International Conference on Space Optics—ICSO 1997

Toulouse, France

2–4 December 1997

Edited by George Otrio

Development of active BGO veto shield for INTEGRAL-IBIS instrument

Paolo F. Sarra, Jens Michael Poulsen, Giuseppe Lesci

International Conference on Space Optics — ICSO 1997, edited by Georges Otrio, Proc. of SPIE Vol. 10570, 105700X · © 1997 ESA and CNES · CCC code: 0277-786X/18/\$18 · doi: 10.1117/12.2326471

Proc. of SPIE Vol. 10570 105700X-1

DEVELOPMENT OF ACTIVE BGO VETO SHIELD FOR INTEGRAL-IBIS INSTRUMENT

Paolo F. SARRA, Jens M. POULSEN, Giuseppe LESCI

Laben S.p.A., s.s. Padana Superiore 290, 20090 Vimodrone (Milano), Italy

ABSTRACT - IBIS instrument will perform fine imaging and accurate positioning of celestial Gamma-Ray emission in the range from 15 keV to 10 MeV. The four sides and the rear of the two imager layers are surrounded by an active BGO "veto" shield with a lower threshold of 100 keV. The area to be shielded is about 8000 cm² for a total BGO crystal weight of about 115 kg. The scintillation BGO light will be collected by PMTs and the PMT pulses will be conditioned in order to provide the two imager layers with fast anti-coincidence trigger signals. This paper presents the shield design implementation, and the technical solutions and processes for manufacturing and qualification of satellite hardware.

1 - INTRODUCTION

The instrument IBIS (Imager on Board INTEGRAL Satellite) will perform fine imaging and accurate positioning of celestial Gamma-Ray emission, simultaneously with the other instruments on board the ESA mission INTEGRAL (International Gamma-Ray Astrophysics Laboratory). IBIS will be sensitive for hard X-ray and gamma-ray emission in the range from 15 keV up to 10 MeV. The imaging characteristics of the telescope are achieved by a coded mask placed 340 cm above a position sensitive detector.

The detector features two imager layers of respectively 16384 cadmium telluride (CdTe) crystals and 4096 caesium iodide (CsI) scintillators, each layer covering an area of about 62 x 62 cm. The two imager layers are separated by a distance of 10 cm.

In order to reduce the background, and thus to increase the sensitivity of the telescope, the four lateral sides and the rear of the two imager layers are surrounded by an active Bismuth Germanate (BGO) "veto" shield. The scintillation BGO light will be collected by Photo Multiplier Tubes (PMTs) and the PMT pulses will be conditioned in order to provide the two imager layers with fast anti-coincidence trigger signals.

LABEN SpA (a Finmeccanica company) has the industrial contract for the design and development of the anti-coincidence shield. The design has been developed taking into account available BGO growth technology, and satellite constraints in terms of mass and power budget. Following a general description of the shield, this paper will report results of light output measurements on a Demonstration Model.

Fig. 1: IBIS cut-away view showing the hopper, the main frame structure, the CdTe and CsI(Tl) supporting structures and the "veto" anti-coincidence shield.

2 - SHIELD CONFIGURATION

The shield dimensions (area and thickness) are determined by the envelope of the imager detectors for what concerns the area of the shield, and for the shield thickness by the combination of required absorption efficiency and shielding material.

The envelope of the IBIS imager detectors to be shielded is composed of four lateral areas $66 \times 16 \text{ cm}^2$ each, and the rear area $62 \times 62 \text{ cm}^2$. The total covered area is about 8000 cm^2 . The choice of BGO as scintillator material becomes clear if one considers the available space and the weight as described below.

BGO has a high absorption/interaction coefficient compared to conventional crystal scintillators like NaI(Tl), CsI(Tl) and CsI(Na). For example at 500 keV the BGO attenuation length is only 1.01 cm compared to 2.91 cm and 2.26 cm for respectively NaI and CsI. In other words for a given linear space a BGO crystal is two to three times more efficient than conventional crystals. For IBIS a shield thickness of 2.0 cm has been chosen.

Further for space applications the weight is of very high importance due to the cost of launching heavy equipment, or vice versa to obtain the best performance (here the shielding efficiency) for a given weight. Although the density of BGO is high, 7.13 g cm^{-3} , compared to conventional crystals (see tab. 1), also in this case there is an advantage by using BGO scintillators. The total weight of

BGO crystal material in IBIS is 115 kg, but if the shield were made of NaI(Tl) or CsI(Tl) crystals with a thickness giving the same absorption efficiency (say at 500 keV) then the weight would be 42 - 49 % higher (see tab. 1).

Parameter	NaI(Tl)	CsI(Tl)	BGO	Lead
Density [g/cm ³]	3.67	4.51	7.13	11.34
Lin. attenuation coeff. [cm]	2.91	2.26	1.01	0.58
Equivalent abs. thick. [cm]	5.77	4.47	2.00	1.15
Equivalent weight [kg]	171	163	115	105

Tab 1: Comparison of common shielding materials at 500 keV

Fig. 2: Shield configuration (top view)

Following the design of the imager layers, the veto shield will also be modular in construction: there will be 8 lateral and 8 bottom modules (see fig. 2). The gaps between the modules have been aligned with the ribs of the mechanical structure of the imager detectors, and the distance crystal-to-crystal minimised in order to reduce as much as possible the radiation leakage. The resulting crystal dimensions are reported in fig. 2. Three types of modules with slight differences in width and length are necessary.

3 - OPTICAL DESIGN

Monte-carlo simulations on the effect of light collection vs. PMT number, size, and position have been carried out by A.J.Bird [Bird96a/96b]. The simulations considered several configurations of PMT to crystal coupling: with U-shaped light guides, without light guides, with side or end readout, domed or flat PMT windows.

The best design for a scientific point of view is shown in fig. 3: two flat PMTs on the centreline and side readout seems optimal. This solution is also the best design from an engineering viewpoint. A similar solution has already been implemented on PDS Lateral Shield [Frontera 96] on board SAX satellite. Proximity mesh PMTs (3 inches Hamamatsu R2238), space qualified during SAX campaign, is the best choice compatible to IBIS mechanical constraints due to their compact dimensions (55 mm length).

Fig. 3: "Single module" shield configuration, and ^{137}Cs source test positions

Crystal optical quality in terms of bulk attenuation length has also been taken into account in the monte-carlo simulations of the light collection efficiency. Assuming good crystal quality (3 m attenuation length), polished BGO surfaces, Millipore wrapping surrounding BGO and single crystal piece having the veto module dimensions, the resulting relative uniformity defined as $(\text{max.} - \text{min.})/\text{max.}$ light collection, is about 20 %.

Since current BGO growth technology is not able to provide crystals in a single piece, simultaneously with the required dimensions and quality, the BGO module has to be composed of two or more pieces. Two pieces with full length and half width, compatible with BGO growth capabilities, is the preferred solution because each PMT sees both BGO pieces (fig. 3). In case of a PMT failure this configuration maintains the module functionality with slight reduced performances. This module configuration will hereafter be named as "single module".

4 - LIGHT OUTPUT MEASUREMENTS

This paragraph describes the first results obtained on BGO samples procured from Institute of Inorganic Chemistry of Novosibirsk (Russia). Two samples, hereafter named L1 and L2 of equal dimensions ($310 \times 75 \times 20 \text{ mm}^3$) were cut from the same ingot. Since the length of the samples is close to the ingot top zone, some inclusions are present in the samples. In particular the L1 sample presents a greater quantity of inclusions than the L2 sample. Declared attenuation length, measured on a sample obtained from the same ingot, is better than 3 m at $\lambda=480 \text{ nm}$.

The test set-up in this report used R2238 Hamamatsu PMTs, 3 inches window diameter, and 70 mm useful photocathode diameter. Nominal gain of 10^5 is declared at 1000 V. The PMT anode pulse was conditioned by means of a Charge Sensitive Pre-amplifier (CSP) with decay time 3 μs . The CSP output signal (about 74 mV/pC) was sent to ADC and spectra analysed by MCA. The CSP calibration gave a conversion factor of 2.45 mV/channels and +51 mV offset.

The crystals were stimulated using collimated ^{137}Cs gamma-ray source (662 keV). The spot size on the crystal was less than 1 cm diameter.

4.1 - BGO samples light output comparison

A first set of measurements was performed on L1 and L2 samples separately in order to compare light output and to assess light collection effects due to the presence of inclusions. One PMT was positioned as shown in fig. 4, at a quarter of the sample length: 77.5 mm. For the sample L1 the position corresponding to the area which presents inclusions was chosen. Viceversa, for the sample L2 the position corresponding to the area which is free from inclusions was preferred. This test configuration will be hereafter named as "half module" configuration.

The samples were wrapped using a single layer of Millipore paper and coupled to the PMT by means of optical grease. Measurements were performed at three PMT high voltage values, i.e., 1000 V, 1100 V and 1200V and repeated at three source positions, i.e., 93 mm (close to the PMT), 155 mm (sample centre) and 279 mm (far from the PMT). Fig. 5 reports light output (^{137}Cs peak channel) versus source position: sample L2 seems to have a light collection 10 % better than samples L1.

The estimated anode charge (L1 sample, far source position, and 1000V PMT high voltage) for "half module" configuration is about 8 pC at 662 keV.

Fig. 4: "Half module" configuration set-up.

Fig. 5: "Half module" light output vs. source position and HV.

4.2 - Light output vs. PMT to crystal optical coupling

Based on previous SAX experience, Dow Corning 93-500 encapsulant was chosen for PMT to crystal coupling. This space grade material joins good optical properties (refractive index 1.41) with the mechanical properties of a shock absorber.

Measurements were performed on sample L1 in "half module" configuration in order to assess the best process to perform the PMT to crystal coupling. For visual inspection purposes the sample was not wrapped with Millipore paper. Measurements were repeated with encapsulants prepared using three curing agent percentages. The couplings were performed in air after curing of the encapsulant. The PMT was powered at 1000 V, and the sample stimulated at central source position. For each encapsulant light output results (^{137}Cs pulse height in mV) are reported in tab. 3. The best coupling was obtained with casting on the PMT and with 2% of curing agent. Low percentage of curing agent provides a softer pad, which maximises air evacuation between PMT and crystal when it is pressed to the crystal. A similar result was obtained with optical grease, but grease cannot be implemented for space based instrumentation.

The casting on the crystal gave a worse coupling because the presence of an air bubble on the centre of the PMT window due to the non-planarity of the PMT glass window.

PMT to crystal integration in vacuum will be investigated in order to optimise the coupling process. The best coupling performed in air was also tested under vacuum (10^{-6} mbar). The light output measured in vacuum was about 3% less than the previous value measured in air. Several cycles "air to vacuum" and viceversa were repeated and light output measured; no additional light output degradation was observed. Considering that a few degrees modification in BGO temperature produces bigger light output variations (see next par.), this effect can be considered as negligible.

curing agent (%)	light output (mV)	note
10	161	
10	512	optical grease added
5	387	
2	401	casting on crystal
2	529	casting on PMT

Tab. 3: PMT to crystal optical coupling

4.3 - Light output vs. temperature

Light output measurements were performed in the IBIS detector temperature range in order to assess the variations on pulse height and pulse peak time, and thus to estimate the temperature contribution to the jitter of the anti-coincidence strobe.

Measurements were performed on sample L1 in "half module" configuration, at the "cold" case and the "hot" case temperatures derived by the IBIS thermal model: -25C and + 22C respectively.

The sample was wrapped using a double layer of Millipore paper and coupled to the PMT by means of Dow coming 93-500 (2% curing agent, PMT casting). PMT was supplied at 1000V and the source positioned in the centre of the sample.

^{137}Cs spectra are shown in fig. 6. The corresponding pulse height and pulse peak time are reported in tab. 4. The measured light output variation of -1.5 %/C is consistent with the BGO light yield and PMT photocathode quantum efficiency variations versus temperature. The increased peak time is in agreement with the slower BGO scintillation decay time at cold temperatures.

temperature (C)	peak height (mV)	peak time (μsec)
-25	1374	1.5
+22	798	1.0

Tab. 4: Light output vs. BGO temperature

4.4 - Light output vs. wrapping/coating

Millipore paper is a brittle material so in order to avoid paper tearing when wrapped BGO crystal is being integrated in its housing, adhesive tapes have to be sticked on the paper.

As an alternative a white diffuser, based on TiO_2 coating, was investigated. TiO_2 powder mixed with Dow coming 93-500 joins white diffuser properties and the mechanical properties of a shock absorber necessary for crystal integration in its housing.

Measurements were performed on four small BGO samples procured from Institute of Inorganic Chemistry of Novosibirsk (Russia). Samples dimensions are: $30 \times 9.7 \times 8.5 \text{ mm}^3$. The largest side of the samples was coupled to a R2238 PMT by means of Dow Corning 93-500.

^{137}Cs measurements were repeated for naked, Millipore wrapped and TiO_2 coated crystals. Results are reported in fig. 7. Similar light output was obtained with Millipore wrapping and TiO_2 coating.

However these results cannot be considered as conclusive due to low statistics and set-up configuration. "Single module" configuration measurements are necessary in order to complete the trade-off analysis.

Fig. 6: ^{137}Cs spectra for BGO temperature: -25 C and +22 C.

Fig. 7: Light output relative to naked crystal vs. wrapping/coating

4.5 - Light output vs. position

Light output uniformity was investigated in the "single module" configuration shown in fig. 3. The L1 and L2 samples were coupled by means of Dow corning 93-500 (10% curing agent). The encapsulant was casted in place, and vacuum was applied before curing in order to eliminate air bubbles in the 0.3 mm thick section.

The glued samples were wrapped with one layer of Millipore paper (adhesive tape reinforced) and coupled by means of Dow corning 93-500 with two R2238 PMTs powered at 1000V by a single high voltage power supply (HVPS). In order to save power the flight configuration foresees one HVPS per shield module.

^{137}Cs measurements were repeated by stimulation of L1 and L2 at source positions shown in fig. 3. The light output versus source position is also reported in fig. 8: separate PMT pulses (P1 and P2) and added PMT pulses (PS) are reported. The light output uniformity as defined in par. 2 is about 14%. Local FWHM resolution of about 28% is achieved (resolution was estimated by means of CSP calibration).

Finally light output measurements was repeated with non-collimated source (broad illumination) of the single module. A ^{137}Cs spectrum is shown in fig. 9 (added PMT pulses). The global FWHM resolution is about 31 %. The estimated anode charge for "single module" configuration is about 14 pC at 662 keV.

Fig. 8: Light output vs. source position for single and summed PMT signals

5 - CONCLUSIONS

The following aims have been achieved:

- BGO quality for large size crystal has been assessed;
- PMT choice (Hamamatsu ruggedised R2238) has been confirmed;
- Optical coupling of PMT to BGO and BGO to BGO with Dow corning 93-500 space grade encapsulant have been tested successfully;

- shield optical design has been validated in flight representative configuration and light output performances of the Demonstration Model are in line with the required specifications. Further activities will complete mechanical integration of the Demonstration Model in order to perform environmental testing of the shield module. In the nearest future the Demonstration Model will also be upgraded to an engineering model including flight representative electronics.

Fig. 9: ^{137}Cs spectra for "single module" configuration and broad illumination. The energy resolution (FWHM) at 662 keV is 31 %

ACKNOWLEDGEMENTS

We would like to express our gratitude to Dr. Ya.V.Vasiliev and V.P.Smakhtin for their expertise in BGO scintillation technology. Most of the optical design was defined by Dr. P.Ubertini, IBIS Principal Investigator, in collaboration with Prof. K.Broenstad and Dr. A.J.Bird. The development activities were funded in the frame of INTEGRAL IBIS program, phase B. Special thanks to F.Baldoli, P.Bastia, F.Monzani and R.Ronchi for supporting the activities.

REFERENCES:

- [Bird 96a] A.J.Bird: "Modelling of possible veto module designs", INTEGRAL IMAGER doc. nr. IN-IM-SOT-TN-0031, April 1996
- [Bird 96b] A.J.Bird: "Veto crystal quality effects & photomultiplier position", INTEGRAL IMAGER doc. nr. IN-IM-SOT-TN-0033, July 1996.
- [Frontera96] F.Frontera et al.: "The high energy instrument PDS on-board the BeppoSAX X-ray astronomy satellite", Astronomy and Astrophysics, September 1996