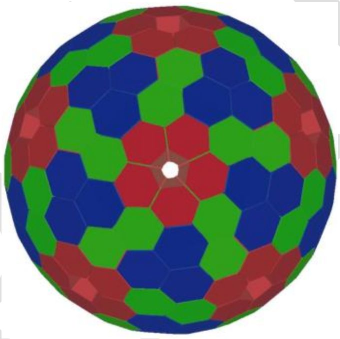
Agata/ProDef/April19/Draft09

AGATA

Advanced Gamma Tracking Array

PROJECT Definition
Phase 2 (2021-2030)



Edited by A. Gadea, G. Duchêne, A. Boston, E. Clement, H. Hess, A. Korichi, J. Nyberg, B.Million, P. Reiter, F.Recchia
Input provided by the AGATA Management Board and AGATA Teams:
(List incomplete)
Ch. Binnin, L. Charles, J. Collado, L. Gibelin, V. Gonzalez, N. Karkour, X. Lafay, I. Lazarus, D. Linget, A. Pullia, G. Vinther-Jorgensen (Hardware&Firmaware), M. Kogimtzis (Monitoring), G. Wittwer (SMART), etc…
N. Dosme, X. Grave, J. Jacob, E. Legay, G. Lallaire, P. Le Jeannic (DAQ Hardware/Software and Slow control & FEE monitoring), A. Lopez-Martens, O. Stézowski (Data analysis & Tracking), F. Crespi, J. Dudouet (Data distribution & re-processing).
M. Labiche (Simulations), J. Ljungvall (Performance), Ph. John (Commissioning).
L. Harkness-Brennan, F. Holloway (PSA), J. Simpson, B. De Canditiis, B. Quintana (Characterization), etc…
R. Menegazzo, A. Lotodé, T. Joannem (Infrastructures), A. Grant, I. Burrows (Mechanics), J. Valiente-Dobon (Complementary detectors).

Overview / Introduction to the AGATA Project and to the Phase 2 of the Project

The AGATA array [1], is the European forefront instrument based on semiconductor Germanium detectors, for high-resolution γ-ray spectroscopy. It is to be used in the nuclear research facilities operating presently in Europe but especially important for the experimental conditions at the future facilities for intense radioactive and high-intensity stable ions.

The European experimental γ-ray spectroscopy community has a long-standing tradition of coordinated efforts to build large scale high-energy resolution arrays. Since the early nineties, it is joining forces to build instruments with the highest possible sensitivity, e.g. the escape-suppressed spectrometer EUROBALL (1995-2004). The escape-suppression technique provides excellent peak-to-total (signal to background) ratios but limits the solid angle covered by the Ge detectors, thus limiting the sensitivity of the arrays.

AGATA is the result of the early European Commission financed initiative, the TMR network 'Development of γ-ray tracking detectors' [2], with the participation of most of the present AGATA partner countries. Between 1996 and 2001 it encouraged the development of the highly segmented position sensitive Germanium detector technology.

The inception of the Ge position sensitive detectors technology has opened the possibility to build arrays of detectors based on the γ-ray tracking concept, providing an unprecedented level of sensitivity and efficiency. Only two arrays with such technology are being built in the world, the European implementation of the tracking array is realized in the AGATA project. The second one, as well under construction at U.S., is the GRETA array [3]

AGATA is being built in a collaborative effort of more than 40 institutes in 12 countries. The conceptual design of AGATA foresees a 4π array with 60 triple clusters containing 180 Ge encapsulated detectors [4]. Nevertheless, smaller sub arrays of AGATA have been implemented, first as a prove of concept for a tracking array at INFN-LNL [5] and later to prove the potential of AGATA in different experimental conditions as well as to profit from the scientific possibilities, as limited as they could be, provided by the early AGATA implementations.

Since 2012 AGATA sub-arrays have been installed at the FAIR/NUSTAR-precursor PRESPEC set-up, placed at the focal plane of the FRS Fragment Separator in GSI, where experiments with in-flight highly relativistic exotic beams were performed, and at GANIL and SPIRAL where experiments with high-intensity stable beams and reaccelerated ISOL radioactive beams will be performed till 2020.

The present document describes how the collaboration intends to progress on the construction of AGATA till the full completion, as recommended in the NuPECC Long Range Plan 2017" document.

The guidelines for the construction of AGATA 4π are:

- Sustainable growth of the AGATA subsystems from a configuration of 60 to the one of 180 Detectors.
- Improving mobility and compatibility for the Hosting labs: FAIR/NUSTAR, GANIL/SPIRAL, LNL/SPES, HIE-ISOLDE, JYFL
- Achieving full Tracking Performance and optimizing the Position sensitivity.
- Improving performance of subsystems: Detectors, FEBEE, DAQ, Infrastructure.

The first step on this new phase of AGATA will be the upgrade of the subsystems for the 60 detectors already existing. This is necessary for some of the subsystems because parts belong to the early AGATA Demonstrator Phase

AGATA Phase 2 Configuration and Performance Figures.

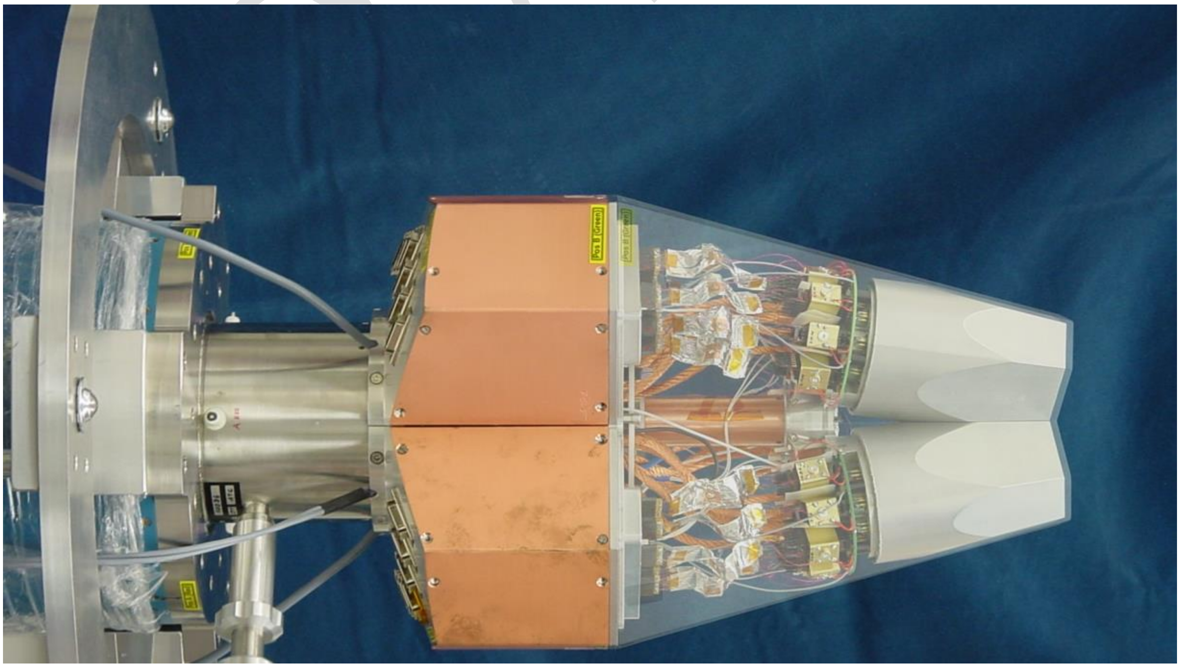
The AGATA collaboration will not prepare a Conceptual Design Report and a TDR for the new Phase. The documents we are preparing are the “White book” with the physics goals and the “Project Definition” with the information on how we plan to build AGATA from 60 to 180 detectors and costs and efforts.

In this chapter we will include all performance information from simulations and else, needed to justify technically in terms of performance the construction of an array of 180 detectors.

Detector Module Subsystem

Introduction

The AGATA Triple Cluster (ATC) detector consists of three asymmetric, 36-fold segmented, hexagonal shaped, encapsulated tapered high-purity germanium (HPGe) detectors. The cluster detector comprises 111 high resolution spectroscopy channels from the core contacts and the 36 segments of each crystal. Three capsules are operated in one vacuum cryostat and they are cooled by a liquid nitrogen Dewar. For all 111 energy signals, cold input stages of the pre-amplifiers (FET with their feedback circuits) are used for lowest noise contribution and highest bandwidth. Although the detectors are operated at liquid nitrogen temperature, the cold part of the electronics has a separate cooling to ensure a minimal electronic noise contribution of the first input stages. The cold input stages, consisting of feedback and drain for each signal, are connected separately by feedthroughs into the warm part of the cryostat, i.e. not cryogenically cooled part, where they are connected to the warm stages of the pre-amplifiers. To monitor the temperature and vacuum properties, two PT100 resistive sensors are mounted inside the cryostat, one close to the germanium capsule and one close to the Dewar. Additionally, information on the filling level and consumption of liquid nitrogen is monitored. Therefore, a capacitance measurement is performed which is based on a metallic cylindrical tube inside the Dewar and the inner wall of the cryostat. The fill level dependent capacitance is converted by a C/V-transducer into a DC voltage signal which permits a direct monitoring of the nitrogen level inside the Dewar.



This AGATA triple clusters (ATC) require a major part of the capital investment within the AGATA project. The ATCs comprise mainly the investment for the germanium capsules and the cryostats. Additionally, expenses are caused by the operational costs, repairs and maintenance.

The complexity of the ATCs require a seamless collaboration between the AGATA detector-group and all other AGATA working groups within the project. This is crucial to achieve the best reachable performance of the spectrometer.

Status February 2019

The situation of the encapsulated HPGe detectors at the end of 2018 is summarized in the following table. In total, 3 symmetric capsules and 47 asymmetric capsules were delivered. Furthermore, the delivery of one detector (A016) ordered by Finland is scheduled for July 2019. The order for 3 more new detectors is expected to be placed within this year. With the delivery of A016, sixteen sets of detectors, A-type, B-Type and C-type, are property of the institutions of the AGATA collaboration.

	Owner		Owner		Owner
A001	GANIL	**B001**	INFN Padova	**C001**	INFN Padova
A002	Italy	**B002**	GANIL	**C002**	GANIL
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 Legnaro	**B007**	IKP Cologne	**C007**	IKP Cologne
A008	IKP Cologne	**B008**	IKP Cologne	**C008**	Liverpool
A009	Liverpool	**B009**	Liverpool	**C009**	CEA Saclay
A010	INFN Milano	**B010**	INFN Milano	**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	**C014**	INFN Milano
A015	IN2P3	**B015**	TU Darmstadt	**C015**	TU Darmstadt
A016	Finland	**B016**	IKP Cologne	**C016**	IKP Cologne

For the physics campaign starting in spring 2019, 44 detectors will be mounted in fourteen AGATA Triple Clusters and one AGATA Double Cluster. An overview of the cryostats and detectors is given below:

Triple Cryostat	Detector	Detector	Detector	Triple Cryostat	Detector	Detector	Detector
ATC01	**A012**	**B001**	**C004**	ATC08	**A009**	**B005**	**C008**
ATC02	**A003**	**B003**	**C005**	ATC09	**A004**	**B008**	**C002**
ATC03	**A002**	**B015**	**C013**	ATC10	**A010**	**B012**	**C003**
ATC04	**A007**	**B007**	**C007**	ATC11	**A011**	**B006**	**C012**
ATC05	**A008**	**B002**	**C009**	ATC12	**A013**	**B014**	**C015**
ATC06	**A001**	**B004**	**C010**	ATC13	**A014**	**B016**	**C016**
ATC07	**A006**	**B013**	**C006**	ATC14	**A005**	**B010**	**C013**
ADC03	**-**	**B011**	**C011**				

Construction

The main task of the detector group will be the constant increase of the number of the AGATA Triple Cryostats in order to reach the maximum efficiency for the experimental campaigns. Therefore, the modular design of the ATC, the basic detector configuration and the proven cryostat technology will be employed also for the future stage of extension. A high reliability and low failure rate of the ATCs is mandatory and reflected in low maintenance effort for the spectrometer. Future developments focus on these aspects and new technical solutions are part of selected research and development projects of the detector-working group.

Cryostat:

The AGATA cryostats will be manufactured in the next phase with the existing modular conception. To improve the reliability of the cryostats, modifications are foreseen to be implemented in the new ordered cryostats.

For the 222 signal cables and approx. 30 grounding connections, a new cryostat was developed which is compatible with the existing feedthroughs. These feedthroughs consist of gold-plated contact pins in insulators of aluminium-oxide ceramic. 18 gold-plated pins are sintered in one connector with a Cu-Ag-alloy and seven connectors are integrated by electron welding in one titanium-housing which together produces a feedthrough for the cabling of one germanium detector. These new feedthroughs are decreasing the vulnerability of vacuum breakdowns after an accidental warm up drastically for the whole system. In total, twelve out of 13 existing Triple Cryostats, are meanwhile upgraded with these new feedthroughs.

The vacuum quality, the pressure and its composition will be improved by an efficient and powerful vacuum getter material. Up to now the getter material was integrated in the Dewar and had to be annealed with the whole cryostat. This procedure is time consuming and the material used in the cryostats is exposed to thermal stress. To cope with this problems, in the new triple cryostats the getter will be mounted in a flexible housing on the cooling finger. This box can be easily dismounted and annealed outside the cryostat what results in less maintenance time. First new getter housings are already installed within three ATCs (ATC10, ATC13 and ATC14).

In future, all existing cryostats will be manufactured with the getter material integrated in the Dewar. To equip the older ATCs with new getter boxes, considerable effort has to be invested and the getter within the Dewar has to be removed. This is foreseen in case of major inevitable maintenance and repair of the ATC cryostats.

Detectors:

The highly segmented HPGe detectors are made of n-type HPGe material. Each crystal is encapsulated into a hermetically sealed aluminium canister. This facilitates the handling of the detectors during mounting and maintenance of the cryostats. The disadvantage of this encapsulation technology is the destructive opening of the capsule in case of detector repair, making the repair more time-consuming and cost-intensive. According to this, a reusable detector housing was developed in cooperation with detector manufacturer, which is completely compatible with the previous capsule. The detectors A013, A014, B015, B016, C015 and C016 are fabricated with the new technology and nearly all are in operation since 2016.

This newly developed detector capsules will be used for all future detector orders.

Pre-amplifier (Electronics):

The Core- (Cologne) and segment pre-amplifiers (GANIL/Milano) are part of the cryostat and delivered by the manufacturer of the cryostats. No changes in the pre-amplifiers are foreseen for the next phase. Here potential difficulties due to obsolete electronic components and maintenance of the preamps is anticipated. For example the cooled analogue electronics has to be modified due to the obsolete field effect transistor FET BF862 which is no longer produced. Here, a new solution has to be found. The same is true for the liquid nitrogen fill level meter which is included to monitor the LN2 level and consumption by an improved capacity readout.

All these developments will be performed in cooperation with the infrastructure group and the electronic group. The fundamental premise is to keep all future developments compatible with the existing ATC design.

Upgrade to 180 detectors

With the increasing number of ATCs, respectively detectors, the man power effort for maintenance will increase considerably. To cope with this task in the future, the workload will be distributed between the four AGATA detector laboratories at University of Liverpool, CEA Saclay, IPHC Strasbourg and University of Cologne and, additionally, to the future AGATA host laboratories. For this task, detector experts are mandatory at all AGATA detector laboratories. Preferably, a reasonable amount of spare ATCs and individual detectors has to be foreseen to maintain continuous operation of the spectrometer with the best performance and efficiency.

To reach the goal of 180 detectors until 2030, the AGATA community has to order 12 detectors and 4 Triple Cryostats per year for the next 10 years.

An overview of the acquisitions costs for the detectors and cryostats is given below, itemised by number of detectors and cryostats expected to be ordered, costs for a single cryostat/detector, total cost and at the end the annual expenditure for the hardware. All costs are given in k€ without taxes. A price increase of 1.5 % per year is included, what corresponds to the inflation and has to be expected. Starting point of the calculation was the last detector/cryostat orders of the AGATA community, for detector 201.5 k€ and cryostat 112 k€ had to be payed (2018 costs).

The total cost, considering 2018 prices would be **29968 k€**

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
number of detectors	12	12	12	12	12	12	12	12	12	12
price/detector	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7	210.7
total costs detector	2528.4	2528.4	2528.4	2528.4	2528.4	2528.4	2528.4	2528.4	2528.4	2528.4
number of cryostats	4	4	4	4	4	4	4	4	4	4
price/cryostat	117.1	117.1	117.1	117.1	117.1	117.1	117.1	117.1	117.1	117.1
costs cryostats total	468.4	468.4	468.4	468.4	468.4	468.4	468.4	468.4	468.4	468.4
Total Costs	**2996.8**	**2996.8**	**2996.8**	**2996.8**	**2996.8**	**2996.8**	**2996.8**	**2996.8**	**2996.8**	**2996.8**

Nevertheless, the costs of the Detector parts in the last 10 years have increased by inflation an average of 1.5% per year. Considering a similar average cost increase from 2021 to 2030, in total, expenses of **32075.2 k€** for the hardware is to be expected.

The distribution of expenses, considering the 1.5% per year inflation, over 10 years project, is summarized in the next table.

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
number of detectors	12	12	12	12	12	12	12	12	12	12
price/detector	210.7	213.9	217.1	220.3	223.6	227	230.4	233.8	237.4	240.9
Total detector costs	2528.5	2566.4	2604.9	2643,9	2683.6	2723.9	2764.7	2806.2	2848.3	2891
number of cryostats	4	4	4	4	4	4	4	4	4	4
price/cryostat	117.1	118.9	120.7	122.5	124.3	126.2	128.1	130	131.9	133.9
tTtal cryostat costs	468.5	475.5	482.6	489.9	497.2	504.7	512.2	519.9	527.7	535.6
Total Costs	**2997.0**	**3041.9**	**3087.5**	**3133.8**	**3180.8**	**3228.6**	**3276.9**	**3326.1**	**3376**	**3426.6**

Maintenance:

Maintaining the AGATA Triple Cryostats and detectors implies division of the repair into several tasks, from technical inspection to diagnostic and repair. The first steps should be done in the host laboratories preferred by the local crew with help, if needed, by the highly trained detector experts. If possible, simple repair work will be done on site, just if it is inevitable the systems will be transported to the detector laboratories to be repaired. With the increasing number of detectors, also the running costs and needed manpower will increase. To cope with this task all detector labs have to be trained to be able to repair the systems without practical guide. The estimate running cost is given in the table below. It takes into account a detector failure rate of 7.5% and costs of 50 k€ per detector repair and maintenance costs of 1.5 k€ per detector and year.

Number of Detectors installed	60	72	84	96	108	120	132	144	156	168	180
estimated number of broken detectors	5	6	7	8	9	9	10	11	12	13	14
Detector repair cost	250	300	350	400	450	500	550	600	650	700	750
maintenance	90	108	126	144	162	180	198	216	234	252	270
Total	340	408	476	544	562	630	698	716	834	902	940

Further developments:

Detectors:

Neutron damage is a major issue for highly segmented n-type HPGe detectors. Fast neutrons create negatively charged lattice defects which are traps for holes. All segment signals are affected by this issue leading to left tailing and a decreasing energy resolution. To approach this issue a reliable annealing procedure will be developed in cooperation with the detector manufacturer. For this a modified HPGe detector capsule is requested allowing a higher annealing temperature (approx. 150 °C) with respect to the existing one (102 °C).

Estimated costs: 150 k€

A long term goal will be the replacement of the actual n-type HPGe detector material by a p-type detector. Therefore, new methods for the doping and passivation of the p-type Germanium detector have to be developed. These developments are pursued within the ENSAR2 JRA PSeGe.

Estimated costs for development of new doping and passivation methods: 300 k€

Estimated costs for development of n-type detector to series maturity: 650 k€

Cryostat:

High-Purity Germanium detectors require cooling to LN2 temperature to operate as gamma-ray detectors. Operating costs, availability, and the hazardous nature of the liquid nitrogen limits the practicality of the Germanium detectors.

Recent advances in electrical (mechanical) cooling technologies have the potential to replace the inconvenient liquid nitrogen cooling. The major problems of standard electrical coolers are the cooling power and degraded performance of the detectors due to vibrations. To adapt the electrical cooling to the AGATA Triple Cryostat further developments are needed to reduce the mechanical vibration and to obtain the needed cooling power.

Estimated costs for development of a electrical cooler: 150 k€

Estimated costs to adapt the electrical cooler to the AGATA Triple Cryostat: 200 k€

Electronics:

Long term developments of the electronic groups, e.g. cold VLSI fast reset preamplifiers with warm digitizer in close proximity and highly integrated digital preamplifiers, necessitate in a first step the development of a test cryostat to test the performance of the new electronics.

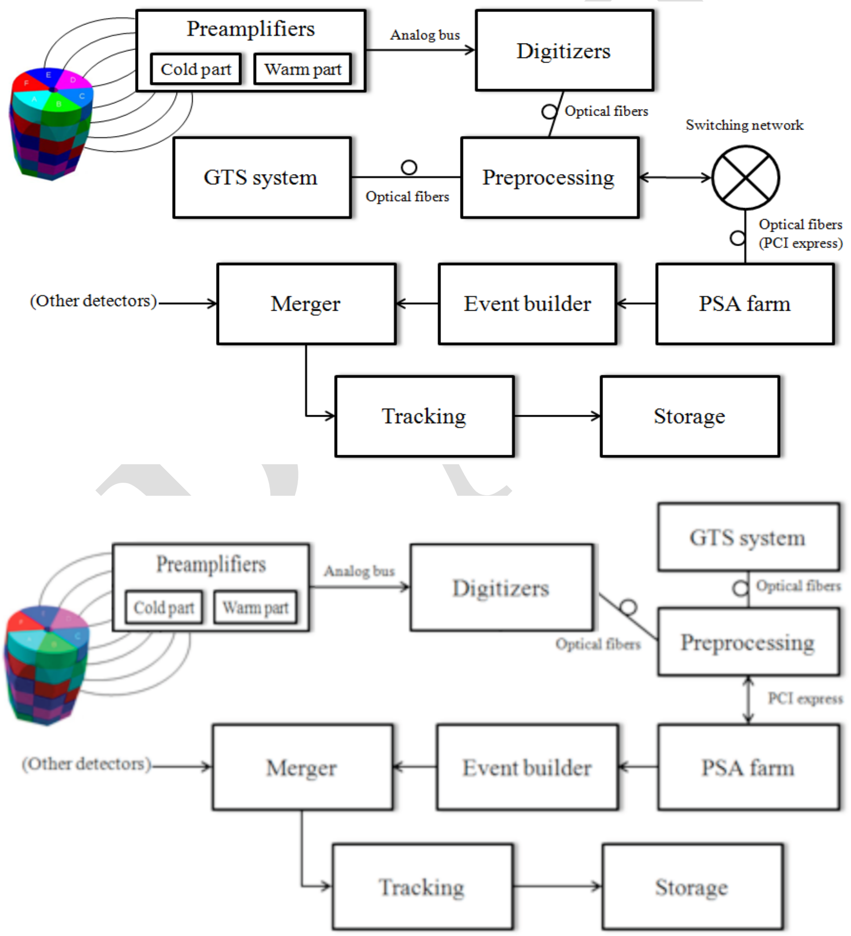
Estimated costs for development of a test cryostat: 80 k€

Estimated costs for the integration of the new electronics in a largely modified AGATA Triple Cryostat: 200 k€

Front End and Pre-Processing Electronics Subsystem

Introduction

The AGATA efficiency and peak-to-total performance figures is achieved by using Pulse Shape Analysis (PSA) and gamma-ray tracking techniques, requiring the array working in Position Sensitive mode. In order to apply the PSA and tracking algorithms, it is necessary to digitize synchronously the 36 (segment) +1 (core) charge pulse and induced signals of each crystal at a 100 Msps rate. The core signal is split in the core pre-amplifier providing two amplification gains. The large counting-rate limit in the AGATA specifications requires a fast trigger in order to reduce data transfer and storage of the signal traces. Moreover the energy associated to the charge signals, has to be determined on-line by using a MWD algorithm.



Schematic diagram of the Phase 0 (top) and Phase 1 (bottom) AGATA Front-End electronics and DAQ chain.

The architecture of the AGATA early electronics is a consequence of the processing and Input/Output capabilities available in a single FPGA at the design time (~2005-2007). Among other features, the Phase 0 and Phase 1 electronics had the pre-processing in a location different from the one of the Front-End electronics (pre-amplifier + Digitizer) connected by a set of long optical fibres.

The data taking flow starts from the preamplifiers. Then, the 100 MHz and 14 bit digitizers convert the signal pulses into digital data that are sent through optical fibres, coupled in groups of 6, to the pre-processing stage. The pre-processing electronics, including the Early Phase 1, is composed of mezzanines that contain the processing logic for 6 segments or the core, and are mounted in an Advanced Telecommunications Computing Architecture (ATCA) carrier card. Another mezzanine card contains a link to the Global Trigger and Synchronization (GTS) system, which provides a common clock and a timestamp, and manages the second level of trigger, which may include events with different multiplicity in the detector, or combined with complementary detectors.

The architecture for the AGATA Advanced Phase 1 electronics (up to 45 capsules) keeps the functionality of the ATCA electronics with a higher integration of the system with 12 channels per optical fibre and one only PCIe card performing the pre-processing and GTS interfacing. A common problem to both AGATA electronics generations is the availability of components for construction, repairing and maintenance due to obsolescence. The evolution in components has also some benefits in terms of power consumption, speed and cost which are worth to be profited. These two aspects make it necessary to watch out this evolution and carry out a Front-End Electronics (FEE) redesign for the Phase 2

Introduction to the Electronics for the Phase 2 of AGATA

The aim of this document is to propose a solution to build a scalable and stable Front-End and Back-End (pre-processing) Electronics system for AGATA beyond phase 1, tracking the best technical solutions for the full 4π array.

Note that in principle we expect to have the same or equivalent pre-amplifiers and signal cabling from the Detector Module to the Digitizer.

Presently the current DIGIOPT12 digitizer boards will be used, with minor modifications due to obsolescence, noise improvements, Differential Non Linearity (DNL) improvements, introducing of a sliding scale, and possible excluding the transceivers from the design.

The pre-processing board will be installed together with the DIGIOPT12 boards and will act as well as control card for the programming and clock distribution.

For the design of the pre-processing and readout, we have considered the following important issues:

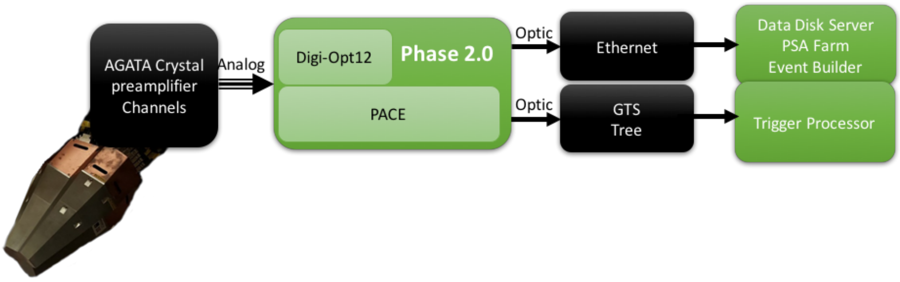
1. Interface between front end electronics and PSA Farm servers should not rely on any customize hardware interface.
2. Simplified and autonomous electronic modules to ease maintenance and minimize impact of possible rework due to obsolete components in future.
3. Highly integrated solution to ease the installation in experimental area.
4. Readout based on high bandwidth network technology (up to 10 Gb/s per crystal).

5. Stable and scalable architecture of the AGATA BEE&DAQ architecture (for which the necessary performances must be fulfilled from 45 up to 180 crystals).
6. High level of monitoring, diagnostic and debugging with friendly graphic user interfaces.
7. Modularity to allow for the use of new technologies when available and suitable for the objectives of cost reduction and higher integration.
8. Maintenance of the system by external companies or using commercial off-the-shelf System on Modules (SoM), is highly recommended since insures the spare parts through the life of the experiment independently of efforts available in the collaboration.
9. Possibility to have a portable version to install them in Scanning tables, Acceptance Test labs, Host labs for detector maintenance labs so that results can be compared using the same instrumentation between experimental area and labs.
10. Built-in self-tests and built-in embedded software so that the system can work without network access to servers and complicated infrastructure. This instrumentation must have an independent and easy software interface to perform a crystal acquisition. If a computer should be connected and needed then this computer is part of the material. It is mandatory to simplify the installation. This must be defined during the project technical definition and not added software every time there is a new option required by the users. All requirement should be known during design and not after commissioning, so that the hardware, firmware and software teams can integrate all requirements in this instrumentation.
11. Open Source software and Firmware available for the full collaboration for future upgrades, training, dissemination etc…
12. All parts fully documented on engineering and user levels.

We also considered for the long term of AGATA the possibility of higher integration and power consumption reduction in the AGATA core and segment pre-amplifier. Exploring the ASIC technology for the AGATA pre-amplifiers, i.e. the integration of the Digitizer and the ADC in the spirit of the Digital Pre-amplifier module. Nevertheless the technology for ASIC and FADC is presently unable to offer a "real" solution for the Digital Pre-amplifier requirements.

Electronics General layout

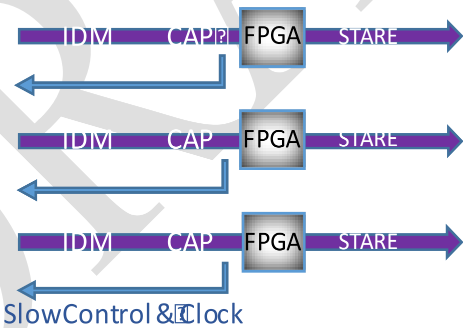
The proposed electronics general layout is shown in the following figure:



General layout of the new electronics

The "parts" of the system are the Digitizer system and the Pre-Processing and Communication system (PACE), both composed of the following parts:

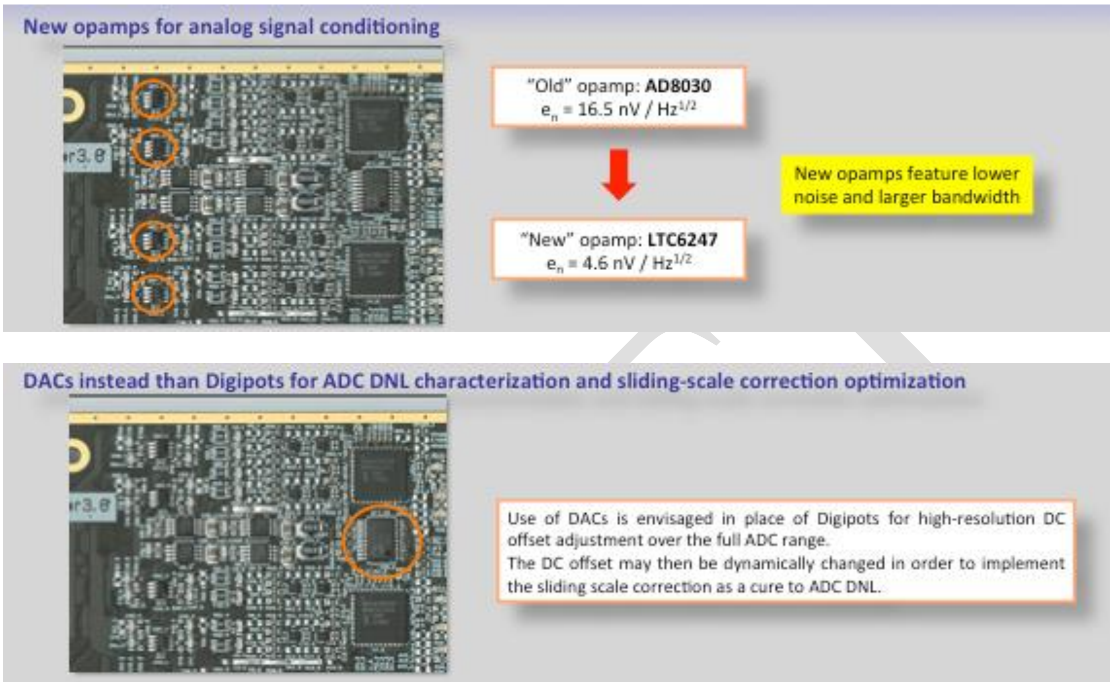
- Digitizer Board (DIGIOPT12).
- The Data Transfer lines.
- Input Data Motherboard (IDM).
- Pre-Processing and Control board (CAP).
- Read-Out board (STARE).
- Trigger and Synchronization Interface (GTS or alternative system).
- The monitoring/Inspection Hardware.
- Pre-processing, control and monitoring Firmware and software.
- Mechanics, Power Supply and Cooling System (Temperature Stabilization).



Data collection, pre-processing and read-out scheme

DIGITIZER: New DIGIOPT12 Board

It has been considered feasible the use of the DIGIOPT12 cards for the Phase 2 of AGATA. The actual version of the DIGIOPT12 board is the outcome of optimizations and improvements guided by the user's feedbacks (including range adjustment, fast trigger channel optimization, filtering of the ADC voltage ref, ...). DIGIOPT12 developments are now focusing on the issues related to ADC Differential Non Linearity (DNL) as seen after Moving Window Deconvolution trapezoidal filtering. In nuclear spectroscopy DNL issue is much more critical than in typical applications of flash ADCs. Nevertheless, DNL is intrinsic of flash ADC architecture, changing FADC model or increasing to 16 bit resolution may not be useful (current FADC already has an internal 16 bit architecture but the two Less Significant Bits (LSB's) are not transmitted because they are at the noise level). After completion of the study of the ADC DNL (in progress) we will implement all changes aimed to mitigate its effect, such as use of sliding scale correction, range optimization, use Digital to Analog Convertors (DACs) instead than Digipots for DC offset setting etc…



Recent and on-going developments in the DIGIOPT12 Board

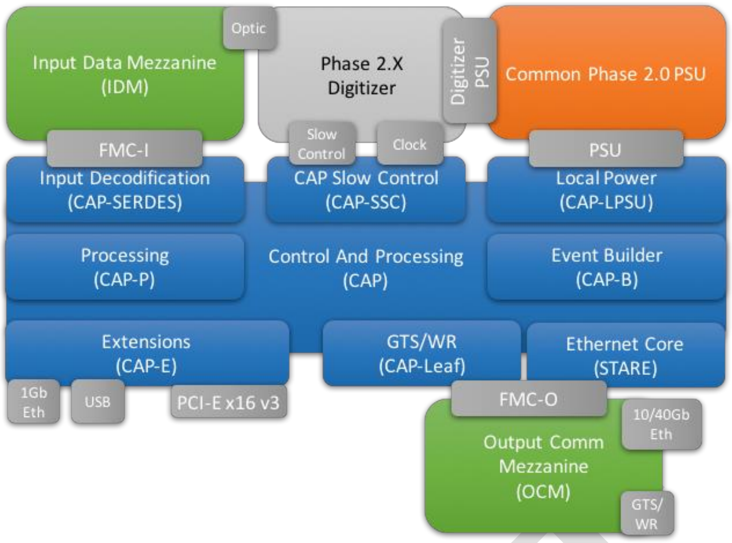
DIGIOPT12 boards have been built until now in an industrial environment. The production yield, evaluated over the production of more than 92 boards, has been excellent and the failures of the boards almost negligible since the three years they are functioning at the setup.

Presently the company is not anymore available and actions to translate the DIGIOPT12 design into the CAD format EAGLE, used by INFN-Milano, is being done. Modification of the design to incorporate the sliding scale hardware will be done.

The production is planned as presently, through an industrial partner.

PRE-PROCESSING.

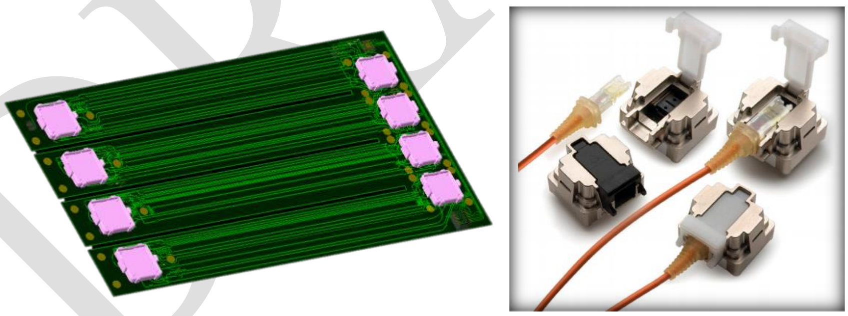
The following figure shows the functional blocks of the Pre-Processing system. Some of them correspond to physical boards and some just to functionalities that should be implemented either on hardware or firmware or split in both domains. In the following subsections a detailed description, both of the hardware and firmware, of these functional blocks is presented.



Electronics functional layout

The Data Transfer Lines

The elimination of the optical transceivers and optical fibres, between the DIGIOPT12 boards and the IDM concentrator of the pre-processing system, represents both a reduction of the power consumption in the boards and a reduction of costs. With this purpose a PCB Flex-Rigid connection has been designed, as a follow-up of the planned vicinity of the DIGIOPT12 boards and pre-processing boards (see following figure).

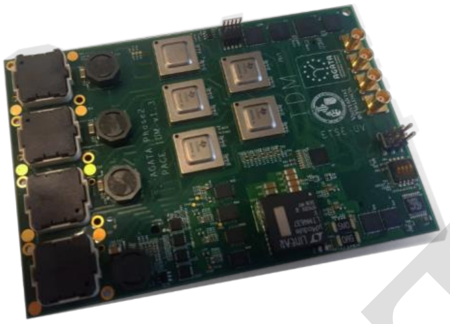


The PCB Flex-Rigid connection (left) replaces the transceiver and optical fibres (right)

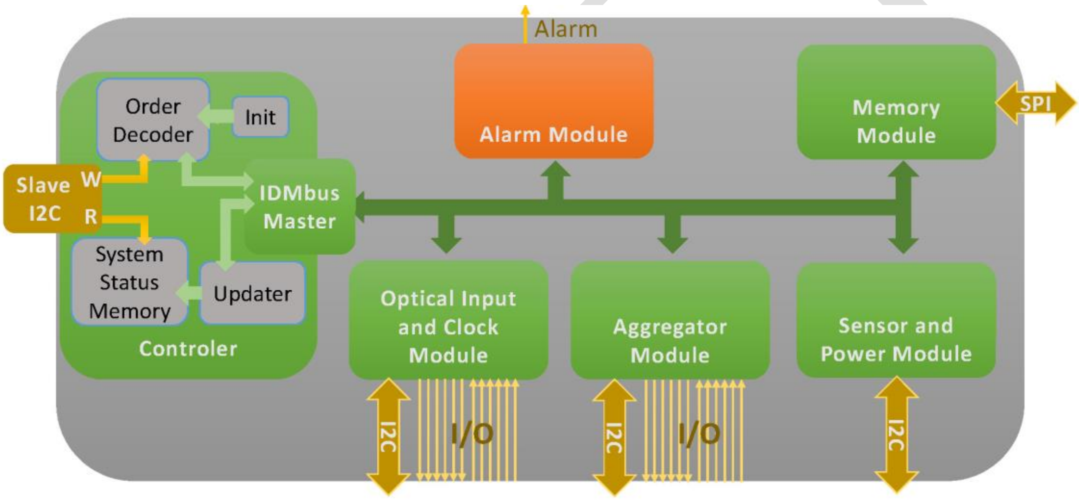
The PCB Flex-Rigid connection has been designed and is ready for production. The cost estimates, even for a small production, is between 200 € and 400 € per Digitizer compared with the 1.6 k€ of the transceiver solution.

The Input Data Motherboard (IDM)

The IDM (see following figures) is the subsystem conceived to input the data coming from the digitizers. It will receive the data from one crystal by copper connection or optical fibre and will implement a reduction in the number of input links to send to the CAP pre-processing board by using low-cost Time Domain Multiplexing devices; in this way, the number of high-speed transceivers used in the FPGA will be reduced. On the Advanced Phase 1 electronics, the Digi-Opt12 board sends approximately 2Gb/s per each of the twelve output channels. This implies an aggregated bandwidth of 76Gb/s for 38 channels (36 segment + 2 core channels).



First version of the IDM board



Functional block diagram of the IDM board

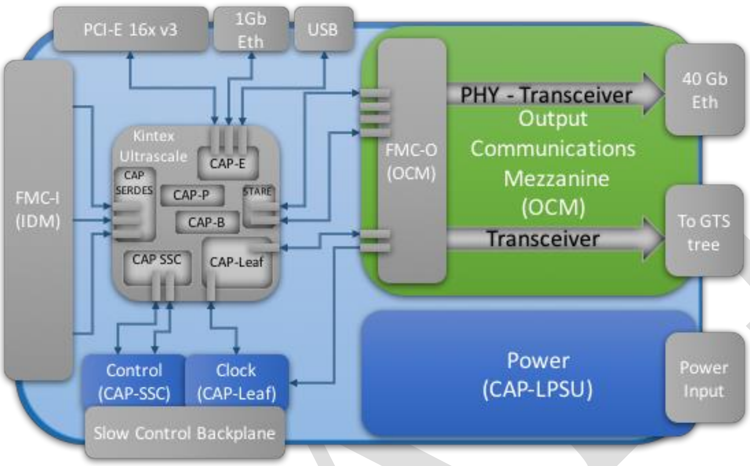
The first implementation of the board, used in the conceptual design of the electronics, has been produced and is being tested.

The Control And Processing board (CAP)

This is the mezzanines managing data flow from detector to PSA Farm servers. The main purpose is to process the data from one crystal, generating the Local Trigger and extracting the Energy and Time information and traces for the PSA analysis in agreement with the GTS Trigger Validation/Rejection cycle. A second task, carried out by CAP board is to provide intelligent slow control through Ethernet IPbus, for all the subsystems included the DIGIOPT12 board. A description of the functionalities will follow in the Firmware section.

In addition, the interface between CAP and the Read-out STARE mezzanine will be designed in order to ensure the possibility of having triggered digitized traces of a capsule in a scope mode (with 10 Gbps bandwidth 6 segments can be displayed, with 20 Gbps 12 segments, per crystal,), also the induced signals in the neighboring segments will be displayed. Finally, the GTS (or equivalent Trigger and Synchronization system) functionalities will be also incorporated.

As mentioned before, the Control And Processing board is the core of the system and holds the Master FPGA. A Virtex new generation FPGA is considered as the best option to perform the crystal data preprocessing based on a balance in cost, processing capability and number of high-speed transceivers.



Control And Processing (CAP) board block design

Presently this board is not yet designed but during the conceptual phase design an evaluation board is being used with two FMC connectors to be able to connect the rest of the mezzanine prototypes.

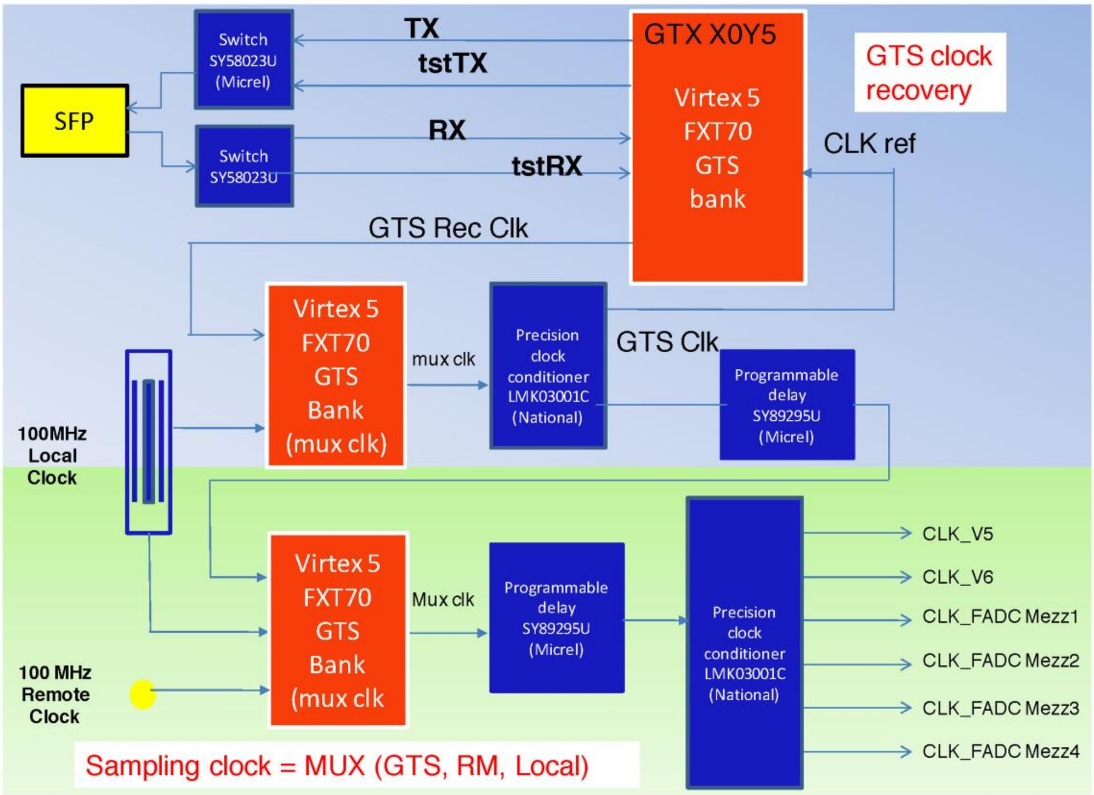
Among the possibilities for the design of the board, the use of Commercial-Off-The-Shelf (COTS) System on Modules (SoM) boards is under evaluation. This will facilitate the design and production as well as to guarantee spare parts. Two possibilities are the Trenz Electronic “TE0808-04-15EG-1EE” or the Origami “OM-B20-Z2-KU-060” Module.

As mentioned before, the CAP board implements the slow control logic for the DIGIOPT12 boards, digitizing an AGATA capsule, as it’s now implemented in the Digitizer Control Card. The system would be scalable and flexible to adapt to future DIGIOPT12 upgrades.

A power supply unit or units would provide all the voltages and current needed for the operation of the system. One key point in the design of this unit is its efficiency that should be as high as possible to minimize the power dissipation and, thus, lower the cooling requirements.

The Clock distribution and GTS leaf

The GTS leaf functionality could be provided by the FPGA in the CAP board with a physical connection (optical fibre) to the GTS tree. It is planned to implement the GTS hardware in the CAP board (see in the following figure the low complexity in the NUMEXO2 implementation). It is also foreseen compatibility with other Trigger and Synchronization systems.



Implementation of the GTS clock recovery and clock management hardware design in NUMEXO2 (courtesy of M.Tripon, GANIL, and collaborators).

The GTS IP firmware, imported from the NUMEXO2 project IP will be already included in the proof-of-concept implementation.

The Serial Transfer Acquisition Readout over Ethernet (STARE) mezzanine

This mezzanine is aiming to provide a standard Ethernet capability to transfer data from experimental hall to the PSA farm servers avoiding dedicated interfaces. The use of high capacity Ethernet network allows remove critical customized cards inside computer farm. A sizeable reduction of fibres between experimental hall and the location of the PSA farm is also expected. In the worst case, we will use only one fibre for one crystal.

The use of 10 Gb Ethernet will allow to cope with the maximum data transfer rates within the AGATA specifications independently of the use of hardware or software trigger processor and will offer the opportunity to use longer traces if needed.

Ethernet protocol offers the possibility to swing data buffers among destination server, optimizing the data flow. The proper destination will be chosen as a function of server load, network traffic and data acquisition system configuration. Beside the load balancing capacity, this technology will offer the opportunity to send data to the different PSA servers.

With the current electronics, the scope mode which is useful for the monitoring of the experiment (visualization of the signals during the run) is not possible. This proposed design will include this functionality. Monitoring one channel in scope mode requires a bandwidth of 1.6 Gb/s.

Two alternative implementations have been considered for the STARE process: first, the Ethernet protocol IP could be embedded in the CAP motherboard –then the necessary hardware is very limited-, the second possible implementation is a dedicated mezzanine with a FPGA.

The interest to integrate this function on a daughter card is in case that the 10 Gb TCP/IP block is not possible to integrate inside the preprocessing FPGA. The FPGA implemented on this card assumes this interface and control the very high speed links with the Ethernet transceivers. The Ethernet link assumes the data readout and the monitoring and setup control. One external clock is also available.

The main functions in the FPGA mezzanine hardware and firmware of STARE are:

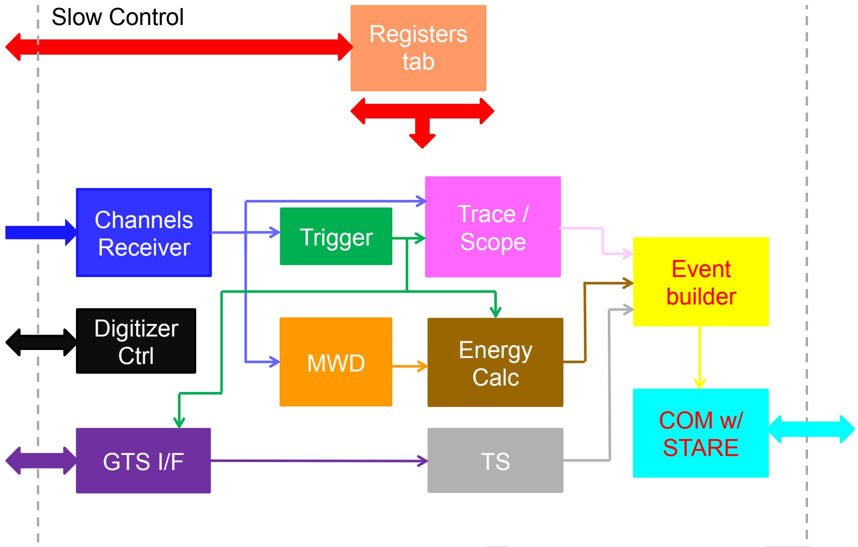
- Electrical interconnections with mezzanine connectors and gigabit transceivers.
- Embedded Linux OS used for readout manager control and global system setup control.
- Readout bloc management.
- Ethernet protocol management (embedded IP).
- Slow control management.
- Gigabit links dispatcher.

In the cost table, the option with an independent mezzanine has been considered and the option using the pre-processing FPGA of CAP will spare the mezzanine production costs.

Firmware and Software for the Inspection and Electronics Control

The electronics architecture being considered is such that it is directly connected to the DIGIOPT12 FADC cards – were there is no logic in the cards- thus it has to support both the slow control of the pre-processing and the DIGIOPT12 cards as well as the synchronization of the FADCs. The processing board will receive the serialized data from the DIGIOPT12 cards through the IDM concentrator board -that allows to profit from the bandwidth of the FPGA serial ports-, it will pre-process them and will take a decision on the trigger request. It will also determine energy and time for the core as well as for the segment channels and it will work on the advanced processing of the baseline. The data will be "Zero Suppressed" and Compressed. A simplified block diagram of the firmware functionalities are shown in the following figure.

The current GGP firmware could not be re-used, partially due to the different architecture, partially because INFN has not make it available to the AGATA collaboration. We have mostly to perform the firmware design from scratch.



Control And Processing board (CAP) Firmware block diagram

The firmware has 5 main interfaces:

- DIGIOPT12 Channels Receiver
  Reception of the digitized channels coming optically from the concentrator (IDM) mezzanines. Includes: Deserialization, Alignment, Buffering, Control signals Management.
- Interface with the FMC readout board (STARE)
  Communication path to be defined. Buffering via an external memory seems necessary before transferring data packets to the STARE board.
- GTS interface
  Available new implementations from EXOGAM2 and from NEDA projects. To migrate to Kintex Ultrascale, re-used and integrated in the global firmware.
- DigiOpt12 Controller

- General Slow control of the full electronics system
  Configure all internal registers. Best option 1Gb-Eth / IPbus interface if bandwidth should be saved on STARE board, the IPbus interface could be extended to transfer channel data in scope mode in order to do long trace analysis and to configure properly the channel settings (trigger, MWD) before an acquisition run.

The data path includes:

- High Frequency Deserializer.
- FADC data Stochastic Latency aligner.
- Internal Trigger Request determination LED/DCFD, triangular shaper and a threshold etc. This includes the evaluation of the segments with net charge signals.

- The possibility to have the logic OR of the "segment" triggers instead of the core trigger.
- Incorporation of the GTS Local Trigger/Trigger Request Timestamp to the data buffer.
- Pre-trigger and post trigger sample storage.
- Advanced baseline determination (all segments with net charge and core).
- MWD Energy Determination (all segments) with the advanced baseline for Phase 2.
- Storage the data for the cores and segments, with selection of segments with net charge and mirror signals for PSA processing for Phase 2.
- Data compression for transmission.
- Management of the GTS Validation/Rejection.
- Delivery to the TCP or UDP FIFO.

Data Transmission path includes:

- The pre-processing board has to perform the slow control of the digitizer boards DIGIOPT12 and the pre-processing card itself. Control commands come from Ethernet and the Control Card should communicate with the different devices using standard serial protocols.
- Ethernet register server for the Configuration and control. It has to manage the slow control of the pre-processing as well as DIGIOPT12 card.(Management by the GEC and Run Control) .
- TCP/hand-shake UDP Data transmission to the DAQ
- Management of the TCP/UDP IP block.

The GTS and clock management includes:

- GTS management, configuration and alignment.
- Management of the Trigger Request (TR) and TR Timestamp.
- Management of the Validation / Rejection FIFOS.
- Receive and broadcast the 100 MHz clock of the GTS with minimum contribution to jitter and skew.

The status of the firmware preparation, still mainly for the proof-of-concept is the following:

- ETSE and IFIC in charge of the IDM data IPS's: Data reception in the IDM Test-bench expected to be fully functional within summer 2019.
- IPHC Strasbourg in charge of the migration of the previous STELLA project.
- GbE + IPBUS for SlowCtrl & Data transfer to PC: done and fully functional.
- SERDES block (compliant w/ FMC112 ADC Data): done and to be tested.

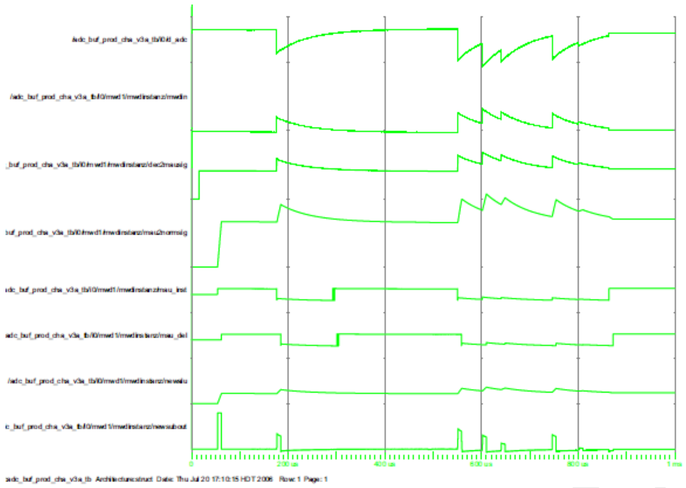
- DSP blocks for algorithms (Trigger, MWD): done and to be tested.
- FIFO primitives & BRAMs for Data buffering: some issues to be investigated.
- READOUT block and I/F with GUI via GbE/IPBUS : Requires modifications.
- Add synchro/timing features based on previous designs : to be done.
- GTS leaf f/w from Numexo (Ganil) : to be done.
- Add features of Control of the DIGIOPT12: to be done.
- Add the block (IDM channels receiver) from Valencia.
- To receive channel data from IDM and to Transfer data to STARE, need to Define transfer protocol, registers tables, data formats & acquisition modes (links with s/w by IPBUS), diag, etc…

Since the outline design is still under discussion, the full list of VHDL code required and hardware required has not yet been finalised. An important U.K. contribution is identified as being in the visualisation and diagnostics. Compared to other systems (like the Lyrtech system in JYFL designed by STFC Daresbury) the availability of signals from firmware algorithms in AGATA for inspection is very poor. It is necessary to visualise, for example, the different stages of the MWD energy algorithm. A good example is that user needs to look at the trapezoid flat top while adjusting the PZ correction for preamplifier decay time to ensure that the flat top really is flat, eliminating any slope by fine-tuning the PZ correction factor. The work would be primarily VHDL, maybe some hardware design, and would include software to work with the visualisation VHDL firmware to display signals.

Proposal for inspection:

- Visualisation of input signals.
- Visualisation of MWD algorithm intermediate results (parameter adjustment).
- Timing of signals from ancillary detectors.
- Timing of trigger signals
- Digital diagnostics for key GTS signals, readout signals

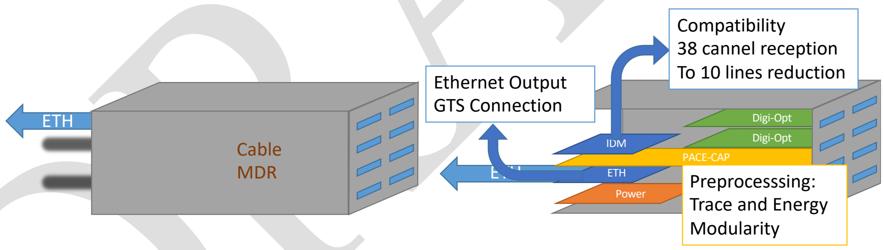
In terms of specifications, all has to be accessible remotely, selected by software. Possibility to compare two channels as well as different signals within 1 channel. All with option to show buses as “analogue”, with a user-friendly GUI



Example of visualization of the MWD processing

Mechanics

The basis for the mechanical design of the PACE system is to keep the one used in the Advanced Phase 1 as far as possible. This includes a 3U rack for the processing of a AGATA capsule with the difference that in the new system this rack will also include the preprocessing hardware now placed in servers connected to the DIGIOPT12 cards with Flexi-Rigid cables. The following figure shows the concept proposed which should be investigated in detail.



Mechanical proposal for the full system

GTS Tree and Trigger Processor

We think nowadays that the GTS system is presenting some problems and/or limitations:

- Presently the number of available independent channels is limited to 255 due to the specifications. Strong limitations when coupling with other detector arrays based on GTS.
- Difficulties to produce the present tree hardware. Obsolete components for the mezzanines, the last trigger processor has been produced by EXOGAM2. Large number of FIFOS needed since the present design each FIFO element has 3 Inputs and 1 Output. A GTS tree for 45 capsules requires presently a minimum of 23 FIFOS and 1 ROOT Mezzanines.

- In strong disagreement with the specifications, found loses in the GTS transfer when approaching 1MHz of trigger request. With 1MHz request from AGATA + NEDA we have from 10% to 15% loses. It is unclear if they are coming from the protocol itself or the performance of the FIFOS or other reasons.
- Slightly different behavior between the ATCA (full GTS protocol) and the GGP and NUMEXO2 (simplified protocol with no identifier), on the Validation success.
- Need broader compatibility on clock and synchronization for complementary instrumentation.

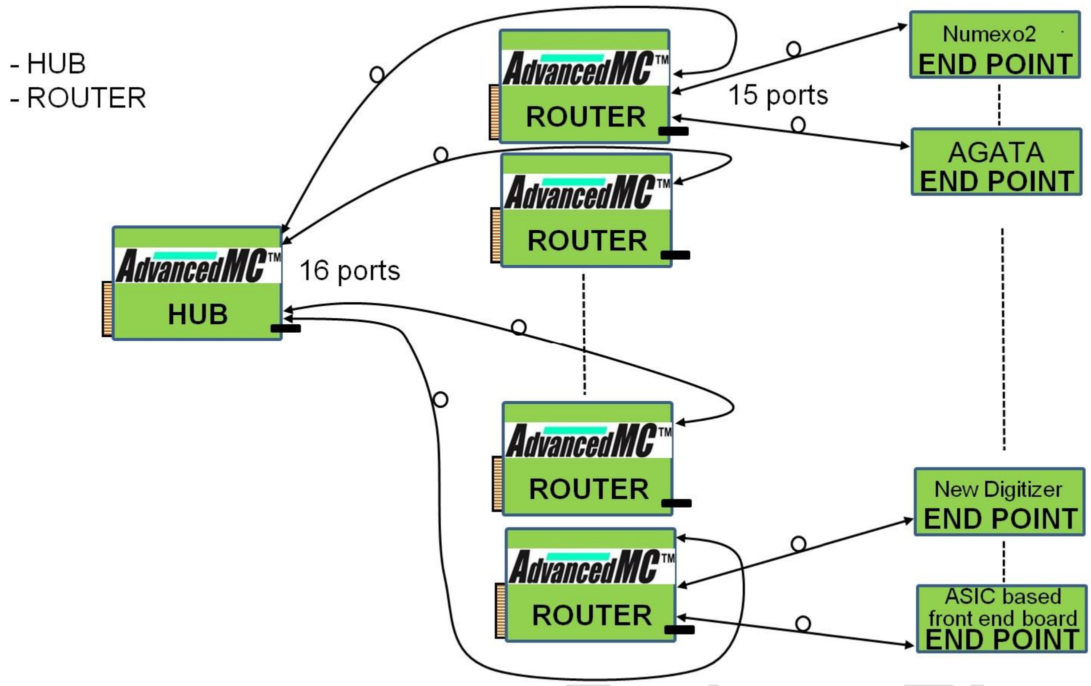
We have presently two alternatives to proceed:

- Upgrade of the present protocol, to be done by INFN-Padova because there are no other experts on the development. Easy back-compatibility. Presently we have no feedback from INFN-Padova on this possible upgrade.
- To pass to other Global Trigger and Synchronization. Drawback is the difficulty to make the system compatible with previous versions of the AGATA electronics. Especially critical for the GGPs, since the pre-processing boards are not very old and the AGATA collaboration has no access to the GGP firmware. One possible Synchronization and Trigger system, Hardware compatible with GTS, would be the SMART system, still at the conceptual level, being proposed by the GANIL GAP (G. Wittwer et al.).

Regarding the Trigger Processor, we plan to continue with the GANIL EXOGAM2 trigger processor for the moment. Several improvements have been planned following the commissioning and the first experimental campaign at AGATA performed with this Trigger Processor.

A formal agreement and the discussion of the AGATA collaboration contribution to these developments is still to be discussed.

Summarizing, we expect to start in 2021 with the present GTS system but we would need to migrate towards the SMART system during he early years of the Phase 2. Note that the pre-processing embedded GTS hardware is compatible with the SMART hardware.



Conceptual design of the SMART Trigger and Synchronization system being developed at GANIL

The GTS cost estimate from the previous Project definition was of the order of 5 k€ per channel, considering all the infrastructure associated.

For the SMART system the HUB cost is foreseen as 5.3 k€ ROUTER cost is foreseen as well of the same order 4.8 k€.
In order to instrument AGATA, it would be necessary to have 12 ROUTER boards, distributed in 2 Micro-TCA crates and 1 HUB board in 1 Micro-TCA crate.

1 Micro-TCA Crate, 1 Power Module (PM) and 1x10Gbe MCH (MicroTCA Carrier Hub/Switch) cost roughly 10 k€. Thus, the total cost of the crates and switches is estimated to be of the order of 30 k€.

It would be necessary as well to have a Trigger Processor with a cost estimate of 5 k€.

The total cost for the Global Trigger and Synchronization system, including the Trigger Processor is estimated to be of the order of 120 k€, i.e. about 700 € per channel (2 k€ per ATC).

Upgrade of Phase 0 Electronics

The early electronics of AGATA called Phase 0 were produced in 2007/2008 and 2011/2012 respectively. In 2022 a sizeable amount of boards will have about 14 years and, as the second batch was produced with obsolete components, there will be great difficulties to maintain the hardware. It is especially critical the situation of the DIGITIZER core and segment boards, designed with Virtex II FPGAs, that are obsolete and the production discontinued since 2012. The maintenance of the board is presently extremely difficult.

We propose in an early stage of the AGATA Phase 2 the full replacement of the 24 DIGITIZER + ATCA channels. A budget of 384 k€ should be considered for this action (note that, differently from the newer channels, the full electronics, DIGITIZER and pre-processing board has to be replaced, with a total cost, per capsule, of 16 k€).

Additionally, in 2025 the project definition foresees a full upgrade of the Pulse Shape processing part (see Pulse Shape and Data Flow section), that requires dispatching capabilities in the pre-processing electronics. This capability is not existing in the Phase 1 electronics since it is still a point-to-point optical fibre read-out. We therefore foresee for 2025 the replacement of the Phase 1 electronics -largely obsolete already now-, for new Phase 2 electronics channels.

Depending on the final processing capabilities and/or the final decision regarding the Trigger and Synchronization system, a partial upgrade of the Advanced Phase 1 Electronics might be required.

Construction

The Electronics Working Group is trying to find a way to get as much as possible parts of the new electronics design, produced in an industrial way, with acceptance tests and commitments for maintenance.

DIGIOPT12 boards: already the present DIGIOPT12 boards have been produced in an industrial environment and it will be done again.

Pre-processing boards: we intend to use SOM (System on Modules) commercial boards for the pre-processing PACE FPGA and the Ethernet STARE interface. Our target are boards with guarantee of production (at least expected) minimum of 15 years. Only the IDM motherboard will be customized since the input-outputs for the connection to the DIGIOPT12 boards, inspection lines, control, etc…, require a custom design.

GTS/SMART: is it being designed as well with SOM boards.

Costs, Timescale & Efforts

The following tables show the estimated budget for the initial production of 30 systems and the task assignment and effort contribution of the Electronics Working Group partners in the development of the proposal.

The present budget implies a cost of about 16 k€ per crystal excluded the Global Trigger and Synchronization system.

Total production costs for 180 channels all included is 2931 k€, assuming that the production will be done in batches of a minimum of 30 units. For the electronics production we are not considering any inflation.

Table 1. PRODUCTION BUDGET IN k€					
DIGITIZERS					
	PCB	MOUNTING	COMPONENTS	SUBTOTAL	
DIGIOPT12 (x120)				216000,00	
				DIGITIZERS	216000,00
PACE SYSTEM					
	PCB	MOUNTING	COMPONENTS	SUBTOTAL	
IDM (x30) (Large Motherboard)	25500,00	20500,00	80000,00	126000,00	
CAP (x30) (SOM based)				42000,00	
STARE (x30) (SOM based)				30000,00	
Power Supplies (x30)	15000,00	1500,00	3500,00	20000,00	
Flexiboards (x30)				12000,00	
Backplanes (x60)	15000,00	3000	2000,00	20000,00	
				PACE SYSTEM	**250000,00**
MECHANICS					
				SUBTOTAL	
CRATE (x9)	500,00			4500,00	
BOXES (x30)	200			6000,00	
COOLING (x30)	400			12000,00	
				MECHANICS	**22500,00**
				TOTAL	**488500,00**

Table 2- Efforts Contribution by Institution.

Institute/Centre/University	Contribution	Man Power
CSNSM Orsay	STARE card implementation, firmware,	4 senior engineers 2019 0.55 FTE, 2020 0.85 FTE 2021 1 FTE 2 FTE requested to IN2P3
CSNSM Orsay	DAQ software development, Control software development.	2 FTE
IPHC Strasbourg	Control and Data path firmware development	2 senior engineers 2 FTE
STFC Daresbury	Preprocessing algorithms, visualization and diagnosis firmware and software development. Prototyping build/test	(3.5 FTE conditioned by the approval of the UK AGATA Grant)
TeDRA - University of Valencia and IFIC-CSIC	IDM implementation and firmware design, PACE systems hardware design Digitizer Mechanics and PS, Hardware implementation	1 senior and 1 junior engineer 1.5 FTE/year Total 4.5 FTE
University of Milan	DigiOpt12 evolution	1 FTE/year Total 3 FTE
GANIL	SMART development (shared also for GANIL systems)	**2 FET/year** **1 year**

Regarding the schedule, the proof-of-concept, scheduled in two phases, will be performed between Spring and Summer 2019. The design of all final boards is expected to be completed by the end of 2019.

The pre-production boards are expected during 2020 to be ready for production at the start of the new MoU for AGATA 4π, early 2021.

The Timescale por the production is the following:

•Proof-of-concept (advanced) due in summer 2019

•Conclusions discussed on AGATA week September 2019

- (Possibly decision on SOMs to be used before September to procure evaluation boards and check firmware compatibility)
- Design of final IDM motherboard (mid 2019 – mid 2020)
- Advanced firmware to be delivered late 2019 to mid 2020
- Hardware/Firmware testing mid 2020 to late 2020
- Production early 2021 to late 2021
- Installation: late 2021 - early 2022

About 6 months of contingency time have been considered in the timescale.

Production and Maintenance Commitment

Production

The future AGATA electronics must comply with industrial products specifications. There are several constraints to take into account in order to reproduce such electronics at any time, and using the same parts list and the same production procedure to achieve the same final product. It is extremely important to construct during the design phase the industrial procedure in order to include such constraints inside the design process. The research laboratories cannot afford such hard work and severe conditions to make documentations, maintenance built-in Test benches, afford obsolete components lifetime etc... Such work must be done in association with an expert private company who is able to maintain, produce and buy in advance specific components, which have a short lifetime on the market place. This is a transverse task that should deal with the global electronics of AGATA. The responsibility of this task is to ensure that every subsystem contains the following items: complete design description document, manufacturing files including all the special mounting notes and different constraints, purchase documents, ATP and ATR (Acceptance Test procedure and report), list of short lifetime parts, integration documents and all the production procedures.

Maintenance

To achieve effective maintenance the chosen company must insure on the shelf enough spare parts and be able to furnish the AGATA collaboration enough items to replace defected ones.

The SOM products will be chosen with an End of Life beyond the completion of the AGATA 4π project.

The experience with the previous generation of electronics shows that replacement of complex components, such as large FPGAs, in the boards is achieved with large difficulties and very seldom works. A maintenance programme based on replacement of the broken SOM products, with moderate costs, will be built.

Documentation

Documentation will be available for future needs, i.e. maintenance, operation, test, etc. Besides, this information, including user manuals, repairing manuals, technical descriptions, CAD files, VHDL codes, software, should be placed in a computer space publicly accessible to all members of the collaboration. This place will be setup making use of the AGATA collaboration space or in a different place if it’s judged convenient.

Pulse Shape Analysis and Characterisation for AGATA Phase 2

Introduction

The large volume highly-segmented HPGe crystals that form the core of the AGATA spectrometer, require the use of Pulse Shape Analysis (PSA) and γ-ray tracking in order to realise the performance required to deliver the key physics goals. Effective γ-ray tracking and the subsequent suppression of events that do not deposit their full energy in the array, requires localisation of individual interactions within the detector volumes with spatial resolution on the order of a few millimetres. This is achieved by combining segmented detector technology with pulse-shape processing to localise interaction points with sub-segment resolution.

When a γ-ray interacts within the crystal volume it produces a charge cloud of electrons and holes, which drift under the influence of the bias voltage toward the central electrode and the segmented electrode, respectively. The motion of the charges induces signals on the core channel and on multiple segments. For a given γ-ray interaction point one segment collects the net charge (energy) deposited while neighbouring segments record transient (image charge) signals that return to zero after the charge collection time. The net segment energy deposition can locate the γ-ray interaction to within the volume of a segment, i.e. several cubic centimetres. However, by exploiting the detailed shape and magnitude of the induced signals, which depend on the exact location of the deposition of energy in the crystal volume, it is possible to locate interactions in the crystal with sub-segment (few millimetre) precision.

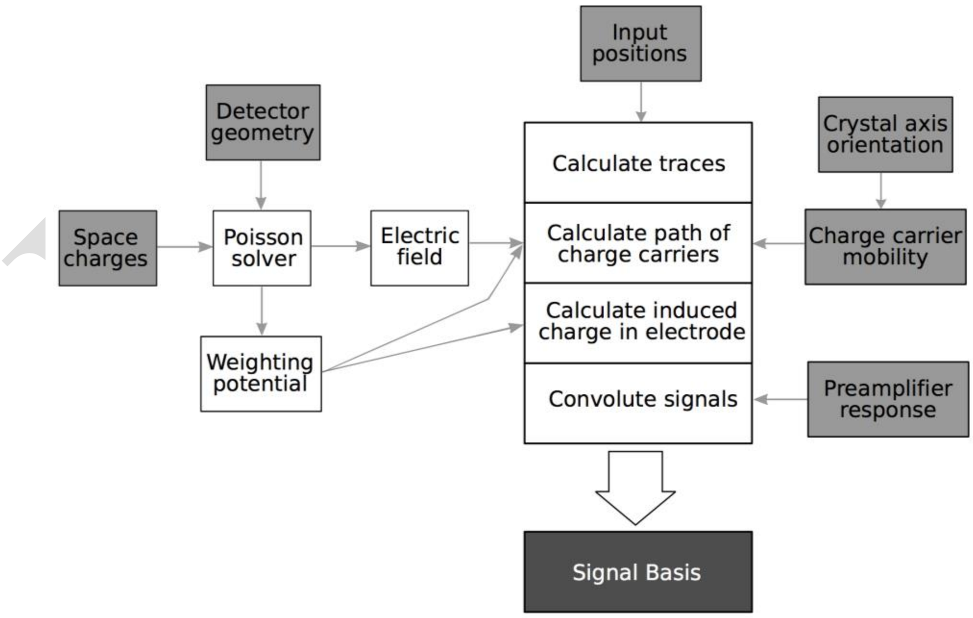


Figure 1: The AGATA Data Library methodology for basis generation

The implementation of the PSA for AGATA depends on first simulating the drift of point charges deposited on a grid of points which span the detector volume utilising the AGATA Data Library (ADL) code [Bart Bruyneel and Benedikt Birkenbach IKP (Eur. Phys. J. A (2016) 52: 70)]. The methodology used to calculate the pulse shape database (signal basis) for each detector type is shown schematically in figure 1. The grey boxes indicate the key input parameters required by the code to enable a reliable basis to be produced. These parameters include the geometrical shape of the detector, the impurity gradient of the crystal, the crystal axis orientation, information on the mobility of the charge carriers and the preamplifier response function. Cross talk correction (both integral and differential) is then subsequently applied. The optimisation of these parameters is achieved through comparison (validation) with experimental data both through a programme of detector characterisation and in beam measurements. With a realistic set of basis signals PSA is reduced to the task of fitting the waveform data, event-by-event, with the best possible linear combination of basis signals.

The PSA algorithm developed and implemented for AGATA phase 1 is based on an Adaptive Grid Search (AGS) approach using a simplified single interaction per segment approximation. This has been well established within the collaboration and has yielded reasonable performance which has enabled the success of the AGATA Demonstrator and AGATA Phase 1 campaigns.

Upgrade/Plans for Phase 2

The physics goals of the AGATA phase 2 campaign will require improvements to the performance, both capability and computational, of the AGATA PSA algorithm. PSA is the most computationally intensive aspect of the AGATA computing system, and thus drives the processor requirements. However, PSA is also a parallel process carried out at the individual crystal level, allowing a relatively straightforward architecture with multiple independent processing nodes.

The existing PSA algorithm uses a simplified single interaction per segment approximation while allowing multiple segments to be considered within a crystal. The algorithm also uses a crystal level calculated basis which has been optimised throughout the first phase of the project in an attempt to maximise the performance of the PSA. The crystal level single hit pattern of determined interaction positions and the subsequent results from the Gamma-ray Tracking algorithm indicate improvements are required at the level of the PSA. For example, clear (non-physical) clustering of interactions is noted within the full crystal volume. This can only be explained if something is not correctly described in the calculated basis. The resulting Peak to Total and efficiency achieved using this basis is subsequently below what would be expected from pure simulations.

The computation performance of the algorithm(s) needs to be optimised to run on highly parallel, multi-core nodes. The existing algorithm is limiting the count rate capability of AGATA phase 1. In moving to AGATA phase 2 the algorithm(s) will be optimised to adapt to the new platforms and to allow flexibility in basis format, PSA outputs, and pre-processing options. Further, to take advantage of the performance gains provided by massively multi-core processors these routines will need to be vectorized and multi-threaded.

In order to improve the capability performance of the PSA a number of improvements are proposed.

(1) An investigation of the dominant factors limiting the performance of the calculated basis. This would include:

a. An evaluation of the impact of the temperature dependence of the mobility parameters

b. The impact of a realistic charge cloud size

c. Crystal dead layer related effects – the dead layer around the core electrode

d. Neutron damage limitations – how the degree of neutron damage influences the efficacy of the signal basis in addition to the energy resolution correction already implemented.

e. The impact of the electronics signal chain (preamplifier grounding/configuration)

These impacts will be evaluated by performing a comprehensive set of experimental characterisation measurements to optimise the computed basis (for example full scans or pencil beam measurements) and a set of in-beam measurements to evaluate the impact on the resulting position resolution achieved. Necessary changes would then be made to the signal basis used by the PSA algorithm to identify interaction locations.

(2) The implementation of the existing AGS algorithm with be optimised for performance throughput. This work will include the addition of the export of PSA position uncertainties from the AGS algorithm to the Gamma-ray tracking algorithm. This will potentially allow performance improvements in the gamma-ray tracking.

(3) The PSA algorithm will be upgraded to include the handling of multiple interactions in a segment. The performance of this algorithm will be evaluated and implemented for phase 2.

(4) An exploration into the use of other (non AGS) PSA algorithms for future implementation. The focus is on the possibilities available using machine learning and will build on initial work that has started within the collaboration.

For the next phase of AGATA, it is expected that the primary experimental data for physics analysis will be stored in the post signal PSA/GRT format of γ-ray interactions and energies. However, the option to output and store waveform data is also required, for example, to enable debugging and testing of PSA and tracking algorithms.

Costs & Efforts

<u>New PSA Farm</u>

The existing AGATA PSA farm will need to be upgraded in order to deliver the performance required for AGATA phase 2. The dual requirements of improved throughput and increased capability in the PSA algorithms make this an essential requirement. The PSA processing will also need to benefit from intelligent use of external triggering in order to improve the efficiency of the trigger validation process.

For the existing AGS and the implementation of the multiple interaction per segment algorithm a CPU based architecture will likely provide the optimum solution. The AGS algorithm requires 10ms per crystal on the existing hardware, the more computationally expensive multiple interaction algorithm requires 10ms per crystal to process the data based on a 2016 Xeon core. Assuming a conservative 4kHz per crystal post trigger this implies 40 cores per crystal or a 7200-core farm for 180 crystals. The alterative, less mature, future algorithms based on a machine learning approach will benefit from a GPU based architecture. This solution will be investigated as part of the continuing R+D. Details on the proposed architectural solution and costing for the non GPU phase of the project can be found in the following data flow subsystem section.

The implementation of the improvements to PSA will need to be staged. The optimised existing AGS algorithm could be implemented on the existing farm and also used to prototype the new architecture. The more advanced multiple interaction algorithm could be implemented with limited performance on the existing architecture but would realistically require the improved computation performance facilitated by the new architecture. The proposed solution for this can be found in the follow Data Flow section of this document.

<u>Effort</u>

The improvements to the PSA basis and associated optimisation of the input parameters will require the AGATA detector characterisation team to coordinate a series of measurements of AGATA crystals. The data collected will be analysed and compared. This will require 4 FTEs of PDRA effort.

The performance optimisation of the PSA algorithms will require software engineers with oversight from physicists to ensure the end user requirements are met, this will require 4 FTE of software engineer support and 1 FTE of a physicist.

The PSA algorithm work will require the effort of both Physicists and software engineers. The implementation and optimisation of the multiple interaction algorithm will require 4 FTE of a Physicist and 1 FTE of a software engineer.

The investigation of other PSA algorithms will require 2 FTE of physicist effort.

Data Flow Subsystem

Introduction

The full 4π AGATA system comprises 60 triple Cluster Ge detectors, the associated electronics, data acquisition and related equipment. The goal of phase is to operate the full array. This section specifies what is required to complete the Advanced phase 2 in terms of cost and FTE for our WG.

The data flow structure (Fig. 15) has been designed for the LNL phase operation and this architecture, which is presently working at GANIL is the foundation/core system to build the advanced phase 2 of the project.

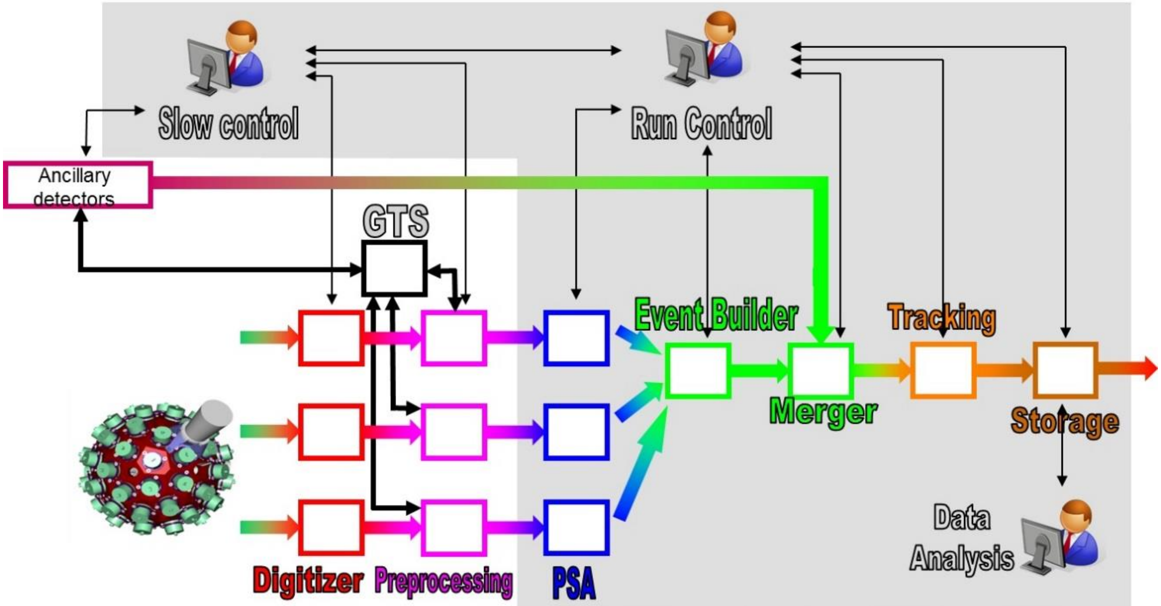


Figure 15: Data Flow structure for Phase 0, phase 1 and beyond.

The computing infrastructure deployed for the demonstrator at LNL, for the GSI and GANIL phases consists of:

- One computing node per crystal to collect data from the pre-processing electronics and for Pulse Shape Analysis .
- Cluster of computing nodes for event building, merging and tracking.
- Set of common nodes for the Run Control, Disk Server, SRM (Storage Resource Management- i.e. data transfer to grid), Slow Control, Data Analysis, spares …
- Disk servers for raw data and for backup
- Switches
- Visualization workstations (the DAQ working group administrates also the

Data Analysis workstations).

The current infrastructure of the data flow is composed of :

- 4 analysis servers
- 45 acquisition servers
- 1 backup server with 50 TB available
- 1 CEPH cluster with 168 TB available @700 MB/s (4 OSDs, 3 Monitors, 1 RBD client)

Beside this infrastructure, one must also consider all the software packages needed for data transport, algorithms integration, control the system and the hardware, graphical user interfaces, slow control system (see Electronics section), backup the system, provide interfaces for data analysis, …

The installation of the DAQ hardware and software was completed in April 2012 and since then improvements and tests have been performed continuously. The Data Flow software and hardware have performed in a very stable way during the AGATA-PRESPEC campaign and still doing so for AGATA@GANIL campaigns.

DAQ upgrade & challenges towards full AGATA:

The AGATA DAQ system will continue to use the architecture of NARVAL/DCOD. The system is based on a set of coordinated processes of 3 kinds : Producers (handle incoming data), intermediaries (filters, mergers, …) and consumers (data storage into files, histograms, …).
One of the main drawbacks of the current infrastructure is due to the constraint imposed by the electronics : hosting the PCIx cards requires one server dedicated to each crystal. This constraint has a cost and strongly constrain the computation model. We could imagine different computing models just based on the physics requirements but this is very difficult given the variety of the requirements and count rates. The future DAQ design can be based on different possible options that will presented below but in all cases they are based on the newly developed feature.

With DCOD/Narval, memory access and network transmission are managed by dedicated modules: the Memory POSIX Handler (PMH) and Common Transport Layer (CTL). They are no more embedded in the DCOD/NARVAL processes and this feature is well suited for the full AGATA as it will provide the required flexibility, modularity and robustness for the full array. Moreover, it will be easier to optimize separate codes and easier to include new protocols in the system. DCOD and the associated PMH/CTL diagram can be seen in Fig.2.

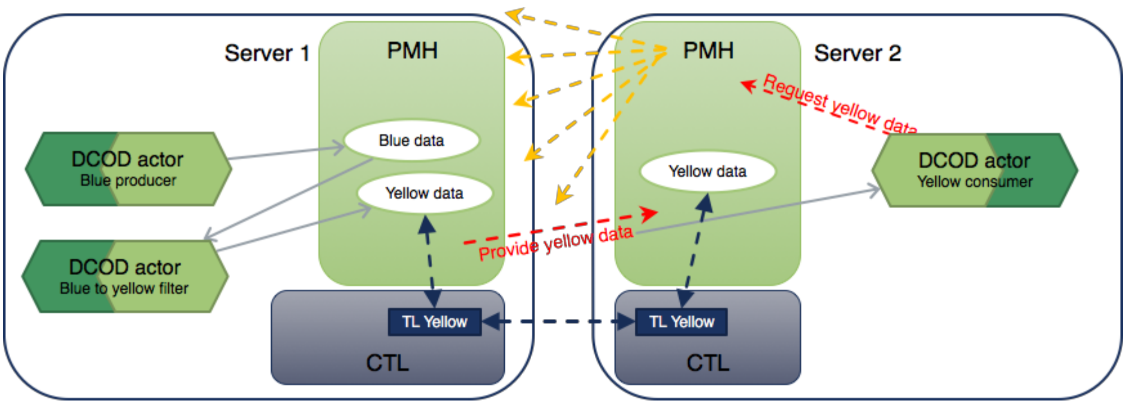


Figure 16: Example data distribution with DCOD and the associated PMH/CTL

The DAQ upgrade will be performed in two phases according to the electronics evolution and in both cases DCOD with its new features will be used.

Phase2 DAQ upgrade (2020-2025):

Event dispatcher and cache miss optimization for a better PSA performance :

With today's algorithms and with future faster processors, one may be able to easily process the PSA at 10 kHz /crystal with one Anode/crystal. With the load balancing feature, different PSA algorithms can be used depending on the event complexity. However, some limitations can not be solved with a more powerful server/computer with the existing algorithms. Two possible options can be implemented :

- ***Event Dispatcher :***

We know that some algorithms can perform better on single hit than multiple hits. If this is the case and if the PSA team elaborate such algorithms, we can set a first level filter that dispatches data to the right algorithm farm and hence improve the performance. The proposed mechanism is displayed in the Fig.3:

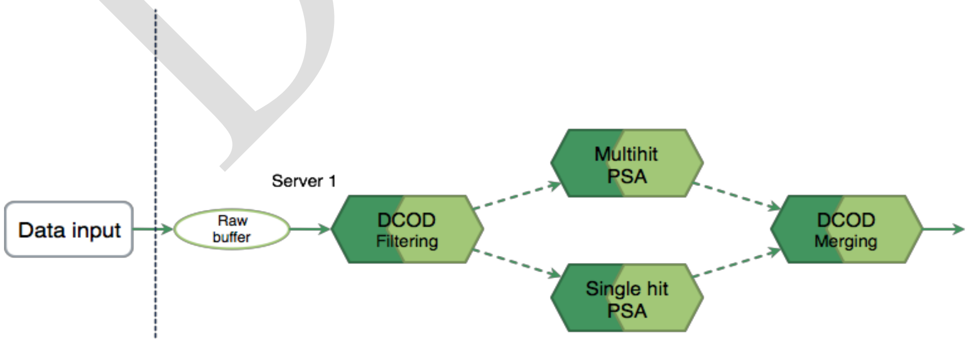


Figure 17 Event Dispatching using two different PSA algorithms

- ***Cache miss optimization :***

We know that the performance of the PSA in terms of rate, is due to the memory access/cache that that is needed all time while running the current PSA algorithm. An innovative option based on splitting the PSA task within a giver crystal over 2 sets of slices.

The total hits in the front of a crystal (slice 1 and 2) correspond to 45% of the events while slice 3 to 6 correspond to 55% of the total events. Because of this, one can split the basis for the relative events and hence perform the PSA for the hits in slice 1-2 in one server and the rest in another one. Today's performance is limited to 4-5 kHz/crystal and the proposed method will allow a gain of factor of 2 for the data processing over the PSA. This is illustrated in the following figure for 2 crystals.

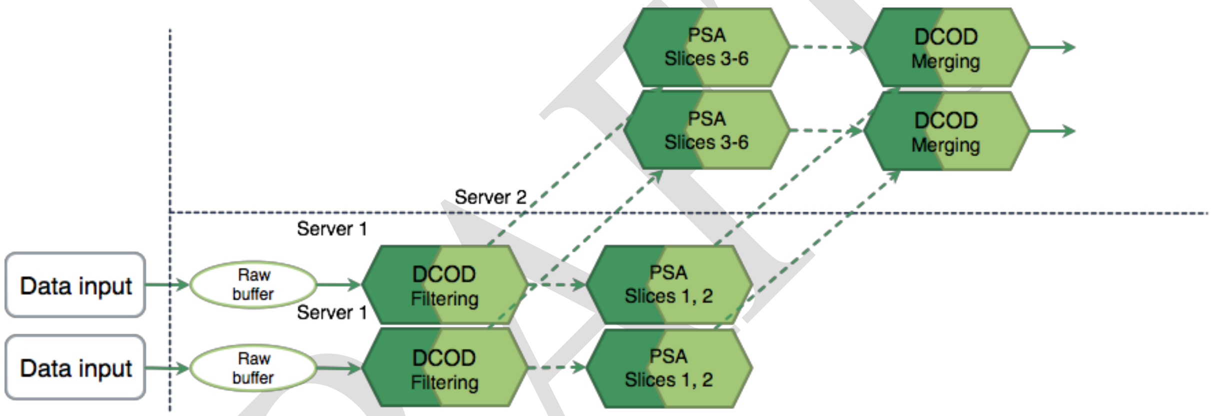


Figure 18 : Schematic view of splitting the PSA job over two sets of slices by splitting the basis

Phase2 DAQ upgrade (beyond 2025):

Once, the new electronics is ready, we can make additional improvement for the DAQ-system since we will no longer deal with servers containing the hardware for the electronics.

The full AGATA will be more complex but the development of DCOD will cope with this complexity as the modularity will be increased.

The new electronics as being designed, is based on the scheme described in Fig5. As the new electronics Boards (NEB) will be based on ethernet and hence no point-to-point connection anymore, the CPU can be distributed over High Performance Computer farms (HPC). In this case 1 node/crystal is not necessary with the load balancing and new technologies

The advantages are clear and the issues that are encountered with the current one will be cleared.

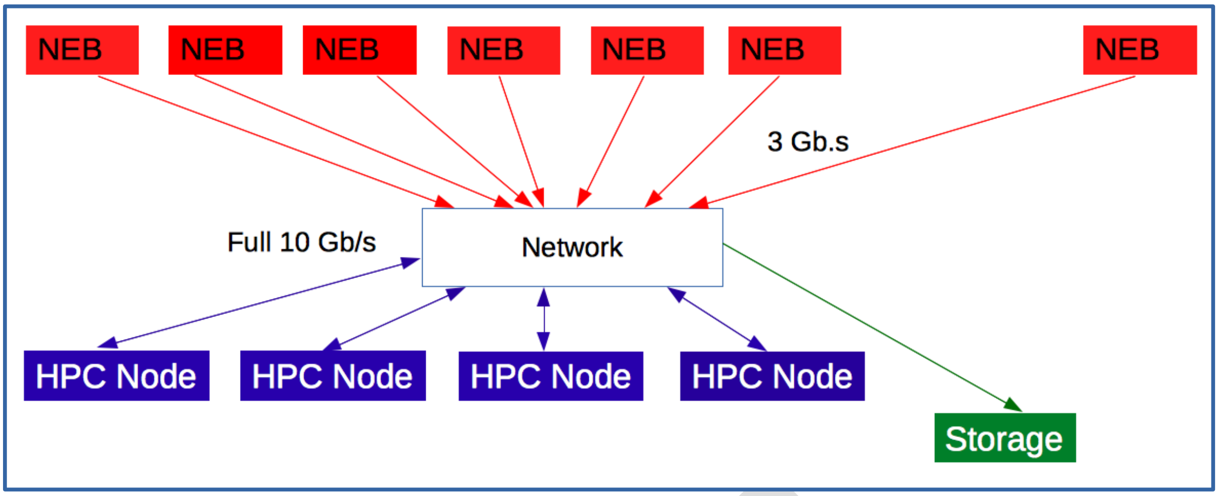


Figure 19: Possible DAQ layout with the new electronic boards

- ***GPU optimization***

With such an electronics, one can use a GPU optimization for an additional improvement of the DAQ-system. The corresponding scheme is shown in Fig.6

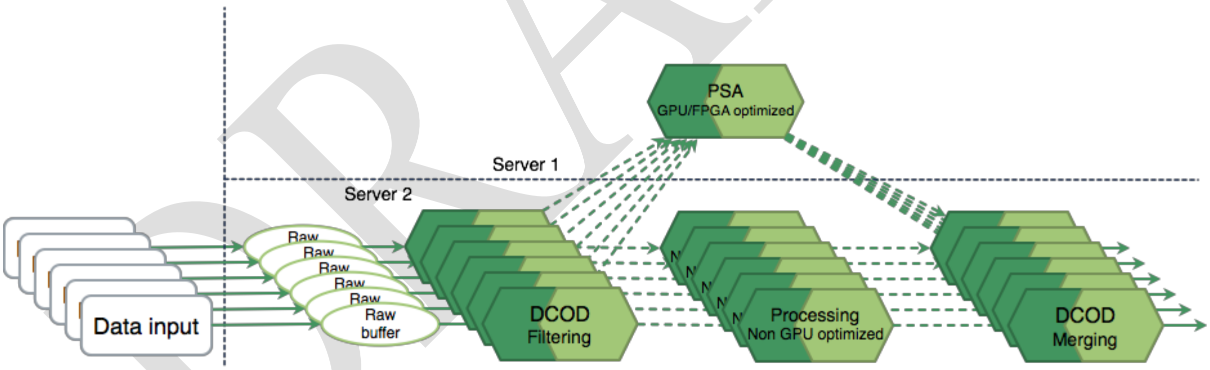
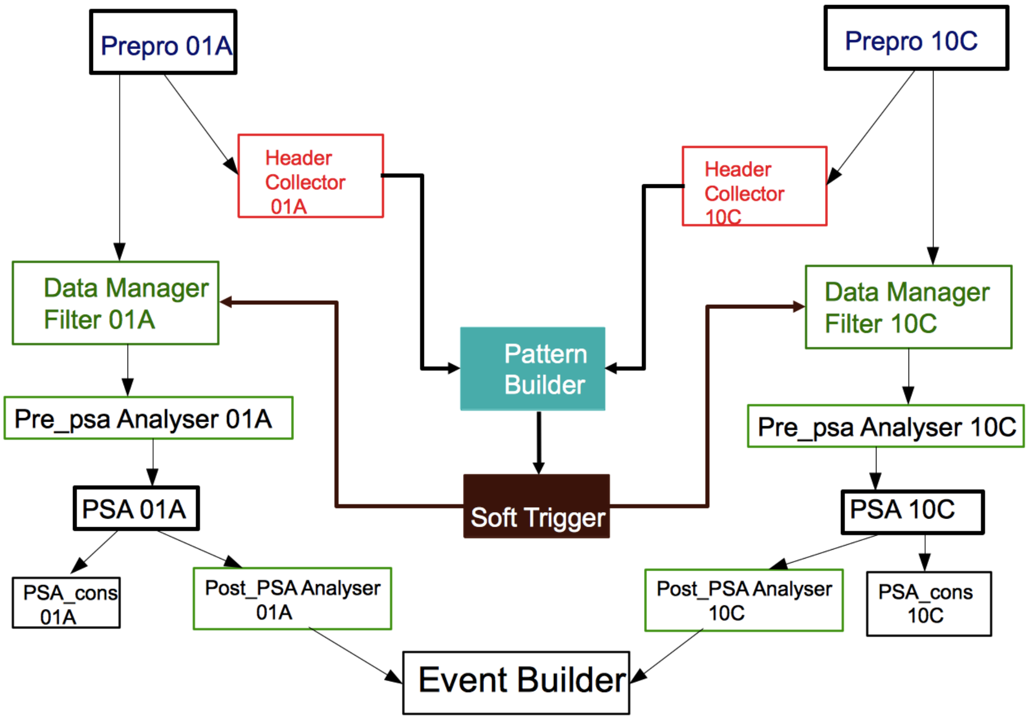


Fig.6 : High performance computing farm sketch for the phase 2

Trigger software implementation :

Beside the advantages of the new electronics scheme in terms of infrastructure and performance, the trigger software that is already implemented represents a major achievement for the DAQ.



New trigger system (software)

The Data flow system needs other improvements and upgrades that are connected with other WG tasks, but will make the operation of the full array more robust.

Other upgrades :

Upgrade/New Monitoring Software to be added in the system :

In the current configuration, a new tool called AgaSpy has been recently developed using DCOD. With AgaSpy, the online monitoring of the experiment can be performed through a selection of relevant spectra for each actor. This action is very important (as one would expect) and becomes mandatory if the raw traces are not stored anymore. However, with this new tool, the number of parameters that need to be checked/controlled becomes extremely large with the increasing number of actors as a function of the crystal number. Clearly, automatic procedures need to be developed in order to safely run the experiment with the proper warning/watchers and messages that should be provided to the users in real time. For example, any possible issue with the DAQ (input/output, bit-swapping, missing channels, TS ordering …) should be reported in real time. More informations into the data flow during the runs such as Crystal failure, LN2 filling, … can also be implemented.

Other features related to monitoring of the electronics (scope visualization, threshold and MWD parameter checking …) can be performed in collaboration with the FEE WG and, hence, need to be clearly defined.

Tracking & challenges beyond where to go with tracking

A straight forward improvement can be expected if the PSA could provide errors on the position and energy of the interactions. Beside this, new developments using hybrid algorithms (Forward+ Backward tracking) and machine learning technology is a possible way to move forward.
Machine learning techniques are used to detect γ-ray burst in optical surveys. It may also possible to employ this new technology for tracking of γ-rays in AGATA. The Compton-scattering formulae as well as the photo-absorption and Compton-scattering could be imposed as rules for the clustering machine learning. We know from previous development, that the Fuzy logic is useful for problems that are well described, but complex and become more complex when there is noise or uncertainties affecting data. However the cluster quality proved to be superior with simulated data as compared to the forward tracking. Machine learning for clusterization is definitely a way to move forward. This new technology may also play a role in the future regarding the treatment of pair-production events.

Manpower is needed as only few people are working on this (and not full time) : A. Korichi, A. Lopez-Martens and T. Lauritsen. At least 3 FTE are needed.

Data analysis challenges towards full AGATA

An existing documentation provides a guide to help the users analyzing the AGATA data produced at the local level processing i.e. before any building of events has been produced. It includes then traces / energy / time calibrations, alignments, cross talk corrections and any other corrections to improve the quality of the data. This procedure will be used for phase2 with possible improvements, for example by implementing a faster/automatic way to perform the data analysis.

A new software called cubix is now available in the GammaWare package. With cubix, one can perform the data analysis in the ROOT environment (for the moment only with 1D and 2D spectra). Gating on γγ matrices can be performed with background subtraction. However, one has to improve the tool in order to play with higher fold coincidences, as we do today with the 3D and 4D 4-play cubes in radware.

Furthermore, with the advent of γ-ray tracking detector arrays, it should be possible to measure entry distributions (HK) and the quasi-continuum of γ rays with better accuracy than was possible with the previous generation of escape-suppressed detector arrays. However, the techniques for doing so may represent more of a challenge for these new tracking arrays. Unfolding the data for the quasi-continuum analysis requires the construction of the response function. Within the AGATA-GRETINA collaboration, we have developed the techniques necessary to measure an entry distribution using γ-ray tracking, but there still additional complications that need to be solved. This development is underway. However, at the moment, only T. Lauritsen and A. Korichi are working on it.

Data re-processing/distribution and storage challenges towards full AGATA

Currently, raw data produced during the experiments are dispatched on the GRID in two different centers, CCIN2P3 and INFN Bologne, used as TIER1: the duplication process is a security in case of failures/losses of one of the TIER1. The GRID itself is seldom used to re-process the data and hence the users usually download their data set to local storage where they can run emulators able to manage part or the full workflow as it is done online with NARVAL/DCOD. The GRID infrastructure is probably too heavy/not suited for these kind analysis/replays. New technologies, i.e. iRODS, are foreseen as future solutions and can be investigated. The chosen solution should also allow efficient and user-friendly re-processing on dedicated infrastructures.

Because of the increasing number of capsules and higher counting rates, storing raw traces needs to be avoided as much as possible: it is simply impossible for high spin experiments. However, there might still be experiments for which raw data can be stored at the trace level. For instance, developments of PSA algorithms linked or not with higher processing level. Indeed there are ideas to use tracking algorithms as a constraint to better identify interaction points in a crystal. As well, through machine learning techniques (deep neural networks) a possibility could be to fill the network with the traces of all the detectors and to get as output the different tracked gamma-rays. Such developments requires a high computing resources offline. It should be noted also that the current software solutions to replay the data which run on single computer (such as femul emulator, GammaWare or NARVAL standalone version) are clearly, as such, not adapted. We do need to set up more advanced solutions adapted to the computing infrastructures to come: virtualization, containers, cloud technologies and heterogeneous hardware (GPGPU / FPGA).

Note that even without traces, data replays (for instance to re-building, re-merging + tracking) could be a long process as we experienced during the NEDA + DIAMANT campaign. A faster analysis represents a challenge to move forward.

Data Managment and Policy

The AGATA collaboration commits to have implemented as early as possible a "responsible data management" policy, as part of Open Science. This means measures will be taken when the data are produced and analysed to make its later storage and dissemination possible.

The AGATA collaboration will contribute to implement and follow a Domain Data Protocols (DDPs) to ensure proper implementation of the AGATA Data Management Program (DMP).

Cost estimates and efforts:

The network infrastructure needs to be scaled according to the number of crystals. This is technically not an issue since the used switches are stackable. A cost estimate can be only tentative since the processor price is subject to fast and unexpected market fluctuations. In addition, the cost is much lower if the order is grouped on a large number of units. As a first cost estimate, the phase 2 with 45 to 180 additional crystals, assuming an upgrade for the processing capability as 2 PC's for each crystal preprocessing and PSA is given below. Racks and cooling infrastructure are not quoted.

If 12 crystals are expected to be delivered every year (see detector section) and if the electronics is ready, the following budget (kE) is required :

New hardware	90 crystals 2π- 2022	135 crystals 3π- 2026	180 crystals 4π- 2030	Cost /unit	Cost Total
Servers/crystal	90	90	90	3	810
switch/20	6	6	8	3	60
backbone switch	1	0	1	5	10
EB, Merge, Tracking	3	3	4	3	30
DAQ servers	5	5	5	3	45
CEPH upgrade	7	7	7	15	315
CEPH monitors	5	5	5	1.5	22.5
Analysis machines	2	2	2	5	30
Phase1 upgrade (servers)	45			3	135
Total					**1457.5**
Total (including , cables ...)	605,5	465,5	479		**1550 k€**

It should be noted that the hardware lifetime is finite. If the machine lifetime may be of 5 years of more, the guarantee is of 3 or 5 years only (and the cost of an extended guaranty does not compete with new machines). After this period, any broken machine or disk array has to be replaced. The performances of the system would anyway profit from any processor upgrade. It is therefore safe and valuable to replace all the servers every 5 years.

Needed efforts : 10 FTE

Data Flow :

- DAQ Developments : 2 FTE from now (during 3 years)
- DAQ Maintenance : 0.5 FTE
- Network system admin : 1 FTE

Tracking :

- Developments : 3 FTE

Data analysis and re-processing and storage :

- Developments : 3 FTE
- Maintenance : 0.5 FTE

Detector Infrastructure Subsystems

- Introduction

The AGATA infrastructure consists of several items that constitute the Detector Support System (DSS). The present DSS is ready for a setup with 15 ATCs at GANIL.

Some items are obsolete and built with now discontinued components. Important upgrades are in progress. These developments will use modern components to build (backward compatible) modules sufficient for an array of 30 ATCs with the possibility to easily extend the production for a full configuration of 60 ATCs.

The extension of the array to 30/60 ATCs will require the production of new LVPS crates and modules, an upgraded LN_2 detector filling system, the purchase/installation of a new HV system, and the production/installation of additional sets of cables, like those developed and produced for the phase 1 of the project. The EMC will be tested and improved when needed.

The implementation of an array with 20 ATCs, as given in the phase1 MoU, will use the first upgraded crates and modules as an intermediate step toward the full array configuration.

The DSS system consists of:

- **Low-voltage power supply (LVPS):** each unit powers 111 HPGe preamplifiers, 3 digitiser front-end electronics for one triple cluster (ATC) and the Profibus. At present, 18 first generation crates and modules are available.

  A new upgraded version is under development with improved characteristics: more compact and with lower power dissipation in agreement with the characteristic of the new V2 and V3 digitizers (see Electronics chapter). The project is the result of the collaboration between the Axis Company and the Irfu, France. The new LVPS crates and modules will be produced by Axis.

- **High-voltage:** a commercial CAEN HV system is presently used. Two SY527 mainframes and 10 A832P cards (12 channels with individual enable) are available from GAMMAPOOL loan. The system can power up to 120 channels, including spares. All components are more than 20 years old: they are now discontinued, and the repair may be problematic. This high-voltage system cannot be integrated in the DSS control system.

  A new system is necessary to power up to 180 channels. Two solutions (CAEN SY4527 mainframe + A1560H boards or ISEG crate + EHS 8260P boards) have been tested. Performance differences are marginal, and both systems represent a valid long-term solution that could be easily integrated in the DSS control system.

- **LN_2 detector filling system (Autofill):** the present autofill system has been developed and produced by GSI. It is composed of 3 groups of modules (Profibus Crate, Valve Control Crate and Valve Power Supply) and each group is capable to manage up to 8 detectors. It can be used to keep a maximum of 24 ATC detectors (cryostats) at liquid nitrogen temperature. The system uses 2-wire connection to monitor the temperature of one PT100 in each cryostat and requires external PLC cards to read the second PT100 and the LN_2 level card in each detector. The control/command processes are running on an industrial PLC. An additional PLC unit is available as spare. The Graphic User Interface (GUI) and the PLC processes are based on MUSCADE, a set of tools, libraries and applications developed at Irfu, France. The LN_2 filling system is connected to a phone dialer to notify the occurrence of alarm conditions.

The upgrade necessary for 30 ATCs has already been defined: the project will be developed by Irfu, France using modern PLCs, hardware and software components. The configuration will be based on industrial items and will include 2 identical groups extended to 16 detectors each. Additional parameters will be monitored with improved performances as requested by the AGATA Detector team. The system can be easily duplicated to operate 60 ATCs. The GUI will handle both the LVPS and the autofill systems using the Profibus communication protocol. The open source EPICS environment will substitute the MUSCADE proprietary development framework.

- **Cables and patch boxes:**
  The DSS modules developed for the AGATA phase 1 of the project are ready for 15 ATCs. Cabling is available for 45 capsules:

  - Cables:
    LVPS cables (±6/12V, 48V, 5V): produced by Irfu, RCE and Axis companies;
    HV cabling: collaboration;
    Profibus network: produced by Irfu and FORCLUM company;
    Preamplifier to digitiser MDR cables: industrial product;
    Optical cables from digitiser and pre-processing cards: industrial product.

  - One patch box per detector (ATC or ADC) with LV (±6/12V) distribution to the capsules and LV filtering, Bias Shut Down (BSD) and LN_2 level monitoring boards. The box is attached to the Dewar.
    21 patch boxes are presently available. They have been produced with LV filters (Irfu, MKM and Axis companies, Strasbourg), BSD (GSI) and LN_2 monitoring boards (IKP-Cologne). Adjustment of the LN_2 monitoring card is done by Cologne, in collaboration with the Detector Module working group.

- **EMC:** The Infrastructure Team is in charge to qualify the global grounding of the array; qualifier CSNSM, France.

- Upgrade for Phase 2

LVPS

Eighteen units of the first generation have been bought from the Axis Company. They can be used with V1, V2 and V3 digitizers and cover the needs of 15 ATCs + 3 laboratories for tests (Axis and Irfu, France and detector development at IKP, Germany).

The upgrade is compatible with the lower power consumption of V2 and V3 digitizers and satisfy the stronger space constraints of the evolving array. The LV modules for 8 ATCs will occupy two 8U high crate units: one including eight 48V modules and a Profibus Controller and one including eight ±6/12V modules and a Profibus Controller. This could allow to separate the 48V modules from the 6/12V modules and reduce the space close to the array if necessary. Four crates (32 modules), are necessary for an array of 30 ATCs (90 capsules + 6 spares) and twice as much for the full array (180 capsules + 12 spares).
Two "standard" 47U cabinets (2.1 m high), placed close to the array, will host the crates with the 6/12V and 48V modules for 30 ATCs. Additional fans installed in each cabinet will guarantee sufficient air circulation. In harsh environment, external air conditioning must be

considered. Two extra systems of two crates with one of each module types are needed at Axis and Saclay and will be available as spare.

Preliminary cost estimate for the first module (8 ATC): 60 k€, next modules: 36 k€ (up to 20% discount for volume production), extra systems 10 k€.
Using only new crates and modules for the whole array, the total cost will be 183 k€ for an array of 30 ATC (90 capsules+6 spares), + additional 144 k€ to reach 60 ATCs (180 capsules+12 spares).

HV

The replacement of the present HV system will be integrated in the DSS control system (software libraries available and standard USB/Ethernet communication protocol).
An additional module could be necessary to adapt the HV shutdown signal from the LN_2 autofill system to the HV boards.

Cost estimate (CAEN):
58.7 k€ for 30 ATC (10.8 k€ Mainframe Full + 12x3.95 k€ A1560 Boards + 0.5 k€ for the signal adapter crate for the HV shutdown),
+ additional 53.2 k€ to reach 60 ATC (5.8 k€ Mainframe Base + 12x3.95 k€ A1560 Boards).

Autofill + PLC + Profibus DP network

The upgraded LN_2 filling system for 30 detectors (+ 2 spare channels) will use industrial components and is based on two identical groups of 16 detectors. Each group will be connected to an independent buffer tank of 300 l. In this configuration, each buffer tank will be refilled twice per day.
For an array of 60 ATCs, the configuration will include four buffer tanks, one for each group of 16 detectors. An alternative could be to use a large volume "external" tank with internal buffer tanks (at least 600 l) used only for emergency fill.
The full system will be integrated in one cabinet (2m high) for 30 detectors, and 2 cabinets for 60 detectors.

Cost estimate: 61,5 k€ for 30 ATC (including 2 spares), to be doubled for 60 ATC.

Cables for 30 / 60 ATCs

- LVPS cables:
  - 45 x 48V cables are available at GANIL, 45 extra cables are needed for 90 capsules + another 90 to reach 180 capsules.
    Cost estimate 2.5 k€ for 90 capsules + 5 k€ to reach 180 capsules,
  - 15 x 6V/12V cable sets (including the 2 cables from LVPS to patch box) are available at GANIL, 15 extra sets are needed for 90 capsules and another 30 sets to reach 180 capsules.
    Cost estimate 10 k€ to reach 90 capsules + 20 k€ to reach 180 capsules.

- HV cables: 45 are available at GANIL, 45 new cables are needed to reach 90 capsules + another 90 to reach 180 capsules,
  Cost estimate 3 k€ for 90 capsules + 6 k€ to reach 180 capsules.

- Other cables:
  Shutdown: 90 cables to reach 90 capsules + 90 extra to reach 180 capsules, (10€/cable),
  Shutdown adapter sets (with new HV system): 90 cables for 90 capsules + 90 extra to reach 180 capsules, (5€/cable),

PT100 cables (3 o 4w) from patch box to Autofill-PLC: 2x30 “cables + new connectors on patch box” to reach 30 ATC + 2x30 extra to reach 60 ATC, (about 50€ for a PT100 20m cable, including connector to patch box + 15€ for the patch box connector)
LN_2 level reading: 15 cables to reach 30 ATC + other 30 to reach 60 ATC, about 45€ for a 15m cable with connector on both sides)

Cost estimate: 220€ €/ATC resulting in a
total amount of 6k€ to reach 90 capsules + 7€ to reach 180 capsules.

- Profibus cable and terminators. Cost estimate: 3 k€.

- The patch boxes for 21 ATCs have been produced by IPHC (Strasbourg).
  Another 10 patch boxes are needed for 30 ATC + 30 patch boxes to reach 60 ATC.
  Cost Estimate cost 2,8 k€ to reach 30 ATC + 8,5 k€ to reach 60 ATC.

  The 70 LN_2 cards for the full array have already been produced.

- MDR cables of 10m are available to complete up to 45 capsules + spares.
  315 MDR cables are necessary to complete 30 ATCs (90 capsules) + another 630 MDR cables to reach 60 ATCs (180 capsules).
  Cost estimate: 130€/MDR cable resulting in
  41k€ to reach 90 capsules + 82k€ to reach 180 capsules.

  Spares for all different cable types are also needed. An extra quantity of ~ 10% should be considered.

- Optical cables:
  - For V1 and V2 electronic channels:
    Optical cables are available to complete up to 45 capsules (with 24 V1 type and 21 V2 type electronic channels + V2 type spare).
    - The MPO optical fibers for Digitizer to pre-processing connexions, from experimental room to DAQ room (60m, max 100m), are provided by the Host Lab.
      The FEE group is taking care of the necessary brace adapters for the new digitizers.
    - From pre-processing/GGP to GTS tree (12 m):
      100 total optical links are already installed at GANIL: 4 for the 24 channels of V1 electronics and 21 for the 21 channels of V2 electronics.
    - LC/LC optical links (1m) from ATCA to GTS:
      40 of these links are presently installed at GANIL and cover all necessities for the 24 channels of V1 electronics. V2 and V3 electronics do not need such optical links.
  - For V3 electronic channels:
    - The optical fibers (1 cable including TX and RX /capsule, 10 Gbps Ethernet, cost estimate 90$/capsule) from pre-processing to DAQ, from experimental room to DAQ room (60m, max 100m), are provided by the Host Lab.
      These optical fibers are not compatible with those used for V1 and V2 types electronics.
    - The connexions from pre-processing (in experimental area) to the Global Trigger System tree (or eventually SMART, anyway placed in the DAQ room) will require:
      One 60m long MPO optical cables grouping 6 of these pairs/group of 6 capsules,
      Plans are to produce around 60 channels of V3 electronics to substitute part of the ATCA V1 electronics.

Global cost estimate: 6,3k€ for 45 V3 channels or 7,8k€ for 60 V3 channels to reach 90 capsules + 12k€ to reach 180 channels.

- The Slow Control will require one 1 Gbps Ethernet connection per capsule to reach the Ethernet. The length of the cables will depend on the position of the Ethernet, still to be defined. In case it will be close to the DAQ room, whether the connection will be done with direct 60m copper cables or through Ethernet switches in the experimental room to group several 1 Gbps cables to 10 Gbps optical fibers to reach the DAQ rom is still to be defined.
  Maximum Cost estimate: 5k€ for 60 capsules to reach 90 capsules + 7,4k€ to reach 180 capsules

EMC

EMC tests and technical improvements will be progressively introduced on the installation under the CSNSM, France supervision. Costs are included in the item costs given in the table.

- Construction

The LVPS upgrade is designed in collaboration with the company Axis that will build the crates and modules.
The Autofill upgrade will be done by Irfu (Saclay).
The cables will be bought by the collaboration.

- Costs & Efforts of phase 2

The following table summarises the costs and responsibilities for the upgrade to 30 / 60 Clusters.

Items	No. units for 30 ATC (90 capsules)	No. units to be added to reach 60 ATC (180 capsules)	Costs/u. (k€)	Costs for 30 ATC * (k€)	Costs to be added to reach 60 ATC * (k€)	Funds provider
LVPS	15 ** 30	30	6,1	100,1** 200,2	158,5 ***	
HV	1 Mainframe Full + 12 HV boards	1 Mainframe Base + 12 HV boards	10,8/5,8 + 3,95	62,7	57,2	
Autofill + PLC + Profibus	1 system	1 system	61,5	67,5	67,5	Saclay
LVPS + HV Cables	45 cables 48V 15 sets 6/12V 45 HV	90 cables 48V 30 sets 6/12V 90 HV	-	2,8 11 3,3	5,5 22 6,6	Irfu, collaboration
Profibus Network	1	1	3	3	3	Saclay
Patch Box	10 **	30	0.28	3,1	9,3	IPHC
Other detector cables	-	-	0,22	6	7	
MDR cables	315	630	0.13	41	82	
Optical links including GTS and Slow Control	V1/V2: available V3: 60	V3: 90	-	9 5,5	13,5 8,5	
TOTAL				**315**** **415,1**	**440,6**	

* Numbers include 10% for spares

** Using existing production

*** Discount for higher volume production

The LVPS upgrade will be done by Irfu, France. The estimated time needed is:

- The prototype requires 4 to 6 months, including tests at Saclay and GANIL.
- The series production requires 2 to 4 months, depending on the number of crates and modules to be produced.

The Autofill upgrade will be done by Irfu, France. The estimated time needed is:

- Development of software and networks: 1.5 man-year
- Electrotechnical concept: 3 months
- Production monitoring for wiring cabinet + tests: 2 months

- Maintenance Commitment

Saclay is in charge of the maintenance of the LVPS and LN2 autofill control systems with the help of the local team for diagnostic and first maintenance.

Regular maintenance would require about **2k€/y** for replacement of fans, internal dedusting, change capacitors and international transportation.

Mechanical Infrastructure Subsystems

Introduction

This section comprises the description of the mechanical support structure of the AGATA array and the requirements for the installation of the AGATA array in any of the possible host laboratories. This mechanical project is based foresees the possibility to be used for a full 4π array. It includes:

- The manufacture of the necessary flanges to enlarge the Honeycomb up to a 30 / 60 ATC array,
- The main support of the array based of a shaft able to sustain and rotate the 2π array, which can be doubled for a 4π array, and
- Mechanical design/manufacture for a new scheme for detector mounting.

Upgrade/Plans for Phase 2

AGATA Main Frame

- *Present main frame (1π)*

The present AGATA main frame installed at GANIL is capable of holding the 15 flanges (1π) of the Modular Detector Mounting structure (honeycomb). This corresponds to 15 ATC's, 45 crystals. It has been designed in such a way that the detectors can be loaded or unloaded at a safe working height. This is done by allowing the structure to rotate so that all detectors can be loaded/unloaded from the horizontal position.

The frame can also translate from the target to an upstream position to allow access to the target area.

- *Future main frame (2π / 4π)*

The future AGATA main frame needs to, ideally, be able to hold the 2π array, to rotate it +/- 90° for detector loading procedure, to translate for access to the target area and it should be expandable to the 4π array and to optimize the compatibility between the different Host Labs. The mechanical design for the 2π array is being performed by STFC (Daresbury Laboratory), and will be validated by the AGATA mechanical working group as well as the future Host Lab. The structure for the 4π array would require to double it.

The main parts of the 2π array main frame are:

- Enlargement of the honeycomb up to 30 (2π) flanges,
- main shaft and its support,
- base raft,
- linear drive,
- cables support.

The honeycomb needs to be enlarged up to 30 flanges by adding 15 flanges to the present ones. When using AGATA in the target point of a magnetic spectrometer 3 cut flanges need to be used on the horizontal plane to allow for a continuous rotation of the system without clashing with the beam tube. Consequently the construction of 19 flanges, including 1 spare, is required.

Cost estimate of 1 flange: 1,5 k€
and for 19 flanges: 29,0 k€

This cost if for material only, machining with be provided by INFN Padova and LNL.

The main structure consists of the honeycomb being mounted to a rotating axle shaft. The axle shaft is hold on a support structure and fixed by two bearings. It is mounted on slide rails to allow for its translation and open access to the target chamber.

Cost estimate of Axle shaft and bearings: 9,8 k€
Cost estimate of Axle support structure: 3,5 k€
Cost estimate of Axle motor drive and gearbox systems: 16,7 k€
Cost estimate of slide rails for target access: 4,2 k€
Cost estimate of the motor gearbox and controls for slide rail system: 8,4 k€
Cost estimate for slide support plates and kinematic mounts: 4,2 k€

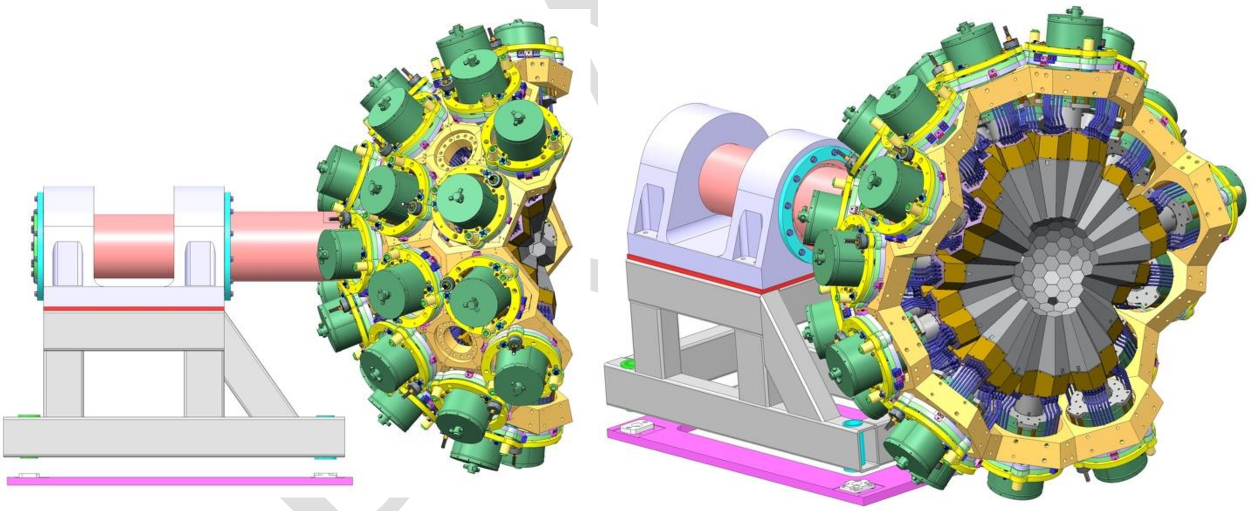


Figure …: AGATA array (2π) mounted on its rotating axle shaft. Platforms and lower supports not shown.

Surveyor pieces and procedure will be incorporated in the design. Additional materials (laser reflectors) installed in the cave prior to final alignment are of the Host Lab responsibility.

A control system with interlocks and step motor is required to ensure that the transition from rotational to transverse operation is undertaken in a controlled and safe manner.

Consideration also needs to be made for the grounding necessities for such a structure and cabling.

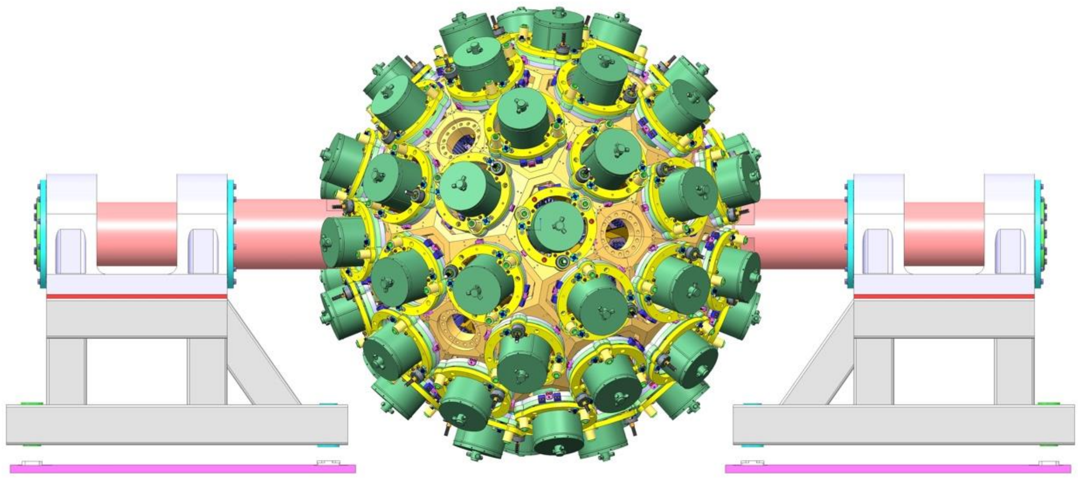


Figure …: AGATA array (4π) mounted on its rotating axle shafts. Platforms and lower supports not shown.

- *New scheme for detector mounting*

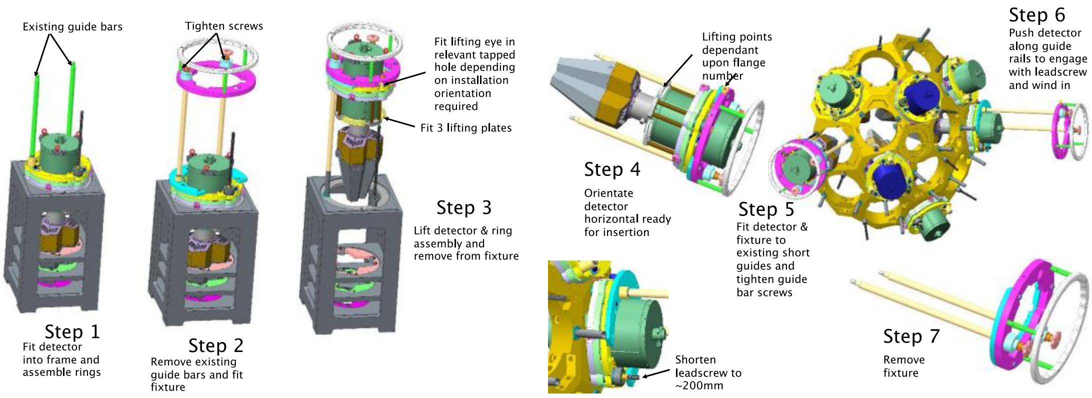
The main frame should be capable of allowing the AGATA detectors to be positioned within 0.5mm of each other. At this stage each detector should have its own adjustment system to ensure that detectors will conform to this requirement. A detector trolley and a detector jig are in use on site to adjust the orientation of the detector with the relative detector holding rings before being inserted in the honeycomb. Up to now 15 detector adjustment mechanics (holding ring systems) are available.

There are 9 detector legs and 3 detector leg adapters available for holding the detectors when not mounted on structure.

Provision must be made to allow detectors to be safely and repeatedly installed to their operating position.

A revision of this adjustment system is under study to simplify the procedure including shortening the leadscrew to avoid clashing with the lower support plates. The 15 flanges presently being used will need to be modified accordingly.

Cost estimate for 1 new ATC cryostat adjuster ring assembly, leadscrew and bars etc: 5,0 k€
and for 15 units: 75,0 k€
Cost estimate of the modifications to be made to the existing flanges: 1,68 k€
and for 15 units: 25,2 k€



The use of an EasyArm crane is planned to allow for precise lifting and safe load/unload of the detector.

Cost estimate of EasyArm crane and lifting jig: 41,9 k€.

Costs & Efforts

Costs summary for 30 / 60 ATC (i.e. 90 / 180 capsules)

item	Number for 30 / 60 ATC	Unit price [k€]	Total price for 30 ATC [k€]	Extra price for 60 ATC [k€]	Needed for 30 ATC
Honeycomb flanges (including 3 cut flanges and 1 spare)	19 / 45	1,5	29	+ 45	2021
Modification of existing HC flanges	15	1,68	25,2	-	2021
Adjustment rings	15 / 45	5,0	75,4	+ 226,2	2021
Axle shat and bearings	1 / 2	9,8	9,8	+ 9,8	2021
Axle support structure	1 / 2	3,5	3,5	+ 3,5	2021
Axle motor drive and gearbox systems	1 / 2	16,7	16,7	+ 16,7	2021
Slide rails for target access	1 / 2	4,2	4,2	+ 4,2	2021
Motor gearbox and controls for slide rail system	1 / 2	8,4	8,4	+ 8,4	2021
Slide support plates and kinematic mounts	1 / 2	4,2	4,2	+ 4,2	2021
EasyArm crane and lifting jig	1	41,9	41,9	+ 0	2021
GRAND TOTAL			230,3	+ 330,0	

Efforts estimate:

The estimate effort from STFC (Daresbury), for the design, trial assembly in the UK and assistance in installation in Legnaro and the following host site is 63 person months.
Production and mounting of the flanges as well as of the detectors by INFN-Padova, INFN-LNL is estimated about 20 person months.

Construction

Construction will be made by an external company.

Installation will be taken care of by Host Lab local team with assistance from INFN-Padova and STFC (Daresbury Laboratory).

Commitments

STFC (Daresbury) will assure the following of the project and the design adjustments when necessary.

AGATA Mechanical Infrastructure at the LNL Host Lab

Introduction

This section comprises the definition of the specific requirements to the various Host Labs for the mechanical infrastructure related to the installation of the AGATA array in one of the experimental areas of the possible Host Lab. As the future Host Lab presently considered is LNL, this specific situation is considered from now on.

The physics program planned at LNL/SPES, with stable as well as radioactive beams, requires to have the possibility to couple the AGATA array to the magnetic spectrometer PRISMA as well as to have it in a standalone configuration. Therefore, the project includes the possibility to shift the target position about 3.6 m off the target point of PRISMA for operation without PRISMA.

Plans for Campaign at LNL (up to 30 ATC)

- Various possibilities being studied for the mechanical design/manufacture of the main support structure for the AGATA array:
    - 2π main support structure facing PRISMA magnetic spectrometer for a 27 ATC array,
    - 2π main support structure facing any other big ancillary detector like NEDA as an example for a 30 ATC array
- Mechanical design/manufacture of the target area (beam line, target chamber and loader)
- Mechanical design/manufacture for services integration.

When coupled to PRISMA the AGATA support system will have to be coupled to the inner rotating PRISMA ring and new outer rotating ring and mounting structure.

In addition to the AGATA detector support, an additional platform needs to be designed to support the digitizers and DSS.

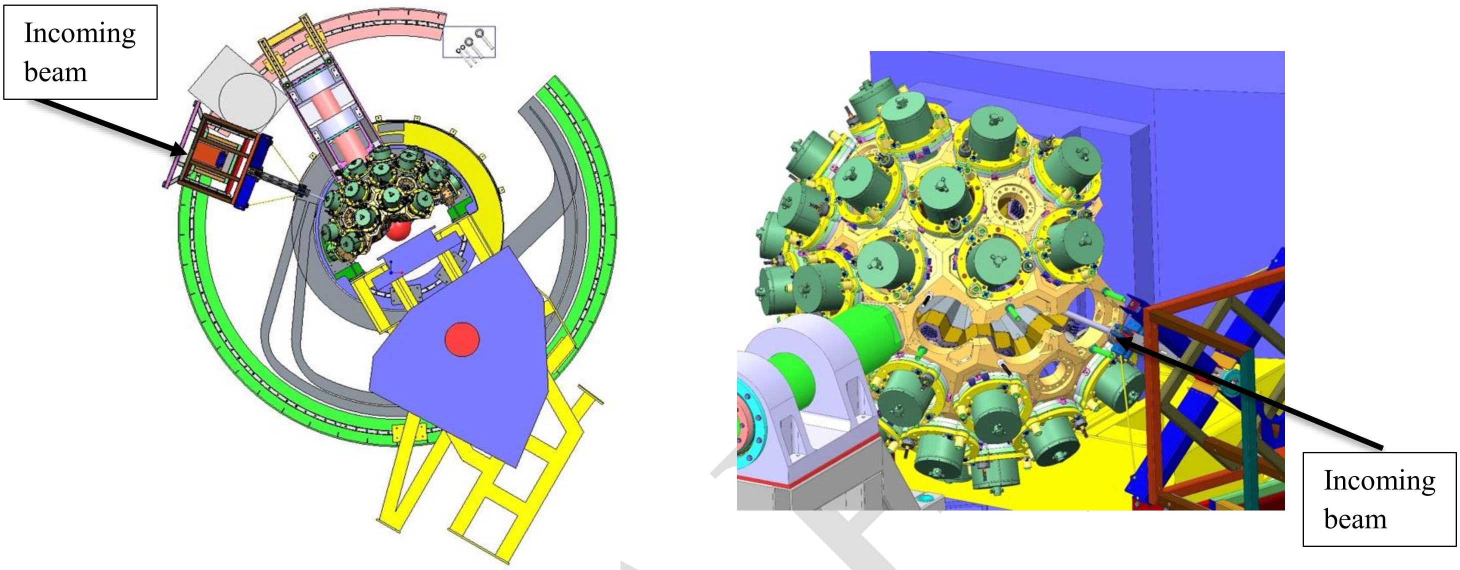


Figure …: left: overview of PRISMA and AGATA at 40°, right: 3D view of PRISMA and AGATA at 70°.

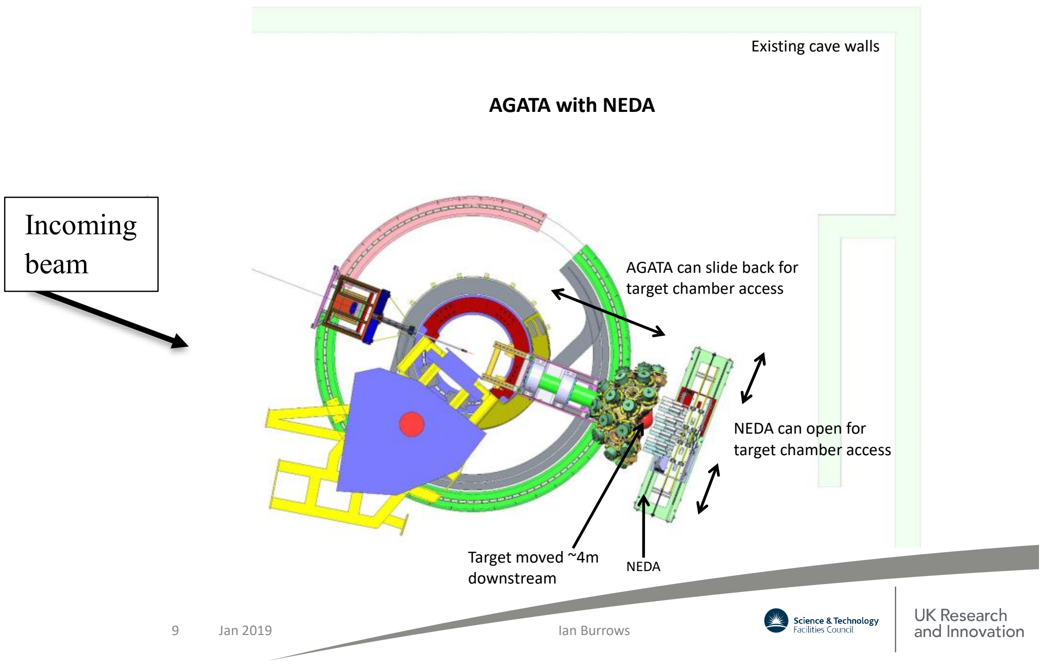


Figure …: overview of AGATA displaced by about 3.6 m away from PRISMA target point to allow for coupling with other big ancillaries as for example NEDA.

AGATA Services

This section considers the mechanical requirements of cabling and water installation to the required parts of AGATA, the positioning and routing of services from digitizers and LV PS to the detectors and the routing of cooling water to the digitizers.

Cable routing from digitizers to detectors.
There is a requirement to have the digitizer positioned within 10 m of the AGATA detectors. The requirements to rotate and translate the detector array imply that cable coilers will be needed to guide all service cables to the digitizers. It is expected that these will be mounted on the additional platform following the different mechanical motion.

Cable routing from Low Voltage Power Supplies to detectors.
There is a requirement to have the low voltage power supplies positioned within 15 m of the AGATA detectors. It is expected that these will be mounted on the additional platform following the different mechanical motion. Sufficient power plant to equip 25 capsules with first digitizers' version and the 20 capsules with the second generation of digitizers as well as further capsules with the digitizers being currently developed (see FEE chapter) needs to be guaranteed and mounted on an UPS.
During any shutdown, the Host Lab need to guarantee that at least the LN2 automat and control will be powered via a safe system.

Routing of cooling water to digitizers.
There is a requirement to have water cooling to the digitizer racks. A cold circuit needs to be prepared and the distribution needs to be mounted on the digitizer platform.
Optical link for V1 and V2 electronics will be guided to the digitizers using articulated cables trays.

All of these items have to be considered and adjusted to the specific situation of all future Host Labs.

Costs for Host Lab

Summary

Item	Price [k€]
PRISMA coupling structure	5,8
PRISMA additional curved support rails and plates	17,3
AGATA support system for use with other big ancillaries (NEDA)	8,4
Additional rail support system for other big ancillaries (NEDA)	9,2
DSS platform	To be defined
Cable routing from digitizers to detectors	To be defined
Cable routing from Low Voltage Power Supplies to detectors	To be defined
Routing of cooling water to digitizers	To be defined

Efforts estimate:
The estimate effort from INFN-Padova and INFN-LNL for the installation of the additional curved support rail and plates and of the shaft and its alignment is estimated about 12 person months.

AGATA Performance Monitoring, Simulations and Commissioning for the Phase 2 of AGATA

Simulations

The response of the AGATA crystals has been modelled using the Geant4 simulation toolkit since the very beginning of the project for the overall design of the array and, more particularly, for a complete array of 180 crystals [1].
During the last few years, as the project advanced step by step, crystal by crystal, into its exploitation phase, the simulation work has been focused on the preparation of the experiment proposals and the data analysis of performed experiments [2, 3, 4]. Each time, the simulated response of the array was revisited considering the increasing number of operational crystals. These experiments have been carried out at different host 'facilities: first at INFN (Legnaro) with 15 crystals, then at GSI (Darmstadt) with up to 24 crystals and finally at GANIL (Caen) with currently 32 crystals. Additionally, these facilities provide different beams in term of energy and optical properties which needs to be taken into account in the simulations together with the different ancillary detectors, mechanical structures, plunger devices and vacuum vessels often used with the AGATA array.

During the next decade, the array is expected to continue to be operated at these 3 facilities however,
with the development of FAIR-HISPEC in Darmstadt, SPIRAL2 in Caen and SPES in Legnaro, the experimental conditions at these facilities will change and will need to be taken into account in the simulation as much as possible. Moreover, interests of using AGATA at HIE-ISOLDE with MiniBall and also at Jyvaskyla have been recently expressed and are being explored using basic preliminary simulations. Further simulation work with more realistic geometries, new event generators and expected additional ancillary devices is likely to be needed for the array to operate under the experimental conditions offered at these new host facilities.

As the number of working crystals increases progressively between the experiment campaigns, basic simulations of photo-peak energy efficiency and peak-to-total ratio curves are usually performed to provide users with some first estimation. These properties of the array are often requested by users for both a nominal and a compact target-detector distance. When the success of an experiment relies on high detection efficiency, the compact configuration is the preferred option to compensate with the limited number of existing crystals. Depending on the reactions of interest, the array's properties may also need to be produced for both low or/and high gamma-ray multiplicities.
Wherever the AGATA array will be used during the period 2021-2030, the demand for a similar simulation work is expected to continue while the number of existing crystals converges toward a complete 4π array.

With real data from well-known sources or beam reactions, the validation of the simulations is possible. One of the remaining questions regarding the performance of the array is why the simulations always overestimate the measured absolute efficiencies. Could this be due to an underestimation of gamma-ray absorption by considering too simple geometries or a crystal dimension smaller than expected, or a more fundamental issue in the radiation transport model? Answers to this question can be provided by performing more realistic simulations.
A lot of effort has been put to implement more realistic geometries of ancillary detectors, reaction chamber, plunger and mechanical structure in the simulation. CAD drawing STEP format files converted into GDML can now be incorporated into the AGATA simulation code to achieve this. Indeed, this has allowed to reducing the gap between measured and simulated efficiency but not completely removed it.

The characterisation of each crystal also provide important information and, in particular, the crystal relative efficiency and a gross value of the thickness of passive Ge area observed essentially around the coaxial contact and at the back of the detector. Here also, the measured relative efficiency is usually a few % lower than the simulated efficiency. With a more accurate location and measurement of the crystal passive area it would be possible to adapt the geometry of each crystal in the simulation to better match the measured efficiency. Since this efficiency is also likely to evolve in time, for instance after each re-processing of a crystal, theffective size of the Ge crystal will need to be updated accordingly in the simulation.

Additional work is also foreseen to develop and complete some event generators. This includes generators for polarisation measurements and generators with simplified and better background estimate.

The characterisation of the sensitivity of the AGATA array as a polarimeter could lead to interesting new physics opportunities. With the development of event generator for polarisation measurements, the simulations would provide crucial preliminary information in that physics research arena.

Attempts to include background measured at some facilities (ex: GSI, GANIL) in the simulation code have already been successful [4, 5]. However, the procedure either relies on previously measured background or a set of different and independent physics background models. In the first case, the background could be quite different from one reaction to another and, if a specific reaction has not been studied before, the simulation prediction then remains somewhat questionable. In the latter case, the procedure is currently tedious as only the outputs of the different models are combined together and there is no tool in place to provide simulated time-stamped background data. So, there is still scope for further development in this area in order to provide more accurate predictions in feasibility studies of future experiments.

Another task that is also important is the maintenance of simulation code, its version control and its dissemination. The AGATA Simulation code is continuously kept up to date with the latest version of GEANT4, while also maintaining compatibility with less recent versions. Currently the code is compatible with GEANT4.10.03 and older version down to GEANT4.7. The version control is managed using Subversion and, for the 2021 to 2030 period, as more communities and applications are using the GIT version control system it is likely that a migration to GIT will happen. Support and training courses will continue to be offered and an update of the Users' guide documentation will also benefits existing and new users.

The development of the code will continue by coupling AGATA with ROOT. The following two options will be considered and at least one will be implemented:

- migrates the AGATA code, including all its event generator/ancillary detector into an existing simulation and data analysis framework such as ENSARROOT, NPTOOL, STOGS.
- Develop the AGATA code from a pure geant4 simulation code to a GEANT4+ROOT code and avoid the current 2-step process of producing an ASCII output file then transform it into a ROOT file. External algorithms based on ROOT to simulate time-stamped AGATA data have already been developed to produce AGATA Data Format ADF files. Additional work will be carried out to integrate this algorithm into the AGATA code. (Similar capabilities exist also within the STOGS framework and could be re-used for AGATA).

Commissioning and Performance

In order to ensure that the energy resolution, detection efficiency and peak-to-total ratio expected after PSA and tracking are indeed achieved (see Section FEE-Introduction), dedicated in-beam runs with AGATA are needed. This is particularly important at beam facilities where AGATA has not yet been used and includes the new European beam facilities SPES, SPIRAL2 and FAIR, HIE-ISOLDE as well as at Jyväskylä.

Furthermore, the host laboratories for AGATA have unique complementary devices. In many cases, a test with sources cannot provide a complete evaluation of the setup. Hence, a through

test using typical reactions has to be performed for validating the functionality of the coupling and to ensure that all impacting effects on AGATA's performance is understood.
As mentioned in previous section, these measurements with either radioactive sources or well-known in-beam reactions are also used to validate MC-simulation codes and tools, which in turn can be applied more reliably for preparing experiments proposals.
Calibrated radioactive source runs should always been 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. Monitoring of performance in the long term is important and it will be crucial to quantify the radiation damage to each of the crystals. It is fundamental to monitor the resolutions and to track the history of each crystals across physics campaign and annealing cycle. Annealing cycles has been shown in the past to have a probability of impacting the functionality of the crystals, it will be interesting to observe and track in the long term to what extent the resolution is recovered and if there could be an effect on the efficiency of each crystal.

During the period 2021-2030 the angular coverage of AGATA will not only be large but also highly granular. In order to profit from this and extract useful physical quantities from angular distributions and correlations (i.e. the multipolarity of emitted gamma-rays, mixing ratio, parity) or to perform measurements depending on the perturbation of the angular distribution/correlation, e.g. g-factor measurements, a deepened understanding of the performance of AGATA will be achieved.

The main challenge is from the needed to normalize the number of counts in a given part of AGATA so that it can be compared to the expected flux of gamma rays into the solid angle covered by the fraction of AGATA. In a classical array using Compton suppressed HPGe detectors and a common dead-time DAQ this can be done by efficiency calibration of the individual detectors in the array. However, in AGATA where the notion of detectors is replaced by the first (and second) interaction position of the tracked gamma-ray the efficiency calibration is no longer simply detector dependant. An added complication comes from the use of a DAQ without common dead time mixing a detector specific part in the problem.

One has to note that in order to correctly assign gamma-ray intensities emitted from aligned nuclei one has to be able to correctly measure angular distributions and even possible correlations.

[1] E. Farnea et al., Nucl. Instr. and Meth. A 621, 331 (2010)
[2] E. Clement et al., Nucl. Instr. and Meth. A 855 (2017) 1-12
[3] N. Lalovic Nucl. Instr. and Meth. A 806 (2016) 258-266
[4] J. Ljungvall, 17th AGATA Week, "*Simulations for lifetime measurements*", 2016, Orsay
[5] D. Bloor, 12th AGATA Week," *Development of a simulation package for fragmentation and Coulex reactions at GSI*", Darmstadt, June 2012.

Complementary Instrumentation for AGATA Phase 2

- Introduction

For many experiments the AGATA array has to be coupled with various ancillary detectors to enhanced its selective power and the performance of the complete setup. For AGATA Phase 2 the following ancillaries may be considered: PRISMA, VAMOS, Super-FRS, NEDA, Diamant, EUCLIDES, MUGAST, DSSD, HECTOR+, PARIS, FATIMA, LYCCA …

This section is concentrated on all aspects of the integration of the various ancillary detectors, in particular for i) Front End Electronics and DAQ, ii) Simulations and Mechanical compatibility, iii) commissioning of the full setup and, as an example, iv) a rapid description of the integration of NEDA and DIAMANT as was done during the 2018 campaign in GANIL.

The activities foreseen for the coming phase 2 of AGATA are regarding both FEE developments and simulations to determine best efficiency with mechanical compatibility of the complementary instrumentations with AGATA in the various Host Labs that will get the AGATA array.

i) Front End Electronics and DAQ integration

The Complementary detectors team developed in the past a general purpose VME interface (AGAVA) for the AGATA GTS, currently the collaboration has 10 AGAVA VME cards that can be used for ancillary detectors with analog Front End Electronics (FEE).

Up to now various ancillaries using analog Front End Electronics (FEE) have been used with AGATA and the DAQ integration was done through an AGAVA interface:
VAMOS/PRISMA, PARIS, FATIMA, Silicon arrays like Spider, DSSSD detectors.
In the 2019 campaign, MUGAST will also use the AGAVA board after an upgrade to become compatible with the new AGATA GTS.

AGAVA VME cards cannot be produced anymore in its present version due to the obsolescence of some of its components. Moreover, many ancillary detectors are now using digital FEE to optimize count rate capability, therefore, Front-End Electronics (FEE) with digitalization capabilities on board (NUMEXO2) compatible with the new AGATA GTS has been developed and used in the AGATA+NEDA+DIAMANT campaign in GANIL in 2018. For future campaigns the upgraded electronics of VAMOS++ will also be based on NUMEXO2 cards.

The early AGATA trigger processor had a maximum number of nodes available (40 nodes) and this represented a limit when two or more detectors with a large number of channels were coupled to AGATA. An EXOGAM2 trigger processor, developed by GANIL, can cope with up to 255 nodes and have been used successfully in the 2018 AGATA+NEDA+DIAMANT 2018 campaign.

ii) Simulations and Mechanical compatibility of AGATA with the Complementary Instrumentation

The simulation of the performance of AGATA and of the complementary instrumentation in realistic conditions is a priority for the Simulation and Complementary Instrumentation working teams. Members of these working teams together with members of the host laboratories local groups will work to perform the simulations for the AGATA installed in the various Host Lab. The Complementary Instrumentation working group will support the host laboratories on checking the mechanical compatibility of AGATA with the experimental setup including complementary instrumentation.

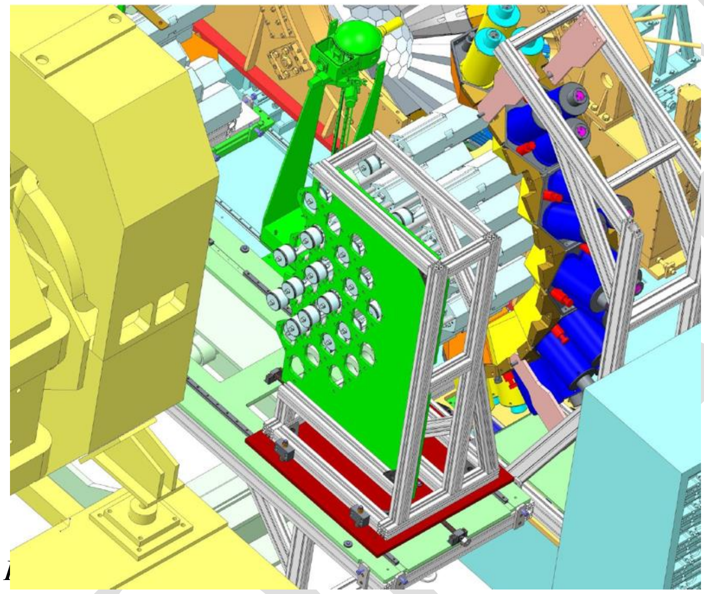
iii) Commissioning of the AGATA + Complementary Instrumentation setup:

The Commissioning of the integrated complementary instrumentation in the AGATA setup, when necessary, will be organised with the help of the Commissioning working team. Either source or beamtime will have to be considered if necessary.

iv) Some more details about the NEDA/Neutron Wall + DIAMANT recent integration in the AGATA setup:

Mechanics integration

NEDA and Neutron Wall have been fully integrated with AGATA, see figure.



Mechanical design of NEDA and Neutron Wall fully integrated mechanically with AGATA. Diamant is placed inside the reaction chamber.

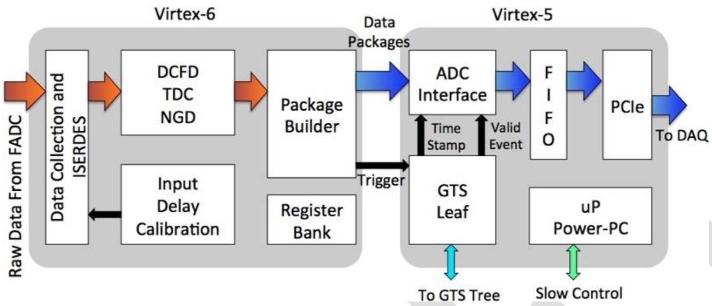
NEDA Front-End Electronics (FEE), unlike its predecessor the Neutron Wall, is fully-digital and envisaged to improve the neutron-γ discrimination, as well as the processing capabilities, integration and overall flexibility. In order to facilitate its coupling with other detector like AGATA, the electronics of NEDA uses the Global Trigger and Synchronisation (GTS) system.

The core of the FEE is the NUMEXO-2 cards, which consist of a set of 4 Flash Analog-to-Digital-Converter (FADC) Mezzanines in charge of digitising the signals coming from the detector through the Single-Ended to Differential conversion NIM module, at 200 Msps. The FADC mezzanines, each contain four Analog-to-Digital (A/D) modules. In addition, the cards contain a motherboard which includes two large FPGAs used to perform the trigger generation, digital signal processing, clocking, data packaging and readout tasks to the servers for 16 independent channels.

The FADC Mezzanine is the daughterboard in charge of the A/D is based on the ADS62P49 sampling device, providing a board with 4 channels sampling at 200 Msps with an ENOB of 11.6-11.7 bits. As for the clock, the main 100 MHz clock from the

GTS is obtained, and processed with a jitter cleaner in order to produce a 200 MHz sampling clock.

The NUMEXO-2 motherboard includes two FPGAs, a Virtex-6 and a Virtex-5, which carry out the pre-processing tasks: data processing, trigger elaboration, package building and formatting, for the Virtex-6 whereas the Virtex-5 FPGA manages the readout via PCIe, slow control via Ethernet, integration of the GTS leaf and implementation of the ADC interface, which is the block in charge of storing temporarily the data before validation by the GTS system. A descriptive view of how the blocks are structured inside the FPGA is depicted in the figure below. In the following paragraphs the functionalities included in the two NUMEXO-2 FPGAs will be discussed.



Block diagram depicting the main blocks in the NUMEXO-2 as well as the interaction among them.

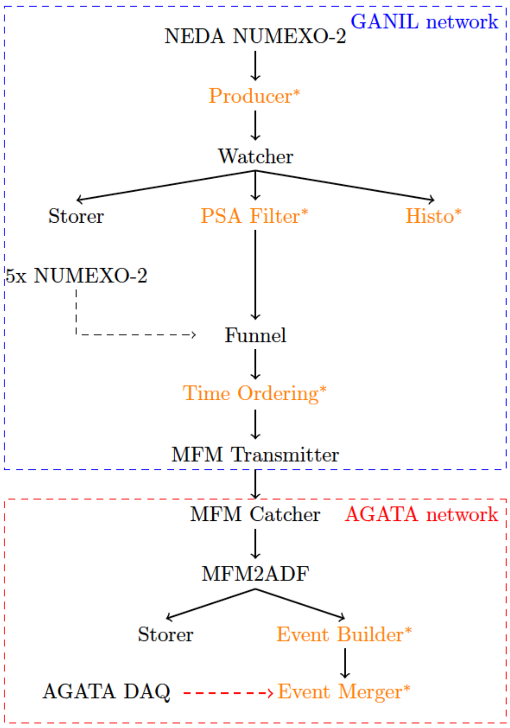
The first-level trigger enables a Pulse Shape Analysis (PSA) for neutron-γ discrimination based on the charge-comparison method, that will provide the Trigger Request used in the GTS Validation/Rejection cycle. Eight LVDS data lanes communicating with both FPGAs at rates up to 400 MB/s allow a sustained counting rate of 20 kHz trigger request in the 16 channels present in the NUMEXO-2 board. The data frames created in the Virtex-6 FPGA are compatible with the MFM GANIL data format specification. As we mentioned in the previous sub-section, the GTS standard has been chosen for NEDA. NEDA uses the NUMEXO-2 4x PCIe v1.0 Endpoint link to read out the data. The data are sent to a server (one server per NUMEXO-2) via an MPO optical fiber. On the receiver side, a commercial PCIe bridge card is hosted in the server and converts the optical input to the PCIe legacy bus standard. The Virtex-5 FPGA includes a PowerPC (PPC) 440 processor, running an embedded Linux OS, that manages the slow control and GTS services.

DAQ integration

As mentioned previously, NEDA has been designed to work coupled to γ-ray spectrometers. In its first implementation at GANIL, the array was used together with AGATA, DIAMANT and the Neutron Wall. In this setup, a total of 54 NEDA detectors and 42 Neutron Wall detectors were used. The signals from the 96 neutron detectors were digitised by six NUMEXO-2 cards. In order to ensure compatibility of the data acquisition systems of NEDA and AGATA, the choice was made to base the data acquisition on the NARVAL system.

The architecture of the acquisition system for one NUMEXO-2 board is presented in following figure.

Slow-control and the alignment of the GTS system is controlled through the ethernet. Each of the 6 NUMEXO-2 boards necessary to accommodate the 96 channels of the NEDA-NeutronWall array, plus one spare board, are optically connected to dedicated servers in charge of the data pre-processing. Commercial PCI-express optical bridges from Samtec are used to make the link between the NUMEXO-2 digitizers and the servers. After this optical transmission, the processed data transit through two different networks: the GANIL network, where all the local processing of the data and the storage of the raw events is done and the AGATA network, on which the two data sets (NEDA and AGATA) are combined. A schematic view of the data acquisition system is shown in the following figure.



Schematic view of the NEDA data acquisition system. The actors marked with an asterisk are actors developed in C++ within the NEDA collaboration. The other actors are standard NARVAL actors. The NEDA acquisition system is shared between two networks: the GANIL and the AGATA network. The transmission of the data between the two networks is performed by one bridge.

- Upgrade/Plans for Phase 2

In the hypothesis of a new SMART Global Trigger System (GTS) it might be necessary to develop an interface for complementary instrumentation not using the SMART GTS. A general-purpose board, as AGAVA for the GTS system, should be develop. The development of such board requires concrete decisions in the Global Trigger and Synchronization system that are to be taken.

- Costs & Efforts

The costs and efforts for the integration of any ancillary detector is the responsibility of the specific collaboration proposing that given ancillary detector. The local team as well as all the AGATA working teams involved (electronics, DAQ, mechanics, commissioning) will help preparing AGATA for the integration. It is then fundamental that they are informed in due time of any relevant technical aspect so that eventual preparation of the AGATA setup can be done when necessary.

- Commitments

The ancillary detector collaboration commits to prepare the ancillary detector in due time for eventual tests (mechanical, electronics, DAQ) that should be done in advance on the AGATA setup, collaborating with the local AGATA project manager to optimize the calendar of the activities on the setup.

In particular it is the responsibility of the ancillary detector collaboration to contact the AGATA DAQ team as well as the Host Lab local DAQ team well in advance so that these teams can prepare their part for the integration of the ancillary in the full AGATA DAQ.

Commissioning tests will have to be discussed with the AGATA commissioning team and local AGATA project manager.

The success of an experiment including a given ancillary detector in the AGATA setup is a success for the relative collaboration as well as for the AGATA collaboration. A failure is a failure for both.

AGATA Phase 2 summary Tables

Costs in k€ per year/procurement goal in Capsules/Clusters

Item	2021 72/24	2022 84/28	2023 96/32	2024 108/36	2025 120/40	2026 132/44	2027 144/48	2028 156/52	2029 168/56	2030 180/60	Total
Detector	2528.5	2566.4	2604.9	2643,9	2683.6	2723.9	2764.7	2806.2	2848.3	2891	27061.4
Cryostat	468.5	475.5	482.6	489.9	497.2	504.7	512.2	519.9	527.7	535.6	5013.8
Electronics	97.7	0	97.7	488.5	488.5	0	488.5	0	488.5	0	2149.4
Electronics Upgrade	390.8	0	390.8	0	0	0	0	0	0	0	781.6
GTS/SMART	0	120.0	0	0	0	0	0	0	0	0	120.0
PSA & DAQ	0	483.0	0	0	0	343.0	0	0	0	357.0	1183.0
Storage	0	112.5	0	0	0	112.5	0	0	0	112.5	337.5
Analysis	0	10	0	0	0	10	0	0	0	10	30
Infrastructure	415.10	0	0	440.6	0	0	0	0	0	0	855.7
Mechanics	230.3	0	0	330.0	0	0	0	0	0	0	560.3
Total	4130.9	3767.4	3576.0	4392.9	3669.3	3694.1	3765.4	3326.1	3864.5	3906.1	38092.7

Cost per ATC and required upgrades:

Item	Cost in k€
Detector (×3)	676.5
Cryostat (×1)	125.3
Electronics (×3)	48.9
GTS/SMART	3.0
PSA & DAQ	29.6
Storage	8.4
Analysis	0.75
Infrastructure	21.4
Mechanics	14.0
Total	927.9

Necessary and upgrade of the early 48 channels of electronics between 2021 and 2023 for a total cost of 781.6 k€, not included in the table of individual ATC costs.

AGATA Operational and Maintenance Costs:

The AGATA Operational Cost are largely the repairing and maintenance costs of the AGATA subsystems. It includes as well the costs of maintaining AGATA under cryogenic temperature all the time based on evaporation of LN2.

The following table is the estimate of the AGATA Operational costs assuming a funding period between 2021 and 2030.
Behind the costs estimates we have the following lifetimes or HTWR:

- Detector Capsule: we had a large statistics of detector failures in the more than 10 years AGATA is already under working conditions. The average time between failures for an AGATA detector is presently estimated in 13.3 years or a failure rate of 7.5%.
- Electronics and Infrastructure maintenance or replacement have been estimated as well in 13.3 years, failure rate 7.5%
- The DAQ items, in particular the processing and Data Flow server farm lifetime is estimated to be about 7 years, corresponding to a failure rate of 14%.

The AGATA funding scheme mostly doesn't foresee spare parts, our maintenance scheme is supporting the repair or replacement of the broken items, considered more logical in a project extending over a large number of years for which spare parts could became obsolete before being employed in the set-up. Only for critical elements, necessary for the operation of the full array, is foreseen the spare element. One example could be the Trigger Processor since its absence would prevent the experimental activity to continue.

Operational / Maintenance Costs

Item	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**
Capsules in setup	60	60	72	84	96	108	120	132	144	156	162	180	180	180
Expected Capsule failures	5	5	6	7	8	9	9	10	11	12	13	14	14	14
failures Under Warranty	1	1	1	2	2	2	2	2	2	2	2	2	1	0
Detectors in setup	20	20	24	28	32	36	40	44	48	52	54	60	60	60
Detectors														
LN2	73.5	73.5	85.5	97.5	109.5	121.5	133.5	145.5	157.5	169.5	175.5	193.5	193.5	193.5
Capsule maintenance/repair	206.0	209.1	265.3	269.3	328.0	388.4	394.3	457.4	522.2	589.0	657.6	728.1	800.6	875.2
Detector&Cryostat maintenance /repair	77.6	78.7	95.9	113.5	131.7	150.4	169.6	189.4	209.7	230.5	243.0	274.0	278.2	282.3
Including Preamplifer exchange…														
and Other repairs (feedthrough, cabling,…)														
Detector laboratories	60	60	60	60	60	60	60	60	60	60	60	60	60	60
Infrastructure														
HV/LV, Autofill, infrastructure	21.8	21.8	26.1	30.5	34.8	39.2	43.5	47.9	52.2	56.6	58.7	65.3	65.3	65.3
Electronics and DAQ														
Elect. maintenance/replacement	0.0	42.0	42.0	100.8	115.2	129.6	144.0	158.4	172.8	187.2	194.4	216.0	216.0	216.0
DAQ maintenance/replacement	63	63	75.6	88.2	100.8	113.4	126	138.6	151.2	163.8	170.1	189	189	189
Other costs														
Grid costs	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Shipping costs	25	25	27	29	31	33	33	35	37	39	41	43	43	43
Mechanics	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Total operation & maintenance costs	**558.8**	**605.1**	**709.4**	**820.8**	**943.0**	**1067.5**	**1135.9**	**1264.1**	**1394.6**	**1527.6**	**1632.3**	**1800.9**	**1877.6**	**1956.2**