2023

Imaging of nucleus-nucleus collisions. — Processes inside nuclei and their consituents, the nucleons are governed by the strong interaction. The NA61/SHINE experiment at the CERN SPS accelerator is one of the experiments optimized for the study of strongly interacting matter, via performing nucleus-nucleus collisions. An important experimental method is the so-called femtoscopic imaging: the quantum mechanical interference pattern of the outgoing particles (pions) carry information on the shape of the colliding and then particle emitting system. In the NA61/SHINE experiment, recent measurements (corresp. author B. Porfy) of femtoscopic correlations in small (Be+Be) systems have unveiled that instead of the naively expected Gaussian shaped source, the emitting source is described rather by a Lévy profile [1].

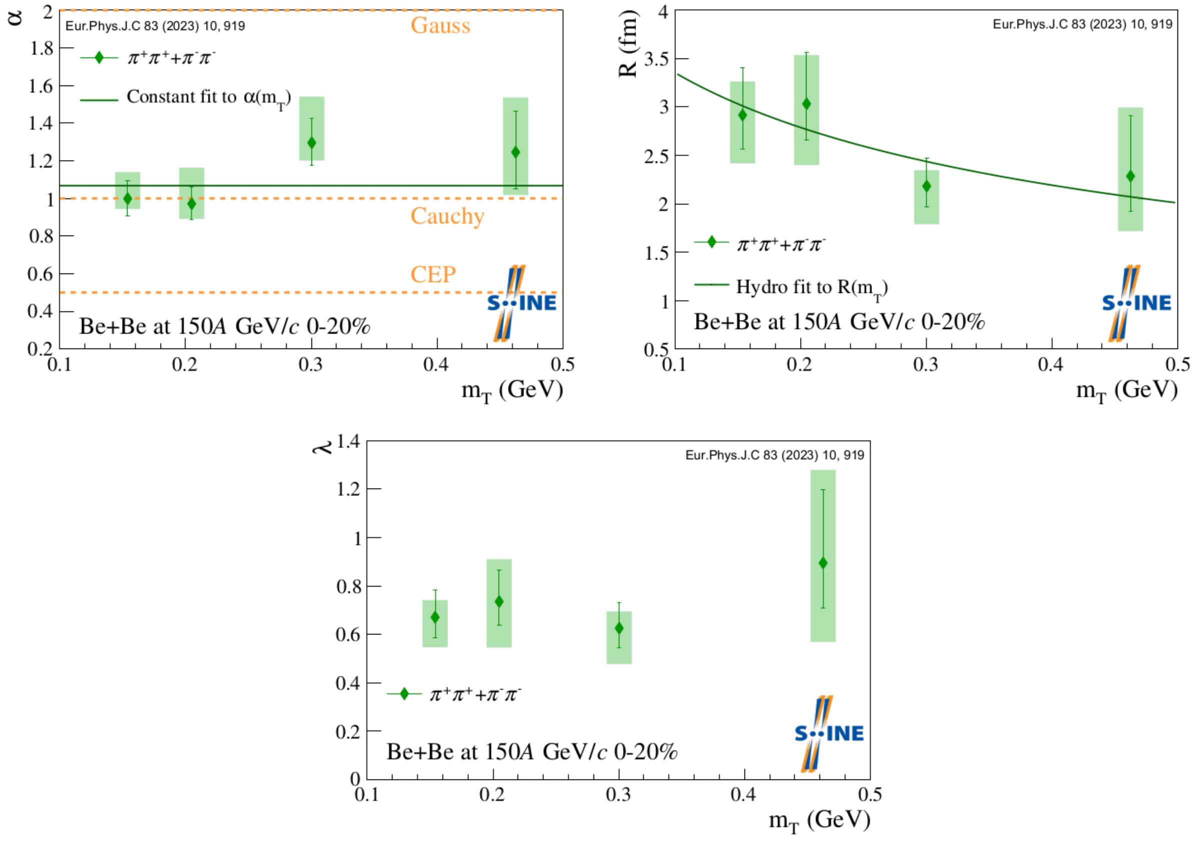

Figure 1. The most important femtoscopic parameters, the Lévy exponent α, the intercept parameter λ, and the source size R as a function of mT , the mean transverse mass of the emitted particle pair. It is seen that α is far from the Gaussian case (≈ 2), and is characteristic to a profile shape with a powerlaw tail (α < 2, in particular α ≈ 1).

A crucial parameter in this context is the Lévy-exponent α, measuring the departure from a Gaussian shape. It is of particular importance due to its potential connection to the so-called critical exponent, in the vicinity of a critical endpoint in the thermodynamical phase diagram of the strongly interacting matter. Fig.1 shows the dependence of important femtoscopic parameters on the transverse mass of the emitted particle pair (basically it measures the transverse kick of particles). The parameter α, within errors, does not depend on the transverse mass, and its value is α ≈ 1, indicating a powerlaw shaped particle emitting source in the pertinent collisions. This is an important experimental input to theoreticians studying the strong interactions.
Grant. — NKFIH K138152 (A.László, 2021-2025)

3D mapping using muography . — Muography is an imaging tool based on the attenuation of cosmic muons to observe the density distribution of large objects, such as underground caves or fractured zones. Tomography base on muography measurements – that is, three dimensional reconstruction of density distribution from two dimensional muon flux maps – brings up special challenges. The detector field of view covering must be as balanced as possible, considering the muon flux drop at higher zenith angles and the detector placement possibilities. The inversion from directional muon fluxes to 3D density map is usually underdetermined (more voxels than measurements) which can be unstable due to partial coverage. This can be solved by geologically relevant Bayesian constraints. The Bayesian principle results in parameter bias and artifacts.

A paper by the group [2] addressed the linearized (density-length based) inversion. After testing the procedure on synthetic examples, an actual high quality muography measurement data set from 7 positions is used as input for the inversion. The result demonstrates the tomographic imaging of a complex karstic crack zone and provides details on the complicated internal structures. The existence of low density zones in the imaged space was verified by samples from core drills, which consist altered dolomite powder within the intact high density dolomite.

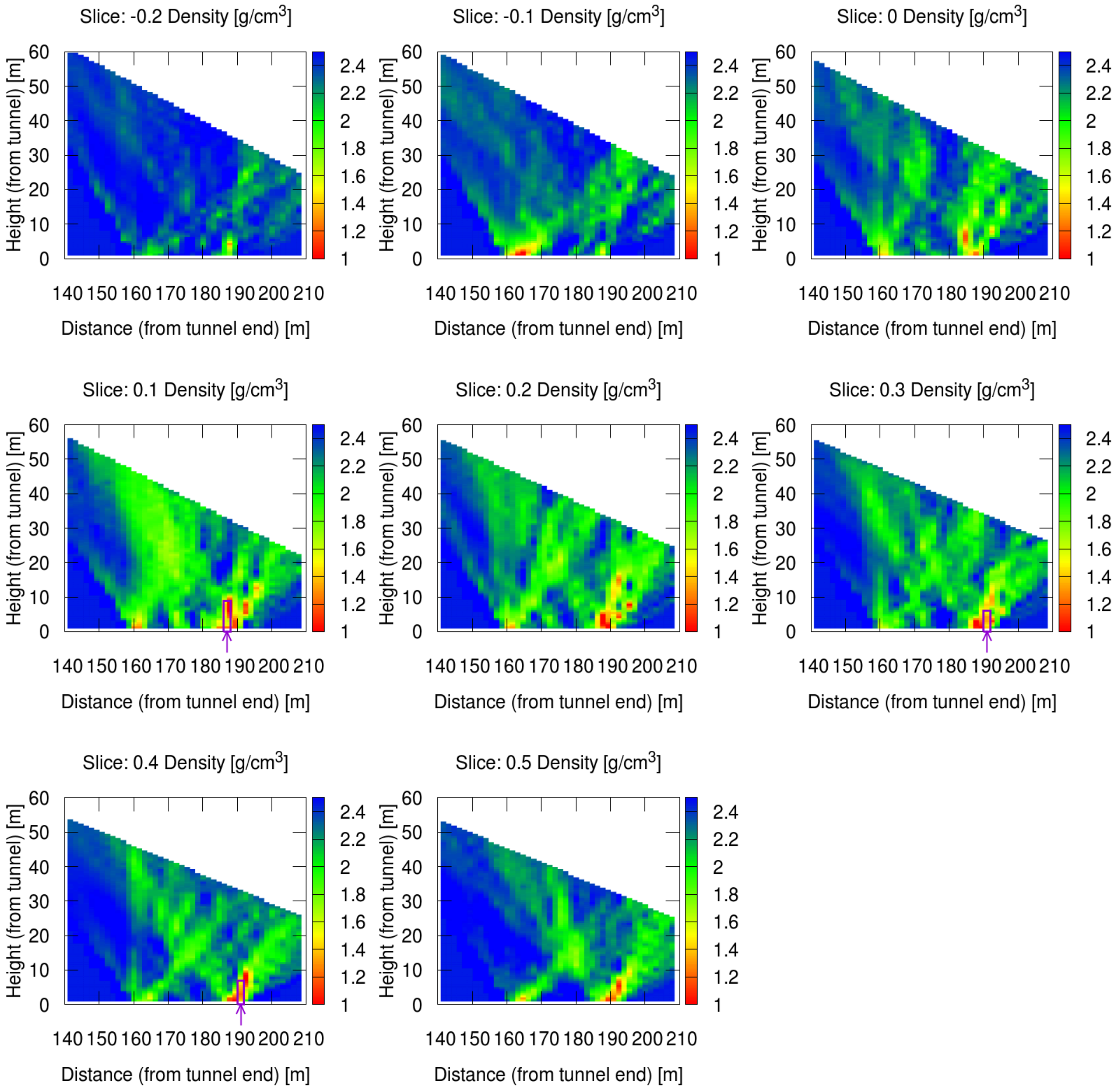

Figure 2. The result of the tomographic inversion (a posteriori density distributions) is shown in relevant slices. On the 0.1, 0.3, and 0.4 slices purple arrows show the validation drill locations.

Muography new applications. — Muography is an emerging research field, and was for the first time introduced as such, as written by selected experts in the field, in Nature Reviews Methods Primers [3]. Cosmic-ray muons have strong penetrating power and a relativistic nature, which means they can be used in a range of technologies, including imagery; positioning, navigation, timing (PNT); and secured communication in environments where conventional techniques are unavailable. Muography grew and developed into a powerful tool for investigating natural phenomena, cultural heritage and PNT. This Primer [3] is intended as an introductory article that introduces new and established muographic techniques. Case studies are provided, with examples from recent interdisciplinary advances.

Despite the fact that only two Hungarians authored the paper (D. V. and László Oláh) due to the limitations on author number, the paper clearly demonstrates that Wigner RCP is an established contributor to the international community.

Besides the results in the past years by the Research Group, a new application, called “Muometric Navigation” (see relevant Wikipedia page) had strong emphasis in the above paper. This has led to a joint patent (filed in Japan, by Wigner RCP and UniTokyo) related to muometric positioning using directional vectors from tracking detectors constructed at Wigner RCP.

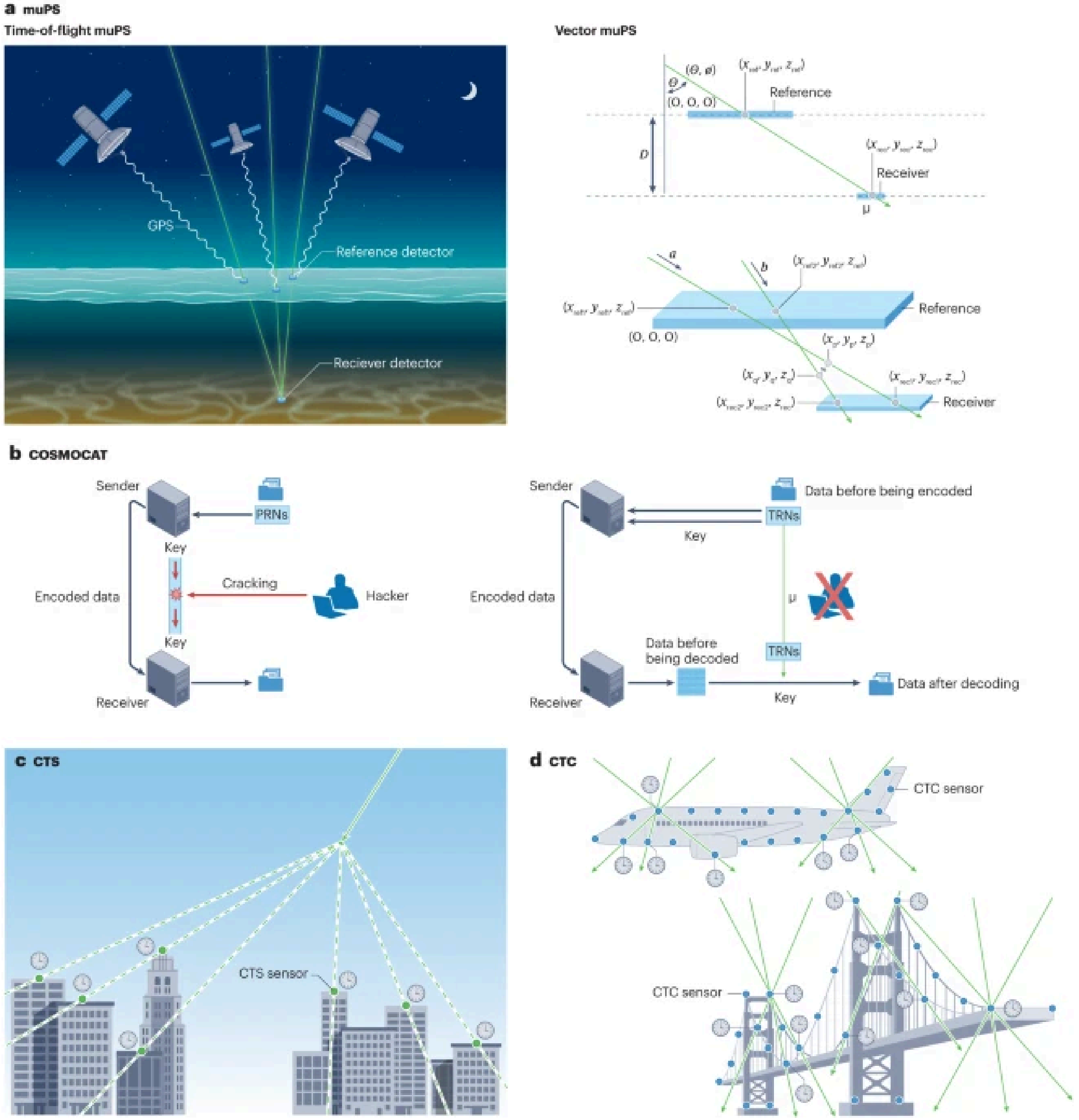

Figure 3. Muometric positioning, encoding and time calibration [3]. Top panels illustrate the navigation possibility, with the Receiver (bottom detector) can get unambiguous positioning signal without GPS (underwater, underground, or inside a large building)

References:

[1] DOI: 10.1140/epjc/s10052-023-11997-8, arXiv:2302.04593
[2] DOI: 10.1093/gji/ggad428
[3] DOI: 10.1038/s43586-023-00270-7

2022

Muography developments. — A major activity of the group is muography instrumentation development, which led to a successful Horizon Europe application, and thus remains a long term research direction. This project, called “**Mine.io**” wishes to define the future of mining industry: within that, exploration and monitoring is of key importance. A strategic collaborative agreement has been reached with the finnish company (small enterprise) Muon Solutions Oy. A key step was the systematic study and practical realization of an outdoor muographic system [1], as well as a collaborative participation in a submarine detector system below the Tokyo Bay [2]. Related to mechanical stability, Figure 1 below shows the vibrational modes of a complete chamber, simulated using FEM, and compared to measurements.

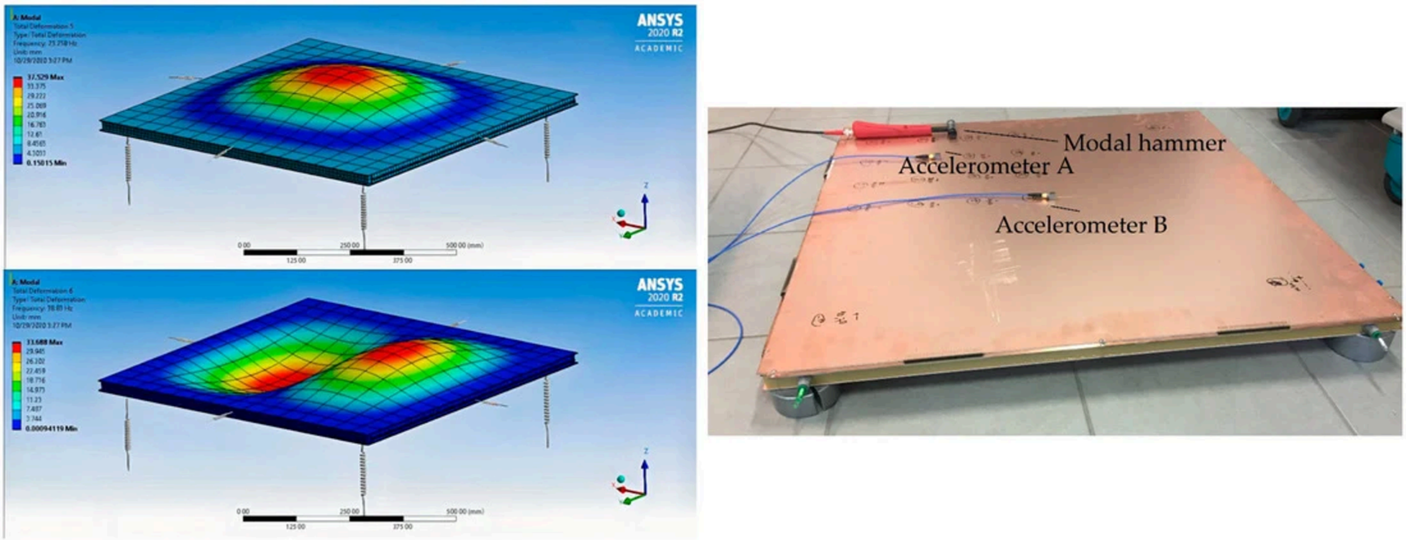

Figure 1. The mode shapes related to the second (top) and the third (bottom) eigenfrequencies in the simulation, from [1]. Measurement setup (right).

A number of successful measurement and installation campaigns were implemented during the year, a notable example is imaging the Manfredonic castle Mussomeli, Sicily, shown in Figure 2. A similar system is planned for the Etna volcano on the island, provided that access is granted by the authorities.

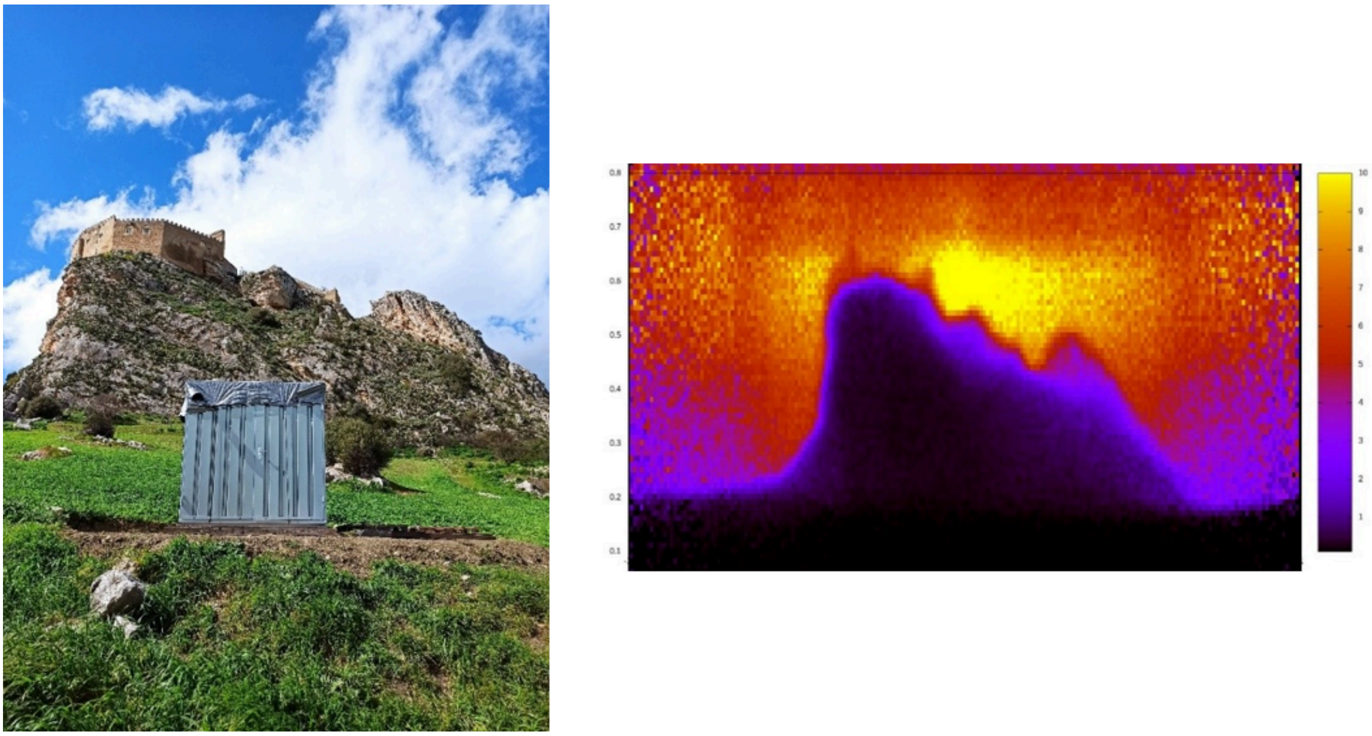

Figure 2. Manfredonic castle in Sicily (left), and as seen by muography (right)

Drift monitoring detector for the CERN NA61 experiment. — A Geometric Reference Chamber (GRC) has been constructed to precisely measure the drift velocity in the experiments large main TPC-s – the measurement is so fast that practically within a single spill (20 seconds) the vertical precision is better than a fraction of a millimeter.

The construction was implemented at the VLAB infrastructure, and used largely compatible construction methods to those of the Muography instruments, which greatly reduced development time and cost. The detector was swiftly installed at NA61 (Figure 3).

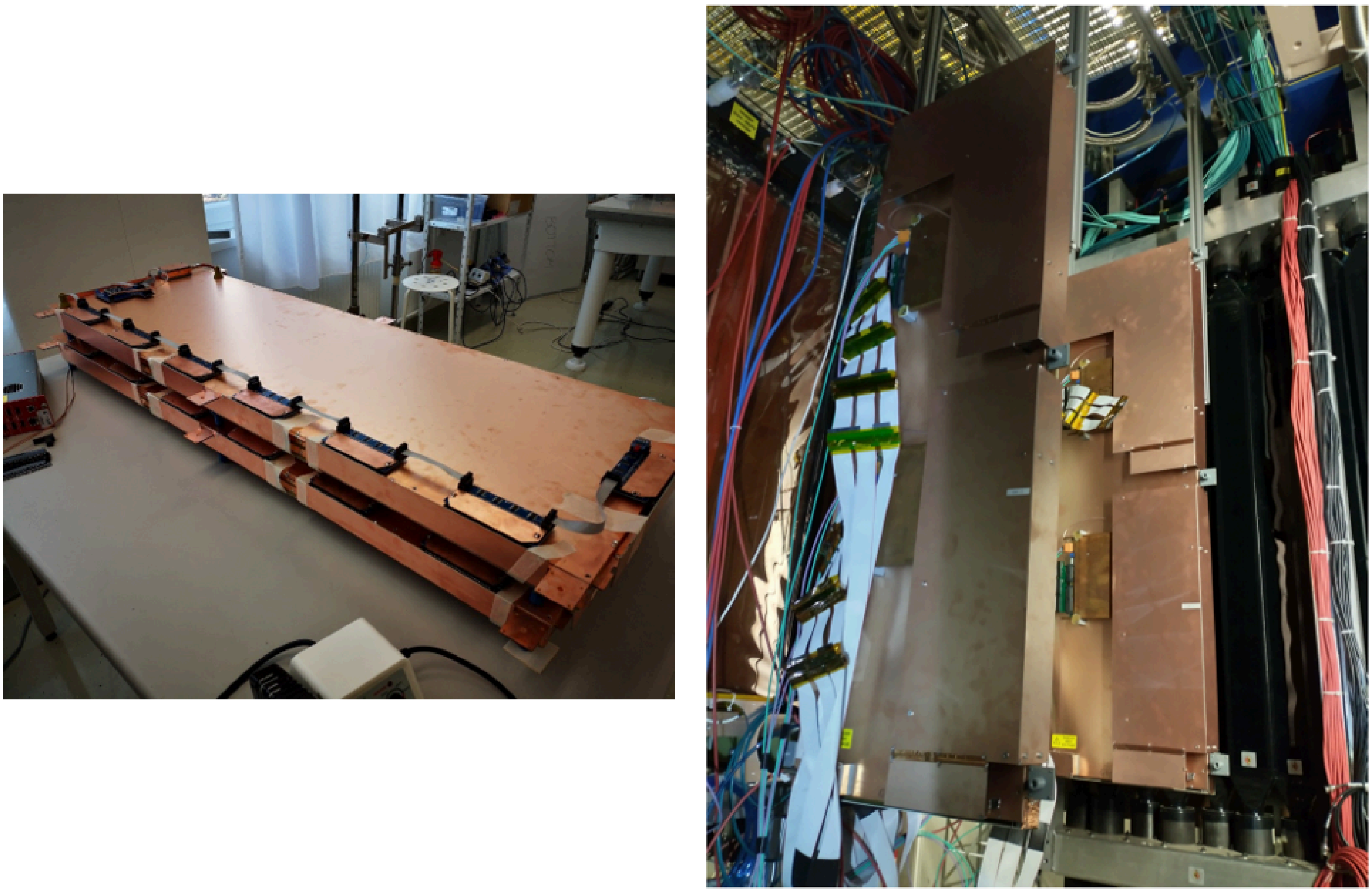

Figure 3 : The 120cm long GRC chamber for the CERN NA61 experiment: during construction (left) and inside the experiment after installation (right).

The detector operated as expected, and proved that the position resolution was well below 0.2mm. Figure 4 shows a typical track and a matching hit in the GRC (left and mid panels). The drift velocity change introduced nearly 2cm systematics in the drift region, which was unambiguously monitored with the upgraded system (right panel).

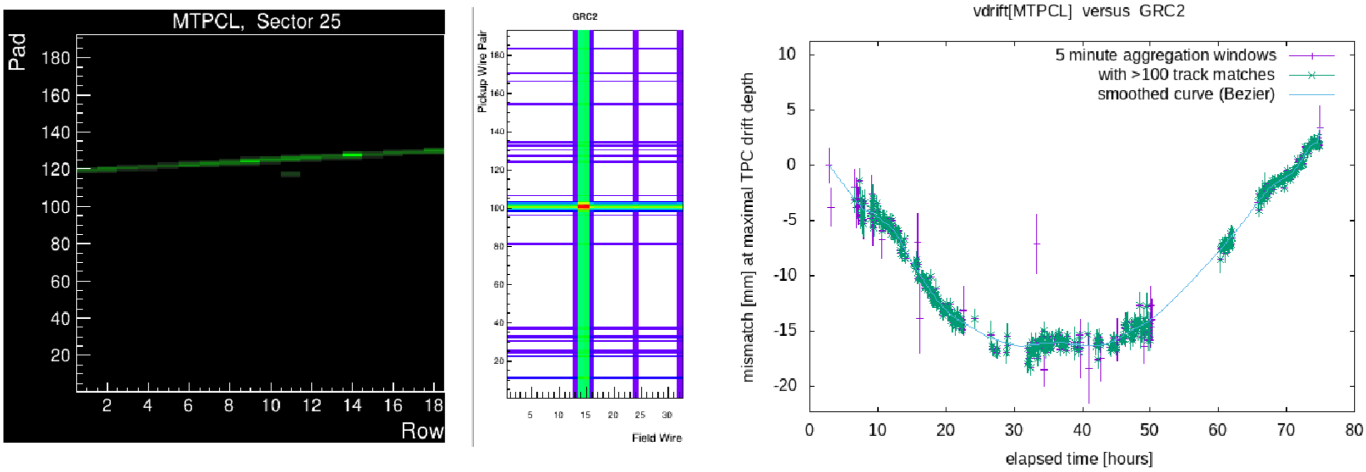

Figure 4: Left: typical event during the test beam. A local MTPCL track is seen to match a (middle) cartesian GRC hit. Right: the time dependent drift velocity correction, expressed in terms of TPC-GRC mismatch at the maximal drift depth.

Excellent research infrastructure: “Vesztergombi High Enery Physics Laboratory”. — Along with other infrastructures at the Wigner RCP, the VLAB became a “Top-50” recognized excellent infrastructure, a designation awarded by the NRDIO (NKFIH). The VLAB is an open laboratory infrastructure, including a wide range of detector development facilities, serving groups of the High Energy Physics Department, as well as others within our outside Wigner RCP. A new laboratory space, of more than 60 square meter, has been renovated and equipped, mostly for muography instrumentation activities.

References:
[1] https://doi.org/10.3390/instruments6040074
[2] https://doi.org/10.1038/s41598-022-20039-4
[3] https://doi.org/10.1038/s41598-022-10078-2

2021

Muography developments. — A major activity of the group is muography instrumentation development, which led to successful national grant applications, and thus remains a long term research direction. One of the key commitments is to increase the Technological Readiness Level (TRL) of the systems, which requires measurements in relevant conditions. Figure 1 below shows a design called “Muon Tomograph Large” (MTL), both in the lab and in an underground measurement (thus paving the way to certification of TRL5). A strategic collaborative agreement has been reached with the finnish company (small enterprise) Muon Solutions Oy. A key step was the systematic study and practical realization of an outdoor muographic system with very low gas consumption (below 3 litres per day) [1], as well as a collaborative participation in a submarine detector system below the Tokyo Bay [2]

Figure 1. MTL3 during final assembly in the lab, and in an underground measurement site in Finland.

Detector physics and new methods. — Cosmic muons penetrate matter, while secondary particles are created, mostly electrons and gamma rays. The amount and the spectra of these secondaries strongly depends on the material composition of the target. This opens a novel way of non-invasive material identification, that could be used in applied physics or even in archaeology. The Serbian-Hungarian collaboration between the Novi Sad University and the Wigner RCP has been earlier the pioneer of these studies, with determined evolution of the required detection system. The COMIS (COsmic Muon Induced Secondaries) is the contemporary setup, assembled in 2021, shown in Figure 2. Parallel layers of modified MWPCs do tracking of the traversing muons, while electron and gamma radiation are detected in the surrounding plastic scintillator array. Combined data acquisition system allows proper triggering and online event-selection.

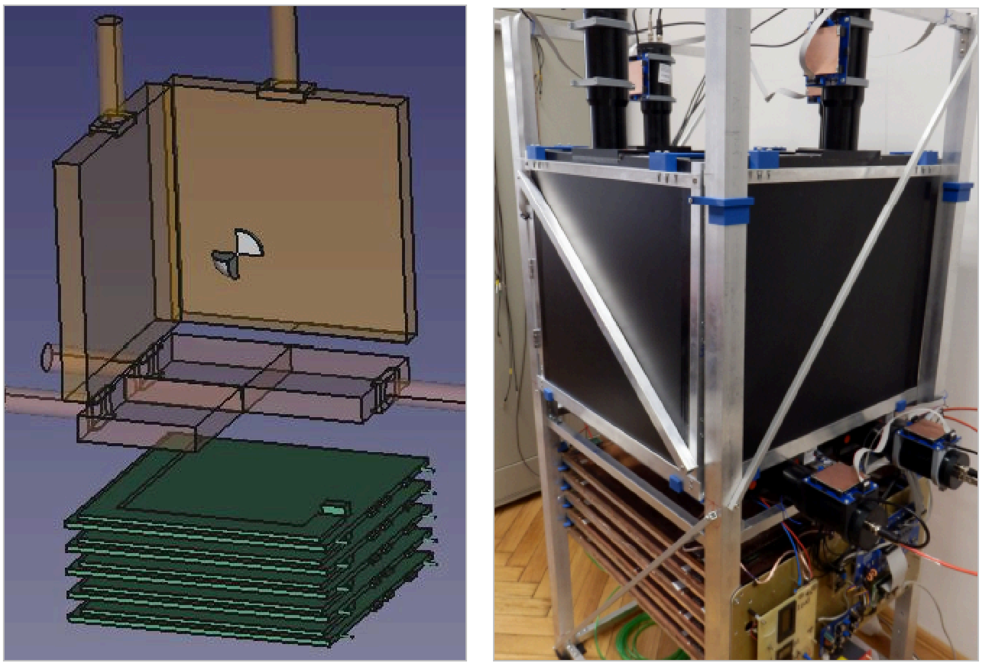

Figure 2 : (Left) The schematic model of the COMIS setup, with front scintillators hidden for better view. (Right) Photograph of physical assembled setup.

Background in CubeSat-based cosmic detectors. — GRBAlpha is a scientific 1U nanosatellite (10x10x10cm^3) which is an In-Orbit-Demonstration mission. It is the pathfinder of a planned 9 satellite fleet that is aimed to detect astrophysical transient sources, including short and long gamma-ray bursts, in the X-ray and gamma-ray regime. It is revolutionary in a sense that the mission costs a fraction of previous "large" satellite missions in terms of cost and manpower.

GRBAlpha was launched 22 March 2021 from Baikonur Cosmodrome in Kazakhstan on board of Soyuz 2.1a rocket as part of a rideshare mission along with 38 other satellites. GRBAlpha is developed and built with the collaboration of several institutes and companies including the Konkoly Observatory and Eötvös Loránd University, Hiroshima University, University of Košice, Nagoya University, Masaryk University and Spacemanic.

A key design parameter, as well as measure of scientific capabilities is the expected backround level, which determines the signal-to-noise ratio of the system. A detailed simulation framework has been developed [3] to evaluate the detector signals from all possible sources, for relevant geometries. As the satellite is actually on-orbit as of now, the simulation results has been verified and are in good agreement with measured data. The satellite simulation geometry and the actual flown unit is shown in Figure 3.

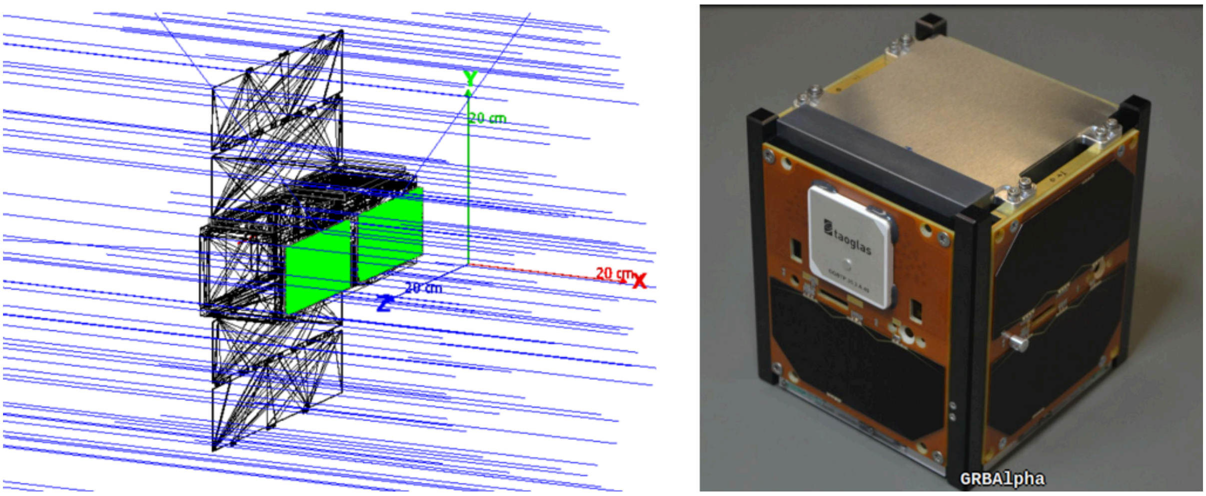

Figure 3. The Camelot satellite, a model of a gamma-detecting microsatellite, within the GEANT4 simulation framework (left). The actually flying GRBAlpha detector (right).

Excellent research infrastructure: “Veszter-gombi High Enery Physics Laboratory”. — Along with other infrastructures at the Wigner RCP, the VLAB became a “Top-50” recognized excellent infrastructure, a designation awarded by the NRDIO (NKFIH). The VLAB is an open laboratory infrastructure, including a wide range of detector development facilities, serving groups of the High Energy Physics Department, as well as others within our outside Wigner RCP.

2020

Muography developments. — As pandemic conditions prohibited installations abroad, detector developments and local demonstration measurements continued to improve the imaging capability of the Muography Observation System (MOS), a structure which is the shared IP of Wigner RCP and the University of Tokyo [1]. Besides useful data gathered at the Sakurajima Muography Observatory, the high performance and low background system has been applied for a spectacular demonstration: how muons can “look through a mountain”. Data taken during 4 months revealed high definition image of the János-hill (see Figure 1), such that it is fully concealed behind the ridge of the Fairy-rock (Tündérszikla).

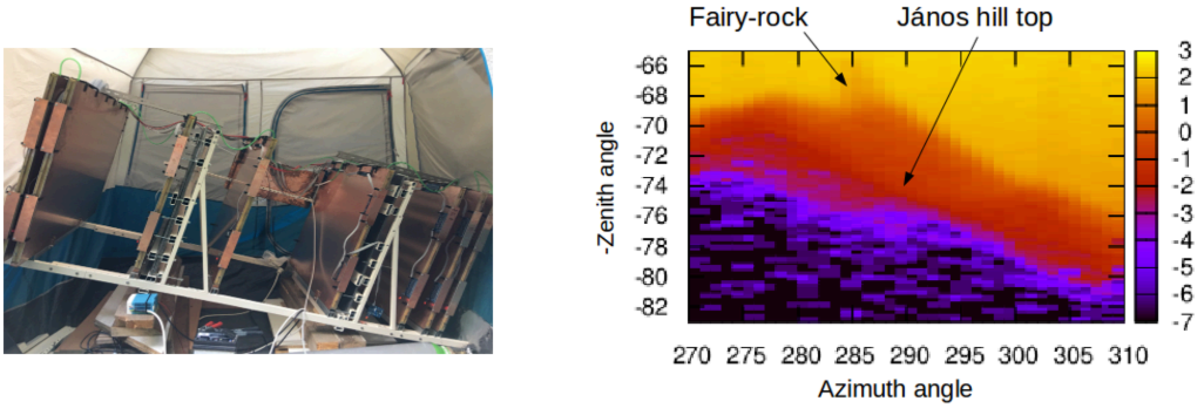

Figure 1. *Seeing through a hill with muons: a MOS-type imaging system (left panel) was installed facing the Fairy-rock in the Buda hills, such that the ridge concealed the János-hill. The muography image (right panel) reveals the silhouette of the background hill.*

Arrangement for calibration-free TPC tracking system. — Time Projection Chamber (TPC) detectors feature excellent tracking performance, efficient usage of available space, and low material budget (low total amount of material along the particle trajectory). One fundamental drawback is that as one of the coordinates is measured by an unknown electron drift time, external triggering and timing components are needed for the operation. Such a detector has been constructed and tested [2] in collaboration with the IMP at Lanzhou (China) shown in Figure 2. As an improvement over the previously mentioned drawback, a special arrangement has been invented and defined as an intellectual property [National patent, 2020. december] which utilizes a pair of TPC units, but with perpendicular drift directions. In fact if the drift directions are opposite, considerable background suppression is achievable, as shown at the NA61 experiment [3], however, the “perpendicular” arrangement eliminates the need of any external timing reference, and external drift velocity calibration.

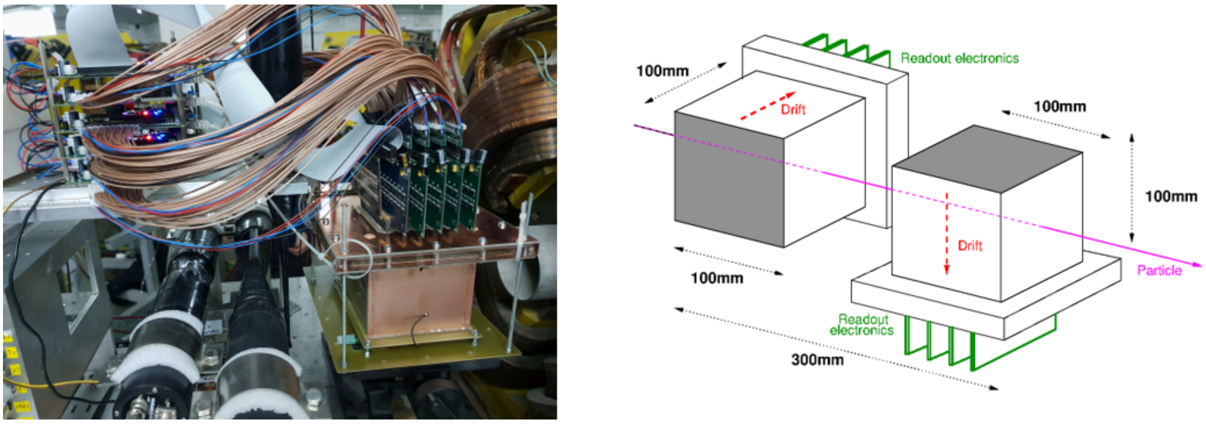

Figure 2. *The TPC detector, one unit, during beam testing (left panel) [2] which may be coupled to an identical unit but with perpendicular drift direction [*National patent, 2020. december*] thus allowing tracking without any external trigger or calibration components.*

Most practical activities and installations in various locations in Europe and Japan had to be shifted to 2021, which will allow to exploit the in-house developments of this complicated year.

2019

Sakurajima Muography Observatory (SMO). — The SMO, built in the collaboration with the University of Tokyo, and Wigner RCP, has become the world's currently largest running muography tracking system by this years expansion, and is taking data continuously with a sensitive area of 8 square meter. The results were published, amongst others, in GRL [1]. The measurement itself targets the Minami-dake and Showa craters of the Sakurajima (Figure 1), for which since 2018, the activity shifted from Showa towards Minami-dake.

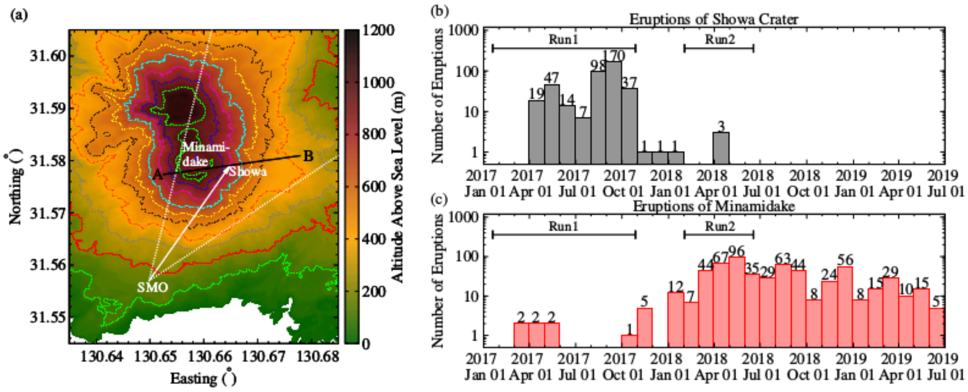

Figure 1. (a) The map of Sakurajima volcano (Geospatial Information Authority of Japan, `http://www.gsi.go.jp`) shows the location, orientation (*white arrow*), and angular acceptance (*white dashed lines*) of SMO. The AB line shows a cross-section across the craters. (b-c) The monthly number of eruptions are plotted for the Showa (b) and the Minamidake (c) craters from January 2017 (`http://www.jma-net.go.jp`). *Arrows* show the durations of Run 1 and Run 2.

Figure 1. Left panel shows the Sakurajima volcano elevation map, with the tracking system at the SMO site. The right panel indicates the monthly eruption activity in the two craters. The measurement for [1], has been divided to two periods, Run 1 and Run 2.

The relevant finding in [1] has demonstrated the connection between the suppressed eruption activity. Figure 2 shows the measured density (inferred from the elevation maps, assumed to be the same for the two periods). The lower part of the Showa crater has increased in density, with the most likely explanation being a volcanic plug formation. It is the first time that such quantitative measurement is available for geo-scientists.

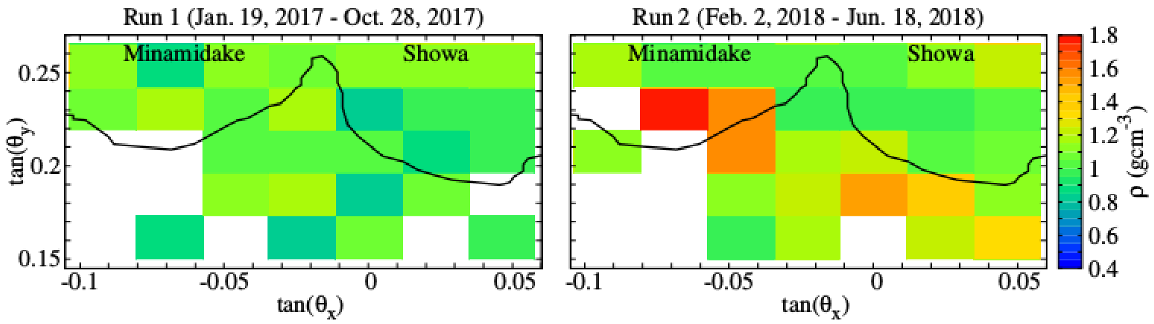

Figure 4. (a) The average densities are plotted with a spatial resolution of approx. 60 m for Run 1. (b) The average densities are shown for Run2. Density values are plotted in those angular bins where density was measured for both Run 1 and Run 2. The shape of craters (*solid line*) was extracted along the AB line of Figure 1a.

Figure 2. Average densities with a spatial resolution of around 60 m (observed from 3km distance), for Run 1 (left) and Run 2 (right). A clear signal demonstrates the increased observable density, hence material deposit [1].

Detector development. — The group continues the detector development activities, related to CERN COMPASS [2] and CERN RD51 [5], as well as the muography applications [3]. The COMPASS ring imaging Cherenkov detector is a novel system based on Micro-mesh and Thick-GEM detector, paving the way for future MPGD-based large particle identification systems.
Using the “Leopard” scanning system, edge effects and GEM faults have been studied [5]. The example on Figure 3 shows an etching defect, which is here demonstrated to be harmless: there is no high-gain region related to the defect.

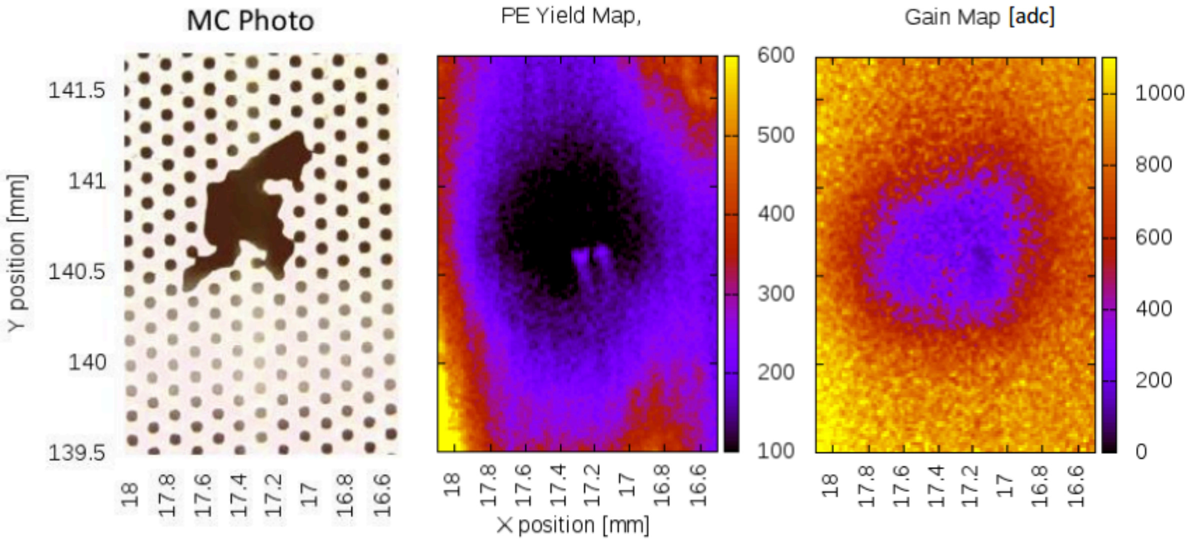

Figure 3. Defect on a GEM: optical microscope image (left), and photo-electron production yield (middle) and gain (right). There is no hot-spot appearing on the gain map [5].

External links:
[1] https://doi.org/10.1029/2019GL084784
[2] https://doi.org/10.1016/j.nima.2019.162378
[3] https://doi.org/10.20965/jdr.2019.p0701
[4] https://doi.org/10.1098/rsta.2018.0135
[5] https://doi.org/10.1016/j.nima.2019.162726

2018

The concluded “Momentum” grant support from the HAS has been converted to a permanent funding starting from this year. The group has concluded commitment to the CERN ALICE TPC Upgrade experiment, as well as completed two Deliverables for the H2020 grants BrightnESS and AIDA2020, respectively. An interesting test of General Relativity has been formulated (A. László). Using detectors developed by the group, an active volcano imaging has been performed (L. Oláh et al), in collaboration with Tokyo University and the NEC company.

Contributions to CERN ALICE TPC Upgrade Collaboration. — The activities of the group in the TPC Upgrade Collaboration has been concluded, with about 400 large size GEM foils processed in Budapest. The Advanced Quality Assurance testing site which was established, is the second step of the TPC construction after production (at CERN), and the foils were forwarded to Germany and the USA.

Imaging with cosmic muons. — The application of cosmic muons for large scale imaging has been a research direction in the group in the previous years. An important application for cosmic muons detectors, developed in the last years by the group, is imaging the interior of volcanos. This direction was pursued by Japanese and various European groups. Gaseous tracking detectors, and in our case, a specific type of an MWPC developed by our group, are highly competitive with the traditional scintillators in terms of cost, weight and power consumption. The detector system has been installed by the Sakurajima volcano in Japan (southern island), see Figure 1, to demonstrate the true applicability and sufficiently low level of background, and to gain experience for the future developments. Presently 4 square meter sensitive area is installed, the largest of its kind in the world, with the results published in Scientific Reports (L. Oláh et al). The japanese NEC company has licensed the MOS for research purposes, and continued its licensing rights and funding also this year.

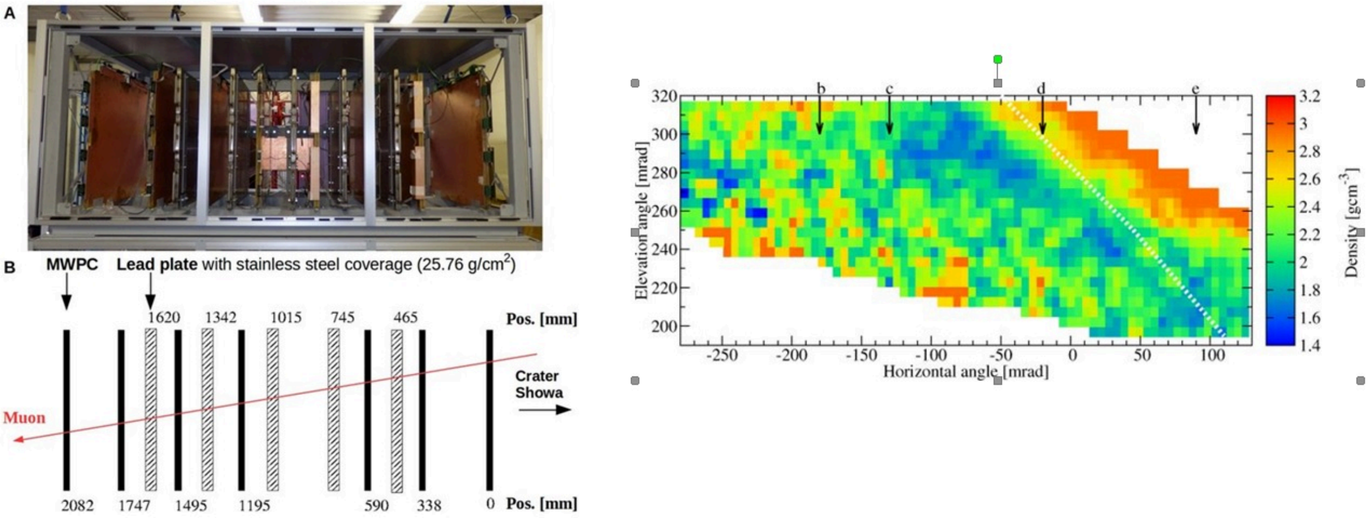

Figure 1. *Outline of the MOS at Sakurajima, with the image of the Showa crater*

General Relativity effects in storage ring

In the paper Class.Quant.Grav.35(2018)175003 (A. László) a mechanism was proposed in order to perform a General Relativity (GR) experiment using spin polarized particle beams. The principle of the experiment is the following.

The magnetic moment anomaly, also called g-2, of particles are measured in magnetic storage rings: in a homogeneous magnetic field the particle spin precesses in the orbital plane at a rate which is proportional to the magnetic moment anomaly. The electric dipole moment (EDM) of particles are measured in combined magnetic and electric storage rings in which the magnetic spin precession is compensated by a suitably chosen electric field, and such settings are therefore called frozen spin storage rings (Figure 2, left panel). If an EDM of a particle existed, it would torque the spin out of the orbital plane in a frozen spin ring setting. In our paper it was shown that due to General Relativity, Earth's gravitational field also would torque the particle spin out of the orbital plane, similar to an EDM effect (Figure 2, right panel). Therefore, it was proposed to consider the optimization of EDM rings in such a way that the pertinent GR effect can also be detected. This would provide an unusual test of GR in laboratory circumstances: for microscopic particles, at relativistic speeds, along non-geodesic (forced) trajectories, and the tensorial nature of GR would be at test, not merely the gravitational drag.

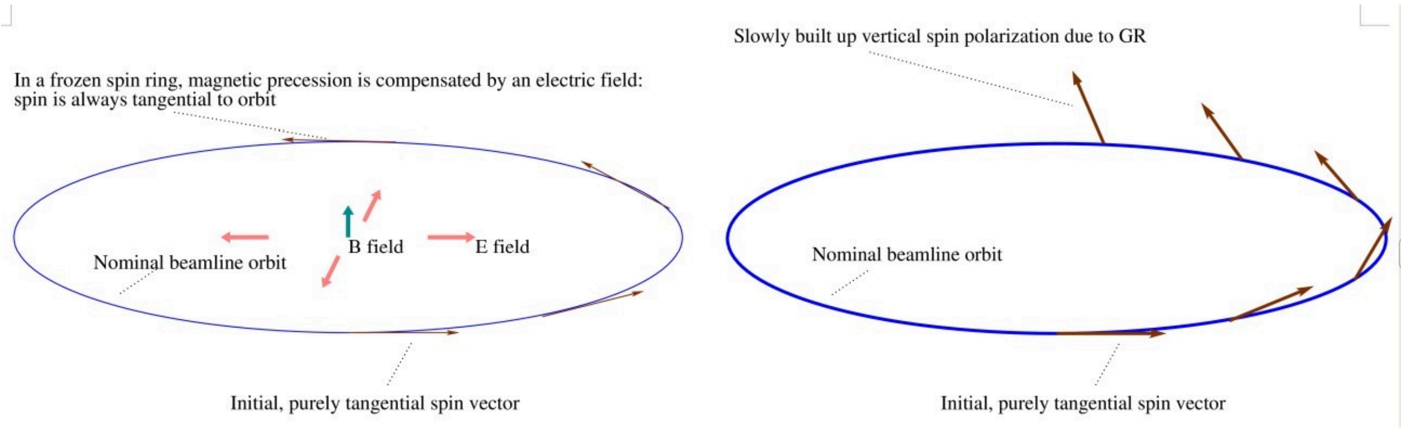

Figure 2. *Frozen spin muon experiment, and precession effect due to General Relativity effect*

Investigation of neutron scattering. — In order to quantify the neutron scattering in the ESS Multi-Blade detector, highly detailed simulations were performed and compared to measurements, shown in Figure 3. This study has revealed that the scattering (causing background and degradation of image contrast) is extremely small, matching the ESS requirements.

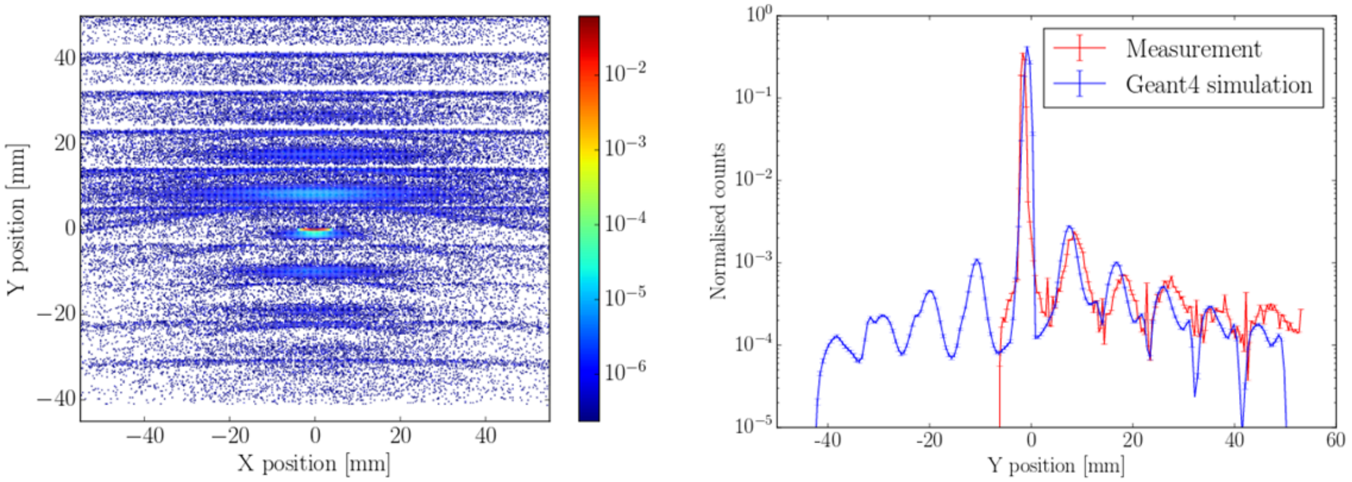

Figure 3. *Scattered neutron position for the Multi Blade detector (in the plane vertical to the beam, left panel), and comparison of the simulations to actual measurement (right panel)*

2017

The year 2017 has concluded the "Momentum" grant support of the group from the HAS, which will continue as a permanent funding. The key focus of the group was the completion of the already existing commitments. This includes contributions to specific CERN experiments, such as the ALICE, NA61 and RD51. Detector physics projects and neutron detector development were financed by H2020 grants. Using detectors developed by the group, an active volcano imaging has been performed in collaboration with Tokyo University and the NEC company.

Contributions to CERN Collaborations. — The activities of the group in the Time Projection Chamber (TPC) Upgrade Collaboration has reached nearly half way, with about 200 large size gas electron multiplier (GEM) foils processed in Budapest. The Advanced Quality Assurance testing site which was established, is the second step of the TPC construction after production (at CERN), and the foils are forwarded to Germany and the USA. Within the framework of the NA61 Collaboration, three new TPC-s were built and installed to capture the forward particles.

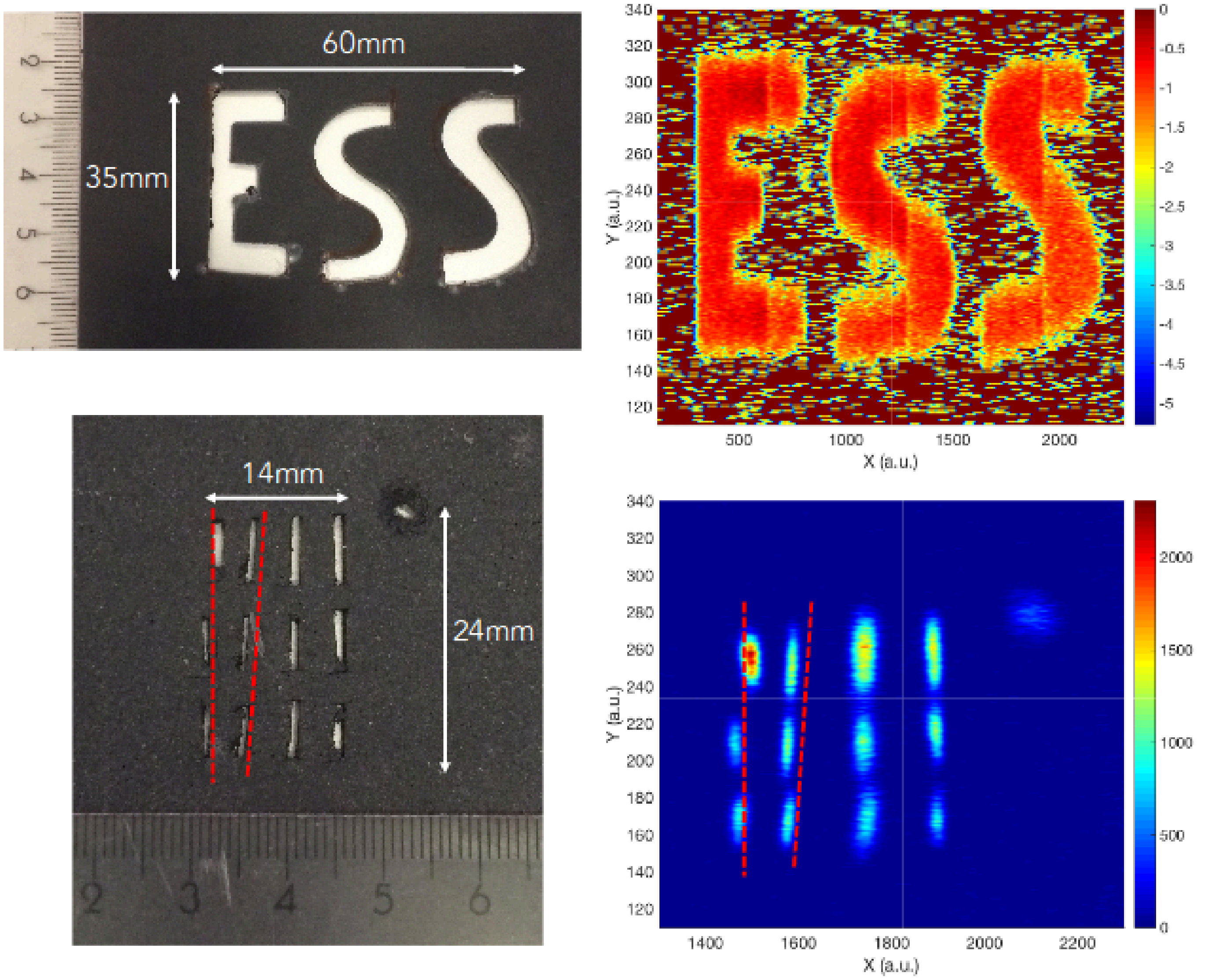

Figure 1. Images taken with the Multi-Blade detector, using neutrons at the Budapest Neutron Center. Precise and high contrast images have been recorded, consistently with the design goal for neutron reflectometry at ESS.

Imaging with cosmic muons. — The application of cosmic muons for large scale imaging has been a research direction in the group in the previous years. An important application for cosmic muons detectors, developed in the last years by the group, is imaging the interior of volcanos. This direction was pursued by Japanese and various European groups. Gaseous tracking detectors, and in our case, a specific type of a multi-wire proportional chamber (MWPC) developed by our group, are highly competitive with the traditional scintillators in terms of cost, weight and power consumption. A utility patent has been filed in Japan, owned jointly by Wigner RCP and Tokyo University, for the so-called “Muography Observation System” (MOS). The detector system has been installed by the Sakurajima volcano in Japan (southern island), to demonstrate the true applicability and sufficiently low level of background, and to gain experience for the future developments. Presently 1.2 square meter sensitive area is installed, which will increase in the coming years. The japanese NEC company, which has licensed the MOS for research purposes, has started a cooperation with the patent owners to understand the market needs for muography.**Multi-Blade detector demonstrator for ESS.** — The high intensity, high position resolution neutron detector, called the Multi-Blade, has been tested with cold neutron beam at the Budapest Neutron Center. The results show that the position resolution, below 0.5mm in one direction, is indeed reached. Other testing has clarified the intensity tolerance of the design, which, by the delicate interplay between geometry and detection mechanism, is higher than most other competing versions. Demonstration images are shown in Fig. 1.

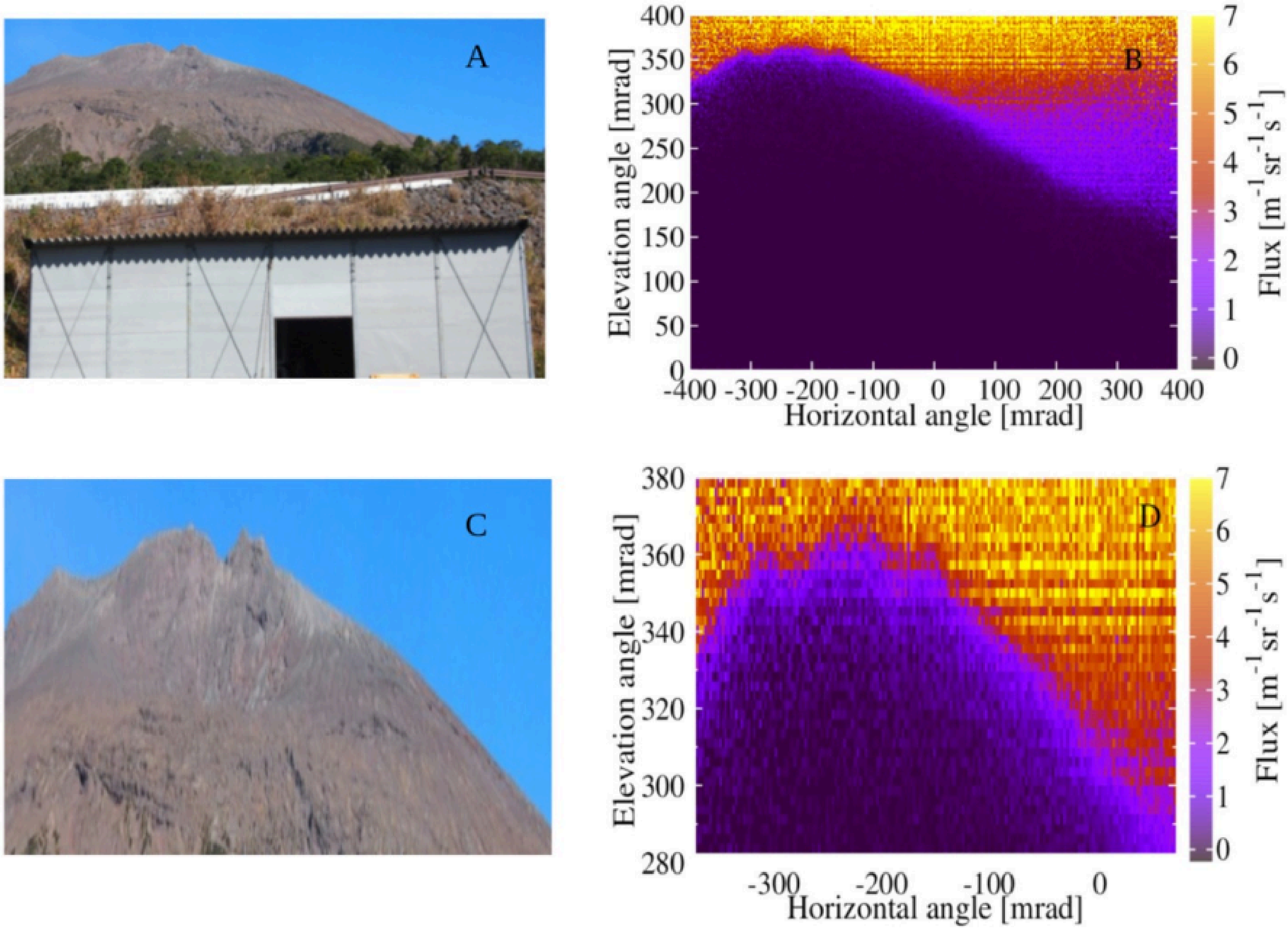

Figure 2. *Visual (left) and muographic (right) images of the Sakurajima volcano in Kyushu (Japan), taken with the MOS. The detectors were developed at Wigner RCP, installed in a structure designed and constructed by Tokyo University.*