Optimization of the veto shield for the INTEGRAL spectrometer SPI with Monte Carlo simulations

Robert Georgii, Giselher Lichti, Thomas Kirchner, Volker Schönfelder

Max-Planck-Institut für extraterrestrische Physik, Giessenbachstr.,
D-85740 Garching, Germany

Peter von Ballmoos, Pierre Jean, Pierre Mandrou, Juan Naya, Gilbert Vedrenne

Centre d'Etude Spatiale des Rayonnements, 9, av. du Colonel-Roche,
F-31029 Toulouse Cedex, France

Bertrand Cordier, Néné Diallo

CEA Saclay, Service d'astrophysique, F-91191 Gif sur Yvette Cedex, France

ABSTRACT

Using Monte-Carlo simulations, an optimization of the mass distribution of the scintillator crystals, which constitute the veto shield of the spectrometer SPI on board of INTEGRAL, has been performed. Special emphasis was put on a realistic model for the radiation environment in the satellite orbit. All the components of the radiation (gamma-rays, protons and electrons) in space were taken into account regarding their relative fluxes. Furthermore the radiation produced by nuclear reactions within the spacecraft structure was estimated using a separate computer code. A simple realistic mass model of the spectrometer with special consideration of the holding structure of the crystals and other material within the opening angle of the spectrometer, was implemented. Different geometries for background reduction were analyzed and the results are presented.

Experiments concerning the behavior of the radiation damage in the scintillator crystals are presented. They give important hints for methods to avoid an increase in the background due to the radiation induced degradation of the crystals.

Keywords: Monte-Carlo simulations, nuclear reactions, radiation damage, γ-ray telescopes, γ-ray instruments, INTEGRAL

1 INTRODUCTION

SPI on board of INTEGRAL is a high-resolution Ge spectrometer, which has an imaging capability due to a coded mask. It is designed to measure γ-rays in an energy range between 20 keV and 8 MeV. It combines a high energy resolution $E/\Delta E \approx 500$ with an angular resolution of about 2^o within a fully coded hexagonal field of view of 14^o – 16^o.[1]

One key parameter for the performance of the instrument is the limiting narrow-line sensitivity S:

$$S \sim \sqrt{\frac{F_B \cdot \Delta E}{A_{eff} \cdot t}} \tag{1}$$

Here F_B denotes the background flux (attention has to be paid to the definition of the background flux in regions near to an instrumental background line, especially near to the 511 keV annihilation line !), ΔE the energy resolution of the Ge-detector, A_{eff} its effective area and t the observation time. Since the effective area and the energy resolution of the Ge-detector is fixed by the design, it can be seen from the equation that a good limiting narrow-line sensitivity can only be achieved in a low-background environment (F_B has to be small!). Therefore one major component, besides the Pulse Shape Discrimination (PSD), for the background reduction will be the AntiCoincidence Subsystem (ACS) of SPI, consisting of an active BGO shield around the detector and along the field of view, the holding structure of the shield and the read-out electronics for the signals of the BGO crystals.

The goal of this paper is to show how this BGO shield is optimized with respect to mass, high shielding power for charged particles and γ-rays, a low neutron production and other parameters, that influence the sensitivity. The main tool in performing this task were Monte-Carlo simulations of the spectrometer using the GEANT code[2] from CERN. Inputs defining the type and the spectral dependence of the radiation environment in space and from the satellite were taken from measurements performed by previous balloon and satellite missions.

The background in the Ge detectors depends very strongly on the ability of the shield to veto undesired particles. An important parameter for the performance of the BGO shield is its detection probability for charged particles. This ability can be influenced by the radiation, which is seen by the satellite if it passes the proton radiation belts (this is especially important for an Ariane orbit). These high-energetic protons can damage the color centers in the BGO, which are important for the scintillation efficiency of the crystal. Therefore tests using a proton accelerator were performed in order to measure the radiation hardness of the BGO crystals.

2 DESCRIPTION OF THE RADIATION ENVIRONMENT

There are several components of radiation seen by SPI on INTEGRAL. In principal they can be separated in two main components, which itself can be subdivided again:

- External radiation: It consists mainly of
  - cosmic-rays protons, electrons and the diffuse cosmic γ-ray background,
  - trapped particle radiation (During the passage of the p belts the instrument will be switched off.),
  - particles and γ-rays from the galactic plane or other γ-ray sources outside the field of view (This component is not considered in the following simulations).
- Internal radiation: It consists of the radiation coming from the spacecraft and from SPI itself (mainly from material inside the veto-shield). It consists of

Table 1: The radiation environment of SPI ordered by reaction types

type of radiation	external sources and prompt reactions	delayed reactions
γ	diffuse cosmic γ-rays, bremsstrahlung, neutron capture, $\pi^{0,\pm}$,e^+,μ^+ decay	decay of activated nuclei
p	cosmic-ray p, spallation, nuclear reactions	—
e^-	cosmic-ray e^-, pair production, Compton scattered e^-, μ^-, π^- decay	β^--decay of activated nuclei
e^+	cosmic-rays e^+ (small), pair production, μ^+, π^+ decay	β^+-decay of activated nuclei
n	spallation, nuclear reactions	—
$\pi^{0,\pm}$	spallation	—

- a neutron
- a γ-ray (delayed and prompt),
- an electron and
- a positron component (both from the decay of activated nuclei).

The external radiation is known from measurements performed by other satellite and balloon missions. For protons the cosmic-ray spectrum from Meyer[3] was used from 30 MeV to 10 GeV. The reason for the lower cut-off at 30 MeV is due to the penetration depth of less than 1.6 mm for protons in aluminum.[4] Since there will be wall thicknesses for aluminum larger than 2 mm in the outer holding structure of SPI the low-energetic part of the proton spectrum will be already absorbed far away from the active detectors. Furthermore the cross sections for nuclear reactions are going down drastically below 30 MeV and the contribution of those reactions can therefore be neglected in this energy range of the protons. The electron spectrum between 100 keV to 10 GeV is also taken from Meyer.[3] The spectra for the charged particles are both referring to the solar minimum period and represent therefore minimal fluxes. The cosmic γ-ray spectrum can be found in Schönfelder et al.[5] and was implemented between 30 keV (this is again the cut-off of 2 mm of Al) and 10 GeV.

Another useful ordering scheme, which is important for the numerical simulations, is shown in Table 1. Here the type of the reactions producing the measured radiation is the order parameter. As shown there are two main components, the prompt and the delayed reactions (compared to the detection time of the Ge-detectors). From the point of view of the simulations, the prompt reactions are much simpler to handle than the delayed ones. This is due to the fact, that there is still no consistent model for nuclei in nuclear physics. Therefore the cross sections of nuclear reactions (involving mainly the weak and strong interaction) can not just be simply calculated from formulae (like for the electromagnetic reactions) but have to be deduced from experimental data, which are by far not completely known today. Therefore the delayed reactions, which all involve the strong and weak interaction during the production of the mother nuclei (activation!) have to be numerically handled different from most of the prompt reactions.

3 NUMERICAL SIMULATIONS

The aim of the simulations was mainly to optimize the thickness of the BGO crystals and their geometrical structure. Furthermore it was important to clarify the role of the different materials within the shielded field of view concerning their influence on the absorption and emission of γ-rays.

The background counts in the Ge detectors are mainly due to the interaction of cosmic radiation with the spectrometer, including photons and hadrons. The cosmic diffuse and the ambient photons (i. e. produced by the spacecraft) interact promptly with the detection system. The hadronic particles induce delayed beta-decays and elastic scattering (for neutrons only) in the Ge. Extended background calculations have been performed with Monte-Carlo simulations to obtain the photonic components. The code GEANT, which was used for this task takes into account the interaction processes of primary and secondary particles (photons, leptons, mesons and hadrons). However, it does not process the weak interaction. Consequently, the β decay rate has to be calculated in a different way as shown in the following section.

3.1 The simulation of the delayed reactions

The β decay components (β^-, β^+) are strongly dependent on the secondary neutron flux that impinges on the detectors. They have been estimated by using a new approach for calculating the neutron spectrum inside the shield in a semi-empirical way[6] based on the measurement of neutron-induced background lines in balloon-borne Ge-spectrometers. This method has been successfully tested on the background spectra of HEXAGONE I (1988), HEXAGONE II (1992) and GRIS (1992) experiments.[6] The deduced neutron spectrum has been rescaled to take into account the difference in the primary proton flux and in BGO shield thickness between SPI and HEXAGONE II, which was taken as the reference. The scaling factor has been calculated by simulating the irradiation of hadronic particles for the two experiments. That are the cosmic-ray protons (taken from Webber et al.[7]), the secondary neutrons induced in the spacecraft in the case of SPI and the cosmic-ray protons, the atmospheric protons and neutrons for HEXAGONE II. The scaling factor is then the ratio of the resulting neutron fluxes entering the Ge detectors for each experiment.

The calculation of the β decay yield was then performed in two steps. The neutron induced reactions like (n,2n) or (n,p) have been derived from cross sections calculated by the code Alice91 or obtained from NEADB (Nuclear Agency on-line Nuclear Data Base). The spallation reactions which are induced by neutrons and protons with an energy higher than 100 MeV were estimated using semi-empirical calculations for the cross sections (see Naya et al.[6] for more details). In order to obtain the β decay spectra, the energy distribution of β particles emitted by each isotope were multiplied by their decay rates. The resulting spectra have been convolved with the response function of the spectrometer. This was done by Monte-Carlo simulations. Then the β particles were injected in the numerical model with or without de-excitation photons depending on the decay process.

The calculation have been performed for several thicknesses of the side and bottom shield. Fig. 1 shows the variation of the background rate in four energy ranges as a function of the veto-shield thickness. In these calculations, the background reduction by PSD has been taken into account. The background rate in the 0.2 - 0.8 MeV range is always decreasing with increasing thickness. This is due to the PSD that eliminates mostly localized β^- decay in the Ge that would be the dominant component at these energies. Consequently, in this energy range, the background is dominated by the shield leakage and therefore decreases with increasing thicknesses. Above 0.8 MeV the background rate is slightly increasing for thicknesses larger then 4.8 cm. This is due to an increasing neutron production in a thicker shield thus leading to a larger instrumental background. Fortunately this effect is not very pronounced and therefore the background rate is not too sensitive to changes in the veto shield thickness between 4 cm and 6 cm.

3.2 The simulation of the prompt reactions

There are mainly two parts of the prompt background which are of great influence for the performance of SPI. These are the cosmic-ray low-energetic γ-rays below 200 keV and hadronic interactions well above 1 MeV.

The latter can be treated by using Monte-Carlo methods. One code exploiting this method is the computer code GEANT developed at CERN for hadronic interactions above 1 GeV.[2] By including special interfaces for the low-energetic interactions like neutron capture, proton spallation, pion production and other nuclear processes,

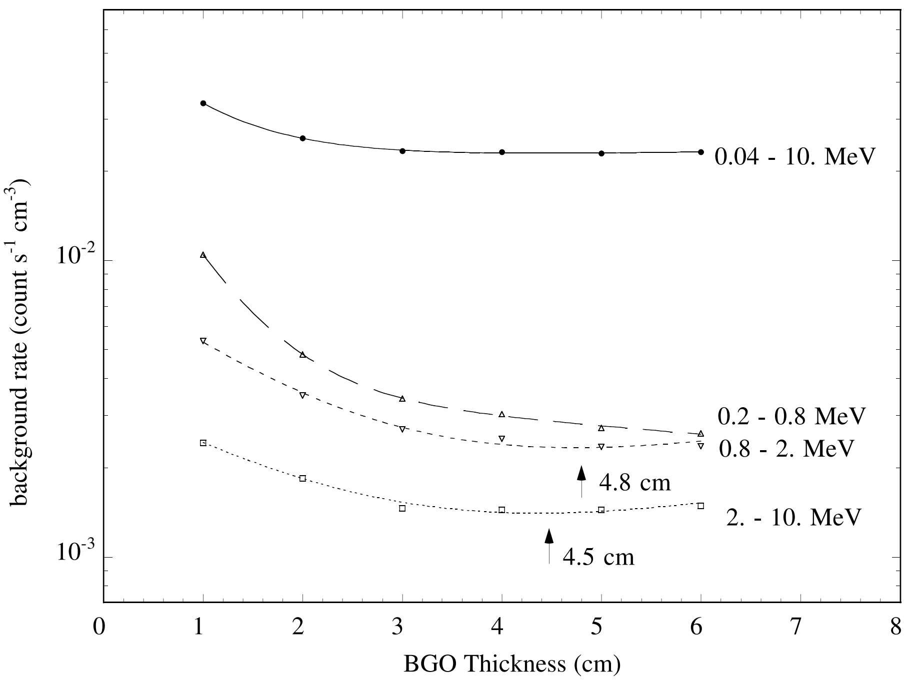

Figure 1: Background rate variation as a function of the BGO shield thickness for 4 different energy bands.

this code can easily be extended to our region of interest around 1 to 10 MeV. As such an interface we used the code GCALOR developed by C. Zeitnitz.[8] It handles a large library of nuclear reaction data and is able to trace neutrons down to the eV-range.

As input the spectra for γ-rays, protons and electrons, as discussed in section 2, were taken and a simple geometrical model of the SPI spectrometer as shown in Fig. 2 was used. The main components of the instrument are the BGO crystals, the Ge detectors and the mask. Furthermore attention was paid to a realistic representation of the instrument configuration. Therefore the cryostat made of beryllium, the detector capsules and the holding structure of the components made from aluminum were taken into account as well.

Due to the electronical read-out concept used for the BGO crystals, there is an "electronical leakage" in the ACS system. Each crystal in the shield has to be electronically blocked for a certain time after a scintillation event. This is done to reduce the dead time of the system by excluding possible after-triggering. On the other hand during this blocking time the crystal is only a "passive" shield and there is a probability for particles passing the shield undetected. The average probability for this effect taking place was estimated to be 0.5 % and is included in the simulation as well.

Different possibilities for the design of the collimator rings were examined. The first design is an active upper and lower collimator ring with an energy threshold of the BGO crystals at 100 keV. The simulation considered the incoming particles to be homogeneously distributed around SPI. In case of an energy deposit larger than 100 keV in the BGO crystals and an energy deposit larger than 20 keV in the Ge-detectors at the same time this event was only recorded as a count in the Ge volumes and filled in an energy spectrum of the Ge-detectors. If there was no "veto" from the BGO crystals the event was recorded as a good event in a second spectrum. In Fig. 3 these two spectra are shown for comparison. It can easily be seen that the total background is receded

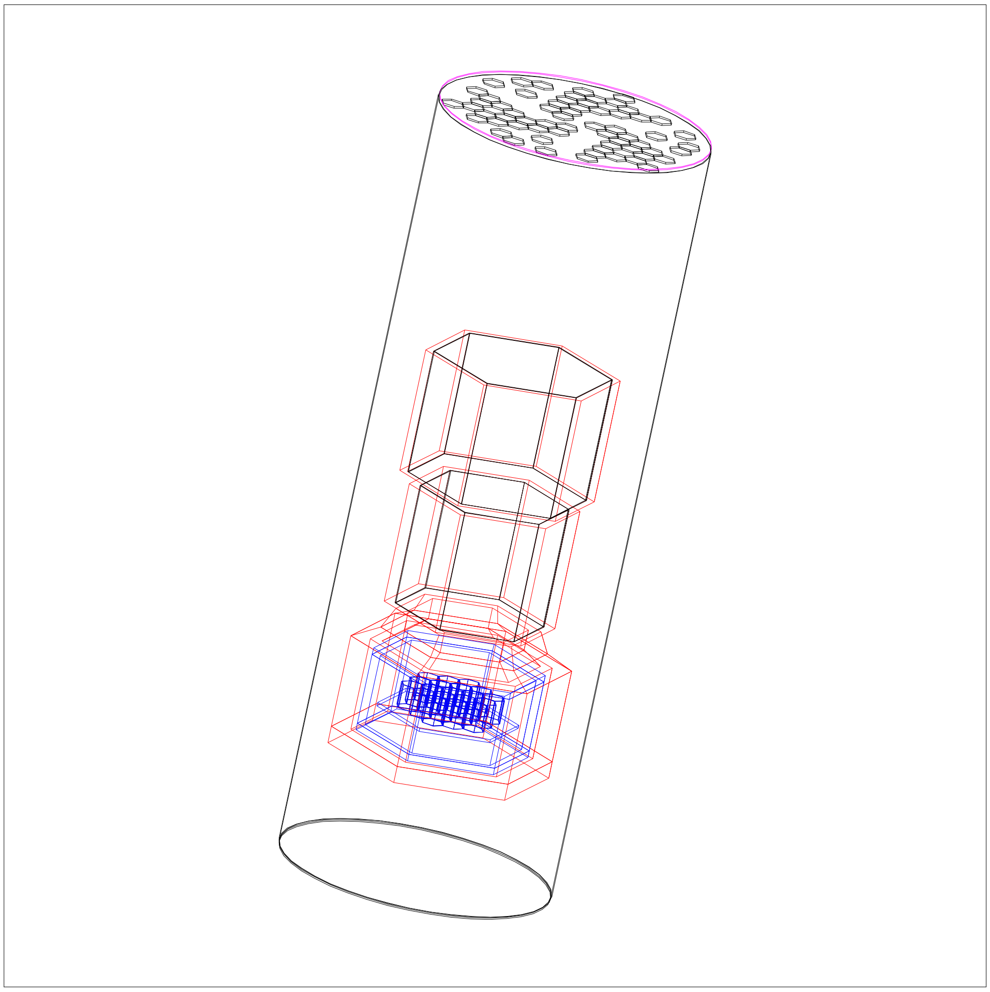

Figure 2: The geometrical model of SPI. The dashed line represents the BGO crystals.

by a factor of 2, when vetoing the "bad" events. This effect is even more drastically seen in the 511 keV line where the background is diminished by a factor of about 10. This clearly shows that the concept of an "active" shield can help to increase the sensitivity of the instrument drastically. To underline the importance of an as complete as possible active shielding, in Fig. 4 a spectrum is shown for the same configuration as above only with the upper collimator ring made from tungsten. In this case the 511 keV line background increases by a factor of 2 compared to the geometry with an upper "active" collimator ring. Therefore the first geometry was chosen to be the baseline for the design of the ACS.

The veto-shield is only effective as an active shield above 300 keV (see Fig. 3), because the γ-rays with less energy are only absorbed via the passive mass of the shield. Therefore the low-energetic background of γ- and X-rays was treated simply by using the well known exponential law for their absorption in matter. Under the assumption of homogenous distributed background outside of SPI the pathlength and therefore the equivalent absorption was calculated for each crystal. Assuming the observer in the middle of the Germanium array this was weighted with the corresponding solid angle. Now the mass distribution was varied for the different components of the shield. As shown in Fig. 5 the transparency could be reduced significantly by this method especially for higher energies.

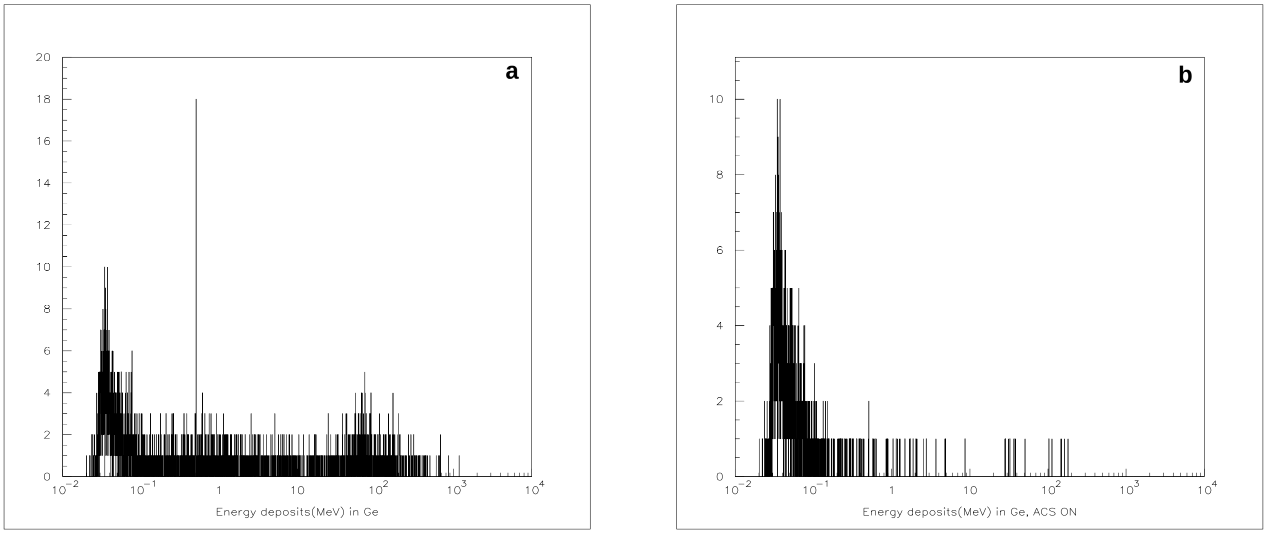

Figure 3: Simulated background in the Ge-detectors with ACS off (a) and with ACS on (b). 10^7 cosmic-ray protons and γ-rays were simulated. The energy threshold in the BGO was 100 keV and 20 keV in the Ge-detectors.

3.3 Conclusions and further investigations

The results from the last section together with the limitation of the thickness of the BGO crystals to be between 4 cm and 6 cm (see section 3.1) and the maximum allowed overall mass of 809 kg for the ACS led to the following wall thicknesses:

- Rear shield, lower and upper side shield: 5 cm
- Lower collimator ring: three steps: 2.8 cm, 2.4 cm, 1.9 cm
- upper collimator ring: 1.6 cm

A problem with the "active" shield is that due to the diffuse background of soft γ-rays and X-rays the counting rates in the BGO are increased drastically. This is a major design driver and a problem for the ACS-electronics. A possible background reduction could be achieved with the full "active" shield geometry, if each crystal is shielded on the outside with additional 0.5 mm Pb, 0.1 mm Ta and 0.4 mm Sn. The Ta and Sn is needed for shielding the 70 keV photons, which will be emitted by Pb after activation. Furthermore they will homogenize the absorption coefficient of Pb and therefore guarantee a good shielding power up to 100 keV. Table 2 shows the absorption of γ-rays in dependence of their energy for this geometry. The impact of this design option on the background in the Ge-detectors still has to be investigated by numerical simulations.

Table 2: The absorption of γ-rays for a low-energy shield for the crystals made of 0.5 mm Pb, 0.1 mm Ta and 0.4 mm Sn.

E [keV]	50	60	80	100	120
Absorption	1	1	0.98	0.98	0.795

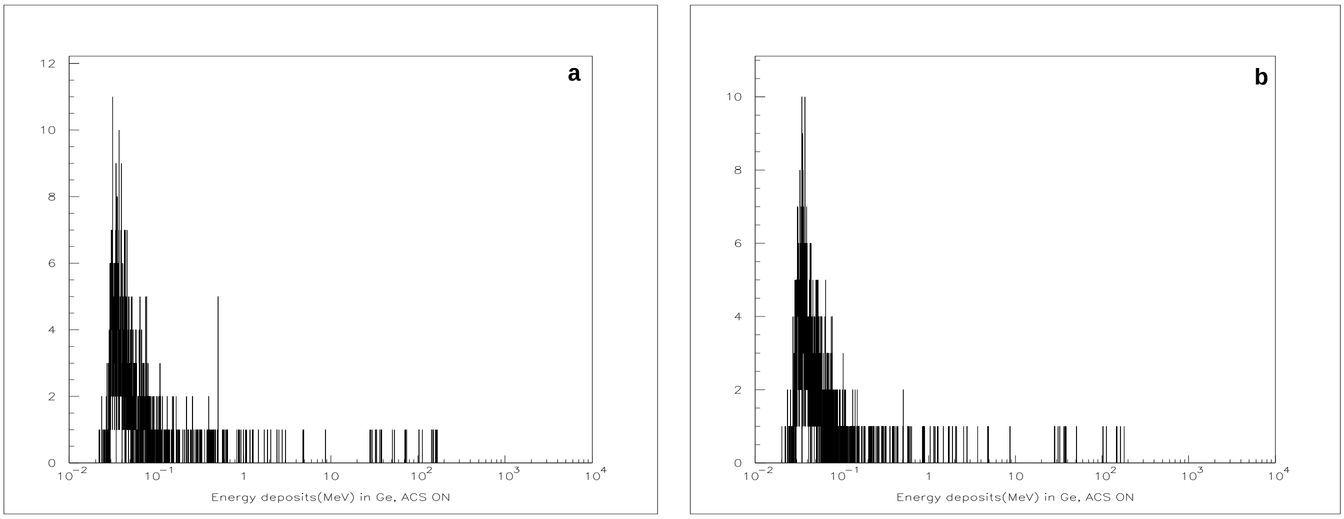

Figure 4: Simulated background in the Ge-detectors with upper ring passive (a) and active (b). 10^7 cosmic-ray protons and γ-rays were simulated. The energy threshold in the BGO was 100 keV and 20 keV in the Ge-detectors.

4 EXPERIMENTAL TESTS OF THE RADIATION HARDNESS

For the efficiency of the veto-shield a high detection probability for charged particles, i.e. mainly for protons, is of high importance. Especially the low-energetic background and the background in the 511 keV line are strongly influenced in the case of a reduction of the performance of the shield in vetoing high-energetic protons.

The limiting factor for the detection of a particle is the effective photoelectron yield of a detector unit made of a BGO crystal and a Photomultiplier Tube (PMT). This yield depends on the properties of the PMT (mainly on the efficiency of the photocathode), the crystal geometry and the light-collection efficiency, which itself depends on the material properties of the crystal (bulk absorption, surface properties etc.). Therefore environmental influences, which are time dependent, will degenerate the light output of the veto-shield.

One major reason for such a degradation of the BGO can be a radiation damage to the BGO crystals due to energetic particles. Since INTEGRAL will pass the proton radiation belts for a time period of ≈ 2 hours (for an Ariane orbit), a proton-induced radiation damage to the BGO has to be expected. An accelerator test using a pulsed proton beam has been performed in order to simulate such a passage of the satellite through the radiation belt. The length of the pulses was chosen to be such, that the proton doses were approximately equal to the doses seen by the BGO during one passage through the belts.

The test was performed at the Emperor-Tandem accelerator of the Technical University and the University of Munich. H^- from an ion source are preaccelerated and chopped via two condensator plates controlled by a freely chosen TTL signal from a pulse generator. This pulsed beam is then sent to the high-voltage terminal. In our case the terminal voltage was 13 MV. Then the ions are stripped and again accelerated to the end of the accelerator. Thus the protons had an energy of 26 MeV. The pulse duration was chosen to be 400 ns. This beam is then energy selected and stabilized via a 90^o magnet. It is guided to a switcher magnet and then directed to the experimental place. There it passes a 100 μm thick Mylar foil in order to leave the vacuum system of the accelerator. Then it hits a 112 μm thick plastic scintillator wrapped in 40 μm thick aluminum for light tightness. This detector is used as a beam monitor in order to control the number of pulses being actually produced by the accelerator. Then it passes a manipulator, for bringing the crystals in and out of the beam and finally hits a Faraday cup, used as beam monitor. The resulting current on the cup is integrated using a high-sensitive current

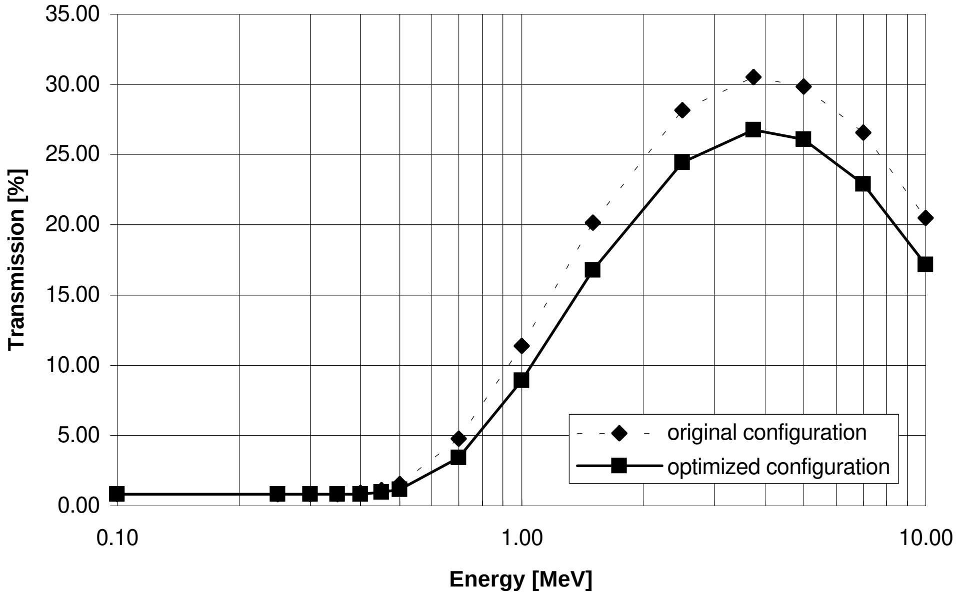

Figure 5: The shielding power of the veto-shield for γ-rays for different wall thicknesses

integrator. The beam area was about 1 cm^2.

First the doses per pulse were determined in order to calibrate the pulse-doses relation. This was done in the following way. The crystals were removed from the beam and the current on the integrator was measured for 100 pulses. In the orbit the flux of 24 MeV protons (this is also the energy the protons have after they passed the Mylar window and the beam monitor) is in the order of 10 protons / (cm^2 s).[9] This gives for a beam area of 1 cm^2 and a passage time of 2 hours $7.2 \cdot 10^4$ protons. By pulsing the accelerator beam it is possible to simulate this low dose. By choosing the beam current accordingly different number of passages of the satellite in an Ariane orbit can be simulated.

9 different crystals which could be brought into the beam via the manipulator were irradiated. Their dimensions were 1x2x5 cm^3. Except for the ninth crystal they were ordered in pairs (1,2: 3,4: 5,6; 7,8) and one out of each pair was doped with 75 ppm Europium. Unfortunately the supplier could not indicate which crystals of these pairs were doped. Crystal number 9 is composed of 2 glued pieces of crystal and has to be treated separately from the other crystals.

Before the irradiation all crystals were annealed for 2 hours at 200^o Celsius in order to "initialize" the measurements and the light yield of all crystals was determined with a ^{22}Na source using the widths and the positions of the 1.274 MeV and the 511 keV line in the energy spectrum. Then they were all irradiated by protons. In Table 3 the parameters for each of the 9 irradiations is shown. The number of the protons was derived from the above explained calibration, which was repeated before and after each of these measurements. After 7, 14, 18 and 77 hours the photoelectron yield was measured again with the ^{22}Na source. The results are plotted in Fig. 6.

It was found from a plot of the photoelectron yield versus time, that the fourth crystal showed no reaction to irradiation. This crystal might have been damaged severely before the irradiation and has therefore to be treated with caution in the following analysis. For the other crystals two trends become obvious from Fig. 6.

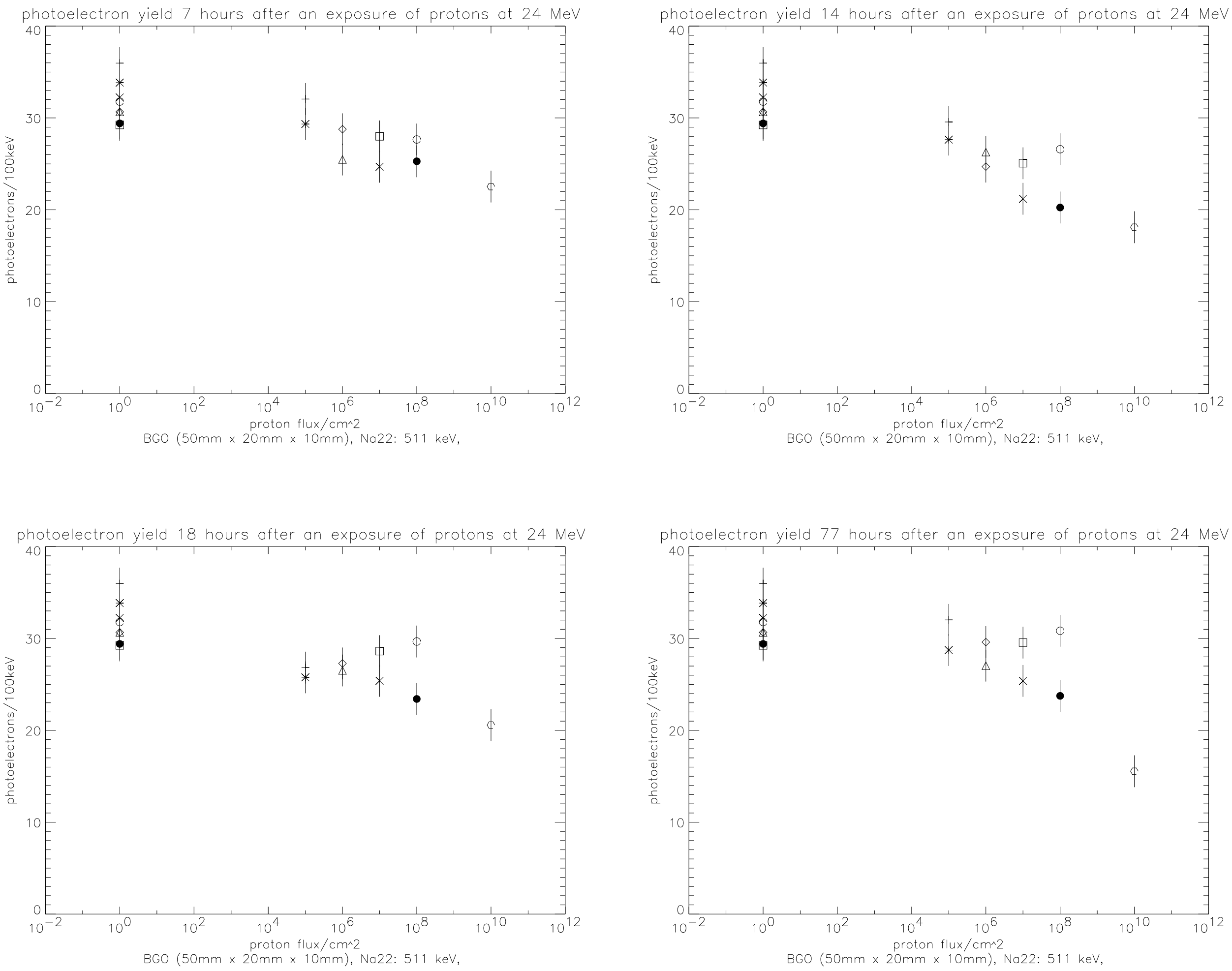

Figure 6: The photoelectron yield as a function of the proton dose. 9 different crystals, each represented by a different symbol have been measured. The light yield of the crystals before the irradiation is shown for comparison at a dose of 1 proton/cm^2.

1. With increasing doses there is a clear degradation of BGO with respect to the photoelectron yield.
2. There seems to be two different classes of crystals. One class shows a much faster recovery after irradiation than the other.

The first point demonstrates, that even for one passage through the belts, which is equivalent to approximately 3 bunches of protons from the accelerator, induces a reduction in the order of 1% in the photoelectron yield. On the other hand this reduction seems not depending linearly on the number of pulses, which is possibly due to the spontaneous recovery of BGO from radiation damage.

The second point might indicate, that BGO(Eu) doped crystals are less sensitive and recover faster from proton damage. This has also been reported by Wei et al.[10] As mentioned above this is only an assumption, since it can not be decided which crystals were doped and which were undoped. This point will be investigated soon in another radiation test experiment.

Table 3: The total proton dose for the 9 irradiations of the different BGO crystals

Crystal	Number of pulses	Protons / Pulse	Total number of protons
1	10	$(2.5 \pm 0.2) \cdot 10^4$	$(2.5 \pm 0.2) \cdot 10^5$
2	10	$(2.4 \pm 0.2) \cdot 10^4$	$(2.5 \pm 0.2) \cdot 10^5$
3	102	$(1.8 \pm 0.2) \cdot 10^4$	$(1.8 \pm 0.2) \cdot 10^6$
4	102	$(1.7 \pm 0.2) \cdot 10^4$	$(1.7 \pm 0.2) \cdot 10^6$
5	1011	$(1.8 \pm 0.2) \cdot 10^4$	$(1.8 \pm 0.2) \cdot 10^7$
6	1069	$(1.6 \pm 0.2) \cdot 10^4$	$(1.7 \pm 0.2) \cdot 10^7$
7	10130	$(1.6 \pm 0.2) \cdot 10^4$	$(1.6 \pm 0.2) \cdot 10^8$
8	10255	$(1.8 \pm 0.2) \cdot 10^4$	$(1.8 \pm 0.2) \cdot 10^8$
9	1014749	$(1.6 \pm 0.2) \cdot 10^4$	$(1.6 \pm 0.2) \cdot 10^{10}$

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