RADIATION TESTS ON SOLID STATE CAMERAS FOR INSTRUMENTATION

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Abstract

Technological advances in solid state camera design have provided a wider choice of equipment for beam diagnostics, but following simulations of the expected radiation environment in the LHC knowledge of their radiation tolerance was required. Several cameras have been progressively exposed to a 60MeV proton beam and their performance degradation monitored. Following these results, further simulations have been carried out on the level of shielding needed to ensure satisfactory operation in the LHC.

OBJECTIVES

Previous experience with CCD based cameras has shown that the performance degrades with as little as 10Gy, which limits the areas in which they can be used and imposes the use of local radiation shielding[1]. It will be very difficult to provide shielding in the LHC, given the high energy of the secondary particles, which are generated by the interaction of the beam with residual gas in the vacuum chamber.

Resolution and Contrast

In order to get quantifiable data on the degradation of the sensors a simplified testing method was used. Rather than using resolution test targets to establish the Contrast Transfer Functions [2] at each radiation test point, a checker-board pattern was used as the target.

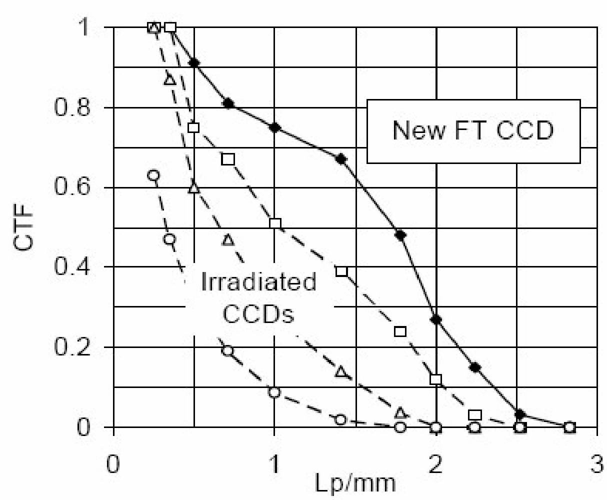

Figure 1: Contrast Transfer Function

It is assumed that the main effect of radiation damage is the loss of contrast, so that by ensuring that each square would correspond to many pixels on the sensor, problems of single pixel damage, optical resolution and speckle would be avoided. Sensors having different pixel sizes can be tested with the same equipment, each pixel in the stored bitmap image would be analyzed and a histogram produced for each radiation level, to show the loss of contrast due to radiation effects. The cameras were also to be tested under operational conditions so that Single Event Upsets (SEU's) could be noted and the risk of damage due to the devices being powered was of interest.

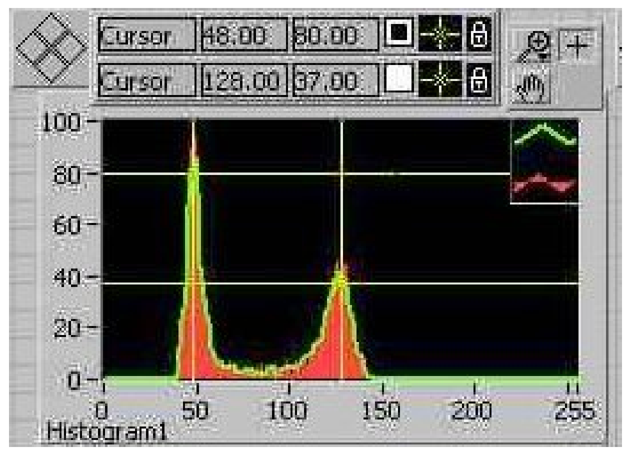

Figure 2: Histogram of pixel brightness for an area of the checkerboard pattern

Radiation Damage

Any semiconductor device operating in a radiation field can undergo degradation due to radiation damage effects. Energetic particles incident on the semiconductor bulk lose their energy to ionising and non-ionising processes as they travel through a given material. The ionising processes involve electron-hole pair production and subsequent energy deposition (dose) effects. The non-ionising processes result mainly in displacement damage effects, i.e. displaced atoms in the detector bulk and hence defects in the semiconductor lattice like vacancies and interstitials.

The solid state arrays use a structure of metal-dielectric-semiconductor that makes them sensitive to ionising radiation due to energy deposition in the gate dielectric and displacement damage in the semiconductor substrate.

Ionization effects refer to the transient effects due to energy deposition in the gate dielectric and silicon bulk. The gate dielectric in the CCD imagers is usually a silicon oxide. 3.6 eV for the silicon and 17-18 eV for the silicon oxide are needed in order to create an electron-hole pair. Electron-hole pairs are created all along the charged particle track, which may be trapped in the silicon oxide or the silicon oxide/silicon interface, swept away by the applied electric field or recombine. The processes taking place are quite fast (in the picosecond range) and depend on irradiation time, temperature, electric field and manufacturing technology.

The main consequences of the ionising processes are changes in the bias voltages applied to the devices (flatband voltage) and increase in the (surface) dark current.

The displacement damage effects are the most important source of CCD malfunction after irradiation with energetic hadrons. The hadrons interact with the atoms of the semiconductor material resulting in the displacement of some of them from their lattice positions and the creation of vacancies and interstitials. The primary defects are usually quite unstable and mobile at room temperature. This reordering might lead to recovery of some defects (annealing) or to the formation of more stable and complex ones, depending on the doping, temperature and excess carrier concentration.

These complex vacancies are the source of (bulk) dark currents in every pixel of a CCD imager. The dark current is non-uniform along the silicon array leading to random telegraph signals and charge transfer inefficiency [3-5].

During the ionisation process (electron-hole pair creation), the electron-hole recombination can be prevented by intrinsic, strong, internal electric fields. This can generate an electrical pulse large enough to disrupt normal device operation. The result can be a non-observable effect, a transient disruption of circuit operation, a change of logic state or a permanent damage to the device or integrated circuit [6,7].

High energy charged hadrons cause SEU through the highly ionising secondary fragments they produce when they collide with silicon nuclei. Neutrons do not create direct ionisation, but randomly interact with silicon nuclei producing charged secondary particles, which will further cause ionisation and possibly SEUs [6]. In general, neutrons at all energies can induce SEU in circuits. Protons seem to be harmless below an energy threshold, but SEUs might increase rapidly with increasing proton energy and finally level off at energies above 60-100 MeV. The energy threshold to induce a SEU has decreased to 20 MeV in the current technologies (in respect with that of 50 MeV at early 1990s) and tends to be further decreased to below 10 MeV due to the continuous decrease of the critical charge (lower applied voltage, smaller charge-collection volumes, increased device density per chip) [6]. As a result, SEU are expected to be one of the main future concerns related to radiation effects.

Radiation Effects in the LHC Tunnel

In the LHC tunnel and close to the beam lines (where cameras are foreseen to be installed) we expect a great variety of particles with energies of up to a few TeV (figure 2). These particles cannot be effectively shielded to protect the silicon arrays. Electronic equipment is expected to suffer the basic radiation effects, i.e. total dose effects, displacement damage and hadron-induced SEU [8].

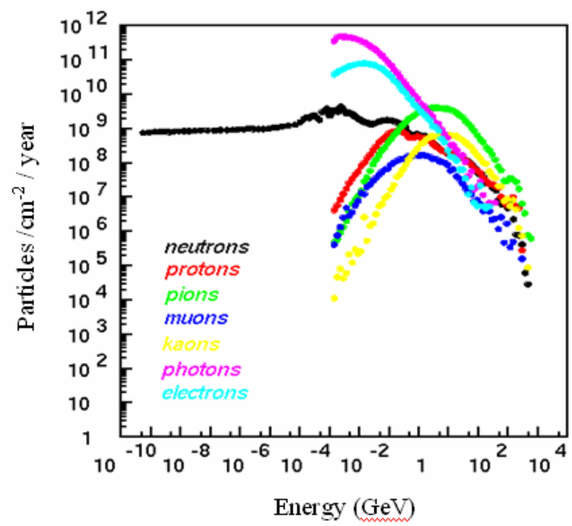

Figure 3: Annual hadron fluence in the LHC tunnel, at the region of the CCD cameras in Point 4, as calculated by Monte Carlo simulations.

Results E2V emCCD Camera

The emCCD camera was progressively irradiated starting with the sensor area but initially keeping the memory and charge amplifiers sections shielded. The gain was set 500x for the tests, which were performed at PSI (CH) using 60MeV protons. However, the 1 cm thick copper shielding used could not stop secondary neutrons that were in the beam, so all sections were exposed to some radiation all the time, including the amplifiers.

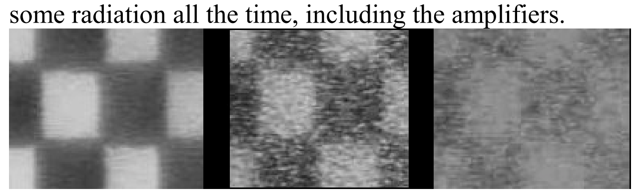

Figure 4: Degradation of the Checker-board pattern with progressive level of radiation: 0, 25 & 73Gy.

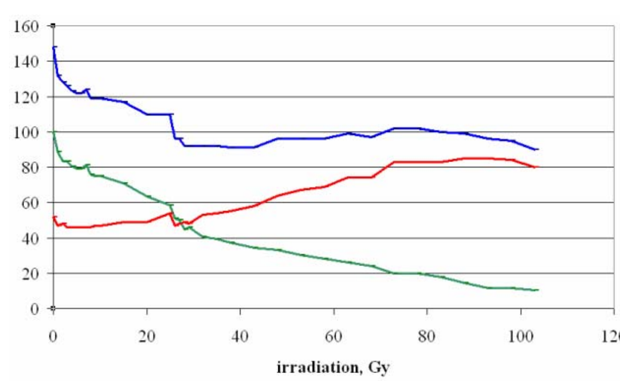

Figure 5: Loss of contrast with increasing radiation dose

The result of the analysis shows that the camera is very sensitive to radiation damage, in particular when the charge amplifier sections were first exposed there was an immediate loss of gain, seen at 25Gy. With radiation damage the contrast and resolution in the image become a function of the gain setting, as, a low gain the contrast and resolution are nearly restored to the pre-irradiation level. However, the conclusion must be that after only 10-20Gy the level of damaged pixels and the loss of gain made the camera unsuitable for use in the LHC as a measuring instrument without suitable radiation shielding.

"Radiation-Hard" Camera Tests

We simulate LHC conditions with 60MeV protons, at Louvain-la-Neuve (BE), using a high flux rate: 7.7 10^8 p/ cm^2 / s. The devices are powered up and working during test, during which we found the image quality with and without beam to be nearly the same.

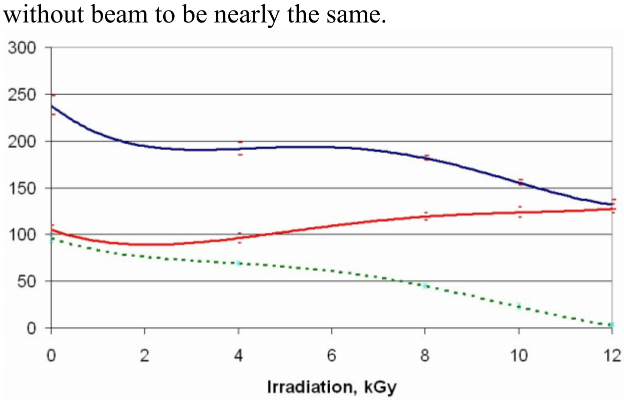

Figure 6: Spectra-Physics CID8712 Camera

The camera is rated to be operational to 1MRad: it was exposed to 1.2 MRad , SEU were not observed, the only effect was a progressive loss of contrast with increasing radiation. The camera has accessible gate bias voltage which can be adjusted to compensate for some of the lost contrast, which is due to the PMOS gate thresholds moving to the off state when irradiated.

The Fill-Factory Star 250 sensor was then irradiated in the same beam up to an integrated dose in silicon of 6MRad, the loss of contrast is almost entirely due to the loss of brightness, the dark levels observed to be quite stable. The SIRA APS250 camera based on this device has variable gain which can partially compensate for this loss of contrast.

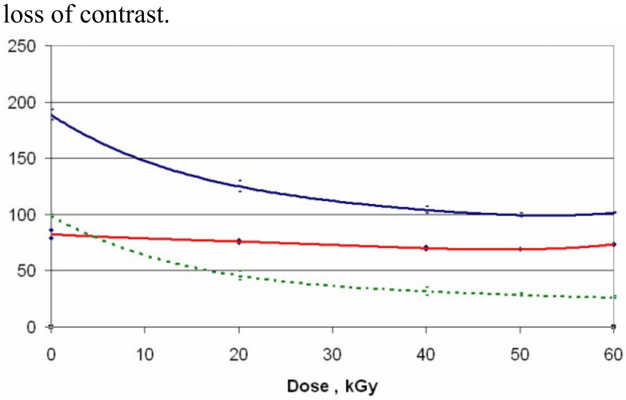

Figure 7: Star 250 Active Pixel Sensor

CONCLUSION

Both cameras have remote control box at ~30m from head, which is not Rad-tolerant. Advanced features such as selectable region of interest are not available on these cameras, but the CID8712 can be synchronized and triggered, while the SIRA APS250 camera, based on the Star250 sensor, will have a simple video output.

Shielding layouts have been simulated, resulting in a protection for the BSRT which reduces the incident radiation to acceptable levels, however this has required reorganization of the vacuum chamber layout to move the radiation sources away from the telescope, which is placed under the vacuum chambers protected by a 10cm thick steel plate supported by 1m thick steel blocks at the ends. These solutions are not easily implemented for other equipment which needs to be closer to the beam-pipes..

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