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Verification of a Next Generation γ-Ray Spectrometer Mechanical Requirements: Gamma-Ray Energy Tracking Array

Eric S. Buice, Collin Anderson, Heather L. Crawford, and Paul Fallon

Lawrence Berkeley National Laboratory, Berkeley, California 94720 USA

esbuice@lbl.gov

Abstract
The Gamma-Ray Energy Tracking Array (GRETA) is a next-generation γ-ray spectrometer designed to support nuclear structure and nuclear astrophysics research. Initially installed at Lawrence Berkeley National Laboratory (LBNL), GRETA will provide 4π sr angular coverage of the target region with high-purity germanium (HPGe) crystals capable of reconstructing the energy and three-dimensional position of γ-ray interactions. This paper presents the mechanical verification results of GRETA. These results pave the way for the full implementation of GRETA at the Facility for Rare Isotope Beams (FRIB) at Michigan State University.

Keywords: γ-ray spectrometer, requirements verification, integrated testing

1. Introduction

The Gamma-Ray Energy Tracking Array (GRETA) is a next-generation γ-ray spectrometer that builds on the prior arrays Gammasphere [1] and GRETINA [2] to guide its development in support of nuclear-structure and nuclear-astrophysics programs at the Facility for Rare Isotope Beams (FRIB) at Michigan State University. GRETA aims to provide high-efficiency detection with 4π sr coverage in nuclear reactions and to reconstruct the energy and position of γ-ray interactions. To support these programs, GRETA must provide accurate knowledge of the location of each Quad Detector Module (QDM) in 3D space and ensure stable operation of all detector units. Accordingly, the high-level mechanical requirements of GRETA are listed in Table 1. The mechanical design of GRETA was described by Buice et al. [4]. A brief introduction to the mechanical design is provided here. The remainder of this paper focuses on the detailed verification of QDM positions performed at Lawrence Berkeley National Laboratory (LBNL) prior to shipment to FRIB.

Table 1. High-level GRETA system requirements.

Requirement	Value
Number of QDMs support	30 (15 per hemisphere)
Position of QDM	≤ 0.40 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 °C
Temperature stability of QDM external electronics (digitizer)	± 2 °C

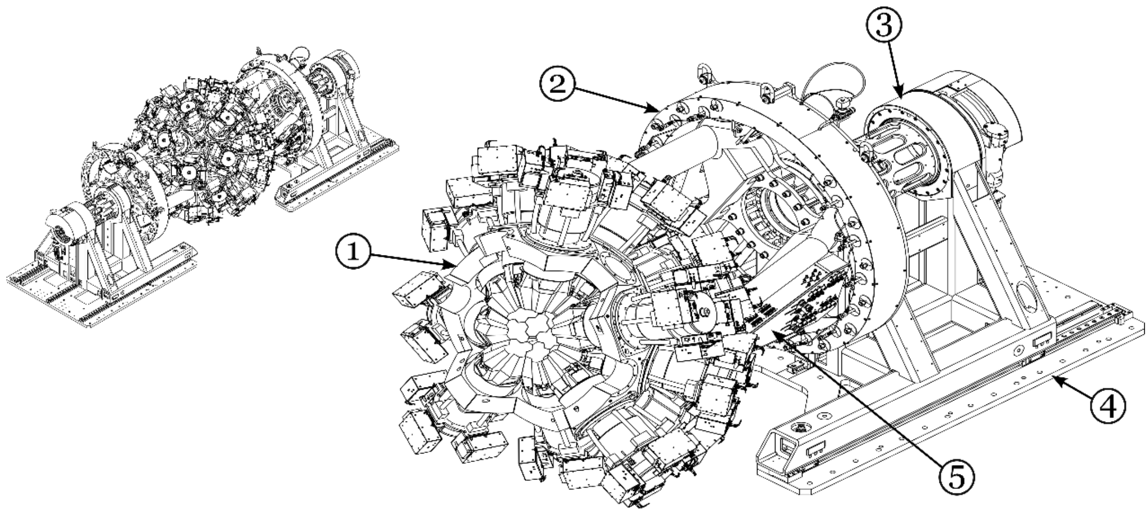

Figure 1. GRETA Assembly. Upper left corner shows the complete assembly with both hemispheres in the closed position. 1. Hemisphere with 15 QDMs installed. 2. Liquid Nitrogen. 3. Support structure with rotary drive. 4. Baseplate with linear drive. 5. Digital IO and glycol cooling enclosure.

2. Mechanical Design Overview

The GRETA mechanical system is illustrated in Figure 1. It is divided into two nearly identical hemispheres that position 30 Quad Detector Modules (QDMs)—15 per hemisphere—to provide 4π sr coverage about a central target position. GRETA comprises four functional elements: (i) a hemispherical mounting structure for the QDMs; (ii) a support frame with ±180° rotation to facilitate QDM insertion and removal; (iii) a base plate with a 500 mm linear translation stage to access the target chamber at the centre of the hemisphere; and (iv) liquid nitrogen and glycol cooling systems to condition the QDMs and associated electronics. Functional elements (i)–(iii) control the final QDM positions and must satisfy the Table 1 requirement of ≤ 0.40 mm in position error. The final QDM positions are critical only in the closed position; consequently, linear and rotational errors are not a primary concern, reducing the apparent complexity of the mechanical design.

2.1 Breakdown of QDM Position Requirement

The QDM position requirement from Table 1 can be further disseminated and can be viewed in Table 2. The first three items pertain to the hemisphere port locations, while the last two pertain to the support frame.

Table 2. Dissemination of the position of the QDM requirement from Table 1.

Requirement	Estimated Error
QDM Port Location (Hemisphere)	± 0.19 mm
QDM Interface Plate Pin	± 0.18 mm
QDM Triplet and Doublet Position Error	± 0.10 mm
Position Error of Support Structure	± 0.10 mm
Support Frame Deformation	± 0.26 mm
Total (Root Sum Square, RSS)	**± 0.40 mm**

2.2 Hemisphere Design – QDM Port

The hemisphere and the QDM are depicted in Figure 2. Each hemisphere comprises three segments, hosting a total of 15 QDM ports. The three segments are referred to as the main body, the doublet, and the triplet sections. To accommodate different experimental configurations, it may be necessary to remove the doublet and triplet sections to provide greater access to the hemisphere centre. The estimated error associated with removing and reinstalling the doublet and triplet is ±0.10 mm.

The QDM position is specified by two items. The first is the hemisphere port location, including the doublet and triplet sections, with an estimated error of ±0.19 mm. Each QDM port is defined on the manufacturing drawing by a surface-profile tolerance of ±0.19 mm, accounting for the QDM port location relative to the hemisphere centre in position (x, y, z), orientation, and flatness. To capture the QDM position during installation, press-fit round and diamond pins are used on each QDM flange. This is defined as a manufacturing tolerance with a positional error of ±0.18 mm. The QDM flange pins interface directly with the QDM interface plate, which has an estimated positioning error of less than ±0.05 mm relative to the QDM end cap. Note that the ±0.05 mm QDM position error is not part of the mechanical estimated errors listed in Table 1 but is assigned to the QDM-system error budget not discussed in this paper.

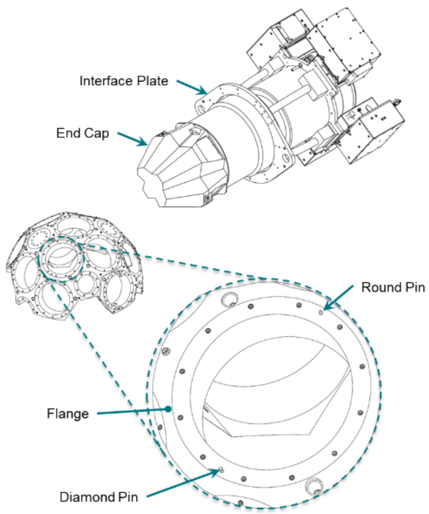

Figure 2. The hemisphere port flange uses of a round and diamond shaped pin to define the location of the QDM (top).

2.3 Support Structure

The support structure is designed to accommodate the installation and removal of the QDMs and to provide access to the centre of the hemisphere where the target chamber would be located. It provides rotation of ±180° to facilitate QDM insertion and removal in a horizontal orientation using a crane and a dedicated lift fixture. A linear drive system provides 500 mm of travel for the entire support structure along the rotation axis, defined perpendicular to the facility beam pipe. The drive-system positional error at the closed position is estimated at ±0.10 mm. To mitigate assembly and alignment errors, three vertical support struts are integrated into the support frame. Each strut provides primary vertical motion of 10 mm and an integrated horizontal motion of 10 mm (perpendicular to the rotation axis), giving a total of five degrees of freedom.

In addition to position errors, the support structure is subjected to different loads depending on the experimental configuration (e.g., removal of the doublet and triplet sections). It is estimated that structural deformation under the corresponding load range of 350 kg to 1,150 kg is ±0.26 mm.

3. Requirements Verification

To verify the different requirements, multiple techniques were implemented and are described below.

3.1 Hemisphere Verification

The hemisphere underwent acceptance verification during manufacture and subsequent post-receipt checks at LBNL using a coordinate measuring machine (CMM). Figure 3 presents the QDM port locations; all ports were within the tolerance specified in Table 2 except for port 10, while port 1 was at the specification limit. Accounting for the CMM measurement uncertainty of ±0.02 mm (2σ), the result could be regarded as within specification. Note that the QDM port location was defined as a surface profile that includes position, orientation, and flatness. When the surface profile is decomposed into its constituent attributes, the position component is within specification and therefore acceptable.

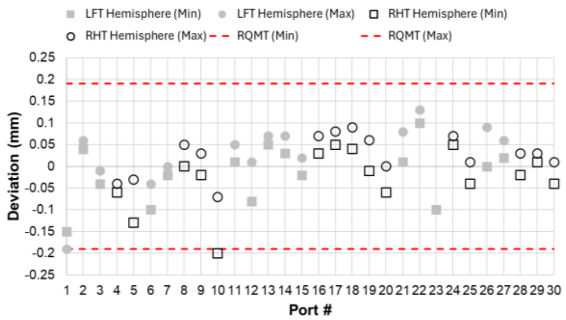

Figure 3. CMM inspection results of QDM port location for all 30 QDM ports.

Part of the hemisphere acceptance tested the locations of the round and diamond pin features on each QDM flange. Measurements with the CMM across all 30 ports yielded a spread from 0.05 mm to 0.15 mm, satisfying the specification in Table 2. The installation and removal of the doublet and triplet sections were performed, with a measured repeatability of ±0.01 mm.

As an additional check, six adjacent QDMs were installed into the hemisphere, and installed gaps were determined with feeler gauges. The nominal design gap between QDM end caps is 1 mm, and measured gaps ranged from 0.9 mm to 1.1 mm (Figure 3). This confirms conformance to the mechanical requirements of the hemisphere.

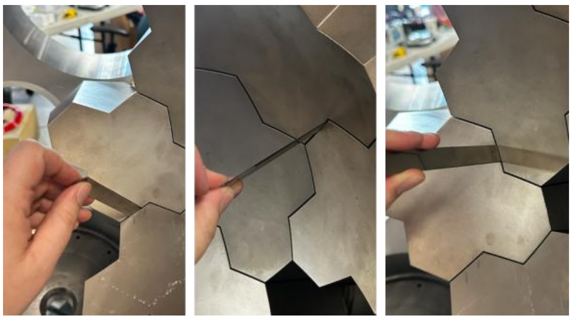

Figure 3. Secondary measurement using feeler gauges to check the gap between QDM end caps.

3.2 Support Structure Verification

The linear and rotational ranges of the support structure were verified using a laser tracker for linear motions and an integrated rotary encoder for rotation about the y-axis. Each hemisphere contains 35 fiducial nests that serve as laser-tracker measurement reference points. Table 3 summarizes the results. The x-axis is defined by gravity, while the z-axis is aligned with the beam direction; these motions are achieved by manual adjustments in combination with the associated rotations. The y-axis motion and the rotation about the y-axis are controlled by a closed-loop controller.

As shown in Table 3, the linear ranges along the x- and z-axes were below the stated requirements due to a design error causing an interference between the structural frame and the linear drive actuator attached to the baseplate. Despite this shortfall, it is deemed acceptable because these adjustments are intended to accommodate alignment errors during installation. Based on experience with similar structures of this size and weight, alignment within approximately 3 mm is typically achievable, so the measured ranges are considered sufficient to align GRETA to the FRIB target chamber.

The rotation about the y-axis also fell short of the ±180° requirement; however, this is not necessary since the largest rotation needed to install or remove a QDM is 170°, making the measured range acceptable.

Table 3. Measured linear and rotational ranges of the support structure.

Direction	Requirement	Linear or Rotation Range
X-axis (manual)	±10 mm	16.5 mm (±8.25 mm)
Y-axis	> 500 mm	> 500 mm
Z-axis (manual)	±10 mm	11.7 mm (±5.85 mm)
Rotation about x-axis (manual)	±0.5 deg	1.46 deg (±0.73 deg)
Rotation about y-axis	±180 deg	+180 deg -172 deg
Rotation about y-axis (manual)	±0.5 deg	1.23 deg (±0.63 deg)
Rotation about z-axis (manual)	±0.5 deg	1.42 deg (±0.71 deg)

During range verification, the relative position error between the two hemispheres was measured with a laser tracker as well. The objective was to demonstrate that the left hemisphere could be aligned to the right hemisphere (taken as the reference position) within ±0.10 mm. The results are presented in Table 4.

Table 4. Alignment error verified by aligning the left hemisphere to the assumed ideal location of the right hemisphere using a laser tracker.

	Left Side	Right Side
X-axis	0.03 mm	0.00 mm
Y-axis	-0.01 mm	0.00 mm
Z-axis	0.07 mm	0.00 mm
Rotation about x-axis	-0.002 deg	0.000 deg
Rotation about y-axis	0.004 deg	0.000 deg
Rotation about z-axis	0.001 deg	0.000 deg

To assess the structural deformation under load, dummy weights were used to emulate QDM mass, and deformation was measured with the laser tracker. Table 5 summarizes the changes between the unpopulated and fully populated hemispheres. The deflection in the x-direction (gravity) is larger than the anticipated ±0.26 mm from the FEA verification. A brief root-cause analysis identified two plausible contributors: (i) the FEA model may have oversimplified or made incorrect assumptions at the angular-contact and radial-bearing interfaces (part of the rotation axis) and other joints (bolted joints, welds); and (ii) angular-contact and radial bearings may not have been preloaded exactly as specified by the manufacturer. Rather than perform additional tests to confirm these potential causes, the test was repeated to check for permanent deformation. The frame returned from the fully populated state to the unpopulated state and back to less than the laser tracker's measurement uncertainty of ±0.1 mm (2σ). On this basis, the results are deemed acceptable for operation, with the understanding that re-alignment would be required if the load configuration changes or use dummy weights to simulate QDM absence/presence.

Table 5. Support structure deformation changes between unpopulated and fully populated hemispheres.

	Unpopulated	Fully Populated
X-axis	0.00 mm	1.63 mm
Y-axis	0.00 mm	0.16 mm
Z-axis	0.00 mm	-0.19 mm
Rotation about x-axis	0.000 deg	-0.001 deg
Rotation about y-axis	0.000 deg	0.039 deg
Rotation about z-axis	0.000 deg	-0.048 deg

4. Summary and Future Work

GRETA was integrated and tested at Lawrence Berkeley National Laboratory (LBNL) to verify the mechanical system and the performance of the fully integrated GRETA assembly (the latter not presented here). Figure 4 shows the installed GRETA system. While the verification demonstrated general compliance with the mechanical requirements, some deviations were observed, notably deformation of the support structure under full QDM loading. Despite these deviations, the results indicate that GRETA is capable of supporting nuclear-structure and nuclear-astrophysics programs at FRIB within the intended operating envelope.

Future work is to repeat the mechanical verifications with GRETA installed at FRIB, using all 30 QDMs, under realistic FRIB operating conditions.

Acknowledgements

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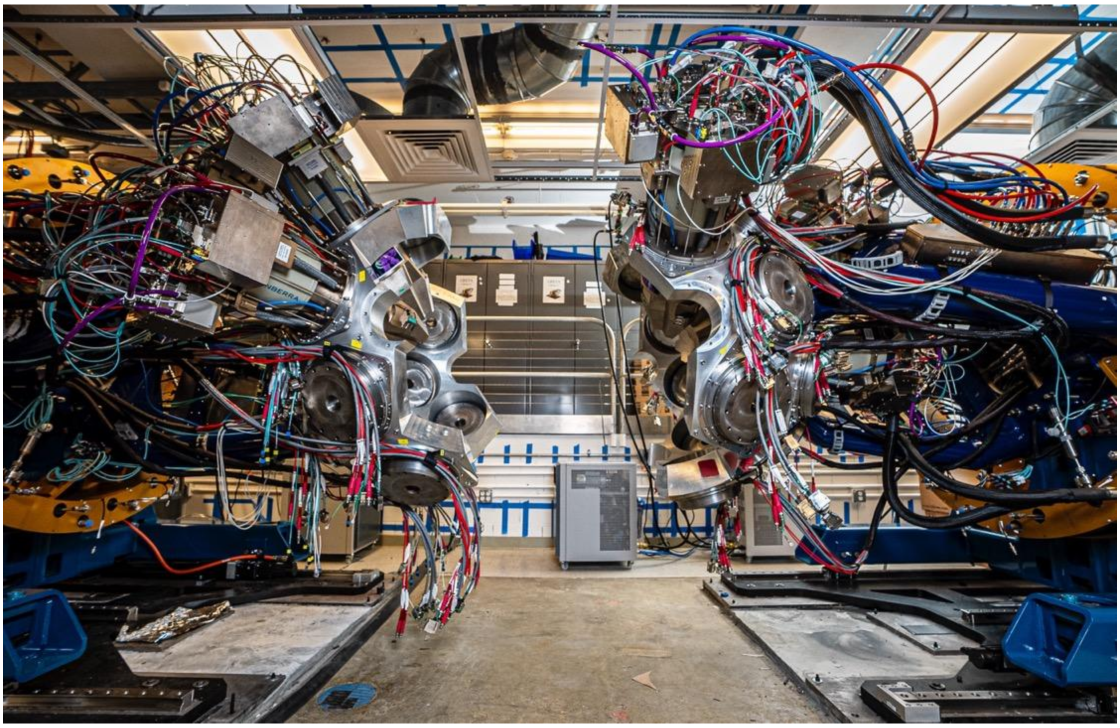

Figure 4. GRETA fully integrated with six QDMs and 24 dummy masses installed into the GRETA mechanical system at LBNL.