SPACE-BASED OPTICAL WIRELESS POWER TRANSFER: PROGRESS TOWARDS A COMMERICAL END-TO-END ARCHITECTURE.

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Introduction:

Optical wireless power transmission is a promising solution for energy-limited spacecraft, such as lunar surface assets. However, deploying high-power lasers and photovoltaic receivers in space remains challenging due to launch conditions, thermal management constraints, steep temperature gradients, radiation, and limited heat dissipation in vacuum. Similarly, achieving high optical-to-electrical efficiency in laser power converter arrays remains difficult due to low maturity of cell array assembly processes, thermal management, and environmental constraints.

We present performance and environmental testing results on two important building blocks of Volta's complete end-to-end optical wireless power transmission, comprised of two major components:

(1) A 1800 W_O single-mode fiber laser platform with integrated thermal control (shown in Figure 1).

(2) A III-V multi-junction laser power converter array achieving >38% efficiency at room temperature (shown in Figure 5).

The laser was subjected to shock and vibration, thermal vacuum, radiation, and life testing. The receiver was subjected to extended operational testing, while individual cells were subjected to cryogenic testing.

Laser Testing:

Shock and random vibration testing. Testing was performed on Volta's laser package's to evaluate the system's ability to withstand the environments likely to be encountered during launch, landing, and other mission phases. The test profile was based on the Falcon 9 Maximum Predicted Environment (MPE) [1]. No visual signs of material degradation or active performance reduction were observed after the trials.

Figure 1. Shock/vibration test fixtures with the laser installed

Thermal vacuum (TVAC) testing. This tesing evaluated the laser's performance under simulated space conditions, with a focus on thermal behavior, beaming time, and optical power consistency. Multiple test methods were employed to characterize performance at varying power levels, temperature biases, and operational settings. The laser was operated under conditions designed to replicate real mission profiles for lunar orbit-to-surface power beaming. Periods of operation followed by idling were used to simulate sequential fly-bys over receiving spacecraft at different locations. The laser demonstrated excellent repeatability in optical power and predictable trends in temperature-driven behavior. In TVAC conditions, lower temperatures extended beaming durations and marginally improved performance, while conversely, higher temperatures limited operational time, underscoring the importance of precise thermal management for sustained performance in space environments.

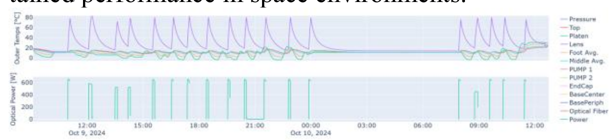

Figure 2. Optical power and thermal behavior during TVAC beaming sessions

Radiation testing. We estimate that, over a hypothetical 15 years mission, the orbital asset at a 50km, circular, lunar orbit would see a total ionizing dose (TID) on the order of 0.2 krad [2][3]. The laser was irradiated with a Co-60 source up to a total dose of 17.8 krads, a level of irradiation much higher than the expected mission dose. The laser output power degraded by ~18% after exposure.

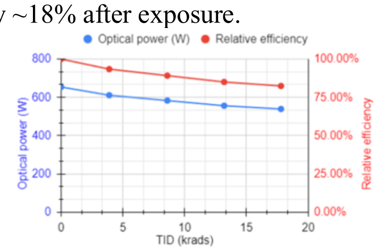

Figure 3. Power and efficiency loss as a function of TID.

Extended lifetesting. This testing validated the longevity and reliability of critical laser components. In total, the laser completed 1,095 hours of active beaming at 25°C, showing an increase in power output from 544 W, as measured after TID testing, to approximately 638 W. It is useful to note that 1,095 hours of operation is analogous to beaming 4 minutes every 2 hours for over 3.5 years. We observed a tendency for temperatures inside the laser to generally be higher in the first part of the test, where annealing took place. Temperatures recorded during the second half of the test, when annealing had ceased, are lower.

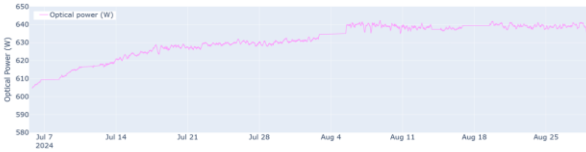

Figure 4. Lifetest temperatures and optical power

Receiver Testing:

Volta has assembled and tested a compact, lightweight laser receiver array using 25 InGaAs/InP cells arranged in a square configuration. The array measures 5 cm x 5 cm and weighs ~50g. Figure 5 shows an image of this cell array.

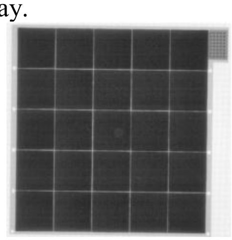

Figure 5. An image of a 5x5 receiver cell array.

Operational testing. The array was tested with a Near-Infrared laser input of 60 W_O average power. Extended testing was performed to assess array performance in a mission case with multiple transmitters servicing a single receiver. The 25-cell array demonstrated stable operation over a period of over 1.5 hours, as shown by Figure 6. The results show sustained operation during hours with optical-to-electrical efficiency approaching 39% and electrical power generated over 24We.

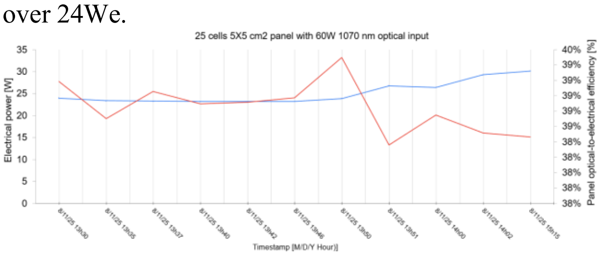

Figure 6. Optical-to-electrical power generation and conversion efficiency of a 25-cell assembly.

Cryogenic cell testing. Volta generated preliminary data on InGaAs/InP type cells operated below 100K. There was a 125K-wide range, from 175K to 300K, where the cell efficiency was measured to be above 45%. This is in line with past studies that have shown individual GaAs cell efficiencies >50% [4].

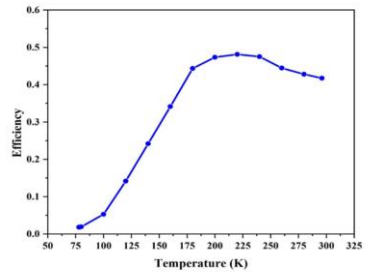

Figure 7. Cell performance from 75K to 300K with maximum efficiency at ~225K.

Volta plans to integrate multiple 5x5 arrays together to create larger receivers capable of generating several hundreds of watts of electrical power. We expect power generated to scale linearly with receiver size.

Conclusion:

This effort details the extensive testing campaign performed on laser transmitters and receivers for optical wireless power transfer for space applications. The fiber laser platform exhibited resilience under vibration, shock, thermal vacuum, and radiation exposure, with performance recovery observed during extended operation due to annealing. Similarly, the photovoltaic receiver array showed stable operation under high optical flux and extremely low temperatures. While challenges remain, particularly in scaling receiver size while simultaneously optimizing thermal control, cryogenic survivability, and mass, the findings presented here represent a critical step toward enabling commercial end-to-end optical power transfer systems for lunar and deep-space missions. Future efforts will focus on further characterization of transmitter performance at orbital beaming distances, the design of larger receiver arrays that preserve manufacturability, and the refining of these technologies to optimize power conversion efficiency and to meet the demanding environments and requirements of future exploration programs.

References:

[1] Falcon Payload User's guide, Space Exploration Technologies Corp. [2] J. E. Mazur, W. R. Crain, M. D. Looper, D. J. Mabry, J. B. Blake, A. W. Case, M. J. Golightly, J. C. Kasper, H. E. Spence (2011) *New measurements of total ionizing dose in the lunar environment*, Space weather, Vol. 9, S07002. [3] S. Zhang et al. (2020) *First measurements of the radiation dose on the lunar surfaces*, Science advances, Volume 6, Issue 39. [4] S. Fafard, D. Masson (2022) *74.7% Efficient GaAs-Based Laser Power Converters at 808nm at 150 K*, MDPI, Photonics