels. With biological objects it is possible for the first time to investigate effects of single heavy ions in tissue or extinguished organs of metabolizing (i.e. moving) systems with a local resolution better than 15 microns. Calibration data for particle detection in CCDs are presented for low energetic protons and heavy ions.

INTRODUCTION

Typical experiments with single heavy ions in physics and applied sciences make use of particle track detectors for particle counting, the analysis of its parameters and geometrical correlations of the accumulated particle tracks. Their well fitting into the requirements of many experiments on earth and in space, easy handling, simple set ups, high efficiency, high reliability and low cost, enforced the investigation and development of a big variety of different detector materials and systems. However, the basic electronic and ionic properties of track forming solids rules out the acquisition of time resolved information, in general. Except with AgCl detectors [1], local and temporal data of single particles can be achieved in extended experimental set ups, only, i.e. [2]. Charge sensitive semiconducting micro devices, arranged as matrix elements on a silicon layer give access to both: time resolved data from prompt electronic signals or read out sequences, as well as local information from the position of the responding element. Out of the big variety of high integrated electronic circuits like memories and charge sensors, Charge Coupled Devices (CCDs) combine particle detector qualities with optical sensing, an interesting feature for applications in many fields with time resolved single particle experiments [3].Easy handling and read out with well established methods of TV techniques and image analysis together with their high resistance against the environmental factors of space flight makes them useful for basic radiobiological investigations with metabolizing systems in the space radiation field. Geometric measurement of particle traversals are simply derived from column and line numbers of pixels affected. The correlation of particle effects measured in single pixels with parameters of the particle are to be investigated at accelerators.

DETECTION OF PARTICLES IN CCDs

The use of CCDs for particle detection is based on the detection of charge carriers being produced by transversing ionizing particles, separated and stored in single pixels, thereafter.

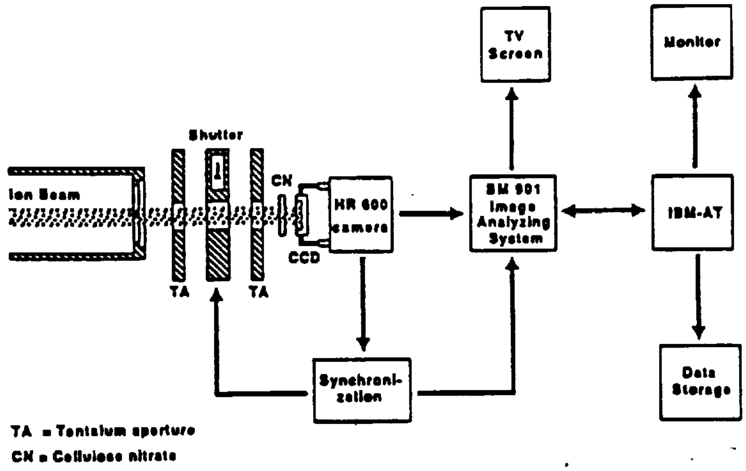

Figure 1: Experimental set up.

Out of all imaging sensor concepts, CCDs of the frame transfer type guarantee a full area sensitivity with a clear-cut correlation of the loci of charge production and storage to the co-ordinates of the read out channels of the pixel matrix.

METHODS AND INSTRUMENTATION

In order to simplify the overall instrumentation for the data acquisition of particle detection and optical imaging, we decided to use standard TV techniques and image analysis. The response of single pixels of a 1/2" format VALVO sensor type NXA 1011 with 600 x 576 pixels of 10 x 15 μm of size, used in a AQUA camera type HR 600 has been analyzed with an image analyzing system BM 901. It permits to digitize and store the data of a sequence of up to 8 full frames with a resolution of 8 bit in real time. Fig. 1 shows the experimental set up.

For a clear correlation of data measured to the effect of ionizing particles, some measures have been taken into account:

1.) The exposures are to be limited to the integration phase of one frame (particle image), only, in order to avoid potential permanent damage of pixels by single high LET particles or by accumulating effects. A TV synchronized shutter system permits short particle exposures into one single frame.

2.) In order to discriminate against the response of single pixels due to any other reason than to actual particle exposure, the particle images have been corrected with frames (dark images) taken prior to the particle exposure, pixel wise.

3.) In the case of particles with sufficiently high linear energy transfer (LET) and range, a 100 μm thick cellulose nitrate (CN) foil in front of the CCD has been exposed together with the particle image for comparison purpose of the pattern of effects on both systems.

CALIBRATIONS

Exposures have been performed with protons, alpha particles and low energetic heavier ions at the accelerator of the University of Frankfurt, with heavy ions of medium energy at

Linie	Column								
	610	611	612	613	614	615	616	617	618
324	0	0	0	0	0	0	1	0	0
322	0	0	1	0	0	0	0	0	0
320	0	0	0	0	0	0	0	0	1
318	0	0	30	156	134	48	36	0	0
316	0	2	48	196	161	48	37	0	0
314	2	0	21	128	115	39	17	0	0
312	0	0	0	4	4	0	0	0	0
310	0	0	0	0	0	1	0	0	1
308	0	0	1	0	0	0	0	0	0

Table 1: Single Event upset in a NXA 1011 charge coupled device caused by an uranium ion (15 MeV/u). Numbers give the 8 bit digitized read out of the pixel elements of the corrected matrix.

GSI, and at GANIL with even higher energies at typical fluxes of 10^4 - 10^5 particles/cm^2s.

The particle exposures result in bright dots on the screen. On the digitized image one or more pixels show significantly higher amplitudes than the average of all. Table 1 shows an event from an uranium ion of 15 MeV/u in an 8 bit-digitized half image. The low background is due to a correction of the pixel matrix with an dark image taken before particle exposure.

A quantitative evaluation of the particle frames is managed by a software package. Using an iterative process, it determines the background in the pixel matrix as the mean of those pixels obviously not belonging to a particle event, and it detects pixels with values being significantly higher than the calculated background. Neighbouring detected pixel elements are put together as particle event. Thereafter a statistical evaluation is performed with respect to individual parameters of the event [4]. In a first step, the mean value of the sum of all pixel elements of each event has been plotted as signal/event against the LET of the particle. In order to exclude noise contributions of single pixel elements, events with a dimension of less than 2 pixel elements along a TV-line have been eliminated.

Fig. 2 shows spectra of particle events with more than one responding pixel as function of the contribution of all corresponding pixels from protons of different energy and 0.5 MeV/n argon ions. Fig. 3 shows the response of low energetic particles (< 5 MeV/n) in one of the tested CCDs at normal incidence against LET.

DISCUSSION

Assuming, that the effect of charged particles is based on ionization and charge separation only (damage on the semiconducting matrix, the insulation layers and dynamic effects being neglected), the pixel elements should show a linear response over a broad range of LET. Its lower limitation is given by the reset noise of thermal electrons and corresponds to a particle LET of about 6 MeV cm^2/g at room temperature. The upper limit is given by the storage capacity for electrons at an LET of some 10^4 MeV cm^2/g.

For low energetic heavy ions, the linearity of the response with LET seems to be reasonable. However, from recent exposures with high energetic heavy ions, we have reason to doubt, that the radiation effects can be described by the LET of the particle.

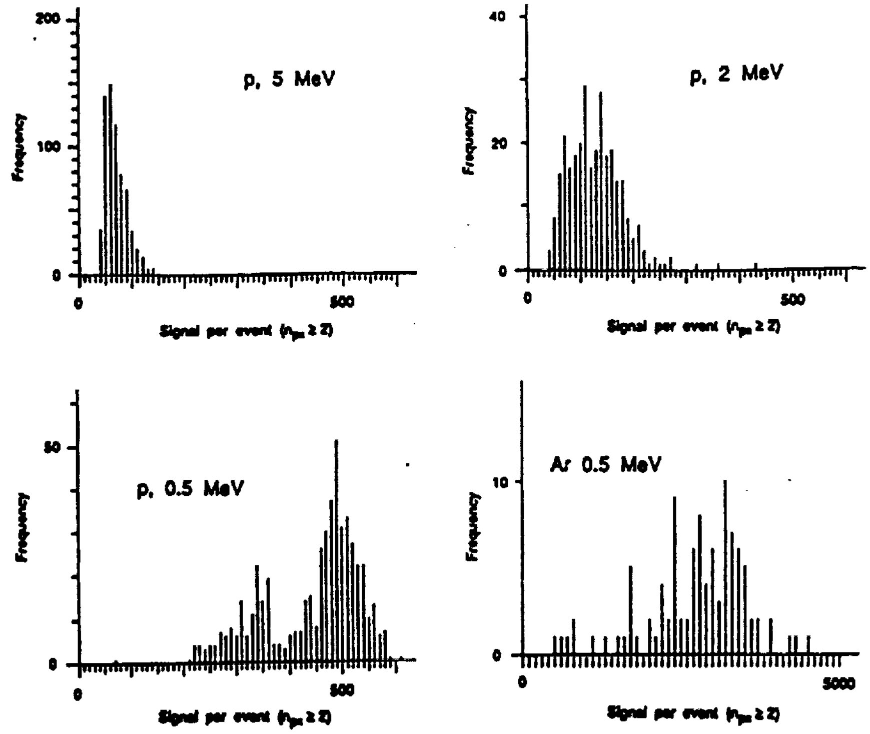

Figure 2: Spectra of proton and Ar particle events.

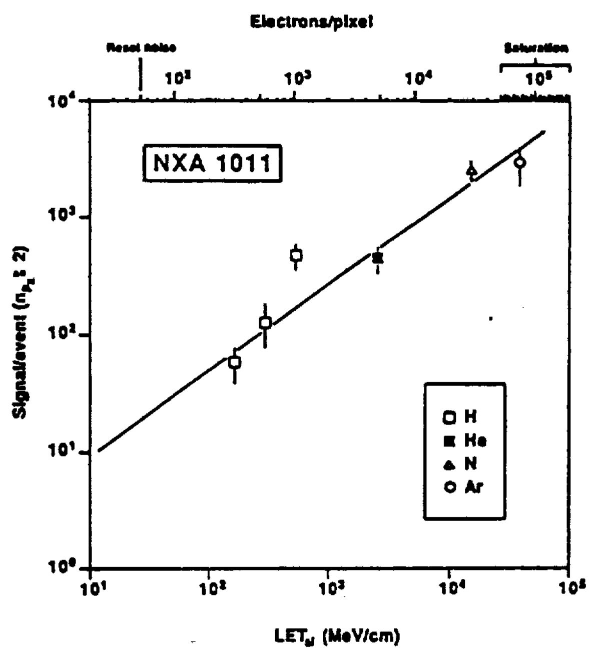

Figure 3: Response of CCD type NXA 1011 plotted against LET. The upper abscissa gives the transformation of LET into the number of electrons per pixel element neglecting other mechanisms than the production of free electrons.

only. First evaluations of exposures with Xe ions of 40 and 400 MeV/u at GANIL and SIS at GSI show a reduced response.

The local resolution for low ionizing particles with an one or two pixel response is limited to the pixel size of 10 x 15 μm. For high LET particles, forming events of big clusters of responding pixels, a better resolution is to be expected from an analysis of its charge distribution, in spite of some limitations due to structural inhomogenity of the CCD matrix [5].

The time resolution is limited by the integration phase of the CCD to 20 ms, according to the instrumentation with standard TV equipment. Leaving standards, it can be increased by orders of magnitude [6].

CONCLUSIONS

It has been shown, that CCDs can be used as time resolving detector for ionizing particles with high local resolution. Low energetic particles show a fairly linear response with LET. For the determination of high energetic particles a new concept is under development. It makes use of the angular distribution of electrons, being ejected out of a thin foil at a short distance on top of the sensors surface and detected in pixels in the vicinity of the particle trajectory. Easy read out, data analysis and high resistivity against mechanical stress factors makes these devices suitable for single particle dosimetry on ground as well as in space environments. For the EUROMIR'95 mission a telescopic device of CCDs for the detection of charged particles inside the spacecraft has been accepted, adequate hardware and software is under development. Together with their optical properties as image sensor, radiobiological investigations of single particle effects in microscopic targets with individual track correlation can be extended to metabolizing (moving) biological objects for the first time [7].

Acknowledgements

For their support with charge coupled devices and exposure facilities Philips Imaging Technology (Eindhoven), GSI (Darmstadt), GANIL (Caen), and IKF (Frankfurt) are gratefully acknowledged.

References

[1] Schopper E., Granzer G., Henig G., Schott J.U., Dardat K., Wendnagel Th., Haasa G., Zörrgiebel F., Proc. of the 8th Conf. on Nuclear Photography and Solid State Track Detectors, M. Nicolai (ed.), Bucarest (1972).

[2] Beaujean R., Schmidt M., Enge W., Siegmon G., Krause J., Fischer E., Isotopic Stack: Measurement of Heavy Cosmic Rays, Science, Vol. 225, No. 4658, 193-195 (1984).

[3] Schott J.U., Charge Coupled Devices (CCDs) - A detector system for particles with time resolution and local assignment with particle trajectories, Nucl. Tracks Radiat. Meas. 15, Nos 1-4, 81-89 (1988).

[4] Lichtenberg G., Erfassung und Auswertung schwerioneninduzierter Ladungsbilder in CCD-Elementen, Diploma Thesis, Fachhochschule Giessen/DLR (1989).

[5] Damerell C.J.S., Farley F.J.M., Gillman A.R., Wickens F.J., Charge Coupled Devices for particle detection with high spatial resolution, Nucl. Instr. and Meth. 185, 33-42 (1981).

[6] Burt D.J., CCD performance limitations: theory and practice, Nucl. Instr. and Meth., A305, 564-573 (1991).

[7] Schott J.U., Kranz A.R., Gartenbach K., Zimmermann M., Investigations of single particle effects in active metabolizing seedlings of *Arabidopsis thaliana*, Nuclear Physics at GANIL, Scientific Report 1989-1991.