AGATA project mid-term review

Preamble

This document consists of two parts, a scientific part and a technical/managerial one, and has been prepared by the AGATA Steering Committee (ASC), the chair of the AGATA Collaboration Council (ACC) and the AGATA Management Board (AMB). In addition, the spokespersons of AGATA campaigns at GANIL and INFN LNL contributed to the content of this document, which covers achievements between 2021 and 2025 (2020-2024 for the scientific part) and describes the plans for 2026-2030, inclusive.

The ASC, acting on behalf of the parties as defined in the AGATA Memorandum of Understanding (MoU), is responsible for the coordination of the project and the scientific policy of the AGATA collaboration. Ordinary members of the ASC are Magdalena Górska (Germany, chair since 2024), Magda Zielińska (France, vice chair since 2024), Giacomo de Angelis (Italy), Piotr Bednarczyk (Poland), Andy Boston (UK), Angela Bracco (Italy), Bo Cederwall (Sweden), Gilbert Duchêne (France), Paul Greenlees (Finland), Ayşe Kaşkaş (Turkey), Stefanos Paschalis (UK), Begoña Quintana (Spain), Peter Reiter (Germany), Dora Sohler (Hungary), Dimitar Tonev (Bulgaria). Members with observer status are Nicolae Mărginean (Romania), Jelena Vesić (Slovenia). Silvia Leoni (Italy) (ACC Chair), and Emmanuel Clément (France) (AGATA Project Manager and AMB Chair) are invited to attend the ASC meetings.

Table of Contents

1. General Introduction

AGATA (Advanced Gamma-ray Tracking Array) is a new generation high-resolution γ-ray spectrometer providing unprecedented Doppler-correction capabilities thanks to a combination of fine detector segmentation, efficient pulse-shape analysis algorithms, and implementation of an innovative γ-ray tracking concept.

The AGATA project involves currently 40 partner institutions from 13 countries and operates on the basis of a Memorandum of Understanding (MoU). The MoU Phase 1 was active from 2010 till 2021 and involved the construction of a fully equipped detector system covering more than 1π, and three experimental campaigns at LNL (Italy), GSI (Germany) and GANIL (France). The current MoU Phase 2, signed in 2021, foresees expanding AGATA to a 3π solid angle configuration (135 individual Ge detectors, or equivalently 45 triple clusters) by the end of 2030. The completion of AGATA in the 4π configuration, and its exploitation at large-scale radioactive and stable beam facilities, have been given full support in the Long-Range Plan of NuPECC, both in 2017 and, with renewed strength, in 2024. A celebration of the first 10(+2) years of science activities with AGATA was held at LNL in June 2022 (see https://agenda.infn.it/event/30956/overview and Nuclear Physics News, 32(4), pp. 34–35) with participation from funding agencies representatives and a large number of AGATA collaboration members.

Fig. 1: Left: Current configuration of AGATA at LNL. Right: CAD images of the 2π structure equipped with detectors, and of the future 4π structure. Figure taken from NuPECC LRP 2024.

As part of the MoU Phase 2 preparation, the project definition (Technical Design Report, TDR) was established, available in ATRIUM-563607 and endorsed during the international review in July 2020. A management plan was attached to the project (ATRIUM-563598) and a risk analysis was also provided (ATRIUM-563604). The tables of costs and efforts are part of the TDR.

As agreed by all parties in the MoU, at midterm the cost tables for the second part of the MoU need to be updated.

In the preparation of the present document, the key questions from the AGATA Resource and Review Board meeting on November 8th, 2024, presented in Appendix 1, were considered. Following these guidelines, we present the scientific highlights from the last 5 years of AGATA operation. This is followed by a discussion involving management aspects, risks, and technical achievements of the AGATA project. Finally, the cost tables from 2021-2025 and estimations for 2026-2030 are presented.

2. Scientific highlights over the last 5 years (2020-2024)

The time frame considered in this document involves the two last years of AGATA operation at GANIL (2020-2021), followed by installation of the array at Legnaro National Laboratories for a campaign that started in spring 2022 and that will continue until summer 2028. The complete list of experiments performed from 2020 till end of 2024 can be found in Appendix 2.

In total, 28 scientific and 19 technical papers were published in the 2020-2024 period, see Appendix 3. In particular, the scientific achievements of the collaboration and the description of technical developments undertaken within AGATA Phase 2 have been a subject of a Topical Issue published in EPJA in 2024.

2.1 GANIL campaign

The physics campaign of AGATA at GANIL ran from spring 2015 until summer 2021, for a total of 29 experiments. In the years considered in the present document (i.e., 2020-2021), 4 experiments were performed, addressing a wide range of physics questions ranging from nuclear structure to reaction dynamics, and from properties of light nuclei that can be described by modern *ab initio* calculations to those of difficult-to-access species in the vicinity of ^{208}Pb, and trying to reach even further by searching for novel ways to populate neutron-rich actinide nuclei. The analysis of two experiments that benefitted from the powerful combination of AGATA with the MUGAST particle-detection array, the VAMOS++ magnetic spectrometer, and the exotic post-accelerated beams available from the SPIRAL1 complex, is now completed and published in high-impact journals:

- Using the ^{19}O(d,p)^{20}O direct reaction in inverse kinematics, the decay of a number of yrast and yrare excited states in ^{20}O was observed, and the lifetimes of excited states were determined from the measured line-shapes via the Doppler-shift attenuation method, with significantly enhanced sensitivity with respect to experiments done with conventional γ-ray arrays. The obtained 2^+_2 and 3^+_1 lifetimes were used to test the predictive power of several state-of-the-art *ab initio* calculations. This showed that disagreements between the experimental data and theoretical predictions, previously observed closer to the dripline, are also present in the less exotic ^{20}O nucleus if one searches to coherently reproduce a large set of transition probabilities [I. Zanon et al, Phys. Rev. Lett. 131, 262501 (2023)].

- In the very first measurement of the $^{47}K(d,p)^{48}K$ transfer reaction, the level scheme of ^{48}K was significantly extended, with level spin-parities assigned and spectroscopic factors determined. The obtained level energies were shown to be sensitive to neutron-proton interactions between neutron $p_{3/2}$ and proton $s_{1/2}$ orbitals, providing a benchmark for shell-model calculations, particularly important when extrapolating towards more exotic systems around the N = 28 "island of inversion" [C.J. Paxman et al, Phys. Rev. Lett (in print)]

The full list of publications from 2020-2024 can be found in Appendix 3. Among the highlights are:

- First measurement of lifetimes of 4^+ states in ^{106}Sn and ^{108}Sn nuclei, and precision re-measurement of 2^+ lifetimes using the recoil-distance method with nuclei of interest identified in VAMOS++. These results are of great importance for shell-model descriptions of this key region of the nuclear chart. In particular, thanks to the precise determination of the B(E2; $4^+ \rightarrow 2^+$) value in ^{108}Sn, it was possible to evaluate the role of seniority truncations as well as that of the pairing and quadrupole components of the interaction [M. Siciliano et al, Phys. Lett. B 806, 135474 (2020)]. The same experiment yielded a number of lifetimes determined in $^{102,104,106,108}Cd$ nuclei, with in particular those obtained for ^{106}Cd discussed in the context of beyond-mean-field calculations, suggesting multiple shape coexistence in this nucleus [M. Siciliano et al, Phys. Rev. C 104, 034320 (2021)] For these studies, M. Siciliano was recognised with the GANIL Thesis Award in 2019. Moreover, the analysis of inelastic-scattering data for ^{106}Cd, collected as a part of the same experiment, provided complementary information on its quadrupole and octupole collectivity [D. Kalaydjieva, PhD thesis, Université Paris-Saclay, 2023 and D. Kalaydjieva et al, to be submitted to Eur. Phys. J. A]

- Extensive information on lifetimes in the ground-state bands of N=50 ^{94}Ru, ^{92}Mo and ^{90}Zr nuclei, obtained using a similar experimental method and detection setup, in combination with state-of-the-art shell-model calculations, led to a conclusion that seniority is largely conserved in the first $\pi g_{9/2}$ orbital. The observed lack of higher-seniority admixtures to ν=2 states offers direct evidence of the validity of the short-range pairing interaction, with far-reaching implications for nuclear structure in the validity of BCS theory and therefore of the quasiparticle representation of the atomic nucleus [R.M. Perez-Vidal et al, Phys. Rev. Lett. 129, 112501 (2022)]

- Coupling AGATA to the NEDA neutron detector array and DIAMANT charged-particle detection setup made possible detailed spectroscopy of very neutron-deficient nuclei at the N=Z line. In particular, the observation of a band crossing in the ground-state band of ^{88}Ru that is significantly delayed compared with its closest N=44 isotones cannot be explained solely by the response of a deformed rotating nucleus in the presence of a normal isovector pairing field, and suggests the importance of isoscalar pairing components [B. Cederwall et al, Phys. Rev. Lett. 124, 062501 (2020)]. Excited states in the T_Z=1/2 nucleus ^{87}Tc were observed in the same study, revealing a rotational response proposed as a new signature of enhanced neutron-proton correlations in odd-mass N~Z nuclei [X. Liu et al, Phys. Rev. C 104, L021302 (2021)]

- From an event-by-event measurement of the velocity differences between the moment of production of ^{23}Mg nuclei and the moment of their γ-ray decay, the lifetime of the key astrophysical state in ^{23}Mg has been obtained, constraining the $^{22}Na(p,\gamma)^{23}Mg$ reaction rate that has a direct impact on the amount of radioactive ^{22}Na produced in novae, a key information to assess the observation limit of future space telescopes, currently under construction. This newly developed experimental method, taking advantage of excellent precision of energy and emission angle of the γ rays provided by the AGATA spectrometer, is a powerful tool to determine lifetimes in the femtosecond range down to 0.8 fs [Ch. Fougères et al., Nature Commun. 14, 4536 (2023)]. These results formed the basis of the PhD thesis of Ch. Fougères that has been awarded the 2021-2023 PhD Prize by the Nuclear Physics Division of the European Physical Society as well as the 2023 GANIL Thesis Award.

2.2 LNL campaign

The AGATA spectrometer was installed at the LNL facility (Legnaro National Laboratories) in late 2021 for a physics campaign involving two major phases. In the first phase, running from 2022 until mid-2026, AGATA is coupled to the large-acceptance magnetic spectrometer PRISMA, as presented in detail in [J.J. Valiente Dobon et al., Nucl. Instrum. Methods Phys. Res. A 1049, 168040 (2023)]. This part of the campaign has greatly benefited from the upgrade of the ALPI linear accelerator control system, improving both the stability of the accelerator and its transmission for heavy-ion beams. This major technical improvement combined with the resolving powers of AGATA and PRISMA has paved the way for the exploration of the neutron-rich side of the nuclear chart. Moreover, smaller ancillary instrumentation for charged-particle detection, such as SPIDER, EUCLIDES, DANTE and SAURON, can be placed within the reaction chamber to fully exploit the experimental opportunities with low-to-medium energy beams delivered by the XTU Tandem. Studies using these complementary devices amount to about 50% of the performed experiments, as shown in Fig. 2.

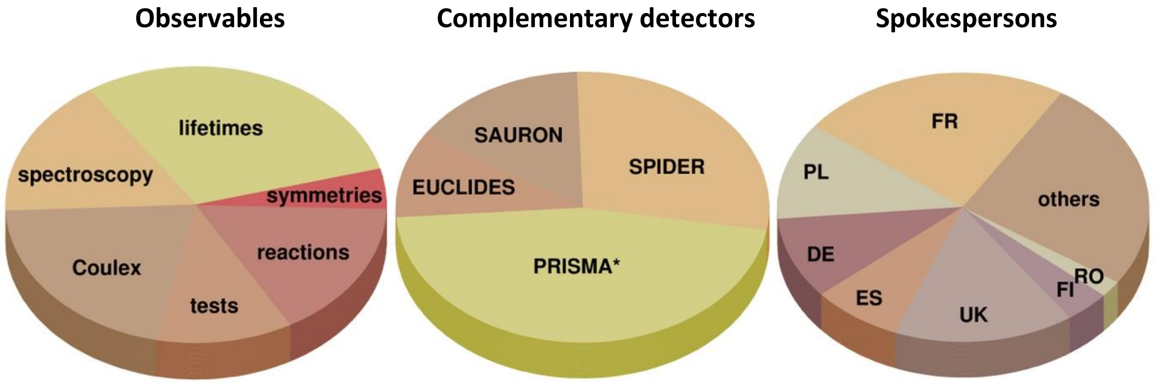


Fig. 2: Statistical information on the 37 AGATA projects performed in the period May 2022 - December 2024 (see Appendix 2 for the full list of experiments). Experiments with PRISMA include also those that use DANTE or $LaBr_3$ scintillators in combination with PRISMA. As all projects involve at least one co-spokesperson with an Italian affiliation, only non-Italian spokespersons have been included in the above statistics. “Others” refer to countries from outside the AGATA collaboration, in the considered period these were Croatia, Norway, USA, Canada and Korea.

The experiments performed address the structure of nuclei throughout the nuclear chart, studied with a variety of experimental techniques. An important share of beamtime is also provided for reaction mechanism studies, as shown in Fig. 2, notably those probing nucleon-nucleon correlations at near and sub-barrier energies, also in the context of the search for Cooper-pair behaviour of neutron pairs tunneling between the reaction partners. Among the main topics of interest of the nuclear-structure research with AGATA at LNL are quadrupole and octupole shapes and correlations, investigated predominately via Coulomb-excitation and lifetime measurements, as well as development of collectivity in the vicinity of doubly-magic nuclei, addressed via measurements of level energies and lifetimes. Studies of superallowed beta decay for fundamental interactions, as well as measurements with nuclear astrophysics implications, are also actively pursued. Using multi-nucleon transfer and fusion-fission reactions, a rich experimental campaign with AGATA and PRISMA addressed the shell evolution and configuration mixing throughout the nuclear chart, with a special focus on the key regions such as the island of inversion around N=20 and the vicinity of the doubly-magic ^{78}Ni. Finally, using the intense light beams available from the Tandem, a dedicated campaign with low-energy RIBs produced in-flight by the EXOTIC facility is envisaged in 2025 in order to investigate properties of exotic nuclei with Z<=6.

One of the strengths of the AGATA array is the capability to measure lifetimes of excited nuclear states for the most exotic, weakly-produced nuclei, providing information on the nuclear wave functions that represent the most stringent tests of existing nuclear models. New techniques and targets are being developed at LNL in order to fully exploit this capability.

In particular, in order to measure lifetimes in nuclei around ^{208}Pb (for example, platinum and osmium isotopes), a reverse configuration of the plunger device was developed that takes advantage of the binary partner identification in PRISMA to determine lifetimes of excited states in the heavy partner.

The goals for early 2026 include a campaign involving a ^{238}U beam that is currently under development. A high level of interest from the European nuclear-physics community in performing this campaign was demonstrated at the dedicated session of the Pre-PAC workshop in May 2024, where projects amounting to over 11 weeks of running time were discussed. They range from level energies and lifetime measurements in the vicinity of ^{78}Ni to reaction-mechanism studies, in particular linked to the production of exotic transactinide nuclei via multinucleon transfer.

In summer 2026, a transition to a different AGATA configuration is envisaged, which will enable coupling the spectrometer to the neutron detection setup NEDA, the high-efficiency scintillator array PARIS, as well as a variety of state-of-the-art gas targets, such as CTADIR, SUGAR and CHYMENE. The new reaction chamber was designed to accommodate silicon detectors for a complete reaction-channel identification. The proposed physics cases complement the main lines of the current PRISMA campaign and involve, in particular, the structure of nuclei near the N~Z line in the context of isospin symmetry and proton-neutron pairing, the evolution of collectivity at high excitation energies, the emergence of deformed high-spin structures, as well as studies of light nuclei for nuclear astrophysics. These projects will benefit from a wide range of complementary detectors that will be compatible with AGATA in the zero-degree configuration, and involve a broad international community.

2.3 Future campaigns

In the second half of 2028, AGATA will be transported to GANIL for a campaign starting in March 2029, which will benefit from experimental opportunities offered by the post-accelerated radioactive beams from the SPIRAL1 facility. For these studies, AGATA will be combined with the magnetic spectrometer VAMOS++, as well as a first implementation of the state-of-the-art charged-particle spectrometer GRIT. This powerful combination will provide outstanding sensitivity to study excited states in nuclei far from stability. Among the physics cases addressed by this future campaign are properties of light exotic systems, important in the context of clustering and ab-initio calculations; measurements relevant for nuclear astrophysics; nuclear deformation studied by low-energy Coulomb excitation and direct reactions; and pairing in light nuclei.

The campaign at GANIL has been approved for a minimum of two calendar years, i.e. until the end of 2030. Beyond that horizon, also other European laboratories have expressed interest in hosting AGATA, namely GSI/FAIR, which will deliver very exotic beams at relativistic energies; LNL, where the new SPES facility will provide beams of post-accelerated fission fragments; HIE-ISOLDE, CERN, offering the largest variety of exotic ISOL beams in Europe; and the University of Jyvaskyla, with intense stable beams for the spectroscopy of heavy and very heavy nuclei. The specific strengths of each of these installations as well as envisaged physics cases are described in the document "Physics opportunities with the Advanced Gamma Tracking Array: AGATA" (W. Korten et al., EPJA 56 (2020) 137).

Following the formal agreement of the AGATA collaboration, the scientific strategy will be decided on the basis of the efficiency of the array and the availability of beams and complementary instrumentation at the different host laboratories. The focus will be on the highest impact physics cases, considering the strong international competition, in particular with the GRETA array. During the construction phase of AGATA, when the full 4π is not available, the optimised scientific output could be achieved by longer duration experiments, although the reduced solid angle coverage would be detrimental for studies relying on observation of γ-ray angular distributions and angular correlations. It is essential to underline that there is a huge improvement in the performance of the array with an increasing order of γ coincidence, which rapidly scales with solid angle coverage. This is evidenced in Fig. 3, which shows, as an example, how the limits in studies of N=Z nuclei, requiring a quadrupole-γ coincidence analysis, can be pushed forward with increased solid angle coverage.

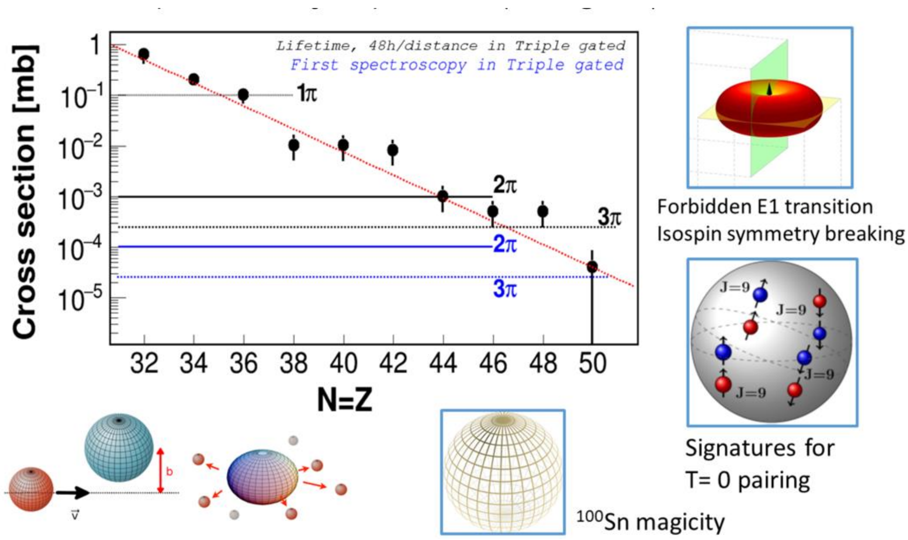


Fig. 3: Estimated limits for a plunger lifetime measurement (black, 48 h per distance) and first spectroscopy (blue, 14 days) as a function of the solid angle covered by AGATA. Beam intensities of 10 pnA (for ^{40}Ca, ^{50}Cr, and ^{58}Ni) and a medium γ-ray multiplicity are considered. Figure taken from W. Korten et al., EPJA 56 (2020) 137.

This simple fact, combined with extraordinary energy resolution of the HPGe crystals and state-of-the-art electronics infrastructure, makes large germanium arrays the most powerful tool in understanding nuclear structure and its impact on the elemental composition of the Universe.

In this context, the full support for the completion of the 4π European flagship array AGATA, and its exploitation at the different host laboratories, has also been given in the major recommendations of the

Long-Range Plan of NuPECC. This includes key statements in the executive summary, both in 2017 and, with renewed strength, in 2024 (https://www.nupecc.org/?display=lrp2024/main).

The 2024 final document emphasises that advancing the frontiers of spectroscopy and lifetime measurements, particularly for low-intensity secondary beams and small cross sections, relies heavily on achieving superb in-beam resolution and high efficiency in gamma-ray spectroscopy. Hence, the gradual implementation of the AGATA array, towards its full completion in the 4π configuration, is seen as mandatory. AGATA is the major workhorse for nuclear structure and nuclear astrophysics precision physics, at both radioactive and stable ion-beam facilities in Europe.

3. Management plan

The AGATA Management Board (AMB) is in charge of defining the Project Definition according to the MoU with the resources made available by the partners under the direction of the AGATA Steering Committee (ASC). The AMB organisation was modified at the start of Phase 2 MoU, taking on board the suggestions of the international review panel.

The "coupling to ancillaries" team was moved to the front-end electronics working group to manage more closely the GTS to SMART migration (clock and trigger distribution) and the use of the new AGATA Trigger Processor, which is a key element in the event selection.

The second important modification was the introduction of several teams linked to the processing, re-processing and analysis of the AGATA data, thereby controlling inside the collaboration all the complex steps from the raw data to those resulting from elaborate analysis and leading to publications. This led to the creation and clear identification of teams and team leaders on the online/offline and interoperability aspects, reprocessing and analysis as well as the introduction of a data manager. Beyond the on-line processing, this organisation ensures a clear support, maintenance and track of the data flow from raw data to final processing. It also clarifies the role of data archiving and its distribution, maintaining the link to the Tier1 centre in CC IN2P3 and CNAF. The team has also the responsibility to migrate the software developments to a production mode available to the AGATA user. The software became a significant and visible task; this organisation highlights the role of the persons involved.

The PSA and Tracking group is now fully focused on the R&D for the Pulse-Shape Analysis and Tracking algorithms. This aspect is particularly important with the development of the Machine Learning (ML) and Neural Network activities in the field of subatomic physics. The team has developed ML frameworks for AGATA, which will be migrated to the production status when consolidated. The working group covers also the capsule scanning activities at Strasbourg and Liverpool. The cross fertilisation of this activity with the PSA R&D team has shown promising perspectives, as demonstrated by the use of machine learning to analyse data from the Strasbourg scanning table and later in the on-line PSA for AGATA.

The organisational chart of the AMB is presented in Fig 4. This scheme has shown to be very efficient and equilibrated, with an optimal balance between the different major share countries. The roles of the different committees and links between them were presented earlier, and together with responsibilities of the managers they are clearly described in the Management Plan (ATRIUM-563598). In particular, appropriate contributions from the different teams are devoted to the support at the host laboratory. No issues were reported regarding the distribution of tasks.

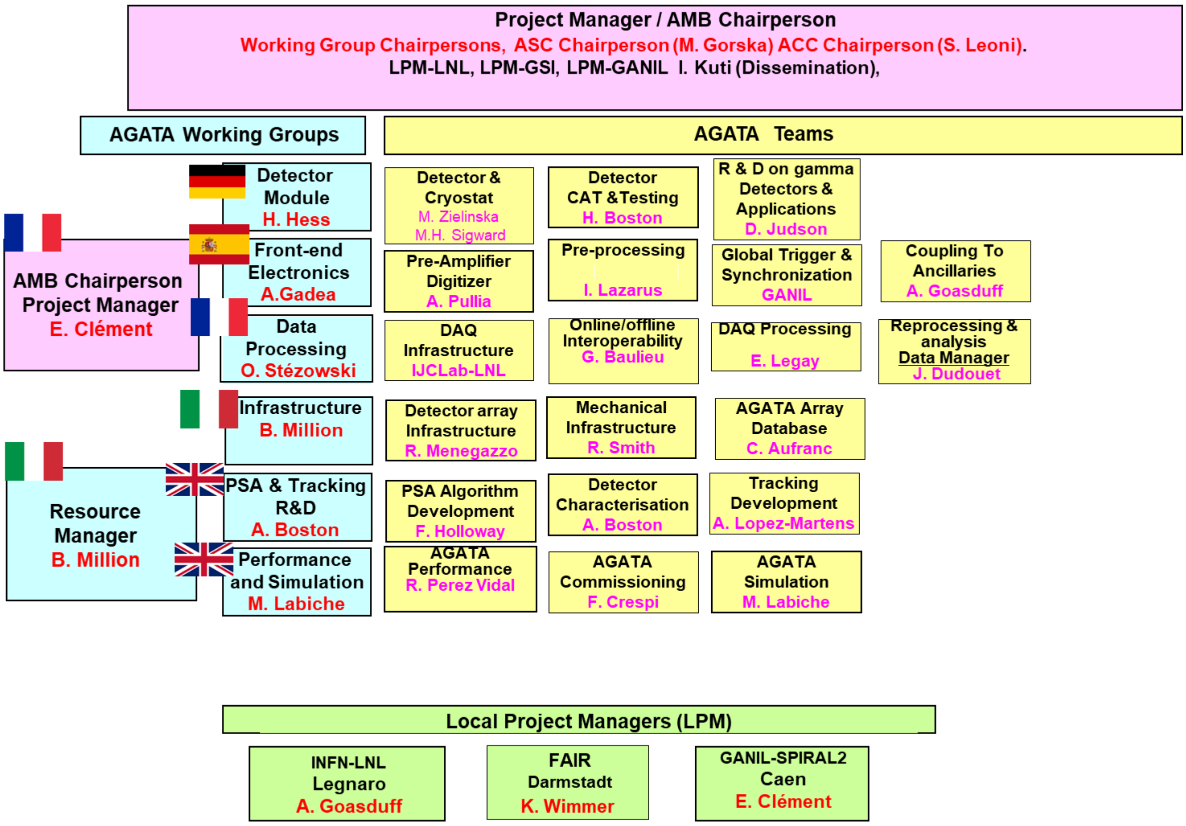


Fig. 4: Organisational chart of the AGATA management board.

In the MoU Phase 2, the AGATA Resource and Review Board (ARRB) was introduced to scrutinise the costs and efforts, supported by the funding agencies of the different partners. The ARRB meets twice a year and the ASC Chair, the Project Manager (PM) and Resource Manager (RM) of the AMB are invited to present the progress of the project in terms of technical achievements, organisation and financial effort.

The AMB manages the CORE funds available in the different countries and institutes and optimises their use for detectors, front-end electronics etc. An annual meeting with the Mirion company supplying the AGATA HPGe capsules is organised by the AMB and the partners willing to place an order to define the price charged for each capsule. Between 2021 and 2024, this coordination effort resulted in savings at the level of 890 k€ (17% of the detector procurement budget). Similar effort is on-going for the front-end electronics with an 8% saving on this item. The Operation Costs (OC) are collected by GANIL on a common account and managed by the RM.

The local project managers are *ex-officio* members of the AMB ensuring the coordination and support between the local team and the AMB Groups and Teams. J.J. Valiente-Dobon was the LNL local project manager from 2019 to 2024. Since January 2025, A. Goasduff is the LNL local project manager.

The AMB meets every month by Zoom and holds two in-person meetings per year (beginning of the year and during the AGATA Week in autumn). The AMB is in charge of the organisation of the annual project meeting (AGATA Week). Four AGATA Weeks have been organised since 2021 (https://www.agata.org/agata_weeks). A new format of AMB meetings including all team leaders (Extended AMB) has been introduced in 2024 to foster the information exchange. Meetings in this format will be held ~3 times per year.

The AGATA web page www.agata.org that showcases the collaboration is maintained by the AMB and the ACC chair and is fully up to date.

The organisation of the collaboration has proved to be very successful and resisted the test of time.

4. Risk analysis

The risk analysis is available in (ATRIUM-563604). 13 risks were identified, with different levels of criticality, for the Phase-2 project. The methodology is described in the linked document. 5 risks were identified as major. We remind here these risks and update on their status.

1. The CTT company is presently the only company constructing the AGATA cryostats. It is a spin-off from the University zu Köln involving a single person. This unique provider provides to the AGATA collaboration the complex cryostats with cold FETs for all segments, which require enhanced cooling capabilities. It is anticipated that the CTT company will close by the end of the decade due to the retirement of the sole person in charge. The AGATA collaboration has started discussions with the Mirion company in order to develop a dedicated cryostat for AGATA as backup option. This development will require R&D investment (time and budget) but is rather secured since Mirion provide cryostats, albeit with a worse performance in the cold electronics part, to the GRETA collaboration. P. Reiter has been appointed by the ASC at the October 2024 meeting to initiate a closer discussion with the two companies. The risk remains **high**.

2. Obsolete electronic components for production and maintenance of the FEBEE in a long-term view. The AGATA collaboration has built customised electronics since the Demonstrator phase. With time, problems arose due to the obsolescence and the difficulties to maintain customised electronics for long periods of time. In order to minimise the risk, the AGATA collaboration has used for Phase-2 more conventional technologies for data readout (Ethernet protocols) and Commercial-Off-The-Shelf (COTS) System on Modules (SoM) boards for the front-end electronics developments. The implementation of the Phase-2 electronics, with the Ethernet data dispatching, is necessary to improve the performance of the array in terms of processing capabilities. Delays in the production of the hardware are observed. These delays are due to delays in the firmware development caused by a lack of human resources, in spite of their correct evaluation in the effort table. This affects the performance of the array in the present campaign at LNL. For Phase 2, we have reduced to the minimum possible the customised parts of the electronics and used new technologies like the COTS SoM with long guaranteed production terms (at least 10 years). In the end, the stability of sub-versions of certain products turned out to be shorter than promised by the manufacturers, due to the obsolete nature of certain minor components. This increased the workload for the engineers involved in the project to cover the various unexpected sub-versions. The AMB has taken the decision in 2024 to secure all the hardware in 2025. The risk is now **low**, but it has repercussions on the spectrometer performance by slowing the investment into detectors.

3. The newly designed SMART clock and trigger system (intended to replace the GTS in the Phase-2 frond-end electronics of AGATA) does not provide the required performance. The prototype is running at GANIL and the hardware was purchased. The implementation into the AGATA Phase-2 electronics remains the last milestone, and its achievement is linked to the availability of human resources in the collaboration. This activity is subject of a contract with the ZeptoNova company, paid from the GANIL OC common account. The risk is now **medium**.

4. Long-term vision of the availability of engineers and technicians working on specific tasks related to the detector, front-end electronics and data acquisition until 2030. The MoU and project definition aim to precisely define and quantify the human resources needed. The role of the ASC and ARRB is crucial to consolidate the available human resources. The risk remains **high** and is **critical** in the next 2-3 years. The collaboration wishes for a stronger involvement of ARRB regarding human resource commitments.

5. Long-term commitment on budget allocated by the partners. The cost of the project was evaluated under the construction plan. The funding applications of the individual institutions contributing to AGATA follow quite different schemes, from yearly budgets to plurennial grants. The failure to fund the expected number of items per year, especially detectors, has consequences for all the collaborators in terms of costs. The mitigation underlines the role of the ASC and ARRB to consolidate the available human resources and funds. The collaboration was constantly looking for national and international grants in R&D on top of the MoU contribution (e.g. INFRATECH applications: IMATRA1 and 2). The current status is that the majority of the highest share countries fulfil their commitments. However, several partners and countries which signed the MoU lack extra effort to compensate the budget impacting the whole collaboration. This led to a reduced solid angle covered by AGATA during the current campaign at LNL and later at GANIL from 2028. The risk remains **high and critical** for the project. The collaboration hopes for a stronger involvement of ARRB regarding the missing financial contributions.

5. Reports from the working groups

In the following, a summary of the technical achievements and milestones to be reached by the end of the MoU, detailed in the project definition, is briefly presented for each working group, with more details given in Appendices 5-10. The technical developments accomplished within Phase 2 of the MoU were also subject of a number of contributions to a Topical Issue in EPJA, prepared with the key involvement of the AMB.

5.1 Detector WG (coordinated by H. Hess)

Partners involved: Germany (IKP Cologne), France (CEA-IRFU, CNRS-IN2P3), Italy (INFN-LNL), UK (Univ. Liverpool)

The AGATA Triple Cluster (ATC) detector is an advanced instrument for high-resolution gamma-ray spectroscopy, pivotal in nuclear structure research. It is composed of three asymmetric, 36-fold segmented, hexagonal high-purity germanium (HPGe) detectors, each featuring 111 high-resolution spectroscopy channels that enhance performance by combining core contacts and segment signals from each crystal. These detectors are housed in a single vacuum cryostat maintained at liquid nitrogen (LN_2) temperature, with a dedicated LN_2 dewar ensuring cooling. Cold input stages of the preamplifiers are integrated into the cryostat to minimise electronic noise. Continuous monitoring of system parameters such as temperature, vacuum conditions, and LN_2 levels, ensures optimum operation of the detectors.

The procurement and maintenance of AGATA detectors requires substantial investment, particularly for HPGe capsules and cryostat systems. The Detector Working Group oversees these processes, ensuring that detectors meet AGATA's performance and scientific needs. HPGe capsules are sourced from Mirion and undergo Factory Acceptance Tests to verify their quality. The WG also tracks procurement schedules, repairs, and deliveries through constant communication with MIRION. Cryostat systems are procured through CTT, and preamplifiers are supplied by IKP Cologne, GANIL, and INFN Milan. Regular preventive maintenance, including inspections and functional assessments, ensures the detectors remain in peak condition. Test facilities in various locations, such as IKP Cologne, Liverpool, IPHC Strasbourg and CEA Saclay, support quality assurance and troubleshooting activities, ensuring the continued effectiveness of the detectors in nuclear research.

Procurement of AGATA detectors and cryostats requires careful financial planning and collaboration among AGATA partner institutions. As of 2025, the price of a single encapsulated HPGe detector from Mirion is set at €231,671, with annual adjustments based on the French Labour Cost Index, capped at 2.5%. Additionally, Mirion offers a volume-based discount system for bulk purchases. Discounts range from 3% for orders of more than one detector in a calendar year to a maximum of 33% for orders of 12 or more detectors per year. This pricing structure allows the AGATA collaboration to achieve considerable savings when purchasing large quantities of detectors, supporting the sustainability of the project. Similar, the dedicated AGATA cryostats, which are essential for housing the detectors, are supplied by CTT at a reference price of 147 k€ in 2024, but like with detectors, cryostat purchases are incentivised with volume-based discounts.

Currently, seventy-four of HPGe capsules, both symmetric (three) and asymmetric (seventy-one), have been delivered to the AGATA collaboration. Additional six detectors are on order, with their expected delivery within a year.

The MoU for AGATA Phase 2 foresees expanding AGATA to a 3π solid angle configuration by purchasing 39 capsules in the period 2021-2015, and another 39 capsules in 2026-2030. While a considerable progress has been made (24 capsules out of 39 have been delivered or are on order), funding challenges in several partner countries, such as Germany, have led to disparities in the procurement speed. Countries like France, Italy and the UK have met their commitments, while Spain has exceeded expectations. The project's success depends on securing consistent funding from all partners, making it possible to benefit from bulk purchasing to optimise costs and avoid delays. Despite rising costs due to inflation, AGATA has successfully negotiated discounts and long-term agreements to mitigate the financial impact.

The maintenance and operational support for ATCs ensures the detectors' continuous reliability. Routine maintenance includes inspections, diagnostics, and repairs, with local staff addressing minor issues and more complex problems handled at specialised laboratories. As the number of detectors increases, so does the demand for maintenance, requiring comprehensive training for all laboratories involved. The collaboration faces challenges in staffing and workload, particularly in IKP Cologne and IPHC Strasbourg, and is exploring strategies to sustain operations, such as hiring new technicians and outsourcing certain tasks. Technological upgrades, such as improved feedthrough systems and enhanced vacuum quality, are being implemented to improve reliability and reduce maintenance time. The collaboration is also actively seeking to reduce repair costs by developing reusable detector housings and exploring alternative suppliers, though some challenges have arisen in these efforts. These initiatives ensure the long-term sustainability and efficiency of the AGATA project.

Neutron damage remains a challenge for highly segmented n-type HPGe detectors, as fast neutrons cause lattice defects, affecting the energy resolution. To address this, a reliable annealing procedure has been developed in collaboration with Mirion, significantly reducing failure rates and, consequently, the overall costs. The procedure has successfully restored energy resolution in 25 detectors, and again volume discounts have been negotiated with Mirion.

The AGATA project is focused on advancing the detector technology to maintain its leadership in high-resolution gamma-ray spectroscopy. Key R&D initiatives include the development of p-type germanium detectors, which offer improved resistance to neutron damage and better energy resolution. Research at LNL aims to enhance detector performance through advanced doping methods and Pulse Laser Melting technology. Additionally, the AGATA collaboration is exploring electric cooling solutions to reduce reliance on liquid nitrogen, improving sustainability and efficiency. The integration of ASIC preamplifiers is also a priority, as these will enhance signal processing and improve the signal-to-noise ratio, ultimately leading to more precise gamma-ray spectroscopy. These innovations, while still in the research phase, are expected to significantly enhance AGATA's capabilities in the second part of the decade, ensuring continued success in nuclear physics research.

A detailed report from the Detector WG can be found in Appendix 5.

5.2 Infrastructure WG (coordinated by B. Million)

Partners involved: Italy (INFN), France (CEA-IRFU, CNRS-IN2P3), UK (STFC Daresbury)

The responsibilities of the Infrastructure Working Group include:

- Development of the mechanical support structure of the array,
- Development and maintenance of the Detector Support System (automated liquid nitrogen filling system, high- and low-voltage power supplies and related cabling),
- Electromagnetic compatibility (EMC) characterisation of the installed components in order to identify and eliminate weak grounding connections,
- Maintenance and development of the AGATA Data Base used to store information about all components of the array and its infrastructure.

Milestones reached during the first five-year period of Phase-2 MoU include development of a more universal mechanical structure that has been designed and constructed by STFC Daresbury and installed at LNL, in a configuration for the 2π array, prior to the current campaign. A more compact Low Voltage Power Supply (LVPS) has been designed under CEA/IFRU responsibility and LVPS modules needed to instrument a 2π array have been produced and installed at LNL. The high voltage system has been replaced, with the current one being dimensioned for a 3π configuration. A new liquid nitrogen filling system has been developed by CEA/IRFU using robust industrial components and installed at LNL prior to the current campaign in a configuration for a 2π setup. Several campaigns of EMC measurements were performed and the identified grounding issues have been addressed.

During the second five-year period of the MoU, the second mechanical hemisphere needs to be produced (shaft, flange, and supports), the last groups of LVPS, and the Autofill extension beyond 2π. Based on the production costs between 2021 and 2024, this would require a total investment of 0.530 M€.

A detailed report from the Infrastructure WG can be found in Appendix 6.

5.3 Front-End Electronics WG (coordinated by A. Gadea)

Partners involved: Italy (INFN), France (CNRS-IN2P3), UK (STFC Daresbury), Spain (IFIC, Univ. Valencia)

The design of the Phase-2 front-end electronics for AGATA was the most challenging R&D of the current phase of the AGATA project. The Phase-2 electronics is intended to replace the Phase-0 system (developed for the Demonstrator phase and used until the end of the GANIL campaign), and to first complement, and then completely replace, the Phase-1 system that has been introduced during the GANIL campaign and is currently used at LNL The objectives of this development were:

- to upgrade the current digitiser board (DIGOPT12),
- to migrate from optical to copper data transfer lines,
- to develop the pre-processing board (PACE, for *Pre-Processing and Communication system*) with the latest generation FPGA,
- to improve the data transfer capabilities up to10 Gb/s per capsule,
- to migrate the clock distribution from the currently used GTS system (*Global Trigger and Synchronization*) to the new SMART protocol,
- to upgrade the trigger module.

Production of the Phase-2 electronics has been delayed by 3 years with respect to the original schedule due to a number of issues which have now been resolved. The development is currently 90% complete, and the mass production started after an internal review in 2024, with a procurement delay of 12 months. The coordinated effort to procure hardware by bulk orders allowed to save 8% on the FPGA budget. The availability of human resources for the front-end electronic engineering are critical and remain the limiting factor, in particular regarding firmware development. The last steps of the engineering, that is mainly maintenance work of the existing firmware, were subcontracted to the ZeptoNova company and the final integration and testing is planned for the end of 2025. Following these tests, it will be possible to instrument a 2π system (90 capsules) with Phase-2 electronics, effectively doubling the solid angle covered by AGATA at LNL.

For the second five-year period of the MoU, the objective is to instrument the 3π solid angle with Phase-2 electronics. No new developments are needed. Accounting for savings resulting from grouping the purchases, we estimate that 0.6 M€ will be necessary to cover all required elements of the front-end electronics for 135 capsules.

A detailed report from the Front-End Electronics WG can be found in Appendix 7.

5.4 Data Processing WG (coordinated by O. Stézowski)

Partners involved: France (CNRS-IN2P3), Italy (INFN)

The Data Processing Working Group maintains the data acquisition system installed at the host laboratory. This includes the ongoing upgrade and maintenance of the local storage disks (/agatadisks/), network backbone, pulse shape analysis and data analysis computing nodes. The group maintains and upgrades the associated data flow software (DCOD, for *Distributed Caen Orsay DAQ*) and advanced data analysis algorithms for on-line, near-line and off-line processing. The WG is also responsible for integration of the Phase 2 electronics into the data flow. Most of this task has been completed and stress tests of the remaining elements of the data pipeline are ongoing.

The elements of data acquisition infrastructure foreseen in the MoU for the period 2021-2025 have been acquired. The associated software has been developed and tested at IP2i and IJClab using the latest technologies on a dedicated DAQ-box located in Orsay. The WG is also responsible for the long-term data storage in CC-IN2P3 and CNAF, which is fully operational.

The data analysis process has been fully integrated into the WG activities since the start of MoU Phase 2. The implementation of massive monitoring for data quality control is achieved. This is a step towards a better Data Management Plan (DMP), FAIRification (for FAIR: *Findability*, *Accessibility*, *Interoperability and Re-usability*) and Open Data.

The remaining investment depends mainly on the PSA nodes. While the new PSA algorithms involving Machine Learning approaches are expected to improve significantly the performance of both PSA and tracking, they will require advanced computing resources such as GPU (Graphics Processor Unit). Hence, a transition to GPU-based architecture is planned in the second five-year period of the MoU. Total estimated investment into the data acquisition infrastructure is estimated at 920 k€.

A detailed report from the Data Processing WG can be found in Appendix 8.

5.5 PSA and Tracking R&D WG (coordinated by A. Boston)

Partners involved: UK (Univ. Liverpool, Univ. York), France (CNRS-IN2P3), Spain (Univ. Salamanca), Germany (GSI)

The PSA and Tracking R&D WG coordinates the development of improved Pulse Shape Analysis and Gamma-ray Tracking algorithms in order to realise the full performance of the AGATA spectrometer. The activities of the WG rely on a continuous pipeline of high-quality characterisation data from the AGATA detectors which are used to improve the waveform simulation packages and to train and implement novel machine-learning approaches.

The WG coordinates the characterisation of AGATA detectors utilising the scanning tables at the Strasbourg, Liverpool, Salamanca and GSI detector laboratories. The improved knowledge of the detector response functions has significantly improved the fidelity of the pulse shape basis used by the PSA algorithms. An innovative approach to improving our understanding of the detector response has been the development of a novel self-calibration method for building this basis of experimental waveforms. Self-calibration codes have been developed by York and tested with specially developed simulation packages and then with experimental source data gathered at LNL. This is the first time that this technique has been successfully developed and validated for gamma-ray tracking arrays.

Novel PSA algorithms have been investigated which efficiently handle multiple interaction events inside a single AGATA segment. A new machine-learning assisted PSA code, “SIMPLEX”, has been developed, and incorporated into AGATA’s PSA processing routines for local level testing. This algorithm will be performance tested in the wider AGATA PSA signal-processing pipeline. The impact of the size of the uncertainty obtained when performing PSA on the quality of the solution provided when applying gamma-ray tracking is also under investigation.

A detailed report from the PSA and Tracking R&D WG can be found in Appendix 9.

5.6 Performance and Simulation WG (coordinated by M. Labiche)

Partners involved: UK (STFC Daresbury, Univ. York), Spain (Univ. Valencia), France (CNRS-IN2P3), Italy (INFN)

The Performance and Simulation working group monitors and analyses the performance of the array starting from raw data to the final processed event including tracking. The WG supported the source and in-beam commissioning at the earliest stage of the LNL campaign. During the intense campaign that followed, the WG is responsible for monitoring of the effect of the neutron dose on the detectors and identification of those that exhibit significant performance deterioration, so that they can be timely removed from the array in order to undergo annealing at Mirion.

The WG uses source and in-beam data to test the AGATA simulation package, maintains it following the GEANT4 releases and continues to develop the code by improving event generators and adding new ancillary detectors. Many ancillary detectors available at LNL, namely PRISMA, OSCAR, GALTRACE, MUGAST and the CTADIR cryogenic target, have been included in the distribution available at the git repository. In preparation for a future campaign at FAIR, an interface of the event generator with the GSI MOCADI ion beam simulation package has been prepared. The implementation of the crystal geometry and sensitivity is being improved based on systematic studies of the measured efficiency and performance as well as tomography measurements at the scanning table at IPHC Strasbourg.

The WG also initiates benchmark measurements with a goal of preparing for specific challenges of the future measurements. This includes notably the response of the array to high-energy photons, with a dedicated beamtime allocated in summer 2024 to study of the decay radiation of ^{66}Ga, produced in the ^{66}Zn(p,n) reaction, in order to assess the AGATA performance up to 5 MeV. The team has also obtained beam time in summer 2025 to benchmark the performance of the 1π AGATA array with high-γ-multiplicity (<30) reactions.

A detailed report from the Performance and Simulation WG can be found in Appendix 10.

6. Financial report

The collaboration has made a huge effort to stay within the budget by trying to keep the prices at a constant level. It was only possible thanks to stable funding received from the partners. The overall costs have been correctly evaluated in the MoU. Future savings are possible via implementing an aggressive procurement strategy, as detailed in the following.

6.1: Core investment funds

The investment funds (CORE) already committed or planned over ten-year period of Phase-2 MoU (2021-2030) are presented in the following tables.

Table 1 reports the first 5-year period (2021-2025) situation. The second column is a reminder of the MoU planned investments per country (and funding agency when relevant) for this period. The last column presents the investment actually committed by the different partners during this period. France, Italy, UK, Spain and GSI have fulfilled their commitment. Several partners (German university consortium, Sweden, Bulgaria, Finland, Poland, Turkey and Hungary) did not obtain the needed investment funds.

Table 1. Summary of the first 5-year period (2021-2025): MoU commitments and situation

Country	**MoU** Total capital investment (2021-2025) without tax [k€]	%	**Funds committed** (2021-2025) without tax [k€]
Bulgaria	278	3	
Finland	278	3	
France *(IN2P3)* *(GANIL)* *(IRFU)*	2249 *(742)* *(1125)* *(382)*	20	2413 *(748,7)* *(1178,2+148)* *(204,2+133)*
Germany *(Universities)* *(GSI)*	2249 *(1799)* *(459)*	20	776 *(776)*
Hungary			
Italy	2249	20	2299
Poland	278	3	
Spain	561	5	603
Sweden	842	8	
Turkey	278	3	
UK	1684	15	1629
Total	**10946**	**100**	**7720**

As a reminder, 53 asymmetric capsules were procured in the AGATA Phase 0 (Demonstrator) + Phase 1 MoU (2010-2021). Moreover, an AGATA-type triple cluster has been funded by Sweden as an in-kind contribution to the DEGAS germanium detector array for the DESPEC experiment at FAIR. Following an agreement between Sweden, the DESPEC collaboration and the ASC it has been made available to AGATA when not in use for FAIR experiments. This increases the number of available detectors for AGATA operations. Furthermore, an ORTEC prototype crystal (currently non-functional) was funded by the UK. In Phase 2, 78 additional asymmetric capsules have to be funded to reach 135 capsules (3π).

Table 2 presents the distribution of the collaboration investments over the different items indicated in the MoU. Column 2 reminds the total cost distribution for the ten-year period of the MoU (2021-2030) as defined in the MoU to reach 135 capsules in the array. In the MoU, each of the two 5-year periods was planned to cover one half of the investment.

Column 3 presents the 7.7 M€ commitment for the various items over the period 2021-2025. In this first period the collaboration was able to add 24 capsules to those purchased in the previous years. Thanks to the number of capsules simultaneously ordered between 2021 and 2025, ~0.6 M€ were saved with respect to individual and unsynchronised procurements by the collaboration members. Similarly, 0.1 M€ were saved by optimising the cryostat procurement. This coordination allowed to mitigate the fast increase of the cost of a detector due to the inflation rate.

Following the MoU prevision of an increase of the array by another 39 capsules in the period 2026-2030, column 4 reports the investment needed per category, updated on the basis of the observed costs during the first five-year period of the MoU and mitigated by the important coordination effort within the collaboration to group purchases and optimise possible discounts. This scenario leads to the completion of an array of 120 capsules, cumulating Phase 0, Phase 1 and part of Phase 2 by the end of 2030.

For this period (2026-2030), the MoU stated an investment of 10.9 M€ for 39 additional capsules. Our estimation is now 11.8 M€. The main reason is the inflation rate observed on the crystal price (+2.5% instead of 1.5% in the 2020 evaluation) and on the cryostat price.

The final costs of the data acquisition hardware and front-end electronics are estimated to be very close to those given in the Project Definition of 2020 due to an unexpected lower inflation rate on some of the components and the effort for simultaneous orders, compensating partially the detector cost increase.

The costs of mechanical and infrastructure elements turned out to be well estimated.

The PSA cost estimation is based on the GPU option for the PSA farm. The CPU option, with a lower performance, corresponds to a reduction of 0.4 M€ between 2026 and 2030.

The difference between 10.9 M€ (constant budget with respect to MoU [2026-2030]) and 11.8 M€ (the same items with respect to MoU [2026-2030]) is equivalent to one triple cluster.

Altogether, for the full period [2021-2030] covering the MoU Phase 2, a total cost of 19.5 M€ is re-estimated for having 120 capsules available to the collaboration, cumulating the Phase 0, Phase 1 and Phase 2, instead of 21.8 M€ planned in the MoU to reach 135 capsules.

Table 2. Cost table for 120 capsules by the end of 2030

	Proj Def Phase 2 2021-2030	Committed funds 2021 - 2025	Planned funds 2026-2030	Planned funds 2021-2030
	135 caps	57 (phase 0+1) + **24 caps**	57+24+**39 caps**	120 caps
Capsules	14,2 M€	4,256	7,753	12,009
Cryostat	3,1M€	1,261	2	3,261
PSA+DAQ Storage Analyse	1,2 M€	0,27	0,92	1,19
Mechanics Infra	1,067 M€	0,439	0,545	0,984
FEBEE	2,3 M€	1,494	0,626	2,12
TOTAL	21,867	**7,72**	**11,844**	19,564

For the completeness of the report, in Table 3 the cost of the construction of a 3π array by 2030 is estimated if all partners fulfil their commitment from 2021 to 2030. Additional efforts to compensate the missing funds in the first five-year period of the MoU are needed between 2026 and 2030 to recover the missing detectors (+54 capsules) and cryostats (+10) for a total of 14.1 M€ and a grand total over 2021-2030 of 21.82 M€, with respect to 21.86 M€ in the MoU. The constant budget is obtained thanks to the high level of investment in detectors (11 new capsules annually) maximising the discount by Mirion between 2026 and 2030.

Table 3. Cost table for 135 capsules by the end of 2030

	Proj Def Phase 2	Committed funds	Planned funds	Planned funds
	2021-2030	2021 - 2025	2026-2030	2021-2030
	135 caps	57 (phase 0+1) + **24 caps**	57+24 +**54 caps**	135 caps
Capsules	14,2 M€	4,256	9,09	13,346
Cryostat	3,1M€	1,261	2,925	4,186
PSA+DAQ Storage Analyse	1,2 M€	0,27	0,92	1,19
Mechanics Infra	1,067 M€	0,439	0,545	0,984
FEBEE	2,3 M€	1,494	0,626	2,12
TOTAL	21,867	**7,72**	**14,106**	21,826

The two panels of Table 4 break down the investment by country for the two scenarios. The left panel assumes the shares from Phase 2 MoU, with updated costs for 120 capsules (the numbers in column 2 of this panel are higher than those in the MoU due to a higher inflation). The right panel gives updated costs for 135 capsules, and assumes an extra effort in the second five-year period of the MoU from the countries that did not fulfil their commitments in the first five-year period of the MoU.

Table 4. CORE funds per country for the period 2026 – 2030. Two scenarios are considered. Left panel – updated costs, 120 capsules by the end of 2030. Right panel – updated costs, 135 capsules by the end of 2030, extra effort in the second five-year period of the MoU from the countries that did not fulfil their commitments in the first five-year period of the MoU.

	as for 2nd period of MoU-2: 2026-2030
	39 additional capsules
	120 capsules
	[k€]
	11 844
Bulgaria	296
Finland	296
France	2 369
Germany	2 369
Hungary	296
Italy	2 369
Poland	296
Spain	592
Sweden	888
Turkey	296
UK	1 777

	as to recover full MoU-2: extra effort on 2nd period for some countries
	54 additional capsules
	135 capsules
	[k€]
	14 106
Bulgaria	380
Finland	380
France	2 369
Germany	3 963
Hungary	380
Italy	2 369
Poland	380
Spain	592
Sweden	1 140
Turkey	380
UK	1 777

6.2 OC: Operation Costs

In Table 5, the distribution of the operation costs (OC) for 2021 – 2024 is presented (the current year is excluded). The first column shows the operation costs evaluated in the MoU. The second column details the operation costs spent by category in 2021-2024. The last column gives the total OC collected in the period.

Presently, the collaboration benefits from a MoU Phase 1 residue at the GANIL common account to compensate for the OC that are missing with respect to the MoU Phase 2, and on the other hand from the improved detector maintenance process, resulting in significant savings. As of 2024, the annual OC represents 2% of the total investment including Phase 0, Phase 1 and the first Phase 2 period.

Table 5. Operation Costs for 2021- 2024

Item	MoU [k€] [2021-2024]	Spent [k€] [2021-2024]	Collected [k€] [2021-2024]
LN2	201	299	
Capsule maintenance/repair	919	481	
Cryostat maintenance/repair	346	374	
HV/LV system, infrastructure	95	100	
Detector laboratory	240	239	
Electronics maintenance/repair	207	416	
DAQ maintenance/repair	274	77	
Grid costs + Data Analysis	96	7	
Shipping costs	102	41	
Mechanics etc.	32	3	
Total operation & maintenance costs (excl. personnel)	**2512**	**2037**	**2016**

The operation costs are calculated and adjusted taking into account the LN2 cost, maintenance and repair of front-end electronics, infrastructure, data acquisition, capsules and cryostats, and the renewal of obsolete components. Consequently, the annual operating costs for the period 2026-2030, presented in the following, have been calculated taking into account the realistic number of detectors in operation at the host laboratory and updated costs of maintenance operations at Mirion and CTT estimated from 2021-2024 data.

Table 6 details the Operation Costs in 2026-2030 per category. The realistic number of detectors at the host laboratory, both installed in the array and at the detector workshop, is indicated. We remind that there is a delay of ~2 years between the purchase order of a new capsule and its use in a fully commissioned Agata Triple Cluster.

Table 6. Operation Costs in 2026-2030 per category, updated to account for the number of capsules at the host laboratory. For comparison, according to MoU Phase 2 the total operation & maintenance costs for 2026 were 862k€.

Item	**2026 (k€)**	**2027 (k€)**	**2028 (k€)**	**2029 (k€)**	**2030 (k€)**
Capsules ordered	89	96	104	112	120
Capsules in Host Lab	75	81	90	96	105
Detectors					
LN2	139	142	147	150	156
Capsule maintenance/repair	243	249	254	260	268
Detector & Cryostat maintenance/repair	104	115	129	140	155
Detector laboratories	60	60	60	60	60
Infrastructure					
HV/LV, Autofill, infrastructure	27	29	33	35	38
Electronics and DAQ					
Elect. maintenance/replacement	89	94	105	112	122
DAQ maintenance/replacement	79	85	95	101	110
Other costs					
Grid costs	24	24	24	24	24
Shipping costs	19	19	19	19	19
Mechanics	8	8	8	8	8
Total operation & maintenance costs	**792**	**825**	**874**	**909**	**960**

Table 7 presents the distribution of Operation Costs per country using the costs from Table 6 and the weighting formula used in the MoU.

Table 7. Operation Cost distribution in 2026-2030 per country

Country	2026 (k€)	2027 (k€)	2028 (k€)	2029 (k€)	2030 (k€)
Bulgaria	25	26	28	28	31
Finland	29	30	32	34	36
France	138	144	152	159	167
Germany	138	144	152	159	167
Hungary	38	40	42	44	46
Italy	138	144	152	159	167
Poland	25	26	28	28	31
Spain	39	40	43	44	47
Sweden	77	80	85	88	93
Turkey	38	40	42	44	46
UK	107	111	118	122	129
Total	**792**	**825**	**874**	**909**	**960**

7. Summary

The AGATA (Advanced Gamma-ray Tracking Array) project is a cutting-edge γ-ray spectrometer initiative involving 40 institutions across 13 countries and managed by the AGATA Steering Committee (ASC), Collaboration Council (ACC), and Management Board (AMB). This report outlines scientific (2020–2024) and technical achievements (2021-2025) as well as future plans (2026–2030). AGATA Phase 1 (2010–2021) saw the development of a 1π array and campaigns at LNL, GSI, and GANIL. Phase 2, underway since 2021, targets a 3π configuration by 2030, with long-term goals of a full 4π array supported by NuPECC's 2024 Long-Range Plan. The scientific case of AGATA, presented in the document "Physics opportunities with the Advanced Gamma Tracking Array: AGATA" (W. Korten et al., EPJA 56 (2020) 137) was evaluated and endorsed by the international review panel in 2020.

Key highlights include high-impact results from campaigns at GANIL and LNL. At GANIL, experiments addressed nuclear structure and reaction dynamics using advanced setups like MUGAST and VAMOS++, leading to major publications in Phys. Rev. Lett., Nature Communications, and Phys. Lett. B. The current LNL campaign focuses on nuclear shapes and collectivity, both for well-deformed nuclei and those in the vicinity of shell closures, studied using instruments like PRISMA, SPIDER, and beams from the upgraded ALPI accelerator. New techniques for lifetime measurements and plans for low-energy radioactive ion beams (RIBs) are being developed. In total, 41 experiments have been performed in the 2020-2024 period, providing a basis for 7 defended and 16 ongoing PhD theses. 28 scientific and 19 technical papers were published in the considered period, including notably 15 publications that were part of an invited Topical Issue in EPJA presenting scientific achievements of the collaboration and technical developments undertaken within the AGATA Phase 2 project. 22 PhD theses based on AGATA data were defended between 2020 and 2024.

Future plans (2029–2030) include a return to GANIL for experiments using post-accelerated exotic beams with VAMOS++ and GRIT. Long-term interest to host AGATA has also been expressed by

GSI/FAIR, LNL (SPES), CERN-ISOLDE, and Jyväskylä. Continued development of AGATA toward the full 4π coverage is essential for advancing nuclear structure and astrophysics research in Europe.

The collaboration is proud that all technical developments foreseen in the AGATA Phase 2 Project Definition have been completed. This involves activities related to detectors, infrastructure, front-end electronics and data acquisition with the associated software.

24 capsules out of 39 foreseen in the MoU for 2021-2025 have been ordered, as well as 10 cryostats. The four detector laboratories of the collaboration (Univ. Liverpool, CNRS/IPHC Strasbourg, CEA/IRFU Saclay and IKP Cologne) are committed to continue their activity within the AGATA project at least until the end of the current MoU. The coordinated procurement of capsules at Mirion resulted in a total saving of 890 k€ in the 2021-2024 period with respect to nominal unit prices applied previously.

The production of the new electronics has been delayed by three years due to difficulties that have now been resolved. The mass production started in 2024 with a one-year production time, which means that by the end of 2025 it will be possible to use the new electronics to read out signals from all the 81 capsules acquired by the collaboration, thus significantly extending the solid angle of the AGATA array at LNL. Simultaneous orders enabled a saving of 8% on the hardware budget and minimised the risk of component obsolescence. The data acquisition infrastructure has been funded and the associated software has been developed and tested at IP2i Lyon and IJClab, Orsay. A significant improvement of the real time processing of the pulse shape analysis, crucial for AGATA performance, has been demonstrated with a gain of a factor of 5. The transition to AI and GPU architecture is being prepared. Great progress was achieved in R&D related to pulse-shape analysis with the advent of machine learning approaches combined with the scanning table data and a collaboration with the GRETA project to implement an algorithm accounting for multiple interactions per segment.

The performance of the array, in particular the effect of the neutron dose on the detectors, is carefully monitored during the intense campaign at LNL, and the detectors that exhibit significant performance deterioration undergo annealing at Mirion financed from the operating costs. Several benchmark measurements were performed in preparation for specific challenges of the future campaigns with SPIRAL1, SPES and FAIR radioactive beams. Simulation packages were benchmarked using source and in-beam data and developed by improving event generators and adding new ancillary detectors.

The initial estimated budget has been maintained for all items. Going forward, the production of the detectors, i.e. the increased solid angle coverage, depends on the funds made available to the collaboration. Optimisation of the overall costs can be achieved by more aggressive purchasing strategy. A five year visibility for the funding and human resource commitment will strengthen the project and reduce risks.

The AGATA array, with its ambitious scientific objectives and cutting-edge technological developments, represents a unique opportunity to achieve scientific excellence in Europe using both stable and radioactive ion beams. Several leading laboratories have expressed strong interest in hosting AGATA to realise their strategic research goals. Achieving these goals relies, first and foremost, on the strength and unity of our collaboration—which we believe is firmly established—and, secondly, on securing the necessary funding from multiple European funding agencies. At this critical juncture, it is essential to seize every available opportunity to obtain the required financial support. We therefore strongly appeal to the AGATA Resource and Review Board (ARRB) for their continued assistance in helping us fulfil these ambitions.

Appendix 1: Guidelines from ARRB for the mid-term AGATA project review

- RRB members agree with a light-format review
- The final report should be available by June 2025. Funding agencies need it to start the process of internal analysis and approval. This takes time

What the report should contain:

- Scientific highlights over the past years (first 5 years of MoU)
- Status on technical developments, with an analysis on missing contributions, risks and uncertainties

- For financial aspects, the following points should be addressed:

  - Financial difficulties have been encountered during the first 5 years by some countries. Past commitments of each country should be analyzed to figure out how things could be changed/improved for next MoU and next 5 years
  - This analysis should be used to identify risks and uncertainties and to guide to understand how next financial effort should and could be shared
  - The objective of constructing 50% of the phase 2 was not attained during the first 5 years. Next five years will represent, financially, more than half of the total cost. How this can be handled? RRB requests that possible scenarios to mitigate and/or handle over-costs are explored. In particular:

- Exploring further options and scenarios for reducing costs such as optimizations, common purchasing, ….
- How the timeline should/could be modified (extended) if financial contributions are less than what would be required to fulfil the full objectives? Which would be the impact of an extended timeline on AGATA science? Several options (and associated timelines) should be described and compared

In addition, options and scenarios for reducing the scope of the project should also be investigated, by minimising the impact on the science that AGATA will be able to carry out. This should be accompanied by a choice of strategic and high-impact physics cases where AGATA, even with a reduced/modified/less-expensive final design

Appendix 2: List of completed AGATA experiments in 2020-2024

A. GANIL campaign (2020-2021)

- *Lifetime measurements of excited states in ^{20}O populated by direct nucleon transfer*, **E.Clément**, **A. Goasduff** (AGATA+MUGAST+VAMOS, E775S)
- *Spectroscopy of ^{48}K from $^{47}K(d,p)^{48}K$*, **A. Matta**. **W. Catford** (AGATA+MUGAST+VAMOS, E793S)
- *Identification of exotic reaction channels in ^{238}U+^{238}U*, **D. Ackermann** (AGATA+VAMOS, E766)
- *Nuclear structure at and around the N=126 shell closure*, **Y.H Kim**, **A. Lemasson** (AGATA+VAMOS, E806)

These experiments formed the basis of the following PhD theses:

- I. Zanon, University of Ferrara (defended 2022)
- A. Utepov, University of Caen Normandie (defended 2023)
- C. Paxman, University of Surrey (defended 2024)
- Y. Cho, Seoul National University (defended 2025)

B. LNL campaign (2022-2024)

- *Evolution of the mixing between single-particle and intruder configurations approaching the island of inversion at N=20*, F**. Galtarossa**, **A. Gottardo** (AGATA+SPIDER+PLUNGER, Exp 22.07)
- *Probing multiple shape coexistence in ^{110}Cd with Coulomb excitation*, **K. Wrzosek-Lipska**, **A. Nannini**, **M. Rocchini**, **P.E. Garrett**, **M. Zielińska** (AGATA+SPIDER+DANTE, Exp 22.41)
- *Coexisting shapes and precision tests of Monte-Carlo shell-model calculations in ^{96}Zr*, **D.T Doherty**, **N. Marchini**, **M. Zielińska** (AGATA+SPIDER+DANTE, Exp 22.18)
- *Understanding the nature of 0^+ states in $^{110,112}Sn$ and ^{108}Cd*, **N. Mărginean**, **M. Ciemała**, **F. Crespi** (AGATA+PLUNGER+PRISMA, Exp 22.42)
- *Test of particle-coincidences with AGATA+EUCLIDES for studies of light-ion fusion at astrophysical energies*, **G. Montagnoli**, **A. M. Stefanini** (AGATA+EUCLIDES, Exp 22.02)
- *Delineating the island of shape coexistence in N~Z nuclei around A = 70 through Coulomb excitation of ^{74}Se*, **W. Korten**, **K. Wrzosek-Lipska**, **E. Clément** (AGATA+SPIDER, Exp 22.11)
- *Pathway to nuclear structure in heavy neutron rich nuclei in the vicinity of N=126 and nuclei northwest of ^{132}Sn via multinucleon transfer reactions***, P. Reiter** (AGATA+DANTE+PRISMA, Exp 22.04)

- *Test of the ^{70}Zn-^{64}Ni alloy target for nuclear structure studies in the vicinity of Z=28 neutron-rich isotopes with AGATA and PRISMA* and *Nuclear structure studies in the vicinity of the Z=28 neutron-rich isotopes with AGATA and PRISMA*, **R.M. Pérez-Vidal**, **S. Bottoni**, **E. Sahin**, **A. Illana**, **J. Benito**, **J. Ljungvall**, **M. Doncel**, **L.M. Fraile**, **A. Gadea** (AGATA+PRISMA, Exp 22.43 and Exp 22.101)
- *Fusion-fission for γ-ray spectroscopy of neutron-rich nuclei around N = 50 and N=126 and nuclei northwest of ^{132}Sn via multinucleon transfer reactions,* **A. Gottardo**, **M. Caamaño**, **D. Ramos**, **J.J. Valiente-Dobon** (AGATA+PRISMA, Exp 22.23)
- *Lifetime measurements for the study of intruder states towards the island of inversion along the N = 20 shell closure,* **I. Zanon**, **D. Brugnara** (AGATA+PRISMA, Exp 22.40)
- *Search for a Josephson-like effect in the ^{116}Sn+^{60}Ni system,* **L. Corradi**, **S. Szilner** (AGATA+PRISMA+LABR, Exp 22.28)
- *Probing nucleon-nucleon correlations in the ^{48}Ca+^{208}Pb system below the Coulomb barrier,* **T. Mijatović**, **L. Corradi** (AGATA+PRISMA, Exp 22.97 and Exp 23.72)
- *The fusion dynamics far below the barrier for ^{12}C + ^{24}Mg by γ-particle coincidences with AGATA+Si-detectors,* **M. Del Fabbro**, **G. Montagnoli** (AGATA+SAURON, Exp 23.12)
- *Octupole correlations in the neutron-deficient plutonium isotopes,* **J. Smith**, **D. Mengoni** (AGATA+PRISMA, Exp 22.85)
- *Investigating the nature of the low-lying states of ^{196}Os via lifetime measurements,* **D. Brugnara**, **M. Sedlak**, **J. Pellumaj** (AGATA+PRISMA, Exp 22.76)
- *Spectroscopy and lifetime measurements toward the Island of Inversion at N = 20,* **K. Wimmer**, **S. Bottoni**, **G. Benzoni**, **P. Aguilera**, **F. Recchia** (AGATA+PRISMA+LABR, Exp 22.78 and Exp 23.68)
- *Search for octupole structures in the light U, Th and Pa isotopes via Multinucleon Transfer,* **A. Goasduff**, **G. de Angelis**, **K. Rezynkina**, **P.A. Butler** (AGATA+PRISMA+DANTE, Exp 22.96)
- *Study of shape coexistence in ^{60}Fe via lifetime measurement of excited 0^+ states,* **G. Pasqualato**, **J. Ljungvall** (AGATA+SPIDER+LABR+PLUNGER, Exp 22.91)
- *Test of CKM unitarity and the existence of Fierz interference through the measurement of superallowed beta decay of light nuclei*, J. Ha, F. Recchia and *Superallowed ^{10}C β-decay branching ratio measurement with high-count rate,* **P. Aguilera**, **J. Ha**, **Y. Son** (AGATA+LABR, Exp 22.72 and Exp 24.12)
- *The emergence of enhanced collectivity near magic nuclei: Coulomb excitation of ^{60}Ni,* **K. Hadyńska-Klęk**, **M. Rocchini**, **N. Marchini** (AGATA+SPIDER+DANTE, Exp 23.08)
- *Decay-out of the oblate, triaxial and highly-deformed bands in ^{136,137}Nd,* **C.M. Petrache**, **O. Stezowski** (AGATA+EUCLIDES, Exp 23.15)
- *Lifetime of the 6.793 MeV state in ^{15}O,* **J. Skowronski**, **E. Pilotto** (AGATA+SAURON, Exp 23.03)
- *Two-phonon octupole excitation in ^{96}Zr,* **D. Stramaccioni**, **J.J. Valiente Dobon**, **A. Gadea**, **T.R. Rodriguez** (AGATA+SAURON, Exp 23.11)
- *Spherical and deformed structures in ^{56}Ni investigated via lifetime measurements,* **F. Galtarossa**, **A. Gottardo** (AGATA+OSCAR, Exp 23.07)
- *Shell and shapes above ^{56}Ni: lifetime measurements in ground-state and side band of ^{60}Zn,* **E. Pilotto**, **G. Pasqualato** (AGATA+OSCAR, Exp 23.09)

- *Accessing neutron-rich nuclei close to ^{208}Pb via multi-nucleon transfer reactions,* **F. Galtarossa**, **T. Mijatović** (AGATA+PRISMA, Exp 23.64)
- *Lifetime measurements around ^{48}Ca,* **C. Fransen**, **A. Gottardo**, **D. Mengoni** (AGATA+PRISMA+PLUNGER, Exp 22.81)
- *Combined lifetime and transition-probability measurements in ^{96}Zr via unsafe Coulomb excitation,* **M. Zielińska**, **F. Ercolano**, **N. Marchini**, **J.J. Valiente Dobon** (AGATA+PRISMA+PLUNGER, Exp 23.54)
- *Searching for intruder bands in ^{106}Pd via Coulomb excitation,* **N. Marchini**, **M. Rocchini**, **D. Kalaydjieva** (AGATA+SPIDER+LABR, Exp 23.54)
- *Fusion of $^{12}C+^{16}O$ at extreme sub-barrier energies,* **M. Del Fabbro**, **G. Montagnoli** (AGATA+SAURON+LABR, Exp 23.49)
- *Performances of AGATA at high energies,* **M. Balogh**, **Md. S.R. Laskar**, **S. Bottoni**, **R.M. Pérez-Vidal**, **S. Pigliapoco** (AGATA+LABR, Exp 23.53)
- *Shape coexistence in ^{82}Se and its relevance in the $^{82}Se \rightarrow {}^{82}Kr\ 0\nu\beta\beta$ decay,* **N. Sensharma**, **M. Siciliano** (AGATA+SPIDER+DANTE+LABR, Exp 24.08)
- *Study of shape coexistence and triaxial deformation in Cr isotopes via lifetime measurements,* **J. Pellumaj**, **R.M. Pérez-Vidal** (AGATA+LABR+PLUNGER, Exp 24.11)
- *Development of a self-calibration technique for gamma-ray tracking arrays,* **S. Chen**, **S. Paschalis** (AGATA+LABR, Exp 24.01)

These experiments form the basis of the following PhD theses:

- M. Del Fabbro, University of Ferrara, Italy (defended 2023)
- L. Zago, University of Padova, Italy (defended 2024)
- A. Kus, University of Liverpool, UK (defended 2024)
- I. Piętka, University of Warsaw, Poland (in progress)
- G. Corbari, University of Milan, Italy (in progress)
- R. Kjus, University of Paris-Saclay, France (in progress)
- R. Nicolas del Alamo, University of Padova, Italy (in progress)
- F. Angelini, University of Padova, Italy (in progress)
- R. Abels, University of Cologne, Germany (in progress)
- G. Andreetta, University of Padova, Italy (in progress)
- H. Ayatollahzadeh, University of the West of Scotland, UK (in progress)
- Y. Son, Seoul National University, Korea (in progress)
- Z. Ahmed, University of Guelph, Canada (in progress)
- D. Stramaccioni, University of Padova, Italy (in progress)
- E. Pilotto, University of Padova, Italy (in progress)
- R.M. Illicachi Guamán, University of Valencia, Spain (in progress)
- I. Plahter Rosenqvist, University of Oslo, Norway (in progress)
- D. Genna, University of Milan, Italy (in progress)
- H. Hilton, University of Liverpool, UK (in progress)

Appendix 3: AGATA publications from 2020-2024

A. Physics publications

1. M. Ciemała *et al.*, *Testing ab initio nuclear structure in neutron-rich nuclei: Lifetime measurements of second 2^+ state in ^{16}O and ^{20}O*, Phys. Rev. C 101, 021303(R) (2020)
2. B. Cederwall *et al.*, *Isospin Properties of Nuclear Pair Correlations from the Level Structure of the Self-Conjugate Nucleus ^{88}Ru*, Phys. Rev. Lett. 124, 062501 (2020)
3. M. Siciliano *et al.*, *Pairing-quadrupole interplay in the neutron-deficient tin nuclei: First lifetime measurements of low-lying states in ^{106,108}Sn*, Phys. Lett. B 806, 135474 (2020)
4. P. Napiralla *et al.*, *Benchmarking the PreSPEC@GSI experiment for Coulex-multipolarimetry on the $\pi(p_{3/2}) \rightarrow \pi(p_{1/2})$ spin-flip transition in ^{85}Br*, Eur. Phys. J. A 56, 147 (2020)
5. W. Korten *et al.*, *Physics opportunities with the Advanced Gamma Tracking Array: AGATA*, Eur. Phys. J. A 56, 137 (2020) [review article]
6. S. Biswas *et al.*, *Prompt-delayed γ-ray spectroscopy of neutron-rich ^{119,121}In isotopes*, Phys. Rev. C 102, 014326 (2020)
7. R. Banik *et al.*, *High-spin states above the isomers in neutron-rich iodine nuclei near N=82*, Phys. Rev. C 102, 044329 (2020)
8. R. Avigo *et al.*, *Low-lying electric dipole γ-continuum for the unstable ^{62,64}Fe nuclei: Strength evolution with neutron number*, Phys. Lett. B 811, 135951 (2020)
9. A. Goldkuhle *et al.*, *Lifetime measurements of excited states in neutron-rich ^{53}Ti: Benchmarking effective shell-model interactions*, Phys. Rev. C 102, 054334 (2020)
10. A. Bracco *et al.*, *Gamma spectroscopy with AGATA in its first phases: New insights in nuclear excitations along the nuclear chart*, Prog. Part. Nucl. Phys. 120, 103887 (2021) [review article]
11. X. Liu *et al.*, *Evidence for enhanced neutron-proton correlations from the level structure of the N=Z+1 nucleus $^{87}_{43}$Tc$_{44}$*, Phys. Rev. C 104, L021302 (2021)
12. M. Siciliano *et al.*, *Lifetime measurements in the even-even $^{102\text{-}108}$Cd isotopes*, Phys. Rev. C 104, 034320 (2021)
13. S. Ziliani *et al.*, *Complete set of bound negative-parity states in the neutron-rich nucleus ^{18}N*, Phys. Rev. C 104, L041301 (2021)
14. A. Fernandez *et al.*, *Reinterpretation of excited states in ^{212}Po: Shell-model multiplets rather than α-cluster states*, Phys. Rev. C 104, 054316 (2021)
15. V. Girard-Alcindor *et al.*, *New narrow resonances observed in the unbound nucleus ^{15}F*, Phys. Rev. C 105, L051301 (2022)
16. K. Rezynkina *et al.*, *Structure of ^{83}As, ^{85}As, and ^{87}As: From semimagicity to γ softness,* Phys. Rev. C 106, 014320 (2022)
17. L. Grocutt *et al.*, *Lifetime measurements of states of ^{35}S, ^{36}S, ^{37}S, and ^{38}S using the AGATA γ-ray tracking spectrometer,* Phys. Rev. C 106, 024314 (2022)
18. R. M. Perez-Vidal *et al.*, *Evidence of Partial Seniority Conservation in the $\pi g_{9/2}$ Shell for the N=50 Isotones,* Phys. Rev. Lett. 129, 112501 (2022)
19. X. Liu *et al.*, *Evidence for spherical-oblate shape coexistence in ^{87}Tc*, Phys. Rev. C 106, 034304 (2022)

20. E. Clément *et al*., *Spectroscopic quadrupole moments in ^{124}Xe*, Phys. Rev. C 107, 014324 (2023)
21. I. Zanon *et al*., *High-Precision Spectroscopy of ^{20}O Benchmarking Ab Initio Calculations in Light Nuclei,* Phys. Rev. Lett. 131, 262501 (2023)
22. C. Fougères *et al*., *Search for ^{22}Na in novae supported by a novel method for measuring femtosecond nuclear lifetimes,* Nature Commun. 14, 4536 (2023)
23. A. Lemasson *et al*., *Advancements of γ-ray spectroscopy of isotopically identified fission fragments with AGATA and VAMOS++*, Eur. Phys. J. A 59, 134 (2023)
24. G. de Angelis *et al*., *AGATA: nuclear structure advancements with fusion-evaporation reactions,* Eur. Phys. J. A 59, 144 (2023)
25. D. Mengoni *et al*., *Advances in nuclear structure via charged particle reactions with AGATA,* Eur. Phys. J. A 59, 117 (2023)
26. R.M. Perez-Vidal *et al*., *Nuclear structure advancements with multi-nucleon transfer reactions,* Eur. Phys. J. A 59, 114 (2023)
27. F. Camera *et al*., *AGATA: Nuclear structure advancements with high-energy γ rays,* Eur. Phys. J. A 59, 168 (2023)
28. J. Dudouet *et al*., *High-resolution spectroscopy of neutron-rich Br isotopes and signatures for a prolate-to-oblate shape transition at N = 56,* Phys. Rev. C 110, 034304 (2024)

B. Technical publications

1. P. Napiralla *et al*., *Approach to a self-calibrating experimental gamma-ray tracking algorithm,* Nucl. Instrum. Methods Phys. Res. A 955, 163337 (2020)
2. J. Ljungvall *et al*., *Performance of the Advanced GAmma Tracking Array at GANIL,* Nucl. Instrum. Methods Phys. Res. A 955, 163297 (2020)
3. B. De Canditiis *et al*., *Simulations using the pulse shape comparison scanning technique on an AGATA segmented HPGe gamma-ray detector,* Eur. Phys. J. A 56, 276 (2020)
4. M. Siciliano *et al*., *Position uncertainties of AGATA pulse-shape analysis estimated via the bootstrapping method,* Eur. Phys. J. A 57, 64 (2021)
5. M. Ciemała *et al*., *Accessing tens-to-hundreds femtoseconds nuclear state lifetimes with low-energy binary heavy-ion reactions,* Eur. Phys. J. A 57, 156 (2021)
6. J. Ljungvall *et al*., *Pulse-shape calculations and applications using the AGATAGeFEM software package,* Eur. Phys. J. A 57, 198 (2021)
7. B. De Canditiis *et al*., *Full-volume characterisation of an AGATA segmented HPGe gamma-ray detector using a ^{152}Eu source,* Eur. Phys. J. A 57, 223 (2021)
8. M. Assié *et al*., *The MUGAST-AGATA-VAMOS campaign: Set-up and performances,* Nucl. Instrum. Methods Phys. Res. A 1014, 165743 (2021)
9. J.J. Valiente-Dobón *et al*., *Conceptual design of the AGATA 2π array at LNL,* Nucl. Instrum. Methods Phys. Res. A 1049, 168040 (2023)
10. F.C.L. Crespi *et al*., *AGATA: performance of γ-ray tracking and associated algorithms,* Eur. Phys. J. A 59, 111 (2023)
11. R. Smith *et al*., *AGATA: mechanics and infrastructures,* Eur. Phys. J. A 59, 116 (2023)
12. O. Stezowski *et al*., *Advancements in software developments*, Eur. Phys. J. A 59, 119 (2023)

13. J. Collado *et al*., *AGATA phase 2 advancements in front-end electronics,* Eur. Phys. J. A 59, 133 (2023)
14. E. Clément *et al*., *Organisation of the AGATA collaboration and physics campaigns,* Eur. Phys. J. A 59, 152 (2023)
15. M. Labiche *et al*., *Simulation of the AGATA spectrometer and coupling with ancillary detectors,* Eur. Phys. J. A 59, 158 (2023)
16. M. Bentley *et al*., *AGATA: in-beam spectroscopy with relativistic beams,* Eur. Phys. J. A 59, 172 (2023)
17. J. Eberth *et al*., *AGATA detector technology: recent progress and future developments,* Eur. Phys. J. A 59, 179 (2023)
18. A. Korichi *et al*., *AGATA DAQ-box: a unified data acquisition system for different experimental conditions,* Eur. Phys. J. A 59, 211 (2023)
19. A.J. Boston *et al*., *AGATA characterisation and pulse shape analysis,* Eur. Phys. J. A 59, 213 (2023)

C. PhD theses based on AGATA results defended between 2020 and 2024

1. J.P. Collado Ruiz, University of Valencia, Spain (2020)
2. L. Kaya, University of Cologne, Germany (2020)
3. B. de Canditis, University of Strasbourg, France (2020)
4. L. Lewandowski, University of Cologne, Germany (2020)
5. V. Girard-Alcindor, University of Caen Normandie, France (2020)
6. X. Liu, KTH Royal Institute of Technology, Sweden (2021)
7. Ö. Aktas, KTH Royal Institute of Technology, Sweden (2021)
8. S. Ziliani, University of Milan, Italy (2021)
9. D. Reygadas Tello, University of Grenoble Alpes, France (2021)
10. I. Zanon, University of Ferrara, Italy (2022)
11. Ch. Fougères, University of Caen Normandie, France (2022)
12. F. Holloway, University of Liverpool, UK (2022)
13. A. Utepov, University of Caen Normandie, France (2023)
14. J. Pellumaj, University of Ferrara, Italy (2023)
15. D. Kalaydjieva, University of Paris-Saclay, France (2023)
16. M. Del Fabbro, University of Ferrara, Italy (2023)
17. T. Milanović, University of Novi Sad, Serbia (2024)
18. M. Abushawish, University of Lyon 1, France (2024)
19. C. Paxman, University of Surrey, UK (2024)
20. L. Zago, University of Padova, Italy (2024)
21. A. Kus, University of Liverpool, UK (2024)
22. R. Molina, University of Paris-Saclay, France (2024)

Appendix 4: Environmental impact

The Phase-2 organigram includes an environmental officer.

Since this position has been introduced, several actions have been taken to reduce the environmental impact of AGATA operation.

- AGATA consumes a large quantity of LN2. Recycling the LN2 would be an ideal solution but has not yet been implemented. However, for the LNL campaign, LN2 transfer lines including the individual cluster deliveries have been vacuum shielded. This investment is now part of the AGATA Detector Support System and will be transferred with the array. These shielded transfer lines aim at reducing the LN2 consumption between the manifolds and the main tank of AGATA. Consequently, the frequency of the main tank refill is reduced.

- Powering down the anodes. The DAQ infrastructure includes: services (/home/, ssh gateway, elog), storage (/agatadisks/), analysis machines, evt-builder (knodes) and PSA nodes (anodes); to date, the anodes are responsible for 80% of the DAQ power consumption. During long shutdowns, the PSA computing nodes are shut down, reducing drastically the power consumption of the nodes themselves and the air conditioning.

- Remote control. Thanks to the development of monitoring tools and web-based run control, daily monitoring of the in-beam data taking can be performed remotely, reducing the travel carbon fingerprint.

In the future, the environmental impact of the data storage will be evaluated and optimised with respect to the host laboratory and user's location.

Appendix 5: Detailed report from the Detector WG

The AGATA Triple Cluster detector is a state-of-the-art instrument designed for high-resolution gamma-ray spectroscopy, playing a crucial role in nuclear-structure studies. It consists of three asymmetric, 36-fold segmented, hexagonal-shaped, encapsulated, and tapered high-purity germanium (HPGe) detectors. Each ATC integrates 111 high-resolution spectroscopy channels, combining core contacts and segment signals from each crystal to provide exceptional performance.

To ensure optimal operation, the three asymmetric germanium capsules are housed within a single vacuum cryostat, which operates at liquid nitrogen (LN_2) temperature, maintained by a dedicated LN_2 dewar. The cold input stages of the preamplifiers are integrated into the cryostat's cold section to minimise electronic noise. System parameters such as temperature and vacuum conditions are continuously monitored using PT100 resistive sensors, while capacitance sensors are used to measure the liquid nitrogen levels, ensuring a stable and reliable performance.

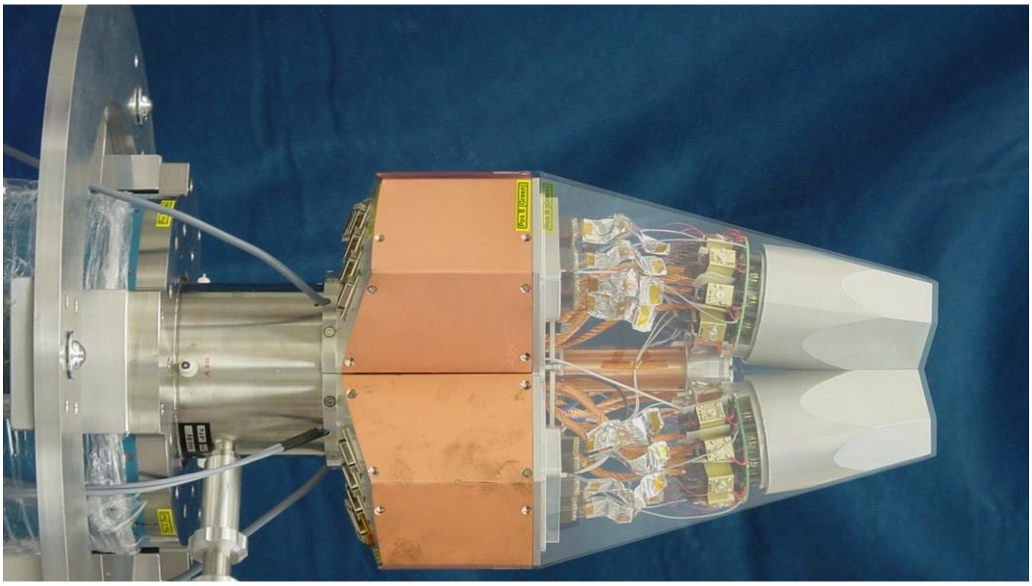


Fig. A1. The AGATA Triple Cluster

A5.1 Procurement, Quality Assurance and Long-term Maintenance

Acquiring and maintaining AGATA detectors requires significant investment, particularly in HPGe capsules and cryostat systems. The Detector Working Group (DWG) is responsible for overseeing procurement, quality assurance, and long-term maintenance to ensure that the detectors meet AGATA's operational and scientific requirements.

HPGe capsules are procured from Mirion based on available funding, with the AGATA collaboration representatives negotiating annual pricing structures. Each capsule undergoes a rigorous Factory Acceptance Test (FAT) conducted by the DWG to confirm compliance with performance specifications. Continuous communication with Mirion assures efficient tracking of production schedules, management of potential delays, coordination of necessary repairs, and timely deliveries.

Cryostat procurement is handled through CTT, with core preamplifiers sourced from IKP Cologne and segment preamplifier manufacturing assigned to GANIL/INFN. CTT integrates the three asymmetric HPGe detectors into a triple-cluster configuration before delivering the final system to the AGATA community via IKP Cologne. From there, the ATC is transferred to the host laboratory for scientific use.

To ensure the long-term stability and reliability of AGATA detectors, the DWG maintains a comprehensive database documenting procurement, delivery, and maintenance activities. Preventive maintenance procedures are conducted regularly, including inspections and functional assessments of the detectors. Continuous monitoring of vacuum integrity, temperature stability, electronic noise levels, and neutron damage levels ensures that the detectors remain in peak condition for high-precision spectroscopy applications.

Several test facilities play a key role in quality assurance and troubleshooting. Test cryostats located at IKP Cologne, IPHC Strasbourg, University of Liverpool, and CEA Saclay are essential for conducting Customer Acceptance Tests (CAT) and diagnosing detectors that fail before they are sent to Mirion for repair. Additionally, two test cryostats equipped with detectors are allocated to the PSA group to support scanning procedures aiming to enhance PSA performance.

This structured approach to the design, procurement, and maintenance of AGATA detectors ensures their continuous reliability and effectiveness in nuclear research. The commitment of the Detector Working Group to monitoring, quality control, and technological advancements remains essential for the success of the AGATA project.

A5.2 Status of Detector Procurement

The procurement of AGATA detectors and cryostats represents a substantial financial commitment, requiring careful strategic planning and coordination among the AGATA partner institutions. Mirion Technologies, the supplier of the AGATA encapsulated HPGe detectors, has outlined a long-term pricing structure for these components. As of 2025, the base price for a single encapsulated AGATA HPGe detector is set at 231671€, with annual adjustments based on the French Labour Cost Index. These adjustments, however, are capped at 2.5% to prevent excessive fluctuations, ensuring the prices remain within a manageable range for budgeting purposes. In addition, Mirion provides a volume-based discount system to encourage bulk purchases, which gradually reduces the price per unit depending on the number of detectors ordered in a given year. This pricing structure helps the AGATA community to maximise cost efficiency when acquiring larger quantities of detectors. The discount follows a linear progression, reducing the price by 3% per unit for orders of more than one detector, up to a maximum discount of 33% for orders of 12 or more detectors in a single year. As a result, the total cost if N detectors are ordered by the collaboration in the same calendar year is calculated using the formula:

$$(231671€ \times N) \times (1 - (3\% \times (N-1)))$$

This calculation does not include additional price adjustments based on the French Labour Cost Index.

Table A 1. Estimated base price evolution for an AGATA capsule (Mirion)

Year	2025	2026	2027	2028	2029	2030
Detector unit price (k€)	231.7	237.5	243.4	249.5	255.7	262.1

Similarly, cryostats, which are essential for housing the detectors, are supplied by CTT at a reference price 147 k€ in 2024. Just like with detectors, cryostat purchases are incentivised with volume-based discounts. When two cryostats are ordered simultaneously, a 5% discount is applied; ordering three cryostats increases the discount to 7.5%, and a 10% discount is given for four or more cryostats in a single order.

Table A 2. Estimated base price evolution for an AGATA triple cryostat (CTT)

Year	2025	2026	2027	2028	2029	2030
Cryostat unit price (k€)	147.0	150.7	153.0	155.3	157.6	160.0

This discount system plays a key role in managing the costs of the procurement of the necessary equipment for AGATA operations.

Currently, seventy-four AGATA HPGe capsules, both symmetric (three) and asymmetric (seventy-one), have been delivered. Six detectors are on order (order placed or to be signed), with expected delivery within 2025-2026. In total, between 2021 and 2025, twenty-four capsules have been funded by the collaboration. These capsules are distributed among AGATA's various collaborating institutions, with each institution contributing to the overall collection of detectors.

Table A 3. Owners of the seventy-four AGATA capsules

	Owner		Owner		Owner
S001	IKP Cologne	S002	GSI	S003	TUM
A001	GANIL	B001	INFN Padova	C001	INFN Padova
A002	INFN	B002	IN2P3	C002	CEA Saclay
A003	Liverpool	B003	Liverpool	C003	Liverpool
A004	Ankara	B004	Ankara	C004	Ankara
A005	Sweden	B005	Sweden	C005	Sweden
A006	INFN Padova	B006	INFN Padova	C006	INFN Legnaro
A007	INFN Milan	B007	IKP Cologne	C007	IKP Cologne
A008	IKP Cologne	B008	IKP Cologne	C008	Liverpool
A009	Liverpool	B009	Liverpool	C009	CEA Saclay
A010	INFN Milan	B010	INFN Milan	C010	IFIC Valencia
A011	IN2P3	B011	INFN Legnaro	C011	IN2P3
A012	CEA Saclay	B012	IN2P3	C012	IN2P3
A013	TU Darmstadt	B013	CEA Saclay	C013	IFIC Valencia
A014	IKP Cologne	B014	INFN Milan	C014	INFN Milan
A015	IN2P3	B015	TU Darmstadt	C015	TU Darmstadt
A016	Finland	B016	IKP Cologne	C016	IKP Cologne
A017	Atomki	B017	Univ. of York	C017	Univ. of York
A018	UWS	B018	Atomki	C018	Atomki
A019	GANIL	B019	UWS	C019	UWS
A020	IN2P3	B020	GANIL	C020	IN2P3
A021	Liverpool	B021	INFN	C021	INFN
A022	Spain	B022	Liverpool	C022	GANIL
A023	GSI	B023	GSI	C023	GSI

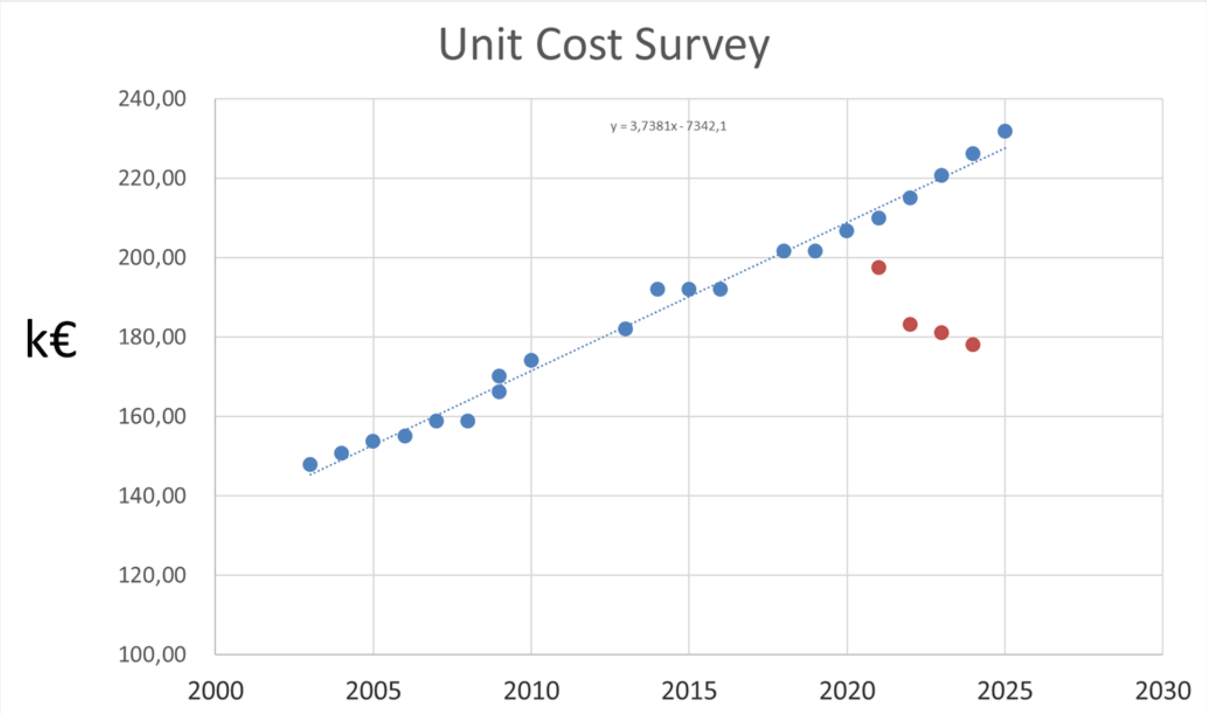
A024	Liverpool				
		B025	CEA Saclay		

The procurement process is part of Phase 2 of the AGATA project, which aims to build upon prior acquisitions to expand the total number of fully equipped AGATA triple clusters. By 2025 a significant portion of the detectors foreseen to be acquired during the first five-year period of the MoU will indeed be procured (24 out of 39), although some challenges related to funding limitations in certain partner countries have led to disparities in the progress of procurement. Some countries, such as France and the UK, have met their financial commitments fully (100%), while others, like Spain, have exceeded expectations (200%). However, countries like Italy (75%) and Germany (37%) have faced difficulties in meeting their targets. These challenges have impacted the speed of procurement, highlighting the importance of securing consistent and equitable funding from all participating nations.

The success of AGATA's procurement strategy relies on the availability of CORE funds provided by MoU partner institutions. Given that the purchase of detectors accounts for a significant portion of the project's budget, it is crucial for all partners to ensure that funding is available for the bulk purchases of components. To optimise costs, AGATA has implemented a strategy of bulk purchasing, which not only improves pricing but also helps avoid delays in the procurement process. By making sure that funds are allocated upfront for these large purchases, the timely acquisition of critical equipment can be ensured.

The historical cost trends indicate a steady increase of the unit price for HPGe capsules, largely driven by inflation. However, through strategic negotiations and coordinated bulk orders, AGATA has been able to reduce the impact of these price increases. Despite the rising costs, the AGATA collaboration has successfully managed to secure more favourable pricing by negotiating discounts and leveraging long-term agreements with suppliers.

To reach an array of 135 capsules funded by 2030 (3π), taking into account the investment until 2024, 54 capsules need to be procured (9.35 M€) and 15 additional cryostats (2.18 M€).



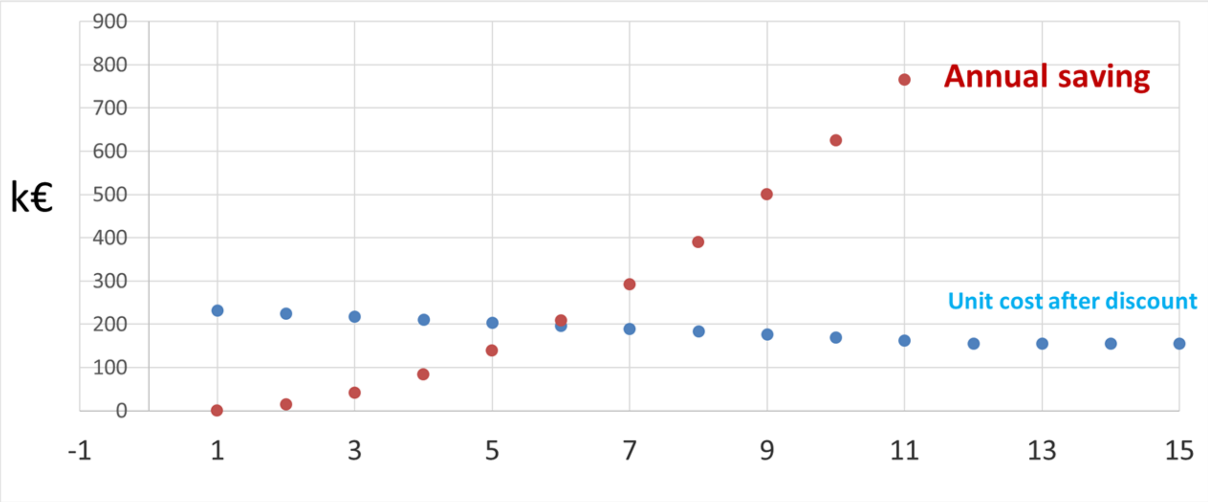


Fig. A2 Top panel: Evolution of the base price of an AGATA capsule (blue) and that of the transaction price (red) taking into account the volume-based discount applied since 2021. Bottom panel: Cost of a single capsule (as of 2025) as a function of the number of capsules ordered in the same year (blue) and the total saving resulting from the simultaneous purchase (red).

Beyond the procurement of detectors, the ongoing maintenance of AGATA's equipment is a critical element to ensure long-term functionality of the array. In 2024, a maintenance effort was funded through the operational costs (via the account hosted by GANIL complemented by a direct IRFU contribution), ensuring that the detectors and associated equipment remained in optimal working conditions. This funding was used for the setup of test benches and for the maintenance of AGATA triple clusters at the host laboratory (24.4k€). Continued funding of the maintenance efforts is essential to ensure the long-term success of the AGATA project, as the detectors must remain in peak condition to support cutting-edge nuclear physics research.

A5.3 Maintenance and Operational Support

Maintaining the AGATA cryostats and detectors follows a structured approach to ensure their continuous operation and reliability for high-precision nuclear research. This process involves technical inspections, diagnostics, and repairs, with initial assessments carried out by local staff at the host laboratories.

For minor issues, repairs are conducted on-site, but problems that are more complex are addressed at the dedicated AGATA detector laboratories. As the number of detectors increases, so does the demand for maintenance and operational support. To manage this growing workload effectively, it is essential for the personnel of all detector laboratories to receive comprehensive training, enabling them to perform repairs independently.

The AGATA collaboration acknowledges the essential daily support provided by the host laboratory at LNL, but notes that staffing levels have remained constant since 2021. At present, only two laboratories - IKP Cologne and IPHC Strasbourg - have the expertise necessary to maintain the ATCs at a high level. This has put considerable pressure on their personnel, and it is unlikely that additional laboratories will join the collaboration in the near future. Bringing new HPGe detectors and triple cryostats into operation is a labour-intensive process that requires up to 370 hours per ATC, which includes tasks like the Factory Acceptance Test (FAT), Customer Acceptance Test (CAT), post-assembly testing, transportation, and on-site commissioning. In the second phase of the present MoU, GSI is willing to contribute to this task.

Regular maintenance is vital for keeping the detectors operational and available for physics experiments. Every two years, each ATC undergoes annealing to maintain vacuum properties, while major inspections, involving necessary repairs and upgrades, are carried out. If neutron damage occurs, the workload and costs associated with repairs rise significantly.

A5.4 Long-term Sustainability and Challenges

The workload associated with these tasks is distributed across the AGATA host laboratories and the four AGATA detector laboratories.

The IKP in Cologne is willing to provide like in the past a large detector infrastructure. This includes three large detector laboratories (i) for mechanical construction and vacuum properties, (ii) with equipment for assembly and electronic commissioning, as well as (iii) an infrastructure that enables the readout of individual detectors in test cryostats with digital AGATA electronics for the final acceptance tests with all 111 energy channels of the complete detector systems. The efforts in Cologne are based on the contributions of a large precision engineering workshop with engineers and technicians who have been driving the AGATA project with all its requirements for over two decades, both in the long term and very flexibly in the event of short-term changes. Likewise, the contributions of the electronics workshop with engineers and technicians are essential for the development, construction and commissioning of the sophisticated analogue electronics to meet the demanding requirements of high-resolution spectroscopy.

IRFU has also recognised the critical role of a dedicated detector lab for the success of future AGATA campaigns, particularly at GANIL, and acknowledges the need to preserve expertise in segmented germanium detectors. To address this, capsule test activities will continue at Saclay as a temporary solution, with further discussions foreseen between IRFU/Saclay and GANIL to determine the future location for AGATA triple cluster maintenance and the required manpower.

No changes are currently planned for the IPHC team in the near future. However, to strengthen the team, a student assistant engineer will be hired on a work-study basis starting from September 2025. Initially, this new team member will assist with scanning, CAT and FAT activities and be trained on ATC integration. Should they successfully pass the CNRS entrance exam within two years, they will transition to working on ATC maintenance and broader AGATA IPHC activities, ultimately replacing an engineer who will retire at the end of the decade.

The future of AGATA's detector and cryostat systems is also influenced by the status of CTT, which is expected to cease operations before 2030. As a result, the AGATA collaboration is considering a reorganization. One potential solution is to increase permanent staff at AGATA laboratories, while another option is to outsource ATC delivery, integration, and major repairs to Mirion. Host laboratories would continue daily operations, while AGATA partners oversee research and development. The ASC is assisting the AMB in evaluating these options, with a draft contract already presented to Mirion for temporary cooperation. Discussions are ongoing, with no concrete updates provided yet, and the future of the agreement remains uncertain.

Both parties, the Lingolsheim site of Mirion and the CTT, stress their keen interest in mutual cooperation and hope that the matter will soon be resolved to mutual satisfaction and that an agreement will be reached quickly. However, no firm information that could be useful for the mid-term evaluation has been provided.

A5.5 Technological Upgrades and Cost Reduction

The AGATA Detector Group remains focused on expanding the number of AGATA Triple Cryostats to maximise the spectrometer’s efficiency in experimental campaigns. The modular design of the ATCs, combined with their established cryostat technology and detector configuration, will continue to play a key role in future expansion phases. Ensuring high reliability and a low failure rate of these cryostats is essential, as it helps minimise maintenance needs for the spectrometer. To this end, the Detector Working Group will explore new technical solutions through dedicated research and development projects.

In the next phase, AGATA cryostats will be manufactured based on the existing modular design, with some modifications aimed at enhancing their reliability. For example, a new cable feedthrough system has been developed to accommodate 222 signal cables and around 30 grounding connections, ensuring compatibility with existing feedthroughs. These new feedthroughs are equipped with gold-plated contact pins embedded in aluminium-oxide ceramic insulators, which are sintered together with a Cu-Ag alloy to form a single connector. These connectors are then integrated into a titanium housing through electron welding. This system significantly reduces the risk of vacuum breakdowns after the cryostat is warmed up, and all ATCs have been upgraded with this technology.

To further improve longevity, a prototype feedthrough using molybdenum gold-plated pins has been developed. These new pins offer better corrosion resistance and have been installed in ATC06 for evaluation.

Moreover, significant improvements in vacuum quality have been achieved with the integration of a high-efficiency vacuum getter material. Previously, this getter material was placed within the dewar and required annealing alongside the cryostat hardware, which was time-consuming and subjected the components to thermal stress. In the new cryostats, the getter material is housed in a flexible container mounted on the cooling finger, allowing it to be easily accessed and replaced without disassembling the detectors. This design allows the getter material to be annealed externally, thus reducing maintenance time considerably. More than half of the cryostats have already been retrofitted with this improved getter system, and all existing cryostats will undergo similar upgrades in the near future.

In parallel, the AGATA collaboration has been committed to reducing the costs associated with encapsulated detectors and their maintenance. The highly segmented HPGe detectors, composed of n-type HPGe material, are each housed within a hermetically sealed aluminium canister, which facilitates handling during the mounting and maintenance of the cryostats. However, a significant drawback of this encapsulation design is that if a detector fails, the capsule must be destructively opened to access the HPGe crystal, a process that is both time-consuming and costly. To mitigate this challenge, the IKP Cologne detector working group, in collaboration with the detector manufacturer Mirion, developed a reusable detector housing. This new housing technology was successfully tested and implemented in production, and it maintains full compatibility with existing detector models. As presented in Fig. A3, the performance of the detectors using the new encapsulation technology is comparable to those using the traditional solution. Since the introduction of this reusable housing, 30 asymmetric AGATA capsules have been procured, and additional six have been upgraded to the new encapsulation technology while undergoing repairs. This has already led to a significant reduction in repair costs from approximately 93 k€ to 50 k€ per unit.

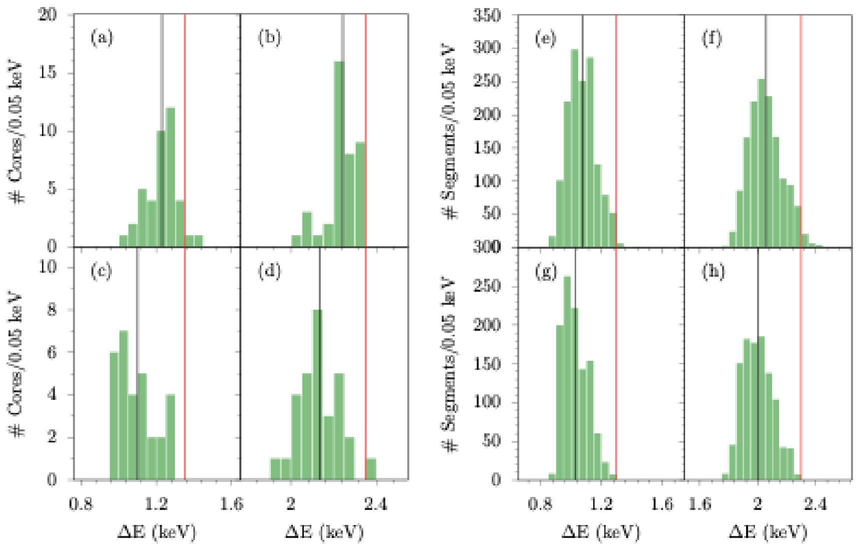


Fig. A3 Summary of energy resolution values (FWHM) (a,b) of 40 core signals from detectors with welded capsules and (c,d) 30 core signals of AGATA HPGe detectors with the new encapsulation technology; (e,f) of 1440 segment signals from 40 welded capsules and (g,h) 1080 segment signals from 30 AGATA detectors with the new encapsulation. The energy resolution values are given for a γ-ray energy of 60 keV (^{241}Am) (a,c,e,g) and of 1.3 MeV (^{60}Co) (b,d,f,h). The AGATA energy specification limits for both γ-ray energies are presented with red lines. Black lines indicate the mean values of the energy resolution.

The collaboration has also worked on diversifying the supplier base for AGATA HPGe segmented capsules. In this context, a collaboration with ORTEC was explored to reduce capsule procurement costs. The University of Liverpool (UK) made an initial investment of 57 k€ into a development undertaken by ORTEC, and its progress was reported regularly at AGATA meetings. While initial results in 2022 were promising, further testing in 2023 revealed significant issues with the quality and reliability of the electric segments. As a result, ORTEC has suspended further development. The AGATA collaboration recognised the financial investment made by the UK in the CORE budget.

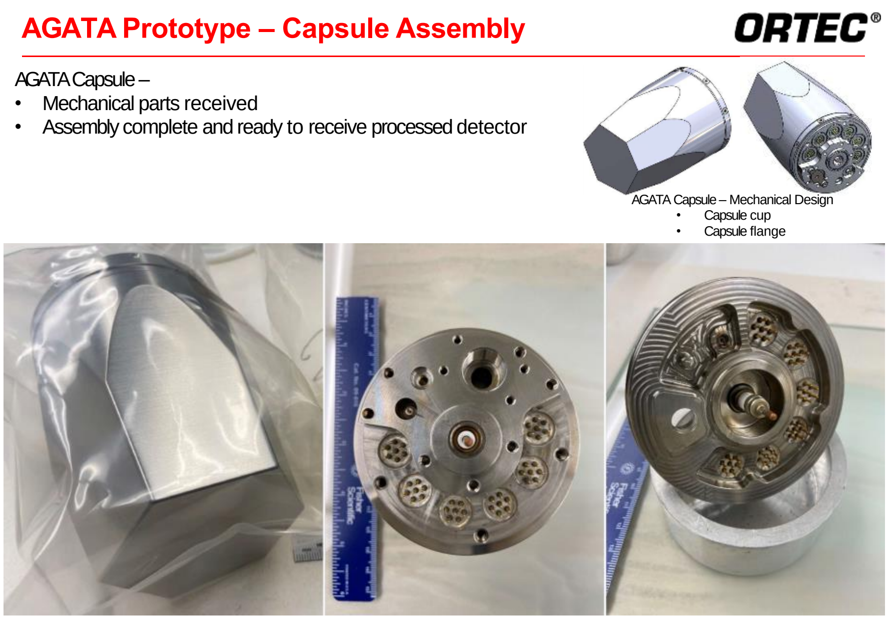


Fig. A4 ORTEC AGATA capsule prototype

Neutron damage continues to pose a challenge for highly segmented n-type HPGe detectors. Fast neutrons create negatively charged lattice defects that trap holes, which disrupts segment signals, resulting in left-tailed energy peaks and a loss of energy resolution. To combat this, a reliable annealing procedure was developed in collaboration with Mirion. In this process, the crystals are annealed while the capsule is vacuum-pumped, which significantly reduces the failure rate of encapsulated detectors and lowers operational costs. The cost of annealing each capsule is presently 8598 €, with volume discounts available for orders exceeding one detector. So far, the AGATA community has successfully annealed 25 detectors with this newly developed procedure, restoring all of them to their original energy resolution (see Fig. A5) without any failures. When annealed within the collaboration without pumping the capsule, one in three failed, requiring full crystal reprocessing at a cost of approximately 50 k€ per unit. Hence, the newly developed annealing procedure resulted in significant cost savings.

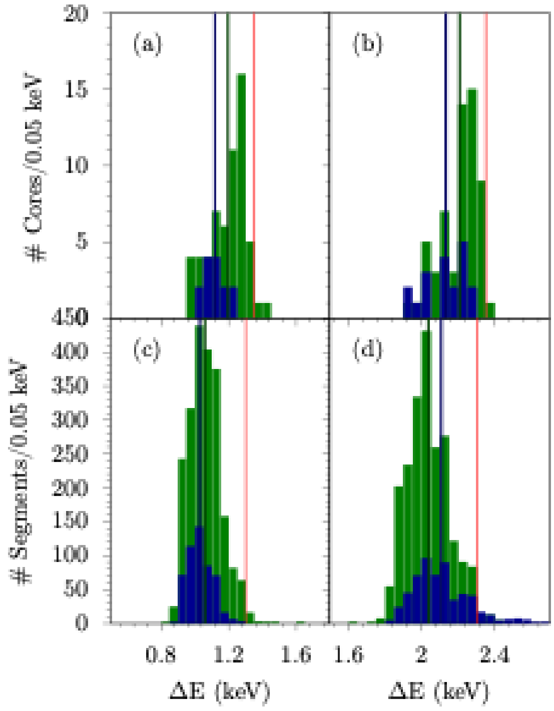


Fig. A5 Summary of energy resolution values (FWHM) of core signals (a,b) and segment signals (c,d) of 59 AGATA HPGe detectors (green bars). The energy resolution values are given for a γ-ray energy of 60 keV (^{241}Am) (a,c) and of 1.3 MeV (^{60}Co) (b,d). Several neutron-damaged AGATA crystals went through the annealing procedure. The energy resolution values (FWHM) of HPGe detectors after annealing are also shown (blue bars). The AGATA energy specification limits for both γ-ray energies are presented with red lines. The mean values of the energy resolution for detectors after delivery are indicated with green lines, and those for annealed detectors with blue lines.

The cold core and segment preamplifiers, which are integral components of the cryostat, are supplied by the cryostat manufacturer. A new cold core preamplifier has been designed to improve core resolution and has been integrated into all systems. Beyond this upgrade, no major changes are planned for the next phase. However, challenges related to obsolete electronic components and preamplifier maintenance have been anticipated. To mitigate these issues, a comprehensive survey of obsolete components has been conducted, and a sufficient stock of discontinued BF862 field-effect transistors (FETs) has been secured to ensure long-term availability.

A5.6 Long-term R&D

The long-term research and development (R&D) initiatives aimed at improving AGATA detector technology are vital for maintaining its role as a leader in high-resolution gamma-ray spectroscopy. As the field progresses, several key innovations will further enhance AGATA's performance. While progress has already been made in areas such as modular cryostat design, reusable detector housings, and annealing techniques, the second part of the decade will see the further exploration of promising developments, particularly p-type germanium detectors, electric cooling solutions, and Application-Specific Integrated Circuit (ASIC) preamplifiers.

A5.7 P-Type Germanium Detectors

A major long-term goal of the AGATA project is the transition from current n-type HPGe detectors to p-type germanium detectors. P-type detectors have several potential advantages, such as increased resistance to neutron damage and superior energy resolution. Research at LNL is focused on new doping and passivation methods to create high-performance p-type detectors. The use of Pulse Laser Melting (PLM) technology will play a key role in developing p-type coaxial detectors with advanced contacts and junctions. This approach aims to enhance the creation of segmented detectors, which are a fundamental component of AGATA's design. In addition, PLM will be used to develop double-sided segmented planar detectors, thus improving the detector's resolution and sensitivity. The transition to p-type detectors promises substantial gains in detector performance and durability in complex experimental environments, though this effort is still in its early stages.

A5.8 Electric Cooling Solutions

Traditional cooling systems, such as those currently used in AGATA, rely on liquid nitrogen to maintain the low temperatures necessary for optimal detector performance. However, this method poses logistic and operational challenges. As part of long-term R&D, the AGATA project is exploring electric cooling solutions as a more sustainable alternative. Electric cooling could offer several benefits, including reduced dependence on cryogenic liquids, lower operational costs, and improved efficiency. While this area of research currently has a lower priority due to resource constraints, the potential for electric cooling technologies to revolutionise AGATA's operations is significant. As more resources become available, research efforts in electric cooling will increase, making it a key focus for the second part of the decade. This type of R&D is also of interest for industry, with e.g. Mirion providing electric cooling for smaller detector assemblies.

A5.9 ASIC Preamplifiers

The development and integration of ASIC preamplifiers is critical for enhancing AGATA's capabilities. The potential of ASICs to reduce noise, increase efficiency, and provide more advanced signal processing is especially important for improving the signal-to-noise ratio (SNR) of the detectors. A better SNR will ultimately lead to more accurate and precise gamma-ray spectroscopy, which is essential for AGATA's success in nuclear physics research.

This development is ongoing in collaboration between LNL and the University of Milan, which brings together LNL's extensive experience in detector technology and nuclear instrumentation alongside the University of Milan's expertise in electronics and circuit design. Through this collaboration, they aim to design efficient and high-performance ASIC preamplifiers that will significantly enhance AGATA's data acquisition capabilities.

While this initiative is still in the research phase, the work being done by these two institutions could become a game-changer in the field. ASICs will provide a more precise control over the signal processing, allowing AGATA to reach even higher levels of performance. However, as noted, the progress of this development is still limited by available resources. Once the necessary funding and technical support become more readily available, the integration of low-noise ASIC preamplifiers into AGATA could significantly contribute to the next generation of gamma-ray spectroscopy.

The AGATA project continues to evolve, with ongoing advancements in detector technology, procurement, and maintenance strategies. The collaborative efforts of partner institutions, along with a strategic focus on cost optimization and technical innovation, ensure that AGATA remains at the forefront of nuclear structure research. In particular R&D activities are not funded within the MoU and rely on funding received from specific institutions. Securing manpower is critical for maintaining these activities. The long-term sustainability of the AGATA project depends on securing continued funding, expanding technical expertise, and ensuring the long-term reliability of the detectors and cryostat systems.

A5.10 Commitment of detector laboratories

The detector activity is supported by four official detector laboratories, which contribute to the maintenance, integration and scanning of the detectors.

The Saclay laboratory is committed to pursue its activity with the perspective of a new technician and the ambition of acquiring the knowhow of the integration of a triple cluster.

The Strasbourg laboratory is committed to maintain its detector laboratory for integration, test and scanning activities until the end of the present MoU.

The IKP Cologne laboratory is facing a difficult situation with personnel. The German community is committed to maintain the experts and knowledge, while not necessarily in-situ in Cologne.

The Liverpool laboratory has updated recently its infrastructure and is committed to pursue its activity for the collaboration.

Appendix 6: Detailed report from the Infrastructure WG

The working group is in charge of providing the mechanical support for the detectors (HoneyComb and shaft) and assists the host laboratories in the local implementation of the array, including geometric alignment. The group is in charge of maintaining the technical blue prints of AGATA.

The second task is the development and maintenance of the Detector Support System (DSS) which includes i) the power supplies for the detector pre-amplifiers and the front-end electronic, ii) the high voltage system, iii) the control system of the automatic LN2 filling and related hardware and iv) the monitoring and data archiving. The local team is in charge of the daily surveillance of the LN2 delivery and refill, assisted by the working group.

The working group is also responsible for the electromagnetic compatibility (EMC) characterisation of the installed components, which needs to be performed at each host laboratory in order to identify and eliminate weak grounding connections.

The last task is the maintenance and development of the AGATA Data Base used to store information about all components of the array and its infrastructure.

Regarding the first task, the goal of Phase 2 was to design and provide a more universal mechanical structure to reduce significantly the installation cost when moving from one host laboratory to another. This task was completed by the STFC team and the supporting structure was installed at LNL prior to the current campaign (see below the design). Beyond 2π, the system will be duplicated to cover up to 4π solid angle. The full support system will be moved as a whole to the next host laboratory. Core funds are needed to complete the second support system including the tools used for the mounting of the detectors.

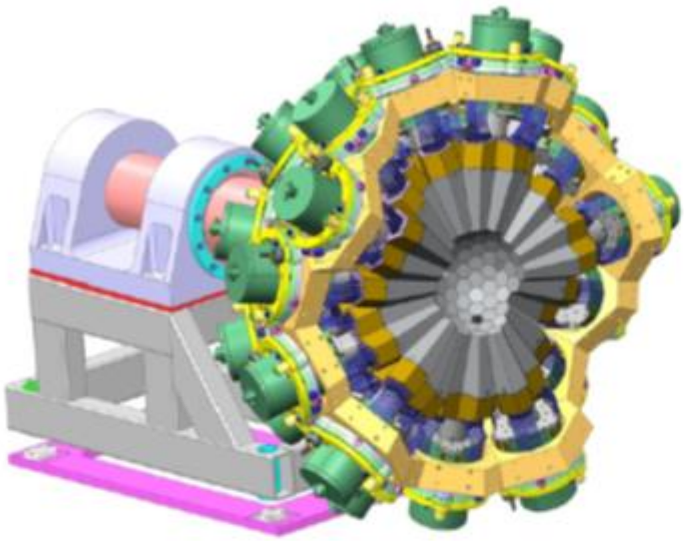


Fig. A6 AGATA structure (shaft and honeycomb) for 2π with detectors

During the LNL installation, an improved system was developed for the detector alignment using dedicated tools together with laser trackers.

Regarding the second task, the Phase 2 LVPS (Low Voltage Power Supply) by CEA/IRFU has been designed, delivered to LNL, and is currently operational in a configuration for the 2π array. Core funds are needed to complete the 3π system. The high voltage system covering up to 3π has been replaced according to commitment. Similar, the Phase-2 LN2 filling system by CEA/IRFU has been designed and delivered to LNL in a configuration for the 2π setup, while Core funds are needed to complete it to suit the 3π system.

In order to optimise the detector performance and minimise the effects of external electronic noise, an EMC study has been performed during the design and assembly of the mechanical structure at LNL, and the identified issues have been addressed. Several campaigns of measurements were conducted by an IJClab expert and the local team after installation of the electronics and detectors, and later on demand of the performance team.

The group has been working on how to improve the transfer of the array between host laboratories. The first task will be the move from LNL to GANIL in 2028. If funds are rapidly available (before 2027), the second HoneyComb + shaft as well as the additional DSS parts can be purchased or manufactured before the end of the LNL campaign and pre-installed before 2028 at GANIL. This will shorten significantly (by several weeks) the time needed to put AGATA into operation at GANIL for its second campaign there. Depending on AGATA's next location, the first 2π system could remain in LNL to enable a fast start of a SPES campaign, or could be sent for pre-installation at GSI/FAIR.

The mechanics team is preparing the integration of AGATA into the GANIL infrastructure, where it will be coupled with VAMOS and GRIT and is continuing to study the integration of AGATA into the GSI/FAIR infrastructure at the Low Energy Branch of NUSTAR behind the SFRS.

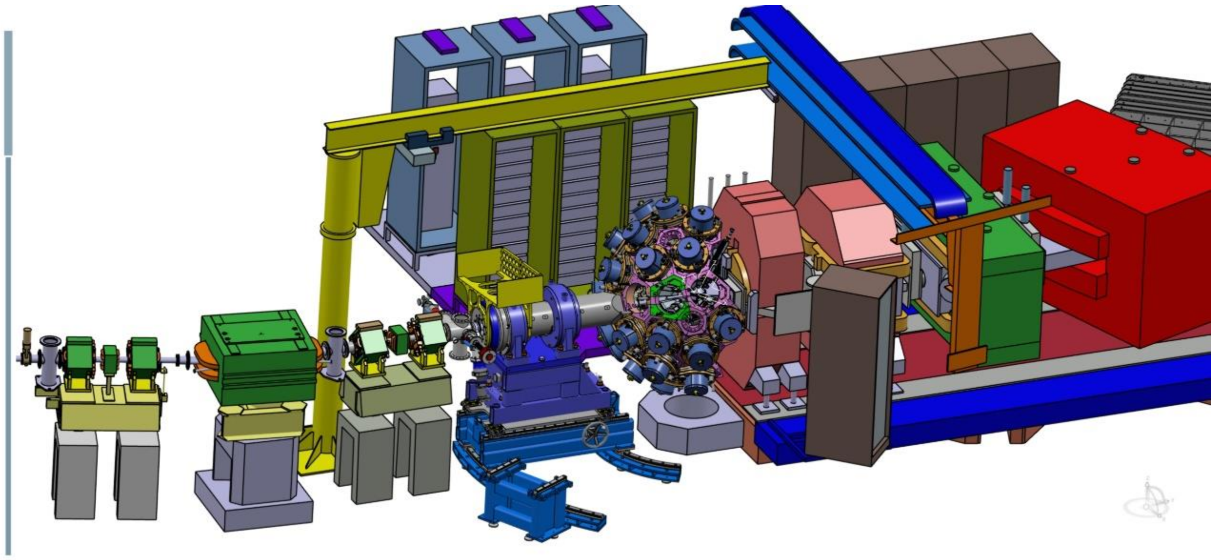


Fig. A7 The AGATA installation at GANIL for operation from 2029

During the second five-year period of the MoU, the second mechanical hemisphere must be produced (shaft, flange and supports) as well as the last groups of LVPS. The Autofill also needs to be extended to instrument the 3π system. Based on the production costs between 2021 and 2024, we estimate 0.530 M€ total investment.

Appendix 7: Detailed report from the Front-End Electronics WG

The working group leads the most challenging development task of the Phase-2 project. It consists in upgrading the DIGOPT12 digitiser from Phase 1 and migrating to copper data transfer line, designing and constructing the PACE board (for Pre-Processing and Communication system) including a new generation FPGA, in SoM (System on Modules) format, for signal processing, trigger and clock synchronization; and readout by the STARE board (Serial Transfer Acquisition Readout over Ethernet) that includes a second powerful FPGA, as well in SoM format. The clock and trigger distribution will be done by the new SMART protocol, replacing the GTS (Global Trigger and Synchronization). The development includes hardware, high speed – high frequency electronics, firmware on processing, trigger, synchronization and UDP readout at 10 GHz, slow control and monitoring. The block diagram is shown in Fig. A8.

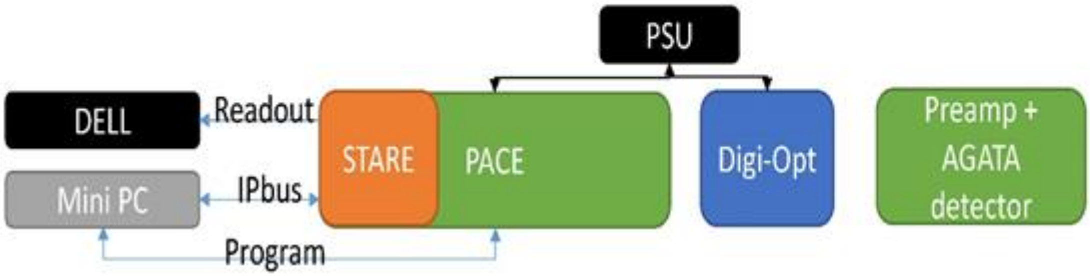


Fig. A8 The Phase-2 Electronics block diagram

<u>A7.1 Hardware design (PACE and STARE)</u>

The design phase is completed, production files (Gerber) are delivered and all the prototypes and pre-production boards were delivered and debugged. The mass production started in 2024. The work was shared between INFN Milan for the DIGIOPT12, IFIC Valencia for the PACE board, and IJClab Orsay for the STARE board. The firmware production was distributed between IPHC Strasbourg, IFIC Valencia, GANIL Caen and IJClab Orsay. The final integration was completed by IFIC Valencia. The software development was distributed between IJCLab Orsay, IP2i Lyon and IPHC Strasbourg. The first PACE board following the mass production start is shown in Fig. A9.

Fig. A9 The PACE Board

A complete Phase-2 electronics chain with fully functional pre-production PACE and STARE boards coupled to an AGATA detector is available at LNL for testing since late 2023, and used in remote control by the different laboratories involved (IFIC, IJCLAB, IPHC). This test chain is shown in Fig. A10.

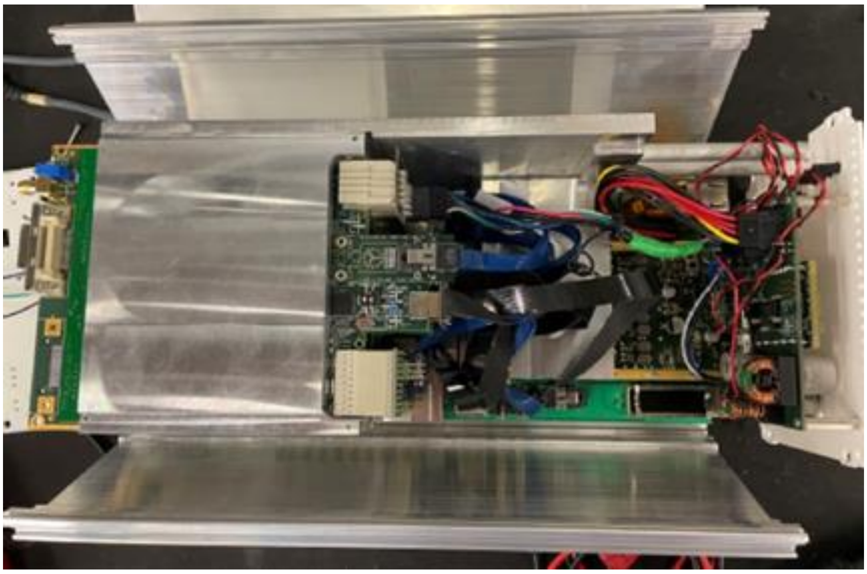


Fig. A10 The LNL test bench for Phase-2 electronics

The specifications are met and the mass production has started for all hardware parts in 2024: 5th of March 2024 for STARE and 16th of May for PACE.

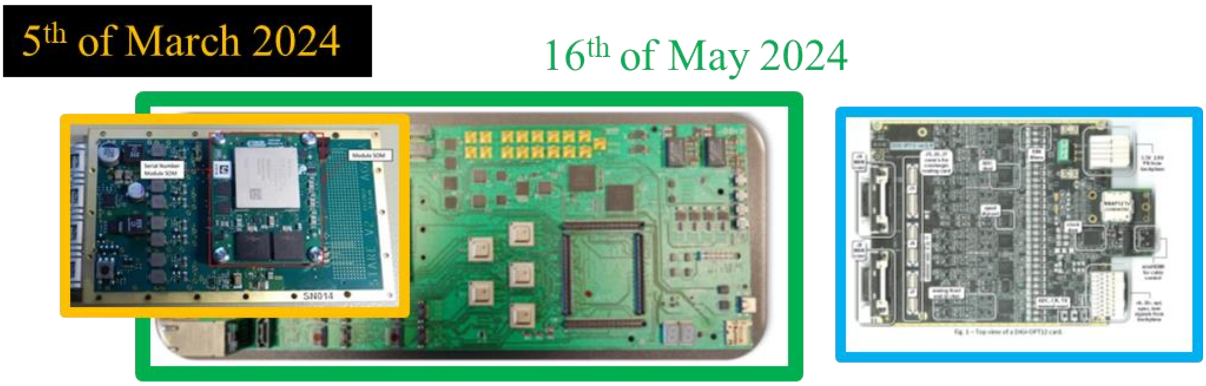


Fig. A11 The Phase-2 mass production milestones

The current status of the hardware production (as of March 27, 2025) is as follows:

- DIGIOPT12: 55 v3.6.1 core boards and 129 v3.6.1 segment boards delivered within 2023. Then a major update of the hardware was necessary, changing the ADC and several other components. This new version is called DIGIOPT12 v3.7. Presently 35 v3.7 core boards and 141 v3.7 segment boards have been delivered or are in production. The total number of DIGIOPT12 boards produced for the Phase-2 electronics is 90 core boards and 270 segment boards, allowing to instrument 90 channels.
- PACE: the production of 90 PACE motherboards is ongoing. Expected completion late March 2025, then the factory acceptance test and the AGATA acceptance test will be performed.

Expected delivery starting from April 2025. Electronic components have been purchased for the full 135 boards production to avoid obsolescence issues.

- STARE: the production of the STARE motherboards was completed late 2024. Presently the boards are being delivered as soon as the corresponding SoMs are available with a lead time of 3 to 4 weeks. Presently 38 complete STARE boards and 25 more are under acceptance tests. Mid 2025 we expect to have more than 100 STARE boards populated with the corresponding SoMs and fully working.
- Regarding the mechanics, enclosures are purchased for 66 units and cooling plates for 140 units are under production. Signal and Power Backplanes are available in quantities of 50 and 60 units respectively and towards mid 2025 we expect to reach 75 and 85, respectively. Power supply units will be produced starting late March 2025 to cover the first 90 units.

A7.2 The firmware

The firmware development has been and is still on the critical path of the project. Its development is in line with the hardware choice and design of the PACE board. Presently, all the different blocks (see below) have been delivered by the partners and integrated in the final firmware embedded in the PACE and STARE SoM FPGAs. The critical aspect to be completed is the integration at the firmware level in the existing system (GTS coupling, network with phase 1, flow, RUDP)

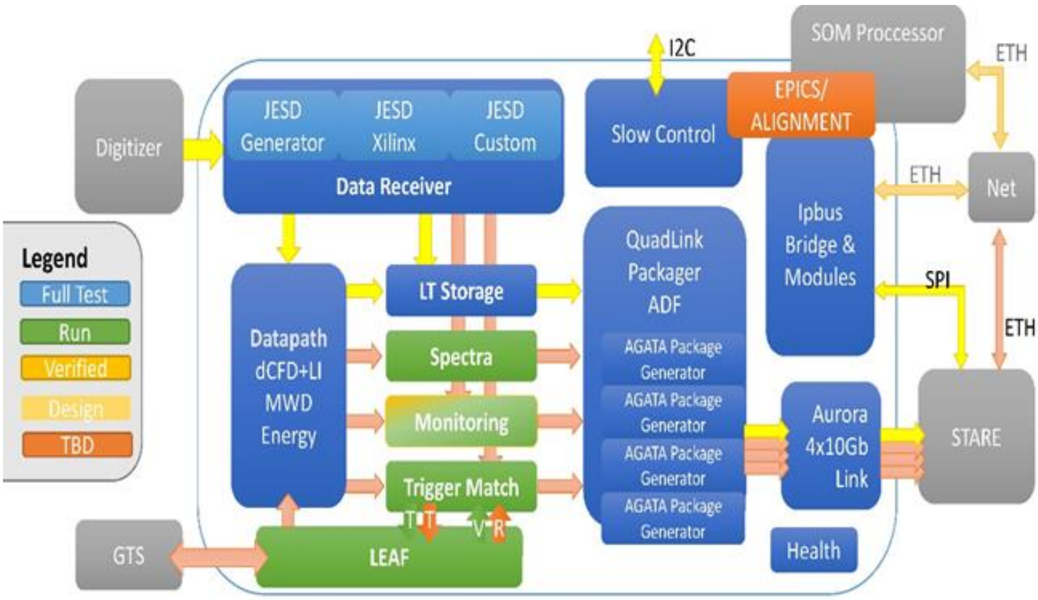


Fig. A12 The AGATA Phase-2 firmware block diagram

Unexpected problems, discussed in detail in the following, resulted in the mass production of the PACE board being delayed by 3 years. This delay impacted also the STARE mass production.

The design phase involving IPHC Strasbourg, IFIC Valencia, INFN Milan, STFC Daresbury and GANIL was on schedule until 2019. The COVID lockdown affected the development at a key moment, with no access to the laboratories and very limited travel. A misunderstanding then arose between the Strasbourg and Valencia teams, which slowed down progress. The restart of the LHC complicated the situation further as members of the Strasbourg team needed to prioritise their commitments to the CMS collaboration. Valencia regained the lead with the help of GANIL for missing parts and IPHC Strasbourg delivered the promised firmware blocks to the collaboration.

The last steps of the engineering, that is mainly maintenance work of the existing firmware, have been subcontracted to the ZeptoNova company in Belgium, where the main developer is working now after having left Valencia. The estimated time to complete the firmware development by ZeptoNova is ~31 working days distributed between February and possibly June 2025.

The proposed contract is established for maintenance of the firmware Phase 2 and has been therefore covered by the AGATA OC. The maintenance services are defined as the necessary maintenance of the existing firmware to integrate it into the existing AGATA system. The ASC approved the ZeptoNova contract.

A7.3 Schedule

The schedule of the tasks required for the integration of the Phase-2 electronics is:

1. Maintenance of the test setup: task completed in March 2025
2. Maintenance of the AGATA Phase-2 Trigger Firmware for GTS integration, SMART integration, Trigger system control, Trigger system architecture and Trigger Match IP block. Work will start mid April and is scheduled to be completed late April 2025 (Note that this is a critical step that will allow to start the integration at the front-end level)
3. Maintenance of the monitoring firmware and update of the control system to consider new versions of PACE SoM. Scheduled during April or May 2025
4. Update of the documentation, update of the programming platform and preparation of the firmware for future energy algorithms development. Scheduled for May and June 2025.

We expect to be able to start integration tests after April 2025 and the final integration (hardware and software) as well as in-beam tests at LNL will be scheduled in 2025 in collaboration with the local team.

The documentation is fully available.

The bottleneck of the front-end electronics development is related to the availability of human resources. It should be stressed that the development is in 90% complete and the mass production has started. The scenario for reducing costs in the Phase-2 project is to optimise the procurement of boards through coordinated purchases between the partners, and therefore a strong commitment from the ARRB, with a better multi-year visibility on the available CORE funds, would be a solution for saving on the purchase budget as opposed to spreading out the investment.

In the first five-year period of the MoU, the investment was lower than expected due to the delays in the development. For the second five-year period of the MoU, the objective is to achieve the final mass production by grouping the purchases. We estimate that 0.6 M€ will be necessary to cover all required elements of the front-end electronics for 135 capsules.

Appendix 8: Detailed report from the Data Processing WG

The data processing group has two main tasks:

1. To maintain at the highest level the online IT infrastructure, a dedicated server farm (currently 4 full racks) installed at the AGATA host laboratory.
2. To provide data acquisition software that enables processing the data from the lowest level (readout of the electronic cards) up to offline re-processing, last stage analysis and data management.

Since AGATA is a travelling array, for any new host laboratory or any new campaign it is required to build the interfaces with the local detectors/acquisition systems. It is also the responsibility of the group to anticipate, integrate and deploy any major evolutions due to new AGATA electronics, new processing algorithms or new computing/network hardware/software technology likely to improve the global workflow.

The Phase-2 objectives require to

a) Integrate the new electronics developed by the Front-End Electronics Group
    - The new readout is based on a standard Ethernet protocol (UDP) with expected data transfer capabilities up to 10Gb/s. In such conditions, the reliability of the data flow should be carefully checked through advanced monitoring.
    - Such a protocol removes the point-to-point constraint of the current electronics, allowing greater flexibility and opening a more efficient use of the available computing power thanks to mechanisms such as dynamic load balancing.

b) Provide solutions to run efficiently new algorithms from the PSA and tracking R&D group
    - Machine Learning approaches are under study and expected to improve significantly the performance of both PSA and tracking. Such algorithms likely require advanced computing resources such as GPU. Adding such computing nodes in the online workflow is a challenge to be anticipated.

c) Develop new global processing workflows including a), b) and able to handle up to 135/180 HPGe crystals.
    - Our online workflow manager (DCOD) has proved to be a solid foundation over more than ten years, but it is mandatory to enhance the system (dynamic load balancing, event dispatcher, soft trigger …)
    - More efficient, scalable, offline reprocessing environment should be provided
    - The complexity and amount of the data and metadata produced strongly increase with the number of crystals in the array, hence they should be managed more efficiently, also by promoting open data and open science approaches.

With the beginning of Phase 2, the group has been reorganised into 4 teams following the processing stages starting from the detector output: 1) “DAQ Infrastructure” maintains and upgrades the TIER0 infrastructure. 2) “Data processing” dedicated to online production. It includes in particular the interface with AGATA electronics and integration of the ancillary data. 3) “Online/offline Interoperability” to ensure continuity up to 4) “Reprocessing & Analysis”. This last team provides to the user the software needed to analyse AGATA data, organises data analysis schools and maintains the access to the data archived on TIER1. A member of the working group is identified as Data Manager of the collaboration. The reprocessing team is in very close contact with the users and the host laboratory. This activity became a major contribution in Phase 2 and is very successful thanks to the involvement of young researchers.

Regarding the main objectives of Phase 2, we provide a list of the milestones reached and **what remains to be done** to achieve them:

a) Complete the integration of the new electronics developed by the Front-End Electronics Group

The new data pipeline to be completed is represented in Fig. A13 with the beginning of the computer-based processing on the right-hand side.

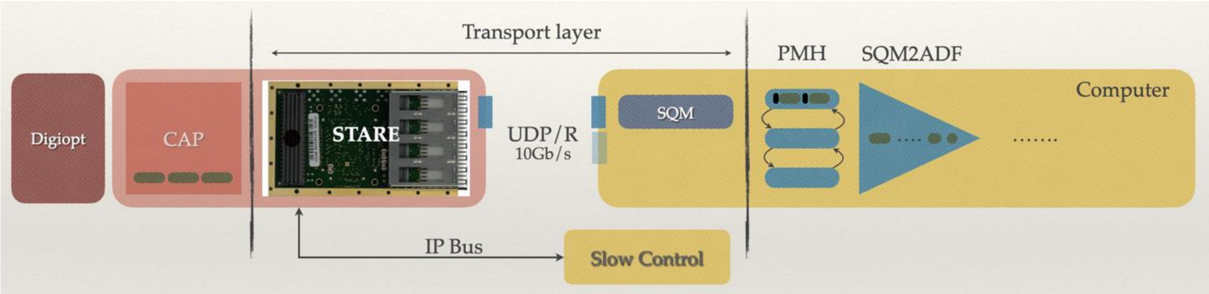


Fig. A13 The Phase-2 data pipeline

Various emulators have been developed and massively used to build and benchmark step-by-step the different elements of the data pipeline.

- The main new blocks (SQM collecting from UDP the events emitted by STARE, pushing them in memory [PMH], then read by a first processing node able to compress data) have been developed separately and demonstrated in thorough tests to handle up to 50kHz and more.
- The topology manager, a tool developed by the collaboration to ensure that the entire online workflow is consistent and well configured, has been extended to handle the new electronic boards
- The User Interface to control, interact with, and monitor the new electronic boards through the IP-Bus protocol is operational.
  - A complete overview is available on a web-based display
  - The interface has been partially tested on development electronic boards
- Data transfer capabilities between STARE and computers (with 10Gb/s network interface) have been extensively studied and so far, at least in the phase in which the v1 electronics is to be used with the v2, it seems possible to handle the data stream from 2 STARE (possibly 3) with a single computer.
- Using a computer-based emulator of the electronic board, a full data pipeline up to PSA has been benchmarked in the online DCOD environment showing that we can already increase by a factor 2-3 the actual PSA rate capabilities of AGATA.
- Equipment has been bought (switch / CPU nodes) to handle in the first step (mixed GGP and PACE electronics) up to 72 crystals equipped with PACE boards + 18 with GGP boards, amounting to a 2π system.
  - 6 switches [48x10Gb/s: 8x100Gb/s] (2 needed per 24 PACE) + 1 [32x100Gb/s] (to transfer data from detectors to the computer room) + 3 [1Gb/s RJ45] (for slow control)
  - 38 CPU nodes available with 10Gb/s interface

The remaining tasks consist in adjusting the data pipeline from the lowest processing level (digitiser) up to the highest one, i.e. from the local data pipeline up to PSA.

- The slow-control interface will be stress-tested in real conditions using in a first step one full board, and then several ones.
- The processing of real events, including PSA, will be validated (currently the correctness of the data formatting out of the board is scrutinised)

- The DAQ infrastructure [10Gb/s] to handle the new pipeline will be installed on site.
- The objective is to get a system operational, initially by combining the current and the new electronics, and then moving on to new electronics only.
- Data transfer with Network Interface Cards able to go up to 25, 40, and possibly 100Gb/s will be stress-tested to optimise the server farm up to 135 Ge crystals.

b) Provide solutions to run efficiently new algorithms from the PSA and tracking R&D group

Since no new PSA/tracking algorithms exist yet at a production level, in the preparation the group developed new solutions to handle heterogeneous material together with studies to try and optimise the current algorithms.

- Studies have been performed to measure the gain in running the current PSA using lower precision
  - A thesis has been published [CPU based] https://theses.hal.science/tel-04901698
  - This is particularly relevant also for GPU based architecture
- The data processing ecosystem has been enriched by adding micro services applications based on containerised applications.
  - We have demonstrated we are able to handle GPU nodes in a server farm running a DCOD environment thanks to efficiency memory inter-process communications (based on the open software *redis* solution)
  - It allows also to add a dynamic load balancing mechanism to run parallel PSA on CPU nodes. Using it, we have been able to process the current PSA at a rate up to 40 kHz.

c) Develop new global processing workflows including a), b) and able to handle up to 135/180 Ge crystals.

What has been done up to 2025

  - To improve monitoring, time series databases, in conjunction with Grafana-based tables, were systematically introduced for all experiments and all technical aspects of the running.
  - At LNL this solution has been implemented since the beginning of the campaign, and continuously enhanced, to oversee the filling of the detectors, to monitor the GGP electronic boards, to have a global view of the server farm (disk, CPU, RAM used) and also to check, though DCOD, that data are treated at expected rates in any branch of the workflow
  - Any new processing node in the workflow is developed to include such kind of monitoring at the deepest level
  - The developed Slow-Control interface makes use also of time series database to monitor, at demand, any useful parameter.
  - A system to collect quality spectra along the processing chain, called AGASPY, is being modernised to remove certain complex dependencies and redundancies, and to dynamically activate a spectrum on demand.

- More advanced data processing capabilities
  - A server farm (fully 10Gb/s) has been set up at Orsay for data-flow R&D purposes. It contains almost 10 nodes (including one GPU node) financed by IN2P3 and French ANR programs. New AGATA machines are added to the farm to be tested, configured and benchmarked before being sent to the TIER0 site.

- This server farm has already been used to stress-test several of the newly developed micro services (load balancing, parallel processing) added to our workflow manager.

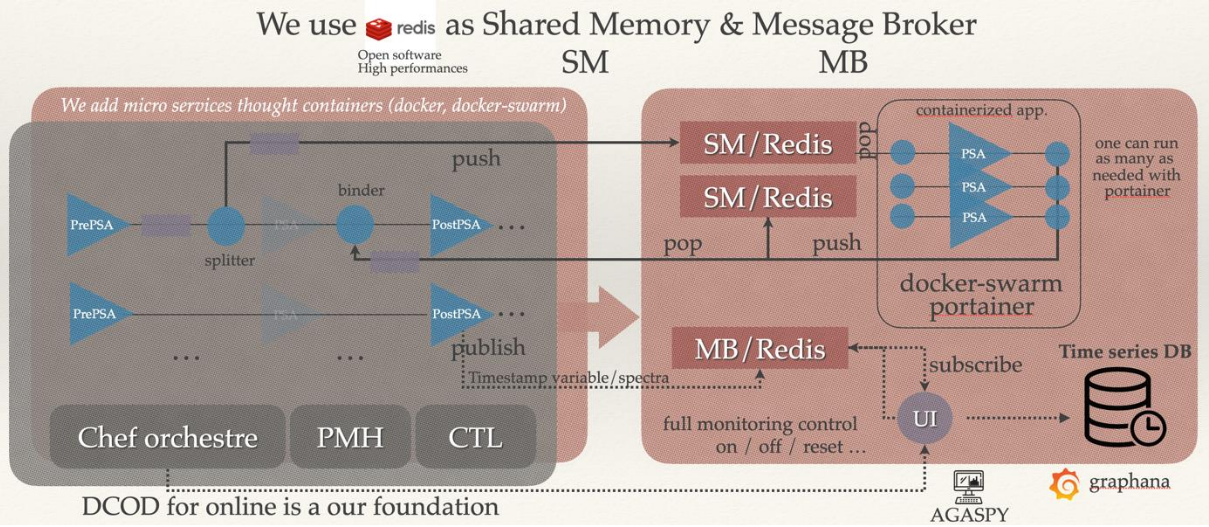


Fig. A14 The Phase-2 data workflow

- As already stated, within such environment emulated HPGe crystals engine (simulator), we already have been able to run the current PSA
  - Up to 40kHz for processing of one HPGe crystal
  - Up to 20kHz/crystal for processing of 6 HPGe crystals
- These new services allow also to build an efficient/scalable offline reprocessing tool
  - Docker on a single PC (tested), docker-swarm on a cluster (tested)
  - It could be extended to cloud-based processing using tool such as kubernetes
- A first version of a process to handle dynamically backpressure (signals dispatched by IP Bus to PACE boards if the RAM memory in a computer node is too full) has been developed

- Data management: toward open data and open science.
  - At the very beginning of Phase 2, reports have been produced to draw the path toward a better management of all the data produced online and possibly offline
    - See ATRIUM-525167-656565-656566 which include first preliminary DMP
    - The conclusions have been presented to the ACC
  - Since then, a FAIRification (for FAIR: Findability, Accessibility, Interoperability and Re-usability) process is going on.
    - The documentation of the various processing has been significantly enhanced, see for instance https://agata.pages.in2p3.fr/handbook/
    - Machine readable ascii files (xml, json, etc …) are systematically used for any new program developed
  - For each experiment, a new subdirectory has been added to the data set saved on the GRID, which contains various additional meta-data files.
  - A docker container has been produced to help users to access data on the GRID from their laboratory without a specific User Interface.
  - A new identification portal, based on INDIGO-IAM, hosted at IJCLab, is currently being configured to replace the current VOMS service.
  - The needs for the second part of Phase 2 in term of data storage and computing model requirements have been reported in (ATRIUM-902780).
  - Thus, the TIER0 data storage (CEPH-based) capacity as been increased to reach 500To.

- Continuous Integration and deployment processes are, thanks to advanced gitlab functionalities, deployed to ensure software robustness (see review paper EPJA)

In the next 5 years, the milestones are the following:

On the Orsay server test farm

- The monitoring will be extensively benchmarked to correct for weaknesses
  - It will be extended also to all processing nodes
- The processing of few tens of emulated crystals will be tested
  - At high/low rates, possibly including new PSA/Tracking
  - The data transfer through the UDP (RUDP) protocol should be mastered to avoid loss
- A new scalable reprocessing environment will be tested and validated
- Advanced data & metadata management tools (solutions such as ami/rucio) will be tested
- Software triggers are to be developed to allow PSA to be performed only on the most interesting events in order to speed up the global processing rates

In the host laboratories (LNL and then GANIL)

- The server farm will be modified to handle new v2 electronic boards
  - Initially coexisting with old v1 boards, then with only v2
- The new processing will be implemented up to the global level
  - A commissioning at high/low rates, possibly including new PSA/Tracking, is to be done

There is no particular threat regarding the software and data flow developments for Phase 2. The increase of local storage is anticipated and scheduled. Keeping the human resources to explore this new architecture at IP2I and IJCLab is crucial from 2026 onwards.

It is important to underline that the AGATA Data Processing working group collaborates closely with the host laboratory teams. The AGATA teams are involved in the preparatory phase of each campaign to ensure electronics, DAQ and analysis coupling. Such tasks are difficult to evaluate in advance since they depend on the properties of ancillaries used in the experimental campaigns that have various levels of complexity. As an illustration, the present scheme and the future one for the next GANIL campaign is presented in Fig. A15.

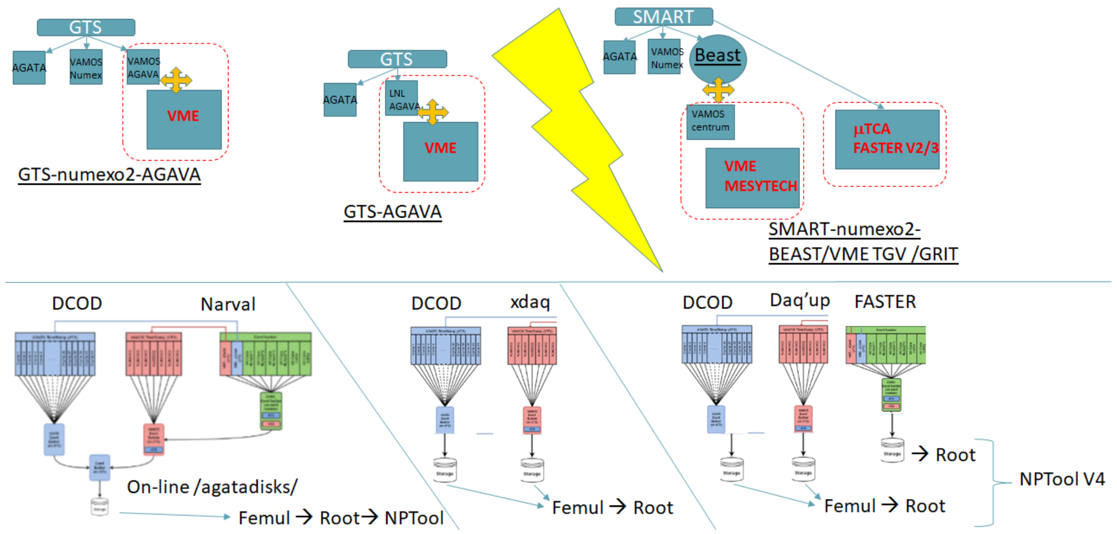


Fig. A15 The different architectures to couple AGATA with the infrastructure of the host laboratories

With the recent IN2P3 and GSI investment the TIER0 (/agatadisks/) will be close to 2Po, fulfilling the objectives of the project definition. The remaining investment depends mainly on the PSA nodes.

Thanks to the installation of the Orsay server test farm, we demonstrated that two STARE inputs at 8kHz each can be processed (Real Time with the current PSA algorithm) on a CPU-based architecture. For the 3π system, 70 x 1U servers (3 IT racks) would be necessary together with the required switches. We estimate the investment to be 500 k€ for the second five-year period of the MoU. This option of course may result in an infrastructure undersized if ultimately a more efficient solution, but heavier in terms of computing power, is to be used.
The collaboration continues to investigate the GPU option, anticipating a new PSA algorithm, but the development is not completed. The GPU-based architecture is more expensive but should enhanced the PSA rate capabilities by a factor ~×3 leading to more exotic channels achievable (lowest cross section). At the current cost of NVIDIA GPU, we estimate the investment to be 920 k€.

The budget estimated in the MoU for Data Acquisition covers the two options.

Appendix 9: Detailed report from the PSA and Tracking R&D WG

The working group has in charge the R&D on the PSA and tracking algorithms. The PSA activities rely on the joint effort of scanning of the detectors, improving signal simulation packages and, more recently, implementing machine-learning approaches. Several scanning tables are running or under commissioning at Strasbourg, Liverpool, Salamanca and GSI. Particular care is taken to convert the data to the standard AGATA format and to make the results of the measurements available to all collaboration members to enable further developments. The groups working with Strasbourg and Liverpool tables are the most active, using them for comparison of various scanning approaches, as well as for dedicated measurements such as detector tomography, PSA experimental basis or neutron damage effect studies. Scans are very time consuming and highly rely on the available human resources in the different laboratories. However, these scanning activities are the only way to improve in a controlled way the response function of AGATA via the PSA.

A9.1 Report from IPHC:

The scanning activities at IPHC were particularly intense in the last year. The analysis of the S001 capsule was completed and published. Comprehensive scan data was collected to investigate the localised charged trapping, including temperature dependence of the trapping. The highlight of the last year is the full scan of the A005 capsule after repair. This scan was organised jointly with the PSA and data analysis teams. An experimental 3D pulse-shape basis was obtained using Machine Learning approaches. This is the very first asymmetric capsule to be fully 3D scanned for tomography and PSA R&D. Data for comparison with Liverpool results have been collected. Additional scans are being performed at the request of the PSA group to look at dead layers due to segmentation and passivated regions. These are being performed in both the horizontal and vertical orientation. Tomographic scans of the full detector at 30-degree steps have taken 12 weeks. Artifacts have been observed on both the tomography and the 3D scan towards the rear of the detector. The 3D neural network experimental PSA basis was compared to the two simulation packages and experimental data recorded at GANIL. The preliminary analysis shows encouraging results which are likely to improve the PSA in AGATA and hence the overall sensitivity of the spectrometer. As next steps, asymmetric B and C capsules as well as a second A-type capsule should be scanned to evaluate the universality of the deduced NN basis to all A, B or C-type capsules of AGATA. The detector laboratory will be available and operational up to the end of the Phase 2 of the MoU for scanning activities.

A9.2 Report from Liverpool:

The Liverpool laboratory has focused on the PSA response function defect for neutron damaged detectors. The analysis of the scan data from A009 (the neutron damaged detector that was subsequently annealed) was performed. A publication on the singles scan findings is in preparation. The Liverpool laboratory has setup a new facility. The move into new scanning lab has taken place. The old scanning table and associated apparatus has been fully setup and commissioned in the new lab. The new scanning table is in position and ready. An AGATA test cryostat has been test mounted in the frame. A new 4 GBq ^{137}Cs source has been ordered and delivered. A side scan of A601 was performed on the old scanning table. A full characterisation will follow on both the old and new tables. A visit to the University of Birmingham neutron facility took place in February 2024. A plan for measurements involving controlled amount of neutron damage is now being finalised. Neutron irradiation tests are planned. The test cryostat was refurbished.

A9.3 Report from Salamanca:

The Salamanca team have collected singles scan data from the A005 detector. The first scan was a 1 cm x 1 cm with an ^{241}Am source to get a view of the segments using a 3 mm collimator. A second scan provided better information about the crystal position using a 1 mm collimator. Some issues with reliability (LN2, electronics) and broken core FET were encountered. The A005 crystal was sent back to Mirion and following a repair, it was scanned in Strasbourg. Meanwhile, another AGATA detector (B003) has been transported to Salamanca to setup a new scanning table. The Salamanca data acquisition system is currently experiencing problems, with no data being written. Operation of this scanning table is a priority because it is equipped with the AGATA electronics chain providing a more reliable comparison with in-beam data.

A9.4 Report from GSI

The upgrade of new personnel is continuing. The Febex based digitization and data acquisition system has been enlarged and was employed for the successful scanning of the A005 AGATA crystal. Employing the GSI gamma scanner a complete data set with > 10^5 events per segment has been obtained and is currently under analysis. Since the crystal showed instabilities seen also earlier, it was decided to send it to Mirion for vacuum check-up. When it is back, it is planned to perform another scanner run, emphasising on studying possibilities to improve the time resolution of AGATA. For that, the time reference of the scanner will be optimised. Furthermore, it will be tried to perform yet another run, illuminating in particular the backside of the crystal.

A9.5 Summary of the scanning tables.

Scanning tables are fundamental devices to improve our understanding of the PSA. The information obtained from the detector scans provides paths towards possible improvements of the PSA. The Strasbourg scanning table will be used to continue the tomography and production of experimental pulse basis. Three new measurements are foreseen between 2026 and 2030: a B- and C-type scan similar to the A005 measurement, and a second A-type capsule to be compared to A005 to evaluate the reproducibility between detectors of a given type. This strategy coupled to the development of a ML approach is likely to induce a breakthrough in the PSA of AGATA. At Liverpool, the effect of the neutron damage on the PSA is a priority. These measurements are mandatory to anticipate the "neutron-aging" of the array. The results from the Salamanca scanning table will provide a comparison with other scanning methods and disentangle the effect of the front-end electronics in the PSA response. The activities at the GSI scanning table will focus on the comparison of the scanning methods using the A005 capsule.

Other longer-term initiatives can be considered, such as a scan of the surface treatment (coating) newly developed at the University of Padova, or an alternative segmentation pattern as proposed in the IMATRA initiatives. It is fundamental that these long-term perspectives are supported by the partners by keeping the human resources available for these activities at a constant level.

A9.6 R&D on the PSA

Beyond the scanning activity, the working group is in charge of the development of the PSA code it-self. The code is maintained and available on the git repository of the AGAPRO package.

Close collaboration with the GRETA project in the United States is part of the team's activities. This collaboration is very fruitful, with exchanges of codes. Both PSA approaches (AGATA and GRETINA) are compared by applying them to the same experimental data. In the first part of Phase 2, the team worked on developing interfaces between the two projects.

One of the main features and priorities of both projects is the ability to disentangle events involving two interactions in the same segment. The team has concentrated its efforts on this issue over the last few years.

The low-level deconvolution of the SIMPLEX and GRETA algorithms has been fully implemented in the AGATA package and is operational. All functions have been refactored into a state where they are reasonably clear to interpret. The ^{98}Zr in-beam benchmark data set from GANIL and ^{22}Na datasets both produce their expected results from the full AGAPRO pipeline. Preliminary results are very promising with an enhancement by ~40% of the peaks area after Orsay Forward Tracking (OFT) in the ^{98}Zr reference data using the new two-interactions treatment. This effort will be continued in the next years.

Aiming to improve the processing rate and overall accuracy of the PSA, two new methods have been developed for a more intelligent processing of the signals. A new machine-learning assisted preprocessing filter has been designed to directly infer how likely an experimental signal is to be comprised of multiple interactions. This will be useful in short-circuiting the two-interaction PSA if requested. Secondly, a crystal-wide PSA postprocessing filter has been designed that makes possible a global fit of the experimental data, which should eliminate any possible complications induced by windowing and recursive subtraction.

In parallel, a new simulation code for PSA have been developed to calculate pulse basis by varying more parameters in the description of the crystals (see).

Other investigations on the uncertainties in the PSA were conducted using the bootstrapping method (see) and their results were used in R&D on the tracking algorithm described in the following section.

Finally, the York team has led the development of the self-calibration technique - a novel method to generate a reliable signal basis utilising the array's tracking properties. Preliminary results of applying this method show promise in generating a high-fidelity signal basis with excellent position reconstruction performance and the added benefit of being generated in situ, with the detectors on the array. This could enable, for example, the generation of a basis before and after an in-beam campaign to capture small variations in the signal shape resulting from, e.g., neutron damage. The performance of the method improves drastically with increasing number of detectors in the array. A dedicated experiment to test the performance of PSA with the self-calibration basis using in-beam AGATA data with Doppler corrections was performed in December 2024 (experiment 24.01, see Appendix 2).

A9.7 R&D on tracking

The R&D on the tracking algorithm is led by the Orsay team. The Orsay Forward Tracking code is the standard AGATA tracking algorithm. A study of the behaviour of tracking when uncertainties dependent on position and energy are used to estimate the error in Compton scattered energies (obtained from positions and compared with those obtained from energy deposition in each interaction given by PSA) has been carried out. The results show that including the position uncertainties from the two available uncertainty databases yields no improvement on tracking performance. The reason is probably the fidelity of the databases, which reflect more the uncertainties in the PSA than the overall position sensitivities of the detectors, electronics and the PSA.

It is clear that the AI technology could bring a breakthrough in the sensitivity of AGATA by improving the quality of the PSA, the efficiency of the tracking and the running time of the data treatment. Promising preliminary results on tracking were obtained using Graph Neural Networks to evaluate the connectivity between energy deposits [M. Andersson, T. Back, NIM A 1048 (2023) 168000].

In the first part of the Phase-2 project, several machine-learning workshops were organised (within the OASIS ANR project): in 2021 https://indico.in2p3.fr/event/25613/ in 2023 https://indico.in2p3.fr/event/28625/ and 2024 https://indico.in2p3.fr/event/32733/.

Appendix 10:
Detailed report from the Performance and Simulation WG

The working group evaluates the performance of the array including notably the commissioning runs, but also in-beam data, and post-processing. It uses source and in-beam data to develop and validate the AGATA simulation code.

The working group maintains the simulation package following the GEANT4 releases and continues to develop the code by improving event generators and adding new ancillary detectors. The AGATA code is currently compatible with GEANT4 releases up to 4.10.07 and soon will be compatible with GEANT4.11.1.2. An AGATA simulation hands-on workshop was organised in January 2021 and a new one is being discussed for 2025.

For the AGATA campaign at LNL, many ancillary detectors or mechanical structures have been added to the simulation git repository (https://gitlab.com/malabi-agata/agata). This includes PRISMA, OSCAR, GALTRACE, MUGAST and the CTADIR cryogenic target.

In the view of the FAIR campaign beyond 2030, a new event generator interface with the GSI MOCADI ion beam simulation package is now included, and the AGATA geometry together with its sensitive volumes have been implemented into the FAIRROOT simulation framework.

Following the results of A-type crystal tomography measurements with the IPHC scanning table and the measured efficiency and performance, improvements on the characterisation of the crystal geometry or sensitivity are being implemented and will continue in the next years, with the tomography of the type B and C crystals.

AGATA represents the state-of-art detector for gamma-ray spectroscopy. In order to ensure that the energy resolution, detection efficiency and peak-to-total ratio expected after PSA and tracking are indeed achieved, dedicated in-beam runs with AGATA are needed. Calibration source runs should always be carried out at least prior to a new campaign and consistency of the results should be compared with both simulations and previous measurements obtained at the same or other facilities. The AGATA data preparation includes a detailed treatment of several experimental effects such as crosstalk, dead-segment corrections, neutron damage, etc.

A10.1 FWHM resolutions

During experiments, the HPGe detectors are exposed to a continuous flux of fast neutrons generated in deep-inelastic collisions, fission and fusion-evaporation reactions. Fast neutrons are well known to produce specific lattice defects in germanium crystals, which act as efficient hole traps. This leads to a reduction in the charge collection efficiency of the detectors observable by low energy tailing on the energy line shape worsening the energy resolution.

Trapping effects are corrected using the position information given by the PSA and the detector specific trapping sensitivity (based on collection efficiencies for electrons and holes). The effects of the neutron damage and its correction based on these principles are illustrated in Fig. A16 for the sum of segments signal and the core contact.

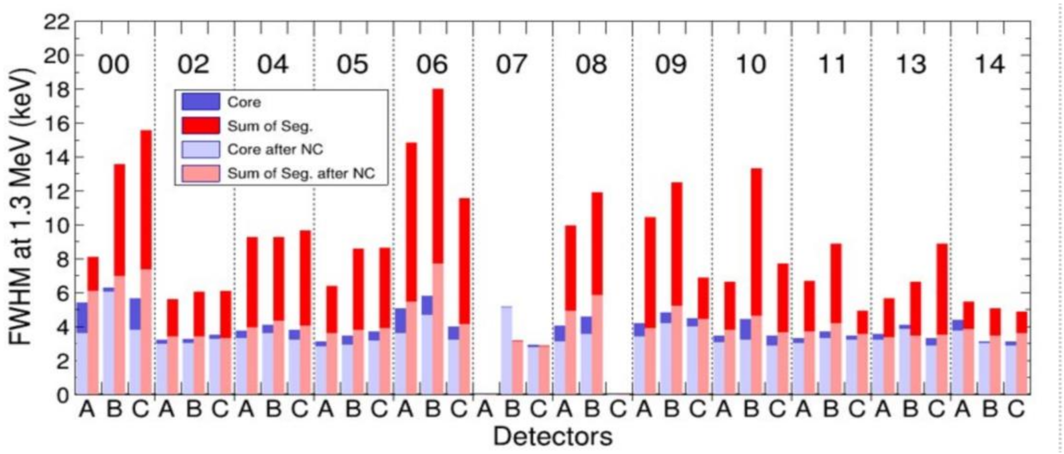


Fig. A16: FWHM resolution at 1.3 MeV for 35 detectors of AGATA measured at LNL (September 2023). Note that detectors with the worst energy resolution have been since then annealed leading to the full recovery of their performance, see Fig. A5.

Following each experiment, the working group provides recommendations guiding the choice of detectors to be replaced in order to maintain optimal performance of the array. Thanks to information on detector resolution collected by the group, it is also possible to observe and track in the long term to what extent the resolution is recovered and if annealing cycles could have an effect on the efficiency of each crystal.

A10.2 Efficiency up to 2.5 MeV

A series of measurements were performed with ^{60}Co, ^{152}Eu and ^{226}Ra calibration sources placed at the target position to check the consistency of the results in comparison with both simulations and previous measurements obtained at other host laboratories. The efficiency was evaluated through the following modes of analysis:

- Core: sum of the individual energy histograms for the core contacts
- Tracked: reconstructed energy by the tracking algorithm which uses the information given by the Pulse Shape Analysis (PSA).
- Addback: sum of all hits in the neighbouring crystals in an event.

In this work, the OFT tracking algorithm was employed. The OFT parameters were optimised for the 1.3 MeV peak, being σ_θ=1.5, P_{track}=0.01 and Cl_{AngRed}=3.

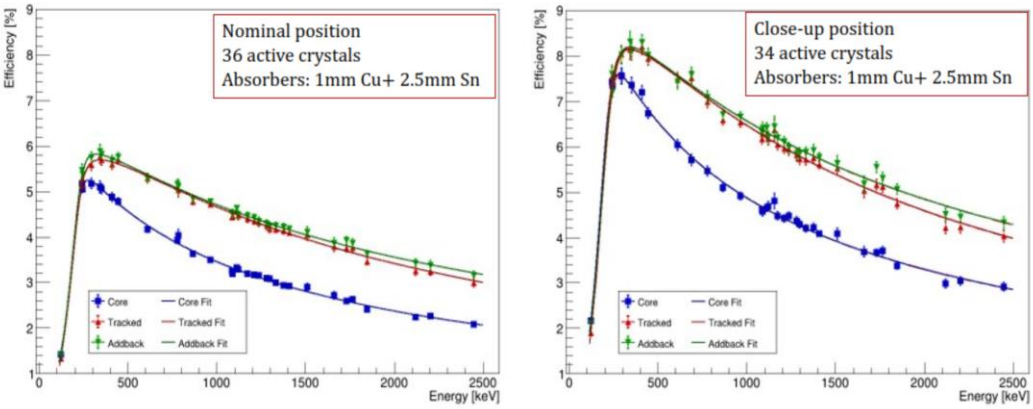


Fig. A17: Efficiency curves for 36 AGATA detectors with absorbers, placed at nominal position (23.5 cm, left panel) and at close-up position (18cm, right panel). The OFT parameters used for the tracking analysis are σ_θ=1.5, P_{track}=0.01 and Cl_{AngRed}=3.

The absolute photo-peak efficiency for the whole AGATA array (September 2023), composed of 36 operational detectors, is presented in Fig. A17 using both configurations of AGATA position. The efficiency curves have been obtained from the spectra collected with ^{152}Eu and ^{226}Ra sources normalised to the absolute efficiency determined at 1.3 MeV. The general drop at energies below 300 keV is due to the presence of absorbers in front of AGATA detectors. The data points resulting from tracking and addback agree within the errors. The efficiencies obtained with tracking and addback are comparable, while gain obtained from tracking in clearly revealed in the P/T ratio: 33% with tracking and 24% with addback. It should be noticed that the optimization of the treatment of the in-beam data and of the tracking should be done for each experiment individually.

A10.3 Efficiency up to 5 MeV

In order to check the feasibility of future experiments with AGATA at LNL, the full characterisation of the AGATA spectrometer is required, especially at high energies where it cannot be obtained with standard radioactive sources. The response of the AGATA array in the range between 2 MeV and 5 MeV is almost an unexplored territory and the extrapolation of the efficiency curve up to high energies can lead to uncertainties of 20% or more. At the same time, simulations need to be validated against experimental data and the tracking algorithms must be accurately calibrated above 3 MeV. A study of the decay radiation of ^{66}Ga, produced in the ^{66}Zn(p,n) reaction, was therefore performed in 2024 to assess the AGATA performance up to 5 MeV. In the left part of Fig. A18 the gamma-ray spectrum of the decay radiation of ^{66}Ga is depicted. The decay transitions are observed up to 4806 keV allowing us to evaluate, for the first time, the performance of the AGATA tracking array in the range between 2 MeV and 5 MeV. Further analysis is on-going to benchmark the absolute efficiency above 3 MeV and the figure of merit of the tracking.

$^{66}Zn(p,n)^{66}Ga$ reaction:

Energy [keV]	Intensity [%]	Rel. uncertainty [%]
833.53	5.90	5.08
1039.22	37.00	5.41
1333.11	1.17	5.13
1918.33	1.99	5.53
2189.62	5.30	5.66
2422.53	1.88	5.32
2751.84	22.70	5.29
3228.80	1.61	5.30
3380.85	1.47	5.44
3422.04	0.86	5.81
3791.00	1.09	5.50
4085.85	1.27	5.51
4295.19	3.81	5.51
4461.20	0.84	5.95
4806.01	1.86	5.38

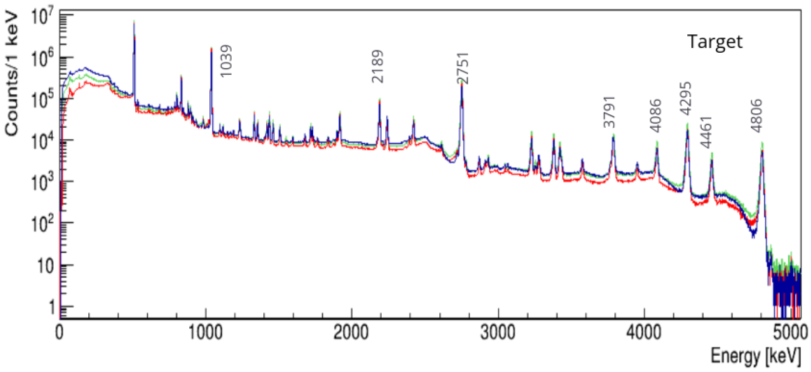


Fig. A18: Left, γ rays with intensity >0.8 % produced in the $^{66}Zn(p,n)$ reaction (Data taken from NNDC database). Right: Spectrum of the decay radiation in ^{66}Ga measured in this experiment.

A10.4 High-γ-Multiplicity Experiments

The team also supported the source and in-beam commissioning at the earliest stage of the LNL campaign and has recently been granted beam time in summer 2025 to benchmark the performance of 1π AGATA array with high-γ-multiplicity (<30) reactions.

This experiment will address the question: what is the optimal configuration for AGATA when measuring high-multiplicity events? The first phase will test AGATA in standalone mode, producing ^{158}Er through the $^{130}Te(^{32}S, 4n)$ reaction (E_{beam} = 140 MeV). ^{158}Er is a classic high-spin case study, featuring very long rotational bands extending to the ultrahigh-spin region, presenting an ideal candidate for stress-testing AGATA's front-end electronics and determining the current experimental limits for event rates. As ^{158}Er has been previously studied with GRETA, GAMMASPHERE, EUROBALL, and AGATA (at GANIL), this experiment provides a unique opportunity to compare AGATA's performance across its development stages and with other state-of-the-art systems. The second phase will integrate the EUCLIDES detector to study ^{155}Dy, produced via the $^{130}Te(^{32}S, α3n)$ reaction. This nucleus also exhibits long rotational bands, and presents an ideal opportunity to leverage EUCLIDES' superior channel selection capabilities and its effectiveness as an ancillary trigger. This configuration aims to achieve exceptionally clean γ-ray spectra while fielding a realistic high-spin experimental scenario.