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Mechanical design of a next generation γ-ray spectrometer: Gamma-Ray Energy Tracking Array (GRETA)

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Abstract

The Gamma-Ray Energy Tracking Array (GRETA), a next generation γ-ray spectrometer, will be a key experimental instrument at the Facility for Rare Isotope Beams (FRIB) at Michigan State University to support nuclear structure and nuclear astrophysics science programs. GRETA will provide a 4π sr angular coverage of the target region with high-purity germanium (HPGe) detectors capable of reconstructing the energy and three-dimensional position of γ-ray interactions using detectors housed in 30 Quad Detector Modules (QDM). This paper will discuss the mechanical construction of GRETA that consists of two each of: linear translation system to provide access to the target chamber, a support frame with integrated ±180 degree of rotation to aid in the insertion and removal of QDMs, liquid nitrogen and glycol cooling systems to cool the QDM and associated electronics, and a hemisphere that the QDMs are mounted to.

Keywords: γ-ray Spectrometer; γ-ray Tracking; Mechanical Design

1. Introduction

The Gamma-Ray Energy Tracking Array (GRETA) is a next generation γ-ray spectrometer that is based on the successes of previous arrays Gammasphere [1] and GRETINA [2] to support nuclear structure and nuclear astrophysics scientific programs at U.S. accelerator facilities. GRETA will be primarly operated at the Facility for Rare Isotope Beams (FRIB) [3] at Michigan State University. GRETA's objective is to provide a high-efficiency detection, with 4π sr coverage, of the γ-rays emitted in nuclear reactions, and to reconstruct the energy and position of the γ-ray interactions. This also requires accurate knowledge of the location of each QDM in space, and stable operation of all detector units. Based on this, the high level requirements of GRETA mechanical system are shown in Table 1. In addition to these requirements, the GRETA mechanical system requires the array to be operational at different locations at FRIB, and for scientific compaigns at Argonne National Laboratory (ANL) [4]. This requires the mechanical system to be designed to be moveable to minimize the loss of experimental time when the GRETA system has to be relocated.

Table 1: High level GRETA system requirements.

Requirement	Value
Number of QDMs support	30 (15 per hemisphere)
Position of QDM	≤ 0.4 mm (x, y, z)
Linear translation	≥ 500 mm
Rotation	±180 degree
LN temperature at QDM dewar	≤ 80 K
Temperature stability of QDM pre-amplifier	± 2 ºC
Temperature stability of QDM external electronics (digitizer)	± 2 ºC

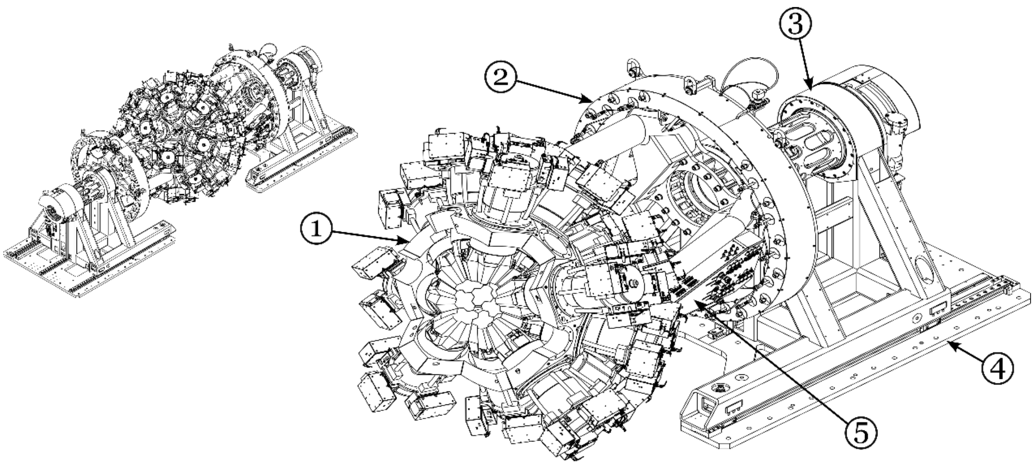

Figure 1. GRETA assembly. Upper left corner shows the complete assembly with both hemispheres in the closed position. 1. Hemisphere with 15 QDMs mounted. 2. Liquid Nitrogen manifold. 3. Support structure with rotary drive. 4. Baseplate with linear drive. 5. Digital IO and glycol cooling enclosure.

2. Mechanical Design of GRETA

The mechanical system of GRETA is shown Figure 1, and is divided into two nearly identical hemispheres to position a total of 30 QDMs (15 for each hemisphere) to provide a 4π sr coverage around a central target position.
GRETA consists of: hemisphere that the QDMs are mounted to, a support frame with integrated ±180 degree of rotation to aid in the insertion and removal of QDMs, base plate with integreged 500 mm linear translation to provide access to the target chamber (center of hemisphere), liquid nitrogen and glycol cooling systems to cool the QDMs and associated electronics.

2.1. Quad Detector Modules: Mechanical Interface

The design of the Quad Detector Modules (QDM), see Figure 2, is described in detail by Descovich, et.al. [5]. Each QDM upon receipt is measured on a coordinate measuring machine (CMM) to determine the orientation and location of the detector endcap such that an interface plate is machined to remove tip-tilt and axial offset of the QDM in order to ensure QDMs are interchangeable to any hole location on the hemisphere. The radial position and clocking of the QDM is controlled with a hole and slot that interfaces to two dowel pins that are pressed fitted into the hemispheres and provides an estimated position error of less than ±50 μm to the nominal QDM position.

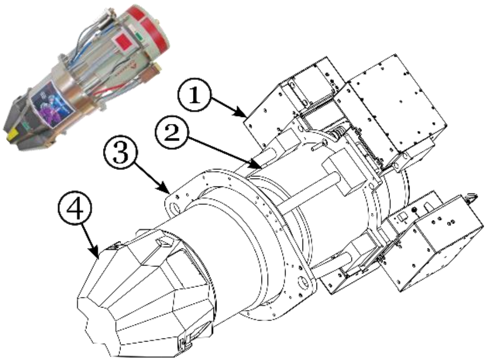

Figure 2. Quad Detector Module (approx. 870 mm long, 55 kg). 1. External electronic boxes (total of four). 2. LN dewar. 3. Interface plate to hemisphere. 4. Germanium crystal cap. Top left is a picture of QDM without the external electronics.

2.2. Hemisphere Design

The hemisphere is depicted in Figure 3. Each hemisphere is constructed of three aluminum sections to support a total of 15 QDMs. These aluminum sections are referred to as: main body, doublet, and triplet sections. The doublet (two QDM ports) and triplet (three QDM ports) sections are mounted to the main body and located with the use of locating pins achieving a repeatability of < 20 μm. Depending on the scientific experiment the doublet and triplet sections can be removed from the main body to provide more access to the center of the hemisphere. In addition to the QDM interfaces the hemispheres provide two interfaces to connect the facility beam pipes (delivers the heavy ion beam into and out of the experimental target chamber) and four smaller ports, (on the main body section), used for auxiliary equipment. The main body of the hemisphere also has three integrated laser triangulation sensors (one hemisphere with the sensor and the other with the mirror target) and limit switches to avoid collision of the two hemispheres when the system is being closed (see the next sections for description of the support structure and linear motion system).

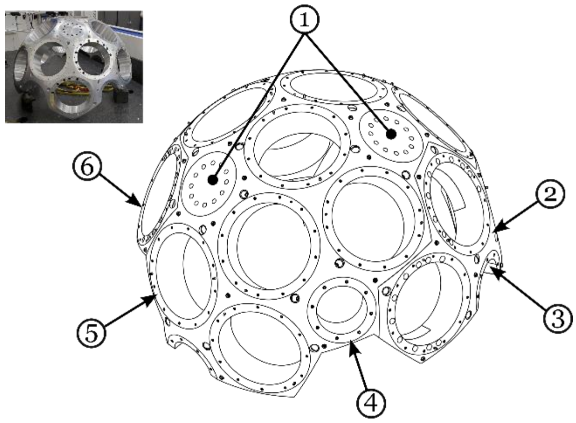

Figure 3. Assembled hemisphere (outer radius 638 mm, 280 kg). 1. Hemisphere to support structure interface. 2. Removal triplet section. 3. Interface to beam pipe (total of two). 4. Interface for auxiliary equipment (total of four). 5. QDM ports (total of 15). 6. Removal doublet section.

The location of the QDM is determined by the port locations which were fabricated to achieve a position error of less than ±190 μm. This error is in addition to the position error achieved by the QDM interface plate.

2.3. Support Structure

The support structure is shown in Figure 4 and is constructed primarly out of steel with the exception of the arms (stainless steel) which provide direct interface to the hemisphere and to the liquid nitrogen (LN) manifold. The support structure is designed to accommodate the installation and removal of the QDMs and allow access to the center of the hemisphere where the target chamber would be located. The support structure provides a rotation of ±180 degree to facilitate the insertion/removal of the QDMs in a horizontal orientation with the use of a crane and dedicated lift fixture. A linear drive system provides 500 mm of travel for the entire support structure along the rotation axis, which is defined perpendicular to the direction of the facility beam pipe. The overall performance of the linear and rotation system is not critical as the primary function is accessibility with the only requirement is to position repeatability of the hemisphere at the closed position to be within ±100 μm. To remove assembly errors and alignment errors, three of the total of six vertical support struts are used. Each strut has a primary motion in the vertical direction (10 mm) but also have integrated horizontal motion (10 mm, perpendicular to the rotation axis of the support structure) providing a total of five degrees-of-freedom. A laser tracker will be used to measure the location of the mounted hemisphere with a total of 35 permanently mounted nests. These nest provide an interface for the spherical mounted retroreflector (SMR) that act as the targets for the laser tracker. By implementing this alignment scheme it is estimated that the alignment of the hemispheres relative to each other will be better than ± 200 μm.

The primary challenge with the support frame is the support of a relatively large cantilevered mass of the hemisphere, QDMs, cables and hoses. The estimated mass the support frame supports is 1,150 kg (including 15 QDMs). Using finite element analysis (FEA) it was determined that the support frame has a first natural frequency of 14 Hz and maximum deflection of 950 mm at maximum loading conditions. The other extreme scenario was also considered with a minimum loading condition of approximately 350 kg resulting in a increase in the first natural frequency to 21 Hz and decrease in deflection to 440 μm. To minimize the impact of the different loading conditions for

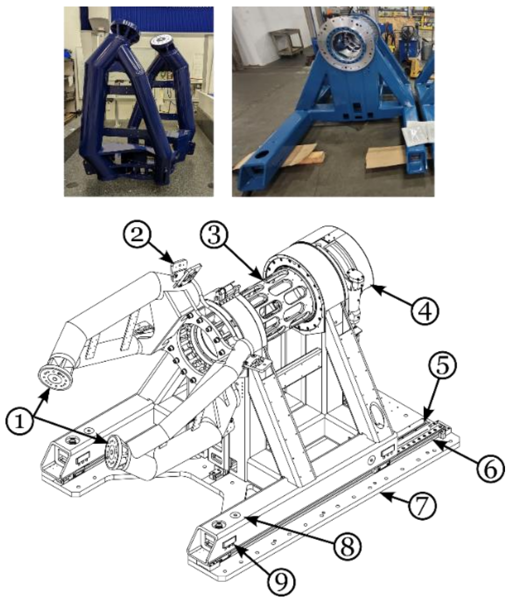

Figure 4. Support structure assembly. 1. Support arm with interface to hemisphere. 2. Interface tabs for LN manifold. 3. Rotation shaft. 4. Rotary drive with absolute encoder. 5. Absolute linear encoder. 6. Linear guide rails (total of three). 7. Support structure baseplate. 8. Support structure lifting interface (total of four). 9. Vertical support and manual alignment adjustor (total of six). Top left and right shows the manufacture support arm and main support structure, respectively.

different experiments the support structure will be aligned to its approximate mid-deflection value such that an observed deflection change of ±260 μm is achieved between minimum and maximum load. It should be noted that if in the event the deflections are larger than anticipated during the different loading conditions, a fall back solution would be to replace the removed QDM with a mass equivalent metallic cylinder such that the loading conditions always remain the same during the experiments.

To accommodate the relocation of the GRETA system from different sites within FRIB with minimal time loss, the GRETA mechanical system would be moved as a complete assembled hemisphere system (QDMs would be removed) as shown in Figure 1. The GRETA structure would be lifted by the four lifting points identified in Figure 4. This keeps the reassembly time of the entire GRETA system to a minimum and thus maximizes experimental time. It should be noted that the GRETA mechanical team is currently designing the cable and hose infrastructure such that all the cables run through the center of shaft and along the support arm to the QDMs. To avoid rerouting the cables during relocation, a patch panel will be implemented at the end of the support structure (opposite side of the hemisphere) such that the cables running to the electronics racks can be disconnected.

2.4. Quad Detector Module Cooling

There are a total of three cooling systems that have been integrated into GRETA. The first two are providing internal cooling of the QDM's Germanium (Ge) crystals and integrated pre-amplifiers. The third system provides cooling for the external QDM electronics.

2.4.1. QDM Ge Crystal Cooling

The cooling of the Ge crystals requires the LN temperature to be delivered to the QDM dewar to be less than 80 K to achieve a Ge crystal temperature of less than 100 K. In order to achieve this, liquid nitrogen (LN) is delivered to the LN manifold through the shaft of the support frame. The LN manifold, see Figure 5, disperses the LN to the 15 individual QDM dewars (3.5 l capacity) approximately every 8 h at a rate of 1.5 l min^{-1}. The flow of LN for each QDM is individually controlled through a solenoid at the exit of the LN manifold supply line, while a flow sensor at the entrance of the return line monitors the flow rate as the LN is returned from a full QDM.

To keep ice from building up on the LN manifold the 'warm' LN flows thru the return line into the exhaust line. While flowing through the exhaust line the LN is further warmed up to be converted into nitrogen gas and allowed to exhaust into the inner portions of the LN manifold, thus avoiding the formation of ice that typically occurs in cryogenic systems. The nitrogen gas is then allow to escape the LN manifold through gaps of the sheet metal cover.

2.4.2. QDM Pre-Amplifier Cooling

The QDM pre-amplifier cooling is accomplished with a closed loop glycol system with a required total cooling capacity for each hemisphere of approximately 1.125 kW (75W for each QDM) with a temperature stability of ±2 ^{o}C. This is achieved using a re-circulating glycol chiller with a cooling capacity of 1.75 kW and temperature stability of ±0.1 ^{o}C. The glycol fluid is connected to a manifold on the support structure that disperses the coolant into 15 branchlines that are routed to each QDM. The supply glycol manifold has a integrated flow switch for each branchline that allows the coolant to be shut off when a particular QDM has been removed, while remaining fully functional for the remainder of the installed QDMs. The return branchline is a copy of the supply line with the exception of the omission of the flow switch.

2.4.3. QDM External Electronics Cooling

The QDM external electronics cooling is also accomplished very similarly to the QDM pre-amplifier system. The only difference between the two is the required cooling capacity per

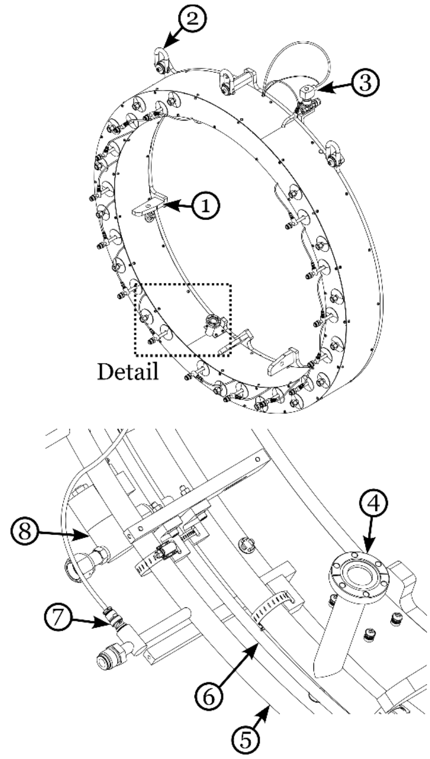

Figure 5. LN manifold (1651 mm outer diameter, 105 kg). The bottom image shows the interior details of the LN manifold with covers removed. 1. Mounting interface to support structure. 2. Lifting points (total of three). 3. Exhaust solenoid of the LN supply line. 4. LN supply flange. 5. LN return line. 6. Exhaust line. 7. Return line flow sensor coming from QDM (total 15). 8. Supply line solenoid flowing to QDM (total 15).

hemisphere being higher, at 3 kW while maintaining the same temperature stability of ±2 °C. The higher cooling capacity requires a second independently controlled re-circulating glycol chiller with a cooling capacity of 3.2 kW with a temperature stability of ±0.1 °C. The glycol cooling is supplied to a single QDM external electronics box and then connected in serial to the remaining three external electronics boxes. Connecting the external electronics boxes in serial significantly reduced the complexity of the system while maintaining the required electronics performance.

3. Mechanical Controls System

The mechanical controls system not only provides functional control of the above discussed sub-systems, but also provides personnel and equipment safety. The controls systems can be divided into three primary areas: motion control, LN supply system control, and glycol cooling control. Each of the controls systems have integrated safety features to ensure safe operations.

3.1. Motion Controls

The motion controls systems controls the linear and rotary motions of both hemispheres. The motion system is configured such that the linear motion can only be performed when the rotary system is at it's home position. The linear motion control system is closed loop control based on absolute linear encoders, with a maximum translational speed of 12.5 mm s^{-1}. However, once the laser triangulation sensors integrated into the hemisphere is within operating range, approximately 20 mm from the closed position, the motion controls system is switched over to the laser triangulation sensors such that collision between the two hemispheres is avoided and is decoupled from installation tolerances. Without the switching between the linear encoder and laser triangulation sensor the GRETA system installation requirements would be significantly more demanding to avoid a collision between the hemispheres and or QDMs.

The rotary motion control portion operates very similar to the linear portion in the sense that it can only operated when the hemisphere is fully retracted from the closed position. This occurs at an approximate reading of the linear encoder of 500 mm from the closed position. The rotary motion control system is closed loop controlled based on the rotary absolute encoder with a maximum rotation speed of 0.08 rad s^{-1}.

Both the linear and rotary motion controls systems have hardstops and limit switches integrated to protect the GRETA system from damage. For the linear motion controls there are three limit switches integrated into the hemispheres. The hemispheres also have the hardstop integrated into them for the closed position such that a minimum gap of approximately 0.3 mm is achieved, thus avoiding collision of any QDMs. The linear motion system does not have any limit switches at the fully retracted location as the system is robustly designed to survive a collision event. The rotary drive system has two limit switches and a hardstop primarly to protect the cabling that is run through the shaft of the support frame from being damaged. Both the linear and rotary drive currents are monitored such that if the current increases due to a collision, or no change of an encoder reading is observed that the system goes into a fault mode switching power off to the controls rack.

The motion controls system uses a touchscreen pendant as an interface for the operator. From the pendant the operator can control both hemispheres independently, but only operating one hemisphere at a time. Multiple E-stop switches are implemented into the system in the event an operator or third party needs to shut down the system.

3.2. LN Supply System Controls

The LN supply system controls provides the ability to automate or manually fill the QDM LN dewars. For this there are two main controllers. One controller, located on the experimental floor, monitors the fill level, pressure and flow rates of the external supply dewars and a second local controller located on the support structure (labled DIO controls in Figure 1) monitors the QDM's temperature, and flow rate. The system also has integrated E-stops, and interlocks to ensure safe operation of the LN system.

3.3. Glycol Cooling Controls

Finally, the glycol cooling controls systems is used to control the two chillers per hemisphere (a chiller for the QDM pre-amplifiers and a second for the external electronics). The control system provides automated control of the cooling system to ensure that appropriate flow rates, pressures, and temperatures are achieved. This is also performed similar to the LN supply cooling system with the use of a controller located on the experimental floor and a second on the support structure. For safety integrated E-stops, and interlocks have been implemented.

4. Summary and Future Work

The GRETA mechanical system was designed to accommodate a total of 30 quad detectors to meet the requirements highlighted in Table 1. Fabrication of the hemispheres, A-frames, and support arms have been completed and verified to conform to the required manufacturing tolerances.

Currently the design of the cable and hose routing through the support frame shaft to the QDMs, and DIO boxes are being completed. In addition to completing the remaining design tasks the procurement of the LN manifold, and smaller components of the linear and rotary drives is progressing well.

The goal is to start assembly of the mechanical system by the end of the second quarter of 2023 which is contingent of ontime delivery of the mechanical sub-systems currently being fabricated.

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References

[1] Lee I-Y, 1990, The Gammasphere, *Nuclear Physics A*, **520**, c641 – c655.

[2] Paschalis S, et al., 2013, The performance of the Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **709** (1), 44-55, ISSN 0168-9002.

[3] Facility for Rare Isotope Beams (FRIB) at Michigan State University, www.frib.msu.edu

[4] Argonne National Laboratory (ANL), www.anl.gov

[5] Descovich M, et.al., 2005, In-beam measurement of the position resolution of a highly segmented coaxial germanium detector, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **553** (3), 535 – 542, ISSN 0168-9002.