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DEVELOPMENT OF A CsI(Tl) SCINTILLATOR FOR INTEGRAL-IBIS INSTRUMENT

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ABSTRACT *- The PICsIT is a scintillator array made up of 4096 CsI(Tl) crystal bars. Each crystal is optically coupled to a custom made low leakage silicon PIN photodiode, to allow for the conversion of light pulses into charge pulses. This design provides a high degree of modularity. In order to collect all the scintillation light, each crystal coupled with its photodiode is wrapped with a white diffusive coating*

This paper presents the design implementation of a single detection unit as well as a single module. Finally the technical solutions under study at Laben to meet the primary scientific requirements for the PICsIT detector are presented, focusing on the following technological areas:

- *crystal surface treatment ad wrapping;*
- *photodiode to crystal optical coupling;*
- *mechanical assembly and single scintillator's test.*

1 - INTRODUCTION

The *INTErnational Gamma-Ray Astrophysics Laboratory* (INTEGRAL) is a high resolution spectroscopy, wide-field imaging with fine angular resolution γ-ray telescope.

IBIS (Imager on Board Integral Satellite) is aimed to perform fine imaging and accurate positioning of γ-ray sources, simultaneously with other on board instruments. IBIS is composed of two imager layers based on CdTe semiconductors and CsI(Tl) scintillators, operating between 15 keV and 10 MeV, and a BGO *veto* shield around these two detectors. Over the detectors there is a shielding device (Hopper), made of tungsten, for the gamma radiation that comes from out of the detector field of view. The whole instrument weight is 370 kg and its dimensions are 939x940x850 mm (fig.1).

The Pixellated Imaging Caesium Iodide Telescope (PICsIT) is composed of 8 modules that form the detector plane and two electronic units external to the detector plane. Each module consists of 512 square cross-section CsI(Tl) pixels and associated front-end electronics. The whole PICsIT instrument weight is 80 kg, its dimensions are 634x616x65 mm and the total active area is about 3000 cm^2 (see fig. 3)

2 - MECHANICAL ASSEMBLY

The module support structure is designed to provide support for 512 detection units and mechanical support for the Front End Electronics.

In order to make the detection units light tight and to separate them optically as well as to have a good mechanical structure, the detection units are inserted in an eggcrate formed by cells with a square cross-section with dimension of 9x9 mm. Each cell is 34 mm long and it has a wall thickness of 0.2 mm. The pixel centre to centre distance is 9.2 mm (fig. 2). The resulting eggcrate has 512 cells and a rectangular cross-section of about 297x153 mm, for an module active area of about 374 cm^2. The cell's surface roughness and its angular radius are mechanically arranged in order to easier insert the pixel. The eggcrate is closed with a bottom panel with 1024 holes for the PD 512 connections. This panel is 3 mm thick, its weight is 384 g and it is light tight. The module has also a top panel made of Aluminium. It is 2 mm thick, its weight is 256 g and it provides a light shield and a EM shield. Both the top and the bottom panel retain the detection units at their right position.

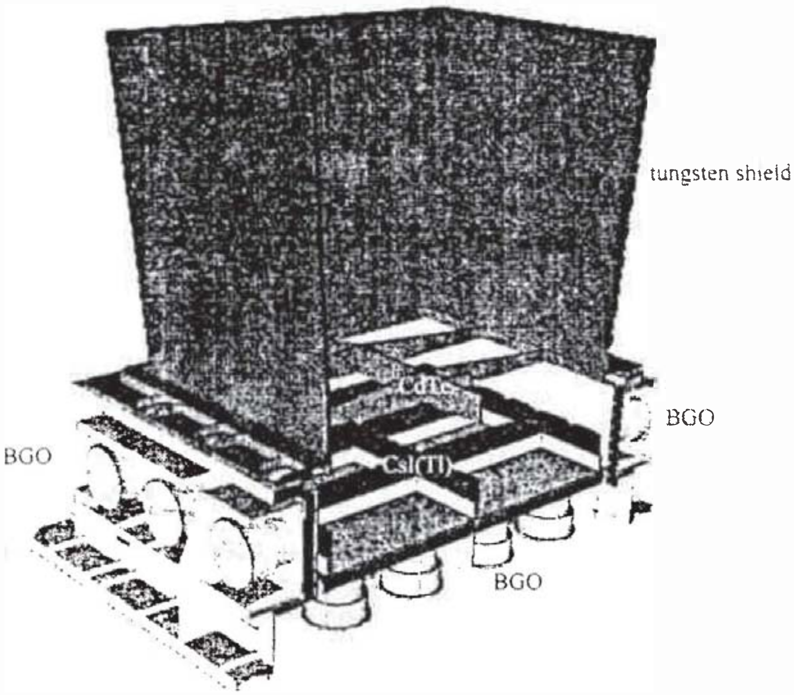

Fig. 1 - The IBIS instrument

In fig. 2 a subassembly of 4x4 detection units inside the eggcrate is shown and in fig. 3 the PICsIT assembly is shown.

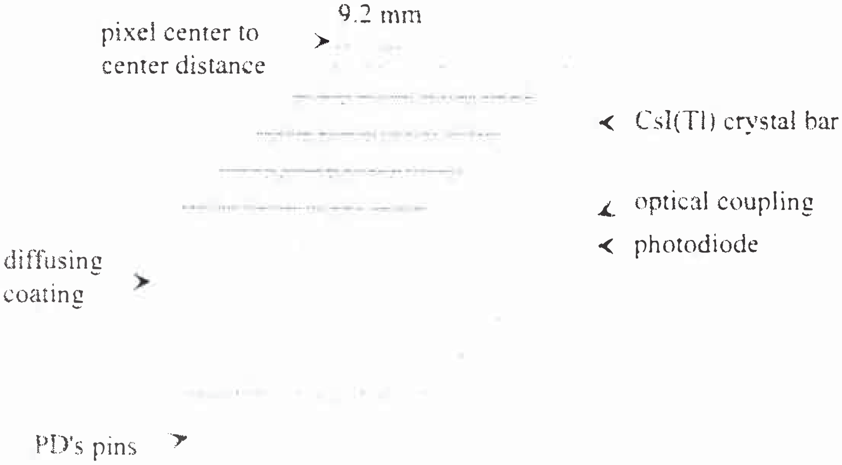

Fig. 2 - Pixel assembly inside the eggcrate

Finally a layer support structure supports the eight modules and it holds them in a plane. They are fixed with screws. The layer support structure itself is a unique piece of the whole IBIS main frame, it is 25 mm high, 653.6x653.6 mm big and made of Aluminium. This system has structural, positioning and thermal functions and it performs the role of interface between the modules and the main frame structure.

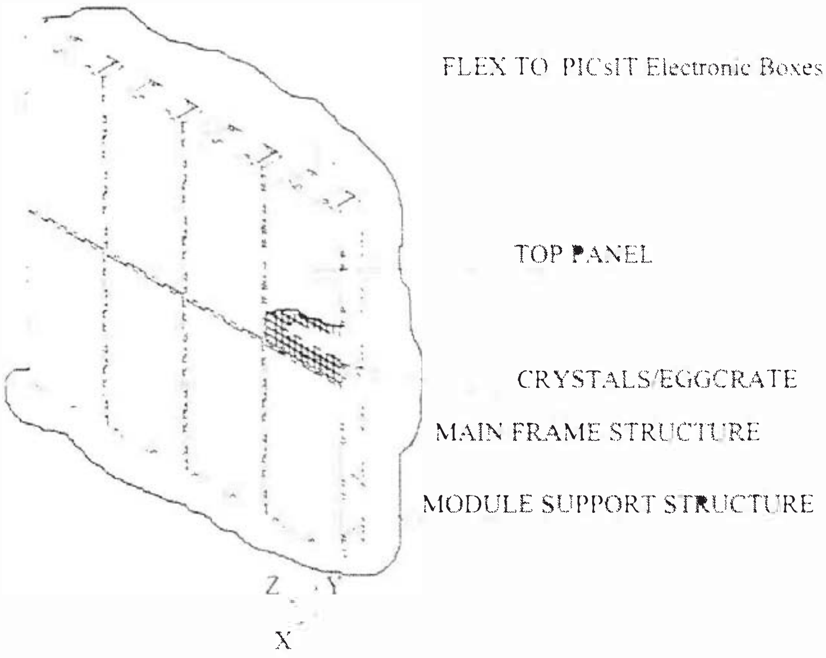

Fig. 3 - PICsIT assembly

3 - DETECTION UNIT CONFIGURATION

CsI(Tl) is the most luminous scintillating crystal known, having a measured absolute scintillation yield of 64800 photons/MeV for γ-ray at room temperature and the maximum of the broad emission is situated at 550 nm. CsI(Tl) is a material with a high γ-ray stopping power due to its relative high density (4.51 g/cm^3) and Z value. It is also highly resistant to thermal and mechanical shock due to the absence of a cleavage plane. CsI(Tl) is soluble in water but it is slightly hygroscopic and it is a relatively slow scintillator with an average decay time of about 1 msec for γ-ray. Electronic with suitable shaping time (4-6 µsec) is therefore used. This limits the count rate the detector can handle. The light yield of the detection unit (CsI(Tl)+photodiode+coating, hereafter *pixel*) is expressed as the number of electrons produced in the photodiode (hereafter *PD*) for an E energy loss. The intensity of the scintillation light is important for an accurate determination of the energy of the absorbed radiation. It depends on several factors temperature, geometry of the scintillator, PD-crystal optical coupling, PD quantum efficiency, thallium concentration in the CsI. In the following pages most of these factors are discussed.
For what concern the thallium concentration, CsI(Tl) shows a broad maximum in the light yield between 700 and 1300 ppm of thallium, which represents typical values of thallium doping. However, significant variations in thallium levels occur throughout the crystal as it is grown, giving rise to non-uniformity in light output from one sample to the next [cfr. Bird 93].

3.1 - Surface geometry

The transmission and type of reflection from the surface is critical in maximising the number of scintillation photons that are detected by the PD. Depending on the ratio between the height and the section of the crystal, the scintillation light reflects more on the lateral faces to reach the PD: the higher the ratio the more reflection on the lateral faces. This imply that they have to be more polished. In fig. 4 different light outputs are shown, depending on the surface treatments for PICsIT crystal bars. Moreover, the optimum is to polish the lateral faces and to roughen the face opposite to the PD. The face that is coupled to the PD has a suitable roughness in order to ensure a good mechanical coupling.

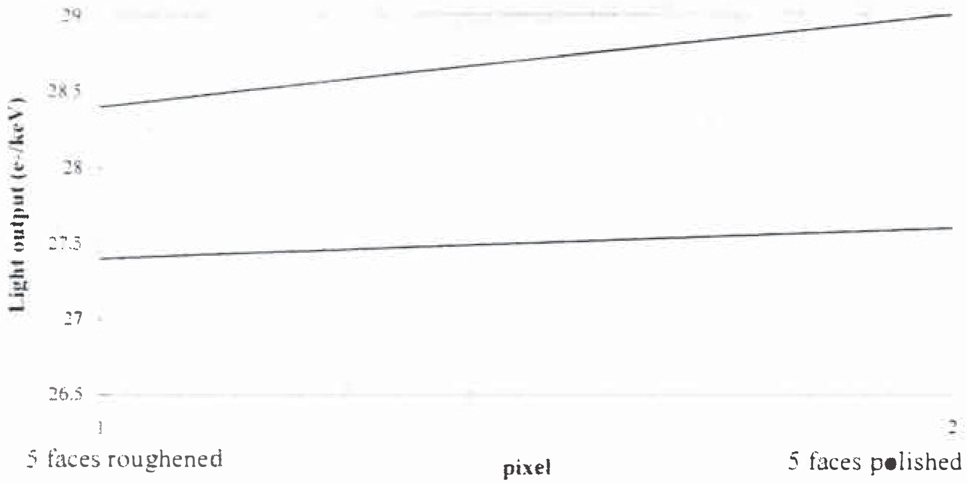

Fig. 4 - Surface treatments

3.2 - Optical coupling

The main effect of the optical coupling on light collection is related to its transparency. Furthermore, in order to improve the detection integration, it is necessary to glue the PD permanently to the crystal. The characteristics of the glue looked for the PICsIT pixel optical coupling are shown in tab. 1. CsI(Tl) has a refraction index of 1.7, the PD's silicon has a refraction index of 3 or 4, depending on the scintillation light wavelength. For a good light collection, the glue should have a refraction index as much between this two values as possible.
After several laboratory tests performed with many glues (see fig. 5), the epoxy resin Stycast 1266 was singled out. All the tested resins are good optical couplings but the Stycast 1266 shows the better radiation hardness in terms of transparency. It is a transparent, high impact, room temperature cure epoxy encapsulant. It is a clear, low viscosity encapsulant which, when fully cured, has outstanding toughness and impact strength.

permanent coupling	
tensile strength MPa	40 - 55
hardness, shore D (units)	75 minimum
index of refraction	1.56
transmission after 200 kRad	0.1%
optical transmission	98%

Tab.1 - Characteristics of the Stycast 1266

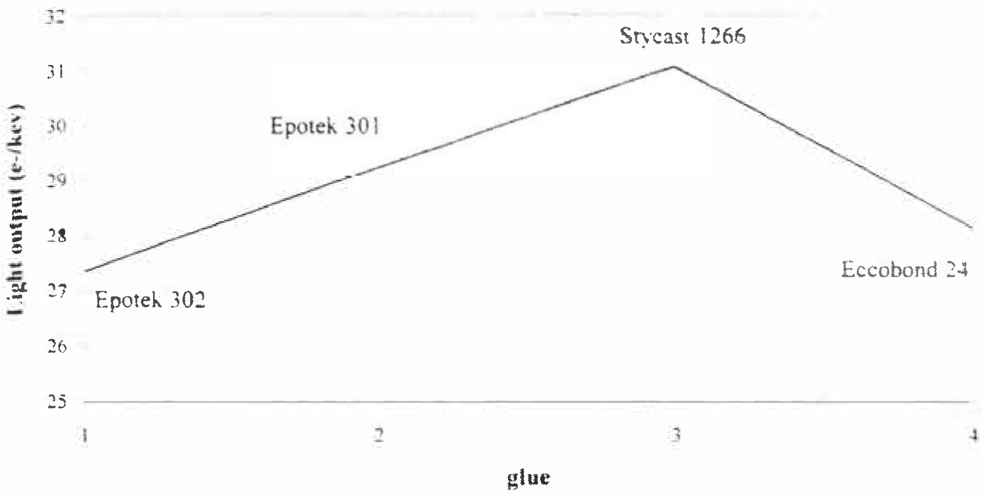

Fig. 5 - Optical couplings

The precise control of the bond geometry is essential, particularly in the removal of any meniscus around the crystal. This is essential in order to avoid excessive light loss at the crystal-photodiode interface. This light loss is due to the light being transported by the adhesive to non-sensitive regions of the photodiode substrate or lost within the packaging.

3.3 - Photodiode

In PICsIT the scintillation light from a crystal is detected by the use of a silicon PD. This is a semiconductor device in which the absorbed light creates free charge carriers (electrons and holes). This configuration has several advantages as described below.
The quantum efficiency of the PICsIT silicon PD is 85% between 500 and 900 nm. It is clear that the highest signals can be expected from scintillation crystals that have an intense emission above 500 nm. CsI(Tl) crystals, characterised by a large scintillation intensity with a maximum at 550 nm, are therefore well suited to couple to PD.
PDs do not require a high voltage power supply but only a bias voltage of about 30 V, they are thin, rugged and insensitive to magnetic fields. Due to very small signal generated by the PD, it is necessary to employ a high quality charge preamplifier with the noise level as low as possible. A silicon PIN PDs is a *unit gain device*.
The thickness of the silicon used in the PICsIT detectors is 0.3 mm in order to achieve the best conversion of the light pulses into charge pulses. Coupled to a conventional (low noise) charge preamplifier, the substantial capacitance of the device (50 pF) is mainly responsible for the noise and it determines for a large part the energy resolution of the detector. Also the dark current of PIN PD (1 nA) may contribute significantly to the noise, especially at larger shaping times. The dark current increases as well with increasing surface area as with increasing temperature. This limits the use of scintillation PD detectors to temperature below 50 °C.
The PD's active area has been as much enlarged as possible in order to collect most of the scintillation light. The PICsIT PD is a custom made device for its unusual dimensions but it has standard electrical performances. In the flight configuration, the PD covers the 84% of the CsI(Tl) active area, instead of the 52% of the standard devices.

The nature of the packaging has been identified as potentially a major cause of light loss within the detector. The PD package has the same dimension as the crystal. Since the PD package covers some part of the crystal then white ceramic is used as packaging material, in order to send back the light in to the pixel and to collect as much scintillation light as possible.
The performance parameters for the photodiode are:

active area	61.3 mm^2
photo sensitivity	(370 + - 2.5%) mA/W at 560 nm
dark current (V_R=30 V, T= 20 C°)	1 nA
quantum efficiency	85%
capacitance (V_R=30 V)	less than 50 pF

Tab. 2 - PD characteristics

3.4 - Diffusing coating

The pixel is wrapped on all sides, except the PD one, in a white light diffusive coating that drives the scintillation light into the PD. This coating allows the required light output of 30 e$^-$/keV.
The crystal thickness has some effect on the light extraction. For a 30 mm long bars, 60%-80% of the scintillation light produced in the γ-ray interaction is extracted.
Since each pixel is inserted in a 9 mm cell (see Par. 2), it has a maximum cross section of 8.95 mm. Moreover the cross section of the bare crystal is different depending on the diffusing coating.
Several kinds of material have been tested, in particular white papers and white pigments. For each test the pixels were previously calibrated with ^{241}Am and then tested with ^{137}Cs.
Between the best white papers are fine pore filter papers. These are sheets of paper with conical holes and very high diffusing properties, due to the hole's diameter near to the scintillation light wavelength. In fig. 6 a comparison between three different papers is shown: A=durapore, B=millipore, C=plastic paper. The 662 keV peak position is an index of the light output: the higher the peak's channel the higher the light output. The millipore paper and the plastic paper are comparable jet the latter is mechanically stronger and therefore more suitable for wrapping.

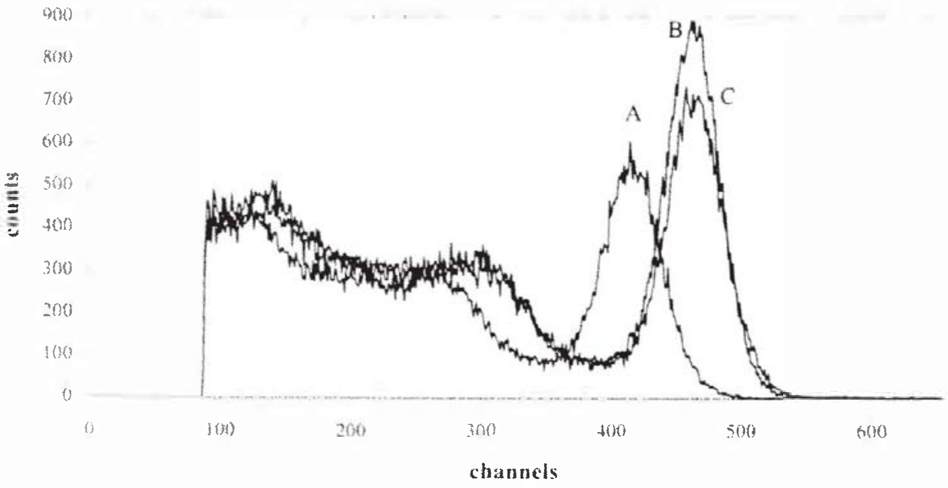

Fig. 6 - ^{137}Cs spectra for different types of white papers

The big disadvantage of the papers is that they're very brittle. Since they are not adhesive, they have to be tightly wrapped around the pixel and maintained in position with some tool. This is, in fact, one of the eggcrate's purposes. Since the cell's walls are rigid, the white paper is not in perfect contact with the pixel and this decreases the light output and the resolution of typically 10%. To hold the paper tight on the pixel, it could be wrapped with some kind of adhesive tape. This allows a) to insert the pixel inside the eggcrate without lose in light output and resolution because the paper is tight held by the tape and not by the eggcrate's walls; b) to insert the pixel without damage the paper against the eggcrate's walls. However, also in this configuration we lose scintillation light because the tape covers the paper's holes and decreases their diffusing performances. The fig. 7 and 8 show respectively the differences in the light output and in resolution between the pixels (not wrapped with the tape) outside and inside the eggcrate.

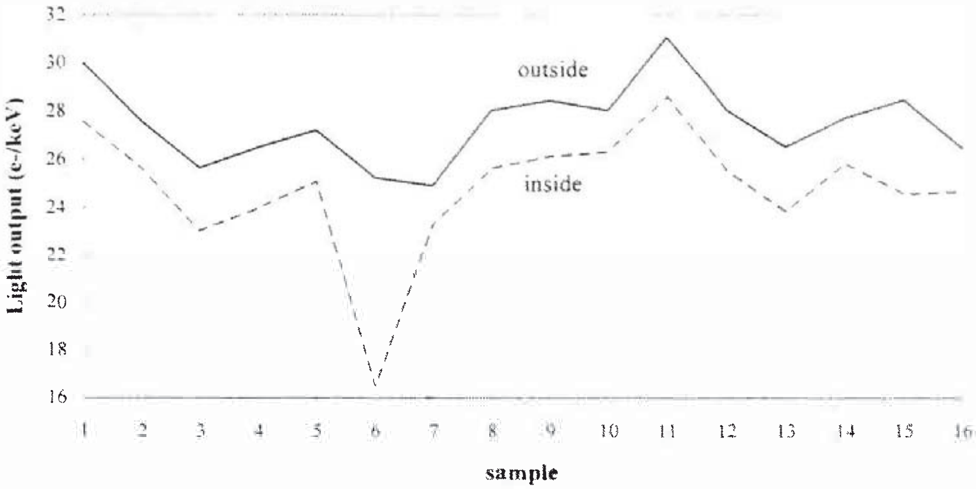

Fig. 7 - Light output decreasing after the pixel's insertion in the eggcrate

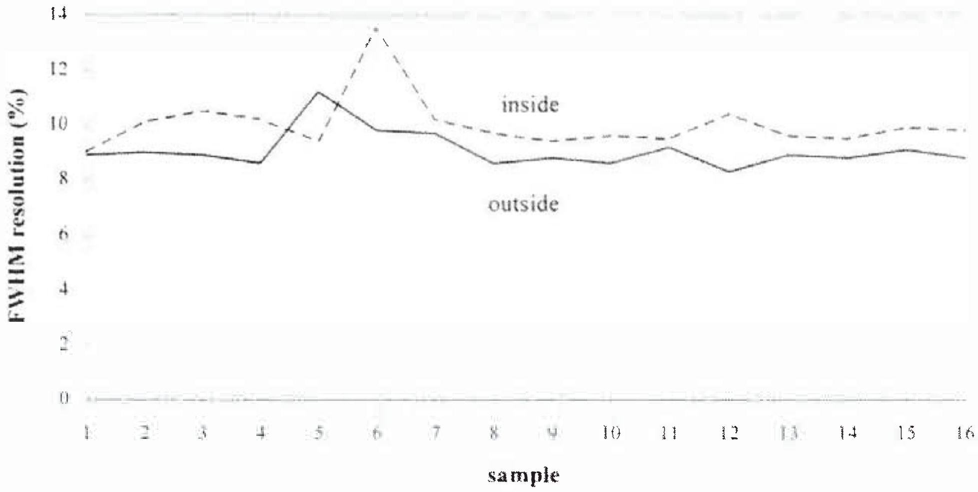

Fig. 8 - Comparison between pixel resolution outside and inside the eggcrate

Beside the papers, there are the pigments. They have to be sputtered or stuck in some way on the crystal surfaces. A white diffusing coating based on a high diffusing pigment mixed with an adhesive potting has been studied. In fig. 9 a comparison between the millipore paper and this coating is shown

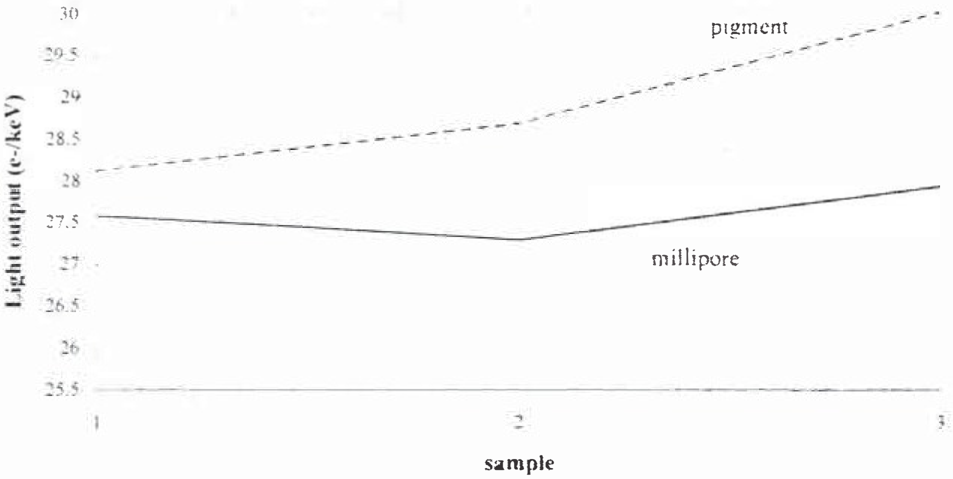

Fig. 9 - Comparison between samples coated previously with millipore paper and then with white pigment

The advantages of this method, besides the higher light output, are the thickness (0.1 mm of the coating are comparable to 0.15 mm of the white paper) and the mechanical aspects. Due to this thinner diffusing coating, PICsIT has a larger active area. Moreover instead of inserting each pixel in a cell, they could be arranged in an array of 4x4 pixels potted together. This should make easier the module assembly that should consists in 32 array of 16 pixels instead of 512 single pixels.

Finally, instead of wrapping the crystal with some kind of material, it has been investigated to treat the crystal surfaces in order to make them diffusing reflectors. Since the CsI(Tl) is quite a soft material, it is possible to roughen its surface. For this purpose, 5 sides of CsI(Tl) crystal bar have been roughened with a flux of granular stone powders with different particle radii. In fig. 10 a comparison between a pixel wrapped with millipore paper and the same pixel with the roughened surfaces is shown. It can be seen that the roughened surfaces alone give a poorer light output (about 50% less) than the millipore paper.

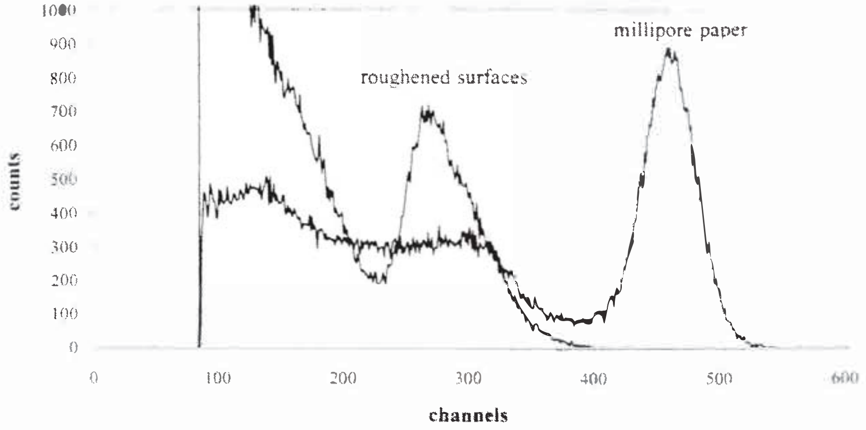

Fig. 10 - Comparison between millipore paper and roughened surfaces

4 - ENVIRONMENTAL TESTS

In order to test the behaviour of the pixel coatings in the space environment, thermal-vacuum tests have been performed. The limit temperatures reached during the tests were +30 °C and - 20 °C, stressing the pixels in order to check any problem.

As shown in fig. 11, there's a reversible path of the pixel's performances, confirmed also by the same pixel light outputs before and after the TV tests (fig. 12). In the space environment the pixel temperature is maintained at about 0 °C. In this gap the light output is lower than at ambient temperature but, as the PD's noise does so too, the signal to noise ratio is still the same. Both the millipore paper and the plastic paper show this behaviour.

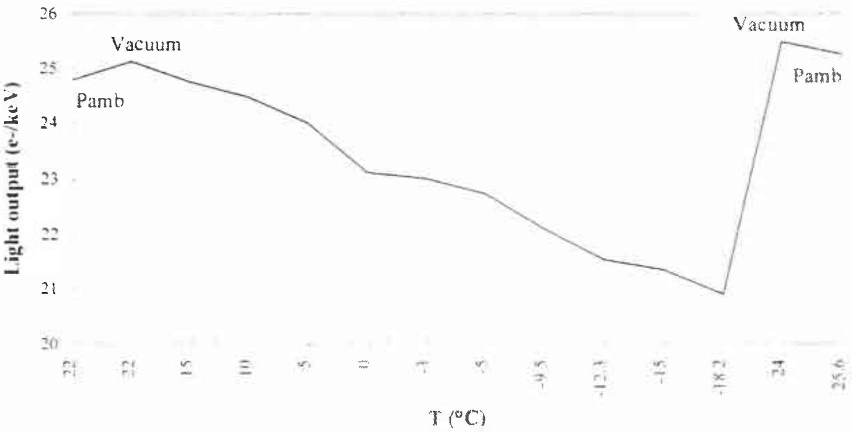

Fig. 11 - Light output variation during the thermal-vacuum test

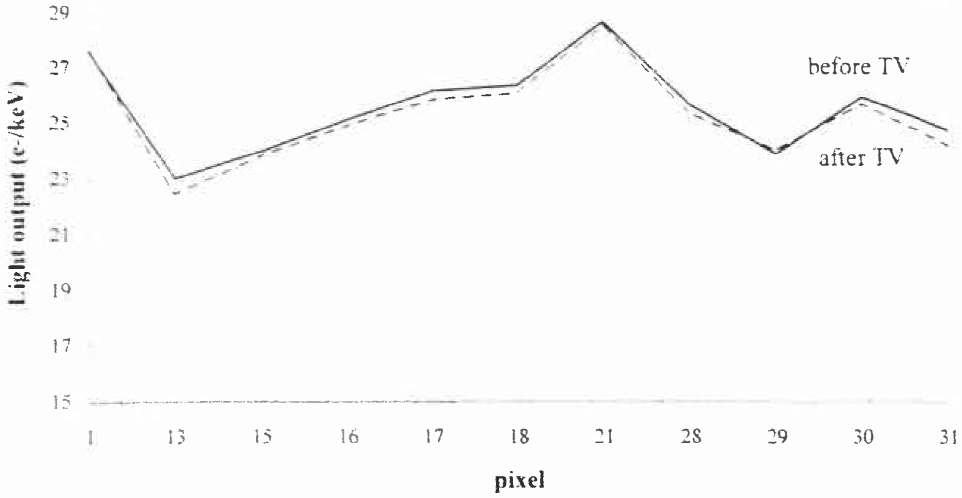

Fig. 12 - Light output before and after the thermal-vacuum test

5 - CONCLUSIONS

At the end of this work, the following aims have been achieved:

- CsI(Tl) lateral polished surfaces show the better diffusing behaviour;
- PD scientific design has been definitively agreed, with the biggest possible active area;
- Stycast 1266 has been identified as the better PD to CsI(Tl) optical coupling, due to its good radiation hardness;
- three excellent diffusing coatings have been identified;
- the environmental behaviours of the pixel with different coatings have been successfully tested, ensuring a good light collection in the space environment.

Further activities will identify the best diffusing coating as well as complete the mechanical integration of the demonstration model in order to perform additional environmental tests. Moreover the demonstration model will be early upgraded to an engineering model including flight representative electronics.

ACKNOWLEDGEMENTS

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