Large area low resource integrated impact detector

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Agenda

1) Introduction, state-of-the-art & detector concept
2) Breadboard design, hypervelocity impact testing & verification results
3) Flight model development plan

Introduction

Observational gap of space debris data

Post-flight analysis of retrieved hardware

Object size $\lesssim$ **0.1 millimeter**

Hörz et al., 2000

In-situ impact detectors onboard spacecraft

Sensitivity limit of ground-based observations

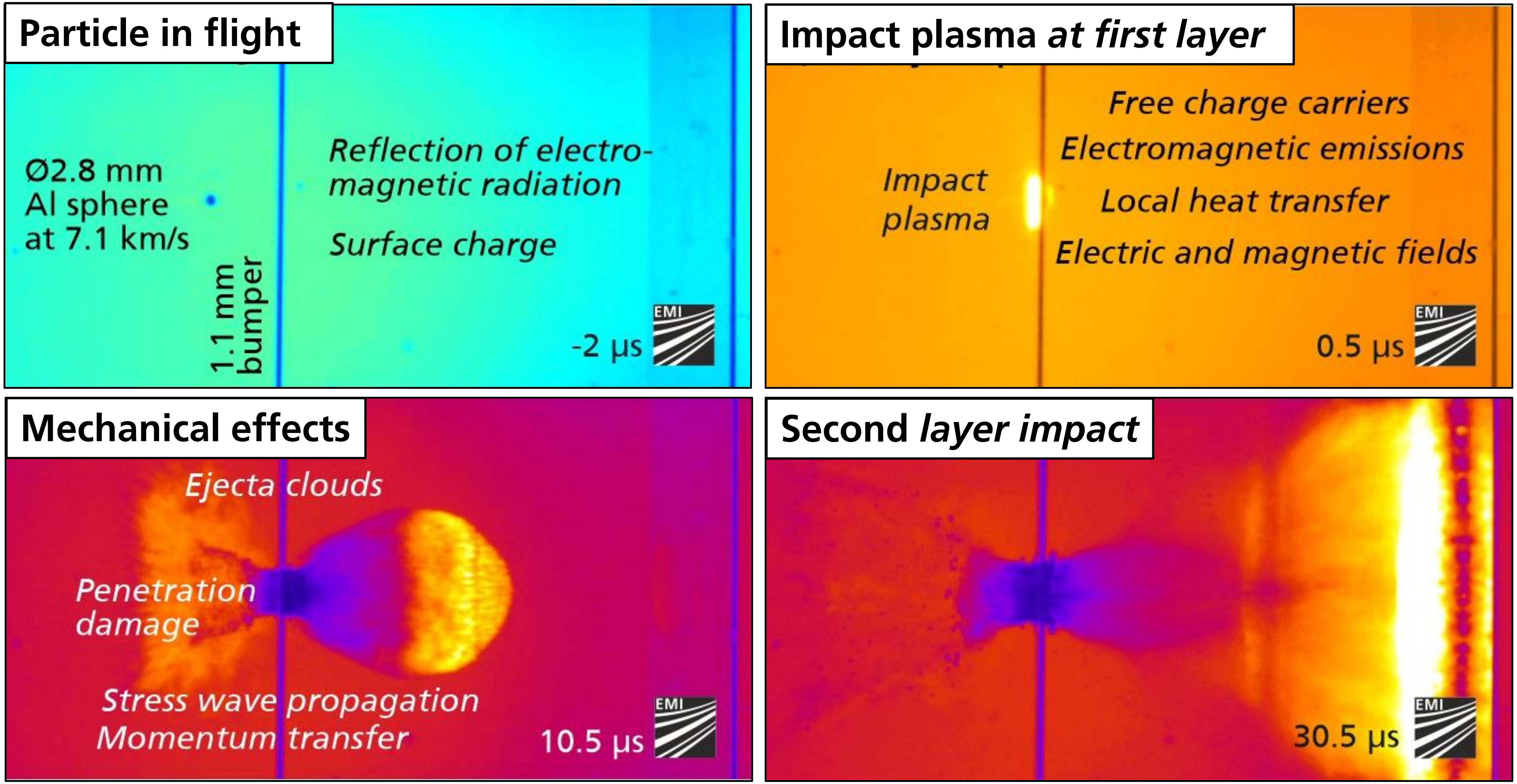
Object size $\gtrsim$ **10 millimeter**

TIRA, Fraunhofer FHR

Introduction

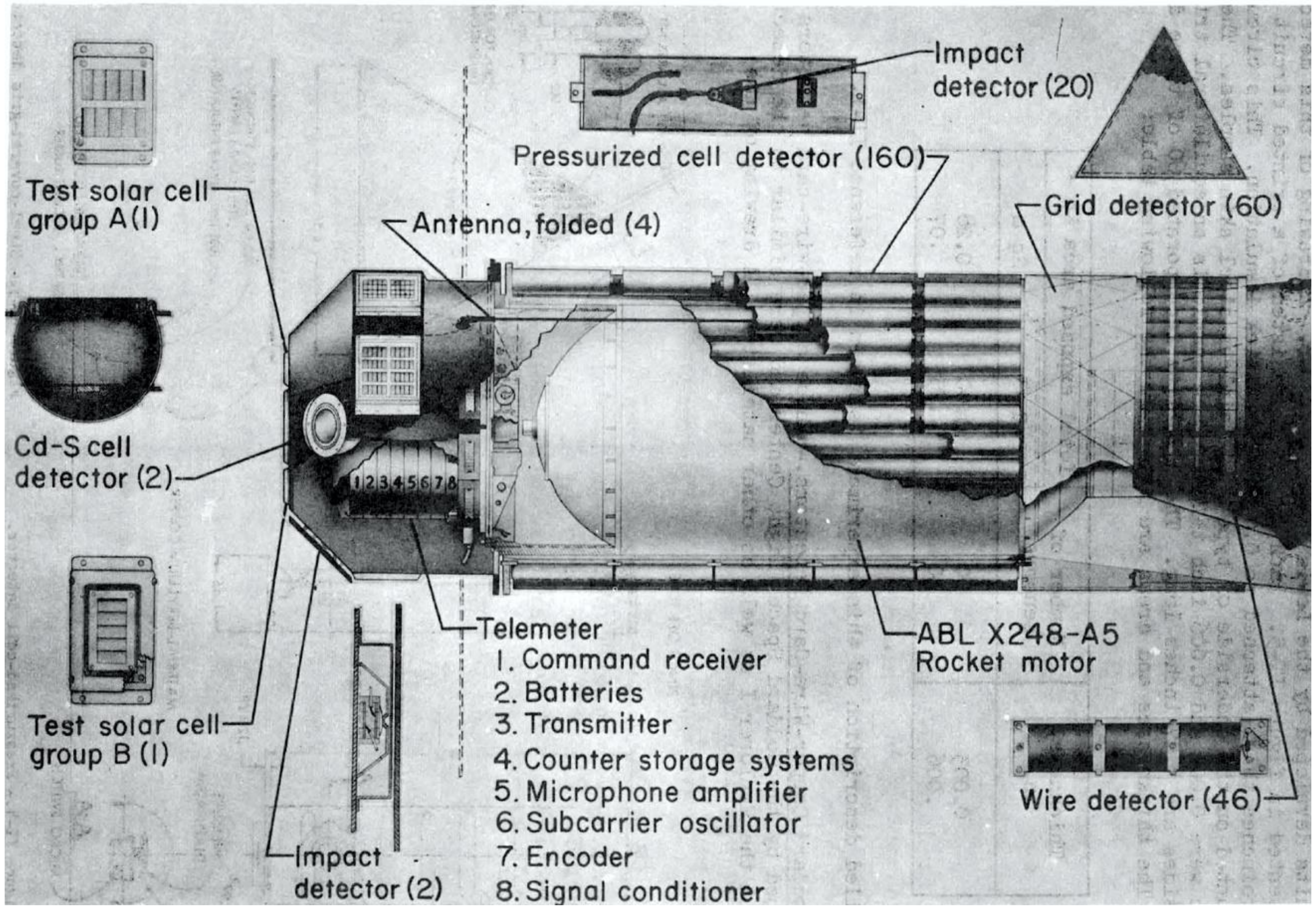
Hypervelocity impact effects for in-situ detection

Hypervelocity impact effects for in-situ detection



Hostorical view

Penetration detectors and microphones

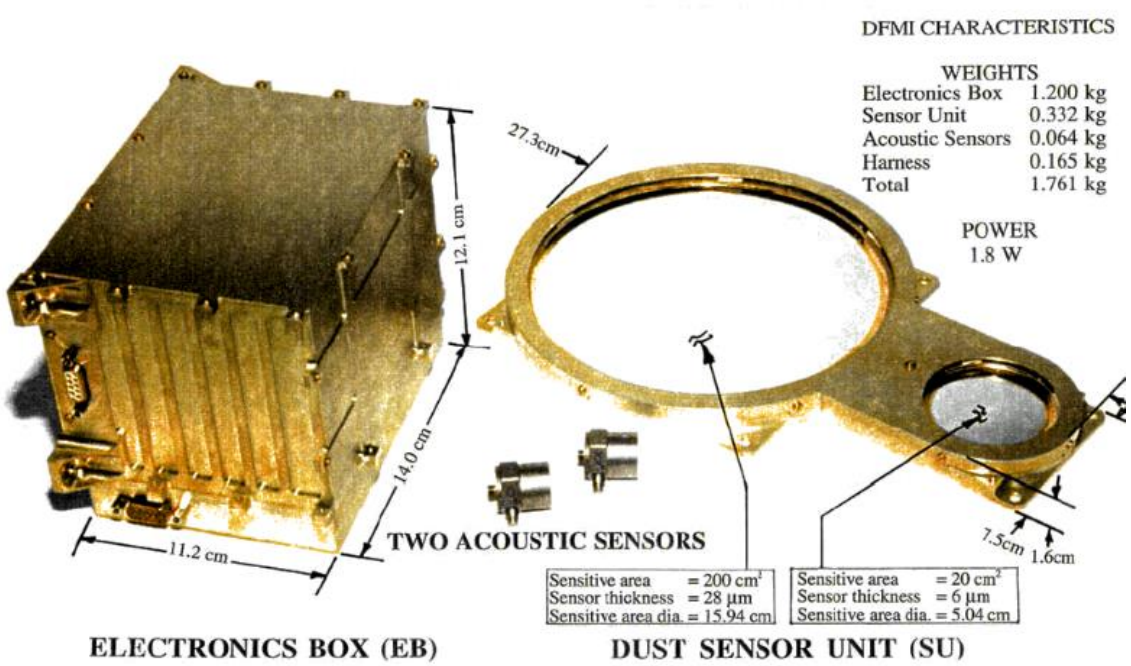


Explorer 13/16 Micrometeoroid Satellites
Richter, 1966

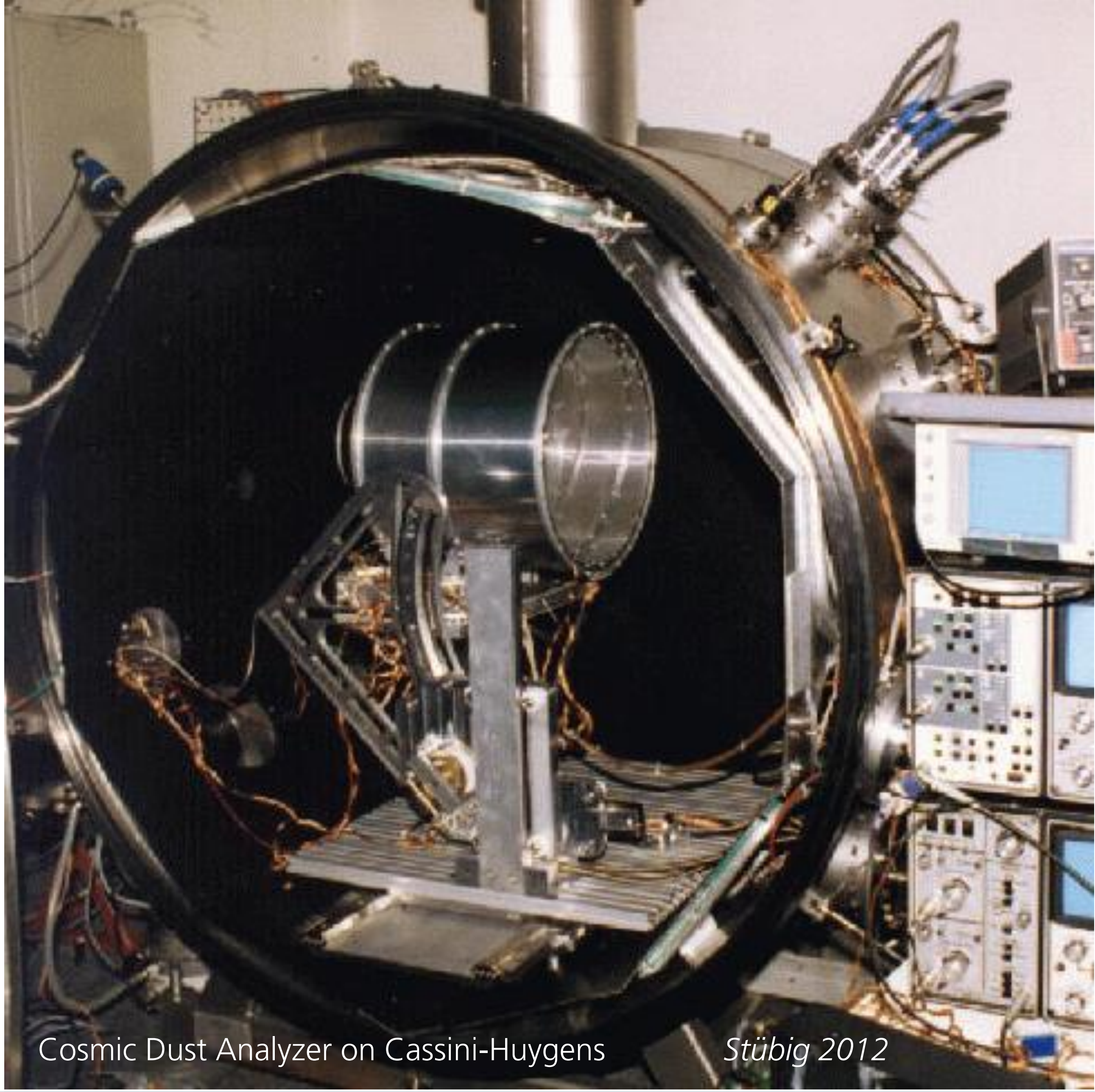
Pegasus C Capacitive discharge detector
Naumann, 1965

Cosmic dust detectors

PVDF foils & charge detectors



Stardust Dust Flux Monitor
Tuzzolino et al. 2003



Cosmic Dust Analyzer on Cassini-Huygens *Stübig 2012*

Space debris detectors

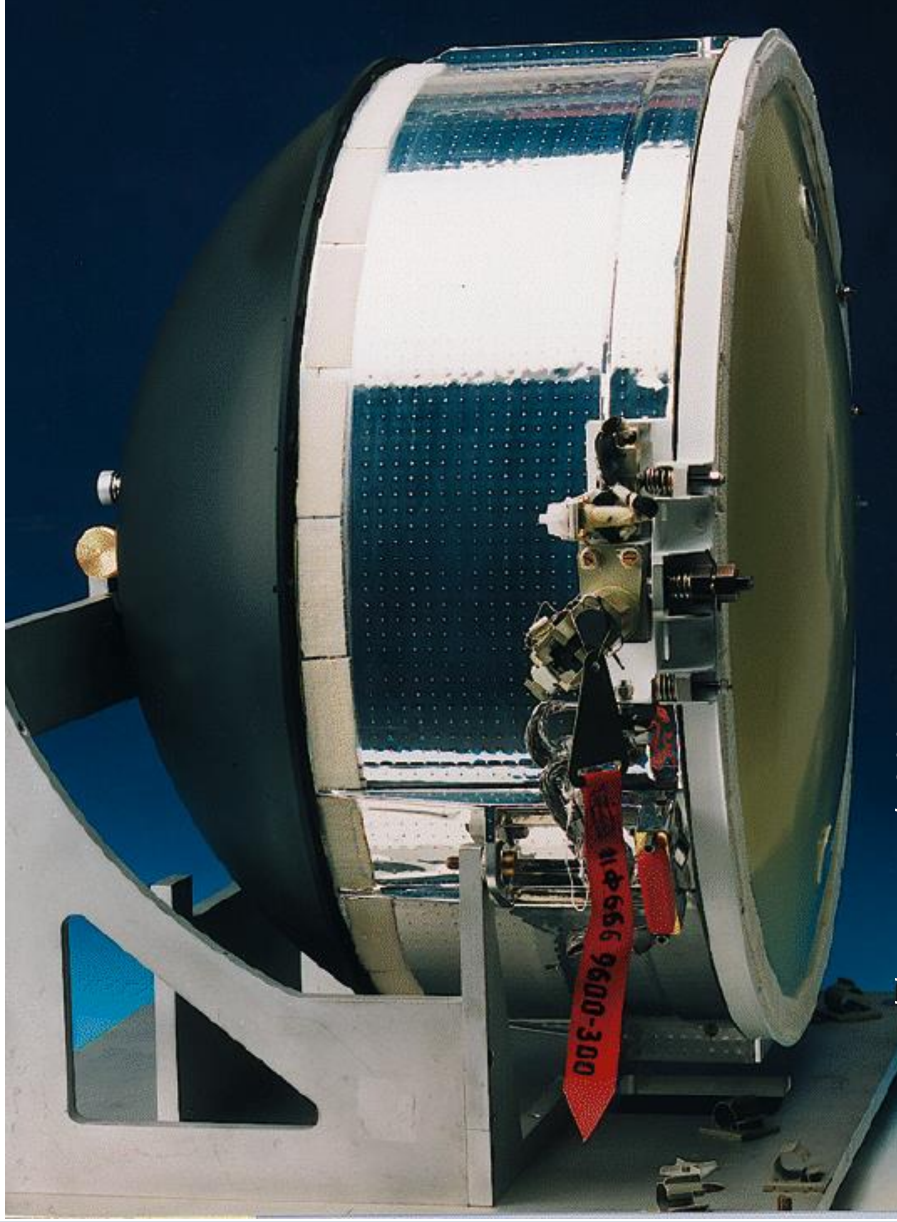
Charge detectors

ESA DEBIE/DEBIE2

Menicucci et al. 2013

➡ Noise sensitive: Failure trigger vs. real impacts: 1000:1

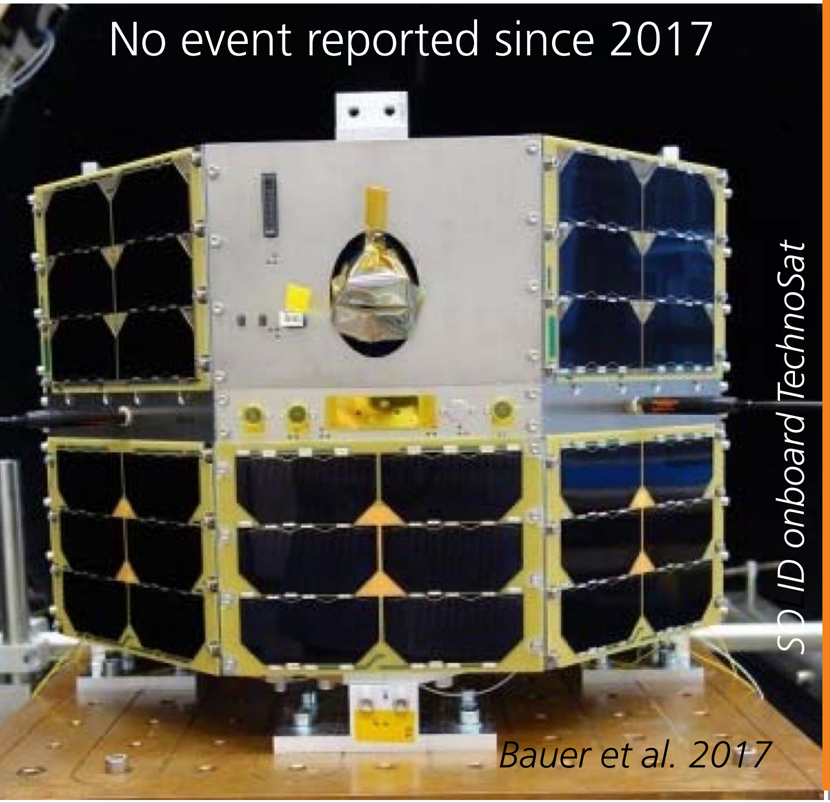
ESA GORID



Drolshagen et al. 2001

Space debris detectors
Recent missions

DLR SOLID

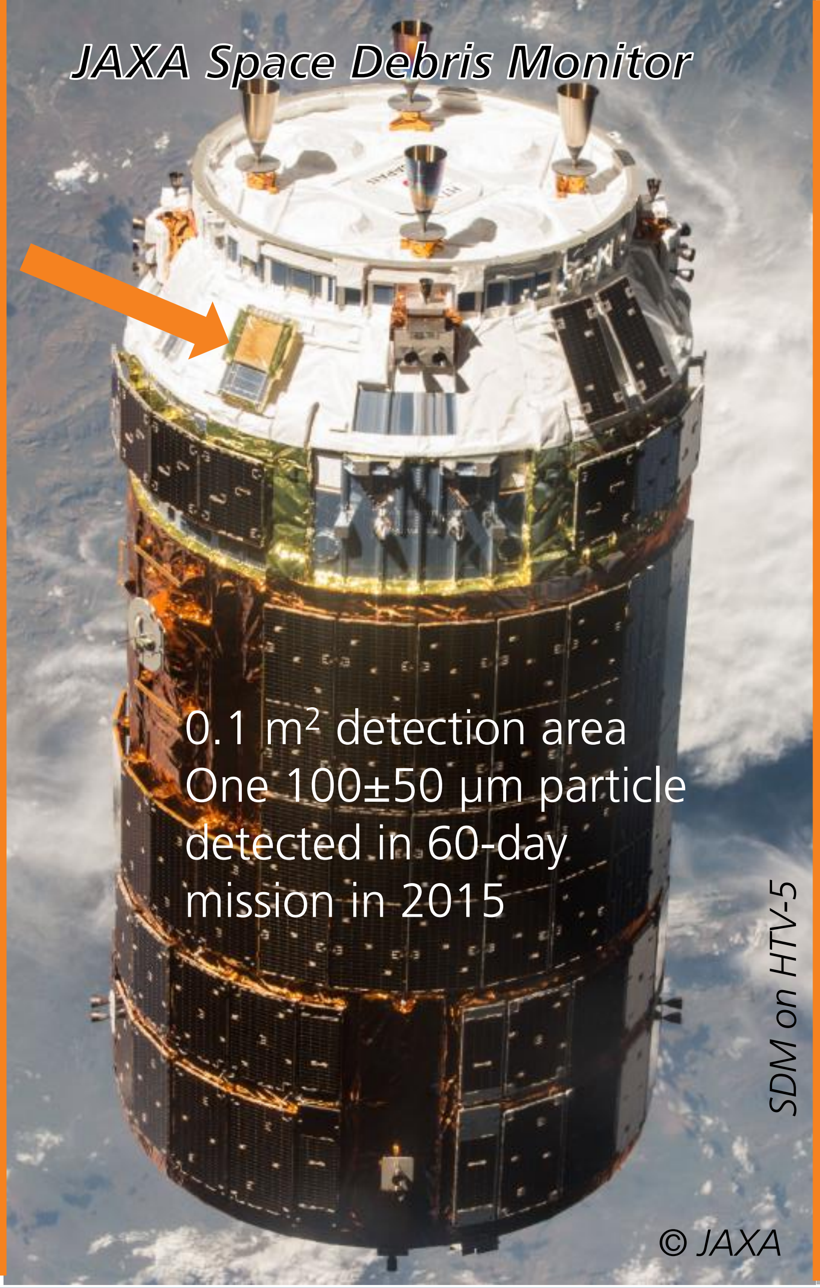


No event reported since 2017

SOLID onboard TechnoSat

Bauer et al. 2017

JAXA Space Debris Monitor



0.1 m^2 detection area
One 100±50 µm particle detected in 60-day mission in 2015

SDM on HTV-5

© JAXA

NASA Space Debris Sensor

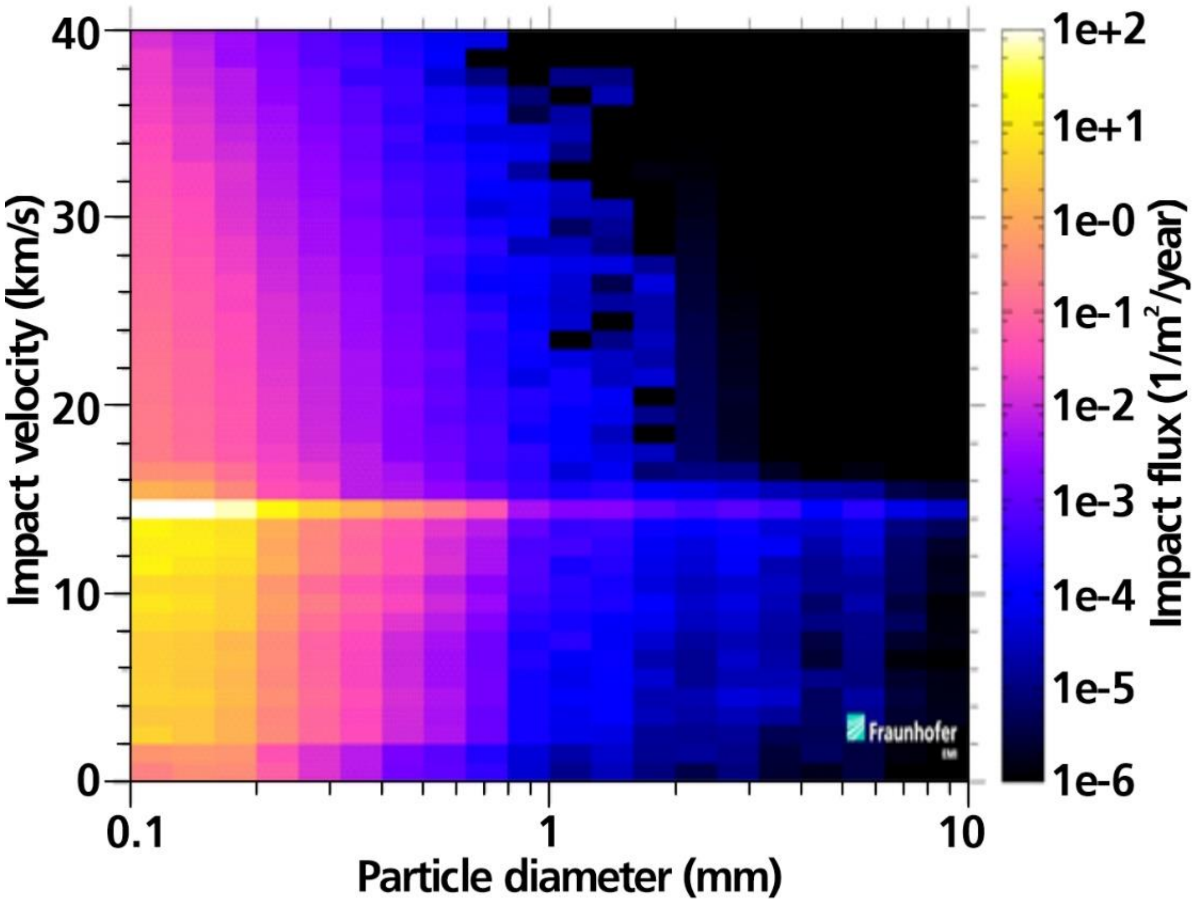
1 m^2 detection area (150 kg)
Anomaly after installation on ISS (Jan 2018), not recovered

Hamilton et al. 2017

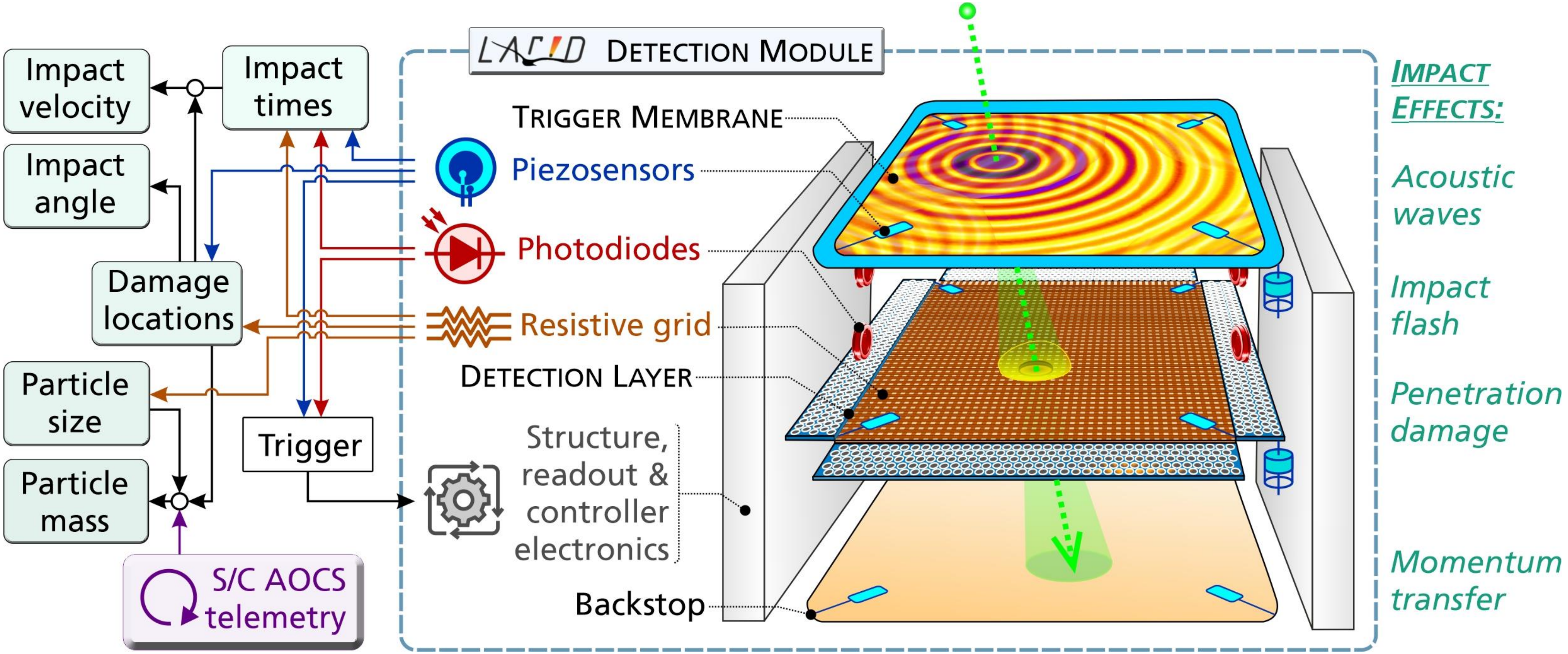
Detector requirements

- Large, scalable detection area: 1..10 m² → Modular system
- LEO, GEO & interplanetary missions
- Performance
  - Impactor size: > 0.1 .. 10 mm
  - Impact velocity: 5 .. 30 km/s
  - Impact location: 1 .. 5 cm
  - Impact angle: 0 .. 60 deg
  - efficiency/availability/purity: 90%

  → Combined sensors
- Design
  - Instrument mass: < 5 kg/m² detection area
  - Power consumption: 10 W/m² detection area



Instrument concept



1) Introduction, state-of-the-art & detector concept
2) Breadboard design, hypervelocity impact testing & verification results
3) Flight model development plan

Fraunhofer EMI

Breadboard design & hypervelocity impact testing

Summary of testing

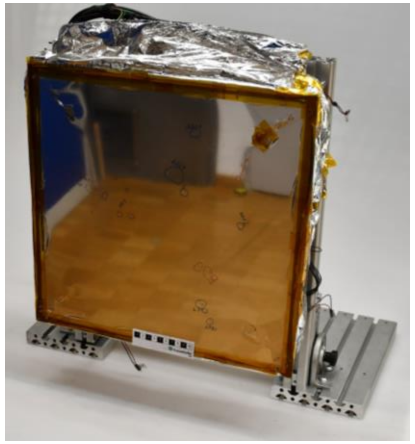
- 16 hypervelocity impact test were conducted on the detector allowing the evaluation of the different sensors to determine the impact parameters.
- 3 primary measurements were made:
  - The distance traveled inside the detector between the two measurement foils.
  - The time of flight between the foils
    - Allowing the calculation of the velocity and angle of impact
  - The size of the impactor

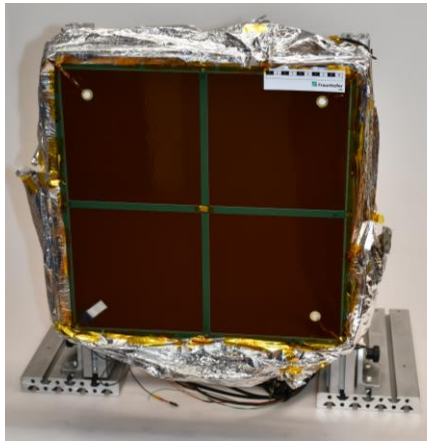
Breadboard design

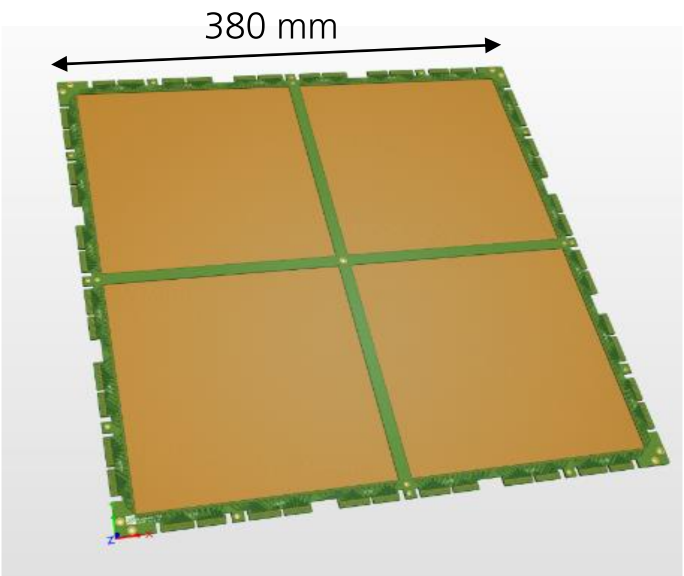
Sensors

The detector was equipped with three measurement systems based on COTS components

The design was modified (layer distance, layer configuration) during the test campaign in an iterative test approach

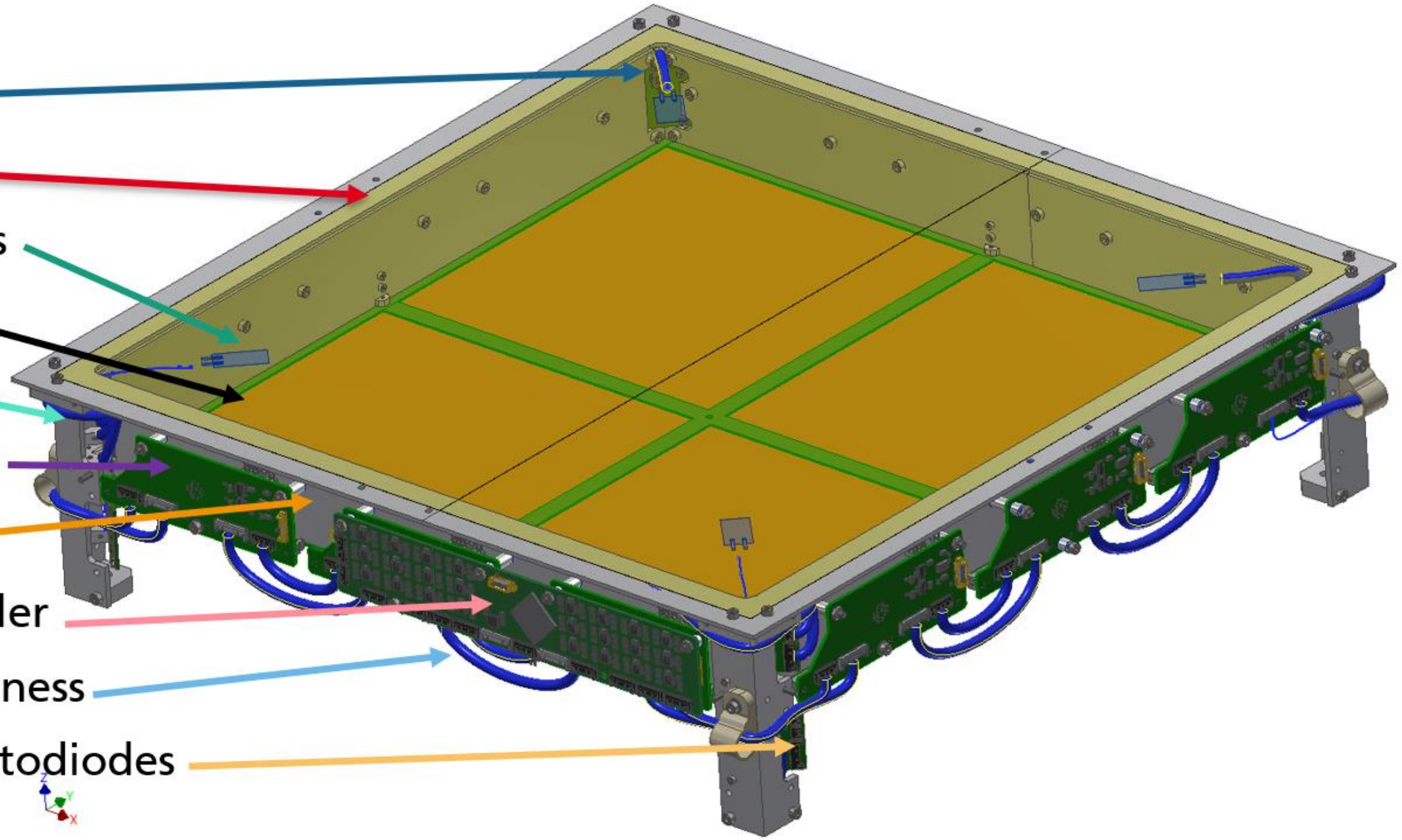




	Piezoceramic acoustic sensors placed on a thin foil (12.5 µm)
	Photodiodes (13 mm^2 detection area) arrayed around and behind the foils
 	A resistive grid that allowed for the determination of which traces have been broken The design was made based on rigid-flex PCB using standard production techniques → 3720 grid lines with each 0.2 µm width on top and rear side of a 188 µm thick layer

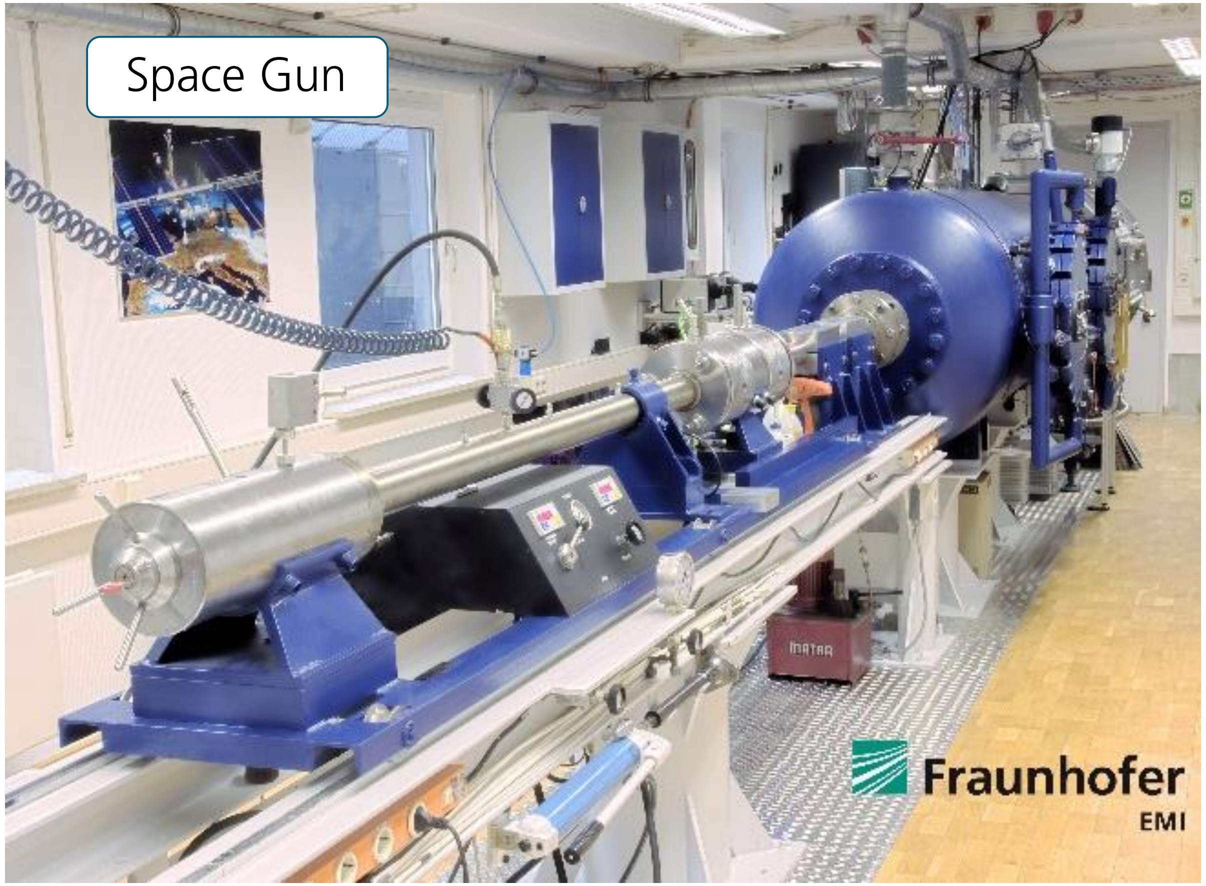
Breadboard design
Overview

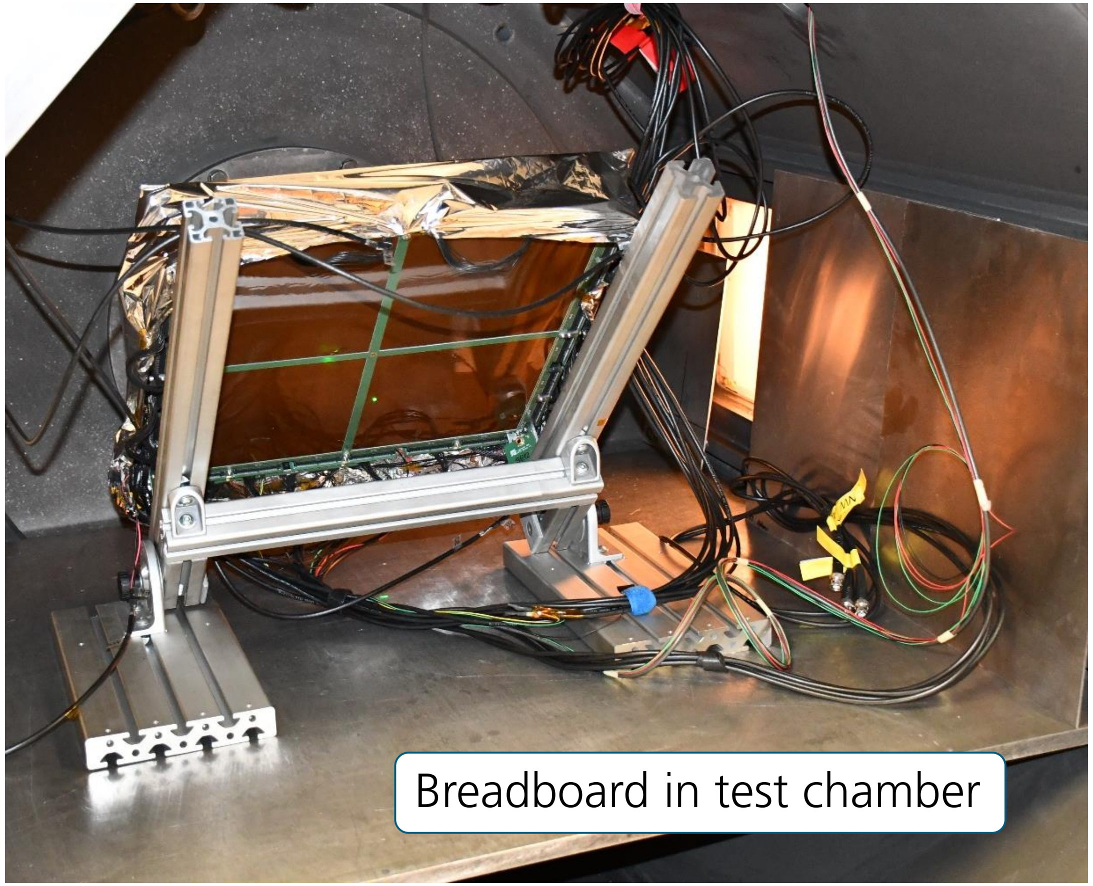
- Photodiode
- Trigger foil
- Acoustic sensors
- Resistive grid
- Angle-beam
- Readout FPGAs
- Side wall
- Module controller
- Breadboard harness
- Second foil photodiodes



Hypervelocity impact testing

Facility & setup





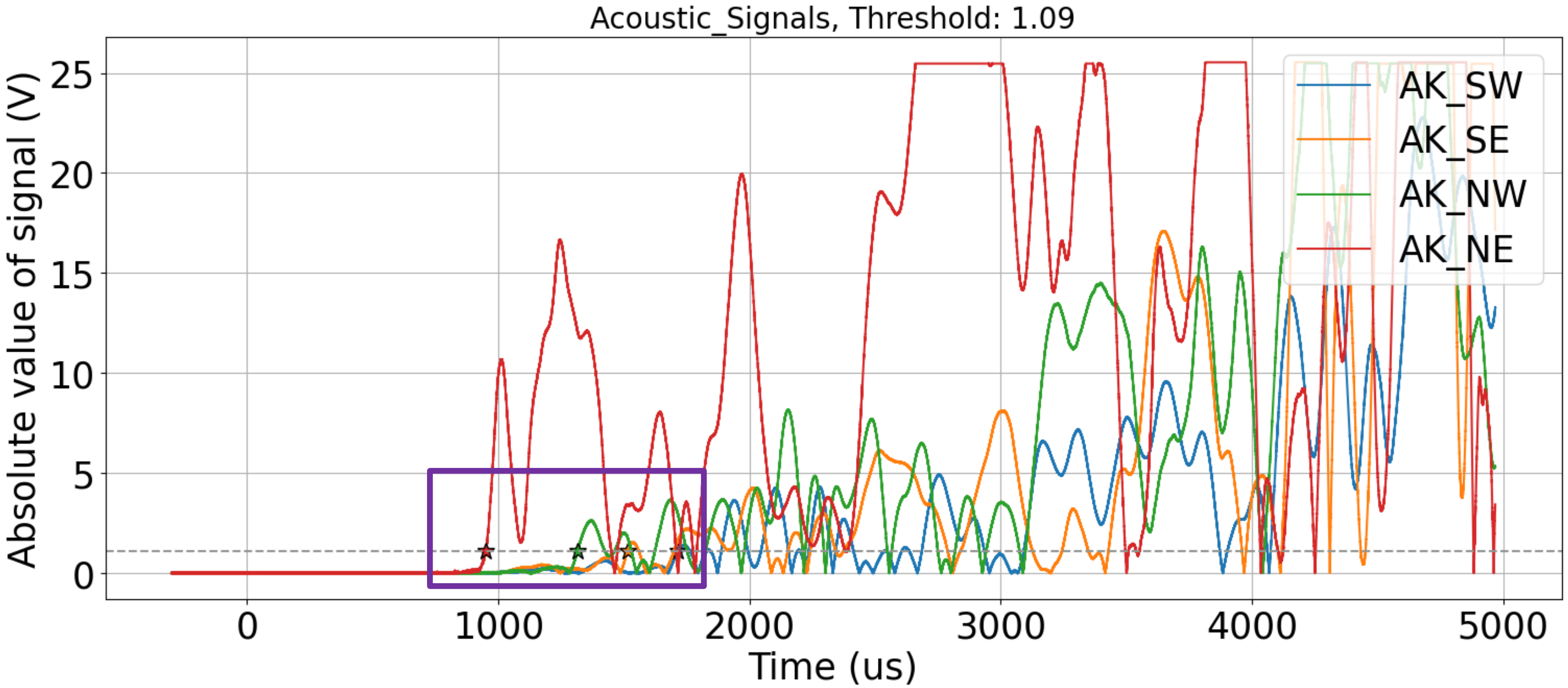
Verification results

Acoustic measurement

- The signals were recorded and a threshold chosen where the start of the wave was observed.

- With this start point the triangulation of the impact point and time of impact can be calculated.

- Determining the wave propagation in a very thin foil (6.35 µm) requires more research. Wave speed, damping and dispersion need to be measured in-situ.



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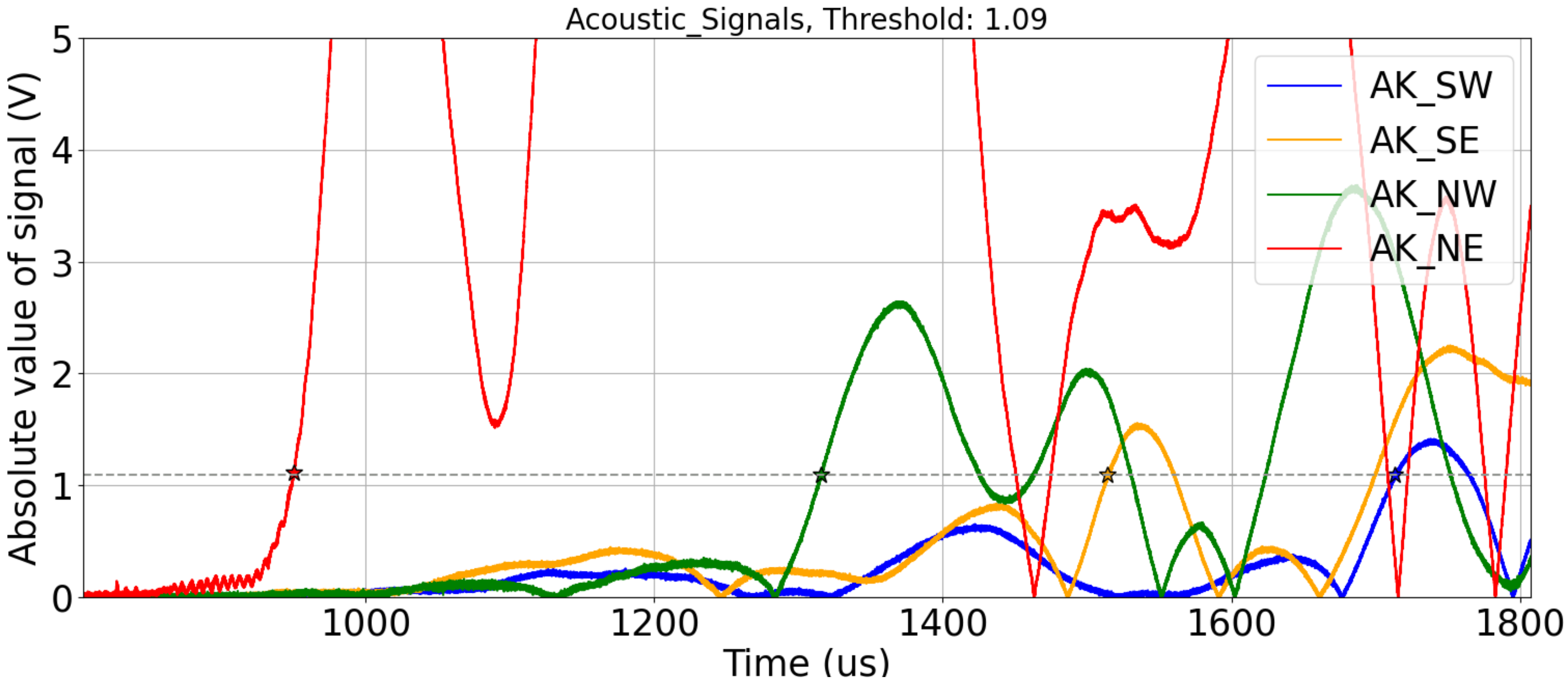
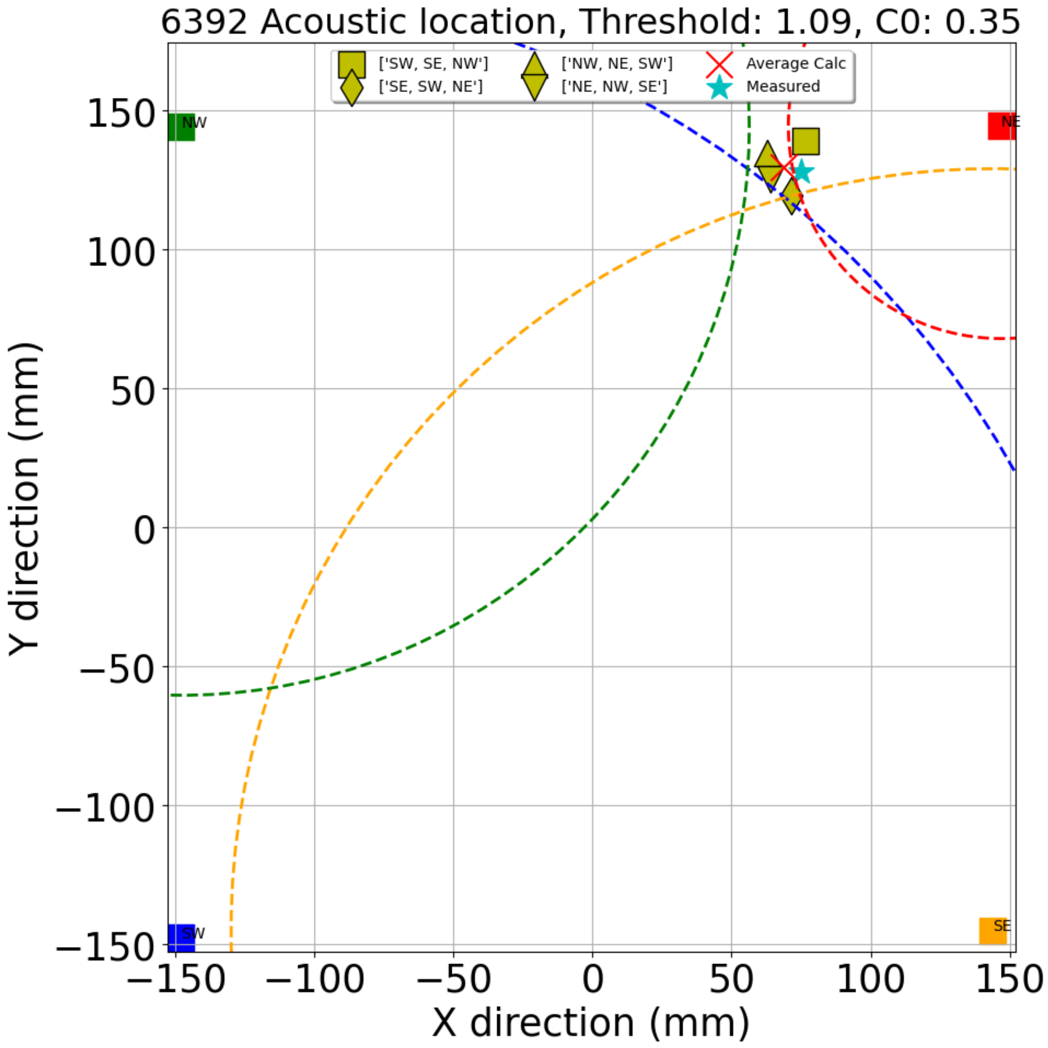


Verification results

Acoustic measurement – Determination of impact location

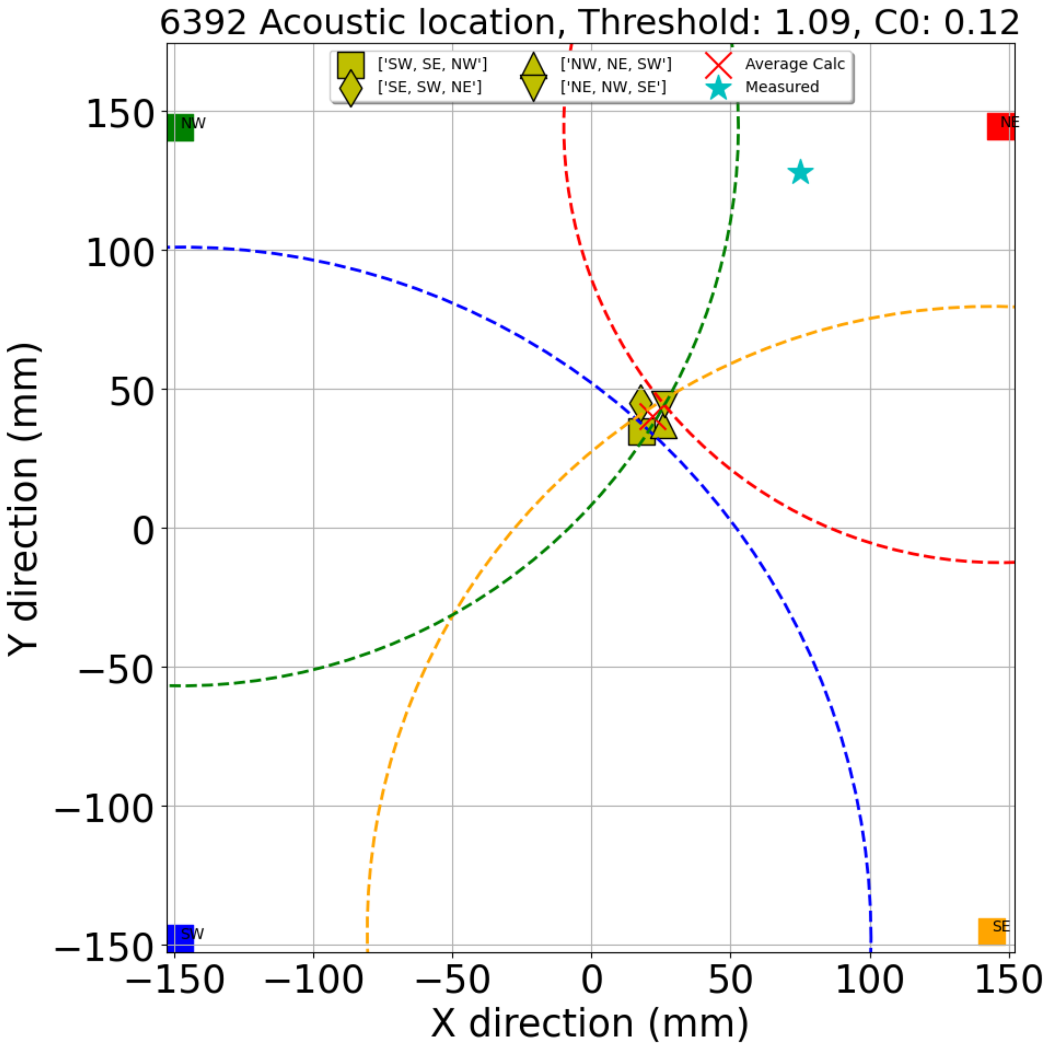
- The solution to the triangulation can give very good results getting with in 10 mm of the impact location and 50 μs of impact time.
- The circles indicate the distance the wave traveled in the time since impact and the intersection of the circles gives the location of the impact.
- That is however dependent on the wave speed used.



Verification results

Acoustic measurement – Determination of impact location

- For example using the literature value for this material gives a result that is more like this.
- The different components of the waves travel at different speeds and it depends on tension in the foil.
- A larger error on location could be minimized by increasing the distance between the foils but that increases the resources needed.



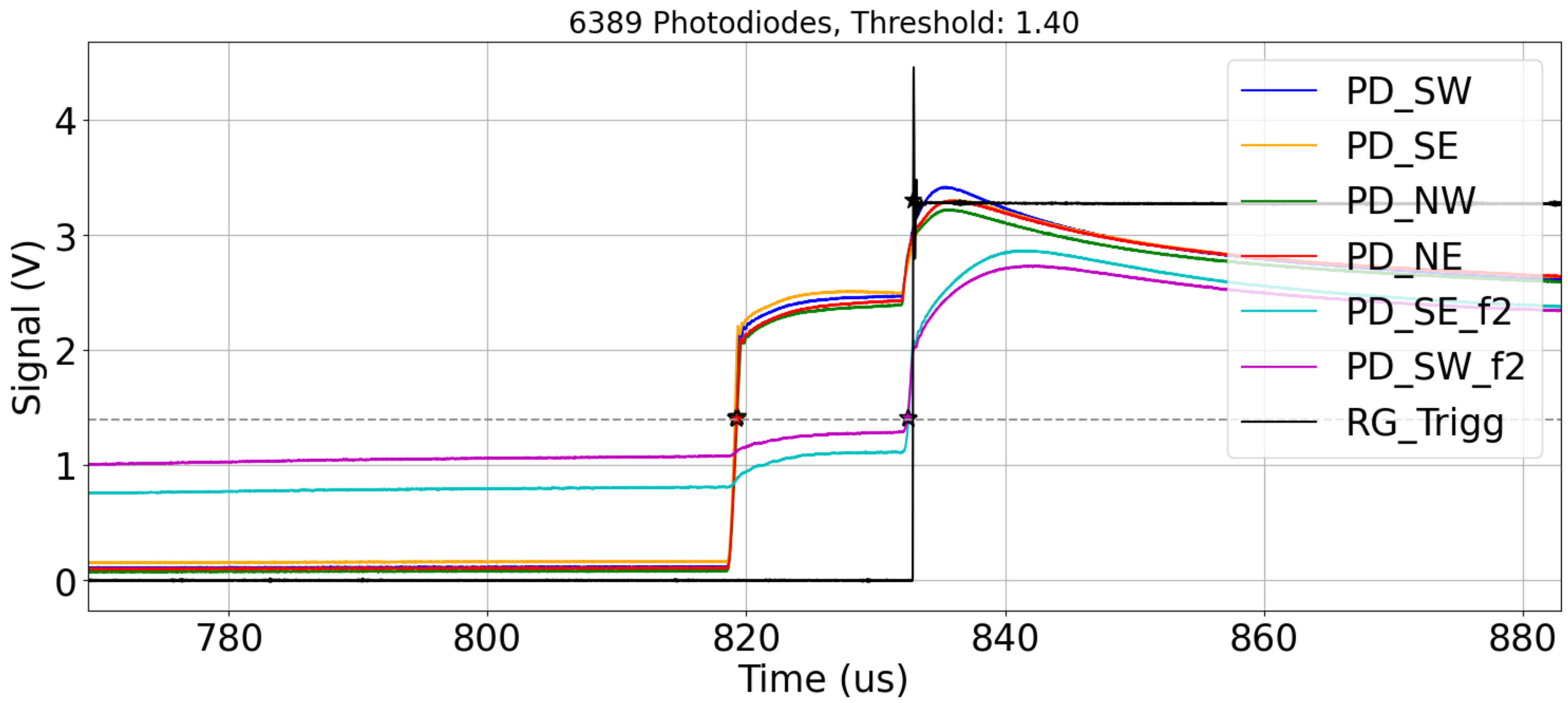
Verification results

Photodiode measurement

- The photodiodes located just behind the trigger foil see the flash from both impacts.

- The photodiodes behind the second foil _f2 also see both but less prominently. These also see the high speed video flash, hence the high starting point.

- Vacuum level during the tests was varied from 3.5e-3 mbar to 100 mBar without notable effect on flash performance.



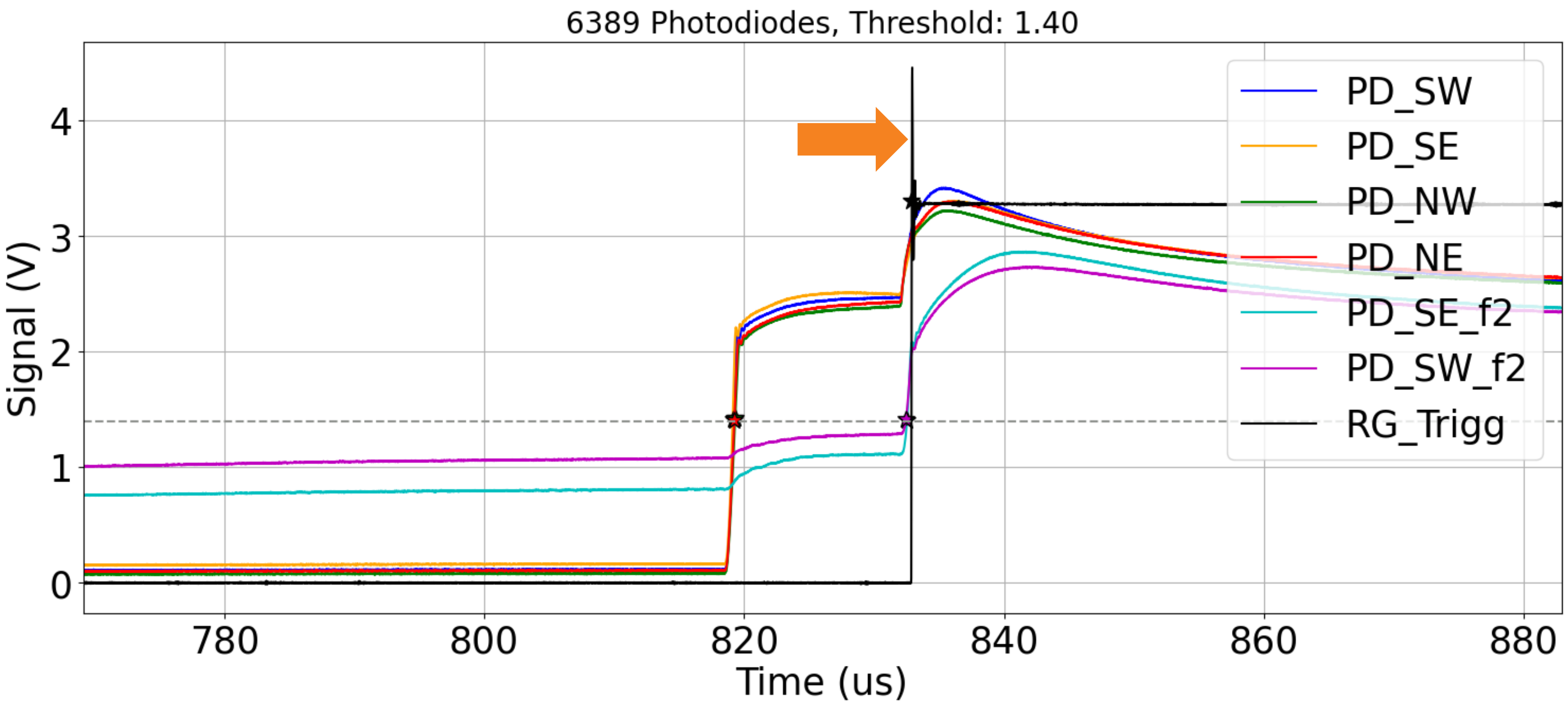
Verification results

Resistive grid - Trigger measurement

- The black line here shows the resistive trigger event.

- In this configuration the resistive grid is the second foil and shows when the first trace is broken.

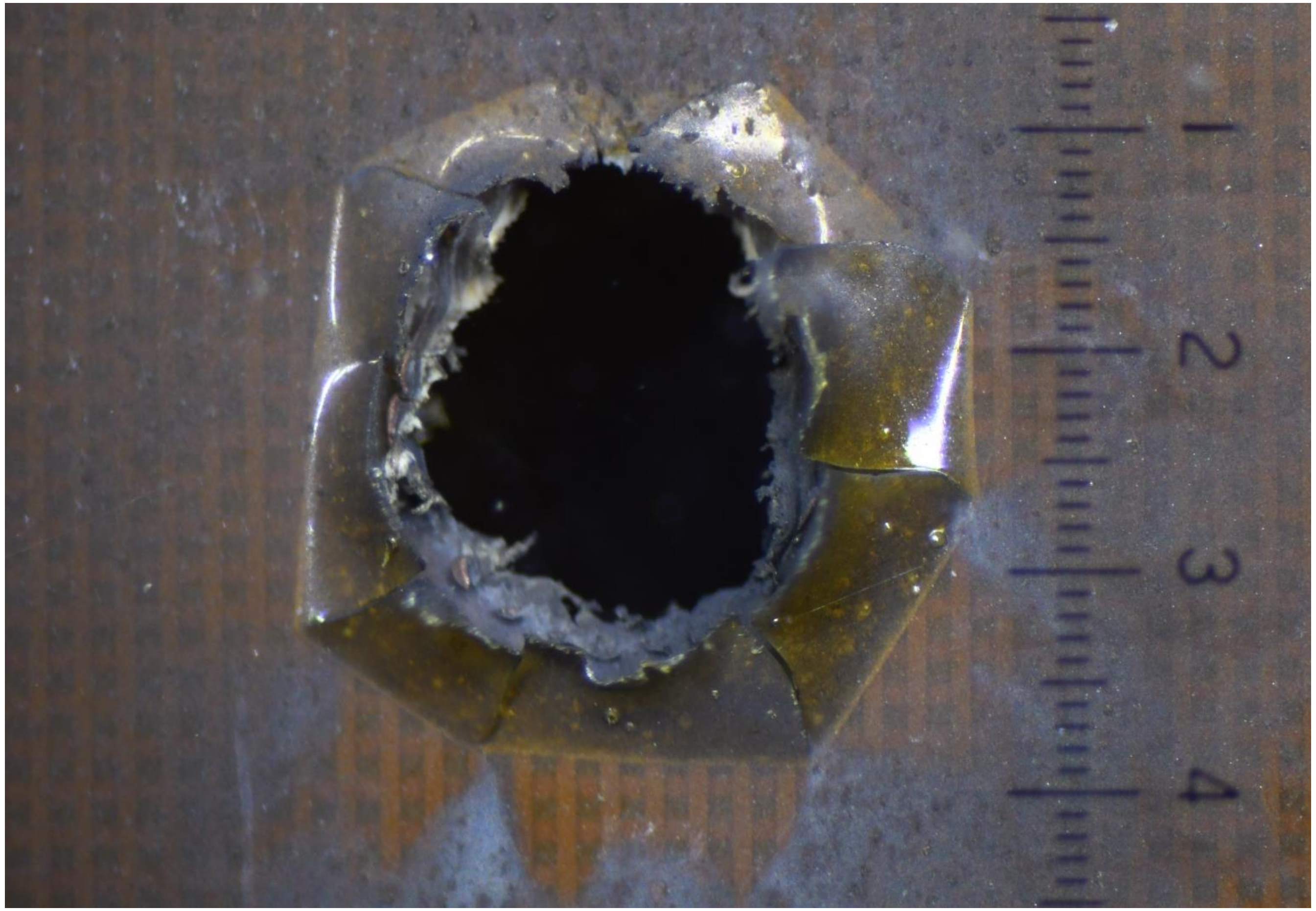
- Very good agreement with the second flash from the photo-diodes gives extra confidence that an impact event occurred and that the measurement is correct.



Verification results

Resistive grid - Determination of impact location and damage size

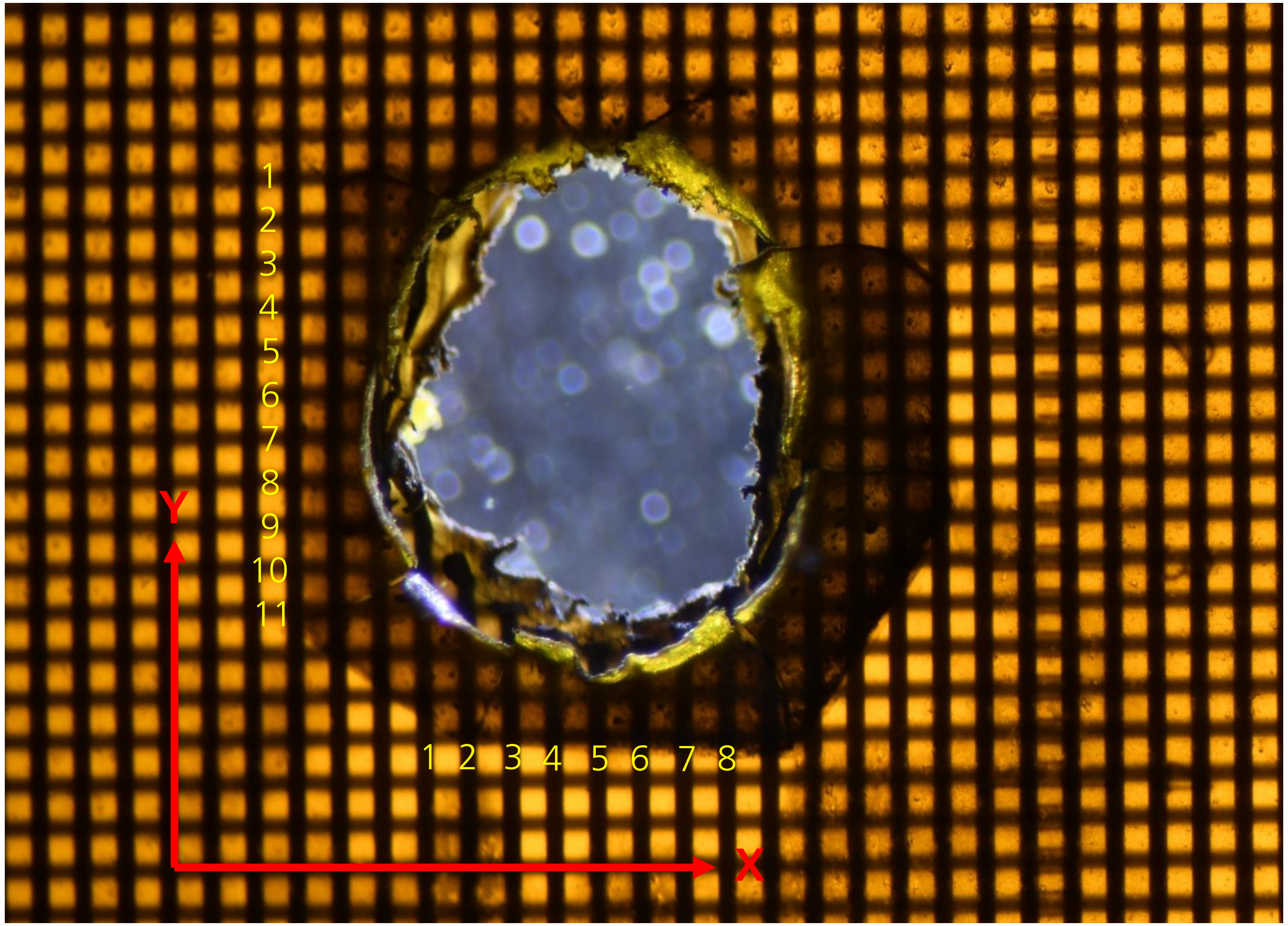
- The 3720 traces on the resistive grid give the location of which trace was broken to the 0.2 mm precision, determined by the spacing of the traces.
- Seen here is a microscope image of a **1.9 mm** hole left by a **Ø 0.8 mm** Aluminum sphere impacting at **6.02 km/s** at **45°** with the resistive grid used as the first layer.
- The damage hole is slightly elongated due to the angled impact.



Verification results

Resistive grid - Determination of impact location and damage size

- Transmission microscope image.
- Hole size from resistive grid read out with 8 traces in X and 11 traces in Y broken.
- Traces are surprisingly robust. The signal remains until they are completely broken. For example what would be the ninth broken trace on the bottom right is still intact despite being bent.



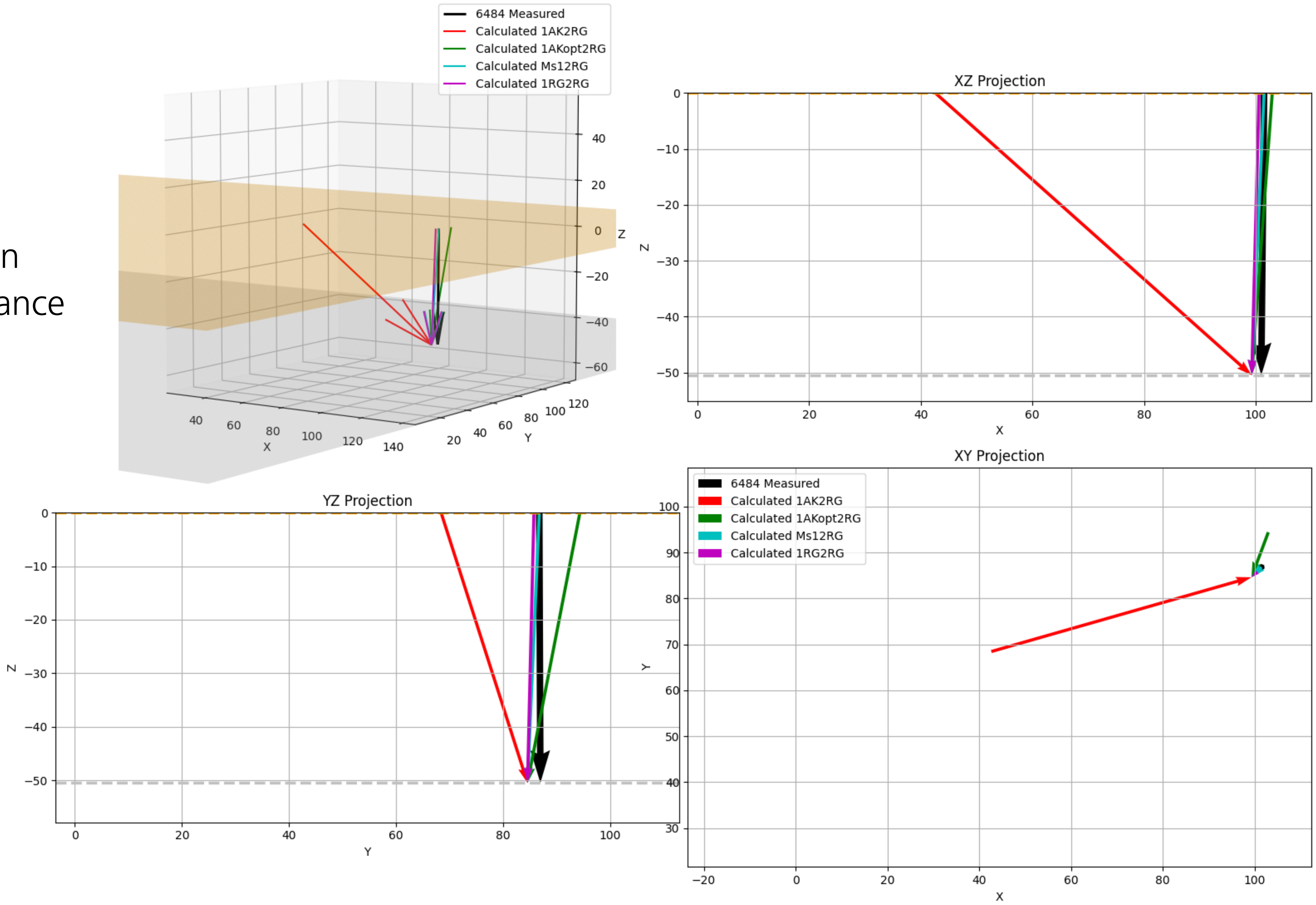
Verification results

Distance Vectors

- With the resistive grid location calculation the complete distance set of information can be visualized.

- Here we see a multi-view look at the vectors calculated representing the path the projectile took through the detector.

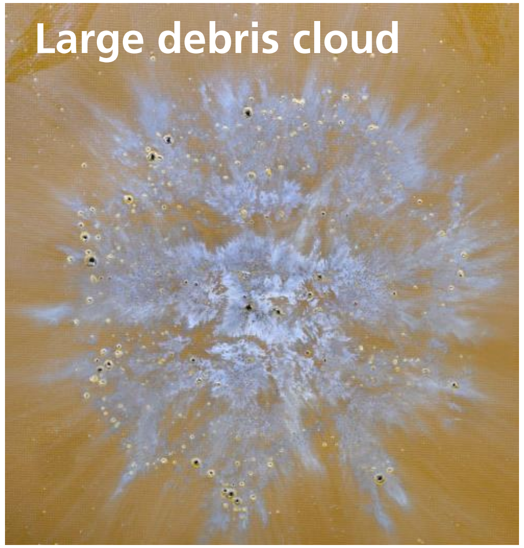
- This is a two resistive grid setup with acoustic sensors on the top resistive grid.



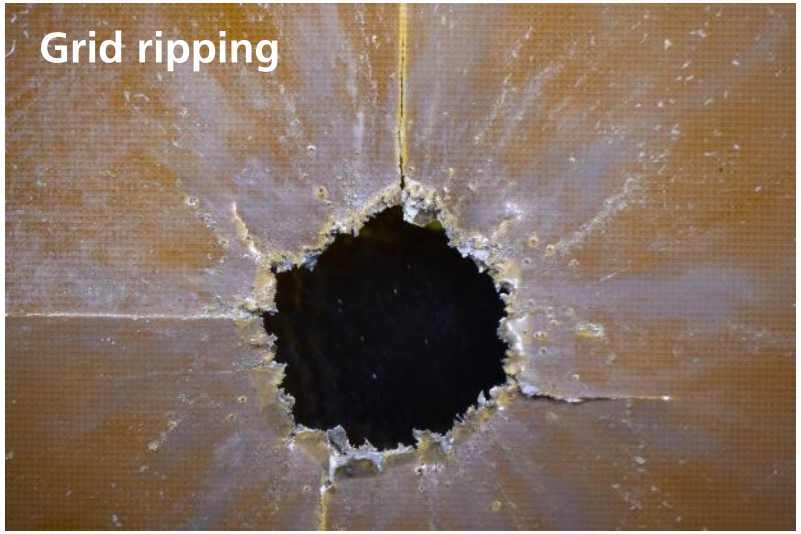
Verification results

Two Resistive grid setup fragment patters on second layer

- The particles fragmented after penetrating the first Resistive grid (188 µm thick).
- Different patterns seen depending on distance between foils and angle of impact
- The best solution is to limit the fragmentation by making the foil thinner.



1.0 mm AL @ 6.54 km/s at 0°
Distance between grids 50 mm



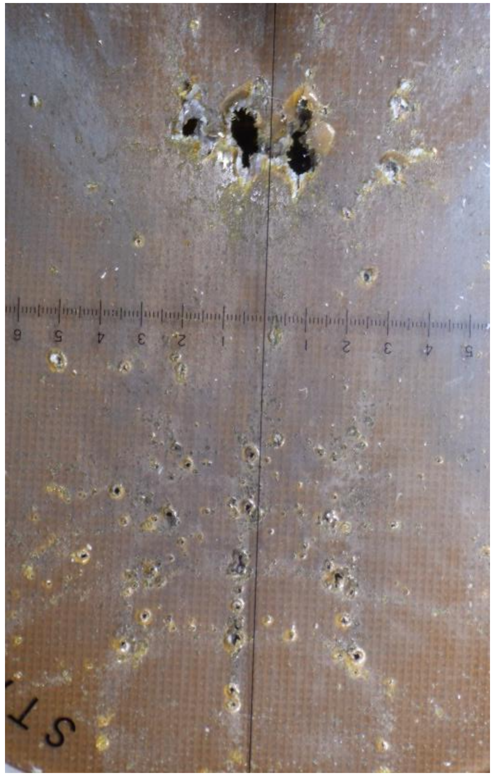
1.0 mm AL @ 6.54 km/s at 0°
Distance between grids 10 mm

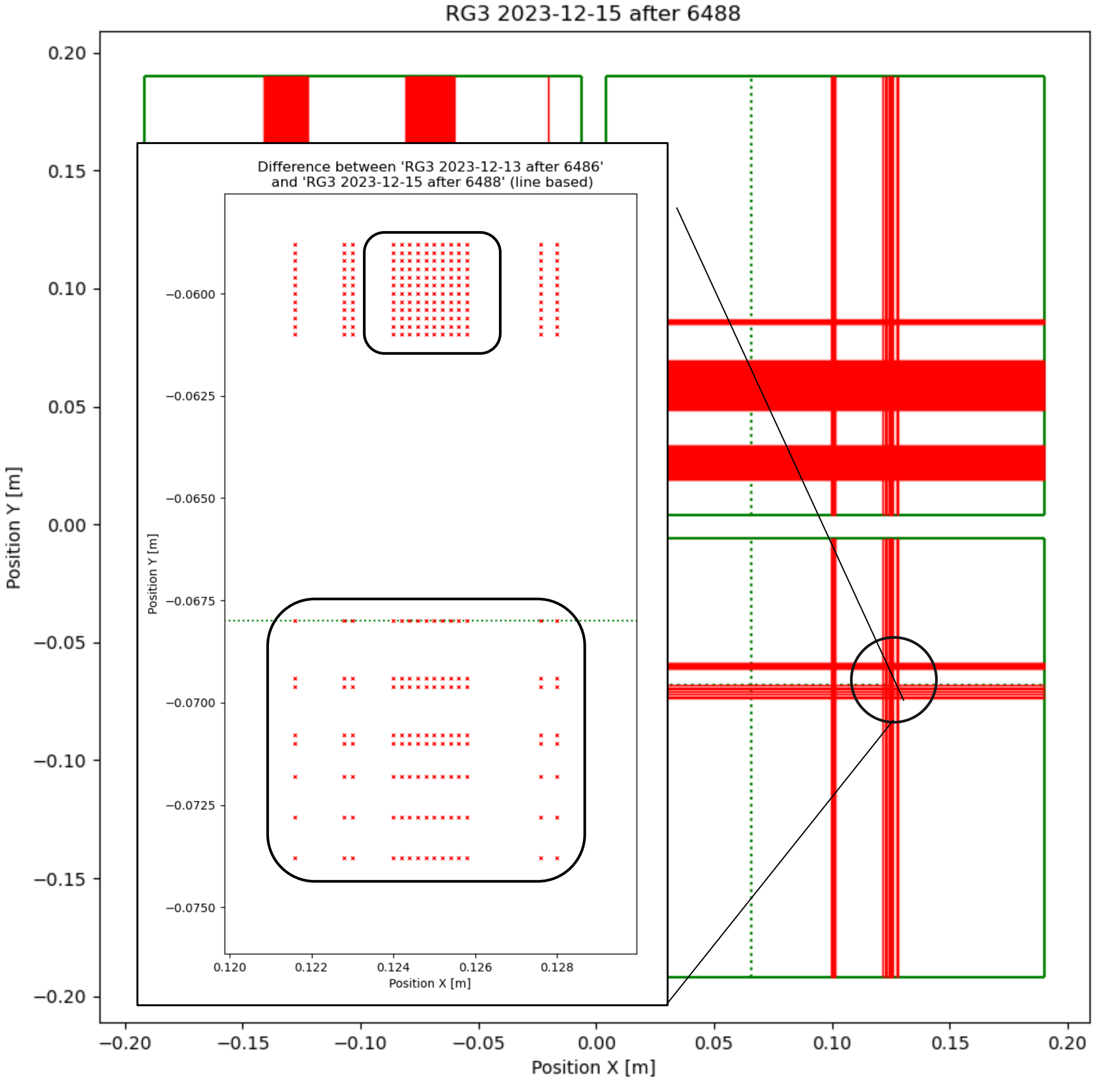
0.8 mm AL @ 6.02 km/s at 45° Distance between grids 10 mm

Verification results

Resistive grid readout example (RG3: phase 4)

- 6488 Second foil
- Ø 0.8 mm Al @ 6.02 km/s at 45° -- Distance between grids 10 mm
- Two smaller damaged area measured
- Resistive grid damage seen in two sections dense hole at 1.8 x 2.2 mm and 7.5 mm gap then a more spread out at section 6.4 x 5.8 mm.

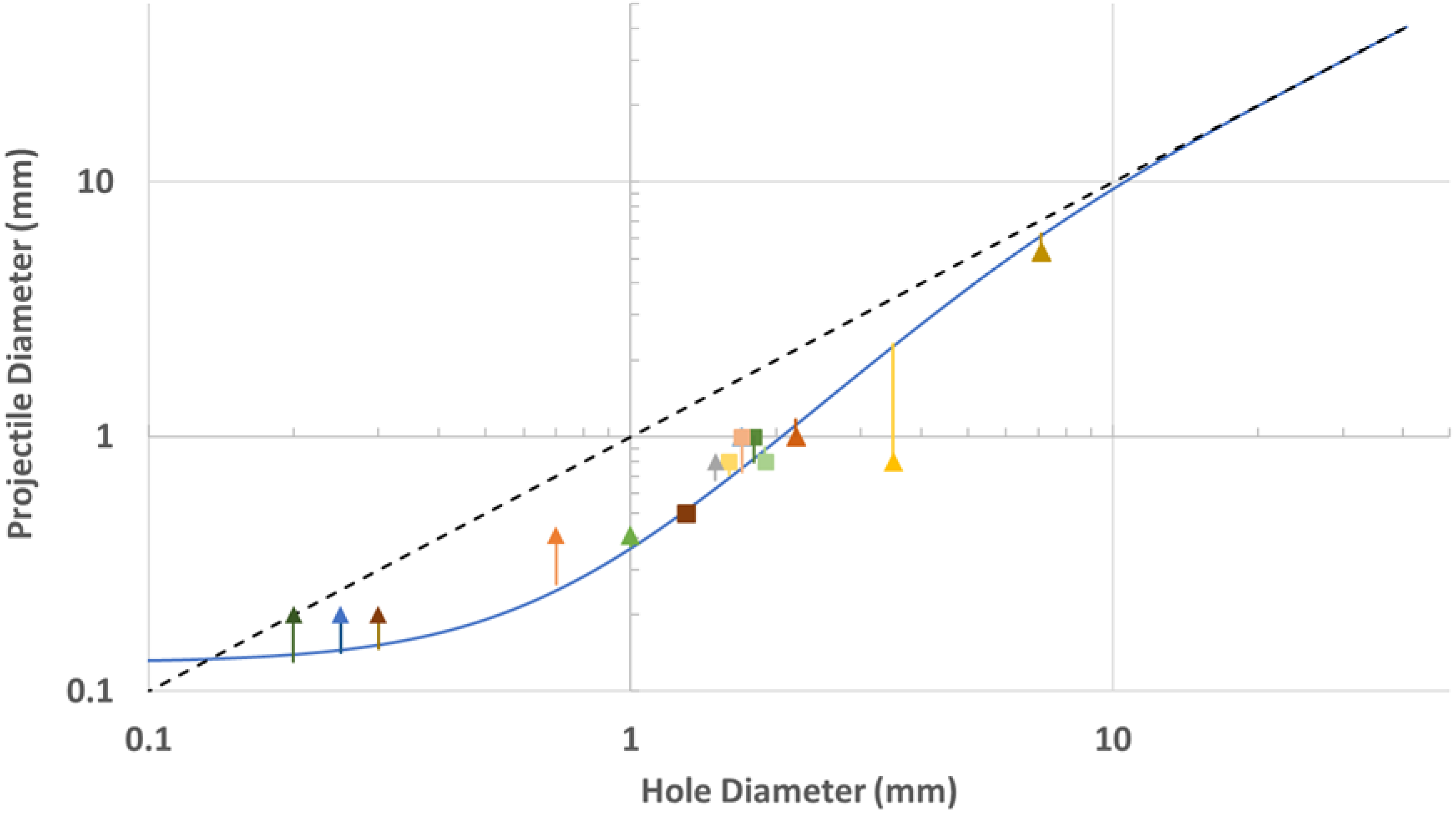




Detector performance evaluation

Particle size

- The resistive grid gives the size of the hole created by the impactor, not the size of the impactor it self.
- Using the model developed by Gardner et. al. the size of the spherical impactor can be estimated based on the material properties of the foil and the impactor velocity and density.
- The data measure showed a good fit to the model created for the resistive grid.

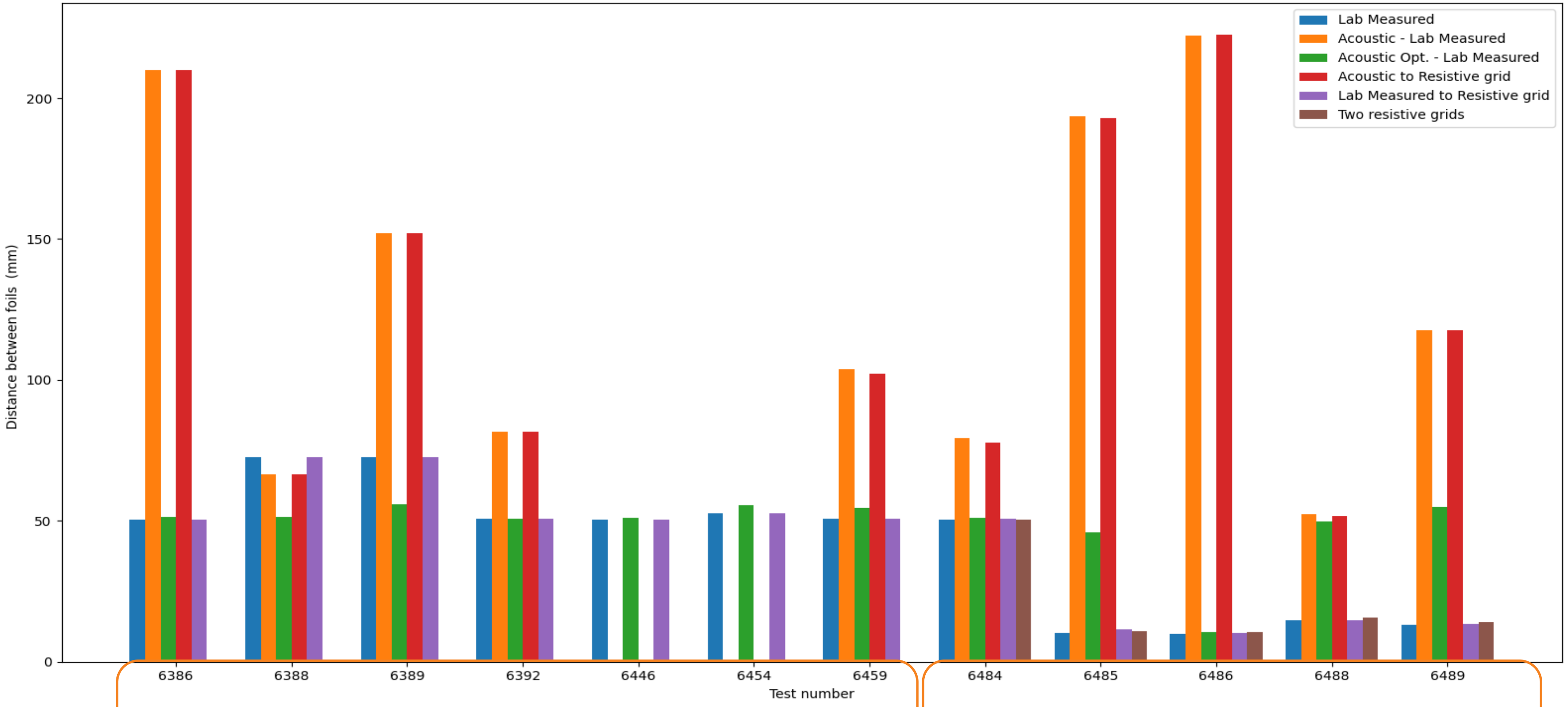


Detector performance evaluation

Trajectory - Distance

Diameter Material	0.41 Alu	0.41 Alu	0.8 Alu	0.8 Alu	1.0 Alu	1.0 Ceramic	5.3 Plastic	1.0 Alu	1.0 Alu	0.8 Alu	0.8 Alu	0.5 Alu
Velocity	6.08	5.77	5.52	5.96	5.99	5.7	5.92	6.54	6.54	6.02	6.02	6.96
Angle	0	45	45	0	0	0	0	0	0	0	45	45

- Selected tests showing the performance of the different sensors to determine the distance.
- Gaps represent a sensor test that did not produce viable data for that test.
- Acoustic Opt. needs more development.
- Resistive grid performed very well consistently. Two grids providing a complete distance measurement.



One trigger foil one resistive grid

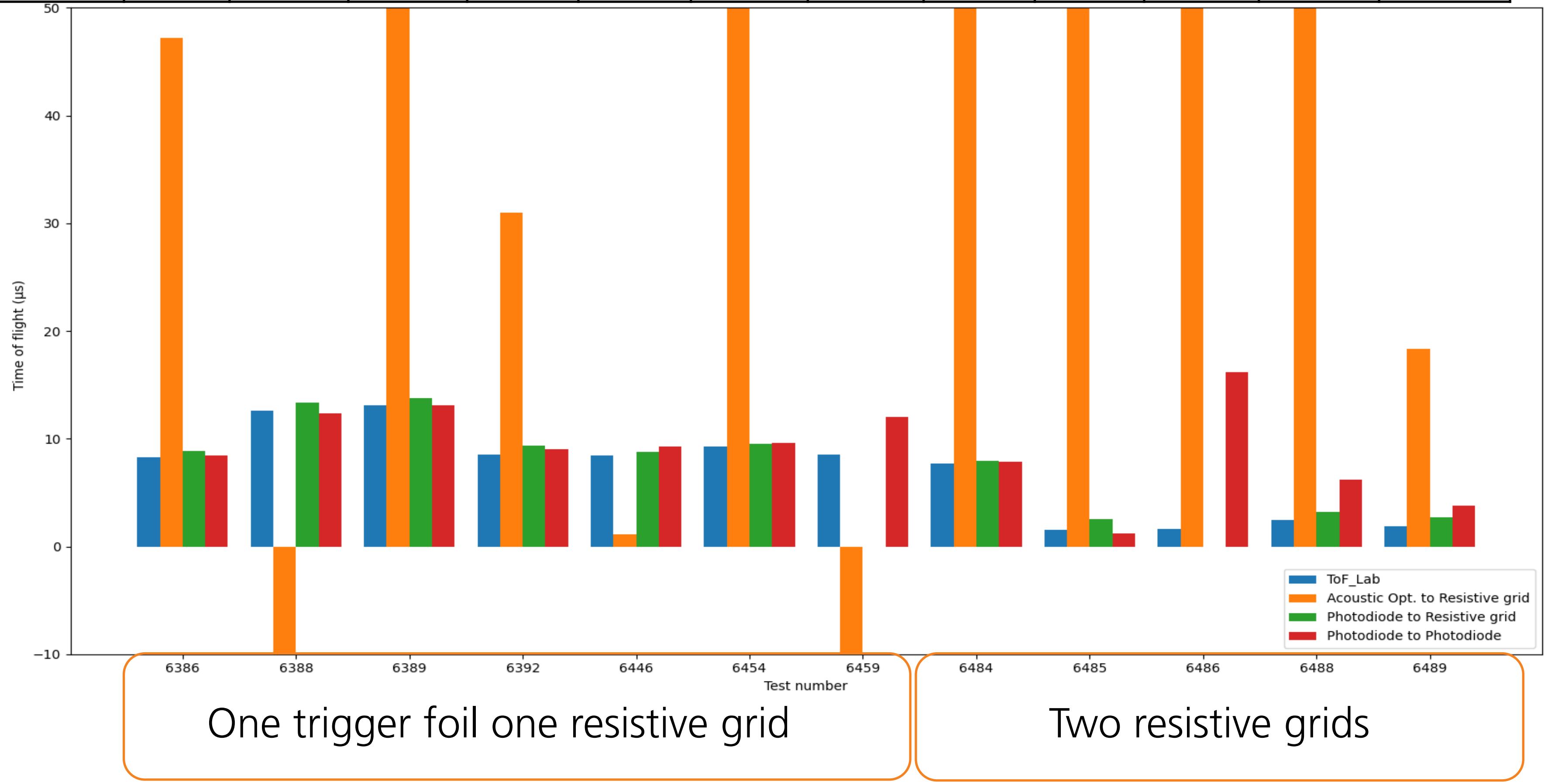
Two resistive grids

Detector performance evaluation

Trajectory - Time of flight

Diameter Material	0.41 Alu	0.41 Alu	0.8 Alu	0.8 Alu	1.0 Alu	1.0 Ceramic	5.3 Plastic	1.0 Alu	1.0 Alu	0.8 Alu	0.8 Alu	0.5 Alu
Velocity	6.08	5.77	5.52	5.96	5.99	5.7	5.92	6.54	6.54	6.02	6.02	6.96
Angle	0	45	45	0	0	0	0	0	0	0	45	45

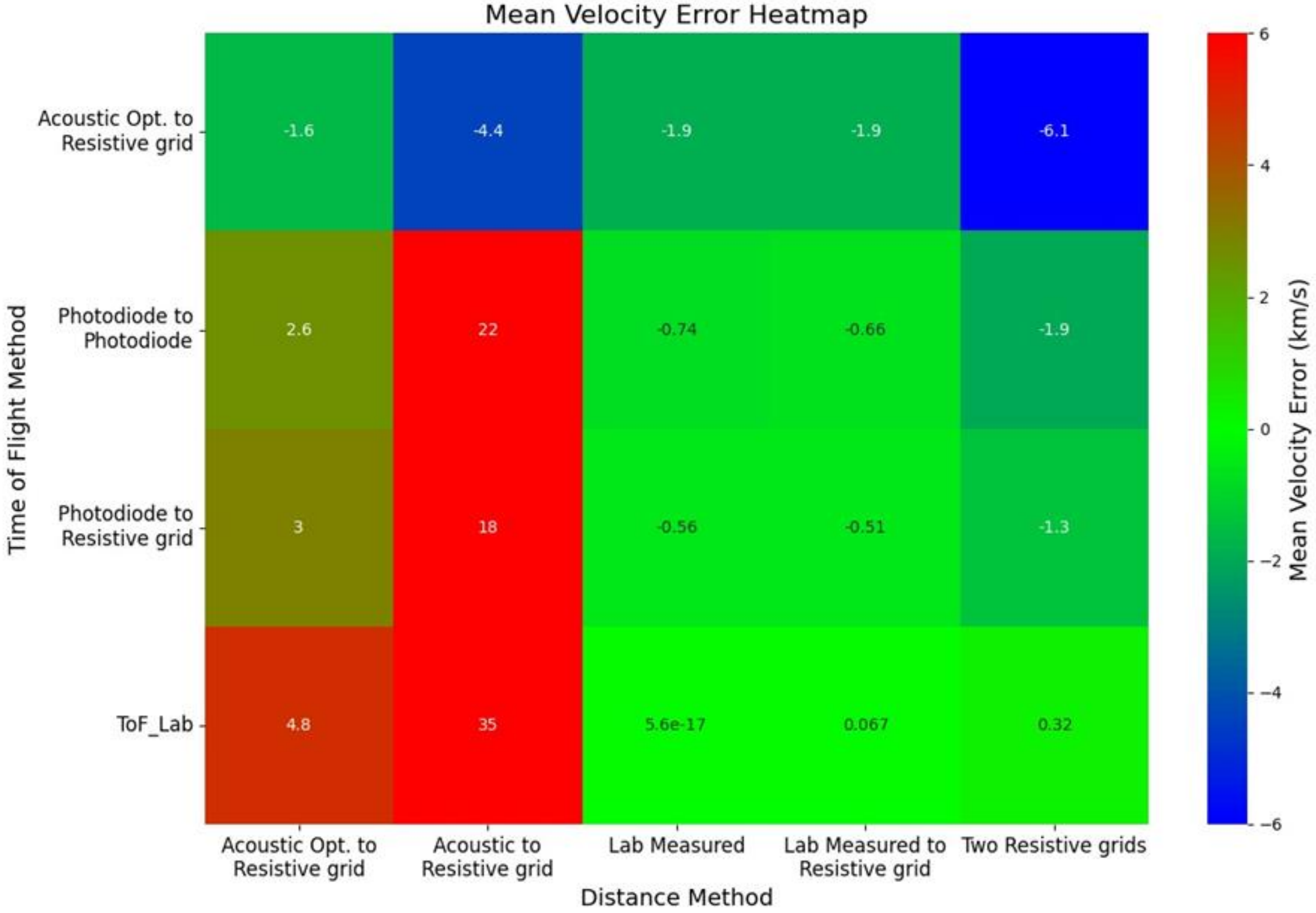
- Sensor performance to determine the time of flight.
- Gaps represent a sensor test that did not produce viable data for that test.
- The acoustic data for the time of flight is significantly worse than for distance.
- Photodiodes very consistent for the trigger foil tests.
- Resistive grid trigger very accurate for all tests.



Detector performance evaluation

Impact velocity

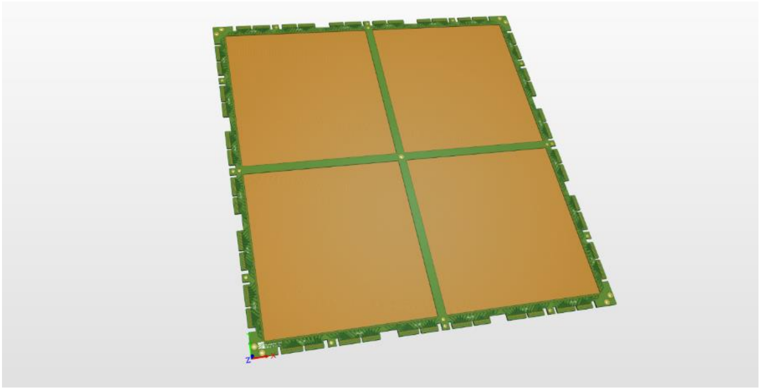
- Taking the distance divided by the time to get the velocity



Detector performance evaluation

Conclusions

- The breadboard in its current configuration has measured impacts at **6 km/s** of impactors as small as **0.4 mm**.
- Determining the velocity, angle of impact and size of the impactor.

	**Acoustic** – sensitive to wave speed and damping in foil. Wave propagation characteristics in thin foils is currently poorly understood. Would need significant development work.
	**Photodiode** – reliable and simple to implement, would improve with an opaque resistive grid. Ready to use could be improved with filter or baffles
	**Resistive grid** – robust and precise commercial product has limitations on smallest impactor size measurable. Custom development of thinner grid the smallest measurable impactor could be lower than 0.1 mm.

1) Introduction, state-of-the-art & detector concept
2) Breadboard design, hypervelocity impact testing & verification results
3) Flight model development plan

Fraunhofer
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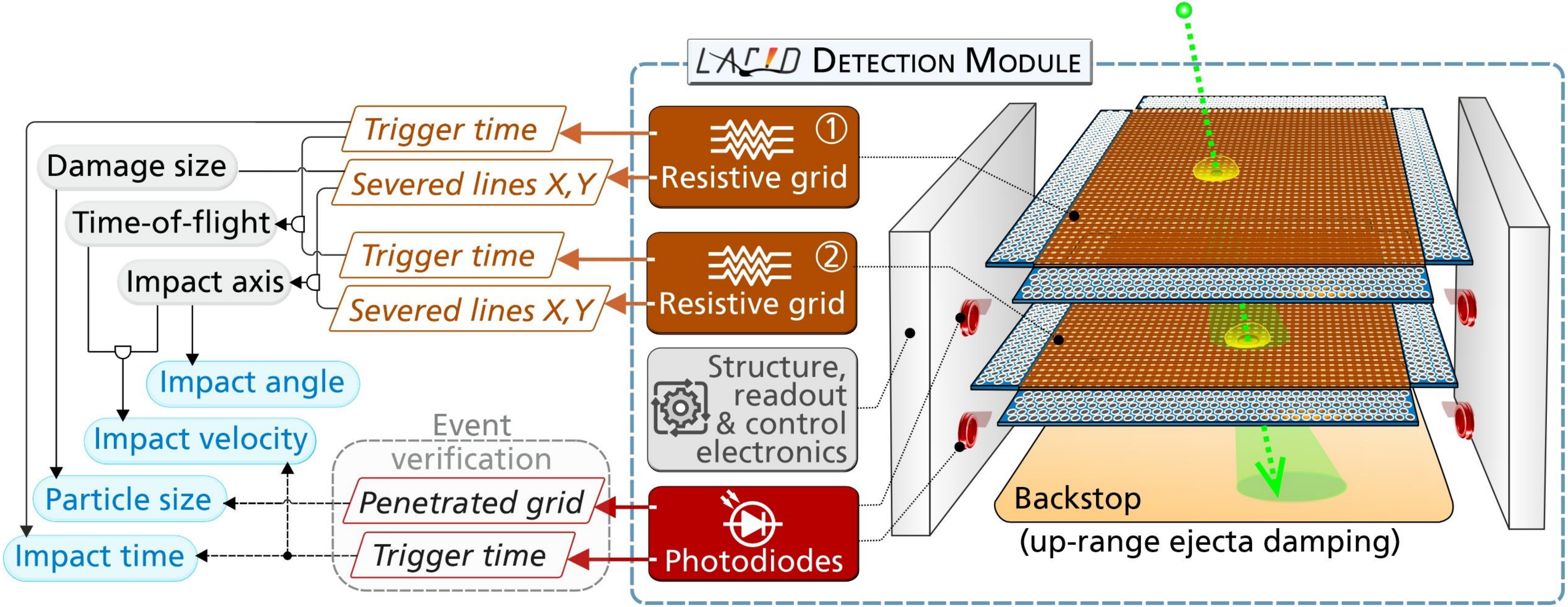
Flight model development plan

Instrument concept



Flight model development plan

- Large, scalable detection area: 1..10 m² ✓
- LEO, GEO & interplanetary missions ✓
- Performance
  - Impactor size: > 0.1 .. 10 mm ✓
  - Impact velocity: 5 .. 30 km/s ✓
  - Impact location: 1 .. 5 cm ✓
  - Impact angle: 0 .. 60 deg ✓
  - efficiency/availability/purity: 90% ✓
- Design
  - Instrument mass: < 5 kg/m² detection area (✓)
  - Power consumption: 10 W/m² detection area (✓)

Breadboard / **optimized detector**

- 0.14 m² per module
- Robust detection method for all orbit environments
- 0.4 mm – 5.3 mm verified with 188 µm grid layer thickness; 0.1 mm viable with thinner grids
- 5.5 – 7.0 km/s verified, upper velocity limit not verifiable in ground testing but no implications expected
- <0.5 cm verified
- 0 deg and 45 deg verified
- < 7% annual loss of detection area (LEO highly polluted), robust detection method
- < 8 kg/m² for breadboard; < 30 W/m² for breadboard — reasonable low resource demand

Flight model development plan

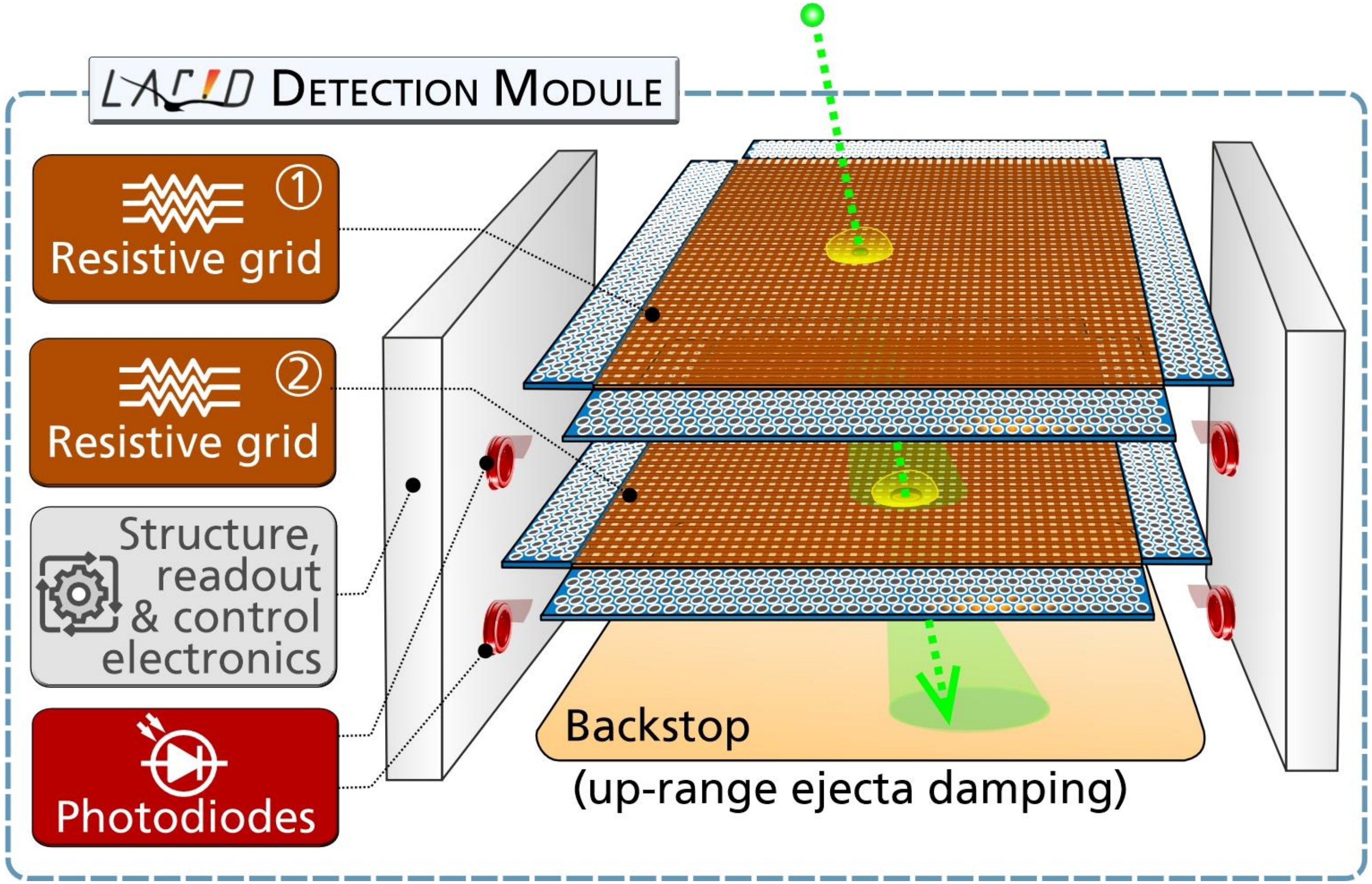
Technical development activities

1) Resistive grid optimization

- Reduce thickness
  (10 µm for COTS flex PCB)
- Add opacity layer
- Optimize grid distance

2) Photodiode optimization

- Add baffle + filter
- Determine light intensity characteristics



Flight model development plan

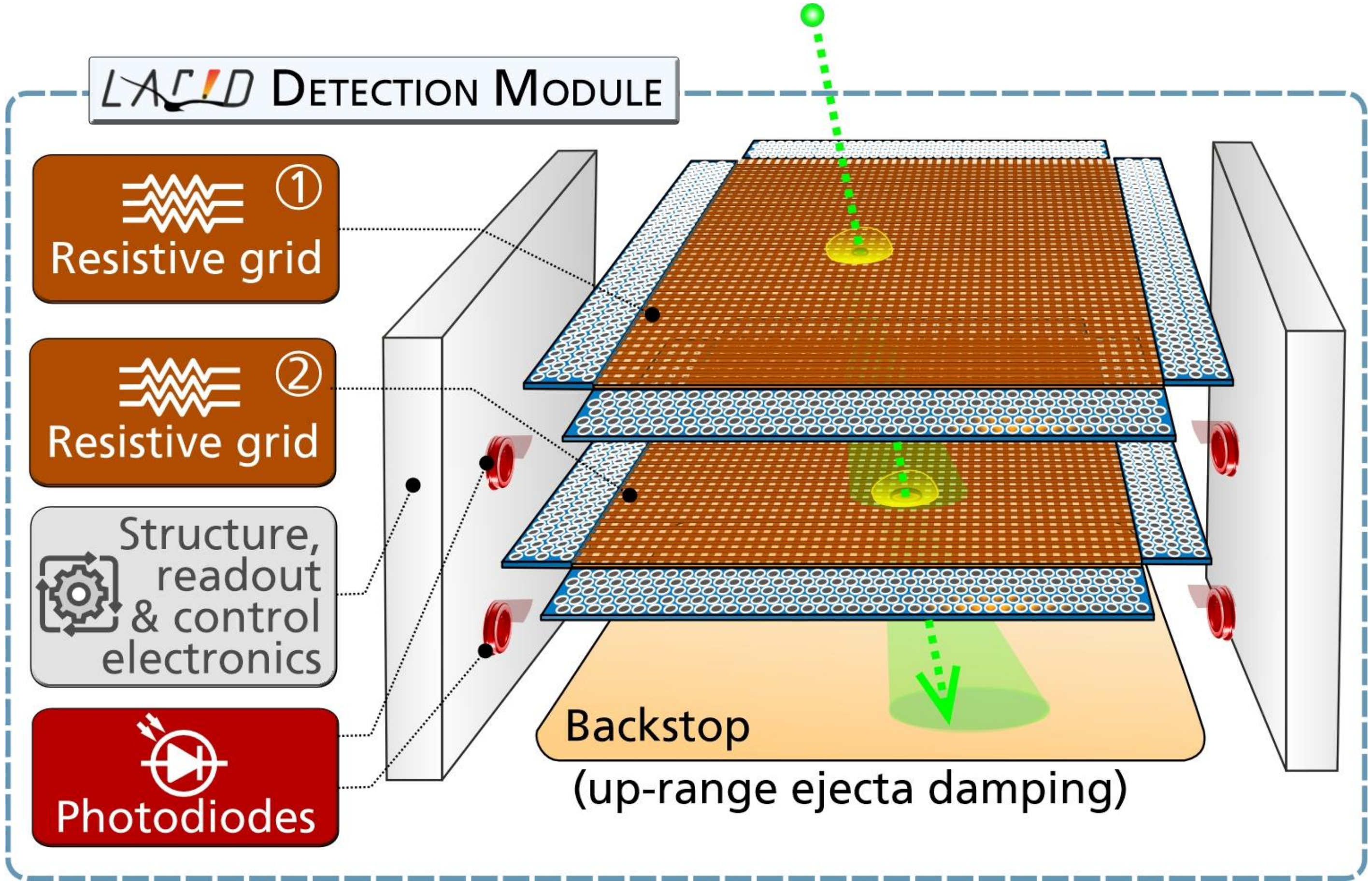
Technical development activities

3) Comprehensive ground testing

- Optimize detector design for particle size range
- Provide statistical database to derive impactor characteristics
- Study characteristics of impact flash and ejecta cloud behind first resistive grid

4) Next development phases

- Develop engineering model for detector optimization testing
- Develop flight model for specific mission scenario

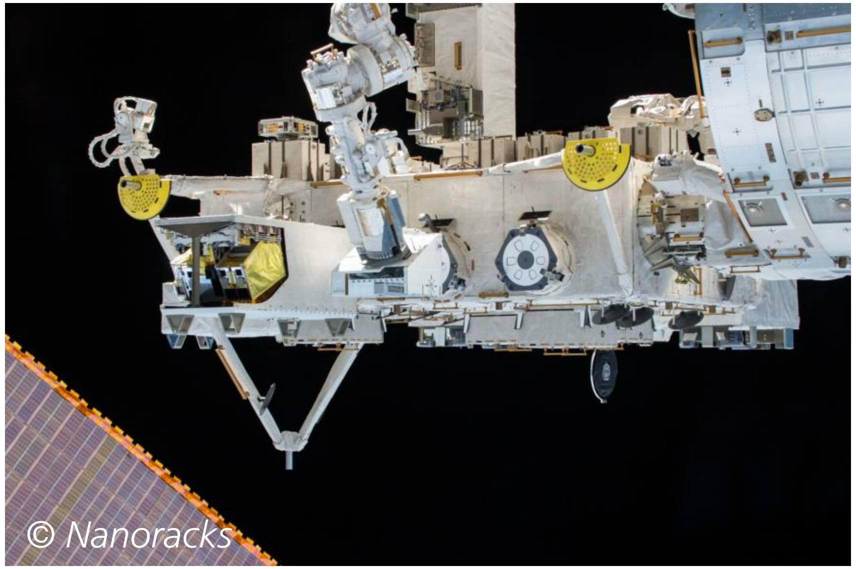


Flight model development plan
Applications scenarios

Detector concept allows flexible adaptation to different mission scenarios

I. **ISS hosted payload on external platform** (Bartolomeo, NREP)

- Large surface area with fast in orbit-demonstration and optional retrieval for post-mission-analysis
- Comprehensive data acquisition possible (full signals) through higher power and data capacity provided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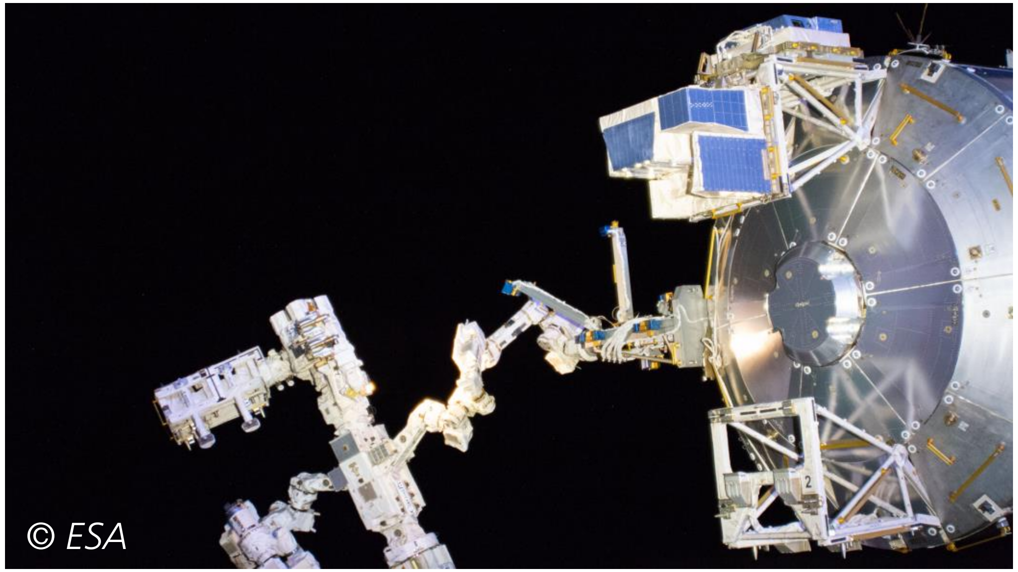
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Flight model development plan

Applications scenarios

Detector concept allows flexible adaptation to different mission scenarios

I. **ISS hosted payload on external platform**

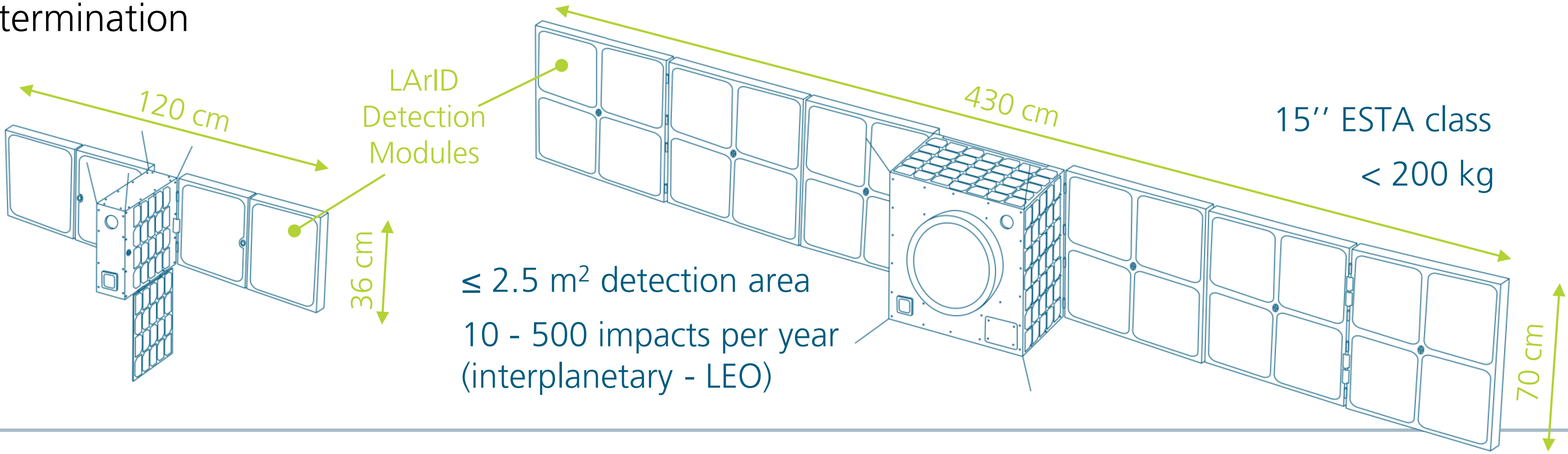
II. **Dedicated small satellite mission**

- Simple satellite bus design, deployable structures for realizing adequate detection surfaces
- Dedicated orbits possible, momentum transfer measurements combined with ADCS can be included for particle mass determination

27U CubeSat, < 50 kg

≤ 0.5 m^2 detection area

2 - 100 impacts per year (interplanetary - LEO)



15’’ ESTA class

< 200 kg

≤ 2.5 m^2 detection area

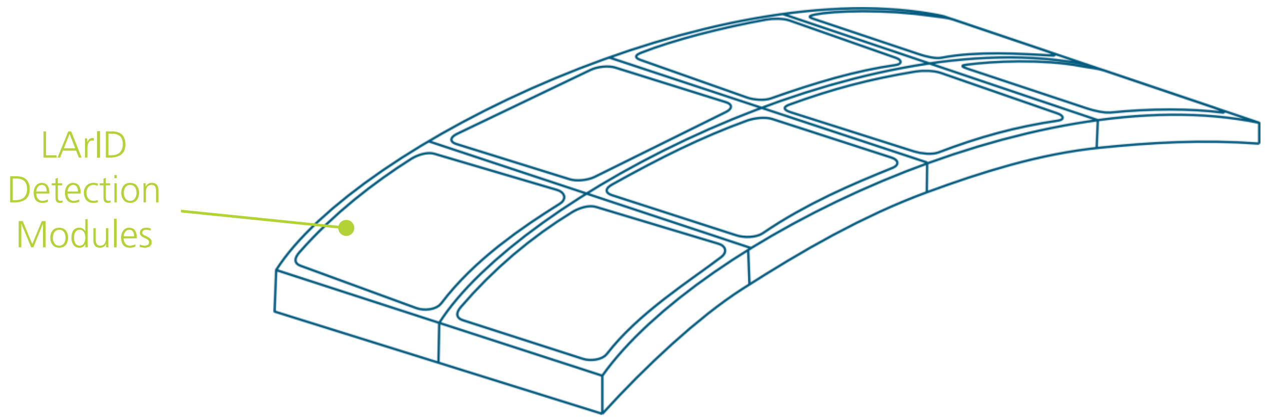
10 - 500 impacts per year (interplanetary - LEO)

Flight model development plan

Applications scenarios

Detector concept allows flexible adaptation to different mission scenarios

I. **ISS hosted payload on external platform**
II. **Dedicated small satellite mission**
III. **Integrated detector system on future space systems**
   - Detector concept and modular low-resource design allows versatile integration in different space systems (upper stages, spacecraft, space stations)



Conclusions

Large Area Low Resource Impact Detector

- The concept of an **in-situ impactor detector** that addresses the **micrometeoroid & space debris observational gap between 0.1 mm and 10 mm** has been successfully tested at breadboard level **TRL4**
- Highly integrated **modular design**: Detection module with **large surface area**, integrated electronics for trigger time and resistance sampling with **low power and mass** footprint
- **Layered impact detector** design to monitor the most important impact characteristics through sampling damage size, perforation times and impact trajectory
  - **Resistive grids** proved to provide reliable and precise information on impact times and trajectory → optimization of grid thickness and layer distance for flight model development
  - **Photodiodes** provide a reliable information on time of layer penetrations → event verification
  - (**Acoustic sensor**) are skipped as their performance showed significant uncertainty and noise issues

Modular design allows implementation for different missions:
1) ISS external payload, 2) dedicated small satellite, 3) integrative part of space stations …

Backup

Verification results

Resistive grid data accumulation

- After each test a new measurement of the resistive grid is made.
- Finding the new impact locations knowledge of the previous locations is needed.
- The red lines show the traces broken after each test.
- After the grid line is broken it will not read a new break if impacted along the length somewhere else.