Advanced Radiation Detectors and Detector Systems Research

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Outline

- Technology Challenges
- Smart Sensing and Electronics Systems
- GRC Advanced Radiation Detector Instrumentation Research
- Benefits of Wide Band Gap (WBG) Detectors
- Future Concept: Compact Full-Field Ion Detector System (CFIDS)

Radiation Detector Systems Research

- CFIDS Components as Separate Detectors
- WBG LET Detectors
- Envisioned Implementation
    - SPAGHETI Deep-Space CubeSat
    - Neutron Spectra for Lunar Prospecting
    - Radiation Sensors for Fission Surface Power
- Summary

Technology Challenges

NASA Space Weather Science and Observational Gap Analysis (2021)

- High Priority I3: Multipoint in-situ particle & fields measurements
- High Priority A2: Measurements of radially distributed particles & fields

NASA STMD Strategic Framework Technology Shortfalls (2024)

- #1526: Radiation Monitoring and Modelling
  - Advanced Space Radiation Environment Characterization Systems
- #1600: Enable Paradigm for System Science to Include Interactions between Subsystems
  - Extreme Multifunction instruments, Components, Common/Shared Elements
  - Reductions in Instrument Size, Weight, Power, Volume, Cost
- #1603: Situational Awareness Sensors and Tools for Astronauts
  - Lunar Space Environment Sensors/Sensor System
- #1627: Advanced Sensor Components for Heliophysics and Lunar-Based Astronomy
  - Field & Particle Detectors

Technology Challenges

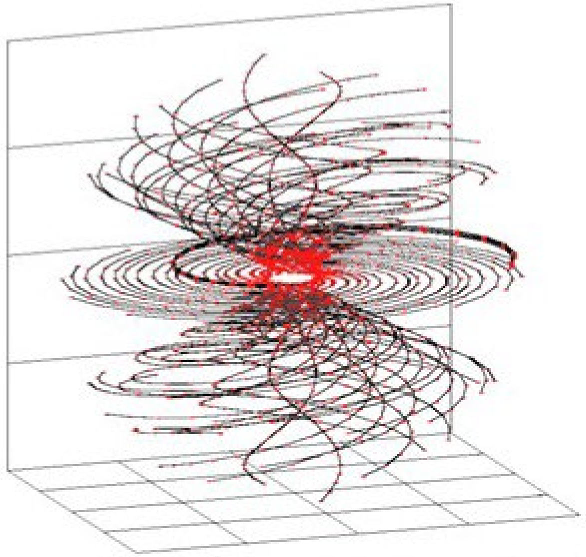
Common Theme:

> "Robust sensors capable of operating for long periods in environment of space are needed to measure the radiation at the destination as well as during the journey."
> — *NASA Technology Roadmap 2012*

Space weather nowcasting and forecasting capabilities are currently limited for extended missions and require measurements at varied locations to respond in a timely manner to changes in the space environment

Enabling Approaches:

- Integrated, multifunctional detector technologies
- Radiation hardened electronics
- New compact detector systems for smaller platforms



Schematic of the path of the solar wind from the Sun

Smart Sensing and Electronics Systems Branch

Description

Conducts research and development of **adaptable instrumentation to enable intelligent measurement systems** for ongoing and future aerospace propulsion and space exploration programs. Emphasis is on smart sensors and electronics systems for diagnostic engine health monitoring, controls, safety, security, surveillance, and biomedical applications**; often for high temperature/harsh environments**.

Microsystems Fabrication Facility

Facilities/Labs

- Microsystems Fabrication Facilities
  - Class 100 Clean Room
  - Class 1000 Clean Room
- Chemical vapor deposition laboratories
- Chemical sensor testing laboratories
- Harsh environment laboratories
  - Nanostructure fabrication and analysis
  - Sensor and electronic device test and evaluation

Core Capabilities (technical areas)

•Silicon Carbide (SiC) - based electronic devices
- Sensors and electronics for high temp (600°C) use
- Wireless sensor technologies, integrated circuits, and packaging

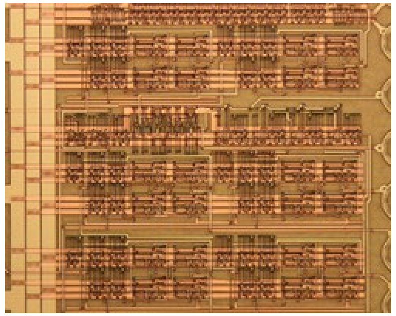
•Micro-Electro-Mechanical Systems (MEMS)
- Pressure, acceleration, fuel actuation, and deep etching

•Chemical gas species sensors
- Leak detection, emission, fire and environmental, and human health monitoring

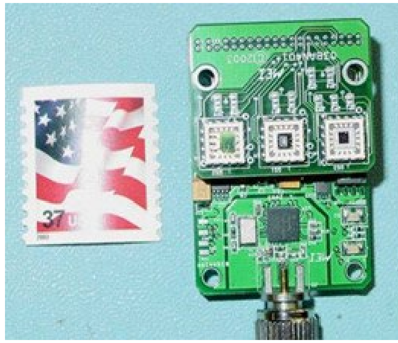
•Microfabricated thin-film physical sensors
- Temperature, strain, heat flux, flow, and **radiation measurements**

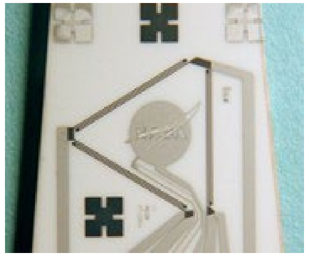
•Harsh environment nanotechnology
- Nano-based processing using microfabrication techniques
- Smart memory alloys and ultra low power devices

SiC Signal Processing



Chemical Sensors





Thin Film Physical Sensors

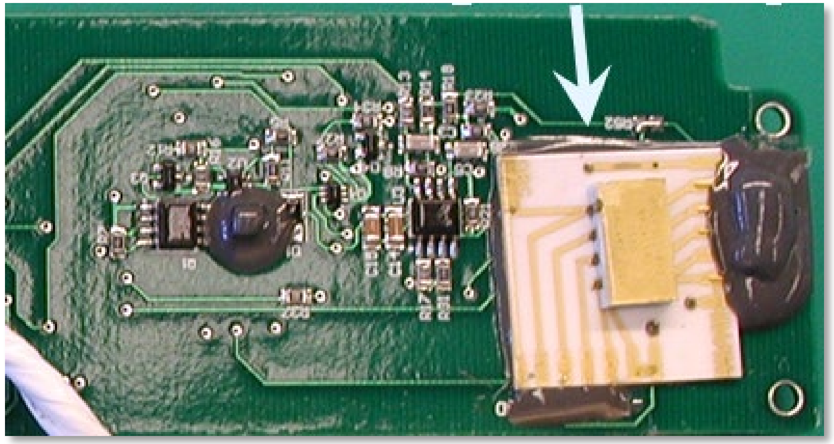
GRC Advanced Space Radiation Instrumentation Research

GRC Expertise and Facilities in:

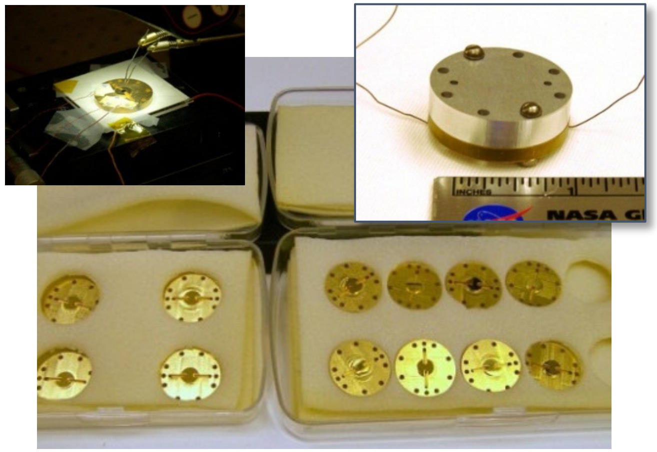
- Harsh Environment Thin Films
- SiC Devices & Harsh Environment Packaging
- Micro-Optics
- Space-Based Instrumentation

These strengths are combined into an in-house Radiation Instrumentation Research effort

In-House Microsystems Fabrication



MISSE 7 SiC JFET & Ceramic Packaging (arrow) on a Rad-Hard Electronics Board for ISS flight



CERES Thin Film Microbolometer Testing and Packaging

GRC Advanced Space Radiation Instrumentation Research

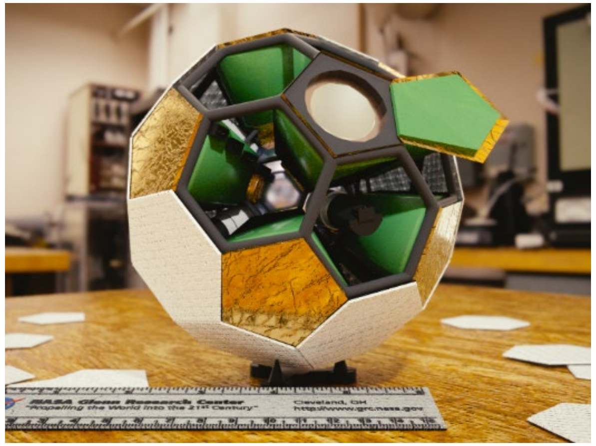
Problem:
- Awareness of space radiation critical in missions beyond LEO (i.e., Moon, Mars, NEOs, etc.) requiring:
  - Embedded instrumentation to provide feedback for "smart", adaptive systems
  - Precision instrumentation to provide improved data to space radiation modeling efforts
  - Compact instrumentation for more complete, real-time situational awareness on small platforms (e.g., CubeSats)
- Current technology limiters are radiation hardness, noise floor, thermal stability, and detector geometry.

Solution:
- Compact integrable detectors with low noise, solid state components allowing spherical geometry enabled by the application of Wide Band Gap (WBG) semiconductors as radiation detectors

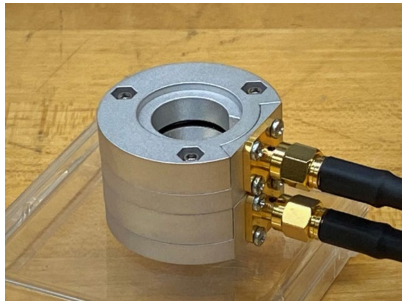
Approach:

Variety of detectors:
- SiC Linear Energy Transfer (LET) Detectors
- Low Power Charged Particle Counter
- Fast Wide Band Gap Cherenkov Detector

Variety of applications:
- Deep Space CubeSats
- In-Situ Resource Utilization
- Fission Surface Power

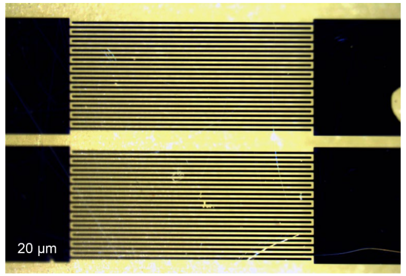


Compact Full-field Ion Detector System (CFIDS) Concept (US Patents 7,872,750 & 8,159,669)



Large Area SiC LET Detectors & Charged Particle Telescope

Fast, Large Area, Wide Band Gap Cherenkov Detector (U.S. Patent 10,054,691)



Low Power Charged Particle Counter (U.S. Patent 10,429,521)

Benefits of Wide Band Gap Detectors: Lower Power and More Robust

Detector	Active Area	Mass	Volume	Voltage	Dark Current	Minimum Power Draw	Maximum Amplitude Signal to Noise	Maximum Operating Tempera-ture	Temperature Sensitivity of Dark Current
LET:									
SOA: Si PIN	1 cm²	0.5 g	185 mm³	100 V	5 nA	0.5 µW	$1x10^5$	60°C	20%/°C
SOA: Si(Li)	30 cm²	35 g	15 cm³	300 V	5 µA	1.5 mW	$8x10^3$	60°C	30%/°C
Proposed: SiC	2 cm²	0.5 g	113 mm³	100 V	0.3 nA	0.03 µW	$3x10^6$	120°C	0.1%/°C
Scintillator Coincidence/Anticoincidence:									
SOA: PMT	20 cm²	170 g	180 cm³	1000 V	5 nA	5 µW	$4x10^5$	50°C	0.2%/°C
SOA: APD	9 mm²	3 g	200 mm³	30 V	5 nA	0.15 µW	$8x10^4$	85°C	30%/°C
Proposed: GaP	4.8 mm²	5 g	170 mm³	5 V	20 pA	0.1 nW	$3x10^5$	125°C	0.5%/°C
Cherenkov Detector:									
SOA: PMT	20 cm²	170 g	180 cm³	1000 V	5 nA	5 µW	$4x10^5$	50°C	0.2%/°C
Proposed: ZnO	2 mm²	11 g	0.80 cm³	10 V	5 nA	0.05 µW	$4x10^4$	125°C	0.05%/°C

Future Concept: Compact Full-Field Ion Detector System (CFIDS)

Mapping of heavy ions > 100 MeV/amu

- Integrated system with solid-state Cherenkov detector and large area detectors in surrounding wedges

High radiation flux rates for 10+ year missions

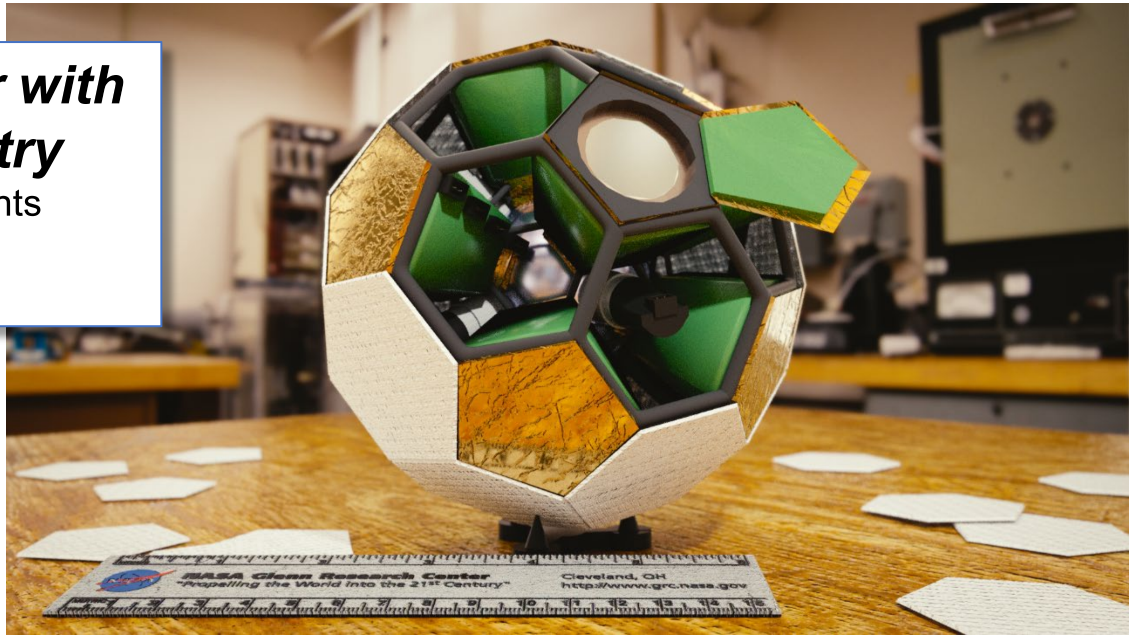
- Precision rad-hard, thermally stable wide band gap detectors used

Low noise, multi-directional measurements at single locations

- Compact, spherical detector system
- Size can be scaled depending on application

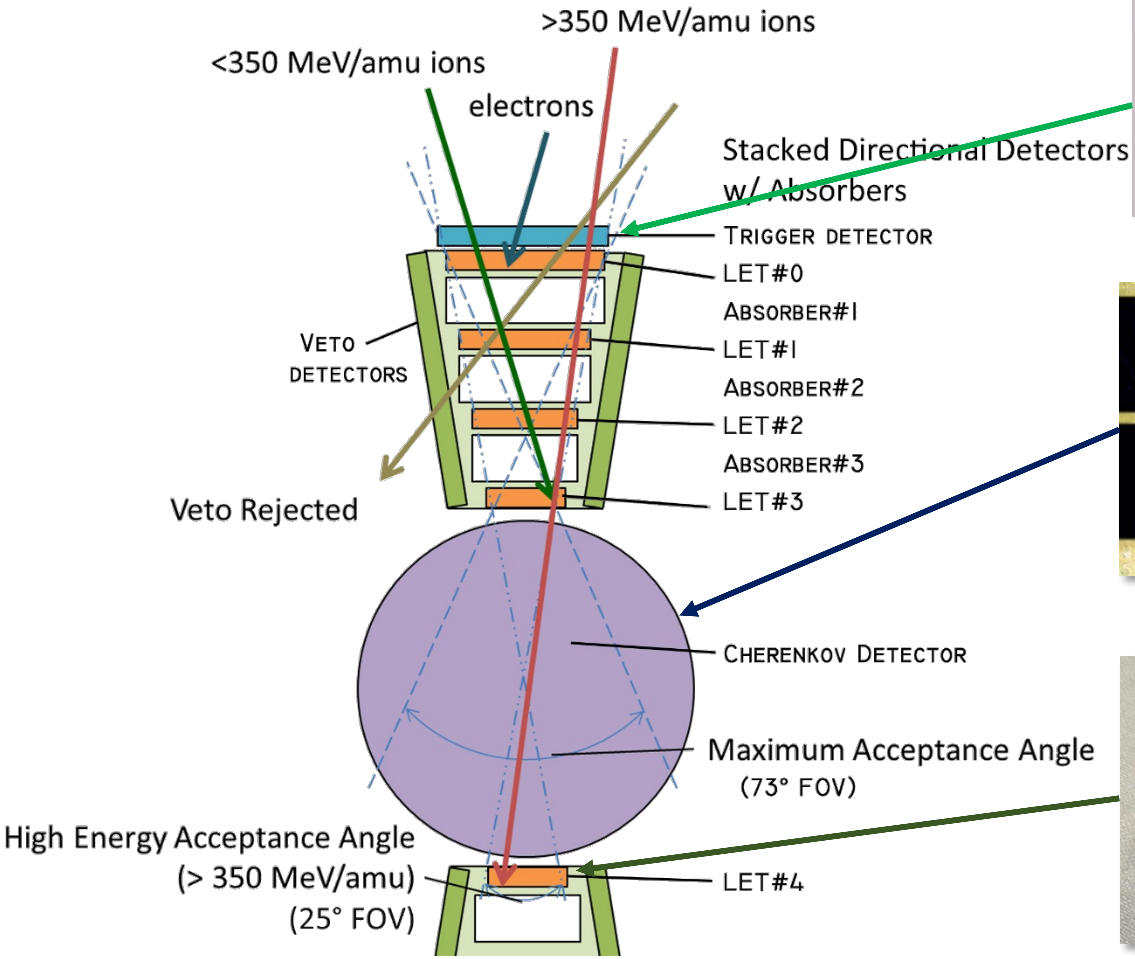
Space radiation detector with spherical geometry

- Technology covered by U.S. Patents 7,872,750 (January 18, 2011) and 8,159,669 (April 17, 2012)

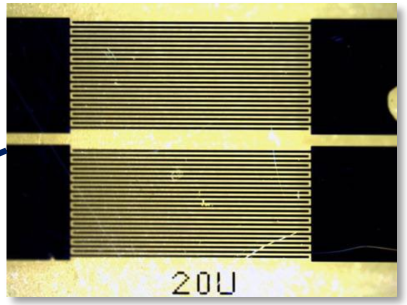


Concept illustration of the CFIDS detector assembly (cables, electronics not shown)

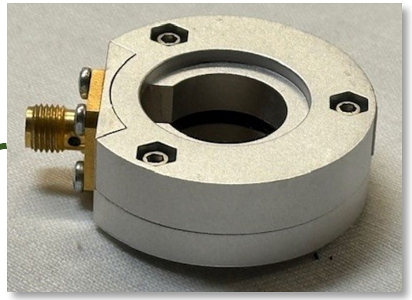
Future Concept: Compact Full-Field Ion Detector System (CFIDS)



GaP Diode for Solid-State Trigger/Veto Detectors



ZnO UV Sensor for Solid-State Cherenkov Detector



Large Area SiC Diode for LET Detectors

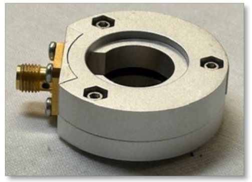
CFIDS comprised of a spherical Cherenkov detector surrounded by stacked LET detectors with absorbers, Coincidence & Anticoincidence detectors for Trigger/Veto functions

Radiation Detector Systems Research

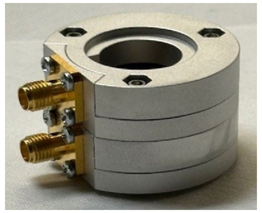
CFIDS Components as Separate Detectors

The individual detectors from the CFIDS may be used separately:

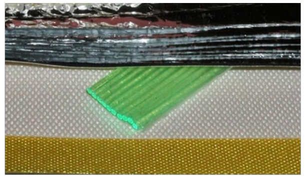
- Individual wide Linear Energy Transfer (LET) detector
  - Center Innovation Fund (CIF) 2015



- Wide Bandgap Charged Particle Telescope (CPT)
  - Size and Number of sections in CPT can be chosen based on application
  - Moderating layers between detector sections can be used or not used
  - Different moderating layers may be applicable
  - Independent Research and Development (IRAD) 2018-2024, LEW-20486-1



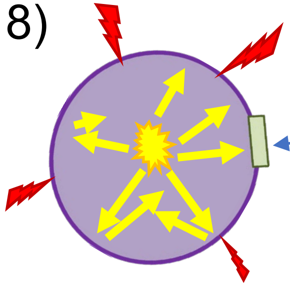
- Scintillator and photodiode detectors for trigger/veto and other sensing
  - (CIF 2013), U.S. Patent 10,429,521 (October 1, 2019)

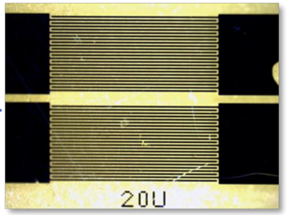


Acrylic ribbon scintillator for ionizing radiation detector

Miniature scintillation/diode ionizing radiation detector

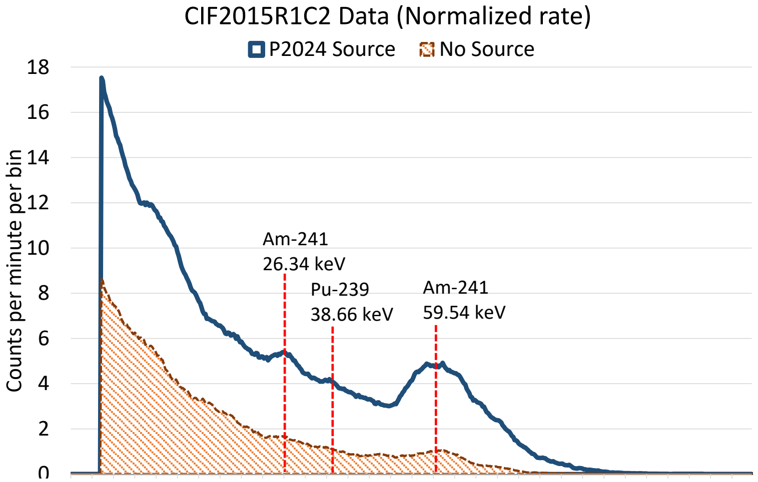
- Cherenkov Detector with ZnO solar-blind UV photodiode
  - (CIF 2012),U.S. Patent 10,054,691 (August 21, 2018)



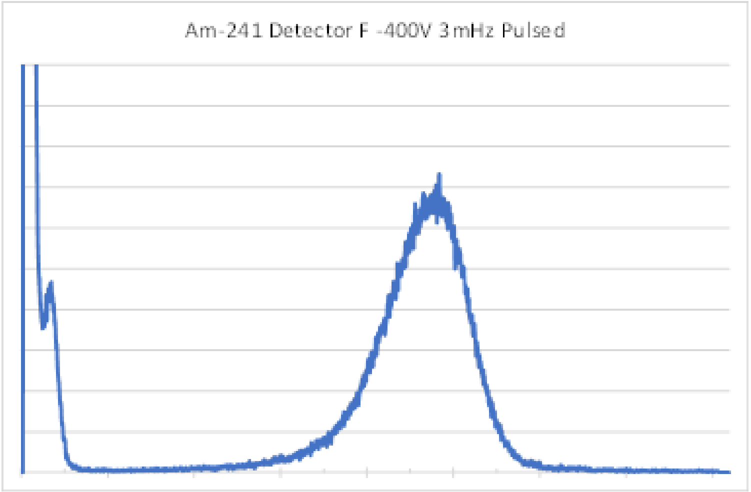


WBG LET Detectors

- Large Area 2 cm² prototype detectors using HPSI SiC
- Observed gamma, alpha (He-4) peaks of Pu-239, Am-241 sources
  - Observed peaks down to 26.3 keV or LET ≥ 75.7 eV/µm
  - Noise floor ≈ 60 eV/µm (20.7 keV), Uncertainty ±30 eV/µm, dE/E = 20% in air
  - Estimate of minimally ionizing proton (3 GeV p) LET = 543 eV/µm in SiC (detectable)
- Characteristic Proof of Concept – validation of key parameters
- Recent improvements in detector design and fabrication has reduced dE/E < 10%



Proof-of-Concept detector measurement of gamma rays from a Pu-239 source



Improved detector measurement of 4.6 MeV alpha particles from an Am-241 source in air

Envisioned Implementation

Applications:

- Compliment to other detectors already in use
  - Provide multi-directional data to help with decision-making about repositioning larger detectors
- Additional Data to fill in gaps in the space weather environment picture
  - Small detectors to be deployed in locations difficult to deploy larger detector
  - Provide additional information from difficult-to-deploy locations

Platforms:

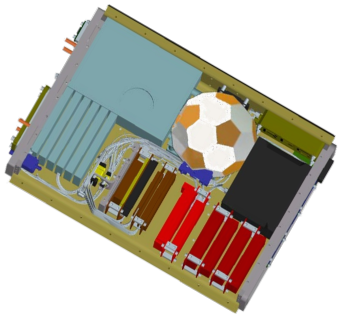
- Small Satellites/CubeSats/etc.
- Rovers
- Fixed monitoring locations

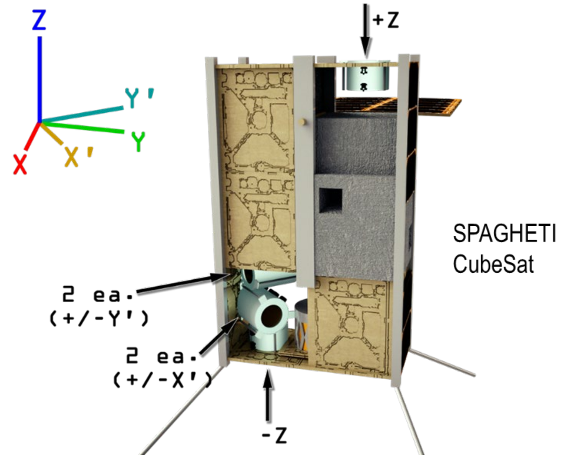
Size:

- Scalable: Size can be changed depending on application
- Modular and configurable

GRC Contributions

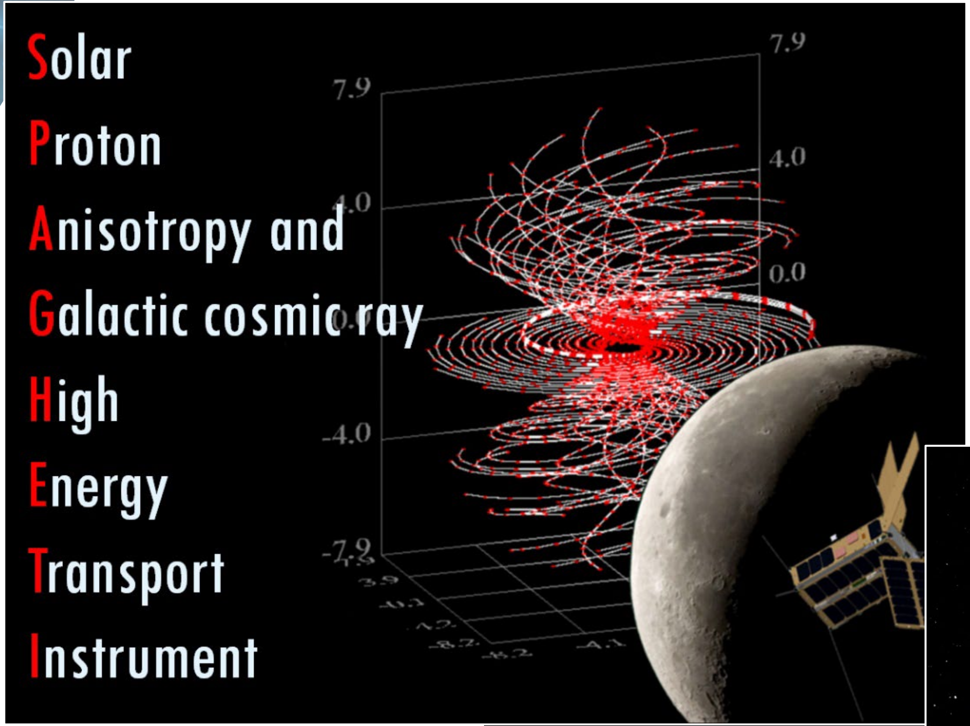
- IRAD Phase III completion on SiC charged particle detector
- Four patents on detector system concepts
- Experience with radiation and high energy particle beams
- Unique capability for SiC processing, instrument development, electronics, packaging and integration within GRC Smart Sensing and Electronics Systems branch





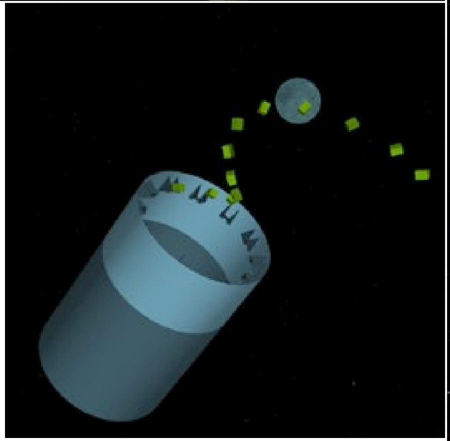
Above Left: Concept drawing of CFIDS in a 6U CubeSat. *Above:* Concept drawing of Charged Particle Telescopes in a 6U CubeSat.

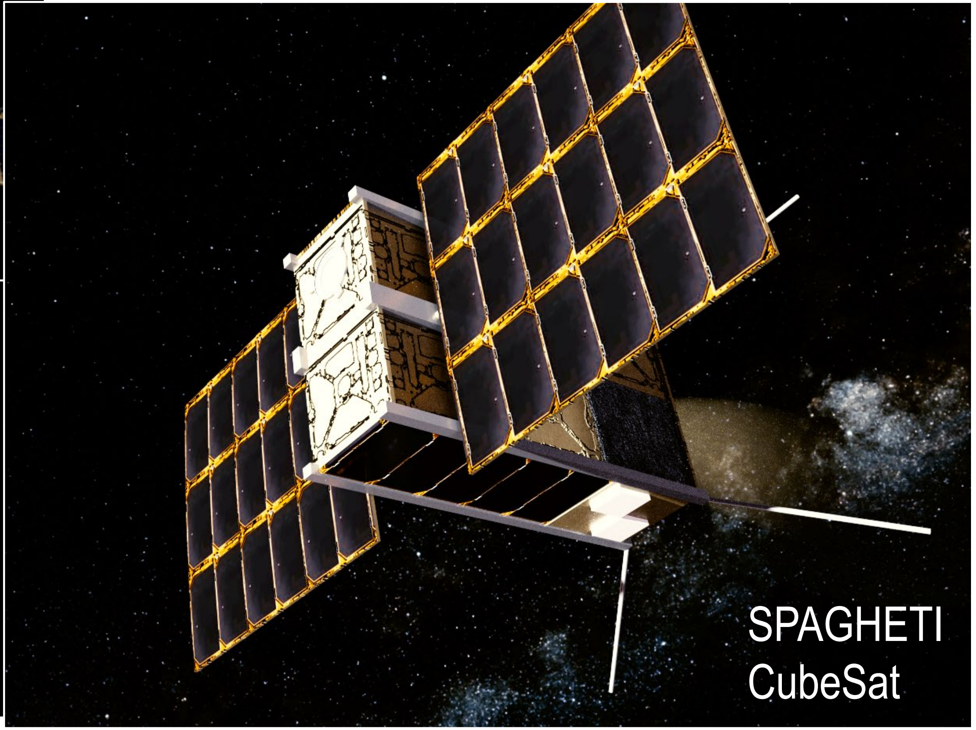
SPAGHETI: Deep-Space CubeSat



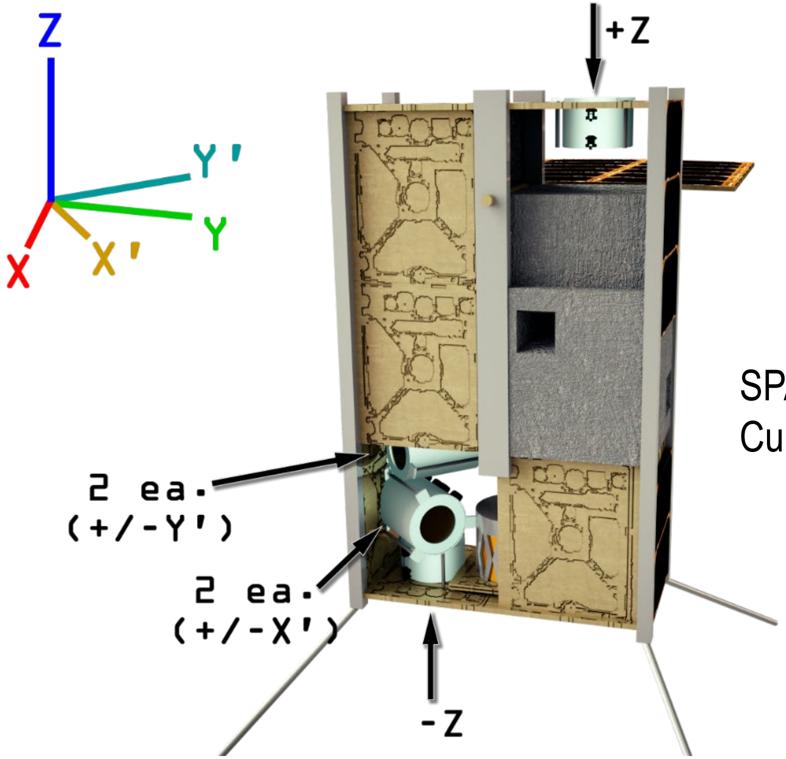
- SPAGHETI would explore the transient variations in ion flux anisotropy in deep space and near the lunar surface

- SPAGHETI was a proposed SmallSat mission for an Artemis 1 launch on a 6U CubeSat bus



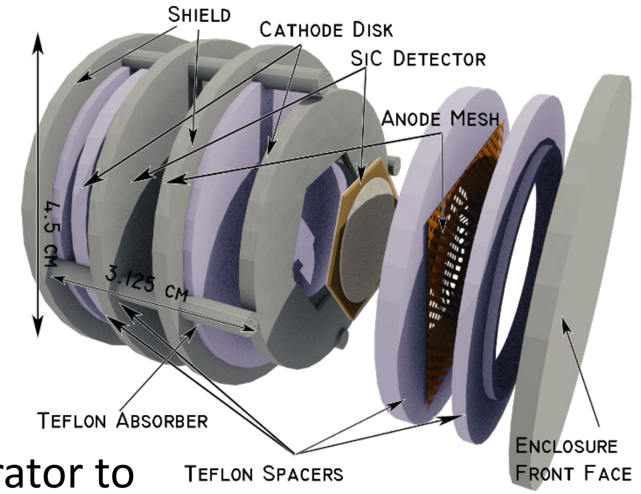


SPAGHETI: Deep-Space CubeSat



SPAGHETI CubeSat

- SPAGHETI would contain 6 packages of WBG LET detector stacks, arranged to provide simultaneous multidirectional measurements

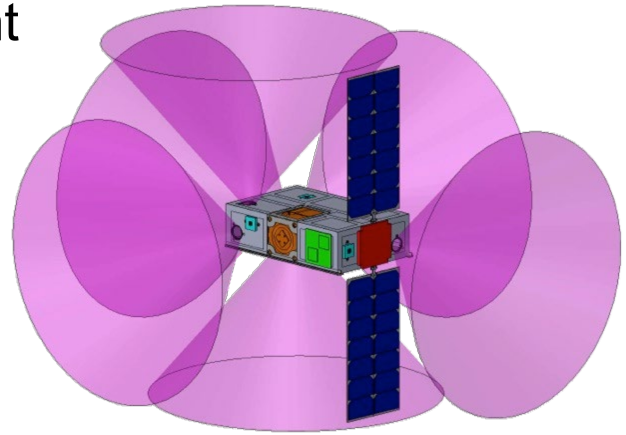


WBG LET Detector Stacks (Charged Particle Telescope)

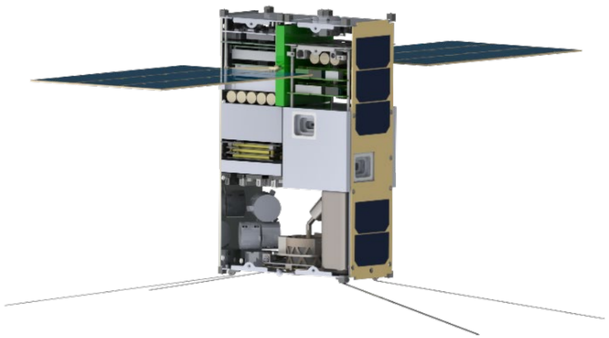
- Each stack would have 2 LET detectors separated by a moderator to allow energy and ion species resolution
- Each detector stack would be directionally sensitive with an 80°field of view and a geometric factor of 0.84 $cm^2 \cdot sr$
- Detector insensitivity to temperature changes would allow compact, low-power operation

SPAGHETI: Deep-Space CubeSat

- GRC-led proposal to Heliophysics Technology and Instrument Development for Science (HTIDeS) program
  - 6 pairs of LET detectors for directly observing anisotropic, transient effects
  - Low lunar orbit (2086×1779 km) using Iodine Ion thruster for corroboration with Lunar Reconnaissance Orbiter/CRaTER instrument data
  - Accelerated Technology Development to Flight for High-Payoff Science
- NASA GSFC / Catholic University of America, University of New Hampshire as Science Team
- Morehead State University selected as CubeSat bus provider via pre-proposal competitive process
  - The Aerospace Corporation, Busek as subsystem providers
- Pre-proposal COMPASS review sessions at GRC with partners to ensure technical awareness of risks
  - Ultimately SPAGHETI as-proposed was not funded for flight

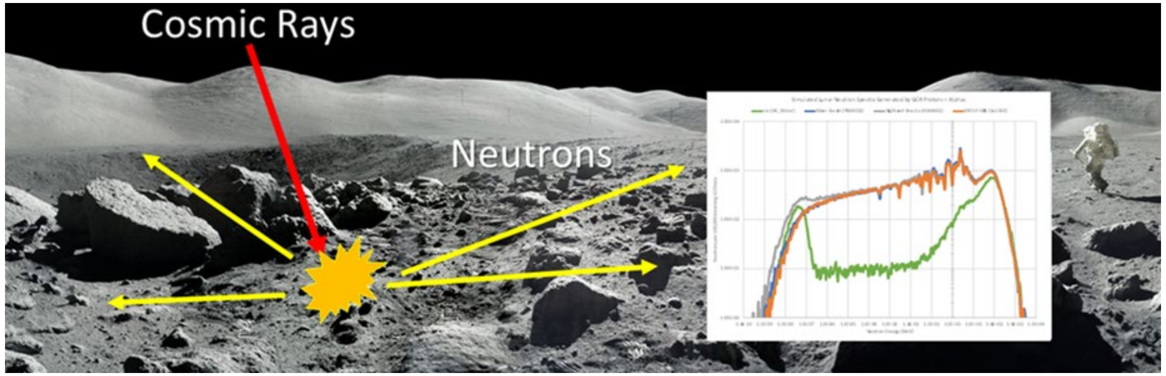


COMPASS SPAGHETI Study



Morehead State U. SPAGHETI Bus as-proposed

Neutron Spectra for Lunar Prospecting



Simulating neutron spectrum produced by cosmic rays interacting with lunar materials

Problem: Evaluation of regolith composition is key for resource assessment in sustained surface operations.

Solution: We will enable implementation of Lunar and Mars habitation by providing an instrument and methodology that will determine the composition of regolith for surface and subsurface locations. This work will improve non-invasive ISRU prospecting for lunar surface operations addressing ISRU Gap 403: "Instruments to determine local regolith mineral and chemical composition for resource assessment."

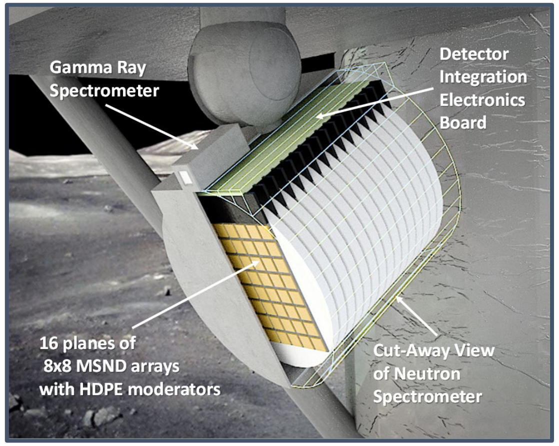
CIF 2022: LEW-20497-1 "Identification of Lunar ISRU Material using Neutron Spectroscopy"

Additional Members for future proposals:

External Partner: *Radiation Detector Technologies (RTD, Manhattan KS) competed as partner for future proposals*

Solution Approach: Use neutrons generated by background cosmic rays to identify subsurface In Situ Resource Utilization (ISRU) materials of interest.

- Develop library of neutron spectra that can be matched for materials
- Develop spectrum "unfolding" process for identification of unmatched materials



Rendering of a proposed Compact Solid State In-Situ Neutron-Gamma Spectrometer for surface prospecting and analysis.

STMD Alignment: This work supports the "Live" STMD thrust, enabling "In-situ Propellant and Consumable Production." The data would apply to neutron spectrometers on the lunar surface, relevant to "Advanced sensors and sensor data analytics."

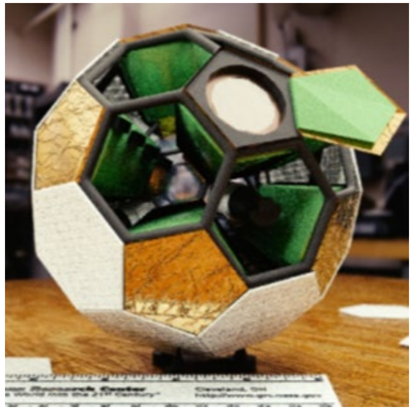
Radiation Sensors for Fission Surface Power

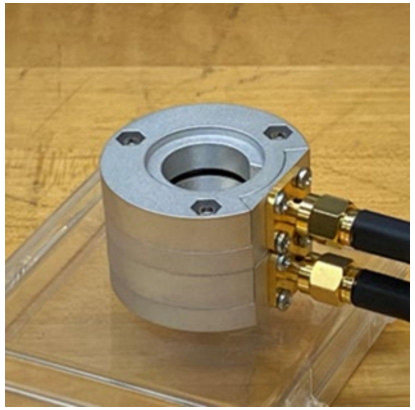
<u>Problem:</u> Robust radiation sensors are needed internal and external to remote nuclear power plants to ensure safe automatic operation.

<u>Solution:</u> Two types of sensors:

- **External sensors:** To be aware of the lunar radiation environment
  - Awareness of how much radiation read by sensors internal to the reactor may be from the space environment
  - Prevents unnecessary automatic shut-down by providing knowledge of how much radiation is naturally occurring in the environment external to the reactor
- **Internal near-core:** For automatic reactor performance monitoring and control
  - Provides data for automated control system
  - Can be integrated with other near-core detectors

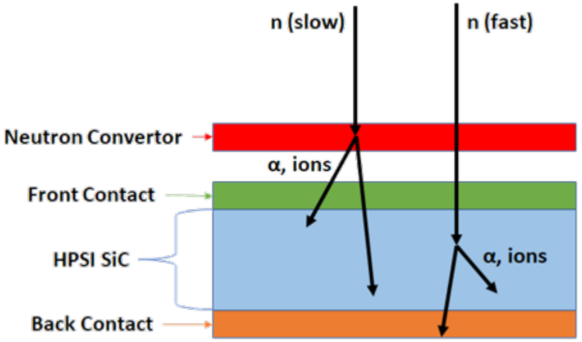
External Environmental Radiation Monitoring

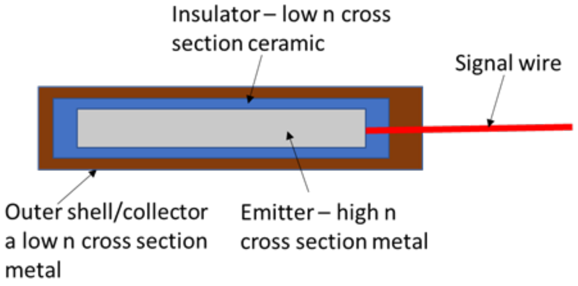




Left: Illustration of a configuration concept for multiple directional detectors. Right: Laboratory demonstrated directional detector.

Near-core Neutron Detectors for FSP Control Systems





Left: SiC neutron detector schematic. Right: SPND configuration concept

Summary

- There is a demonstrated need for more robust, long-lived radiation monitoring sensors to allow more timely understanding for the harsh environment of deep space
- NASA GRC is leveraging expertise in harsh environment thin films, SiC devices & harsh environment packaging, micro-optics, and space-based instrumentation to advance radiation detector technology
- Application of wide band gap semiconductors as radiation detectors holds the promise of improved low-power, robust detectors such as a Compact Full-Field Ion Detector System for Deep Space CubeSats
- Large-area radiation detectors based on wide-band gap silicon carbide are under development and have been demonstrated bench tests
- Applications for these detectors include:
  - Science CubeSats for in-situ studies of SEP and GCR interactions in planetary environments
  - Lunar prospecting using secondary neutron spectra
  - Environmental and operational monitoring for fission surface power systems