PERFORMANCE OF AN ADVANCED DUST TELESCOPE

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ABSTRACT

A *Dust Telescope* is a combination of a *Trajectory Sensor* with an analyzer for the elemental composition of micrometeoroids or space debris. Dust particle trajectories are determined by the measurement of the electric signals that are induced when a charged grain passes through a position sensitive electrode system. The position sensitive system consists of four planes of wires where each wire is connected to a separate charge sensitive amplifier. The amplifier is based on CMOS technology and was developed in cooperation with the ASIC Laboratory in Heidelberg. Furthermore, a 32 channel transient recorder (TR) running with 20 MHz and 10 bit resolution was developed and manufactured in order to store the individual signals. This system allows the accurate determination of the particle velocity vector. The elemental composition of particles is analyzed by a time-of-flight system for the ions which are generated upon the particle impact. The large area of this mass analyzer is 0.1 m^2 and has a mass resolution above 100 for all possible impact locations. This paper describes the performances of the laboratory model of the *Trajectory Sensor* and shows the study results of the mass spectrometer.

Key words: interstellar dust; interplanetary dust; trajectory sensor; spectrometer; DUNE; ASIC; dust detector.

1. INTRODUCTION

The analysis of micron sized particles in the vicinity of the Earth provides knowledge about the relative fluxes of interplanetary dust, interstellar dust and space debris. Many particles entering our solar system encounter the Earth and they are heated up in the upper atmosphere without reaching the surface. However, bigger meteorites still might contain some presolar grains. These particles can be identified by their isotopic signatures, but only a small fraction (10^{-5}) of all meteoritic material on Earth is identified to be interstellar. However, the dust samples on Earth are limited and those reaching the surface are processed by heating in the Earths atmosphere. The only way to perform unbiased measurements and to separate natural meteoroids from space debris are in-situ measurements in the Earth environment. For this purpose it is required to determine the grain trajectory and elemental composition quite accurately. So far no dust detection system exists which achieves this task. Here we report about a new instrument system of a combination of a *Trajectory Sensor* (TS) with a time-of-flight spectrometer (Large Area Mass Analyzer, LAMA). The two components are part of a *Dust Telescope* which was introduced in Grün et al. (2000), Svedhem et al. (2001), Srama et al. (2004) and Grün et al. (2001).
The overall problem of the sensitive detection of space debris and micro meteoroids is the low flux which requires a large sensitive area. On the other hand the accurate in-situ determination of particle properties like speed, trajectory and composition is difficult with a big instrument.
High-resolution dust mass analyzers that provide elemental composition of dust particles have been flown on missions to the comet Halley (Kissel 1986) and are currently flying on the Stardust mission (Kissel et al. 2003) (Tab. 1). The instruments employed a time-of-flight mass spectrometer in order to obtain the elemental composition of the plasma generated upon impact of cometary dust particles onto the sensor. A mass resolution of $\frac{m}{\Delta m} > 100$ was achieved by the means of a reflectron that provided energy focusing of the ion beam. Because of the very high dust fluxes expected near the comet only a very small sensitive area of 5 cm^2 was necessary to obtain thousand high resolution dust mass spectra.

The Stardust spacecraft carrying the Cometary and Interstellar Dust Analyzer instrument (CIDA) flew by comet Wild 2 in 2004. CIDA, too, is an impact mass analyzer employing a reflectron stage in order to provide high resolution ($\frac{m}{\Delta m} > 100$) mass spectra. The sensitive area of this instrument is 90 cm^2 and an analysis of a few tens of cometary grains were provided (Kissel et al. 2004).
A medium resolution impact mass spectrometer ($\frac{m}{\Delta m} =$

Table 1. Mass resolution of impact ionization time-of-flight spectrometers.

Mission	Area(cm^2)	$\frac{m}{\Delta m}$	Type
Helios	120	5-20	1m linear drift tube
Cassini	100	20-50	0.2 m linear drift tube
Giotto, VeGa	5	100	1 m reflectron
Stardust	90	100	1 m reflectron
LAMA	1000	>120	1 m reflectron

$20-50$) of 100 cm^2 sensitive area is part of the Cassini CDA instrument (Srama et al. 2004a). On its way to Saturn it has measured several impact spectra of interplanetary or interstellar dust particles and in the vicinity of Saturn several 100 spectra of Saturn stream particles (Kempf et al. 2005).

2. THE LARGE AREA MASS ANALYZER

The low dust flux in interplanetary space (approx. $10^{-4} m^{-2} s^{-1}$) requires a dust analyzer with a large (0.1 m^2) sensitive area and a wide field-of-view ($> 50°$). This could not be achieved with the previous dust analyzers. Therefore a new Large-Area Mass Analyzer (LAMA) was developed that meets the requirements of a sensitive impact area and a mass resolution of $\frac{m}{\Delta m} > 100$ (Rachev 2004). The main tool to model and analyze the large-area mass spectrometer was SIMION 3D, a software package developed by David A. Dahl at the Idaho National Engineering & Environmental Laboratory. This software allowed us to model complex structures and calculate the electric field distribution inside and to determine ion trajectories and flight times (Rachev et al. 2004a).

For LAMA a configuration with cylindrical symmetry has been chosen with a ring-shaped impact target. Two different configurations were studied: LAMA1 has a short tube length in order to minimize the instrument size, whereas LAMA2 is slightly larger due to an increased field free region between the acceleration grid and the ion reflector in order to incorporate a *Trajectory Sensor* (Fig. 1 and 2). The impact detector consists of a flat annular shaped impact target at +5 kV potential and a grounded acceleration grid mounted 50 mm in front of the target. Potential rings provide a smooth electric field close to the edges. The acceleration distance of 50 mm is several times bigger than the 3 mm for Cassini CDA or the 10 mm of CIDA onboard Stardust. Thereby, the effect of shielding within the impact plasma cloud is reduced because the ion cloud is allowed to expand into a much wider volume before acceleration becomes effective.

In front of the impact detector there is a field-free drift region and the ion reflector has two parabolic shaped grids on the potential of 0 V and approx. +6000 V. Ion

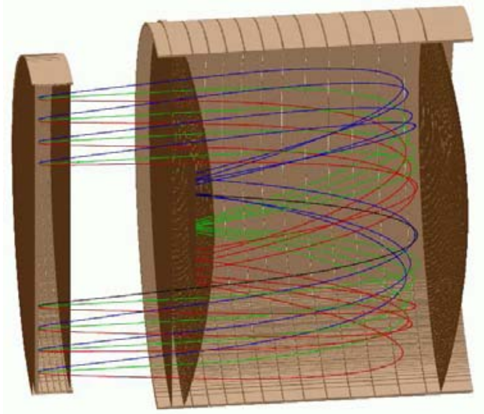

Figure 1. LAMA2 Simion simulation of ion trajectories starting at the target (left) with the ion emission angles of $-90°$, $0°$ and $+90°$. The starting ion energy at the annular target was set to 50 eV. An ion detector of 110 mm radius is necessary to collect all generated ions. Both potential lines and ion trajectories are shown for different impact positions on the target. LAMA2 uses two parabolic grids with a focal length of $f_{o1} = 540\ mm$ and $f_{o2} = 600$ mm.

trajectories originating from different impact positions are shown in the left panel of Fig. 1 and are spatially and timely focused onto the ion detector. It was assumed that ions have up to 50 eV energy spread and that they are emitted at different angles with respect to the target normal. An ion detector with a radius of about 120 mm measures highly resolved spectra. The design is based on a configuration that was originally proposed by Oren and Svedhem and that used hemispherical reflectron grids. Here, parabolically shaped reflectron grids have been considered because of enhanced spatial focusing characteristics. For a given potential of the upper reflectron grid the axial position of the ion detector with optimum spatial focusing was determined. After the ion detector position was found for a given reflectron configuration,

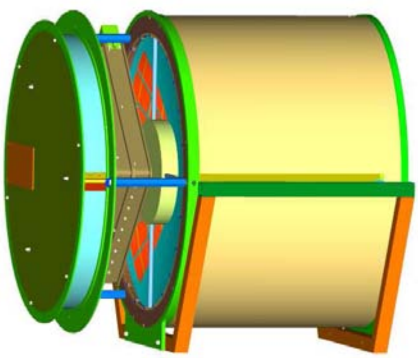

Figure 2. LAMA2 with the target section (left), the Trajectory Sensor (between target and reflector) and the reflector (right).

the distance of the impact detector and the potential of the reflectron grid were varied to find the optimum mass resolution. The grid curvatures and the distance of the reflectron grids have been varied as well.

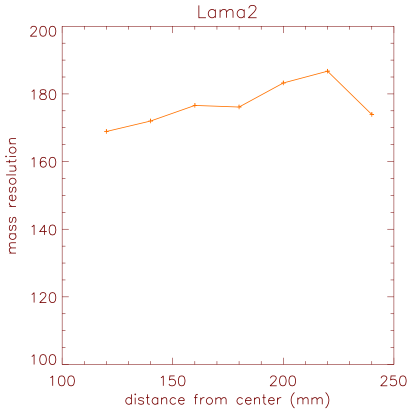

Figure 3. LAMA2 mass resolution of ions reaching the ion detector as function of the ion start position.

Ions of the impact plasma are described by a variety of properties such as starting positions at the target, emission angles, and inital energies. These parameters strongly influence the spectrometer capabilities and finally the mass resolution. Here, impact locations from 120 to 240 mm radius, ion energies between 0 and 50 eV, and emission angles between $-90°$ and $90°$ have been considered for the calculation of the mass resolution (Fig. 3). However, only ions with initial energies below 3 eV reach an ion detector of a common size (microchannel plate with a radius of 25 mm, Fig. 4).

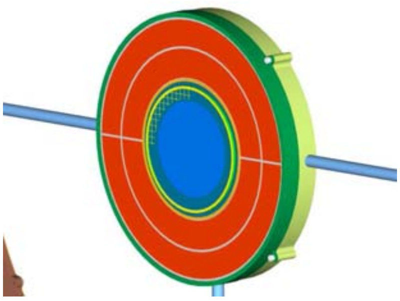

Figure 4. The ion detector of LAMA with the microchannel plate in the center. The concentric rings are ion collector electrodes attached to charge sensitive amplifiers.

Higher ion energies up to 50 eV require an ion detector size as large as 110 mm radius. Several different configurations were found that provide a mass resolution $\frac{m}{\Delta m} > 150$ for all impact locations on the target. There is also a weak dependence of the the mass resolution on the impact location and on the width of the ion beam. But for all impact positions between radius 120 and 240 mm the mass resolution is $\frac{m}{\Delta m} > 170$ with an ion detector diameter of 120 mm.

A laboratory model of LAMA2 has been manufactured by the company Astro- und Feinwerktechnik, Berlin, and is ready for tests at the Heidelberg dust accelerator facility (Fig. 5) The reflector was manufactured with a reduced open area in order to simplify the manufacturing. However, the electric field geometry was fully preserved. An overview about the general properties of LAMA and the *Trajectory Sensor*are listed in Tab. 2.

Table 2. Properties of the Trajectory Sensor and LAMA. The instrument mass, power and dimensions are estimations. The dust mass range given assumes a particle density of 2000 kg/m^3 and a surface potential of 5 V.

Property	*Trajectory Sensor*	LAMA2
Mass [kg]	7.5	15
Power [W]	8	11
Sens. area [m^2]	0.25	0.1
Dimensions [m]	0.5x0.5x0.25	0.65Dx0.72
Aperture [+/-deg]	56	40
Measurement range		
Dust velocity [kms^{-1}]	3-100	1-100
Dust charge [fC]	0.1-100	-
Dust mass [kg]	$5 \cdot 10^{-17} - 5 \cdot 10^{-8}$	$10^{-18} - 10^{-8}$
Dust trajectory accuracy	+/-2°	+/-40°
Dust composition $\frac{m}{\Delta m}$	-	>100

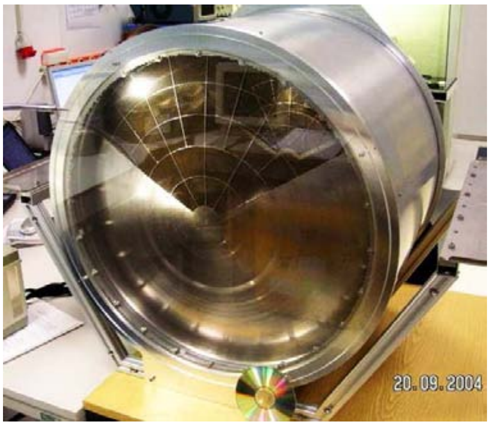

Figure 5. The laboratory model of LAMA2 at MPI-K.

3. THE TRAJECTORY SENSOR

The trajectory sensor determines in-situ the speed, mass, primary charge and trajectory of micrometeoroids and its concept was first described by Auer (1975). The measurement is based on charge induction of the particle primary charge onto individual metal wires. Each wire is connected to a separate charge sensitive amplifier (CSA) of high sensitivity. Particles in interplanetary space carry normally a positive potential of approx. 5 Volts due to the dominating photo electron current. Particles with a size of r=1 micron carry already a charge of $Q = 4\pi\varepsilon_0 r\Phi = 5.6 \cdot 10^{-16}$ C, where ε_0 is the permittivity $(8.85 \cdot 10^{-12} \frac{C}{Vm})$ and Φ is the surface potential in Volts. This charge corresponds to 3500 electrons and can easily be measured with advanced techniques. Here, an ASIC (Application Specific Integrated Circuit) based on $0.18\ \mu m$ CMOS technology was developed by A. Srowig which shows a noise of only 90 electrons in a bandwidth range between 10 kHz and 10 MHz (Srowig 2004). The noise of a CSA is depending on the detector capacitance. Therefore, the capacitance of the wires with respect to signal ground (detector frame) has to be as low as possible. It is approx. 5 pF for a thin wire with a length of 300 mm. A charged particle flying through a set of wires generates an induced charge on the most adjacent wires. The wire geometry determines how much charge is measured at the individual channels. Here, only 30% of the primary charge might be detected at one channel for the instrument shown in Fig. 6.

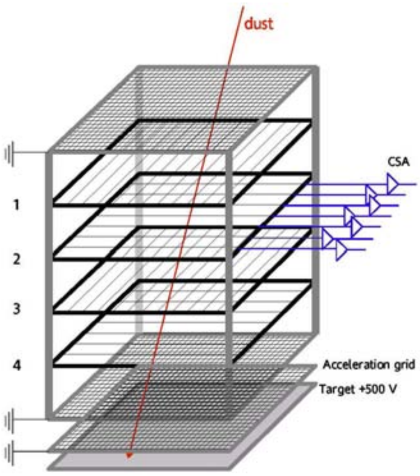

Figure 6. Schematics of the Trajectory Sensor. Four planes with perpendicular wires allow the reconstruction of the particle trajectory. The distance between the wires and the planes are 20 mm and 40 mm, respectively. The connection of CSAs to individual wires is shown only for one plane. An impact detector at the bottom will trigger the signal recording.

For the trajectory information it is necessary to locate the particle at two positions in the instrument volume. Each position sensor consists of two perpendicular planes separated by 40 mm from each other. Each plane is formed by a quadratic frame holding 16 parallel wires. An electronics board is located inside the metal frame and carries the 16 front-end (FE) amplifiers (ASICs) connected to the individual wires. The FE-ASIC also includes a logarithmic amplifier to allow for a measurement range between 10^{-17} and 10^{-13} C and an undisturbed signal transfer to the transient recorder (TR) (Fig. 7).

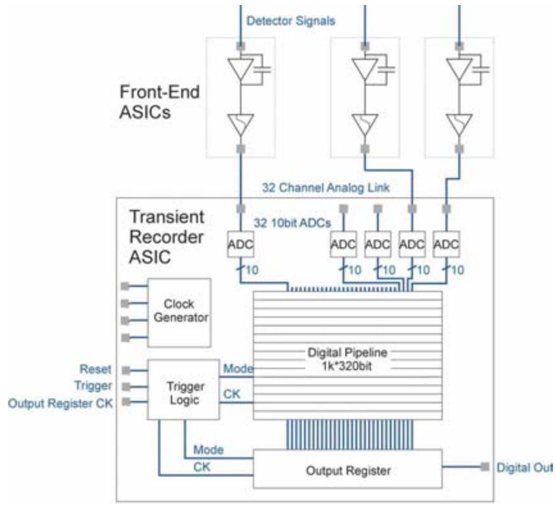

Figure 7. Electronics concept of the FE-ASIC (top) and the TR-ASIC (bottom). The transient recorder converts and stores up to 32 signals with a buffer depth of 1024 samples.

The CSA of the ASIC consists of a folded cascode with a capacitive feedback of 270 fF. The net signal is a bipolar current and the net charge after the measurement is zero. A high feedback resistor minimizes the influence on the signal and keeps the signal noise very low. On the other hand, the ambient plasma might lead to significant baseline shifts. This problem is addressed by the possibility to decrease the CSA feedback resistor for some time leading to a suppression of DC signals. The FE (CSA and logarithmic amplifier) has a conversion gain of 404 mV/fC and shows a noise of approx. 90 electrons. The logarithmic amplifier behind the CSA is implemented as a series of two differential amplifiers with on-chip biasing. A feedback circuit controls the operating point and stabilizes the baseline.
The 10 bit ADC is based on successive approximation, consumes only 3 mW and runs with up to 25 MHz (Fig. 8). Therefore the power consumption of the total recording system (FE and TR) is dominated by the CSA of approx. 50 mW per channel.

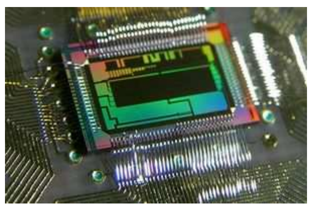

Figure 8. The DUNE-1.1 TR-ASIC developed by the ASIC Laboratory Heidelberg in cooperation with the MPI-K, Heidelberg.

The ASICs have been manufactured and integrated at the laboratory model of the *Trajectory Sensor* (Fig. 9) and the recorded signals are shown in Fig. 10. The tests confirmed the simulated low-noise behaviour of the electronics.

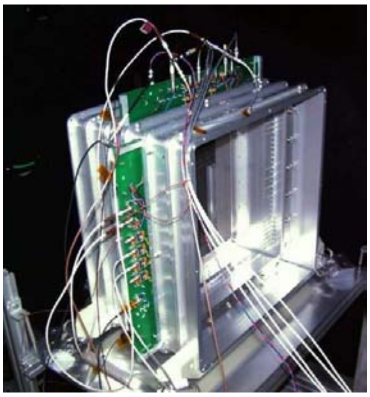

Figure 9. Laboratory model of the Trajectory Sensor during tests at the Heidelberg dust accelerator facility. The wires of this laboratory model have a length of 300 mm leading to a cross section of the frame of 360x360 mm. The height of the Trajectory Sensor is 240 mm.

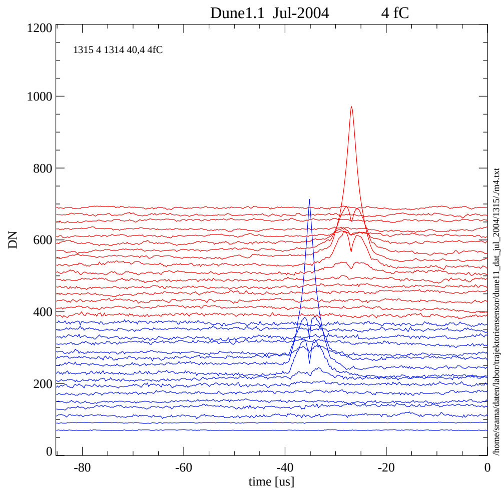

Figure 10. Signals of a particle passing the wire planes of the Trajectory Sensor. The particle speed and charge was 5 km/s and 4 fC, respectively.

A particle with a radius of 1 micron and a surface potential of 1 Volt carries a charge of 700 electrons. Assuming an induction efficiency on the wires of 50% , a signal of 350 electrons is expected. The amplifier noise of 100 electrons gives a SNR ratio of 3.5 which is sufficient under normal conditions. However, the grain surface potential is low under the low energy plasma conditions in the Low Earth Orbit (-0.5 V) leading to a higher mass threshold of approximately 10^{-10} g. The high energy plasma conditions in the Geostationary Orbit lead to surface potentials between -30 and +3 V. The measurement threshold of those particles is expected to be as low as 10^{-15} g (50 nm). In contrast, in interplanetary space the photo emission dominates the grain charging process leading to surface potentials of +5 V. Here, a 0.1 micron particle carries 350 electrons. Tab. 3 gives the measurement threshold for particles with a surface charge of 1000 electrons by the application of Equ. 1

$$m = \frac{4\pi\rho}{3}\left(\frac{Q}{4\pi\varepsilon_0\Phi}\right)^3 \tag{1}$$

Table 3. Mass threshold for the detection of grains with a charge of 1000 electrons.

Φ [V]	Size r [μm]	mass [g]
0.5	3	$2.3 \cdot 10^{-10}$
1	1.5	$2.8 \cdot 10^{-11}$
5	0.3	$2.3 \cdot 10^{-13}$
10	0.15	$2.8 \cdot 10^{-14}$
30	0.05	$1.0 \cdot 10^{-15}$

The error factor of the grain mass calculation is dominated by the uncertainty of the grain surface potential and the particle density. Due to the logarithmic compression of the analog signal between the CSA and the ADC, the quantization noise has no significant influence on the grain mass determination. However, the sensitive charge measurements might be affected by the ambient plasma (spacecraft environment, solar wind). This requires operating tests of the *Trajectory Sensor* in a vacuum chamber under environmental plasma conditions.

An analysis of the signal times observed on the wire planes (Fig. 10) gives a start and stop signal to calculate the particle speed with an accuracy of approx. one percent. This clearly allows the specification of the orbital parameters of individual grains, which in turn are characteristic for the various dust sources (interstellar, space debris, interplanetary). Furthermore, this detector type measures accurately the grain charge Q and thus provides directly the grain mass m by Equ. 1. Parameters are the particle density ρ, the permittivity ε_0, and the particle surface potential Φ. The detection of micrometeoroid primary charges in space by the Cassini-CDA instrument was reported in Kempf et al. (2004) and it was shown, that this approach to determine the particle mass is more accurate than other methods.

4. SUMMARY

A dust telescope performs in-situ measurements of dust in space. It consists of two components: A *Trajectory Sensor* and a Large Area Mass Analyzer. The *Trajectory Sensor* has been tested in the dust accelerator laboratory with self-developed ASIC electronics. The tests revealed a very low noise behaviour of the ASIC-based charge

sensitive amplifier of 90 electrons, which is required for the measurement of 1 micron sized grains with a surface potential of 1 Volt. For the multi-channel processing a low-power 32-channel transient recorder was developed and successfully tested. A SIMION study was performed for a Large Area Mass Analyzer with a sensitive area of 0.1 m^2 and a mass resolution of $\frac{m}{\Delta m} > 150$. This time-of-flight spectrometer for the analysis of hyper-velocity dust impacts has a reflectron with two parabolic grids. A laboratory model is in the integration state and dust impact tests are expected to occur in summer 2005.
These components are well suited to investigate the micro-meteoroid environment in interplanetary space or in the near Earth environment. For the first time, this instrument allows the in-situ analysis of the properties of micron sized particles together with the identification of its source.

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