# HASP Student Payload Application for 2015

Payload Title: Gannon University's Cosmic-Ray Calorimeter (GU-CRC2)

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|---|---|---|
| Payload Class: (check one)<br>☐ Small ☒ Large | Institution:<br>Gannon University | Submit Date:<br>12/19/2014 |

**Project Abstract**

Gannon University's Cosmic Ray Calorimeter #2 (GU-CRC2) will be a revision of GU-CRC, which is being developed independently for another ballooning platform that will fly in early March 2015. The GU-CRC was designed to detect and measure the energy of primary cosmic rays in the energy range of $10^9$ -$10^{11}$ eV (electron volts) with the purpose of measuring the ratio of protons to helium as a function of energy at balloon float altitude. While GU-CRC2 will adopt many of the components from the previous edition and share the same primary objectives as its predecessor, its functionality will be further refined for 1) the HASP interface for large payloads, 2) more robust operation of its subsystems, and 3) measurement and data collection over a longer duration of flight.

The proposed system, like its previous edition, will implement a calorimeter composed of alternating layers of tungsten, CsI(TI) scinillating crystals, and silicon photomultipliers; a charge detector composed of plastic scinillaters and silicon photomultipliers; an FPGA-based trigger module; a microprocessor; and a power module all enclosed within an insulated frame.

| | |
|---|---|
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| | | |
|---|---|---|
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## BACKGROUND AND OBJECTIVES

Gannon University's Cosmic Ray Calorimeter #2 (GU-CRC2) will be a revision of GU-CRC, a payload that is being developed independently for another ballooning. The GU-CRC was designed to detect and measure the energy of primary cosmic rays in the energy range of $10^9$ -$10^{11}$ eV (electron volts) with the purpose of measuring the ratio of protons to helium as a function of energy at balloon float altitude [1]. While GU-CRC2 will adopt many of the components from the previous edition and share the same primary objectives as its predecesor, its functionality will be further refined for 1) the HASP interface for large payloads, 2) more roubust operation of its subsystems, and 3) measurement and data collection over a longer duration of flight.

Cosmic rays are composed primarily of ionized atomic nuclei, mostly protons (~90%) and helium (~9%). These particles travel near the speed of light with energies measured between approximately $10^8$ – $10^{21}$ eV. As the energy of these particles increase, however, the flux decreases quickly. Figure 1 in the Drawings section shows the relationship between cosmic ray particle energy and its flux. Due to the relatively small aperture of the proposed payload and the relatively short duration of the flight, the expected energy range of data detected with GU-CRC2 is expected to be between approximately $10^9$ – $10^{11}$ eV.

Cosmic rays are influenced by magnetic fields in the galaxy which bend the flight path from what would otherwise be a straight line. These deviations from a straight path are so significant that cosmic ray particles entering earth's atmosphere appear to be traveling in random directions. The acceleration source of these particles have not been definitively established, but it is generally believed that they are accelerated in supernova remnants. Recent findings from Fermi's Large Area Telescope instrument seem to support this notion. If these particles are accelerated in similar fashion and have similar propagation histories, then it would follow that all the particles would behave similarly and follow similar power laws. This would suggest that the proton-to-helium ratio is consistent across the entire relevant power spectrum. Recent measurements have indicated that this is not be the case [2].

The proposed system, like its previous edition, will implement a calorimeter composed of alternating layers of tungsten, CsI(TI) scinillating crystals, and silicon photomultipliers; a charge detector composed of plastic scinillaters and silicon photomultipliers; an FPGA-based trigger module; a microprocessor; and a power module all enclosed within an insulated frame. A breakdown of the proposed system is given below in the section titled SYSTEM OVERVIEW. The combination of hardware and software in this system will work to accurately record the energy and charge of as many particles as possible in flight in order to determine the ratio of proton-to-helium particles at various energy levels.

The first edition of GU-CRC is scheduled to launch in the first quarter of 2015 as part of a separately funded project. The payload is expected to have a float time of approximately 2 hours at an altitude of about 120,000 feet. Upon completion of the flight, once the payload has been recovered, the recorded data will be collected and analyzed. The second version of the project, GU-CRC2, will improve upon the original system. Using the data collected from the original flight as a baseline, we will refine and improve the system to achieve more accurate and more reliable information. We will be able to modify our existing hardware to better handle the high altitude conditions and better combat any radiation interference that may have negatively impacted the operation of the previous edition. We will be able to improve electrical circuitry and software in the system and furthur revise the trajectory algorithm. GU-CRC2 will have a significantly longer float time allowing for a greater number of events to be recorded, thus increasing the maximum energy at which the proton-to-helium ratio can be measured. These measurements will help reveal the nature of cosmic-ray particles and how they are accelerated through space.

## SYSTEM OPERATION

A top-level overview of the proposed payload can be found in the Drawings section (see Figure 2).

### I. Enclosure

The mechanical enclosure for the payload is shown in Figure 3 and will be constructed of aluminum which will provide the system with relatively lightweight rigidity and support. There will be a layer of Styrofoam lining the inside walls of the frame to provide a source of thermal insulation that is easy to shape and mold. The thermal and mechanical effectiveness of this design has been proven multiple times in previous payloads during the required thermal and vacuum testing procedures as well as in flight.

### II. Data Collection Module

The Data Collection Module is comprised of 2 major instruments: a calorimeter and charge detector, shown in Figure 4 and described in greater detail below.

a. Calorimeter

The calorimeter consists of 6 layers of tungsten absorber alternated alongside 6 layers of Thallium doped Cesium Iodide CsI(TI) scintillating crystals and silicon photomultipliers (SiPMs). The primary purpose of the tungsten is to encourage primary cosmic-ray particles to rapidly shower upon impact, thus depositing more energy inside the calorimeter before exiting the other side. The extreme density of the tungsten maximizes the amount of showering while only necessitating thin layers of the metal. This makes tungsten a highly effective and efficient absorber.

The CsI(TI) scintillating crystals emit light in proportion to the amount of energy deposited by a charged particle. In the calorimeter, the crystals are arranged in a 5 x 1 matrix with subsequent layers oriented alternatingly between the x and y orientations. These alternating orientations will later allow the trajectory of the particle to be calculated through three-dimensional (3D) space. The accuracy of recreating the particle's path is important for determining where on the charge detector the particle entered to avoid false readings due to reflected secondary particles.

The light energy translated by the crystals will be read by SiPMs. SiPMs are similar to other photomultipliers, such as photomultiplier tubes (PMTs), in their ability to detect light with a very short response time (approximately 100 ps) and amplify the current produced by the incident light by a factor of $10^6$. SiPMs and PMTs differ in that SIPMs require only a fraction of the voltage and take up far less space, allowing them to easily fit in a compact design. Due to their small surface area, however, less light will be collected, resulting in a smaller detectable pulse. To maximize the amount of light captured, the scintillators will be wrapped in Teflon to reflect stray photons back into the detector. The electric pulse generated by each SiPM will be passed into an integrator board which will calculate the area under the pulse, hold the integrated analog data, compare the data to expected values, and send digitized results to the Trigger Module.

b. Charge Detector

The charge detector is responsible for calculating the magnitude of positively charged particles entering the module. Due to its low cost and fast response time, the charge detector will be made of plastic scintillators. Again, SiPMs will be used to read the light energy detected by the scintillator. The amount of light detected is proportional to the square of the elemental charge of the particle detected. This relationship is represented by the equation $l = Z^2$, where $Z$ is the charge of a particle in units of elemental charge. Thus, Helium nuclei (charge of $Z = +2$) will give off a reading 4 times the magnitude of a proton (charge of +1), allowing easy distinction between particles entering the system. Because there is a chance that secondary particles will reflect back up into the charge detector after entering the system, the charge detector will be split into a 5 x 5 array of detectors. This separation will be used with the trajectory calculations to determine point of entry and actual peak charge value in the case that a particle is reflected back through the charge detector in the opposite direction. The electric pulse generated by each SiPM in the charge detector will be passed into a peak detector board which will amplify the pulse, hold the analog value, compare the amplified value with accepted values, and send the digitized information to the Trigger Module.

## III. Trigger Module

An FPGA will have the responsibility of identifying when the data collection module has data that is worthy to store for later analysis. It will be used to identify cosmic ray events that manage to penetrate both the charge detector and five out of six layers of the calorimeter. After such an event the trigger module will then send a signal to the MCU to save this data. If data is received but is not within these parameters, a signal will be sent to the Data Collection module to erase the data and prepare for another event.

## IV. Microprocessor

The microprocessor will be responsible for managing data storage. The microcontroller will be connected to a Secure Digital card, which serves as the system's storage device for recorded information. When the Trigger Module determines that valid data has been read, it passes a signal to the microprocessor. The microprocessor then retrieves the analog data from the integrator boards and peak detector boards, passes the data through an Analog to Digital converter, and writes the data to the SD card. Data stored on the SD card will be analyzed after the unit is recovered post flight.

The microcontroller will also be responsible for communication between the payload and the ground crew. The microprocessor will be able to transmit downlink data containing event data and system health information (see Table 3) including operating temperature and accept serial commands from the ground crew (see Table 4).

### V. Power Module

Multiple power conversions will be necessary to convert the provided 30 VDC supply to properly power the on-board electronics. Since the power supply is susceptible to fluctuations from about 29 to 33 VDC, signal conditioning will be implemented in conjunction with 32V, +/-12V, and 5V DC to DC voltage converters. A breakdown of the power system may be referenced in the Drawings section (see Figure 5).

## TECHNICAL SPECIFICATIONS

Our payload will meet the specifications and requirements of a "**large payload**" [3][3].

### I. Mechanical Specifications

a. Total payload mass will be well under the 20 kg constraint for large payloads. Mass breakdown is given below:

**Table 1**. Payload Mass

| Item | Mass (kg) | Uncertainty (kg) | Comments |
|---|---|---|---|
| Tungsten Plates | 7.57 | 0.15 | Calculated from density |
| CsI(TI) crystals | 1.42 | 0.06 | Calculated from density |
| Frame/Structure | 0.75 | 0.15 | Estimation based on previous payload |
| Electronics | 1.00 | 0.30 | Estimation based on approximate mass of individual components |
| TOTAL | 10.75 | 0.65 | |

b. The proposed payload will mount onto the "large payload" mounting plate following specifications provided on the HASP_Interface_Module document. Mechanical drawings outlining the dimensions of our proposed system may be viewed in the Drawings section (see Figure 3).

c. There are **no** components that would pose a physical hazard to HASP or the ground crew at any point preceding or succeeding launch.

### II. Power Specifications

a. The power budget for the proposed payload will easily fall within the 75W (2.5 Amps @ 30 VDC) power limitation. A breakdown of the power budget is given below:

**Table 2**. Power budget

| Item | Voltage (V) | Current (mA) | Power (W) |
|---|---|---|---|
| Micro-Controller Arduino | 5 | 120 | 0.60 |
| Micro- Controller Mojo 3 | 5 | 130 | 0.65 |
| Peak detector (x5) | 5 | 14 | 0.35 |
|  | 32 | 0.54 | 0.09 |
| Integrator (x6) | 5 | 1.4 | 0.04 |
|  | 32 | 0.54 | 0.10 |
|  | +12 | 37 | 2.66 |
|  | -12 | 23 | 1.66 |
| Power conversion loses |  |  | 1.85 |
| TOTAL |  |  | 8.00 |

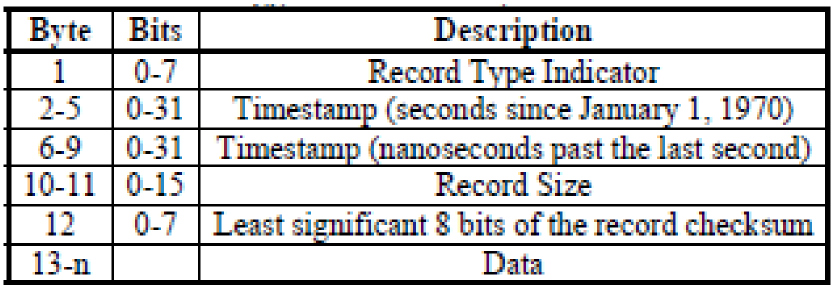
b. Power systems wiring diagram may be viewed in the Drawings section (see Figure 5).

## III. Downlink Telemetry Specifications

a. Serial data downlink format: Packetized

b. Approximate serial downlink rate (in bits per second): 3 bps

c. Data will be used to monitor the health and operation of the payload during flight. Data format will follow HASP suggested payload data format as specified below:



| Byte | Bits | Description |
|---|---|---|
| 1 | 0-7 | Record Type Indicator |
| 2-5 | 0-31 | Timestamp (seconds since January 1, 1970) |
| 6-9 | 0-31 | Timestamp (nanoseconds past the last second) |
| 10-11 | 0-15 | Record Size |
| 12 | 0-7 | Least significant 8 bits of the record checksum |
| 13-n |  | Data |

Data (bytes 13-73) will provide the following tentative information:

| Item | Record Length | Description |
|---|---|---|
| Event data | 13-53 | Information regarding most recent particle detection |
| System status | 53-60 | Information regarding system operation and settings |
| RTC | 61-67 | Time information on events and status updates |
| Temperature | 68-73 | Temperature data in degrees Celcius |

d. No analog channels will be used.

e. No discrete lines will be used.

f. No on-board transmitters will be used. All modules will be connected using direct wiring.

### IV. Uplink Command Specifications

a. Command uplink capability required: Yes

b. Will commands be uplinked in regular intervals: No

c. How many commands do you expect to uplink during the flight:

➔ Approximately 1-3 commands per hour during the first few hours to ensure payload operation and desired configurations. For the remainder of the flight, 1 or 2 commands per hour may be sent to diagnose problems or correct abnormal behavior. Under ideal conditions, no commands need to be sent while downlink data indicates expected operation.

d. The following tentative commands may be used to interface with the system:

| Command | Hexadecimal Value | Description |
|---|---|---|
| Ping | 0x00 0x00 | Request a response to verify system operation |
| Reboot | 0x00 0x01 | Reboot the microprocessor |
| Request event | 0x00 0x02 | Obtain last recorded event |
| Set event interval | 0xFX 0xXX | Adjust interval at which event data is sent through downlink [see notes] |

[Notes] “XXX” represents an integral number in hexadecimal format for seconds ranging from 30 to 600 seconds that is represented by 10 binary bits.

e. No on-board receivers will be used. All modules will be connected using direct wiring.

## INTEGRATION AND TESTING

### I. Integration with HASP

There will be four phases of integration with each phase corresponding with up to one day of work. The integration team is anticipated to consist of approximately 1 faculty advisor and three students. Phase 1 will involve an in-lab instrument check out to ensure all instruments are working properly prior to integration with HASP. Phase 2 will include the integration of all electrical components within the system. Phase 3 will involve a comprehensive system test. The comprehensive system test will be performed by connecting the payload to all appropriate connectors including the power supply. We will power the instruments on and off, record temperature information, and ensure data channels are working properly. We will test the serial communication in both directions by sending commands to the system and receiving status updates back from the system. We will run the system for approximately five minutes to collect atmospheric muon data. Data from this short run will be compared against previous measurements for validation of instrument performance. Events stored in onboard memory during testing will be analyzed in greater detail to calculate travel path of primary cosmic rays. Phase 4 will be used to correct any outstanding issues. When data is shown to be reliable and consistent with simulated results, the system will be considered successfully integrated and flight ready. The payload enclosure will then be sealed.

### II. Flight-line Set-up and Prelaunch: Not applicable.

### III. Flight Operation Procedures (list of commands to be transmitted during each phase of flight)

| | |
|---|---|
| a. During climb-out: | Instrument Power On |
| b. Flight Configuration Setup: | None |

c. Failure Response:

Payload operation will be verified through the coincidence rate of cosmic ray events.

i. If system stops transmitting data –

In this instance the command 'reboot' should be sent to the payload. If no data is then received from the payload, power should be cycled.

ii. If system temperature is too high –

If the temperature of the system exceeds that of its maximum allowed temperature the payload should be turned off for 10 minutes then turned back on.

iii. If system does not return data at expected interval –

A command will be sent to change the data transmission interval. If this is ineffective, the same procedure as (i) should be executed.

d. Termination : Instrument Power Off

## PROJECT MANAGEMENT

### I. Team Structure

The design and implementation of this payload is an interdisciplinary undergraduate research project which will serve as the basis for the Senior Design project of three students in the Electrical and Computer Engineering department of Gannon University (these students are indicated by an asterisk (*) by their name in the table below). The current team consists of eleven undergraduate students under the guidance of two faculty advisors.

| Student | Position | Concentration | Email |
|---|---|---|---|
| Aaron Neiman*† | Project Lead | Computer Engineering | neiman001@knights.gannon.edu |

| Student | Position | Concentration | Email |
|---|---|---|---|
| Leslie Moukoro† | Engineering Lead | Electrical Engineering | moukoro001@knights.gannon.edu |
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| Codi Wasser*† | Engineering Team | Computer Engineering | wasser002@knights.gannon.edu |
| Brandon Lawrence† | Engineering Team | Electrical Engineering | lawrence021@knights.gannon.edu |
| Donovan Starks† | Engineering Team | Electrical Engineering | starks003@knights.gannon.edu |
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| Jennifer Hu† | Science Lead | Pre-med/Biology | hu004@knights.gannon.edu |
| Paul LeVan | Science Team | Mathematics | levan006@knights.gannon.edu |
| Omar Siddiqui | Science Team | Biology | siddiqui001@knights.gannon.edu |

| Faculty Member | Position | Concentration | Email and Phone |
|---|---|---|---|
| Dr. Wookwon Lee | Advisor | Electrical & Computer Engineering | lee023@gannon.edu<br>814-871-7630 |
| Dr. Nicholas Conklin | Co-advisor | Physics | conklin003@gannon.edu<br>814-871-7740 |

## II. Timeline and Milestones

This project, as a continuation of a previous development scheduled to launch in the first quarter of 2015, will use many of the components and methods of the previous rendition. Work for that project has been well underway. From the student team listed above, a subset has been created to attend to the immediate development and modifications necessary for the transition (these students are indicated by a dagger (†) in the table above).

Our tentative timeline and milestones are as follows:

- Design of payload modules (1/10/2015 – 3/1/2015): student members complete design of individual system modules and unit testing.
  **Deliverables**: Test plan for unit and integration tests

- Module integration (3/2/2015 – 4/15/2015): student team members complete integration of all modules into a payload, complete FMEA, and integration testing.
  **Deliverables**: Payload Specification and Integration Plan (PSIP)

- Preparation for on-site integration at CSBF (4/18/2015 – 5/13/2015): complete any necessary revision/refinement of the modules and payload; assemble the payload onto the HASP plate; travel arrangement for student members.
  **Deliverables**: a complete payload prototype, ready to go; Submit Preliminary & Final PSIP

- Submit Final FLOP: July 2015

- Payload integration (8/3/15-8/7/2015, to be confirmed): team members on site for integration (at least 3 team student members and 1 advisor are anticipated to participate)

- HASP launch (9/7/2015): at least 1 team member on site (anticipated) to participate if necessary

## III. Funding

The majority of the equipment used for our proposed payload will be harvested from a previous flight. There are additional funds available from faculty advisors' research funds to accommodate student travel for integration and purchase of parts as necessary to upgrade the payload.

# DRAWINGS

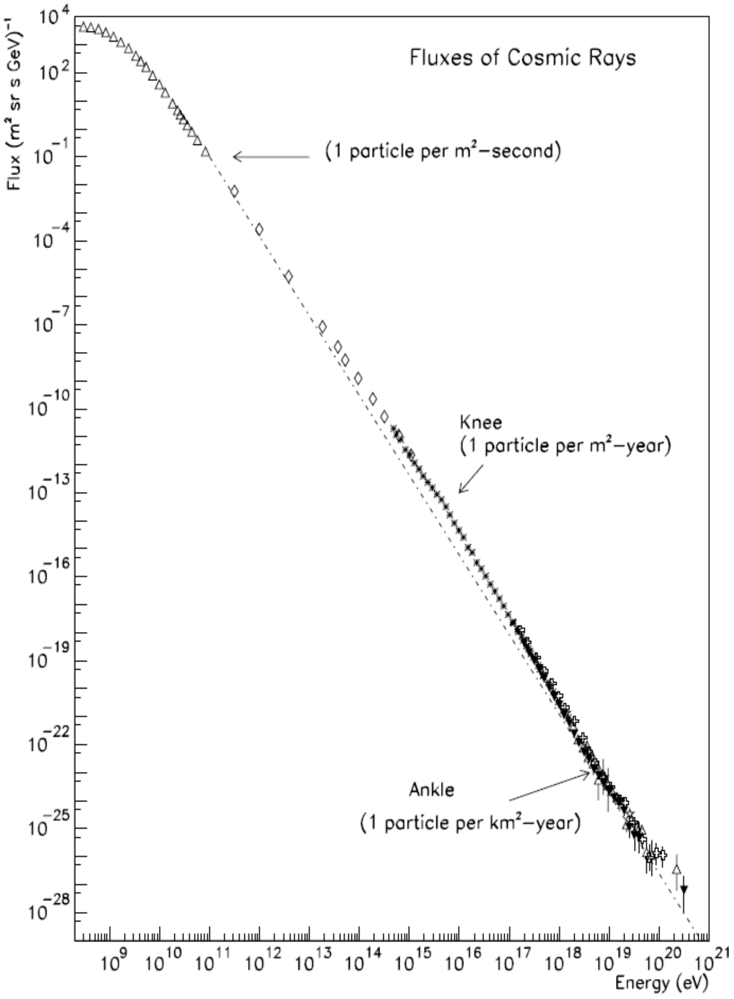


**Figure 1 – Cosmic-ray Flux as a function of energy [4].**

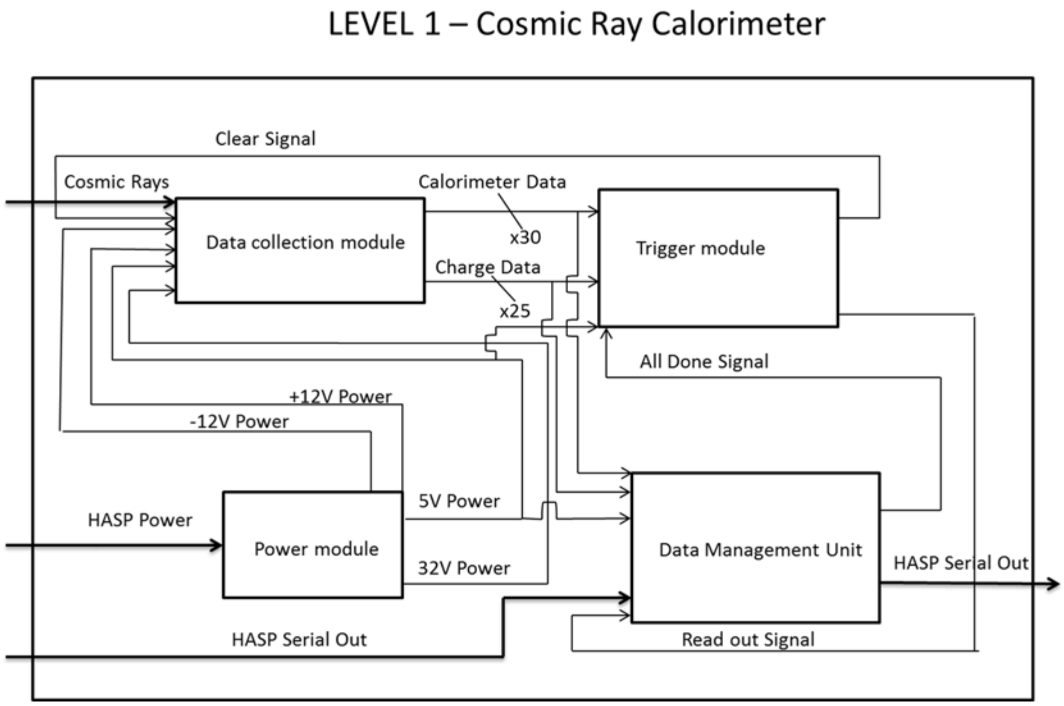
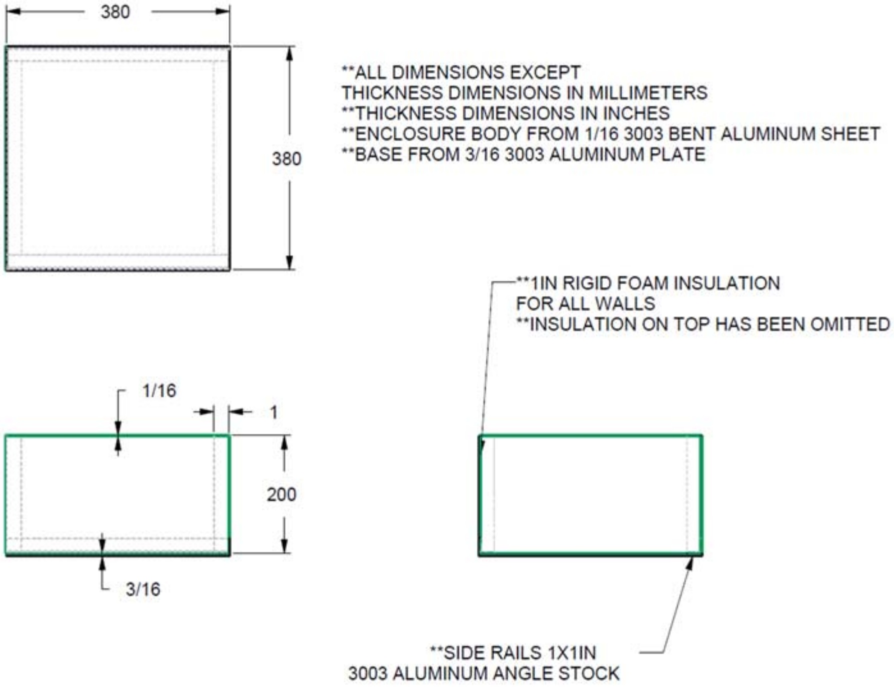


**Figure 2 - Top level representation of GU-CRC2 and major functional modules.**



**ALL DIMENSIONS EXCEPT
THICKNESS DIMENSIONS IN MILLIMETERS
**THICKNESS DIMENSIONS IN INCHES
**ENCLOSURE BODY FROM 1/16 3003 BENT ALUMINUM SHEET
**BASE FROM 3/16 3003 ALUMINUM PLATE

**1IN RIGID FOAM INSULATION
FOR ALL WALLS
**INSULATION ON TOP HAS BEEN OMITTED

**SIDE RAILS 1X1IN
3003 ALUMINUM ANGLE STOCK

**Figure 3 – External dimensions of GU-CRC2 enclosure. The outer layer is composed of lightweight aluminum. The inside wall is made of insulating Styrofoam.**

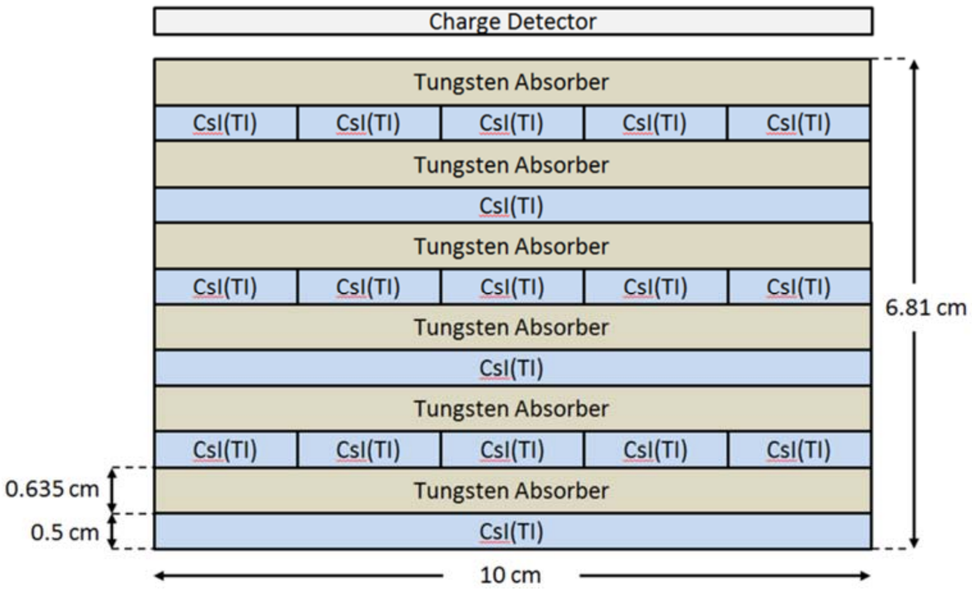


**Figure 4 - Side View of Data Collection Module. Alternating layers of Tungsten Absorber encourage showering while CsI(Tl) crystals arranged in 5 x 1 matrices of alternating orientations collect energy and trajectory data.**

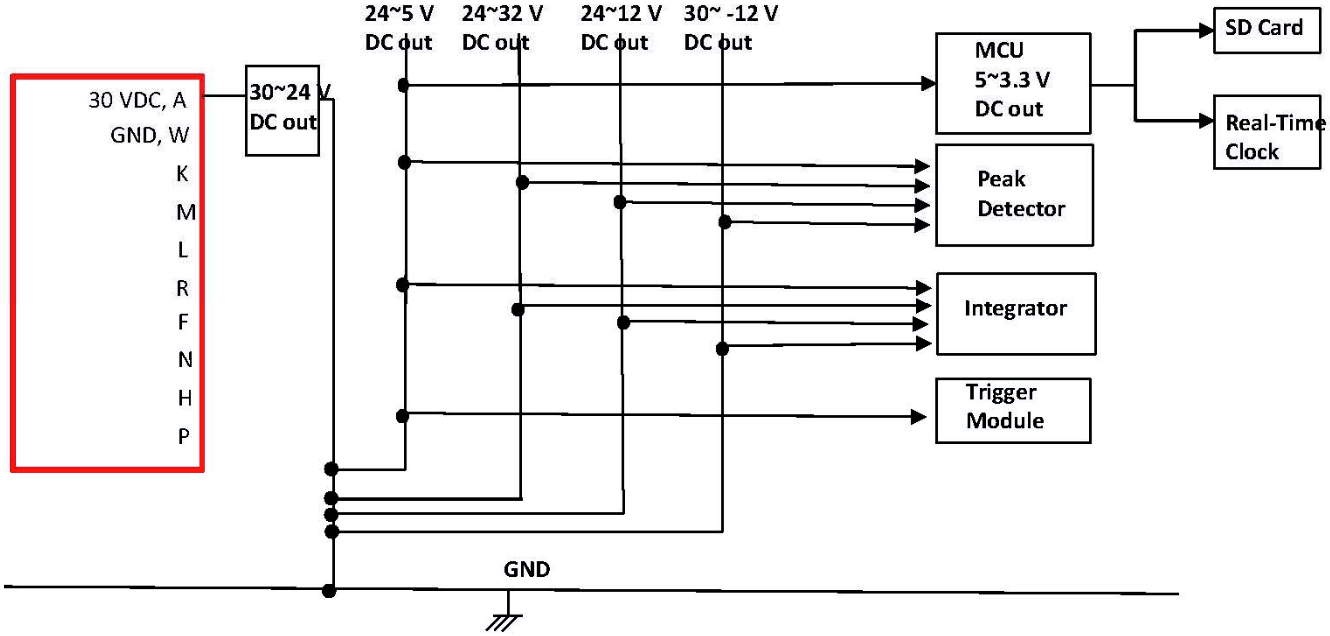


**Figure 5. Electrical circuit diagram of the EDAC pins and the primary voltage conversion components**

## REFERENCES

*[1]* N. Conklin and W. Lee, “Gannon University’s Cosmic-Ray Calorimeter (GU-CRC),” Dept. of Physics and Dept. of Elec. and Comp. Eng., Gannon University., Erie, PA. Rep. 2012.

*[2]* O. Adriani, G. Barbarino, G. Bazilevskaya, R. Bellotii, M. Boezio, E. Gogomolov, L. Bonechi and M. Bongi, "PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra," Science, vol. 332, pp. 69-72, 2011.

*[3]* “HASP – Student Payload Interface Manual (Version 02.17.09) ,” [Online]. Available: http://laspace.lsu.edu/hasp/documents/public/HASP_Interface_Manual_v21709.pdf. [Accessed 24 November 2014].

*[4]* S. Swordy, "The Energy Spectra and Anisotropies of Cosmic Rays," *Space Science Reviews,* vol. 99, pp. 85-94, 2001.