PROCEEDINGS OF SCIENCE

Measuring Cosmic Rays with the RadMap Telescope on the International Space Station

Martin J. Losekamm,[a,b,*] **Thomas Berger,**[c] **Peter Hinderberger,**[a,b] **Thomas Kendelbacher,**[d] **Carl Kuehnel,**[d] **Karel Marsalek,**[c] **Luise Meyer-Hetling,**[a.b] **Stephan Paul,**[a,b] **Thomas Pöschl,**[a,b] **Sebastian Rückerl**[b,e] **and Hans J. Zachrau**[f]

[a]*Technical University of Munich, School of Natural Sciences, James-Franck-Str. 1, 85748 Garching, Germany*
[b]*Excellence Cluster ORIGINS, Boltzmannstr. 2, 85748 Garching, Germany*
[c]*German Aerospace Center (DLR), Institute of Aerospace Medicine, Linder Höhe, 51147 Cologne, Germany*
[d]*Airbus U.S. Defense & Space, 555 Forge River Rd, Webster 77598 TX, USA*
[e]*Technical University of Munich, School of Engineering and Design, Boltzmannstr. 15, 85748 Garching, Germany*
[f]*Nanoracks LLC, 503 Forge River Rd, Webster 77598 TX, USA*

E-mail: m.losekamm@tum.de

The RadMap Telescope is a new radiation-monitoring instrument operating in the U.S. Orbital Segment of the International Space Station (ISS). The instrument was commissioned in May 2023 and will rotate through four locations inside American, European, and Japanese modules over a period of about six months. In some locations, it will take data alongside operational, validated detectors for a cross-check of measurements. RadMap's central detector is a finely segmented tracking calorimeter that records detailed depth-dose data relevant to studies of the radiation exposure of the ISS crew. It is also able to record particle-dependent energy spectra of cosmic-ray nuclei with energies up to several hundred MeV per nucleon. A unique feature of the detector is its ability to track nuclei with omnidirectional sensitivity at an angular resolution of two degrees. In this contribution, we present the design and capabilities of the RadMap Telescope and give an overview of the instrument's commissioning on the ISS.

The 38th International Cosmic Ray Conference (ICRC2023)
26 July – 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)099

1. Introduction

Protecting exploration spacecraft and their crew from the exposure to cosmic and solar radiation is one of the major challenges of missions to the Moon, Mars, and other deep-space destinations [1, 2]. At present, uncertainties in predicting the medical consequences of exposure to the space radiation environment greatly limit the maximum permissible duration of crewed deep-space missions [3]. This uncertainty to a large degree stems from our incomplete understanding of the biological effects of highly ionizing radiation [4, 5] but is also due to a lack of detailed data on the radiation environment beyond Earth orbit. Though some spacecraft have carried radiation-monitoring instruments, these missions provided, with few exceptions [6], only short-term measurements. The only data on radiation exposure during transit to Mars, for example, stems from a single series of measurements by the Mars Science Laboratory, taken while it was en route to the red planet [7]. Long-term observations with instruments capable of accurately resolving the various components of the deep-space radiation environment are urgently required to help resolve the current uncertainties [8].

We present the RadMap Telescope, a compact yet powerful radiation monitor that not only demonstrates new sensor technologies but also aims to combine the capabilities of several current-generation devices in a bid to reduce the number of instruments required aboard future spacecraft. We highlight its most important design features and briefly summarize current operations on the International Space Station (ISS) before giving a first look at on-orbit data.

2. Monitoring of Cosmic Radiation for Crew Radiation Protection

The space radiation environment is a complex field of particles and nuclei that stem from multiple time-varying sources. It is dominated by galactic cosmic rays (GCR)—consisting of mostly electrons, protons, and fully ionized nuclei created and accelerated in astrophysical sources throughout our galaxy—with energies spanning many orders of magnitude. The most abundant GCR are protons and helium nuclei; heavier nuclei (i.e., those with higher nuclear charge) make up only about 13% of cosmic rays [9] but play an important role in radiation protection because they inflict severe damage in biological systems [10]. The flux of GCR is highest at energies of several hundred MeV to several GeV per nucleon. Another source of (mostly) protons and helium nuclei is the Sun, which emits them in high-intensity bursts at irregular intervals. These so-called solar energetic particles (SEP) have energies of tens to hundreds of MeV per nucleon [11]. Despite the particles'[1] lower energies, SEP bursts can nonetheless be a critical threat to astronauts because of their high intensity, especially if the crew is in a lightly shielded environment at the time of a burst (for example, only wearing their spacesuits during extravehicular activities) [12]. A third source are particles (mostly protons and electrons) trapped in radiation belts around planets with magnetic fields, for example Earth [13].

The radiation environment in currently operational spacecraft, for example on the ISS, is monitored with a suite of different sensors [14, 15]: Personal dosimeters, both active and passive, are worn by the crew to determine the radiation dose individual astronauts are subjected to. Area monitors, ranging from simple dosimeters to particle telescopes and small spectrometers, record the radiation environment at fixed locations throughout the spacecraft with varying degrees of detail. The data from different sensors is often combined to get a better picture of the radiation environment,

[1]We henceforth use the terms *particles* and *nuclei* interchangeably, unless specifically noted otherwise.

as most sensors available today are too limited in their capabilities to provide a full picture by themselves. In addition, different shielding conditions in different sections of a spacecraft (for example, the various modules of the ISS) necessitate the placement of sensors at several locations.

With the development of the RadMap Telescope, our objective was to develop a detector technology that can provide comprehensive measurements of the charged-particle radiation environment inside crewed spacecraft. We did not necessarily intend to construct an instrument that is more precise at every measurement it can perform than detectors specialized on specific measurements. We rather aim to combine the capabilities currently distributed across several systems such that the instrument can provide as many of the measurements required for protection of the crew as possible. Another objective is to perform a detailed analysis of the radiation environment to help improve shielding in current and future spacecraft. This means that RadMap needs to provide biologically meaningful dose and dose-rate measurements in real time, record particle-dependent energy spectra for protons and nuclei, and determine the directionality of incident radiation. We put special emphasis on the latter capability: To our knowledge, the RadMap Telescope is the first instrument deployed in space that can track particles with omnidirectional acceptance—i.e., with a field of view covering the full solid angle. We can thus determine a spacecraft's shielding effectiveness without needing to re-locate or turn the instrument, thereby reducing the uncertainty of such measurements. The instrument is designed to be most sensitive to the part of the radiation spectrum most relevant to radiation protection, i.e. to particles and nuclei with energies of tens of MeV to a few GeV per nucleon.

3. Instrument Design

At the heart of the RadMap Telescope is an active-target detector made from 1024 scintillating-plastic fibers arranged in layers with alternating orientation in a roughly cubic volume. The segmentation of this Active Detection Unit (ADU) given by the fibers allows us to record the energy-loss profile, and hence the change of the linear energy transfer (LET), along a particle's track through the detector. From this information, we can not only determine a particle's energy and the direction it came from but also establish its identity using a method called Bragg curve spectroscopy [16]. The particle identification is most precise for protons and light ions with energies that translate to a penetration depth that is shorter than or comparable to the size of the detector's active volume; it becomes increasingly imprecise for heavier nuclei and at higher energies. We use silicon photomultipliers (SiPMs) with a peak sensitivity closely matching the primary emission of the scintillator to determine the number of scintillation photons created in each fiber individually. Besides their mechanical robustness and insensitivity to external electromagnetic disturbances, the main advantages of SiPMs are their compactness and large dynamic range. The latter two aspects were the key enabling factors that made the development of RadMap's ADU possible. The omnidirectional sensitivity results in a geometrical acceptance of $1013\,\mathrm{cm^2 sr}$ if only a single fiber must be hit; to allow reconstruction of particle tracks, at least four fibers must produce a signal, resulting in a slightly lower acceptance of $925\,\mathrm{cm^2 sr}$ [16]. For high-energy particles passing through the detector, our track reconstruction based on artificial neural networks achieves an angular resolution of about 2°. We can determine the energy of protons with energies up to 200 MeV that randomly traverse the detector with a resolution of about 7%. For protons stopping in the detector under an ideal angle of incidence, we

Active Detection Unit		
Sensitivity		Charged particles
Geometrical Acceptance	*	925 cm^2sr (reconstruction threshold)
		1013 cm^2sr (detection threshold)
Energy Range	*	>71 MeV for H
		>292 MeV for He
Energy Resolution	*	7% for H with $E < 200$ MeV
	**	1% for H with $E < 90$ MeV
Angular Resolution	*	2°
Charge Separation	**	99% for H through N
		98% for O
		92% for F
M-42 Dosimeter		
Sensitivity		Charged particles, gammas, neutrons
Energy Range		60 keV to 18 MeV
Resolution		1.5 keV to 0.5 MeV

Table 1: Sensitivity ranges and resolutions of the RadMap Telescope's two main sensors. The ADU's sensitivity ranges and resolutions scale with the charge and mass of a particle; we provide values for H and He as reference. All values for the ADU were obtained from simulations of the full instrument, including housing and electronics. To calculate the parameters, we used simulations with either (*) an isotropic flux of particles with a broad energy spectrum or (**) particles entering the detector under an ideal angle and stopping inside the active volume.

have experimentally demonstrated that we can achieve energy resolutions as good as 1%. Since our reconstruction requires strong changes of the energy loss to be visible, the energy resolution decreases for higher particle energies and, because of ionization quenching [17], for heavier nuclei. Above a certain (as yet undetermined) threshold, we can only record a particle's (constant) LET and the energy it deposited in the detector. The capabilities of the ADU are summarized in Tab. 1.

The RadMap Telescope is equipped with two additional sensor systems that complement the main detector's measurement capabilities. Four commercially available RadFET dosimeters, exposed and read out in different configurations, provide measurements of the total ionizing dose (TID) in silicon. More importantly, we developed a customized version of the M-42 dosimeter designed at the German Aerospace Center (DLR) [18] and integrated it into the outer housing of RadMap. The M-42 is based on a planar silicon PIN diode with an active area of 1.23 cm^2 and a thickness of 300 μm. It records energy depositions in silicon between 60 keV and 18 MeV with a resolution ranging from 1.5 keV and 0.5 MeV, respectively. Several copies of the dosimeter were an integral part of the dosimetry suite of the MARE experiment that recently flew around the Moon aboard NASA's Artemis 1 mission. Another copy will be part of the upcoming Peregrine Mission 1 to Oceanus Procellarum on the near side of the Moon. We will thus be able to directly compare the data we record on the ISS to measurements taken in lunar orbit and on the lunar surface, helping to provide better estimates of the radiation exposure during future missions to the Moon.

The 1024 SiPM signals of the ADU are digitized by 64 application-specific integrated circuits (ASICs) developed by Integrated Detector Electronics AS for the readout of solid-state photodetectors [19]. A single Xilinx field-programmable gate array (FPGA) builds events out of the individual data

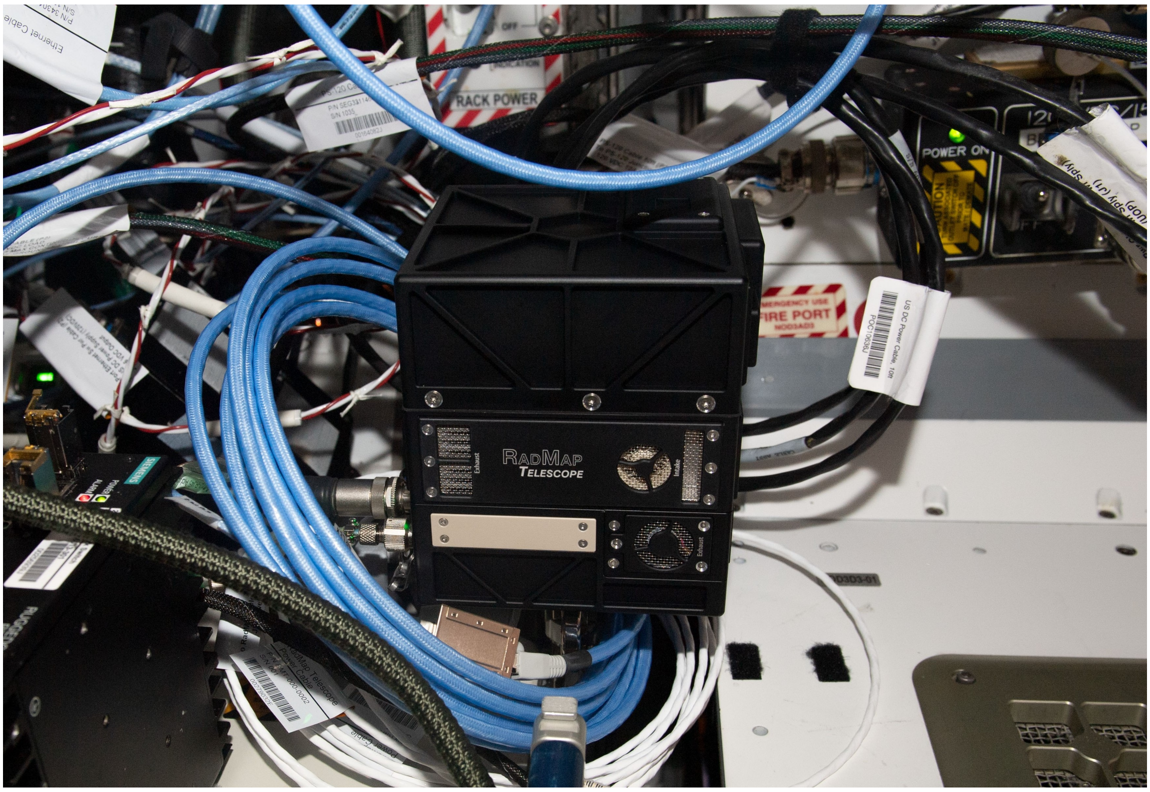

Figure 1: The RadMap Telescope deployed in the Node 3 module of the ISS. © NASA

streams, applies trigger conditions and event-selection cuts, and passes the events to the instrument's main computer for further processing via a PCIe interface. The latter is built around an NVIDIA Jetson TX2i compute module, equipped with a quad-core ARM A57 central processing unit (CPU) and a 256-core Pascal graphics processing unit (GPU). This quite powerful system allows us to test a variety of real-time data-processing algorithms, ranging from simple compression to the full event-by-event analysis of data using neural networks trained on simulation data.

4. On-Orbit Operations — A First Look

The instrument was launched to the ISS aboard the SpaceX CRS-27 resupply flight on 15 March 2023 and successfully deployed to its initial operating location in the Node 3 module (as part of the U.S. ISS National Laboratory) on 26 April 2023 (see Fig. 1). The instrument's compact size of about 16 cm × 14 cm × 14 cm allows a flexible deployment throughout the station; astronauts can easily attach RadMap to the seat tracks on any of the racks in the U.S. Orbital Section. We requested a total of four operating locations—in Node 3, in the Japanese Experiment Module, in the European Columbus Module, and in the U.S. Laboratory—to be able to assess whether we can determine differences in the shielding configuration and effectiveness in the various modules. In Columbus and in the U.S. Laboratory, RadMap will be located close to flight-proven instruments operated by European and American partners, allowing us to cross-check our measurements.

As of July 2023, the RadMap Telescope has been commissioned and is fully operational, though

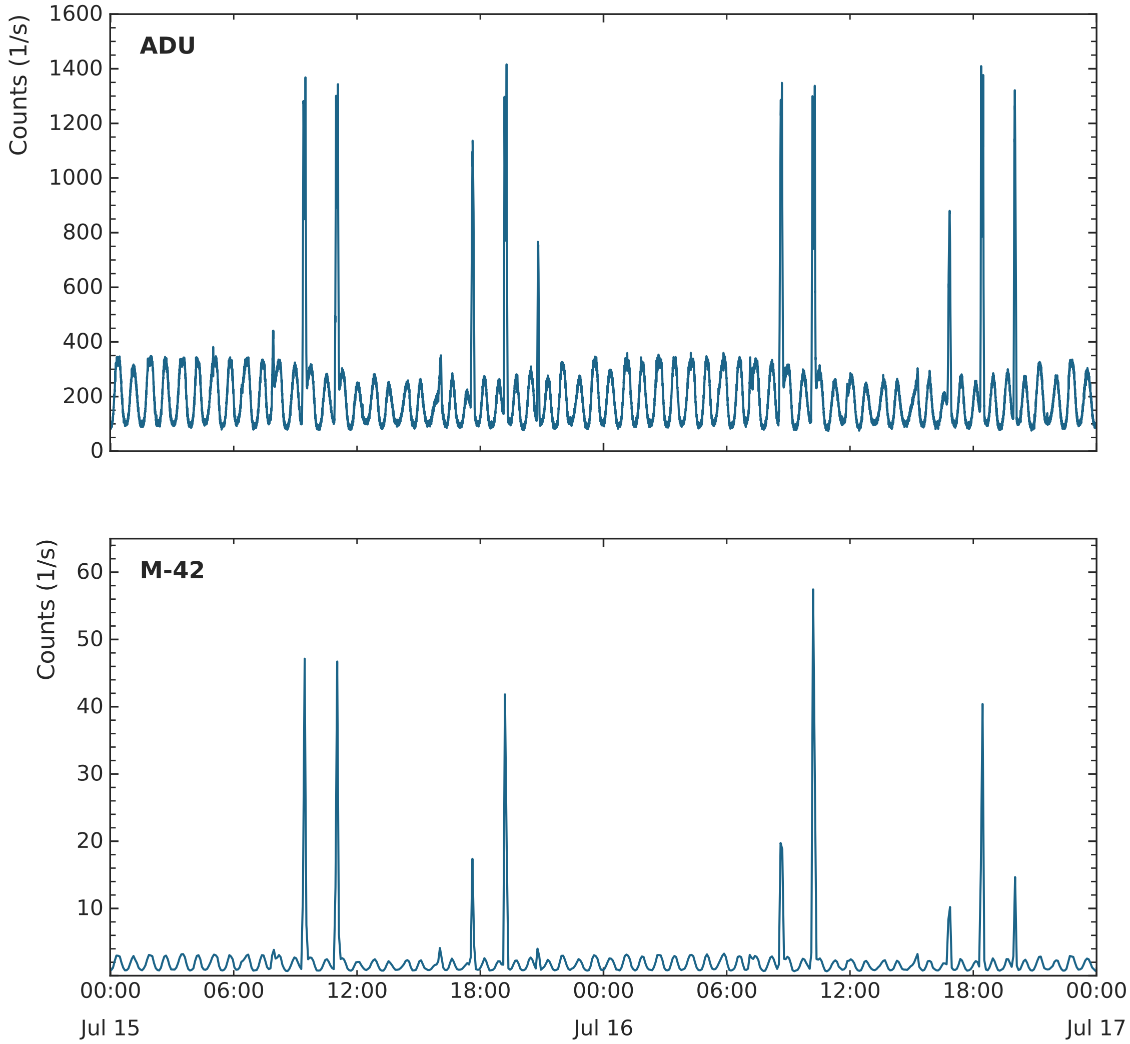

Figure 2: Count rates in the ADU (top) and the M-42 dosimeter (bottom) for a 48-hour period starting on midnight of 15 July 2023.

we are still performing some fine-tuning of the ADU's operational parameters. With all sensors active and data being compressed only (i.e., not being fully analyzed in real time), the instrument consumes about 16 W on average. Since most power is spent on the base load of the main computer and the power distribution unit, we expect to be able to significantly reduce the power consumption in future versions of the instrument that require less computational performance for testing processing algorithms. For initial operations, we are performing no real-time event selection on the ADU data but record every event for which at least one fiber was hit by a particle. At an average trigger rate of about 200 events per second, we currently record up to 1.6 GB of compressed raw data per day.

Fig. 2 exemplarily shows the count rates in the ADU and in the M-42 dosimeter for a 48-hour period starting on 15 July 2023. The differences in count rate between the equatorial and polar regions are well visible as oscillations with a roughly 90-minute period in both data sets. Also visible are short periods of much higher event rate when the ISS orbit intersects with the South

Atlantic Anomaly. A detailed analysis of the first on-orbit data is still ongoing.

5. Summary

The RadMap Telescope is a technology demonstrator that helps to address the need for more detailed studies of the space radiation environment and of the shielding effectiveness of crewed (and uncrewed) spacecraft. The ADU's active volume is very similar in chemical composition to human tissue, allowing good estimates of depth-dose distributions relevant for biomedical analyses. The M-42 dosimeter provides complimentary measurements of the dose in silicon. Both sensors are sensitive to particles with energies most harmful to biological systems and can characterize them with high precision. First data from initial operations on the ISS show that the instrument is working as expected, with a detailed analysis of its performance still pending. Co-locations with flight-proven sensors in two station modules will allow us to cross-check our measurements with those of operationally validated instruments.

Acknowledgments

The RadMap Telescope was deployed to the International Space Station under a user agreement with the U.S. ISS National Laboratory. The instrument development was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through grant 414049180. Additional funding was provided by DFG under Germany's Excellence Strategy – EXC 2094 – 390783311.

References

[1] J. Chancellor, G. Scott and J. Sutton, *Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit*, *Life* **4** (2014) 491.

[2] Z.S. Patel, T.J. Brunstetter, W.J. Tarver, A.M. Whitmire, S.R. Zwart, S.M. Smith et al., *Red risks for a journey to the red planet: The highest priority human health risks for a mission to Mars*, *NPJ Microgravity* **6** (2020) 33.

[3] J.C. Chancellor, R.S. Blue, K.A. Cengel, S.M. Auñón-Chancellor, K.H. Rubins, H.G. Katzgraber et al., *Limitations in predicting the space radiation health risk for exploration astronauts*, *npj Microgravity* **4** (2018) 8.

[4] M.H. Barcellos-Hoff, E.A. Blakely, S. Burma, A.J. Fornace, S. Gerson, L. Hlatky et al., *Concepts and challenges in cancer risk prediction for the space radiation environment*, *Life Sciences in Space Research* **6** (2015) 92.

[5] C.E. Hellweg, T. Berger, D. Matthiae and C. Baumstark-Khan, *Radiation in Space: Relevance and Risk for Human Missions*, SpringerBriefs in Space Life Sciences, Springer, Cham (2020), 10.1007/978-3-030-46744-9.

[6] M.D. Looper, J.E. Mazur, J.B. Blake, H.E. Spence, N.A. Schwadron, J.K. Wilson et al., *Long-Term Observations of Galactic Cosmic Ray LET Spectra in Lunar Orbit by LRO/CRaTER*, *Space Weather* **18** (2020) .

[7] C. Zeitlin, D.M. Hassler, F.a. Cucinotta, B. Ehresmann, R.F. Wimmer-Schweingruber, D.E. Brinza et al., *Measurements of Energetic Particle Radiation in Transit to Mars on the Mars Science Laboratory*, *Science* **340** (2013) 1080.

[8] A. Fogtman, S. Baatout, B. Baselet, T. Berger, C.E. Hellweg, P. Jiggens et al., *Towards sustainable human space exploration—priorities for radiation research to quantify and mitigate radiation risks*, *npj Microgravity* **9** (2023) .

[9] J.A. Simpson, *Elemental and Isotopic Composition of the Galactic Cosmic Rays*, *Annual Review of Nuclear and Particle Science* **33** (1983) 323.

[10] K.H. Chadwick, *Understanding Radiation Biology*, CRC Press, Boca Raton, FL (2019), 10.1201/9780429288197.

[11] D.V. Reames, *Solar Energetic Particles*, Lecture Notes in Physics, Springer, Cham, 2nd ed. (2021), 10.1007/978-3-030-66402-2.

[12] M. PourArsalan, L.W. Townsend, N.A. Schwadron, K. Kozarev, M.A. Dayeh and M.I. Desai, *Estimates of Radiation Exposures for Human Crews in Deep Space from the January 15, 2005, Solar Energetic Particle Event Using the Earth-Moon-Mars Radiation Environment Module*, *Nuclear Technology* **175** (2017) 202.

[13] W. Li and M.K. Hudson, *Earth's Van Allen Radiation Belts: From Discovery to the Van Allen Probes Era*, *Journal of Geophysical Research: Space Physics* **124** (2019) 8319.

[14] J.A. Caffrey and D.M. Hamby, *A review of instruments and methods for dosimetry in space*, *Advances in Space Research* **47** (2011) 563.

[15] L. Narici, T. Berger, D. Matthiä and G. Reitz, *Radiation Measurements Performed with Active Detectors Relevant for Human Space Exploration*, *Frontiers in Oncology* **5** (2015) 1.

[16] M.J. Losekamm, S. Paul, T. Pöschl and H.J. Zachrau, *The RadMap Telescope on the International Space Station*, in *2021 IEEE Aerospace Conference*, IEEE, 2021, DOI.

[17] T. Pöschl, D. Greenwald, M.J. Losekamm and S. Paul, *Measurement of ionization quenching in plastic scintillators*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **988** (2021) 164865.

[18] T. Berger, K. Marsalek, J. Aeckerlein, J. Hauslage, D. Matthia, B. Przybyla et al., *The German Aerospace Center M-42 radiation detector–A new development for applications in mixed radiation fields*, *Review of Scientific Instruments* **90** (2019) 125115.

[19] D. Meier, J. Ackermann, A. Olsen, H. Otnes Berge, A. Hasanbegovic, M. Altan et al., *SIPHRA 16-Channel Silicon Photomultiplier ASIC*, in *AMICSA&DSP*, 2016, DOI.