

The GRETINA Spectrometer

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Abstract. The GRETINA spectrometer is a first generation, gamma-ray tracking spectrometer capable of determining the Compton scattering path of gamma-rays incident on the detector volume. This ability allows the Ge detectors to be close packed allowing the detector to be scaled to high efficiencies while maintaining good peak-to-total. GRETINA currently consists of 7 4-detector modules giving approximately 1π solid angle coverage with a calorimetric efficiency of 6.3% and tracked efficiency of 4.7% at 1.3 MeV. The array's sensitivity to the position of the gamma ray's first interaction point enables precision event-by-event Doppler correction which allows one to achieve 1% energy resolution even for sources moving at a large fraction of the speed of light such as those encountered at fragmentation facilities such as NSCL and the future FRIB.

1. Introduction

The availability of large volume, segmented HPGe crystals has enabled the development of the first generation of high-efficiency, general purpose, gamma-ray tracking spectrometers. Two such projects are currently being pursued: the Gamma-Ray Energy Tracking In-beam Nuclear Array (GRETINA) [1] in the United States and the Advanced GAMMA Tracking Array (AGATA) [2] in Europe. The idea behind these spectrometers is to construct a spherical shell of Ge detectors around the target position of maximal efficiency. Interaction points of the incident gamma rays in the crystals are located, grouped into clusters, and tracked using the Compton scattering relation [3]. There are several distinct advantages to this approach compared to previous high-efficiency spectrometers such as Gammasphere [4]. Tracks with a set of interaction points which do not fit the Compton scattering relation, whose origin is assumed to be the target position, can be rejected as likely not depositing their full energy in the active detector volume of the array. This allows such arrays to operate with high peak-to-totals without the need for Compton suppression enabling the array to be scaled to high efficiencies. Furthermore, the ability to track the gamma ray means that multiple gamma rays depositing energy in a given crystal can in principle be disentangled thereby avoiding summing.

GRETINA began its first major physics campaign at NSCL/MSU in conjunction with the S800 spectrometer in 2012 and the value of this new technology was quickly established. The ability to apply precision Doppler correction of the gamma-ray energy based on the location of the first interaction point in the crystal enables one to maintain 1% energy resolution for sources moving at a high fraction (40%) the speed of light while maintaining high efficiency and peak-to-total. This allows for precision spectroscopy of isotopes close to the driplines produced in fragmentation reactions. GRETINA is now completing its second physics campaign at ATLAS/Argonne to take advantage of radioactive beams produced by Cf fission source CARIBU. In this paper we will give a



brief description of the technical implementation of GRETINA, its online data analysis algorithms to determine the gamma-ray tracks, its current performance characteristics, and the outlook for future development.

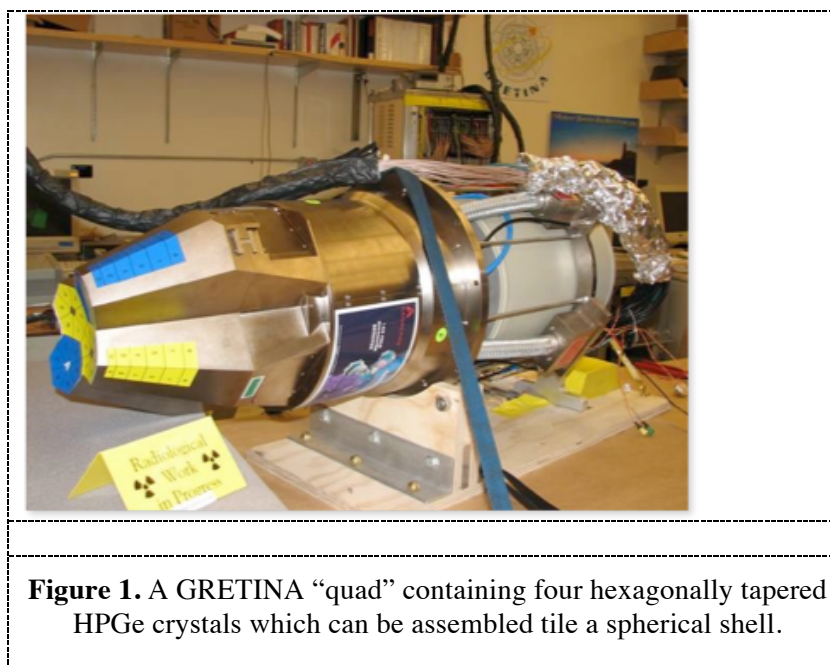
2. Technical Description

The technical aspects of Ge tracking detectors are more complex than that of previous arrays based on Compton suppression. Interaction positions in the crystal are located by examining the charge on each segment during charge collection with (primarily) the hit segment determining the radial position of the interaction while the image charges in adjoining segments locate the interaction position in ϕ and z . To achieve good position resolution the crystal itself is highly segmented and each segment pad is instrumented with high-speed digitizers to record the waveform. For GRETINA with 28 crystals, each with 36 segments, 1000 such channels are required.

2.1. The Detector Module

GRETINA employs large-volume, 36-way segment HPGe crystals with base diameter of 8 cm and length of 9 cm that are tapered to allow for spherical packing. The tapering is that of an irregular hexagon to allow efficient tiling of the spherical shell. The geometry chosen requires 120 hexagons to tile the complete sphere. GRETINA currently consists of 7, 4-detector modules yielding approximately 1π solid angle coverage. Each detector is individually encapsulated and four crystals are packaged in a single cryostat as shown in fig. 1.

The central contact preamplifier for each crystal utilizes cold Field Effect Transistors (FET) inside the cryostat to optimize resolution while the segments employ warm FETs outside the cryostat. This choice was made to simplify servicing the large number of channels. Each segment and the central contact have a separate preamplifier board that is mounted in a compartment directly behind the crystals in the detector module. The large heat load introduced by the 148 preamplifiers in the module necessitates the use of a liquid cooling system to maintain the preamplifier compartment at a reasonable temperature.



2.2 Electronics

In order to locate the interaction points within the segmented Ge crystal, it is necessary to record the charge on each segment pad as a function of time. This requires that each segment and the central contact to be instrumented with a high-speed digitizer to record these waveforms for analysis. To perform this function a specialized 10-channel, VME based digitizer was developed [5]. Banks of four such digitizers are used to instrument the 36 detector segments and the central contact. Signals are digitized at a frequency of 100 MHz with a dynamic range of 14 bits employing an AD645 ADC by Analog Devices. An onboard Field Programmable Gate Array (FPGA) (Xilinx XC3S5000) processes these data streams providing a leading edge discriminator used by the trigger systems, an energy, pileup flag and 48-bit timestamp which is used later in the processing pipeline for event building. The high-resolution energy is determined from the trace produced from the ADC by a trapezoidal filtering algorithm [6] which is baseline corrected.

GRETINA also has a programmable digital trigger system which initiates readout of the digitizers based on the number of prompt and/or delayed hits in the Ge central contacts, the trigger condition of external devices or combinations of the two. The trigger also distributes a global, 48-bit clock to all digitizers to synchronize the system to a 10ns clock and provide timestamps to uniquely assemble events from all the detector modules.

2.3. Computing

The computing system of GRETINA consists of several components. The local readout of digitizers is done using VME-based, single-board computers (Emerson MVME5500) with one such readout computer allocated for each crystal. These use the real-time operating system vxWorks upon which custom readout software was developed. This system is responsible for local event building at the crystal level, control of the digitizers, forwarding data to the online analysis system where the location of interaction points are determined, and basic performance monitoring.

The online data processing is done in a 63-node linux cluster. Each node has two four-core processors and 8Gb of memory. Data from the cluster is transferred from the local readout computers via a 10 Gb optical link utilizing a standard TCP-based network protocol. Most nodes in the cluster are allocated to the task of signal decomposition, which is the rate-limiting step, although resources are also be allocated for Compton tracking, global event building and monitoring. Data is stored to a network-based filesystem using the Network File System (NFS) protocol or to high-capacity storage nodes with local raid arrays.

As with Gammasphere, GRETINA employs a unified control system employing EPICS (Experimental Physics and Industrial Control System) [7]. This is a network-based, distributed control system that had been adapted to a wide-variety of computing platforms. In GRETINA it is used to configure the digitizers through the local readout computers, the trigger system as well as processes running on the cluster. This gives the experimenter a unified view of GRETINA as a whole. The system itself is also easily scriptable making it straightforward to develop configuration and diagnostic scripts for various detector configurations.

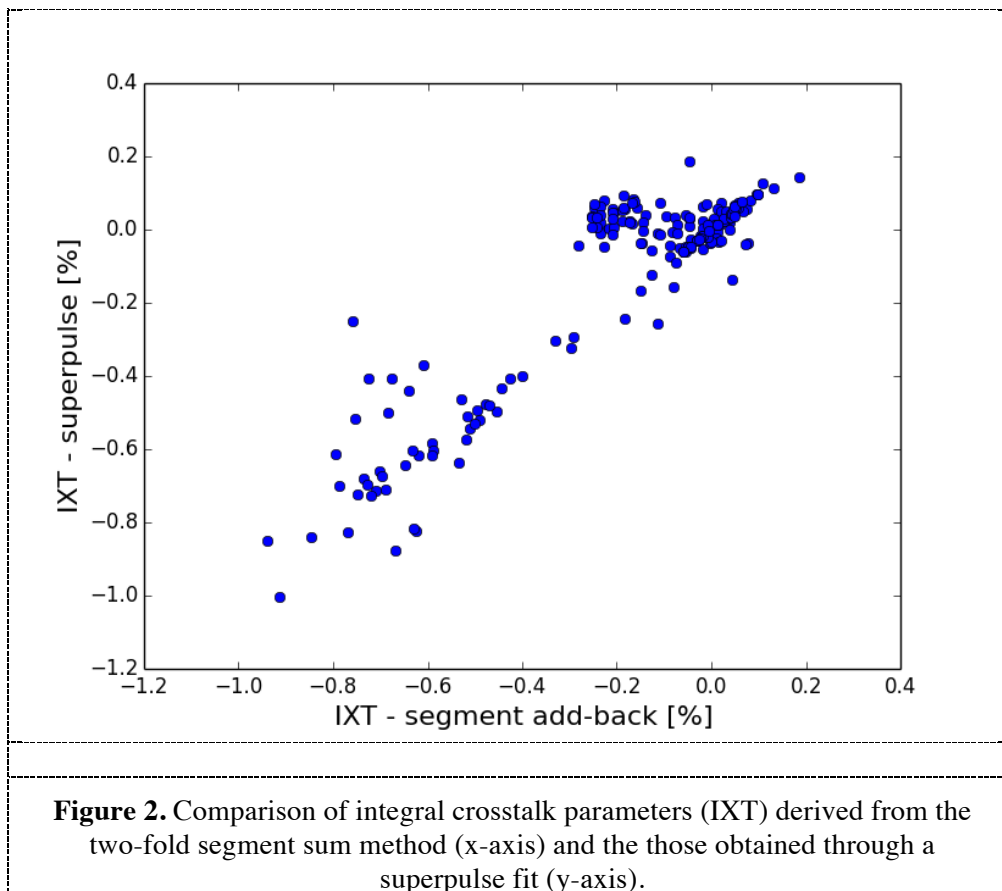
3. Signal Decomposition and Compton Tracking

In order to locate interaction points within the crystal, a procedure termed signal decomposition is performed [8]. Given the crystal geometry, impurity concentration and profile, one first simulates the

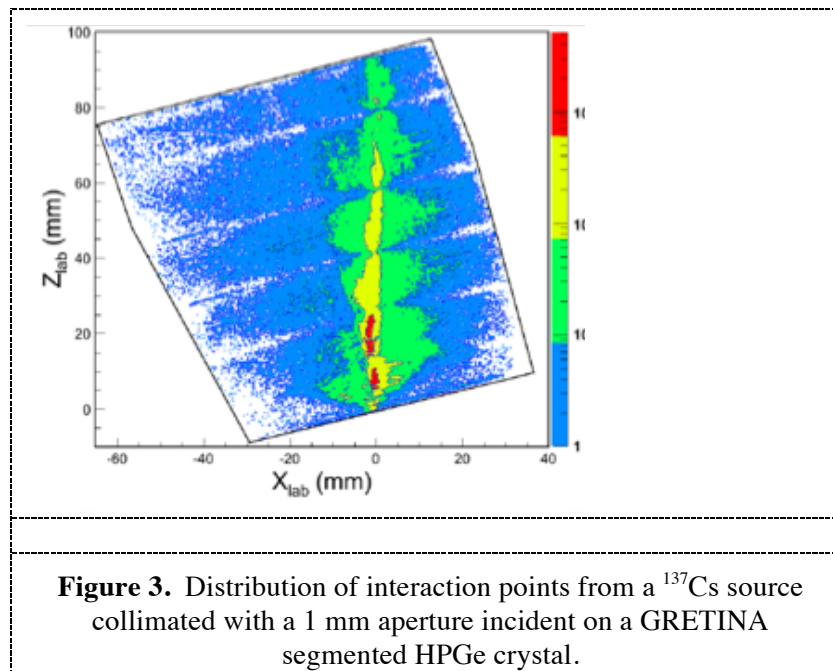
signals on each segment contact for unit charge as a function of position in the crystal. This is done on a grid of points that span the volume of the detector and a library of such signals is created. Against this library linear combinations of basis signals are fit against the experimentally determined waveforms to determine the positions and relative energies of interaction points. In this way the experimental positions of the interaction positions are “decomposed” and assigned positions within the crystal.

The basis must be corrected for the electronic response of the detector module and electronics. These response parameters include shaping introduced by the preamplifier, time offsets, as well as integral and differential crosstalk. Correcting for differential crosstalk is especially important as this is easily confused with the image charge signals that locate interaction points in phi and z within the crystal.

Given the large number of response parameters that need to be fit and the difficulty in measuring differential crosstalk directly, an automated method known as the superpulse method [8] was developed. Here, a ^{60}Co source is placed at a fixed distance from the detector and the waveforms for events where a single hit segment are recorded. The same configuration is then simulated and the parameters are fit against the averaged experimental signals given a realistic response model. These parameters are then applied to each signal in the basis with the same response model. Detailed comparisons of fit response parameters with direct measurements of shaping time, differential and integrated crosstalk show this method to work well. An example is shown in Fig. 2 where integral crosstalk coefficients between segments of a crystal derived from both segment sums and the superpulse method are shown to be in good agreement.



There are two main phases to the signal decomposition algorithm employed. The first is an adaptive grid search where a best fit to pairs of interaction points within a given segment are made on the grid points as defined in the basis. Following this a non-linear fit is performed where one can move off of grid points and the time offset is fit. Points that fall within a certain minimum distance of each other are coalesced into a single point weighted by their energies. This algorithm is computationally efficient requiring $\sim 10\text{ms/core}$ on modern computing platform. The first hit position resolution (σ) of the interaction points has been determined to be 2 mm both from collimated source tests and inferred from in-beam Doppler correction. Fig. 3 shows a representative distribution of an interaction points from a collimated ^{137}Cs source.



Following signal decomposition the interaction points from individual crystal are tracked [9]. Interaction points identified in the signal decomposition are time-correlated and sorted into global events and the position of the interaction points are transformed from local crystal coordinates to world coordinates. Interaction points are then clustered into groups of likely gamma rays based on their angular separation. Then group-by-group, one examines each permutation of points to find which best fit the Compton scattering relation. The best fit is then assigned a figure of merit value on which it is decided if the gamma-ray likely deposited its full energy in the array or scattered out.

4. Performance

There are several performance metrics that contribute to the overall sensitivity of the detector array which include energy resolution, efficiency, peak-to-total, and rate. These have been carefully studied during the physics campaigns at NSCL/MSU and at ATLAS/Argonne. The energy resolution of the central contact signals was found to be 2.4 keV at 1.3 MeV and 1.7 keV at 0.12 MeV when mounted in the array. The mean segment energy resolution is 2.6 keV at 1.4 MeV and 1.6 keV at 0.12 MeV. These measurements were taken with trapezoidal filter parameters of 5 μs for the integration time and 1 μs for flat-top time.

As GRETINA employs tracking, the topic of efficiency is multifaceted as efficiency gains are realized by tracking gamma rays across multiple crystals. Hence, the specific geometric arrangement of the 7 modules in the frame is important. Also, as the location of interaction points given by signal decomposition is not exact, there is a tradeoff between efficiency and peak-to-total. The base calorimetric efficiency of the array with 7 modules in a close-packed configuration is 6.3%. This is essentially the arrays' maximum singles when tracking is not applied. As mentioned previously, if one applies a figure-of-merit cut to the fit of the Compton track of the gamma ray, one can significantly increase peak-to-total at the cost of efficiency. Defining a 25% FOM cut, which reduces the array efficiency to $6.3\%(0.75) = 4.7\%$, one achieves peak-to-total of 49% (again in the close-packed configuration).

As with efficiency, there are also two aspects to the rate performance of GRETINA. The singles rate, the maximum rate at which a single Ge crystal can operate, is 20 kHz and is limited by the shaping time in the trapezoidal filter to retain good energy resolution without incurring excessive pileup. Unlike conventional spectrometers, GRETINA performs the additional step of online signal decomposition to locate interaction points. This occurs post-trigger and is limited by the computational power available for signal decomposition in the online signal processing cluster and network/backplane bandwidth constraints. The current maximum processing rate for signal decomposition is 30 kHz that, assuming an average of 1.5 detectors hit per gamma, yields a rate of 20000 gamma/s for the 7-module array post-trigger. This rate can be in principle increased by increasing processing power in the cluster and improving bandwidth from the digitizers to the readout controllers.

5. Outlook and Conclusion

The original GRETINA project specified an array of 28 crystals grouped in 7 modules to give 1π solid angle coverage. Since project completion two additional quad modules have been procured and a third is in process. The ultimate goal is to construct a shell with 4π solid angle coverage (30 modules). A second area of development is in signal decomposition and tracking algorithms. While the position resolution of the primary (generally first) hit is high, $\sigma = 2$ mm, the position resolution of secondary interaction points is degraded and is subject to producing false artifacts. A detailed, source-based, detector scanning program will be carried out to examine the response of the detector in detail and compare against simulation.

GRETINA has demonstrated the viability of gamma-ray tracking in large volume, coaxial Ge detectors which will allow such spectrometers to be built to unprecedented efficiencies and therefore sensitivities. Furthermore, its precision event-by-event Doppler correction capability due to its position sensitivity allows the spectrometer to maintain high energy resolution for high velocity sources such as those produced in fragmentation reactions. These capabilities have extended the science reach of current facilities such as NSCL and will prove key in carrying out the proposed science program of FRIB [10].

6. Acknowledgements

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