A TRAJECTORY SENSOR FOR SUB-MICRON SIZED DUST

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ABSTRACT

Dust particles' trajectories are determined by the measurement of the electric signals that are induced when a charged grain flies through a position sensitive electrode system. The objective of the trajectory sensor is to measure dust charges in the range 10^{-16} to 10^{-13} C and dust speeds in the range 6 to 100 km/s. The trajectory sensor has four sensor planes consisting of about 16 wire electrodes each. Two adjacent planes have orthogonal wire direction. A charge sensitive amplifier ASIC has been developed with a RMS noise of about $1.5 \cdot 10^{-17}$ C. The signals from 32 electrodes are digitized and sampled at 25 MHz rate by an transient recorder ASIC (Application Specific Integrated Circuit). First tests with a laboratory set-up have been performed and demonstrate the expected performance.

1. INTRODUCTION

The value of meteoroid trajectory sensing is demonstrated by meteor astronomy. Accurate triangulation of meteor tracks provide the heliocentric orbit of the meteoroid that causes the meteor phenomenon. Several meteor streams have been associated with known comets. Other meteors, especially those for which meteorites have been recovered on the ground were identified with orbits arriving from the asteroid belt. Therefore, even early micrometeoroid detectors in space [1] attempted to record the trajectories of dust particles as well. However, these attempts failed because of inappropriate methods to cope with the low dust fluxes in space. Only the large-area dust detectors on Ulysses and Galileo (0.1 m^2 sensitive area) provided the first statistically significant measurement of different dust populations in interplanetary space [3]. Among the populations identified were a stream of interstellar particles traversing the planetary system on hyperbolic trajectories.

Dust particles, like photons, are born at remote sites in space and time, and carry from there information that may not be accessible to direct investigation. Meteor observations yield accurate trajectory information from which we can derive their place of origin: comets, asteroids, or even interstellar space. Laboratory analysis of collected micrometeoroids provide the particles' bulk properties and detailed chemical information from which we are able to infer properties of the environments out of which the particles were formed and in which they were subsequently altered. The combination of both methods, trajectory analysis and chemical analysis on the same particle, is called dust astronomy. Recent developments of dust detectors allow us to combine sensors of these capabilities into a single dust telescope that is carried by a dust observatory satellite in space [4]. Targets for a dust telescope are dust from the local interstellar medium, meteor stream dust, cometary, asteroidal, and dust emitted from planets and their satellites.

Dust particles' trajectories are determined by the measurements of the electric charge signals that are induced when the charged grains fly through appropriately configured grid systems [5]. A state-of-the-art dust telescope is capable of providing mass, velocity, physical and chemical information of dust grains in space. The break-through in trajectory sensing of individual dust grains came when Cassini's Cosmic Dust Analyzer (CDA) unambiguously measured the electric charge on dust particles in interplanetary space before they impacted the detector [6]. Several micron-sized dust particles were recorded that carried positive charges of a few femto-Coulomb (1 fC = 10^{-15} C).

The charge q [V] on a spherical dust particle of radius r [m] is given by $q = 4\pi\varepsilon_0 \Phi \kappa r$, with surface potential Φ [V] and permittivity ε_0=8.859 $\cdot 10^{-12}$ C/Vm and shape factor κ. The shape factor κ = 1 for spheres and κ > 1 for other shapes [7]. Dust particles in interplanetary space are charged to an electrostatic potential of about $\Phi \approx$ +5 V mostly by the photo effect from solar UV radiation [8]. A dust particle of 0.2 µm radius and a potential of 5 V carries a 0.1 fC charge. In regions of dense plasma like in the inner planetary magnetosphere charging by electron capture prevails leading to negative potential of a few Volts. This was verified by CDA's measurements of dust charges in the inner Saturnian magnetosphere which resulted in dust potentials of about -2 V [9]. In the Earth's ionosphere up to about 1000 km height dust potentials of about -0.5 V are expected. At such

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Proc. 'Dust in Planetary Systems', Kauai, Hawaii, USA.
26--30 September 2005 (ESA SP-643, January 2007)

potential only particles of 2 µm radius will be detectable at a charge of 0.1 fC.

Measurements of the induced charges when a dust particle flies through an array of appropriately configured electrodes provide a contact-less means to analyse its trajectory. In the last years a dedicated dust trajectory sensor has been developed, built and tested. The dust trajectory sensor will provide a ten times increased sensitivity of charge detection over Cassini's CDA sensitivity (1 fC) such that even in interplanetary space statistically significant numbers of dust trajectories can be obtained. The sensor measures dust charges ≥0.1 fC and allows us to determine trajectories of submicron-sized grains with accuracies of ~1° in direction, and ~1% in speed. This development is described in the next section.

2. TRAJECTORY SENSOR CONFIGURATION AND ELECTRONICS

A simple square trajectory sensor consists of four sensor grids mounted between two electrical shielding grids (Fig. 1). The distance between grid planes is 40 mm. Each sensor grid consists of 15 parallel wire electrodes (wires separated by 20 mm), each electrode has a capacitance of about 5 pF and is connected to a separate charge-sensitive amplifier (CSA). The wire directions of adjacent sensor grids are orthogonal. Each pair of adjacent wire electrodes within a sensor grid acts as a one-dimensional position-sensitive detector:

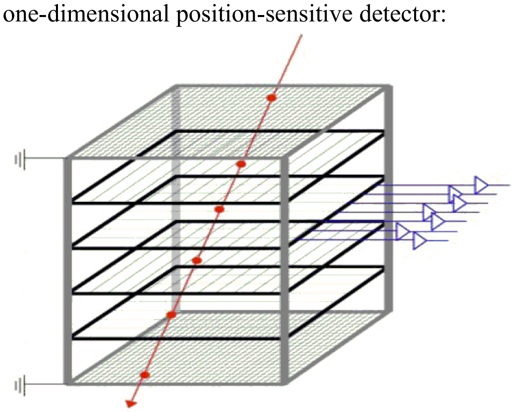

Figure 1. Dust trajectory sensor schematics. Four planes carry 15 electrode wires each equipped with a charge-sensitive amplifier (CSA). Two shield grids are placed in front and behind the charge sensing wires. A dust particle enters the sensor from the top and crosses all planes. The bottom carries an impact detector which releases the trigger signal (not shown).

The wire that senses the highest induced charge is closest to the dust particle's trajectory. Neighbouring wires sense lower charges. The ratios of charge amplitudes yield the exact coordinate of the grain's location of passage through that grid plane [4]. From such a geometric configuration requirements for the sensor electronics are derived. Fig. 2 shows the field-of-view for a trajectory sensor and the laboratory model used in the tests described in this paper. As usual the sensitive area is strongly dependent on the incident angle. It is highest for particles with normal incidence (angle zero). The azimuth angle (rotation angle about the detector boresight axis) plays a minor role and leads to slightly higher sensitive areas for large angles of incidence. For axis-symmetric sensors (circular target and aperture) the azimuth angle has no influence (crosses in Fig. 2).

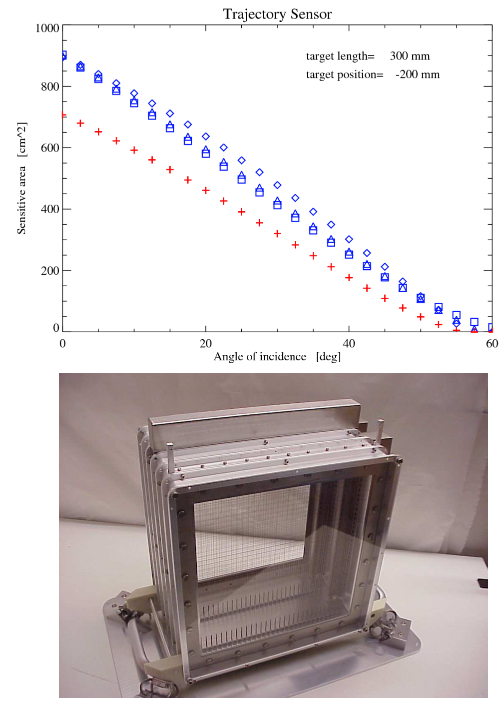

Figure 2. Top: Sensitive area of a trajectory sensor with a target size of 30 cm x 30 cm. The sensor height is 20 cm. The diamonds, triangles and squares represent azimuth angles of 0°, 22,5° and 45°, respectively. For comparison the sensitive area of an axis symmetric sensor (circular target) with a target diameter of 30 cm is given (cross symbols). Bottom: Dust trajectory sensor lab set-up for dust accelerator tests. The size is about 350x350x250 mm³.

The central element of the trajectory sensor is the low noise CSA. The design was guided by three goals, (1) to minimize amplifier noise (<<0.1 fC), (2) to discharge electron currents from the solar wind plasma, and (3) to minimize power consumption. Both an Application Specific Integrated Circuit (ASIC) and a CSA version made from discrete components have been developed that meet the requirements. Signals from all electrodes are digitized in separate analog-to-digital converters (ADC) and stored in a fast pipeline storage. In most applications a trajectory sensor is combined with a dust impact detector which is located behind the trajectory sensor. Since the dust impact signal is generally much bigger than the induced charge signal the impact signal is used as a trigger. Alternatively, the induced wire signals can be taken for triggering. This might be necessary for a combination of a trajectory sensor and a dust collector (aerogel). It was also shown in [2] that impacts on aerogel of hypervelocity particles generate an impact charge which can be taken for triggering.

The transient time for the 250 mm passage through the trajectory sensor (height 200 mm) and the impact detector (assumed height 50 mm) depends on the component of the particle speed perpendicular to the sensor planes. For perpendicular speeds between 6 and 100 km/s the transient time is between 42 and 2.5 µs. At a 25 MHz sampling rate 333 to 20 samples are digitized of the induced charge signals between two planes. Such a sampling rate is considered acceptable for reconstruction of the signals with sufficient accuracy. However, slowing down the sampling frequency of the ADC (e.g. 4 MHz instead of 25 MHz) allows for the detection of low-speed particles with velocities down to 1 km s^{-1}.

Key elements of the trajectory sensor are the charge-sensitive amplifier (CSA) and the transient recorder. An ASIC version (Fig. 3) was developed in cooperation with the Kirchhoff Institute for Physics of the Heidelberg University [10]. The ASIC uses the UMC 0.18 µm CMOS process which is inherently radiation hard to Mrad levels. It consist of two individual chips: the front-end and the transient recorder chip.

The front-end chip contains the CSA and a logarithmic amplifier for the compression of the dynamic range from 10^{-16} C to 10^{-13} C. The upper limit of 100 fC allows for the measurement of particles as large as 200 µm radius (assuming a surface potential of 5 Volts and a particle density of 2000 kg/m³). Those particles are rare in space such that no saturation effects of the electronics are expected. Even in the case of strong signals, the particle's trajectory can be derived from the induced and unsaturated signals of adjacent wires.

For a 5 pF electrode capacitance the rms noise performance is $1.5\cdot10^{-17}$ C (95 electrons at room temperature), in a bandwidth from 10 kHz to 10 MHz. The noise performance is sensitive on the input capacitance, lower input capacitance will decrease the noise even more. The feedback capacitance is 270 fF. The feedback resistance is externally controlled by a bias voltage. Typically, the feedback resistance is 3 GΩ but in case the electrode collects higher external charging currents the feedback resistance can be reduced in order to drain off this charge. The logarithmic amplifier is controlled by an external direct-current feedback circuit to its inverting input. By appropriate choice of a band pass filter the noise performance of the amplifier chain is optimized. The noise performance of the charge-sensitive amplifier has been traded off against power consumption. For the above stated performance the power consumption of a single front-end chip is 50 mW, i.e. for 64 channels a total front-end consumption of 3.2 W is required.

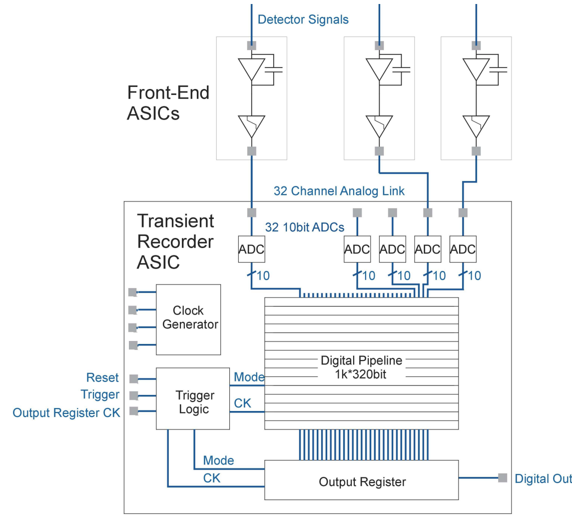

Figure 3. Block diagram of both the front-end and transient recorder ASICs.

The transient recorder chip has 32 channels of analogue-digital converters with an accuracy of 10 bits and 32 digital pipelines of 1000 samples depth. This corresponds to 40 µs buffer time at a typical 25 MHz sampling rate. The ADC clock is provided by an on-chip circuit and its frequency is controlled by an external voltage. For some applications an external clock signal can be provided. The data conversion is done with 10 bit successive approximation register ADCs. The conversion is completed by a reset signal in the 10th cycle which makes the ADC insensitive to Single-Event Upsets. The pipeline consists of a synchronous SRAM ring-buffer. An external trigger signal (e.g. derived from the dust impact onto an impact detector placed behind the trajectory sensor) stops the recording and all data is serially read out.

The data processing of the transient recorder is optimized for the trajectory sensor described above (sensitive area ~ 0.1 m^2) with a total flight path of 250 mm until impact (trigger). However, it can be easily adapted to a larger trajectory sensor of 1 m^2 sensitive area just by linearly scaling all dimensions by a factor of about three. In this case the clock frequency which cycles the transient recorder has to be reduced by the same factor without a change in performance. Also the same transient recorder chip can be used with a sampling frequency of 25 MHz. In case the total flight pass is twice as long as before two transient recorders have to be used in parallel but at half the frequency. In this case an external clock provides the frequency to the transient recorders except for one shifted by half a clock period.

3. LABORATORY TESTS AND RESULTS

First dust accelerator tests at the Max Planck Institute for Nuclear Physics have been performed with the described set-up. A network of 30 front end microchips (two planes with 15 wires each) and two

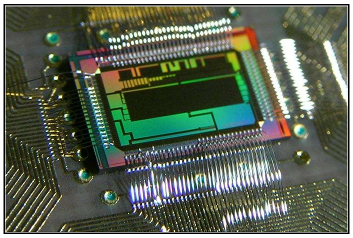

Figure 4. A micro-photograph of the DUNE 1.1 transient recorder chip (ASIC).

transient recorder chips were integrated with the sensor. The trajectory sensor was installed in the vacuum chamber mounted on top of a movable table in order to vary the position of the sensor with respect to the dust beam. The tests were performed with iron particles with speeds up to 30 km/s (0.1 to 1 µm grain size) which demonstrate the expected performance.

Two sensor planes (1 and 3) are equipped with preamplifiers and the transient recorder. Behind the trajectory sensor an impact sensor was placed to give the trigger signal which stops data recording and starts read-out of data. Figure 5 shows 30 traces recorded during a single shot. One signal in each plane has a triangular shape indicating that the dust particle flew very close to the corresponding wire electrode. The signals from the neighbouring electrodes display a dip at the time of closest proximity when the particle is directly in the wire plane (electric shielding by the closest wires).

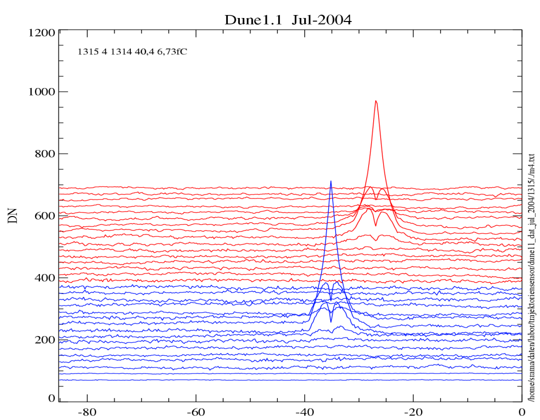

Figure 5. Trajectory sensor wire signals of two planes (upper and lower 16 signals). The external trigger occurred at time zero. The signals were caused by a particle carrying a charge of 7 fC.

Examples of the match between measured charge signals from two different dust particles (top and bottom diagram) and a simple theoretical model are shown in Fig. 6. This comparison allows us to determine the dust trajectory and speed. Signals from six adjacent wire electrodes are shown for a particle flying as close as 1.5 mm to the wire (strongest peak in Fig. 6, x=1.5 mm). The vertical dashed lines mark the penetration times through the four planes of the trajectory sensor. The RMS noise of the signals is less than 0.02 fC. The accuracy of the determination of the penetration position in one plane is approx. 0.2 mm which corresponds to a trajectory angle of much better than 1 degree in the examples shown.

Finally, noise interference tests with the trajectory sensor have been performed: The trajectory sensor was placed in the vacuum chamber of the dust accelerator facility and an electron current of 10 µA was focused on the sensor aperture (electrons emitted by a glowing tungsten wire in front of the sensor). The detector preserved its functionality during this test and induced signals of dust particles were detectable.

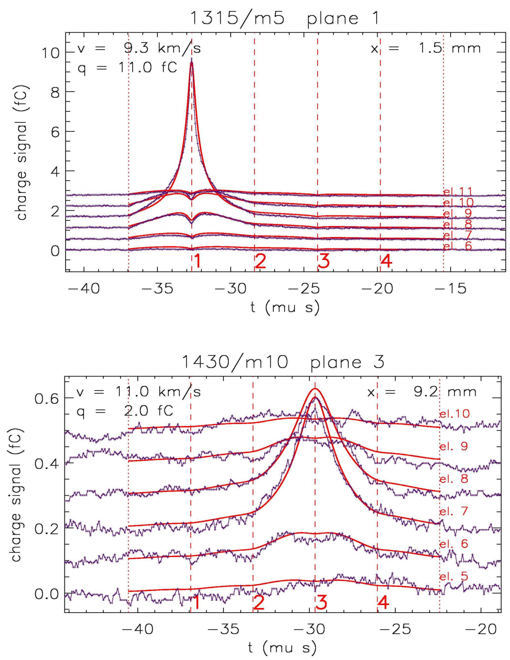

Figure 6. Charge signals of two dust particles recorded at six electrodes closest to the particle trajectory in one plane (noisy blue curves, a colored version of this paper is available electronically). For comparison theoretical derived signals (smooth red curves) are plotted over the measured signals. The upper diagram shows signals of a particle with 9.5 km/s and a charge of 11 fC. The lower diagram shows signals of a 11 km/s particle carrying a charge of 2 fC. Theoretical signals (smooth red curves) are shown for comparison.

4. SUMMARY AND OUTLOOK

Accurate dust trajectory measurement is possible with a trajectory sensor measuring the electric charge of a dust particle when it flies through an array of wire electrodes. A lab set-up of a dust trajectory sensor which was equipped with newly developed ASIC electronics was tested at the Heidelberg dust accelerator. The instrument has the following characteristics:

- 0.1 m^2 sensitive area
- 0.1 to 100 fC charge range
- 6 to 100 km/s speed range (alternatively 1 to 16 km/s)
- 1% speed accuracy
- 1° directional accuracy
- < 1 mm position accuracy

The charge range corresponds to particles of 0.2 to 200 μm radius at 5 V surface potential or to particles of 2 to 2000 μm radius at 0.5 V. The ASICs are versatile and can adopt other configurations like e.g. a 1 m^2 trajectory sensor.

The typical application of the dust trajectory sensor is in combination with a large-area mass analyzer or any other type of impact detector constituting a dust telescope. Such an assembly adds trajectory information to impact data like e.g. chemical composition [11,12]. A special application is the combination of the trajectory sensor and a dust collector. The trajectory sensor will provide not only trajectory information but also the impact position so that a unique correlation between collected particles and trajectory information can be made.

Acknowledgements: This research is supported by NASA grant NAG5-11782 and by DLR grant 50OO0201.

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