Injection Molding of Large Plastic Scintillator Tiles at Optical Quality

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Abstract

This proposal describes an R&D program towards injection molding large, thin plastic scintillator sheets with fine trenches. To this end, we plan to leverage the experience in calorimeter system design of the ORNL Physics Division with the machining and manufacturing expertise of the ORNL Manufacturing Demonstration Facility together with the long standing R&D history on large, subdivided plastic scintillator tiles of the JGU Mainz group. We provide a detailed description of the R&D necessary with the milestones and the cost estimations for the project. A successful establishment of such a technology would result in a production of large scintillator tiles with high cost savings up to 90% compared to the current baseline of machining flat plastic scintillator sheet materials.

1 Introduction and Motivation

The advent of small size silicon sensors has enabled the possibility of devising particle physics experiments with calorimeter systems of previously unfeasible readout segmentation in all three spatial dimensions. Together with individual particle momenta and trajectories obtained from the tracking systems, the detailed spatial information of shower energy deposits enable the application of Particle Flow Algorithms (PFAs) which promise to improve the jet energy resolution of a given experiment beyond what would be possible with calorimetric reconstruction alone.

In electron-proton(ion) collisions at EIC, most of the hadronic, highly energetic particles are created by breaking up the incoming proton or ion using the electron. However, as the incoming proton/ion has a significantly larger kinetic energy than the incoming electron most of the hadrons will fly in the same direction as the original hadron beam, into the hadron(forward) end cap. Thus jets of particles with single particle energies of up to 150 GeV, might reach the forward hadronic calorimeter, based on simulated PYTHIA events for e+p collisions at 18×275 GeV^2. These jets are comprised of 10-12 particles on average, collimated within a jet radius of $R = 1$. As in particular above $|\eta| = 3$ the tracking resolution worsens rapidly, especially in the forward region, the hadronic and electromagnetic calorimeters need both excellent energy resolution as well as sufficient spatial resolution to resolve individual particles within these jets. To achieve this the forward calorimeter systems for EIC detectors have to be highly segmented and integrated with the least amount of dead space in between comparatively small towers.

Among the various pursued technology options for high granularity hadronic calorimeters, one of the most promising choices is the combination of small plastic scintillator tiles of a few square centimeters in size, read out by an individual silicon photomultiplier (SiPM) per tile. This concept was originally established by the analog hadronic calorimeter (AHCAL) developed as part of the CALICE collaboration. Over the past 15 years of development, the current baseline of the AHCAL concept has settled towards $30\,\mathrm{mm} \times 30\,\mathrm{mm} \times 3\,\mathrm{mm}$ plastic tiles which are individually wrapped in reflective foil. This design has been largely followed by other projects, e.g. by the currently ongoing CMS HGCAL upgrade.

While the performance of a calorimeter read out by individually wrapped scintillator tiles is outstanding, the sheer number of tiles to be assembled into a given experimental configuration poses significant challenges in the construction of such calorimeters. Automated wrapping and tile assembly setups have been developed to tackle these issues, but do not circumvent the fundamental issue of handling and processing individual tiles. An alternative approach would be to construct continuous two dimensional matrices of scintillator tiles which contain a larger number of individual readout channels but can be handled as a single unit. Such "megatiles" have been proposed and utilized in various previous experiments[1] in the past, where individual readout cells were established in a continuous piece of plastic scintillator sheet by machining optical separation notches and refilling the resulting gaps with an optically opaque filler material (usually a mixture of epoxy and titanium-dioxide). A similar concept has been pursued by JGU Mainz for the CALICE AHCAL. These "AHCAL Megatiles" are machined from 4 mm to 6 mm plastic scintillator stock in several time and labor intensive steps as outlined in Figure 1. The result is a $36\,\mathrm{cm} \times 36\,\mathrm{cm}$ Megatile consisting of 144 optically isolated sub-tiles as shown in Figure 2. This Megatile exactly fits one whole AHCAL readout board, which can then be assembled and handled in one piece.

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[1] examples include the CDF end plug upgrade (1994), D0 Run II Inter Cryostat Detector (1999), CMS HCAL (1996)

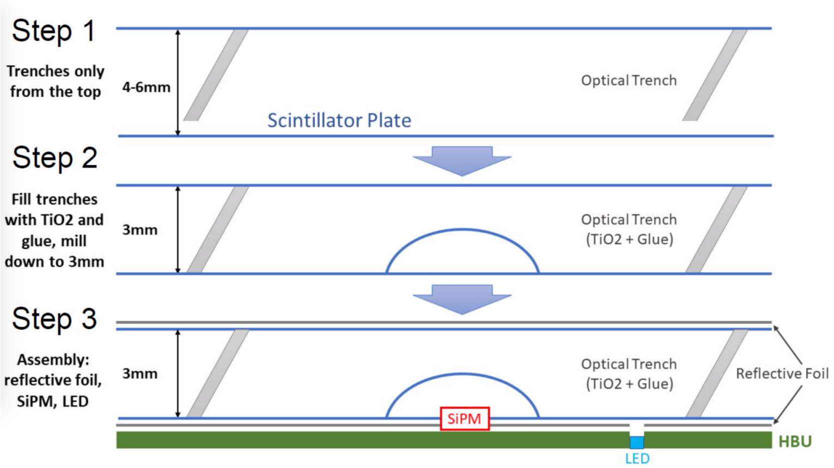

Figure 1: Construction and assembly steps of a JGU Megatile.

While the assembly of the Megatile into the calorimeter is significantly eased compared to assembling individual tiles onto a readout board, much of the advantage gained is lost from the time needed to machine and process the raw scintillator stock into a Megatile. If instead of machining the Megatile structure from plastic scintillator sheets, the Megatile could instead be injection molded including all necessary surface features, the overall production effort and cost would reduce by orders of magnitude.

The plastic scintillator production facility at Fermilab has already demonstrated the general feasibility of injection molding polystyrene doped with scintillating additives. However, injection molding relatively large, thin sheets of polystyrene with the required thin separation trenches at the optical quality needed for an application in calorimetry poses a significant challenge, which we plan to address with this proposal.

R&D for injection molding processes is a difficult and cost intensive, since the initial cost to produce a suitable mold prototype is relatively expensive and requires expert knowledge on injection molding processes that is not generally available within the particle physics instrumentation community. However, the ORNL Manufacturing Demonstration Facility (MDF) - represented by Dr. Elliott in this proposal - has significant expertise not only in injection molding processes, but specifically in the cost effective production of steel molds by additive manufacturing (3D printing) via binder jet methods. ORNL MDF has previously collaborated with a local manufacturing company (Innovate International) with extensive know-how and machinery for injection molding, which can be used to further consult on mold designs and technical issues.

Establishing the feasibility of injection molded large area, high granularity plastic scintillator megatiles would pose a game-changing cost reduction for future high granularity calorimeters for the EIC and other future experiments. To illustrate the potential cost savings, the proposed EIC detector 1 plans to use around 1600 m^2 of plastic scintillator sheets for its LFHCAL forward hadronic calorimeter. Based on quoted material and machining costs from established vendors, one square meter of machined scintillator tiles would cost about $4000, for a total procurement cost of about $6.4M with a total delivery time of two years. In contrast, assuming

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and STAR Barrel EMC (2002)

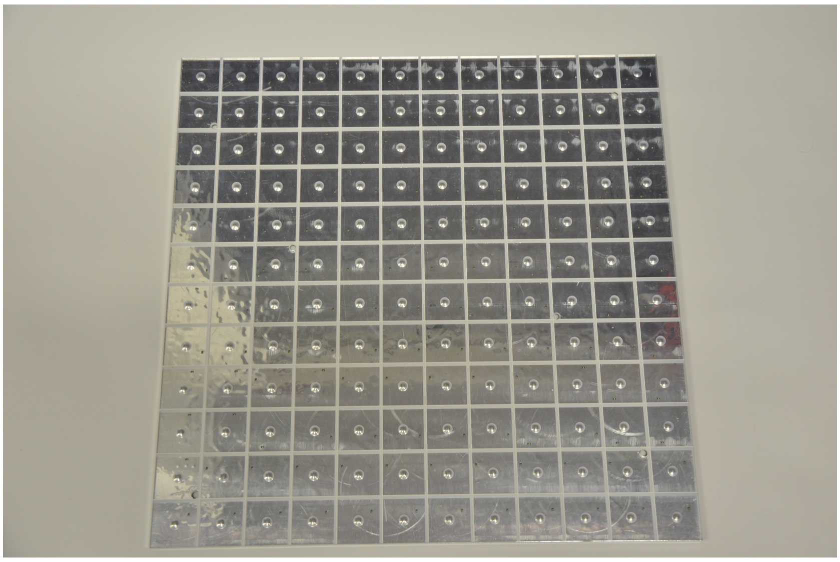

Figure 2: A finished JGU Megatile.

\$10/Kg of polystyrene raw material, initial mold costs of about \$40K and a molding rate of about 2.5 m^2 per production hour at a cost of \$180/h, the overall cost of producing the same amount of tiles via injection molding is $\$ <$ 600K, taking less than six months to complete. This represents a potential cost reduction of at least 90 % while taking only a quarter of the time.

The combined promise of significantly decreased cost and production time drives the pressing need for this proposed R&D. In addition, an important reduction of risk is associated with not having to rely on one of the two large global vendors of plastic scintillator sheet stock.

For this proposal, we combine the expertise of the ORNL Physics Division in calorimeter system design and simulation, characterization of plastic scintillator materials and assemblies with the world leading manufacturing and machining experience of the ORNL Manufacturing Demonstration Facility and its partners and the long standing involvement of the JGU Mainz group in designing, engineering, producing and characterizing Megatiles for the CALICE AHCAL project.

2 R&D Needs

We expect the injection molding of large area, high aspect ratio tiles with fine features in the separation notches and fiber channels to pose a significant engineering challenge. Ultimately this R&D program will explore the necessary design trade-offs between the geometric requirements from physics performance consideration and the engineering realities of achieving a feasible, reproducible, high yield production of such tiles. Further, this program will establish the necessary procedures to post-process molded tiles before they could be assembled into a given calorimeter system.

To this end, we plan to produce three types of molds and corresponding tiles with progressively larger sizes, aspect ratios and higher geometric complexity. For each produced mold, a test injection molding run will be performed to produce a few dozen tiles of each type. Since we expect some start up difficulties in this endeavor, we budget for one additional mold production and two additional injection molding test runs with respect to the three envisioned tile type iterations.

Significant fractions of the tile processing, characterization and analysis works will be carried out by a postdoc and a graduate student at JGU Mainz, who will be partially supported from this proposal. The postdoc and student will be supervised locally at JGU Mainz by Prof. Büscher and Prof. Masetti.

3 Plan for FY23

In the initial funding period for this project, we plan to produce three types of molds and corresponding tiles. The mold design will be based on existing tile designs, which we expect to need significant modifications based on the engineering inputs from the injection molding experts at ORNL MDF and potentially Innovate International, as required.

Each produced tile type will be inspected and characterized for their metrology, optical quality, response uniformity and scintillation lightyield at ORNL. Samples of each tile type will be sent to JGU Mainz for potentially required post-processing and characterization on their local test stands.

The first tile type to be produced will be based on the tile design developed for the inner HCAL of the sPhenix experiment. These 200 mm × 100 mm × 7 mm tiles do not have any separation notches and their only feature is a wavelength shifting fiber ridge embedded into its surface, as shown in Figure 3. We will aim for a fairly conservative mold design with conservative draft angles for this fairly simple tile.

The lack of detailed feature on the tile surface will enable a relative straightforward evaluation of the optical quality of the tile by measuring the optical transmittance at various points over the surface of the tile. Detailed metrology of the produced tiles will inform us on the mechanical tolerances we can expect when injection molding the polystyrene material. Depending on the guidance from the process experts, we might plan to include some geometrical test structures into a corner of the tile design to better inform design choices in the following tile designs.

We also plan to characterize the tile response to charged particles by re-using existing sPhenix iHCAL tile test setups. In parallel, a sample of these tiles will be sent to JGU Mainz for further material studies and testing of their established post-machining and -processing routines.

The second tile type to be produced will closely follow the ”8M” tile design proposed for the EIC detector 1 LFHCAL proposal. These 200 mm × 100 mm × 4 mm tiles feature eight fiber ridges on their surface and a number of deep separation trenches to divide the tile into its eight individual 50 mm × 50 mm sub-tiles, see Figure 4. Depending on the input from the process experts, the feasible width and depth of the separation trenches needs to be determined before the mold can be fabricated.

The separation trenches will be filled with an optically isolating glue partially at ORNL and partially at Mainz to cross-check the procedures and discover potential procedural differences that might lead to differing tile properties.

Apart from the optical evaluation described above, a key characterization measurement for this tile type will be a quantitative estimate of the light crosstalk between individual sub-tiles through the filled separation trench and the necessarily remaining scintillator materials at the

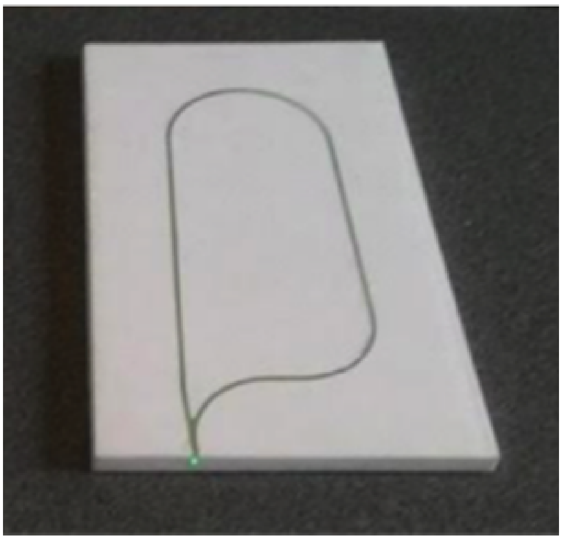

Figure 3: A prototype sPhenix iHCAL tile.

bottom of the trench. Depending on the realized time scales of the planned LFHCAL R&D test beam campaigns, injection molded tiles from this production might be characterized in test beams as well.

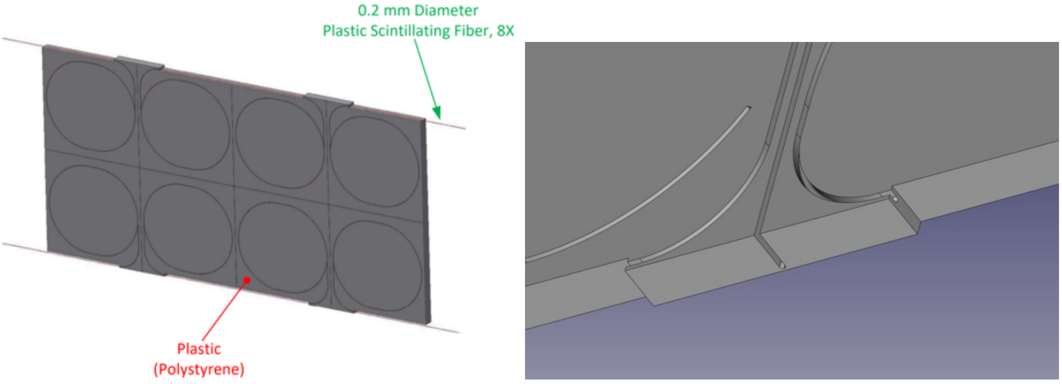

Figure 4: CAD drawing and detail view of an LFHCAL ”8M” tile.

The third and final tile type to be produced is a full CALICE ”Megatile” based on the JGU Mainz designed described before and shown in Figure 1, 2. We expect significant technical challenges from the large area, low thickness and considerable mechanical instability from the large number of separation trenches on the tile. If a direct injection molding of this design is deemed not feasible at that point, we have several options to simplify the process: One option would be to mold the tile with an additional millimeter of material thickness, which is then milled off as part of the post-processing at JGU Mainz. Another option is to produce a smaller version of the same conceptual design, such as a 6 × 6 tile design of 18 cm × 18 cm size instead of the full 36 cm × 36 cm Megatile.

A small part of the produced tiles will be processed at ORNL, while most of the produced tiles will be sent to JGU. This tile type can be directly mounted to the existing Megatile characterization test stand available at JGU, shown in Figure 5. The test stand enables extensive lightyield and cross talk characterizations, including ageing studies on a calibrated reference readout as used in the current CALICE AHCAL prototype calorimeter systems. Depending on the performance figures acquired on the test stands, and the timelines of future AHCAL test beam campaigns, the injection molded tiles might be integrated into the larger CALICE AHCAL testbeam prototype for a direct comparison to previously fabricated (machined) Megatiles as well as calorimeter layers equipped with individually wrapped scintillator tiles.

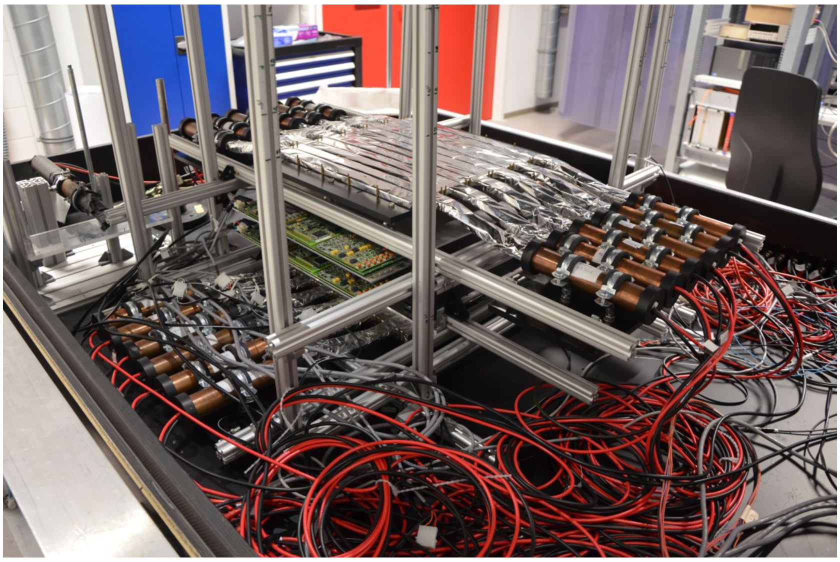

Figure 5: The JGU Mainz test stand for AHCAL Megatiles.

3.1 Milestones/Deliverables

- **Nov 2022**: mold design for iHCAL-type tile
- **Dec 2022**: test injection mold for iHCAL-type tile
- **Jan 2023**: mold design for LFHCAL-type tile
- **Feb 2023**: test run for LFHCAL-type tile
- **Mar 2023**: characterization LFHCAL-type tile
- **Apr 2023**: mold design AHCAL-Megatile
- **May 2023**: test run AHCAL-Megatile
- **June 2023**: post processing AHCAL-Megatile
- **Sep 2023**: characterization AHCAL-Megatile
- **Sep 2023**: technical report on injection molding of large area plastic scintillator tiles

3.2 Project Cost

Table 1 describes the proposed baseline funding for the project scope described above.

Table 1: Funding allocation for FY23.

Institute	**Item**	**Cost per item in $**	**Number of items**	**Total cost in $**
ORNL RNP	tile prototype quality assessment		0.2 FTE	(in-kind) 0
ORNL	mechanical engineering tile/mold	180/h	100h	18K
ORNL	raw materials, shipping			5K
ORNL MDF	mold printing	5000	4	20K
ORNL MDF	mold machining	5000	4	20K
ORNL MDF	injection molding run	6000	5	30K
ORNL RNP	travel	5000	1	5K
JGU	postdoc support		0.2 FTE	14K
JGU	graduate student support		0.2 FTE	7K
JGU	tile post processing	90/h	100h	9K
Total				**128K**

Table 2: Funding matrix FY23.

Institute	**Production**	**Characterization**	**Engineering**	**Total cost**
ORNL	$75K	$5	$18K	$98k
JGU	$9K	$21K	$0K	$30K
Total	$84K	$26K	$18K	

3.2.1 Reduced Funding Scenarios

In case of a 20 % reduction in granted budget, we believe we can still carry out most of the milestones described above, however at greater risk on each individual step and less available contingency. If a given injection molding test run fails because of an insufficiency in the mold design, we would have to move on to the next tile design, taking the lessons learned from the failed design into account as much as possible. In the case we assess the risk to simply continue with the next tile prototype too high, we might have to reduce the overall scope to only two produced tile types. In the −20 % scenario, the proposed travel would be canceled as well.

In case of a 40 % reduction in granted budget, the scope of the whole project would have to be reduced to a maximum of two tile types. In that case the first tile type would be skipped, and the project would start with a LFHCAL-style tile, potentially with some minor modifications for a more conservative approach. Even at reduced scope to two tile types, there would be little to no contingency for failures on the way.

4 Plan for FY24-26

The research plan for potential follow-up funding periods entirely depends on the results obtained from this initial proposal.

In case all the milestones of FY23 are reached without issues, more effort could be spent on optimizing the raw material chemical composition, optimizing the scintillating dopant mixture and concentrations, while using existing molds in test runs with these varying material compositions for a direct comparison of the produced tiles.

Similarly, more intricate tile designs could be invented and simulated based on the learned engineering constraints on injection molded tiles.

In the case that the tiles produced from this proposal do not meet our requirements on mechanical stability and optical quality, more R&D should be done on the engineering and production side of things. This could be supported by more engineering time, potentially more external consulting and ultimately further attempts and producing molds and producing tiles in test runs.

In any case, a potential follow-up funding should aim to move the injection molding procedure out of ORNL MDF and into a commercial injection molding facility, to lead the way to potential true large scale production of injection molded plastic scintillator tiles in the future.

5 Cost Effectiveness

The described proposal outlines an R&D program that aims to establish a production technology with the potential reduce the cost of plastic scintillator tiles for future high granularity calorimeter project by 90 % or more. The local collaboration between the ORNL Physics Division and the ORNL Manufacturing Demonstration Facilities as well as their local partners of Innovate International guarantees short travel distances for most of the required in-person elaborations. We assume that most international communication between ORNL and JGU Mainz can take place via well established digital channels, planning for only a single international travel trip on this project.

6 Diversity, Equity and Inclusion

The proponents of this proposal recognize the importance of a diverse, inclusive environment that offers equitable opportunities for everyone. Both participating institutes operate extensive DEI programs to further the goal of a diversified academic workplace.

ORNL committed to provide and foster a safe research and work environment where diversity is essential, equity is inherent, and inclusion is innate. ORNL represents over 60 nationalities in its over 5800 employees. Within the senior leadership of the laboratory, 35

ORNL is the only national laboratory to be named a Top 10 supporter of HBCUs and was named Best Employer for 2021 for providing opportunities in STEM for underrepresented groups.

JGU is committed to diversity and equal opportunities. Their efforts in the field of diversity aim at promoting and encouraging the differences and individuality of their members and to see them as an opportunity and enrichment rather than only as a challenge. JGU is currently part of the diversity-audit ”Vielfalt gestalten” as one of five participating universities in Germany.

A Appendix

A.1 Specific Expertise of Contributors

A.1.1 ORNL Physics Division

The ORNL relativistic nuclear physics (RNP) working group is part of the ORNL physics division. The RNP group has been, and continues to be, involved in the design, construction and operation of the calorimeter systems of various collider based nuclear physics experiments such as the STAR EMCal, PHENIX EMCal, ALICE EMCal as well as the proposed ALICE FoCal upgrade. The RNP group is currently the main proponent of the LFHCAL proposal for EIC detector one.

The contributions from the RNP group have made a significant impact on the design of the ECCE calorimetry, tracking and PID systems from extensive studies based on detailed simulations and full reconstruction codes. The results from these studies have shaped the currently planned layout of EIC detector one to great extent. The mechanical design of the LFHCAL has been supported by mechanical engineers from the ORNL nuclear fusion group.

Within the ORNL physics division, the working group of Mike Febrraro is specialized in the design, production and characterization of organic scintillator materials. This working group has developed significant expertise in injection molding plastic scintillators for the LEGEND experiment and also developed 3D printing capabilities for organic scintillator materials.

A.1.2 ORNL Manufacturing Demonstration Facility

ORNL MDF is a test facility for novel manufacturing techniques and schemes focusing on materials, software and systems. ORNL MDF possesses world leading expertise in additive manufacturing techniques, spanning all material classes from polymer composites to metals. Their developments of novel materials and production processes resulted over a dozen R%D100 awards since its foundation in 2012. To compliment the numerous available additive manufacturing devices, MDF houses has high precision machining and metrology facilities.

A.1.3 JGU Mainz

JGU is hosting a strong research program on fundamental particle and astroparticle physics, ranging from neutrino physics, dark matter searches and flavour physics to high-energy collider physics at the LHC. With the PRISMA detector laboratory, JGU has unique infrastructure for the development of innovative detector technologies. This includes in particular a Laboratory for Scintillation and Fluorescence Detectors for the development, machining and characterisation of scintillators, as well as on-campus testbeam facilities at the MAMI accelerator.

JGU reseachers have been pursuing R&D of highly-granular sampling calorimeters using scintillators and SiPM readout for many years within the CALICE collaboration. This included the development of scintillator tiles coupled to surface-mounted SiPM detectors, a concept that has been demonstrated with the construction and successful testing of a prototype with more than 20k channels.