Characterization of avalanche photodiodes (APDs) for the CUbesat Solar Polarimeter (CUSP) mission

Cologgi F.[a], Alimenti A.[a], Fabiani S.[b], Torokthii K.[a], Silva E.[a], Del Monte E.[b], Baffo I.[f],
Bonomo S.[d], Brienza D.[c], Campana R.[h], Centrone M.[i], Contini G.[g], Costa E.[b], Curatolo A.[c],
Cucinella G.[d], DevAngelis N.[b], De Cesare G.[h], Del Re A.[g], Di Cosimo S.[b], Di Filippo S.[d],
Di Marco A.[b], Di Persio G.[b], Donnarumma I.[c], Fanelli P.[f], Leonetti P.[g], Locarini A.[e],
Loffredo P.[b], Lombardi G.[b], Minervini G.[j], Modenini D.[e], Muleri F.[b], Natalucci S.[c], Nigri A.[d],
Perelli M.[d], Rossi M.[b], Rubini A.[b], Scalise E.[b], Soffitta P.[b], Terracciano C.[c], Tortora P.[e],
Zaccagnino E.[c], and Zambardi A.[g]

[a]Dept. of Industrial, Electronic and Mechanical Engineering, Roma Tre University, Via V.
Volterra 62, 00146 Rome, Italy
[b]INAF-IAPS, via del Fosso del Cavaliere 100, 00133, Rome, Italy
[c]Agenzia Spaziale Italiana, via del Politecnico snc, 00133 Rome, Italy
[d]IMT s.r.l., via Carlo Bartolomeo Piazza 30, 00161 Rome, Italy
[e]Dept. of Industrial Engineering and Interdepartmental Center for Industrial Aerospace
Research, Alma Mater Studiorum Università di Bologna, Via Fontanelle 40, 47121 Forlì, Italy
[f]DEIM, Università degli studi della Tuscia, Largo dell'Università, 01100 Viterbo, Italy
[g]SCAI Connect s.r.l., Via Vincenzo Lamaro 51, 00173 Roma, Italy
[h]Dip. di Ingegneria dell'Impresa "Mario Lucenti", Università degli Studi di Roma "Tor
Vergata", Via Cracovia 50, 00133 Roma, Italy
[i]INAF-OAR, Via Frascati 33, 00040, Monte Porzio Catone, Italy
[j]INAF Headquarters, Viale del Parco Mellini 84, 00136, Roma, Italy

ABSTRACT

The CUbesat Solar Polarimeter (CUSP) project is a CubeSat mission orbiting the Earth aimed to measure the linear polarization of solar flares in the hard X-ray band by means of a Compton scattering polarimeter. CUSP will allow the study of the magnetic reconnection and particle acceleration in the flaring magnetic structures of our star. CUSP is a project in the framework of the Alcor Program of the Italian Space Agency aimed at developing new CubeSat missions. It is approved for a Phase B study. In this work, we report on the characterization of the Avalanche Photodiodes (APDs) that will be used as readout sensors of the absorption stage of the Compton polarimeter. We assessed the APDs gain and energy resolution as a function of temperature by irradiating the sensor with a ^{55}Fe radioactive source. Moreover, the APDs were also characterized as being coupled to a GAGG scintillator.

Keywords: CUSP, X-ray polarimeter, APD characterization

1. INTRODUCTION

The CUbesat Solar Polarimiter (CUSP) project aims to measure the polarization of the X-ray emissions from solar flares. This will open new possibilities in the study of these highly energetic events,[1] both for an in-depth comprehension of the phenomenon and to develop solutions to protect human technological infrastructures from the potential risks related to solar flares.[2]

The payload of CUSP is made up of an X-ray Compton polarimeter composed of plastic and inorganics scintillators.[3–5] The light produced by the scattering and absorption of the X-ray photons with the scintillators
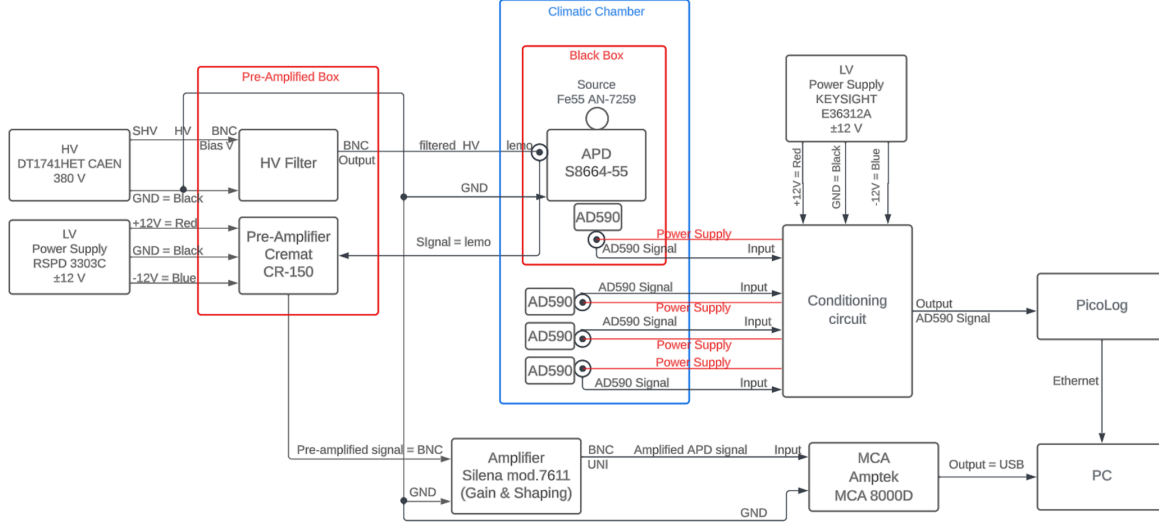

Figure 1: Block diagram of the set-up used for the characterization of the APD.

is read by an array of avalanche photodiodes (APS) which will work in time coincidence with the output signal produced by multianode photomultiplier tubes (MAPMT). An accurate characterization and calibration of the sensitive devices is fundamental for the polarimeter performances. In this work, we focus on the characterization of the APD.[6] The APD gain G_{APD} and energy resolution $\delta E/E$ are measured as a function of the bias voltage V_b, and temperature T, while a ^{55}Fe radioactive sample is used as an X-ray photon source and placed first in direct contact with the APD and then interposing between these the $Gd_3Al_2Ga_3O_{12}$ (GAGG) inorganic scintillator that will be used in the final configuration of the polarimeter. $G_{APD}(V_{bias}, T)$ is then measured in the temperature range $-20 < T/(^{\circ}C) < 60$ between 260 V and 410 V. In particular, the measurement of $G_{APD}(V_{bias}, T)$ will be fundamental to designing the feedback loop control system able to keep G_{APD} stable, during the orbiting of the CubeSat, just by acting on V_{bias}.

In this work, we describe the measurement system designed to perform this calibration, and the first results obtained in a climate chamber on two APDs are shown.

2. THE MEASUREMENT SYSTEM

The block diagram of the designed measurement system is shown in Figure 1. The APD bias voltage V_{bias} is generated by the High Voltage (HV) source DT1471HET CAEN and filtered with the HV filter on the Cremat CR-150 evaluation board. Once the APD is illuminated by a radioactive source, the charge pulses are pre-amplified by the Cremat CR-110R2.2 charge amplifier, setting a 1.4 V/pC conversion factor, and a characteristic time $\tau \approx 1.4\,\mu s$. Then, in order to reduce the pulse pileup, the Silena 7611 spectroscopy amplifier is used for the pulse shaping. Finally, the Amptek MCA8000D multi-channel analyzer is used in the pulse-height analysis mode to record the number of events detected on each channel. To control T, the APD is set in a climate chamber (Angelantoni, model DY2000), and four AD590 T sensors are placed in the chamber for fine-tuning and measurement of T.

The APD gain G_{APD} measurements are performed by acquiring the amplitude of the voltage pulses in input to the MCA. Thus, the conversion factor between the charge generated by each impinging photon and the amplitude of the voltage pulses is fundamental for the accurate G_{APD} measurement. However, the evaluation of this conversion factor would require an accurate knowledge of all the amplification/attenuation introduced by each component in the measurement system. An easier alternative consists in using a reference APD with known G_{APD}, and using this to calibrate the realized measurement system. In our case the Si S8664-55 Hamamatsu photodiode, serial number AA4400, was used as reference ($G_{ref} = 50 \pm 1$ at $\sim 25\,^{\circ}C$ and with $V_{bias} \approx 433$ V).
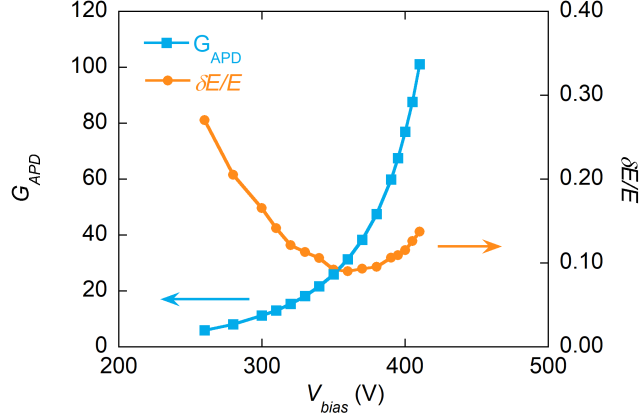
Figure 2: APD gain G_{APD} (blue squares–left scale) and energy resolution $\delta E/E$ (orange circles – right scale) as a function of the applied bias voltage V_{bias}. Data are acquired by placing the ^{55}Fe samples directly illuminating the APD.

Thus, by exploiting the MCA linearity, G_{APD} is evaluated as follows:

$$G_{APD} = \frac{Ch_{pk}G_{ref}}{Ch_{ref}} \ , \tag{1}$$

where Ch_{pk} represents the MCA channel number at which the pulses histogram peak is detected, and $Ch_{ref} = 1052 \pm 1$ is the MCA channel corresponding to G_{ref}.

Finally, the energy resolution $\delta E/E$ is measured by fitting the histogram peaks with Gaussian curves and evaluating:

$$\frac{\delta E}{E} = \frac{\text{FWHM}}{Ch_{pk}} = 2.35\frac{\sigma_{pk}}{Ch_{pk}} \ , \tag{2}$$

where σ_{pk} is the measured standard deviation, and $FWHM$ the corresponding full width at half maximum.

3. RESULTS AND DISCUSSION

First, the shaping time t_s of the spectroscopy amplifier was set by reducing it below the threshold for which $\delta E/E$ was observed to no longer be sensitive to t_s. This happens for $t_s < 3$ μs. Once t_s is set up, the V_{bias} effect on $\delta E/E$ and G_{APD} is first evaluated at room temperature. Thus a ^{55}Fe sample is placed in contact with the reference APD and V_{bias} changed. The result is shown in Figure 2. The measurements shown in Figure 2 allow us to assess: (i) the calibration of the measurement system by exploiting Eq.(1), (ii) the optimum V_{bias} useful to minimize $\delta E/E$.

The so-calibrated system was then used to characterize the response of two APDs in a climate chamber. The temperature was swept in the range $-20 < T/(°C) < 60$ in steps of 10 °C, while the APD bias voltage in the range $280 < V_{bias}/(V) < 410$ in steps of 10 V. The results are shown in Figure 3. G_{APD} is shown to increase when T is decreased, as expected and in agreement with the literature.[6] The measurement of the surface $G_{APD}(T, V_{bias})$ thus allows tuning a feedback loop useful to hold G_{APD} stable, by acting on V_{bias}, despite of the unavoidable T variation of the polarimeter in the orbiting CubeSat. This, however, will cause variations of $\delta E/E$ which in turn is dependent on T and V_{bias} as experimentally found and shown in Figure 3-(b).

Finally, the results show a small variability of the main features of the obtained calibration curves among different APDs. In future, the work will be extended to a larger number of APDs to perform statistical analysis.
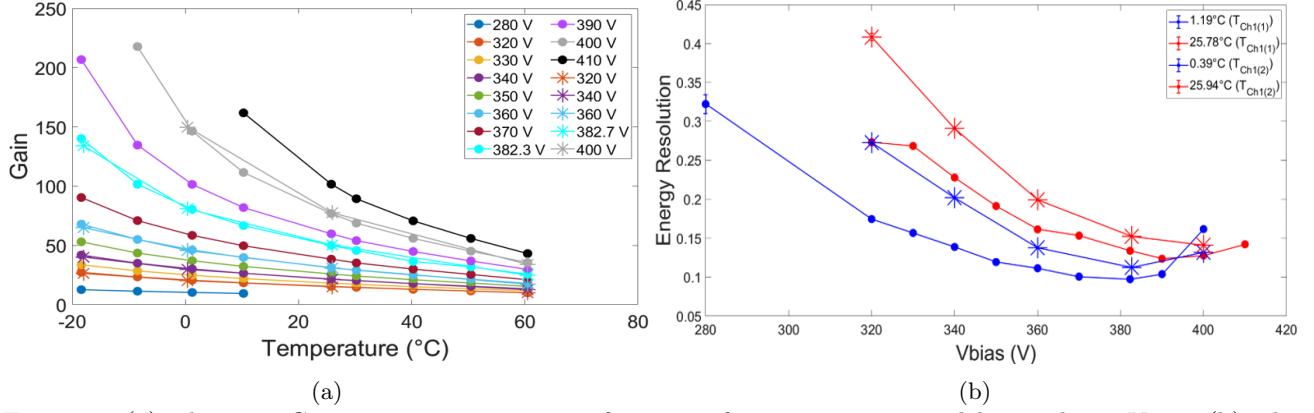
ACKNOWLEDGMENTS

Figure 3: (a) The gain G_{APD} measurements as a function of temperature T and bias voltage V_{bias}. (b) The energy resolution $\delta E/E$ measurements as a function of temperature T and bias voltage V_{bias}. Both plots show a comparison between G_{APD}, and $\delta E/E$, when measured on two APDs (full circles and asterisks).

REFERENCES

[1] Tandberg-Hanssen, E. and Emslie, A. G., [*The physics of solar flares*], vol. 14, Cambridge University Press (1988).

[2] Joselyn, J. A., "The impact of solar flares and magnetic storms on humans," *Eos, Transactions American Geophysical Union* **73**(7), 81–85 (1992).

[3] Fabiani, S., "Instrumentation and future missions in the upcoming era of x-ray polarimetry," *Galaxies* **6**(2), 54 (2018).

[4] Fabiani, S., Baffo, I., Bonomo, S., Contini, G., Costa, E., Cucinella, G., De Cesare, G., Del Monte, E., Del Re, A., Di Cosimo, S., et al., "Cusp: a two cubesats constellation for space weather and solar flares x-ray polarimetry," in [*Space Telescopes and Instrumentation 2022: Ultraviolet to Gamma Ray*], **12181**, 106–114, SPIE (2022).

[5] Fabiani, S., Del Monte, E., Ilaria, B., Sergio, B., Daniele, B., Riccardo, C., Centrone, M., et al., "The cubesat solar polarimeter (cusp) mission overview," in [*Space Telescopes and Instrumentation 2024: Ultraviolet to Gamma Ray*], **13093**, SPIE (2024).

[6] Ikagawa, T., Kataoka, J., Yatsu, Y., Kawai, N., Mori, K., Kamae, T., Tajima, H., Mizuno, T., Fukazawa, Y., Ishikawa, Y., et al., "Performance of large-area avalanche photodiode for low-energy x-rays and γ-rays scintillation detection," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **515**(3), 671–679 (2003).