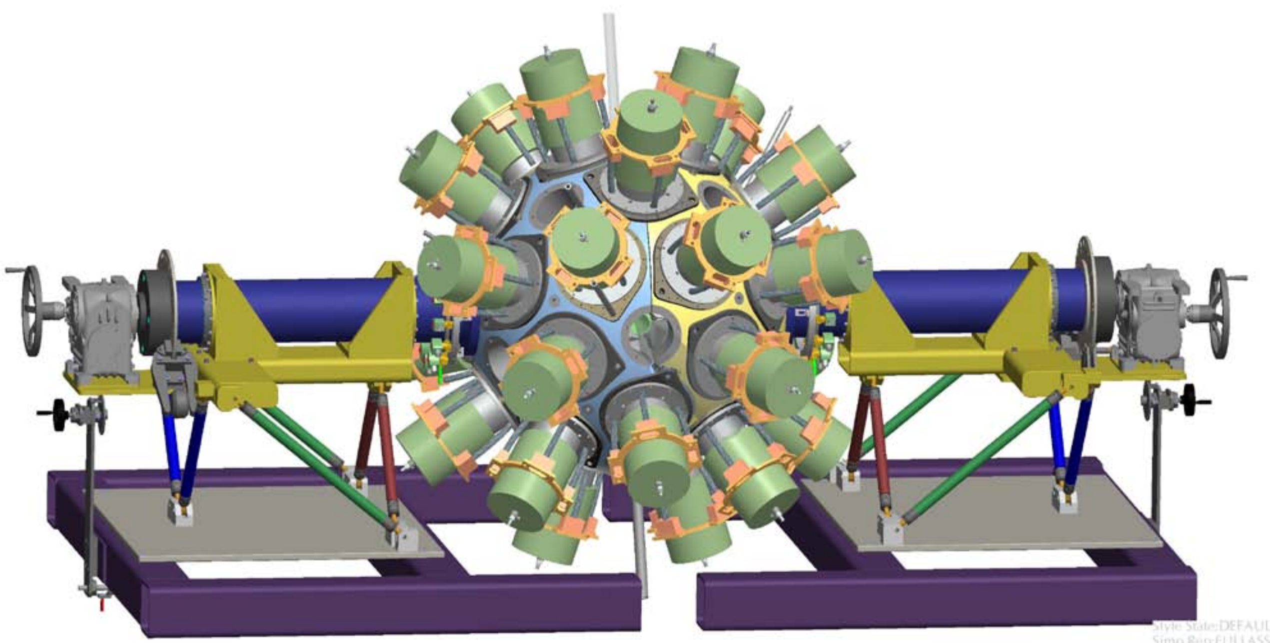
# THE FUTURE OF GAMMA-RAY SPECTROSCOPY:

# GRETA,

# THE GAMMA-RAY ENERGY TRACKING ARRAY

**Summary and Addendum to the White Paper submitted to the 2007 NSAC Long Range Plan**

**(The original GRETA White Paper is available at http://grfs1.lbl.gov/)**



**February 2010**

## 1. Summary

This is a time of great opportunity and excitement in nuclear physics. Current generation radioactive beam facilities in the US and abroad are beginning to offer tantalizing glimpses of new physics in the terra-incognita of rare isotopes with extreme proton to neutron ratios. Next generation facilities are being constructed or planned in Europe, Japan and the US. To fully exploit the opportunities of these facilities requires the development of a new technology, γ-ray tracking, and the construction of a highly efficient Ge detector array. Here we propose to capitalize and build on US leadership roles in Ge detector development by building the 4π Gamma-Ray Energy Tracking Array, GRETA. GRETA will exploit the technology, developed by the collaboration over the last ten years, for the 1π GRETINA array. A rapid and smooth transition from construction and commissioning of the GRETINA array to the full GRETA will obviously optimize the science output, but it is essential to maintain the highly specialized technical expertise in the community and to minimize overall cost.

GRETA has five main advantages over existing γ-ray detector arrays:

- High efficiency (50%Ω) – due to proper summing of scattered γ rays and no solid angle lost to suppressors.
- Good peak-to-background ratio (60%)- tracking also reject Compton events.
- Excellent Position resolution (2 mm) – determined by tracking.
- Polarization sensitivity – from the angular distribution of the 1st scattering.
- High counting rate (50 kHz) capability per crystal – due to the large number of segments.

For many experiments GRETA will provide orders of magnitude improvement in resolving power over present arrays, see below. This improvement will enable US scientists to address many key questions in nuclear structure, nuclear astrophysics and fundamental interactions. Construction of GRETA has been a recommendation of the community in the last two NSAC Long Range Plans and GRETA has been the most requested instrument for the future US radioactive beam facility, FRIB (Facility for Rare Isotope Beams), and will be vital to optimize the science output both near the Coulomb barrier and at fragmentation energies.

The ultimate goal of this project is the exploitation of the compelling science opportunities in nuclear structure, astrophysics and weak interactions enabled by the synchronized completion of the powerful 4π GRETA array combined with the unique capabilities of FRIB. However, we understand the total cost of this $53M project may not be easy to fund immediately but we point out that the project naturally lends itself to a staged increment of its resolving power as additional detectors are added. We hope that the DOE will develop a funding mechanism so that our goal of achieving a 4π GRETA array can be accomplished by 2020.

## 2. Continued US Leadership

The construction of the 4π Gamma-Ray Energy Tracking Array (GRETA) will ensure continued US leadership at the forefront of nuclear structure physics, nuclear astrophysics, fundamental symmetries and Ge detector technology far into the future. The construction and use of GRETA addresses the following key objectives of research opportunities at FRIB.

**Scientific Opportunities at FRIB:** The scientific opportunities presented by a 4π γ-ray tracking detector array cover a broad range of topics. Many key questions in nuclear structure, nuclear astrophysics, and weak interactions can only be studied using radioactive ion beams (RIB's) and γ-ray spectroscopy. GRETA will provide orders of magnitude improvements in resolving power over existing Ge arrays and thus will greatly extend the science reach of FRIB.

GRETA will be a major detector at FRIB. The need for a 4π γ-ray tracking detector for the research program at FRIB has been emphasized in a number of working group meetings and has been documented in several reports. GRETA is vital to optimize the science reach at all beam energies. For experiments using low energy reaccelerated beams, the excellent energy resolution, high efficiency and ability to handle high γ-ray multiplicities are important for the study of complex nuclear level structure of exotic nuclei produced with low cross sections. For the study of the most exotic nuclei near the drip lines, produced by in-beam fragmentation, the good position resolution is essential for reducing Doppler broadening and restoring the energy resolution. The 4π coverage is also important for nuclear astrophysics and fundamental symmetries experiments.

**γ-ray Detector Technology:** For many years the US has been the leader in the development of γ-ray detector systems, notably Gammasphere the world's most powerful and productive γ-ray spectrometer. More recently, we proposed and led a fruitful R/D effort to develop the tracking technique, and our new GRETINA array, will provide the first implementation of this remarkable technique. Currently, US research groups are in leading positions in many research programs using RIB facilities. A large US user community will lead experiments using GRETINA and the proposed GRETA array at these facilities bringing both detector expertise and scientific leadership. The timely construction of GRETA will maintain and expand the US leadership role in many research programs.

## 3. Outstanding Scientific Opportunities

The technology of "γ-ray tracking" can revolutionize γ-ray spectroscopy in a way that large arrays of γ detectors did more than a decade ago. During the last few years this technology has been shown to be feasible and GRETINA, a 1π tracking-detector, is under construction. However, the momentum in developing γ-ray tracking to its full potential must continue towards GRETA, a full 4π spectrometer that will enable us to fully exploit the science opportunities at FRIB and other facilities.

GRETA was first mentioned in the 1996 NSAC Long Range Plan and was recommended as one of the initiatives in both the subsequent 2002 and 2007 Long Range Plans,

2002 LRP: ***"The detection of γ-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science. The physics justification for a 4π tracking array is extremely compelling, spanning a wide range of fundamental questions in nuclear structure, nuclear astrophysics, and weak interactions. This new array would be a national resource that could be used at several existing stable and radioactive beam facilities, as well as at RIA."***

2007 LRP: ***"Thus the construction of GRETA should begin upon successful completion of GRETINA. This γ-ray energy tracking array will enable full exploitation of compelling science opportunities in nuclear structure, nuclear astrophysics, and weak interactions."***

As a first step towards GRETA, a physics-rich pilot program was devised to allow technical development to advance at full speed. This led to the proposal of GRETINA, a tracking-array with 25% coverage of solid angle. The GRETINA project is moving forward according to schedule with a start of operation date in 2011. A major community workshop entitled "Optimizing GRETINA Science: A workshop dedicated to planning the first rounds of operation" was held at the University of Richmond in October 2007. The physics opportunities at each laboratory were discussed in detail leading to unanimous agreement on a sequence order for the first rotation cycle. Detailed infrastructure issues at each of the laboratories were discussed. Additional community workshops and meetings are anticipated to continue to chart the course of the GRETINA science and the pathway toward GRETA.

For most experiments, **GRETA will improve the power of GRETINA by a factor of 10 – 100**, see below. Of course the gains made possible with GRETA will be specific to the type of physics experiment being performed. In the following Table and Figure, taken from the 2007 GRETA White Paper (available at http://grfs1.lbl.gov/), the improvement in resolving power or sensitivity of GRETA is calculated and compared to GRETINA, Gammasphere or SeGA for a variety of different experiments and reaction types.

| Experimental Technique or Reaction Type | $\langle E_\gamma \rangle$ MeV | v/c | $M_\gamma$ |
|---|---|---|---|
| **1. Stopped - Hi $E_\gamma$** | 5.0 | 0.0 | 4 |
| **2. Stopped - Low $E_\gamma$** | 1.5 | 0.0 | 4 |
| **3. Hi-spin - Normal Kinematics** | 1.0 | 0.04 | 20 |
| **4. Hi-spin - Inverse Kinematics** | 1.0 | 0.07 | 20 |
| **5. Coulex/Transfer** | 1.5 | 0.1 | 15 |
| **6. Fast Beam Fragmentation** | 1.5 | 0.5 | 6 |
| **7. Fast Beam Coulex - Hi $E_\gamma$** | 5.0 | 0.5 | 2 |
| **8. Fast Beam Coulex - Low $E_\gamma$** | 1.5 | 0.5 | 2 |

*Table showing the variety of different experimental techniques or reaction types along with characteristic γ-ray energies, recoil velocities and γ-ray multiplicities, see also the Figure below.*

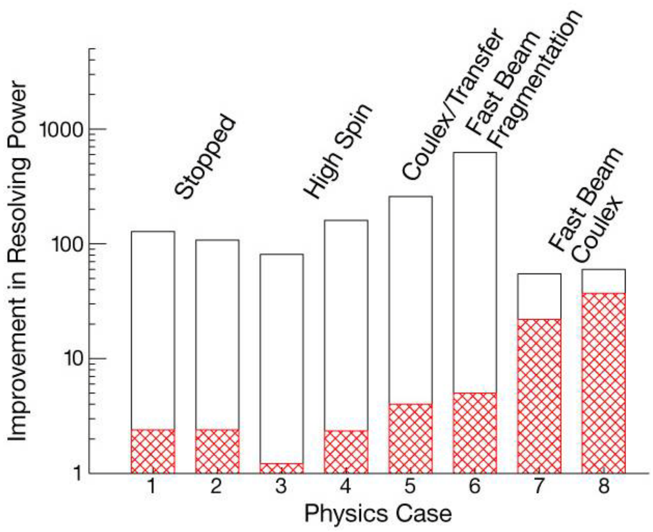



*Figure showing the improvement in resolving power or sensitivity of GRETA compared to Gammasphere or SeGA (whichever array was optimally suited) for a variety of different experimental cases given in the table above. The hatched bars correspond to the expected performance of GRETINA. The calculations do not consider any contributions from auxiliary detectors.*

Such gains in resolving power will greatly extend the reach of the physics making GRETA a critical component for the future FRIB facility. Indeed, it has been the most requested instrument in all community workshops devoted to proposed experiments there. Prior to FRIB, GRETA can also play an essential role in optimizing physics opportunities at other facilities. A flavor of the physics opportunities is presented below.

The key scientific questions guiding the research efforts in our community in recent years and towards the future, were outlined in the 2002 and 2007 Long Range Plans. They included,

2002 LRP:

- ***What are the limits of nuclear existence?***
- ***How do weak binding and extreme proton-to-neutron asymmetries affect nuclear properties?***
- ***How do the properties of nuclei evolve with changes in proton and neutron number, excitation energy, and angular momentum?***

2007 LRP:

- ***What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?***
- ***What is the origin of simple patterns in complex nuclei?***

It is clear that a $\gamma$-ray energy tracking detector will be needed to address these questions. The physics impact of GRETA will cover a broad range of topics and the device will be in high demand. The science program envisioned touches upon many core aspects of nuclear structure, nuclear astrophysics and fundamental symmetries that try to answer the key questions discussed in the recent LRPs. While GRETINA is being constructed, rapid progress toward the full $4\pi$ GRETA array is essential to fully capitalize on the science opportunities at existing and future RIB facilities, such as FRIB.

An in depth discussion of a number of specific scientific opportunities can be found in Section 3 of the 2007 GRETA White Paper (http://grfs1.lbl.gov/). These include:

- **How do extreme proton-to-neutron asymmetries affect nuclear properties, such as shell structure and collectivity?**
  For example,
  - Doubly magic nuclei far from stability.
  - The alteration of shell structure far from stability.
  - Symmetries and excitation modes in exotic nuclei.
  - The nucleus as an open quantum system.
- **What are the properties of nuclei at the limits of mass and charge?**
- **What are the properties of nuclei at the limits of angular momentum and excitation energy?**
- **Nuclear astrophysics, fundamental interactions and rare processes.**

## 4. Status of GRETINA and the extra scope needed for GRETA

The Department of Energy made the Critical Decision-0 (CD0) for GRETINA in August 2003 to construct a tracking detector covering one-fourth of the total solid angle. The construction (CD3) started in June 2005. Currently the project is proceeding according to schedule and is planned to be completed (CD4) in February 2011.

The scope of the work continuing towards GRETA consists of

- completing the construction of the GRETA γ-ray tracking detector array beyond the GRETINA MIE, and
- carrying out experiments at forefront RIB facilities using the GRETINA setup plus additional detector modules as they become available.

The detector manufacturer can deliver four detector modules per year. Thus, the optimum transition from GRETINA to GRETA allows the addition of 4 detector modules per year starting in 2013 with the completion of 23 modules in 2019. Hardware construction includes purchasing Ge detectors, and computing equipments, fabricating electronics modules, as well a new mechanical structure to support the 4π system. Since GRETA is essentially an extension of GRETINA, no major engineering design work is anticipated.

As mentioned earlier, a preliminary plan for experiments using GRETINA at US accelerator facilities, the 88-Inch Cyclotron, NSCL, ATLAS and HRIBF has been developed by the GRETINA Advisory Committee with input from the community. The first round of experiments is expected to begin in 2011 and be completed in 2013. During this period, as additional detectors become available, they could be incorporated into the GRETINA setup. Thus the project lends itself to a staged approach. Regular community workshops and physics meetings will be held during this period. Near the end of the first US GRETINA campaign we anticipate new siting decisions based on the status of the array and the physics opportunities available at the various international and US RIB facilities.

In the following, we will give a short summary of the technical status of GRETINA as of February 1, 2010 and the scope of GRETA. It will show that the technology of γ-ray tracking detector is on hand and we have the competency to carry out the construction of GRETA.

**Mechanical support**
The mechanical support consists of two quarterspheres for detector mounting and support structures which can translate 0.75 m transverse to the beamline to allow target chamber access and can rotate about a horizontal axis for horizontal detector removal or replacement.

The quarterspheres were delivered to LBNL in December 2008 and in February 2009 respectively. Both parts were accepted after detailed CMM measurement and analysis The Fabrication and procurement of support structure components was completed in April 2009. Both quarterspheres and the support structures have been installed on the existing “rail cars” in Bldg 88 Cave 4C.

GRETA will need a new detector support structure to accommodate 30 detector modules. The basic same design for GRETINA could be used. The liquid nitrogen filling system of GRETINA can be expanded to handle 30 detector modules.

**Detector**
The manufacture of two-dimensionally segmented coaxial germanium detectors which provide signals with sensitivity for locating interaction points in three dimensions is a critical technology developed for this project.

GRETINA consists of 7 detector modules each with 4 crystals. In addition, there will be 2 spare crystals available for quick replacement to minimize down time. All detectors were ordered and 6 modules were received. The acceptance test and characterization of the detector were being carried out at LBNL and NSCL. So far, three modules were accepted, one was returned for repair, and two were under test. The last module is expected in March 2010, and the two spare crystals will follow soon after.

GRETA will require an additional 23 quad-crystal modules of the same design to be combined with the 7 GRETINA modules to form the 4π coverage.

**Electronics**
The main electronics consist of digitizer and router/trigger modules, both sit in VME crates. The digitizer records signal at a sampling rate of 100 MHz and a resolution of 14 bits. The trigger and timing system

carries out complex trigger decisions and distribution clock and trigger information to the acquisition system. We have produced and tested all the modules (130 digitizer and 16 router/trigger), some of them are being used for detector testing and most of them were installed in the electronics shack, together with the VME crates and crate controllers, in preparation for detector assembly in CAVE4C of the 88-Inch Cyclotron. Low and high voltage power suppliers for the detectors are all in place also. Two types of interface modules for power and signal were in production.

GRETA will require an additional 368 digitizers and 15 trigger modules to instrument the remaining 23 detector modules. In addition, VME crates and low and high voltage power suppliers need to be purchased.

**Signal decomposition and tracking**

In order to perform γ-ray tracking, the positions and energies of the γ-ray interactions in the Ge must be accurately determined from the signal waveforms. The procedure must handle cases where two or more interactions occur within one of the detector segments. The GRETINA decomposition algorithm uses a two-step process which starts with an adaptive grid search for one and two interactions per segment followed by a sequential quadratic programming (non-linear least-squares) fit which allows multiple interactions in multiple segments within a crystal. We have shown experimentally that this algorithm can achieve an average position resolution of at least 2 mm.

It is important that the signal decomposition be performed in real time, so that large quantities of waveform data need not be stored. On the current generation of 2 GHz processors, the algorithm requires less than 16 ms of CPU core per crystal.

The tracking process uses the energies and positions of the interaction points produced by the signal decomposition to determine the scattering sequence for a particular γ-ray. Algorithms have been developed to track events based on Compton scattering, pair-production and photo electric interactions. Tracking efficiency achieved ranged from ~100% to 50% with γ-ray multiplicity changed from 1 to 25. The current tracking algorithm needs ~10% of the planned computing power.

The computing system for GRETINA will have about 70 computer nodes for decomposition and tracking. The procurement and installation of 30 nodes have been completed, as well as the LN control computers along with associated hardware. A total of 30 TB data storage units were installed and in use for detector characterization. Production version of the multithread decomposition program was updated and successful tested under cluster conditions with known data.

The computing needs for GRETA will be moderate**.** Given our experience with GRETINA and improvement in price/performance in computer clusters, we expected a modest cluster will be sufficient for GRETA's increased computer needs.

A summary of the hardware deliverables of the various GRETA subsystems is presented in the following. Electronics equipment will require 10% spares.

| **Item** | **Quantity** |
|---|---|
| **Mechanical System** | |
| Support structure | 1 |
| Liquid nitrogen filling system | 1 |
| Target chamber | 1 |
| **Detector Modules** | |
| Four-crystal modules | 23 |
| **Electronics** | |
| These are part of the detector module | |
| Digitizer Modules | 3680 channels |
| Trigger and Timing System | 1 (15 modules) |
| Power Supplies | 92 channels |
| Cables | Set |
| **Computing system** | |
| Data storage system | 1 |
| Network switching system | 1 |
| Data Processing Farm | 1 |

**Auxiliary Detectors**

For GRETINA a number of auxiliary detectors are being developed and additional ones are being considered at the present time. They will play an important role. These systems will also be used to great effect with GRETA too. A major advantage of GRETINA (and GRETA) is the energy resolution for in-beam studies. This results from the considerably smaller opening angle (~2$^o$ in $\theta$ and $\phi$ compared to $\Delta\theta=7^o$ and $\Delta\phi=36^o$ for Gammasphere). But in order to make good use of this angular resolution for Doppler corrections the angle of the recoiling nucleus in normal kinematics reactions must now also be determined with comparable angular resolution. In addition, for reverse-kinematics transfer reactions, high angular resolution for the detection of the target-like fragments will be needed to provide good angular distributions. Thus, a new generation of auxiliary detectors is necessary with higher segmentation (angular resolution), and for some applications with higher counting rate capability, than any of the existing devices. Some of the devices currently under development or being considered include:

**MicroWall.** This is a 256-element CsI(Tl)-detector system equipped with 4 multi-anode (8x8-pixel) photomultipliers presently under construction. With position tracking, it will provide good light-ion ($\alpha$ and p) pulse-shape discrimination (PSD) and angular resolution of 1.0$^o$ in $\theta$ and 1.0-2.5$^o$ in $\phi$, with a $\theta_{max}$ of 58$^o$. When augmented with thin fast-plastic scintillators (FPS) in a phoswich arrangement (FPS, CsI)**,** it will provide *Z* resolution for light target-like fragments (Z = 6-12). Its segmentation is the same with that of SuperHERCULES. It will have a Microchip PSD readout system in VME protocol. Further expansion of this to a 2$\pi$ device is possible.

**SuperHERCULES.** This is a highly segmented evaporation residue detection system. It will use very thin fast-plastic detectors coupled to 4 multi-anode phototubes (8x8 pixels each) will have the same angular resolution with that of the **MicroWall,** and will share its readout system.

**Nanoball.** This is a new highly segmented light charged particle system with 4$\pi$solid angle coverage. This detector will use CsI(Tl) detectors with mini-photomultiplier tubes and digital readout. It will perform at higher rates and with better PSD resolution than the current Microball.

**CHICO 2 and SuperCHICO:** CHICO 2 is an inexpensive upgrade to the current CHICO detector which replaces the current cathode to improve $\varphi$ resolution from 9º to 1º. CHICO 2 is then well suited for use with GRETINA. The next stage is SuperCHICO which will be a smaller 4$\pi$ position-sensitive heavy-ion detector with an angular resolution of 1º × 1º for $\theta$ and $\phi$ respectively and specially designed for use with GRETA. CHICO2 and SUPERCHICO are required for the kinematic reconstruction of transfer, Coulomb excitation, and fission reactions and will lead to an improvement of a factor of 3 in $\gamma$-ray energy resolution.

**Plunger:** While several “plunger” devices exist for measuring lifetimes using the recoil distance method with present large $\gamma$-ray arrays it will be advantageous to either update these devices or develop a new system with the goal of having retarding-foil capability. The plunger should be optimized for use with GRETINA (and GRETA) including the above auxiliary detectors in a combined arrangement.

**Other Auxiliary Systems:** Additional innovative auxiliary systems are welcome and will receive due consideration.

# 5. Schedule and Cost for GRETA

In this section, we give a high level summary of the cost and schedule of GRETA. The estimated cost to complete GRETA, beyond the cost of GRETINA, is $53.25M including escalation and contingency. The schedule is determined by the delivery of the germanium detector modules. We used the same delivery rate, 4 modules per year, as the GRETINA modules.

**Schedule**

The figure on the following page shows the schedule of the high level WBS elements of GRETA and the table below shows the date of the Critical Decision milestones.

| Critical Decision | Date in FY quarter |
|---|---|
| CD-0 | Q1 FY12 |
| CD-1 | Q4 FY12 |
| CD-2 | A: Q4 FY12; B: Q4 FY13 |
| CD-3 | A: Q4 FY12; B: Q4 FY13 |
| CD-4 | Q2 FY20 |

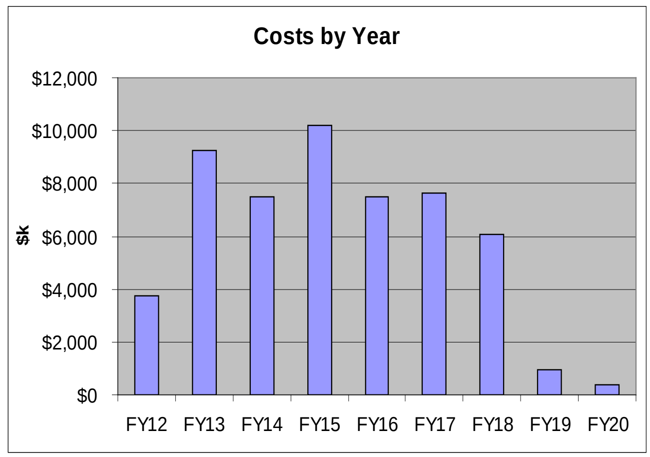
*Critical Decision Milestones*

The preparations for CD1/2A/3A starts in Q1-FY12 for the long-lead time procurement of the first six detector modules. The first order for detector modules is issued soon after CD2A/3A. A new batch of electronics and computing systems are also procured and assembled to instrument these detector modules delivered for the long lead procurement. The design of the 30 module detector support structure then starts. In parallel, preparations to place the contract for the remaining 17 detector modules will be underway. Production starts after CD2B/3B in Q4-FY13.

We use the same approach used for GRETINA: the detectors are procured one year in advance, and they start being delivered one year after the order. We assume that the vendor will be able to deliver detectors at the same rate they are delivering now: four modules per year. All detector modules are received by FY19, and the remaining of FY19 and FY20 are used to assemble all the systems and to perform the qualification tests. Project Management and Environment and Safety are ongoing activities during the duration of the project.

**Cost**

Based on the schedule discussed above, we developed a funding profile in actual year dollars, as shown below. The table on the following page shows the breakdown cost summary for the GRETA in actual year dollars. All estimates have been inflated using escalation rates of 3% per year for material and labor assuming a funding profile that covers FY12 to FY20. This cost takes into account that GRETINA will be completed and its electronics, computing system and detector modules will be available to complete this 4π GRETA detector.




*The funding profile for GRETA.*

This cost estimate is based on the GRETINA cost estimate. It takes into account that most of the design is done during the GRETINA project, and that GRETA will concentrate mainly in the procurement of more detector modules, and hardware for the Electronics and Computing System, as well as the testing and assembly into a system. However, the Mechanical Systems will require a new design of the hemispheres, to accommodate the additional 23 detector modules (a total of 30 modules).

The cost of the materials was projected to larger quantities (which includes savings). The estimated unit price estimate of the detector modules is €860k per module (projected price in FY12) and an exchange rate Euro/Dollar of 1.45. In the current estimate, we applied escalation to this price. Although it is likely that we could obtain a fixed price contract in Euros, as we were able to do for GRETINA detectors or a price savings

Contingency allocation reflects the risk reduction due to knowledge and experience acquired with GRETI-

NA. We have set the detector module contingency at 15%, which takes into account the risk of Dollar/Euro fluctuations in the exchange rate.

This cost estimate also assumes approximately the same level of redirected effort from Argonne National Laboratory, Lawrence Berkeley National Laboratory, the National Superconducting Cyclotron Laboratory at Michigan State University, Oak Ridge National Laboratory, and Washington University in St. Louis.

## The Management Structure of GRETINA/GRETA

**1. Management Advisory Committee**

- James Symons (LBNL)
- Jim Beene (ORNL)
- Robert Janssens (ANL)
- Konrad Gelbke (MSU)

**2. Contractor Project Manager**

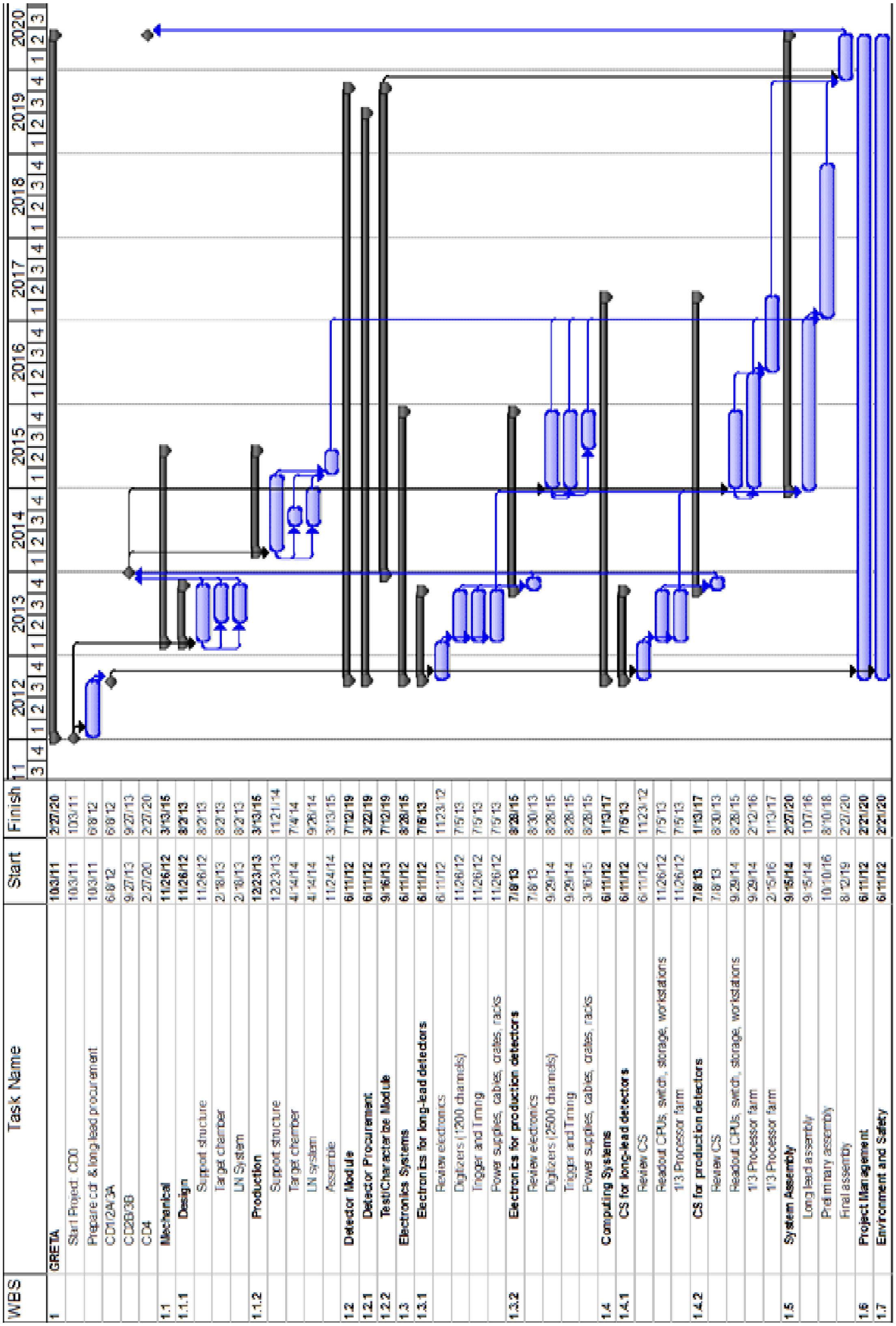
- I-Yang Lee (LBNL)

**3. GRETINA Advisory Committee**

- Con Beausang (Univ. of Richmond)
- Doug Cline (Univ. Of Rochester)
- Kim Lister (ANL)
- Augusto Macchiavelli (LBNL)
- David Radford, **Chair** (ORNL)
- Mark Riley (FSU)
- Demetrios Sarantites (Washington Univ.)
- Kai Vetter (LLNL)
- Dirk Weisshaar (MSU)

**4. Working Groups and Chairs**

- **Physics**: Mark Riley (FSU)
- **Auxiliary Detectors**: Demetrios Sarantites (Washington Univ.)
- **Electronics**: David Radford (ORNL)
- **Software**: Mario Cromaz (LBNL)
- **Detector Development**: Augusto Macchiavelli (LBNL)




The detailed schedule for GRETA

| WBS | Description | Cost ($k) | Cont | Cont ($k) | Total ($k) |
|---|---|---|---|---|---|
| **1** | **GRETA** | **$45,265** | **18%** | **$7,984** | **$53,249** |
| | Prepare CDR and Long Lead Procurement | $340 | 25% | $85 | $425 |
| **1.1** | **Mechanical** | **$1,190** | **25%** | **$298** | **$1,488** |
| 1.1.1 | Design | $410 | | | |
| | Support structure | $350 | | | |
| | Target chamber | $0 | | | |
| | LN System | $60 | | | |
| 1.1.2 | Production | $780 | | | |
| | Support structure | $540 | | | |
| | Target chamber | $60 | | | |
| | LN system | $120 | | | |
| | Assemble | $60 | | | |
| **1.2** | **Detector** | **$34,810** | **15%** | **$5,371** | **$40,181** |
| 1.2.1 | Detector Procurement | $33,320 | 15% | $4,998 | $38,318 |
| 1.2.2 | Test/Characterize Module | $1,490 | 25% | $373 | $1,863 |
| **1.3** | **Electronics Systems** | **$3,450** | **25%** | **$863** | **$4,313** |
| 1.3.1 | Electronics for long-lead detectors | $1,195 | | | |
| | Review electronics | $210 | | | |
| | Digitizers (1200 channels) | $520 | | | |
| | Trigger and Timing | $115 | | | |
| | Power supplies, cables, crates, racks | $350 | | | |
| 1.3.2 | Electronics for production detectors | $2,255 | | | |
| | Review electronics | $290 | | | |
| | Digitizers (2500 channels) | $1,045 | | | |
| | Trigger and Timing | $245 | | | |
| | Power supplies, cables, crates, racks | $675 | | | |
| **1.4** | **Computing Systems** | **$1,530** | **25%** | **$383** | **$1,913** |
| 1.4.1 | CS for long-lead detectors | $575 | | | |
| | Review CS | $170 | | | |
| | Readout CPUs, switch, storage, workstations | $175 | | | |
| | 1/3 Processor farm | $230 | | | |
| 1.4.2 | CS for production detectors | $955 | | | |
| | Review CS | $175 | | | |
| | Readout CPUs, switch, storage, workstations | $220 | | | |
| | 1/3 Processor farm | $310 | | | |
| | 1/3 Processor farm | $250 | | | |
| **1.5** | **System Assembly** | **$525** | **25%** | **$131** | **$656** |
| | Long lead assembly | $185 | | | |
| | Preliminary assembly | $200 | | | |
| | Final assembly | $140 | | | |
| **1.6** | **Project Management** | **$3,165** | **25%** | **$791** | **$3,956** |
| **1.7** | **Environment and Safety** | **$255** | **25%** | **$64** | **$319** |

Table: The Cost of GRETA