A PATH TO SPACE-BASED POWER TRANSMISSION USING SPACE RESOURCES: ADDITIVE MANUFACTURING DEMONSTRATION OF A CAVITY MAGNETRON FOR SOLAR POWER SATELLITES. A. Valsalan[1], X. Walls[2], and A. Ellery[3], [1]Carleton University (1125 Colonel By Dr, Ottawa ON K1S 5B6; anjanavalsalan@cmail.carleton.ca), [2]Carleton University (1125 Colonel By Dr, Ottawa ON K1S 5B6; xavier-wallsperez@cmail.carleton.ca), [3]Carleton University (1125 Colonel By Dr, Ottawa ON K1S 5B6; alexellery@cunet.carleton.ca).

Introduction: Since 1968, Space-Based Power Transmission (SBPT) concepts have been investigated as an alternative clean energy source. Solar Power Satellites (SPS) are a form of SBPT that has the potential to provide uninterrupted energy to Earth and to other planets for exploratory missions is their main selling point [1]. Two of the main drawbacks for SPS are their sheer size and the high investment required to implement them [2]. A possible solution to decrease the high investment is to manufacture SPS in space using space resources. Additive manufacturing (AM) of products for In-Space Manufacturing (ISM) is an area that is currently being explored. Metal structures and tools have been printed using AM methods such as Directed Energy Deposition (DED) and Laser Powder Bed Fusion (LPBF) out of materials such as Aluminium [3]. Electron Beam Additive Manufacturing (EBAM) has also been suggested as a reliable option for space manufacturing using lunar resources [4]. These methods would have no issues manufacturing the structural components of an SPS. This paper provides a proof of concept on the use of AM methods to create a cavity magnetron.

Background: Currently, solid-state power amplifiers (SSPAs) have been suggested as optimal transmission devices coupled with flexible antenna arrays for efficiency and control, such as Caltech's MAPLE driven by CMOS RFICs [5]. In this work, the concept of SBPT via microwaves is showcased by 3D printing a magnetron. These devices are simpler and are made of fewer components compared to (SSPAs) offering a simple and cost-effective solution. Magnetrons are also capable of producing high-power outputs using minimal material, a critical aspect when minimal payload weight is required and when resources are scarce in space. Magnetrons have a proven track record in microwave power transmission experiments [6]. Magnetrons could be suitable for preliminary demonstrations in-orbit before investing in more expensive phased-arrays which require complex synchronization.

Cavity magnetrons are typically composed of an anode and a cathode sandwiched between two magnets that form an external magnetic field with flux lines that are parallel to the axis of the cathode [7]. The anode is traditionally formed from a cylindrical copper block due to its high electrical and thermal conductivity. The Cu block is machined to have resonators and resonant cavities that lead to the interaction space between the anode and cathode [8]. The cathode is typically made of a thoriated W filament, which is electrically heated to emit electrons that interact with the radio frequency (RF) fields of the anode which acts as a slow-wave structure [9]. A negative potential is applied across the cathode, and when acted on by a perpendicular magnetic field, the electrons begin to move in spoke formation away from the cathode. The electrons then interact with the cavities of the anode and begin to oscillate at microwave frequencies [9].

To eliminate the reliance on Earth-based supply chains, magnetron components must be fabricated directly in space using extraterrestrial materials. Lunar regolith contains significant amounts of Fe, Ti, Al, and Si. W-rich minerals have been found in some lunar highland regolith samples. Lunar KREEP is also a potential lunar resource. Lunar anodes could be made of Al due to its good thermal and electrical conductivity. The Lunar cathode can use W that is extracted from W-rich highlands regolith. Alnico magnets could be produced on site using Fe and Al extracted from lunar regolith while Ni and Co could be sourced from metallic meteorites on the Moon (i.e. IAB or IIIAB). Rare earth magnets such as NdFeB or SmCo could also be produced from REE obtained from lunar KREEP.

Design and Simulation: A commercial (2M214) magnetron for microwave ovens was dissected and used as a reference for the design of the AM magnetron (Figure 1). The dissected magnetron was a 10-vane cavity magnetron with double strapping rings and a probe antenna attached to a vane.

Figure 1: Cross-Section of the reference 2M214 magnetron

Hull and Hartree voltages were calculated along with the cutoff static magnetic field. These values influenced the applied voltage and magnetic field for the design. The initial model of the magnetron was created using Fusion 360 and then simulated in CST Studio Suite to verify the operating frequency and the electron motion (Figure 2).

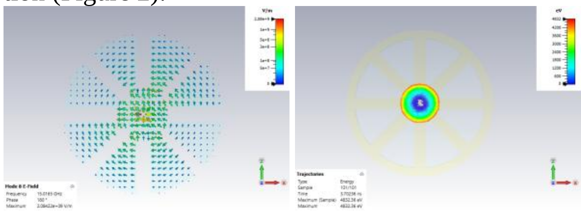

Figure 2: Eigenmode and Particle Tracking Simulations

An iterative process was used to adjust the geometry of the anode design until appropriate frequencies were obtained and the electrons moved as expected for a magnetron. Once a preliminary model was obtained, the geometries were fine-tuned to ensure that the 3D printing methods could be executed effectively. The model was simplified by foregoing the strapping rings which required overhangs in the anode, as well as the cathode filament. The cathode from 2M214 was instead incorporated into the magnetron design. All wall thicknesses were increased to facilitate a minimum size of 1mm and all overhang angles were adjusted to be greater than 45°. With these changes made, final simulations were done to verify the adjusted magnetron model (Figure 3).

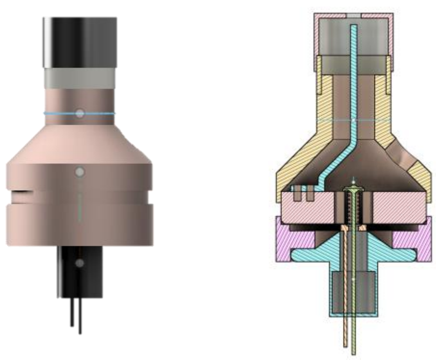

Figure 3: Finalized Magnetron Model with Cross-Sectional View

Additive Manufactured Magnetron: LPBF was chosen as the first AM approach because it allows printing highly dense, complex-shaped parts with detailed features that required minimal post-processing [10]. The LPBF experiments were carried out at the University of Waterloo's Multi-Scale Additive Manufacturing Lab using Cu14500 powder and an EOS M290 Printer. The magnetron parts were post-processed by cleaning up the outer surface using a lathe and ensuring that the components were within specified tolerances. The antenna was secured to the anode using two screws to ensure that it would remain in a central position along the cathode axis. The cathode, adapter ring, anode and anode cap were joined together using silver solder. An alumina ring and steel cap were attached using Ceramabond to create the completed magnetron (Figure 4).

Figure 4: Post-Processed 3D-Printed Magnetron Parts and Fully Assembled Magnetron

Conclusion: This study provides a proof of concept for a cavity magnetron using AM technologies. The next goal is to extend these manufacturing processes by using space resources such as substituting Cu with Al. This research represents a critical step toward establishing a self-sustaining SBPT infrastructure reducing dependance on Earth supply chains.

References:

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