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HERSCHEL PACS PHOTOCONDUCTOR: SIMULATION OF THE PROTON GROUND TESTS

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1 INTRODUCTION

In March 2004 a series of measurements were performed at the accelerator facility UCL-CRC to test the response of the Herschel PACS spectrometer photoconductor detector during and after proton irradiation [RD1].

A simulation of the test setup has been performed at ESTEC/TEC-EES with the Geant4 toolkit. The first part of the work was dedicated to the simulation of the UCL-CRC test setup. A second part was dedicated to the simulation of the expected irradiation of the PACS photoconductor detector during the mission, due to the Cosmic Ray and the Solar Event fluxes.

The two works combined will hopefully help the interpretation of the test results and provide a way to extrapolate the observed detector behaviour to the expected behaviour in space.

This document describes the simulation tools, the configuration used for geometry, physics and particle source, and finally the outcome of the study.

In its present status, the document is provided as a contribution to the discussion over future detector ground test and comparison between the irradiation results and the simulation of the test conditions.

2 DOCUMENTS

[RD1] Test plan and procedure for investigation of Glitch event rate and collected charge variation in the Ge:Ga detectors during proton irradiation at UCL-CRC (Test report), PACS-ME-TP-009, issue 1.2, 10/3/2004
[RD2] Geant4. URL: http://www.cern.ch/geant4
[RD3] MULASSIS. URL: http://reat.space.qinetiq.com/mulassis
[RD4] GRAS. URL: http://www.estec.esa.int/wmwww/wma/R_and_D/gras
[RD5] CRÈME-96. URL: https://creme96.nrl.navy.mil
[RD6] JPL-91: http://www.spenvis.oma.be/spenvis/help/background/flare/flare.html#JPL
[RD7] MPE Document: Distribution over glitch heights.

3 METHODS

For a comparison of the detector proton irradiation during the test to the expected radiation environment during the mission, simulations have been performed both with the UCL beam proton spectrum and with the Cosmic Ray proton spectrum obtained from the CRÈME-96 model. For the geometry description, several models have been considered to cover both the beam test setup and the shielding of the Herschel spacecraft for the behaviour in space.

Details on the used tools, the geometry, the particle source and the physics description are provided in the following sections.

3.1 Simulation tools

The simulations have been performed with the Geant4-based MULASSIS tool, with the addition of the GRAS analysis package.

- Geant4: version 4.6.2.p01 (27/7/2004) [RD2]

- MULASSIS: version 1.3 (23/8/2004) [RD3]
- GRAS: (1/10/2004) [RD4]

3.2 Geometry

3.2.1 TEST AT UCL-CRC

A first study is performed with a simplified model, in which the geometry of the test setup is approximated to a 1D, layered geometry, which can be simulated with the MULASSIS tool. Details on layer thickness and material are given in Table 1.

Layer	Thickness	Materials			Description
#		Setup 1 (no absorber)	Setup 2 (1 absorber)	Setup 3 (2 absorbers)	
1	1.78 m	Air	Air	Air	Air and absorbers
2	5.00 mm	Air	Polystyrene	Polystyrene	
3	2.00 m	Air	Air	Air	
4	2.10 mm	Air	Air	Polystyrene	
5	2.00 m	Air	Air	Air	
6	6.00 mm	Aluminium	Aluminium	Aluminium	Dewar
7	21.00 mm	Air	Air	Air	
8	1.00 mm	Aluminium	Aluminium	Aluminium	
9	10.00 mm	Air	Air	Air	
10	1.00 mm	Aluminium	Aluminium	Aluminium	
11	13.00 mm	Air	Air	Air	
12	0.40 mm	Copper	Copper	Copper	
13	38.00 mm	Air	Air	Air	
14	4.00 mm	Aluminium	Aluminium	Aluminium	
15	15.00 mm	Air	Air	Air	
16	0.45 mm	Aluminium	Aluminium	Aluminium	Crystal Case
17	1.00 mm	Air	Air	Air	
18	1.00 mm	Germanium	Germanium	Germanium	Crystal
19	1.00 mm	Air	Air	Air	Crystal Case
20	0.45 mm	Aluminium	Aluminium	Aluminium	

Table 1. Thickness and material information for the layered test geometry model used in the MULASSIS simulation. The three setups differ in the absorber materials.

3.2.2 IRRADIATION IN SPACE

One layer of Aluminium of 11 mm thickness approximates the spacecraft structure, which partially shields the photoconductor detectors from the external radiation. Only the crystal case have been introduced after this shielding, before the crystal layer itself (i.e. no extra absorbers nor Dewar layers are present in this geometry model). Details on layer thickness and material are given in Table 2.

Layer #	Thickness	Materials	Description
		Space Setup	
1	11.00 mm	Aluminium	Vacuum and absorbers
2	10.00 mm	Vacuum	
3	0.45 mm	Aluminium	Crystal Case
4	1.00 mm	Air	
5	1.00 mm	Germanium	Crystal
6	1.00 mm	Air	Crystal Case
7	0.45 mm	Aluminium	

Table 2. Thickness and material information for the layered spacecraft geometry model used in the MULASSIS simulation.

3.3 Input spectra

3.3.1 TEST AT UCL-CRC

For the simulation of the test setup a mono-energetic proton source at E=70 MeV has been used. This corresponds to the nominal energy of the protons at the exit of the accelerator line. All subsequent energy losses (in air, in the degrader and in the walls of the detector Dewar) are simulated by the tool.
Several options have been considered for the spread of the energy at the exit of the beam line: σ_E= 0, 1 keV, 1 MeV.

3.3.2 PROTON IRRADIATION IN SPACE

For the simulation of the radiation during the mission, we used the proton spectrum given by the CRÈME-96 model [RD5]for the conditions Solar Minimum, Near-Earth Interplanetary. The spectrum is shown in Fig. 1.

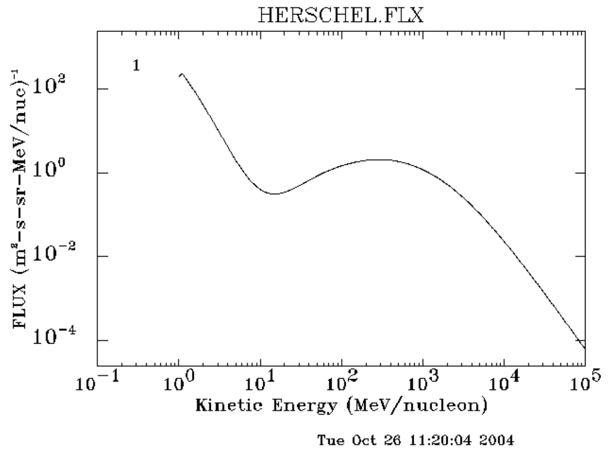

Fig. 1. Proton spectrum given by the CRÈME-96 model for the conditions Solar Minimum, Near-Earth Interplanetary orbit.

3.4 Physics

In all cases, the physics list includes both electromagnetic (the Geant4 standard electromagnetic module) and hadronic physics. The spectrum of the Cosmic Ray protons goes up to very high energy. The interactions of the high-energy particles are described with the MULASSIS physics scenario named “binary”, which includes, besides all electromagnetic physics, the description of hadronic interactions for protons up to 10 GeV. For the purpose of comparison with the behaviour with a simpler (but incomplete) physics description, results with only electromagnetic physics (MULASSIS “em” scenario) included are also shown.

4 RESULTS

4.1 *Test at UCL-CRC*

4.1.1 STABILITY OF RESULTS WITH RESPECT TO THE MEAN BEAM ENERGY

A first investigation was done about the stability of the fluence and dose results with respect to the mean proton energy. This is important to understand the systematic effects of a possible constant bias or time variation of the central value of the proton energy spectrum. The energy spread is kept to 1 keV, while the mean energy is varied from 69.0 MeV to 71.0 MeV at steps of 0.5 MeV. The physics description is the complete one with hadronic interactions included (“binary”)

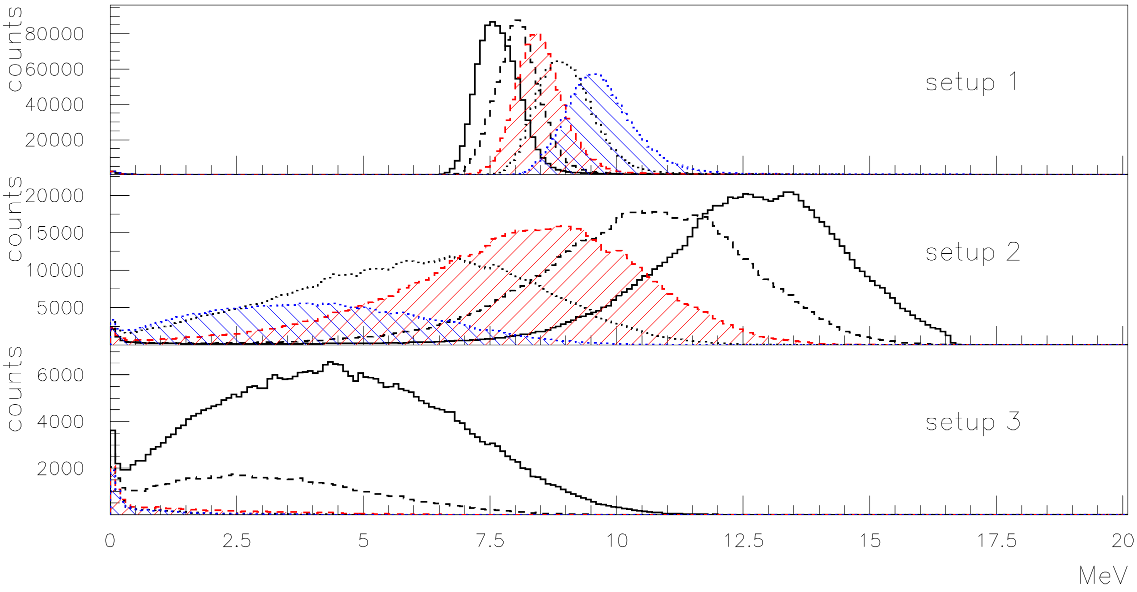

Fig. 2. In each plot, energy deposit spectrum in the crystal for a initial mean proton (kinetic) energy varying from 69.0 MeV to 71.0 MeV, at steps of 0.5 MeV, while the energy spread is 1 keV. The histogram at 70.0 MeV is displayed in red; the one at 69.0 MeV is displayed in blue. From top to bottom, results for setup 1, 2 and 3 respectively. The total number of events simulated for each configuration is 10^6.

4.1.2 “BINARY” PHYSICS LIST

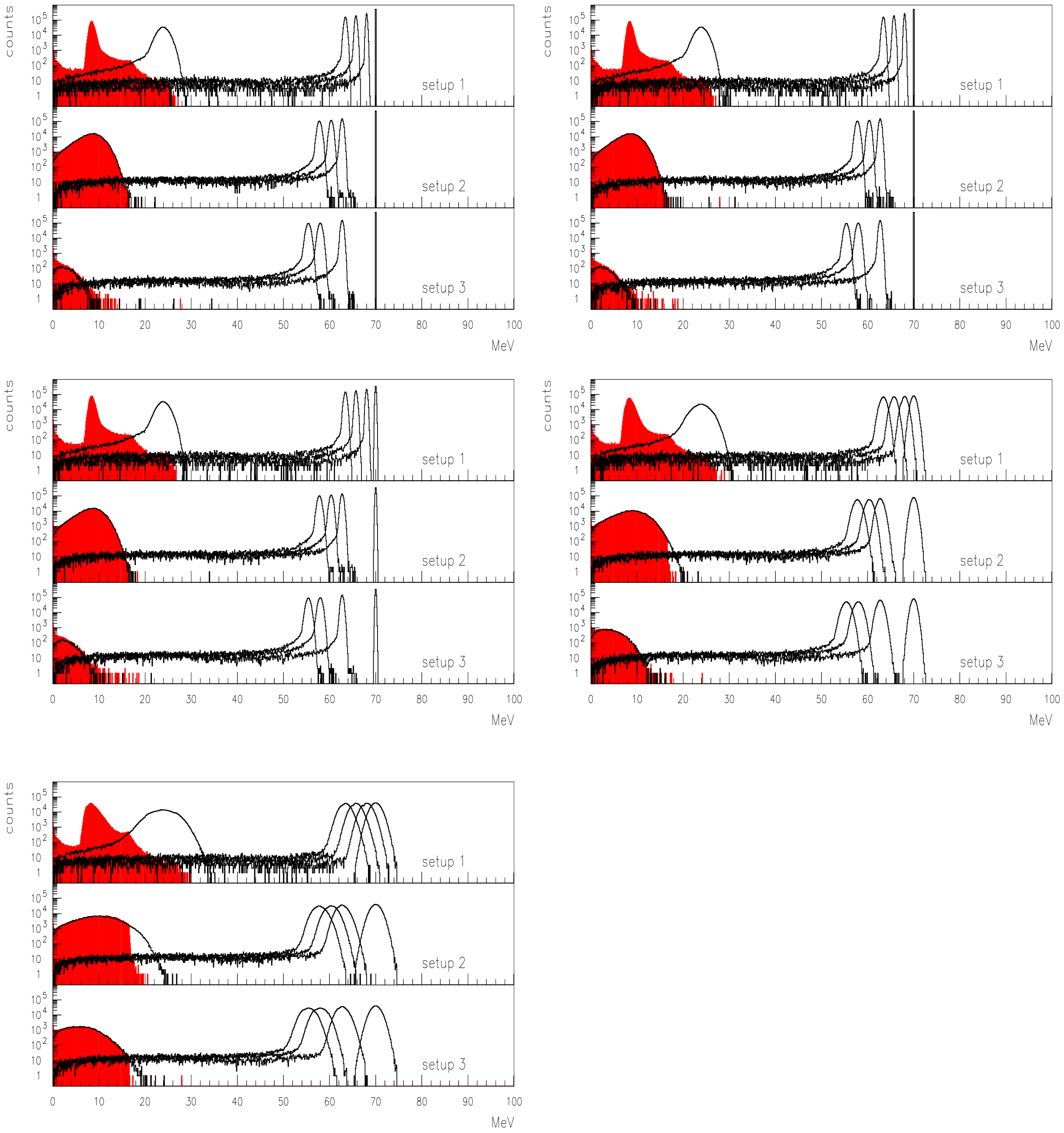

Fig. 3. In each group of plots, from top to bottom, proton fluence histograms for setup 1, 2 and 3 respectively. The initial proton (kinetic) energy is 70 MeV, with a spread of 1 keV. In each plot, in black, from right to left, the histograms represent the proton fluence spectrum sampled at the source, after the first and the second degrader, at the entry of the Dewar and at the entry of the crystal. The red histogram represents the energy deposit spectrum in the crystal. The total number of events simulated is 10^6. The different groups of plots have different energy spread: from top to bottom, 1 keV, 10 keV, 100 keV, 500 keV, 1 MeV.

4.1.3 “ELECTROMAGNETIC” PHYSICS LIST

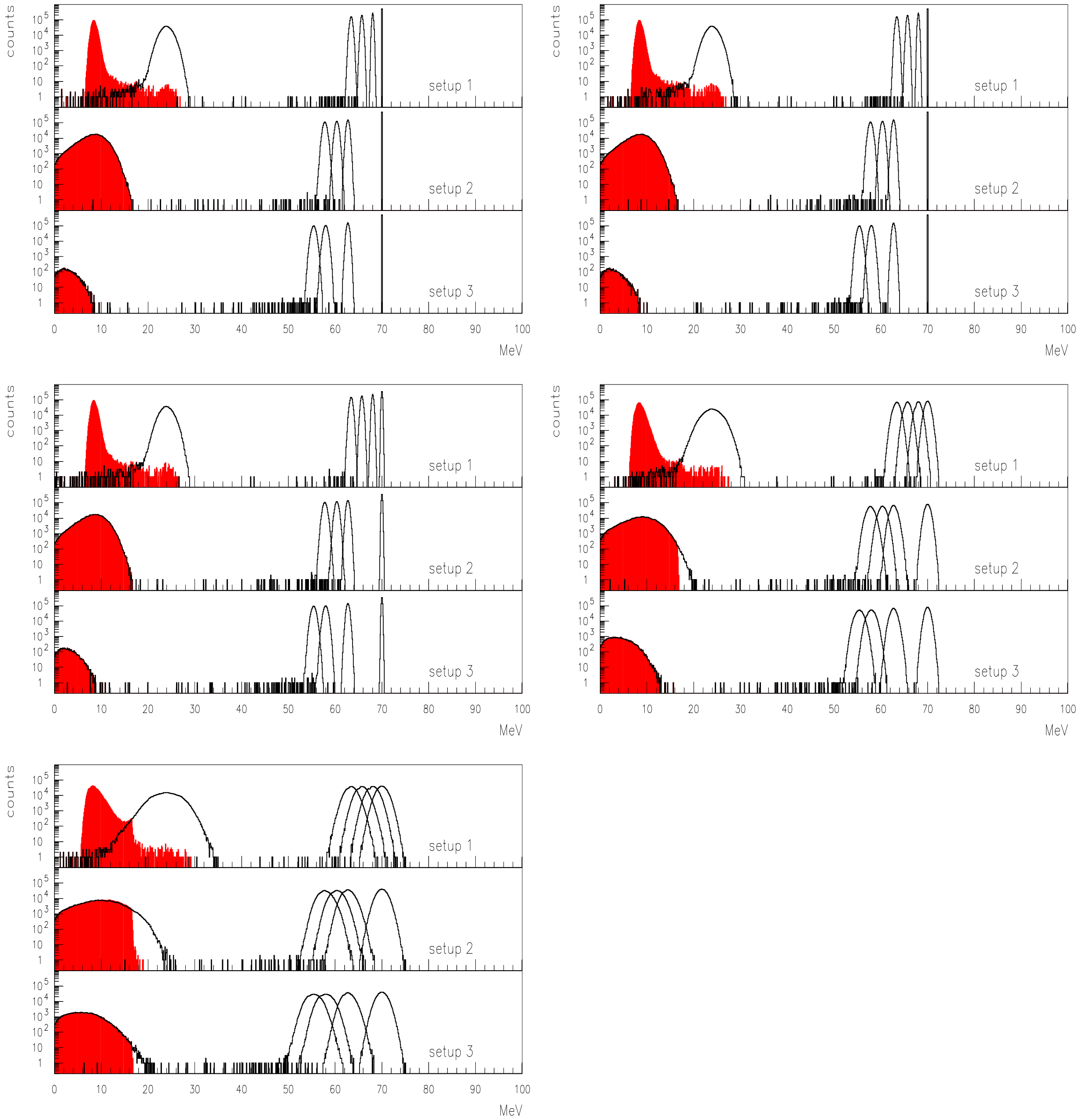

Fig. 4. Same as Fig. 3 but for the incomplete “em” physics list.

4.1.4 COMPARISON WITH TEST DATA

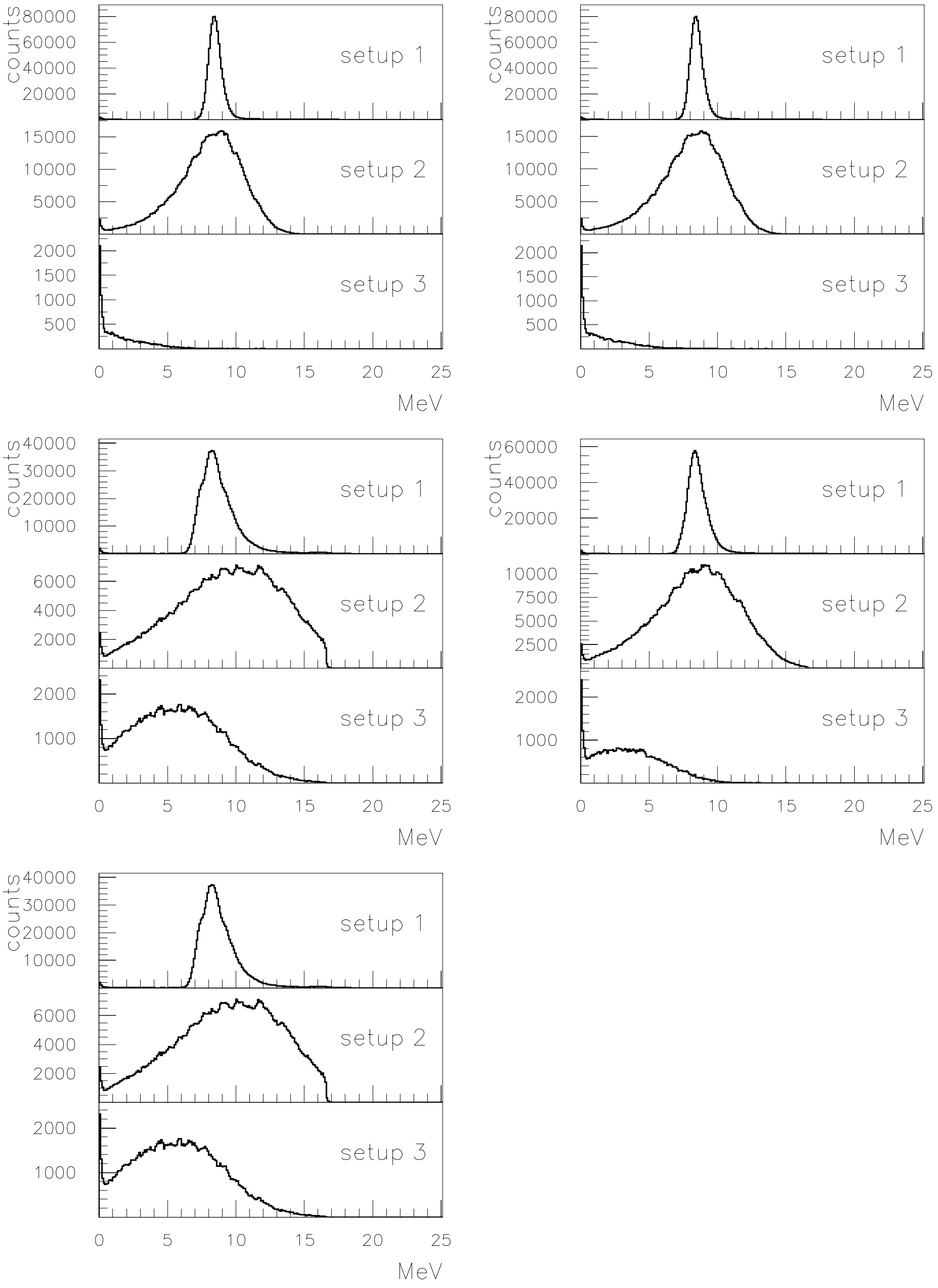

Fig. 5. Complete "binary" physics list: In both figures, from top to bottom, energy deposit spectrum in the crystal for setup 1, 2 and 3 respectively. The total number of events simulated is 10^6. The initial proton (kinetic) energy is 70 MeV. From top to bottom, the beam energy spread is set to 1 keV, 10 keV, 100 keV, 500 keV and 1. MeV. The histograms correspond to the red histograms of Fig. 3, expanded and in linear scale.

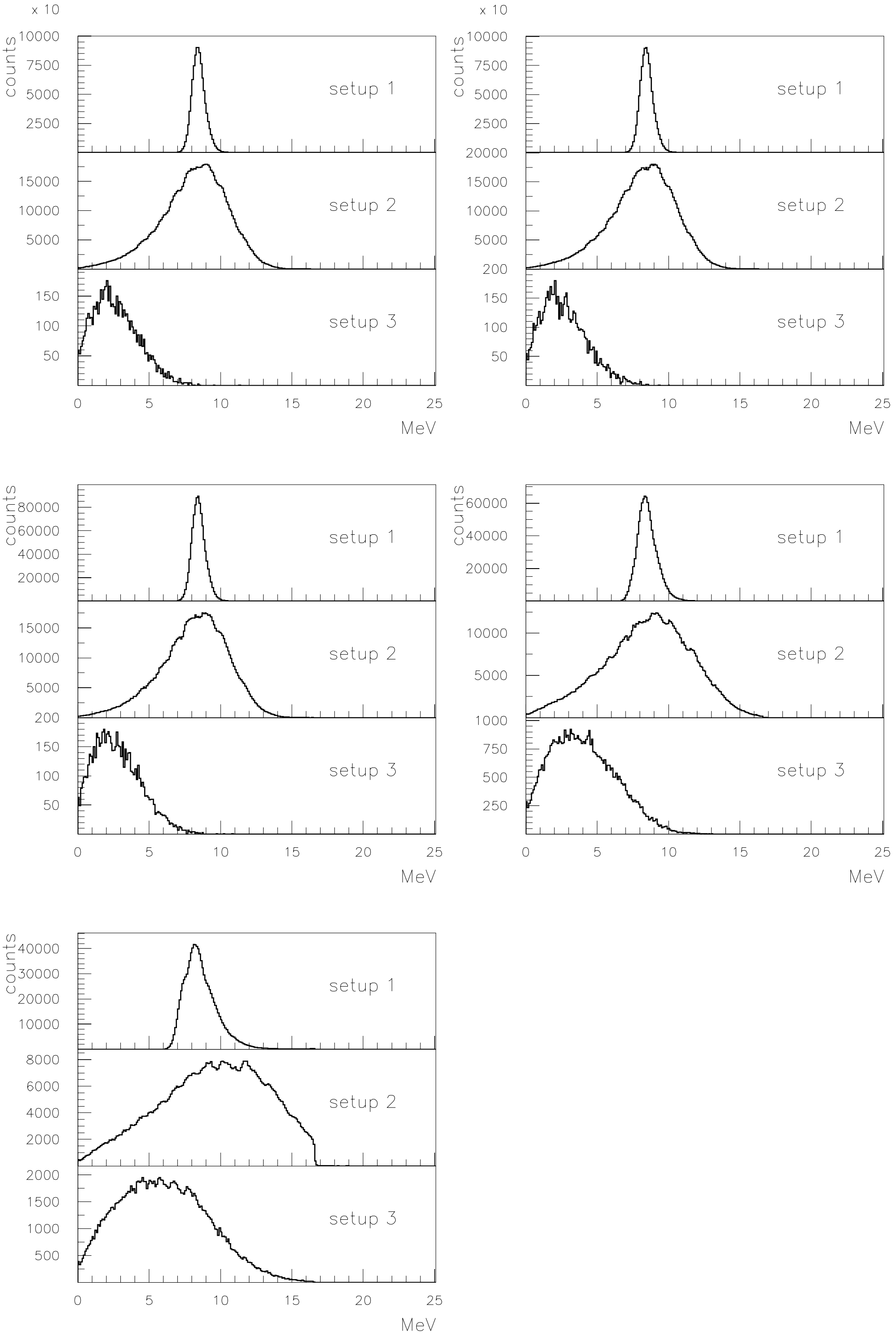

Fig. 6. Same as Fig. 5 but for the incomplete “em” physics list, for an energy spread of 1 keV to 1 MeV.

An example of the distribution of the glitch heights, analysed with a dedicated algorithm [RD7], is given in Fig. 7. The spectrum corresponds to the Setup 2 geometry model (one absorber along the proton path in air).

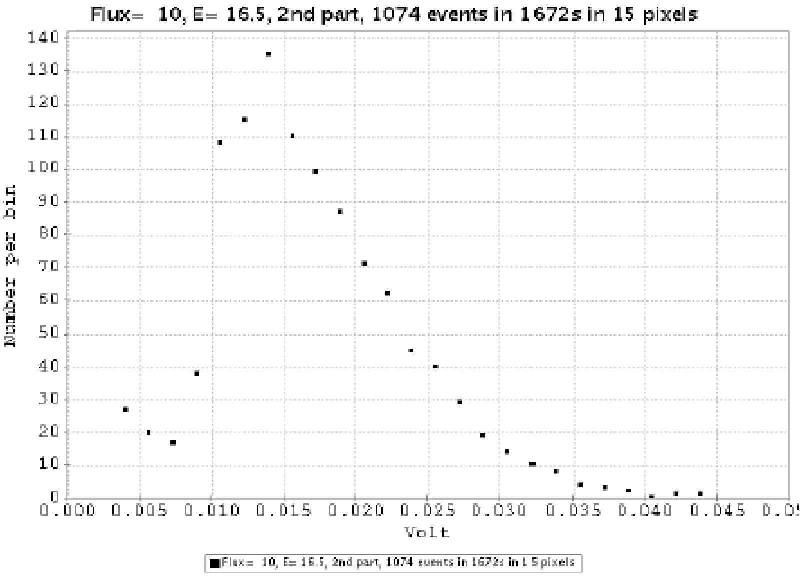

Fig. 7. Example of distribution of glitch height as recorded during the tests, subsequently analysed with a dedicated algorithm [RD7].

4.2 Proton irradiation in space

The energy deposit spectrum in the crystal layer for the “space setup” and the proton spectrum derived from the CRÈME model is shown in Fig. 8. The spectrum shows a Landau shape, typical of the energy loss in thin absorbers.

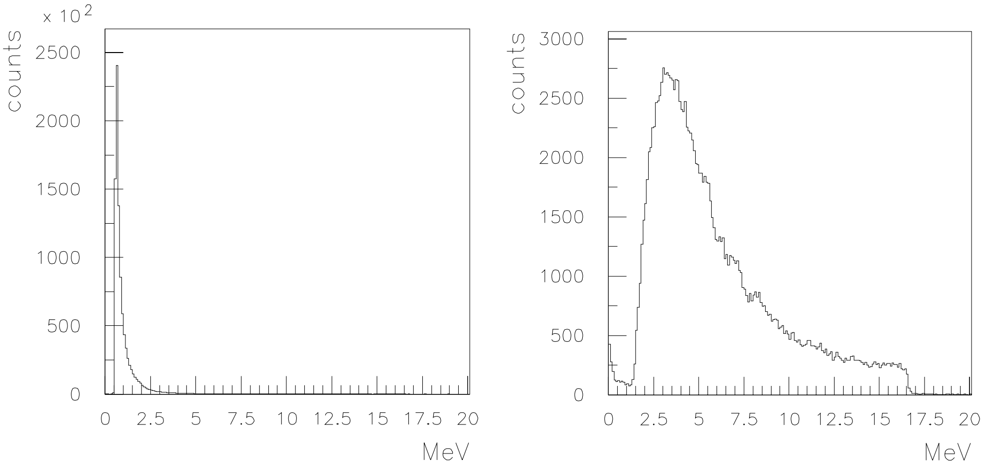

Fig. 8. Energy deposited in the crystal layer for the complete physics (“binary”). The total spacecraft shielding before the crystal case is approximated by a 11 mm Aluminium layer. The primary proton spectrum is obtained (LEFT) from the CREME-96 model and (RIGHT) from the proton spectrum measured during the October ’89 solar event.

4.3 Summary

A tentative summary of the results is presented in Table 3, which summarizes the energy deposit spectra in terms of Mean and RMS for the test setup 1,2,3, with energy spread 1 keV and 1 MeV and for the space setup for the CRÈME spectrum, for the "binary" physics scenario.
It is worth noting that the table does not represent a complete summary of all the features of the spectra presented in the previous figures.

Binary	Energy 70 MeV, Spread = 1 keV			Energy 70 MeV, Spread = 1 MeV			CRÈME
	Setup 1	Setup 2	Setup 3	Setup 1	Setup 2	Setup 3	Space setup
Mean (MeV)	8.6	8.0	1.6	8.8	9.3	5.8	1.3
RMS (MeV)	1.3	2.5	1.8	1.7	3.8	3.2	3.1

Table 3. Summary of the energy deposit spectrum mean and RMS for the test and the space conditions. Complete ("binary") physics description.

Em	Energy 70 MeV, Spread = 1 keV			Energy 70 MeV, Spread = 1 MeV			CRÈME
	Setup 1	Setup 2	Setup 3	Setup 1	Setup 2	Setup 3	Space setup
Mean (MeV)	8.5	8.1	2.7	8.7	9.5	6.1	1.0
RMS (MeV)	0.5	2.3	1.6	1.3	3.7	3.1	0.9

Table 4. Summary of the energy deposit spectrum mean and RMS for the test and the space conditions. Incomplete ("em") physics description.

5 DISCUSSION AND CONCLUSIONS

The prompt behaviour of the detector under irradiation certainly depends on the physical dose that is deposited by the single particles in the sensitive crystal volume. However, the same nominal beam conditions generate different detector behaviour at the beginning or at the end of long irradiation periods. Moreover, the overall behaviour of the photoconductor seems to have a long-term trail after single prompt effects.
This seems to indicate that the glitch height distribution alone might not be enough for a complete understanding of the radiation effects and a correlation to the simulation results, and that detector specific mechanisms are involved, which can not be described only in terms of a prompt energy deposition by the protons.

Energy deposit spectra are provided for a comparison with the test data. The energy deposit shows a significant dependence on the beam parameters. In absence of precise information about the stability and the spread of the beam energy at the exit of the beam pipe, spectra of the energy deposit are given for a range of beam energy central values and spreads. The plots can also be used as an indication of possible systematic errors due to unstable or unknown beam tuning during past and future tests at the same facility.

The spectrum for the energy deposit obtained with Setup 1 is narrower than the one in Setup 2, but both show a discrete stability with respect to the beam energy spread.

The stability of the results with respect to beam parameters such as the mean and spread of the proton energy is critical when the typical range of the protons is close to the total shielding before the sensitive crystal volume, as in Test Setup 3. Such conditions should be avoided to guarantee the reproducibility of the experimental results, unless the beam parameters are known with good precision and are stable.

The energy deposition spectrum simulated with the space geometry model and the cosmic ray proton spectrum differs greatly from the one simulated in the test conditions. For this reason, the suggestion is to use the beam configuration that maximises the energy of the protons at the crystal, which corresponds to no absorbers before the Dewar, i.e. Setup 1. For comparison with the results obtained during the test analysed in this document, we suggest in addition to acquire part of the data with the beam configuration corresponding to Setup 2.

The feasibility of cosmic ray tests could be studied. The typical energy deposit of a cosmic ray muon is similar to that of protons in space. The low rate in the small crystal sensitive volume has to be taken into account. The setup of a coincidence trigger might be needed; the insertion of scintillation detectors close to the photoconductor crystals, to increase the cosmic ray geometrical acceptance, may require modifications in the test Dewar.

The study has been performed with an approximated 1D geometry model. A more precise 3D model, which could show different energy spectra, is under development. In addition, only proton irradiation has been considered in this study for the simulation of the L2 environment. The simulation of the alpha particle component is under development.