TEST RESULTS FOR A HIGH-VOLTAGE MULTI-JUNCTION-CELL CONCENTRATOR ARRAY DIRECT-DRIVING AN ELECTRIC THRUSTER

Henry W. Brandhorst Jr.[1], Steve R. Best[1], Julie A. Rodiek[1], Mark J. O'Neill[2] & Michael F. Piszczor[3]
[1]Space Research Institute, Auburn University, AL 36849
[2]Entech Solar, Inc., Ft. Worth, TX 76177
[3]NASA Glenn Research Center, Cleveland, OH 44135

ABSTRACT

Auburn University is working in conjunction with Entech Solar, Inc. to perform a "direct drive" experiment using a high-voltage (600 Voc) Entech Solar SunLine concentrator array that has multijunction solar cells coupled to a Russian T-100 Hall Effect Thruster (HET). This may well be the first time a Hall thruster has been run directly from III-V-based multi-junction solar cells and at this high voltage. This paper will discuss the set-up and testing results. Testing will include the addition of SLA hardware in a vacuum chamber to measure plume impingement effects at various positions relative to the exhaust axis of the thruster.

INTRODUCTION

Auburn University is working in conjunction with Entech Solar, Inc. to perform a "direct drive" experiment using a high-voltage (600 Voc) Entech Solar SunLine concentrator array that has multijunction solar cells coupled to a Russian T-100 Hall Effect Thruster (HET). This may well be the first time a Hall thruster has been run directly from III-V-based multi-junction solar cells and at this high voltage. This paper will discuss the set-up and testing results. Testing will include the addition of Stretched Lens Array (SLA) hardware in a vacuum chamber to measure plume impingement effects at various positions relative to the exhaust axis of the thruster. A schematic of planned testing can be seen in Fig. 1.

The goal of this task was to define the most meaningful combined high voltage SLA concentrator array and Hall-effect thruster demonstration tests relevant to solar electric propulsion (SEP) to test SLA reliability and provide information to help advance the SLA's qualification level. This is the next step under a Phase II STTR with NASA Glenn Research Center for the development of Stretched Lens Array (SLA) hardware for Solar Electric Propulsion (SEP) missions and is being performed at Auburn University's Space Research Institute. The Entech Solar SunLine triple-junction concentrator array is very similar to the SLA design.

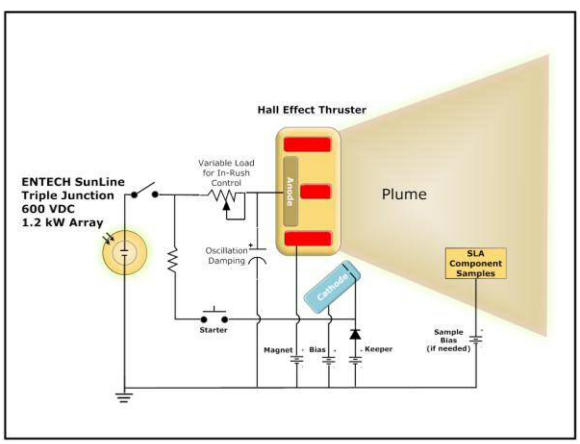

Fig. 1. Schematic of planned direct-driven HET and SLA test configuration.

TESTING RATIONALE

Key issues relevant to the combined SLA and Hall-Effect Thruster (HET) demonstration include planned testing for interactions between typical SLA test articles under bias potentials ranging 0V to 600V and exposure to the HET plasma effluents. Also, these tests should evaluate the SLA's high array voltages application to directly drive SEP systems. The reason for this experiment can be understood by viewing the schematic of a typical SLA-SEP mission with the spacecraft in earth orbit as seen in Fig. 2. The array will point toward the sun while the spacecraft orbits the earth, and some interaction will take place between the array and the HET thruster plume, especially at the inner corners of the array as this move through the outer regions of the plume. While this SLA array technology design has high efficiency, low mass, and radiation-hardness, the SLA must also tolerate plume interactions with the thruster.

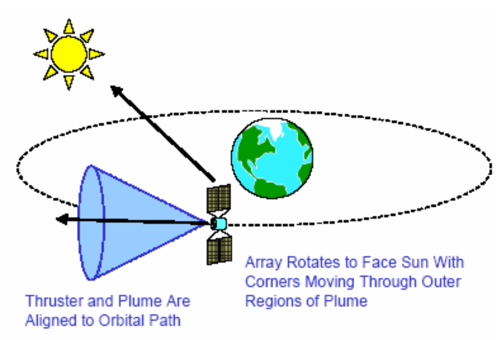

Fig. 2: Typical solar electric propulsion mission schematic.

SLA BACKGROUND

The SLA developed by Entech Solar Inc. is a space solar array that uses refractive concentrator technology to collect and convert solar energy into useful electricity. The concentrator uses a stretched Fresnel lens (8.5 cm aperture width) that refracts the incident light onto high-performance multi-junction photovoltaic cells (1.0 cm active width) as seen in Fig. 3. SLA's unique, lightweight, and efficient design leads to outstanding performance ratings:

- Areal Power Density: > 300 W/m^2
- Specific Power: > 300 W/kg for a 100 kW Solar Array
- Stowed Power: > 80 kW/m^3 for a 100 kW Solar Array
- Scalable Array Power Capacity: 4 kW to 100's of kW's
- Super-Insulated Small Cell Circuit: High-Voltage (up to 600 V) Operation
- Super-Shielded Small Cell Circuit: Excellent Radiation Hardness at Low Mass
- 85% Cell Area Savings: Up to 75% Savings in Array $/W Versus One-Sun Array

The SLA's intrinsic design characteristics protect against electrical discharge, micrometeoroid impacts, and radiation degradation. It provides arc-free high voltage operation because the cells are fully encapsulated providing a sealed environment. The SLA is a cost effective solution with 50-75% savings in $/W compared to planar solar arrays. SLA's small cell size, which is 85% smaller than planar high-efficiency arrays, allows the cell circuit to be super-insulated and super-shielded without a significant mass penalty.

The Entech Solar SunLine triple-junction concentrator array, which will be used to power the thruster in this experiment, is very similar to the SLA design. Actual SLA test hardware will be used inside the vacuum chamber to test plume impingement effects at various positions relative to the exhaust axis of the thruster.

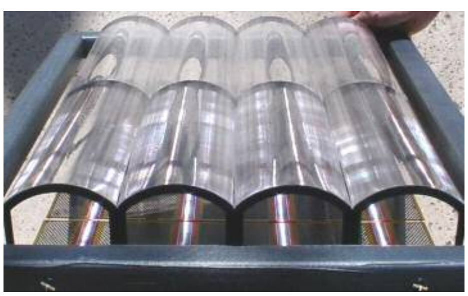

Fig. 3. SLA demonstrator in sunlight

PAST HIGH VOLTAGE TESTING

The SLA enables high voltage operation and sustainability in a high voltage environment which is especially dangerous for solar arrays. The issue of spacecraft charging and solar array arcing remains a serious design problem. A beneficial design feature of the SLA is the entire cell and cell edges are fully encapsulated by a cover glass that overhangs the cell perimeter and the silicone adhesive covers the cell edges providing a sealed environment limiting the chance of electrostatic discharge.

Ground testing of solar arrays at high voltages can determine potential charging issues that need to be addressed prior to launch. Corona discharge tests have confirmed the durability of this array design for high voltage operation. Currently there is no standard space corona test but Auburn and Entech Solar Inc. have performed testing based on guidelines for the terrestrial test from the European community, "Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges [1]." (IEC 343). The purpose of corona testing is to determine the lifetime of solar array designs under high voltage stress in the space environment.

This test will help prove the SLA can operate at high voltage (>300 V) for extended times for Hall or ion thrusters. The SLA can be specifically optimized for SEP by the ability to direct-drive Hall-effect thrusters. This technology designed by NASA Glenn can minimize the inefficiency, mass, cost and complexity of the power management and distribution interface between the solar array and electric thruster [2]. The initial drawback is that the solar array must be able to operate at the voltage level needed to drive the electric thruster. This voltage is much higher than the present operation voltage of space solar arrays of 100 V. Serious discharge, arcing, and ground-fault problems have occurred on orbit with even the present operating voltage. SLA overcomes this challenge by fully encapsulating the entire cell circuit to create a sealed environment. This can be accomplished without a huge mass penalty due to the 8X concentration and fewer cells needed to provide the same amount of power.

Initial long-term ground tests of Stretched Lens Array photovoltaic circuit samples (see Fig. 4.) have been performed with samples at very high voltage (2,000-5,000 VDC) under water which crudely simulates space plasma. Auburn has conducted similar tests in vacuum using the same type of fully encapsulated receiver samples. The sample is maintained at room temperature under a vacuum of approximately 6x10^{-5} torr. One sample underwent testing at 2,250 V for 289 days and showed no change. The SLA is also fully compliant with the new NASA-STD-4005 Low Earth Orbit Spacecraft Charging Design Standard.

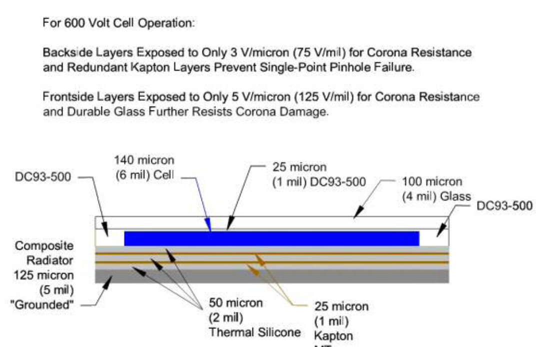

Fig. 4. Test sample configuration

Hypervelocity impact tests were performed on an Entech Solar, Inc. concentrator solar cell module and the silicone lens material at Auburn University demonstrating the SLA's resistance to micrometeoroid impacts and electrostatic discharge even at voltages as high as 600 V. Micrometeoroid impacts on solar arrays can lead to arcing if the spacecraft is at an elevated potential. No surface arcs occurred despite particle impact penetrations of the covers. Additional tests were performed with the stretched lens in place over the samples, and the lens provided excellent shielding of the cell circuits. The sample was also exposed to rear-side impact test shot with bias voltage at –1027V. Although there were many impacts no arcing was observed. In addition, the SLA lens acts as a meteoroid bumper and thus provides additional protection.

CURRENT TEST SET-UP

The high-voltage solar array used for testing was transported from Entech Solar to Auburn University (Fig. 5) where it has been interfaced with the Hall-effect thruster in the large vacuum chamber (Fig. 6). The array uses two of Entech Solar's color-mixing lenses to focus sunlight onto two photovoltaic receivers each using 240 series-connected triple-junction Spectrolab cells to provide 600 Voc output at open-circuit conditions. The peak power point is around 500 V, and the total power output of the array is approximately 1.2 kW under clear sky conditions. The Russian thruster is a Model T-100 SPT, designed and constructed by the Keldysh Research Center (KeRC), and capable of operating up to 1.3 kW. This thruster is on loan to Auburn from the NASA Glenn Research Center.

Fig. 5. Entech Solar SunLine installed at Auburn Univ.

Auburn's Electric Propulsion (EP) test facility has a 9.2 m^3 stainless-steel vacuum chamber, 1.8 m diameter by 3.6 m length. Modifications funded previously as a NASA commercialization program center, Center for Space Exploration Power Systems (CSEPS), improved the vacuum system quality for use in electric propulsion applications. For research applications like the Hall direct-drive demonstration, the use of a cryogenic pumping capability consisting of cryopanels in the chamber interior and externally mounted cryopumps provides a low contamination environment free of oil back streaming issues problematic when using oil diffusion pumps. Cryogenic temperature sensors monitor chamber component temperatures during tests.

Fig. 6. T-100 Hall thruster and cathode

TEST RESULTS

Figure 7 show multiple views of the T-100 HET plasma discharge while under direct drive power from the Entech Solar SunLine PV array. Many other settings during several of the parameter sweeps provided additional information. Visual effects are the discharge confinement during Xe flow reduction and increase in anode fall voltage (e.g. Fig. 7.b), and variability thought to be related to the passing of thin, high altitude cirrus cloud lines dropping the power (Fig. 7c) temporarily, then recovered. Testing, data reduction and analysis is ongoing and data charts will be presented to illustrate trends and dynamic behaviors.

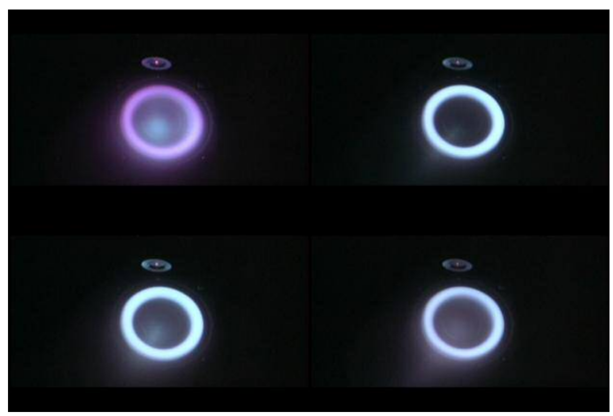

Fig. 7. HET under direct-drive by SunLine PV array; (a.) Magnet coil current 5 A, (b.) Xe flow rate reduction increasing anode fall voltage, 369W, 286V,1.29A, Xe @17 sccm, Coil 5 A, (c.) effect of thin, high-altitude cirrus clouds slightly obscuring sunlight, 218W, 170V,1.28A, Xe @17 sccm, Coil 5 A, (d.) 478W, 384V,1.246A, Xe @12.2 sccm, Coil 5 A.

Figure 8 illustrates one set of data from these SunLine-HET direct-drive runs. The HET anode power and current are plotted revealing profiles similar to those previously collected of the SunLine's I-V characteristic. The HET's nominal operational voltage is typically 300 V but by reducing the xenon flow to the anode, the anode voltage drop was increased allowing operations more closely aligned with the SunLine's maximum power point. The HET's magnetic coil was adjusted for minimum anode current.

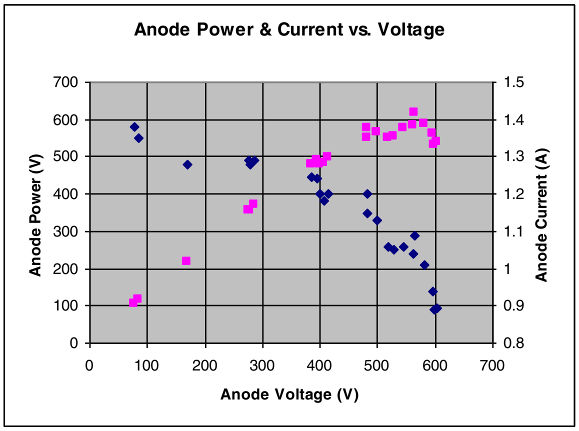

Fig. 8. SunLine direct-drive of T-100 HET.

CONCLUSION

This may well be the first time a Hall thruster has been run directly from III-V-based multi-junction solar cells and at this high voltage. The T-100 HET operated very stably throughout the variations of anode voltage, current, and Xe flow rate even with variable solar conditions including thin clouds passage. This test demonstrates a level of compatibility of Hall thrusters powered under direct-drive from a high voltage array. Furthermore, the 'squareness' of the PV I-V curve did not during our operation seem to cause any major operational problems as the HET's electrical parameters aside from the need to re-tune the magnet current and adjust Xe flow rate for most efficient operation. Tests of the SLA sample modules (See Figs. 9 & 10) a good option for solar electric propulsion missions.

REFERENCES

[1] IEC International Standard #343 (1991): "Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges."

[2] Hamley, J. A., Sankovic, J. M., Lynn, P., O'Neill, M. J., Oleson, S. R., "Hall Thruster Direct Drive Demonstration," *33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Seattle, 1997.

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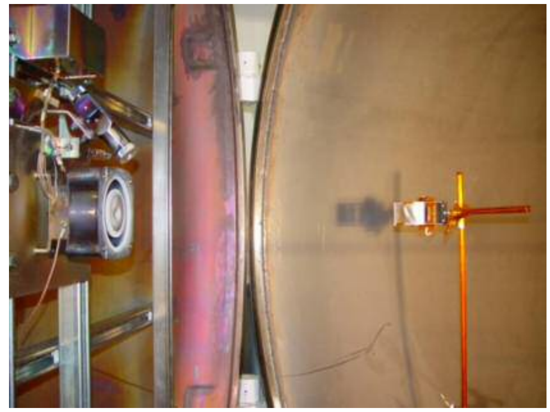

Fig. 9. SLA test article in vacuum chamber with Hall thruster

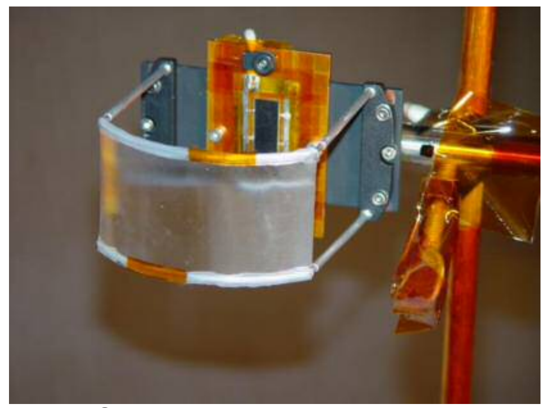

Fig. 10. SLA sample module