M. Salatino · P. de Bernardis · L.S. Kuzmin · S. Mahashabde · S. Masi

Sensitivity to Cosmic Rays of Cold Electron Bolometers for Space Applications

XX.XX.20XX

Abstract An important phenomenon limiting the sensitivity of bolometric detectors for future space missions is the interaction with cosmic rays. We tested the sensitivity of Cold Electron Bolometers (CEBs) to ionizing radiation using gamma-rays from a radioactive source and X-rays from a X-ray tube. We describe the test setup and the results. As expected, due to the effective thermal insulation of the sensing element and its negligible volume, we find that CEBs are largely immune to this problem.

Keywords Bolometers, Cold Electrons, Cosmic Rays, Space Instrumentation

1 Introduction

The sensitivity of bolometers to cosmic rays is well known (see e.g.1) and has been an important issue for several space-based astronomy missions, including the recent Planck-HFI2. For future ultra-sensitive space-based surveys of the sky in the mm/sub-mm range, like the proposed missions COrE3, Millimetron, PRISM4, etc., which aim at noise performance limited by the low photon background achievable in space, this will be the main factor limiting their ultimate sensitivity (see e.g.5). In space one expects a mix of high energy protons (with kinetic energy up to 1 GeV6), neutrons and photons. For example, at balloon altitude, the typical fluxes are of the order of 1, 2, 30 m−2s−1 respectively. Cold Electron Bolometers (CEBs)
represent a promising mm/sub-mm detection technology, in alternative to the now common bolometers based on Transition Edge Sensors. In a CEB a nanoabsorber is coupled capacitively to the radiation collecting antenna by means of SIN tunnel junctions. The same SIN junctions provide cooling of the nanoabsorber removing hot electrons (see e.g. 6). We have carried out a test campaign, irradiating CEBs built in Chalmers 7,8 using both gamma rays from radioactive sources and X-rays from an X-ray tube. We show below that the results obtained in this way are also useful to estimate the effect of protons, taking into account the different spectra and cross-sections of protons and photons. In the case of missions requiring large throughput detectors, like the SWIPE instrument on the LSPE balloon 9, the effect of cosmic rays on standard bolometers can be very significant, due to the large absorber area. Here we describe the experimental setup, the measurements and the results.

2 Experimental setup

Due to the extremely small volume of the CEB absorber and to the relative decoupling of electron and phonon systems at low temperatures, we expect that the CEB cross-section for ionizing particles is very small. We prepared our experimental setup to check this hypothesis. The CEB is cooled down to about 304 mK with a $^3$He fridge pre-cooled by a pulse tube refrigerator. A window and a stack of filters defines the sensitive bandwidth of the detector (10% wide centered on 340 GHz). The chip we have tested couples to mm-wave photons through a small cross-slot antenna. The optical responsivity has been checked repeatedly during the measurement campaign and found to be very stable. With optimal DC bias, the electrical responsivity is around $2 \times 10^7$ V/W. The detector signal is amplified by a factor 100 and filtered with a band pass filter (LF cut-off=0.1 Hz, HF cut-off=300 Hz, gain=10, Sec 3) or a 6th order low-pass filter (200 Hz cut-off, gain=10, Sec 4). See Fig. 1, 2 for the setup and the response to mm waves. The rms fluctuation of the output signal in Sec 4 is of the order of 3 mV rms. This means that, at the detector, the noise level is $210 \text{nV/} \sqrt{\text{Hz}}$. Using the responsivity above, we find a NEP $\sim 2 \times 10^{-14}$ W/$\sqrt{\text{Hz}}$. This NEP is significantly higher than the achievable NEP for this kind of detectors. In our setup the dominant sources
of noise are preamplifier noise (we did not have any cold JFET as an input stage) and the high photon background from the 300 K laboratory. A source of ionizing photons is placed in front of the HDPE window of the cryostat. The (negligible) absorption of ionizing photons by the window and the stack of filters is computed from literature data.

3 Measurements with a radioactive source

We used a radioactive source made of the radionuclide $^{137}$Cs, with an activity 0.15 MBq. (85.10±0.20)% of this emission consists of photons with an energy of (661.657±0.003) keV. From the geometry of our detector, the activity and distance of the source (20.3 cm), and the intervening absorption, we can compute the event of rates in two cases. If the entire CEB detector area ($4 \text{mm}^2$, silicon 280 $\mu$m thick) is sensitive to ionizing particles we should observe one event every about 50 s; if only the Al absorbers (total area 5 $\mu$m$^2$, thickness 10 nm) are sensitive the event rate should be as low as about 1 event per month.

The noise power spectrum of $V_{\text{out}}$ does not change in presence of the radioactive source, nor its offset. For 662 keV photons the dominant interaction with the CEB is Compton scattering. Assuming that all the energy acquired by a target electron is converted into a detectable signal, and taking into account the time response of our detection chain (∼0.4 ms), the signal amplitude produced by each hit should be 1-4 mV at the detector; given the amplification of the readout electronics, it should be easily detectable. We collected more than 16 hours of measurements finding none of such events. We conclude that either the only part of the CEB chip sensitive to gamma-rays is the tiny CEB absorber (Fig. 3), or the energy acquired by target electrons is not converted into a detectable signal.

4 Measurements with a X-ray source

Having failed to detect ionizing particles with the radioactive source, we wanted to further check our hypothesis using a source of ionizing particles producing a much higher flux, so that even if the sensitive volume is extremely small we should detect some effect. We used a Microfocus X-ray source (Hamamatsu model
The effect of a large flux of X-ray photons on a CEB. **Top:** Record of a Geiger counter 1m away from the X-ray source during the tests; the increase in the count rate corresponds to source activity. **Center:** Voltage at the output of the CEB readout ($V_{\text{out}}$) in the same period, under maximum source power (10W). **Bottom:** Warm-up (!) of the $^3$He evaporator in the same period. The recovery to the initial temperature takes much longer than the recovery of the CEB offset.

We sent different fluxes of X-photons in the energy range (10-100)keV. Spillover of X-rays was monitored by a Geiger counter 1m away from the X-ray source (Fig. 5, top). For large fluxes (high current in the source) and high energy (large accelerating voltage) ($V \times i > 2W$) we observed a shift in the detector signal offset (Fig. 5, center) and a heating of the $^3$He evaporator (Fig. 5, bottom). Both the heating of the evaporator and the offset shift are proportional to the integral of the Kramers’ law over the X-ray energies (Fig. 6).
From the data of Fig. 5 it is evident that the arrival of a large number of X-ray photons per unit time results in a shift of the detector signal offset, without any significant change of its noise level. Either the temperature change of the evaporator produces the change in the offset, or each single X-ray hit produces a spike smaller than the instantaneous noise and the offset change results as an integrated effect of many small spikes. A combination of both effects is also possible. We note, however, that the rms of the signal, both before and after irradiation (detector and electronics noise only), and during the irradiation (detector and electronic noise plus X-rays hits), is very similar, with standard deviation around 3 mV.

We can estimate the expected voltage signal produced by a X-ray photon hit on the CEB as follows. Assuming that all photons are emitted at the wavelength of maximum luminosity, with an efficiency of $1\%$, we get a flux of about $10^{13}$ photons/s. Over a solid angle $42^\circ$ FWHM wide and at the distance of our detector, we have $\dot{N} = 7 \times 10^{10}\text{ s}^{-1}\text{ cm}^{-2}$.

The expected event rate on the detector is given by $\dot{N}AP$, where $A$ is the area sensitive to energy deposition, and $P$ is the interaction probability. As before, we studied two cases: photons interactions with the CEBs absorber and with the CEBs area sensitive to the microwaves and the corresponding substrate. In the first case we should have one event every 12 minutes, while in the second case we should have many events for a single time constant. The typical energy loss of a 50 keV photon by Compton interaction is 1.5 keV. So in the two cases we obtain an expected power transferred to the detector of the order of 0.3 pW for the absorber and 6 nW for the detector area and substrate. Given an electrical responsivity of $2 \times 10^7 \text{ V/W}$, the expected signal, after amplification, should be 6 mV for the absorber and 130 V for the whole detector area. The lack of saturation of our detector demonstrates that the area of the detector chip is efficiently insulated from the absorber, so that the energy deposited elsewhere (e.g. in the substrate) is not transferred to the absorber. The 6 mV spikes due to energy lost directly in the absorber are not easy to separate from a 3 mV rms noise. Moreover, from the Kramers’ law we expect that most of the spikes are of smaller amplitude. Also, this estimate assumes that the energy lost by an X-ray photon is entirely converted into a useful signal in the absorber. We operated the X-ray tube for a total time of about 14 minutes at different current and voltages, of which only 10s at the maximum current and voltage. So it is not surprising that we were unable to detect any of these spikes. We can safely conclude that, at the NEP level we operate, our detector is effectively immune to X and gamma rays.

Despite of the fact that these results have been obtained using X- and gamma-rays, we believe they are relevant for cosmic rays as well. In fact the energy deposition of protons is maximum for 100 keV protons, resulting in 1.2 keV deposit (similar to the energy deposition we have tested here with photons) and decreases for higher energy protons: a 1 GeV proton would deposit only 5 eV as can be demonstrated using the proper protons stopping power data. So we can safely conclude that the lack of detected events and the lack of noise increase using X-rays implies that the same will be true under irradiation with cosmic rays in space.

This conclusion is corroborated by the fact that in space conditions, the flux of ionizing particles will be many orders of magnitude lower than in this experiment (about $5\text{ cm}^{-2}\text{ s}^{-1}$). Having demonstrated that only the tiny absorber area
is sensitive to ionizing particles, this means that these detectors in space will be effectively immune from cosmic rays hits.

5 Conclusions

We have tested the sensitivity of CEBs to ionizing radiation using photons from a radioactive source and an X-ray tube. We have confirmed that the sensitive area is only the CEB absorber and not the entire detector area. We have also demonstrated that if signal spikes are produced by X-rays, these are smaller than the rms noise of our detector, at a NEP level of $2 \times 10^{-14} \text{W/} \sqrt{\text{Hz}}$. These experimental results confirm CEBs as very promising detectors to be used in future space missions requiring ultra-sensitive mm to IR detectors.

Acknowledgements The authors wish to thank Dr. D. Fargion and Dr. I. Dafinei for allowing us to use some of their instruments for our measurements. This research has been funded in Italy by the Italian Space Agency (grant I/022/11/0 LSPE).

References

1. A. Caserta, P. de Bernardis, S. Masi, and M. Mattioli, Nuclear Instrumentation and Methods in Physics Research A294, 328, (1990).
2. Planck collaboration, arXiv:astro-ph/1303.5071, (2013).
3. COR collaboration white paper, arXiv:astro-ph/1102.2181, see also www.core-mission.org.
4. PRISM collaboration white paper, arXiv:astro-ph/1306.2259, see also www.pism-mission.org.
5. S. Masi, E. Battistelli, P. de Bernardis, L. Lamagna, F. Nati, L. Nati, P. Natoli, G. Polenta, and A. Schillaci, A&A 519, A24 (2010).
6. L.S. Kuzmin, Proc. SPIE, Millimeters and Submillimeter Detectors II 5498, 349 (J. Zmuidzinas, W.S. Holland, and S. Withington, Glasgow, 2004).
7. L.S. Kuzmin, J. Phys. Conf. Ser. 97, 012310 (2008).
8. L.S. Kuzmin, Cold-Electron Bolometer, in book: BOLOMETERS, ed. A.G.U.Perera, INTECHWEB.ORG, ISBN 978-953-51-0235-9 (2012). Chapter 4, doi:10.5772/32259.
9. P. de Bernardis, et al., Proc. SPIE, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VI 8452, 84523F (W.S. Holland and J. Zmuidzinas, Amsterdam, 2012); arXiv:astro-ph/1208.0282.
10. LSPE collaboration, Proc. SPIE, Ground-based and Airborne Instrumentation for Astronomy IV 8446, 84467A (I.S. McLean, S.K. Ramsay, and H. Takami, Amsterdam, 2012); arXiv:astro-ph/1208.0281.
11. National Nuclear Data Center, Brookhaven National Laboratory. [http://www.nndc.bnl.gov/](http://www.nndc.bnl.gov/)
12. R. Klockenkämper, Total-reflection X-ray fluorescence analysis. (John Wiley and Sons, New York, 1997), p. 13.
13. A.H. Compton and S.K. Allison, X-Rays in Theory and Experiment. (D. Van Nostrand Company, Inc., Princeton, 1963), p. 89-90.
14. NIST PSTAR database: [http://www.nist.gov/pml/data/star/](http://www.nist.gov/pml/data/star/)