Detection of microparticle impacts on spacecraft via their plasma effects

ESA contract 4000107623/13/NL/AF

Executive Summary

Report I-51/15

Prepared by:
M. Schimmerohn

Management:
M. Schimmerohn

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Freiburg, Germany

Fraunhofer Institute for High-Speed Dynamics
Ernst-Mach-Institut, EMI
Director: Prof. Dr.-Ing. habil. S. Hiermaier

EMI Freiburg,
Eckerstrasse 4, 79104 Freiburg, phone +49 761 2714-0
EMI Efringen-Kirchen,
Am Klingelberg 1, 79588 Efringen-Kirchen, phone +49 7628 9050-0
www.emi.fraunhofer.de

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Management:

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DN: c=DE, o=Fraunhofer, ou=EMI, ou=People, cn=Martin Schimmerohn
Datum: 2015.11.11 17:03:25 +01'00'

Schimmerohn, Martin
Group Manager – Spacecraft Technology Group

Frank Schaefer

Digital unterschrieben von Frank Schaefer
Datum: 2015.11.11 22:11:46 +01'00'

Prof. Dr. F. Schäfer
Head of Department – System Solutions
Deputy Director of Ernst-Mach-Institut

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2 Microparticles and observations of impact-induced plasmas

Microparticles are one of the least known components of the space environment. Their observation and investigation is complicated by their small size and their high velocity. Hence, microparticle characteristics like shape, composition, density, and surface charge are associated with considerable uncertainty [SCHI13].

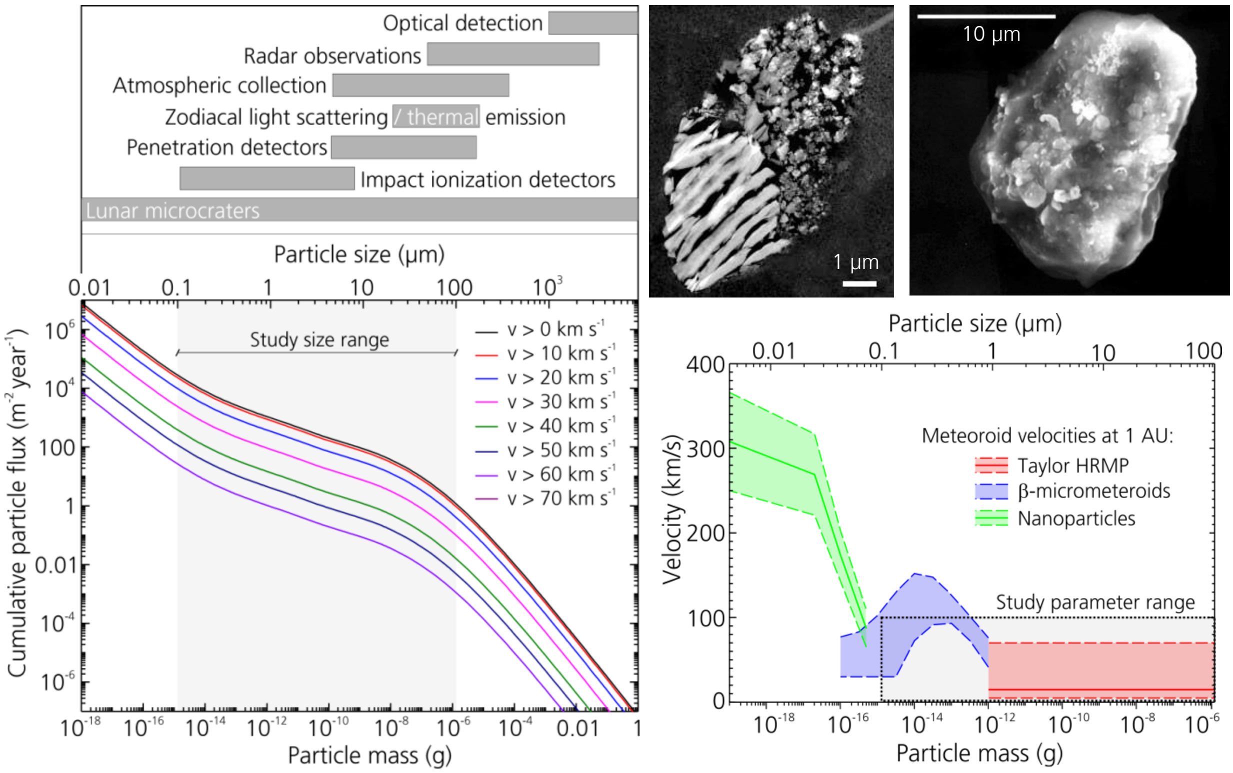

Figure 1: Microparticles and their characteristics. The left diagram (a) shows cumulative meteoroid fluxes at 1 AU according to the standard Grün model [GRÜ85] with Taylor HRMP velocity distribution [TAY95]. The mass/size coverage of underlying datasets is displayed per evaluation method. The variation of microparticle shape and composition is observable in the examples of microparticles shown on the upper right: A dark-field image of a comet dust particle captured in aerogel during NASA's stardust mission [] and a secondary electron image and a space debris particle collected in Earth's stratosphere [ROS99]. The lower right diagram illustrates the microparticle velocities based on observations [TAY95] and calculations for submicron particles [MAN10].

As Figure 1 shows, the knowledge about microparticle characteristic is strongly based on observation of indirect effects. On the one hand, this indicates that the accuracy of microparticle impact modeling is limited by the available data. On the other hand, this stresses the need for more in-situ detection and motivated the performed study.

When impacting on a spacecraft surface, a plasma cloud is generated by shock wave and surface ionization processes due to the considerable kinetic energy carried by the microparticle. The transient cloud consists of vaporized and ionized particle as well as surface material and is referred to as impact plasma. This transient plasma cloud rapidly expands to the meter scale within microseconds, thereby interacting with spacecraft surface components.

The impact plasma cloud shows a range of distinct phenomena that may be used to trace back the conditions of impact and the microparticle characteristics. The effects range from the production of free charge to electromagnetic wave generation. In the past, detectors based on electric coupling to impact plasmas were designed, including complex charge collection detectors with long heritage. Other effects revealed themselves as anomalies on instruments which were dedicated to tasks other than particle detection. These effects showed up as impact-correlated voltage spikes on radio astronomy and space plasma instruments.

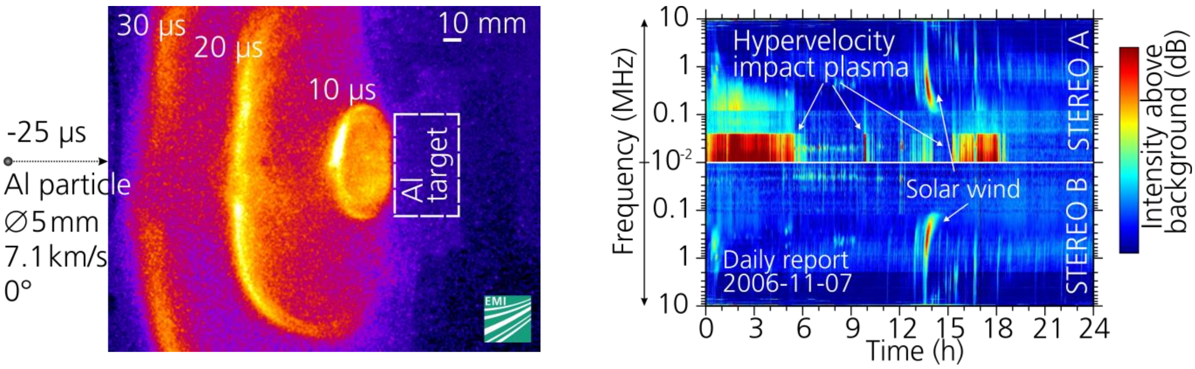

Figure 2: Impact plasma cloud and interactions. An evolving impact plasma cloud is shown on the left high-speed photo combination. Impact parameters and the times of expansion state are indicated. Noise signals may be generated by the expanding plasma cloud when it interacts with spacecraft antennae. The right spectrograms of the WAVE instrument onboard STEREO A/B show noise signals that have been attributed to such impact related interactions (adapted from [KAI13]). This triggered the question whether, and under which conditions, this effect may be applied for a dedicated impact detection sensor.

Figure 2 shows the most prominent impact plasma features that may be exploited for detection: light emissions and charge generation. The light emissions, which are visible for a few microseconds at the impact location, have been used to sample cloud characteristics [HEU13]. Unambiguously correlating between particle characteristics with light emission intensity, however, has proven to be challenging, as 1) the measured signals are photosensor related, 2) simulations are complex, and 3) simple models are currently not available. While recommending to follow up investigations on light emissions, in this study, we focus on the detection of plasma cloud charges by antennae. The important benefit of this detection concept is its simplicity: in principle, the detector assembly merely comprises an array of metal rods serving as antennae, while the spacecraft surface is used as detection surface.

3 Impact plasma modeling

The feasibility of impact detection via impact plasma cloud interaction with antennae as well as the respective detector requirements are studied based on numerical simulations. The rationale behind this is to allow for a wide parameter range of both particle characteristics and sensor configurations that are not completely accessible through ground experiments. Effort was taken to develop a comprehensive impact plasma model and to implement an algorithm including the plasma cloud formation and evolution, as well as the signal response of an antenna when interacting with the evolving plasma cloud.

Different approaches from different scientific/technical fields of application are combined to model the antenna signal as a function of impact parameters. Those fields include impact physics (shock state and impact vaporization), astrophysics (properties and ionization of a gas mixture under high pressure), laser physics (plasma expansion) and space physics (signal generation).

For the overall model, a "semi-empirical" approach was chosen. "Semi-empirical" in this case means that neither a kinetic method (e.g. particle in cell methods to solve the Vlasov equations) nor a finite method with spatial and time discretization (e.g. hydrocodes to solve the hydrodynamic conservation equations) was used. Instead, practical analytic solutions, problem-specific differential equations and empirical relations (including both experimental data and results of numerical simulations) are used as far as possible. The premise was to limit the computational effort for the parametric study.

A detailed description of the developed model is given in TN3 [SCHI15]. Here we provide the basic physical approaches:

- The nominal theory for plasma generation is the thermal volume ionization. Material is dissociated and ionized under the effect of strong shock waves that propagate in the impacting particle and the impacted surface structure. This is the dominant mechanism for high impact velocities. However, for lower velocities different surface ionization processes become dominant. As no quantitative model for the surface ionization exist, we treat this velocity regime like an initial value problem that uses the volume ionization routine for simulation and available empirical charge yield relations as boundary condition.

- The shock state is computed with the planar impact approximation and semi-empirical equation of states to quantify the increase of temperature and entropy in the shocked materials.

- The number of vaporized atoms is determined by the entropy method from the shock state in consideration of empirical shock pressure decay laws.

- The ionization of the generated gas cloud goes through different phases during expansion. The initially extremely dense cloud is in Saha equilibrium with mixture concentrations of ion species calculated accordingly. At some point during expansion, the thinning cloud goes into a phase of non-equilibrium recombination, during which the degree of ionization drops rapidly. Under certain circumstances, if/when the mean free path of electrons grows larger than the cloud size, the plasma cloud becomes collisionless and charge separation effectively takes place at the cloud boundary.

- We assume a self-similar expansion of the plasma cloud. Density and temperature gradients form as a result of the isentropic expansion models. The velocity distribution is considered linear for reducing the gas-dynamic equations. The implemented expansion models also include the effect of charge separation in case of collisionless plasma clouds.

In the model, the evolving plasma cloud expands over the spacecraft surface and covers an antenna which is located in a specific distance and orientation with respect to the impact location. Through the free charge carriers in the plasma cloud, the potential of the antenna is disturbed. This happens on a shorter timescale than needed for equilibrium establishment with space environment currents. Four different mechanisms are considered to cause a measurable effect at the passive antenna:

1) The direct detection of charge carriers flowing to the antenna surface covered by the impact plasma cloud. Only the net-sum of charge is detected. Therefore, a signal is only generated in case the cloud is collisionless and electrons hurry ahead the cloud boundary, or cloud electrons are collected by the spacecraft potential.

2) The collection of cloud charge carriers by the charged spacecraft surface. This causes a change of the spacecraft potential with respect to the antenna. Thus, contrary to the other signal generation mechanisms, it is independent of direct interactions of antenna and plasma cloud.

3) The disturbance of the antenna potential by blocking the photoelectron return current in the impact plasma cloud.

4) The disturbance of the antenna potential by emission of secondary electrons through the primary particle flux of ions in the fast expanding plasma cloud.

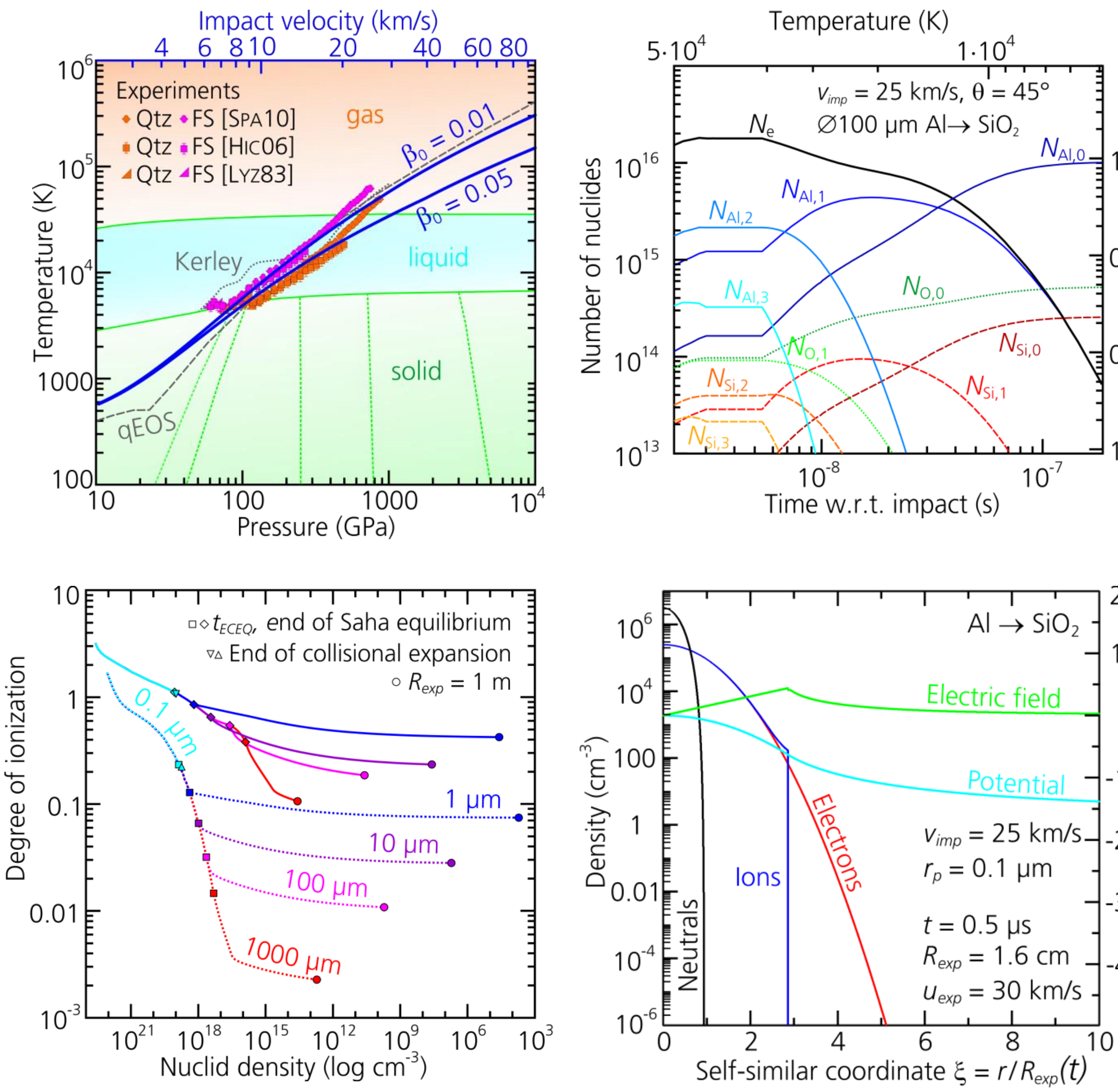

Figure 3: Plasma cloud computation. The upper left diagram shows the pressure-temperature computation of the shock state (for SiO_2, phase boundaries are indicated). The blue line represents the model results compared to the given experimental results. The upper right shows the equilibrium plasma composition of a plasma cloud during expansion. The lower left presents different ionization paths as a function of particle sizes and impact velocity. The lower right diagram shows the spatial dependence of normalized flow velocity, electron and ion densities, electrostatic potential and electric field for the self-similar solution of collisionless plasma expansion.

Figure 3 shows examples of plasma cloud formation and expansion characteristics as computed with the implemented plasma model.

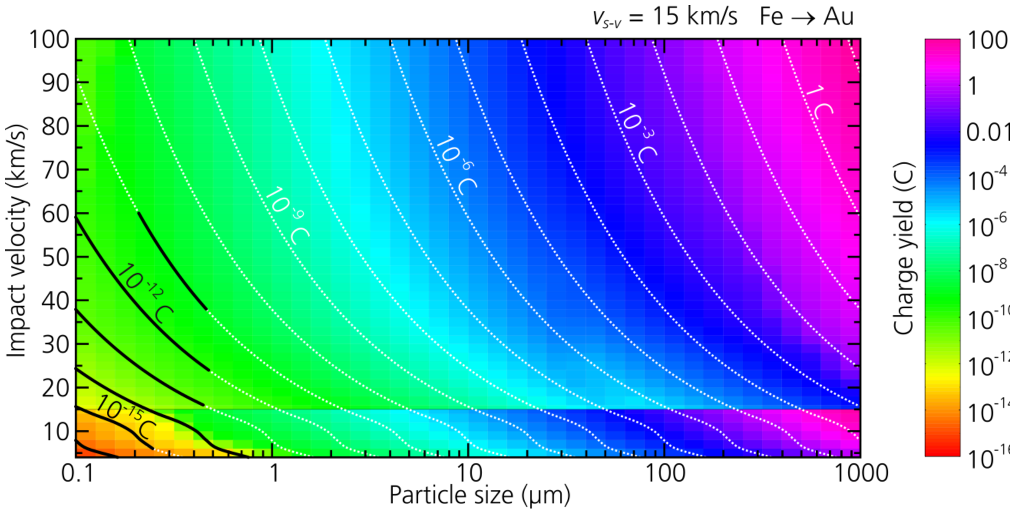

Figure 4: Validation of overall model results. Shown is the charge yield computed by the model w.r.t. the impact conditions, i.e. particle size and velocity, in a 3D map. The two ionization regimes, surface and volume ionization, are indicated by a discontinuity at 15 km/s, which is the chosen transition threshold. The contours represent the empirical charge yield relations (black lines represent validated range of these relations, dotted white lines represent extrapolations). More experimental investigations are needed to validate the complete parameter range.

The comprehensive plasma model has been implemented in software. For validation we compared the overall model outputs to available experimental results, i.e. empirical charge yield relations. The model shows a good agreement to these data in the validity range of these equations as shown in Figure 4. However, a discontinuity is visible in the transition range between surface and volume ionization in particular for larger impactor sizes. More experimental investigations are needed to validate the complete parameter range and, if needed, to modify the model approach for the low velocity regime.

4 Analysis of sensor signals

The developed impact plasma model was applied in a parametric study to investigate the correlations between the induced sensor signals and the microparticle characteristics, the impact conditions, as well as the sensor configuration. A typical simulation scenario is shown in Figure 5.

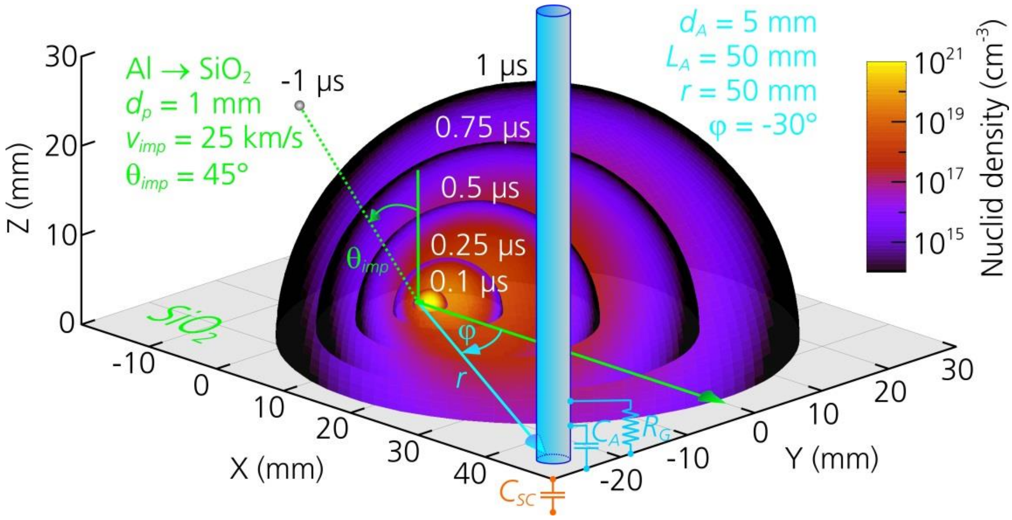

Figure 5: Geometry of the impact event and the sensor for the parametric study. Exemplary values for impact parameters (green) and sensor parameters (blue) are given. The cloud evolves in time according to the impact conditions (shown here for the expansion during the first microsecond). The sensor signals depend on impact parameters through cloud characteristics, sensor position (radial distance r and angle coordinate φ) and configuration (antenna length L_A and diameter d_A) with respect to the cloud.

We found that the cloud characteristics are quite similar for different material combinations and depend more strongly on the cloud expansion state. The expansion velocity of the cloud boundary is typically comparable to the impact velocity. As Figure 6 shows, the cloud changes its properties rapidly during expansion. The cloud expansion has two components, a radial component driven by the thermal pressure of the gas and a horizontal component that retains part of the impact directionality due to shock front geometry in oblique impacts. We identified analytical expressions for the relationships between cloud characteristics and impact parameters. The same applies for the correlation of particle characteristics and generated sensor signals.

The study results have shown that important particle characteristics can be traced back by sampling antennae response. Specifically, it was found that the currently unconsidered emission of secondary electrons due to the fast cloud ions is the most appropriate mechanism for impact detection. The other effect used is the recollection of impact plasma cloud electrons by the charged spacecraft.

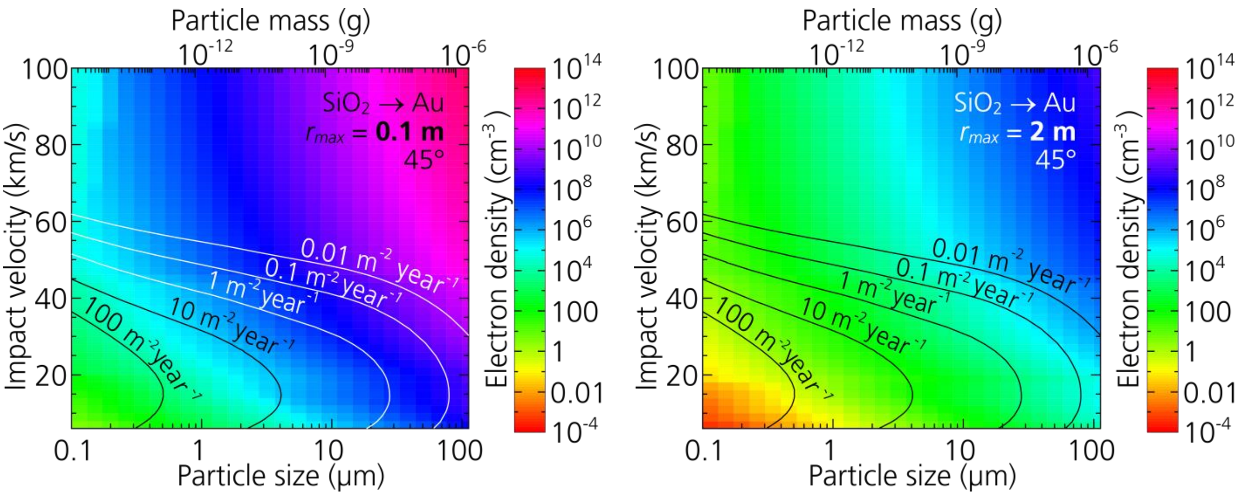

Figure 6: Electron density for different expansion states of the plasma cloud generated by impact of silica particles on a gold target. The density falls rapidly during expansion, but the relative distribution is maintained. The contours represent the meteoroid impact fluxes according to current distribution models (see Figure 1).

Figure 7 shows examples of the parameter correlation analysis, particularly the signal amplitudes as a function of sensor design and position with respect to the impact. The signals show variations that are sensitive to impact parameters.

In order to demonstrate the feasibility and the capabilities of an instrument based on antenna-impact plasma interactions, we performed simulations using a configuration as shown in Figure 8. In the given example, we considered a hexagonal array of seven unbiased antennae. Using this this simple sensor configuration, we can efficiently trace back the most important impact parameters with good accuracy, i.e. particle size/mass, impact angle, and impact velocity vector.

Based on the analysis results, the instrument requirements have been derived. For the sensor design, this comprises:

1) The sensor itself, as indicated above, has a quite simple design. A sensor shall consist of an array of a minimum of six orthogonal antennae with equidistant positioning and a grid spacing of ca. 30 cm.

2) Each antenna has a length of 40 cm length and a diameter of 1 cm-2 cm. We consider standard values for spacecraft monopoles for the antenna wiring. The antennae are passive (i.e. not biased.

3) The detection surface shall be made of a plane layer from homogeneous material with a minimum thickness of 1 mm.

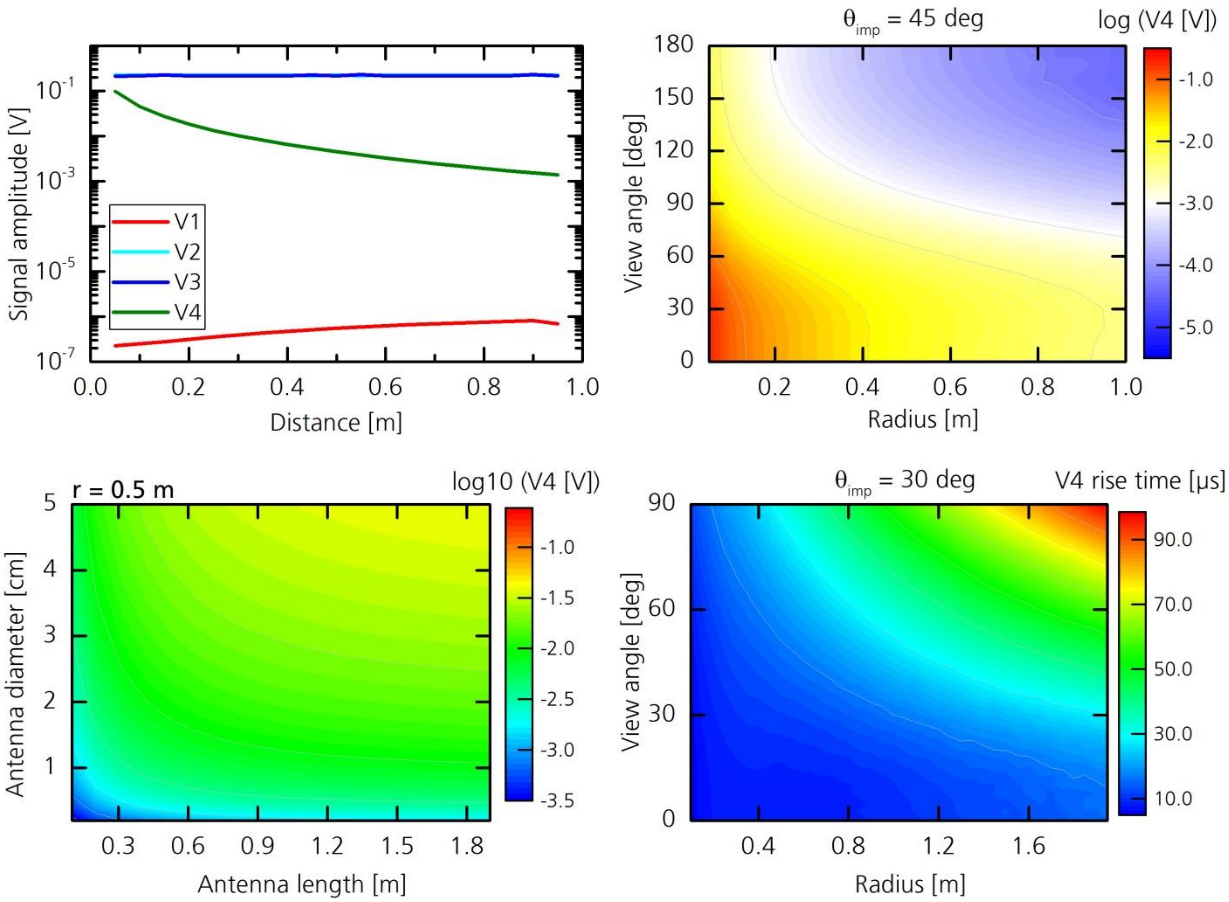

Figure 7: Correlations between impact parameters and sensor configuration. Upper left: Absolute detectable voltages (for the different detection mechanisms) as a function of distance between impact site and antenna. V2 and V3 are basically identical on the employed scale. Upper right: Signal amplitude of plasma-induced secondary electron emission as a function of relative antenna – impact site configuration in polar coordinates for different impact angles. Lower left: The same signal as function of antenna geometry. Lower right: Signal rise times at 30° impact angle as a function of antenna position.

The performance requirements for the electrical front end have been assessed considering micrometeoroids of 0.1 – 100 µm size. For the studied sensor configuration, the signals need to be sampled with a:

4) minimum of 0.1 µs temporal resolution, and

5) minimum of 0.01 mV signal resolution with the maximum intensity of ca. 5 V.

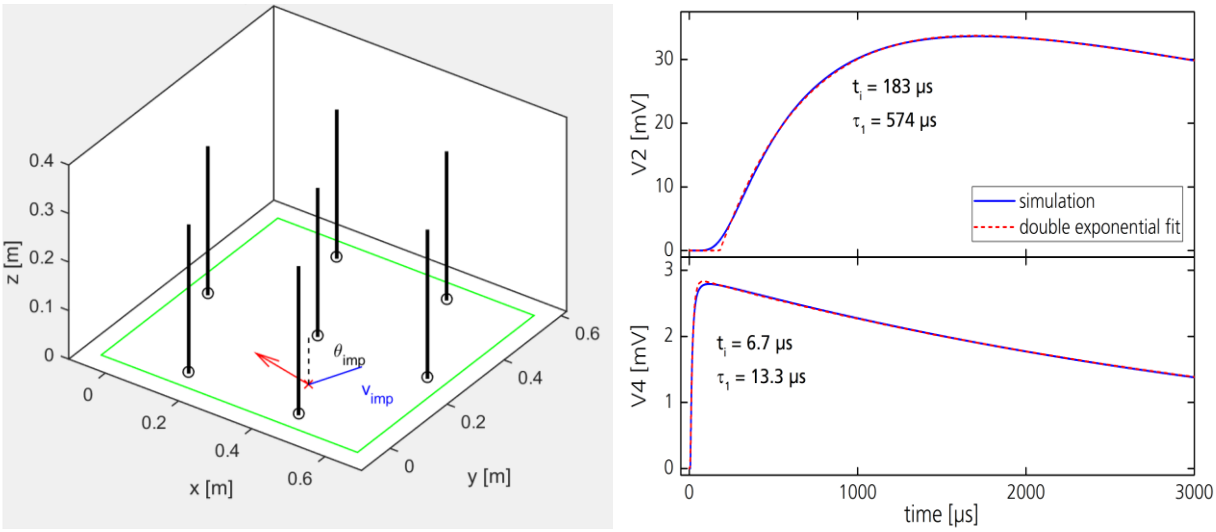

Figure 8: Exemplary case study of impact detector. The impact detector consists of an array of antennae with 40 cm length in hexagonal configuration (left scheme). The position of impact is indicated by the impact vector (blue) and the plasma cloud direction (red). The impact parameters are recovered by using triangulation and simple analytical fit functions for the simulated sensor signals as shown in the right diagrams. In this example, the impact location and the impact velocity was determined with a deviation less than 5 %, the impact angle and the particle mass were sampled with a deviation less than 15 %.

In order to fully exploit the antenna signals, we need to know the actual charge state of the detection surface. Therefore, the impact detection system shall also include an instrument for in-situ monitoring of the surface charge at the detection surface. We consider a combination with a compact, flight-proven state-of-the-art charge detector for this purpose. Furthermore, additional impact detecting instruments would improve the sensor performance by providing an independent reference. One could think about coincidently detecting the impact flash (or antenna-plasma interactions) through optical methods. Moreover, other impact features, including the mechanical damage may be employed, e.g. by PVDF film detectors, or by monitoring the acoustic noise inside the impacted surface. Without going into details of other impact detection methods, we generally recommend the use of a complementary and coincident measurement of particle impacts.

5 Technology development roadmap

Finally, we identified the technology development activities and the effort needed to implement the assessed concept of impact detection in an applicable sensor system. The development roadmap is shown in Figure 9.

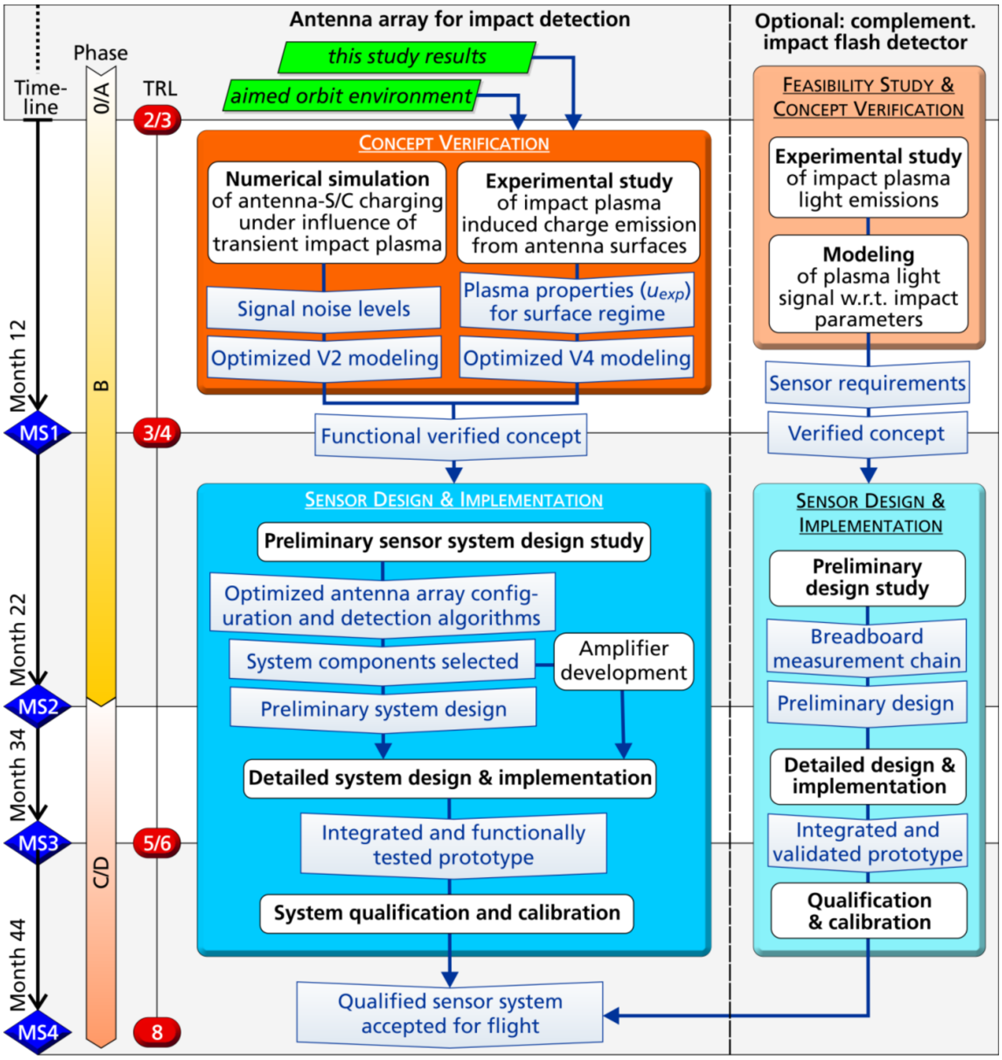

Figure 9: Technology development roadmap for the impact detector. The technology development activities and their results are shown along an indicative timeline, as well as associated milestones and mission phases. The starting point for the baseline development of the antennae based detector is indicated in green. An impact flash detector is taken as an example for the complementary impact detector. This activity is separated from the baseline activity to point out its optional character. If this option is selected, parallel activities may be linked or even combined. The TRL level are defined in compliance to the ISO definition.

The overall objective of the technology development is to design and fabricate a flight ready impact detection sensor based on the measurement of impact plasma interactions with antennae. An important feature of this concept is its principal realization by means of a relatively simple technical system. Therefore, the focus of the described plan is set on a relativly simple and robust sensor system. The design is applicable for different mission environments, i.e. interplanetary missions with small and fast micrometeoroids or Earth orbit missions with additional fluxes of larger and slower (but still hypervelocity) space debris objects.

Starting point of the technology development plan are the results of this study. The equivalent mission phase may be stated as phase 0/A. For arriving at phase B/C and increasing the readiness level to TRL 3/4, we consider a concept verification study with two parallel activities, each of which is dedicated to experimentally verify one out of the two mechanisms, spacecraft electron collection (V2) and secondary electron emission (V4) through cloud interaction. Specific application cases, in particular the intended orbit region and the spacecraft surface considered for detection, could be chosen for the concept verification in order to concentrate the study effort.

In case the optional development of a complement impact detector is selected, the early design phase may be combined with the experiments needed to verify the impact plasma induced secondary emissions. For experimentation, it is important to include a wide particle range, i.e. by using different impact facilities at the current levels of accelerator technology (all available in Europe).

The results from the concept verification form the basis for the sensor system design activities. By means of these activities, the system will be advanced from TRL 4 to TRL 8. Starting point are the evaluated results and the breadboard models from the previous activity. The complete system design will be elaborated in the preliminary design study. The design study shall include 1) the optimization sensor configuration and analysis algorithm, 2) definition of instrument architecture, and 3) the selection of adequate system components. Considering the last aspect, we have so far not identified critical technologies, which need to be developed for sensor implementation. Standard COTS-components may be used for instrument implementation.

The effort of the design, the integration and the test activities strongly depend on the selected model philosophy and the extent of qualification testing. For the presented baseline schedule, we assessed an overall duration of 44 months without considering programmatic risks.

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