Test Results of Direct-Drive of HET using a High-Voltage Multi-Junction-Cell Concentrator Array

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Abstract: Auburn University's Space Research Institute working with Entech Solar, Inc. has been conducting a "direct drive" experiment using a high-voltage (600 Voc), III-V multijunction Entech Solar SunLine concentrator array coupled to a Russian T-100 Hall Effect Thruster. This possibly is the first time III-V-based multi-junction solar cells have been used to run a Hall thruster powered directly at high voltage. This paper will discuss the set-up and testing results. Testing included the addition of Entech Solar's Stretched Lens Array hardware in a vacuum chamber to measure plume impingement effects at various positions relative to the exhaust axis of the thruster.

I. Introduction

Auburn University is working in conjunction with Entech Solar, Inc. to perform a "direct drive" experiment using Entech Solar's high-voltage (600 Voc) SunLine concentrator array that has III-V 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 an high voltage array using III-V multi-junction solar cells. This paper will discuss the set-up and testing results. Testing includes the addition of Entech Solar's 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.

II. Testing Goals and Project Sponsor

There are two primary goals of this project. One was to observe the operational effects between the Entech Solar SunLine concentrator array when directly driving the HET thruster. The other goal was to define meaningful demonstration tests to observe some of the effects of HET ion plume exposure to components and construction design of Entech Solar's SLA assembly. These tests are relevant to solar electric propulsion (SEP) to test SLA

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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 SLA hardware for SEP missions and is being performed in the Electric Propulsion (EP) Facility at Auburn University's Space Research Institute. The Entech Solar SunLine triple-junction concentrator array is very similar to the SLA design.

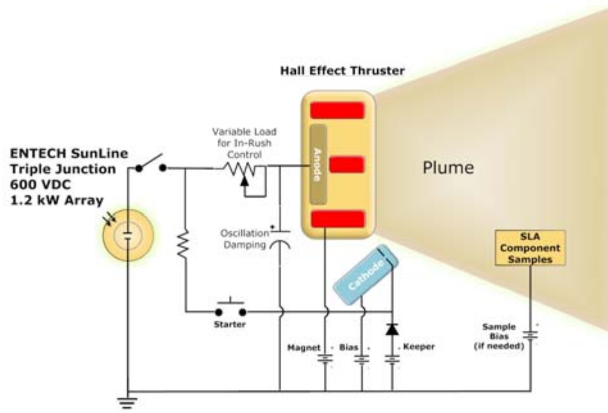

Figure 1. Schematic of planned direct-driven HET and SLA test configuration.

A. Testing Rationale

Key issues relevant to the combined SLA and Hall-Effect Thruster operational demonstration include planned testing of operational interactions and stability between the SLA and HET. The main power of HET's is through the anode discharge. The SLA will be used to directly drive the anode circuit at the high voltage potential from the SunLine array subject to solar flux and thruster load.

Also, these tests should evaluate the HET plume exposure effects upon the SLA components subject to its high array voltages application while directly driving SEP systems. Typical SLA test articles under bias potentials ranging 0V to 600V and exposure to the HET plasma effluents. An example schematic approximating planned test setup can be seen in Fig. 1. 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.

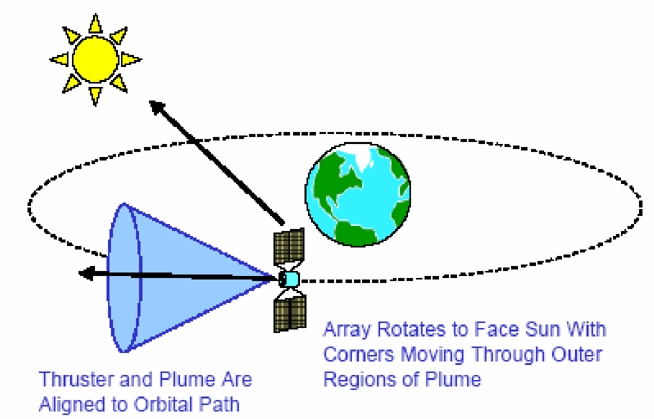

Figure 2. Typical solar electric propulsion mission schematic.

B. 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 modified, stretched Fresnel-type lens (8.5 cm aperture width) that refracts the incident light at 8X concentration 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:

Figure 3. SLA demonstrator in sunlight. Note light concentrated on PV stripes.

- Areal Power Density: > 300 W/m2
- Specific Power: > 300 W/kg for a 100 kW Solar Array
- Stowed Power: > 80 kW/m3 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 provides a degree of protection 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.

C. Past High Voltage Testing

The issue of spacecraft charging and solar array arcing remains a serious design problem. The SLA enables high voltage operation and sustainability in a high voltage environment which is especially dangerous for solar arrays. 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.

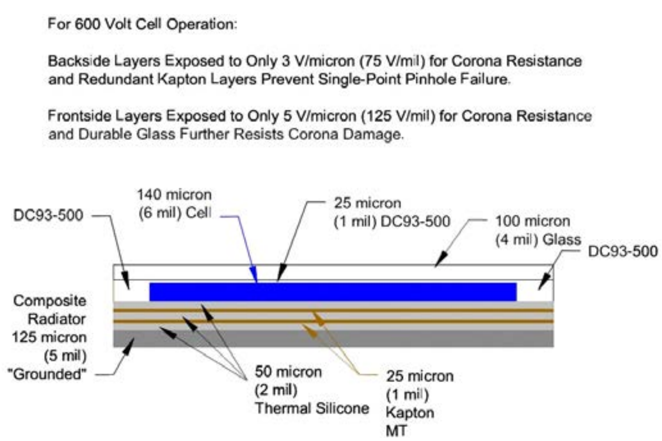

Figure 4. Test sample configuration.

Using Auburn University's Hypervelocity Micrometeroid Impact Test Facility, tests were performed on an Entech Solar, Inc. concentrator solar cell module and the silicone lens material 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.

D. Current Test Setup

The SunLine 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.

Figure 5. Entech Solar SunLine during installation at Auburn University.

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 currently on loan to Auburn from the NASA Glenn Research Center.

Auburn's Electric Propulsion (EP) test facility seen in Fig. 7 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 back-streaming oil issues problematic when using oil diffusion pumps. Cryogenic temperature sensors monitor chamber component temperatures during tests.

Figure 6. T-100 Hall thruster and cathode..

Figure 7. Auburn University Space Research Institute's Electric Propulsion (EP) 9.2 m^3 **test facility shown during testing of T-100 HET and SLA sample exposure.**

E. Test Results

Figure 8 shows 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. 8.b), and variability thought to be related to the passing of thin, high altitude cirrus cloud lines dropping the power (Fig. 8c) temporarily, then recovered. Despite the variation in sourced power from the SunLine arrays, the discharge was basically stable and did not shut-off as a result. It had been thought by some that due to the higher I-V fill-factor ("squareness") that the discharge would be unstable on the high voltage side of the Maximum Power Point (MPP). This did not appear to be an issue during any of our tests. Testing, data reduction and analysis is ongoing and data charts will be presented to illustrate trends and dynamic behaviors.

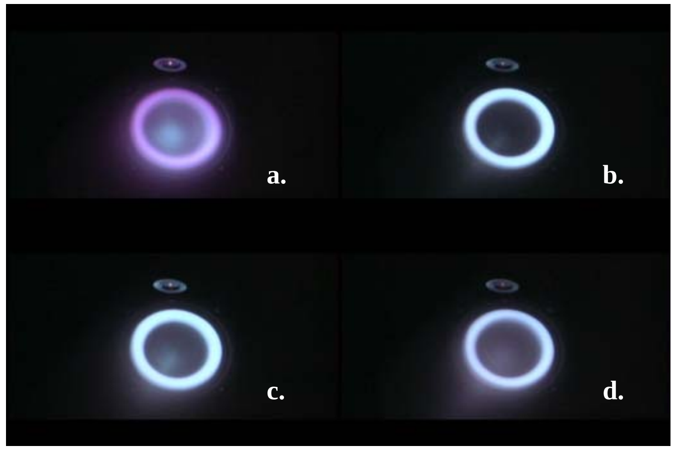

Figure 8. HET under direct-drive by SunLine PV array; (a.) Magnet coil current 5 A, (b.) Xe flow rate reduction increasing anode fall voltage, 369W, 286V,1.29A, Xe @17 sccm, Coil 5 A, (c.) effect of thin, high-altitude cirrus clouds slightly obscuring sunlight, 218W, 170V,1.28A, Xe @17 sccm, Coil 5 A, (d.) 478W, 384V,1.246A, Xe @12.2 sccm, Coil 5 A.

Figure 9 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 T-100 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 operation was optimized by tuning the magnetic coil's current and thus, magnetic field strength, for minimum anode current.

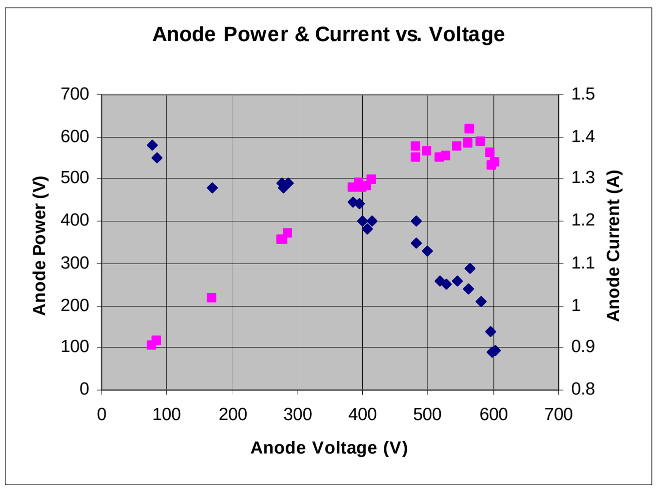

Figure 9. SunLine direct-drive of T-100 HET.

For the portion of tests relating to the exposure of the SLA sample modules, especially the lens, to the HET's ion plume impingement, the SLA sample modules were installed in close proximity of the HET thruster exhaust, as shown in Figs. 10 & 11. The SLA test modules were located approximately 50 degrees from the thruster's exhaust axis, and approximately 1 meter away. Here tests have been run to compare the ion plume's outer flux erosion effects on first, an uncoated-lens version of the SLA assembly. Tests are currently underway with a coated-lens version of the SLA assembly. Results are pending conclusion of tests and review.

III. 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 seem to cause any unstable operational problems during our operation. Standard HET discharge optimization such as re-tuning the magnet current and adjusting Xe flow rate for most efficient operation appears to be sufficient. The III-V multi-junction SunLine concentrator array was very compatible with the T-100 HET operation. SLA sample exposure effects to ion plume impingement are ongoing and will be reported later.

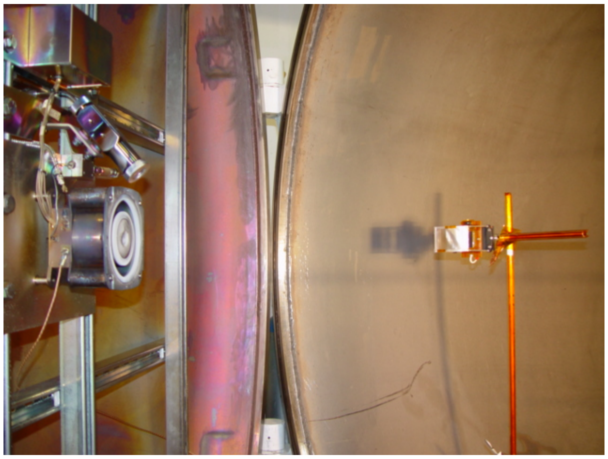

Figure 10. SLA sample module in vacuum chamber with Hall thruster.

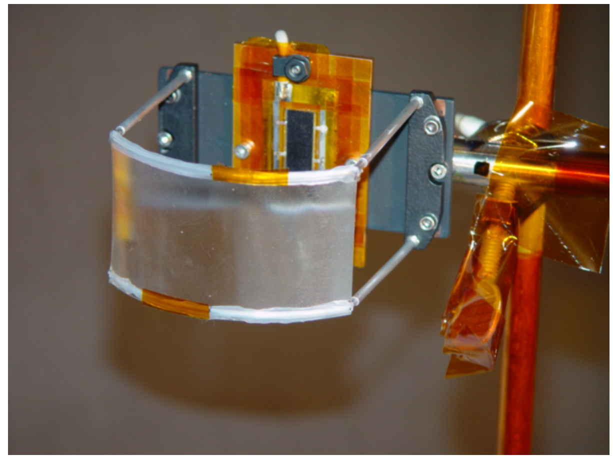

Figure 11. Close-up of SLA sample module pointing toward HET.

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[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.