



AFRL-AFOSR-VA-TR-2018-0392

Enhanced Test Facility for Survivability and Characterization of Evolving Multiscale Materials in Extreme Plasma Environments

**John Dennison
UTAH STATE UNIVERSITY**

**10/05/2018
Final Report**

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) 27-09-2018		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) Jan 2017 - Sep 2018	
4. TITLE AND SUBTITLE Enhanced Test Facility for Survivability of Characterization of Evolving Multiscale Materials in Extreme Plasma Environments				5a. CONTRACT NUMBER FA9550-17-1-0113	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Dennison, John, R				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UTAH STATE UNIVERSITY USU 1415 Old Main Hill LOGAN UT 84322-4415 Kellie Sue Hedin kellie.hedin@cc.usu.edu 435.797.0470 Senior Grant & Contract Officer, Division of Sponsored Programs				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) USAF, AFRL DUNS 143574726AF OFFICE OF SCIENTIFIC RESEARCH 875 NORTH RANDOLPH STREET, RM 3112 ARLINGTON VA 22203-1954 PATRICIA S. GORSKI 703.696.6208 patricia.gorski@us.af.mil				10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR/PK1	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution A - Approved for Public Release					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A major upgrade to the Utah State University Space Environment Effects Materials Test Facility has been completed. Two new synergistic vacuum test chambers were developed, through addition of novel instrumentation to existing systems. This has greatly enhanced and extended capabilities and ranges to investigate environmental effects on materials and components and to determine long-term survivability of space assets. One chamber probes electron emission, charging, and charge-transport properties of samples under extremes in electron-, ion-, and VUV/UV/Vis/NIR radiation-fluxes and cryogenic to high temperatures. A companion chamber provides versatile, cost-effective, long-duration aging of these samples in extreme simulated space conditions. Notable enhancements include: (i) multiple simultaneous electron and photon fluxes over extended energy ranges to test synergistic effects; (ii) enhanced capabilities for high-precision and high-accuracy electron-, ion- and photon-induced electron yield, emission and transport properties of conducting through extreme insulating materials; (iii) extended wavelength ranges, sensitivity, and imaging speed of absolute VUV/UV/Vis/NIR radiation detection for discharge and luminescence studies; (iv) extended range, sensitivity, and acquisition sp					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)
U	U	U	UU		

Reset

Final Report for
Defense University Research Instrumentation Program (DURIP)
Fiscal Year 2018
PA-AFOSR-2017-0001

Enhanced Test Facility for Survivability and Characterization of Evolving Multiscale Materials in Extreme Plasma Environments



Principle Investigator

Dr. J.R. Dennison
Physics Department
Utah State University
Logan, UT 84322-4415
(435) 797-2936
JR.Dennison@usu.edu

Institutional Representative

Kellie Hedin
Sponsored Programs Office
Utah State University
Logan, UT 84322-1415
(435) 797-0470
Kellie.Hedin@usu.edu

Start Date: 1 January, 2017

End Date: 30 June, 2018

Report Date: September, 27, 2018

TABLE OF CONTENTS

1. Project Overview 2

2. Areas of Study..... 3

3. Description of USU SEEM Test Facility ENHANCMENTS..... 4

 3.1.1 Space Materials Analysis Research Test (SMART) Chamber..... 5

 3.1.2 Low and High Temperature Sample Stage Assemblies 13

 3.1.3 Electron/Ion Sources 19

 3.1.4 Optics Sources 20

 3.1.5 Electron/Ion Detectors..... 21

 3.1.6 Optical Detectors 22

4. PROJECT STATUS..... 23

5. Appendix I – Related SUPPORT 25

6. APPENDIX II – Related Publications 28

7. APPENDIX III – Related PRESENTATIONS..... 30

8. APPENDIX III – Related PRESENTATIONS..... 34

Project Manager: Dr. Ali Sayir, AFOSR/RSA

Enhanced Test Facility for Survivability and Characterization of Evolving Multiscale Materials in Extreme Plasma Environments

*J.R. Dennison
Materials Physics Group
Utah State University*

Abstract

A major upgrade to the Utah State University Space Environment Effects Materials Test Facility has been completed. Two new synergistic vacuum test chambers were developed, through addition of novel instrumentation to existing systems. This has greatly enhanced and extended capabilities and ranges to investigate environmental effects on materials and components and to determine long-term survivability of space assets. One chamber probes electron emission, charging, and charge-transport properties of samples under extremes in electron-, ion-, and VUV/UV/Vis/NIR radiation-fluxes and cryogenic to high temperatures. A companion chamber provides versatile, cost-effective, long-duration aging of these samples in extreme simulated space conditions. Notable enhancements include: (i) multiple simultaneous electron and photon fluxes over extended energy ranges to test synergistic effects; (ii) enhanced capabilities for high-precision and high-accuracy electron-, ion- and photon-induced electron yield, emission and transport properties of conducting through extreme insulating materials; (iii) extended wavelength ranges, sensitivity, and imaging speed of absolute VUV/UV/Vis/NIR radiation detection for discharge and luminescence studies; (iv) extended range, sensitivity, and acquisition speed of surface voltage measurements; (v) VUV radiation for photoyield testing and radiation damage; and (vi) compatibility with greater sample sizes and geometries, including larger area components (up to 1U Cubesat faces). Ensuing research focuses on scientific models and wide-ranging applications related to the evolution of complex materials (including layered and nanostructured materials and composites) due to exposure to extreme plasma environments, electric fields, temperatures, and vacuum. Applications to space power and propulsion, remote sensing, and space situational awareness will also be pursued.

1. PROJECT OVERVIEW

A reoccurring theme in many of the research activities identified in the AFOSR *Broad Agency Announcement* is the characterization, evolution and survivability of diverse materials subject to extreme conditions. This project developed instrumentation to investigate the underlying principles of charging and discharge of materials under extreme conditions and the related emission of both charged particles and photons. The project emphasized the extension of our previous studies to: (i) more complex materials (including novel, layered and nanostructured materials and composites); (ii) the evolution of materials and their signatures due to exposure to extreme environments; and (iii) more extreme conditions (including plasmas, extended particle and photon fluxes, higher electric fields, and extended cryogenic to elevated temperatures).

The USU Space Environment Effects Materials (SEEM) Test Facility is perhaps the leading research center for the study of charging properties of spacecraft materials in the US, and one of the premier facilities worldwide. The MPG performs state-of-the-art ground-based testing of electrical properties of both conducting and insulating spacecraft materials, particularly electron emission, conductivity, luminescence, and electrostatic discharge. Our efforts in this field over more than two decades have been primarily motivated by the space community's concern for spacecraft charging caused by plasma environment electron-, ion-, and photon-induced currents and for radiation modification and damage of spacecraft materials and components. Our experience, facilities, and capabilities related to charging and radiation effects on spacecraft materials are directly relevant to basic science issues and to design and survivability issue facing the Air Force. The MPG has studied how variations in temperature, accumulated charge, exposure time, contamination, surface modification, radiation dose rate, and cumulative dose can cause both recoverable changes and permanent modification in these electrical properties, or changes in related structural, mechanical, thermal and optical properties of materials and systems.

The DURIP project implemented a major upgrade for the SEEM Test Facility, through development of two new synergistic system components. Two existing UHV vacuum test chambers were extensively modified with the addition of custom instrumentation described herein. This has greatly enhance and extend our capabilities to test and quantify the effects of extremes in electron-, ion-, VUV/UV/Vis/NIR radiation-fluxes, temperatures and vacuum encountered in extreme environments and to determine long-term survivability. The new Space Materials Analysis Research Test (SMART) chamber will probe spacecraft charging and charge transport properties of materials samples and small components under a wide variety of environmental conditions. Some notable enhancements include:

- (i) multiple simultaneous electron and photon fluxes over extended energy ranges to test synergistic effects;
- (ii) enhanced capabilities for high-precision and high-accuracy electron-, ion- and photon-induced electron yield, emission and transport properties of extreme insulating to conducting materials;
- (iii) extended range, sensitivity, and acquisition speed of surface voltage measurements;
- (iv) extended wavelength ranges, sensitivity, and imaging speeds of absolute VUV/UV/Vis/NIR radiation detection for discharge and luminescence studies;
- (v) extension of the incident photon range to include VUV for photoyield and radiation damage testing;
- (vi) investigations over extended low and high temperatures, from ~40 K to ~700 K; and
- (vii) compatibility with greater sample sizes and geometries, including larger area components (up to 1U Cubesat faces) and dusts.

The new Space Survivability Test (SST) chamber provides long-duration exposure of samples and small components to simulated space conditions, with real-time *in situ* monitoring of key material properties.

One such critical issue is the effect of radiation dose on the electron emission and transport properties related to charging, as well as optical, thermal and mechanics properties. Radiation induces defect creation, which is the ultimate cause of the damage and the changes in properties. The MPG have studied radiation

effects on conductivity [34], electrostatic breakdown, RIC, electron emission], and cathodoluminescence. These are complemented by our theoretical efforts to model the effects of defect generation.

The existing EET and new SMART chambers provide necessary test facilities to characterize many aspects of radiation damage. Radiation damage can be induced with low level sources such as the electron beams and UV sources in the SMART and SST chambers. The SMART and SST high intensity VUV Lyman- α sources extend UV damage studies to higher energies, covering the full range of more intense space electromagnetic radiation. The proposed higher energy 80 keV electron gun enables RIC studies in the SMART chamber. A low-activity 100 mC Sr⁹⁰ beta source has recently been developed for use in the existing EET chamber, as well as the new SST and SMART chambers. It provides a low-level, broadband (~0.2-2.6 MeV) source similar to the ambient GEO plasma spectrum for environmental and radiation damage tests at higher energies and deeper penetration. We have conducted studies at even higher doses and energies at the nearby Idaho Accelerator Center (IAC), which has numerous electron and proton accelerators and radioactive sources. IAC facilities used with an additional MPG test chamber [33] measured radiation damage effects [34] and RIC as a function of temperature, dose rate and electric field [33,77] for samples subjected to 0.3 to 25 MeV electron beams.

2. AREAS OF STUDY

A problem closely related to dynamic materials and contamination is the charging behavior of multi-layered materials, with layer dimensions or inhomogeneities in material composition on length scales comparable to or less than the penetration depth of radiation into materials (typically less than a few μm). Composite and nanostructured materials with inhomogeneities on similar length scales have also been studied. At some level, the contamination problem addresses material changes on a temporal scale, while layering and nanostructured materials address changes on a spatial scale.

Our ongoing studies of emission, discharge], cathodoluminescence, and conductivity of layered composites and nanodielectric materials have been related to preliminary multilayer models of penetration, emission, conduction, and luminescence under development by the MPG. The range model also relates to our interest in the synergistic effects due to simultaneous electron beam and broad distributions of incident electron energies more representative of the true flux distributions encountered in real situations than standard monoenergetic beam tests. The new multiple electron sources over extended energies will be invaluable for layering studies, multiband experiments, and layered/composite models.

We have also found that layered, composite, and nanodielectric materials exhibit unexpected arcing, cathodoluminescence, electron emission, and conduction behavior that is dependent on their structural scales compared with electron or photon penetration lengths. The enhanced sensitivity, increased spatial resolution and much fast image acquisition rates of the proposed cameras will enable more detailed studies.

Understanding charge deposition and transport in layered materials is closely related to our ongoing pulsed electro-acoustic (PEA) project, funded by AFOSR. While measurements of the electron emission and displacement currents, the evolving surface potential, and the electrostatic breakdown of materials exposed to particle fluxes have provided important information on spacecraft charging, the “holy grail” of materials characterization in spacecraft charging is a non-destructive method to directly measure the magnitude and the spatial and temporal evolution of internal charge layers on length and time scales appropriate to practical spacecraft charging problems.

PEA measurements offer the potential of just such a direct method. PEA techniques measure the displacement currents resulting from motion of internal charge distributions caused by ultrasonic probe pulses. Spatial resolution of $\leq 1 \mu\text{m}$ is required to adequately resolve charge distributions for incident electrons with energies at the highest fluxes in space environments; electrons at these energies (1-50 keV) have relatively small penetration ranges (~1-10 μm) into typical thin film spacecraft materials. Another recent enhancement is “open PEA” systems that provide access to samples by electron beam irradiation, a significant improvement in simulating space conditions in laboratory tests.

The MPG and Box Elder Innovations have an AFOSR-sponsored Phase I/II STTR project to develop

such a high resolution PEA sensor with $<1 \mu\text{m}$ spatial resolution sufficient to investigate charging more commonly encountered in the space environment. The objective is to construct a new high-resolution PEA detector to be used in conjunction with a spacecraft charging test chamber. Obviously, the SMART chamber would be an ideal location for such a new PEA sensor. The SMART chamber has all requisite charging sources and detectors. Its open design would facilitate inclusion of the new PEA probe.

Recent MPG charging studies observed electron-induced photon emission—including cathodoluminescence, arcs, “flares” and bremsstrahlung—from dielectric surfaces as they underwent electron beam bombardment. Initial studies of charging and luminescence, including cryogenic tests at $<40 \text{ K}$, led to a model of the total emission intensity dependence on external parameters including: deposited particle energy, flux and power; exposure and recovery time; and sample temperature, structure and thickness. The initial studies primarily focused on space-based observatory materials, including carbon and fiberglass composite structural materials with epoxy layers, multiple variations of bulk and carbon-loaded polyimide, nanodielectric composites, optical glasses, and the optical coating SiO_2 . Measured emission spectra provided substantial information about the nature and occupancy of the defect densities of states.

With the development of new, more advanced and sensitive space-based observatories and sensors, it is important to study and understand photon emission of such materials induced by the space plasma environment on an absolute scale. To minimize stray light contamination and maximize optical detection sensitivity, it is important to minimize the photon emission within the collection bandwidth of the materials within the field of view of the collection optics or of the collection optics themselves. Our high sensitivity studies have been able to measure absolute spectral radiance data at $<10\%$ of the stray light intensity of the natural zodiacal background. Measured emission spectral data over $\sim 200 \text{ nm}$ to $\sim 5000 \text{ nm}$ is essential in determining the stray light contamination levels in specific applications.

The enhanced capabilities for the new DURIP system, which provide higher resolution images, higher sensitivity cameras and spectrometers, and better absolute calibration, have already proved vital to additional studies in this important area. The optical sensors, coupled with the electron current detection, also provided enhanced capabilities to study fast ESD signals; the $<4 \mu\text{s}$ acquisition speed of the new cameras will be particularly useful.

The environmentally-induced optical emissions i have also been found to be of interest for space object identification and space situational awareness applications. Initial estimates of intensities in radio to x-ray wavelengths produced by representative space fluxes—based largely on USU measurements—found that many such emissions could potentially be observed by co-orbiting LEO or GEO satellites and in some cases perhaps even from ground-based observations. Even if emissions are not sufficient during lower-level emission during quiescent space conditions, there may be observable signals during intense solar activity, from dedicated luminescent sensors on satellites, or from active probing. It is also conceivable that luminescence spectra or bidirectional reflectance signatures could indicate material composition, material degradation or contamination, or surface charging.

We have already begun to use enhanced capabilities of the SMART chamber (including optical cameras and spectrometers and an x-ray spectral detector) to determine if these emissions are of sufficient intensity to provide characteristic signatures of insulating components of a space asset, such as solar array cover glasses or thermal insulation coatings.

3. DESCRIPTION OF USU SEEM TEST FACILITY ENHANCEMENTS

This DURIP project enabled a major enhancement of the USU Space Environment Effects Materials (SEEM) test facilities, prominently including third generation sources and detectors based on extensions of earlier custom state-of-the-art systems designed and built at USU. There are two new synergistic tests chambers, the Space Materials Analysis Research Test (SMART) chamber and the Space Survivability Test (SST) chamber. For both of these new chambers, the custom design was accomplished at USU and the main vacuum chambers and stands have completed. New DURIP funded sample stages, sources and

Table I. USU DURIP Project Budget Summary

Instrumentation Category	DURIP Equipment		
	Equipment	Chamber	Figure
SMART Vacuum Chamber Enhancements	USU, Kratos, MDC, other	SMART	1
Space Survivability Test Vacuum Chamber Enhancements	USU, MDC	SST	5
Cryo Test Chamber	USU MDC,	Cryo	9, 11
Sample Stages and Test Fixtures			
Low Temp. Sample Stage Assembly	USU, ASR	SMART, SST, Cryo	10, 11
Closed cycle He refrigerator	ASR	SMART, SST, Cryo	9, 10, 11
SST Test fixtures	USU	SST	6, 7, 8
Conductivity, RIC, Impedence test fixtures	USU	Cryo	9
Electron Sources			
Low Energy (20 eV-5 keV) electron gun	Staib	SMART, EET, Cryo	9
High energy (5 keV-80 keV) electron gun	Staib	SMART, EET, Cryo	9
Electron flood gun	USU	SMART, EET, Cryo	12
HGRFA electron flood gun	USU	SMART, EET, Cryo	2, 12
Optical Sources			
UV/Vis fiber optic source	Stellarnet	SMART, SST, EET	15
NIR fiber optic source	Stellarnet	SMART, SST, EET	15
VUV Kr Resonance Sourcece	Resonance Limited	SMART, SST, EET	15
Electron/Ion Detectors			
HGRFA	USU Custom	SMART, SST, Cryo	2, 3, 4
Surface voltage probe	USU Custom	SMART, SST, Cryo	2
Impedance Analyzer	HP		
Electrometers	Keithley	SMART,EET,SST,Cryo	16
Digital Oscilloscopes	Tektronix	SMART,EET,SST,Cryo	16
Electrometers	USU	SMART,EET,SST,Cryo	16
Optics Detectors			
Vis/NIR video camera	Syntronics	SMART, SST, EET	14
NIR video camera	Sensors Unlimited	SMART, SST, EET	14
UV/Vis/NIR Spectrometer	Stellarnet	SMART, SST, EET	14
NIR Spectrometer	Stellarnet	SMART, SST, EET	14
X-ray detector	Moxtex	SMART,EET	13

detectors are described below, organized by the type of instrumentation. Table I identifies the major components of the upgrades.

3.1.1 Space Materials Analysis Research Test (SMART) Chamber

The SMART chamber probes electron emission, luminescence, charging and charge transport properties of materials samples and small components under an extended set of extreme conditions. It uses an existing UHV surface analysis (Kratos) test chamber—with accompanying pumps, gauges, load- lock system and stand as the vacuum skeleton (see Fig. 1).

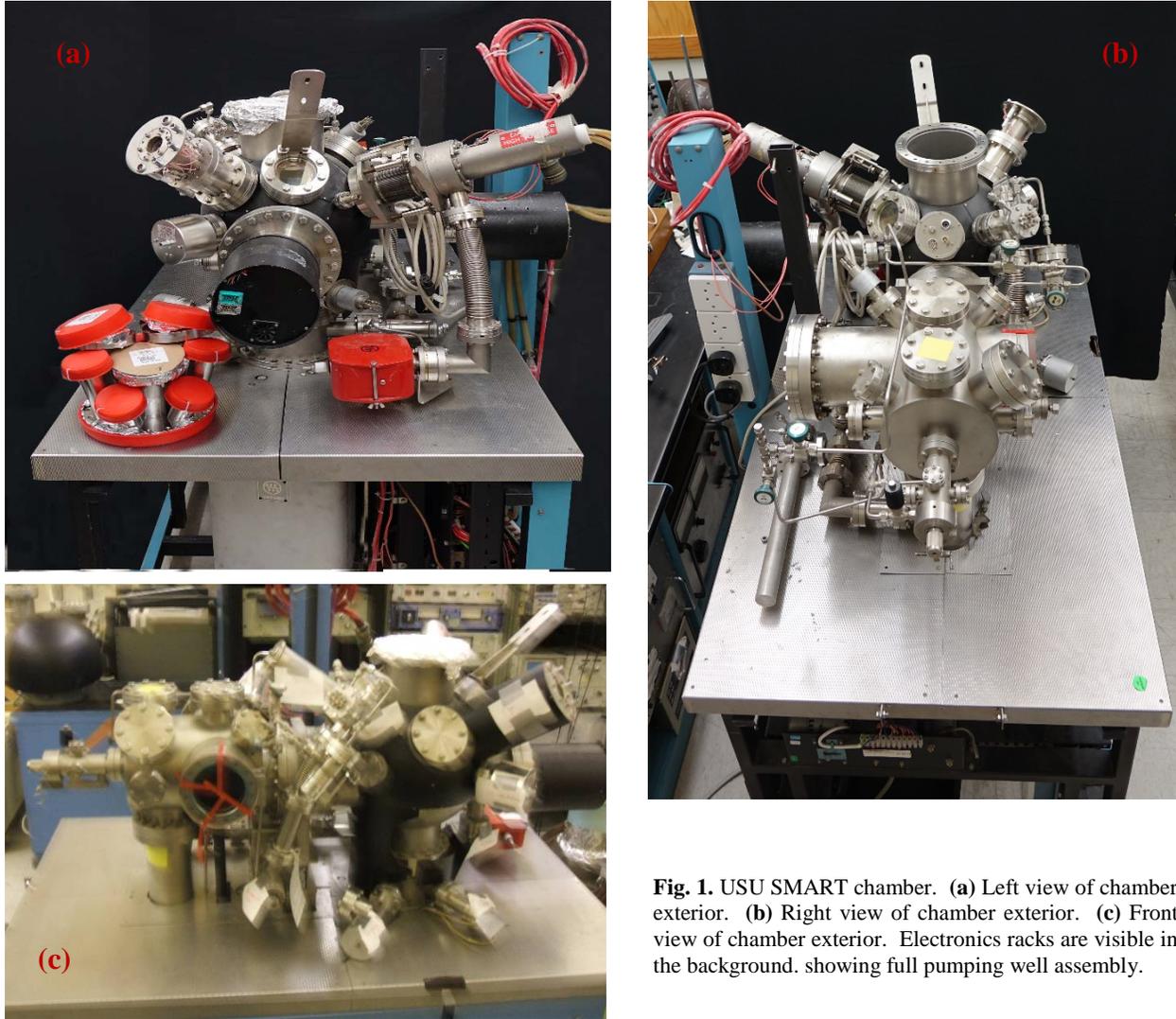


Fig. 1. USU SMART chamber. **(a)** Left view of chamber exterior. **(b)** Right view of chamber exterior. **(c)** Front view of chamber exterior. Electronics racks are visible in the background, showing full pumping well assembly.

EXISTING COMPONENTS

- A SPHERICAL CHAMBER
- B ION PUMP
- C GATE VALVE
- D SMALL ION GUN
- E LARGE ION GUN
- F SECONDARY ELECTRON DETECTOR
- G SLR CAMERA
- H MONOCHROMATOR

OPTICAL SOURCES

- I MONOCHROMATOR UV SOURCE
- J PHOTO-ELECTRON GUN UV SOURCE
- K TIMING LIGHT

OPTICAL DETECTORS

- L InGaAs CAMERA
- M XYBION CAMERA
- N INTEGRATING SPHERE
- O EMISSIVITY PROBE
- P X-RAY DETECTOR
- Q COLLIMATING LENSE
- R UV MONOCHROMATOR
- S WEBCAM

ELECTRON/ION DETECTORS

- T FLIPPER
- U HGRFA

ELECTRON/ION SOURCES

- V HEED GUN
- W SSC FLOOD GUN
- X LOW-ENERGY ELECTRON GUN
- Y PHOTO-ELECTRON FLOOD GUN

NEW VACUUM COMPONENTS

- Z TURBO PUMP
- AA XYZ TRANSLATOR
- BB ROTARY FLANGE
- CC CUSTOM BOTTOM ADAPTER FLANGE
- DD CUSTOM TOP ADAPTER FLANGE
- EE SAMPLE STAGE
- FF CRYOSTAT

Components are identified in the legend. Color coding distinguishes the existing components (**GREY**), new vacuum components (**BLUE**), electron/ion sources (**RED**) and detectors (**ORANGE**), and optical sources (**YELLOW**) and detectors (**GREEN**).

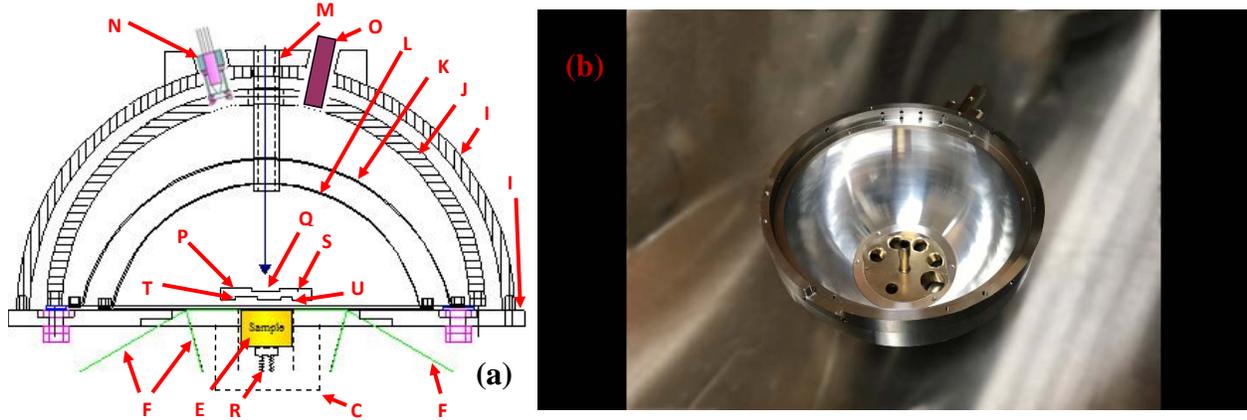


Fig. 2. Custom Hemispherical Grid Retarding Field Analyzer (HGRFA). (a) Cross section of HGRFA and surface voltage detectors. Components are identified in the table below. (b) Video of HGRFA detector assembly. (c) Photograph of SVP, mounted on HGRFA, with the collecting hemisphere removed. (d-f) Surface Voltage Probes (SVP). (d) Schematics of the electrostatic field probe (EFTP) assembly showing charge distribution within the EFTP assembly. Shown are the sample (left), EFTP (center), and electrostatic field probe, (right). (e) SVP, Faraday cup, and phosphor screen probes using novel pantograph mount in combination with a precision *in vacuo* XY translation stage. (f) Photograph of sample side of HGRFA SVP assembly.

LEGEND		
A4 HGRFA Hinged Mount	I4 HGRFA Hemispherical Shield	R4 Sample Current Lead
B4 Sample Carousel/HGRFA Rotation Shaft	J4 HGRFA Collector	S4 SVP Faraday Cup
C4 UHV Stepper Motor	K4 HGRFA Bias Grid	T4 SVP 7 mm Dia. Au Electrode
D4 Sample Block Faraday Cup	L4 HGRFA Inner Grid	U4 SVP 3 mm Dia. Au Electrode
E4 Sample (10 mm)	M4 HGRFA Drift Tube	V4 SVP Wiring Channel
F4 Sample Block	N4 Electron Flood Gun	W4 EFTP Vacuum Feedthrough
G4 Cryogen Reservoir	O4 LED Light Source	X4 EFTP Witness Plate
H4 HGRFA Face Plate	P4 Surface Voltage Probe (SVP)	Y4 Electrostatic Field Probe
	Q4 Au Electron Emission Standard	Z4 Probe XYZ Translator

A companion UHV chamber, the Space Survivability Test (SST) chamber (see Fig. 5), is designed to simulate space environments to facilitate long-duration tests of material modification due to extreme environment interactions. Small scale tests can be customized for much more economical testing than in other existing large scale environmental chambers. Critical environmental elements to be simulated in the SST chamber include UHV, a FUV/UV/VIS/NIR solar spectrum, an electron plasma flux, and temperature extremes. A temperature range from <30 K to >450 K is achieved using the two sample stages. The versatile sample holder and radiation mask allow for cost-effective, customizable investigations of multiple small-scale samples under diverse conditions. *In situ* monitoring capabilities allow characterization at frequent intervals during the course of the exposure cycle, while the samples are still under vacuum. An automated data acquisition system monitors and records the temperature, pressure, electron, and photon fluxes. Calibrated reflectivity, absorptivity, and emissivity of the samples can be measured using *in situ* IR absorptivity/emissivity probes and an integrating sphere coupled with external fiber optic spectrometers.

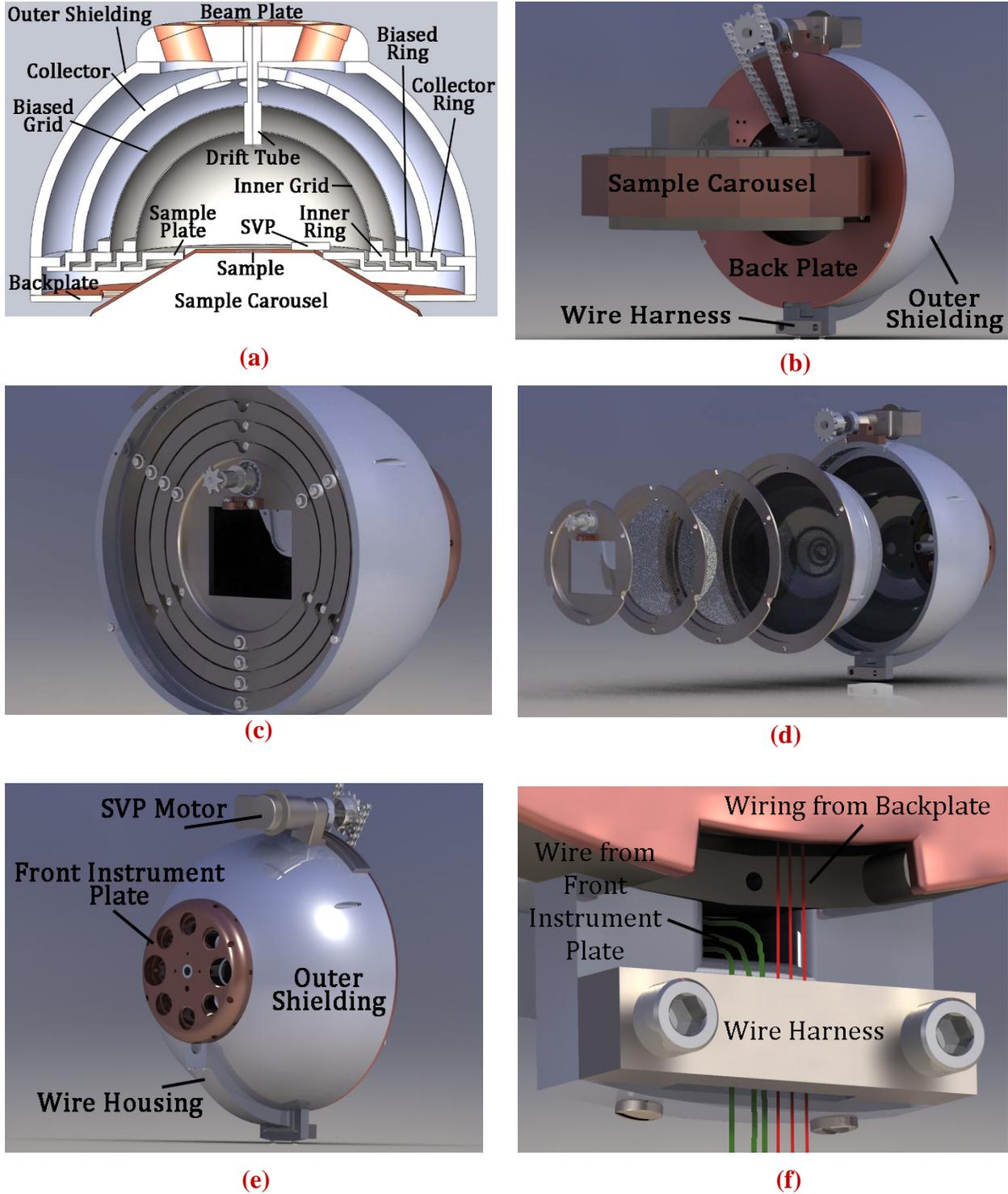


Fig. 3. Custom Hemispherical Grid Retarding Field Analyzer (HGRFA) design drawings. (a) Cross section of HGRFA and sample stage. (b) Assembly drawing of HGRFA and sample carousel. (c) Assembled view of the HGRFA detector hemispheres, sample side. (d) Exploded view of the HGRFA detector hemispheres. (e) Assembled view of the HGRFA detector hemispheres, electron gun side. (f) Detail of wiring harness and strain relief.

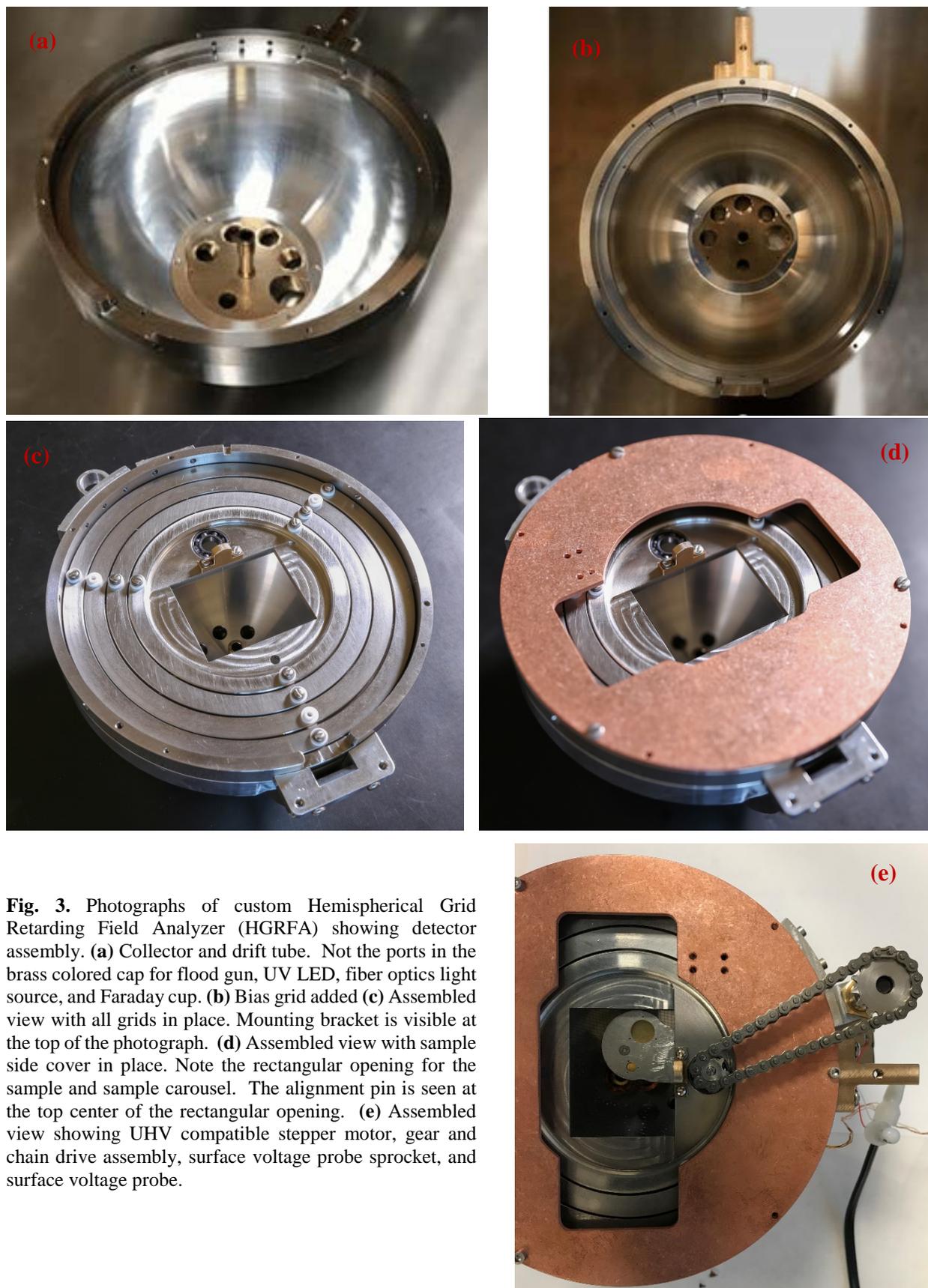


Fig. 3. Photographs of custom Hemispherical Grid Retarding Field Analyzer (HGRFA) showing detector assembly. (a) Collector and drift tube. Note the ports in the brass colored cap for flood gun, UV LED, fiber optics light source, and Faraday cup. (b) Bias grid added (c) Assembled view with all grids in place. Mounting bracket is visible at the top of the photograph. (d) Assembled view with sample side cover in place. Note the rectangular opening for the sample and sample carousel. The alignment pin is seen at the top center of the rectangular opening. (e) Assembled view showing UHV compatible stepper motor, gear and chain drive assembly, surface voltage probe sprocket, and surface voltage probe.

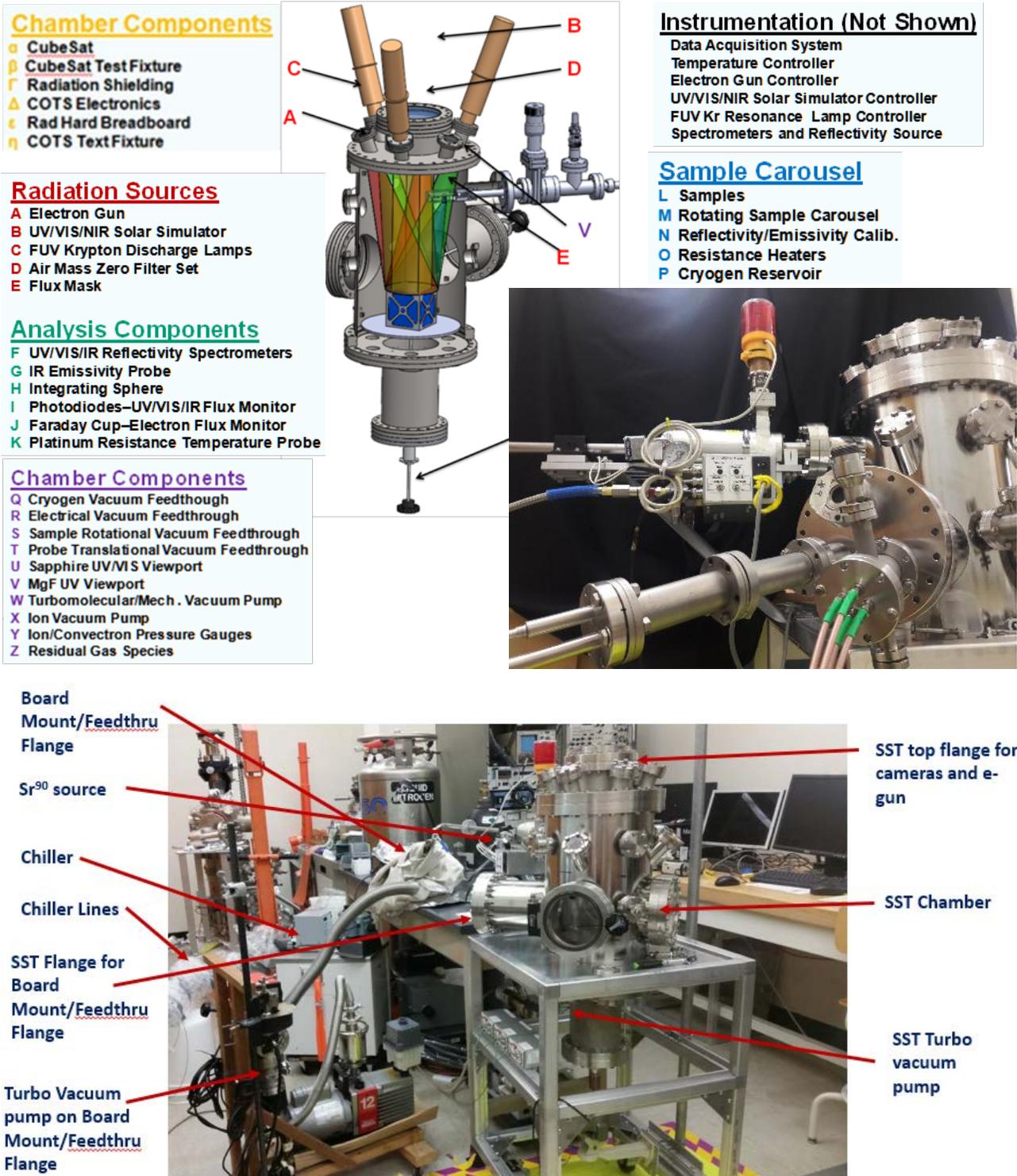


Fig. 4. USU Space Survivability Test (SST) vacuum chamber. **(Top Left)** Chamber vertical cutaway view showing electron (red), NIR-Vis-UV (blue), Far UV (yellow), and Sr⁹⁰ beta radiation (green) flux trajectories. **(Middle Right)** Photograph of vacuum chamber showing the Sr⁹⁰ source translation stage, shutter, and warning light. Electrical and liquid nitrogen feedthroughs are visible in the lower center foreground. **(Bottom)** Space Survivability Test (SST) Chamber during testing.

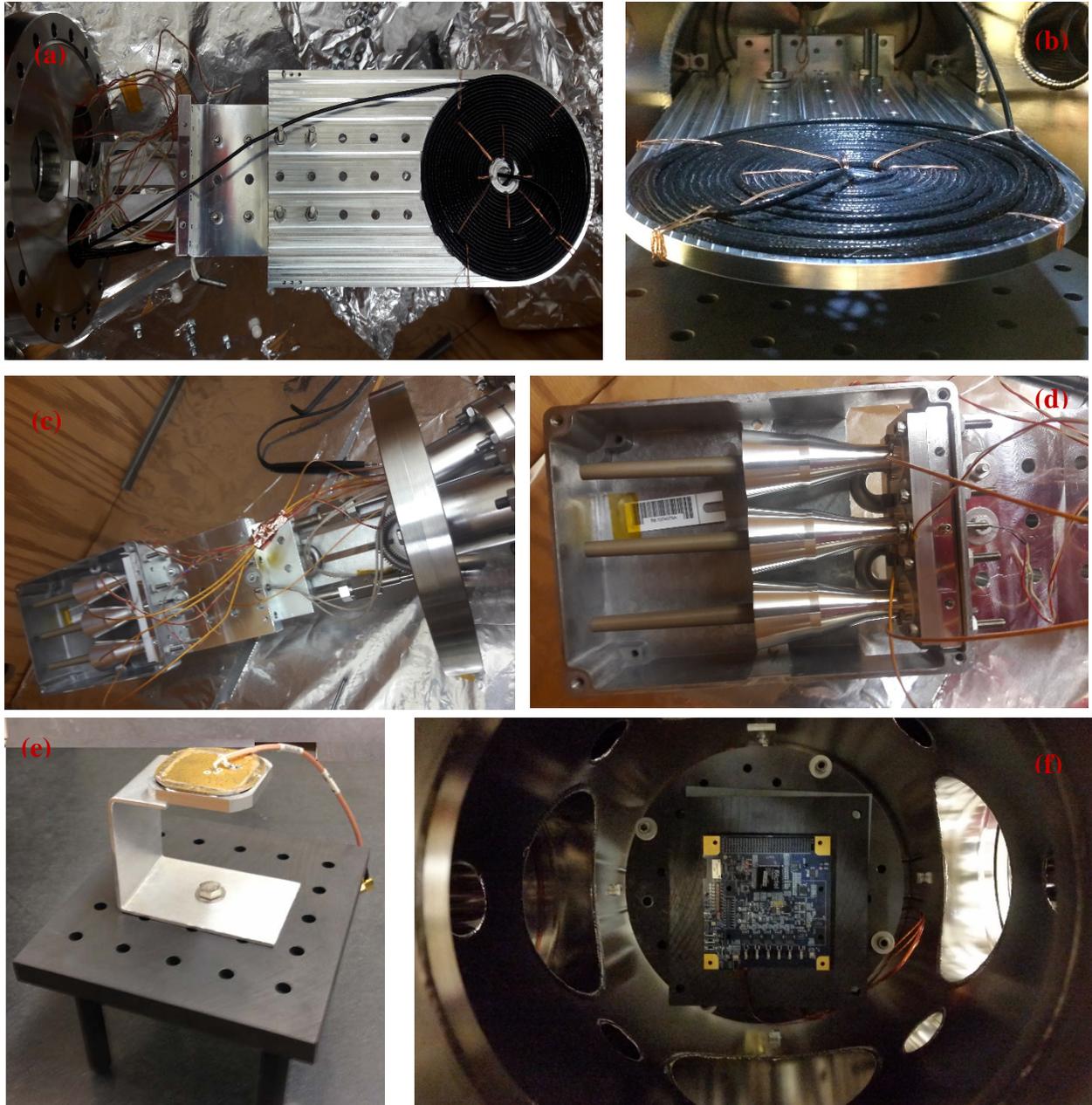


Fig. 5. USU Space Survivability Test (SST) vacuum chamber test fixtures. (a) Fixture for testing radiation effects of RF cables at low temperature. (b) Close up view of Cable test fixture showing long coiled cable in flat geometry to achieve uniform irradiation doseage. RF, conductivity, and arcing tests were conducted *in situ* during extended ~100 Mrad irradiation tests. (d) Fixture for testing radiation effects of RF antennas at low temperature. (e) Test fixture for radiation damage tests of optical focal plane array. Optical element is mounted on the radiation-hard graphite breadboard used for many different tests. (f) COTS test fixture with a custom electronics board under radiation testing. View is taken from the top of the SST chamber looking down

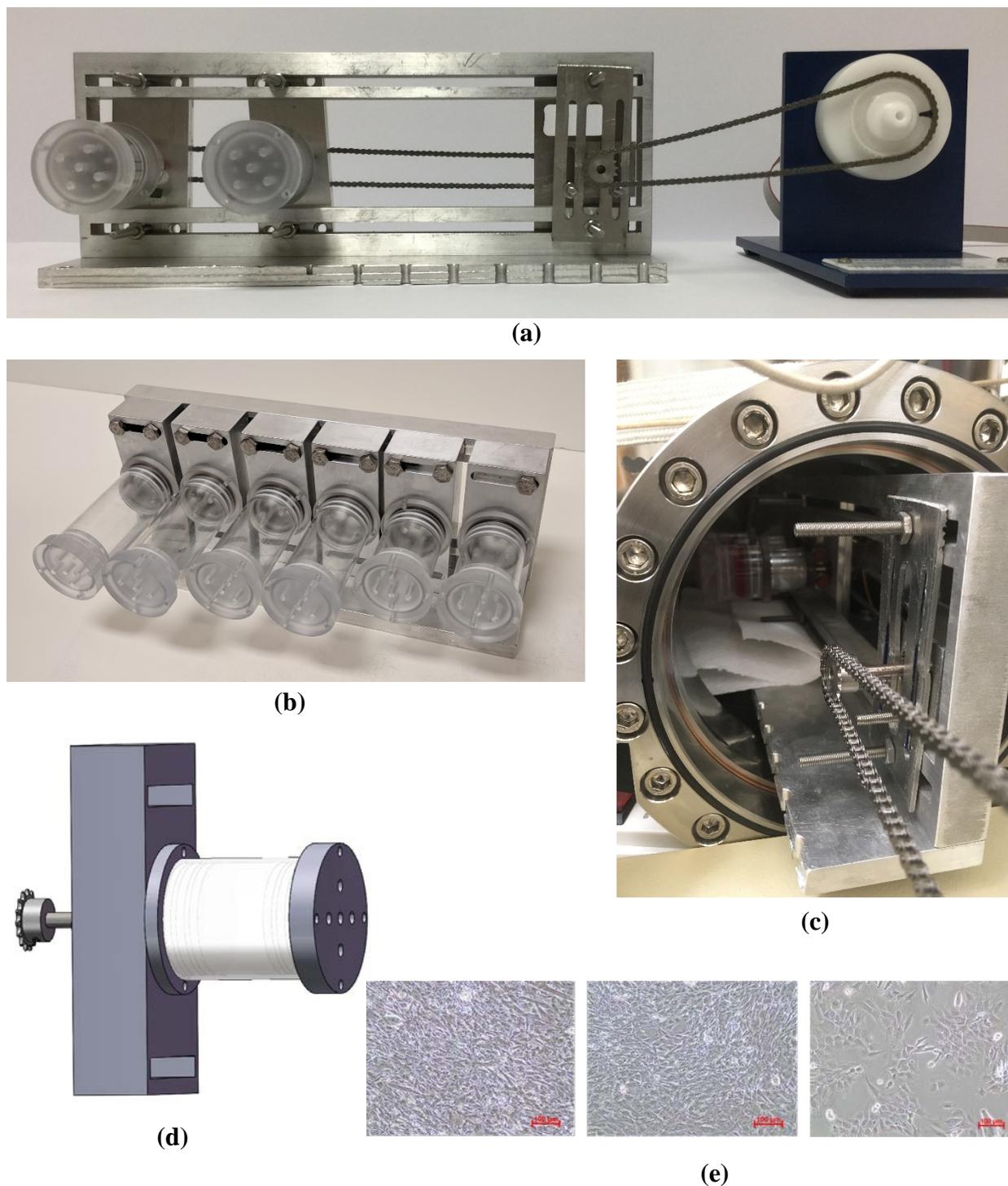


Figure 7. USU Space Survivability Test (SST) vacuum chamber biological test fixtures for simultaneous radiation and microgravity environments. The custom assembly holds skeletal and cardio-muscular cells on biological compatible spherical substrates. Penetrating beta radiation from the Sr^{90} source is used. Microgravity is simulated by having the cell substrates falling through a viscous fluid at terminal velocity while the test fixture is rotating. (a) Two test containers attached to the stepper motor with a chain drive. (b) Six test containers mounted on the custom test fixture. (c) Test fixture being inserted into the SST vacuum chamber. The chain drive is visible in the foreground. (d) Assembly drawing of the test container. (e) Scanning electron microscope images of muscle cells with (left) no irradiation, (center) modest irradiation, and (right) heavy irradiation.

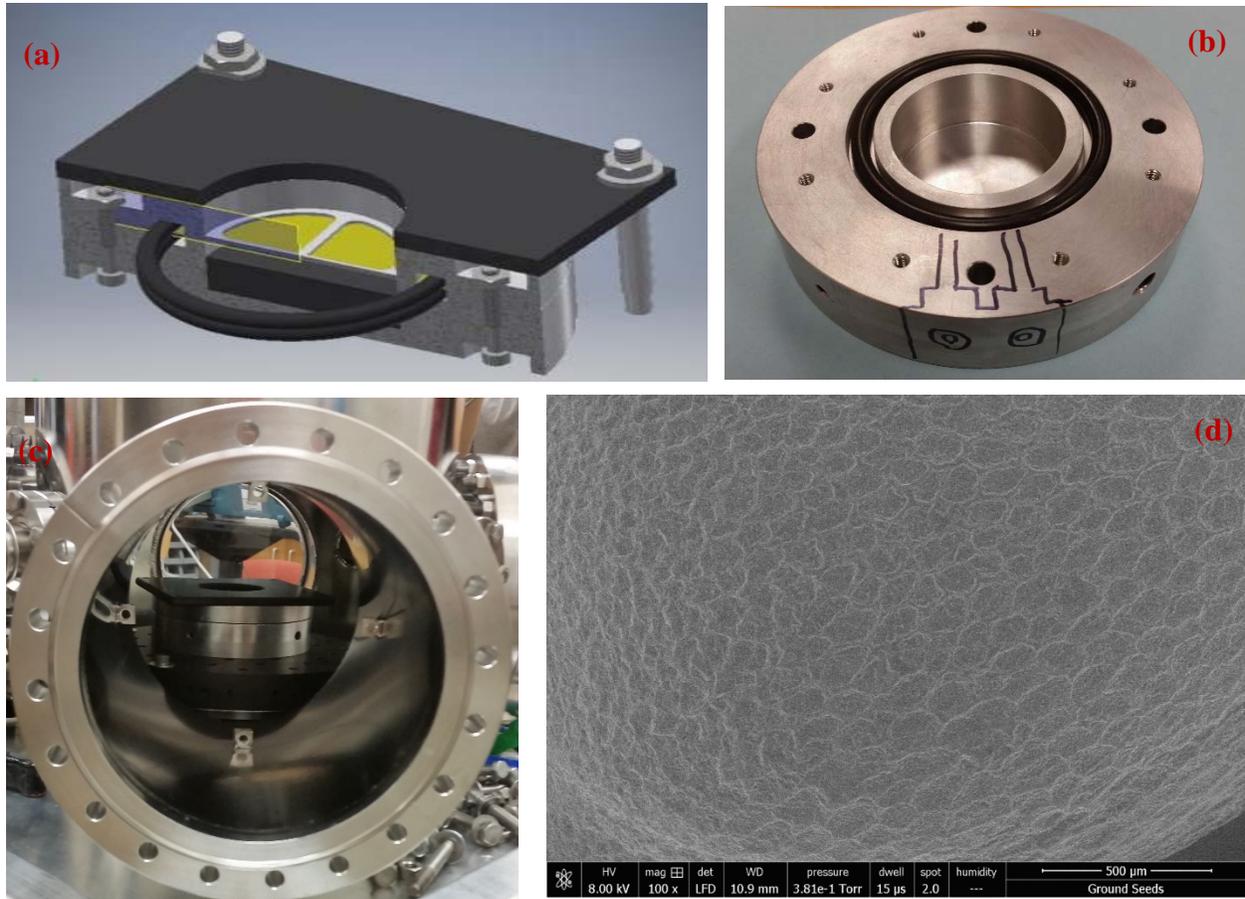


Figure 6. Custom test cell for maintaining samples in controlled atmospheric conditions within the USU Space Survivability Test (SST) vacuum chamber. This has been used as a test fixtures for biological samples under for radiation. (a) Cut-away view of cell. (b) View of cell with thin stainless steel radiation window removed. (c) Test fixture mounted inside the SST chamber. Note the graphite radiation mask on the top of the cell, which is resting on the radiation-hard graphite breadboard. (c) Scanning electron micrograph of an irradiated radish seed. Space effect of seed flown on a Russian space capsule were tested.

Numerous custom test fixtures have been designed for various project in the SST chamber. Figure 5 shows a number of these custom test fixtures. These include: (a) a fixture for testing radiation effects of RF cables at low temperature. (b) a fixture for testing radiation effects of RF antennas at low temperature. (c) a test fixture for radiation damage tests of optical focal plane array, and (d) a COTS test fixture with a custom electronics board under radiation testing. Figure 6 shows a custom test cell for maintaining samples in controlled atmospheric conditions within the USU Space Survivability Test (SST) vacuum chamber. Figure 7 shows the USU Space Survivability Test (SST) vacuum chamber biological test fixtures for simultaneous radiation and microgravity environments.

3.1.2 Low and High Temperature Sample Stage Assemblies

Measurements of the electron transport and emission properties of spacecraft materials—particularly extreme insulators—has become an important issue for spacecraft and IR observatories that operate in low temperature environments. Of particular concern is that conductivity—and hence discharge—of critical

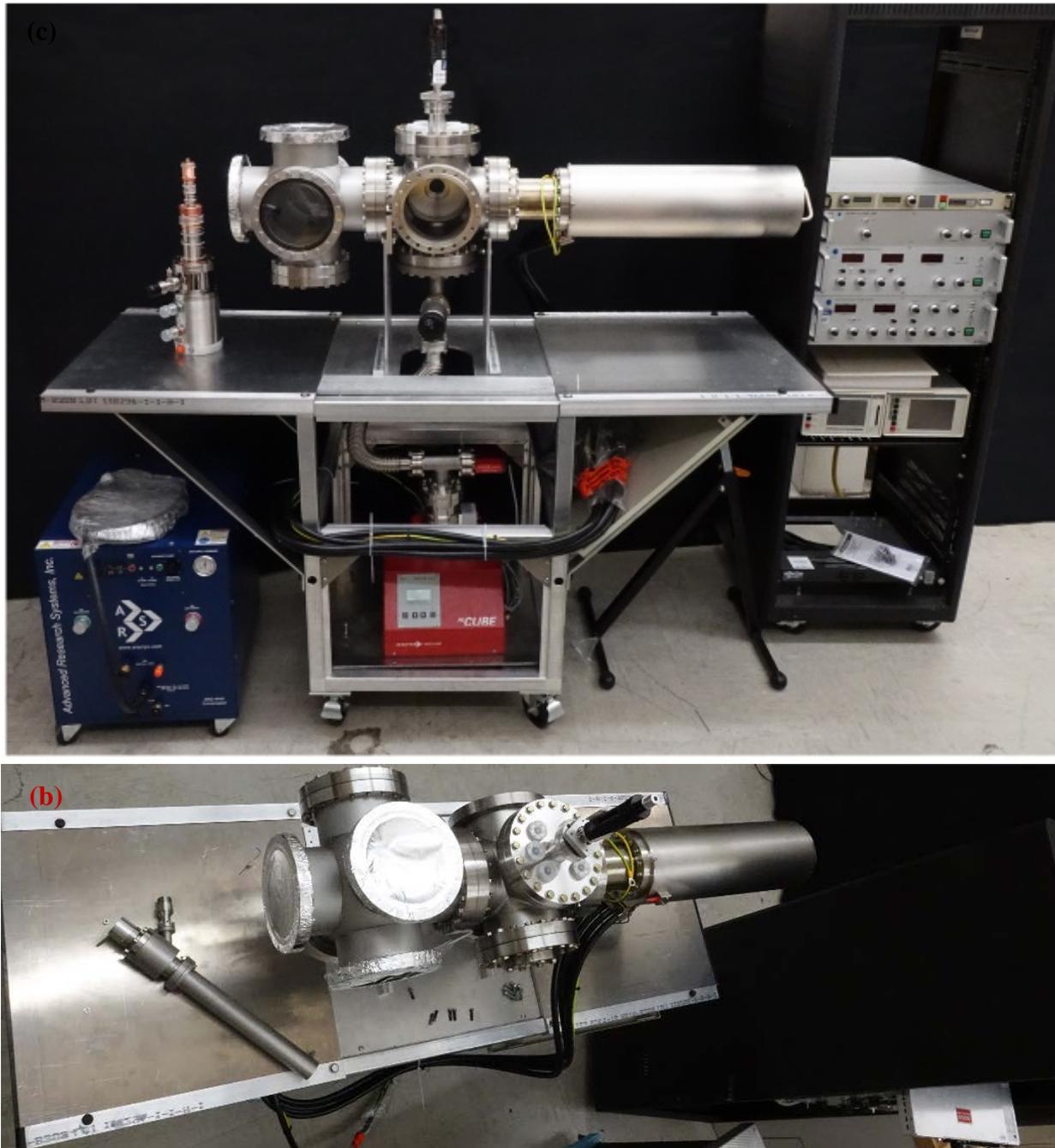


Fig. 8. USU Irradiation chamber. **(a)** Front view of chamber exterior. 80 keV electron gun is shown mounted horizontally on the right side of the chamber. The closed-cycle He cryostat is to be mounted diametrically opposed to this electron gun, horizontally on the left side of the chamber. A translation stage with a sample mount, shutter, and Faraday cup is visible in the open port. The red turbomolecular pumping system is below the main chamber. The electron gun power supplies and control units are visible in the equipment rack at right. The vacuum gauge and temperature controller are in the rack below. The cryostat compressor is the blue unit at the lower left. **(b)** Top view of the irradiation chamber. The high energy electron gun is at right and the low energy electron gun is laying out on the chamber stand at left.

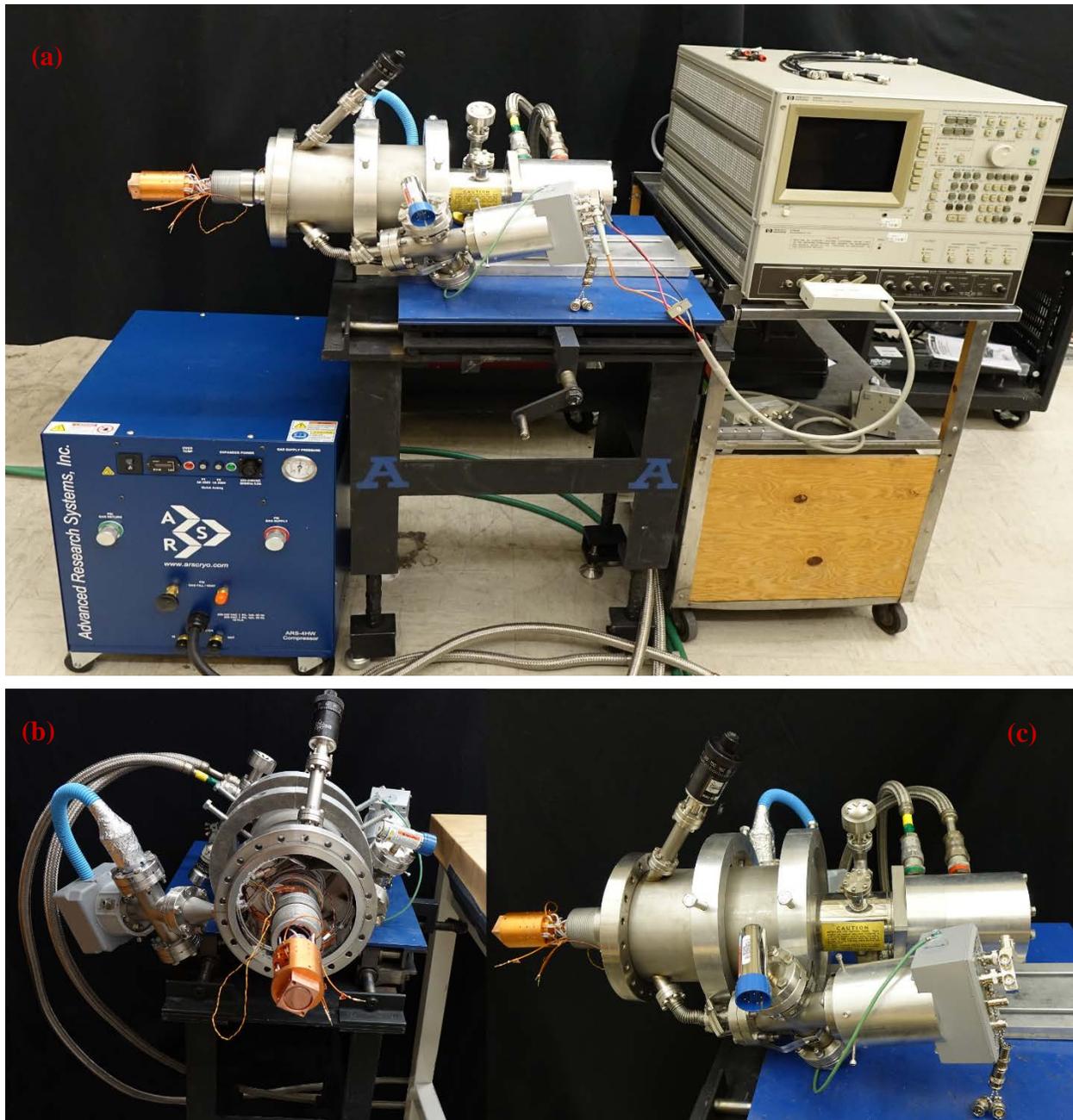


Fig. 9. Low Temperature Stage Assembly. Shown are the closed cycle He refrigerator and compressor, cryostat cabling and feedthroughs, custom cryostat “sample round”, and impedance analyzer,

components rapidly diminishes at low temperature, leading to the potential for catastrophic charging. Other low temperature phenomena like enhanced cathodoluminescence or arcing, and embrittlement are also of concern. High temperatures from intense radiation or plasmas affect material integrity, radiation damage, conductivity, emission and optical properties.

Therefore, two sample stages for extreme low (<30 K) and high (>650 K) temperatures have been designed and are being built using design elements from our EET and cryostat chambers. The stages are interchangeable and will work on either the SMART or SST chambers. The sample stage carousels are versatile designs that allows for a variety of configurations and sample sizes. The horizontal orientation of

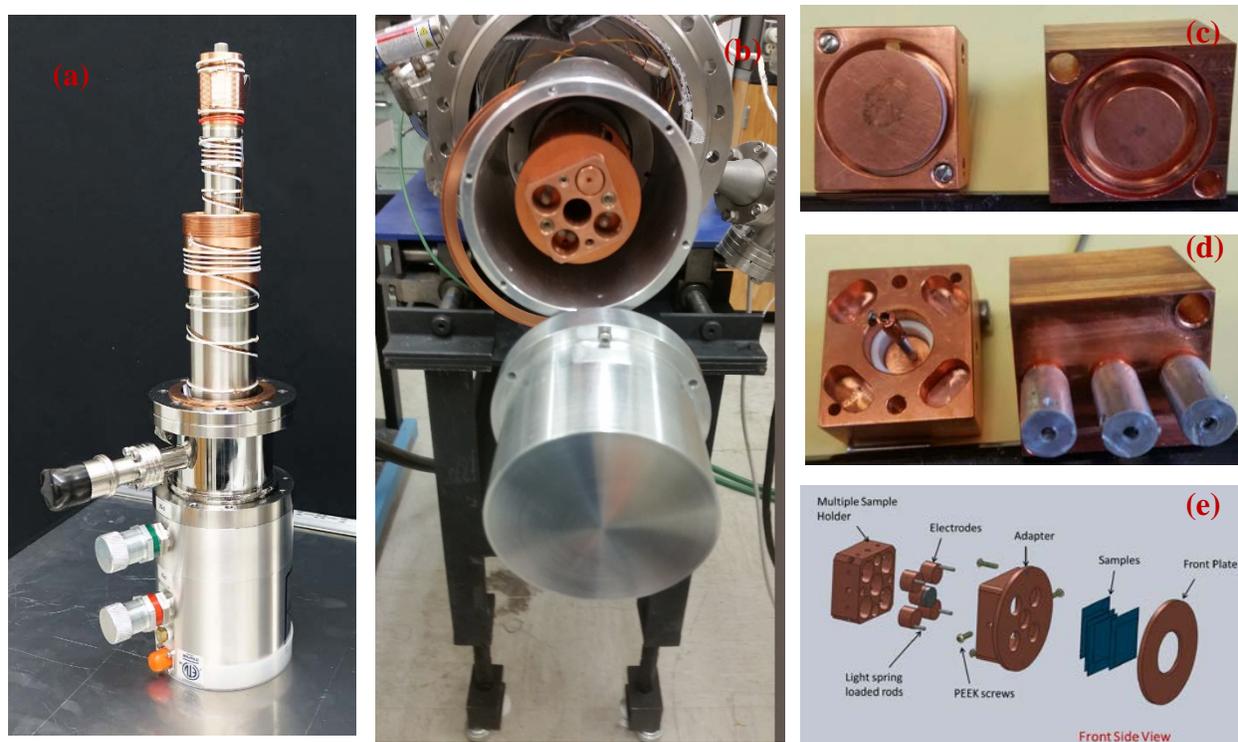


Fig. 10. Low-temperature stage. (a) Closed-cycle He cold stage. (b) Sample stage and first-stage cryo-shield on end of cryostat. (c) Electrodes for conductivity and permittivity custom cryostat test fixture. (d) Electrical connections for conductivity and permittivity custom cryostat test fixture. (e) Exploded view of custom radiation induced conductivity cryostat test fixture.

the samples in these two holders—in contrast to the vertically mounted samples in the existing EET chamber—allows study of loose (*e.g.*, dust) and nonviscous materials.

A third generation low temperature sample stage compatible with our sample carousels has been built and is shown in Figs. 9, 10 and 11. The stage is attached to a closed cycle He cryostat shown mounted on the cryo chamber in Fig. 9. Temperatures from <30 K to > 350 K can be sustained for weeks to within ± 0.5 K by a standard PID temperature controller and Si diodes sensors under Labview command. The He cryostat requested has extended capacity to cool a large mass radiation shield attached to the cryostat's first stage and a sample mounting stage attached to the cryostat's second stage. The cryostat can cool the sample at a rate of up to ~ 2 K/min, reaching the lowest temperature in about 2 hr. Temperatures ≥ 350 K can be achieved using resistive heating elements attached to the radiation shroud and sample mount. The interchangeable sample carousel with multiple sample holders can be quickly exchanged with the use of spring-loaded, electrically-isolated electrode connectors. Samples are electrically isolated, but maintain good thermal contact with the sample carousel. The sample stage has a large wiring cavity to facilitate various low-noise electrical connections, in addition to allowing room for bulk and control heaters (see Fig. 11). The large thermal mass of the sample stage helps maintain a constant sample temperature and helps minimize vibrational noise. Even for sensitive fA current measurements, surface voltage measurements, and optical intensity measurements, vibrations caused by the cryostat compressor and expansion stage do not increase the noise substantially [64]. The entire cryostat and sample stage can rotate 360° using a differentially pumped rotational platform on the SMART and SST chambers. The cryostat and sample stage also have XYZ translational motion to accommodate different sample sizes and allow them to be properly positioned in front of the various beams.

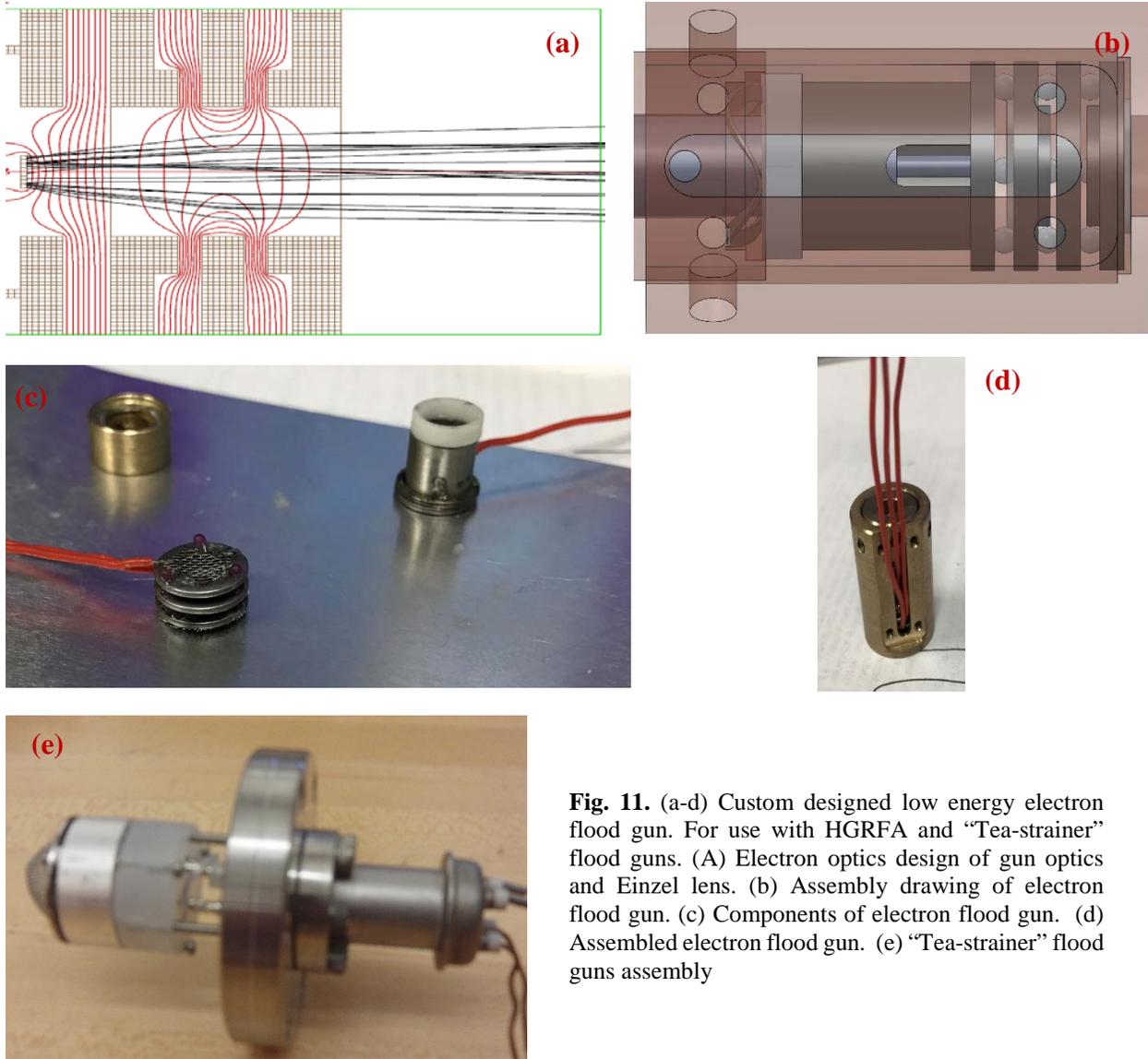


Fig. 11. (a-d) Custom designed low energy electron flood gun. For use with HGRFA and “Tea-strainer” flood guns. (A) Electron optics design of gun optics and Einzel lens. (b) Assembly drawing of electron flood gun. (c) Components of electron flood gun. (d) Assembled electron flood gun. (e) “Tea-strainer” flood guns assembly

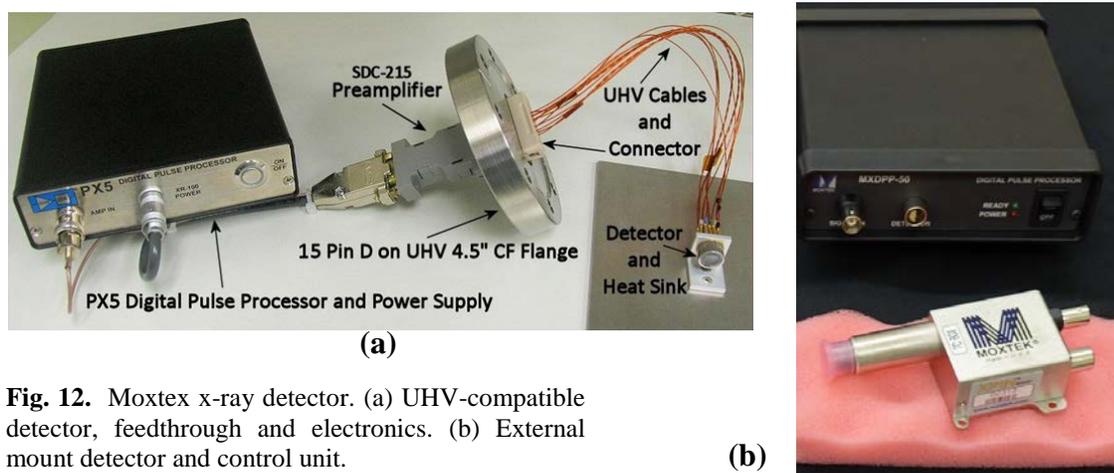


Fig. 12. Moxtex x-ray detector. (a) UHV-compatible detector, feedthrough and electronics. (b) External mount detector and control unit.

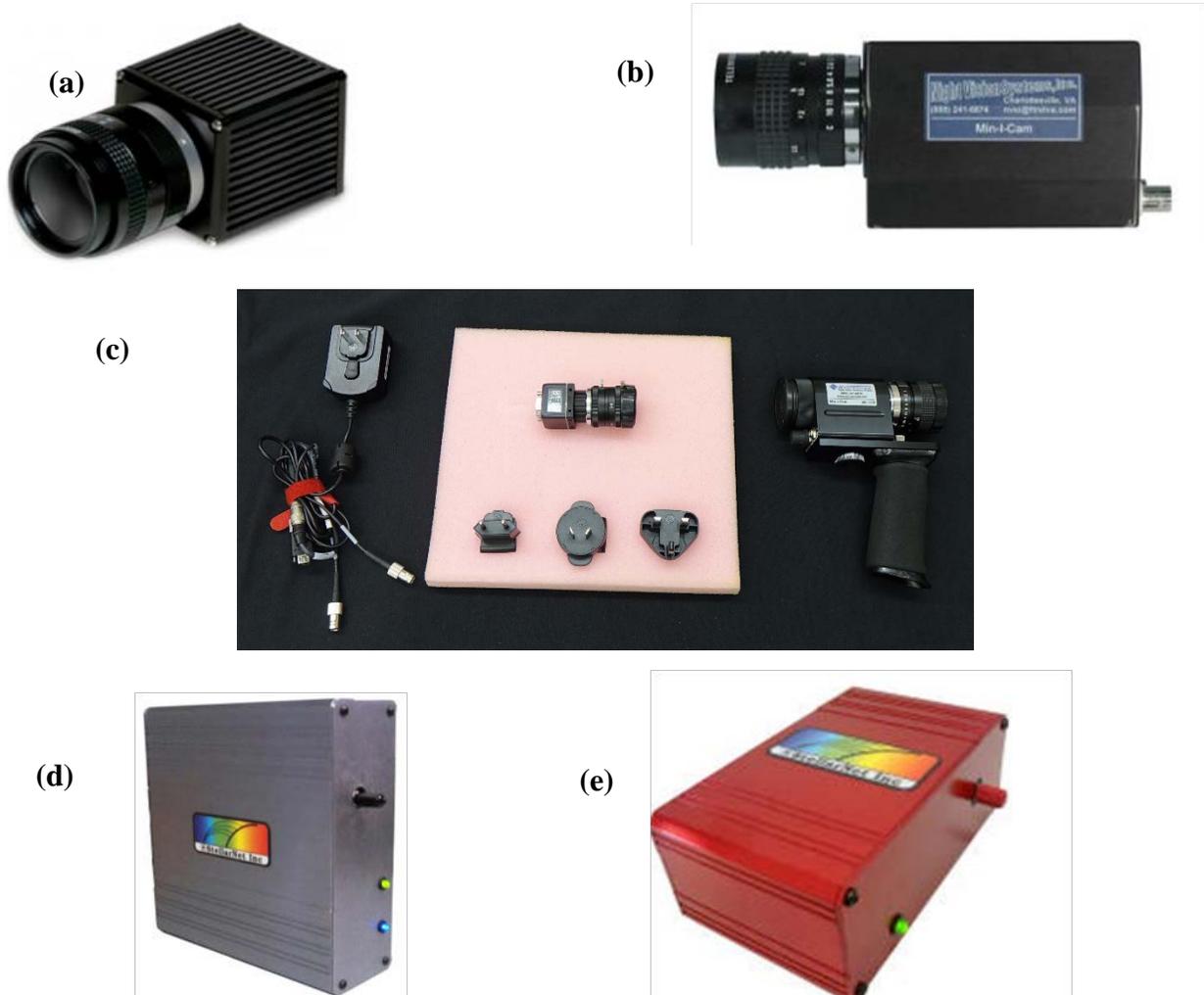


Fig. 13. Optical detectors. (a) SYntronics Vis/NIR video camera. (b) Sensors Unlimited NIR video camera. (c) Full components for video cameras. (d) Stellarnet UV/Vis/NIR fiber optics spectrometer. (e) Stellarnet NIR fiber optics spectrometer.

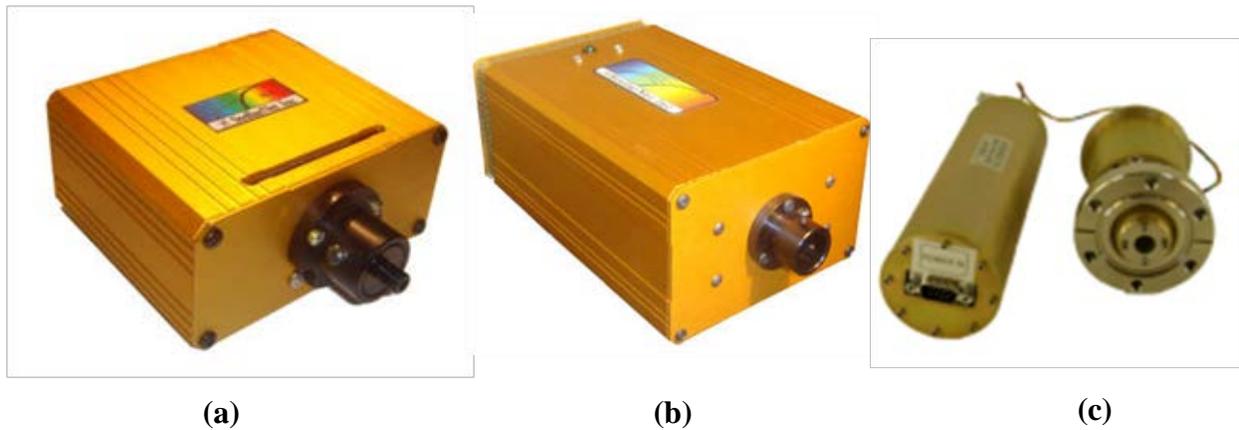


Fig. 14. Optics Sources. (a) Stellarnet UV/Vis fiber optics source. (b) Stellarnet (NIR fiber optic source. (c) Resonance Limited VUV Kr resonance lamp sources.

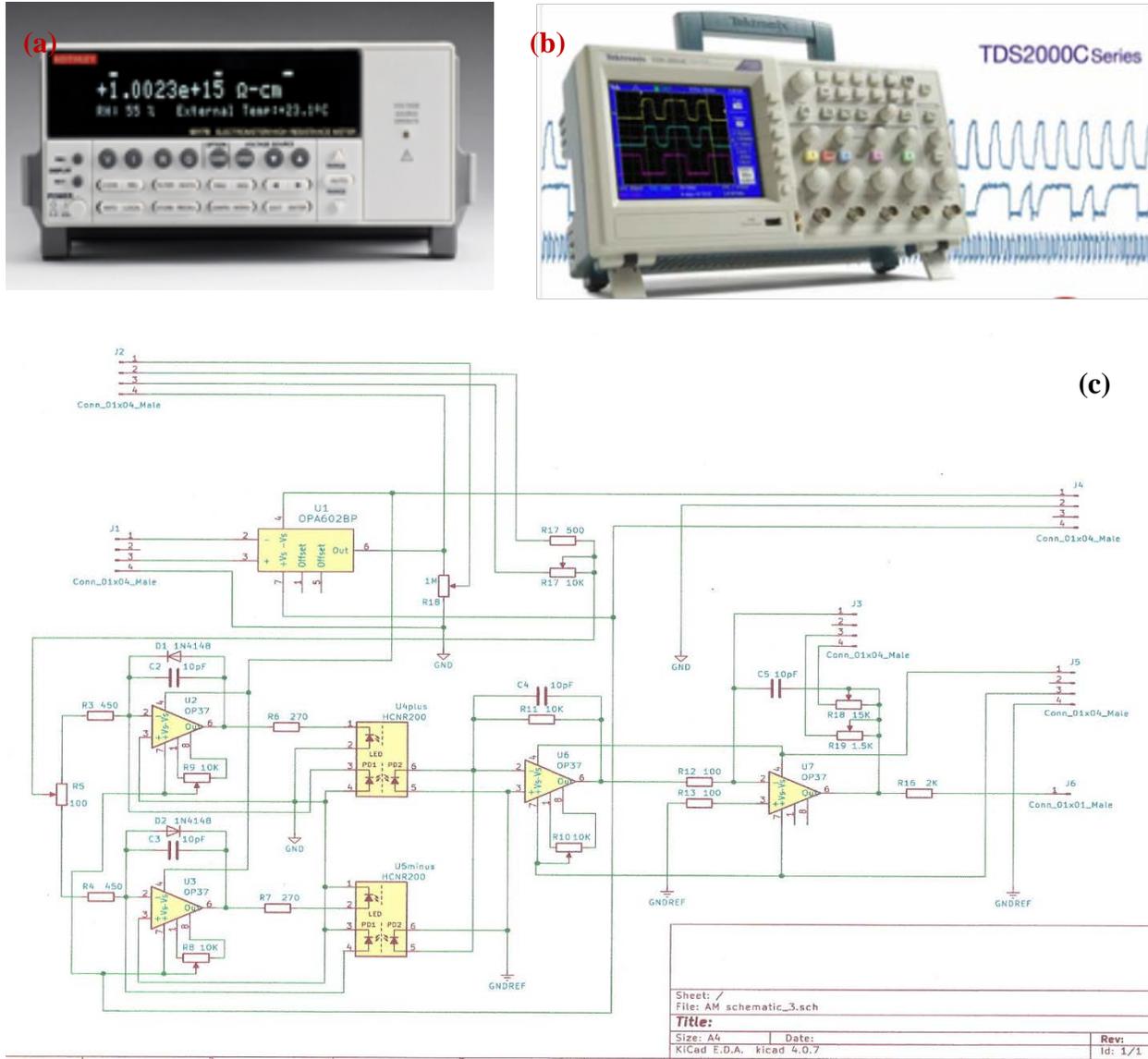


Fig. 15. Current detection electronics. (a) High resolution electrometer. (Digital storage oscilloscopes. (c) Custom high, speed, high-gain, picoammeter.

The sample stages will be outfitted with a number of modular *in situ* sensors developed for the PEA chamber that can be positioned in either the sample position or in front of various electron, ion and photon sources or detectors. These include (i) Faraday cups to measure charged particle fluxes and beam profiles, (ii) a series of calibrated photodiodes with bandpass filters to measure light intensity in different spectral regions, (iii) reflectivity standards for calibration of the UV/Vis/NIR reflectivity and emissivity probes, (iv) surface voltage and electric field calibration plates, and (v) temperature probes.

3.1.3 Electron/Ion Sources

The electron sources for the SMART chamber provide focused ($<100 \mu\text{m}$) and flood ($>10 \text{ cm}$), monochromatic beams over the full range of energies with appreciable flux in space environments ($<10 \text{ eV}$ to $>80 \text{ keV}$; $<0.1 \text{ pA/cm}^2$ to $>1 \mu\text{A/cm}^2$) (see Figs. 2 and 9). These include:

- (i) a custom-designed, high-flux ($<10 \mu\text{A}/\text{cm}^2$), low energy flood gun ($\sim 5 \text{ eV}$ to $<5 \text{ keV}$) with a TaO filament electron source, using an established USU design [53] based on work by Frederickson.
- (ii) a commercial focusable low-energy electron gun (20 eV to 5 keV) with a $\sim 0.1 \text{ pA}/\text{cm}^2$ to $1 \mu\text{A}/\text{cm}^2$ flux with a robust, low thermal-spread TaO electron source.
- (iii) a commercial focusable medium-energy electron gun with a $\sim 1 \text{ pA}/\text{cm}^2$ to $1 \mu\text{A}/\text{cm}^2$ flux over an energy range of 1 to 80 keV with a robust, low thermal-spread (and low light emission) LaB₆ electron source,
- (iv) an existing 100 mCi Sr⁹⁰ beta source [83]), with a low-level, broadband ($\sim 0.2\text{-}2.6 \text{ MeV}$) source.

Energy selection, focusing and deflection of all electron sources is computer controlled via Labview programs, greatly enhancing testing throughput currently limited by manual settings. All electron sources will produce $>11 \text{ cm}$ diameter, reasonably uniform beams, allowing testing of much larger samples than currently possible. The focusable guns have rapid pulsing ($<20 \text{ ns}$ to DC), with extended blanking capabilities of the gun. The flood guns have slower pulsing ($<2 \text{ ms}$ to DC). This pulsed capability is critical for work with highly insulating materials and for new methods for measuring radiation induced conductivity. A critical feature is that all of these four electron sources that can be run independently and simultaneously. This allows investigations of the synergistic effects of multiple energy electron fluxes. The medium-energy electron gun has a 80 keV range, so as to allow measurements of RIC in thin film polymer and ceramic insulators; this new capability is based on work done when Dennison was at AFRL and had access to a 100 keV electron gun.

The SST chamber will use only the two custom flood guns to provide broad electron beams, with an estimated $<2\%$ intensity variation over the full $11 \text{ cm} \times 11 \text{ cm}$ sample area [53,99]. These sources provide highly reliable sources, with $<0.1\%$ variation in beam energy, that are suitable for long duration exposures required for environmental aging tests. The flood guns can produce current densities orders of magnitude large than typical space fluxes for accelerated testing. The low-energy flood gun has three W filaments that can be exchanged without a vacuum break. The high-energy flood gun D₂ lamp UV sources are exterior to the chamber for easy and rapid bulb replacement. Again, simultaneous use of dual monoenergetic beams and the Sr⁹⁰ source allows a reason-able simulation of synergistic broad band energy fluxes encountered in typical space environments [99].

3.1.4 Optics Sources

The two optical sources for the SMART chamber, coupled with the electron detectors, provide photoyield and work function measurements of both conductors and insulators.

The two optical sources for the SST chamber provide high-intensity, broad band light over a continuous range from 180 nm to 2000 nm, plus a narrow band at $<0.1 \text{ eV}$ at an energy very near the intense solar Lyman- α H line.

- (i) Incident NIR/VIS/UVA/UVB radiation (200 nm to 1700 nm) will be provided by a solar simulator source, a class AAA Solar Simulator. This was to be purchased with DURIP funds. However, new LED technology make use of high intensity LEDs at about 12015 bands, ideal for customizable light sources that far exceed older broadbands sources with fixed filters. Hence, we are building our own custom LED solar simulator to shape the incident radiation spectrum to within 25% of the ASTM E927 standard. Light will enter the test chamber from the external solar simulator through a standard 4" diameter quartz window mounted on a 6" flange. Light intensity feedback is used to control the intensity temporal stability to $<2\%$. Spectral quality will be controlled with an in situ fiber optic spectrometer, which will provide direct PID feedback to the LED controllers. LED lifetime is very long, no longer requiring replacement of an external Xe bulb.
- (ii) Incident VUV intensity radiation will be provided by four Krypton line sources [C3; Item 6C] with a primary emission line at 123.6 nm and $\sim 7 \text{ mW}/\text{sr}$ flux. This provides an adequate substitution for the dominant solar hydrogen Lyman alpha line at 121.6 nm. Intensity will be continuously monitored during the sample exposure cycle with standard calibrated solar cells; one cell will be mounted external

to the vacuum chamber and one cell will be mounted internally on the sample mounting block [I3]. The bulb lifetime is approximately >2000 hr, requiring infrequent replacement of the external Kr bulb.

There is an estimated <2% intensity variation up to four (4) suns light intensity over the full 11 cm x 11 cm sample area.

3.1.5 Electron/Ion Detectors

Several innovative detectors for incident and emitted electron and ion fluxes and energies and surface voltages will be incorporated in the SMART and SST chambers and the Low and High Temperature Sample Stage Assemblies described above. The beam and sample currents will be monitored in real-time using *in situ* phosphor screens and energy-discriminating retarding-field Faraday cups located in the center of the sample mount. These large area 2D measurement capabilities, coupled with the video cameras, provide an extremely versatile system for electron emission, surface voltage, discharge ESD, and cathodoluminescence measurements.

For conducting samples, electron guns are operated using a continuous, low-current beam of electrons, and DC-currents are measured with standard ammeters sensitive to $\lesssim 10^{-13}$ A. New electrometers and better shielding on the sample mount will extend this to an order of magnitude lower current measurements. The pulsed system developed at USU to measure electron emission from extreme insulators uses custom detection electronics developed at USU with fast (<0.2 μ s rise time) sensitive/low noise (10^8 V/A / 10 pA noise level) ammeters for determining insulator emission with minimal charging effects (see Fig. 16). These new electrometers are currently being built using a new circuit design, which is about an order of magnitude faster, an order of magnitude higher gain, and an order of magnitude lower current sensitivity. An additional set of these picoammeters will be constructed; seven signal channels will be sent to two fast (100 MHz, 2 GS/s) digital storage oscilloscopes. A simple interface box equipped with resistive and induction (Pearson coil) sensors will be duplicated to detect fast current pulses with the oscilloscopes.

The primary detector for proposed emission studies will be a third-generation custom hemispherical grid retarding field analyzer (HGRFA), for emitted-electron/ion energy discrimination (see Figs. 2, 3 and 4). By ramping the grid bias, precision secondary and backscattered electron yields and energy spectra of the emitted electrons can be measured using this detector. Improved concentricity and rigidity of the high transmission grids will improve the energy resolution of the third generation HGRFA to better than 100 meV, which is currently limited to $\lesssim 0.5$ eV by non-radial fields between the samples and grids. The HGRFA features an aperture and drift tube for incident electron/ion admission and a fully-encasing hemispherical collector for full capture of emitted electrons, which is particularly well suited and calibrated for absolute yield measurements. The hemispherical grid detection system has been carefully calibrated (both through calculation and measurement) to account for detector losses, allowing yield accuracies of better than 2% for conductor yields and better than 5% for insulator yields. The HGRFA can be independently positioned in front of any sample using an existing linear translation stage. HGRFA have been built, one each for the SMART, Cryo and EET chambers. Final wiring is being completed and test is about to begin

Proposed electron emission measurements from insulators will use a similar combination of methods used in the existing EET chamber to enhance control the deposition and neutralization of charge. In the existing system, each pulse of ~ 5 μ s deposits ≥ 15 fC or $\geq 10^4$ electrons-mm²; remarkably, this still significantly affects the yields from high yield extreme insulators. Charge deposition per pulse will be significantly reduced by using lower current, more stable, more spatially-uniform beams from the new electron guns, delivered in shorter pulses of ≤ 20 ns. Monitoring the emission current profile with the digital storage scopes should allow even more sensitive measurements of the yield, as charge accumulates during a single pulse. A low energy flood gun and a variety of visible and UV LED light sources are mounted on the new HGRFA housing at near-normal incidence to provide neutralization of surface charging between pulses (see Fig. 4). Use of new, intense higher energy UV LEDs should enhance photo-discharging. A collimating lens mounted on the HRFA and attached to a fiber optic cable and vacuum feedthrough allows

external light sources to be used or a photospectrometer to analyze emitted light from the sample. The flood gun also acts as a low energy ($\sim 1\text{eV}$ to 100 eV) focused electron source.

A broad range of surface voltages will be measured using two devices, a custom-designed capacitive surface voltage probe (SVP) for high resolution, lower surface voltages and a modest resolution x ray detector for higher surface voltages. The initial design low voltage probe developed at USU has been successfully used for a number of studies. The third generation SVP has a surface voltage range from $<1\text{ V}$ to $>10\text{ kV}$, voltage resolution $\lesssim 0.3\text{ V}$, and spatial resolution $\lesssim 1\text{ mm}$. The system uses movable capacitive sensor electrodes that can be swept across the sample using two *in vacuo* stepper motors and XY translation stage (see above) to measure surface charge distributions on samples *in situ*, using a non-contact electrostatic field probe method that does not dissipate significant sample charge. The Electrostatic Field Transfer Probe concept used here is based on the concept that a transfer probe electrode positioned near the sample can induce a surface voltage on an external witness plate proportional to the sample surface voltage, that can be easily measured outside of the vacuum. There are distinct advantages in having the electrostatic field probe outside the vacuum chamber. The required proximity of an *in vacuo* electrostatic probe to the sample means that stray electron beam radiation—from secondary scattering, insufficient beam columniation, or beam rastering—can charge the sensitive electrostatic probe, causing erroneous readings. Because it is difficult to discharge a probe in the vacuum, this can lead to large, unpredictable and persistent voltage offsets and can even damage the probe which cannot be readily repaired *in vacuo*. The sensor of our existing electrostatic field probe and the witness plates are mounted in a metal enclosure that provides electrostatic shielding and reduces leakage voltages. The probe is a much smaller detector than commercial electrostatic field probes; this allows the SVP to be used simultaneously with the HGRFA (see Figs. 4(a) and 4(c)). The primary advantage of positioning the SVP inside the HGRFA is that surface voltage measurements can be made rapidly, while the sample and HGRFA are accurately aligned with the incident beam. Further, the SVP in this position can act as a shield for the sample preventing any stray electrons or light from charging or discharging the sample. There is also a $360\text{ }\mu\text{m}$ diameter Faraday cup and a Au electron emission calibration disc in the source side of the probe that can be swept across the sample to center the beam on the sample and calibrate the HGRFA. Use of new *in vacuo* stepper motors will allow for much faster response for the SVP. A new custom position encoder has been designed, built and tested for these vacuum stepper motors.

Higher surface voltages will be measured with a novel method using a compact *in vacuo* x-ray detector mounted in the SMART chamber. Higher energy incident electrons interact with the core electrons of the sample to emit high energy photons. The resulting broad band bremsstrahlung emission has an upper cut off energy set by the incidence energy of a monochromatic electron beam. Since a sample surface voltage will act to modify the landing energy of the incident electrons, but will not affect the emission energy of the x-rays, the resulting shift in the x-ray spectrum cut off energy is a direct measure of the surface potential. The proposed x ray detector and associated multichannel analyzer has a resolution of $\sim 160\text{ eV}$ and can measure x-rays (and surface voltages) up to very high energies. The same detector can also be used for elemental surface analysis, by looking at core-level emission peaks. Use of electron-induced x-ray emission, particularly from discharge arcs, has recently been identified as a possible source for space situational awareness applications; the x-ray detector will allow evaluation of this possibility.

3.1.6 Optical Detectors

Light detection is accomplished with several cameras and two spectrometers. The cameras will be positioned with views through vacuum port windows to get a clear view of the sample; this allowed for data collection of photon emission from the sample as a result of the cathodoluminescence and arcing caused by the electron beam interacting with the sample. Sensitivity of the new cameras will be approximate an order of magnitude better than those of the current system, which can already detect extremely faint light at about 10% of the zodiacal background level [69,87,88]; this will allow electron-induced optical emission measurements with incident electron fluxes closer to ambient space conditions.

An existing Single Lens Reflex CCD camera will take high spatial resolution visible light data ranging from ~400 nm to 700 nm with 20 Mpixel images. The camera typically operates at 30 s shutter speeds at full aperture with a 55 mm lens, giving it an average spectral response of $\sim 4 \cdot 10^9$ Counts/(W/cm²·sr·μm). Our present modest spatial resolution image-intensified CCD video camera is sensitive to light from ~400 nm to 900 nm and collected data at 30 frames per sec, with a spectral response of $\sim 4 \cdot 10^{10}$ Counts/(W/cm²·sr·μm) using an existing 55 mm lens. The proposed replacement has ~4 times the pixels leading to a typical spatial resolution of ~20 μm with about an order of magnitude enhanced sensitivity [Item 8D]. In addition, the new camera can take high speed data up to $\sim 10^4$ frames/sec over a limited area; this combination will allow high resolution imaging of high speed arc emissions. Our present modest spatial resolution InGaAs NIR video camera was operated at ambient room temperature collecting data at 60 frames per second. It has a 800 nm to 1700 nm bandwidth, with a spectral response of $\sim 1 \cdot 10^9$ Counts/(W/cm²·sr·μm) using a 35 mm lens. The new NIR video camera has increased sensitivity, thermoelectric cooling for reduced noise, and allows very rapid image acquisition (up to ~4 μs) over limited user-defined pixel ranges. An existing InSb video camera has also been used for NIR (1 μm to 5.5 μm) detection; this instrument is used less frequently and so it is borrowed from collaborators at SDL. This detector has a spectral response of $\sim 7 \cdot 10^7$ Counts/(W/cm²·sr·μm) through a MgF₂ viewport.

Two new fiber optics-based spectrometers provide UV/Vis/NIR photon spectral measurements from ~250 nm to 1700 nm. The UV/Vis spectrometer (~200 nm to 1080 nm) has a wavelength resolution of ~1 nm, while the NIR spectrometer (~1000 nm to 1700 nm) has a ~3 nm resolution. An *in situ* 4 cm diameter MgF collection optic gathers the light emitted by the sample and focuses the signal to a 1 μm fiber optic cable routed via a fiber optic UHV flange to the spectrometers. These spectrometers are also used in conjunction with 1" diameter integrating spheres with fiber optic connections mounted in the SMART and SST chambers to provide *in situ* measurements of the diffuse reflectivity of the samples over this ~250 nm to 1700 nm spectral range with ~1 nm resolution. An existing dual W/deuterium fiber optic light source is used as the reflectivity source.

The infrared emittance of the samples will be measured *in situ* over the 2.5 -20 μm wavelength range in both the SMART and SST chambers. Modest resolution is achieved using a simple non-contact IR thermal probe and comparing the measured value of this probe to direct measurement of the sample temperature using precise thermocouple or Si diode sensors. The compact size allows positioning the detector within the vacuum chambers for frequent measurements. This is particularly critical to monitor sample modification in the SST chamber during long duration sample exposure.

All detectors will be calibrated using NIST traceable methods, allowing for absolute spectral radiance values to be obtained. A fiber optic W/deuterium light source with NIST traceable absolute intensity calibration can be attached to the integrating spheres in the SMART and SST chambers to provide *in situ* absolute intensity calibration of the cameras. Wavelength calibration of the spectrometers is achieved using an existing fiber optic Xe/Ar calibration source. White Spectralon and black optical reflectivity standards will be mounted on the sample holders in both the SMART and SST chambers. These will normally be covered by the integrating sphere to minimize surface contamination and degradation, but can be exposed for calibration measurements. The standards also provide direct color calibration for the reflectivity spectrometers, emissivity probes, and optical cameras.

4. PROJECT STATUS

The proposed DURIP budget has provided all the necessary funds to purchase the major capital equipment items need to implement our ambitious plan for the development of the Space Environment Effects Materials (SEEM) Test Facility outlined above. The DURIP award started on January 1, 2017 and had a one year duration. Since there was a more than two year interval between when the proposal was written and awarded, most of the equipment bids had to be fully redone. Indeed, there were a number of items—including the UV/Vis and NIR video cameras, low and high energy electron guns, and solar simulator—which had major technological upgrades available. All the equipment was specified and orders

placed in the original one-year grant period. However, a six month no cost extension was requested because there were inevitable delays in delivery of the custom equipment. All equipment arrived by June 30, 2018 when the no cost extension ended.

All the enhancements for the existing SMART vacuum chamber and stand have already been completed. Final design and fabrication of the four key custom instrumentation components (low and high temperature sample stages, HGRFA detector assembly, and surface charge detection system) are completed, based on modifications to the existing plans presented in this proposal as required for the specific equipment purchased. Final assembly and system testing and characterization are still in progress on some components. will be done in the fourth quarter.

There have already been very significant new tests made and projects tackled using the new DURIP equipment. Most notable is the many projects already completed using the SST test chamber. Additional capabilities for electron emission testing have already been realized. New capabilities for radiation induced conductivity and permittivity tests under extreme conditions—most notably at temperatures down to ~40 K—are already being incorporated into ongoing tests. Most notably, this is central to tests for NASA Europa missions.

The Appendices show the output related to the DURIP capabilities during the grant period and into the future. Appendix I list past, current, and pending funding related to the DURIP instrumentation. Appendices II, III and IV list past and pending publications, presentations and student theses related to the DURIP instrumentation.

5. APPENDIX I – RELATED SUPPORT

GRANTS & AWARDS:

Pending Funding

- [F1] NASA Natural Environments Branch, “Extensions of the NASA/AFRL NASCAP Spacecraft Charging Materials Database through Data Mining,” JR Dennison, (\$50,000, February 2019 to January 2020).
- [F2] AFRL Space Environment Effects Program, “Extensions of the NASA/AFRL NASCAP Spacecraft Charging Materials Database through Data Mining,” JR Dennison, (\$50,000, February 2019 to January 2020).
- [F3] DOE Sandia Laboratory, “Studies of Radiation Induce Conductivities of Perovskite Materials,” JR Dennison, (\$108,000, January 2019 to May 2020).
- [F4] Times Microwave Systems, “Deep charging effects of GEOS environment on coaxial cable: Phase II,” JR Dennison, (\$25,000, November 2018 to October 2019).
- [F5] SpaceX, “Extended Measurements of Electron Induced Arcing of SpaceX AIP Components,” JR Dennison, (\$30,000, January 2019 to December 2019).
- [F6] Johns Hopkins Applied Physics Laboratory, “Spacecraft Charging characterization of candidate spacecraft materials,” JR Dennison, (\$115,000, January 2019 to June 2020).
- [F7] Thermal Management Technologies, “TMT Phase Change Materials Radiation Testing,” JR Dennison, (\$23,000, November 2019 to October 2020).
- [F8] NASA Goddard Space Flight Center, “Temperature dependent conductivity for sapphire for LUCY Mission,” JR Dennison, (\$14,500, December 2019 to November 2020).

Current Funding

- [F9] NASA JPL, “Electron Transport Studies of Europa Lander Mission Materials,” JR Dennison (\$199,247, June 2018 to June 2019)
- [F10] Small Business Technology Transfer Research (STTR), Air Force Research Laboratory, “Volume Charge Distribution Measurement in Thin Dielectrics: Phase II-Extended,” Lee Pearson and JR Dennison (\$420,000 (\$120,000 USU), January 2018 to December 2019).
- [F11] NASA JPL, “Electron Transport Studies of Europa Clipper Mission Materials,” JR Dennison (\$49,042, August 2017 to June 2019)
- [F12] Education Partnership Agreement Between the Department of the Air Force (AFRL/RVBXR Space Vehicles Directorate, Battle Space Environments Division, Space Particles Section) and Utah State University, 2014-AFRL/RV-EPA-01, JR Dennison, (\$0, December 2014 to November 2019).

Funding During Project

- [F13] Air Force Office of Scientific Research, Defense University Research Instrumentation Program (DURIP), “Enhanced Test Facility for Survivability and Characterization of Evolving Multiscale Materials in Extreme Plasma Environments,” JR Dennison, (\$498,869, January 2017-to May 2018).
- [F14] SpaceX, “Studies of Electric Charging Properties of SpaceX Dielectric Coating Material,” JR Dennison, (\$34,444, January 2018 to August 2018).
- [F15] Utah NASA Space Grant Consortium Faculty Research Infrastructure Award Program, “Effects of Space Ionizing Radiation on Cell Viability,” Elizabeth Vargas with JR Dennison, (\$20,000, April 2017 to April 2018).
- [F16] Space Dynamics Laboratory, “Beta Radiation of Optical Materials,” JR Dennison, (\$5,500, February 2018 to August 2018).
- [F17] Space Dynamics Laboratory, “UV Degradation of Optical Materials,” JR Dennison, (\$3,500, February 2018 to August 2018).
- [F18] Berkley Applied Space Laboratory, “Electron Emission Studies of Solar Probe Plus Niobium Alloy Materials,” JR Dennison, (\$15,000, September 2016 to October 2018).
- [F19] NASA Glenn Research Center Innovation Fund FY17, “Secondary Electron Suppression with Carbonized Aerogels,” Dale Force and JR Dennison (\$45,953 (\$25,000, USU), October 2016 to September 2017; (\$29,581, USU) October 2017 to April 2018).
- [F20] Space Dynamics Laboratory, “UV Degradation of Solar Arrays and Cover Glass Materials,” JR Dennison, (\$4,975, July 2017 to March 2018).
- [F21] Varex Imaging, “Electron Emission Studies of Low Electron Yield Layered Materials,” JR Dennison, (\$16,000, October 2017 to June 2018).

- [F22] SpaceX, “Measurements of Electron Induced Arcing of SpaceX AIP Components,” JR Dennison, (\$35,481, August 2017 to February 2018).
- [F23] Space Dynamics Laboratory, “SteelHead GPS LNA and active components test,” JR Dennison, (\$3,479, July 2017 to December 2017).
- [F24] Small Business Technology Transfer Research (STTR), Air Force Research Laboratory, “Volume Charge Distribution Measurement in Thin Dielectrics: Phase IIB,” Lee Pearson and JR Dennison (\$420,000 (\$126,000 USU), December 2015 to December 2017).
- [F25] Times Microwave Systems, “Deep charging effects of GEOS environment on coaxial cable,” JR Dennison, (\$35,593, May 2016 to December 2017).
- [F26] Nokomis, “Electron Emission Studies of Multipactor Coating Materials,” JR Dennison, (\$4,033, May 2017 to July 2017).
- [F27] Utah NASA Space Grant Consortium Faculty Research Infrastructure Award Program, “Space Survivability Test Facility for CubeSats, Components and Spacecraft Materials,” JR Dennison, (\$20,931, April 2016 to April 2017).
- [F28] Space Dynamics Laboratory IR&D, “Radiation Modification of Space Flight CCD Array,” JR Dennison, (\$8,450, July 2016 to March 2017).
- [F29] ViaSat, “Simulated Space Radiation Effects on Spacecraft Components: Phase I and II,” JR Dennison, (\$76,191, May 2016 to December 2016); Phase III,” JR Dennison, (\$38,403, October 2016 to June 2018).
- [F30] Lockheed Martin, “Electron Emission Studies of Orion Backshell Materials,” JR Dennison, (\$24,000, May 2016 to April 2017).

STUDENT FUNDING:

Pending Funding

- [F31] USU Undergraduate Research and Creative Opportunities (URCO), “Optical Properties of Radiated Polymers,” (\$2,000, September 2018 to May 2019) [for Ashlan Keeler with J.R. Dennison].

Current Funding

- [F32] USU Undergraduate Research and Creative Opportunities (URCO), “Relaxation of Radiation Effects in Polymer,” (\$2,000, May 2018 to December 2018) [for Alex Hughlett Nelson with Brian Wood and J.R. Dennison].
- [F33] NASA Utah Space Grant Consortium Graduate Student Fellowship, “Multilayer Models of Electron Emission and Charge Transport with Spacecraft Charging Applications.” (\$30,000, September 2015 to August 2017) [for Greg Wilson with J.R. Dennison].
- [F34] Presidential Doctoral Research Fellowship, Office of Research and Graduate Studies and College of Science, “Pulsed Electroacoustic Measurements of Internal Charge Distributions in Dielectric Materials,” J.R. Dennison for Zack Gibson, (\$74,000, August 2016 to July 2020).

Funding During Project

- [F35] USU Physics Department Undergraduate Student Summer Research Internship, “Developing a Database of Spacecraft Charging Materials Properties for Spacecraft Materials ” (\$4,000, May 2018 to August 2018) [for Phil Lundgreen with J.R. Dennison].
- [F36] USU Undergraduate Research and Creative Opportunities (URCO), “Testing of Microcontrollers Radiation Damage Threshold to Determine Their Stability for Satellite Use,” (\$2,000, January 2018 to August 2018) [for Jonh Decana with Brian Wood and J.R. Dennison].
- [F37] NASA Space Technology Research Fellowships (NSTRF), “Enhanced Predictions of Time to Critical Dielectric Breakdown of Materials under Prolonged Exposure to Space Plasma Environments,” JR Dennison for Allen Andersen, (\$264,604, August 2014, to July 2018).
- [F38] USU Graduate Research and Creative Opportunities (GRCO), “Developing a Database of Spacecraft Charging Materials Properties for Spacecraft Materials ” (\$1,000, September 2018 to May 2018) [for Phil Lundgreen with J.R. Dennison]
- [F39] USU Undergraduate Research and Creative Opportunities (URCO), “Temperature Dependence of Secondary Electron Emission of Highly Disordered Polymers,” (\$2,000, May 2017 to May 2018) [for Jordan Lee with Greg Wilson and J.R. Dennison]
- [F40] USU Physics Department Undergraduate Student Summer Research Internship, “Development and Applications for the Space Survivability Test Chamber.” (\$4,000, May 2017 to August 2017) [for Matthew

Robertson with J.R. Dennison].

- [F41] USU Physics Department Undergraduate Student Summer Research Internship, “Development and Applications for the Space Survivability Test Chamber.” (\$4,000, May 2017 to August 2017) [for Jordan Lee with J.R. Dennison].
- [F42] USU Undergraduate Research and Creative Opportunities (URCO), ” Temperature Dependence of Electrostatic Breakdown in Highly Disordered Polymers,” (\$2,000, January 2017 to June 2017) [for Trevor Kippen with Allen Andersen and J.R. Dennison].

6. APPENDIX II – RELATED PUBLICATIONS

REFEREED PUBLICATIONS:

In Preparation

- [P1] Jodie Corbridge Gillespie, J.R. Dennison, Neal Nickles, “Secondary Electron Emission of Annealed Graphitic Amorphous Carbon: The Role of Evolving Bandgap,” to be submitted to *Phys. Rev. B*.
- [P2] Sterling Smith, J.R. Dennison, T.E. Doyle, Mark Holtz, T. Dallas, “Vibrational Dynamics of Annealed Graphitic Amorphous Carbon Using the Embedded Ring Approach,” to be submitted to *Phys. Rev. B*.
- [P3] JR Dennison, Alec Sim, Greg Wilson, and Jodie Corbridge Gillespie, “Charge Transport and Electron Emission of Disordered Materials: Extensions of the Walden-Wintle Model for Charge Injection with Electron Beams,” 2015, to be submitted to the *Journal of Applied Physics*.
- [P4] Phillip Lundgreen, JR Dennison, R.C. Hoffmann, and J. Abbott, “Triggering Threshold Spacecraft Charging with Changes in Electron Emission from Materials,” to be submitted to the *Journal of Spacecraft and Rockets*.
- [P5] Gregory Wilson, J.R. Dennison, R.E. Davies, Jason Kite, and W.Y. Chang, “Effects of Evolving Surface Contamination on Spacecraft Charging,” to be submitted to *Journal of Spacecraft and Rockets*.
- [P6] JR Dennison, Jodie Corbridge Gillespie, Allen Andersen, Amberly Evans Jensen, Justin Dekany, Gregory Wilson, Alec M. Sim, and Ryan Hoffmann, “Synergistic Models of Electron Emission and Transport Measurements of Disordered SiO₂,” to be submitted to *IEEE Tran. Plasma Science*, 2017, 8 pp.

Submitted

- [P7] L. Olano, M.E. Dávila, JR Dennison, and I. Montero, “Dynamic secondary electron emission in rough composite materials,” *Journal of Applied Physics*, 2018.
- [P8] Gregory Wilson and JR Dennison, “Electron Range Computational Tool for Arbitrary Materials over a Wide Energy Range,” *IEEE Trans. on Plasma Sci.*, 2018.
- [P9] Allen Andersen and JR Dennison, “Wireless Detection of Electrostatic Discharge Events,” *IEEE Trans. on Plasma Sci.*, 2018.
- [P10] Brian Wood, Justin Christiansen, Greg Wilson, T.C. Shen, and JR Dennison “Secondary Electron Yield Measurements of Carbon Nanotube Forests: Dependence on Morphology and Substrate,” *IEEE Trans. on Plasma Sci.*, 2018.
- [P11] Brian Wood, David King and JR Dennison, “Time-Evolved Constant Voltage Conductivity Measurements of Common Spaceborne Polymeric Materials” *IEEE Trans. on Plasma Sci.*, 2018.
- [P12] Phil Lundgreen, Justin Christensen, and JR Dennison, “Comparison of Models for Materials Parameters Used in Spacecraft Charging Codes,” *IEEE Trans. on Plasma Sci.*, 2018.

Published

- [P13] Allen Andersen and JR Dennison, “An Enhanced Operational Definition of Dielectric Breakdown for DC Voltage Step-up Tests,” *Proceedings of the 2017 IEEE Conference on Electrical Insulation and Dielectric Phenomena—(CEIDP 2017)*, 2017.
- [P14] L. Olano, I. Montero, M.E. Dávila, and JR Dennison, “Dynamic secondary electron emission in materials,” *Proceedings of the 9th International Workshop on Multipactor, Corona and Passive Intermodulation (MULCOPIM)*, ESA/ESTEC (Noordwijk - The Netherlands), April 7 2017. DOI: [10.1088/1361-6463/aa78b7](https://doi.org/10.1088/1361-6463/aa78b7)
- [P15] Krysta Moser, Allen Andersen and JR Dennison, “Dependence of Electrostatic Field Strength on Voltage Ramp Rate for Spacecraft Materials,” *IEEE Tran. Plasma Science*, **45**(8), 2017, 2036-2039. DOI: [10.1109/TPS.2017.2717873](https://doi.org/10.1109/TPS.2017.2717873)
- [P16] Justin Christensen, JR Dennison, and Justin Dekany, “Temporal and Spatial Correlations in Electron-induced Arcs of Adjacent Dielectric Islands,” *IEEE Tran. Plasma Science*, **45**(8), 2017, 2025-2030.. DOI: [10.1109/TPS.2017.2689791](https://doi.org/10.1109/TPS.2017.2689791)
- [P17] Allen Andersen, Krysta Moser and JR Dennison, “Perspectives on the Distributions of ESD Breakdowns for Spacecraft Charging Applications,” *IEEE Tran. Plasma Science*, **45**(8), 2017, 2031-2035. DOI: [10.1109/TPS.2017.2655885](https://doi.org/10.1109/TPS.2017.2655885)
- [P18] L. H. Pearson, J. R. Dennison, E. W. Griffiths, A. C. Pearson, “PEA System Modeling and Signal Processing

for Measurement of Volume Charge Distributions in Thin Dielectric Films,” *IEEE Tran. Plasma Science*, **45**(8), 2017, 1955-1960. DOI: [10.1109/TPS.2016.2632627](https://doi.org/10.1109/TPS.2016.2632627)

OTHER PUBLICATIONS:

In Preparation

- [P19] Brian Wood, Jonh Mojica Decana, Alex Souvall, Weni Olsen, and JR Dennison, “Radiation Survivability Tests of CubeSat COTS Electronics and Computer Hardware,” Paper Number SSC18-P-, *33th Annual AIAA/USU Conference on Small Satellites*, (Logan, UT, August 8-13, 2019).
- [P20] JR Dennison, Allen Andersen and Gregory Wilson, “Detection of Correlated Arcs from Electron Irradiation with Wifi Antennas,” *Proceedings of the 2019 IEEE Conference on Electrical Insulation and Dielectric Phenomena—(CEIDP 2019)*, October, 2019.
- [P21] Justin Christensen, Jordan Lee, and JR Dennison, “Measurements of the Intrinsic Electron Yield of Highly Insulating Material,” *AIAA SciTech Forum, San Diego, CA*, (San Diego, CA, January 7-11, 2019).
- [P22] Matthew Robertson, Justin Christensen, and JR Dennison, “Electron Yield of Carbon-Composite Nanodielectric Material,” *AIAA SciTech Forum, San Diego, CA*, (San Diego, CA, January 7-11, 2019).

Submitted

- [P23] Jacob Kleiman, Z. Iskanderova, L. Kirshtein, Brian Wood, JR Dennison, and Carl. Best, “Long-term Stability in GEO-simulated Environment of Space Polymers Treated by Ion-beam Techniques,” *Proceedings of 12th International Conference on Protection of Materials from Space Environment (ICPMSE)*, Biarritz, France, October, 2018.

Published

- [P24] Justin Christensen, Phil Lundgreen, and JR Dennison, “Comparison of Models for Materials Parameters Used in Spacecraft Charging Codes,” *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [P25] Gregory Wilson and JR Dennison, “Electron Range Computational Tool for Arbitrary Materials over a Wide Energy Range,” *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [P26] Allen Andersen and JR Dennison, “Wireless Detection of Electrostatic Discharge Events,” *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [P27] Brian Wood, Justin Christiansen, Greg Wilson, T.C. Shen, and JR Dennison “Secondary Electron Yield Measurements of Carbon Nanotube Forests: Dependence on Morphology and Substrate,” *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [P28] Brian Wood, David King and JR Dennison, “Time-Evolved Constant Voltage Conductivity Measurements of Common Spaceborne Polymeric Materials” *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [P29] Zachary Gibson, JR Dennison, Lee Pearson, Erick Griffiths, Anthony Pearson, Virginie Griseri, “Pulsed Electroacoustic Measurement Spatial Resolution Limitations: Sample Adhesion Effects of Sample Adhesives Acoustic Properties on Spatial Resolution of Pulsed Electroacoustic Measurements,” *Proceedings of the 2018 IEEE Conference on Electrical Insulation and Dielectric Phenomena—(CEIDP 2018)*, Cancun, Mexico, October, 2018.
- [P30] Greg Wilson and JR Dennison, “Electron Range Model,” *Proceedings of the Utah NASA Space Grant Consortium Research Symposium*, May 5, 2018, Orbital ATK Conference Center, Ogden, UT, 9 pp.
- [P31] L. Olano, I. Montero, M.E. Dávila, A. Jacas, M.A. Rodriguez and JR Dennison, “Dynamic secondary electron emission in dielectric/conductor mixed,” *Proceedings of the 9th International Workshop on Multipactor, Corona and Passive Intermodulation (MULCOPIM)*, ESA/ESTEC (Noordwijk - The Netherlands), April 7 2017.
- [P32] Greg Wilson and JR Dennison, “Hemispherical Grid Retarding Field Analyzer Redesign for Secondary Electron Emission Studies,” *Proceedings of the Utah NASA Space Grant Consortium Research Symposium*, May 8, 2017, Weber State University, Ogden, UT, 9 pp.

* Full references available at <https://digitalcommons.usu.edu/mp/>

7. APPENDIX III – RELATED PRESENTATIONS

PRESENTATIONS:

In Preparation

- [X1] Brian Wood, Jonh Mojica Decana, Alex Souvall, Wendi Olsen, and JR Dennison, “Radiation Survivability Tests of CubeSat COTS Electronics and Computer Hardware,” Paper Number SSC18-P-, *33th Annual AIAA/USU Conference on Small Satellites*, (Logan, UT, August 8-13, 2018).
- [X2] JR Dennison, Allen Andersen and Gregory Wilson, “Detection of Correlated Arcs from Electron Irradiation with Wifi Antennas,” *Proceedings of the 2019 IEEE Conference on Electrical Insulation and Dielectric Phenomena—(CEIDP 2019)*, October, 2019.
- [X3] Justin Christensen, Jordan Lee, and JR Dennison, “Measurements of the Intrinsic Electron Yield of Highly Insulating Material,” *AIAA SciTech Forum, San Diego, CA*, (San Diego, CA, January 7-11, 2019).
- [X4] Matthew Robertson, Justin Christensen, and JR Dennison, “Electron Yield of Carbon-Composite Nanodielectric Material,” *AIAA SciTech Forum, San Diego, CA*, (San Diego, CA, January 7-11, 2019).
- [X5] Justin Christensen, Jordan Lee, and JR Dennison, “Measurements of the Intrinsic Electron Yield of Highly Insulating Material,” *AIAA SciTech Forum, San Diego, CA*, (San Diego, CA, January 7-11, 2019).

Accepted

- [X1] Zachary Gibson, JR Dennison, Lee Pearson, Erick Griffiths, Anthony Pearson, Virginie Griseri, “Pulsed Electroacoustic Measurement Spatial Resolution Limitations: Sample Adhesion Effects of Sample Adhesives Acoustic Properties on Spatial Resolution of Pulsed Electroacoustic Measurements,” *Proceedings of the 2018 IEEE Conference on Electrical Insulation and Dielectric Phenomena—(CEIDP 2018)*, Cancun, Mexico, October, 2018.
- [X2] Jacob Kleiman, Z. Iskanderova, L. Kirshtein, Brian Wood, JR Dennison, and Carl. Best, “Long-term Stability in GEO-simulated Environment of Space Polymers Treated by Ion-beam Techniques,” *12th International Conference on Protection of Materials from Space Environment (ICPMSE)*, Biarritz, France, October, 2018.
- [X3] Lori Caldwell, Eryn Hanson, Alexandra H Nelson, Charles Harding, JR Dennison, and Elizabeth Vargis, “Simulating Muscle Atrophy due to Microgravity and Ionizing Radiation,” 34th Annual Meeting of the American Society for Gravitational and Space Research, Washington, DC, October 31-November 3, 2018.
- [X4] Zachary Gibson, JR Dennison, Lee Pearson, Erick Griffiths, and Anthony Pearson, “Charging Effects of High Voltage Probe Pulse on Pulsed Electroacoustic Measurements,” *American Physical Society Four Corners Meeting*, University of Utah, Salt Lake City, UT, October 12-13, 2018.
- [X5] Ashlan Keeler, JR Dennison, John Stauder, Brian Wood, Jonh Carlos Mojica Decana, “Optical Transmission of Radiated Optical Filters,” *American Physical Society Four Corners Meeting*, University of Utah, Salt Lake City, UT, October 12-13, 2018.
- [X6] Jordan Lee, Brian Wood, Ashlan Keeler, JR Dennison, and TC Shen, “Characterizing Vibrationally Induced Damage of Carbon Nanotube Forests,” *American Physical Society Four Corners Meeting*, University of Utah, Salt Lake City, UT, October 12-13, 2018.
- [X7] Matthew Robertson, Justin Christensen, Greg Wilson and JR Dennison, “Electron Yield of a Carbon-composite Nanodielectric,” *American Physical Society Four Corners Meeting*, University of Utah, Salt Lake City, UT, October 12-13, 2018.
- [X8] JR Dennison, Gregory Wilson, Jonh Mojica and Brian Wood, “Real-time Video Processing of Arcing Events to Determine Coincidence,” *American Physical Society Four Corners Meeting*, University of Utah, Salt Lake City, UT, October 12-13, 2018.
- [X9] Gregory Wilson, Matthew Robertson, Jordan Lee, and JR Dennison. “Electron Yield Measurements of Multilayer Conductive Materials,” *American Physical Society Four Corners Meeting*, University of Utah, Salt Lake City, UT, October 12-13, 2018.
- [X10] Brian Wood, Jordan Lee, Justin Christensen, Gregory Wilson, JR Dennison, T.-C. Shen, “Characterization of Electron Yield Suppression with Carbon Nanotube Forest Grown on Silicon Substrates,” *American Physical Society Four Corners Meeting*, University of Utah, Salt Lake City, UT, October 12-13, 2018.
- [X11] Alexandra Nelson, Lori Caldwell, JR Dennison, Eryn Hanson, Elizabeth Vargis, “Simulating Microgravity with a Rotary Cell Culture System (RCCS) ,” *American Physical Society Four Corners Meeting*, University of Utah, Salt Lake City, UT, October 12-13, 2018.

- [X12] Kip Quilter, Megan Loveland, Alexandra Nelson, and JR Dennison "Effects of Radiation on the Electrostatic Discharge of Polymers," *American Physical Society Four Corners Meeting*, University of Utah, Salt Lake City, UT, October 12-13, 2018.

Presented

- [X1] Jonh Carlos Mojica Decana, Brian Wood, Ryan Martineau, Michael Taylor, and JR Dennison, "Tests of Radiation Damage Threshold of Raspberry Pi Zero in LEO Environment for OPAL CubeSat Project," USU Fall Undergraduate Research Orientation, Logan, UT, September 7, 2018.
- [X2] Gregory Wilson and JR Dennison, "Electron Range Computational Tool for Arbitrary Materials over a Wide Energy Range," *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [X3] Allen Andersen and JR Dennison, "Wireless Detection of Electrostatic Discharge Events," *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [X4] Matthew Robertson, Justin Christensen, and JR Dennison, "Electron Yield of Carbon-Composite Nanodielectric Material," *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [X5] Brian Wood, Justin Christiansen, Greg Wilson, T.C. Shen, and JR Dennison "Secondary Electron Yield Measurements of Carbon Nanotube Forests: Dependence on Morphology and Substrate," *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [X6] Brian Wood, David King and JR Dennison, "Time-Evolved Constant Voltage Conductivity Measurements of Common Spaceborne Polymeric Materials" *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [X7] Justin Christensen, Phil Lundgreen, and JR Dennison, "Comparison of Models for Materials Parameters Used in Spacecraft Charging Codes," *15th Spacecraft Charging Technology Conference*, Kobe University, (Kobe, Japan, June 25-29, 2018).
- [X8] JR Dennison and Elizabeth Vargis, "Space Environment Effects: Payoffs of UNSGC Research Infrastructure Awards," *Utah NASA Space Grant Consortium Annual Meeting*, May 5, 2018, Orbital ATK Conference Center, Ogden, UT.
- [X9] Greg Wilson and JR Dennison, "Electron Range Model," *Utah NASA Space Grant Consortium Research Symposium*, May 5, 2018, Orbital ATK Conference Center, Ogden, UT.
- [X10] Lori Caldwell, Elizabeth Vargis, and JR Dennison, "Using Combined Microgravity and Radiation to Simulate Skeletal Muscle Damage in Space," *Utah NASA Space Grant Consortium Research Symposium*, May 5, 2018, Orbital ATK Conference Center, Ogden, UT.
- [X11] Jonh Carlos Mojica Decana, Brian Wood, Ryan Martineau, Michael Taylor, and JR Dennison, "Tests of Radiation Damage Threshold of Raspberry Pi Zero in LEO Environment for OPAL CubeSat Project," *Space Weather Workshop*, Westminster, CO, April 16-20, 2018.
- [X12] Lori Caldwell, Charles Harding, Eryn Hanson, A Nelson, JR Dennison, and Elizabeth Vargis, "Characterizing the Effects of Radiation on Muscle Cells," *Institute of Biological Engineering*, April 2018
- [X13] Lori Caldwell, Charles Harding, Eryn Hanson, A Nelson, JR Dennison, and Elizabeth Vargis. "Characterizing the Effects of Radiation on Muscle Cells," *USU Student Research Symposium*, Logan, UT, April 12, 2018.
- [X14] Jonh Carlos Mojica Decana, Brian Wood, Ryan Martineau, Michael Taylor, and JR Dennison, "Radiation Damage Threshold of Satellite COTS Components: Raspberry Pi Zero for OPAL CubeSat," *USU Student Research Symposium*, Logan, UT, April 12, 2018.
- [X15] Zachary Gibson, JR Dennison, Lee Pearson, Erick Griffiths, and Anthony Pearson "Effects of Acoustic Coupling Layer Electrical Conductivity on Pulsed Electroacoustic Measurements," *USU Student Research Symposium*, Logan, UT, April 12, 2018.
- [X16] Tyler Kippen, Allen Andersen and JR Dennison, "The Effects of the Beta Transition on Dielectric Breakdown in LDPE," *USU Student Research Symposium*, Logan, UT, April 12, 2018.
- [X17] Allen Andersen and JR Dennison, "Using Quantile-Quantile Plots to Compare Experimental Apples and Oranges in Physics Lab," *37th Annual Meeting of the Idaho-Utah Section of the American Association of Physics Teachers*, Brigham Young University-Idaho, Rexburg, ID, February 23-24, 2018.
- [X18] Jordan Lee and JR Dennison, "Electron Yield Properties of Low-Density Polyethylene," *Utah Conference on Undergraduate Research*, Southern Utah University, Cedar City, UT, February 9, 2018.
- [X19] JR Dennison, "Electron Transport Studies of Europa Clipper Mission Materials," *Invited Talk*, NASA Jet Propulsion Laboratory, REASON Europa Project, Pasadena, CA, January 8, 2018.

- [X20] Allen Andersen and JR Dennison, “An Enhanced Operational Definition of Dielectric Breakdown for DC Voltage Step-up Tests,” *Proceedings of the 2017 IEEE Conference on Electrical Insulation and Dielectric Phenomena—(CEIDP 2017)*, Fort Worth, TX, 2017.
- [X21] Zachary Gibson, Lee Pearson, Erick Griffiths, Anthony Pearson, and JR Dennison, “Pulsed Electro-Acoustic Measurements of Charging and Relaxation in Low Density Polyethylene,” *American Physical Society Four Corner Section Meeting*, Colorado State University, Fort Collins, CO, October 20-12, 2017.
- [X22] David King, Brian Wood, and JR Dennison, “Measuring and Modeling the Conductivity of Highly Insulating Materials” *American Physical Society Four Corner Section Meeting*, Colorado State University, Fort Collins, CO, October 20-12, 2017.
- [X23] Tyler Kippen, Allen Andersen and JR Dennison, “Temperature Dependence of Electrostatic Discharge in Highly Disordered Polymers,” *American Physical Society Four Corner Section Meeting*, Colorado State University, Fort Collins, CO, October 20-12, 2017.
- [X24] Phillip Lundgreen and JR Dennison, “Development of Updated Spacecraft Materials Database for Mitigation of Charging Risk,” *American Physical Society Four Corner Section Meeting*, Colorado State University, Fort Collins, CO, October 20-12, 2017.
- [X25] Matthew Robertson, Justin Christensen, Greg Wilson and JR Dennison, “Electron Yield of a Carbon-composite Nanodielectric,” *American Physical Society Four Corners Meeting*, Colorado State University, Fort Collins, CO, October 20-21, 2017.
- [X26] Brian Wood, JR Dennison, Justin Christensen, and Greg Wilson, “Electron Yield Measurements of Vertically Aligned Multi-Walled Carbon Nanotubes,” *American Physical Society Four Corners Meeting*, Colorado State University, Fort Collins, CO, October 20-21, 2017.
- [X27] Lori Caldwell, Charles Harding, JR Dennison, Elizabeth Vargis, “Characterizing the Effects of Radiation on Muscle Cells,” *Biomedical Engineering Society (BMES) Annual Meeting*, Phoenix, AZ, October 11-14, 2017.
- [X28] Lori Caldwell, Elizabeth Vargis, Charles Harding, and JR Dennison, “Characterizing the Effects of Radiation on Muscle Cells,” *33rd Annual Meeting of the American Society for Gravitational and Space Research*, Seattle, WA, October 25-28, 2017
- [X29] Zackary Gibson, JR Dennison, and Lee Pearson, “The Pulsed Electro-Acoustic Method,” *USU Physics Colloquium*, Utah State University, Logan, UT, November 3, 2017.
- [X30] Matthew Robertson, Jordan Lee, and JR Dennison, “Electron Yield of Challenging Materials: Low Density Polyethylene and Carbon-composite Nanodielectrics,” *USU Physics Colloquium*, Utah State University, Logan, UT, October, 3, 2017.
- [X31] JR Dennison, “Effects of Temperature and Radiation Dose on Radiation Induced Conductivity,” *Invited Talk*, Sandia National Laboratories: Electronic, Optical and Nano Materials Division, Albuquerque, NM May 16, 2017.
- [X32] JR Dennison, “Enhanced Test Facility for Survivability and Characterization of Evolving Multiscale Materials in Extreme Plasma Environments,” *2017 Aerospace Materials for Extreme Environments Program Review*, Air Force Office of Scientific Research, Kirtland Air Force Base, Albuquerque, NM, May 15, 2017.
- [X33] JR Dennison, “Of Mice and Materials: Payoffs of UNSGC Research Infrastructure Awards,” *Utah NASA Space Grant Consortium Annual Meeting*, May 8, 2017, Weber State University, Ogden, UT.
- [X34] Greg Wilson and JR Dennison, “Hemispherical Grid Retarding Field Analyzer Redesign for Secondary Electron Emission Studies,” *Utah NASA Space Grant Consortium Research Symposium*, May 8, 2017, Weber State University, Ogden, UT.
- [X35] Alex Souvall, Ben Russon, Greg Wilson, Brian Wood and JR Dennison, “Myriad Investigations Using the USU Space Survivability Tests Facility,” *Utah NASA Space Grant Consortium Research Symposium*, May 8, 2017, Weber State University, Ogden, UT.
- [X36] L. Olano, I. Montero, M.E. Dávila, A. Jacas, M.A. Rodriguez, and JR Dennison, “Dynamic secondary electron emission in dielectric/conductor mixed,” *9th International Workshop on Multipactor, Corona and Passive Intermodulation (MULCOPIM)*, ESA/ESTEC (Noordwijk - The Netherlands), April 5-7 2017.
- [X37] Tyler Kippen, Allen Andersen, and JR Dennison, “Temperature Dependence of Electrostatic Discharge in Highly Disordered Insulating Polymers,” *National Council on Undergraduate Research*, Memphis, TN, April 6-8, 2017.
- [X38] Windy Olsen and JR Dennison, “Microcontroller and Memory Card Survivability in Space Conditions,” *USU Student Research Symposium*, April 13, 2017, Logan, UT.
- [X39] David King and JR Dennison, “Temperature Dependent Conductivity of Polymers,” *USU Student Research Symposium*, April 13, 2017, Logan, UT.
- [X40] Alexandra Hughlett and JR Dennison, “Reduction of Radiation Effects in Polymers,” *USU Student Research*

- Symposium*, April 13, 2017, Logan, UT.
- [X41] Allen Andersen and JR Dennison, “A New Physical Model for DC Partial Discharge in Polymeric Insulators,” *Bull. Am. Phys. Soc.* **61**(1) Part II, (2017). *American Physical Society March Meeting 2017*, March 13-17, 2017, New Orleans, LA.
- [X42] JR Dennison, “Satellite Survivability in a Harsh Space Environment: A Materials Perspective,” *Invited Talk*, SDL-USU Technical Lecture Series, Logan, UT, February 28, 2017.
- [X43] Tyler Kippen, Allen Andersen, and JR Dennison, “Temperature Dependency of Electrostatic Breakdown in LDPE and PEEK,” *Utah Conference on Undergraduate Research (UCUR) Meeting*, Brigham Young University, Provo, UT, February, 28, 2017.
- [X44] Alexander Souvall, Takuyuki Sakai, Takahiro Shimizu, Yuta Takahashi, Midori Morikawa, Shusuke Okita, Akihiro Nagata, Toshihiro Kameda, Shaunda Wenger and JR Dennison, “Space Environment Effects of Ionizing Radiation on Seed Germination and Growth,” *Utah Research on Capitol Hill*, Salt Lake City, UT, January 26, 2017.

* Full references available at <https://digitalcommons.usu.edu/mp/>

8. APPENDIX III – RELATED PRESENTATIONS

GRADUATE STUDENTS DIRECTED:

Current Graduate Students

- [T1] Zack Gibson (PhD, 2021); Jodie Corbridge Gillespie (MS, 2014; PhD, 2018); David Oliphant (PhD, 2018); Phil Lundgreen (MS, August 2019); Matthew Robertson (PhD, 2021), Greg Wilson (PhD, August 2018).

Graduated

- [T2] Allen Andersen, “The Role of Recoverable and Irrecoverable Defects in DC Electrical Aging of Highly Disordered Insulating Materials,” PhD Thesis, May 2018.
- [T3] Justin Christensen, “Electron Yield Measurements of High-Yield Low Conductivity Dielectric Materials,” MS Thesis, 109 pp., August 2017.

UNDERGRADUATE STUDENTS DIRECTED:

Senior Theses

- [T4] Jordan Lee, “Electron Yield Properties of Low-Density Polyethylene, Senior Thesis, Utah State University, Logan, UT, May 2017.
- [T5] Jonh Carlos Mojica Decena, “Radiation Damage Threshold of Satellite COTS Components: Raspberry Pi Zero for OPAL CubeSat,” Senior Thesis, Utah State University, Logan, UT, May 2017.
- [T6] Tyler Kippen, “Temperature Dependence of Electrostatic Discharge in Highly Disordered Polymers,” Senior Thesis, Utah State University, Logan, UT, May 2018.
- [T7] Alex Souvall, “Radiation Effects for Thruster Materials for CubeSat Missions,” Senior Thesis, Utah State University, Logan, UT, December 2017.
- [T8] Windy Olsen, “Microcontroller and Memory Card Survivability in Space Conditions,” Senior Thesis, Utah State University, Logan, UT, May 2017.
- [T9] David King, “Constant Voltage Conductivity with Temperature and Radiation Effects,” Senior Thesis, Utah State University, Logan, UT, May 2017.
- [T10] Katie Gamaunt, “UV Degradation of Optical Transmission in Polymers,” Senior Thesis, Utah State University, Logan, UT, May 2017.
- [T11] Krysta Moser, “Dependence of Electrostatic Field Strength on Voltage Ramp Rate for Spacecraft Materials,” Senior Thesis, Utah State University, Logan, UT, January 2017.