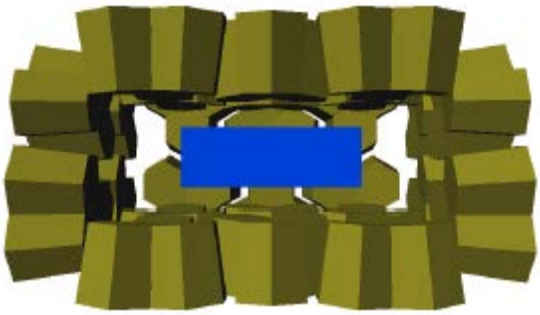
Technical Report
for the Design, Construction and Commissioning of the DESPEC Germanium Array Spectrometer DEGAS



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The DESPEC Germanium Array Spectrometer (DEGAS) is a high-purity germanium γ-detector array for high-resolution spectroscopy of electromagnetic decays from exotic nuclear species. It is a key instrument of the Decay Spectroscopy (DESPEC) experiment at FAIR. At DESPEC rare isotopes produced by the Super-FRS will be stopped in an active implanter (AIDA) surrounded by DEGAS measuring γ rays from α, β, proton, neutron and isomeric decays.

The main objectives of DEGAS are i) the efficient detection of γ rays in an energy range from 50 keV to 5 MeV emitted from nuclei throughout the full implantation area of 24 x 8 cm^2 given by the focal plane of the Super-FRS and ii) the discrimination of the prevailing intense background radiation. To overcome the prompt radiation flash associated with the implantation process a high detector granularity and fast saturation recovery are mandatory. To detect γ rays from rare isomers with long lifetimes in particular proper shielding respectively identification of background radiation is essential.

DEGAS builds on the vast experience obtained with the VEGA and RISING projects at the FRS at GSI. The construction of DEGAS will proceed in three phases. For phase I it is planned to re-use EUROBALL Cluster detectors previously employed at GSI in the RISING stopped beam campaign. For optimal solid angle coverage, detector units will comprise of three crystals in a common cryostat. Cryostats will be electrically cooled to facilitate a compact detector arrangement. Electrical cooling also provides the wanted flexibility to use DEGAS modules for other FAIR experiments in LN free zones. Shielding will be based on the EUROBALL “back-catcher” veto scintillation detectors. In phase II AGATA-type γ-ray tracking detectors are planned to replace the most background affected EUROBALL detectors. Contrary to the conventional EUROBALL coaxial Ge detectors, tracking detectors enable efficient detection and rejection of both particle and γ background. The developments done for the AGATA project and the experience gained with the PRESPEC-AGATA project at GSI will be exploited by DEGAS. The third phase is planned to include the results of long-term developments of highly segmented planar Ge detectors for the ultimate “imaging” array. The third phase is not included in the current funding scheme for DESPEC and is only discussed briefly in this design report.

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1. Introduction and Overview

The DESPEC collaboration will address, in particular, the spectroscopy of very short-lived nuclei and isotopes of refractory elements which are not available at ISOL based radioactive beam facilities. The DESPEC experiment [Tec-05] will be located at the low energy branch of the Super-FRS facility, which is unique in several aspects. The access to the primary structure information of the most exotic nuclei will be possible with exotic beam species implanted into an active stopper detector. The time delay between the moment of production of the isotope and its decay offers a filtering possibility, thus helping to increase the signal-to-background ratio in decay spectroscopy. The subsequent α, β, γ, proton and neutron decays of those species will be measured with a compact multi-task array consisting of double sided silicon strip detectors, γ-ray detectors for high-resolution spectroscopy, fast timing measurements and calorimetry, and neutron detectors. In nearly all such set-ups it will be sensible to incorporate highly efficient, highly granulated Ge γ-ray detection systems close packed around the stopped ions.

The DEGAS project is dealing with the development and implementation of such a large efficiency array for γ-ray spectroscopy. The project is suggested to be carried out in three phases. Phase I will constitute the basic detection set-up, similar in its characteristics to the previous RISING array at the FRS facility at GSI, and suited for unique day-one experiments at the Super-FRS at FAIR. While the RISING array approximated a spherical detector, optimized for an implantation area of about 8 x 8 cm^2 in its center, DEGAS needs to cover an implantation area of about 24 x 8 cm^2, demanded by the wider focal plane of the Super-FRS at FAIR. This will be properly achieved by reconfiguring the EUROBALL Ge crystals of RISING [REG-05]. In addition it is foreseen to employ the EUROBALL Back-catcher scintillators as active shielding against the enormous background radiation, which severely limited the approachable lifetime region for isomer spectroscopy with RISING.

Phase II of DEGAS will be the completed state-of-the-art set-up with enhanced measurement capabilities for the full envisaged experiment program of the DESPEC collaboration as described in the FAIR CDR and the NUSTAR IMoU. This will be achieved be replacing the phase I detectors directly behind the implanter with γ-tracking detectors of the type used in the AGATA project [AKK-12]. Such tracking detectors enable efficient detection and rejection of both particle and γ background being most abundant behind the implantation zone, where it cannot be shielded. In addition, AGATA-type detectors provide higher efficiency and improved P/T ratios compared to EUROBALL detectors. Phase III is planned to include the results of on-going long-term developments of highly segmented planar and point-contact Ge detectors to build a γ-imaging array. This would allow tracing-back the origin of each γ ray, thus enabling ultimate suppression of background radiation and identification of the location of decaying nuclei in the implanter. The third phase is not included in the current funding scheme for DEGAS and is only discussed briefly in this design report.

The full DEGAS γ-detection system is a key instrument of DESPEC and is envisioned to be operated in experimental campaigns or single investigations as frequently and as regularly as possible. In addition, when the DESPEC experiment is not running the collaboration envisions employing single detector units and sub-systems of DEGAS for other experiments as well to maximize the physics output with DEGAS. This policy is made possible by the inherent modularization, flexibility and versatility of the DEGAS detectors and their infrastructure, but also by design solutions optimized for simple operation and easy maintenance.

In the following, some implications of the physics experiments to be pursued with DEGAS are briefly outlined. The constraints and limitations given by a fragmentation facility, the relevant detector technology and the disposable resources will be discussed thereafter. Both physics requirements and practical boundary conditions lead to the then proposed design for the γ-detectors, their electronics and infrastructure. Finally the important issues concerning construction, installation and commissioning as well as planning and implementation of the DEGAS project are addressed.

2. Physics Requirements and Design Considerations

2.1 Physics Requirements and Constraints

The physics of exotic nuclei, having large neutron or proton excess, is one of the main frontiers in contemporary Subatomic Physics. Short-lived, rare nuclei constitute a challenge for our picture of the strongly interacting many-body system of an atomic nucleus. Established entities such as magic numbers cease to be valid when going towards the drip-lines, exotic shapes appear as well as unforeseen decay modes and new collective phenomena. Furthermore, there is a strong connection to astrophysical processes and the elemental abundances in the Universe, in particular through the r-process, which takes place across a range of very neutron-rich nuclei.

Decay studies lie at the very frontier of the field of exotic nuclei, since once the existence of an isotope has been demonstrated, the next elementary information one seeks is how it decays. Decay spectroscopy often provides primary information on excited states of nuclei far from stability. The advantage of the decay experiments is that they can be based on a relatively small number of events. Useful intensities for γ spectroscopy may vary between 10^{-3} /s and 10^{3} /s. If the number of decays is sufficiently high, detailed spectroscopy will be possible and then questions such as isospin symmetry can be tested in mirror nuclei or the long standing Gamow Teller quenching problem in β decay can be addressed. On a more fundamental level super-allowed Fermi transitions in odd-odd N=Z nuclei can be used to explore issues such as the unitarity of the CKM matrix in the Standard Model description of electroweak interactions. For the most exotic nuclei one can expect some unusual decay modes such as β-delayed multi-neutron emission (see Fig. 1), β delayed fission, or even direct neutron radioactivity. Another very important aspect of DESPEC is the possibility to study the decay properties of isomeric levels in nuclei which survive the flight time from the moment of production until the time of arrival to our set-up.

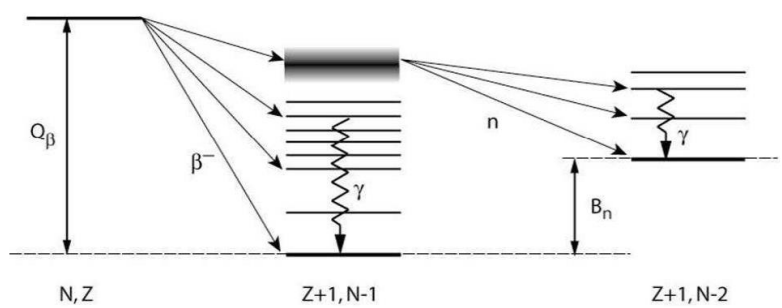

Fig. 1: *The β delayed neutron and γ decay processes.*

The α- and β-decay processes we are interested in end in excited states of the daughter nuclei which subsequently decay by γ emission. Characteristics are single transitions to the ground state or short decay cascades. The expected transition energies are typically in the 50 keV to 2 MeV range but may go beyond this range to a maximum of about 5 MeV in rare cases. For isomer decays the situation in terms of energies is similar. However, high K-isomers may be associated with rather long cascades of γ transitions of up to $M_\gamma \approx 10$. Isomeric lifetimes cover a wide range from nanoseconds to years. Fragmentation processes are a universal tool to produce any kind of isomers and the widest range of α- and β-decaying isotopes.

At fragmentation facilities exotic nuclei will be produced by the interaction of intense high energy ion beams on thick targets. A fragment separator located behind the production target serves primarily to select and identify the specie of interest and drastically reduce the number of accompanying ions which are a source of unwanted signals in the detectors. To study the decay properties, the ion beams are slowed down and stopped in an implanter that can be either a passive plate of light matter (e.g.

plastic) or an active implantation detector, usually a Double Sided Silicon Strip Detector (DSSSD), producing a large hit signal in a given pixel (identified by two orthogonal strips). The implanted ion can be identified in Z and A by the ion tracking detectors of the separator which also provide the exact implantation time as a reference. In case of an active implanter the much smaller signal produced in the hit pixel by the emitted α- or β-particle in the subsequent decay can be used to tag the delayed γ radiation. Decay-particle tagging discriminates efficiently the external (or ambient) background. A high degree of pixilation of the implantation detector minimizes the false associations of decays and ion implantations and permits identification of the background, which otherwise seriously may degrade the measurement. At the same time this will set limits on the numbers and rates of implanted species. Random event summing and electronic pulse pile-up would be consequences of too high rates.

For isomer decay experiments decay tagging is not possible (besides cases with appropriate internal conversion). For this class of experiments the high ambient radiation and particle background, unavoidable with fragmentation facilities, is therefore the most critical limitation. Above all is the "prompt flash" of electromagnetic radiation from atomic interactions of an impinging ion with all tracking detectors, degraders and the implanter. The main atomic radiation contributing to this background are K- and L-shell X rays from ionized target atoms, radiative electron capture of the target electrons into the projectile K and/or L shells, primary bremsstrahlung from target electrons produced by the collisions with the projectile, and secondary bremsstrahlung from energetic knock-out electrons which re-scatter in the target and/or the surrounding material [ANH-84, ANH-86, HOL-92]. The atomic cross-sections of all these processes strongly depend on the atomic number of the projectile and the target. Depending on the remaining energy of the ion near the γ-detector array electromagnetic radiation up to several 100 keV energy is emitted (see Fig. 2) with typical multiplicities of $M \approx 30$ above 10 keV energy. For optimal transmission and focusing of the beam particles their energy has to be kept high before implantation. Typically after the last dipole magnet of the beam transport system the energy is 250-350 A·MeV and will be subsequently degraded by the tracking detectors and a dedicated degrader element to 70–80 A·MeV in front of the implanter. Besides the already mentioned atomic interactions there is a high probability (of the order of 10% or more) for nuclear interactions with the matter in the way of any ion. Knock-out, secondary fragmentation, inelastic collisions and Coulomb excitation lead to a high flux of neutrons, protons, other light particles and γ radiation, all boosted towards the area around the implanter, adding to the prompt radiation flash. A sizable fraction of the protons and neutrons undergo subsequent nuclear reactions, further increasing the prompt background. Finally, moderated neutrons fill the whole experimental area and lead to material activation. Therefore during experiments the γ- and the neutron-radiation levels are permanently elevated.

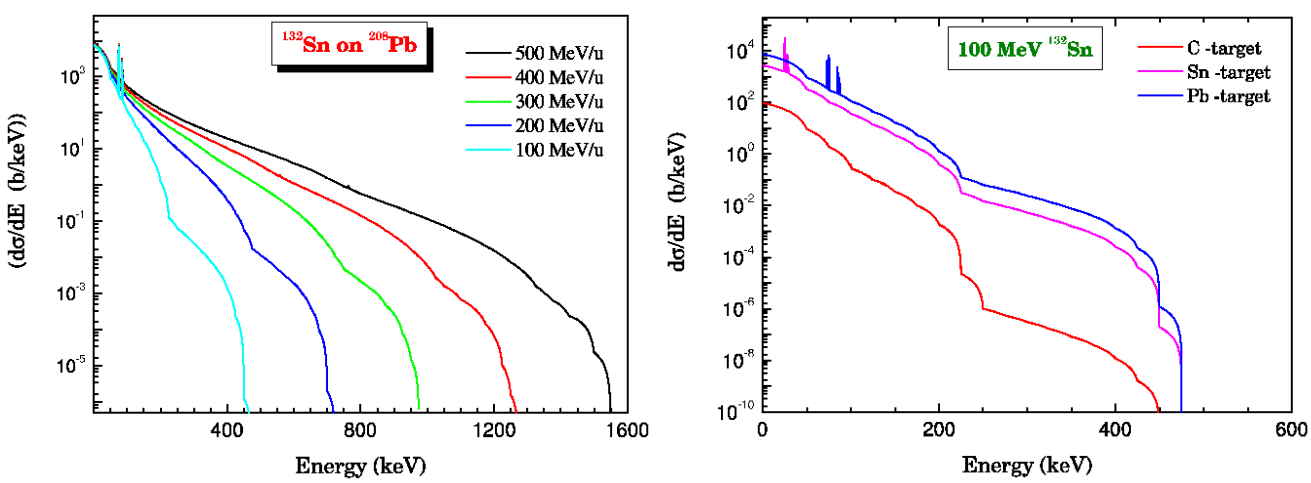

Fig. 2: *Energy dependent atomic background cross sections for typical beam particle energies and "target" materials.*

This background situation limits the useable time range for isomer studies. Transitions from isomers with lifetimes below the time resolution of the γ detectors are practically unmeasurable because of the overwhelming “prompt flash” contribution to the γ spectra, while the peak to background ratio gets also worse with increasing lifetimes as more environmental radiation gets accumulated. In addition for lifetimes up to the dead time of the detectors the detection efficiency will be reduced due to the “prompt flash,” inevitably occupying a certain fraction of γ detectors. The dead time can be as short as the minimal signal distance for proper pile-up recognition and correction in case of subsequent low energy γ rays. However, if a detector gets hit by a high energy charged particle the dead time until the detector recovers can be in the millisecond range unless fast overload recovery pre-amplifiers are used.

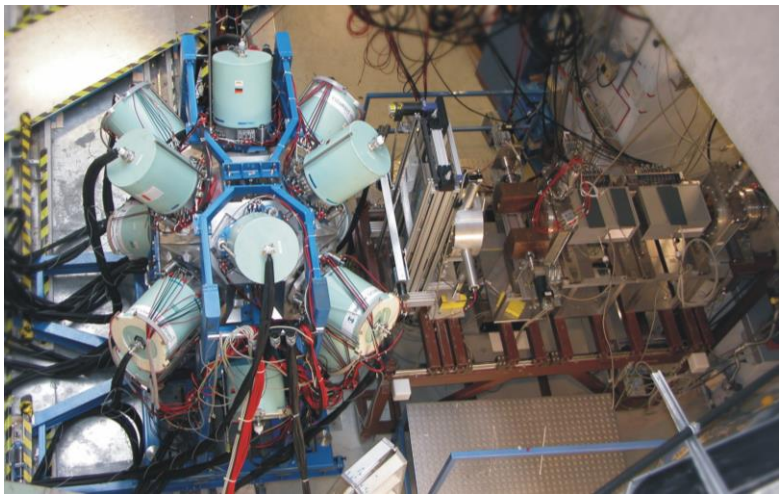

Fig. 3: *RISING set-up with 15 EUROBALL Cluster Ge detectors on the left and FRS tracking detectors on the right.*

The RISING [PIE-07, REG-08] stopped beam experiment employed from 2006 to 2009 for decay γ spectroscopy at the FRS at GSI is well suited to exemplify what has been discussed so far. The set-up, shown in Fig. 3 consisted of 105 EUROBALL Ge detectors arranged in three rings of five seven-fold cluster units. Its γ-detection efficiency, shown in Fig. 4, is still unsurpassed. For isomer studies a passive plastic stopper was used, while for β-decay runs two dedicated Si-strip detector arrays were available. Beam tracking and identification was performed with the standard FRS detector suite. Since 2012 EUROBALL Cluster detectors are being operated at RIKEN, Japan in the decay spectroscopy project EURICA very similar to RISING.

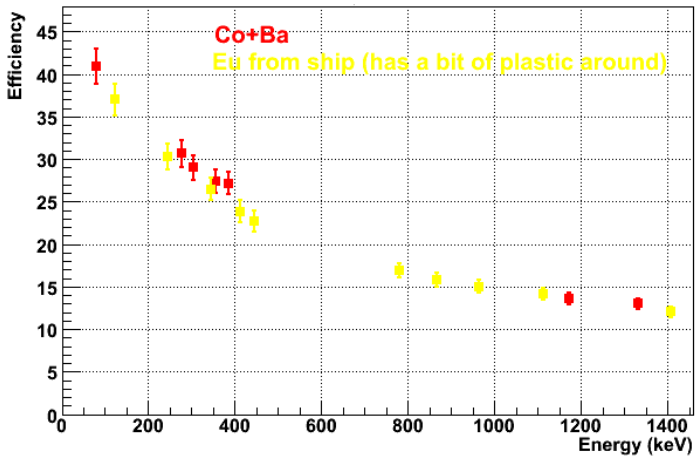

Fig. 4: *Measured RISING full energy peak efficiency.*

Fig. 5 shows on the left side the distribution of isotopes of a typical cocktail beam produced from a ^{208}Pb primary beam after it has interacted with a ^{9}Be target. Implanting this distribution in the passive stopper allowed simultaneously measuring a whole series of isomers. The right hand side of the figure illustrates the background accumulated within 20 µs (top panel) and 350 µs (bottom panel) after implantation. For heavy systems accumulation times were limited to about 1 ms, corresponding to maximal isomer lifetimes of a few 100 µs, before the P/B ratio would impede any proper line assignment. Fig. 6 gives an example of a high-spin isomer discovered with RISING. Finally Fig. 7 demonstrates with the γ spectrum tagged by the β decay of only 280 implanted ^{100}Sn nuclei the detection limit of RISING.

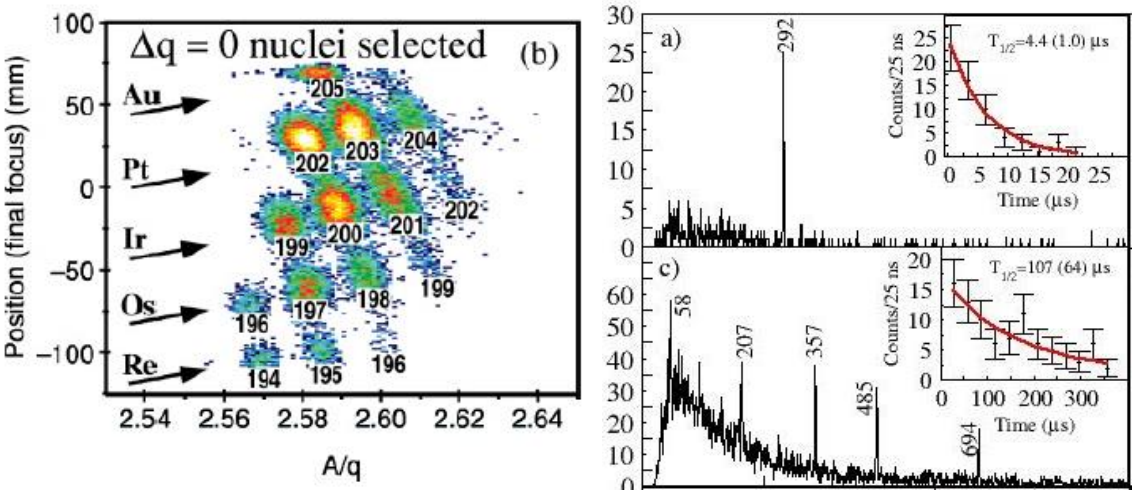

Fig. 5: *Left: Typical implanted beam cocktail produced by fragmentation of a primary ^{208}Pb beam; right: Delayed γ spectra gated on ^{188}Ta (top) and ^{190}W (bottom).*

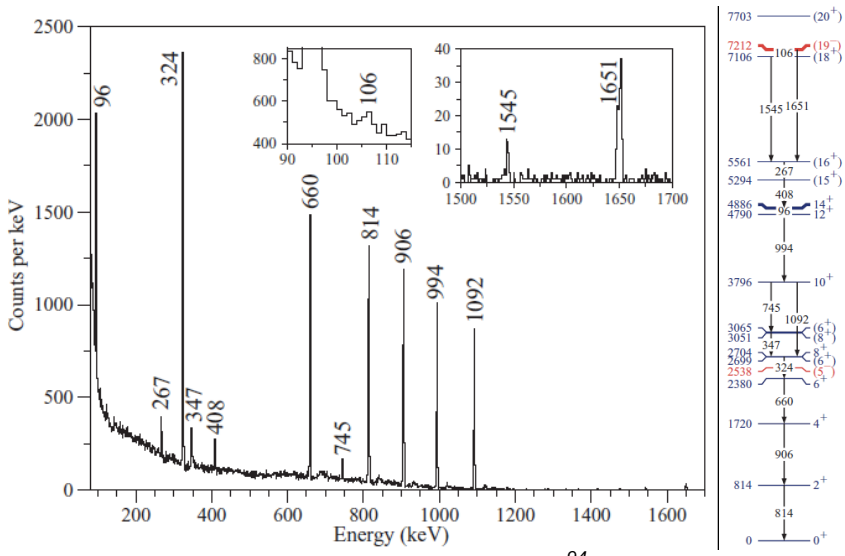

Fig. 6: *High-spin isomer in ^{94}Pd.*

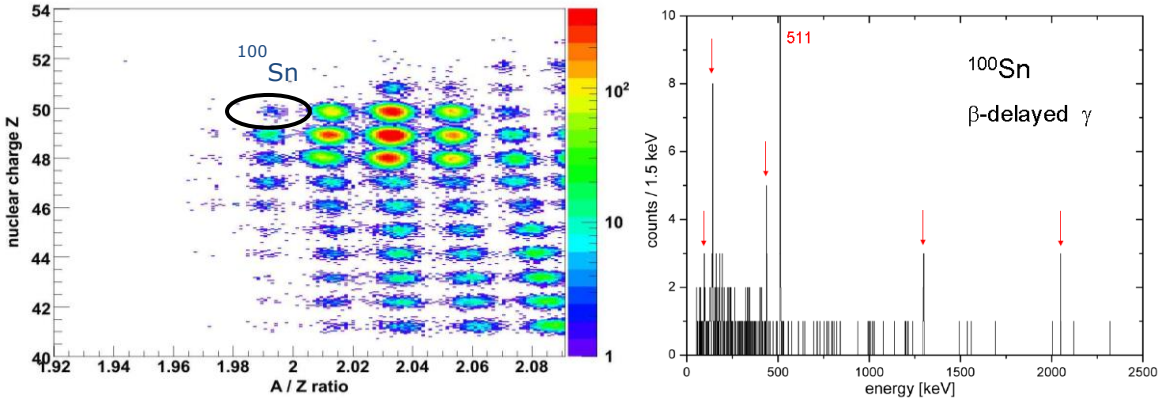

Fig. 7: *The γ spectrum obtained from the β decay of only 280 implanted ^{100}Sn nuclei.*

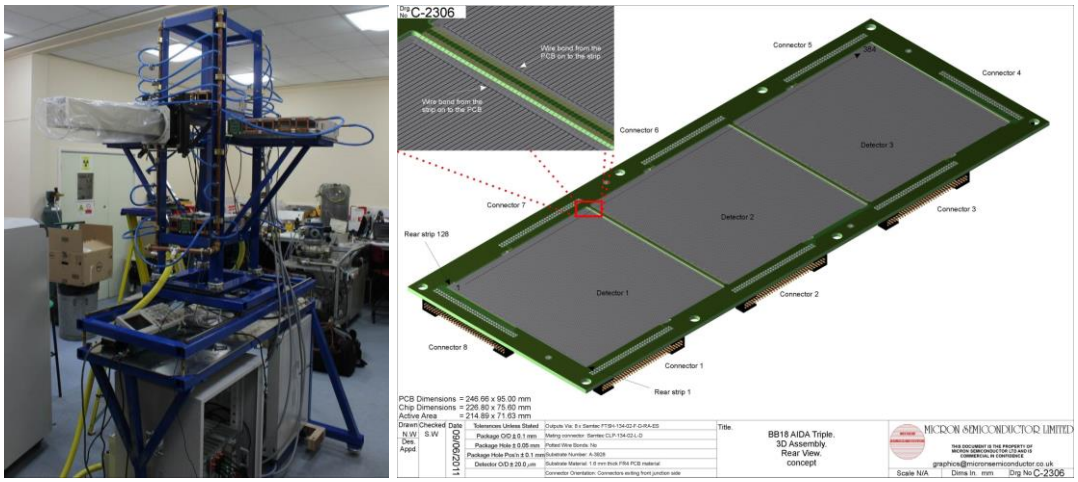

Fig. 8: *AIDA 8 x 8 cm^2 compact prototype and 8 x 24 cm^2 DSSSD layout.*

For DESPEC the particle tracking and identification detectors will be similar to what has been employed with RISING at the FRS. Also the background situation will be quite similar. A major improvement will be the newly developed Advanced Implantation Detector Array (AIDA). It has been designed to work both in stand-alone mode and in conjunction with other detectors, in particular with DEGAS. The coupling with AIDA is one of the main design constraints of the DEGAS spectrometer. The basic unit of AIDA is an 8 x 8 cm^2 DSSSD with 1 mm thickness and 128 strips in both horizontal and vertical directions. Stacks with up to 8 DSSSD layers provide sufficient stopping power to implant any cocktail of isotopes produced and selected by the Super-FRS. In addition the full energy of α- respectively β-decay particles can be detected subsequent to the implantation. A prototype configuration is shown in Fig. 8. The beam coming from the Super-FRS has a wide spatial distribution, in particular in the horizontal direction. In the full AIDA configuration thus an array of three DSSSD stacks in a row will be mounted in order to maximize the coverage of the focal plane.

A narrow configuration of AIDA uses only the central part of the focal plane distribution. This is acceptable for isotopes produced by primary Be fragmentation and achromatic Super-FRS ion optics. In that case most of the produced fragments of one selected species are focused to the implanter, while the other fragmentation products of the cocktail beam have to be cut with slits as far upstream as possible. However, background radiation is then considerably increased. For isotopes produced by primary fission, a limitation to the central part of the focal plane would lead to severe losses of transmission and even more drastic influence from the background. The narrow configuration will be

employed for DTAS and BELEN, where there are unavoidable design limitations. However, for DEGAS the wide configuration is necessary to enable the full physics program. The large transverse dimension of 24 cm of the DSSSDs in such a geometry as a consequence prevents employing the RISING detector configuration.

2.2 Detector Design Requirements

Following from the preceding discussion a γ-detector system designed for the above mentioned spectroscopic studies at DESPEC primarily needs to have maximal sensitivity to measure discrete γ transitions in the presence of strong background sources. High sensitivity is achieved by i) large intrinsic full energy efficiency, ii) large covered solid angle, iii) large peak-to-total (peak to background) ratio, and iv) high energy resolution. Therefore all four qualities need to be maximized together. In addition high granularity is required to cope with the high hit multiplicities to be anticipated. The time resolution needs to be at least of the order of the smallest isomer lifetimes of interest. The rate capability of the detection system must be sufficient to cope with the highest implantation (i.e. prompt flash) rates to be expected. The system must also be designed such that single detector units and sub-arrays can be configured and operated in a flexible and easy way for multiple purposes. All these criteria are discussed in the following in some detail.

<u>Solid angle coverage and detector granularity</u>

The secondary ions produced by the Super-FRS have a large spread in the focal plane. Therefore the implantation detector AIDA subtends an area of 24 x 8 cm^2. Ideally the γ-detection system should cover a solid angle close to 4π around the implanter. Actually only a rectangular hole in upstream direction needs to be kept open for the beam particles to reach the implanter. The high energy ions getting implanted in the active stopper produce a flash of X rays and γ rays with total multiplicities up to $M \approx 30$. To avoid blinding the detector for subsequent decay measurements the granularity of the DEGAS detector elements should be $N_{Det} >> 30$. This condition prevents nameable summing effects even with the highest γ multiplicities $M \approx 10$ to be expected with decay events. A large number of detector elements help also to obtain a high γ-γ coincidence efficiency, required for the proper assignment of level sequences and decay chains.

<u>Full-energy efficiency</u>

In the decay spectroscopic study of exotic nuclei, one expects γ-ray emission with wide energy range from 50 keV to 5 MeV. The highest possible photo-peak efficiency throughout this energy range is crucial for the identification of γ rays emitted from isotopes with extremely low production cross sections, as well as for the detection of weak decay channels in abundant decay channels.

<u>Energy resolution and P/B-ratio</u>

Since the sensitivity of a γ spectrometer is proportional to its peak-to-background ratio (P/B) the energy resolution should be maximal for the whole range of energies from 50 keV to 5 MeV. The narrower the peak, the lesser is the background below it. For decays with high γ multiplicities as well as complex level schemes with many decay paths, the density of lines in the γ spectra also ask for ultimate energy resolution to be able to resolve close lying lines. Besides the resolution the P/B-ratio is determined by the response of the detectors. Optimally the fraction of events not being fully absorbed in the active detector volume should thus be very small.

<u>Background suppression</u>

For α- and β-decay experiments particle tagging allows correlation of measured γ rays to the corresponding decay event. In this case the P/B-ratio is governed by the response of the γ detectors. For isomer decay experiments, apart from internal conversion, tagging is not possible and the background is dominated by the environment. Therefore suppression of background radiation is

essential. Depending on beam species and beam rate, total maximal background rates of up to 10 kHz have been measured with RISING at the FRS and are expected for DEGAS as well. This background is composed mainly of γ rays and X rays, but includes also neutrons and charged particles. Since the γ measurement sensitivity is proportional to the P/B ratio and the background scales with the accumulation time, i.e. the lifetime of an isomeric state, the accessible lifetime range is proportional to the background suppression factor. Active or passive shielding thus needs to be as effective as reasonably possible. Furthermore, detectors with γ-tracking or γ-imaging capability are preferable in particular for the detectors mostly affected by background radiation or those that cannot be shielded properly. Foremost these are the detectors covering the solid angle behind the implanter, as they view directly upstream into the most background contaminated region.

Time resolution and rate capability

The minimal lifetime principally measurable is given by the ability of the detection system to distinguish prompt flash radiation from a subsequent decay. This depends predominantly on the rise time of the detector signals. Therefore the rise time of the employed detectors should be as short as possible, with a signal processing optimized for best timing. In turn, good timing is also essential for the determination of isomer decay times. Complementing DEGAS with fast timing detectors or neutron ToF detectors also necessitates best possible time resolution. One may expect decay events spanning over a wide range from isomers with a few nanoseconds to α decays with many days. Therefore the detection system must be able to correlate ion implantation and γ decay without inherent time limit. Related to the correlation time is the implantation rate. The useful ion implantation rate is considered to be between 10^{-3} /s and 10^{3} /s. However, as worst case for the maximal rate it is assumed that only 10% of a beam cocktail corresponds to the wanted isotope, resulting in a maximal rate of 10^{4} /s. AIDA is designed for this limit and ideally the DEGAS system should be able to cope with the same flash rate as well.

Angular correlation studies

The γ-detector array should have the capability to do different types of angular correlation studies to assign the spin of excited states populated in the decay process. Care will be taken to make provision for studies of γ-γ correlations, electron-γ correlations, proton-γ correlations as well as alpha-γ correlations. For these measurements, maximum solid angle coverage as well as large granularity with optimum choice of angles of detectors in the array is required. Such a configuration will also help in the measurement of static quadrupole moments for exotic isomers.

Polarization sensitivity

Measurements of γ-ray polarization will provide important information related to the parity of the decaying states and hence to key structure information. For the polarization asymmetry measurement of an emitted γ ray, the direction of alignment of the nucleus can be defined by the detection of an additional γ ray in the array. The γ rays for which polarization has to be measured need to be detected using a granulated detector. The polarization sensitivity increases strongly with this parameter as well as with the position sensitivity of the germanium detectors. The AGATA-type tracking detectors are therefore ideal for such measurements. One can also use the direction of the accompanying particles for defining the reaction plane required for the polarization measurement.

Versatility

The DEGAS array should have a modular nature to incorporate other detector systems in order to optimize the physics potential. This can be for instance the FATIMA fast-timing detectors or the MONSTER neutron ToF modules. To maximize the physics output with DEGAS when DESPEC is not running, single detector units and sub-systems of DEGAS shall be employed for other experiments. Therefore modularization and flexibility of the DEGAS detectors and their infrastructure is important, but also simple operation and easy maintenance.

2.3 Detector Design Perspectives

In general there are two types of γ detectors thinkable for the above requirements: inorganic scintillators and solid state detectors. The most powerful scintillator array for nuclear spectroscopy is the Heidelberg-Darmstadt Crystal Ball spectrometer, a 4π array composed of 162 large volume NaI(Tl) crystals read out by PMTs. The quoted full-energy peak efficiency of 62% for ^{60}Co and a P/T-ratio of 67% are un-surpassed. However, the sensitivity is severely impaired by an energy resolution of 7%, which makes the device also inappropriate for measuring any complex decay scheme or longer decay chains. Even the best scintillator material on the market, $LaBr_3$(Tl), offering about 2% energy resolution, falls short of the requirements. Furthermore, its severe self-radioactivity precludes any non-tagged decay studies.

Despite intense R&D efforts still only germanium based solid state detectors are applicable for powerful γ spectrometers. Ge diodes offer an excellent energy resolution of ≤ 0.2% for ^{60}Co energies and an adequate time resolution of ≈10 ns. Standard crystal volumes of 350-450 cm^3 provide good γ-ray absorption, and shaped crystals can be arranged into detector clusters to further enhance their efficiency and P/T-ratio. Such cluster modules are well suited for constructing large solid angle arrays. The only drawback is the need to operate Ge diodes at temperatures < 100 K to prevent thermal signal noise and possible breakdown. The necessary cryostats somewhat deteriorate the detector solid angle coverage and its physical response. Moreover, in case of liquid nitrogen (LN) cooling, the bulky LN dewars limit the cluster packing possibilities.

Up-to-date the most powerful Ge-detector array for decay spectroscopy is the RISING spectrometer (see fig. 3). RISING was built from 15 7-fold Ge Cluster detectors originally designed for the EUROBALL-III spectrometer. Each crystal is encapsulated in a thin, vacuum-tight Al capsule to protect the sensitive surfaces of the Ge diode and to allow easy handling and maintenance of the detector elements. All EUROBALL detectors are owned by the EUROBALL Owners Committee (EOC) and are maintained and repaired by the Gamma-Spectroscopy Department of GSI on their behalf. The EOC provides the detectors on request based on experiment proposals.

Although the EUROBALL Clusters were already built in the 90's their performance did not deteriorate, and since 2006 only three detectors developed noise problems requiring re-processing. Re-processing by a company costs only about 1/3 of the price of a new detector. Therefore there are no obvious reasons why they should not be used for another couple of years until more powerful spectrometer designs will become available. Therefore the DESPEC collaboration agreed to the suggestion of the DEGAS working group to design and construct DEGAS in three phases, starting with an adopted EUROBALL detector array, upgrading it with AGATA-type γ-tracking detectors, and pursue a long term development of γ-imaging detectors for an ultimate future array. Consequently the first two phases are covered in this TDR.

<u>DEGAS phase I</u>

For DEGAS phase I RISING in its "stopped beam" configuration needs to be reconfigured to account for the wider implantation area of the Super-FRS. This can be achieved by either using the EUROBALL seven-fold Cluster detectors in a different geometry or reconfiguring the detector capsules into new cryostats in order to improve the solid angle coverage and to adapt the system for its extension in phase II. As discussed in the next chapter the best solution is achieved by reconfiguring the EUROBALL detectors to three crystals in a triple cryostat. The design of the triple cluster cryostats is identical to that of the FAIR/PANDA project and will include electrical cooling. To improve the background suppression active BGO shields covering the outside of the Ge detectors shall be employed. The EUROBALL Back-catcher elements will be reconfigured for that purpose. The RISING Pb-wall, shielding upstream radiation, would not be efficient due to the large beam tube diameter of the Super-FRS. Therefore only the side faces of the Ge detectors shall be shielded. The RISING front-end electronics is obsolete and needs to be replaced as well as the data acquisition system. Here the

main emphasis is on new pre-amplifiers with fast recovery after a radiation flash, improved slow control and easy operability of the DAQ.

DEGAS phase II

Due to their high efficiency and inherent background rejection capabilities AGATA type γ-ray tracking detectors have been identified as the optimal basis for the second and possibly third phases of the project. It is therefore planned to replace the EUROBALL detectors behind the implanter with an end-cap of AGATA triple cluster detectors in phase II. The mechanical holding structure of phase I will be designed such that the EUROBALL detectors to be replaced have their own sub-structure which can be easily exchanged by a dedicated honeycomb structure similar to the one of the AGATA demonstrator in Fig. 9. For electronics and data acquisition the solutions developed for AGATA can be employed. The cryogenic infrastructure necessary for AGATA will be available from HISPEC.

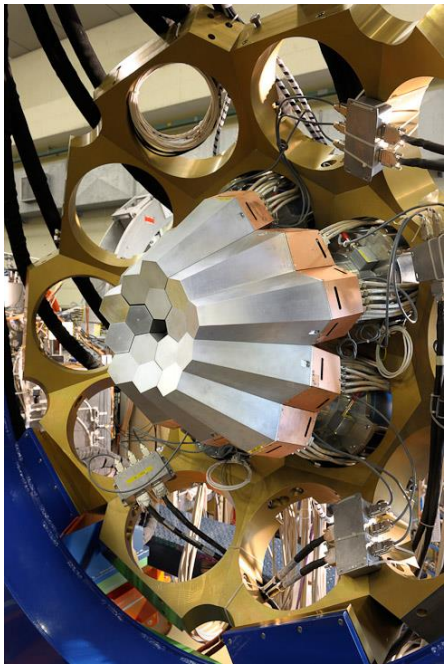

Fig. 9: *The AGATA Demonstrator mechanical holding structure including five AGATA triple clusters.*

For the time periods when AGATA will be available for experiments at FAIR a very large sensitivity can be achieved by including a multitude of detectors from the AGATA system in the array. The possibility to use a double-sided Ge strip detector as combined ion implantation and decay detector and forming a part of the γ-ray tracking array will be studied. Such a system will even have some imaging capability.

DEGAS Phase III

It has turned out that the original goal of the project, to introduce dedicated high-resolution γ-ray imaging detectors in decay spectroscopy, requires a long-term development program. The tremendous potential improvement of the sensitivity of a dedicated imaging array, enabling distinction between different implant positions in addition to the selection of decay events from background events already possible by including AGATA-type detectors, justifies this effort. Therefore, R&D on planar Ge-stacks or point-contact detectors that can be used in conjunction with AGATA-type detectors for high-resolution imaging and possible scintillator-Ge hybrid solutions will be continued, aiming for a future detection system suitable for DESPEC decay and HISPEC in-beam experiments in a third phase. The final segmented planar HPGe detectors for DEGAS phase III and other detectors resulting from this development work will need additional funding outside the framework of the current FAIR cost book.

2.4 DEGAS Requirements Specifications

The requirements specifications for the three phases of DEGAS as they follow from the above discussion are summarized in Table 1. The RISING array is used as a general benchmark. The design proposed in the following sections of this document fulfils these specifications or goes even beyond them in some cases. Other desired characteristics like polarization sensitivity are inherent to composite Ge detectors and even more to tracking/imaging detectors and are therefore not listed in the table.

In general it is required for all phases that

- At least substantial sub-arrays can be operated in LN free areas
- Single detector units and sub-arrays including electronics and associate infrastructure can be employed outside the DESPEC experiment
- Setting-up, operating and maintaining DEGAS must be kept as easy as possible and must be possible by a trained local team

Table 1: *DEGAS requirements specifications*

Property	RISING	Phase I	Phase II	Phase III
Array type	Composite Ge detector array	Composite Ge detector array	Phase I complem. by γ-tracking dets.	γ-imaging array
Energy range (keV)	50-5000	50-5000	50-5000	50-5000
Noise threshold (keV)	24	15	15	10
Energy resolution (at 1.3 MeV)	2.3 keV	2.3 keV	2.3 keV	2.0 keV
Full energy γ-detection efficiency (at 1 MeV)	16%	16%	18%	>20%
Effective full energy efficiency after prompt flash blinding	13.9%	14%	16%	20%
P/T-value	34%	34%	40%	>50%
Time resolution (at 1.3 MeV)	13 ns	10 ns	10 ns	< 10 ns
Overload recovery time	≤ 1ms	100 ns/MeV	100 ns/MeV	100 ns/MeV
Relative background suppression	1	5	10	100
Coverable implantation area	16 x 8 cm^2	24 x 8 cm^2	24 x 8 cm^2	24 x 8 cm^2
Max. acceptable event rate (kHz)	3.5	10	10	10

3. Conceptual Design, Modelling, Simulations and Prototyping

3.1 Detector configurations

The conceptual design of the Ge array for the DESPEC experiment has been done by means of Monte Carlo simulations using the GEANT4 tool kit. For all configurations described below, unless it is specified, 10^5 events have been considered for each emission position.

Two different configurations for AIDA have been considered in the simulations. The first one consists of seven silicon layers of 240 × 80 × 1 mm^3 dimension, 5 mm apart, (labeled as AIDA_long) while the second one is based on seven silicon layers of 80 × 80 × 1 mm^3 dimension, 5 mm apart, (labeled as AIDA_short) in both cases placed at the center of the array. The latter one uses only the central part of the focal plane distribution and is used to check if a more compact design would lead to higher relative sensitivity eventually compensating the drawbacks discussed in section 2.1. For both scenarios the central strip detector has for the purpose of the simulations been divided into 192/64 1 cm^2 pixels, respectively, and the photons are emitted from the center of each pixel. Hence 192/64 equidistant emission positions are considered. An Al housing of 1 mm thickness covering 260 × 100 × 600 mm^3 and 100 × 100 × 600 mm^3 respectively, has also been included (see Fig. 10).

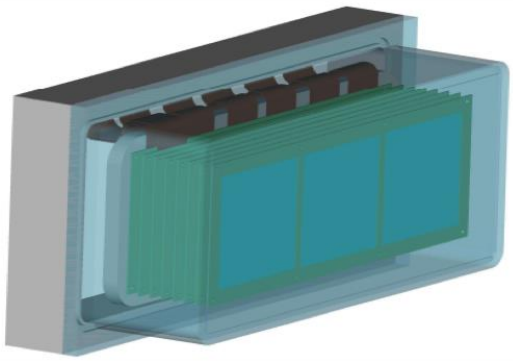

Fig. 10: *The model of the AIDA implantation detector with its Al housing as considered in the simulations.*

The γ-spectroscopy experiments at DESPEC will follow the principles of RISING with enhanced detection capabilities in several areas. Therefore, the RISING setup in its stopped beam configuration at GSI has been considered as a benchmark for the conceptual design of the DESPEC Ge array. Accordingly the set-up has been modelled and simulated. The geometry comprises 15 cluster detectors of seven crystals in a symmetric configuration. The in total 105 EUROBALL crystals are placed at around 22 cm from the center of the implantation array (Fig. 11). The existing configuration can only be coupled to the AIDA_short configuration due to dimensional constraints. Photo-peak efficiency as well as P/T values at 1 MeV γ-ray energy for this configuration are shown in Fig. 12. It should be noted that all the values extracted from the simulations have been calculated considering add-back per cluster.

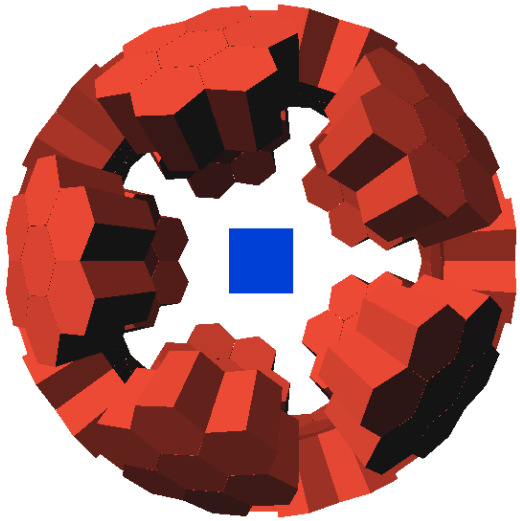

Fig. 11: *RISING "stopped beam" configuration coupled with the short AIDA implantation detector.*

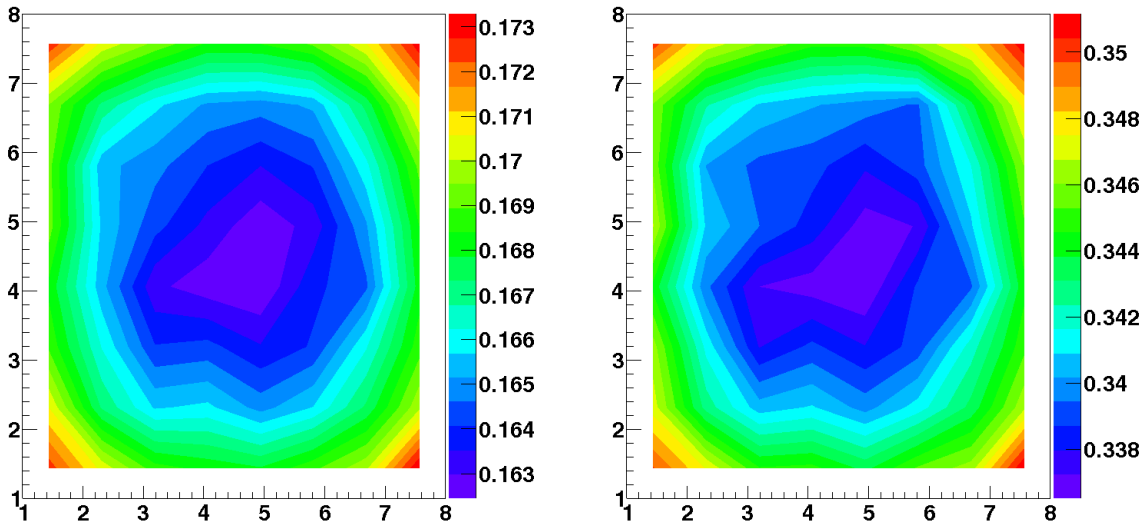

Fig. 12: *Photo-peak efficiency (left panel) and P/T values (right panel) for the RISING configuration at 1 MeV γ-ray energy.*

Phase I configurations

For DEGAS phase I several scenarios based on seven-fold and triple detector units with the short and wide version of AIDA have been investigated. Generally no significant efficiency gain with the narrow AIDA variants compared to the wide ones was observed. Therefore solely the full focal plane version of AIDA will be considered for DEGAS. For all basic geometries (see Fig. 13) triple clusters had a larger efficiency due to smaller gaps between units. Two geometries are used to illustrate the findings. The first one is based on a re-arrangement of the 15 EUROBALL clusters (in the standard seven-crystal configuration) in a compact half-sphere geometry with respect to the AIDA implantation detector (Fig. 13, left). Photo-peak efficiency as well as P/T values at 1 MeV γ-ray energy for this configuration when AIDA_long is considered are shown in Figure 14.

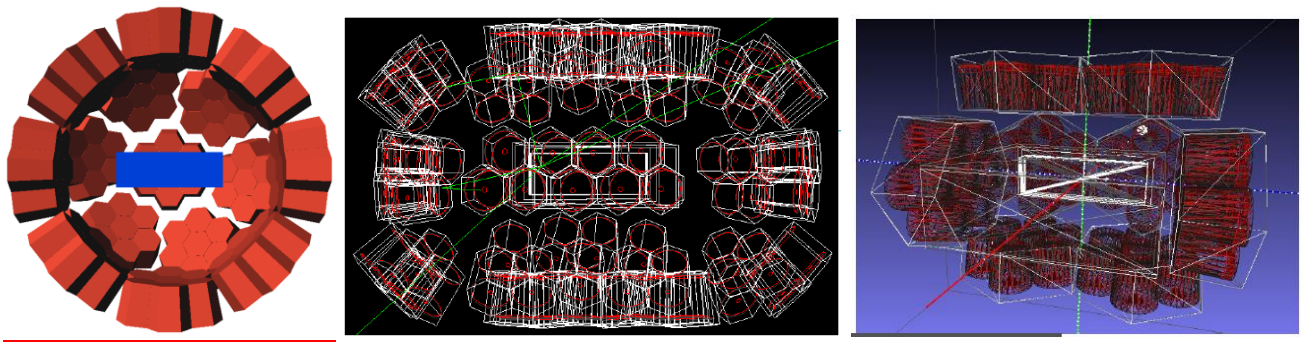

Fig. 13: *Investigated basic geometries: half-sphere, shell, box*

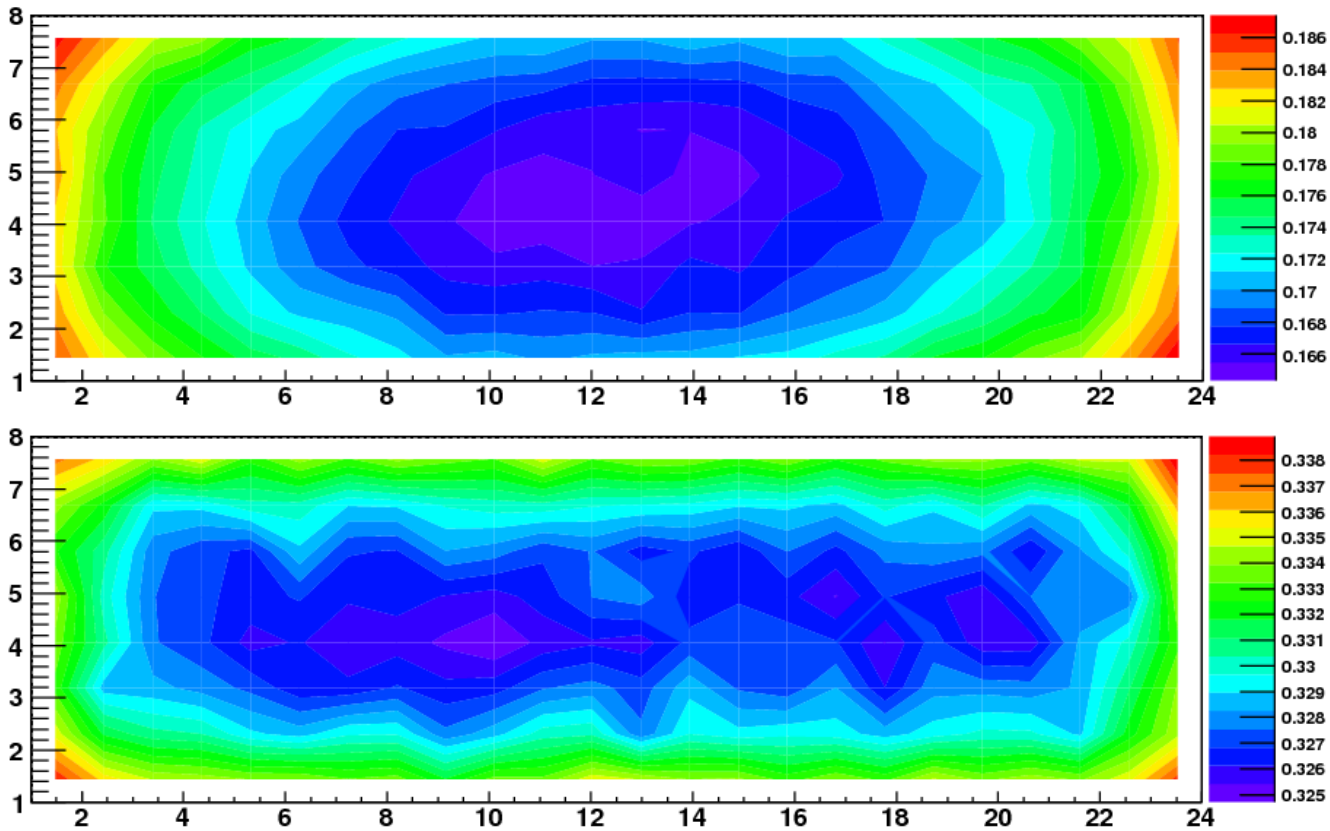

Fig. 14: *Photo-peak efficiencies (top panel) and P/T values (bottom panel) of the DEGAS phase I configuration based on 15 EUROBALL clusters in a compact half-sphere geometry at 1 MeV γ-ray energy for the central implantation detector in the AIDA_long configuration.*

For the second example the EUROBALL cluster detector capsules will be brought into a triple configuration to improve the photo-peak efficiency. The main motivation is to optimize the solid angle coverage of the Ge detectors surrounding the implantation detectors. It will also enable easier coupling with a larger number of AGATA-type detectors in phase II. The geometry considered consists of the coupling of 26 EUROBALL triple clusters in a box configuration as shown in Fig. 15. Optimal packing and efficiency is achieved by maintaining a flat surface of the detector heads, i.e. orienting the central triple unit axis perpendicular to the respective box surface.

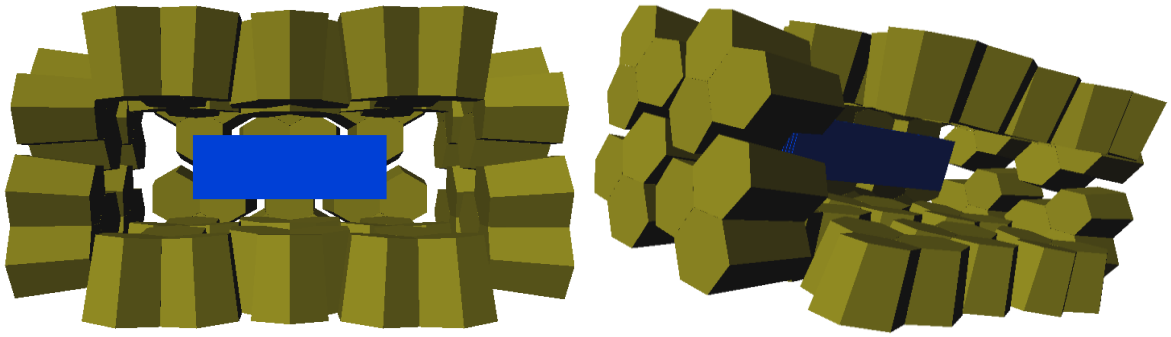

Fig. 15: *DEGAS phase I configuration based on 26 EUROBALL triple clusters in a box configuration coupled to the AIDA_long configuration.*

This geometry, using 78 crystals, turned out to be significantly more efficient than any other configuration. While the RISING benchmark has a simulated photo-peak efficiency of 16.2% at 1 MeV γ energy, the EUROBALL box reaches 21.2%. Due to the asymmetric arrangement the rate in end-cap detectors is about 2.1 times the mean rate of the side detectors. For α- and β-decay experiments this is not critical. However, for short lived-isomers, higher rate, or larger subtended solid angle, means also increased vulnerability to prompt flash blinding. The expected rates of light and heavy charged particles penetrating the end-cap detectors are not critical for the detector integrity. Accumulated crystal defects can be annealed like for neutrons. An estimate of the efficiency reduction due to blinded detectors from the prompt flash reveals a remaining effective efficiency directly after implantation of $\approx$ 5% for the end-cap detectors (before it was 8.4%) keeping an efficiency of $\approx$ 15% for the full array, compared to 13.9% for RISING. To improve this situation significantly higher granularity is required as provided by the highly segmented AGATA detectors.

Phase II configurations

Due to their high efficiency and inherent background rejection capabilities (see below) AGATA type γ-ray tracking detectors have been identified as the optimal basis for the second phase of the project. It is therefore planned to complement or replace EUROBALL cluster detectors with AGATA-type detectors in a new configuration around the active implantation Si detectors.

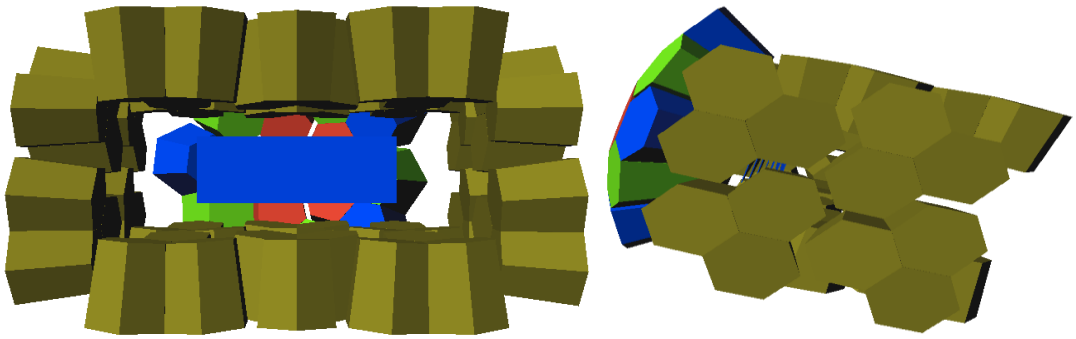

Fig. 16: *Composite system for the second phase based on the coupling of 20 EUROBALL clusters in a box configuration with an end-cap of 5 ATC.*

Based on the box geometry of phase I, the 6 EUROBALL triple clusters (end-cap) placed downstream AIDA can be replaced with 5 AGATA Triple Clusters (ATC) (Fig. 16). Here the background rejection of the AGATA type detectors is optimally exploited as they are viewing upstream towards an area strongly affected by beam related background. Moreover, the prompt-flash blinding is minimized due to the high granularity imposed by the 36-fold segmentation of AGATA diodes. The efficiency at 1 MeV of 21.4% of this configuration is only marginally larger compared to the efficiency of the phase I set-up. However, the effective efficiency directly after a flash is now estimated to be $\approx$ 19%. Even larger

resistance to prompt flash blinding in the compact box geometry would be achieved by replacing the EUROBALL triple clusters at the top and bottom by AGATA-type detectors.

The AGATA array will be the core instrument for the HISPEC experiment [Tec-05]. When HISPEC does not run it might be interesting to employ the available AGATA detectors for a dedicated DESPEC γ-spectroscopy campaign. The use of AGATA type detectors, due to their tracking and imaging capabilities, will improve the sensitivity of the system and will lead to significant background reduction, increasing the P/B ratio of the array. Two examples have been investigated: 1) 10 ATC together with 15 standard EUROBALL (seven-fold) clusters and ii) 16 ATC together with 35 EUROBALL triple clusters. Both configurations are shown in Fig. 17. Photo-peak efficiency as well as P/T values at 1 MeV γ-ray energy for the first of these configurations are shown in Fig. 18.

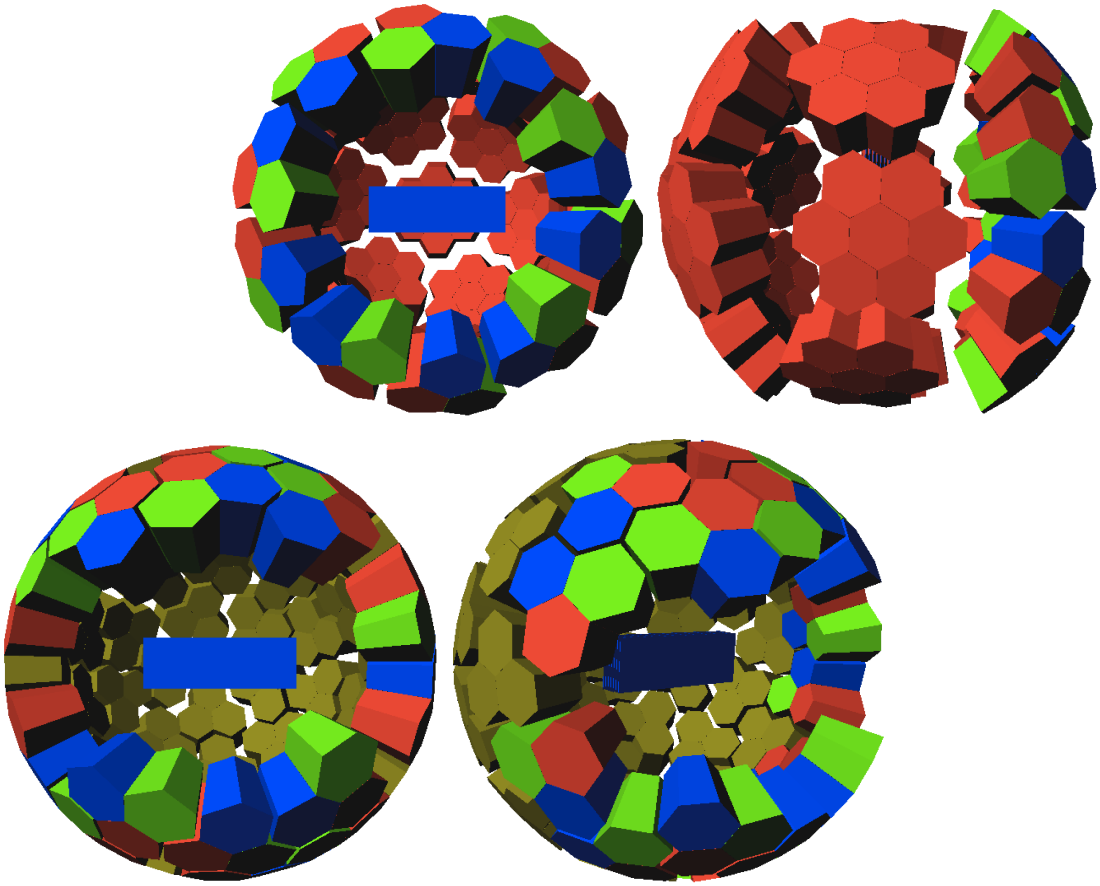

Fig. 17: *Composite system for the second phase based on the coupling of 15 standard EUROBALL seven-fold clusters with 10 ATC (top) and 35 EUROBALL triple clusters with 16 ATC (bottom).*

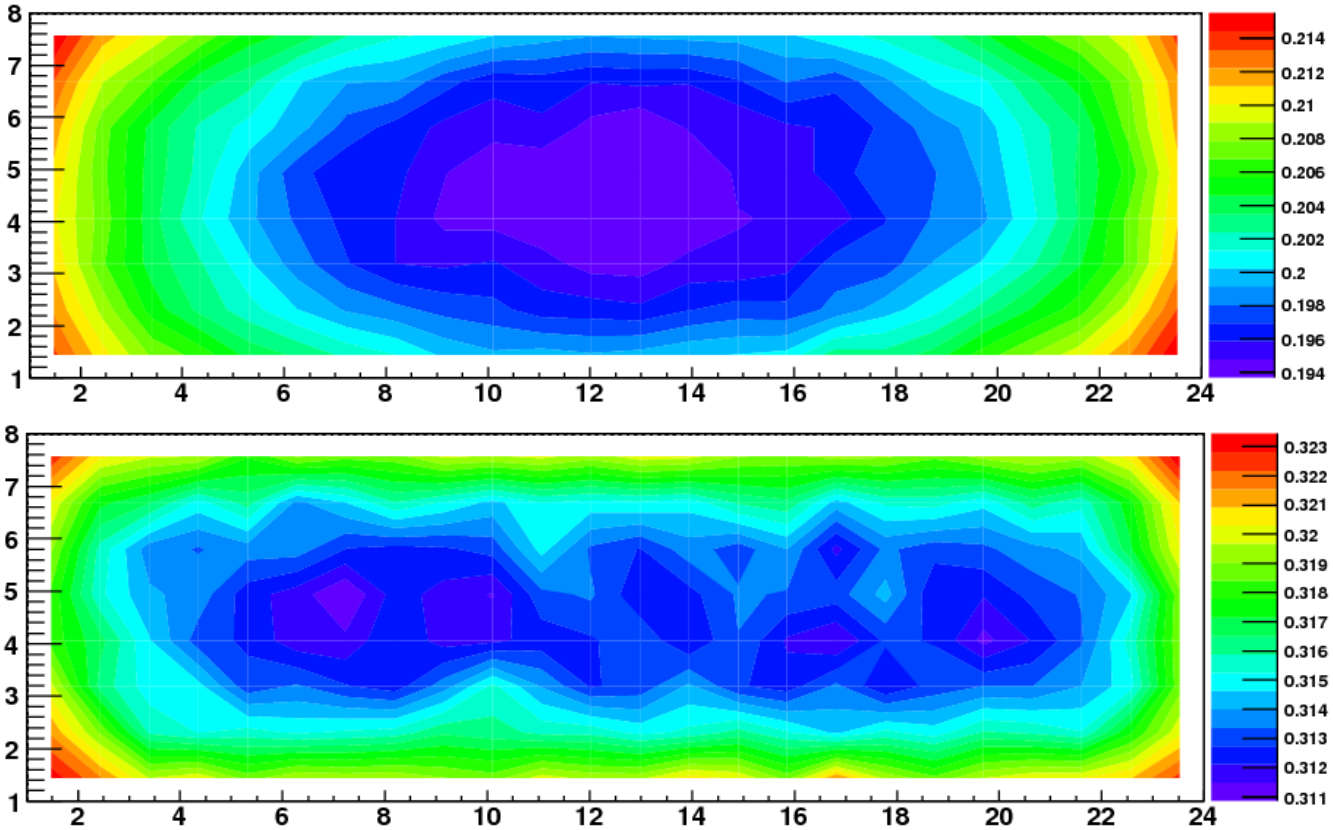

Fig. 18: *Photo-peak efficiency (top panel) and P/T values (bottom panel) for the configuration of phase 2 based on the coupling of 15 EUROBALL clusters with 10 ATC at 1 MeV γ-ray energy.*

Simulation results and conclusions

The results obtained for the different phases of DEGAS are summarized in the following. In Fig. 19 the peak efficiency curves, from 100 keV to 2 MeV, for some of the investigated geometries are shown. Photo-peak efficiencies for a point-like source of 1 MeV γ-ray energy placed at the center of the implantation array are summarized in Table 2 for the AIDA_long configurations. In addition the effective efficiency remaining after prompt flash blinding is given, and the $\gamma\gamma$-coincidence efficiency values obtained for a ^{60}Co source are also included.

For phase I it is obvious that the compact box structure is the best geometrical arrangement. It surpasses the RISING efficiency considerably and competes well with RISING in the effective efficiency after a prompt flash. The flash blinding is avoided by replacing the EUROBALL end cap by AGATA-type detectors, boosting the effective efficiency to unprecedented values. This improvement certainly justifies the use of AGATA-type detectors in phase II. When the full AGATA array from HISPEC becomes available a spherical configuration is worth considering. Although it does not provide any advantage in terms of efficiency over the box structure, it will have significantly improved background reduction capabilities and hence still better sensitivity.

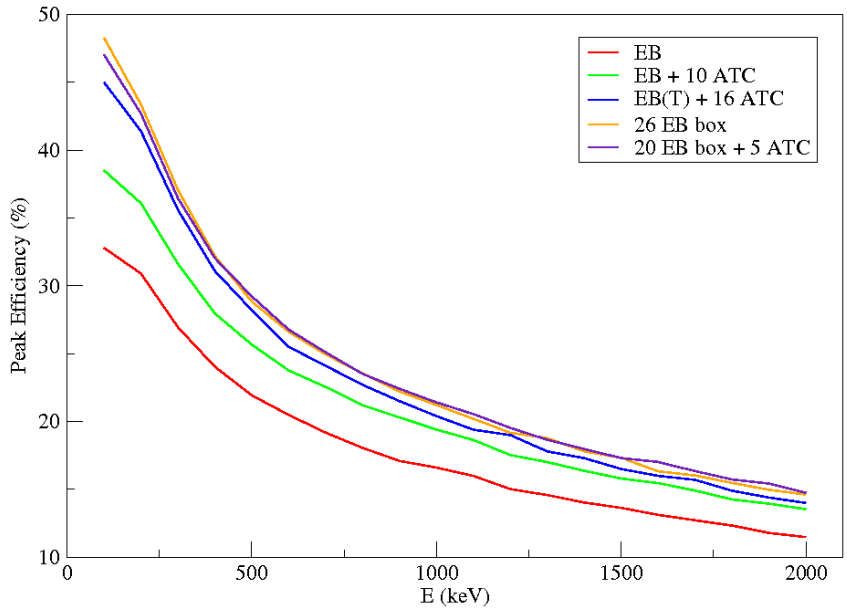

Fig. 19: *Photo-peak efficiency curves for the different phases of DEGAS using the AIDA_long configuration.*

Table 2: *Photo-peak efficiency (ε_p) at 1.0 MeV, $\gamma\gamma$-coincidence efficiency for a ^{60}Co source ($\varepsilon_{p\gamma\gamma}$) and effective efficiency ($\varepsilon_{p\text{-}eff}$) after prompt flash blinding obtained for the different phases of DEGAS when the AIDA_long configuration is considered.*

GEOMETRY	ε_p (%)	$\varepsilon_{p\gamma\gamma}$ (%)	$\varepsilon_{p\text{-}eff}$ (%)
RISING (benchmark)	16.2	2.2	13.9
26 Triple EB clusters (box)	21.2	4.1	≈ 15
20 Triple EB clusters (box) + 5 ATC	21.4	4.2	≈ 19
Phase I (seven-fold) + 10ATC (incl. AGATA)	19.4	3.3	
Phase I (Triples) + 16 ATC (incl. AGATA)	20.4	3.6	

3.2 Background suppression

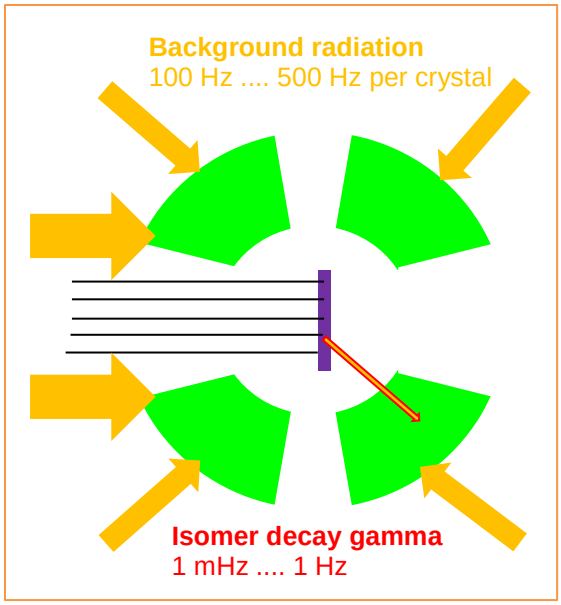

Fig. 20: *The background problematic.*

For the class of isomer decay experiments the environmental radiation background (see Fig. 20) is the most severe limiting factor for the sensitivity and thus the accessible range of isomer lifetimes. This background is dominated by X rays and γ rays with some contribution of neutrons and charged particles. To suppress the background in Ge detectors active or passive shielding can be applied. Gamma-tracking detectors offer in addition suppression through the tracking information. This becomes particularly important for detector units which cannot be shielded, i.e. the endcap detectors of the box geometry.

3.2.1 Background reduction by active and passive shielding

The RISING set-up used a 1 m^2 quadratic Pb-wall of 10 cm thickness placed about one meter upstream from the implantation point to reduce the severe background radiation from the FRS and its heavy ion tracking and identification detectors. Since the opening for the beam pipe in the center of the wall was only 16 cm wide, the shielding was reasonably effective. Such an approach would fail in the case of the Super-FRS, where the beam pipe diameter is 38 cm. Therefore it is foreseen to place thick Pb or W-alloy absorbers in front of the upstream side faces of the DEGAS detectors. To shield the back side of the detectors active scintillator shields are foreseen.

For that purpose the EUROBALL Back-catcher detectors will be employed. These detectors are formed by hexagonal BGO crystals of 5 cm thickness, fully covering the rear side of EUROBALL crystals. As the Back-catchers are arranged in two half-rings of three crystals each (see Fig. 21), forming a collar around the central cold finger flange of the seven-fold Clusters, they need to be reconfigured to fit the triple arrangement of DEGAS. In addition it might become necessary to slightly cut them along one edge to provide sufficient space for the cold finger flange and wiring of the triples. For ultimate performance the distance between the Ge capsules and the electrical cooler as well as the electronics compartment needs to be kept short. Therefore the previously used long PMTs cannot be employed to read-out the scintillation light of the BGO elements. Instead their rear sides will be covered with Si-PMs.

Fig. 21: *EUROBALL Back-catcher element.*

The suppression factor of external electromagnetic radiation by the BGO elements lies between 10^3 for low energy X rays and $\approx 10^1$ for 2 MeV γ rays. To take advantage of these excellent values the gaps between the BGO crystals must be minimized. While adjacent Ge triples are close-packed, the gaps along the edges of the box-like detector arrangement need to be covered by additional scintillation detectors with adopted shapes. The design of the full BGO layer around the Ge detectors is on-going and has to go hand-in-hand with the final Ge detector positioning, considering also the mechanical holding structure of the device. Taking into account final gaps a total suppression of external radiation of >90% is estimated independent of the γ energy.

Besides reducing external background active shields will also detect γ rays escaping from Ge detectors, thus improving the P/T ratio essentially.

3.2.2 Background reduction using AGATA-type detectors

The use of AGATA-type γ-ray tracking detectors in a mixed geometry will lead to a dramatic improvement in the background reduction performance of the DEGAS array due to their inherent imaging capabilities. To demonstrate these capabilities a GEANT4 Monte Carlo simulation including six AGATA triple-cluster detectors has been performed. Background radiation from different sources outside the active stopper was considered. Three different mono-energetic γ-ray sources at 661, 1000 and 1460 keV are considered here in order to illustrate the performance. In the first of two simulated data sets 1.000.000 events have been generated for each source from the (0,0,0) position at the center of the implantation detector (AIDA). In the second simulated data set (also with 1.000.000 events) the 1 MeV source remains at the center of AIDA while the 661 and 1460 keV are considered as background sources from outside the Ge detector array at (50,0,0) and (-50,0,0) cm, respectively.

The Orsay Forward Tracking code (OFT) [LOP-04] developed within the AGATA Collaboration has been used in this study after being optimized to enhance the background rejection capability of the system while keeping a high tracking efficiency. In Figure 22 a comparison between both data sets after tracking is shown. The spectrum in blue corresponds to the first data set in which all sources are placed at the center of the implantation detector, the (0,0,0) position, and the γ-rays are tracked as coming from (0,0,0) while the spectrum in red corresponds to the second data set in which the 1MeV, 661 keV and 1460 keV sources are placed in the (0,0,0), (50,0,0) and (-50,0,0) cm positions, respectively, but the γ-rays have been tracked as originating from the center of the implantation array. Hence, the 1 MeV source is considered as a γ-ray associated with a “real” event (R in the figure) while the 661 and 1460 keV sources emulate “background” radiation (B in the figure). In Figure 23 the same comparison in linear scale is shown. The inset shows the spectra expanded around the photo-peak from the 1460 keV background photons.

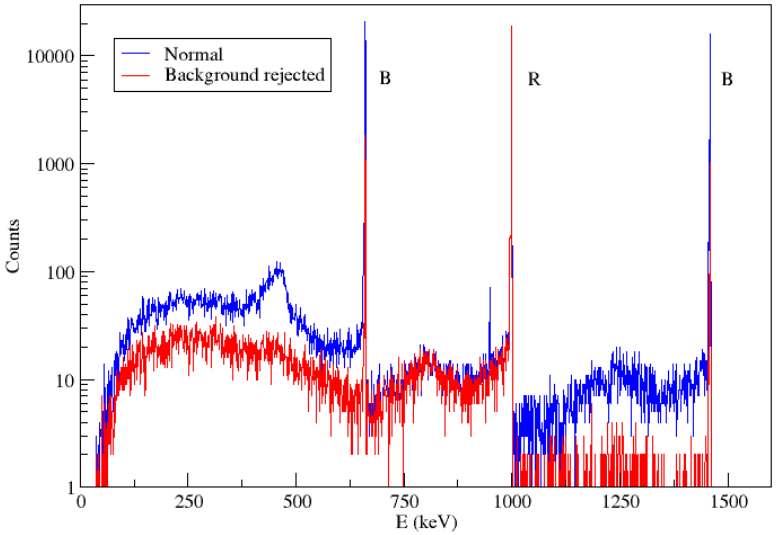

Fig. 22: *Gamma-ray energy spectra from simulated data (log scale) illustrating the background rejection capabilities of AGATA type detectors. The blue spectrum corresponds to the first data set in which all photons are emitted from the center of AIDA and are tracked accordingly while the spectrum in red corresponds to the second data set in which the 1000 keV, 661 keV and 1460 keV sources are placed at (0,0,0), (50,0,0) and (-50,0,0) cm, respectively, but have been tracked from the central position, (0,0,0). R and B identify the photo-peaks corresponding to"real" events at 1000 keV and "background" events at 661 keV and 1460 keV, respectively.*

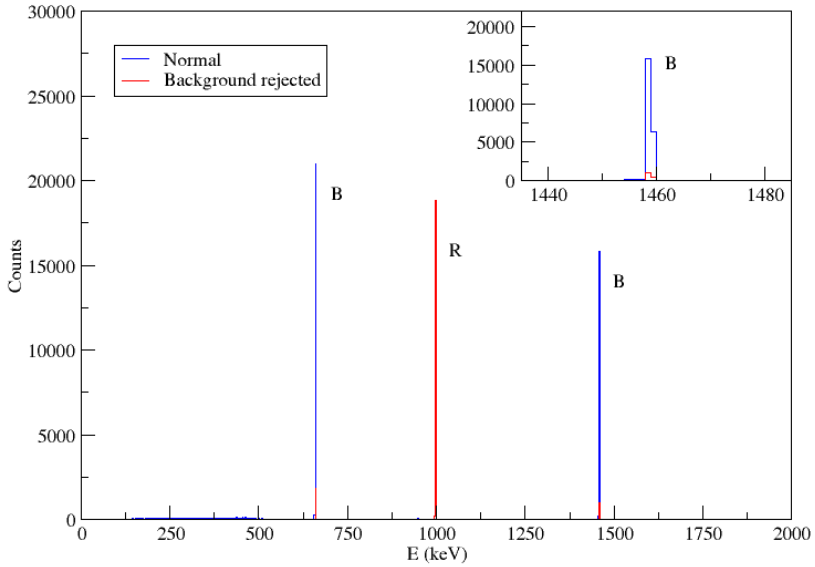

Fig. 23: *Spectra as in Fig. 22 shown in linear intensity scale. The inset shows a zoom around the 1460 keV background photo-peak.*

The background reduction capability of the system has been studied for different source positions. We use the tracking efficiency, defined as the number of reconstructed photo-peak events divided by the real number (simulated) of photo-peak events, as a measure of the background rejection capability of the detector system. It is important to note that it is independent of the origin of the source as long as the source position is identified correctly. In Table 3 the tracking efficiency values obtained for several positions are shown. It can be seen how for the "real" events the tracking efficiency is about 70% while for the "background" events (when the photons are tracked as if coming from the stopper detector while they are emitted from an external background source) it is reduced to around 25%. Furthermore, the P/T ratio is significantly higher when the tracking is applied from the right position (around 70%) than for background radiation (around 45%) at different external positions as expected.

Hence, the AGATA-type detectors enable efficient identification and suppression of background radiation emanating from outside the active stopper detector. A composite system including even a rather limited number of AGATA-type detectors leads to a dramatic improvement in the background rejection capabilities of DEGAS, fulfilling one of its main objectives.

Table 3: *Tracking efficiency obtained for sources placed at different positions. The "*" correspond to events simulated from the given positions but tracked as emanating from the center of AIDA, (0,0,0). Numbers in green correspond to those plotted in Fig. 22 and Fig. 23.*

Position	661 keV	1 MeV	1460 keV
(0,0,0)	67 %	70 %	70 %
*(50,0,0) cm	23 %		20 %
*(-50,0,0) cm	33 %		27 %
*(0,50,0) cm	27 %		22 %
*(0,-50,0) cm	27 %		22 %

3.3 DEGAS Phase I Cryostat

As discussed above to achieve optimal performance the EUROBALL detectors need to be re-configured into triple units. Therefore the old EUROBALL seven-fold detector cryostats are no longer suitable and new cryostats need to be built. Since the sensitive Ge crystals are encapsulated the assembly can be performed by the collaboration. Currently there are two attempts to construct triple cryostats for EUROBALL detectors, the GALILEO design, under development at LNL, Legnaro for the upgrade of the GASP array into GALILEO, and the PANGEA (PANda GErmanium Array) triple cluster, a project between GSI and IKP-Mainz for the FAIR/PANDA collaboration. The unique feature of the PANGEA cryostat is its minimal cross section actually defined by the footprint of the triple crystal arrangement, and the use of an electrical cooling engine (X-Cooler II,III from MMR, respectively Ametec). Such a solution is mandatory for DEGAS since the close packing and flat detector unit orientation severely limits the space available behind the detectors for the cryostats. Moreover, DEGAS sub-systems must be employable at sites where LN operation is prohibited. Therefore the DEGAS I cryostat will follow the PANGEA design.

The only mechanical difference is that the PANGEA triple cryostat has a flexible neck between the cooling engine and the detector head which will be replaced by a simple rigid tube for the DEGAS cryostat (see Fig. 24). The PANGEA triple cryostat comprises on board preamplifiers, High Voltage (HV) modules, a Bias Shut Down (BSD) module, a Power Supply (PS) module (generating all the

voltage needed from 48V supply), ADC modules based on the nanoMCA module of the company LabZY and a control module based on a microcomputer. Many of these features can be directly employed or adopted to the needs of DEGAS. Since most of the features of the PANGEA triple have been already studied and verified the performance of the future DEGAS triple can be easily predicted.

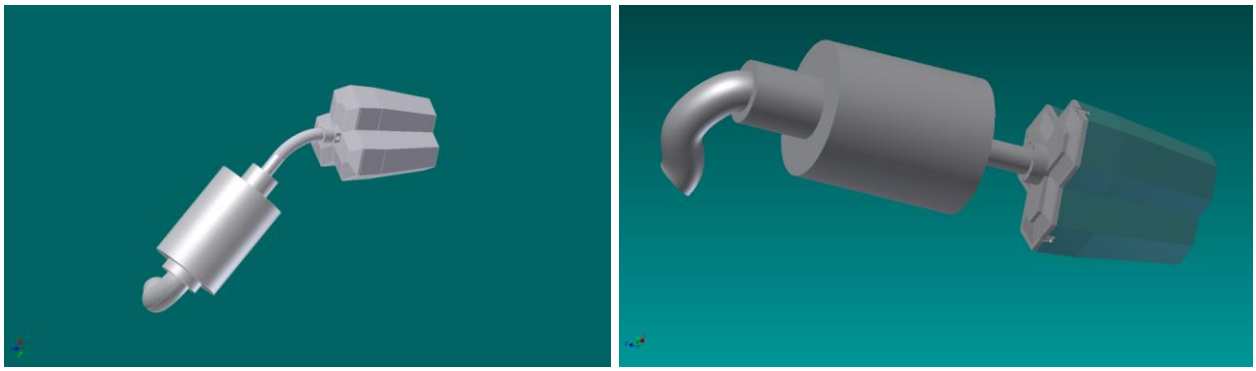

Fig. 24: *Schematic view of PANGEA (left) and adopted DEGAS cryostats.*

3.3.1 Cryogenic design

The DEGAS Triple Cluster is supposed to have an electrical cooling engine instead of the classic LN2 cooling. This type of cooling is rather simple [KOJ-08], does not need of any refilling system (Autofill), does not need of any safety system and has significantly reduced sizes. The effective diameter is only 204 mm (see section 3.3.2), which makes it difficult to find a suitable dewar vessel with a reasonable size. A too small vessel would require too frequent filling, which reduces the performance of the detector and potentially decreases its reliability. If the detectors are arranged in a spherical geometry this problem does not exist, the projection of the edges defines a much larger dewar vessel, but such an arrangement would exclude the box geometry chosen for the DEGAS array.

The germanium crystals and the cold structure are installed in a vacuum cryostat where three processes determine the energy transfer between the room temperature cryostat walls and the low temperature assembly: heat radiation, thermal conductivity and residual molecular heating. A careful design of the components and appropriate materials choice is essential to reduce the heat absorbed by the germanium crystals sufficiently to enable electrical cooling.

The HPGe detectors are typically operated within the range of 77-110 K which determines a temperature difference between the warm cryostat walls and the cold frame of about 200 K. The triple crystal assembly possesses a large surface of the detector cup surrounding the capsules hence predetermining an elevated radiative heating which may dominate even the overall heat transfer.

Beyond that, the warming impact of the thermal bridges, mechanical components used for fixing the cold structure to the warm section of the cryostat and the internal cabling between the crystal housing and the vacuum feed-through play a substantial role. The fixing elements of the detector system under optimization, namely labyrinths and spacers are critical parts and an accurate dimensioning is needed in order to achieve minimal heat transfer at the same time preserving γ-spectroscopy properties and the functionality required. The space limitations impose minimal gap between the capsules assembly and the cryostat walls. However, at some critical gaps width, the residual gas of the evacuated inner space contributes significantly to the detectors warming and this effect depends on the vacuum level.

In a comprehensive study at GSI of the heat transfer processes, each one separately and in combination, and their impact on the detector performance have been investigated [KOJ-12]. The dominating heat transfer mechanisms have been identified and appropriate mathematical modelling has been applied. Temperature distributions within the detector structure were calculated for various environment and cooling conditions and the functional characteristics of the assembly needed to reach

the operational temperature range, were determined. Different design solutions were compared and proper materials selected.

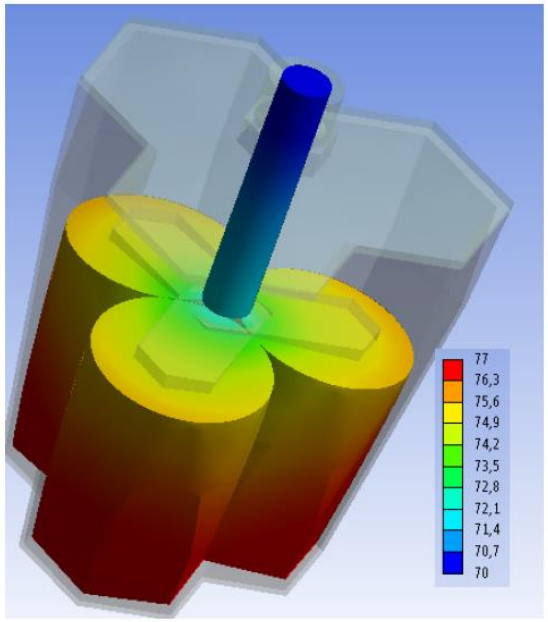

Fig. 25: *Temperature distribution along the Ge-capsules and the cold finger when the temperature of the cooling part is 70 K and the ambient temperature is 295.15 K. The emissivity of the Ge-capsules is 0.2 when the emissivity of the processed inner surface of the cryostat is 0.1.*

After optimization of the cryogenic layout the emissivity of the Ge capsules is minimized, resulting in a small temperature gradient within the crystal of a few K only as shown in Fig. 25. Another important component is the distance holder of the cold finger. While the labyrinth-like structure used with the EUROBALL seven-fold cryostat has a heat loss of ≈0.4 W, the newly developed design shown in Fig. 26 accounts only for 0.077 W. A lot of emphasis was put into optimizing the cold-finger and its thermal connection employing for instance ultrasound bonding [ENG-11]. This and many other improvements lead to a cooling power of < 8 W for the DEGAS triple, small enough for electrical cooling engines.

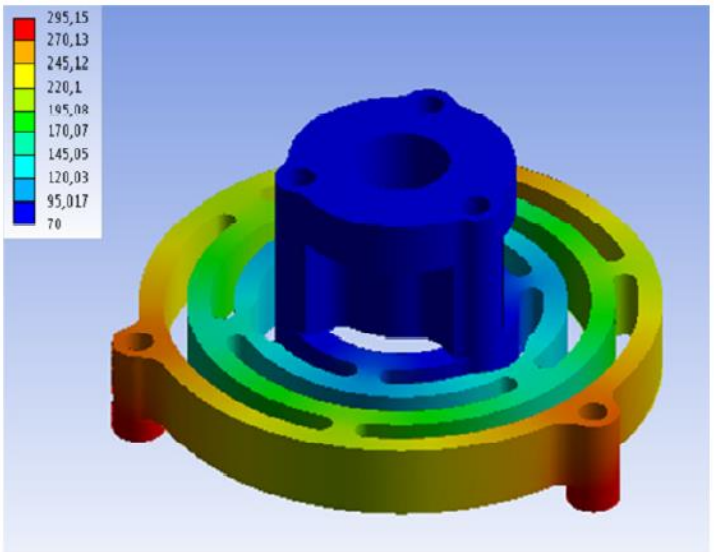

Fig. 26: *Temperature distribution along the surface of the polyethylene four rings fixing labyrinth and the structural steel sleeve.*

Finally a prototype employing a single EUROBALL capsule has been constructed to validate the design solutions [FAR-09]. This detector compared very well with the model simulations. Employing an X-Cooler II cooling engine it cools down very fast as shown in fig. 27 (right) and is in use since 2011 as isomer scanner at the FRS without any problems.

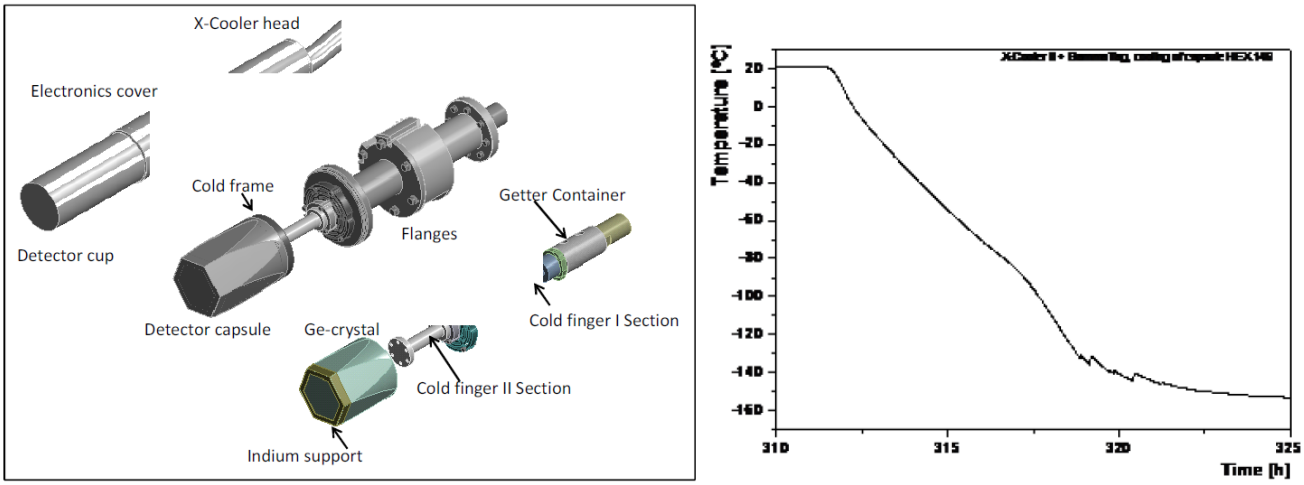

Fig. 27: *Electrically cooled EUROBALL detector prototype (left) and its cooling time (right).*

The cooling engine for the DEGAS Triple cryostat is supposed to be either an X-Cooler III or CryoTel engine type CT or GT (company sunpower). All of them are sufficiently powerful – the type GT has 16 W cooling power, the X-Cooler III and type CT have 11 W, compared to 6-8 W suggested by the study of the detector thermodynamics. X-Cooler III has a flexible connection between the cold head and the aggregate (which reduces somewhat the functionality) and the CryoTel engines are fed by a 48V power supply with a very compact assembly. The sizes of the cooling head of X-Cooler II and the CryoTel are similar.

3.3.2 Mechanical lay-out

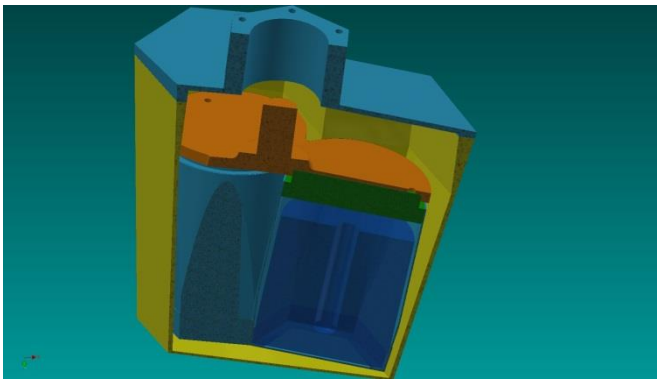

Fig. 28: *Layout of the detector head.*

The detector head (see Fig. 28) contains the capsules arranged in triangle geometry with a distance between the capsules outer surface and the detector end cap inner surface of 3 mm. The end cap wall made from aluminum is 1.5 mm thick. The capsules are fixed on a cold frame which is connected to the cold finger. The cold line has a flexible section which reduces the microphony.

The vacuum space is common for the detector assembly, but is decoupled from the connection space. The connection to the cooling head and cooling engine has its own vacuum space which allows replacement of the cooling aggregate without breaking the detector vacuum. By this way the cooling aggregate can be replaced by another one or another type including the use of a dewar vessel. The

vacuum inside is to be maintained better than 10^{-6} mbar (including the detector head) and a noble gas absorber is to be applied.

The preamplifier compartments and the rest of the electronics are installed in the space further up, surrounding the cooling head, thus facilitating the installation of the back catchers close to the germanium crystals. In this way the noise pick up is reduced considerably. Additionally, the temperature maintenance inside of the electronics compartment is facilitated due to the compact size. The temperature fixing is supposed to go by natural convection, if needed additional cooling may be provided.

The cryostat has a special mechanical interface for fixing to the setup structure. This can be either the end cap lid with its hexagonal extension or the electronic compartment base flats.

3.4 DEGAS Phase III considerations

It has turned out that the original goal of the project, to introduce dedicated high-resolution γ-ray imaging detectors in decay spectroscopy, requires a long-term development program. The tremendous potential improvement of the sensitivity of a dedicated imaging array, enabling distinction between different implant positions in addition to the selection of target-like events from background events partially already possible by including AGATA-type detectors, justifies this effort. Therefore, R&D on planar Ge-stacks, quasi-planar and point-contact detectors and possible scintillator-Ge hybrid solutions will be continued, aiming for a future detection system suitable for DESPEC decay and HISPEC in-beam experiments in a third phase.

Planar strip Ge detectors provide the necessary position resolution for imaging. However, the necessary guard ring around the active volume leads to drastic losses in usable solid angle and thus the achievable efficiency falls below the RISING benchmark. There are promising alternatives as for instance the quasi-planar geometry for which first prototype crystals (see Fig. 29) have been produced.

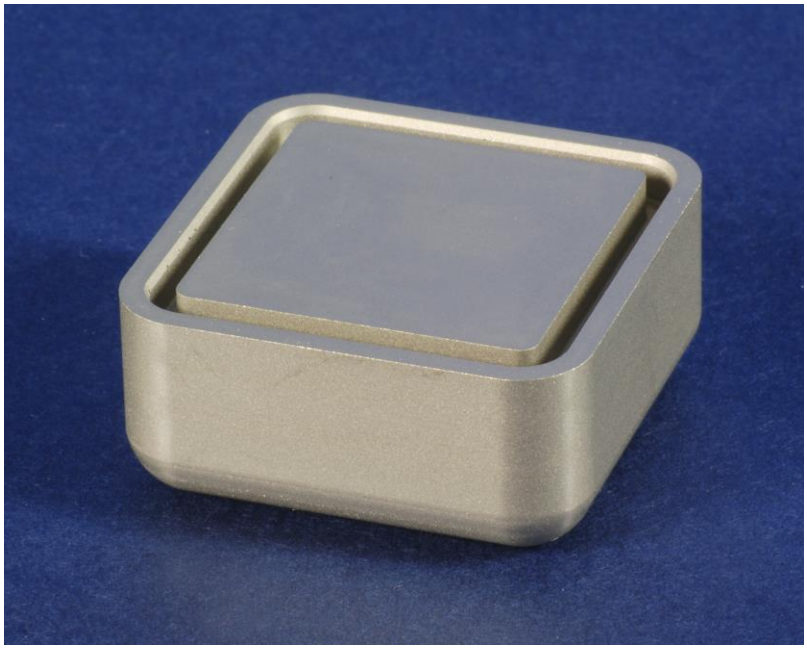

Fig. 29: *Quasi-planar prototype Ge diode with a volume of 32.5x32.5x12.0 mm^3 and a dead zone outside the HV insulation groove of only 4.2% of the total volume.*

Following a recent idea such a detector type could serve as an implantation detector providing an alternative to the DSSSD detector stack of AIDA. Obviously it has considerable interaction efficiency for decay γ rays and will improve the tracking and imaging sensitivity, when used in conjunction with the AGATA-type γ-ray tracking detectors. The higher Z will also enhance the β- and α-detection efficiency of the system.

The final Ge detectors for DEGAS phase III and other detectors resulting from this development work will need additional funding outside the framework of the current FAIR cost book and is outside the scope of this report.

4. Electronics and Data Acquisition

The DEGAS front-end electronics has the task to manipulate the Ge detector signals such that they can be digitized in sampling ADCs in order to record the signal information for later analysis. Furthermore, fast signals for trigger and timing purposes need to be produced. In addition the signals of the shielding scintillators need to be processed and stored in the data stream as well as general control information, like HV values and crystal temperatures. As DEGAS will be coupled to complementary instrumentation foremost to the Super-FRS detectors and AIDA, it requires the possibility of synchronization and merging of the respective data streams. While the phase I detectors will follow the standard NUSTAR DAQ system evolving from the GSI MBS system, the phase II AGATA-type detectors will take advantage of the developments performed in the nuclear structure community for the instrumentation of the AGATA γ-ray spectrometer.

As will be discussed in the following sub-sections there exist ready-to-use EDAQ solutions for both phase I and II of DEGAS. However, the turnover time of electronics hardware is a few years only, with fast performance improvements and cost reductions on one side and problems with component availability and maintenance for outdated products on the other side. Therefore it is the policy of the DESPEC collaboration to choose certain hardware modules or software systems only at the time when they are needed to be purchased. Besides the performance of the selected EDAQ solution a key quality is always easy and reliable operation respectively maintenance.

4.1 Front-end Electronics

Table 4: *Specifications of the AGATA preamplifiers available for DEGAS and the intended improvements.*

Property	AGATA	DEGAS II
Conversion gain	100 mV/MeV	same
Noise	800 eV (0 pF)	same
Rise time	13 ns	same
Decay time	50 µs	same
Integral non-linearity	< 0.025%	same
Output polarity	Differential, Z = 100 Ω	same
Fast reset speed	≈10 MeV/µs	same
Integrated pulser	yes	same
Power supply	±6.5 V, ±12.5 V	±6.0 V, ±12.0 V
Power consumption	< 980 mW	< 500 mW
Dimensions	62 x 45 x 7 = 19530 mm^3	< 5000 mm^3

The pre-amplifiers for the Ge detectors require, besides the traditional good energy and timing properties, also fast and clean transfer functions to register unperturbed signal traces for pulse shape analysis, see Table. 4. Input stage FETs are supposed to be operated cold. Fast reset in case of detector overload due to energetic particle hits is required. The phase I EUROBALL crystals are currently being equipped with a hybridized version of the preamplifier PSC821. This preamplifier has sufficient dynamic range (over 20 MeV) and large frequency band (up to 50 MeV) which defines good timing properties -typically 7 ns time resolution. However, it does not provide fast reset and thus needs to be replaced or modified. Currently it is anticipated to use the pre-amplifiers of AGATA, developed by a collaboration of GANIL, the University of Milan and the University of Cologne which fulfil all the basic requirements [PAS-08]. The AGATA core preamplifier includes an on-board precision pulse generator and allows for an extremely wide dynamic range using the built-in reset technique. The AGATA-type detectors of phase II may also use this core pre-amplifier and related segment pre-amplifiers, where three channels are integrated on one PCB. Also, the front-end electronics will include additional pre-amplifiers to be used with the Si-PMs, which will be installed on-board of the active shields.

Presently several groups are proceeding with an R&D to understand the feasibility of ASIC-integrated reset pre-amplifiers. The reason for that is the present limit on integration in the PCB, requiring a sizeable volume for the pre-amplifier housing, and the substantial power consumption that produces rather hot regions in the detector cryostat, increasing the necessary cooling power.

As the HV-system employed for RISING and AGATA is almost obsolete, for both the DEGAS and the AGATA detector units the HV is supposed to be generated on board. This development is based on a new generation HV-modules from the company iseg. Along the advantage of reduced EMC vulnerability, the saved HV cables improve the reliability and reduce the cost. Moreover, the cost for the HV-system (crate and HV cards) is also substantially smaller. The front-end electronics power supply will be based on a 48 V industrial power supply generating all on-board voltages needed. This improves the EMC compatibility and also reduces the cost for the power supply units and infrastructure. Depending on the Si-PM choice, HV-modules for Si-PMs will also provide bias voltage (e.g. 30 V or 70 V).

In the long run the goal is to include digitization and (pre-) processing of the data as well on board of all DEGAS detectors. A step in this direction is the nanoMCA module produced by LabZY. With this module under development in the PANGEA project, Ge pulses are digitized and processed in order to obtain the amplitude and the time reference. Along with the transfer of already processed data, the waveforms can also be transported and stored for further processing. Since the module has a size of only 50 x 30 x 8 mm^3 and its power consumption is < 800 mW it provides a valuable basis for the EUROBALL triple detector. For completion DAQ and slow control should be done on board as well. There are very compact microcomputers available which are sufficiently powerful to maintain tagging and packing of the data, transport via optical links and all slow control communications. These microcomputers have been tested and their capability for serving as base logger has been confirmed by another project within PANDA. While a complete on board EDAQ system is an option for the EUROBALL triple detectors for phase II already, for the AGATA-type triples with their 111 channels a considerably higher integration density and lower power consumption is necessary, requiring additional development before implementation in phase III.

4.2 Digitization

The principal goal of the digitizer is to interface the detectors and the data processing system. In order to do that, the digitizer module will receive the signals from the Ge pre-amplifiers and digitize them with 14 bit sampling ADCs to guarantee the required dynamical range. A sampling rate of the order of 100 MHz is required for pulse shape analysis and proper software signal time determination.

The RISING project used DGF-4C digitizer modules from XIA. These modules were CAMAC-based and provided only 40 MHz sampling rate, therefore an analogue timing branch composed of a standard TFA-CFD-TDC timing circuit was necessary. As these modules are obsolete and do not

meet the requirements, new digitizer modules are required for DEGAS phase I. Currently there are three options of which one will be chosen in due time.

The first option is to employ the new 16 channel SIS3316 FADC module from SIS. As this is an industrial product, it is very reliable, robust and durable. Long term disposability and maintenance by the company is very likely. As it is a standard VME module it can be easily integrated into the MBS based NUSTAR DAQ system. The integrated FPGA allows generation of energy and time information as well as read-out of signal traces. The cost per channel is a reasonable ~ 400 €/channel.

The second option would be to take the FEBEX system developed at GSI. The FEBEX ADC has 14 bit, samples at 65 MHz and provides 16 differential analog inputs on a 100 mm x 160 mm euro-board form factor. It is readout via MBS/PC with a PEXOR card (PCI-Express optical receiver) and costs ~ 50€/ch. It will be maintained by the GSI/FAIR electronics department and will be used by several NUSTAR experiments. Moreover, a new version with 100 MHz sampling is in preparation.

Finally, there is the option to use the DIGI-OPT12, a new compact 12-channel digitizer with optical output developed at LNL Legnaro for the GALILEO and AGATA germanium detectors. Minimum power consumption of 1 W/ch, high integration (120 mm x 160 mm form factor), and high flexibility are the key words of this technical development. The module matches the AGATA preamplifier specifications as well as the LLP (Local Level Processing) digital electronics requirements, and is easily reconfigurable as “Core” or “Segment” digitizer. Moreover, it provides a fast analog trigger output. The cost of this solution would be ~ 250 €/ch.

For the AGATA-type detectors of phase II the DIGI-OPT12 digitizers are the preferable choice because these modules are compatible with the AGATA pre-processing system.

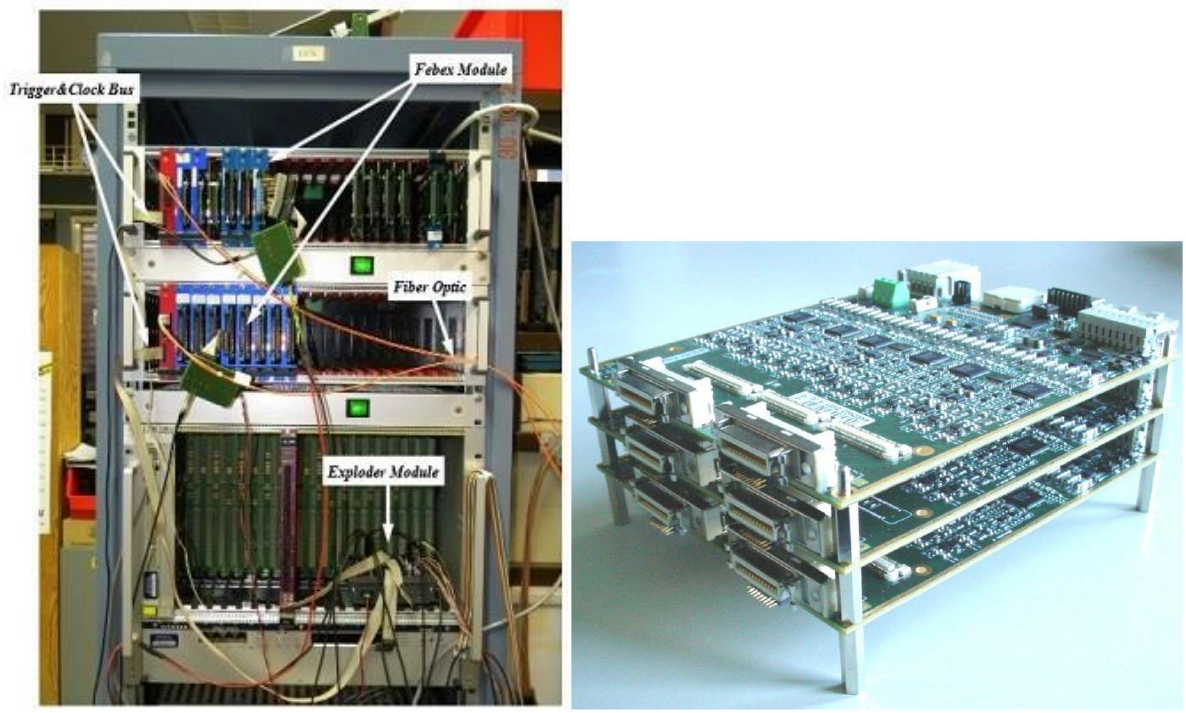

Fig. 30: *FEBEX digitizer test stand (left) and 36 channels DIGI-OPT12 stack (right).*

For the BGO shields of phase I a conventional VME based digitization scheme, e.g. employing CAEN V792 QDCs can be used. Timing information can be obtained with standard analog discriminators and V1290 MH-TDCs. An interesting alternative under investigation is the idea to build dedicated pre-amps, digitizers, (pre-) processing, bias and slow control on-board the BGO modules, like it is planned for the Ge detectors.

4.3 Data Acquisition

The phase I data acquisition will be based on the standard NUSTAR MBS DAQ system available by that time. This could be for instance a VME-based MBS system reading the before mentioned VME modules of the phase I Ge and BGO detectors. A CES RIO6 controller would serve the VME crate, a TRIVA7 would be used as trigger and synchronization unit and the new VULOM5 for the trigger logic. Synchronization with the Super-FRS and DESPEC ion tracking and identification detectors as well as with AIDA would be done with local White-Rabbit interfaces. Such a DAQ system is fast enough to handle the maximal particle rate of 10^4 /s and the associated γ rate. Flexible trigger conditions can be applied, for instance to define tagging time ranges or to veto prompt flash γ events. Similarly DEGAS detector sub-systems for other experiments can be easily configured.

Adding AGATA-type detectors in phase II requires additional data processing for the necessary pulse shape analysis and tracking (see Fig. 31). In essence the role of the pre-processing system is to take data from the digitizer system, extract all the useful data which can be calculated on a per-channel basis in real time, and pass on these parameters, along with the leading edge of the digitized trace from the incoming pulse, to the Pulse Shape Analysis (PSA) system. The pre-processing also interfaces with the Global Trigger and Clock system (GTS) from which a clock for the digitizer and the timestamp information is derived. In some cases the front end data rate might exceed the processing capacity in the PSA, or one of the following data acquisition sub-systems (tracking, event builder or tape server). The global trigger mechanism can be used to reduce the front end data rate in these cases by pre-selection based on criteria such as multiplicity (number of active crystals) or coincidence with ancillary detectors or coincidence with beam pulses. The counting rate in the core contact is much higher than that in any of the segments. Nevertheless, since the segment electronics is triggered by the core, the rate at which the segments collect data traces is the same (high) rate as the core contact. The processing rate for traces in the segments will, therefore, be the same as in the core, although many of the traces will contain no data and could be rejected by a zero suppression algorithm (currently there is no plan to implement zero suppression because the PSA wants access to all the data including the apparently empty channels.

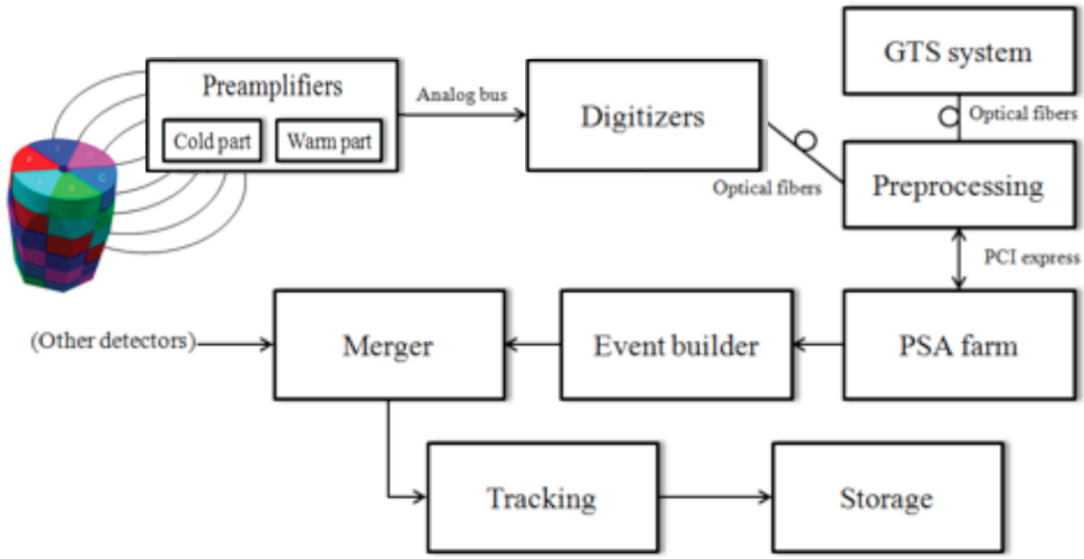

Fig. 31: *Schematic diagram of the AGATA electronics chain to be used for DEGAS phase II.*

The need for triggering in the core requires special interconnections with the global triggering system. This connection is used also as the interface point for receiving the clock and timestamps. The optical fiber links from the digitizer electronics are mainly unidirectional (transferring data from digitizer to pre-

processing). However, the control fiber is bi-directional (full duplex) so that clocks and control signals can be sent to the digitizer. The pre-processing hardware takes the incoming data streams and store traces started by the crystal level trigger information derived from the core signal (and optionally validated by the global trigger system too). The traces are processed to extract parameters such as energy, time and preamplifier time over threshold. It then passes the leading edge of the pulse trace to the PSA, along with these parameters. The digitizing speed is 100MHz, so the pre-processing hardware also uses 100MHz clock rates for incoming data. The GTS interface provides the system clock and a trigger system. The trigger system can be used to reduce the counting rate, for example by a multiplicity filter or by a coincidence requirement with an ancillary detector or with beam pulses. Where rate reduction is not required, the pre-processing runs in trigger-less mode which means that all the processed data are sent on to the PSA stage. In this case a software trigger is performed downstream, after PSA and tracking. The maximum delay (latency) which can be accommodated in the pre-processing hardware while the GTS trigger decision takes place has implications for the amount of storage required in the pre-processing. It is estimated that up to 20 μs of trace length could be needed for processing and therefore the maximum trigger latency is 20 μs. The role of the pre-processing is to take the continuous data stream from each of the digitize ADCs and extract useful information to be passed on to the PSA. The useful information is, as a minimum, a set of traces corresponding to a γ-ray interaction in the detector. So, the first task is to decide which part of the incoming data stream is useful- this is achieved by running a digital trigger algorithm on the detectors core contact data stream. When this trigger finds a pulse in the data it extracts a data trace and generates a local trigger output which indicates to all the segment electronics that they should also extract a trace from the data stream. Traces are stored locally, within each pre-processing channel. At this point there are two options for how the pre-processing behaves. If the data handling system bandwidth can handle the full data from all γ rays generated during the experiment then the pre-processing will just go ahead and put the traces in an output buffer. However, for reasons of either constraints in the EDAQ or over-ambitious raw γ ray count rates it may be necessary to make a judgment on the usefulness of the pulses detected by the pre-processing, saving only the best ones. In this case the pre-processing enquires via the GTS about whether other detectors were also active in coincidence with this one and whether the GTS system criteria for saving the data are met. In this mode of operation the traces are held in each channel local memory for up to 20 μs while the GTS makes a decision. Either an event reject or an event-accept response is generated for each local trigger based on the GTS decision. If the EDAQ bandwidth matches the γ-ray rate, a solution with no GTS trigger decision can be made and the event-accept signal is generated for all detected pulses. For events which are accepted, the pre-processing stores a trace of the digitized leading edge of the pulse from the core and all 36 segments in a buffer waiting to be sent to the PSA. In addition to selecting useful portions of the incoming data stream using a trigger algorithm, the preprocessing will also apply other algorithms to the data streams. The first of these algorithms is the Moving Window Deconvolution (MWD) algorithm to determine the γ-ray energy by filtering the incoming pulse digitally. The second algorithm is associated with the preamplifier inhibit signal. The inhibit is activated when the preamplifier is saturated by a high-energy charged particles (e.g. a pion) that deposits in the detector much higher energy than the rays. The preamplifier recovers by injection of charge from a constant current source, so the length of the recovery time (i.e. the width of the inhibit pulse) is directly proportional to the energy deposited by the high energy charged particle. All data is being concentrated presently into a single FPGA before transmission via PCI express to the PSA farm on demand by the PSA. The same FPGA handles the trigger interconnections.

Coupling of the AGATA DAQ system with the MBS system is achieved with a special GTS leaf interacting through an AGAVA module. This coupling mechanism is well established and has been successfully used in the PRESPEC-AGATA campaign in 2012 to 2014 and will also be employed for the HISPEC experiment. Even in phase II the maximal data load of DEGAS will be < 30 MB/s. Therefore, no bandwidth or storage problem is to be expected with the standard NUSTAR DAQ system.

5. Infrastructure and Mechanics

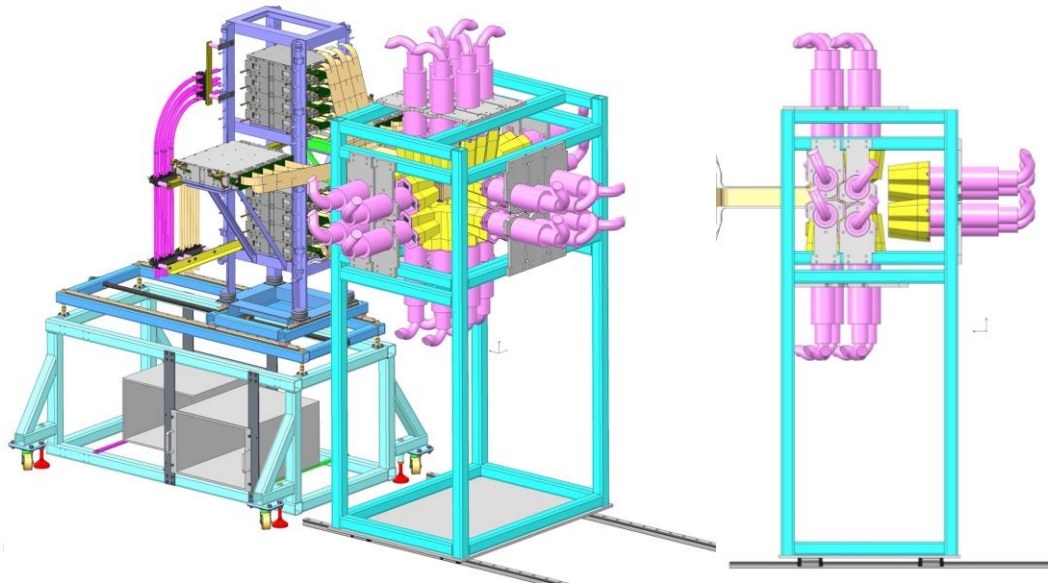

Fig. 32: *Schematic view of the DEGAS phase I mechanical assembly.*

For the DESPEC experiment a standard set of heavy ion tracking and identification detectors and the AIDA implantation device need to be fixed in the set-up, while other key instruments like DTAS, BELEN and DEGAS exclude each other and need to be interchanged depending on the experimental requirements. Therefore the mechanical holding structure of DEGAS needs to be movable. Figure 32 shows schematically the proposed design. As there will be open space downstream of the implantation zone with a total length of 3.4 m from implanter to the flange of the buncher/spectrometer in the Low-Energy Cave, DEGAS can be maneuvered in and out by retracting it from the AIDA snout. This allows also maintenance of the AIDA DSSSD stacks when necessary.

Moving phase I triple Ge detectors in and out is easily done, as each unit is attached to a holding plate. If BGO shields are mounted for the additional weight crane assistance could be helpful. The phase I electronics including infrastructure fits in a small rack that can be placed for example below the detector system. No other media than standard electrical power and cooling water is needed. Data transfer and interfacing to a user control system will be done by the standard network connection provided in the experimental area.

For phase II of DEGAS the end-cap detectors would be removed and replaced by a honeycomb frame forming a calotte of five triple AGATA-type detectors. AGATA digitizers and pre-processing electronics will be placed downstream, possibly on a common platform. The AGATA-type triple detectors will need LN cooling. For that purpose the automatic filling system to be built for HISPEC shall be employed.

6. Radiation and Safety Issues

DEGAS is going to be operated mainly in the NUSTAR Low-Energy-Cave, which will see low intensity primary and secondary radioactive ion beams. Hence, both short-lived and accumulated radioactivity is at a comparatively low level as at, for example, the present S4 focal plane area of the FRS at GSI. Similar radiation protection measures (proper for an access restricted area) will be applied at the future experimental area. The same holds for any other experimental area where DEGAS detector units may be employed. The activity of the encapsulated laboratory radioactive sources to be used for calibration purposes are within the allowed limits (e.g. 370 kBq ^{152}Eu).

No particular mechanical hazards are expected. Care should be exercised in handling the heavy pieces (detector modules and shielding elements). The highest electrical hazard is associated with the

use of standard and well-grounded HV supplies of ≤ 5 kV (current < 1 μA) to bias the Ge detectors and ≤ 1 kV (current < 1 mA) to bias scintillator PMTs.

Cryogenic cooling with liquid nitrogen is limited to the AGATA-type detectors. Equipment and handling procedures for DEGAS will be similar to RISING and PRESPEC at GSI. A closed automatic LN filling system with exhaust removal will be installed and the experimental area will be equipped with permanent oxygen alarm monitors. Any handling of the cryogenic system will be limited to well-trained personnel.

No hazardous gases or lasers are associated with the operation of DEGAS.

7. Quality Assurance and Acceptance Tests

Due to the proposed staged process of the production of DEGAS detector units including electronics and associated infrastructure and the overall rather limited amount of individual components, their assembly, quality assurance, and acceptance tests will be performed by the DEGAS collaboration itself on test benches at GSI and TIFR using standard radioactive sources.

As soon as they become available the DEGAS units are intended to be used in physics experiments at the S4 area of the FRS and other accelerator facilities, which in turn enables early commissioning of the DEGAS system. If needed, other test beam facilities within the collaborating institutes may be used as well.

8. Calibration and Commissioning

The calibration of the response of DEGAS is a vital part of the detector commissioning. This includes absolute and relative efficiency, energy and time. This work will be performed in a first stage with laboratory sources having a simple and well-defined decay scheme: ^{22}Na, ^{60}Co, ^{137}Cs, ^{152}Eu and ^{241}Am. In a second stage, beams of species with well-known decay intensity distributions will serve to verify the effect of the implantation setup on the spectrometer response.

The use of test beams will serve to verify another important issue: the discrimination of background intrinsic to measurements with relativistic heavy ion beams, separated, slowed down and implanted at the center of the DEGAS spectrometer. The different background components will be identified. The proper background reduction procedure (passive shielding and/or active discrimination) will be studied. Schemes for the quantification of residual background components and their subtraction will be investigated.

9. Installation and Logistics

DEGAS detector units will be assembled and maintained locally at GSI/FAIR and can be easily transported on the campus using proper carts.

Transportation of components will be done by standard procedures of partially highly fragile instruments from the various assembly and test laboratories to GSI/FAIR. For the mechanical holding structure, planned to be pre-assembled in the Daresbury laboratory, size and weight require specific handling.

Installing and aligning the detector holding structure at the experiment position requires the use of the standard cranes existing (S4 area) or planned (Low-Energy Cave). Mounting and dismounting of detector units will be possible by two persons. Particularly the heavy AGATA-type units require a crane for safe handling.

The electronics racks are going to be placed in the near vicinity of the DEGAS detector set-up, i.e. the cabling can be done easily with standard procedures.

10. Time Schedule

Figure 33 provides an overview of the time planning for DEGAS. Due to the modularity of the DEGAS detectors decent sub-arrays can be built already in 2016 for tests and commissioning and first experiments at the FRS at 2017 as soon as SIS beams will be available again. The full phase I set-up is planned to be operational by the end of 2018, well in time for experiments at the different focal points of the Super-FRS. For the second phase AGATA detector procurement should start already in 2015 to account for the long production time required by the producing company Canberra Eurisys. By 2020 the phase II array is supposed to be ready for experiments at the LEB-Building of NUSTAR.

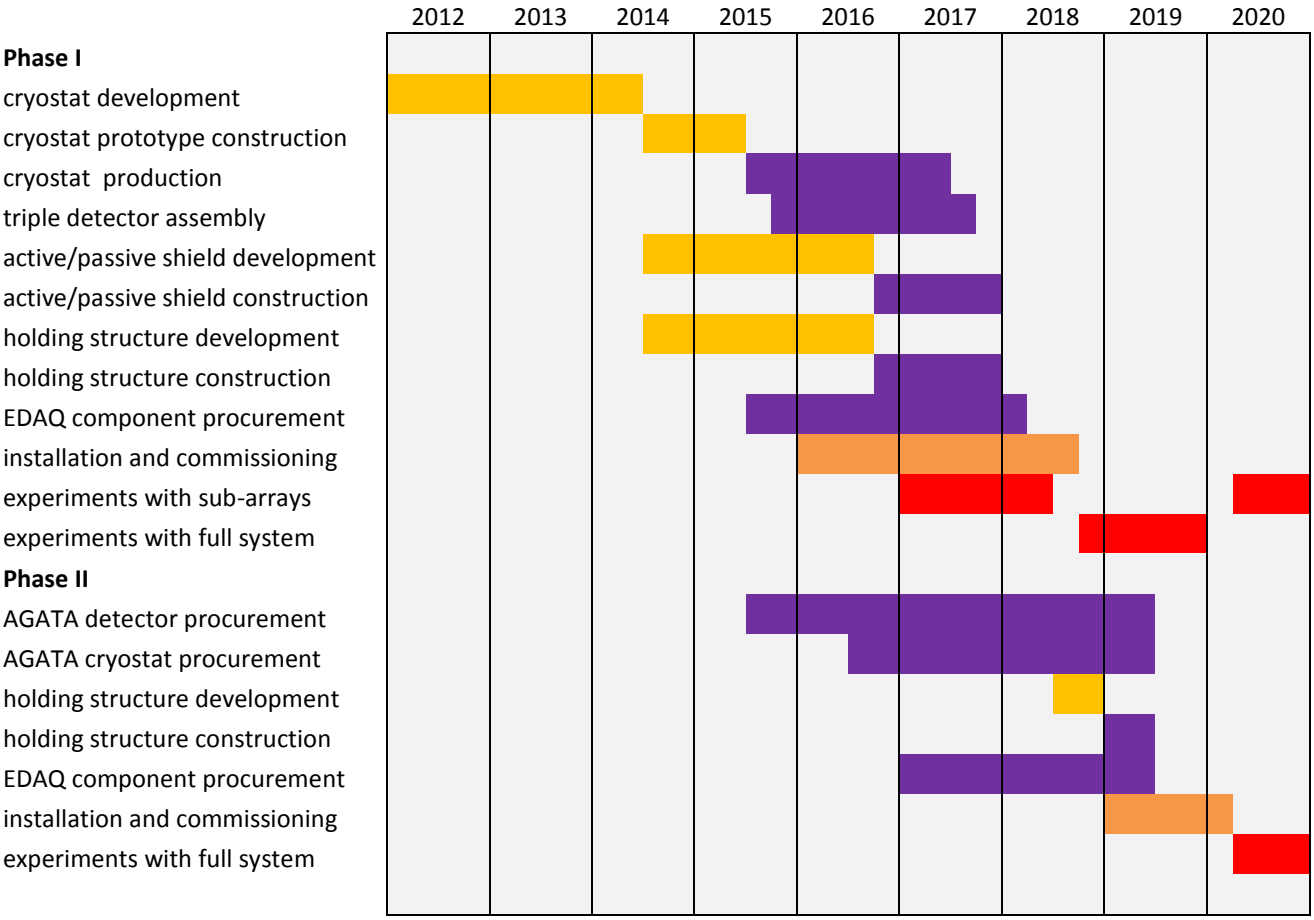

Fig. 33: *DEGAS time plan for phase I and II.*

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