Technical Proposal for the SPIRAL 2 instrumentation

TITLE of the Project: EXOGAM2

Abstract (Max 15 lines):
High-resolution gamma-ray spectroscopy is a major tool to understand the structure of atomic nuclei. It is used to explore many different facets of nuclear structure and many different experimental techniques are required. The intense beams (stable and radioactive) from SPIRAL2 offer new horizons to gamma-ray spectroscopy and studies like the structure of nuclei at or even beyond the proton drip line, the evolution of shell structure far from stability, the physics of very heavy elements or the investigation of the spin degree of freedom in exotic nuclei will be possible. This physics programme discussed within the community covers a broad range of experimental conditions requiring in particular a very high counting rate capability and a better Doppler correction. This is why the SPIRAL2 international Scientific Advisory Committee "urged the community to equip EXOGAM with digital electronics", which will ensure high quality signals needed to study gamma rays from reactions induced by the SPIRAL2 beams. EXOGAM2 is a proposal to equip the sixteen HPGe EXOGAM detectors, the clovers, as well as their suppression shield with a highly integrated digital electronics for this purpose. The collaboration is currently being built.

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Table of contents

1. Introduction and Overview
1.1 Introduction

EXOGAM is an array of HPGe detectors designed to exploit radioactive beams from SPIRAL. The original design (see http://www.ganil.fr/exogam/) consists in 16 large segmented Clovers surrounded by a modular anti-Compton shield. The signals from the Clover (core and segments) as well as from the anti Compton shields are processed presently using VXI electronics.

The EXOGAM Clover detectors have an electronic segmentation, which should give enough information to better Doppler correct gamma-ray energies. This is possible through a localization of the first interaction point, which is significantly better than the size of the individual segments i.e. 2 cm at the front face. Extensive studies (i.e. the scanning of a detector in Liverpool and an in-beam test at GANIL) performed on the EXOGAM Clover have shown that the localization should be around 1-2 cm.

The position is extracted from the net charge in a segment, which basically gives the interaction radius while the mirror charges in the neighbouring segments give the azimuthal angle. To exploit this possibility, it is necessary to develop a digital electronics for EXOGAM, which analyses the rise time of the preamplifier signals and derive the useful information online.

In addition, there are several new issues, which motivate a significant upgrade:

1. A bottleneck of EXOGAM is the counting rate capability. This is due first of all to the original design specifications since EXOGAM was initially planned to exploit the radioactive from SPIRAL1 (hence low intensity and very limited count rate). And this is also particularly true for any Ge detector since the count rate in a detector is typically limited to 10 kHz to avoid pile-up. This is a severe limitation in many cases like, for instance, in a situation where a large production of fission fragments or X-rays is expected on top of the search for rare events. The R&D work performed within AGATA indicates that it should be possible with a new dedicated electronics to reach a rate of 50 kHz with standard techniques. Other works push the limits much further away under some specific choices based on new algorithm to measure energy. A gain along this line is directly connected to the possibility to reach more exotic nuclei.
2. The use of pulse shape analysis will help in reducing the Doppler broadening of the photopeaks. To compensate the low intensity of the most exotic radioactive beams, the detectors must be as close as possible to the target, leading to a large solid angle sustained by the individual segments. Even with a beam energy at the Coulomb barrier, the effect is far from being negligible especially in inverse kinematics and looking at gamma ray energies more than 1 MeV (which is a common case). Considering *only* the angular aperture, and in first approximation, the broadening of the peak is going as a function of $\sim 2\beta E_\gamma \sin(\Delta\theta)$. This leads for instance to an increase from 3 keV to more than 10 keV for 1 MeV gamma-ray at a recoil velocity of 2% of the light velocity and at $\theta = 90°$ when the detector is moved from 15 cm to 4 cm from the target. In inverse kinematics ($\beta \sim 5\%$), this leads to an increase from 7 to 24 keV. This effect is even more dramatic when using a fast beam (i.e. from fragmentation reaction) where the emitting nuclei have a recoil velocity of the order of v/c ~ 30-40%…
3. The intense activity in the AGATA context is extremely fruitful for EXOGAM, which benefit from the several years of R&D performed in this collaboration. This is true in every upgrade foreseen for EXOGAM as will be detailed further in this proposal.
4. The existing electronics is based on the VXI standard, works in a common dead time mode with a DT32 bus readout mechanism. This system worked very nicely for years with large gamma-ray arrays like EUROGAM, EUROBALL. However it contains

intrinsic limitations in terms of throughput, flexibility and moreover on maintenance. All over the world, large arrays that could be compare to EXOGAM (MINIBALL, TIGRESS) use or develop digital electronics.

5. Not only the gamma-ray arrays are developing their own digital electronics but also other large spectrometers like VAMOS, FAZIA, etc. are envisaging or already building/purchasing this new kind of electronics. The experience gain in the use of EXOGAM at GANIL demonstrates how crucial is the coupling with other devices. These couplings must be realized in a very efficient way and again, using the same kind of electronics will facilitate these combinations.
6. On top of all these motivations, is the future physics program associated to the advent of high intensity beams that will be available at GANIL in the near future: radioactive beams from SPIRAL2 as well the stable beam directly from the LINAC.

This is why, it is time to think to a new phase of EXOGAM, called thereafter EXOGAM2, which in consists in a complete redesign of the electronics.

1.2 The physics case

EXOGAM has been designed to perform the gamma-ray spectroscopy of exotic nuclei produced by means of reaction induced by radioactive beams from SPIRAL. Our feedback on the use of EXOGAM for the last 5 years indicates that this array is requested in about 40% of the proposals submitted to the GANIL PAC and that the array is also frequently used with stable beams at low as well as intermediate energies. The current physics case for EXOGAM can be roughly classified in a few sections:

- Shapes and shape coexistence in neutron deficient nuclei (large ground state deformation in light rare earth nuclei, shape coexistence in Kr isotopes)
- Spectroscopy of N~Z nuclei (isospin symmetry breaking in mirror nuclei, single particle excitations around ^{100}Sn, T=0 versus T=1 pairing)
- Shell structure far from stability (spectroscopy of neutron rich nuclei around ^{54}Ca, ^{78}Ni, N=20 and the island of inversion)
- Spectroscopy of transfermium elements
- Exclusive reaction mechanism measurements (cross section measurements for transfer, break-up, fusion, elastic and inelastic scattering using beams of borromean nuclei)

In most of the experiments, EXOGAM was used in coincidence with an auxiliary detector (the VAMOS spectrometer, the DIAMANT and TIARA charged particle arrays or CD detectors, the Neutron wall). EXOGAM detectors have also been use with LISE and eight Clovers have been coupled to the SPEG spectrometer.

In the near future, these physics lines of research will be pursued and significantly extended. Indeed in most of the cases the experiments ended up with question marks for two reasons: 1) technical limitations and 2) these first experiments with radioactive beams have just started to reveal what could be done.

A large fraction of the present physics case for EXOGAM2 is directly coming from the scientific discussions in the context of the SPIRAL2 Letter of intent (LoI) and one should refer to the relevant LoI's to get more detail: "high resolution gamma-ray spectroscopy at SPIRAL2" and "S^3: Super Separator Spectrometer, a tool for the study of high intensity stable beams at SPIRAL2". It is clear that these very large programs have been written for gamma-ray spectroscopy at large i.e. including EXOGAM2 and AGATA.

High-resolution gamma-ray spectroscopy is a major tool to understand the structure of atomic nuclei. It is used to explore many different facets of nuclear structure and many different experimental techniques are required to study these. We have thus decided to divide the science case into several major topics, which are outlined below.

Proton drip-line studies and N=Z nuclei

Neutron-deficient nuclei at or sometimes even beyond the proton drip line were studied extensively in the past decades. A large amount of data has been accumulated even for high-spin states using fusion-evaporation reactions with stable beam and target combinations. This has led (and still leads) to the acquisition of considerable knowledge on these nuclei and associated physics. However, it is clear that deeper and more fundamental questions arise from the available information, such as: Do we understand pairing in the isospin $T=0$ and $T=1$ channels? Which (nuclear?) effects break isospin symmetry? Can we follow the demise of isospin for heavy $N\sim Z$ nuclei or nuclei with a large proton excess? Are there exotic shapes and decay modes and, related, where exactly is the proton drip line? Do proton skins or even halos exist? Are there 'Islands of Inversion' on the neutron-deficient side of the chart of the nuclides? In addition to these nuclear physics questions, there is considerable interest from nuclear astrophysics (*rp* process) and weak interaction (CVC conservation and unitarity of the CKM matrix) associated with medium-heavy $N \leq Z$ nuclei.

All these open questions demand more detailed γ-spectroscopic studies of neutron-deficient nuclei, employing both high-intensity stable and radioactive beams at energies around the Coulomb barrier. In view of the extremely small production rates for the nuclei of interest a unique and efficient event-by-event identification is needed, using either (proton- or super-allowed β-decay) tagging techniques of the nuclei in the focal plane of a spectrometer and/or a measurement of the evaporated light-charged particles and neutrons. Alternatively, Coulomb excitation and transfer experiments could be employed directly on the radioactive nucleus in order to measure other nuclear properties (electromagnetic moments, spectroscopic factors, etc).

Key experiment: *Fusion evaporation or pair-transfer will be used to populate N~Z nuclei. The modification of low-lying states as compared to seniority-like level schemes will be looked for. For pair transfer experiments, the spectra and angular distribution associated with pair transfer will be measured.*

For fundamental interaction physics, the segmentation of EXOGAM detector is not required but the efficiency is. The measurement of branching ratios to test the CVC hypothesis will be performed at the low energy facility (LIRAT, DESIR). In the same areas, the measurement of the neutrino-less double-beta decay in e.g. ^{100}*Mo will be measured. The structure of intermediate nuclei (via beta decay) as well as the initial and final deformation (via Coulomb excitation) will be measured.*

Shell structure of neutron-rich nuclei

Extending the knowledge of nuclear properties towards neutron-rich nuclei is of fundamental importance for the understanding of nuclear structure and nuclear models at large values of isospin, the latter of which has been largely derived from the properties of nuclei observed close to stability. Significant changes of the shell structure are predicted for neutron-rich nuclei, and to investigate the evolution of the shell structure is one of the key objectives of SPIRAL2. Open questions include: the evolution of the nuclear effective interactions in the monopole and multipole terms, the quenching of the known shell gaps and development of new ones, the evolution of the nuclear collectivity (onset of deformation in light n-rich nuclei), the shape phase transitions (dynamical symmetries) and the onset of exotic shapes. These experimental open questions can be studied by exploring the nuclear spectrum of excited states up to medium-high angular momentum and by direct measurement of transition probabilities.

Neutron-rich nuclei are much more difficult to access than their proton-rich counterparts. In particular it is difficult to access states with spins exceeding those populated in beta decay or through fragmentation or fission reactions. Multi-nucleon transfer and deep-inelastic reactions performed at energies 10-20% above the Coulomb barrier are well suited to populate states up to spin 20 ħ in neutron-rich nuclei. The production cross-section generally follows the N/Z equilibration line. Deep-inelastic reactions with intense neutron-rich beams from SPIRAL2 on ^{238}U targets permit to reach neutron-rich nuclei well beyond the scope of experiments with stable beams. The nuclei of interest are generally produced with small cross sections and have to be distinguished from a very large background from other reaction channels (including fission). The required selectivity can be reached by coupling an efficient γ-ray spectrometer (AGATA or EXOGAM) to a large-acceptance magnetic spectrometer (VAMOS). The spectrometer is rotated at the grazing angle in order to detect the recoiling fragments, which are uniquely identified in Z and A. The measurement of the recoil velocity can be used to further improve Doppler correction. In this way the γ-rays are uniquely assigned to unknown nuclei and additional selectivity is achieved by analysing γ-γ coincidence data.

Key experiment: *Measurement of low-lying states in odd-A isotopes/isotones adjacent to nuclei with closed shells (around ^{78}Ni, ^{132}Sn). This requires EXOGAM2 in coincidence with a spectrometer (VAMOS or SPEG)*

<u>Nuclear shapes and "high-spin" spectroscopy</u>

The shape of an atomic nucleus is a fundamental property, which is governed by a delicate interplay of the macroscopic liquid-drop properties of nuclear matter and microscopic shell effects. The nuclear shell structure is drastically altered as one moves from spherical nuclei to regions of high deformation. Rotation adds a further dimension to the nuclear many-body problem. Studying the evolution of nuclear shapes and shape coexistence, collective modes such as rotations and vibrations, and the measurement of nuclear moments gives important insight into the nuclear structure and is often a critical test for theoretical models. Many fundamental questions related to nuclear shapes and the breaking of spherical symmetry are not well understood: Why are prolate shapes so much more abundant than oblate shapes? What leads to axial symmetry breaking and what are the consequences of triaxiality for the three-dimensional rotation of nuclei (wobbling, chirality)? New high-rank symmetries corresponding to tetrahedral and octahedral shapes are predicted for certain nuclei far from stability that remain to be discovered experimentally. Phenomena at the extremes of deformation are very sensitive to details of the nuclear force.

Fusion-evaporation reactions with neutron-rich beams from SPIRAL2 give access for the first time to high-spin states in moderately neutron-rich nuclei and will further push the experimental spin limit into a new regime where new phenomena are expected to occur, for example hyperdeformation, the Jacobi shape transition, the termination of collective rotation, and the total quenching of pairing correlations. This kind of experiments will be done with AGATA, which has a much larger resolving power at high spin than EXOGAM. However, in order to understand the elementary excitations in nuclei far from stability, the spin degree of freedom in nuclei further from stability needs to be investigated. Appropriate tools for such studies are multiple Coulomb excitation, transfer and deep inelastic reactions. New collective modes are expected in exotic nuclei with large neutron excess. Projectile Coulomb excitation experiments with radioactive beams at energies below the Coulomb barrier are an ideal tool to investigate collective excitations in exotic nuclei and yield access to quadrupole moments and the nuclear shapes involved. These low to medium spin experiments will be one of the favourite playgrounds for EXOGAM.

Key experiment:

- *Low-energy excitation spectra, including non-yrast states and excited 0^+ states, lifetimes, transition moments and static quadrupole moments, isomer spectroscopy. These states will be populated via multistep Coulomb excitation, fusion-evaporation and deep inelastic collisions. Required new beams: ^{56}Ni, ^{68}Se, ^{72}Kr… from SPIRAL1; ^{94}Kr, ^{132}Sn, ^{142}Xe… from SPIRAL2. This kind of experiment requires EXOGAM with a spectrometer at 0° or VAMOS in gas filled mode).*

- *K-isomers and rotational bands built on top of them in e.g. Hf and W isotopes. These will be populated in fusion-evaporation reaction induced by neutron-rich radioactive beams (^{94}Kr). This kind of experiment requires EXOGAM, the neutron wall, a charged particle array (DIAMANT) and a spectrometer at 0° or VAMOS in gas filled mode.*

Collective Modes

The measurements of low-lying collective states when going from magic to mid-shell nuclei provide key information about the transition from nearly pure two-quasiparticle excitations determined by shell structure to quadrupole and octupole collective states on the one hand, and about the transition from vibrational to rotational nuclei on the other hand. It also gives valuable benchmarks for models of large-amplitude collective motion and for the shell model. The comparison of the strength distributions of near-symmetric and asymmetric nuclei gives constraints on the nuclear energy density functional providing information about bulk properties of nuclear matter.

Key experiment: *Coulomb excitation of nuclei along isotopic chains of Kr (from A=72 to A=94), Xe (from A=112 to A=145) or Sn (from A=125 to A=134). Measurement of gamma-ray energies and strength as well as angular distribution. This kind of experiments requires an as pure as possible beam.*

At higher excitation energies, collective modes are a powerful tool to investigate nuclear shapes and their evolution, the influence of thermal environments on low-lying modes, and the elastic response of nuclear matter. Because these properties are expected to change when going away from the valley of stability, the study of collective modes in exotic nuclei will provide new insight into the structure of these nuclei and the nuclear many-body problem in general. Selective γ-spectroscopy measurements are essential to carry out such investigations.

The employment of high-intensity neutron-rich beams from SPIRAL2 will allow studying vibrational and rotational collective phenomena at finite temperature, making use of both inelastic scattering and fusion-evaporation reactions. In particular, we plan to investigate the properties of giant resonancevstates of different types in exotic systems, such as Giant Dipole Resonances (GDR). The GDR built on specific nuclear shapes and deformations are interesting both for nuclear structure at finite temperature and for the understanding of dynamical modes in fusion reactions. In particular, they provide information on the damping mechanisms of collective modes, on the charge equilibration time, and on the symmetry energy of the nuclear matter at densities lower than the saturation value. In addition, the study of *warm rotational motion*, namely of the nuclear rotation at moderate excitation energies above yrast ($U \approx$ 2-4 MeV), both in normal deformed and super deformed configurations, will provide valuable information on the disappearance of quantum numbers with temperature, namely on the onset of the chaotic regime in the atomic nucleus.

Key experiment: *Coulomb excitation of neutron rich beams (Sr, Kr, Zr, Sn) on light target. Fusion evaporation with neutron-rich Kr, Xe and Sn beams. Measurement of gamma-ray energies and strength as well as angular distribution. This kind of experiments requires an as pure as possible beam.*

Nuclear electromagnetic moments

Significant changes in the nuclear shell structure away from the valley of β-stability have been observed experimentally during the last years, showing that new nuclear features are to be expected at extreme isospin. The measurement of electromagnetic nuclear moments, with their sensitivity both to the single-particle and collective properties of the nuclear wave function, is an indispensable tool for the nuclear structure investigations of exotic nuclei. The magnetic dipole moments are very sensitive probes to the valence nucleons and are one of the first rigid tests of the nuclear models. The electric quadrupole moments, being a fingerprint of the distribution of the electric charges in the nucleus, give insight into the nuclear deformation and the developments of exotic shapes. The static electromagnetic moments give precise information on a particular nuclear state and the composition of its wave function, while the dynamic moments (transition probabilities) depend on both nuclear states involved and reveal the interrelations between different structures in the nucleus. We intend to study static electromagnetic moments using perturbed angular distributions and correlations, transient fields, and β-NMR after tilted-foils polarization. Furthermore we plan to measure transition probabilities via lifetime and Coulomb excitation techniques, the latter being sensitive to static quadrupole moments.

Key experiment: *measurements of nuclear moments of isomeric states along magic nuclear chains (Ni or Sn isotopes) or adjacent nuclei that should give a detailed information of the development of the nuclear shell structure far from stability. The idea is to populate and align those states in single- or multi-nucleon transfer reactions with radioactive beams.*

In addition the use of the tilted-foils technique at S3 should allow obtaining polarized nuclear ensembles - a requirement in order to determine the sign of the static quadrupole moments of the isomeric states. This type of measurements would be of special interest in the regions where shape coexistence is being discussed and direct experimental information can be of great importance.

In order to perform nuclear moment measurements using the Time-Dependent Perturbed Angular Distribution method we would not need the segmentation of EXOGAM but rather its high efficiency and high count-rate capability. The additional requirement of a good time resolution (< 10 ns) is of crucial importance. Both for the measurements of magnetic dipole moments and of electric quadrupole moments a specific configuration of the EXOGAM detectors will be needed (e.g. detectors positioned in a horizontal plane at specific angles). An installation of either a permanent- or of an electro-magnet around the target/implantation host would be needed for the magnetic moment measurements. Possible use of high count-rate particle detectors around target is also envisaged in order to perform particle-gamma correlation measurements.

Spectroscopy of very heavy-elements

The synthesis of super-heavy elements must be accompanied by nuclear structure studies. The production cross-sections of the transfermium nuclides are sufficiently high to make it possible to carry out detailed spectroscopic studies.

The different objectives are:

- to determine the orbitals responsible for the observed configurations in such nuclei and their properties;
- to study collectivity, in particular for those nuclei around the small islands of deformation (^{254}No and ^{270}Hs);
- to study the role of K-isomerism with respect to their lifetimes and α/sf-ratios and compare this to the ground state;
- to determine the masses of the nuclei to estimate the fission barriers.

In all cases, the underlying question is the single-particle structure of these elements. Deformed nuclei are of particular interest since high-lying orbitals from the SHE region approach the Fermi level as the deformation increases. Two complementary experimental approaches can be used to address these objectives. In the first approach, collective properties using prompt in-beam gamma or electron spectroscopy are studied. Since the pioneering observation of a rotational band in ^{254}No both at Argonne and at the University of Jyväskylä, collective properties have been observed in the even-even nuclei ^{250}Fm and ^{252}No, the odd-neutron nucleus ^{253}No and the odd-proton nuclei ^{251}Md and ^{255}Lr. A prime observable in these experiments is the moment of inertia, which can be directly compared to theoretical calculations. In odd-mass nuclei, the decay pattern, i.e. the relative intensity of rotational band intra- and inter-band transitions allows the Nilsson label of the band head to be assigned through deduction of the gyromagnetic factor. Since low energy transitions are highly converted in the heaviest nuclei, electron spectroscopy is mandatory to probe the low-lying states of rotational bands. Combination of both gamma ray and electron spectroscopic techniques is a promising method, which is being developed at Jyväskylä with the SAGE spectrometer. The counting rate capability of the array installed around the target limits the beam intensity that can be used.

The second complementary approach consists of a combined electron and gamma spectroscopy after alpha decay. Alpha decay is very selective since it is sensitive to the details of the initial and final wave functions. Alpha-electron and alpha-gamma coincidences provide additional information concerning the spin and parities of populated states. Since no detector is installed around the target, the highest possible beam intensities can be used.

Combination of both delayed and prompt approaches is ideal, although limited by the target detector performances. Deduction of rotational structures built on high K-isomers is a typical example of such studies.

So far, mainly cold fusion-evaporation reactions using Pb-like targets and Ca-like beams have been used for both prompt and decay spectroscopy. These reactions populate nuclei on the proton-rich side of the β-valley of stability. It is now essential to explore the neutron-rich side of the nuclear chart. Hot fusion reactions using actinide targets are an alternative, which is part of the Dubna program with the VASSILISSA separator and the focal plane array GABRIELA. Radioactive neutron-rich beams from SPIRAL2 are a third alternative, which allow access to different regions.

The radioactive beams from SPIRAL2 will provide a unique opportunity to reach the deformed island of stability around ^{270}Hs. Symmetric reactions using neutron-rich beams of Xe or Kr are promising, although detailed reaction mechanism studies are a mandatory prerequisite. The necessary reaction mechanism studies are the subject of another SPIRAL2 Letter of Intent (Ch. Schmitt *et al.*). The required developments in instrumentation and techniques will be presented in the second part of this proposal. Experiments using existing stable beams from GANIL will obviously also benefit from these developments.

Key experiment: *Coulomb excitation of ^{254}No to measure electromagnetic transition rates. Recoil decay tagging following fusion-evaporation with EXOGAM2+VAMOS then EXOGAM2+S^3. This requires high intensity stable beams (CSS1, CIME, LINAG).*

Reaction mechanisms

The isotopic distribution of low energy fission fragments is known for very few actinides and only in the light fragments part of the asymmetric distribution. However, the structure effects being responsible for most of the fission characteristics (asymmetry, deformation, neutron multiplicity,...) are observable in the heavy fragment part, where neutron richness allows for approaching magic numbers. Due to the unknown contribution of neutron and proton numbers, controversy exists on the interpretation of these characteristics and neutron or proton shells. Multi-nucleon transfer in inverse kinematics allows for producing exotic actinides and combined to a spectrometer for the complete isotopic identification of the fission fragments. In the future, prompt neutron emission (kinetic energy and angular distributions) may be studied in coincidence (access to deformation and dissipation). The production of heavy fission fragments in coincidence with gamma detector may provide breakthrough data for spectroscopic studies near ^{132}Sn.

The synthesis of SHE is also the combination of several mechanisms, which can be studied through the production experiment. After the contact configuration, the competition between fusion and quasi-fission is a turning point towards the SHE. This competition appears to evolve rapidly according to the total mass of the system and is widely debated in the formation models. Moreover, the structure of the partner nuclei plays a very important role in the fusion process. The next step is the survival of the compound nucleus. The competition between evaporation (particle and gamma) and fission is studied through several models, with some successes. Nevertheless, some points are still open. For example, the disappearance of shell effects with the temperature should be critical in the survival of the compound nucleus, and it seems that they still exist, or are very quickly restored with evaporation, even for high excitation energy. This has been shown in recent experiment measuring the long lifetime components in the fission of superheavy compound nuclei. Experimentally, a lot can be learned through the study of the evaporation residue production cross sections (see Ch. Schmitt Letter of Intent), with careful measurements of the different evaporation channels and their excitation function.

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Reactions at Coulomb barrier energies induced by halo nuclei: with SPIRAL1, beams of low energy ^{6,8}He can be used to study the delicate balance between internal and collective degrees of freedom. Exclusive measurements involving the combined detection of gamma-rays, charged particle and neutrons could be pursued at GANIL. This led to the simultaneous measurements of elastic scattering, fusion, transfer and break-up cross sections. From this data set, the influence of the neutron halo of the projectile on the reaction mechanism could be inferred. This points directly toward the role of dynamical effects in quantum tunnelling at energies at or even below the Coulomb barrier.

In direct reaction studies gamma rays are detected in coincidence with charged particles to measure accurately the energy of the populated bound states. This is realized via a coupling of EXOGAM with MUST2 and TIARA. This setup would be replaced by AGATA coupled to GASPARD when available.

Radiative capture cross section measurements: these experiments would be run in LISE using intense heavy-ion stable or radioactive beams providing a very good beam rejection at 0° and an efficient, high resolution gamma-ray array like EXOGAM are available. This physics programme would be complemented on VAMOS coupled to EXOGAM.

The goal of this proposal for EXOGAM2 is to upgrade the existing EXOGAM array in order to cope with the physics constraints arising from the scientific goals mentioned above. In the following are summarized the design specifications that have been extensively discussed in collaboration meetings and workshops.

2. Introduction and Overview

As already mentioned, EXOGAM is composed of 16 HPGe clovers surrounded by BGO and CsI scintillators. Detectors channels are linked respectively to preamplifiers and photomultipliers, very close to the detectors; their outputs are sent to D-size VXI processing modules. In its 16 detector geometry, we thus have the following number of channels:

- Each clover is made up of 4 Ge segmented crystal. Each crystal is segmented in four parts leading to one inner and four outer detector channels. For the full array, it leads to 64 inner channels and 256 outer channels. The inner channels are processed in 8 ECC modules and the outer channels in 16 GOCCE modules
- For each Ge crystal, the photomultipliers of the BGO and CsI are ganged together giving 4 BGO and 4 CsI outputs. For the full array, it means 256 BGO channels and 256 CsI channels. BGO and CsI channels are processed in 16 ESS modules

ECC, GOCCE and ESS cards are mainly developed in analog technologies leading to an uncompressed analog processing time. The acquisition mode is based on the common dead time and handled by the specific MK2 trigger module. Thanks to STR8080 and STR8032 modules in which the fast DT32 readout process is implemented, the total dead time readout is highly reduced compared to the common VME readout. Nevertheless, the DT32 process is featured by a high susceptibility to EMI radiations leading to a high number of unknown items and thus to an increase of the dead time with the counting rate.

From early meetings about instrumentation for physics experiments with SPIRAL2 beams and more especially from the EXOGAM workshop held at GANIL on 24th-27th April 2007, several items were discussed to renew the EXOGAM electronics, which fit with the requirements of the new instrumentation of SPIRAL2 detectors. These items are as following:

- Better location of gamma interactions: this can be achieved with measurements of rise time and mirror charge of outer preamplifier signals; only a full digital electronics can processed these parameters.
- Dead time reduction: trigger-less mode and fast serial links for data readout must be implemented.
- High-energy resolution at high counting rates: a new method based on a Kalman filter and so-called ADONIS (see Annex 1) has been studied for the inner energy measurement.
- Radioactive environment: most of the electronics must be set outside the cave and differential or optical links between devices are recommended.
- VXI electronics reliability: because of DT32 readout problems, components obsolescence, lack of VXI boards expertise, it is more and more difficult to run EXOGAM acquisition with a high reliability and with a low rate of errors.

Following the EXOGAM workshop, a group of experts was set up in order to examine various technical proposals and to give his recommendation to the EXOGAM steering committee. Four proposals were submitted:

- AGATA + TDR: it is mainly based on the digitizer developed for AGATA Ge detector and on the time stamping and readout TDR system running at Jyväskylä laboratory.
- Industrial: it is mainly based on commercial modules and on the TDR system.
- Full AGATA: it is fully based on the electronics developments made for AGATA
- ATCA: it is based on the development of a new digitizer (which fits the various types of EXOGAM detector channels) and the implementation of processing and trigger modules developed for AGATA.

For two main reasons, cost and compliance with AGATA, the last proposal has been recommended and named EXOGAM2 electronics.

2.1 Design specifications

Here below are the main features which were written by the experts group and therefore which must be fulfilled by EXOGAM2 electronics:

- Ge channels:
  - Inner channel: two analog to digital channels with 6MeV and 20 MeV ranges.
  - Inner energy resolution: 2.3 keV@ 1.3 MeV (with a counting rate < 50kHz).
  - Outer channel: 6 MeV range.
  - Discrimination: digital, on the 6 MeV inner channel, threshold > 30keV. The Inner Trigger Request is the logical reference signal for the whole channels of the crystal; ITR starts the parameters computing and takes part to their validation process.
  - Time resolution: 10ns (1ns expected). The time interval measurement is done between ITR and an external signal such as RF beam or fast detector signal.
- BGO and CsI channels:
  - Energy resolution: 15%
  - Energy range : 20 MeV
  - Veto: signal is sourced by the logical OR of CsI and BGO digital discriminators; sub-event is rejected or marked depending on the veto position in the window triggered by ITR.
- Counting rate: < 100kHz per crystal.
- Crystal parameters readout:
  - Inner: E6MeV, E20MeV, Time, Time Stamping
  - Outer: E6MeV, Emirror, T30, T60, T90
  - BGO and CsI : EBGO, ECsI, Veto pattern
  - Readout rate: 6 Mbytes/s per crytal (considering about 60 Bytes).
- Trigger modes:
  - Trigger-less: Each time a crystal is hit, ITR signal originated from the crystal inner channel crystal validates the whole parameters of the crystal.
  - Event trigger: A validation window or reject signal is sourced if the EXOGAM multiplicity level, which is programmed in the trigger module, is respectively reached or not. For each crystal, parameters are put in the event readout block if its ITR signal matches with the validation window.
  - Common dead time: when detectors are coupled, the EXOGAM multiplicity is combined with ancillary detector logical signals. As a result, the validation window or reject signals are sourced.
- Coupling with ancillary detectors:
  - The Global Trigger System and the AGAVA VME module, which are under development for AGATA, are suitable for coupling detectors.

2.2 Simulations

The EXOGAM array is fully described in GEANT4 and full calculations have been performed. These are available in the EXOGAM project definition. In addition to these, EXOGAM2 will add two features: the pulse shape analysis and the very high counting rate capability.

For this latter, tests are being pursued to check the applicability of the method. The first part has already been done and concluded that the ADONIS method can be applied with an EXOGAM Clover with its resistive preamplifiers (see Annex 1). The second test is scheduled early 2009 to time stamp the data and to go very high rates.

Concerning pulse shape analysis, source and in-beam measurements have been carried out in Liverpool and GANIL. The preliminary results of the in-beam data show that the limited sensitivity of the EXOGAM to pulse shape (see Annex 2). In our test, the position resolution was estimated between 13 and 16 mm. This should lead to an improvement of roughly 20% in energy resolution (note that Doppler correction was not applied in these preliminary analysis).

There is still a large amount of work to fully analyse these data. The final report is expected mid 2009. In addition to these measurements, simulations calculations are currently being performed based on the experimentally measured "virtual" segmentation of the EXOGAM Clovers. This will give us the possibility to extract realistic predictions for the energy resolution improvement using different Doppler correction techniques. The implementation in GEANT4 is fully done.

2.3 Design and construction scheme

The general layout for EXOGAM2 is shown below in Fig. 1 and one can identify four main parts:

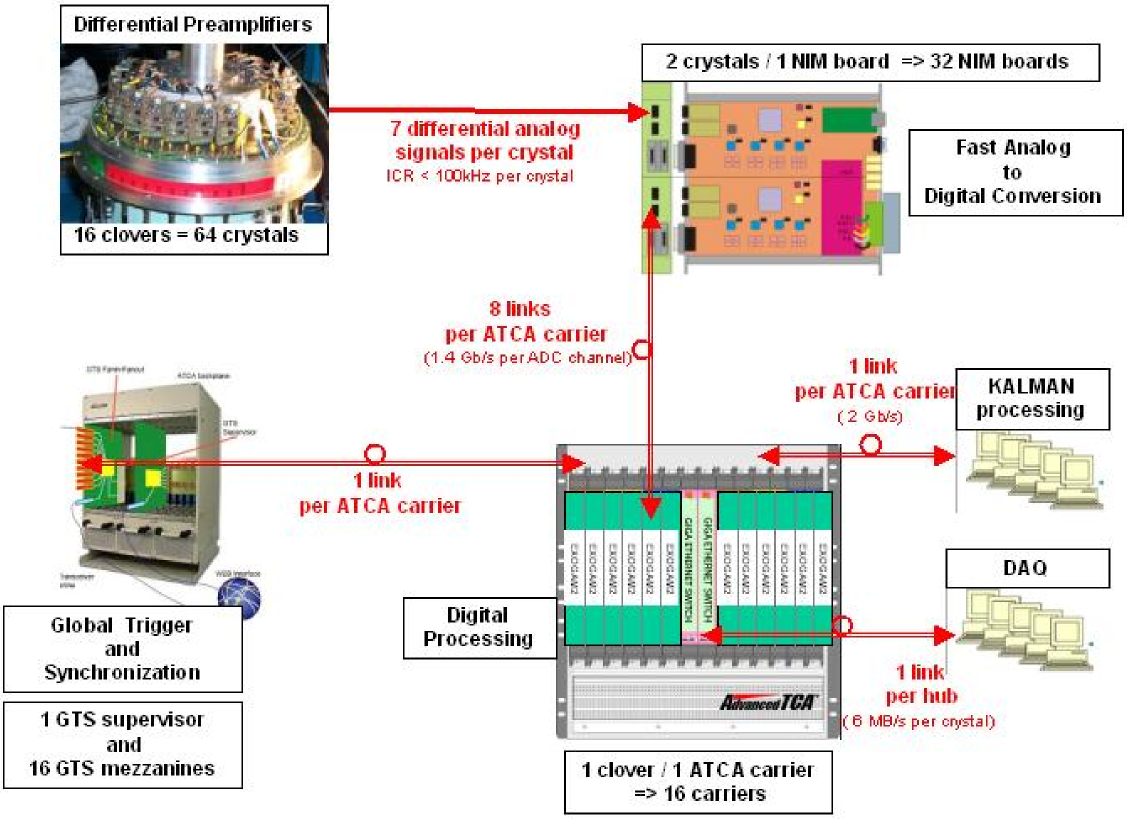


Figure 1: general layout of the EXOGAM2 electronics

- The **pre-amplification**: it is the analog front end electronics set which collects charges coming from the channels of 16 Ge clovers and integrates currents coming from PM of BGO et CsI shielding. Analog outputs are sent via 10m long differential lines to the following stage.

- The **digitization**: it is a NIM standard electronics set which analog to digital converts signals coming from the pre-amplification stage. Detector channels of two crystals are processed in two fold 8 AD channels implemented in one NIM module. The raw binary samples of each fast ADC are serially sent via an optical link at 1.4 Gb/s to the following stage.

- The **digital processing**: it is an ATCA standard set which processes the energy, time and time stamping parameters of the crystals. One ATCA carrier houses the electronics processing of binary samples originating from one clover. The computed parameters are downloaded to the DAQ system via a Gigabits Ethernet link; thank to two switches located in the ATCA crate, the 6MB/s per crystal rate can be easily achieved. Moreover, inner raw binary samples can be sent via one extra fast link (possibly extra PCI express) to processors in which ADONIS algorithm is implemented.

- The **Global Trigger and Synchronisation system**: it is an ATCA electronics set housing the trigger processor and fan in fan out mezzanines. GTS mezzanines are optically linked to ATCA carriers in order to transmit Inner Trigger Requets to the GTS and receive GTS signals such as validation, reject, event number, time stamping.

These four parts will be now described into more details.

2.3.1 The pre-amplification stage

The Ge charge pre-amplifiers and the BGO-CsI integrators will be re-used from the previous EXOGAM setup; however some modifications must be studied in order to take into account new constraints such as high counting rates and high level of EMI radiations.

Ge channels :

Here are the present features of the inner and outer channels:
- Gain : 200 mV/MeV (no load)
- Output : common mode, 50Ω impedance
- Decay time: 50µs (+/-10%)

Following modifications must be studied:
- Differential outputs with 100Ω impedance
- Value of the feedback resistor, gain of the CSP second stage, injection of an opposite charge. These modifications are aimed to prevent CSP saturation while counting rate is increasing up to 100 kHz at 1MeV average energy. Impact of these modifications on the energy resolution must be measured.

BGO and CsI channels:

Here are the present features of these channels:
- Gain: 170 mV/MeV (no load)
- Output : common mode, 50Ω impedance
- Decay time : 10µs (+/-10%)

Integrators outputs must be modified: differential outputs with 100Ω impedance

In Fig. 2 is presented a sketch of the new connection box and its links to the front-end pre-amplifiers electronics and to the NUMEXO2 digitizer. This box is required for differentiation and ease of connection while not modifying any connector on the detector cryostat.

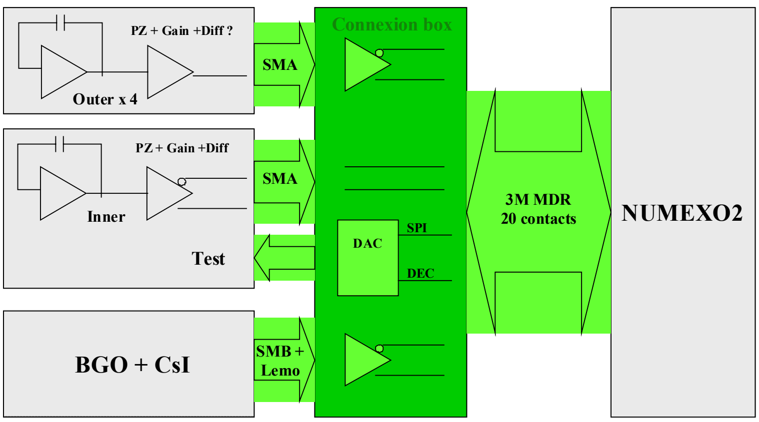


Figure 2: connection box and links with the digitiser and the detector electronics

2.3.2 The digitizer

The analog to digital conversion of the signals coming from two crystals pre-amplifiers is carried out in one NIM module.

The 7 analog outputs of one crystal (ie 1 inner, 4 outers, 1 BGO and one 1 CsI) are sent through one 10 twisted-shielded pairs cable (3M Mini Delta Ribbon) to individual conversion channels, except the inner signal sent into two channels because of the two required energy ranges. The block diagram of one half NIM module is shown in Fig. 3.

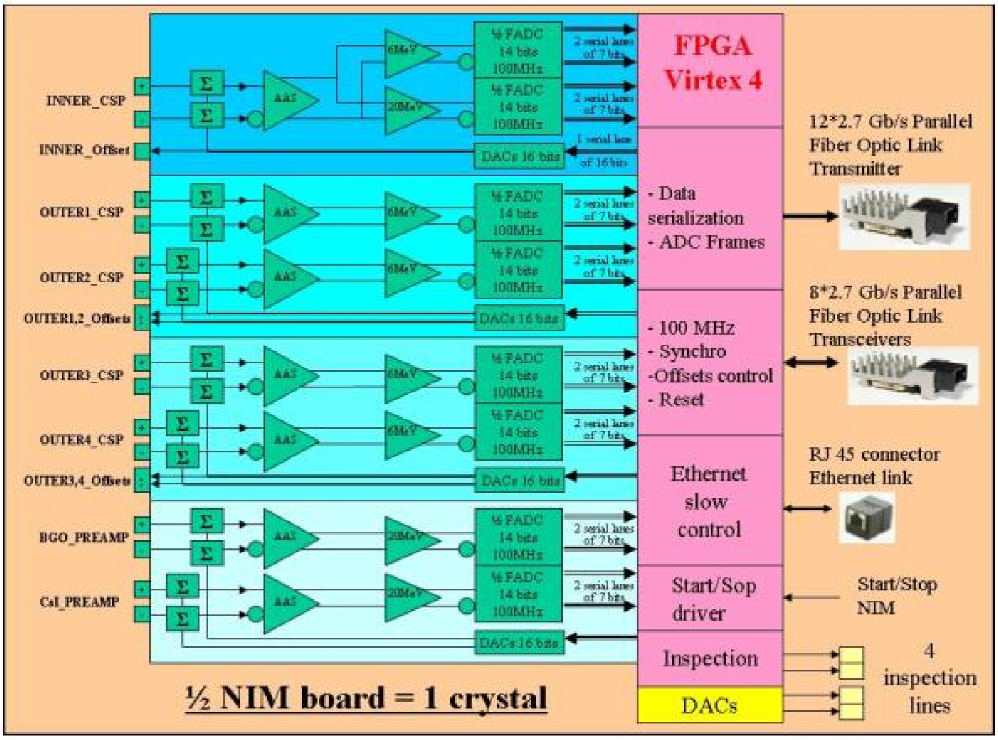


Figure 3:layout of the EXOGAM2 digitiser

Each conversion channel is made up of:

- A differential analog stage with two low noise current feedback op-amps (AD8002 @ 2nV/sqHz). It combines the pre-amp signal with a test signal and a base line control signal.
- Two Digital to Analog Converters (16 bits, 1µs settling time, differential outputs). One is devoted to test the conversion channel. The other one controls the base line level in order to keep signal amplitudes within the conversion range; the base line level is digitally computed in the ATCA carrier logic and binary data are sent back to the NIM digitizer for driving this DAC.
- A low noise and fast differential opamp (AD8139 @ 2.2nV/sqHz). It is aimed to adapt the common mode voltage and the range at the input of the Fast Analog to Digital Converter.
- The FastADC (TI ADS6244 : dual ADC 14 bits, 100 MHz, 2 serial digital outputs per ADC). The analog to digital conversion process is continuously running.

FastADCs, DACs are digitally controlled by a Virtex 4, a Field Programmable Gate Array of Xilinx company.

The main functions that are implemented in the Virtex 4 are:

- The de-serialization in the IOSERDES blocks of the digital samples coming from both serial lines of one ADC. Each sample is a 14 bits word with 10ns time step. The de-serialization is controlled by the bit clock and frame clock of the dual Flash ADC.
- The encoding and serialization of these samples in the MGT blocks. For each conversion channel, the serial rate at the Virtex 4 ouput is slightly bigger than 1.4 Gb/s.
- The distribution of the 100MHz clock to Fast ADCs. This clock is sourced by the GTS.
- The route of the START/STOP signal inside the Virtex 4, from its reception to its distribution to the output towards the optical fibre. Challenge is to source a signal, which complies with the expected 1ns resolution.
- The management of the traces memory in the oscilloscope mode. Assuming a memory with a 2 Mega bytes depth and a 10 ns time base, it means 1 Mega samples stocked (ie 10 ms scanned time).
- The control of the DACs.
- The management of the Ethernet slow control. Main slow control tasks are:
  - The setup of the Fast ADCs and of NIM board registers.
  - The control of the synchronisation process, which is initiated by the SYNC signal coming from the GTS. The purpose of the synchronisation is to measure the relative delay of transmission between the optical lines sourcing the samples fom the NIM digitizer to the ATCA carrier.
  - The control of the test procedures; it consists in feeding the input of the conversion channel with a pulse control by the Virtex 4 and ckecking the data at the output of the ADC. This self-test is aimed to validate the conversion channel.
  - The management of the analog and logical inspections lines and the readout of the traces: both are aimed to remote control that the NIM board is running properly.

Thanks to Linux and ENX driver implemented in the PPC processor of the Virtex 4, the NIM digitizer is easily and friendly controlled.

Fig. 4 below shows a sketch of the NUMEXO2 digitizer; it shows the location of the electronics of two crystals on the NIM board and its front panel connectors.

Some connectors are common to both crystals:

- On the rear panel :
  - The RJ45 connected gives access to the Ethernet Slow Control
  - The DIN9 connector is devoted to a serial communication It is useful in case of Ethernet trouble.
  - Two Lemo 00 coaxial connectors are connected to the inspections lines; if daisy chained, they make an inspection bus.
- On the front panel :
  - Two Lemo 00 coaxial connectors are devoted to the reception and to the tansmission from board to board of the NIM Start-Stop signal.
- On the PCB board :
  - Two JTAG connectors are used for downloading programs into Virtex4.

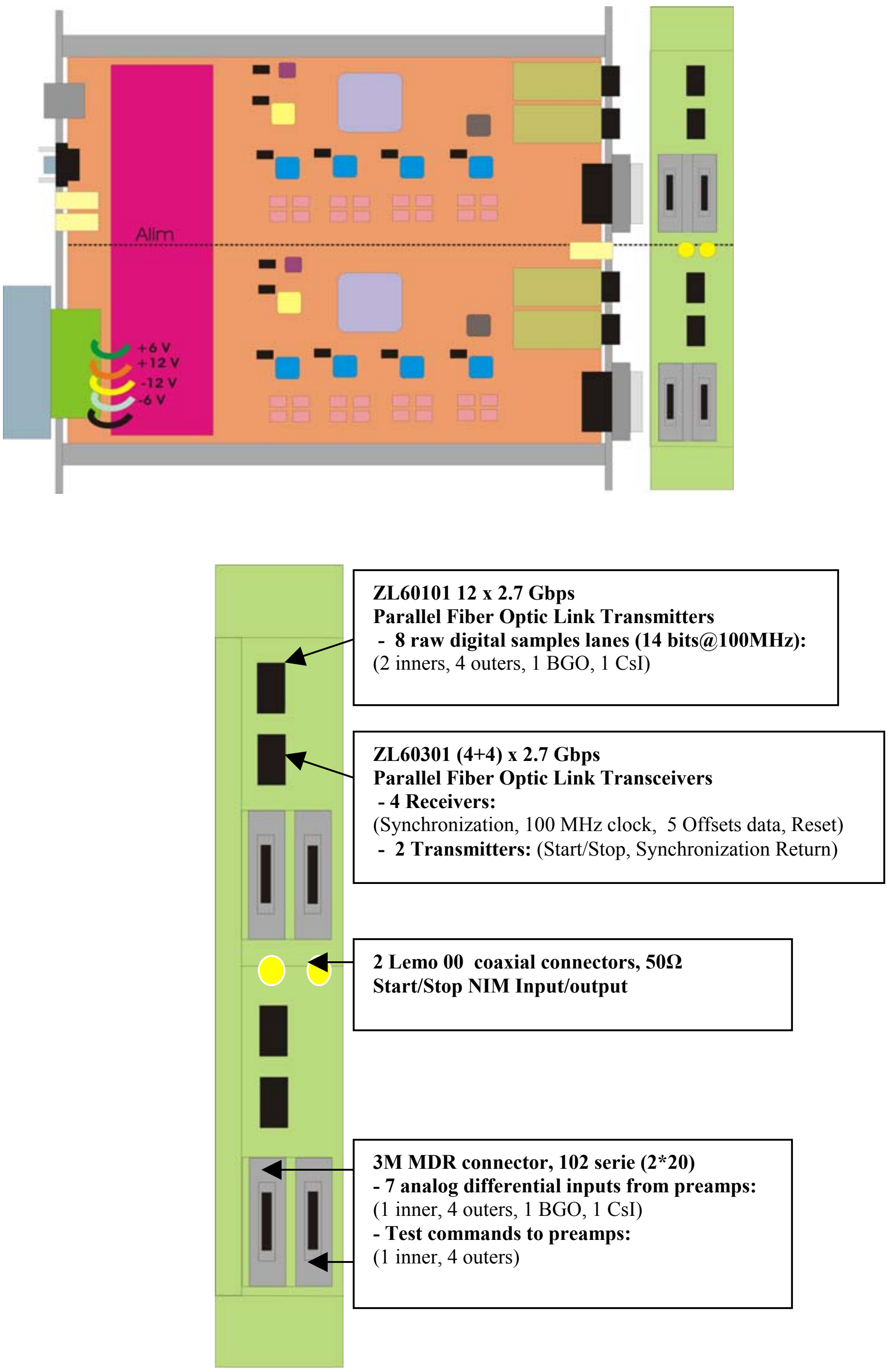


Figure 4: top: implementation of the electronics for two crystals on the digitiser board. Bottom: front panel connectors

To fully equipped the 16 EXOGAM clovers, 32 NUMEXO2 NIM boards must be manufactured.

A one-crystal prototype is under construction. The main goals are:
- To precise the functional block diagram of the Virtex 4 and components around it.

- To define the location of components on the PCB, to identify critical lines, to fix layers and analyse the power distribution.
- To implement in the Virtex 4 the main functions: FADC raw samples reception and transmission at high rate, clock and synchronization distribution, slow control and inspection.
- To control the integrity of raw binary data which are sent by the prototype along 70m long binary fibres to an evaluation board.
- To feature the main parameters (linearity, resolution) of the analog to digital conversion stage.
- To define the algorithm of the binary discrimination giving the best time resolution.
- To implement the Moving Window Deconvolution for the Energy processing.
- To develop tests and synchronisation procedures.

Fig. 5 shows a simplified block diagram for the main components handled by the Virtex 4.

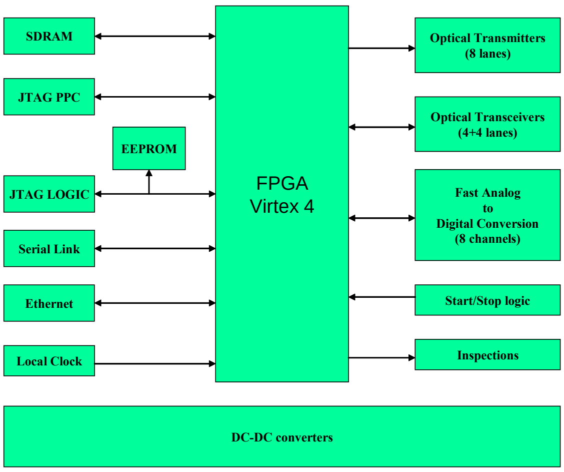


Figure 5: Block diagram for the main components controlled by the Virtex4 FPGA

To fully feature NUMEXO2 prototype, it will be optically linked to a test bench (see Fig. 6). It consists in two boards, a SEGMENT mezzanine plugged on a TESTMEZZ mother board retrieved from hardware and software AGATA developments. This test-bench is under the responsibility of the CSNSM laboratory, which is involved in the AGATA electronics.

The main tasks and timetable for designing and featuring the pre-amplifiers and NUMEXO2 have been established. It is merely a two years project.

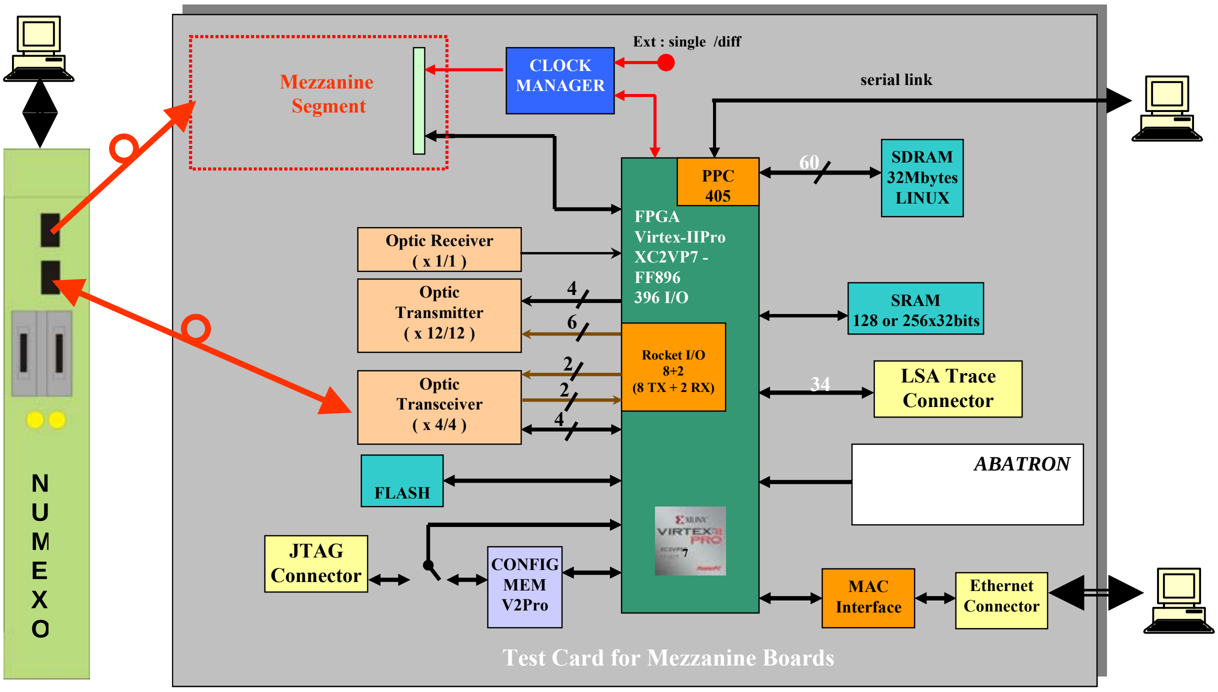


Figure 6: the test bench to fully evaluate the NUMEXO2 digitizer

2.3.3 The ATCA processing boards

The processing unit is made up with four mezzanines plugged on one ATCA carrier. These boards have been designed for AGATA detector. The mass production, for the AGATA Demonstrator, has started and it is foreseen to get one processing unit in mid 2009 in order to study the hardware and software modifications to be brought for EXOGAM2.

ATCA stands for Advanced Telecommunications Computing Architecture. It is targeted to requirements for the next generation of "carrier grade" communications equipment. This series of specifications incorporates the latest trends in high speed interconnect technologies, next generation processors, and improved reliability, availability and Serviceability (RAS). ATCA short form specifications can be found at:
http://www.picmg.org/pdf/PICMG_3_0_Shortform.pdf

There are two kinds of mezzanines:
- GTS mezzanine: it is the link between the GTS processor and the carrier. It transmits trigger signals and the common 200MHz clock (see above the GTS chapter).
- SEGMENT mezzanine: Raw samples coming from digitizers are processed in this mezzanine. Parameters (Energy and rise time samples) are validated and time stamped by the core signal discriminator; then this block is put in a FIFO pipeline. This is the first level of validation of the whole channels of one crystal. The second level involved the GTS processor and hence the whole detector. The GTS validation process extracts these parameters and submits the event block to the carrier readout.

The carrier board has four main functions:
- Power distribution to the mezzanines.
- Hardware resources control via the I2C bus.
- Trigger signals, clocks and synchronisation signals management.
- DAQ communication management via the fast links (basic and fabric interfaces, SFP connectors) for the setup and the mezzanines parameters readout.

Details on these boards can be found at the following websites:

Carrier board and GTS mezzanines: http://agata.pd.infn.it/

SEGMENT mezzanines: http://www-csnsm.in2p3.fr/-AGATA-Weeks-.html

The following descriptions put mainly the emphasis on the modifications as compared to the original AGATA design.

CRYSTAL mezzanine:

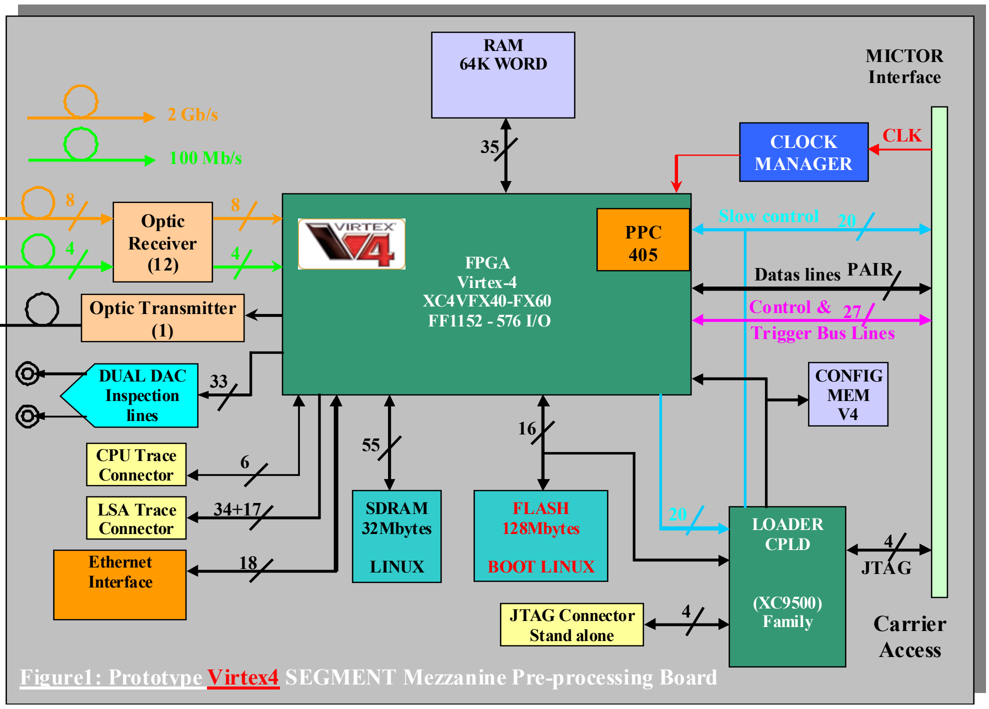


Figure 7: general layout of the CRYSTAL mezzanine, a modified AGATA SEGMENT mezzanine

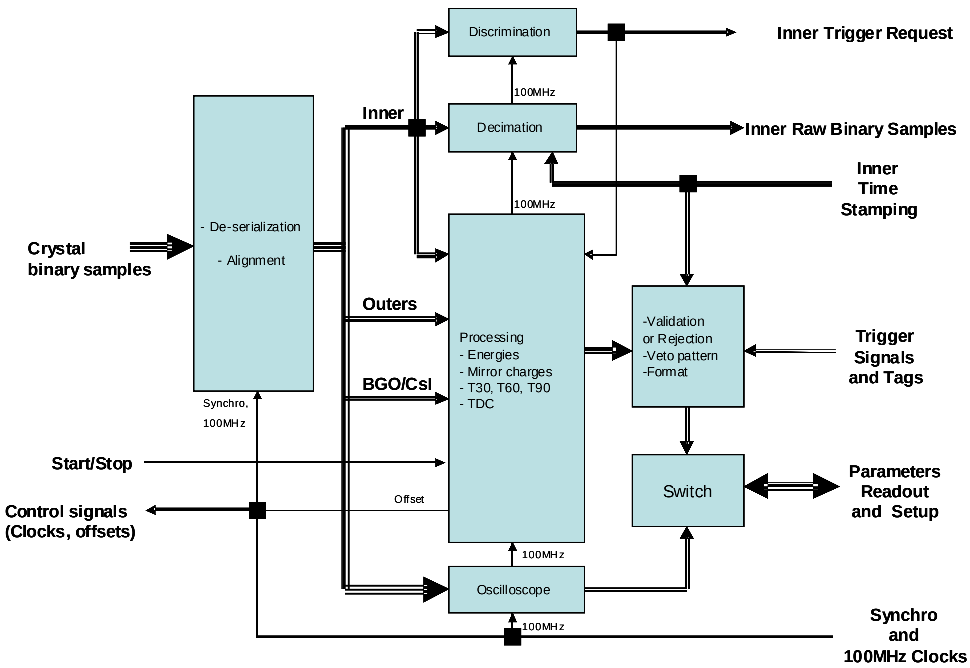


Figure 8: Virtex4 block diagram

Fig. 7 shows the block diagram of the SEGMENT mezzanine designed for AGATA by the CSNSM laboratory. Because optical inputs are different, the hardware will be slightly modified. The mezzanine will be renamed CRYSTAL. Many C software and VHDL firmware files will be retrieved from AGATA and modified for fulfilling EXOGAM2 requirements; some files will be added.

The Virtex 4 block diagram is shown in Fig. 8 and below is the list of the main files, which must be implemented.

Main files to be implemented in the Virtex 4:

- Linux operating system
- ENX driver (link between PPC and logic FPGA)
- Setup Slow Control
- Synchronisation process
- MGT and SERDES blocks
- Discrimination block
- Validation and time stamping process
- Moving Window Deconvolution
- Time measurement block
- Parameters and raw inner samples readout block
- Traces and inspection block
- Self test process

The design, manufacturing and test of CRYSTAL mezzanines will be done by the CSNSM laboratory. Up to 64 CRYTAL mezzanines are needed to equip EXOGAM detector in its full 16 clovers array.

<u>ATCA carrier</u>:
The block diagram of the AGATA carrier card is presented in Fig. 9.

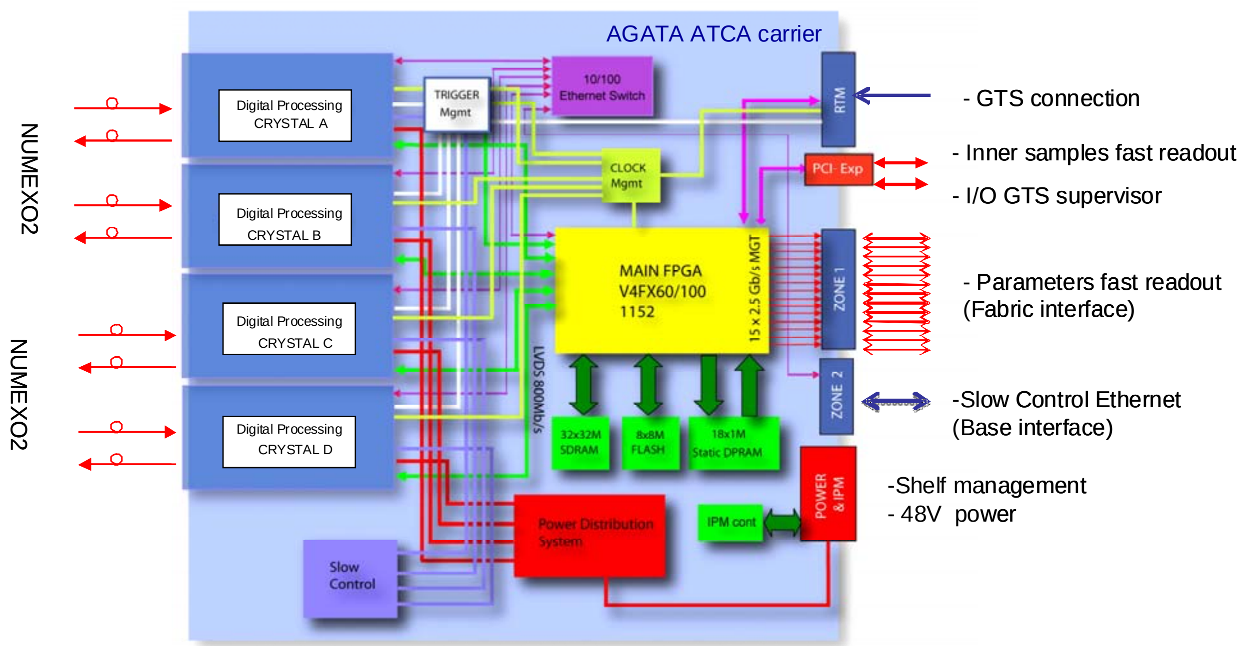


Figure 9: The AGATA carrier card

It is planned to retrieve the AGATA carrier and to avoid making any hardware modification. Basic EXOGAM2 requirements have been studied:

- Because four CRYSTAL mezzanines are plugged on the carrier, there is no more room for a GTS mezzanine (as it is in the AGATA hardware setup); solutions to embed GTS functions or move GTS mezzanine onto the Rear Transition Module, at the backside of the carrier, must be investigated.
- Thanks to the versatility of signals attribution at the interface mezzanine-carrier, an Inner Trigger Request can be easily sourced from each CRYSTAL mezzanine and feed the Trigger FFGA.
- The parameters readout can be done via the Base Interface (Gbits Ethernet) zone. If rate is not high enough because of the traces readout, the Fabric Interface resources can be implemented.
- The extra SFP connector is fully compliant with the raw samples rate required for the implementation of the ADONIS algorithm in PC units, located some meter away from the ATCA shells. The transmission protocol, PCI express or custom protocol is not yet defined. But, some specifications have been issued:
    - The maximum transmission rate is 2.5Gb/s
    - Only the inner channels are processed with ADONIS. It means four inner raw samples are transmitted.
    - 14 bits raw samples at 20MHz is high enough for such algorithm
    - 2 bits must be added at raw samples for labelling the inner channels.
    - 8 bits time stamping and base line correction level are added at raw samples of each inner channel.

As well, software and firmware implemented in the three main FPGA components (FPGA0, FPGA1 and FPGA2) of the carrier will be retrieved and modified to fulfil the EXOGAM2 requirements. Below are listed the main VHDL and C files to be retrieved, modified or developed:

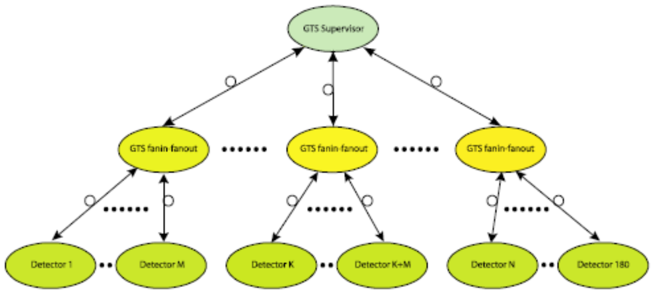
- Software files to be retrieved or modified:
    - Linux [FPGA0]
    - ENX [FPGA0]
- Firmware files to be retrieved:
    - Buses:
        - JTAG management [FPGA1]
        - I2C: I2Cmain driver [FPGA0], I2C3 management [FPGA1, FPGA2]
        - IPMB [FPGA0, FPGA1, FPGA2]
        - Serial bus [FPGA2]
        - Ethernet: IP [FPGA0], ZL50407 switch management
        - PCI express [FPGA0]
    - MGTs
        - MGT blocks [FPGA0]
        - (CHi-MGTj) connections [FPGA1]
        - Setup registers management.
        - Synchronisation procedure
        - Trigger window mechanism for event validation
        - Physical parameters readout from mezzanines to carrier FPGA0
        - TDC function
        - Firmware files to modified or developed:
    - Management of the 4 Inner Trigger Request: validation and time stamping
    - Management of the 4 inner samples: readout from mezzanines to FPGA0, formatting, protocol transmission via the SFP connector.
    - Implementation of the fast readout protocol developed by the LPC laboratory
    - Physical data readout: data formatting and labelling, veto data compression, transmission via both ATCA switches.

2.3.4 The Global Trigger System and Synchronisation

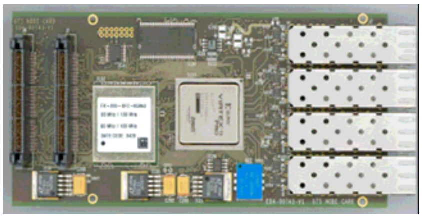
The trigger hardware system is a set of GTS fan in fan out mezzanines and GTS processor board housed in one ATCA shell, and a set of GTS mezzanines plugged on ATCA carriers. This AGATA trigger system has been chosen for EXOGAM2. The specifications of AGATA Global Trigger and Synchronization hardware can be found at: http://agata.pd.infn.it/

An overview of the GTS topology and functionalities is shown in Fig. 10.

The GTS has a tree topology; the root node (GTS supervisor) acts as the source of global information and sinks all trigger and service requests from the processing carriers. Up to four carriers can be optically linked to one GTS fan-in fan-out mezzanine



GTS tree topology

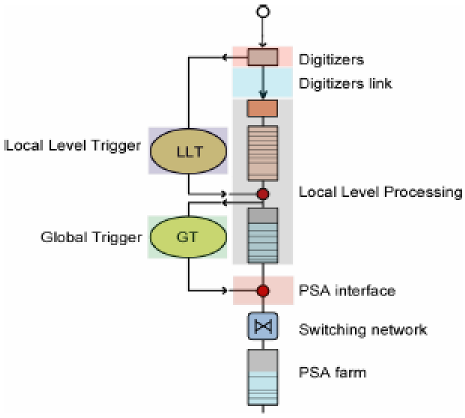


GTS mezzanine

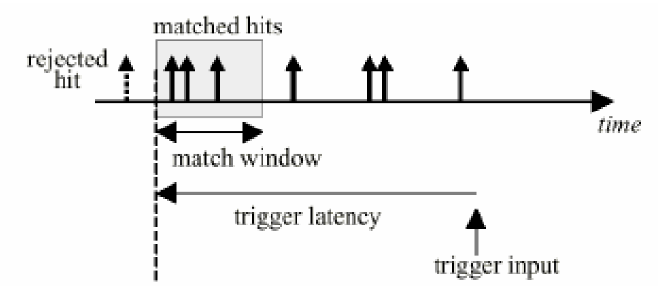
Figure 10: overview of the Global Trigger System

The central purpose of the trigger is to select events from logical signals and to synchronise data, both coming out from the digital processing of CRYSTAL binary samples.
The columnar model of the binary samples flow is represented in Fig. 11 (top); it shows two levels of selection:

- Local Level Trigger: each time a CRYSTAL is hit, an Inner Trigger Request issued from the digital discrimination of the inner binary samples is sourced. ITR signal is the first level of accepting for keeping in FIFO pipeline raw binary samples of the CRYSTAL channels.
- Global Trigger: a combination of ITR signals is analysed by the GTS processor; as a result, a Global L1 accept signal is sent to the carriers. The validation mechanism is represented in Fig. 11 (bottom); at the time of the L1 validation arrival (trigger input), from the current value of GTS clock the trigger latency is subtracted.



The AGATA readout column



The window based trigger matching

Figure 11: top: the AGATA readout data flow and associated two-level trigger. Bottom: the GTS validation mechanism

To synchronise data resulting for the digital processing of CRYSTAL samples, a common clock and time stamps are sourced by the GTS system. The GTS functionalities are summarized and commented from the EXOGAM2 point of view:

- Common Clock: a 200MHz clock is supplied by the trigger processor (root node) via GTS mezzanines to all carriers and digitizers.
- Global Clock Counter: the actual Global Clock Counter is latched by the Trigger Request; as a result the 48 bits pattern is used to tag CRYSTAL fragments and read by the event builder for merging crystal fragments into an event block.
- Global Event Counter: the actual Global Event Counter is one count incremented by L1 validation; as a result the 16 bits pattern is sent to the GTS network to carriers for tagging CRYSTAL fragments.
- Trigger Controls: the Trigger Control must guarantee that CRYSTAL mezzanines are ready to receive L1 Accept. Messages are sent from GTS mezzanines embedded in carriers for warning the trigger processor that buffers are almost full. Trigger Controls can be sum up in five main tasks: throttling of the L1 validation signal, sending fast commands (reset, initialisation), fast monitoring feedback from carriers, sending calibration and test trigger commands, monitoring dead time.
- Trigger Requests: inner Trigger Request, issued from the digital discrimination of the binary samples of the inner pre-amplifier, is sent through the GTS network to the GTS processor. Inner Trigger Requests which are collected are combined and processed in the processor for

multiplicity or coincidence with ancillary detectors. As a positive result, L1 validation is sent to carriers.

- Error Reports: carrier buffer overflows, local faults, built-in self tests can be reported for proper corrective actions.

To equip EXOGAM2 in its 16 clovers full array setup, GTS system must be made of 4 GTS mezzanines housed in the GTS supervisor ATCA shell and 16 GTS mezzanines plugged in the 16 ATCA carriers. Software and firmware files will be retrieved from AGATA GTS system. The file, which must be modified by the user, is the trigger validation conditions file.

2.4 Calibration procedures

No special requirements as compared to the current EXOGAM array.

2.5 DAQ and Controls

The EXOGAM2 software DAQ system has basically four main functionalities:

Data Flow:

The goal is to transport and process the data flow from the EXOGAM detectors up to the data storage. Data sources are the NUMEXO2 digitization boards. The NUMEXO2 outputs are sent to the ATCA crystal mezzanine boards via optic fibers, where energies are computed in a Virtex FPGA. Then all data coming out of the ATCA boards are merged together thanks to an Event Builder based on the Narval acquisition system. At the end of the chain, data have to be provided to the physicists in an understandable and user-friendly way thanks to a Data Format library, and are stored on a large disk array.

Narval, originally developed by IPN Orsay, is currently used at GANIL. It is a distributed and entirely configurable software which can be easily adapted to the different configurations. Some specific actors will have to be designed to answer to the different steps of the project, especially for the event builder of the whole system.

Slow Control:

The Slow Control is in charge of setting up and monitoring the electronics: NUMEXO2 digitizers, ATCA carrier boards, mezzanines and GTS Trigger Processor.

The main functionalities Slow Control has to provide are:

- define which electronic boards are present in the system;
- initialize the different boards with correct values;
- save all the setup parameters of the whole electronics or a part of the electronics;
- restore a previously saved setup;
- monitor some key parameters of the boards (*e.g.* temperatures …);
- handle error/alarm events and pass them to the Run Control;
- accept some basic commands from the Run Control (setup, go, stop, get state).

The Slow Control system will be designed with a client/server approach. It will mainly consist in a Slow Control Core (SCC) communicating on one side with the different boards and on the other side with a graphical user interface, which will behave as a client of the Slow Control Core. The communications between the Slow Control Core and its graphical interface will be implemented with the SOAP/XML network protocol and a WSDL (Web Service Description Language) interface.

Having in mind to put as much intelligence as possible inside the electronics, boards containing a Xilinx Virtex FPGA with a PowerPC core will embed the ENX command server running under the Linux operating system, which provides advanced network services (TCP/IP, HTTP, SOAP…). ENX is a CSNSM/IPN Orsay development written in ADA language with a SOAP communication protocol and a plug-in mechanism to adapt to each particular type of board. Plug-ins can be developed in ADA or C++.

Run Control:

The Run Control has the main purpose to control and monitor the DAQ components. It coordinates the several activities necessary to put the EXOGAM2 system and its data acquisition software into operational state. Actions like initialization, setup, start and stop of the data acquisition are performed by the operator through the Run Control system. It interacts with the Slow Control system in order to assure the correct configuration and setup of the electronic devices, before data taking is started. It also provides the monitoring of the acquisition, error report and logging capabilities.

The main tasks are outlined here:

- configure the DAQ for a run by selecting data flow active components;
- save/restore a configuration;
- basic commands to control all the active components (setup, start, stop);
- monitor the DAQ (status, data rates);
- handle error/info messages;
- log book;
- display spectra.

As the Slow Control, the Run Control system will be designed with a client/server approach. It will also consist in a Run Control Core (RCC) communicating on one side with the data flow active components and on the other side with a client graphical user interface. The communications between RCC and its graphical interface will be implemented with the SOAP/XML protocol and WSDL interface.
The RCC will be based on the general purpose RCC skeleton currently developed at GANIL.

Analysis and calibration tools:

EXOGAM2 data acquisition system will include a set of tools for online/offline data analysis and for calibration/characterization of the whole electronic chain, based on Ganil Root Utilities (GRU) and ViGRU visualization software.

2.6 Target requirements

Same as for EXOGAM

2.7 Beam requirements

All different types of beams produced by the existing CSS, SPIRAL1, SPIRAL2 and LINAG will be useful for this research program:

- very intense stable heavy-ion beams (from 10^{11} to 10^{14} pps) provided by the LINAG accelerator (^{48,40}Ca, ^{58}Ni, …)
- neutron-rich radioactive beams of, e.g., Kr, Sn, Xe, Nd, …
- neutron-deficient radioactive beams with $T_z \leq 0$, e.g., ^{18}Ne, ^{34}Ar, ^{56}Ni, ^{58}Cu, ^{72}Kr, …

Usually with the highest possible intensity; from 10^3 pps are needed for Coulomb excitation measurements while $>10^8$ pps are required for fusion-evaporation reactions. The requested beam energy covers a range from 3-5 MeV/A to 10-15 MeV/A.

Some general comments concerning beam requirements considerations are summarized:

- In many cases **beam purity** is of highest concern and impurities should not exceed the 1% level.
- **High quality of the beams** and in particular **radioactive beams** (emittance, halo, …) is very important in order to use position-sensitive detectors around the target point for the high-resolution gamma-ray spectroscopy and the coincidence with the particles. More quantitatively, the beam emittance should be ~5p.mm.mrad; the energy resolution should be better than 1%.
- **Good timing properties** (below 1ns) are needed for all experiments using “fast” ancillary detectors, e.g. for neutrons.
- Experiments with radioactive beams usually require **stable beams to set up the detectors** under clean conditions (higher intensity, less background).
- **Source development for CIME** is needed in order to deliver stable isotopes of all elements that are available as radioactive beams from SPIRAL2.
- **Parallel beam delivery via the new direct beam line from CIME to G1 and G2** would also greatly benefit from such source development.

A specific comment is beam pulsing to determine the t=0 in the TDPAD technique for long-lived (>50ns) isomers. In that case, beam pulsing on a microsecond range without substantial loss in beam intensity is required. For lifetime below 50ns, the CSS/CIME RF (~10 MHz) are good enough.

3. Implementation and Installation

3.1 Experimental hall and Annex facilities

EXOGAM2 is a modular and powerful setup, which can be installed in several experimental areas like:

- G1 connected to VAMOS
- G2 connected to the Neutron wall or standalone
- G3 with SPEG
- D4-D6 with LISE
- S^3 (secondary target or focal point)
- DESIR area

In these various experimental areas, EXOGAM2 will be used either in full geometry (G1, G2, G3, S3 secondary target point) or with a limited number of detectors, typically 5 but up to 8 with a dedicated mechanical structure (D4, D6, S3 focal plane, DESIR). In this latter case the segmentation of the detector is *in general* not required since the gamma rays are emitted from nuclei at rest (decay experiments). For the full setup space is needed to install the existing platform.

Apart from the detectors and the associated mechanics, the front-end digitizers, associated NIM crates, optical fibres to the data acquisition room, the autofill system, the low and high voltage power supplies, the target loader will be located in the experimental area.

The EXOGAM detectors need regular filling with LN2. The standard autofill system uses a buffer dewar installed in the area between the detectors and the main external dewar. It is highly recommended that LN2 is supplied in all these areas via a permanent direct connection to a main external dewar.

Sufficient power should be provided for these crucial systems. An Uninterruptible Power Supply (UPS) with sufficient autonomy should be provided to secure the critical part of EXOGAM in case of power failure. The sensitive parts of EXOGAM, which should be supplied by this UPS, are: the low and high voltage power supplies and the autofill system.

The data acquisition system will be located outside the experimental. Therefore an optical connection should be installed between the digitizers and the acquisition. This acquisition will consist in carrier and mezzanine cards using the ATCA standard. These cards will be installed in and ATCA cabinet cooled via water-air heat exchanger. The room where the acquisition will be installed must be air-conditioned to avoid condensation and water with an input temperature between 6 and 15°C with an outflow of 2.8 m^3/h should be available.

Laboratories are needed to store, measure, maintain and repair detectors and electronics. The setup of these annex facilities, including the requests from EXOGAM2, are part of a separate document (dealing with the renewal of the acquisition areas of GANIL) taking into account not only the request from EXOGAM2 but also those from AGATA. These should be seen as “Ge detector” annex facilities and laboratories rather than EXOGAM2 only.

3.2 Detectors-Machine interface

The usual (currently existing) signals should be provided: high frequency from accelerators, signal to a fast acting valve to stop the beam if for instance silicon detectors are used with EXOGAM, presence of the beam in the area, cables between main control room and the area for beam alignment purposes, etc.

3.3 Assembly and installation

No specific requirements in addition to what already exist for EXOGAM.

4. Commissioning (work plan, cost, necessary manpower and other resources)

The EXOGAM2 technical architecture described above shows four main parts, which must be commissioned at first individually and secondly together. Two steps must be considered:

- step 1: commissioning of the prototypes (no ATCA modules) for one crystal. Resolutions, linearity, optical transmission and time stamping must be evaluated with a generator and a source. This step will involve GANIL, CSNSM, and New Delhi manpower.
- step 2: commissioning of pre-serial modules (ATCA modules included) in order to qualify the electronics of one clover before starting the manufacturing of the whole set of boards. In addition to the tests mentioned above, Ethernet readout and GTS tests must be carried out. It implies test with generators, sources and if possible in-beam tests. For these tests, GANIL physicists and engineers will be involved.

There is no extra cost associated at the step 1 and step 2 commissioning
Extra human resources must be found as mentioned in the table presented in section 10 to test and commission the whole system.

5. Operation (running cost, necessary manpower and other resources)

Spare components are taken into account within the project to ensure a smooth operation of the overall system. The running costs for EXOGAM2 will consist in repairing daughter/motherboards, changing components, cables and connectors, maintaining infrastructure items like crates, cooling racks and power supplies. Specific tools and equipment of the electronics laboratory (apart from the standard ones already available today for EXOGAM) are planned in the project (i.e. very high frequency oscilloscope, test benches, evaluation boards, etc.).

Based on our experience of EXOGAM, the running costs associated to electronics for EXOGAM2 should be of the order of 10k€ per year at most.

The manpower required to ensure a smooth operation relies not only on the GANIL manpower involved in the project but also on the experts involved in AGATA. Indeed, since a large fraction of the EXOGAM2 electronics design is based on AGATA (Carrier and GTS from the University of Padova), the maintenance of these boards is also based on the way the AGATA electronics will be maintained. A close connection between the two projects must be ensured to optimise the manpower resources connected to this maintenance issue.

For normal operation, the rooms planned in the project aiming at a global renewal of the acquisition areas at GANIL are sufficient for EXOGAM2 and AGATA when at GANIL (see 3.1).

6. Safety issues and proposed solutions

EXOGAM2 consists in an upgrade of the EXOGAM electronics. The risk analysis considers the following potential issues:

- Cryogenic
- Anoxia
- High voltage

Radiological issues are not considered since the detectors are outside the target chamber.

In addition the upgrade EXOGAM2 does not modify any of the risks already associated today with EXOGAM. Therefore the protection and safety devices and rules presently applicable to EXOGAM (safety equipments and training) still remains and are not altered.

7. Organisations and Responsibilities

7.1 Management Board

The EXOGAM2 collaboration is currently being built. It will include partners from EXOGAM as well as newcomers. It has a project leader (G. de France) and a technical coordinator (M. Tripon). The management structure and in particular the steering committee will be setup once all the partners with associated tasks and responsibilities will be identified. For now the EXOGAM steering committee is in charge.

7.2 WBS - work package break down structure

The work package structure for EXOGAM2 is shown below. Only the identified and most probable partners are indicated in the last column. Discussions are going on with others.

Task Number	Task name	Description of Task	Participating Members (coordinators in bold)
1	MGT	Management	**GANIL**
2	PSA	Pulse Shape Analysis	**Liverpool** , GANIL
3	MWD	MWD and base line control implementations	**GANIL**, IPHC*, New Delhi*
4	ADONIS	ADONIS implementation	**LPSS**, GANIL
5	VFEE	Very Front End Electronics	**GANIL**
6	DIGIT	Digitizer	**GANIL**, CSNSM, New Delhi*
7	PROC	Pre-Processing	**CSNSM**, **GANIL**, IPNO*, Padova*
8	DAQ	DAQ	**GANIL**
9	GTS	Trigger and Time stamping	**GANIL**, Padova*, Krakow*
10	FR	Fast readout	**LPC Caen***, GANIL
11	MT	Manufacturing and tests	**GANIL**, to be found
12	EXP	Experiments	**GANIL**, CSNSM

*Collaboration agreement under discussion

7.3 Schedule for the signature of Memorandum of Understanding
The Memorandum of Understanding should be signed before June 2009.

8. Planning

Equipment	End of R&D	Start of construction	End of construction
Pre-amplifiers, motherboards and interconnection box	Q4 2009	Q1 2010	Q4 2010
NUMEXO2 digitizer	Q4 2010	Q1 2011	Q2 2011
CRYSTAL mezzanine	Q2 2010	Q3 2010	Q4 2010
ATCA carrier	Q4 2010	Q1 2011	Q2 2011
GTS	Q4 2010	Q1 2011	Q2 2011

10. Manpower

Task	Required FTE	Institutions providing the FTE
MGT	20	GANIL
PSA	20	GANIL, Liverpool
MWD	10	GANIL, IPHC*, New Delhi*
ADONIS	64	LPSS, GANIL
VFEE	25	GANIL
DIGIT	65	GANIL, CSNSM, New Delhi*
PROC	80	CSNSM, GANIL , IPNO*, Padova*
DAQ	10	GANIL
GTS	20	GANIL, Padova*, Krakow*
FR	5	LPC Caen*, GANIL
MT	45	GANIL, to be found
EXP	30	GANIL, CSNSM

11. Options and possible further upgrades (list)

One upgrade already anticipated but not included as such in the EXOGAM2 budget requirement is the implementation of the ADONIS method to deal with very high data rates. This part is still in an R&D phase even though some works have been already realized which showed that the ADONIS method can be successfully applied with an EXOGAM Clover (see Annex1). This programme will be pursued and finalized in 2009 by the proof of principle to time stamp ADONIS data taken from a Clover at very high rate.

12. Relations with other projects

As already mentioned previously, EXOGAM2 will be used in several experimental areas. Until now, EXOGAM has already been in: G1coupled to VAMOS, G2 stand alone or coupled to the Neutron Wall, D4/D6 coupled to LISE, G3 coupled to SPEG and in LIRAT. In the future it is expected to be also installed in the S^3 building as well as in the DESIR area.

The necessary coupling to many different auxiliary detectors will be realized using the AGAVA module developed by the AGATA collaboration to couple existing detectors to AGATA.

13. Other issues

Annex 1

Report on tests using ADONIS with an EXOGAM Clover at GANIL

Tests at GANIL, Caen on 29/04/2008, in the presence of Michel Tripon (GANIL), Emmanuel Clement (GANIL), Thomas Dautremer (CEA), Vladimir Kondrasovs (CEA), Thierry Montagu (CEA).

Experimental setup :

- Detector (Clover SO2) cold, polarized (3500 V) and stable for several days.
- Energy resolutions measured the 28/04/08:
  Inner C 2.20 keV@1.33 MeV
  Inner B 2.4 keV@1.33 MeV
  Inner A 2.34 keV@1.33 MeV
  Inner D 2.39 keV @ 1.33 MeV

- Adonis bin unmodified as compared to the previous tests on CSP GANIL only (this means very little amplification when the first stage is by-passed)
- ^{60}Co source of 50 kBq, and 30kBq
- ^{152}Eu the source of

Experimental measurements :

Clover channel	Source (activity)	Energy resolution measured with ADONIS (keV)
Inner D	^{60}Co (1600 cps)	2.32@1.33 MeV tail on the left
Inner D	^{60}Co (4000 cps)	2.50@1.33 MeV tail on the left
Inner D	60 Co (5000 cps)	2.37@1.33 MeV – separation de 256 (i.e. reject of 20 %) – the tail is compensated but still not completely
Inner A	^{60}Co (4300 cps)	2.41@1.33 MeV tail on the left

Inner A	2 x ^{60}Co sources (8700 cps)	2.36@1.33 MeV- separation de 256: the tail is compensated but still not completely
Inner A	2 x ^{60}Co sources + 1 x ^{152}Eu source (15000 cps)	2.37@1.33 MeV - separation de 256: the tail is compensated but still not completely (2.4 keV @ 1408 MeV)
Inner A	2 x ^{60}Co sources + 1 x ^{152}Eu source (21000 cps)	2.38@1.33 MeV - separation de 256 (i.e. reject of 50 %) – the tail is compensated but still not completely (2.61 keV @ 1,4 MeV)
Outer A4	2 x ^{60}Co sources (3500 cps)	3.64@1.1 MeV no separation 3.38@1.1 MeV with maximum separation

The screenshots are provided in the annex of the document.
The tail is particularly visible behind a logarithmic scale. Note, however, that it is lower by nearly two orders of magnitude as compared to the peak maximum.

What is the separation parameter?
This setting allows selecting pulses, which are separated by a certain time from the immediate neighboring ones (previous and next). The larger the time separation, the better the energy estimate. We have used this setting to "compensate" the effect of tailing on the left side of the photopeak found during measurements.

Observations :

- When Increasing the power of the “biais” parameter (setting parameter in Adonis), we eliminate the tail. This setting is at the expense of a worse resolution, which rises to 2.7 keV @ 1.33 MeV.
- At 20 000 cps and increasing to the maximum of the separation, we get resolution of 2.36 keV.

Comments :

Left tail:
as mentioned in the table, this tail has always been present during the measurements. We made an initial interpretation based on a poor compensation of the 1ms pole of the Adonis chain, resulting in the observation of spurious peaks leading to this tail.

This first interpretation appears to be wrong in the light of inter-comparison with data collected by E. Clement. Indeed, these spectra have also this tail, which invalidates that it is due to the Adonis + Clover coupling.

The origin of this tail is therefore related to the detector itself. It could be related to:

- Peripheral effects: incomplete, or at least different, charge collection. But this is not supported by a test using a lead collimator.
- Neutron damage and trapping leading to incomplete charge collection.

- Ballistic deficit

Conclusions :

At the end of these tests, we can conclude positively on the use of the Adonis method with the resistive preamplifiers of the Clovers. We have obtained energy resolutions that are comparable to those obtained when using the usual EXOGAM electronics.

These tests have shown that although the compensation pole is not perfect, it does not deteriorate the resolution.

These results contrast with those obtained 3 years ago. Indeed, the results (disappointing) obtained at that time have shown that the association clover + Adonis could not achieve the usual energy resolutions. The modification of the Adonis electronics concentrated on the first stage, while it was by-passed in the present tests.

Annex :

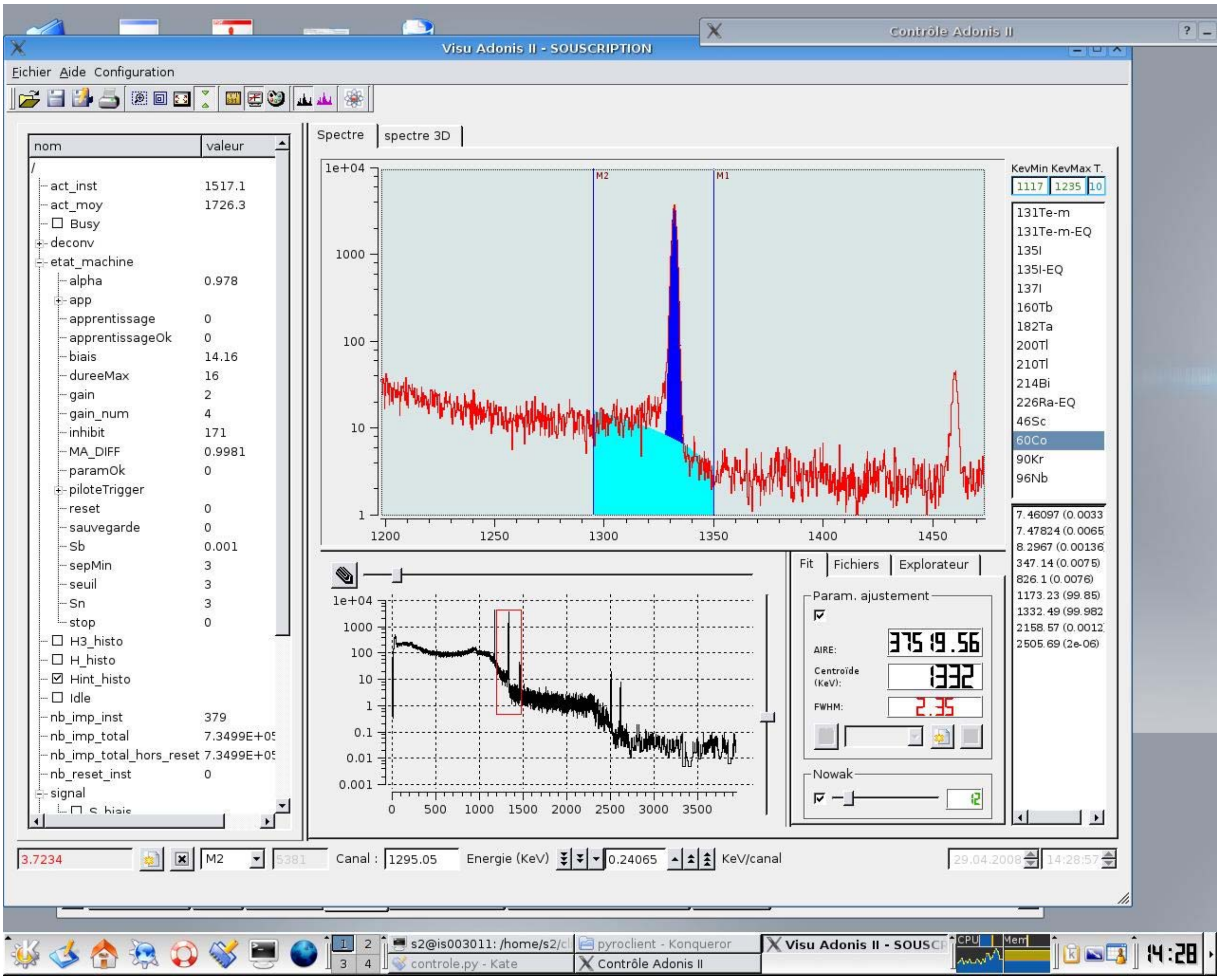


Figure 1: Energy resolution @ 1332 keV - Activity 1500 Hz

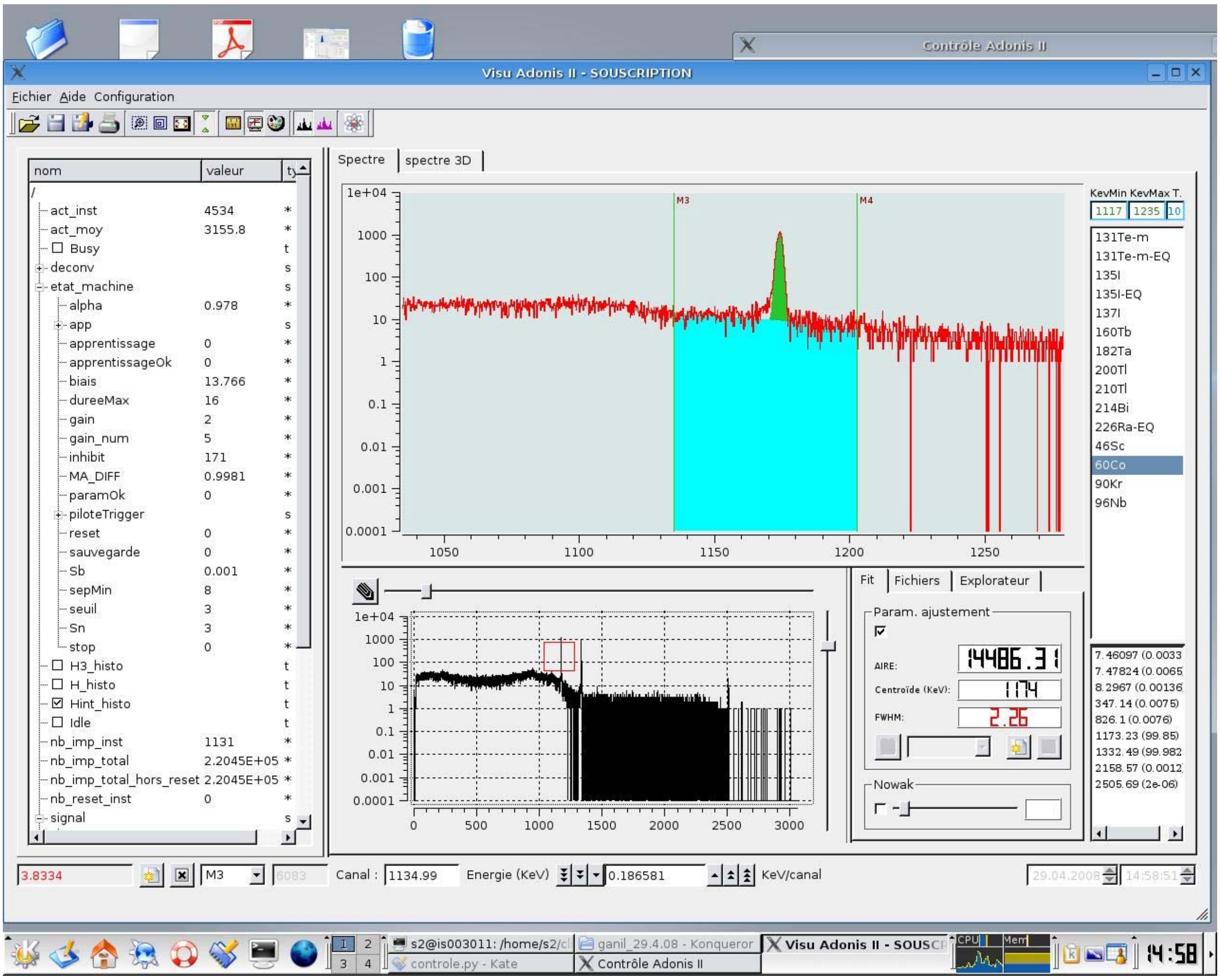


Figure 2: Energy resolution @ 1174 keV - Activity 4500 Hz

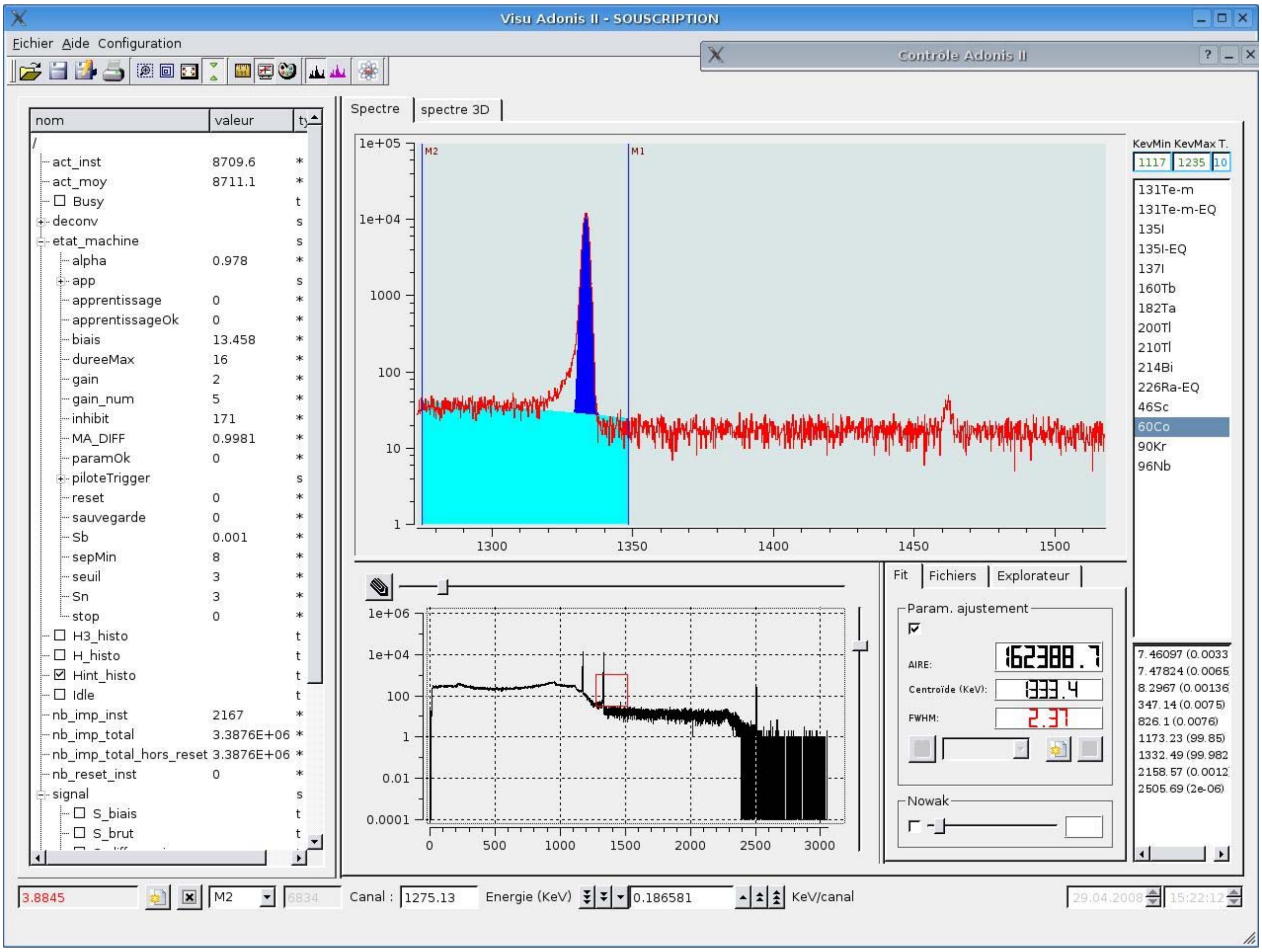


Figure 3: Energy resolution @ 1332 keV - Activity 8700 Hz

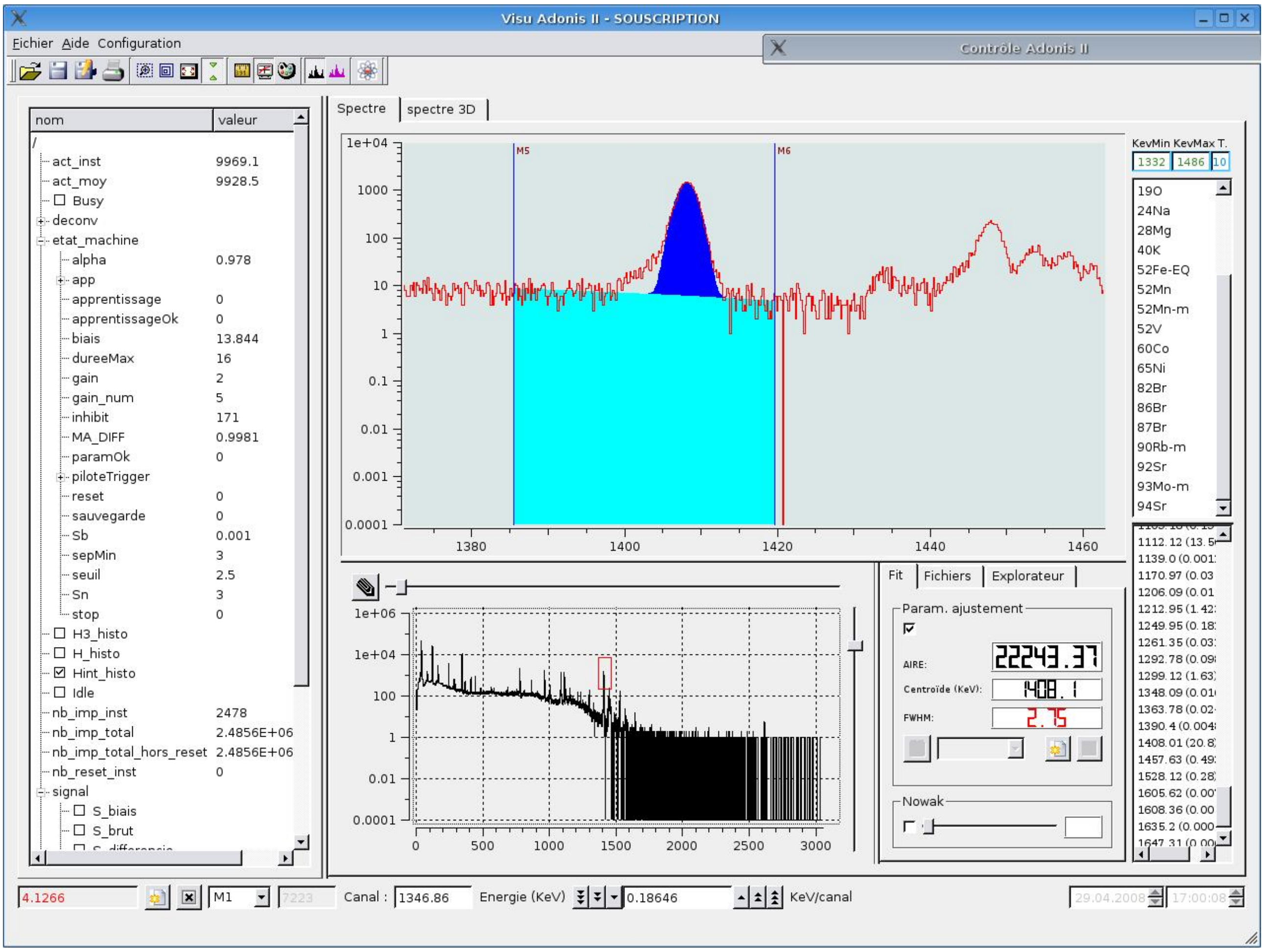


Figure 4: Energy resolution @ 1408 keV - Activity 10000 Hz – Europium alone

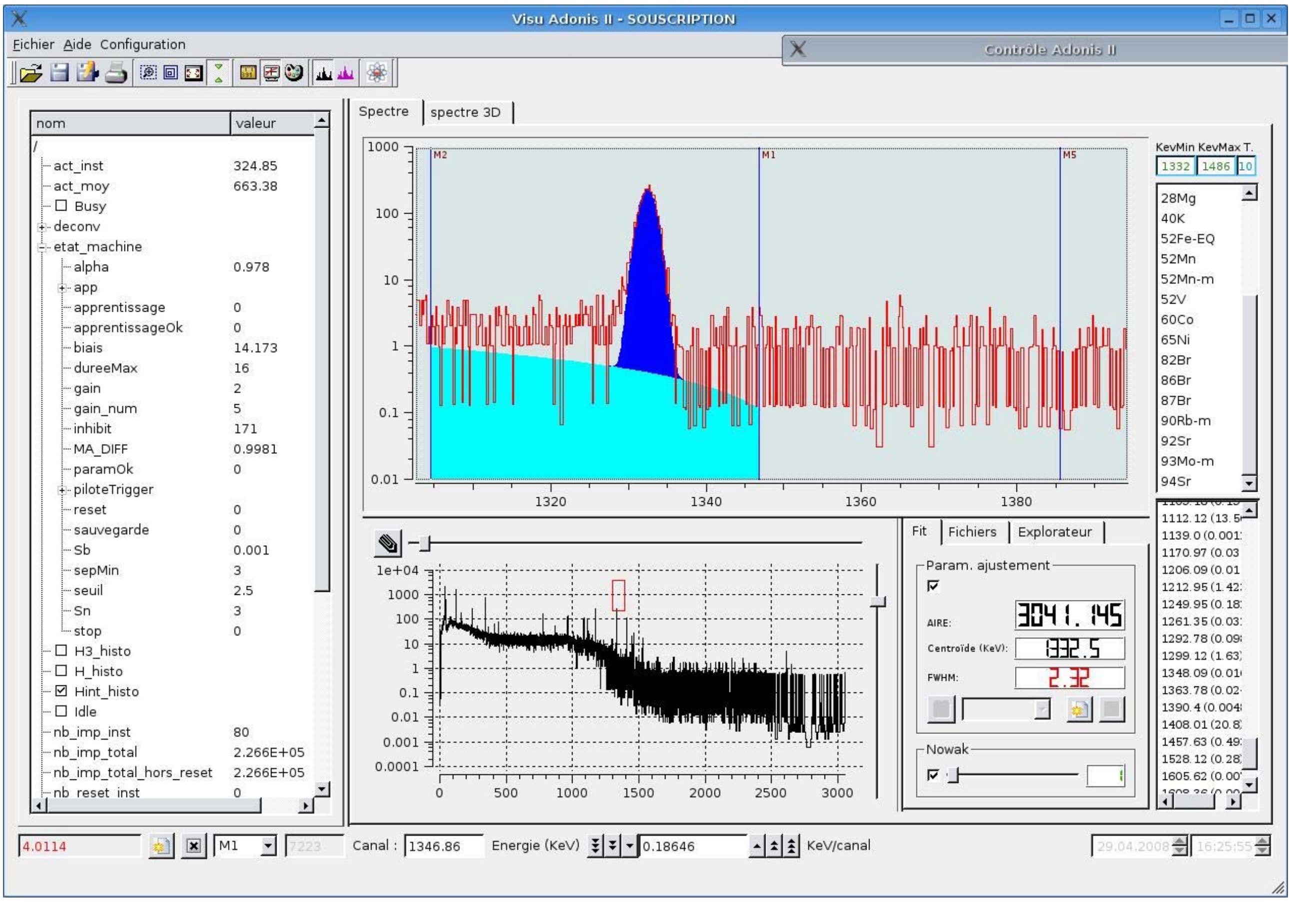


Figure 5: Energy resolution @ 1332 keV - Activity 300 Hz – with lead collimator

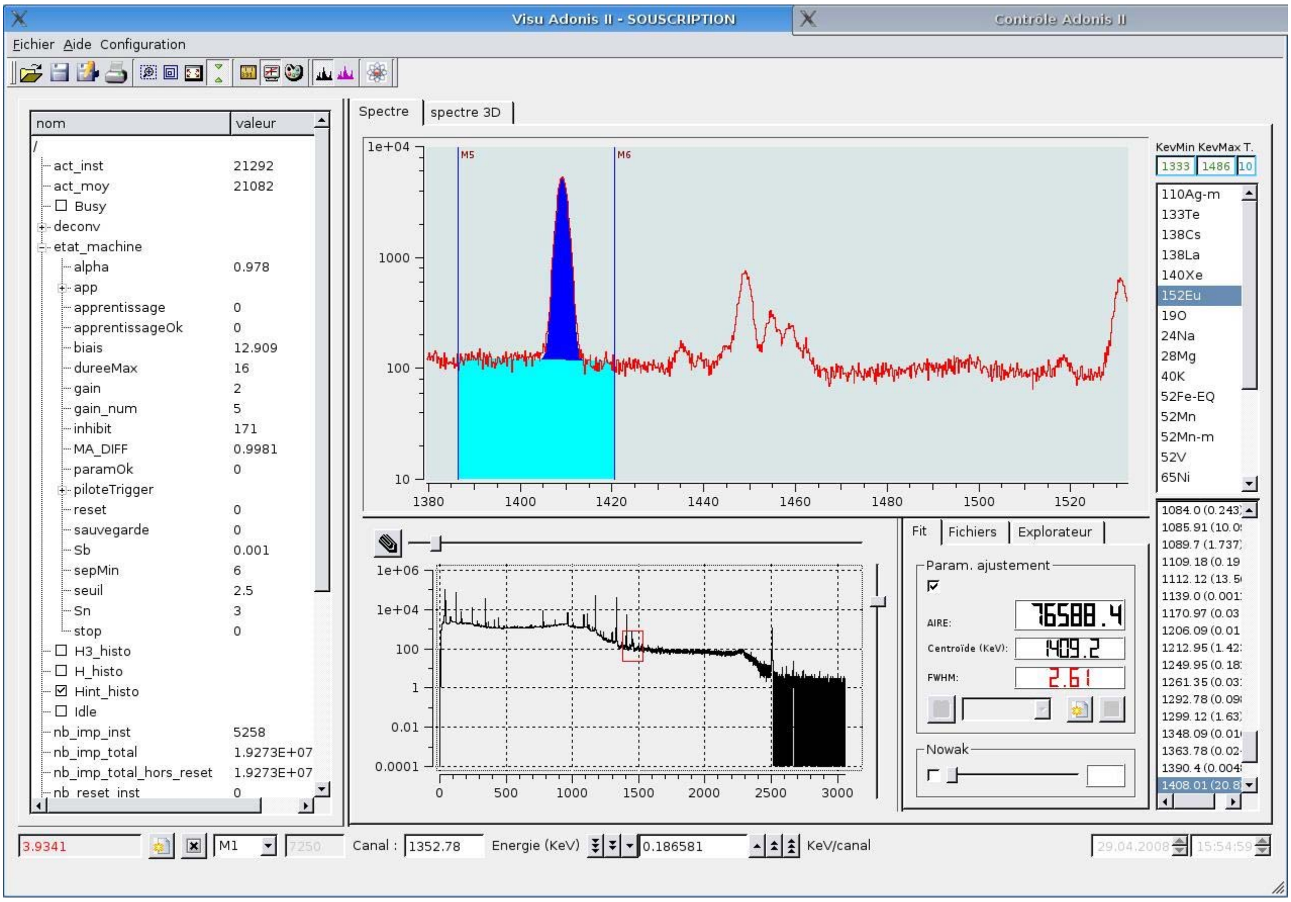


Figure 6: Energy resolution @ 1408 keV - Activity 20000 Hz

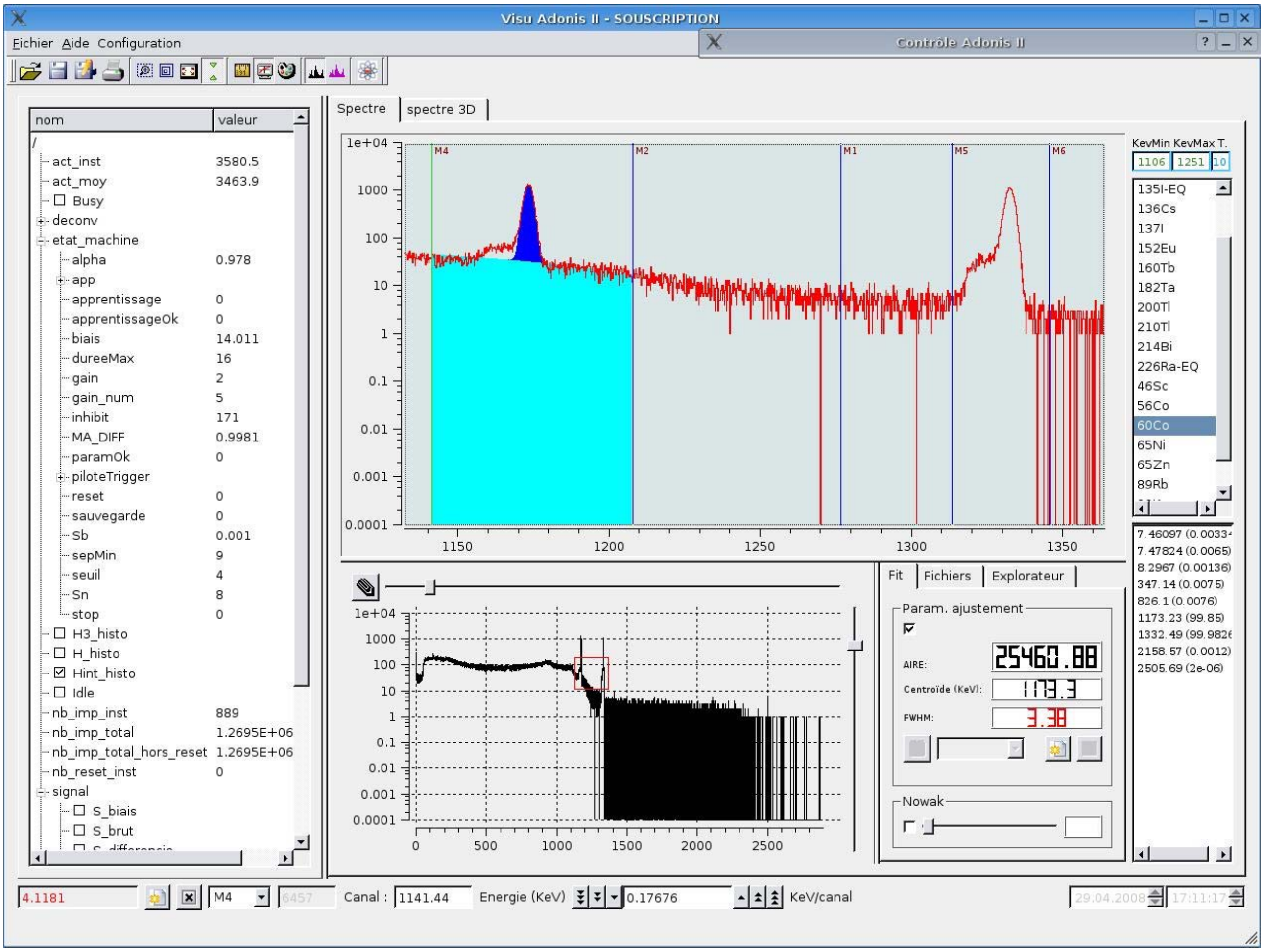


Figure 7: Energy resolution @ 1173 keV on Outer A4 – Cobalt alone.

Annex 2

The feasibility of performing PSA with Ortec and Canberra EXOGAM clovers

C. Unsworth, A.J. Boston, H. Boston, R. Cooper, G. DeFrance M. Dimmock, A. Grint, D. Oxley, P.J. Nolan

Data

In-beam gamma-ray spectra were collected using two HPGe clover detectors from the EXOGAM array at GANIL. ^{94,95}Mo were populated by the fusion evaporation reactions ^{12}C (^{86}Kr,3n) ^{95}Mo and ^{12}C (^{86}Kr,4n) ^{94}Mo, using a 3.7MeV/A ^{86}Kr beam on a 450μg/cm^2 ^{12}C target; the v/c of the recoiling nuclei was 7.8%. The acquisition system was triggered by any core event and 1.6μs of data from all forty preamplifier pulses (four centre contacts and sixteen outer contacts per detector) was digitised using 80MHz/14 bit FADCs in ten four channel GRT4 VME cards [Laz03]. The two EXOGAM clovers, one Ortec and one Canberra, were mounted at 90° to the beam at distances of 12.06cm and 11.64cm from the target. The experiment ran for four days and approximately 1Tb of data was collected from 4x10^7 events.

Gain coefficients for all channels were calculated using GF3 fits to ^{152}Eu calibration spectra. The standard deviation, σ, of the baseline noise was calculated for each digitised trace. Pulses were then classified as being real charge pulses, image charge pulses or noise based on the number of sigma in the maximum deviation from the baseline. The data were then pre-sorted by geometrically suppressing the zero pulses to reduce the size of the data set to 104 GB. Pulse shape analysis (PSA) routines have then been applied to improve the position resolution of the system, two separate techniques were used and then combined, T30-T90 gating and image charge asymmetry (ICA).

Channel Numbering

Figure 1, below, shows the numbering of electronics channels used during analysis. Channels 1-4 represent the core signals and channels 5-20 the segments, for the Canberra-Eurisys clover. The Ortec clover uses a similar scheme for channels 21-40.

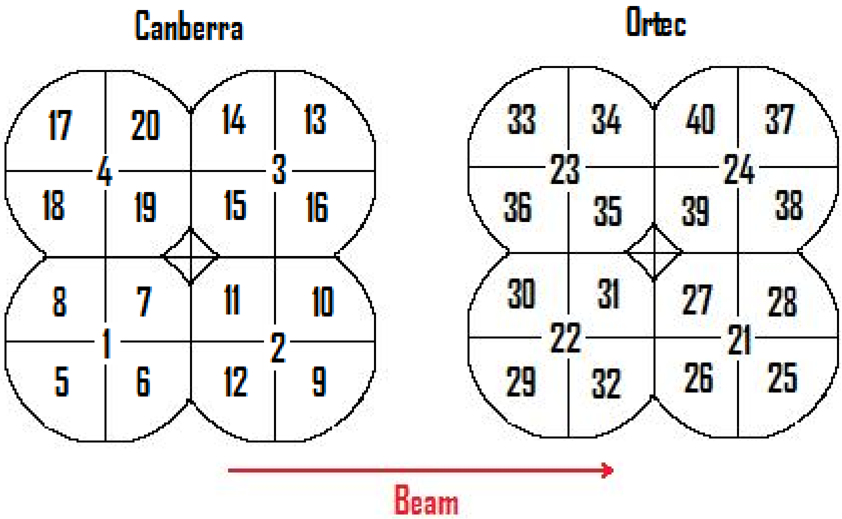


Figure 1 - Numbering of electronics channels relative to beam direction

T30 – T90 Gating

The shape of the charge pulse produced by a semiconductor detector is characteristic of the position of interaction along the line of charge transport, as well as the direction of charge transport relative to the crystal lattice. The sensitivity to position arises from the asymmetry in transport velocities of holes and electrons and is best parameterised by using time for a pulse to reach certain fractions of its maximum height, the risetime. Figure 2, below shows the calculation of risetimes for a typical pulse.

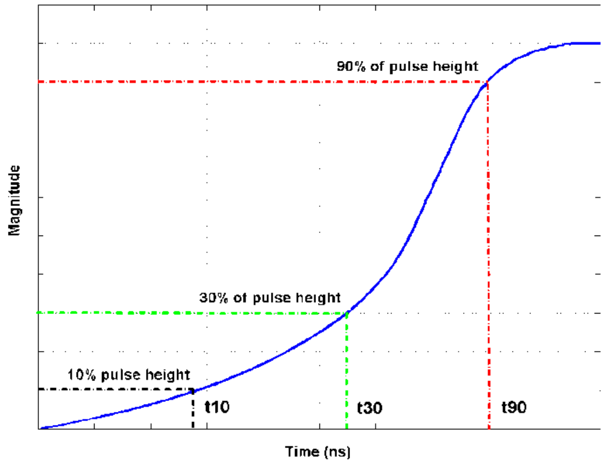


Figure 2 - Calculation of risetimes for a typical pulse.

It has been shown from scan data [Gro05] that T30 (t30 – t10) and T90 (t90 – t10) values can be used to localise the radial position of an interaction in an EXOGAM crystal. Figure 3, below, shows the T30-T90 distribution for an Ortec EXOGAM clover, collected on the Liverpool scanning table and gated on scanning table position [Gro05] (left) and the T30-T90 distribution collected in-beam at GANIL, from one segment of the Ortec clover for fold 1 events (right).

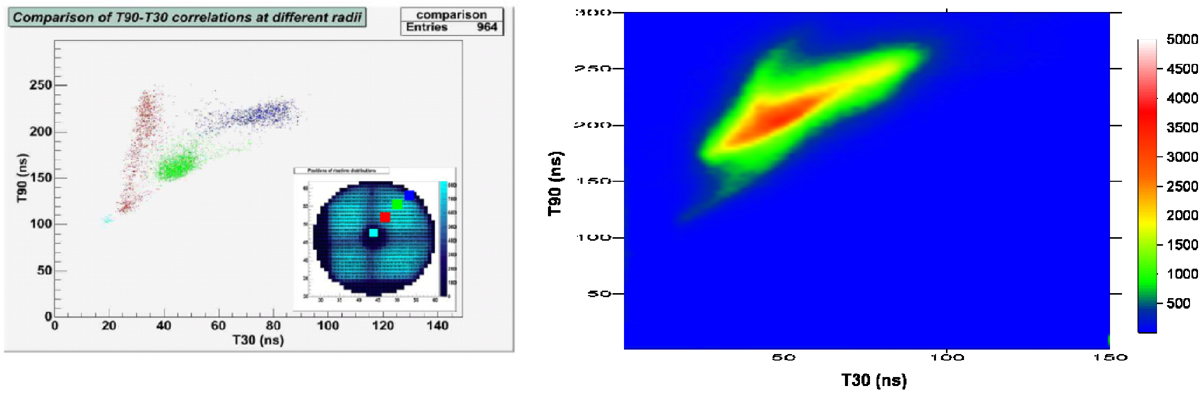


Figure 3 - T30-T90 distribution, gated on scanning table position [Gro05] (left), T30-t90 distribution collected in-beam at GANIL for fold 1 events (right)

Image Charge Asymmetry, ICA

When charge is collected in a detector, the changing electric field induces an image pulse on electrodes neighbouring the interaction segment. The total area of an image pulse is proportional to the energy deposited in an interaction and the proximity of the point of interaction to the electrode on which the image pulse is induced. Figure 4 (below left), shows the area of image charge pulses induced in segment 25 of the Ortec clover for the in-beam experiment.

For a particular interaction the image charge areas of neighbouring segments can be used to define the image charge asymmetry parameter, A_{ic}.

$$A_{ic} = \frac{Q_l - Q_r}{Q_l + Q_r}$$

A histogram of A_{ic} values for interactions in a segment yields a distribution such as that shown in Figure 4 (below right).

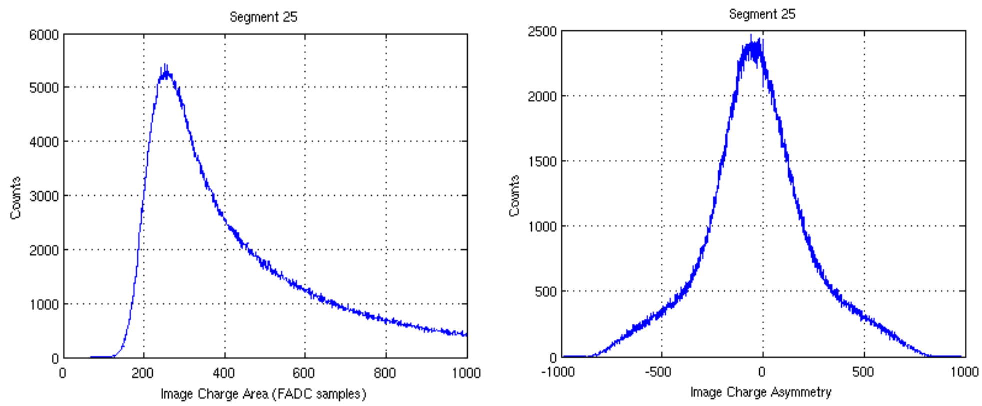


Figure 4 - Segment 25 image charge areas (left), Image asymmetry for events in segment 25 (right)

Applying cuts to the distribution in Figure 4 (right) can localise the position of interaction relative to the segment boundaries and hence can increase the granularity of a detector. Initially three asymmetry zones have been defined by cutting the distribution at the FWHM points however analysis of scan data will allow calibration of this later.

Results

The crystal geometry, internal cabling and preamplifier electronics are different for Ortec and Canberra-Eurisys EXOGAM clovers. These differences result in different risetime and image charge asymmetry distributions for the two types of clover and as such pulse shape analysis must be considered separately for each.

Spectra collected during the experiment contained both Doppler broadened peaks from the reaction products and stopped peaks from beam activated components of the apparatus support structures. These stopped peaks provided a useful measure of the intrinsic detector resolution with which to compare the results of PSA. In order to gauge the performance of the PSA, we will compare the stopped peak at 834 keV with the Doppler broadened peak from the ^{94}Mo $2^+ \rightarrow 0^+$ transition at 871.6 keV [Kha98]. All peak fits were performed using GF3 with a flat background and zero skew component to the Gaussian. Unless otherwise stated, energies are measured from the core of the relevant crystal and incremented to spectra based on the hit segment or zone within a segment.

Statistics

Figure 5, below shows the core and segment fold for events in the Ortec clover. During this initial investigation, full PSA has been applied only to events in the Ortec clover where both segment and core fold are equal to one; this amounts to 35% of total events. The same methods can be applied to events in either detector where the core fold is equal to the segment fold i.e. when only one segment per crystal fires; this extends the fraction of included events to 68%.

Techniques developed for the MINIBALL array allow the deconvolution of image and real charge pulses for events where neighbouring segments are hit. Applying these techniques to EXOGAM would allow a further improvement in the fraction of events included although this method could not be applied to events where opposite segments are hit.

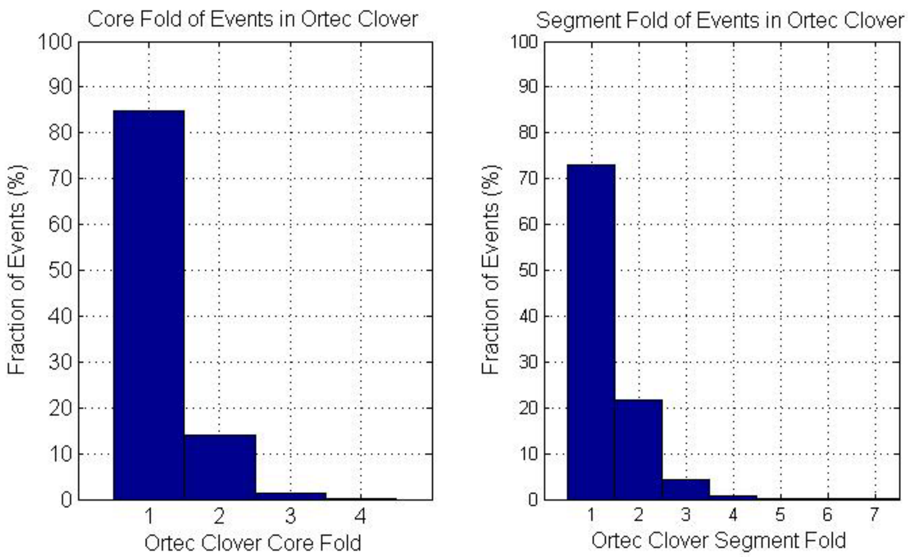


Figure 5 - Core and Segment Fold for Ortec Clover

Ortec Clover

For comparing the performance of the detector with different combinations of applied gates we will present results for segment 25. The intrinsic resolution of the Ortec detectors was measured to be 3.6(2) keV for the stopped peak at 834 keV. Producing a spectrum from the in-beam data showing energies for any interaction in the whole of segment 25 produces a FWHM of 7.9(2) keV.

The fraction of events falling into each risetime and asymmetry zone is shown in Figure 6 below.

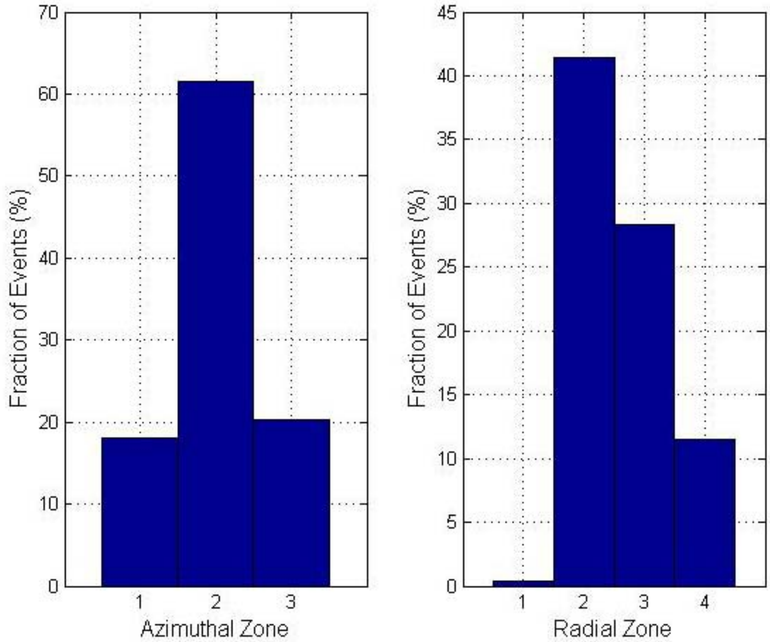


Figure 6 - Fraction of events falling into each azimuthal (left) and radial (right) zone

Asymmetry gating applied to the Ortec clover produced three zones, a central zone containing almost two thirds of the counts and two edge zones containing the remainder. Table 1 below shows the FWHM and areas for the 871.6 keV peak; it can be seen that one of the edge zones shows a much improved resolution while one shows a slight degradation, the resolution of the large central zone is unaffected.

Zone	FWHM (keV)	Area (Counts)	Event Fraction (%)
Whole Segment	7.9(2)	3348	100
1	8.7(6)	593	17.7
2	7.9(3)	2036	60.8
3	5.6(3)	717	21.4

Table 1 – FWHM and areas for Azimuthal Segment 25 Gating

Figure 7, below, shows overlaid spectra for the 800 – 1000 keV region together with a schematic image of the asymmetry zones for a crystal. A large central zone divides two edge zones within each segment, each one of which runs approximately perpendicular to the other. In an experimental situation, one of these zones will be running perpendicular to the beam axis and as such will define a small range of theta angles and allow for a good Doppler correction. The other edge zone runs parallel to the beam and contains positions across the full range of theta angles covered by the segment; as the positions cut out by this gate cover a smaller angular range than those included, the resolution is actually worse than that of the whole segment. In the case of segment 25, bottom right in Figure 7, zone 3 defines the narrow theta range and is at a larger angle than the rest of the segment, as such it produces a narrow peak with a lower energy centroid than the other zones in the segment.

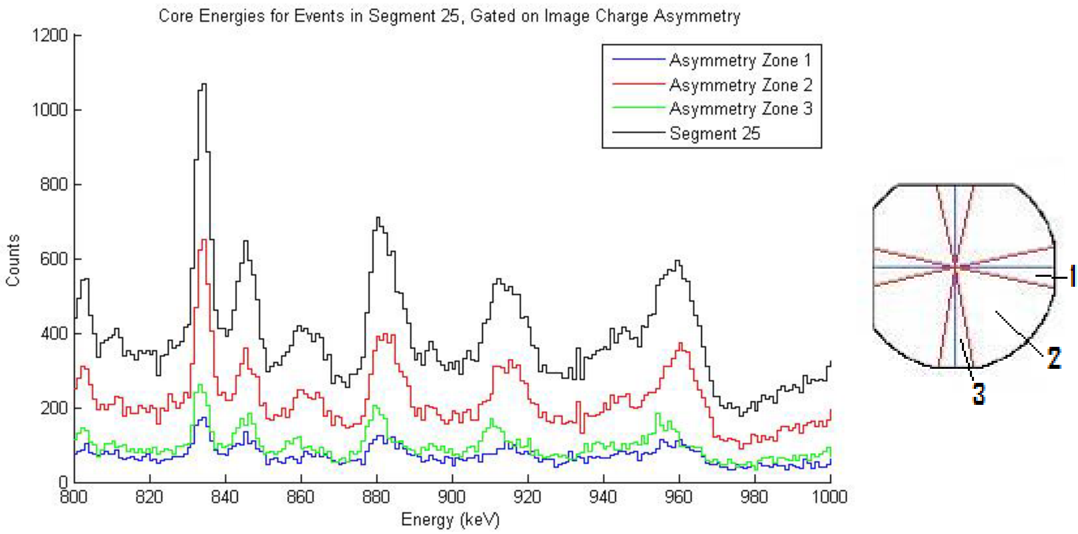


Figure 7 - Application of ICA gates to Segment 25

Gating on the T30–T90 distribution for segment 25 produced two small regions containing few points at the extremes of radius and two larger regions of intermediate radius, Table 2 shows FWHM and areas for these zones. Some improvement in resolution is seen in zones 1 and 2, while a worsening in resolution is seen in zones 3 and 4. Figure 8 shows the spectra produced by risetime gating together with a schematic image of the zones produced. Zone 1, the smallest radius, defines a small area of Germanium in front of the detector core; this zone isolates a narrow range of theta and so produces good energy resolution but contains very few counts relative to other zones. Each successive zone after that defines a wider range of theta than the last and as such the general trend is a reduction in energy resolution. Zone 2 contains the most counts and zone 4 the least. Due to the low statistics, peak fitting in zones 1 and 4 is less reliable than elsewhere.

Zone	FWHM (keV)	Area (Counts)	Event Fraction (%)
Segment 25	7.9(2)	3348	100
1	7.8 (1)	85	2.4
2	6.7(2)	1863	52
3	10.2(5)	1244	35.0
4	11.6(12)	368	10.3

Table 2 - FWHM and areas for risetime zones in segment 25

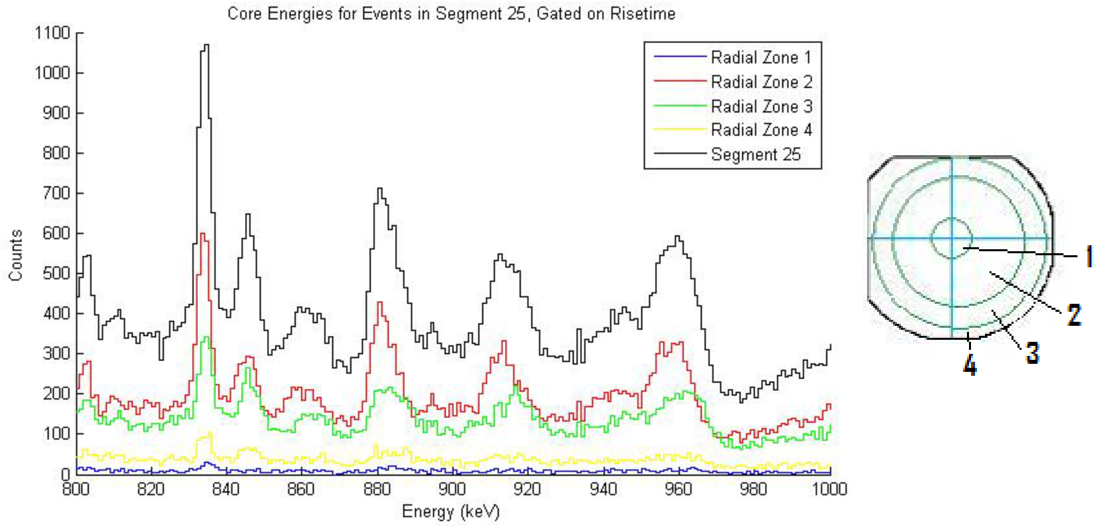


Figure 8 - Application of T30 - T90 gates to Segment 25

Figure 9, below, shows the number of segment 25 events falling into each zone when combined risetime and asymmetry gating is applied.

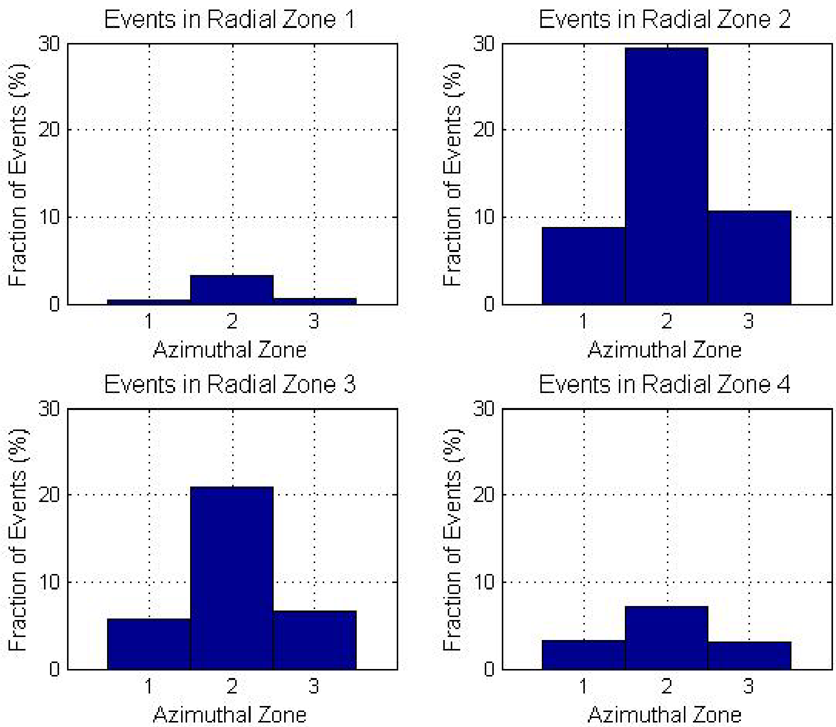


Figure 9 - Number of segment 25 events in each zone with combined gating

Table 3 below, shows the value of FWHM for combined gating in segment 25; missing values are those where statistics were too low to allow fitting.

Zone	Asym1	Asym2	Asym3
Rise1	-	4.2(9)	-
Rise2	5.9(4)	6.9(3)	5.5(3)
Rise3	5.4(9)	9.1(5)	-
Rise4	-	9.8(15)	-

Table 3 - FWHM and areas for combined gating

Figure 10, below shows the spectra produced when selected combined gates are applied together with a schematic image of the combined zones. The counts shown in the spectra have been scaled and shifted arbitrarily to allow comparison of peak widths between zones with unequal numbers of events. The central asymmetry zone combined with risetime gating slightly narrows the theta range of positions relative to the risetime gating alone and hence produces a modest improvement in resolution. One of the edge asymmetry zones, the one in which a large improvement was seen, is divided by lines parallel to the beam direction and hence little change is seen. The other edge zone however, which saw poorer resolution than the segment as a whole, is divided by 3 lines perpendicular to the beam direction and as such sees a significant improvement in resolution.

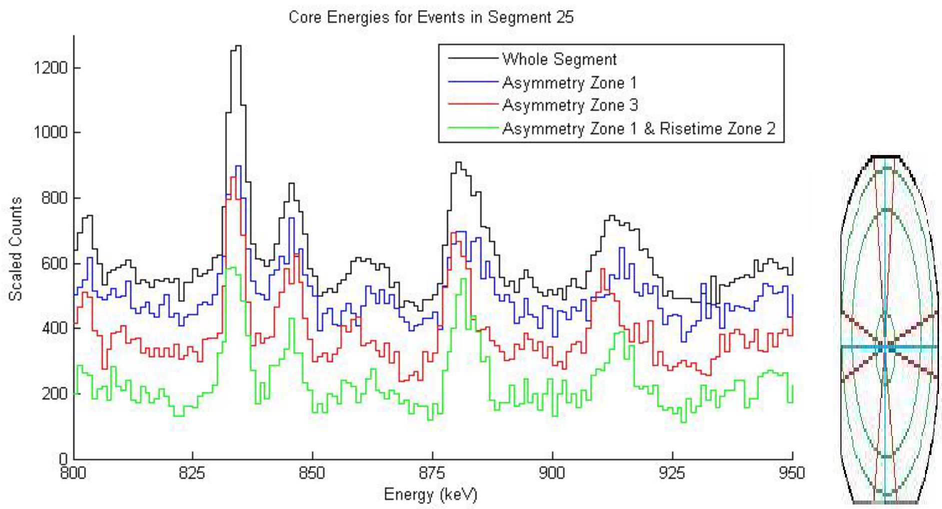


Figure 10 - Combined gating applied to Segment 25

Calculating the position resolution associated with the energy resolution values we have found is complicated by the asymmetric geometry of the zones we have identified within crystals. If however we assume the zones to be cubic regions in a continuous Germanium shell we can approximate the resolution achieved.

Zone	Energy Resolution (keV)	Approximate Position Resolution (mm)
Segment 25	7.9(2)	19.0
Asym 3	5.6(3)	13.0
Asym 1, Rad 2	5.9(4)	13.5
Asym 2, Rad 2	6.9(3)	16.0

In the next few months we will be working on optimising the gating of all of these zones to produce the best resolution possible. It may be possible to further divide the segment into four asymmetry zones but doing so is also likely to increase the number of events being assigned to the wrong zone, further investigations of this will be carried out. We will also be using scan data and measured peak shifts in the spectra to calculate the angle of each zone and hence produce a Doppler corrected total projection spectrum for the whole clover. At this point it seems likely that a significant variation in resolution will be seen between the central and edge regions of segments, if this proves to be the case we will produce two spectra, one optimised for energy resolution and one optimised for efficiency.

Canberra-Eurisys Clover

Due to the failure of one digitiser card and to a cabling problem, only two of the crystals in this clover were fully operational for this test.

The crystal geometry and electronics of the Canberra-Eurisys (CE) clover differ significantly from the Ortec design. The CE crystals are more symmetric than Ortec's and have a shorter flat edge where the crystals meet which results in a larger void space at the centre of the clover. Risetimes on the CE detector are faster than Ortec by approximately 10 ns to t30 and 40 ns to t90; this results in a compression of the T30-T90 distribution.

A CE clover was characterised on the Liverpool scanning table but the data have not been analysed as yet, investigation of this data is necessary before conclusions can be drawn from the in-beam test.

Figure 13, below, shows the ICA distributions for four segments in the same crystal of the CE clover. Initially it was thought that the asymmetric nature of these distributions was due to an electronic or coding error however the data from the other working crystal is consistent; cross-talk between segments may have a significant influence on the distributions. The most asymmetric distribution, that from segment 13, is from a segment in the corner of the clover while the most symmetric, segment 15, is from the inner most segment. While intuitively a symmetric distribution is preferred, these distributions may provide the ability to divide the segments further than is possible with the Ortec clover due to the more even spread of events over the distribution. Further understanding of these data and their effect on the performance of PSA in CE EXOGAM clovers will be gained from analysis of the CE scan data.

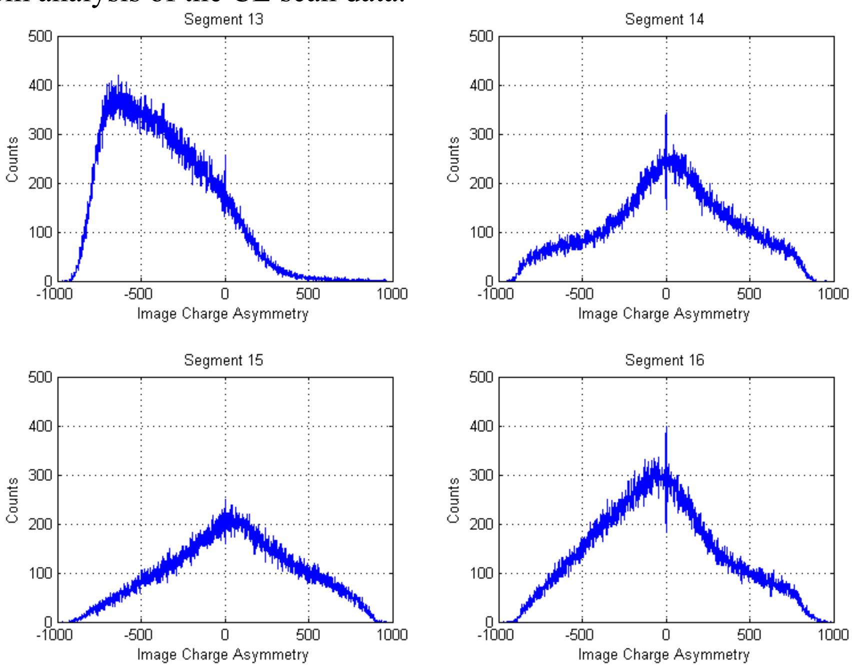


Figure 11 – CE Asymmetry Distributions

Dynamic range

Consideration has been given to the question of whether EXOGAM PSA would benefit from using two digitisers to capture traces over two different dynamic ranges with the aim of improving the signal to noise ratio for image charges. While a greater signal to noise ratio would always be preferred, there is no evidence to suggest that this would result in a large improvement as the limitation of ICA techniques in this detector is the large distance to the neighbouring contacts found at interaction positions near the centre of segments.

Conclusion

We have applied pulse shape analysis (PSA) to an Ortec EXOGAM clover using both risetime and image charge asymmetry to localise the position of interactions within segments. The analysis has so far only considered events where only one segment per crystal is hit which amounts to approximately 68% of events. It will be possible to extend the technique to events where neighbouring segments are hit using methods developed for MINIBALL which deconvolve image and real charge pulses. The performance of PSA varies as a function of interaction position within a segment, with the best results being found near segment boundaries where image charge magnitudes change quickly with position.

Due to the asymmetric geometry of the regions localised within detector segments, it is difficult to define a precise position resolution however using approximations resolutions of 13 – 16 mm have been calculated.

Similar results are expected from the Canberra-Eurisys clover however further consideration of scan data is needed before conclusive results are found for this detector.

References

[Gro05] S. Gros, Characterisation of an EXOGAM clover Germanium detector, PhD Thesis, University of Liverpool, April 2005.

[Kha98] B. Kharraja et al, Nuclear Structure of ^{94,95}Mo at High Spins, Phys Rev C Vol 57 No 6 (1998)

[Laz03] I.H. Lazerus et al. IEEE Nuclear Science Symposium, (2003) N29-36