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Microcalorimeter array for the measurement of kinetic energies of small particles in space

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ABSTRACT

This paper describes a novel calorimetric measurement method for the in situ measurement of the kinetic energy of micrometer-sized particles in space. An incoming particle hits the detector area with a typical velocity of about 10 km/s and the resulting impact heating of the absorber material is measured by an array of microcalorimeters utilizing a 16 × 16 array of thermopile heat power sensors. Experimental tests with accelerated dust particles as well as with laser pulses have proven the capability of this measurement principle. The detection threshold for heat deposition is about 10 nJ for a gold absorber of 2.8 μm thickness. At the moment, a flight model of the calorimetric particle detector is being developed and will be ready to be launched into space in the near future.

1. Introduction

The potential hazard to spacecraft from collisions with other objects is an important topic for the space community today. In particular space debris, i.e. residues from human activities, increasingly endangers the unlimited usability of near-Earth space. Besides the actual payloads such as satellites, a countless number of small debris objects from more than 4600 launches worldwide has been released into space until today. Estimations give numbers of about 100 million objects larger than 1 mm, and smaller particles are even more numerous. Micrometer-sized particles are, for example, the slag residues of rocket engines, paint flakes or small fragments from explosions. In the case of a hyper-velocity impact (HVI), even particles in the micrometer regime can cause substantial damage due to the high relative velocity of typically 10 km/s. The diagram in Fig. 1 gives an overview of the impact energy range to be expected from the impact of a small particle. The kinetic energy of the particle

$$E_{\text{kin}} = 0.5 \cdot m \cdot v^2 \qquad (1)$$

is plotted over the mass m for three different impact velocities v. Assuming a density of aluminum and a spherical shape, the corresponding particle diameter can be obtained from the upper abscissa. With three magnitudes of size, from one micrometer to one millimeter, the impact energies range over more than 10 decades, from about 10^{-8} J to 10^{2} J.

According to a study [1] on the particle flux in low-Earth orbit (LEO), the flux rate increases significantly for smaller particle size. Fig. 2 visualizes the cumulative particle flux rate at an orbital height of about 500 km, derived from various measurement data of different instruments or analysis methods, respectively. The flux rate for particles of a given size or larger is plotted on double-logarithmic scales against the particle size. The large scatter of the data points over about one order of magnitude can be explained by various causes, e.g. measurement uncertainties, selection effects of the different instruments or methods applied as well as the small sample sizes of low statistical significance—to mention just the most important ones. The diagram indicates that for particles larger than 20 μm, an impact rate of about one impact per month can be expected on a target area of 0.1 m^2.

The orbital elements of about 12500 larger (>10 cm) debris objects, observable by radar and optical methods, have been cataloged so far and their dynamical orbital motion is constantly being monitored. In case of a predicted danger of collision, operating satellites may fly appropriate evasion maneuvers. In contrast to this active hazard control, collisions with the numerous unknown small particles in the micrometer and millimeter regime cannot be avoided. However, the risk posed by those particles can be reduced by appropriate shielding measures, and possibly by choosing appropriate orbits or orbital orientations of the satellites.

In order to estimate the risks for a specific spacecraft, the probability of small particle impacts is assessed by statistical methods using models of the particulate environment of the Earth such as MASTER (Meteoroid and Space Debris Environment Reference Model) [2] of ESA (European Space Agency). The model data base has to be validated by means of actually measured data, for exam-

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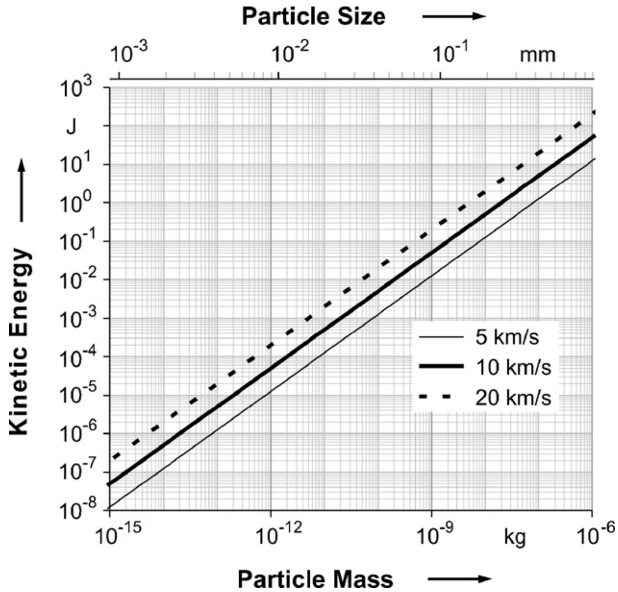

Fig. 1. Impact energies of small space-particles: kinetic energy vs. mass and size (Al sphere assumed) for three impact velocities.

ple by data obtained from the investigation of impact craters on retrieved surfaces or by in situ measurements. In general, reliable data of satisfying quality can only be obtained by in situ measurements in space. It is desired to gain, as far as possible, data with regard to the following particle parameters as these provide the means for identifying a particle's origin:

(1) Time of occurrence. From this information, the particle flux rates can be deduced.
(2) Velocity vector. By means of this parameter, the orbital trajectory of the particle can be determined for a known time of occurrence.
(3) Mass. This quantity can also be calculated from the kinetic energy if the velocity is known.
(4) Material.

Current measurement data of small space-particles in Earth's environment is very sparse and is related to measurement uncertainties which often exceed one order of magnitude. Quantity as

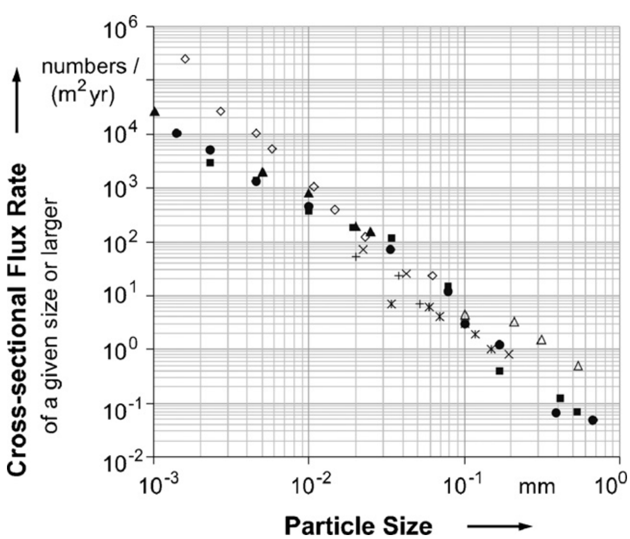

Fig. 2. Cumulative particle flux rate in LEO, derived from various measurement data as indicated by the different symbols [1].

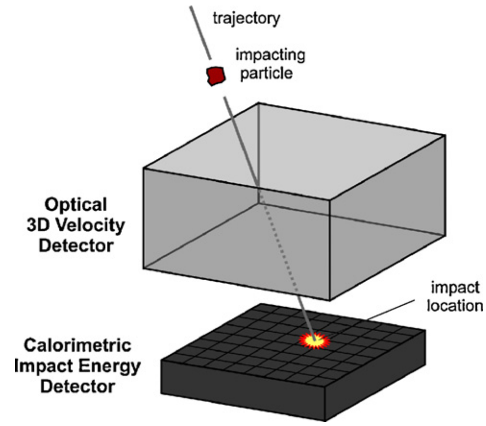

Fig. 3. Two-stage detector AIDA.

well as quality need to be greatly improved. Although the analysis of retrieved hardware provides only a mean value of the impact rate over years of exposure time, which is not satisfying, it might give the chance to determine the chemical composition of the impacted particles in the laboratory. Time-resolved in situ measurements of microparticles have been performed by GORID [3] and DEBIE-1 [4], providing data from a geostationary orbit and from approximately 600 km altitude, respectively. But it turned out that influences from the radiation environment of the Earth compromise the quality of the data and that it is therefore advisable to find more robust detection methods.

Based on these considerations, the development of an in situ detector with improved measurement capabilities has been initiated. The proposed detector setup named AIDA – Advanced Impact Detector Assembly – is intended to detect particles of a size down to 20 μm arriving at a speed of 10 km/s. A combination of two independent detector stages measures the particle's velocity vector and kinetic energy (see Fig. 3) [5–7]. The mass value of interest is then evaluated from Eq. (1). An incoming particle first traverses an optical velocity detector before it arrives at the impact stage. The two-stage concept offers flexibility with respect to the optimization of the measurement performance considering sensitivity, measurement range, measurement uncertainty and susceptibility to disturbances. The feasibility of an adaptation to the specific needs of a particular space mission is another advantage. The AIDA detector would, for the first time, allow the accurate determination of the particle's orbital parameters. The energy measuring impact stage AIDA-cal is treated in detail in the following.

2. Calorimeter design

The basic principle of the calorimetric impact energy measurement is the conversion of kinetic energy into heat. When impacting a target, a substantial part of the particle's kinetic energy heats the target material and a corresponding temperature increase is observed. The potentially measurable calorimetric heat is

$$E_{cal} = \eta \cdot E_{kin}, \qquad (2)$$

where η describes the energy conversion efficiency of the hypervelocity impact, as there are always some energy losses from ejecta, plasma and radiation which do not contribute to the heating of the target material. Knowledge about the conversion efficiency is still quite poor, but our calibrations by hyper-velocity impact tests finally provided first experimental values (see below) calculated from the measured temperature increase of small impact-heated targets.

Under the idealization of adiabatic heating of a small calorimetric energy absorber of heat capacitance C_a, the deposed heat leads to a temperature increase of

$$\Delta T = \frac{E_{cal}}{C_a}. \quad (3)$$

This quantity is inversely proportional to the absorber's heat capacitance, i.e. high sensitivities require small absorbers. Other design criteria imply a fast response time and a wide temperature range appropriate to space missions. Therefore, the developed calorimeter design features a segmented target area using a microcalorimeter array with miniaturized multijunction thermopile sensors to measure the impact heating. As these thermopiles already sense temperature differences, they are well suited for applications with large variations of the ambient temperature.

On closer examination of the real measurement process, the deposed impact heat E_{cal} flows from the small impact zone into the surrounding material and thus some time is needed to reach the thermal equilibrium of the hit absorber. Assuming some conductive and radiative heat losses, the condition of thermal equilibrium holds only approximately and the temperature sensor will display a time-dependent output signal characterized by a sharply rising pulse slope followed by a gradual decay. Thus, the temperature increase to be measured ΔT_{meas} should somewhat depend on the impact location as well as on the applied filtering and signal analysis methods. Introducing a signal transmission factor κ as the relation between measurement and adiabatic theory in order to account for these influences, Eq. (3) becomes

$$\Delta T_{meas} = \kappa \cdot \Delta T = \kappa \cdot \frac{E_{cal}}{C_a}. \quad (4)$$

For well insulated small absorbers with fast thermal response, the factor κ is about 1, however, it should be noted that values greater 1 may occur if ΔT_{meas} is determined while the best possible thermal equilibrium over the absorber foil is not yet fully reached and if the impact zone is in the immediate vicinity of the temperature sensing location.

Fig. 4 shows the basic design of a microcalorimeter element. The impacting particle heats a thin metallic energy absorber plate which is in contact with the center of the temperature sensing thermopile sensor through a drop of heat conducting glue. An absorber material of preferably high thermal diffusivity such as gold or silver, for example, is required to reach a uniform temperature distribution shortly after the impact. The deposed thermal energy drains through the thermopile's thin membrane of low thermal conductivity which is spanned over a thick silicon frame, and the temperature difference between the heated center of the membrane and the cold frame is transformed into a proportional voltage by a serial circuit of thermocouples.

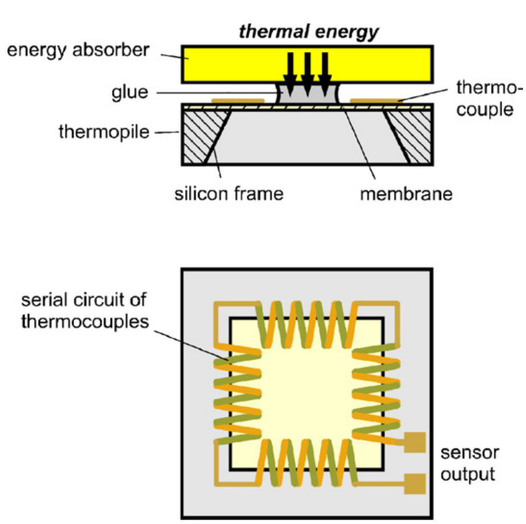

Fig. 4. Microcalorimeter design: cross-sectional side view of a calorimeter element (top), top view of a thermopile sensor (bottom).

The sensitivity and the measurement range of the calorimeters can be adapted to the needs of a specific space mission by simply changing the thickness of the thin metallic absorbers. In this regard, the upper range limit of the calorimetric detector is generally reached at the onset of fatal impact damage, which at last would be the case when the impacting particle perforates the thin absorber foil. The damages resulting from hyper-velocity impacts are commonly described by damage equations derived from HVI test data [8].

The technical realization of the microcalorimeter array is based on a customized thermopile array chip produced by means of silicon wafer technologies. With an element size of 3.6 mm squared, the 256 sensors of the two-dimensional 16 × 16 array cover a total detection area of about 33 cm^2. A serial circuit of 100 radially arranged BiSb/Sb thermocouples generates a total thermopower of 13.5 mV/K [9]. An anti-series connection of two sensors serves to halve the number of calorimeter channels. By taking the positive or negative sign of an impact signal into account, information about the impact position is still obtained unambiguously.

Matching absorber arrays made of gold foil were produced by laser ablation techniques using a micromaterial processing laser system featuring a pulsed ultraviolet (355 nm) laser and a four-axis translation stage to move the workpiece. The focused laser beam cuts the flat foil into individual square-sized absorbers which are kept connected at their corners for better handling. Depending on the foil thickness and on the desired gap width, several consecutive runs of the laser beam are necessary for the ablation process and the array structuring could take many hours due to the required precision. An example of a laser-structured absorber array is given in the microphotograph of Fig. 5, showing the gaps between four adjacent gold absorbers of 50 μm thickness and their corner joint. Although the absorbers are largely thermally insulated against each other, the small thermal bypass from the small corner joints results in some unwanted position-dependent signal losses and cross-talk between adjacent sensor elements.

The calorimetric detector consists of the basic components *thermopile sensor array*, *energy absorber array* and *measurement electronics* plus *data acquisition software*. Its large thermopile array chip is connected to the electronics main board via a sensor adapter board. The measurement electronics features 128 parallel channels of analog bandpass amplifiers (bandwidth 30 Hz, gain 150), multiplexers, a microcontroller with an integrated 16 bit analog-to-digital converter (ADC) providing an input resolution of 0.244 μV, as well as a USB interface for the communication with the controlling computer. The digitalization of all channels is achieved at an effective rate of 100 samples per second each, which is sufficiently fast for the transient heat signals to be measured.

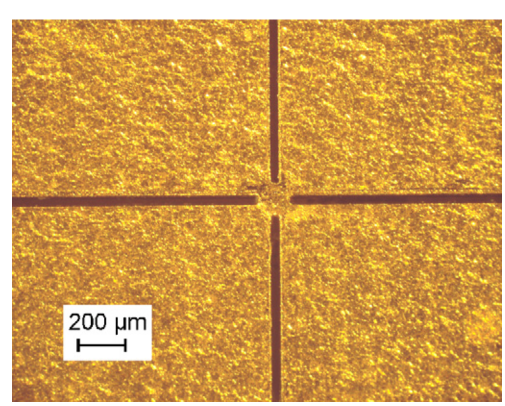

Fig. 5. Microphotograph of a gold absorber array.

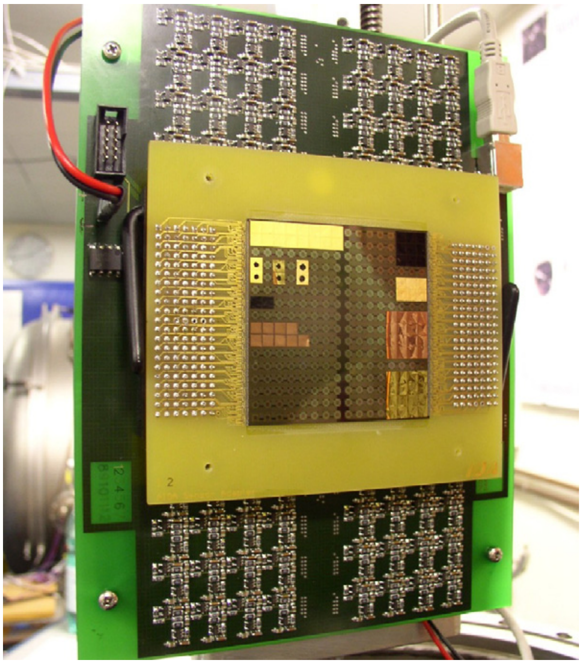

Fig. 6. AIDA-cal *Breadboard Model* featuring thermopile sensors equipped with different absorbers.

In the frame of the research and development activities, two different hardware versions have been manufactured so far, a so-called *Breadboard Model* (BM) and a *Development Model* (DM), respectively. Corresponding photographs of both sensor boards are shown in Figs. 6 and 7. The first version was specifically designed to achieve highest sensitivity in order to verify the new measurement principle by HVI tests. For this reason, it uses very thin gold absorbers of 2.8 μm thickness. In contrast to this design, the second version is equipped with much thicker absorbers (50 μm Au) that are required for the detection of larger particle impacts, which are of particular interest to the space debris community.

In order to limit the number of calorimeter channels with their power-consuming electronic components, several sensor elements were electrically connected in series. The BM uses an anti-series connection of two thermopiles each, the DM one of two 4×4 sub-arrays, thus reducing the total number of channels to 128 or 8, respectively. The latter design was chosen in order to be able to extend the active target area by a 3×3 configuration of DM modules, as it will be an important criterion for future space hardware to provide large target areas at low power consumptions. A drawback is, however, that the increased electrical source resistance of 32 sensors in series – instead of only 2 – generates more thermal voltage noise, which – consequently – raises the achievable detection threshold for small heat signals. The thermal noise of the calorimeter's electrical source resistance is proportional to the square-root of the number of sensors in series according to

$$U_{\text{Noise}} = \sqrt{4 \cdot k \cdot n \cdot R \cdot T \cdot B}, \qquad (5)$$

where k denotes Boltzmann's constant (1.38×10^{-23} J/K), n the number of sensors in series, R the electrical resistance of a single thermopile sensor, T the temperature and B the noise bandwidth.

Neglecting some possible improvements in signal-to-noise ratio that might be achieved with thicker absorbers and their broadened pulse signals – the measurement bandwidth might be reduced in this case, the sensitivity of the two different calorimeter versions should differ by a factor of about 70. This theoretical value holds for 2.8 μm thick absorbers and 2 sensors in series compared to 50 μm and 32 sensors.

3. Calibration

The measurement performance of the AIDA-cal *Breadboard Model* was experimentally tested by means of hyper-velocity impact tests as well as by laser pulse heating. Both tests were carried out in a vacuum environment. All experimental results presented in this section refer to measurements achieved with thermopile sensors equipped with gold absorbers of a thickness of 2.8 μm.

Due to the fact that there are no HVI facilities available that would allow the acceleration of larger single micron-sized particles to velocities of several kilometers per second, calibrations with hyper-velocity impacts are restricted to comparably small kinetic energies. Therefore, microcalorimeters equipped with thicker absorbers and thus reduced sensitivity, which would require higher energy levels for calibration purposes, need to be calibrated by a different method. In this regard, the method of laser pulse heating provides a versatile means as the pulse energy, the laser spot location and the pulse repetition rate can be flexibly varied.

For a future hardware to be used in space, the data analysis has to be fully automated. Hundreds of calorimeter channels will then have to be analyzed simultaneously and the restricted on-board computational power, the memory as well as the downlink capacities will set limits to feasible analysis methods. For this reason, the determination of signal peak values might be more suitable than evaluating pulse integral values over a defined integration time, a method that is widely applied in calorimetry, which could, of course, yield smaller measurement uncertainties.

3.1. *Hyper-velocity impact tests*

The novel calorimetric measurement method based on the conversion of kinetic energy into heat was experimentally verified by hyper-velocity impact tests carried out by means of a dust accelerator. The facility accelerates charged micrometer-sized particles to speeds of several kilometers per second. A van-de-Graaff belt generator provides the high voltage (2 MV) required for the electrostatic acceleration. Smaller particles reach higher speeds, as the acceleration depends on the charge-to-mass ratio. Before arriving at the target, charge-sensitive detectors measure the velocity and charge of each particle and this data is saved in a log file. All HVI tests were performed with accelerated iron dust impacting at normal incidence. The particle beam covered several calorimeter elements due to its large diameter of about 9 mm. The logged particles had the following specifications: mass 10^{-16} kg to 10^{-13} kg (0.4 μm to 2.5 μm diameter for Fe spheres), impact velocity 1.5 km/s to 9 km/s, kinetic energy 4 nJ to 400 nJ.

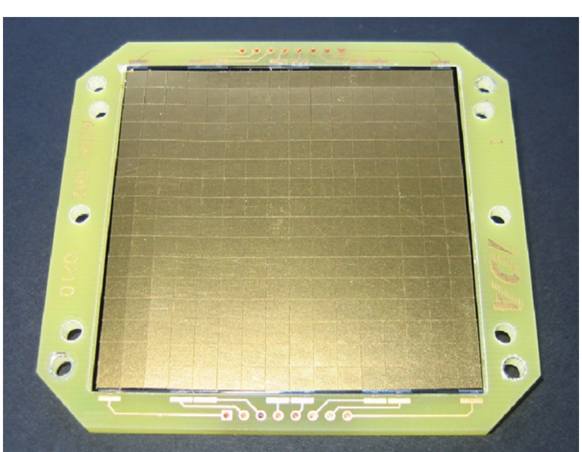

Fig. 7. Sensor board of the *Development Model* equipped with 50 μm Au absorbers.

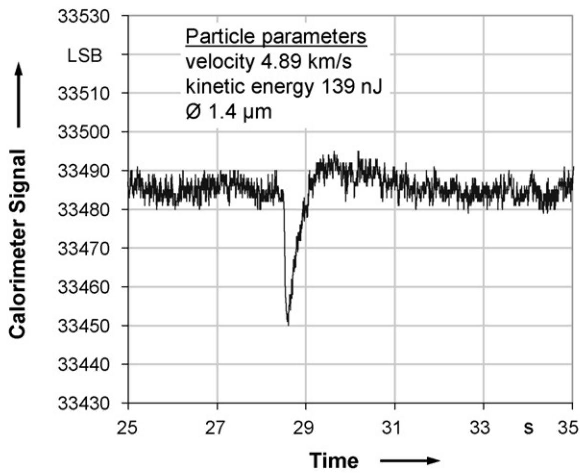

Fig. 8. Calorimeter signal of a particle impact.

Fig. 8 visualizes a typical example of an HVI signal of the calorimetric detector, measured on a calorimeter element of negative polarity, i.e. producing a negative signal pulse. The digitized calorimeter signal is expressed in the unit LSB (Least Significant Bit) of the 16-bit ADC, which provides output codes ranging from 0 to 65535. Because of the anti-serial connection of two thermopiles each, the output offset of the ADC is adjusted to its mid-range value of 2^{15}. The bandpass filtered heat signature of the presented example has a pulse amplitude of about 34 LSB. This HVI event was caused by a dust particle of 1.2×10^{-14} kg mass (diameter 1.4 μm) which impacted at 4.89 km/s, i.e. carrying a kinetic energy of 139 nJ.

A measurement characteristics for hyper-velocity impacts was experimentally determined from an analysis of 131 impact events. The diagram in Fig. 9 plots the measured signal pulse amplitude against the kinetic energy of the impacting particle on double-logarithmic scales. The electrical noise of the temperature measuring chain is largely caused by the thermal noise of the thermopile sensors according to Eq. (5), yielding a detection threshold of about 4 LSB for the smallest heat pulses, which corresponded to a kinetic energy of 20 nJ. For the energy range from 20 nJ to 200 nJ, the measured values scatter around a linear regression line with a factor of about 2 to 3. A substantial, if not the dominant, part of this scattering is likely caused by a dependence on the impact location, as additional tests with laser pulse heating have indicated (see below), and rather not by different energy conversion efficiencies.

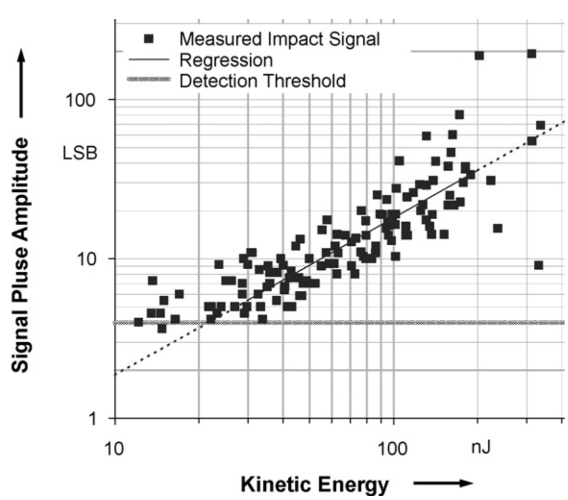

Fig. 9. Characteristics of the microcalorimeter array equipped with 2.8 μm Au absorbers.

The few impacts at higher energies indicate a stronger scattering, possibly caused by impact perforation. Impact holes were, in fact, found in a microscopic inspection of the gold absorber surfaces. Impacts that perforate the absorber foil obviously have different heat transfer mechanisms and should therefore yield different energy conversion efficiencies. In addition to likely damages to the underlying thermopile chip, the onset of impact perforation practically defines the upper limit of the detector's HVI energy range where the linear measurement characteristic ceases.

The comparison of the calorimeter signals with the known kinetic energies from the particle log file provides a first experimental determination of the conversion efficiency η for hyper-velocity impacts [7]. This analysis was carried out under the simplification of an idealized heat measurement and thus applies the theoretical value of the calorimetric sensitivity of 1.88 nJ/LSB calculated from the absorber's heat capacitance and the sensitivity of the temperature measuring chain consisting of thermopile, band-pass filter and digitizer, and further assuming a mean value of the position-dependent signal transmission factor of $\kappa = 1$. It shows that about 40% (mean 38%, standard deviation 14%) of the particle's kinetic energy heated the target material. No dependence on the impact velocity could be observed within the velocity range covered.

3.2. *Laser pulse heating*

Laser pulse heating provides a feasible method for testing and calibration purposes in the laboratory. Energy depositions of particle impacts are simulated by a pulsed laser beam which can be focused into a tiny spot, directed at a specific location on the absorber surface. The calibration tests of our studies were performed with an electrically pulsed diode laser of 5 mW nominal output power, in which different pulse energies were achieved by varying the pulse duration. All tests were carried out with blackened absorber fields in order to obtain a high absorption of the red laser radiation.

A result from these laser pulse tests is presented in Fig. 10, showing the measured calorimeter signal pulse amplitude plotted against the laser pulse duration, which proportionally scales the irradiated laser energy. All data points were evaluated by an offline analysis of the bandpass-filtered calorimeter signal. The diagram proves a linear characteristics over a range of more than two orders of magnitude. Assuming a noise level of 4 LSB and a maximum pulse amplitude of +/−2^{15} LSB, the measurement range for heat depositions could extend to almost four orders of magnitude.

The performed laser pulse tests indicate a dependence on the heating position in the order of about 50%, which is expressed in Eq.

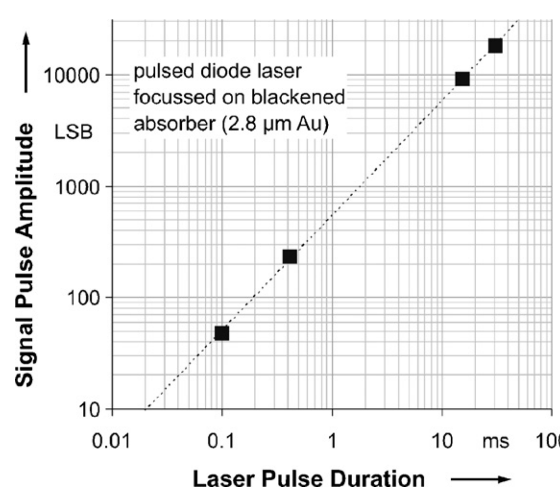

Fig. 10. Laser pulse heating in vacuum.

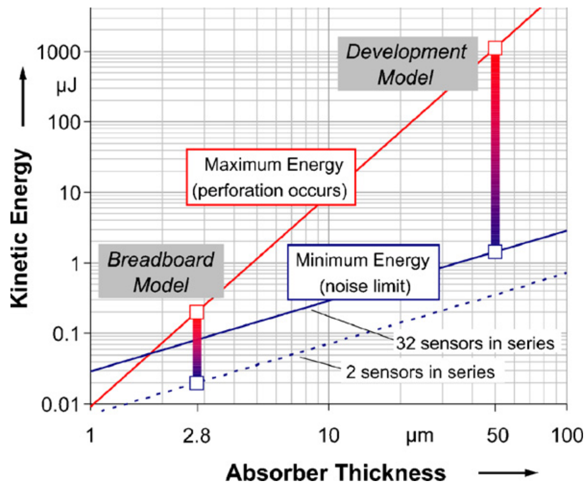

Fig. 11. Measurement range for Au absorbers of different thickness.

(4) by the impact transmission factor. This dependence is presumably caused by the thermal bypass of the small joints connecting the absorbers at their edges. Optimizations of this unwanted behavior might be achieved by a thermal FE modeling of the calorimeter array [7]. By means of smaller joints and an increased distance between the absorbers and the thermopiles, these thermal losses might be reduced and consequently, the smoothed dependence from impact position would lead to smaller measurement uncertainties.

Future calibrations with laser pulse heating should preferably use lasers of shorter wavelength, blue or ultraviolet radiation if possible, in order to achieve sufficiently high light absorption at the metallic surface of the energy absorbers. Instead of using blackened absorbers, the calibrations have to be performed with the metallic absorbers in order to avoid possible influences from differing emissivities of the surface material that would otherwise give incorrect calibration results due to different radiative losses.

4. Conclusions and outlook

This paper presents a novel calorimetric measurement method for the in situ measurement of the kinetic energy of micrometer-sized particles in space. A prototype detector setup using a microcalorimeter array of 256 elements of 3.6 mm × 3.6 mm size was developed and tested. The calorimeters, each consisting of an energy absorber made of gold foil attached to a thermopile sensor, successfully detected the thermal signatures of hyper-velocity impacts of iron dust particles impacting at normal incidence. It was possible to measure the efficiency of the conversion of kinetic energy into absorbed heat for the first time. Additional tests with laser pulse heating proved a linear characteristics ranging over several orders of magnitudes. The sensitivity and the dynamic range of the calorimetric detector can be adjusted to the specific needs by scaling the thickness of the energy absorber. Fig. 11 visualizes the calculated measurement range of different microcalorimeter versions. The predictions are based on HVI test results obtained with a detector prototype (*Breadboard Model*), further assuming a constant energy conversion rate of 40%, independent of the impact velocity and the material pairing of impactor and target. The energy detection threshold for the smallest detectable HVI heat signals is limited by the detector's thermal noise, whereas the maximum energy level is defined by the impact perforation resistance of the thin metallic energy absorbers.

The energy range of a microcalorimeter increases proportionally to the absorber thickness if its target area is kept constant. Although a thicker absorber would be able to detect particles over a wider range of size, the reduced sensitivity would result in smaller count rates as the smallest particles are the most numerous ones in space (see Fig. 2). For this reason, when designing future flight hardware, one will have to strike a balance between the desired particle count rates and the particle sizes achievable. Furthermore, it has to be considered that the covered energy range should be in accordance with the particle sizes that could be detected by the velocity detector of the envisaged two-stage AIDA detector assembly. Compared to the tested sensitive *Breadboard Model* design with 2.8 μm thick gold absorbers, absorbers of higher damage resistance are required for future space hardware in order to be able to measure larger particle impacts. As thicker absorbers (e.g. with 50 μm Au foil) lead to a proportionally reduced calorimetric sensitivity, correspondingly higher pulse energies are required for calibration. Because of missing HVI facilities that could provide tests with larger micron-sized particles in the required energy range, the calibration of these less sensitive microcalorimeters will have to be performed by means of laser pulse heating.

A so-called *Development Model* of the AIDA-cal detector has recently been completed which demonstrates that the basic technologies needed for consecutive developments towards a space-flying detector setup have been generally developed. A future flight model will consist of a detector assembly of 9 sensor modules offering a total target area of 300 cm^2. Its on-board measurement hardware will have to analyze the full data stream of all detector units in real-time in order to save only data of suspected impacts for later downlinks. The development of a flight model will start in late 2008. It is expected that this novel energy measuring detector will be ready to be launched and tested in space in a few years.

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