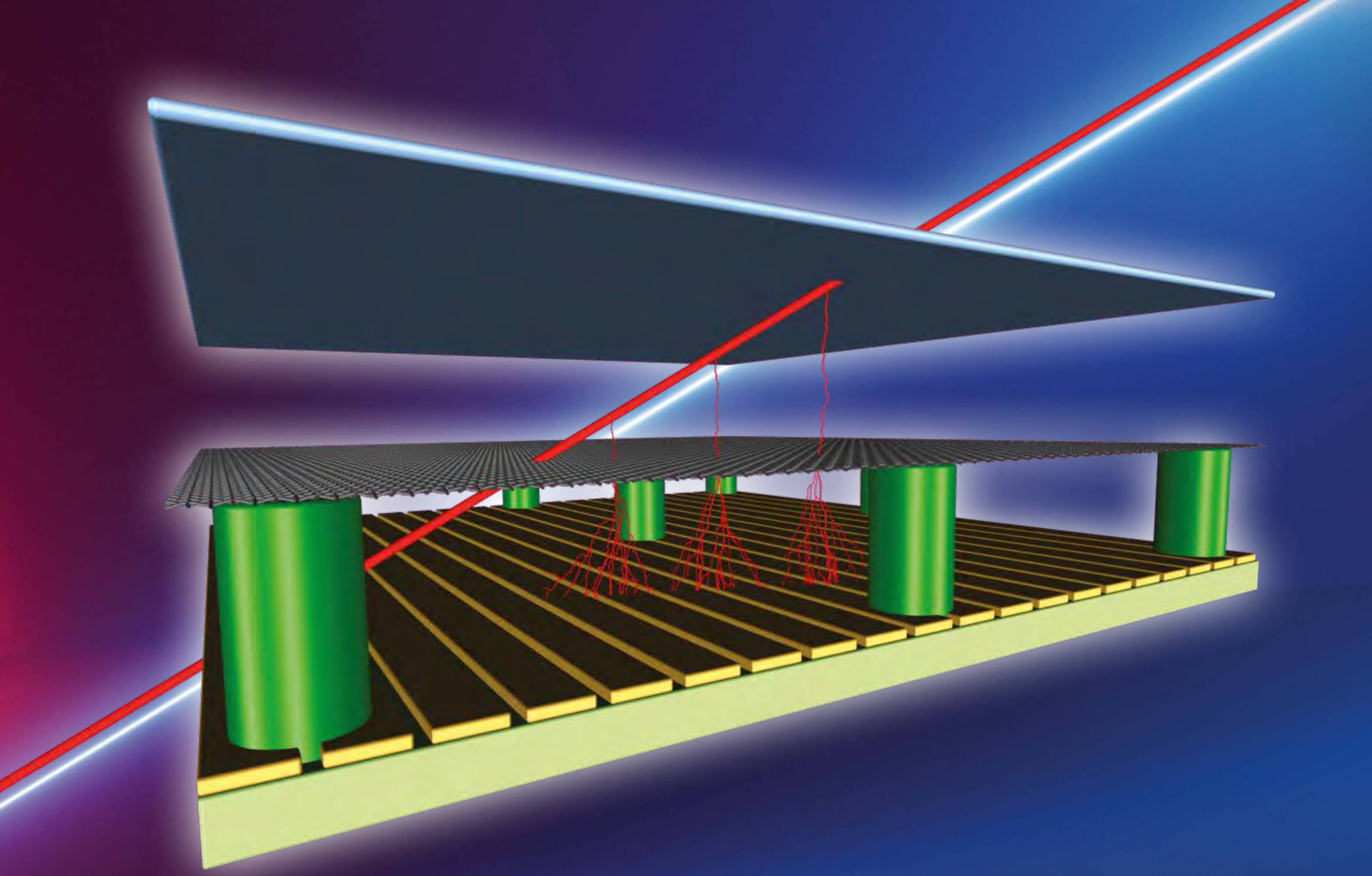
N° 99 - 2022

ScintillationS

The adventures of **Micromegas**



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The adventures of Micromegas

Index of tribulations of
MicroMegas : MicroMesh Gaseous Structure detector

N.B. The names and acronyms used in the issue are defined in the glossary (p.30) and marked in the articles by the index[g].
The references given in square brackets appear in the bibliography or at the end of the article; they are abbreviated according to the conventions indicated on p.31.

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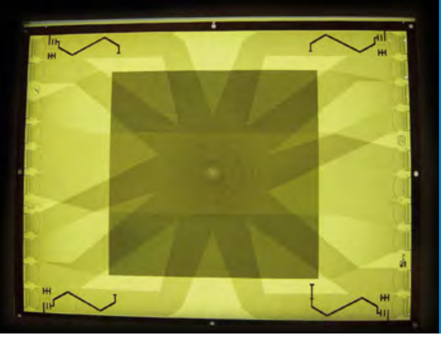

The legend of Micromegas

At IRFU, Micromegas has become a mythical object, the key to the running of most experiments. According to the needs of physics, it is reshaped, extended, curved, and inserted at will into the experimental devices, precise, efficient and resistant. This special issue recounts all the adventures of Micromegas since its genesis, protean hero in the realm of subatomic physics.

We will start by presenting this family of detectors, the analysis of their technical lineage in order to place them in the context of the evolution of gaseous ionization detectors. We will then recall the first years of Micromegas experiments: first trip to CERN to study the spin of the nucleon (COMPASS), followed by a period in the United States to understand the structure of the nucleon with CLAS12 at CEBAF. In a few years, the plane becomes cylinder and 3D reconstructions offer a new field of measurements to physicists. The issue presents the multiple evolutions made to push back the technical constraints and increase the performances of Micromegas - resistance to particle fluxes, resolutions for position and time measurements.

To date, Micromegas devices are able to adapt to the specifications of most of the experiments carried out by the IRFU laboratories. The transformations are ongoing: Micromegas is involved in the search for rare events associated with new particles, theoretical hypotheses that need to be confronted with observation; it is also used near the pyramids in Egypt, in search of secret cavities, and in cylinders, around a cryogenic target to measure the trajectories of charged particles during studies of nucleon and nucleus structure. For its designers, the discovery potential of Micromegas was promising for particle physics experiments. This excerpt from an article* by Yannis Giomataris in 2010, in homage to Georges Charpak, shows that: "[...] In this research [at CERN in 1992], we were using a parallel-plate gas detector, and by optimizing it, we experimentally demonstrated the advantage of a small amplification stage. This triggered the idea of building a device with an even smaller amplification stage and from this was born the concept of a new detector: the Micro-Mesh gaseous structure, the MicroMegas, which our group at Saclay has developed since 1995. Georges used to say that this detector and other new concepts belonging to the family of micro-grid gas detectors would revolutionize nuclear and particle physics, just as his own detector had done.".

Micromegas was thus born with this vision of an evolving, surprisingly powerful detector, capable of responding to the great challenges of physics. This founding myth has accompanied the development of various IRFU thematics. Whether it is to explore the structure of the nucleon and nuclei, to search for new particles, or to perform three-dimensional imaging, the evolutions and applications of Micromegas have followed the experiments that are illustrated in this issue.

That this emblematic detector was born in a department uniting the domains of matter physics and detection deserves to be emphasized: physicists, designers and technical experts have worked together on developments that have pushed back the limits of experiments and made it possible to advance our fundamental knowledge. New questions arise from this change of horizon in our understanding of the particle world, for which increased performance is required.

MicroMegas has thus gone beyond its historical composite name, the result of a technical acronym, to symbolically become that legendary character, "Micromegas", inhabitant of Sirius who explores the universe in Voltaire's philosophical tale. Accompanied by a dwarf from Saturn, Micromegas sets out to meet the creatures of the solar system. On their way, they meet microscopic humans with whom they converse about the question of measurements. *Micro* and *mega*, the Sirian is *small* in the Universe, *tall* compared to his fellow traveler, both infinitely tall compared to the microbes that they do not see on Earth.

Voltaire (1694-1778).
Micromégas (écrit en 1738-1739, publié en 1751).
Chapitre septième, 7.4 Conversation avec les hommes.

Micromégas et le nain Saturnien rencontrent des Terriens.
Illustration** de l'édition de 1778

« Le voyageur s'adressant aux sages : « dites-moi, je vous en prie, à quoi vous vous occupez ». « Nous disséquons des mouches », dit le philosophe, « nous mesurons des lignes, nous assemblons des nombres; nous sommes d'accord sur deux ou trois points que nous entendons et nous disputons sur deux ou trois mille que nous n'entendons pas ».
Il prit aussitôt fantaisie au Sirien et au Saturnien d'interroger ces atomes pensants, pour savoir les choses dont ils convenaient. « Combien comptez-vous, dit-il de l'étoile de la Canicule à la grande étoile des Gémeaux ? ».

Ils répondirent tous à la fois : « trente-deux degrés et demi. Combien comptez-vous d'ici à la Lune ? Soixante demi-diamètres de la terre en nombre rond. Combien pèse votre air ? » Il croyait les attraper, mais tous lui dirent que l'air pèse environ neuf cents fois moins qu'un pareil volume de l'eau la plus légère, et dix-neuf cents fois moins que l'or de ducat. Le petit nain de Saturne, étonné de leurs réponses, fut tenté de prendre pour des sorciers ces mêmes gens auxquels il avait refusé une âme un quart d'heure auparavant. »

*Voltaire, **Éléments de la philosophie de Newton (1738) :***
« L'homme n'est pas fait pour connaître la nature intime des choses ; il peut seulement calculer, mesurer, peser et expérimenter ».

The two travelers finally find themselves measured by these very particles that they considered uninteresting at first, only moved by a random agitation. They can only glimpse these tiny creatures through a cleverly designed magnifying glass... Big-small? These relative notions are fundamental questions of scale, decided by the precise and accurate measurements of some of these insignificant humans. Micromegas detects a realistic intelligence among those who are interested in measuring the world rather than dissecting metaphysical questions. He meets humans who prove to be ingenious, with great capacities of reflection, observation and inventiveness, seeking to build new objects to scrutinize Nature, and whose know-how is applied to weigh, estimate the size, measure, count what surrounds them.

The physicist, engineer-technician-researcher, is then that human being endowed with reason and practicality, who builds detectors to understand the world through estimates of mass and size scales, by measuring all observable structures. With their Micromegas, complex works of art at the crossroads of microelectronics, detector science and mechanical macrostructures, the IRFU explorers set out to meet microscopic particles in order to decipher phenomena governed by fundamental laws on the scale of the Universe.

Valérie Lapoux

* I. Giomataris (Y.G), Le courrier du Cern, November 2010, https://cerncourier.com/cws/article/cern/44361
** "Micromégas, Romans et Contes" M. de Voltaire, board p. 32, by Ch. Monnet, designer ; G. Vidal, engraver ; Bouillon : Ed. de la Société typographique, 1778.
Photo/picture credits: (French National Library) BnF, Réserve des livres rares, Rés. P Y2 1809 (2).

The genesis of Micromegas

An interview with one of its creators, Ioannis Giomataris, by Fabien Jeanneau and Pierre Manil

To enlighten us on the origins of Micromegas and on the prodigious transformation of an idea into technology... we consulted one of its inventors: Ioannis Giomataris*. He welcomes us in his laboratory where he pursues his dreams and experiments on "his" detectors.

Ioannis, can you tell us how you started the odyssey of Micromegas?

The story begins in 1994, when I arrived in Saclay. In collaboration with the Fermilab laboratory in Chicago and with the CERN, we were trying to develop an optical detector, nicely named "the trigger for beauty", to select B[1] mesons resulting from proton-proton interactions. Existing gas detector technologies posed several problems (discharges, breakdowns, noise limitations). To overcome these problems, different ideas were proposed. With Leon Max Lederman and Georges Charpak, we had already published in 1991 a first idea[2] ("A trigger for beauty"!) - it will be at the origin of Micromegas. Georges had been living in Paris for two years. I was his closest collaborator. Our relations were very friendly. We talked about physics, not only in the lab, but also during the summer vacations, because Georges used to invite his colleagues when he went to Cargèse, in Corsica[3], with his family.

What was the operating principle of this detector?

The *Hadron Blind Detector* (HBD) had to present a parallel plate architecture, which has been used for the last 50 years. It had to include two stages separated by a grid: one for ionization and the other for amplification. In this sense, the Micromegas did not represent a new architecture. But at the time, these detectors were sort of "mega structures". At that time at CERN, it was accepted that the optimal distance between the grid and the anode plane, called the ***gap*** (amplification space), should be 4 to 5 mm to guarantee a feasible solution. It was considered technically impossible to maintain a grid very close to the anode plane while keeping a very good parallelism because of the electrostatic force. This problem was later solved. Nowadays, to produce a Micromegas, we are able to set up a grid at 50 or 100 µm from the anode plane...!

In developing the HBD, we tried to decrease the amplification gap to proportionally reduce the background noise due to parasitic gas ionization. By going down to 2 mm, we observed a clear improvement. Better, we observed at the same time a better stability of the detector... without understanding why. Going down to 1 mm, the grid, bent by the electrostatic force, caused too many gain inhomogeneities. This project was finally not selected for the LHC. We have carried out developments[4] in other collaborations at CERN: COMPASS[g], n_TOF[g],...

The idea was there

Yes! However, we had not yet been able to explain why we were getting such good results by strongly reducing the amplification space. We sometimes thought about it with George, but since he had received the Nobel Prize (in 1992), these opportunities were rarer and rarer.

What allowed Micromegas to really emerge?

In the winter of 1994, I participated in a meeting on the LHC at Jussieu, involving most of the particle physics laboratories. We met over coffee with Georges (Charpak) and Philippe (Rebourgeard), to discuss detectors that could withstand the very high particle fluxes, while presenting good temporal performances. The idea of using parallel faces reappeared. Although unstable in the responses to gain inhomogeneities, they presented very good performances in these extreme conditions of high flux. These instabilities - we had the intuition but not yet the proof - were due to the large amplification space. We quickly thought of building a first prototype equipped with small gaps (Fig.1).

I knew where to get 5-micron thick microgrids from an American supplier, but we had to find a solution to position the grid properly with a spacing corresponding to sub-millimeter spacers!

I had my own idea... Six years ago, I was working as a visitor at IN_2P_3 in Strasbourg on the fast RICH[5], a Cherenkov counter with wire chambers. For similar reasons, we decided to bring the wires closer to the anode plane... with spacers. As a good fisherman, I proposed to use fishing wire, known to be very precise because it is obtained by drawing. We placed these wires every centimeter on the anode plane as spacers, and despite some dead zones, it worked very well. Later on, this fishing wire will be replaced by small pillars deposited industrially by photolithography to hold the grid.

I now had all the necessary ingredients to realize the first Micromegas prototype, including a small team with the technician Jean-Pierre Robert, who unfortunately left us in 2017. What remained was to figure out how to assemble them.

One of the problems was to hold the grid by stretching it on a frame. After several unsuccessful attempts and a few torn grids, we managed to successfully transfer glue via three successive frames. Once the grid was properly stretched, the detector gave signals with a good homogeneity of response and a good energy resolution.

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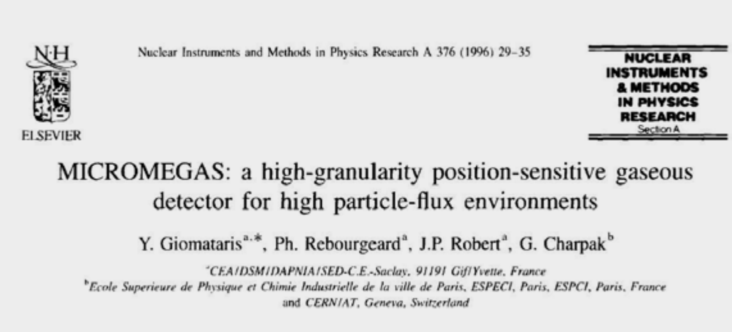
* *In the original Greek: Ιωαννης Γιοματαρης. The Greek first name was spelled in the early articles Yannis, hence the references where we meet Y. Giomataris (see banner p. 5). Then it was written Ioannis, which is now retained in the articles: I. Giomataris. For references, the initial will be written in accordance with that taken for each article.* ***Ιωαννης*** *will be I.G. in the issue.*

[1] B mesons: a meson is composed of a quark and an antiquark. A B meson has a bottom "B" antiquark and a quark, which can be a bottom (B), up (u), down (d), strange (s) or charm (c) quark.

[2] *A trigger for beauty*, G. Charpak, Y. Giomataris, L. M. Lederman, CERN-PPE-91-22-REV; FERMILAB-PUB-91-65 ; *NIM* ***A 306*** (1991) 439-445. *A Hadron-Blind Detector, G. Charpak, Y. Giomataris, et al, NIM* ***A 310*** (1991) 589-595.

[3] His house was a stone's throw from the Institut d'Etudes Scientifiques de Cargèse, established by the physicist Maurice Lévy in the 1960s. This then became an important center for summer schools in theoretical physics, bringing together distinguished physicists and many theorists of the Standard Model of particle physics. Georges used to participate in summer schools and there was a constant interaction between his house and the center.



MICROMEGAS: a high-granularity position-sensitive gaseous detector for high particle-flux environments

Y. Giomataris[a,*], Ph. Rebourgeard[a], J.P. Robert[a], G. Charpak[b]

[a] CEA/DSM/DAPNIA/SED-C.E.-Saclay, 91191 Gif/Yvette, France
[b] Ecole Superieure de Physique et Chimie Industrielle de la ville de Paris, ESPECI, Paris, ESPCI, Paris, France and CERN/AT, Geneva, Switzerland

After a few weeks, we had enough results to write a paper[6] (Fig. 2). It will be published in 1996 after protecting our invention by a patent [p. 31, B97] which presented the new detector as "likely to have a significantly higher spatial resolution (...) and to detect much higher particle fluxes" than the **MWPC**[g].

We have measured a spatial resolution of the order of ten microns (in sigma; better by a factor of 10 than that of wire chambers, around 100 µm) and a time resolution of a few nanoseconds. However, we also highlighted a very high flux spark problem... which will take us years to solve.

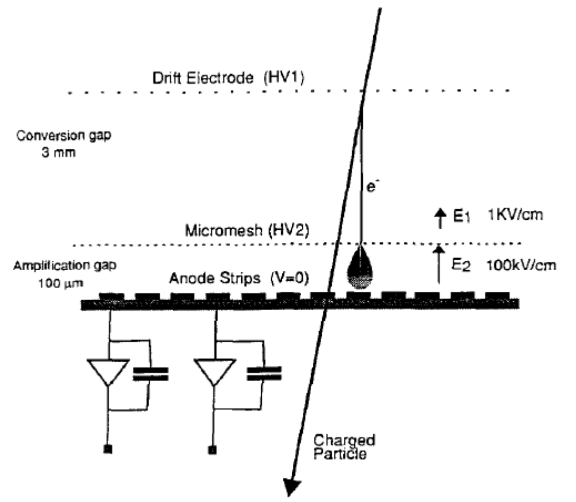


Figure 1. Principle of operation of the detector. Figure extracted from the internal report and the article[6] of 1996.

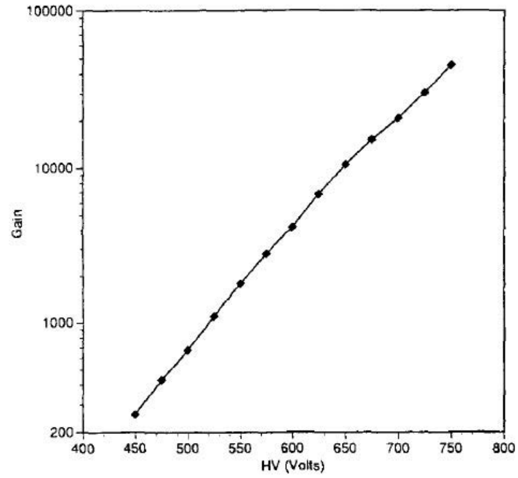


Figure 2. Results obtained: linear increase of the gain in the gas as a function of the voltage applied to the anode, for a mixture of argon gas and 10% methane (CH_4) at atmospheric pressure.

How did you validate the detector under experimental conditions?

The first tests of the detector subjected to high fluxes (10^9 protons per mm^2 and per s) were carried out in 1997 at Saclay on the van de Graff accelerator (Tandem) at DAPNIA[g]. The first spatial resolutions obtained were excellent, of the order of a few tens of micrometers. The gain was stable with a "magic" gas mixture, made of 85% argon and 25% dimethyl ether (DME). As expected, our detector showed better performance than the wire chambers, for much higher fluxes (by at least a factor of 100). We then went back to CERN to measure the fine parameters of the detector: spatial and time resolutions... by varying the composition of the gas mixture: argon with a few percent of isobutane or DME. The results of these tests at Tandem and at CERN (resolution of 50 ± 20 µm) were the subject of a second publication [*see p. 31*]. Stability with respect to high particle fluxes, excellent resolution and speed, the detector was then considered promising for the LHC. With the support of Michel Spiro, we set up a large group at IRFU to follow this test campaign and we joined the optical trigger group - the beginning of a fruitful collaboration.
Our initial results had proven to be very good.

How were these good results received by the scientific community?

A few years later, I was invited to CERN with Fabio Sauli (inventor of GEM[g], *Gas Electron Multiplier*, about a year after Micromegas) to discuss the use of gas detectors to equip COMPASS. It is following this discussion that Micromegas was used for the first time in a physics experiment, with detectors of several tens of centimeters. The idea met its first application.
In 1998, the main conclusion of our work was that the excellent spatial accuracy of the detector would answer the needs of most particle physics experiments for trajectory reconstruction. The Micromegas adventure continued with many technical evolutions accompanying the development of detectors for the projects[4] that were born around the world: n_TOF, CLAS12, T2K, MIMAC, CAST, NSW... Improved, miniaturized, curved, industrialized, it remains today a reference detector for physics.

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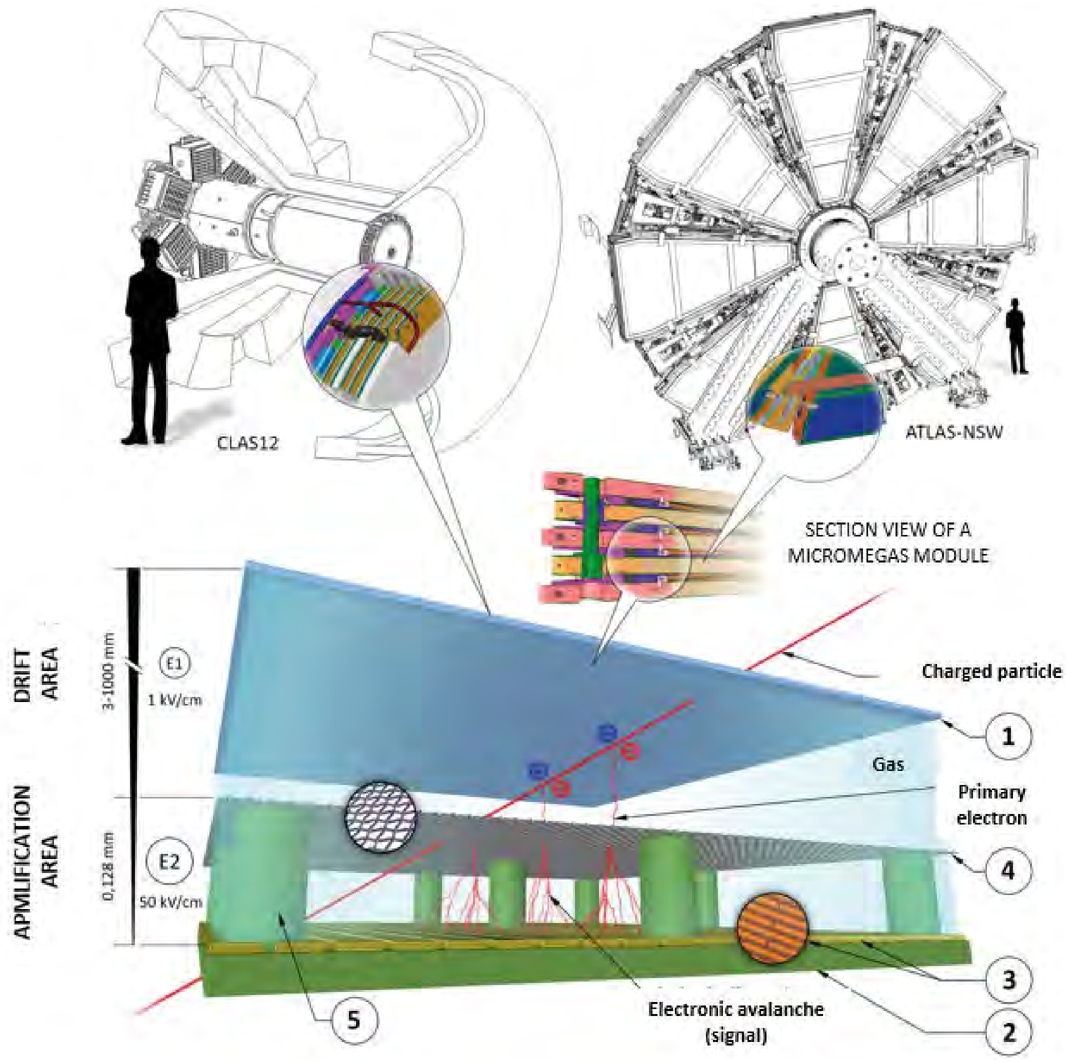
[4] All are discussed in this issue and the names are given in the glossary.
[5] *RICH: Ring Imaging Čherenkov detector, a ring particle detector for imaging, operating on the principle of the Cherenkov effect.*
[6] *I. Giomataris, Ph. Rebourgeard, J.P. Robert & G. Charpak, Micromesh Gaseous Structure, NIM A 376, 29-35 (1996). See page 31 in the bibliography, with the reference to the first version, the internal DAPNIA report of 1995.*

Photo credits: banner p. 4, photo by Y. Giomataris, © IRFU; photo of G. Charpak in his laboratory at CERN, November 1964 © CERN; banner p.5, photos of a prototype of Micromegas © IRFU; figures: Elsevier NIM A.

The operating principle of a Micromegas



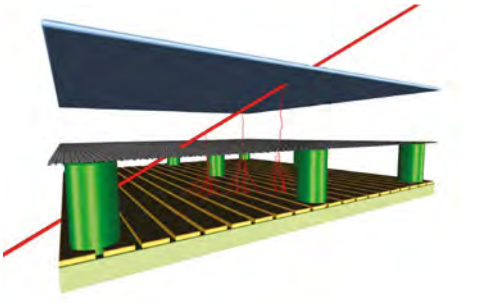
A Micromegas detector consists of three parallel planar elements:
- the cathode **(1)**,
- the anode plane **(2)** composed of microstrips **(3)**,
- the microgrid or *micromesh* **(4)** placed on pads **(5)**, which divides the Micromegas into two zones.

The specificity of a Micromegas detector is the great asymmetry of these two zones: electric field **E1** on a few millimeters for the **drift zone**; strong electric field **E2** on 128 µm for the **amplification zone**. These are the key parameters of the detector operation.

The incident charged particle (red track) first crosses the **drift zone** where it ionizes the gas and releases **primary electrons**. These electrons drift under the influence of the electric field E1 to the microgrid, where they undergo an electronic funneling effect directly related to the ratio of the fields E1 and E2. These electrons then enter the **amplification zone where the E2 field is much higher than the E1 drift field**, so much so that they are accelerated enough to ionize the gas themselves, leading to the creation of a succession of secondary electron sprays: this **electronic avalanche** considerably amplifies the electrical signal due to the initial energy deposit of the particle. Collected by the microstrips and read by an adapted electronic, these signals allow to determine the location of the track in the detector. The positional resolution can be improved by increasing the segmentation of the anode (pixelization).

The two diagrams at the top of the figure illustrate the diversity of applications of the technology: on the left, the implementation of curved Micromegas tiles in the cylindrical detectors of the CLAS12 spectrometer, on the right, the 1200 m² of the New Small Wheels (NSW) detector developed to upgrade the ATLAS detector at CERN.

Photo credits: illustrations:Th. Hardy, IRFU, DIS.



The genealogy of Micromegas

By Thomas Guy and Vincent Bontems
(IRFU, LARSIM)

To understand the originality of the Micromegas lineage within the tree of gas ionization detectors, we analyze the key steps of the history of these detectors using the tools of genetic mechanology.

Genetic mechanology is the study of the invention of technical objects and the evolution of technical lineages[1]. Its principles are elaborated by the philosopher Gilbert Simondon in his work *Du mode d'existence des objets techniques*, where he specifies that " the beginning of a lineage of technical objects is marked by synthetic act of invention constituting a technical essence"[2]. From this invention, a technical lineage develops through the succession in time of objects based on the same principle of functioning and whose technical essence remains stable through the evolutionary lineage. To the usual classification of technical objects based on their function, Simondon substitutes a classification based on their *functioning*.
We will therefore retrace the evolution of the operating principles of ionization gas detectors in order to determine, within this tree structure, which are the lineages leading to the invention of Micromegas.

In general, according to Simondon, phases of minor and major progress follow one another within a technical lineage: first, there is a series of gradual improvements during which the components adjust and adapt. When these minor improvements have completely optimized its functioning, the object is "saturated": to progress further, a break is needed, a global reconfiguration of the object. This reconfiguration does not modify the technical essence of the lineage, the internal operation being preserved, but gives birth to a new generation of more "concrete" technical individuals[2].

In order to identify the technical essence corresponding to the Micromegas lineage, we combined the principles of Simondon's genetic mechanology with diagrammatic tools borrowed from a knowledge management method (MASK)[3], developed at the CEA by Jean-Louis Ermine. The **SCFC** (source, target, flow, field) diagram thus allows us to identify the operating principle of all Micromegas (Fig. 1) and to place the lineage within the general tree structure where it appeared.

Although very general, this diagram allows us to link the Micromegas to the *family of ionization gas detectors* whose internal operations are ionization and amplification. The Micromegas lineage is more specifically related to the branch of detectors collecting information in the form of an electrical signal. Our methodology thus leads us to discard, among other things, cloud chambers and bubble chambers, which, despite their important role and similar function in particle physics, did not deliver information in the form of an electrical signal. The historian of science Peter Galison also emphasized the differences between these two instrumental traditions, that of "image-producing instruments"[4] such as bubble chambers, and that of "logical counting devices," where he put not only wire chambers but also spark chambers (which we do not do because the internal operations are different).

Once the essence of our lineage was defined, we tried to trace its genealogy by identifying the different inventions that have generated technical lineages that at least partially realize the "technical scheme" of ionization gas detectors producing an electrical signal. The result of this investigation was formalized in the form of the "lineage diagram" (MASK)[3] in Figure 2.

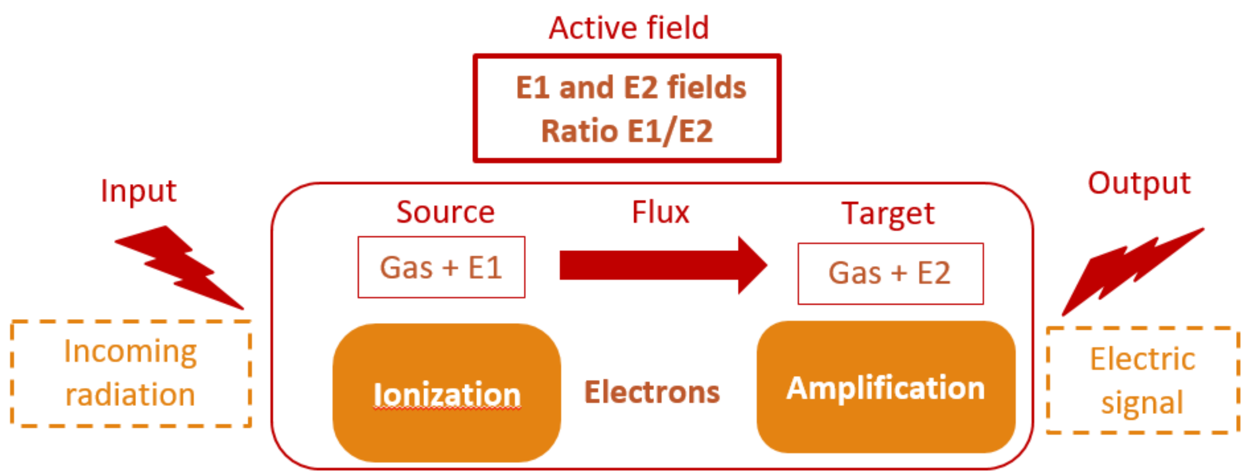
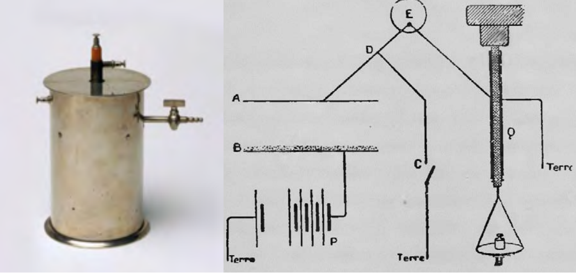
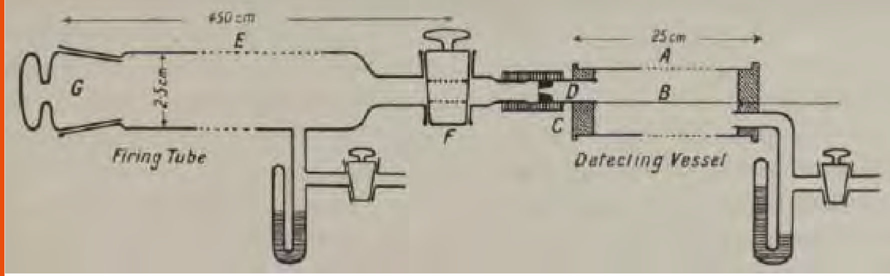


Figure 1: SCFC diagram of Micromegas. The Source system is linked to the Target system by a Flux (here it is the primary electron flux). To the set Source - Target - Flow, we add an Active Field which represents all the parameters influencing the process. The geometrical structure being fixed with the planes and spaces indicated on the operating diagram (p. 6), it is necessary to specify that in the "active field" composed of the electric fields E1 and E2 applied between the planes of the detector, the E2 field is very large compared to E1, which is a fundamental characteristic of the operation of Micromegas.

[1] Voir « *Mécanologie et méthodologie de l'instrumentation* » by V. Bontems and V. Minier in the n° 94 of Scintillations.
[2] *Du mode d'existence des objets techniques*, G. Simondon, Paris, Aubier, 1958 (expanded reprint, Flammarion, 2012).
[3] *MKSM : méthode pour la gestion des connaissances*, J.-L. Ermine, in Ingénierie des systèmes d'information, Paris, Hermès, 1996.
MASK : Méthode d'Analyse et de Structuration des (K)Connaissances, J.-L. Ermine, in *La gestion des connaissances*, Paris, Hermès Lavoisier, 2003.
[4] *Bubbles, sparks, and the postwar laboratory*, P. Galison, in *Pions to quarks: particle physics in the 1950s*, Cambridge University Press, 1989.



Ionization chamber.
P. Curie (1900)



Proportional counter.
E. Rutherford et H. Geiger (1908)

The first lineages of ionization gas detectors were born at the beginning of the last century with, on the one hand, the ionization chambers[5] used by the Curies (1901) and, on the other hand, the first Geiger-Muller tubes developed by Rutherford and Geiger[6] (1908).

It is the hybridization (1928) of these two technical schemes, leading to the so-called Geiger-Klemperer counter, which gave rise to the lineage of proportional counters[7] from which the Micromegas are derived. These proportional counters operate in the region of proportionality (number of collected charges, N_{coll}, proportional to the number of created charges N_{cr}), which is an intermediate zone between the regions of ionization ($N_{col} = N_{cr}$) and saturation (N_{coll} independent of N_{cr}). This allows to differentiate the signals according to the type of radiation (alpha, beta) and to have a "limited" avalanche zone in the anode region. Note that the structural distinction between cylindrical and planar detectors is not relevant here, the lineage being defined by its internal operations and not by its geometrical structure.

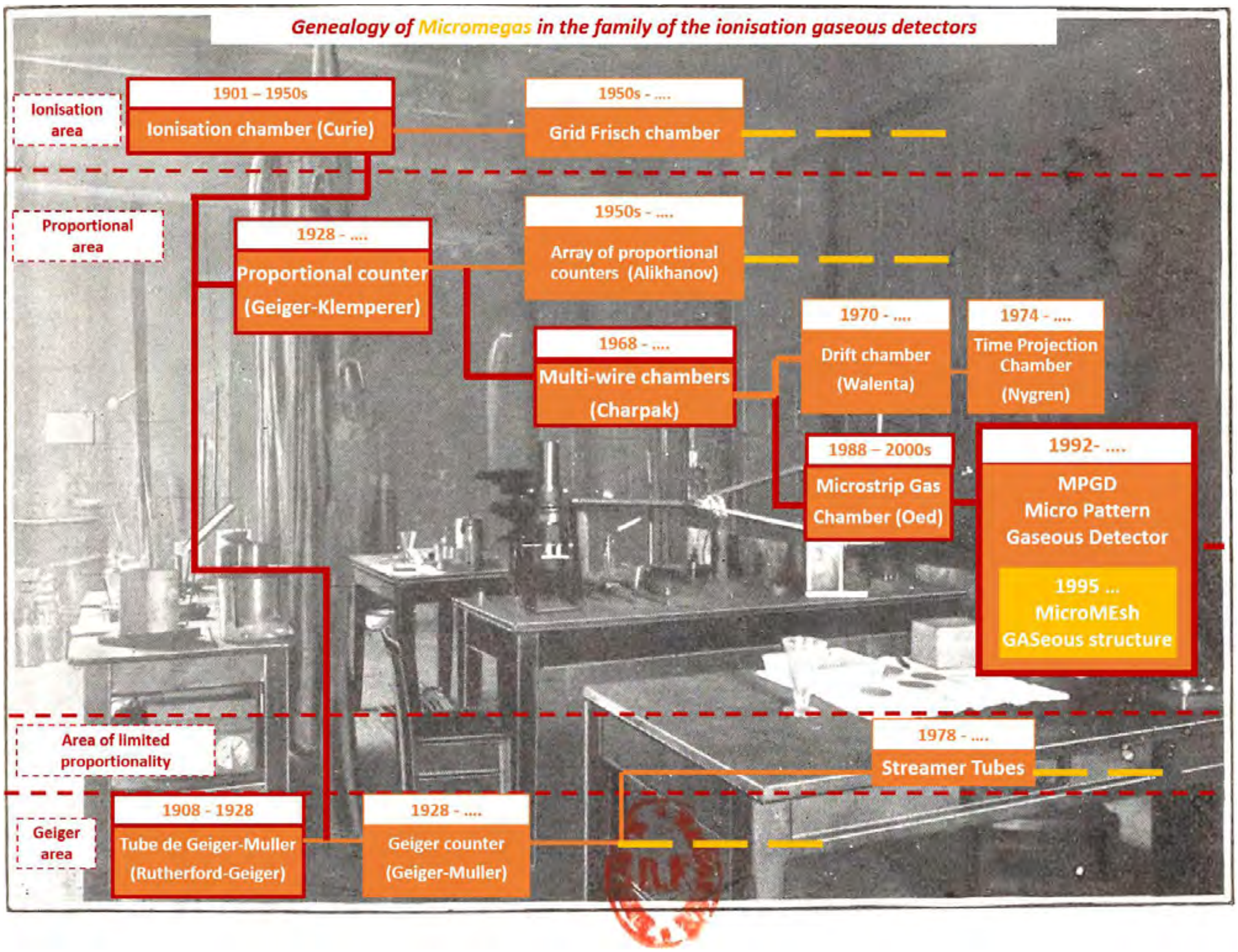
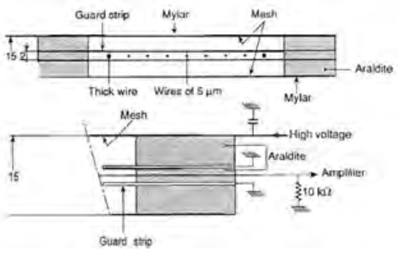
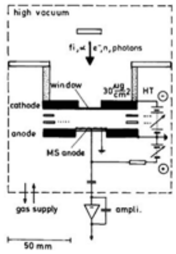


Figure 2. Tree structure of the gaseous ionization detectors producing an electric signal (we distinguished according to the involved region of ionization). For each lineage, the start and possibly the end dates are indicated. In the background, one can see the "radioactivity measurement installation" in the Curie laboratory. [Source : BNF, Gallica gallica.bnf.fr/ark:/12148/bpt6k10653183].

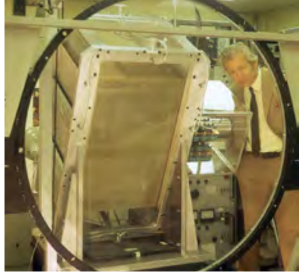
[5] The banner shows a picture of the ionization chamber designed and built by Pierre Curie (1859-1906), and developed from 1895 to 1900 *[photo © Science Museum London]*. The principle of measurement is shown in the figure taken from the report presented to the International Congress of Physics of 1900 (t. III p.79), *Les nouvelles substances radioactives et les rayons qu'elles émettent, in common with Mme Curie*;
In *Œuvres de Pierre Curie*, Société Française de Physique, Gauthier-Villars, 1908 (pp. 374-409).
[6] *An electrical method of counting the number of alpha particle from radioactive substances*, E. Rutherford et H. Geiger, *Proceedings of the Royal Society* (vol. 81, no. 546), 1908. https://doi.org/10.1098/rspa.1908.0065
[7] C. G. Montgomery, D. D. Montgomery, *The Discharge Mechanism of Geiger-Mueller Counters*,
Journal of the Franklin Institute **231**, pp.447-467 (1941). https://doi.org/10.1016/S0016-0032(41)90498-2



Multi-wire chambers.
G. Charpak (1968)



Microstrip anode detection.
A. Oed (1988)



G. Charpak and a particle detector
at CERN in 1973 [© CERN]

A crucial threshold of concretization was crossed in 1968 with the invention by the future Nobel Prize winner Georges Charpak[8] of the ***multi-wire proportional chamber*** (MWPC). This new generation of instruments[9] revitalized the lineage of gas ionization detectors by integrating the technical scheme allowing an electrical output of the signal. The dating of the earlier major realizations (1901 - 1908 - 1928 - 1968) suggests that the progress of the lineage was in deceleration, while the dating of the later realizations (1968 - 1988 - 1995) indicates an acceleration of the realization process. In our opinion, this acceleration is linked to the fact that the multi-wire chambers, which allow the computer processing of the data, replace the technical sets resulting from the lineage of the visual detectors (bubble chambers) to make trajectography, thus absorbing a part of their evolutionary potential. The choice of the gas, another parameter of the operation modeled on the diagram of figure 1, was also a determining factor for the success of this new generation of detectors. Fabio Sauli evoked in his book[9] the "*magic gas*" adopted by Charpak's group, which led to "*simpler specifications for the reading electronics*" and contributed to the expansion of MWPC technology.

Another important step in the evolution of the line of gaseous ionization detectors is the move to the micrometer scale with the birth of "***micro-pattern gaseous detectors***" (MPGD)[9], gaseous detectors with high granularity and small distances (less than a millimeter) between anodes and cathodes. This change of scale was made possible by the development of microelectronics and the early work of Anton Oed[10]. A global reconfiguration of the device then crosses a threshold in performance, especially in terms of resolution and response time.

Within the MPGDs, the ***Micromegas[11]***, invented in 1995, are unique in that the transition to the micrometric scale is also made for the used grid. The introduction of this grid, invented in 1944 by Otto Frisch, was initially intended to shield the space above the amplification region, but it also proved useful in reducing the drift and response times of the detector - thus realizing what Simondon calls the "convergence of functions" by a "superabundance of effects" of an invention that solves several problems at the same time. The name Micromegas signals this high degree of concreteness: by applying the change of scale to the anode-cathode distances as well as to the grid, these detectors have greatly increased their internal synergy.
Extending the formalization of a lineage by studying its rate of concretization also allows to formulate hypotheses.

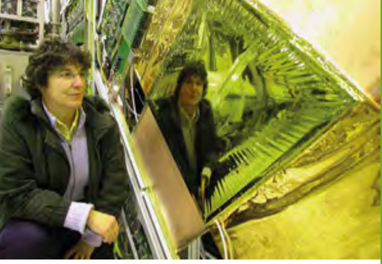
A preliminary modeling of the genealogy of the Micromegas thus incites to explore certain temporal zones: for example, 1948 appears as a "missing" stage induced by the symmetry of our date collection. This comes from the fact that we were simply analyzing the lineages without specifying the invention of possible elements essential to their appearance. However, it so happens that in 1948 the first articles[12] were published suggesting the use of multi-wire counters, an idea that would be taken up again twenty years later for the development of multi-wire chambers and that would contribute to the renaissance of the lineage of gas detectors of which the Micromegas are one of the achievements.

Finally, what about the progress made after 1995? If we take up the series of stages that led to Micromegas, we must remember as main dates of concretization 1901 - 1908 - 1928 - 1968 - 1988 - 1995, which, by looking for a symmetrical extension, leads us to look for what would have happened in 2003. However, this year corresponds to the development of the "Bulk[9]" technology. This all-in-one manufacturing process makes it possible to integrate the microgrid with the reading electrode in order to build a monolithic detector; it represents a progress of concretization even if undesirable effects relativize its scope (difficulty to clean impurities in the case of detectors of large surface for example).

Beyond this date, retrospection, and even more so prospective, becomes hazardous: the tree of ionization gas detectors has indeed given birth to multiple lineages that remain active today, some in hypertelic forms, i.e. over-adapted to certain "niches" (Geiger counters), others with a much greater genericity and important perspectives in terms of gain of concretization. But within the competition between the different lineages, the Micromegas line undeniably has a strong generic potential.


Thomas Guy and Vincent Bontems.

[8] *The use of multiwire proportional counter to select and localize charged particles*, G. Charpak, R. Bouclier, T. Bressani, J. Favier, Č. Zupančič, Nuclear Instruments and Methods, vol. **62**, pp. 262-268 (1968). https://doi.org/10.1016/0029-554X(68)90371-6 [Figures of banner p.9 © 1968 Elsevier B.V].
[9] [Ndlr, V.L] *F. Sauli, Gaseous Radiation Detectors, section 1.2 "Personal memories on gaseous detectors" ; chapitre 8 MWPC ; chap.13 MPGD. See the complete reference and the citation concerning the MWPC and the magic gas in the bibliography, p.31.*
[10] *Position-sensitive detector with microstrip anode for electron multiplication with gases, A. Oed, Nuclear Instruments and Methods in Physics Research* A **263**, pp. 351-359 (1988). https://doi.org/10.1016/0168-9002(88)90970-9 *[Figures of banner p.9 © 1988 Elsevier B.V].*
[11] See the first articles on the developments of Micromegas, references in p.31.
[12] *The properties of some new type of counters*, S. C. Curran et J. M. Reid, *The review of scientific instruments* **19,** 67 (1948). https://doi.org/10.1063/1.1741220

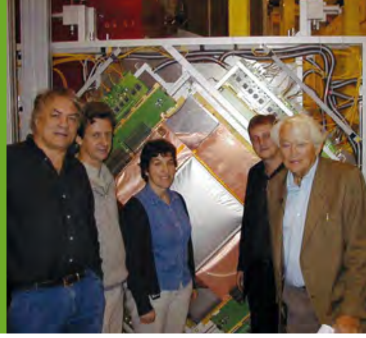


Fabienne Kunne in front of Micromegas at CERN

A state-of-the-art detector for COMPASS

or how Micromegas goes from the lab to CERN

By Fabienne Kunne for the COMPASS team* of IRFU



The COMPASS (Common Muon and Proton Apparatus for Structure and Spectroscopy) particle physics experiment studies the internal structure of the proton and the spectroscopy of hadrons. Within this collaboration, the IRFU team is more particularly involved in studies of the structure of the nucleon in terms of quarks and gluons and their contributions to the proton spin. The COMPASS device is installed at CERN on the Super Proton Synchrotron (SPS) beamline, which delivers muons and hadrons from 160 to 200 GeV. The Micromegas technology has been privileged for these studies, which led IRFU to contribute decisively to the realization of this experiment and to the construction of state-of-the-art detectors. The experimental conditions of the beams led to improve the performances of Micromegas and to make its operation more reliable.

1996 - A team[1] from the Service de Physique Nucléaire (SPhN) of the DAPNIA[g] (ancestor of the IRFU) decides to join the COMPASS[2] collaboration at CERN. For the envisaged measurements, the mission is to develop a spectrometer on the old beam line of the SMC[3] experiment, i.e. a set of detectors capable of identifying and measuring the characteristics of the particles resulting from the interaction of the beam in the target. The expected beam intensities are ten times higher than before. The 200 GeV muon beam strikes a proton target. The complete device that was designed in the 1996s is shown in Figure 1. The particles produced are ejected forward, and pass through a series of specific detectors. The SPhN team is responsible for the development of the charged particle detectors that will have to operate in the most radioactive area of the spectrometer: they will be located just behind the long solid target, wedged between the leakage fields of its solenoid and the first dipole of the spectrometer. Their role will be to give the position of the particle just after the interaction in the target and just before entering a magnet in charge of slightly deviating its trajectory to deduce its moment. As the energy of the particle is measured further away, it is crucial that the crossing of the detectors does not alter this energy or only slightly.

The required performances are extremely constraining. No existing detector can meet these requirements: flux of 10^5 particles/mm^2, spatial resolution of the order of 80 µm, temporal resolution of the order of 10 ns, all on a relatively large surface, 40 by 40 cm^2 and with low material.

At the Service d'Études des Détecteurs (SED) of DAPNIA, a new detector is under study. In the early 1990s, Georges Charpak and Yannis Giomataris came up with the idea of a new type of microstructure gas detector (p. 4). Named Micromegas, it presents on paper an astonishing potential: thanks to a microgrid separating the space of ionization and drift of the created electrons and, on the other hand, the space of amplification where the avalanche of electrons is created, it becomes possible to accept high rates of incident particles. Indeed, the multiple ions created near the anode, in the small amplification space between the microgrid and the anode plane, have only this short distance to travel before being captured by the microgrid. In a few tens of nanoseconds, the detector is operational for the next particle. The idea was quickly adopted, and active R&D began to adapt these detectors to the COMPASS experiment.

Small prototypes are built and tested with radioactive sources and with beam. A serious problem quickly appeared during tests with the pion beam: discharges between the microgrid and the tracks occurred at almost every event, blinding the detector for several seconds, making it temporarily unusable.

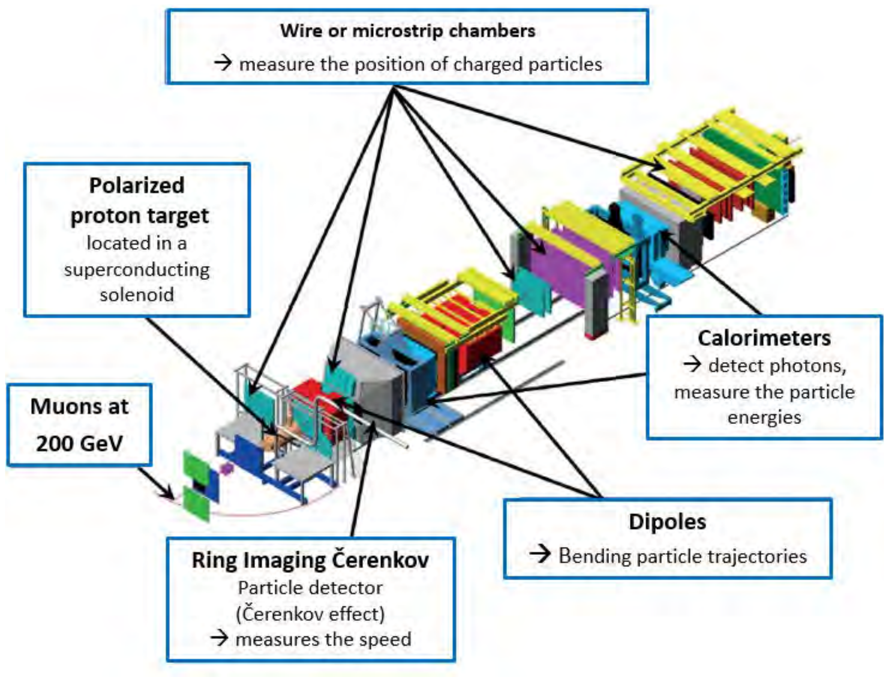


Figure 1. Complete view of the experimental setup of the COMPASS experiment. The Micromegas are implanted among the set of wire and microstrips chambers that provide the position of the charged particles along the beam axis. (Image ©CERN). The banner on p.11 shows three views of the device from the overhead crane of the experimental area.

[1] The team was composed of physicists and technicians from DAPNIA. On the picture (banner p. 10, right) taken at CERN in 2001 during the first uses of Micromegas in physics, we see some of the physicists of the pioneer measurements: Alain Magnon, Claude Marchand, Fabienne Kunne, Philippe Rebourgeard and Georges Charpak, in front of the Micromegas chamber of COMPASS.

[2] The COMPASS collaboration brings together 26 institutes from 14 countries, including Germany, Italy, France and Russia. For more information, www.COMPASS.CERN.ch.

[3] SMC : *Spin Muon Collaboration.*

After many studies, three improvements will allow to get rid of this problem of discharges:
- Extensive measurements using different gas mixtures make it possible to highlight the relationship between the mass of the gas and the discharge rates (see p. 22). For the first time, gas mixtures based on neon rather than argon are chosen.
- As the discharge rate strongly depends on the gain of the detector, IRFU decides to develop a fast and low noise electronic strip reader (SFE16). By operating with weaker signals, the gain is reduced.
- To accelerate the recovery time of the microgrid after a discharge, the strips are individually decoupled by capacitors. Thus, only a few strips are involved in the discharge and the microgrid voltage only decreases by a few volts, which are quickly restored.

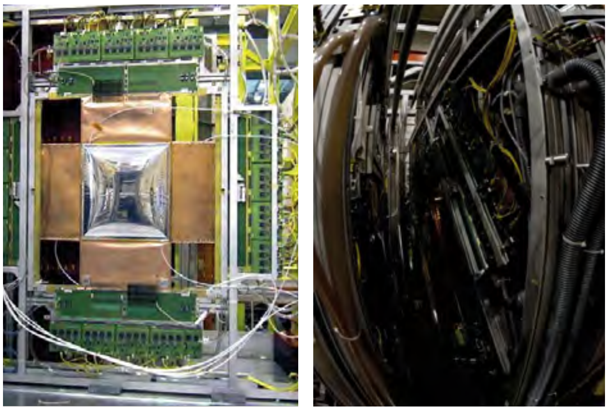


Figure 2. Left: view of a Micromegas detector iin the COMPASS experimental set-up. Right: plans of detectors along the beamline.

Never used in a physics experiment before COMPASS, the first generation Micromegas detectors had 1 024 copper strips on 40 x 40 cm^2, and a large microgrid, four microns thick, made of nickel. The chosen electronics were very robust and very powerful. The choice of the gas mixture (neon, ethane and CF_4) had been optimized for the reduction of the number of discharges with neon, the width of the signals with ethane and the size of the multiple scattering and the speed with CF_4. For more than 10 years, these detectors remained the largest operational microstructure detectors.

For the implementation in COMPASS, the strips were extended by 60 cm to be able to move the electronics (and especially the material it represents) away from the acceptance of the spectrometer, so as not to disturb the energy measurements of the particles. An inactive zone of 5 cm diameter has been provided in the center of the detectors to let the beam pass, in order to limit the occupation of the electronic strips passing in the center.

The ingenious mechanics of the detector support on slides allowed them to be inserted or removed at any time in pairs to exchange electronic cards, or even to extract complete detectors. This was particularly useful in the early years, when the production quality was not yet optimal and problems were frequent. Nevertheless, the detectors gave excellent results. The progress was followed with great interest by the physicists of the large experiments under construction at the LHC. Indeed, compared to the characteristics of the original wire chambers, the capacity to support high particle fluxes (of the order of 1 MHz/cm^2), and the significant sizes of the Micromegas detectors were very promising.

At that time, within the COMPASS collaboration, the competition was tough with our colleagues who were developing *Gas Electron Multiplier* (GEM) detectors to implement them in the same spectrometer, a little farther from the target, where the operating conditions were easier: lower particle rates, no magnetic field, smaller detectors (only 30 by 30 cm^2). Their choices to solve the essential problems of discharges were different, with three preamplification stages (the "triple GEM"), to limit the gain per GEM.
Although realized with different techniques, the two types of detectors, Micromegas and GEM, will be finalized at the beginning of the 2000s with rather similar performances.

The Micromegas detectors operated with excellent efficiencies, close to 98%, spatial resolutions of 70 to 110 µm (depending essentially on the experimental conditions related to the external magnetic field which could reach two teslas) and a time resolution around 10 ns. The discharge rates were low enough to keep the efficiency stable.
In 2006, a new large aperture magnet (superconducting solenoid surrounding the polarized target) was implemented in COMPASS. The magnetic field was such that the large nickel microgrids were deformed, happily modifying the ionization and amplification spaces. Solutions were found in a hurry to replace the grids of the most affected detectors. The ionization area was increased to 5 mm, large copper grids were made from GEM foil and the gas mixture was slightly modified. Thus, the Micromegas detectors withstood once again the harsh experimental conditions of COMPASS, until these changed at the end of the 2000's for a new phase of the experiment, but that is another story...

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The Web page of the IRFU project: https://irfu.cea.fr/Phocea/Vie_des_labos/Ast/ast_technique.php?id_ast=392

* *The* ***IRFU project team*** *was composed of the DPhN group and groups in the detector services (Sed), electronics and computer science (Sei) and systems engineering (SIS), which became DEDIP and DIS. Project leader, Ph. Rebourgeard, followed by A. Delbart ; Ph. Abbon, Y. Bedfer, C. Bernet (2002-2005), Ph. Briet, P. Deck, E. Delagnes, A. Donati, D. Durand, R. Durand, A. Giganon, F. Gougnaud, F. Kunne, J.-M. Legoff, Th. Lerch, A. Magnon, D. Neyret, S. Panebianco (2002-2005), E. Pasquetto, H. Pereira (1999-2001), D. Pierrepont, S. Platchkov, S. Procureur (2003-2006), G. Tarte, D. Thers (1997-2000), M.Usseglio.*

Photo credits: P.10 photograph of the left banner, Michael Hoch ; to the right : COMPASS collaboration. Figures 1 and 2, banner p.11 : CERN.

Micromegas unveils its curves with Clas

By Jacques Ball, Michel Garçon et Stephan Aune, for the CLAS12 team* at IRFU

IRFU has been a pioneer in the study of Generalized Parton Distributions (GPDs), which provide complete information on how quarks and gluons arrange themselves to form a proton or a neutron. The corresponding experiments[1] are the flagship program of the new electron accelerator, CEBAF[2] at 12 GeV, located at JLab[2]. They consist in using electrons to probe the interior of the nucleon at the quark level, while ensuring that the nucleon remains intact in the process. Thus, in this type of reaction, an electron interacting with a proton produces an electron, a proton and a photon; the probed proton receives little energy (between 50 MeV and 1 GeV) and recoils under the shock with a rather large angle, in the same way as a billiard ball that is barely touched. Most of the energy of the reaction is evacuated by the photon. The processes involved in this scattering have a production rate a million times smaller than in standard reactions where the proton does not remain intact after scattering.

For these measurements, it is necessary to ensure that the low energy scattered proton exits the target with a minimum of interactions. A thin detection system is therefore needed around the target. In 2005, discussions were held to evolve the detection systems: this evolution accompanied the transformation of the CLAS[3] spectrometer into CLAS12[3], necessary to adapt to the characteristics of the 12 GeV beams. This period coincides with the "revolution" of the bulk detector (see below the box). It was immediately realized and demonstrated at SEDI (now DEDIP[g]) that a detector with integrated microgrid would make it possible to conceive a thin curved detector (*Fig. 1 and box*) whose mechanical rigidity would even be improved.

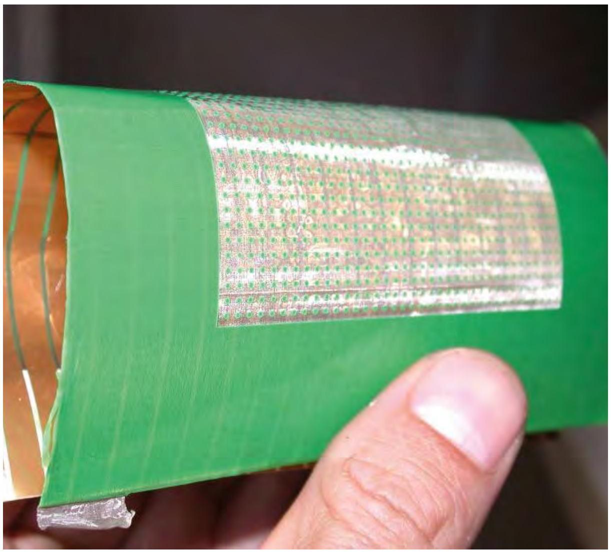


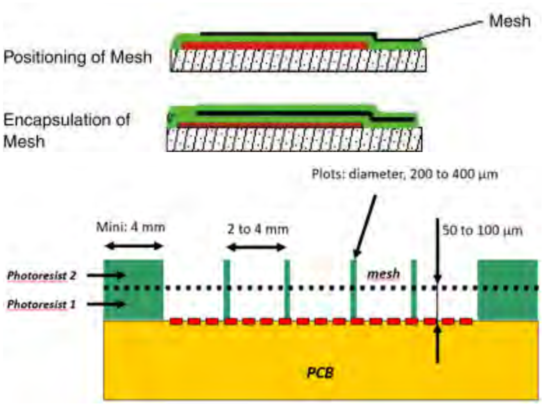
Figure 1. One of the first curved tiles made with a curved plane in bulk technique, produced on "stripped" (strip-covered) mylar (50 µm) (the resistance between anode and grid is infinite).

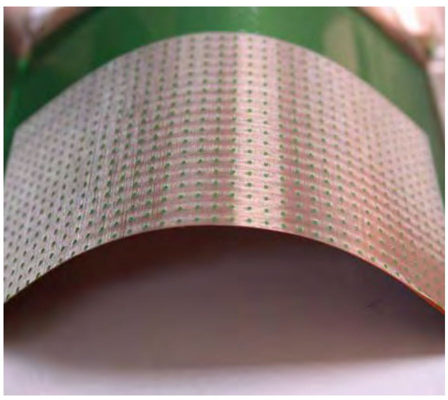
For physicists, this opens the way to a compact cylindrical detector (*see the detector placed on the table, in the photo of the banner p.13*) which is both thin and fast, ideal characteristics for the measurement of the searched process.

Bulk technology has opened the way to curved detectors

Micromegas is called "bulk" "bulk" because the grid is encapsulated on the frame of the printed circuit, the PCB[g].

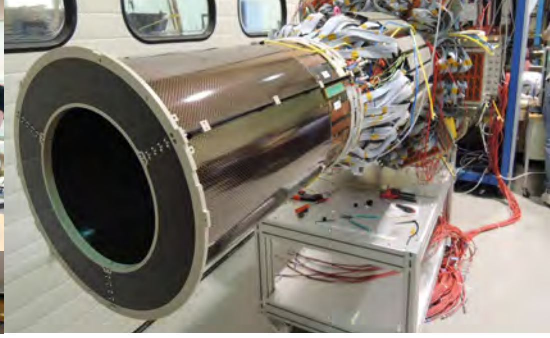
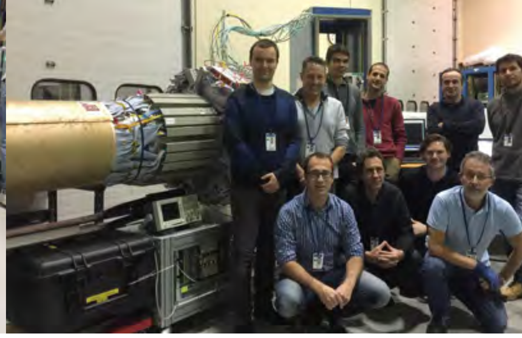
It is integrated by a global assembly with the base layer reading plane. It is a joint invention of CERN and the CEA of Saclay (2003). It has been the subject of a patent [*B11*] and a publication [*NIM06*]. In practice, how is the bulk built? The diagram below illustrates the manufacturing principle. The goal is to make a sandwich with the mesh between two layers of a resistive material (polyamide) sensitive to light (the *Photoresist*) on a PCB. Typically, the thickness of the grid is 30 microns (µm) and the gap between grid and plane is 128 µm. The grid is held in position by two sets of spacers before being encapsulated between the polyamide films. The whole detector (the floor including the strips and the grid) is one-piece after lamination, ultraviolet exposure through a mask and then chemical treatment (polymerization).





The diagrams show: on the left, top, the bulk technique with the grid (black line) positioned between two layers (green) of Photoresist; bottom, the bulk obtained after laminations and treatments.
Right: photograph of a curved bulk on copper-plated kapton (200 µm).

[1] Experiments studying the process of Deeply Virtual Compton scattering are often accompanied by the acronym DVCS. These DVCS processes result in the scattering of an electron on a proton by exchange of a virtual photon and the re-emission of a real photon by the proton in the final channel.
[2] Continuous Electron Beam Accelerator Facility at the Thomas Jefferson National Laboratory (JLab), located in Newport-News, Virginia (JLab was formerly called Cebaf).
[3] Clas: CEBAF Large Acceptance Spectrometer; CLAS12, the 12 GeV spectrometer.

On their side, our American colleagues were working on a project of a silicon vertex detector, which it was envisaged to combine with the Micromegas trajectograph to obtain the best resolutions of angle and energy measurements. During a workshop of the CLAS12 collaboration in 2006, the first estimates indicated that a combination of two layers[4] of silicon and four double layers of Micromegas would optimize the accuracy of the measurements. The final agreement was a compromise of "(3) + (2*3)", acceptable in view of complete simulations.

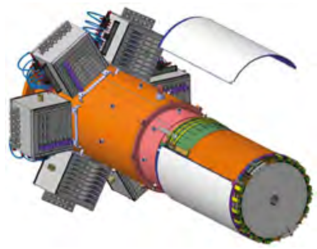


Figure 2. 3D model of the vertex detector. For CLAS12, the central detector consists of three double layers of Micromegas (covering about 3 m^2 with 10,000 channels of electronics) with three silicon planes; the detector located at the front has six annular planes of Micromegas. Both offer little material to the passage of the particles.

However, it was a long way to go to realize the complete trajectograph, the Micromegas Vertex Tracker (MVT) of CLAS12 (*schematized in Fig.2 and presented in photo, Fig.3*). To overcome important technical constraints, innovative developments were accomplished during the R&D phase. Works were required both on the structure, on the operating mode of the detector as well as on the electronics:

- Detectors built on thin support layers of 100 to 200 microns thickness were realized with the bulk technology. The tests showed that the performance of the curved Micromegas was not degraded, and this down to radii of 10 cm. The curved tiles were therefore reliably constructed without loss of performance.
- Since the tracker was to be operated inside an intense magnetic field of five teslas, new gas pressure and electric voltage conditions were investigated based on simulations of the detector physics, which led to changing the gas mixture and drift fields and modifying the microgrid. The new calculated conditions were tested in laboratory with measurements of the Micromegas responses to cosmic radiation.
- To optimize the mechanical integration of the detectors and their electronics in a very compact device, the readout electronics were moved far upstream of the trajectograph, with cables of 1.5 to 2.2 m in length adapted to reduce noise.
- Because of the intense hadron flux in the vicinity of the target, a high rate of breakdowns was expected, around a few hertz per detector. The resistive strip technology developed at CERN in 2010, and the associated electronics - adapted to high fluxes (see p.11), were therefore adopted.
- The configuration of the system and the nominal conditions of CLAS12 (in particular the high particle fluxes of a few tens of MHz and the trigger rate of 10 to 20 kHz) required an evolution of the readout electronics (with a number of channels around 15,000) and the design of new boards, ASICs[g] integrated circuits developed by IRFU. These DREAM[g] electronics were then used for other applications of Micromegas (p.26).

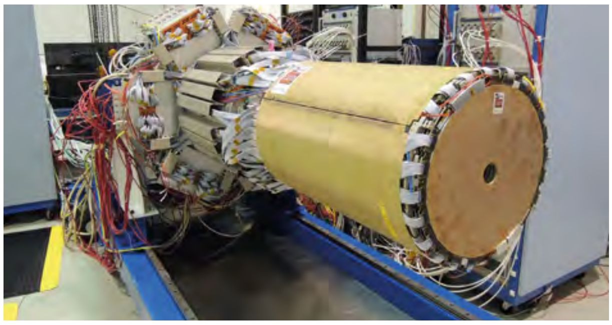


Figure 3. CLAS12 Micromegas Trajectograph (MVT) during laboratory set-up for testing in June 2017 with cosmic ray data taking.

This long period of R&D, supported by the *Agence Nationale pour la Recherche*, was fruitful: marked by seven publications, it led to the construction of another, smaller cylindrical trajectograph for the Asacusa[5] experiment at CERN, as well as the filing of two patents[6]. It also inspired the initial design of the MINOS detector (p. 20). The resistive bulk technology (p. 22) was adopted during the project.
The ultimate outcome of this type of cylindrical trajectograph would be to be used as an advantageous alternative to time-projected chambers (TPC) and silicon detectors used in high energy physics. Lower cost, slightly lower material thickness... Micromegas has not said its last word...

In 2017, mission accomplished: the MVT trajectograph, delivered to the JLab in June, took its first physics data during the fall. This was an experiment in which an IRFU physicist was co-spokesperson and coordinator.
The future of the MVT is also shaped by the experimental programs planned with the future electron-ion collider (EIC) in the United States.

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Micromegas trackers for hadronic physics, S. Procureur, Modern Physics Letters A **28** (2013) 1340024.
https://doi.org/10.1142/S0217732313400245
CLAS12 project pages on the IRFU website: https://irfu.cea.fr

*** The CLAS12 team of the IRFU having contributed to the development of the Micromegas trajectograph:** on the photos of the banners, from left to right, p.12: Jacques Ball, Michel Garçon, p.13 on the left, the team in front of the curved detector: Julien Giraud, Rémi Granelli, Olivier Meunier, Sébastien Procureur, Franck Sabatié, Maxence Vandenbroucke, Stephan Aune, Irakli Mandjavidze ; p.13 right, top row: Maxime Defurne, Marc Riallot, David Attié, Yassir Moudden, I. Mandjavidze, R. Granelli ; bottom row: F. Sabatié, S. Aune, M. Vandenbroucke, O.Meunier without forgetting A. Acker (who is not on the picture).*

[4] A layer is defined here as a set of two detectors, each measuring one coordinate.
[5] Asacusa: Atomic Spectroscopy And Collisions Using Slow Antiprotons, experiment for the production and hyperfine spectroscopy of antihydrogen atoms. https://home.cern/fr/about/experiments/asacusa
[6] One of the patents concerns the mechanical design [B14A] and the other the innovative principle of electronic multiplexing [B14B], see p.31.

Photo credits: IRFU and CLAS12 ; Figure 2, 3D image: A. Acker, DIS.

Micromegas unfolds its petals and makes the wheel

By Fabien Jeanneau and Philippe Schune,
for the ATLAS-NSW team* at IRFU

Micromegas detectors are mainly used as trajectographs in order to track the trajectory of charged particles on one or two dimensions with a good accuracy. Their major advantage is to offer large detection areas at reasonable costs, which can be used to extend the angular coverage of the devices. Moreover, thanks to their low density, they can be assembled with several successive detection layers without altering the characteristics of the incident particles. These two properties (large surface area and relative transparency) led the ATLAS team at IRFU, in association with other laboratories, to propose this technology to replace the "New Small Wheels" (NSW) detectors of the ATLAS muon system.

With CMS, the **ATLAS**[g] multidetector is one of the instruments that equip the Large Hadron Collider (**LHC**) at CERN. These two experiments, the most complex particle physics experiments of the 21st century, aim to understand the fundamental constituents of matter and their interactions. They have already led to the discovery of the Higgs boson in 2012. In the next fifteen years, they aim to verify the standard model of particle physics with great precision.

In order to extend the measurement range of the experiments, the performance of the machine will be improved to explore higher energy regions and increase the current[1] luminosity[g] by a factor of five, after 2025.

The LHC detectors in the most radiation-exposed regions were designed to operate at nominal luminosity (10^{34} cm^{-2} s^{-1}) and energy, i.e. for protons accelerated to 7 TeV.

Under the new conditions, the flux of particles created during collisions as well as the associated background noise, and thus the radiation passing through the detectors, will be multiplied by 10. The equipment will then undergo a significant aging, hence the need to change some parts of the ATLAS experiment.

This degradation is obviously well known and has been taken into account since the design of the experiment. Consequently, more or less long shutdowns are planned in the programming of the LHC beams: they are intended for the maintenance of the equipment or the installation of new detectors, with the aim of preserving and improving the performances necessary for the continuation of the physics programs.

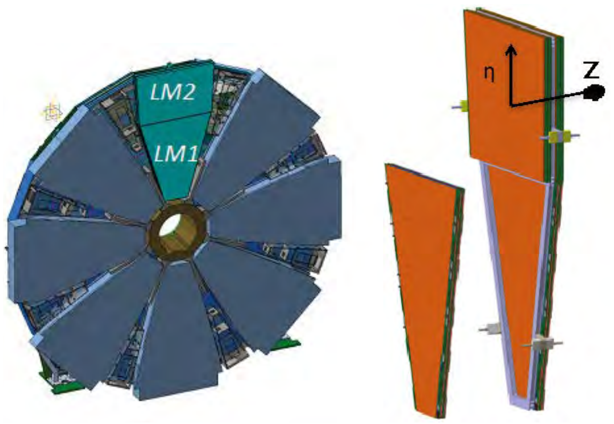

Figure 1. Overview of an NSW wheel (left).
IRFU is in charge of the construction of the large modules (LM1).
Detail of the fixation of the modules in a petal (right).

For the first phase of these improvements (in 2019-2020, during the LHC shutdown), IRFU is involved in replacing the small wheels of the current muon system with the teams of the ATLAS-NSW collaboration.

Small wheels? Not really! Each wheel will measure 10 meters in diameter and will consist of 16 detection planes (eight STGCs Small Thin Gap Chambers and eight Micromegas Modules) (*Fig. 1*) to multiply the number of points along the trajectory of incident muons. This program began with a long R&D phase as early as 2008, which led to the selection in 2013 of the Micromegas and sTGC technologies to equip this system, replacing the current gas detectors (drift tubes and cathode chambers). Micromegas technology is also competitive in terms of the cost of solid detectors, which is 500 times higher per unit area. Five international teams (Germany, France, Greece, Italy and Russia) are involved in the fabrication of Micromegas, and IRFU is in charge of building a quarter of the MM detectors, i.e. a total of 32 trapezoidal chambers made up of four 3 m^2 reading planes. A "MM" module of four detection planes is made up of five composite panels that support the different electrodes.

The new **NSW** wheels will have to participate in a first selection of the events of the experiment, by collecting in particular the trajectories of the muons, pointing towards the collision vertex at the center of ATLAS. These "good" events, very rare in the data flow, will then be recorded by the whole ATLAS experiment. The sTGCs, a little faster than the Micromegas, will be dedicated to this first selection. To increase the lever arm and thus the precision of the muon incidence angle measurement, the sTGCs have been positioned on the external faces of the detection zone. The Micromegas, whose measurements are more precise, are on the inside.

The muon system is above all a trajectograph which must allow to identify with precision the muons coming from the interaction point located in the center of the detector. To reconstruct the moment of these particles with a resolution of 15% at one TeV, the trajectory crossing points will have to be measured with a precision of 100 microns according to the η coordinate. In addition, the detector will have to withstand rates up to 15 kHz per cm^2 (for the planes closest to the beam axis). It will have to operate under these extreme conditions without performance degradation for a period of 15 years. This implies strong constraints on the construction of the Micromegas detectors, which will have to be flat to within $\pm$ 100 µm, with 450 microns wide detection strips, and parallel to $\pm$ 40 µm on a complete module (*see axes in Figure 1*).

[1] In 2017, the LHC collected 50 fb^{-1} of data.

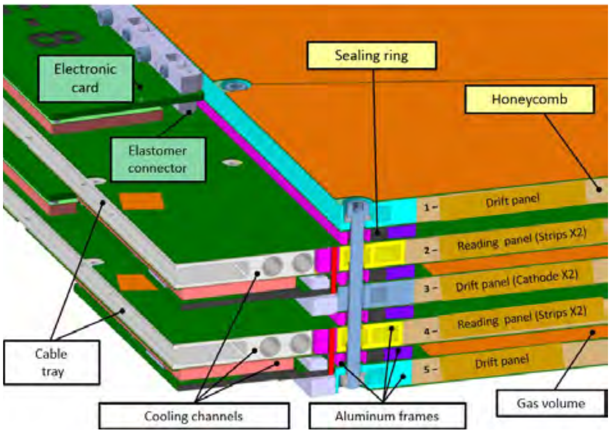

Figure 2. Cut view of a Micromegas module (readout strips, pillars, and grid are not shown). The schematic shows the component parts of a Micromegas (drift zones, cathode, strips) inserted in the honeycomb structure separated by the aluminum frames. The part of the embedded electronics (connectors and cards visible in green) is cooled at the level of layers n°2 and n°4.

The detectors in charge of the precision measurements will thus be the Micromegas made up of quadri-plane modules, each plane comprising about 5,000 strips, i.e. about 20,000 per complete module.
In addition to the mechanical challenge posed by the precise assembly of these detectors (*Fig. 2*), it must be emphasized that the construction of Micromegas detectors of this size constitutes a world premiere. All the means are implemented to reach the high precision and the performances expected by the physics experiments, starting with the infrastructures. The constraints on the manufacturing conditions concern the stability of hygrometry and temperatures as well as cleanliness. IRFU has therefore equipped itself since 2017 with a new clean room, the CICLAD[2] platform (*Fig. 3 and banner p.15*) for the development and characterization of large detectors. Its first application was the production of 400 m^2 of Micromegas detectors for the ATLAS-NSW project.
Such an environment is necessary to build the elements which will constitute the quadruplets, and also to ensure the good operating of the detector whose electrical behavior depends on the cleanliness of the surfaces during the assembly.

This clean room is complemented by a set of precision instruments to check the flatness and thickness of the detection planes as well as the alignment of the strips. The two precision marbles of CICLAD are equipped with aerostatically supported mobile gantries, allowing dimensional checks with an accuracy of a few micrometers and automatic glue coating of components.

In 2017, Module-0, a full-scale prototype, was built. After verification of the quality criteria (tightness, high voltage resistance), the functional performances were evaluated during the beam tests performed in the Fall, followed by the production phase. After the integration at CERN from 2019 to 2020, ATLAS will be refurbished to wait for the new LHC data taking periods and to work in particular with the beams planned in the high luminosity mode from 2026.

Figure 3. Interior of the CICLAD clean room during the gluing of one of the five reading panels on the MM module by members of the ATLAS-NSW team.

Figure 4. Cosmic test bench of Module 0, the first full-scale test module built at Saclay. The functionalities of the module are controlled using the natural source of cosmic radiation. This bench allows to validate the performances of the Modules produced at Saclay.

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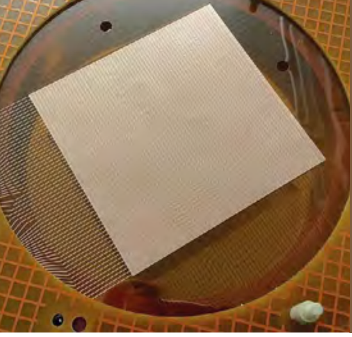
ATLAS Muon Spectrometer "ATLAS-muons" https://irfu.cea.fr/Phocea/Vie_des_labos/Ast/ast_sstechnique.php?id_ast=387

*** The NSW team at IRFU:** *Philippe Schune (Scientific Manager), Fabien Jeanneau (Project Manager), J. Allard, F. Bauer, J. Beltramelli, H. Bervas, T. Bey, S. Bouaziz, M. Boyer, G. Cara, T. Chaleil, J. Costa, C. Dacien, G. Decock, D. Denysiuk, D. Desforges, G. Disset, G-A. Durand, R. Durand, E. Ferrer-Ribas, A. Formica, A. Giganon, J. Giraud, P-F. Giraud, C. Goblin, J.-C. Guillard, S. Hassani, B. Jose, D. Jourde, J. Elman, Ch. Lampoudis, J.-F. Laporte, D. Leboeuf, M. Lefèvre, C. Loiseau, J. Manjarrés, Ph. Mas, M. Mur, A. Peyaud, Y. Piret, P. Ponsot, G. Prono, M. Riallot, V. Robichon, G. de la Rochefoucauld, F. Rossi, T. Chevalerias, M. Usseglio, Th. Vacher, M. Vandenbroucke, A. Vigier.*

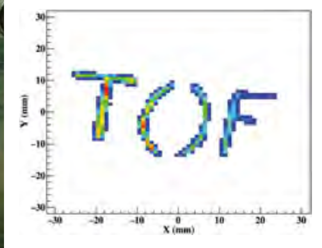
[2] CICLAD: Conceptual design, Integration and Characterization of large detectors. This platform includes a 140 m^2 clean room. Open to researchers and to industry, it enriches the technological offer of the "IRFU Detectors" complex. It has received funding from the Île-de-France region.

Photo credits: IRFU, CEA DRF.



Micromegas takes neutrons on the fly

By Franck Gunsing,
Eric Berthoumieux and Emmeric Dupont
for the n_TOF team* at IRFU



Neutron-induced reactions are involved in many applications of nuclear physics, from reactors to astrophysical processes. In order to carry out the necessary measurements and to improve their precision, the international collaboration n_TOF[g] (*Neutron Time of Flight*) [1,2] implements neutron detection devices. For the measurement of the neutron time of flight, Micromegas is used because of its very good accuracy in time. With its 2D structure, the detector has also become a neutron profiler that can be operated on neutron beam production facilities, such as GELINA[1] (at Geel), or NFS[g] (at GANIL, in Caen).

The best method to determine the kinetic energy of a neutron with a very high accuracy and over a large energy range is the time-of-flight method. It consists in measuring the time interval between the instant of its production and the instant of its detection. The required accuracy is of the order of a few nanoseconds over a time range of 100 ms, but the density of the measured signals is high. A pulsed beam of protons or electrons passing through a massive target will produce neutrons with various energies at a given time. After passing through a moderator (usually water) to broaden the covered energy range, the neutrons can interact with a sample placed at a given distance, typically between 5 and 500 meters. The time of this detection gives the time taken by the neutron to travel this distance and thus its kinetic energy. The Micromegas detectors measure two types of quantities: the effective cross-sections[g] (which are none other than the rate of reactions induced by the neutrons) and the spatial profile of the neutron beam. They directly measure neutron times of flight by detecting fission products or α (^{4}He) nuclei.

The architecture of these detectors must minimize the material crossed by the beam in order to impact its properties as little as possible. This "transparency" is obtained by limiting the mechanical supports in the beam, by using the **Microbulk**[g] technique and by favouring operation at atmospheric pressure, or lower, for the gas. The recoil protons, coming from the hydrogen in the gas, make for the moment very difficult the measurement of reactions where a proton is emitted. They are a source of background noise when light particles such as alphas must be detected. The beam diameter is typically 20 to 80 mm depending on the collimators. In order to measure the beam spot, which varies with the neutron energy, Micromegas detectors are used as profilers. These detectors are segmented, either in pixels or in strips. The latest development for a profiler is to combine transparency with strip segmentation [3]. This 2D detector consists of a Microbulk with a microgrid segmented into 60 strips of one millimeter width, and the anode segmented perpendicularly (*Fig. 1 and photo of the banner, left*). The active detection area is 6 by 6 cm^2.

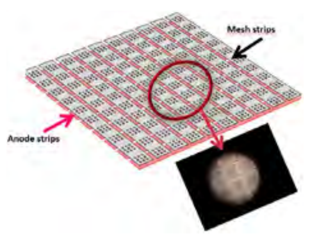


Figure 1. View of a 2D detector with the segmentation of the microgrid and of the anode plane, obtained by chemical etching of a thin Kapton foil (25 or 50 µm) covered on both sides by 5 µm of copper.

The positions were measured with this detector (*without time of flight*) using a copper mask (photo of the banner, right) and a 5.9 keV X-ray source: the graph (banner) shows the reconstructed image [3]. The electronics and the acquisition system are based on **AGET**[g] chips in order to be able to process the signals of the 120 strips over the whole time-of-flight window. Since 2002, the detectors have evolved according to the two measurement principles (Fig.2). These detectors have been used at n_TOF or at Gelina[1]. Their transparency criterion is guaranteed through the adopted Microbulk technique.

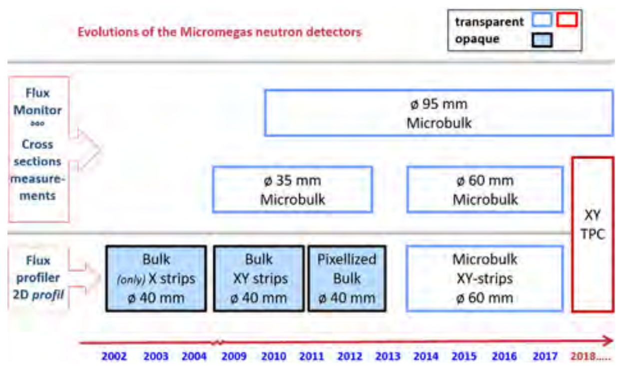


Figure 2. Evolution of Micromegas neutron detectors for time-of-flight devices.

The transparent microbulk technique is now well mastered and regularly used for the measurement of neutron-induced reactions. Thanks to its transparency to neutrons, the detector can remain in the beam to carry out measurements of the profile at n_TOF. The latest generation, with a diameter of 60 mm, has been validated and will be used at NFS (*see p.17*). The developments include the miniaturization and the integration in the chamber of the amplification and filtering elements in order to optimize the noise conditions while respecting a short enough signal to reduce the pile-up effects. It is also envisaged to develop a chamber capable of measuring proton-producing reactions with a hydrogen-free gas to avoid recoil protons. 2D detectors are used to measure energies with good resolution and to reconstruct particle trajectories, with an efficient separation of signal and background noise. Their evolution could lead to time-of-flight systems giving access to detailed properties of the nuclei, such as the angular distribution of the emitted particles. These characteristics also allow us to consider applications to experiments that require pushing the limits of rare event selection (*see boxes on p.29*).

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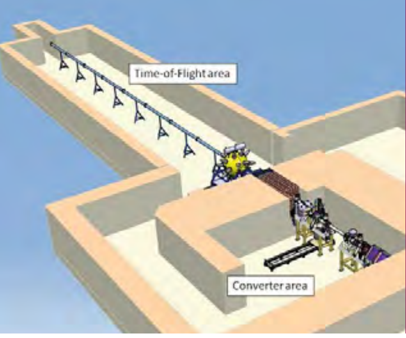
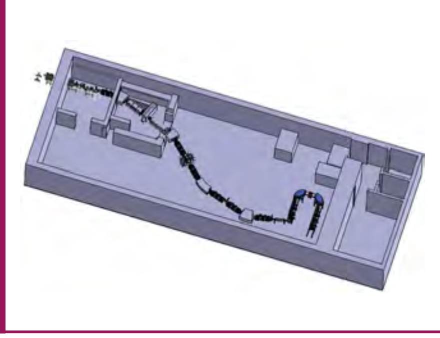
[1] *The GELINA (GEel LINear Accelerator) facility is located at Geel in Belgium and belongs to the European Commission's Joint Research Centre (JRC).*
https://ec.europa.eu/jrc/en/research-facility/linear-electron-accelerator-facility

Photo credits: IRFU and NTOF Collaboration at CERN.



Low pressure detectors for S³ and NFS: With or without Micromegas?

By Diane Doré, Antoine Drouart and Julien Pancin,
For the NFS and S³ teams* at IRFU and GANIL



Built as part of the SPIRAL2[g] project, the GANIL linear accelerator[1] will produce ion beams (from hydrogen to nickel) at energies ranging from a few MeV per nucleon to about 30 MeV per nucleon. These beams will be distributed in experimental areas[2]: S³ and NFS, for which IRFU has had major contributions, both for the beamline and for the detection systems. Do the Micromegas detectors have a role to play in the SPIRAL2 experiments?

The S³ programs focus on the characteristics of heavy and superheavy nuclei. They will allow to better understand how exotic heavy nuclei can be produced by different mechanisms: fusion, fission, multi-nucleon transfer... The nuclei must be identified after the reaction, at the focal plane of the spectrometer, and their trajectories and velocities must be determined by the time-of-flight method. But the nuclei to be detected have high masses (more than 100 nucleons) and low energies (less than 2 MeV/nucleon). As conventional detectors introduce dispersions in energy and position that degrade the required resolutions, prototypes of special detectors, the SED (*Secondary Electron Detectors*) have been designed. Their composition reduces the interactions with the beam. They are well suited for measurements performed at the focal plane of the S³ spectrometer. A SED consists of a thin emissive foil inclined at 45° on the beam trajectory, with an electron detector placed outside the beam axis. This gas detector can be a Micromegas or a wire chamber filled with isobutane at about 6.5 mbar. It measures the electrons stripped by the nuclei of the beam which cross the polarized foil at -10 kV. A new wire chamber of large size (of the order of an A5 sheet), and Micromegas detectors of 7 cm side were studied. The detection choices resulted from the combination of constraints on spatial (less than a millimeter) and time (around 300 ps, in full width at half height) resolutions. For the first time, these two parameters have been measured for a Micromegas at very low pressure in SED configuration. The different prototypes have achieved spatial resolutions of the order of 0.5 mm and time resolutions of the order of 400 ps. In spite of these good results, several reasons led to the choice of SED detectors with SED-MWPC wire chamber: a good time resolution of about 300 ps (FWHM) and a low electrical capacitance even for large detection areas. Even at high counting rates, these SEDs have performances that have nothing to envy to Micromegas, knowing however that at these low pressures, a Micromegas must operate in pre-amplification mode[3] to reach its nominal performances.

The same issue has emerged in the case of the instrumental developments for the NFS installation which will produce high intensity (mono-energetic) neutron beams over an energy range from a few hundred keV to 30 MeV. Stopping the deuteron beam on a thick beryllium target will produce, for example, a 5 MeV neutron flux of the order of 10^6 n/cm²/s at a distance of 1 m from the collimator exit. These neutrons will be used to study various nuclear physics processes, such as fission or evaporation. The aim is to measure both the interaction probabilities between the incident nucleus and the target (reaction cross sections) and to characterize the products (fragments, neutrons, photons, etc.).

The beams of neutrons, protons, deuterons or alphas will allow other studies to be carried out with applicative aims, by measuring the activation of materials on the NFS area. This concerns in particular the measurements used to better know the nuclei and to enrich the databases and evaluations necessary for various fields, such as the production of nuclear energy, the resistance of materials used in space or the estimation of the performances of instruments in development phase. Various experiments are planned in the NFS time-of-flight room. IRFU is the driving force behind the Falstaff[4] physics project which aims to study the fission of actinides by characterizing the fragments and the correlation with the multiplicity of evaporated neutrons. The observables are the charge, velocity and energy of the fragments. Originally, several options were considered for the choice between low pressure gas detectors, semiconductors or Micromegas.
The choice was made to use SED-MWPC[g] detectors for time-of-flight measurements, since their time resolution is better than that of Micromegas. For the measurement of energy, the resolution to be reached is 1%. The phenomenon of amplification of proportional detectors could increase the uncertainty on the measurement of energy. This is why an ionization chamber was preferred. The whole device planned to equip each "arm" of Falstaff is presented on *figure 1*.

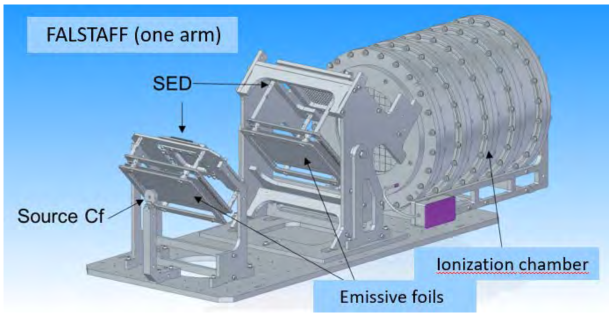


Figure 1. Experimental device for a Falstaff arm. [Image: Irfu, Marc Riallot).

One NFS room will be used for time-of-flight measurements to determine the energies of the incident neutrons. In order to characterize the neutron fluxes in this room, the NFS collaboration will combine several types of detectors, including a Micromegas, whose function is similar to that of the instrument used on n_TOF (p. 16).
The S³ and NFS areas will thus make cohabit various devices, chosen among the detectors most adapted to the specific characteristics of the nuclei to be studied. Micromegas will be one of them!

*** The IRFU and GANIL involved in the development of Sed, des Micromegas and Falstaff (F):** *D. Doré (F), A. Drouart, G. Frémont, M. Kebbiri (Sed, F), Ph. Legou (F), J. Pancin, M. Riallot (Sed, F), Ch. Spitaels, L. Thulliez (F, 2014-2017).*

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[2] Top views of the two experimental areas are shown on the drawings in the banner, on the left, *Neutron for Science*, NFS, https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/nfs and on the right, the *Super Spectrometer Separator S³* https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/s3
[3] Pre-amplification mode: when amplification starts at the drift zone.
[4] FALSTAFF: Four Arm cLover for the STudy of Actinide Fission Fragments.

Photo credits: GANIL, IRFU.

KABES and T2K, or the art of trajectography at all scales!

By Edoardo Mazzucato for the KABES* NA48 and T2K teams at IRFU**

During the 2000s, IRFU (then DAPNIA) played a leading role in the realization of the *Kaon Beam Spectrometer* KABES for the NA48-2 project at CERN, as well as in the construction of the TPC[g] time projection chambers for the T2K experiment in Japan. If these instruments contrast in size and in the Micromegas technology used, they both can achieve the three-dimensional reconstruction of charged particle trajectories with exceptional performances.

Precise measurements of particle trajectories and times are crucial information for high energy particle physics experiments. When studying very rare phenomena, it is necessary to use high-intensity and high-density particle beams which make these measurements delicate. The KABES project aimed at detecting the incident particles at high intensities (of the order of 30 million particles per second) of the NA48-2 experiment of the *Super Proton Synchrotron* (SPS). The objective of this experiment was to search for CP symmetry violation in some decay channels of charged K^+ and K^- kaons. The KABES magnetic spectrometer was then designed to measure the profiles of the Kaon beams. This counting was essential to determine a difference between the data collected with the two beams and thus to obtain a signature of the CP violation.

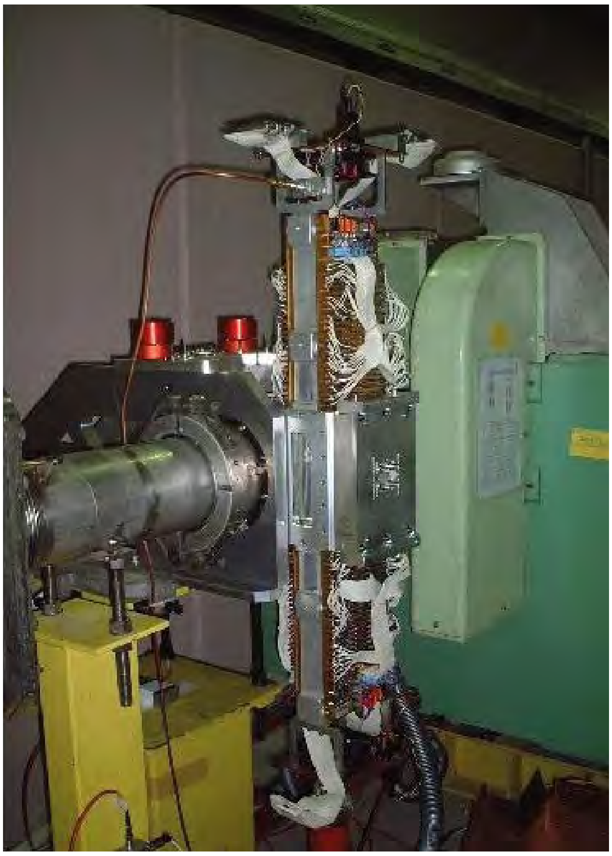

Figure 1. One of the KABES detectors moved horizontally 20 cm out of the beam line to see the entrance window.

KABES has been realized by the DAPNIA[g]. Installed on the 60 GeV/c hadron ($\pi^\pm$, $K^\pm$) beam line of the NA48-2 experiment, it consists of a set of small gas detectors (Fig. 1) operating in TPC mode. *The banner on p.18* shows a set of two KABES TPCs being assembled, with the field cage visible behind the grid in the foreground. This electrostatic cage surrounds the entire space between the cathode plane and the anode plane to create a uniform drift electric field. The precise measurement of the time and position of the beam particles relies on the use of first generation Micromegas detectors with an amplification gap of 50 µm. The time resolution of the order of 10^{-9}s allows the identification of traces in an intense flux of several MHz/cm^2 and ensures a resolution of about 50 µm in the electron drift direction. The vertical coordinate, obtained with an accuracy of 100 µm from the charge measured on the readout tracks, allows the determination of the beam pulse to within 1%, even at high flux.

During tests of a prototype KABES station in July 2002, the charged particle flux reached the rate of 2.0 10^7 per second over an average area of 10 cm^2, and 2.0 10^6 per second for the most exposed tracks.
KABES was successfully operated in 2003-2004 in an intense beam of 2.0 107 particles per second over an area of about 4 cm^2. The grid current, proportional to the particle flux, acted advantageously as a beam counter. Thanks to the small thickness of material exposed to the beam, the operation of KABES proved to be very stable, with a low discharge rate.

The association of a TPC with Micromegas, developed by DAPNIA, has provided the NA48-2 experiment with a formidable tool to carry out many precision measurements related to charged kaon decays [1].

T2K in Japan

An ambitious program on the measurement of neutrino oscillations [2] is carried out in the framework of the T2K experiment currently in operation. The design of the device started in the 2000s. The large TPC chambers are located near the ND280 detector (it provides measurements near the emission source), at the J-PARC site in Tokai. These TPCs [3] are an essential element of T2K since they provide the counting of neutrinos close to their production point and thus before they have had a chance to oscillate [2]. This measurement provides the normalization of the experiment.

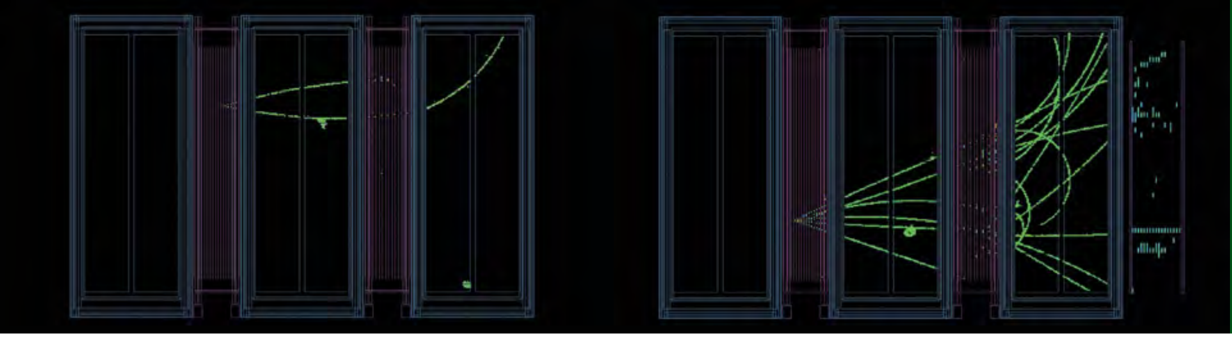

Figure 2. View of a panel on one of the three large surface TPCs (9m² each). This panel, under integration, is composed of 12 Micromegas modules. The three TPCs form the T2K near detector, in charge of characterizing the neutrino beam.

Figure 3. Elements of the Micromegas "bulk" detector mosaic for the time-projection chambers of the T2K experiment in Japan.

The three TPCs are placed on either side of targets (composed of enclosures containing a scintillating liquid) in a magnetic field of 0.2 tesla. They occupy a total volume of 18 m^3 and offer a detection surface of 9 m^2 (Fig. 2) covered by 72 Micromegas modules (view of a module, Fig. 3) whose operation is based on the "bulk" technology (p.12) developed jointly by DAPNIA and CERN.

These instruments, which have no less than 124,000 readout channels with a fine granularity of less than one cm^2, provide high-resolution 3D images with sub-millimeter precision on the position of the tracks (Fig. 4).
The whole signal processing chain -specific front-end integrated circuit, front-end electronics, acquisition software, track reconstruction software- is designed and produced at IRFU.
In operation since 2010, the T2K TPCs continue to track neutrino interactions in a charged particle flow without fail.

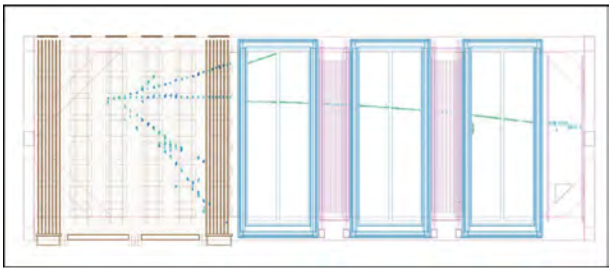

Figure 4. Schematics of the T2K TPC chambers, with the observation of the effects of a neutrino interaction in a scintillator target (pink) visualized by the TPCs (blue enclosed volumes) of the T2K ND280 near detector. The green lines represent the tracks left by the charged particles produced in the target and detected in the three TPCs. The images in the banner (p.19) also show examples of the interaction of a neutrino in the target, visualized by the trajectories reconstructed (in green) by the TPCs.

IRFU has been one of the pioneers in the construction of these precision instruments, notably in the design and realization of the Micromegas detectors and their readout electronics. From 2021, the T2K physics program will enter a new phase with the use of more intense beams and an improved experimental setup. IRFU will undoubtedly play a major role in the realization of new TPCs that could use resistive Micromegas. Micromegas still has many years to come in the T2K experiment!

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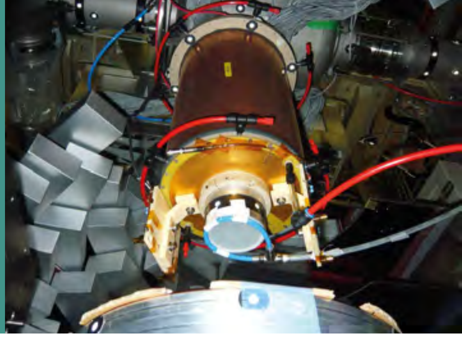
https://doi.org/10.1016/j.nima.2011.02.036 .

** Members of the IRFU project team: P. Baron, J. Beucher, F. Blaszczyk, M. Boyer, D. Calvet, P. Colas, X. De La Broise, E. Delagnes, A. Delbart, F. Druillole, C. Giganti, I. Giomataris, J. Giraud, S. Herlant, E. Mazzucato, J.-Ph. Mols, E. Monmarthe, F. Nizery, F. Pierre, D. Pierrepont, J.-M. Reymond, J.-L. Ritou, A. Sarrat, M. Usseglio, G. Vasseur, M. Zito.

Photo credits: Figures 1 et 3 : IRFU ; figures 2 and 4 : T2K.

The 3D trajectography of nuclear reactions with the MINOS active target

By Alain Delbart for the MINOS team* at IRFU



To determine the evolution of the structure of nuclei very far from the valley of stability - so-called exotic nuclei -, it is necessary to measure their first excited states, but these nuclei are produced at very low intensities (less than 1/s), so it is necessary to be able to optimize the luminosity of the reactions and the energy resolution: MINOS (MAgic Numbers Off Stability) is the instrument specially designed and built by IRFU (2010-2013) to carry out these experiments of spectroscopy of exotic nuclei.

MINOS [1] has been operated since 2014 at the RIBF accelerator of the Japanese Nishina Research Institute at RIKEN[1]. It consists of a thick cryogenic target (10-15 cm long, and 4 cm in diameter) of liquid hydrogen at -253°C, surrounded by a 30 cm long cylindrical time projection chamber (TPC).

The TPC is used to determine with a few millimeters of precision the interaction point of the radioactive ion beam. This TPC is presented in cut view on figure 1 and in profile along the beam axis on the photo on the right (in the background, the cryogenic system for the target can be seen). It consists of two cylinders defining the electric field (inner and outer field cages) and between which a mixture of argon, isobutane and carbon tetrafluoride circulates. The TPC is closed on one side by a copper plane heated to 6 000 V (cathode) and on the other side by a Micromegas bulk reading plane ("imager" anode).

This active area of the imager is pixelated, it has 3 604 sensitive pixels. The correspondence between the signal and the spatial area of the hit pixels allows the reconstruction of the trajectories in three dimensions (*box, figure 2*).

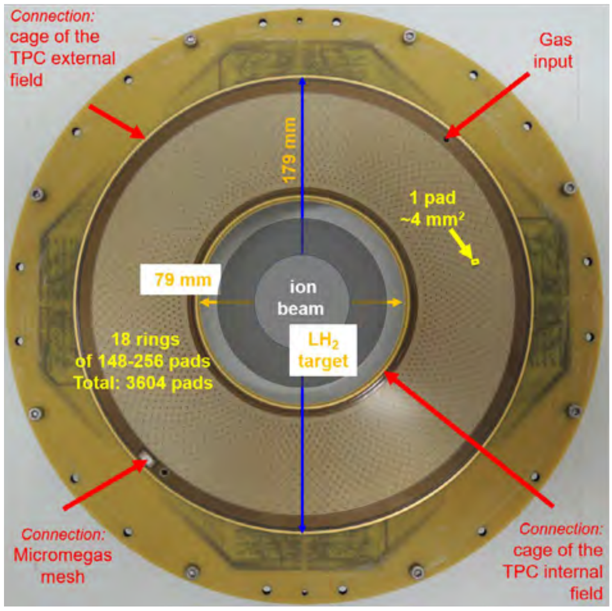


Figure 1. Bulk Micromegas reading plane of the MINOS TPC (seen from inside the TPC).

The reconstruction of trajectories in 3 dimensions via pixelization (*V.L.*)

By combining a cylindrical Micromegas detector surrounding a thick reaction target, cylinder arranged along the beam line, we can measure the vertex, point of interaction of the nuclei reacting with the nuclei of the target. The electrons are stripped from the molecules of the gas contained in the cell around the target. The signal is created by the flow of guided and multiplied electrons. The electrical signal is generated on some pixels of the detector and transmitted to the electronics, we thus have the spatial location thanks to the localization of the pixels, and the measurement of the arrival time of the electrons, which allows a reconstruction in three dimensions of the trajectories.

The photons emitted in flight by the excited nuclei during the reactions are detected in the DALI2 photon spectrometer composed of 186 detectors (metallic blocks, with NaI, visible on the photo of the banner, around the TPC). From the reconstruction of the trajectories, the reaction location –vertex- is determined which allows to make with precision, on the energies of the photons detected in DALI2, the Doppler effect corrections corresponding to the energy shift due to the emission in flight of the photon. The photon energies are obtained in coincidence with the particles measured in the TPC and with the incident and outgoing nuclei of the reaction, identified by spectrometers on the RIBF beamline.

This allows us to determine which reactions correspond to the emission of two protons. These reactions, denoted (p,2p), are mainly studied to obtain the spectroscopy of the nuclei of interest. The TPC can reconstruct the trajectories of the two protons resulting from the interaction with a sub-millimeter spatial resolution.

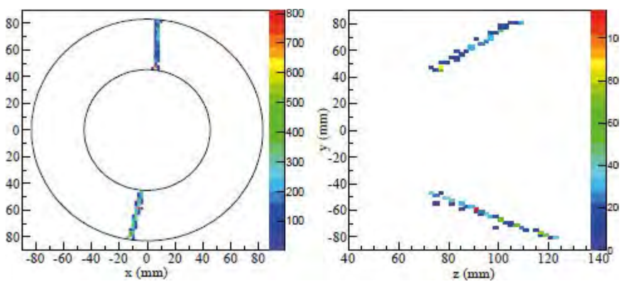


Figure 2. Event reconstructed by the TPC in 2D projection on the Micromegas plane. The reference frame of the cylindrical MINOS TPC is here (x,y) for the transverse section and (y,z) for the profile along the chamber axis. We see in these two planes traces of the reconstructed trajectories for two particles detected in the TPC. The tracks of two protons in the TPC are obtained by selecting the events associated with the measurements in coincidence with the nuclei of interest identified before and after the reaction (p,2p) that produces two protons on the proton target: this is the pair where the nucleus before the target has a nucleon number (mass) A, and a proton number Z, and the nucleus after the target has mass A-1; proton number Z-1. For example: the reaction of 111Nb on proton produces two protons and the ^{110}Zr nucleus.

This Micromegas detector has the particularity of being a hollow cylinder for the passage of the hydrogen target: its realization called upon the ingenuity of the technicians of the MPGD[g] laboratory at IRFU to integrate the woven grid at 128 microns above the printed circuit. The granularity of the imager (~5 pixels per cm^2) is such that the design of the printed circuit required the use of 12 internal layers and more than 18,000 metallized holes to extract and transmit the electronic signal from each of its pixels to the readout electronics located 80 cm away from the detector.

The reading of the signals of each pixel is done with front-end electronics cards entirely developed at IRFU; they were initially designed for the reading of the TPCs of the T2K experiment (p.19). They are equipped with the AGET[g] chip consisting of 64 reading channels. A new data acquisition board has been specifically developed for this system, it is called FEMINOS for Front end Electronics Minos (FEM) [2]. The set of pixels to be encoded requires twenty electronics cards, each of which has four AGET chips. The 20 cards can read about 5 000 channels with a maximum rate of several kHz. The signal processing and acquisition for MINOS were notably the development purpose of the MORDICUS software at IRFU [3].

From 2014 to 2017, six TPCs were built and tested at Saclay before being sent to Japan for their operation during various scientific campaigns, including the three "SEASTAR"[2] whose objective was to measure for the first time the excited 2^+ states of about twenty very neutron-rich nuclei, only produced in the laboratory, on the Japanese RIBF facility, at very low intensities (from a few particles to sometimes less than one per second). During these campaigns, new areas of the table of nuclei were examined (Figure 3) and the analysis of the measurements led to a harvest of striking results on the spectroscopy of exotic nuclei.

MINOS is a unique instrument for these studies. It is currently combined at RIKEN with the DALI2 photon detector. It is envisaged that it will be associated with higher performance assemblies, either in Japan, or at other accelerator facilities (GSI in Germany) to continue explorations of exotic nuclei, by this 3D trajectography technique in coincidence with the detection of gammas. Its scientific future is promising with the beams of very unstable nuclei produced or planned in the large international accelerators.

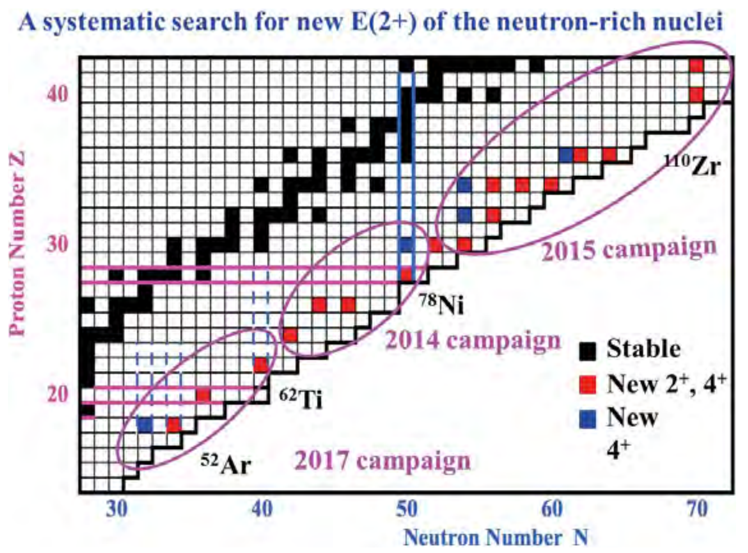


Figure 3. Domain of the table of nuclei, as a function of the numbers of protons Z and neutrons N, showing the location of the very neutron-rich isotopes for which new states have been measured during the three campaigns: the squares (red and blue) show the nuclei for which the first states (2^+, 4^+) have been obtained for the first time.

References:
[1] Scintillations, N°92 (Oct. 2015), p.2, « Force et excès dans le noyau ». Site du projet : http://minos.cea.fr
A. Obertelli et al., *European Physical Journal A* 50: 8 (2014) https://doi.org/10.1140/epja/i2014-14008-y
[2] *The readout electronics and data acquisition system of the MINOS vertex tracker*, S. Anvar, H. Baba, H. Bervas, D. Besin, D. Calvet, F. Château, X. Coppolani, A. Corsi, A. Delbart, A. Giganon, A. Gillibert, C. Lahonde-Hamdoun, V. Lapoux, A. Obertelli, A. Peyaud, E. Pollacco, G. Prono, C. Santamaria, H. Zaghia, Real Time Conference (RT), 2014 19th IEEE-NPSS, https://doi.org/10.1109/RTC.2014.7097530
[3] *Mordicus-hw: A C++ framework for backend electronics control and configuration*, S. Anvar, F. Château et P. Sizun, (RT), 2014 19th IEEE-NPSS, https://doi.org/10.1109/RTC.2014.7097459

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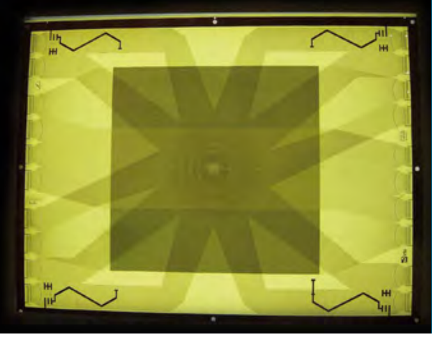
DPhN : Anna Corsi, Alain Gillibert, Valérie Lapoux, Alexandre Obertelli (scientific manager of the project), Nancy Paul (2014-2018), Emmanuel Pollacco, Clémentine Santamaria (2013-2016). Before the campaigns (R&D Minos, 2010-2014) : DEDIP, Shebli Anvar, Caroline Lahonde-Hamdoun, Didier Lebœuf, J. Ph. Mols, Gilles Prono; DPhN : Laurent Audirac (2011-2013).
Photograph of the banner on p.20 from left to right (1st campaign, May 2014) : (bottom) J.M. Gheller, A. Obertelli, G. Authelet ; (middle) A.Delbart ; (top) V. Lapoux, C. Péron, C. Santamaria, F. Château, D. Calvet, A. Payaud, E. Pollacco. Page 21: international collaboration of SEASTAR (2014).

[1] RIBF: *Radioactive Ion Beam Facility*, accelerator of radioactive nuclei belonging to the Nishina research center of the RIKEN Institute, the *Nishina Center for Accelerator-Based Science*. https://www.nishina.riken.jp/index_e.html
[2]. SEASTAR : *Shell Evolution And Search for Two-plus energies At RIBF*, series of three spectroscopic measurement campaigns, performed with beams provided by RIBF at RIKEN, https://www.nishina.riken.jp/collaboration/SUNFLOWER/experiment/seastar/index.html

Photo credits: banners p.20-21, left: IRFU, right: V.L.



Micromegas evolutions: segmented, resistive, bulk and hybrid

By Damien Neyret and Sébastien Procureur, for the IRFU project teams

At the end of the 2000s, new Micromegas detectors were developed to operate at very high particle flux, as illustrated here by the COMPASS experiment. To make them operational in such conditions, many paths have been explored such as increasing the granularity (very high pixel density in the beam area), using resistive strips or associating Micromegas with another micro-structure detector, the GEM.

Micromegas hybrid and pixelized detectors for the COMPASS experiment

In 2009, after a decade of service in the COMPASS experiment (p. 10), it appeared that the Micromegas detectors were not perfectly adapted to the new phase of the experiment that would start in 2014. The new physics measurements planned would require high intensity muon and hadron beams. Under hadron beam, these detectors were working at the limit of their possibilities, with high discharge rates that could induce detection inefficiency and accelerated aging. Under muon beam, it was necessary to reinforce the reconstruction of the particle tracks at very small scattering angles, where the Micromegas detectors were inactive. A new generation of these detectors was then developed with two main objectives: 1/ to make them active in their central part in order to detect particles at very small angles; 2/ to reduce the impact of discharges on their operation in order to support large hadron fluxes (*see box below*).

The first COMPASS detectors were rendered inactive in their center because the signal flux from the readout tracks would have been too high there. Indeed, the reading electronics cannot distinguish two signals too close together in time, on the order of microseconds. If the signal flux reaches the order of MHz, some are lost and the particle detection efficiency becomes too low. The readout strips in the central area have thus been divided into rectangular pixels (Figure 1) of a few millimeters in length, each read by an electronic channel in order to limit the flux per channel. 1280 pixels of two different lengths cover a central zone of 5 cm in diameter, ensuring a sufficiently low signal flux (less than 200 kHz) to maintain a very good detection efficiency, greater than 95%, in this zone.

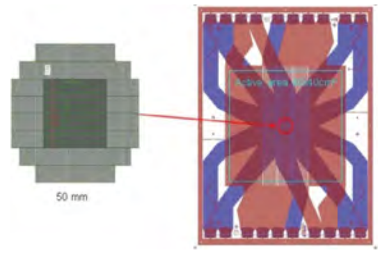


Figure 1. Drawing of the reading strips as well as of the set of strips linking to the connectors. The pixel area (shown on the left) has 1280 pixels.

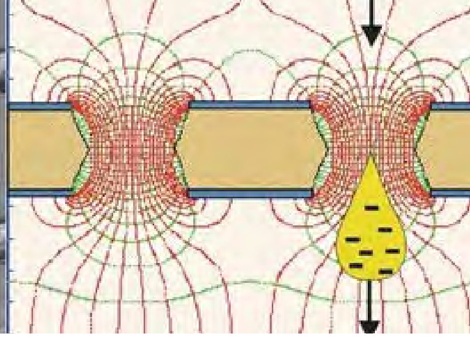
Electrical discharges, "breakdowns" and resolution of the problem in resistive mode

The development of breakdowns in Micromegas is often a limiting factor in extreme conditions of use, in particular in very high particle fluxes. These breakdowns are generally linked to a too strong accumulation of charges in the amplification space (typically a surface density of a few billion electrons per mm²) and generate gain drops as well as a possible degradation of the detector in the long term.

The phenomenon of electric discharge in a gas is a very old problem, and many physicists have been interested in it, in particular F. Hauksbee, F. Paschen, J.S. Townsend, L. Loeb or H. Raether. In the case of Micromegas, it quickly appeared that these discharges could considerably affect the detection efficiency, especially in hadron beams. The first systematic studies on COMPASS showed the influence of the gas mixture used and the gain of the detectors on the rate of discharges, but without understanding the real cause of this "aversion" of Micromegas for hadrons. In 2007, simulations showed that the hadron rates in the future CLAS12 Micromegas would be much higher than those recorded on COMPASS. In order to quantify the associated discharge rate, simulations (with the Geant4 code) were carried out on the energy deposits in the detector. It turned out that nuclear reactions between the incident hadrons and the different materials of the detector caused the emission of very ionizing particles likely to create a number of charges higher than the Raether limit[1] ($\sim 10^7$ electrons) and thus to initiate a discharge process. These simulations[2] have been shown to be in good quantitative agreement with the measurements performed under beam for COMPASS and CLAS12. By taking into account the transverse scattering of electrons in the gas and by reinterpreting the Raether limit as a critical charge density, these simulations also allowed to understand, again quantitatively, the reduction of the discharge rate observed in a hybrid detector by combining a Micromegas with a GEM foil.

[1] *Raether limit: phenomenological limit of the flux of charged particles between electrodes, without breakdowns. It corresponds to the maximum value of the multiplication in an electron avalanche.*

[2] S. Procureur et al., Origin and simulations of sparks in MPGD, JINST 7, C06009 (2012).
https://doi.org/10.1088/1748-0221/7/06/C06009
S. Procureur, S. Aune, J. Ball, Y. Bedfer, M. Boyer, H. Colas, A. Giganon, P. Konczykowski, F. Kunne, C. Lahonde-Hamdoun, N. Makke, C. Marchand, O. Meunier, A. Morreale, B. Moreno, H. Moutarde, D. Neyret, S. Platchkov, F. Sabatié, *Discharge studies in micromegas detectors in a 150 GeV/c pion beam*, NIM A Vol. 659 (2011), pp. 91-97, https://doi.org/10.1016/j.nima.2011.08.033



Discharges in Micromegas

The impact of discharges on the operation of Micromegas detectors has been studied for several years at IRFU and in other laboratories. Known technologies to reduce this effect were based on the use of layers of resistive materials on the reading plane. One of the first promising developments was the addition of resistive strips (Figure 2) between the readout tracks and the microgrid. The presence of these strips allows to extinguish the breakdown formation very quickly and to evacuate the charges towards the ground. This protection effect was verified during tests in intense hadron beams, during which no degradation of the amplification was observed in the detector.

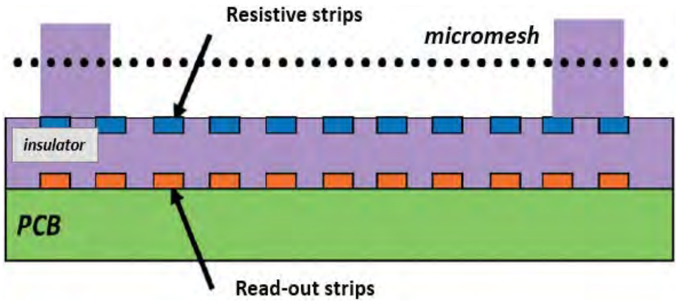


Figure 2. Schematic (cut view) of the resistive strip detector (Alexopoulos et al.). The resistive strips (blue) are placed opposite the readout strips (orange), and separated by a 75 micron thick insulating layer.
The dotted lines represent the microgrid.

Hybrid detection, happy marriage: microgrid and GEM

These resistive layer technologies were mostly adapted to read strips, much less to pixels. We then adopted an original hybrid solution (Figure 3) by inserting, two millimeters above the microgrid of a non-resistive Micromegas, a GEM foil for pre-amplification of primary electrons. The picture on the left banner, p.23, shows a hybrid detector being assembled, with the GEM foil in place. This foil, formed from a 50 µm layer of polyimide[3] coated with 2 µm of copper on both sides, is pierced with evenly spaced holes of 70 µm diameter. This structure of the GEM foil can be seen in the photo of the banner on p.23 (center), with the field line pattern on the right. By applying a voltage of about 300 V between the two copper faces, these are amplified in the holes with an overall gain of 10 to 20. This pre-amplification reduces the gain and thus the electrical voltage of the microgrid, thus reducing the discharge probability of hybrid detectors by a factor of 10 to 100 compared to a Micromegas with the same gain.

A collaboration between IRFU and a company specialized in the production of printed circuits, Elvia (located in Coutances), was launched to transfer to the industrial company the bulk technology used in these detectors, in order to manufacture all the circuit boards of the 12 detectors necessary for the experiment.

This collaboration resulted in a mass production of the detectors[4], which were installed in the COMPASS spectrometer in April 2015, in time for data taking starting in May.

During measurements, the detectors operated with performance in line with the specifications, with detection efficiency above 96% at high flux, spatial resolution on the order of 70 µm, and time resolution of 10 ns.

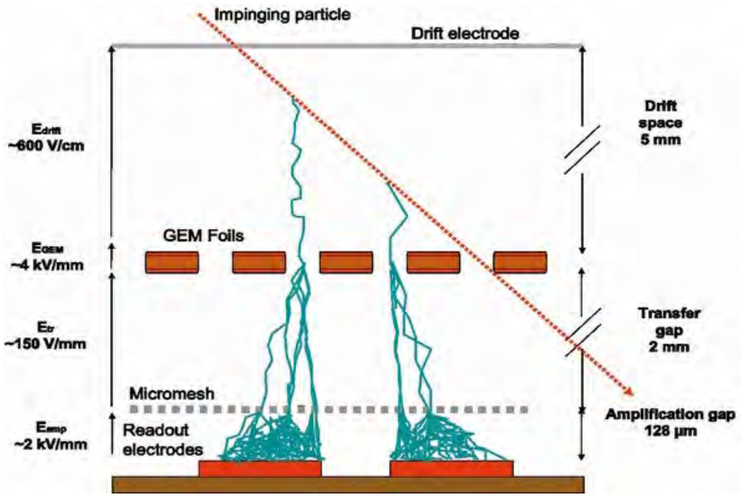
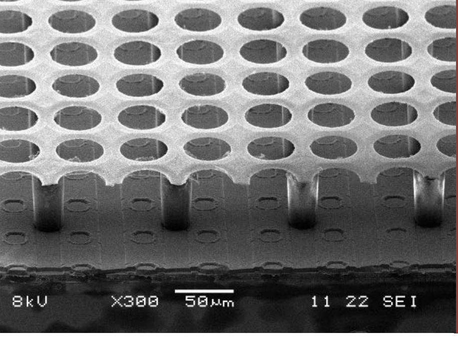


Figure 3. Operating principle of a hybrid Micromegas detector. A GEM foil placed 2 mm above the microgrid is used for pre-amplifying the ionization electrons, allowing to reduce the gain of the Micromegas and thus the grid voltage.

For more information, see the project web page: http://irfu.cea.fr/Phocea/Vie_des_labos/Ast/ast_sstechnique.php?id_ast=3415

[3] Polyimide : a plastic material resistant to heat and electric fields.
[4] Photograph of the banner on p.22, right: the detectors at CERN, installed on their support frame. They are arranged in different orientations to measure the particle tracks in three dimensions.

Photo credits. Images, figures 1 to 3: IRFU; photographs of the banner on p.22: left V.L, right: CERN; p.23: IRFU.



The development of electronic chips InGrid reading planes (TimePix)

By David Attié, for IRFU project teams*

The use of pixels in Micromegas detectors started in 2005 with the combination of a grid simply placed on a MediPix2 chip [1] designed by the MediPix collaboration [2] for applications in the medical field, in radiography and computed tomography[1] where X-rays are used to probe the human body. As Medipix chips detect and count photons arriving on one of the pixels of the active surface, this technology has been applied to increase the image rendering capabilities of X-ray tomography techniques, as well as for mammography and radiography systems (in beta and gamma) of biological samples. With the new chips developed to measure photon energies and tracks (Medipix3 type chips), the different photon energy levels are indicated by images provided in color. This "color" imaging technique for X-ray measurements provides physicians with more accurate images of their patients, which can facilitate diagnosis.

The new Piggyback architecture

To provide discharge protection for electronics while maintaining high gain and energy resolution performance, one technique is to fabricate an anode from a resistive layer on a ceramic substrate. The resistive layer is deposited on a thin ceramic substrate by a process that provides high dynamic range for the resistivity ranges (10^6 to 10^{10} MΩ per square). The special feature of this structure is that the active part is completely dissociated from the reading element. This gives greater flexibility in designing the layout of the anode structure and that of the readout electronics. The signal is transmitted without significant loss by capacitive coupling to the reading pads.
This setup can be combined with the ASIC[g] pixelized electronics board devices. The readout pattern is organized independently of the overall design of the pixels, their layout and connections. Since this detection structure can be mounted on the back of any readout plane, it has been named "Piggyback Micromegas" [5].
This *Piggyback* architecture has been used with the new Medipix2 type readout chips. One of its applications concerns X-ray polarimetry, especially in the space domain. Piggyback has been used with the Caliste chip [6].

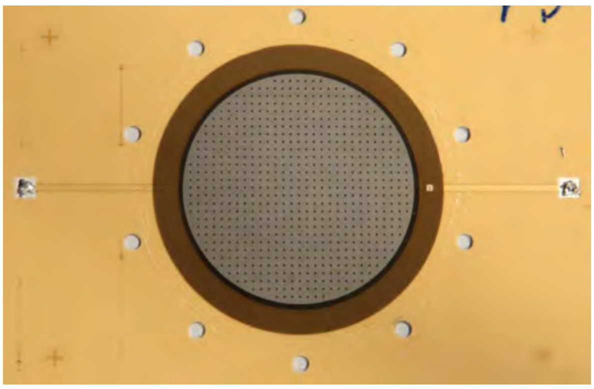


Photo of the Piggyback detector (in sealed mode) used for the tests. The diameter of the active area is 6 cm.

A TimePix collaboration (CERN, Nikhef, Saclay) was formed at that time to develop a chip derived from Medipix2 , adding the possibility of having information on the arrival time of the radiation on each pixel as well as on the charge of the electrons. The TimePix chip [3], like the MediPix chip, is a matrix of 256 × 256 pixels of 55 µm² covering an active area of 1.4 × 1.4 cm². Each pixel is composed of a preamplifier, a shaping filter and a counter operating at a frequency of up to 100 MHz.

The IRFU team participated in the discussions during the design of this chip, then in the R&D on the resistive layers for its protection against breakdowns during operations with Micromegas and finally in the implementation of post-processing on silicon aiming to integrate a Micromegas detector directly on the chip. This technology, called InGrid for Integrated Grid [4], is represented on the image of the banner, where we can see the Micromegas detector on a Timepix chip. The resistive protection layer used from now on consists in depositing about ten microns of silicon nitride (Si_3N_4) on the pixels before the construction of the InGrid. The pillars (between the pixels) and the holes of the grid (aligned with the pixels) are built using photolithographic techniques on silicon. The grid is about 1 µm thick and is made of aluminum sputtering like the protective layer.

During the R&D phases of the chips, specific architectures were developed to protect the pixelized electronics from discharges, including Piggyback (*see box*) adapted for the Medipix2 chip. Such a device provides a three-dimensional image of each primary electron resulting from the ionization of the gas molecules by the charged particle passing through it. Figure 1 illustrates the tracks of two electrons, coming from a strontium-90 source and drifting in the gas, under an electric and magnetic field.

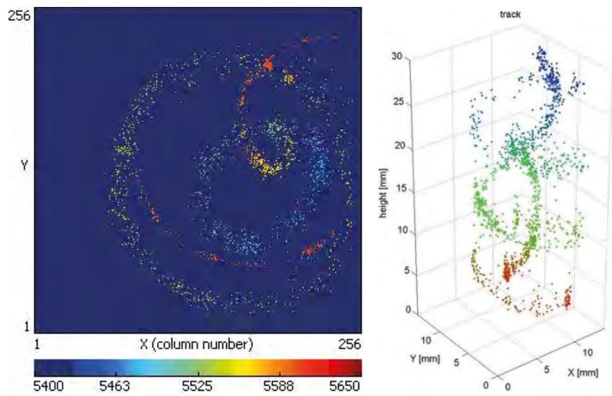
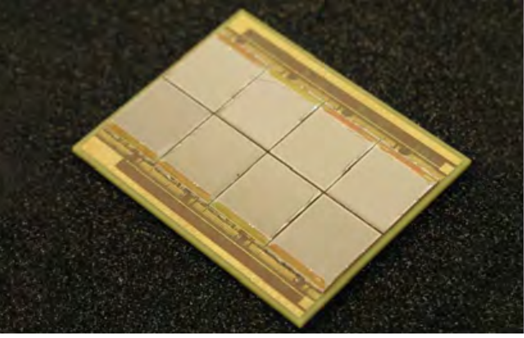
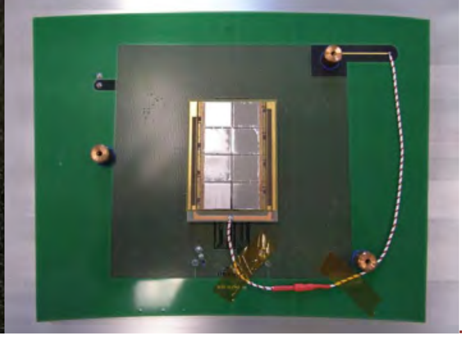
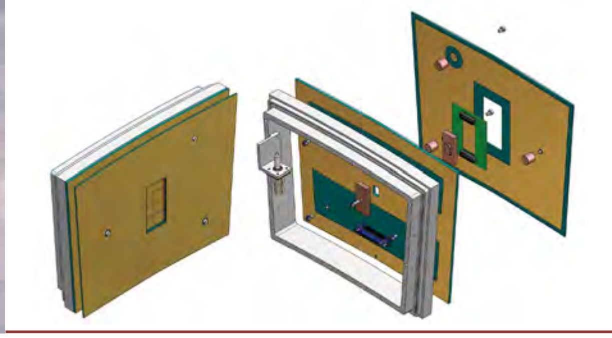


Figure 1. Helix-shaped tracks of electrons (from a ^{90}Sr source) drifting in the gas volume under an electric and magnetic field; left, the data recorded in "time" mode; right, the reconstruction in three dimensions.

[1] Computed tomography (CT) is a technique that combines X-ray measurements and computers to produce cross-sectional images of the human body or biological samples.

In 2010, IRFU realized a 2×4 Timepix chips array with *InGrid* named *Octopuce*. The banner (p.25) shows a picture of Octopuce on the left; in the center, the array is implemented and bonded on the frame for a large prototype time projection chamber TPC[g]; on the right, the schematic shows the assembly of the backplane and the mezzanine board[2]. This device provides a detection area of 2.8 × 5.6 cm². That same year, this readout plane (unprecedented for a TPC with more than 520,000 pixels) took measurements for the first time using the 6 GeV electron beam provided by the German DESY synchrotron in Hamburg. The recorded data correspond to the beam tracks seen by the Octopuce (Fig. 2). Each point of the image corresponds to an electron resulting from the ionization of the gas atoms during the passage of the high energy electron coming from the beam. It can be seen that the density of the ionization along the track is not uniform. Small electron clouds are formed by denser packets.

Since then, an effort to produce the *InGrids* industrially has resulted in a readout plane of 160 TimePix and *InGrid* systems (20 octoboards), or more than 10 million pixels with single electron resolution. This device was put into operation in 2015 by the University of Bonn at DESY and in 2017 at PHIL (LAL). Figure 3 shows an event in the presence of a magnetic field (one tesla, 1T): the helix-shaped tracks of several low-energy particles of positive and negative charges are shown.

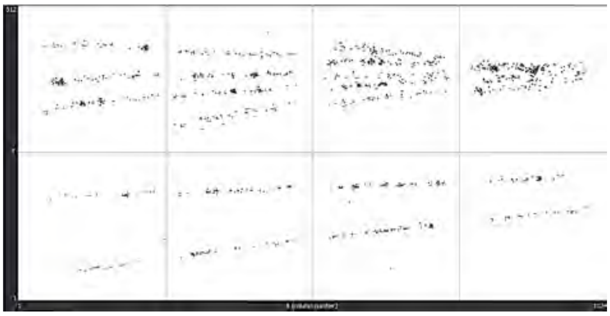


Figure 2. Tracks from the 6 GeV electron beam, recorded by the Octopuce at DESY.

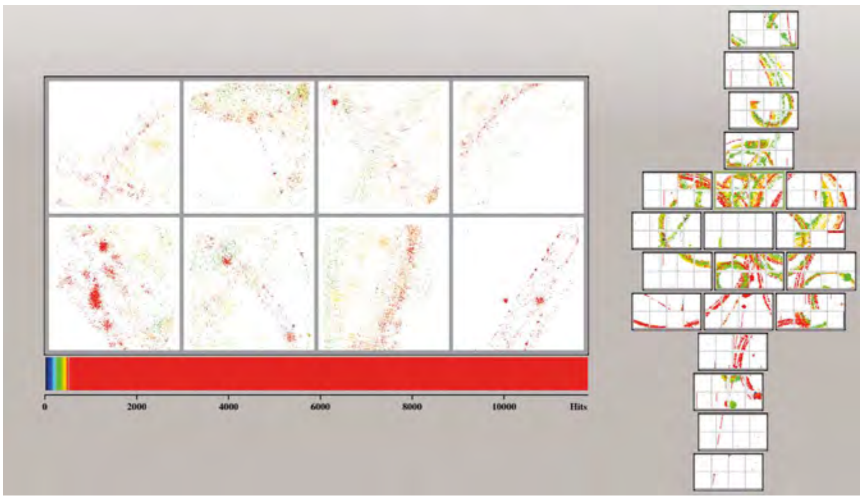


Figure 3. Plot of a multi-particle event during the data collection in a beam with a magnetic field of one tesla.

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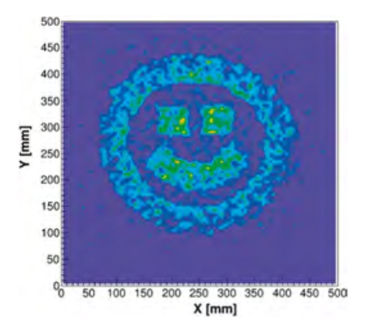
[6] D. Attié, C. Blondel, L. Boilevin-Kayl, D. Desforges, E. Ferrer-Ribas, I. Giomataris, O. Gevin, F. Jeanneau, O. Limousin, A. Meuris, T. Papaevangelou, A. Peyaud, NIM A **787** (2015) 312-314. https://doi.org/10.1016/j.nima.2015.01.007.
See also: *Caliste-MM: Polarimetric measurements at the Soleil facility,* P. Serrano, P. Da Silva, E. Ferrer-Ribas, O. Limousin, P. Mercere, F. Orsini, NIM A **912** (2017) 274-277. https://doi.org/10.1016/j.nima.2017.11.079

**** The Piggyback (P) and Timepix (T) teams at:** D. Attié (P,T) , P. Colas (P,T), X. Coppolani (T), I. Giomataris (P), F. Jeanneau (P), E. Ferrer-Ribas (P), Th. Papaevangelou (P), A. Peyaud (P), M. Titov (T).*

[2] *Mezzanine board:* electronics board mounted in parallel to the motherboard. It contains the chips and programmable load functions, making it easy to connect the wires.

Photo credits: IRFU and CERN, MediPix and Timepix collaborations.



Get out the muo device!

By Sébastien Procureur
For the team* of muographers of IRFU

The adventure of Micromegas crossed that of muography at IRFU. This meeting is the real fruit of chance, almost an accident, and appears five years later as a necessary evidence. The history of this relationship also illustrates in a remarkable way the potential of development and innovation of the Institute thanks to the perfect complementarity of the profiles, notably in the technical services.

We are at the end of 2011, in the CLAS12 lab of the DÉDIP[g]. The team is working on the realization of a large and very precise cosmic test bench for the curved detectors intended for the JLab. A quick calculation indicates that such a bench requires more than 6,000 channels of electronics - which we do not have - just for the reference detectors. Stephan Aune has then the idea to create double-sided Micromegas, with on one side 32 wide strips to roughly localize the particles, and on the other a comb of 32 x 32 fine strips to refine the position. And here is 50 x 50 cm² of detection with the equivalent of 1,024 strips, but with only one connector of 64 strips! With the skill of our late colleague, Marc Anfreville, six detectors were soon created. But the concept poses some problems: ambiguity of localization for wide-angle strips or multi-strips, not to mention the difficulty of making two functional **bulks**[g] on the same PCB[g] support each time. With the help of Raphaël Dupré, we solve these problems in August 2012 via a new patented multiplexing system ([B14B], p.31), called *genetic*, using the fact that a particle leaves a signal on several adjacent strips. The connectivity is subtle (Fig. 1), but only one side is needed, and the multiplexing adapts to the particle fluxes.

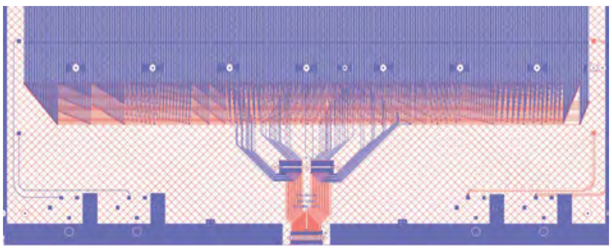


Figure 1. Connection diagram of the genetic multiplexing (MultiGen) between the reading strips and the electronic channels.

The "**MultiGen 1D**" detector was born, followed in 2014 by the MultiGen 2D with a resistive film allowing bidirectional detection on a single floor. All that is missing is the dream electronics (*Dream*[g]), and the whole unit displays a 2D efficiency of 97% despite an electrical capacitance of 2 nF due to the length of the cables (8.5 m of strips plus 2 m of dabs?). What was at first only a laboratory trick soon became a project that was declined in several instruments. *In deviation muography (see box)*, we start with David Attié the fabrication of a large imager of one square meter, **M-Cube**. Given the number of detectors to be produced, it became essential to transfer the manufacturing know-how to an industrial company. The road is long, but in 2015, the company Elvia delivers its first functional 2D MultiGen, and more than twenty will be produced in 2016 (Fig. 2).

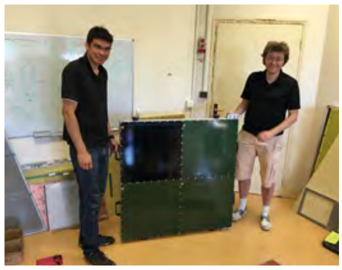
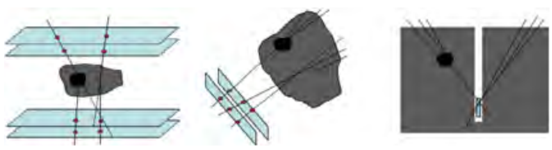


Figure 2. A panel of the M-Cube imager held by David Attié et Sébastien Procureur.

In parallel, simulations show that these detectors are accurate enough to reconstruct the shape of dense objects - such as lead bricks - in only 20 minutes. We then propose the "***TomoMu***" device, the first portable and interactive muon tomograph, equipped with four MultiGen. Intended for scientific popularization, its great precision is illustrated on the image on the banner (*p.26, left*), named "Muona Lisa" and obtained with an assembly of lead bricks. *TomoMu* is now used in a reception room of the Dédip[g] during visits organized in our laboratories, as a demonstration during the "*Fête de la Science*" or for student work.
The robustness of the detectors also encourages us to develop a muon telescope, like the telescopes used in volcanology. But the outside is a hostile environment for a detector used to the hushed atmosphere of experimental halls. In 2015, we installed a prototype telescope, ***WatTo*** (Water Tower), at the foot of the Saclay water tower. Its operation is ensured by a small board box containing the front-end electronics, a nano-computer for acquisition, a hard disk for data storage, and an "in-house" card for the control of high voltages via miniature modules powered by 12 V. A truck battery and a regulator complete the device, which does not consume more than a low consumption bulb (35 W).

Muons and the muography

Muons are elementary particles, heavy and unstable cousins of the electron (lepton family). They are produced in a natural way by the interaction of cosmic rays with the Earth's atmosphere. The flux of muons at ground level is relatively low, about 150 per square meter per second. Unlike many other particles, muons are very penetrating, about half of the flux from cosmic rays can pass through a five meter thick concrete wall. Measuring their **transmission** in an object allows us to determine the density of the material: the higher the number of muons passing through it, the lower the density in the considered direction. This is the principle of muography, which is used to probe the interior of a structure, where photography only sees its surface aspect. On the other hand, and taking into account the limited flow of muons, the exposure times in muography are much longer, from a few days to a few months depending on the studied structure. For smaller objects, it is possible to reduce the exposure time by using muon **deflection** instead of **transmission**. It is then necessary to place detectors on each side of the object to reconstruct the trajectory of muons upstream and downstream. This method makes it possible to reconstruct the 3D density of the object, which is then called **muon tomography**. Muon tomography [1] can be applied as a non-destructive probing technique in various fields: archaeology, volcanology, civil engineering, nuclear reactor dismantling studies...



Muography: deviation technique (left diagram) for 3D images, and transmission measurements (middle and right) for 2D reconstruction. The areas of higher density (which deflect and absorb more muons) are in black within the gray objects.

WatTo (2015)

TomoMu (2015-)

M-Cube (2016-2017)

ScanPyramids (2016-)

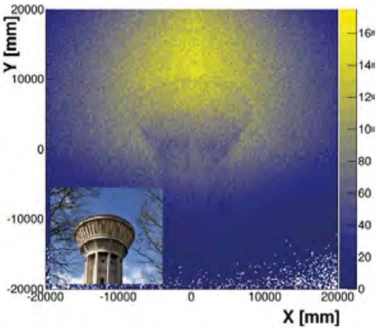


Figure 3. Muography of the water tower at the CEA center in Saclay, made with the WatTo telescope in 2015.

During more than three months, connected to the main power supply and then to solar panels, the telescope performs several static and dynamic muographies of the monument. Nothing spares the telescope: problems of mass and shielding, coherent noise affecting the auto-triggering of the electronics, variations in gain due to changes in temperature and pressure, humidity, intermittent sunshine, onlookers, storms.... In particular, it appears necessary to equip it with temperature and pressure sensors to adjust the high voltages directly and thus compensate for the gain variations. A first feedback system (electronic servoing) will be set up by Simon Bouteille during the measurement campaigns. In the end, the main lesson of this campaign is that a Micromegas telescope can work outdoors. And the images obtained confirm the potential of the telescope, with resolutions 20 times better than the classical scintillator telescopes (Fig. 3).

By the greatest of coincidences, the end of the WatTo experiment coincides with the launch in Egypt of the ScanPyramids[1] mission, the aim of which is to probe four pyramids of the 4th dynasty, notably that of Khufu. Coordinated by the HIP Institute[2] under the authority of the Egyptian Ministry of Antiquities, this mission proposes in particular to use muography to access the deepest areas of the pyramids. The images of the water tower are convincing and in early 2016, we obtain the authorization to install three muon telescopes around the pyramid of Khufu. Several significant changes are made to these instruments: better electromagnetic and thermal shielding, lightened mechanics, more precise electronic servoing, operation on 3G key, online data analysis before transfer to the network. The technical objective is to validate in the most extreme conditions the autonomous operation of a Micromegas telescope, and its remote control from Saclay. Thanks to the strong involvement of Elvia, which manufactured six detectors in less than two months, the three telescopes were sent to Egypt and deployed in June 2016 around the northeast edge of the pyramid. Objective: to demonstrate their imaging performance by detecting a known cavity 3 m long, located in 20 m of rock and at a distance of 150 m from the telescopes!

And it works: two and a half months and 70 million events analyzed later, the cavity is detected with a threshold higher than 5 sigmas (during these measurements, an excess of one muon per day is recorded compared to an area without cavity). A second cavity, this one unknown, is also identified a little higher along the ridge. In 2017, the results of the Japanese instruments of the University of Nagoya, located in the Queen's Chamber, reveal the presence of a large void above the large gallery. A campaign of dedicated measurements was then set up to confirm the presence of this void and to specify its position. The Japanese instruments, much closer, obtain a precise image of this elongated void. But the very close shots make a precise triangulation difficult. In spite of their great distance and their very unfavorable angle of observation from outside, two telescopes of the CEA manage to detect, not only the great gallery, but also this void named "Scan Pyramids Big Void". The results are summarized in figure 4. This detection allows a more precise triangulation of the void. It is the first detection of such a deep cavity of a pyramid from the outside, and opens many perspectives in archaeology. The analyses of the campaign have been published in the Nature review [2].

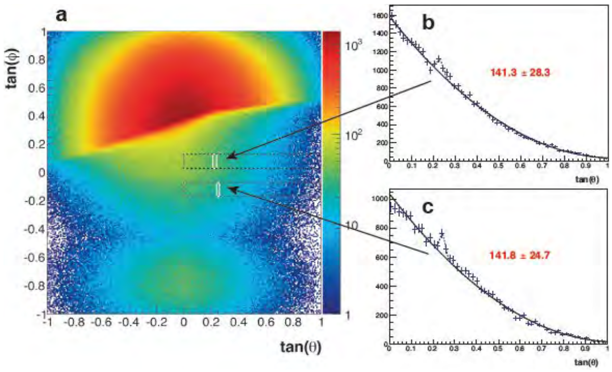


Figure 4. Results from one of the two telescopes of the last measurement campaign: (a) muography of the pyramid; (b and c) histograms of the muon number in two slices of the muography. The excess measured on the histogram (c) corresponds to the lower white rectangle on (a), and points in the direction of the "grand gallery". The excess visible on (b) corresponds to the new "void", represented by the upper white rectangle.

Beyond the imaging of a water tower or a pyramid, the media coverage of these activities has aroused the interest of several industrial companies. To meet this growing demand, two additional 1 m² telescopes will be built within the framework of the Mimosa[3] project. Discussions are underway to commercialize these instruments, notably for studies in the field of civil engineering.

References:
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[2] K. Morishima *et al.*, *Nature* **552**, pp. 386–390 (2017) (publication co-authored by the ScanPyramids team of IRFU). https://doi.org/10.1038/nature24647

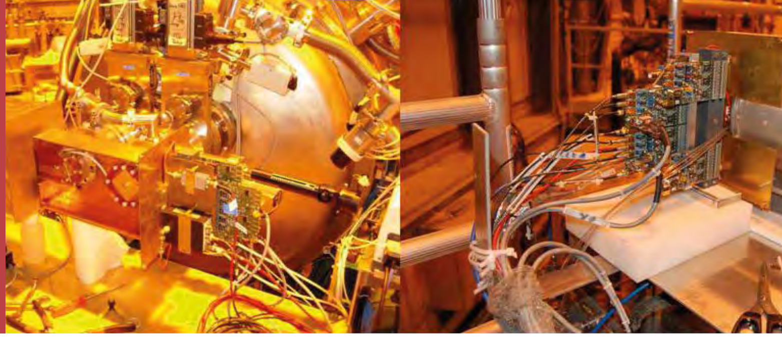
***The IRFU team.** On the photo of the banner p.26, one can see the team at the foot of the pyramid and next to the detection installation (the muon telescope located under the tent). From left to right: Patrick Magnier, Simon Bouteille, Mehdi Tayoubi, David Attié, Marc Riallot, Sébastien Procureur, Irakli Mandjavidze. The muon team is also composed of Denis Calvet, Xavier Coppolani, Hector Gomez and of Mariam Kebbiri.*

[1] The ScanPyramids mission aims to scan several great pyramids of Egypt: http://www.scanpyramids.org/?lang=fr
The press release of CEA: https://www.cea.fr/Pages/actualites/sciences-de-la-matiere/Le-CEA-route-pour-resoudre-mystere-pyramides-Egypte.aspx
[2] The Institute of Heritage Conservation, Heritage Innovative Preservation HIP, http://www.hip.institute
[3] The Mimosa project (2017-2020, project leader: David Attié) consists in creating a House of Muography in Île-de-France. This platform, unique in the world, aims to design, produce and make available to society penetrating imaging systems for imaging or metrology of buildings and massive objects.

Photo credits: IRFU, CEA DRF.

On the hunt for rare events: Micromegas takes "axion"

By Esther Ferrer Ribas for the CAST and IAXO team* at IRFU



How can we recognize an experiment dedicated to the detection of rare events? It is an experiment of very high sensitivity, capable of detecting very low energy events (between 1 and 10 keV) occurring with a very low probability (for example, a few events per month...). It is necessary to ensure that these rare events give a signal different from that of natural radioactivity or cosmic radiation. Thus, such an experiment relies on a whole series of strategies: first, select materials with a very high radiopurity[1], such as copper, kapton, plexiglass... Then, use shielding to minimize the contribution of ambient radioactivity and cosmic radiation; often these experiments are carried out underground, taking advantage of the natural shielding provided by the surrounding rock. Finally, develop and optimize detection systems capable of finely differentiating the events of the signals of interest from those of the background noise.

As such, gaseous detectors are a particularly interesting option, because the shape of the track left by the event particles in the gas is highly informative about the type of particles. Moreover, in gaseous detectors, fine pixelization readout planes (400-500 μm) can be used that allow a very good distinction between the shape of the particle signals and the background noise, thus a very good signal-to-noise ratio.
MPGD[g] are excellent candidates, both simple and robust, for the detection of rare events. Why use Micromegas detectors in particular? Their advantages are numerous: their excellent energy resolution (on average 20% -width to half-height- at 5.9 keV for bulk detectors, and around 13% for Microbulk detectors), very good stability and good gain homogeneity, as well as the possibility of manufacturing them with materials of very high radiopurity[1], following a manufacturing process that is now perfectly mastered.

The first application of the use of Micromegas detectors in the field of rare event detection was the CAST experiment, CERN Axion Solar Telescope, whose objective was the detection of solar axions with a telescope. To understand what axions are, we have to go back to Gérard t'Hooft, Nobel Prize in Physics in 1999, who showed that quantum chromodynamics should not treat a quark and an antiquark in the same way (violation of the charge-parity symmetry, CP).
However, this violation has never been observed. A solution to this problem of non-violation of the CP symmetry, proposed in 1977 by Roberto Peccei and Helen Quinn, postulates the existence of a new symmetry of quantum chromodynamics, which implies the existence of a new particle: the axion. To date, this new particle, neutral, stable and of low mass (between a few $\mu eV/c^2$ and a few eV/c^2), has never been observed either. If it exists, it should be produced in the center of the Sun, in its hottest part.

To detect these possible axions, the strategy consists in pointing the CAST telescope in the direction of the Sun, thanks to an adjustable platform, the "helioscope", which can follow the course of the sun one hour and a half, at dawn, and at sunset. The principle of axion detection is based on the Primakoff effect, according to which axions can be converted into photons (X-rays) when they are subjected to a strong magnetic field.

The CAST telescope is thus constituted of a high-field dipole to optimize this conversion. *The banner pictures on p.29* show this dipole on the platform. The photon thus produced is emitted exactly in the trajectory of the axion which transmits all its energy to it. This detection principle had been used before in two experiments in the 90s, giving the first limits to the mass of these particles. CAST is based on the same concept: to efficiently measure the photon emitted following the transformation of the axion in an intense magnetic field with a detector having a very low background noise. CAST uses one of the LHC dipole prototypes. This magnet has a very strong magnetic field of nine teslas and consists of two 9.2 m long cylindrical elements at the end of which are placed the systems designed to detect the X-rays from the hypothetical axions. It is expected to measure at most one event every 30 hours, according to theoretical models.

In the early 2000s, Ioannis Giomataris bet on obtaining a very low background with the Micromegas technology [1] (see p.4). In 2002 a first unshielded Micromegas prototype built on the basis of radiopure materials was installed with two other types of detectors. It is a TPC[g] surrounded by a passive shielding and a CCD (Charge Coupled Device[2]). The first data collection starts in 2003, with very encouraging results on the suppression of the background noise for the Micromegas detector. The Micromegas team of CAST decides then in 2005 to make a test of data taking with a first provisional shielding. This test shows the excellent potential of this technology, which leads the collaboration to replace the aging TPC by two Micromegas detectors (*the banner on p.28 shows the device*).
In the meantime, the Micromegas detectors evolved, and a new technology was born: the Microbulk Micromegas, a kapton and copper-based technology developed in collaboration with Rui de Oliveira's team at CERN, allowing excellent energy resolution while offering an unequalled level of radiopurity. IRFU then launched, in collaboration with the University of Zaragoza, the development of three Micromegas detectors of the Microbulk type, this time with shielding. In 2007, three of the four CAST X-ray detectors are Micromegas detectors. Thanks to simulations and tests carried out in the Canfranc underground laboratory in Spain, the background is constantly improving (*see Fig. 1, more than two orders of magnitude in 10 years!*), by refining the coverage of the passive shielding (copper and lead) and by including an active muon shielding (with plastic scintillators).

In the final phase of the search for solar axions, between 2013 and 2015, the sensitivity of the experiment has been further improved. This good result is due to a new Micromegas detector [2] whose design benefited from our good control of background sources, acquired throughout the experiment. This led to a measured background of the order of 10^{-6} keV^{-1} cm^{-2} s^{-1}, the lowest ever measured in the CAST experiment (*Fig.1, black points, end 2013*). The results obtained from the CAST data, recorded between 2014 and 2015, were published in Nature Physics in 2017 [3].

While the existence of the axion has not been confirmed to date, the CAST experiment has achieved, thanks to the performance of these detectors, the best limit in the world on the coupling constant of this particle (in other words, the probability of conversion between axion and photon) for all possible masses of axions over the interval covered by CAST.

[1] Radiopurity corresponds to low levels of radioactivity of the considered samples. We want to measure the activity of elements like ^{232}Th, ^{238}U and ^{40}K. With Microbulk reading planes, the maximum activity to be measured for these radiopure materials is less than 30 $\mu Bq/cm^2$ for Th and U and less than 60 $\mu Bq/cm^2$ for ^{40}K.
[2] *Charged Coupled Device*, a charge transfer device that converts a light signal into an electrical signal.

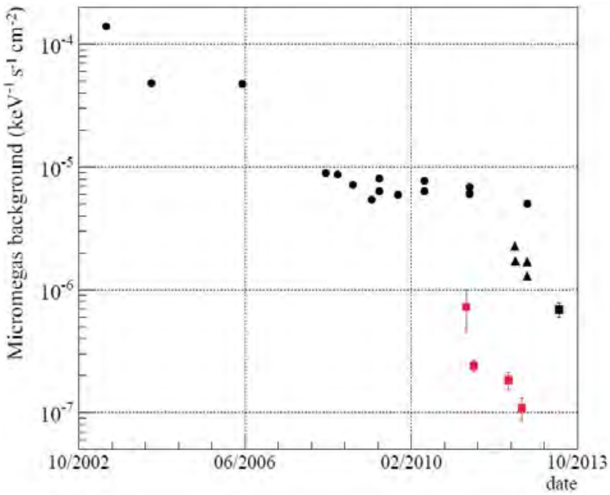


Figure 1. The background evolution measured in the Micromegas detector from 2002 to 2013. The black points show the improvement with the new detector installed from 2010 to 2013. For comparison, the red points show measurements in the underground Canfranc Laboratory with different shielding configurations.

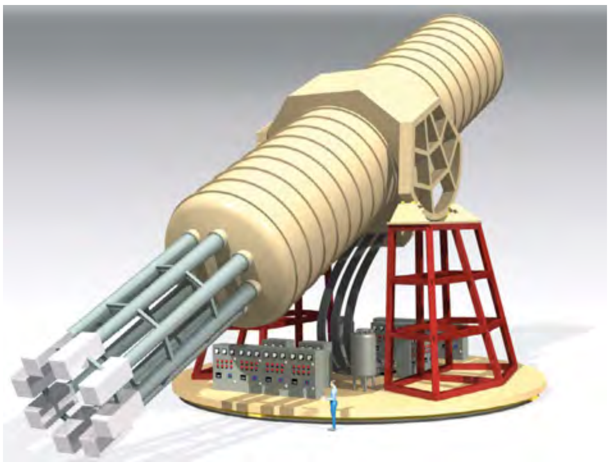


Figure 2. Overview of the future IAXO experimental setup at CERN.

To go even further, CAST's teams are developing a new generation of detector: IAXO (International Axion Observatory), optimized for axion search experiments. The device (*Fig. 2*) will include a new 20 m long toroidal magnet, equipped with X-ray telescopes to concentrate the possible axion signal on a very small surface, and finally Micromegas[3] detectors with increased performances. The goal of this experiment is to improve the sensitivity by four to five orders of magnitude compared to the CAST experiment, and, why not, to finally detect this famous axion!

PandaX-III, an experiment for double beta decay

The experimental setup of PandaX-III will include a large TPC, using the Microbulk technique, and developed at Zaragoza. This experimental setup will operate with a high pressure gas mixture, a necessary condition for double beta decay measurements. The PandaX-III experiment will take place in several phases. In the first phase, it is planned to build a TPC with 3.5 m^2 of Microbulk detectors, and four more TPCs are planned.

Beyond Micromegas: a sphere to search for the (hidden) dark matter of the Universe, *by Ioannis Giomataris*

To interpret astrophysical observations, it is necessary, in some models, to postulate the existence of new particles. These massive particles would correspond to the missing mass of our Universe, postulated in models beyond the standard model (see Scintillations n°95). The detection of these hypothetical particles named WIMPS[g] would be the indication of a new physics. Their characteristics have been examined in the framework of different models, some of them considering very massive particles of 100 GeV. In alternative models, they could be less massive than anticipated, with masses between 0.1 and 10 GeV.

The search for such light dark matter requires a new detection technique. This is the goal of the NEWS-SNOLAB[g] project, conceived by IRFU with an international collaboration: to build a spherical detector of 1.4 m diameter in the underground infrastructure of SNOLAB (2 km under the surface) with the objective of obtaining a much better sensitivity than other experiments. The idea is to develop a new gas detector made of a metallic shell and a metallic sensor (2 mm diameter) placed in the center of the sphere and carried at high voltage. This proportional spherical detector (invented by the author!) will thus be able to combine a large volume of drift with a proportional amplification at the level of the central ball serving as sensor. The avalanche takes place around the small ball with a field inversely proportional to the square of the distance to the ball. The development of sensors and prototypes is carried out at Saclay in the IRFU laboratories.

The access to large volumes (thus large masses), the very low energy threshold below keV, the possibility to differentiate the position according to the radius, the simplicity of the detector make it an ideal detector for low mass Wimps, inaccessible to all other techniques.

To be continued in the decade 2020-2030!

For more information: Neutrino properties studied with a triton source and a large spherical TPC, I. Giomataris, J. Vergados, Nucl. Instrum. Meth. A **530** (2004) 330-358. https://doi.org/10.1016/j.nima.2004.04.223

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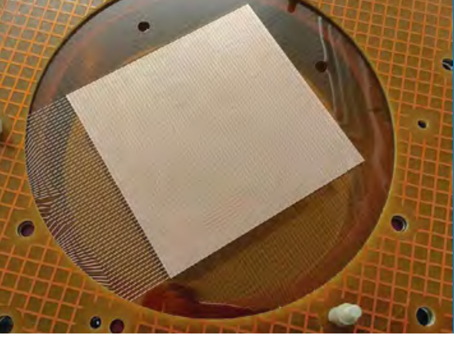
[3] The CAST Collaboration, New CAST limit on the axion–photon interaction, Nature Physics vol. 13, pp. 584–590 (2017). https://doi.org/10.1038/nphys4109
For more information, see the CERN website on the CAST experiments: https://home.web.cern.ch/science/experiments/cast and IAXO http://iaxo.web.cern.ch

** The IRFU team that contributed to the R&D and testing of Micromegas:* S. Aune, E. Ferrer-Ribas, I. Giomataris, Th. Papaevangelou.

[3] Other detector technologies are under study: CCD, *Transition Edge Sensors (TES) and Metallic Magnetic Calorimeters (MMC).*

Photo credits: CERN (banners p.28 and 29, collaborations CAST, IAXO).



The glossary of Micromegas

Dictionary of adventures across the planet

Experiments, facilities, laboratories, institutes, electronics, devices

AGET *Asic for GET, cf GET,* **p. 16**
ASIC *Application Specific Integrated Circuit.*
ATLAS *A Toroïdal Large Apparatus*, large toroidal detector of the LHC for particle physics experiments
https://home.cern/science/experiments/atlas ; https://atlas.cern **p. 14**
Bulk, the "global" or massive bulk technology allows an "all-in-one" assembly of the grid and the reading plane (floorplan), the grid is encapsulated on the PCB. It is developed in particular for large systems exceeding a few tens of cm. Micromegas "microbulk" also have an assembled structure with a more precise technology adapted to small dimensions. The process allows industrial manufacturing. **p.12 [NIM06], , p.22.**
CAST CERN Axion Solar Telescope
https://home.cern/fr/science/experiments/cast **p.28-29**
CEBAF *Continuous Electron Beam Accelerator Facility* at JLAB **p. 12**
CERN *Conseil Européen pour la Recherche Nucléaire* (original name in 1952); later became the European Organization for Nuclear Research. https://home.CERN/fr/about This center near Geneva gathers a set of facilities (accelerators, experimental areas) for nuclear and particle physics experiments: LHC, nTOF, SPS...
CLAS *CEBAF Large Acceptance Spectrometer* (see CEBAF).
CLAS12 « Clas - 12GeV » with the increase of the electron beam energy to 12 GeV. https://www.jlab.org/physics/hall-b/clas12 **p. 12**
CMS *the Compact Muon Solenoid*, LHC detector at CERN.
https://home.cern/science/experiments/cms ; https://cms.cern
COMPASS *Common Muon and Proton Apparatus for Structure and Spectroscopy* au CERN https://wwwcompass.cern.ch
https://home.CERN/fr/about/experiments/COMPASS **p. 10, p. 22-23**
DAPNIA *Département d'Astrophysique, de physique des Particules, de physique Nucléaire et d'Instrumentation Associée.* Department of Astrophysics, Particle Physics, Nuclear Physics and Associated Instrumentation. This department of CEA-Saclay was created in 1992 and existed under this name until 2008, before being renamed IRFU.
DAP Department of Astrophysics, ex-SAP sector.
DEDIP Department of Electronics, Detectors and Informatics (Computer Science) for Physics of IRFU, ex Sedi, ex-SED and SEI
DPhN Department of Nuclear Physics, ex SPhN division.
DPhP Department of Particle Physics, ex-SPP.
Dream *Dead timeless Readout Electronics Asic for Micromegas.* Generation of ASIC electronics developed by DEDIP.
Dream DEDIP laboratory: Real Time Detection, Acquisition Electronics and Microelectronics.
FALSTAFF *Four Arm cLover for Fission Fragments*, detection system for the NFS area at GANIL. **p. 17**
GANIL *Grand accélérateur National d'Ions Lourds*, Large National Heavy Ion Accelerator, in Caen, Normandy, managed by the CEA and the CNRS. https://www.ganil-spiral2.eu
Gap *space or amplification interval between the grid (mesh) and the anode plane, of the order of 100 to 500 µm. cf* **p. 4-6**
GEM *Gas Electron Multiplier*, alternative sensor technology to Micromegas **p. 10**
GET *Generic Electronics for TPC*, electronics for different types of TPC, the development of the project funded by ANR (French funding agency) was led by IRFU.
Hybrid Detector associating a Micromegas stage with one or more GEM foils.
IAXO *International Axion Observatory* http://iaxo.web.CERN.ch **p. 28-29**
InGrid Industrial global manufacturing technology with Micromegas integrated on silicon. **p.24-25**
JLAB *Jefferson Laboratory*, USA. https://www.jlab.org
KABES *KAon BEam Spectrometer*, spectrometry device for precision measurements of charged kaon parameters, on the NA48 Experiment located on the SPS proton synchrotron at CERN **p. 18**
LHC *The Large Hadron Collider*, large hadron collider (protons or heavy ions) at CERN. https://home.cern/science/accelerators/large-hadron-collider
Medipix Micropixel integrated circuit. **p. 24-25**
Mesh ; **Micromesh,** Microstrips : **p.4, 6, 12, 22** ; **Microbulk** : cf Bulk
Micromegas MicroMegas, MICRO-MEsh GAseous Structure
MPGD *Micro Pattern Gaseous Detectors.* **p. 9**
MIMAC *MIcro-TPC Matrix of Chambers*, set of TPC micro-chambers for the direct search of Wimps particles, candidates for the dark matter. p. 5
MINOS *MagIc Numbers Off Stability, studies of "magic numbers far from the valley of stability", detector (active target and TPC) used for spectroscopy studies of exotic nuclei.* **p. 20-21**
MultiGen Genetic Multiplexing. **p. 26**
MVT *Micromegas VertexTracker.* **p. 12-13**
MWPC *Multi-Wire Proportional Chamber, known as the wire chamber.* **p. 5, p. 9**
NA48 (evolutions: **NA48-1, NA48-2**), experiments at CERN to study the CP (charge-parity) symmetry violation.
https://na48.web.cern.ch/NA48 **p. 18-19**
NEWS (New Experiments With Spheres) at SNOLAB
https://www.snolab.ca/science/experiments
NSW *New Small Wheels*, new "small" muon detection wheels for ATLAS. **p. 6, p.14-15**
NFS *Neutrons For Science*, SPIRAL experimental area.
ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/nfs **p. 17**
N_TOF *Neutron Time of Flight*, neutron time-of-flight facility at CERN.
https://home.CERN/fr/about/experiments/ntof **p.16**
PCB *Printed Circuit Board.* **p. 12, p. 26**
Pad (micropad): plot.
Piggyback Micromegas manufacturing technology with a new reading circuit where the anode is made of a resistive layer on a ceramic substrate. **p.24-25**
Résistif Micromegas with a resistive layer on the reading electrodes to reduce the amplitude of the discharges (several hundred volts) and the breakdown rates. **p. 22-23**
S³ *Super Separator Spectrometer*, SPIRAL2 experimental area.
www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/s3 **p. 17**
SNOLAB Infrastructure of the SNO Sudbury Neutrino Observatory underground laboratory in Canada; this extension is specialized in dark matter and neutrino studies. https://www.snolab.ca/science/experiments **p. 29**
SPIRAL2 *Séparation et Production d'Ions radioactifs en ligne, de 2e génération, on-line separation and production of radioactive ions planned* at GANIL. https://www.ganil-spiral2.eu/ganil/presentation/spiral2/la-phase-1
T2K *Tokai To Kamiokande*, experiment and device for neutrino oscillation measurements in Japan (Scintillations n°96). **p. 18-19.**
TPC *Time Projection Chamber.* **p. 12, p. 18**
WIMP *Weakly Interacting Massive Particle : particle interacting weakly with matter, candidate for the dark matter searched in the Universe. (Scintillations n°95).* **p.29**

Definitions

Luminosity. The performance of an accelerator is quantified by the number of collisions it produces. It corresponds to L, the luminosity, the number of collisions per second; it is expressed as the number of colliding particles per unit area per second and has the unit $cm^2\ s^{-1}$. To evaluate the luminosity integrated over a period of time, it is also expressed in inverse of femtobarn (fb^{-1}); the barn ($10^{-24}\ cm^2$) is the unit of cross section, probability of an interaction during the collision between two particles. A luminosity of 10 fb^{-1} corresponds to one million billion collisions (per cm^2 and per s).
Cross section of a reaction. Probability of interaction between the projectile and the target of the reaction. It is obtained from the number of detected events, proportional to the number of incident particles per unit area of the target, to the number of nuclei composing the target, to the cross section and to the efficiency of the detection.

The projects mentioned in this issue: ATLAS, CAST, CLAS12, COMPASS, Falstaff, Minos, NFS, NSW, N_TOF, S³, ScanPyramids, are explained in the pages of the "experiments/projects" of the IRFU Web site:
https://irfu.cea.fr/Phocea/Vie_des_labos/Ast/index.php?aff=technique

The bibliography of Micromegas

Books and articles, reports and patents

To learn more about the origins and history of wire chambers, their emergence as a new concept within gaseous detectors created for particle physics, some references to articles and books by Georges Charpak as well as books and journals that describe his work and the development phases of wire chambers.

Georges Charpak,
Speech given on the presentation of the Nobel Prize in 1992.
Nobel Lecture: Electronic Imaging of Ionizing Radiation with Limited Avalanches in Gases, Nobelprize.org.
http://www.nobelprize.org/nobel_prizes/physics/laureates/1992/charpak-lecture.html
Speech by Georges Charpak on December 10, 1992 at the banquet:
"My very modest contribution to physics has been in the art of weaving in space thin wires detecting the whisper of nearby flying charged particles produced in high-energy nuclear collisions. It is easy for computers to transform these whispers into a symphony understandable to physicists. (...) The techniques being developed for matching the needs in radiation detectors of the future high-energy colliders foreseen at CERN or in the USA will clearly bring the ideal solution for the imaging of radiations: each quantum will be detected, one by one, with an accuracy of a few microns. (...) As a fallout, you will learn everything you want to know about the Higgs field, the hidden matter of the Universe, and marvellous new particles which are haunting the dreams of physicists and will become familiar notions to you".

Articles
Abbreviated notation: Nuclear Instruments and Methods in: **NIM** ; Nuclear Instruments and Methods in Physics Research Section A noted in the references of the articles of the n° in Nucl. Instrum. Methods Phys. Res. **A** and here in **NIM** A.
• *Evolution of the Automatic Spark Chambers*, G Charpak, Annual Review of Nuclear Science, Vol. 20:195-254 (1970).
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• *Some observations concerning the construction of proportional chambers with thick sense wires*,
S. Brehin, A.Diamant Berger, G. Marel, G. Tarte, R. Turlay, G. Charpak, F. Sauli, NIM **123**, 225-229 (1975).
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• *Applications of nuclear scattering to radiography*
- *Nuclear scattering applied to radiography*, J.Saudinos, G. Charpak, F. Sauli, D. Townsend, J. Vinciarelli,
Physics in Medicine & Biology, Vol. 20, pp. 890-905 (1975) https://doi.org/10.1088/0031-9155/20/6/002
- *Nuclear scattering radiography*, G. Charpak, J. Saudinos, *Progress in Nuclear Medicine* 7: 164-174 (1981).
http://www.ncbi.nlm.nih.gov/pubmed/6976592

References on the operation and evolution of gas detectors
•Fabio Sauli, *Gaseous Radiation Detectors, Fundamentals and Applications*, *Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, Cambridge University Press*, 2014.
https://doi.org/10.1017/CBO9781107337701
p.7, Section 1.2 *"Personal recollections" "The original MWPC could achieve avalanche gains around 10^5; detection of the signal emitted by fast particles (a few tens of electron pairs) required the use of low-noise amplifiers, which was possible but demanding for the electronics of the time. A major discovery of Charpak's group, and perhaps a reason for the rapid spread of the technology, was a gas mixture in which saturated gains greater than 10^7 could be achieved, providing amplitude pulses independent of the electron discharge by the primary ionization, thus leading to a simpler specification for readout electronics. Appropriately, the mixture (argon-isobutane with a trace of freon) was named "magic gas" (Bouclier et al, 1970)."*
• Glenn F Knoll, *Radiation Detection and Measurement*, 3e édition 2000. John Wiley and sons, ISBN 0-471-07338-5. 1st edition: https://archive.org/details/RadiationDetectionAndMeasurementGlennF.Knoll3rdEd1999

Selection of works by Georges Charpak *(published by Odile Jacob)*
* G. Charpak, Richard-L Garwin, et Venance Journé, *De Tchernobyl en tchernobyls* (2005)
* G. Charpak, *Feux follets et champignons nucléaires* (2000)
* G. Charpak et Henri Broch, *Devenez sorciers, devenez savants* (2002)
* G. Charpak, Pierre Léna, et Yves Quéré, *L'enfant et la Science : L'aventure de La main à la pâte* (2005)
* G. Charpak et D. Saudinos, *La Vie à fil tendu* (1993).

Articles in tribute to Georges Charpak
Georges Charpak (1924-2010), Physicist who transformed the measurement of high-energy particles.
I. Giomataris, Nature 467, 1048 (2010) https://doi.org/10.1038/4671048a
Charpak, un grand homme de science, I. Giomataris, Courrier du CERN, 30 novembre 2010. http://CERNcourier.com/cws/article/CERN/44361

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François-Marie Arouet, known *as Voltaire (1694-1778). Micromégas, Histoire Philosophique, original edition 1752.*
Printer and bookseller: M. Lambert. Printed monograph, 92 p.; in-12°. BnF, Réserve des livres rares, Res Y2 3583 ; ark:/12148/btv1b86157424

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[NIM96] *MICROMEGAS: a high-granularity position-sensitive gaseous detector for high particle-flux environment*, Y. Giomataris, Ph. Rebourgeard, J.P. Robert & G. Charpak, NIM A 376, 29-35 (1996).
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N.B. For the acronym, the authors thanked C. Allegrini...and François Voltaire!
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[NIM98] *First beam test results with Micromegas, a high-rate, high-resolution detector*, G. Charpak, J. Derré, A. Giganon, Y. Giomataris, D. Jourde, C. Kochowski, S. Loucatos, G. Puill, Ph. Rebourgeard, J.P. Robert, NIM A **412**, 47-60 (1998). https://doi.org/10.1016/S0168-9002(98)00311-8

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Jacques Derré, *Un nouveau détecteur gazeux est en train de naître dans les pépinières du DAPNIA*, https://irfu.cea.fr/Scintillations
N.B. A box provides the recipe for the manufacture of the Micromegas puff pastry.
[NIM06] *Micromegas in a bulk*, I. Giomataris, R. De Oliveira, S. A. Andriamonje, S. Aune, G. Charpak, P. Colas, G. C. Fanourakis, E. Ferrer, A. Giganon, Ph. Rebourgeard, P. Salin, Internal report 2004 DAPNIA-04-80; NIM A 560 (2006) 405-408. https://doi.org/10.1016/j.nima.2005.12.222

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[B97] Détecteur de position, à haute résolution, de hauts flux de particules ionisantes (WO9714173 A1, le 17/04/1997)
G. Charpak, I. Giomataris, Ph. Rebourgeard, J.-P. Robert.
[B98] Détecteur de particules à électrodes parallèles multiples et procédé de fabrication de ce détecteur (EP0872874 A1, le 21/10/1998) G. Charpak, I. Giomataris, Ph. Rebourgeard, J.-P. Robert.
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[B11] Procédé pour fabriquer un espace d'amplification d'un détecteur de particules à avalanche (WO2011050884 A1, le 05/05/2011) I. Giomataris, R. De Oliveira (CERN).
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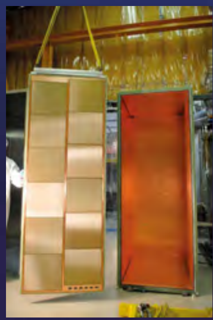
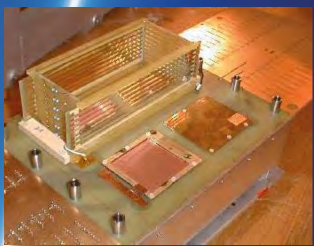
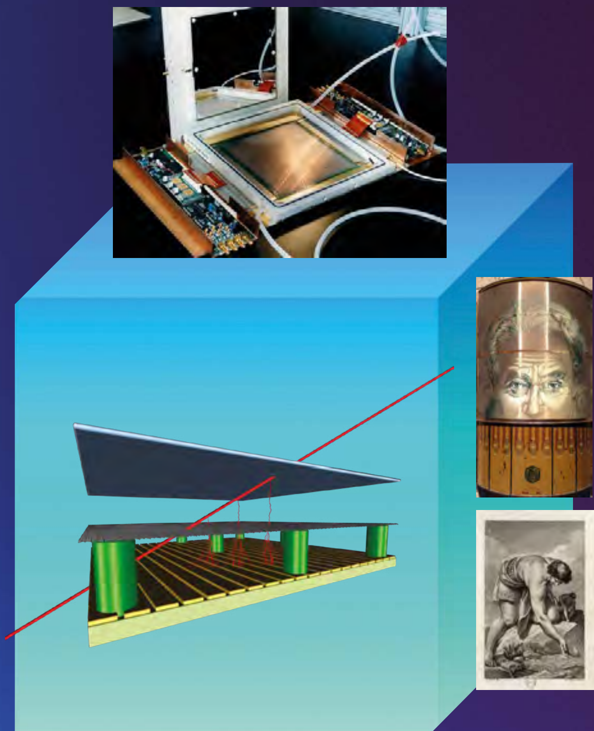
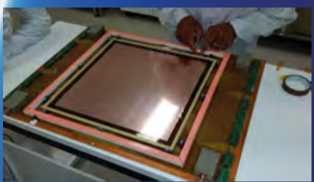
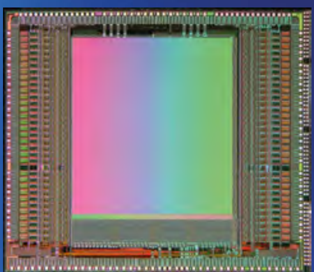
The transformations of **Micromegas**

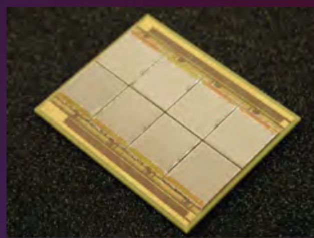


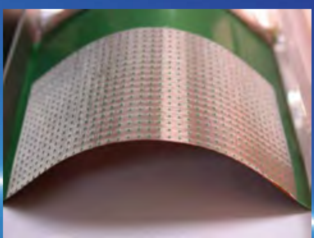


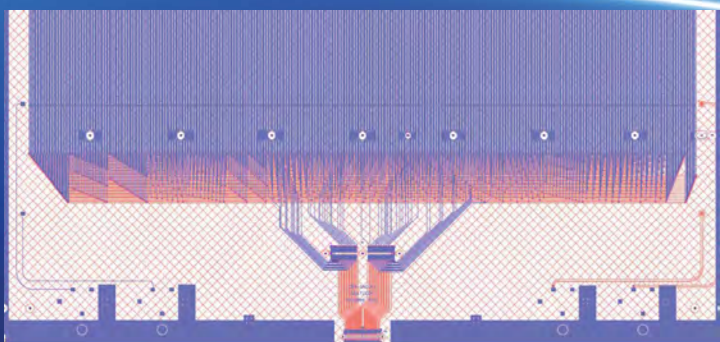


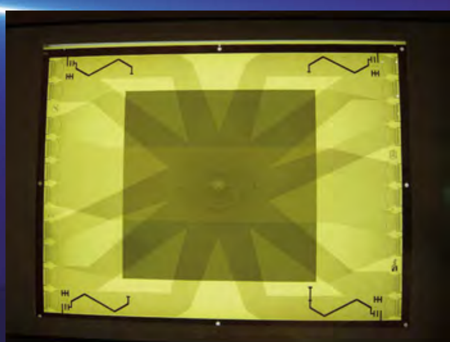












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