Virtual Prototyping and FEM Analysis of the Crystal Eye Detector

Fabrizio Renno[1[0000-0002-2529-4434]], Stefano Papa[1[0000-0002-4469-7861]], Domenico Marzullo[2[0000-0001-9764-1725]] Felicia Carla Tiziana Barbato[3[0000-0003-0751-6731]], Giancarlo Barbarino[4[0000-0001-9253-3397]]

[1] Università degli Studi di Napoli Federico II, Napoli, Italy
[2] Università degli Studi di Trieste, Italy
[3] Gran Sasso Science Institute (GSSI), L'Aquila, Italy
[4] Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli, Italy

stefpapa@unina.it

Abstract. The main aim of this article is to describe the design of a new sensor to study the electromagnetic field portions of gravitational waves. On August 17, 2017, the observation of the gravitational wave event started the era of multi-messenger astronomy. Therefore, new tools and optimal synchronization of the available telescopes are needed. The sensor that is designed is a cross-cutting technology, it is named Crystal Eye: a wide field of view in the energy field from 10 keV to 10 MeV with a structure made of pixels. As the detector will be involved in the mission in 2023, the virtual prototype phase needed for optimization and production of the payload has been completed. Particular attention was paid to the results of the FEM analysis carried out to examine and predict the thermal and vibration behavior of the conceived mock-up during the launch phase and under strong temperature variations in the space environment.

Keywords: Virtual Prototyping, Vibration and thermal analysis, Detector, FEM.

1 Introduction

An established thesis in astrophysics is that impacts or mergers of two neutron stars produce considerably relativistic and collimated jets that supply energy to γ-ray bursts of short endurance [1-3]. This was only a theoretic concept until the X-ray part interested by the GW170817 gravitational-wave event was detected [4]. The so far considerable belief that gravitational-wave events from analogous fusions should be linked to γ-ray bursts, and that their prime part should be watched off axis, was so confirmed. Together, scientists were able to observe X-ray and, thereafter, radio frequencies which result to be coherent with a quick γ-ray blast viewed off-axis. The find of X-ray emissions that coincide with the transitory of a kilonova gives the observation link that was missing between the short γ-ray blasts and the gravitational waves from the neutron-stars fusions, and provide independent corroboration of the collimated nature of the γ-

ray blast emission. [5]. So, all the best and most versatile devices are needed to detect something even when and where no information is expected. The main currently active experiments in the space environment that can detect the γ-ray and X-ray range are *Chandra and XMM Newton'*, unfortunately characterized by a small field of view. Although this feature allows to point a source and to obtain a good imagine of that, it reduces the observation of the Universe to a very small zone. The Fermi γ-ray blast monitor instrument (Fermi-GBM) is not very accurate because it is designed to be a wide sight experiment [6]. So, an enhanced and more efficient detector is needed.
Today, many tools (software and hardware) can be used to design, improve, and optimize products. So, for instance, CAD, CAE, CFD methodologies are "consolidated" instruments for the realization of Digital Mock-Ups (DMU) and for testing purposes. Furthermore, the use of the FEM methods can be very useful to analyze and foresee the thermal and vibration behavior of the mock-up during the launch or in the adverse conditions of the space environment due to the high temperature variations [7, 8]. In addition, the modern production technologies for the realization of the prototypes, such as Additive Manufacturing techniques, represent a fundamental tool to get enhanced physical prototypes. They are supported by design and optimization methods aimed at selecting adequate materials and shapes to improve performances and to reduce the weight of the final model, and so the costs. Traditionally, by means of conventional methods these kinds of products are made by many elements which need to be machined and jointed (by welding or screws). On the contrary, 3D printing, particularly with metals, is increasingly being used in the manufacture of components in aerospace industry (i.e. rockets parts, propulsion modules or engines elements) because it enables these components to be manufactured as a single piece in one-shot process [7]. Furthermore, the application of these new methodologies to the field of aerospace experimentation allows to test the weight reduction, the material efficiency and the behavior of the artifacts in this way produced, in unconventional operating conditions, providing further study data. The analysis of the responses of the prototypes can also contribute to the standardization of an innovative process for the design and development of products to support the experimental studies target of the Project.

2 The new detector

2.1 Crystal Eye

As mentioned before, there are several currently active experiments in the space environment that can detect the gamma and X-rays, as for instance XMM-Newton' and Chandra [6]. They are a consequence of an old way of designing sky observatories and they have the main drawback related to the limited field of view and so, even if these detectors allow to get good results, they decrease the observation of the Universe to a very small zone. Therefore, the Crystal Eye proposal starts from a new approach for the Universe observation, and it will be the advanced version of the Fermi-GBM detector, designed for a mission on the International Space Station (ISS). It will be a new and crossover technology among all sky telescopes and monitors: an observatory with a really wide field of view (local observation equal to 2π), analyzing the range of energy from 10 keV to 10 meV with a structure full of pixels. Main target is to improve the field of view of the GRBs allowing a better localization due to the monitor with a low-cost mission spatial resolution. Furthermore, the compact dimensions (that allow an astronaut to move it easily) and the wide field of view with small pixels are the prerequisites chosen to make this device competitive with the other systems. Therefore, the main objectives of the program are to raise awareness of events with X-rays, low-power γ-rays and identify long-term variability X-ray founts, promote multi-wave length visualization of various entities, and search for scattering cosmic X-rays. The detector conceived is a hemispherical multi-level structure made by a double layer of LYSO pixels covered by a veto dome. The final model has been realized starting from a hemisphere with a 140 mm radius. Furthermore, it has been built with a full parametric approach to modify each feature of the virtual prototype in real time. In addition, it has been designed to be 3D printed. It will be characterized by 112 pixels on two scintillators layer designed to observe the down-going X and γ-rays and to reject the up-going ones (Fig. 1).

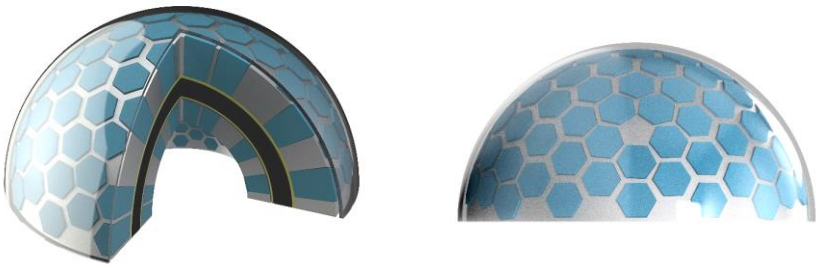

Fig. 1. CAD model of the Crystal Eye detector.

The smaller size and the larger number of contiguous pixels will improve the spatial resolution and, therefore, the localization of the source. Fig. 2 shows the position of the pixels (characterized by hexagonal top and bottom surfaces). Each one consists of a hexagonal pyramid of LYSO read by adequate Silicon Photomultiplier (SiPM) matrices. A regular polygonal mesh with 112 hexagons and 4 pentagons defines their location assuring the symmetry with respect to the zenith. The external veto dome will be made by a scintillator material with a dig where an optical fiber will guide the collected light to the SiPMs. The wiring will be placed between the pixel layers and an adequate insulation.

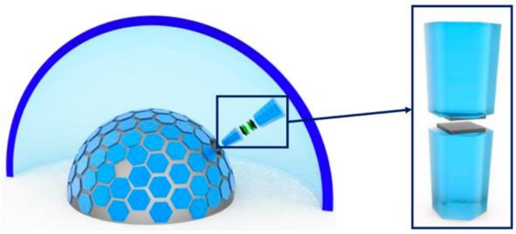

Fig. 2. Exploded view of the detection module of the Crystal Eye prototype.

2.2 Crystal Eye pathfinder

A compact prototype of the conceived Crystal Eye model, based on only four pixels, will be launched on September 2023 aboard of the Space Rider, an uncrewed orbiting laboratory of European Space Agency (ESA) designed to give reusable access to the space. The Crystal Eye pathfinder was designed as a lightweight version of the complete detector that can provide basic results that act as a potential physical assessment. The system is characterized by an electronic board and four pixels (Fig. 3). Each one consists of a hexagonal pyramid of LYSO read by adequate Silicon Photomultiplier (SiPM) matrices as previously defined for the full detector. The two months Space Rider mission will follow the LEO orbit (as the International Space Station) and a Solid-State Drive will gather the data (also sent to the ground base).

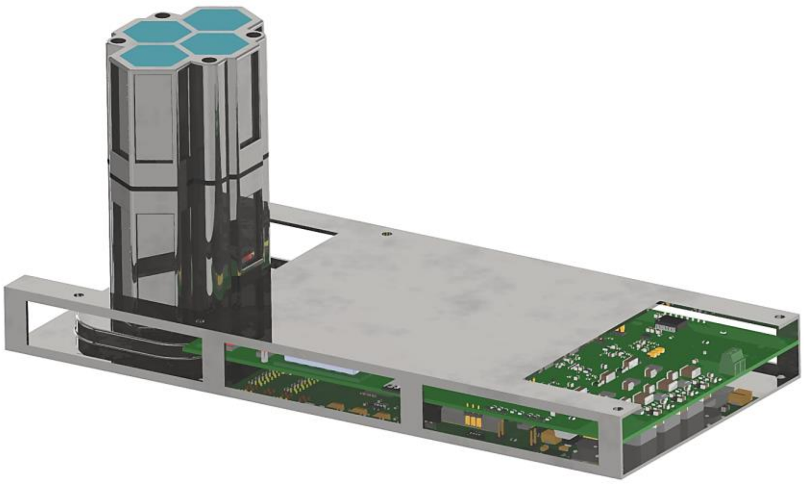

Fig. 3. Crystal Eye pathfinder: lightest version of the full detector.

3 FEM analysis

First aspect analyzed is related to the high shocks, stresses, and strains that the pathfinder will have to support especially during the launch and landing phases. Several tests have been carried out as the system shall withstand the mechanical loads which consists of static accelerations up to 6g. So, the boundary conditions and the constraints have been defined to analyze the behavior of the system in adverse conditions. Specifically, the screwed connection on the base of the pathfinder have been simulated by means of "body-to-ground" joints. Static analysis has been conducted out assuming 6g accelerations in all directions evaluating the total displacements and the Von-Mises stress distribution (Fig. 4) and no specific concerns have been identified at this stage (maximum equivalent stress < 80MPa).

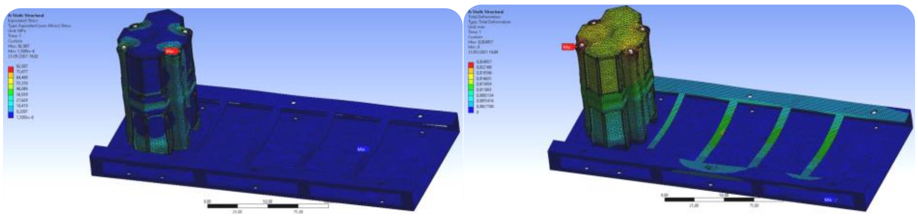

Fig. 4. Equivalent stress and deformation analysis of the Crystal Eye pathfinder.

Afterwards, modal analysis was carried out to investigate natural frequencies of the system and to support the random vibration and the response spectrum analysis.
Specifically, three types of environmental loads have been applied at the interfaces: random vibroacoustic, sine and shock payload spectrums.
No critical loads close to the natural frequencies of the system have been identified. The natural frequencies of the system and the related participation factors are reported in Fig. 5: the system results quite rigid, presenting the first natural frequency at 225 Hz, taking the 57% of the total mass in the X direction. The modal analysis has been limited to the first 20 modes since higher frequencies are not considered interesting with respect to the applied loads (Fig. 5).

KINETIC ENERGIES, MODAL MASSES, TRANSLATIONAL EFFECTIVE MASSES SUMMARY

				EFFECTIVE MASS					
MODE	FREQUENCY	MODAL MASS	KENE	X-DIR	RATIO%	Y-DIR	RATIO%	Z-DIR	RATIO%
1	225.0	0.5244E-03	523.9	0.8701E-03	57.54	0.1839E-14	0.00	0.2353E-04	1.56
2	394.9	0.9731E-05	29.96	0.2132E-05	0.14	0.2622E-11	0.00	0.4217E-04	2.79
3	490.5	0.8166E-05	38.77	0.2719E-05	0.18	0.3611E-12	0.00	0.9278E-05	0.61
4	526.5	0.2182E-04	119.4	0.3384E-06	0.02	0.1034E-10	0.00	0.6714E-04	4.44
5	665.0	0.1109E-03	968.2	0.9470E-11	0.00	0.9202E-04	6.08	0.2564E-09	0.00
6	668.2	0.5322E-05	46.90	0.3151E-07	0.00	0.4836E-07	0.00	0.5450E-06	0.04
7	699.3	0.5225E-03	5044.	0.4430E-13	0.00	0.8754E-03	57.89	0.3783E-11	0.00
8	802.4	0.1059E-04	134.6	0.6834E-06	0.05	0.2116E-11	0.00	0.1365E-06	0.01
9	938.7	0.1510E-04	262.7	0.3381E-05	0.22	0.8847E-09	0.00	0.3412E-04	2.26
10	947.0	0.1302E-04	230.5	0.2294E-09	0.00	0.1923E-04	1.27	0.1805E-08	0.00
11	1123.	0.3342E-03	8318.	0.2594E-04	1.72	0.3746E-11	0.00	0.1150E-02	76.07
12	1184.	0.1561E-04	431.8	0.4628E-11	0.00	0.3020E-05	0.20	0.2537E-09	0.00
13	1307.	0.2205E-04	743.5	0.9113E-05	0.60	0.4568E-08	0.00	0.5450E-04	3.60
14	1315.	0.2401E-04	819.2	0.5246E-08	0.00	0.7271E-05	0.48	0.2921E-07	0.00
15	1371.	0.8008E-05	297.0	0.3566E-05	0.24	0.2348E-11	0.00	0.2996E-04	1.98
16	1449.	0.9405E-05	389.8	0.1758E-09	0.00	0.5787E-06	0.04	0.2527E-08	0.00
17	1459.	0.2491E-04	1047.	0.3033E-05	0.20	0.2538E-09	0.00	0.1297E-04	0.86
18	1493.	0.8510E-05	374.7	0.4306E-05	0.28	0.1218E-11	0.00	0.4511E-06	0.03
19	1578.	0.4938E-05	242.7	0.1962E-09	0.00	0.4637E-07	0.00	0.1853E-09	0.00
20	1659.	0.1226E-04	665.8	0.3679E-09	0.00	0.1496E-06	0.01	0.4990E-10	0.00
sum				**0.9254E-03**	**61.19**	**0.9978E-03**	**65.98**	**0.1425E-02**	**94.24**

Fig. 5. Results of the modal analysis of the Crystal Eye pathfinder.

Through the floor response spectrum analyses, problems related to critical hotspot at screwed connections have been identified. The physical issues have been solved revising the screwed connections layout, having more distributed reaction forces close to the center of gravity, while the artificial numerical hotspot have been checked locally decreasing the mesh dimension. The worst load condition has been identified in the shock environment payload.
The mechanical behavior of the pathfinder has been improved by means of some modification of the structure. So, the cut-outs of the top face of the base have been removed.

Afterwards, as the pathfinder will be exposed to high temperature variations for a two-months period, the thermal behavior of the system has been tested and evaluated. The optimal pathfinder thermal environment for operation and measurement shall vary between 15°C and 35°C. Considering the temperature limits of the electronic card (-20°C and +85°C) and of the SiPM (-20 and +35°C) several analyses have been carried out contemplating unconventional operating conditions due to the Solar irradiance and the orbit that the Space Rider will describe. Thermal conduction with the interfacing systems has been deemed as well as radiation to the external environment. All the external surfaces of the pathfinder have been covered with reflective material to reduce the impact of the direct sunrays and so to decrease the thermal effects on the several electronic components in the system (Fig. 6).

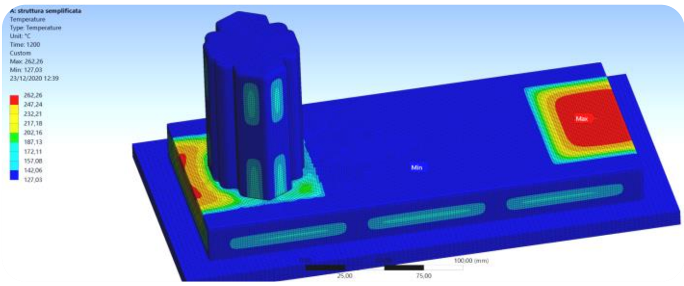

Fig. 6. Results of the thermal analysis of the Crystal Eye pathfinder.

4 Conclusions and future works

The conceptual design and the virtual prototyping of the new Crystal Eye are described. Thanks to its architecture, the detector Crystal Eye will explore the gravitational waves events in terms of electromagnetic portion and will provide continuous monitoring and analysis of the Universe after these events with a better precision than other detectors. The Virtual Prototyping and FEM analysis phases have been performed with particular attention to the thermal and vibration behavior of the conceived mock-up during the launch phase and under high temperature variations in the space environment. The virtual tests have revealed good performances of the structure designed, in terms of responses to the adverse temperature conditions (from -20° to +85°C) considering the worst cases related to the temperature limits of the several components, and the problems come out during these phases have been solved modifying the virtual prototype thanks to the parametric approach used from the very beginning of the project.

In the next months, the engineering phase will be terminated and the Physical Mock-Up of the compact model of the Crystal Eye detector will be quickly completed thanks to 3D printing. Therefore, the shock and vibration tests on the Physical Mock-Up will be performed respecting the time scheduled in the Space Rider project.

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