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

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ABSTRACT: Auburn University is working in conjunction with ENTECH, Inc. to perform a "direct drive" experiment using a high-voltage (600 Voc) ENTECH SunLine concentrator array that has multijunction solar cells coupled to a Russian T-100 Hall Effect Thruster. 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. 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 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 hardware for Solar Electric Propulsion missions and is being performed at Auburn University's Space Research Institute. The ENTECH SunLine triple-junction concentrator array is very similar to the SLA design.
Keywords: Solar Electric Propulsion, Direct Driving, Concentrator Array

1 INTRODUCTION

Auburn University is working in conjunction with ENTECH, Inc. to perform a "direct drive" experiment using a high-voltage (600 Voc) ENTECH 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.

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 SEP missions and is being performed at Auburn University's Space Research Institute. The ENTECH SunLine triple-junction concentrator array is very similar to the SLA design.

Key issues relevant to the combined SLA and HET demonstration need to include testing for interactions between typical SLA test articles under high bias potentials (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.

SunLine-HET direct-drive runs have been completed successfully. It is quite a breakthrough and this paper will discuss the set-up, testing, data reduction, and analysis of results to illustrate trends and dynamic behaviors.

2 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-

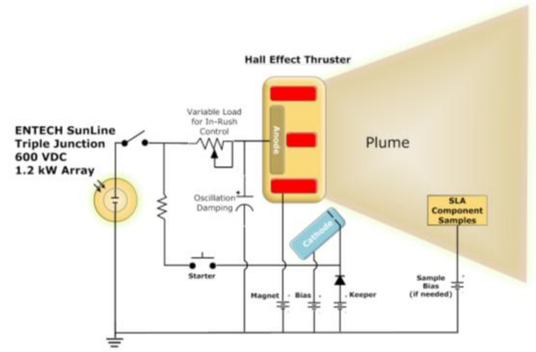

Figure 1: Schematic of planned direct-driven HET and SLA test configuration.

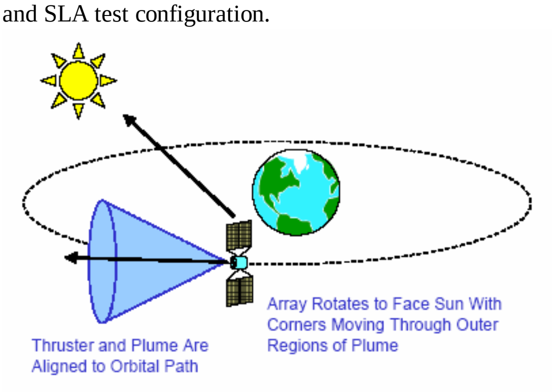

Figure 2: Typical solar electric propulsion mission schematic.

hardness, the SLA must also tolerate plume interactions with the thruster.

3 SLA BACKGROUND

SLA is a unique ultra-high-performance, ultra-light, cost-effective photovoltaic concentrator array using refractive concentrator technology. Unlike reflective concentrators, these refractive Fresnel lens concentrators can be configured to minimize the effects of shape errors, enabling straightforward manufacture, assembly, and operation on orbit. By using a unique arch shape, these Fresnel lenses provide more than 100X larger slope error tolerance than either reflective concentrators or conventional flat Fresnel lens concentrators.[1]

Flexible blanket and rigid panel versions of the SLA have been develped and tested over the last decade. A 3.75 kW scale (2.5 x 5.0 m) building block of the Stretched Lens Array on the SquareRigger platform has been successfully demonstrated as seen in Fig. 3. That demonstration confirmed that the specific power goal of > 300W/kg is achievable.

Because of its 8.5X geometric concentration ratio, SLA saves over 85% of the required area, mass and cost of the multi-junction solar cells per watt of power produced. Significantly, the total combined areal mass density (kg/m^2 of sun-collecting aperture area) of the lens material, the radiator sheet material, and the fully assembled photovoltaic receiver is much less (about 50%) than for a one-sun multi-junction cell assembly alone. Thus, SLA has a substantial inherent mass advantage over planar, one-sun multi-junction-cell solar arrays. Similarly, due to its 85% cell area and cost savings, SLA has a substantial inherent power cost advantage ($/W) over such planar multi-junction-cell arrays. The Stretched Lens Array offers unprecedented performance (>80 kW/m^3 stowed power, >300 W/m^2 areal power, and >300 W/kg specific power) and cost-effectiveness (50-75% savings in $/W compared to conventional solar arrays).

SLA's small cell size also allows super-insulation and super-shielding of the solar cells to enable high-voltage operation and radiation hardness in the space environment. SLA's demonstrated high performance and radiation tolerance, coupled with its substantial mass and cost advantages, will lead to many applications especailly in high voltage, high radiation environments. SLA's unique attributes make it an optimal choice for SEP missions.

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.

Figure 3: Full scale SLASR panel

4 SLA HARDWARE TESTING

Some obstacles to SEP include the use of high voltage operation to reduce cable mass and permit direct drive thruster operation along with durability and resilience to the space environment. Ground testing of the array is essential to help prove the reliability of space operation.

Corona testing had proven 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.

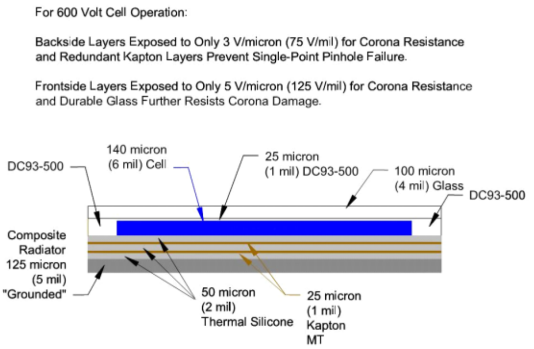

Figure 4: Test sample configuration

To test the sustainability of SLA in high voltage operations, array segments, seen in Fig. 4, are under test for corona breakdown. ENTECH has fabricated and tested a number of such single-cell SLA receiver samples at very high voltage levels (2,250 to 4,500 V) in an underwater hi-pot test for very long periods of time. Auburn University has conducted similar tests in vacuum using the same type of fully encapsulated receiver samples. These tests are being conducted using the guidelines found in ESA's IEC International Standard #343 (1991): "Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges [3]." The samples underwent testing at 2,250 V for ten and a half months and showed no change. Due to the SLA's inherent protection against electrostatic discharge it is especially well suited for electric propulsion missions. The SLA is also fully compliant with the new NASA-STD-4005 Low Earth Orbit Spacecraft Charging Design Standard.

Hypervelocity testing at Auburn University showed the SLA's resistance to micrometeoroid impacts and electrostatic discharge even at voltages as high as 1000V. Micrometeoroid impacts on solar arrays can lead to arcing if the spacecraft is at an elevated potential. Therefore, hypervelocity testing of the solar array is necessary. A concentrator solar cell module supplied by ENTECH, Inc was tested at Auburn University's Hypervelocity Impact Facility. The module consisted of a string of concentrator multijunction solar cells in series completely covered with cover glass. The overhang extended well beyond the cell boundaries and was also filled with silicone providing a sealed environment. The test sample in the last test is shown in Fig. 5. No surface arcs occurred over the sample despite visible 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.

Figure 5: Stretched lens array module after testing

5 CURRENT TEST SET-UP

The SunLine high-voltage solar array used for testing was transported from Entech Solar to Auburn University (Fig. 6) where it has been interfaced with the Hall-effect thruster in the large vacuum chamber (Fig. 7). 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. [4] This thruster is currently on loan to Auburn from the NASA Glenn Research Center.

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 back-streaming oil issues problematic when using oil diffusion pumps. Cryogenic temperature sensors monitor chamber component temperatures during tests.

Figure 6: Entech Solar SunLine during installation at Auburn University.

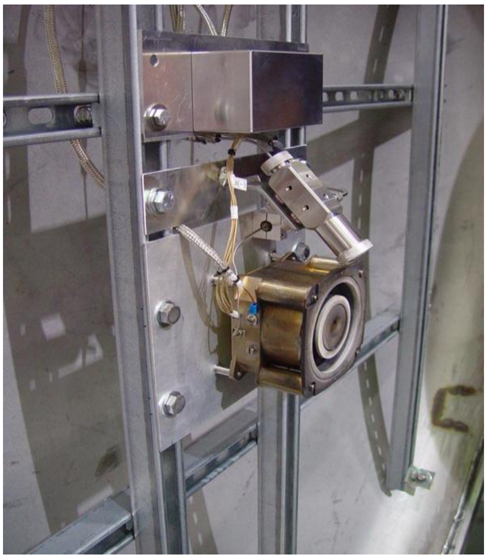

Figure 7: T-100 Hall thruster and cathode

6 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

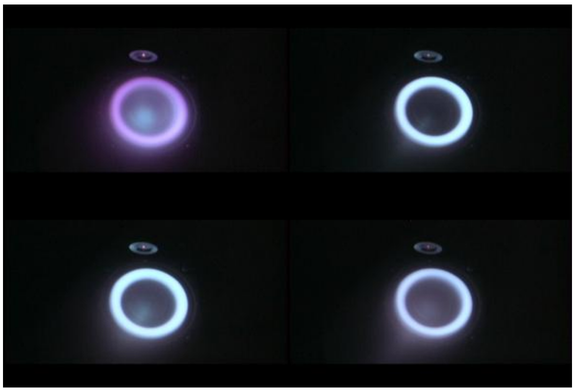

Figure 8: HET under direct-drive by SunLine PV array; (a.) Magnet coil current 5 A, (b.) Xe flow rate reduction increasing anode fall voltage, 369W, 286V,1.29A, Xe @17 sccm, Coil 5 A, (c.) effect of thin, high-altitude cirrus clouds slightly obscuring sunlight, 218W, 170V,1.28A, Xe @17 sccm, Coil 5 A,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

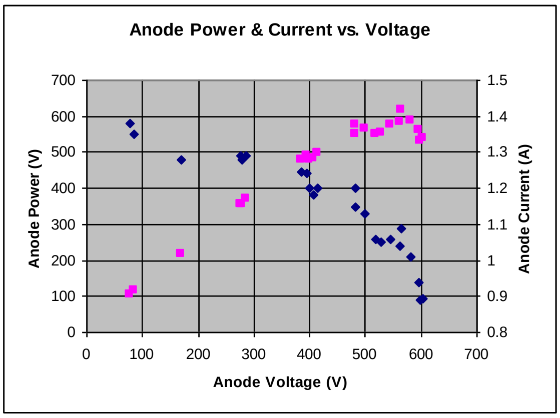

Figure 9: SunLine direct-drive of T-100 HET.

dynamic behaviors.

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.

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 Fig. 10. 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.

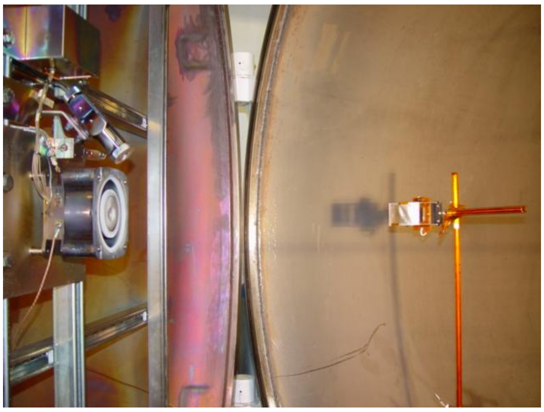

Figure 10: SLA test article in vacuum chamber with Hall thruster

7 SUMMARY

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.

8 ACKNOWLEGMENTS

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