MME 533 Literature Review: Beamed Power

Alexander Benson

Abstract—**Beamed power describes the transmission of power via electromagnetic radiation. In most contexts light in the high frequency radio-wave or low frequency microwave spectrum (1mm wavelength) is used. Direct current is converted to light, aimed at a receiving array, and converted to energy. Depending on the application the form of that energy might be plasma or current.**

Beamed power has numerous potential applications the foremost being space-based solar-power satellites and reducing launch costs by beaming power to a rocket nozzle.

I. INTRODUCTION

Beamed power is a transmission technology and not a power source. The invention and maturation of beamed power is a complicated story involving; the invention of the rectifying antenna (patented 1969[1]), the slow and uncertain growth of DC to RF conversion[2], and the decline in costs of space/photovoltaic technology[3], [4]. In its most traditional form, beamed power is the process of converting electrical power to microwaves (especially 1mm wavelengths) and directing the resultant beam to a rectifying antenna/array, see figure 1 for a small form version and figure 2 for the corresponding conversion process.

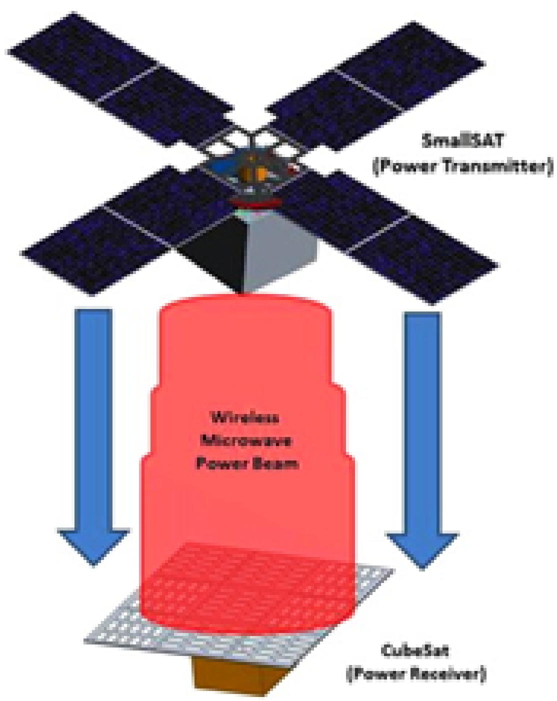

Fig. 1. Artist's rendering of a small solar power satellite and beaming system[5]

As the field matures, the utility of beamed power beyond space to earth is being explored and may see real-world use before a space-based solar power satellite is viable. These ideas include rocket propulsion using beamed power[4], [5], [6], space to space power transfer[5], and earth to air applications[8]. Rocket propulsion is of especial interest given the interplay between the price of a space based solar system and the price of launch costs. If beamed propulsion proves to be an effective and reliable means to launch, the economic availability of space-based projects will increase.

II. THE FUNDAMENTALS AND PRINCIPLES OF BEAMED POWER

The process of beaming power will be broken down into 3 steps for the purpose of this report: conversion from current to light, transmission through an atmosphere or space, and receiving. Conversion is the most complicated aspect to describe given the range of available methods for converting current to a desired wavelength; magnetrons, gyrotrons, klystrons, and free electron lasers. The physics of all these components is somewhat outside the intended scope of this paper and only magnetrons and gyrotrons will be covered with any degree of depth. Transmission of power through space has few concerns and will probably be a popular method for propelling small probes over long distances[9] however there are many complications to transmitting power through an atmosphere[10]. The method for receiving power depends, somewhat, on the application. Many propulsive applications bypass any conversion to electricity and instead generate thrust either by igniting a photosensitive compound[6] or by converting atmospheric gas to plasma and using the resultant force to accelerate[11].

1) Conversion: The conversion of DC to RF is a Selection of Gyrotron vs. Magnetron is context dependent. NASA has considered both in the past. Magnetrons show up more frequently when the power source is space-based[12] whereas gyrotrons are preferred for Earth based applications[11]. Cyclotrons are a derivation on a broader range of technology classed as "magnetrons". Magnetrons have and will continue to refer to the simpler cavity technology capable of generating a fixed wavelength determined at time of manufacture and other simple converters. Magnetrons generate electromagnetic radiation via the process of: electrons leaving the cathode (typically a rod in the center, see figure 4), the electron moves within a high magnetic field, resonance between the electron and the cavities results in electromagnetic emissions along a narrow spectrum[13]. The gyrotron builds upon these principles, firing a controlled electron beam into a cavity which moves in a helical pattern. These electrons emit electromagnetic radiation according to similar principles to the magnetron before returning to the anode, figure 5[14]. The clearest advantage of the gyrotron over the magnetron is in the ability

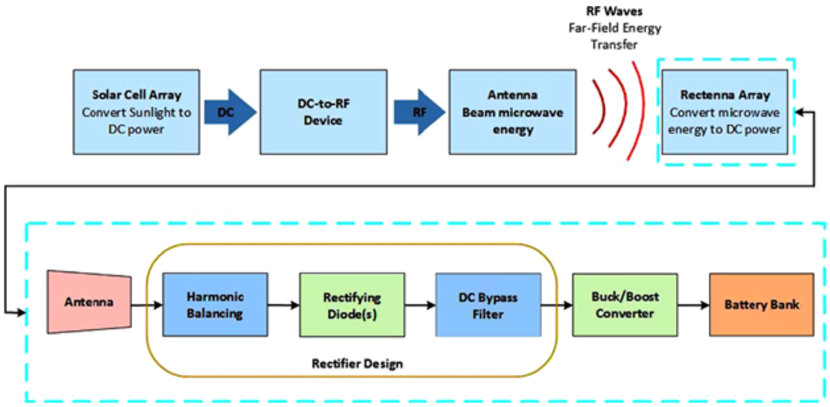

Fig. 2. A Diagram of the Energy Conversion Process[5]

of the gyrotron to emit high frequency wavelengths, however the magnetic fields necessary to produce these wavelengths at the megawatt and gigawatt scale could be cost-prohibitive[14].

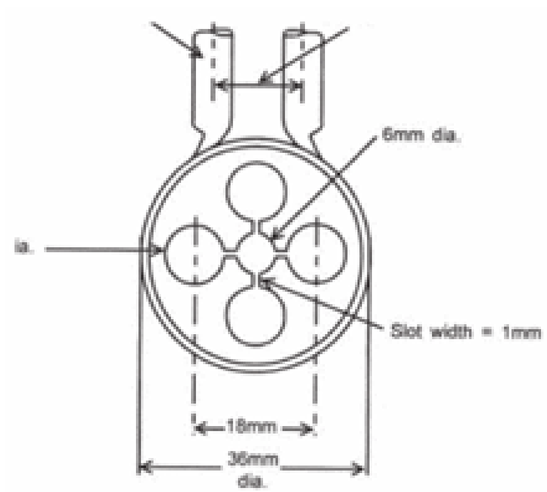

Fig. 3. Simplified schematic of a multicavity magnetron[13]

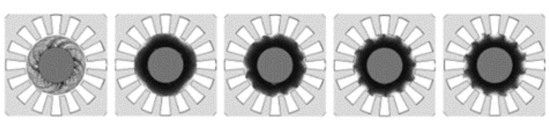

Fig. 4. A time elapsed simulation of electron motion and density in a spatial harmonic magnetron[15]

The preference for magnetrons in space-based applications vs. gyrotrons is not explicitly stated by decision makers, such as NASA. Based on the construction of the systems and reasonable extrapolations from context; magnetrons are more cost effective, easier to manufacture at scale, and there is no benefit to be gained from the high-frequency capabilities of gyrotrons[2]. On Earth, however, the ability to utilize high frequency wavelengths allows for variation in the wavelength of the beam; high frequency wavelengths have applications in the generation of plasma in the atmosphere[7] and in igniting photosensitive polymers (though the latter uses a CO2 laser)[5].

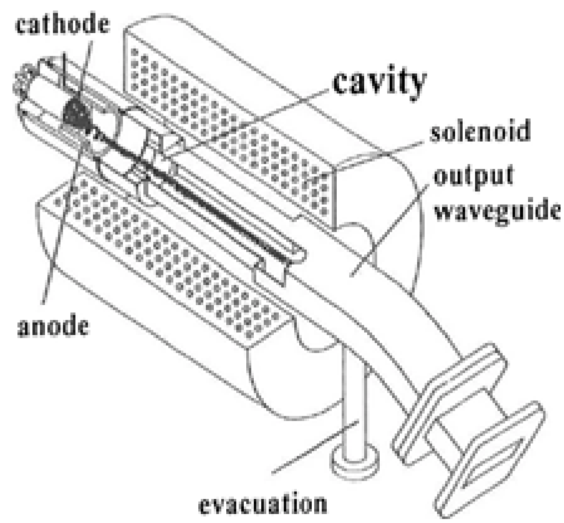

Fig. 5. Layout of the first gyrotron[14]

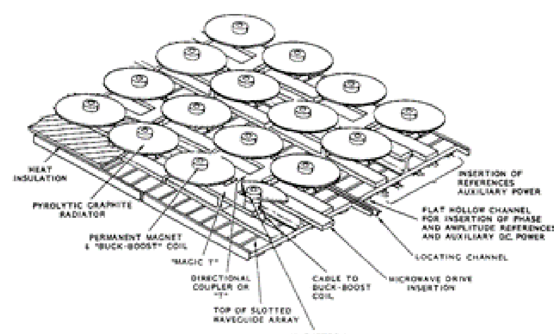

Fig. 6. Proposed magnetron transmitting array in the Solar Power Satellite[12]

A. Transmission

The transmission of energy in the form of a beam has several complications within an atmosphere. There are limitations to the amount of energy transmissible through the atmosphere, past this limit the atmosphere ionizes resulting in a phenomena known as electrical breakdown[10, p.3]. The Kerr effect is a phenomena in which, at high energy densities of light in a fluid/gas, the medium will self-focus and break the beam into individual filaments, resulting in losses above a high power threshold. “Thermal blooming” describes the heating of the atmosphere and fluid dynamic processes induced by a high power and localized source of light with the net effect of defocusing the beam. There are also losses to atmospheric aerosols and atmospheric turbulence. These losses are summarized by figure 7.

Propagation Mechanism	$\lambda = 2.0\ \mu m$	$\lambda = 2.0$ mm
Electrical Breakdown, $r_{eff} = \begin{cases} 1\text{ m} \\ 10\text{ m} \\ 30\text{ m} \end{cases}$	3.1×10^{11} W 3.1×10^{13} W 2.8×10^{14} W	3.1×10^{8} W 3.1×10^{10} W 2.8×10^{11} W
Kerr Effect	1.5×10^{9} W	1.5×10^{16} W
Thermal Blooming (CW), $r_{eff} = \begin{cases} 1\text{ m} \\ 10\text{ m} \\ 30\text{ m} \end{cases}$ Thermal Blooming (Pulsed, 1 μs)	166.7 W 16.7 W 5.6 W 3.7×10^{7} W	3.5×10^{6} W 3.5×10^{5} W 1.2×10^{5} W 7.7×10^{11} W
Turbulence	> 0	> 0

Fig. 7. Threshold power levels beyond which losses are induced. Aperture is varied where applicable[10]

B. Receiving

Except for the rocket propulsion methods previously, converting beamed microwaves to energy is always done via rectifying antenna (aka a “rectenna”). This is achieved by a grid of half-wave dipoles and solid-state diodes which convert long-wave light into direct current. For most applications rectennas should be non-directional; sacrificing a theoretically higher efficiency in favor of a higher net-efficiency in practical applications. Rectennas are relatively efficient and RF-DC efficiencies exceeding 80% have been achieved[16].

The first use of a rectenna for beaming power was in an experiment in 1963. The goal was to create a helicopter without an onboard source of power, see figure 8[16]. At the scales necessary for the efficient transfer of power at the solar satellite scale, these arrays are large. A NASA/DOE joint effort in 1979 proposed a rectenna array formed by an ellipse of 10km by 13.2km with 10 billion rectenna elements located at a latitude of 35°.

The broader system described in the NASA/DOE joint venture was comprised of a $50km^2$ solar array with a solar array efficiency of 13%, transmission (DC to RF) efficiency of 78%, and rectenna efficiency of 89% and a net efficiency of 7% of irradiance[17, pp. 193–194].

There is ongoing research into constructing rectennas from multiwalled carbon nanotubes, figure 9. The benefit to be gained from carbon nanotubes is in the wider range of wavelengths that carbon nanotubes can absorb with the same efficiency as a traditional rectenna[18].

C. Concerns

There are environmental concerns to focusing intense microwaves at a surface for extended periods of time. It is not clear what the effect on humans would be if exposed to microwaves, there has been research linking cataracts to microwave exposure[19] however beyond that it the concern for human exposure seems to be one born of caution rather than a specific concern. Intense concentrations of light such as that of a solar satellite could be potentially lethal given the amount of power, however concentrations below 400W/m2 are considered non-hazardous to humans and animals larger than insect life[9]. On the receiver end, the most efficient rectennas designed to date operate at 2.45Ghz, the same bandwidth as

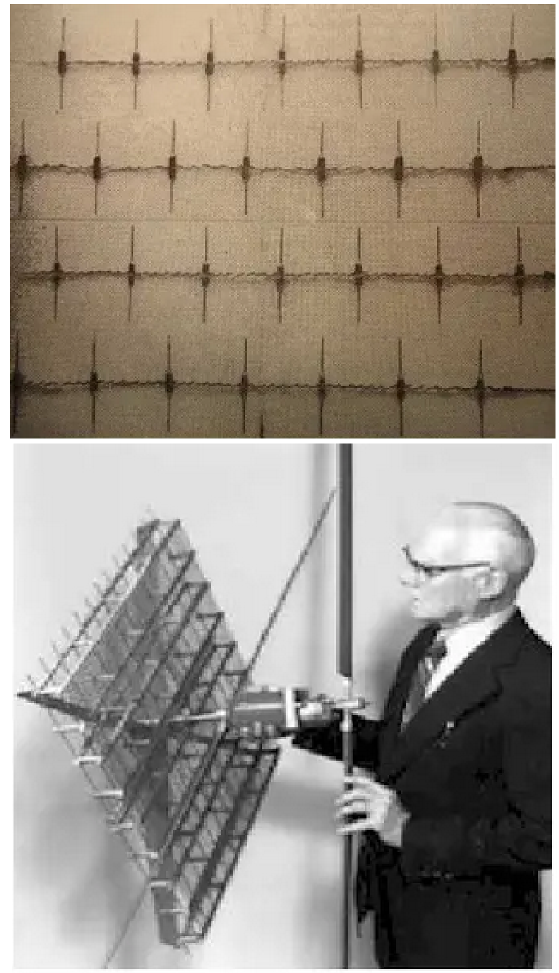

Fig. 8. Components and the assembled rectenna in the first beamed power experiment[16]

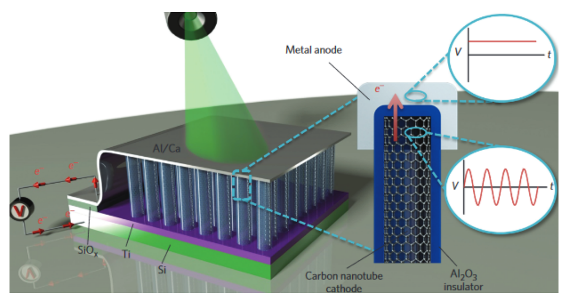

Fig. 9. Schematic of a carbon nanotube base rectenna, Al/Ca is a semi-transparent electrode[18]

most communications technology[16].

III. Applications

A. Space Solar Power

Space Solar Power is a concept investigated regularly by NASA[2], [4], [10] and subcontractors, such as Boeing[20]. There is a constant tone of confidence in the proposals made by NASA; emphasizing the challenges implicit in constructing the solar arrays proposed, which range from 20MW to 5GW while also emphasizing the near-term feasibility of the idea[2]. Figure 10 is one example of the many different ideas envisioned; the "Sun Tower" was planned to be a series of 18 solar panel "towers" capable of producing 20MW each[2, p. 353].

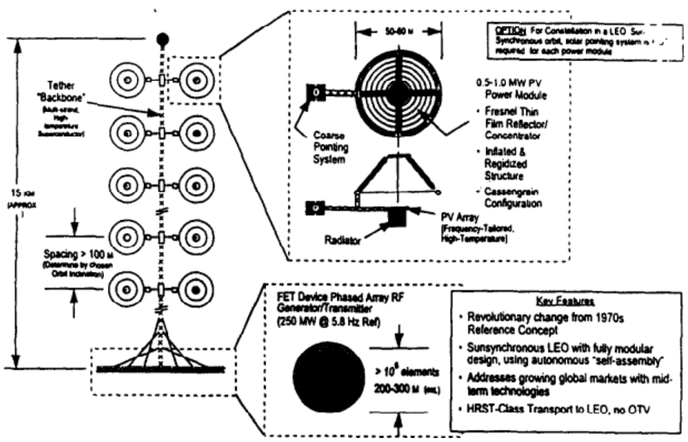

Fig. 10. NASA's "Sun Tower" Proposal for Space Solar Power, circa 1997[2]

Figure 11, by comparison, is a high-level cost-breakdown of how a space solar power system might achieve a relatively competitive levelized cost of electricity of $0.05/kWh[4]. Space solar power may not be possible based on figure 11. Comparing launch costs can be somewhat complicated, low-earth orbit costs are always lower than geostationary orbit costs. Regardless, current launch costs are still significantly higher than the $300-350 cited [21], see figure 12. It is possible that the decreasing cost of photovoltaics might offset current launch costs[3], however it is unlikely that the highest watt to dollar photovoltaics will meet the weight requirements necessary to offset the high launch costs. The beamed power component of the solar power system has been ready since the 1980s; rectennas have been achieving high efficiencies for decades and magnetrons are mass-produced in the modern microwave economy[2].

B. Propulsion

Beamed propulsion is a promising field given its potential for reducing launch costs[1]. Primary research today either utilizes a solid fuel capable of producing efficient thrust when exposed to a laser[6] or by inducing atmospheric air

[1]Fuel contributes significantly to rocket mass. By locating the primary energy source elsewhere the rocket does not have to carry as much fuel mass in early stages; allowing for smaller and more affordable components.

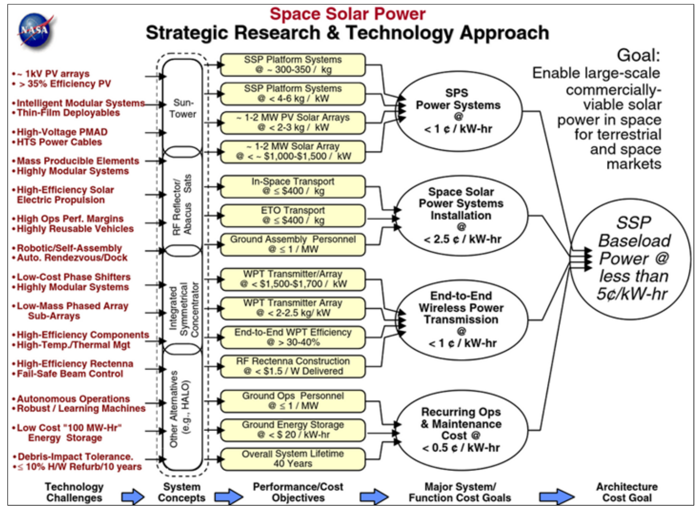

Fig. 11. Projection of a potential 2021 SSP, circa 2001[21, p. 16]

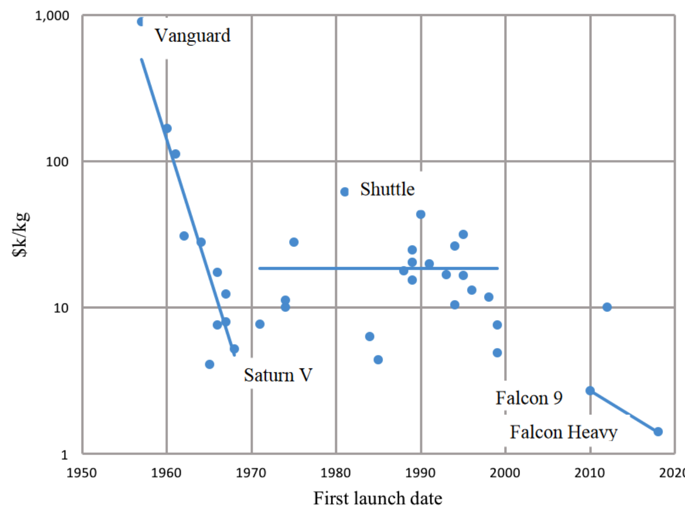

Fig. 12. Estimated launch costs over time[21]

to breakdown into plasma and using that plume for thrust[11]. Broadly speaking, the general scientific trend indicates that the solid fuel variants will not see significant use outside of small rocket applications[6][2]. Takahashi indicates that an atmospheric plasma solution could be more practical for heavier applications and cost effective at scale. One proposal claimed that a microwave system based launch would be more affordable than a conventional rocket after 42 launches; after 2000 launches the system would be fully amortized. It is notable that microwave based systems are preferred by Takahashi given the affordability of magnetrons; the cost-savings offsets any benefits from higher energy wavelengths[11].

IV. Conclusion

Beamed power as a technology remains a solution capable of being implemented now provided certain near-future needs are met. Solar-power satellites in the 1970s were not limited by

[2]Given that these rockets could operate in vacuum, unlike the plasma variants, this may be acceptable.

the capabilities of beamed power; launch costs and solar panels did not meet the requisite prices and efficiencies necessary for a feasible solar power satellite. Given the emergence of a viable private space industry, the rise in the efficiency of solar panels simultaneous with a drop in their price, and the near-term potential of plasma induced thrust, it is likely that beamed power will see use soon.

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