Rectennas for Synchrotron Radiation Energy Conversion in D-^{3}He Tokamaks

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Abstract

Rectennas, or rectifying antennas, provide the potential for highly efficient conversion of synchrotron radiation to electricity in a D-^{3}He tokamak fusion reactor. This paper will give an overview of energy conversion using rectennas in a tokamak and describe the key issues for rectenna development and operation.

1. Overview

Rectennas (rectifying antennas) were developed in the 1970's, partly in support of research on Solar Power Satellites. The present state of the art is that thin-film rectennas have been demonstrated at 2.45 GHz with 85% RF-to-DC conversion efficiency [1]. The circuit can be simple, consisting of an antenna, one or a few diodes, and a few resistors and capacitors. For space power transmission, the system of generator, transmitter, and receiver is large at 2.45 GHz, so an incentive exists for developing higher frequency systems. Much of the information in this paper results from research programs at NASA Lewis Research Center and elsewhere aimed at such systems.

The concept of directly converting synchrotron radiation to electricity at an efficiency of approximately 80% using rectennas was originated by Grant Logan [2]. The idea is to channel synchrotron radiation out of the tokamak using overmoded waveguides and convert it in a separate chamber. In D-^{3}He tokamak reactors, it may be possible to transform as much as 50% of the fusion power into synchrotron radiation. Although 2.45 GHz technology exists, the technology remains to be demonstrated at frequencies of interest for fusion—about three orders of magnitude higher. Nevertheless, the rectenna option appears feasible, as it requires integrated circuit technology well within the state of the art, and high frequency diodes are developing at a rapid pace. Rectenna costs are uncertain, but appear reasonable based on extrapolation from costs for large production runs of large-scale integrated circuits.

The remainder of this paper will discuss the critical questions for the use of rectenna energy conversion. These are:

- Can a large fraction of the fusion power be generated as synchrotron radiation with reasonable physics assumptions?
- Is rectenna conversion of synchrotron radiation compatible with synchrotron current drive?
- What will the synchrotron radiation spectrum be?
- Can synchrotron radiation be wave-guided from the plasma chamber to a conversion cavity with acceptable losses?
- What efficiency can rectennas achieve in the frequency range of interest?
- What will be the cost of a rectenna conversion system?

2. Plasma Power Balance and Current Drive Considerations

To use rectenna conversion most effectively in a power plant, a high fraction of the fusion power should be generated as synchrotron radiation. This places more stringent requirements on energy confinement, since the synchrotron radiation is an added energy loss channel. Because the total synchrotron power loss is proportional to $(BT)^{2.5}$, high synchrotron radiation fractions push parameters toward high magnetic fields and temperatures higher than optimum from a power density point of view. Also, it may be necessary, rather than simply desirable, in this conversion mode to enhance transport of the ash above that of the fuel ions to avoid choking of the fusion burn. Nevertheless, it appears to be a smaller physics step to go to high synchrotron radiation fractions from minimum synchrotron radiation than it is to go from D-T to D-^{3}He.

The spectrum of synchrotron radiation will be spread from ~1.5–30 THz, peaked at ~5–10 THz, based on calculations for ARIES-III [3, 4]. Reflections from the tokamak chamber walls will tend to depolarize the spectrum, and the calculations discussed below assume a random polarization. Assuming that the chamber walls are highly reflecting and that the waveguide is a total absorber, most of the synchrotron radiation produced will be lost out the waveguide, rather than absorbed in the first wall.

The question of whether synchrotron radiation conversion by rectennas is compatible with synchrotron current drive has been raised. The original synchrotron radiation current drive concept used a "scalloped" first wall, with one side of the scallop highly reflective and the other very absorptive. The essential physics is to have differential momentum absorption. By properly recessing and angling the synchrotron waveguide in a D-^{3}He tokamak, the same preferential absorption would occur. In either method, only the absorbed synchrotron radiation power would be a net loss to the plasma.

3. Design Issues

3.1. Waveguide Design

A highly overmoded, circular waveguide can be used for transporting the synchrotron radiation from the plasma core to a separate conversion chamber lined with rectennas [5]. The waveguide losses will be less than 5% of the total power entering the waveguide for a

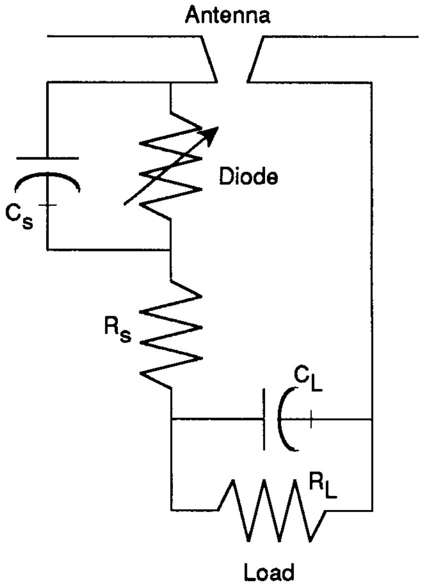

Figure 1. *One potential rectenna circuit [2].*

ratio of waveguide length to diameter of 30. Depending on shield design considerations, the waveguide diameter would be 10–20 cm for 3–6 m of length and then it would widen to reduce losses until the conversion cavity was reached. Because heat absorbed in the waveguide wall will probably be rejected, a design goal of 2–3% loss seems reasonable.

The waveguide would be evacuated to approximately the tokamak chamber pressure (and might even be the vacuum pumping port), so no microwave transmission window is required.

3.2. Rectenna Design

The state of the art in integrated circuit technology design is 100 times smaller than the approximately 0.1-mm range required for the synchrotron radiation conversion antennas. A possible circuit option is shown in Fig. 1 [2]. The key circuit component that is not presently available at the high frequencies of interest is the diode. However, the field of vacuum microelectronics (for field-effect diodes) has been progressing rapidly in frequency. Monolithic microwave integrated circuits have been constructed which have achieved a cutoff frequency of 1.25 THz [6]. In the relevant time frame, the availability of suitable diodes appears likely.

The efficiency of full-wave rectifying circuits has been calculated to approach 100% with log-spiral antenna geometries that give a frequency range of 2–10 times the nominal resonant frequency [5]. If such geometries are compatible with the integrated circuit design, broad-band coverage of this amount would suffice to keep the number of differently tuned rectennas small. The cavity could then be covered with a variety of differently resonant rectennas, since the reflectance off of a non-resonant rectenna should also approach 100% efficiency.

Present thinking about rectenna design is that the basic geometry would be a dielectric slab with the antennas facing the synchrotron radiation, with coolant channels through the dielectric, and with the remaining circuit components on the opposite side of the slab, as shown in Fig. 2. Connecting the antennas to the other components appears to be feasible using stripline techniques. The key difficulty in designing circuits at the very high frequencies of interest is capacitive coupling. The design goal of 1 MW/m^2 heat dissipated appears to be feasible, although detailed thermal hydraulics calculations remain to be done.

Experimental programs exist in two regimes that bracket the range of interest for D-^{3}He tokamak reactors [7]. Currently, these are all relatively small programs at modest funding levels.

Present rectenna costing is based on the assumption that the costs will be comparable

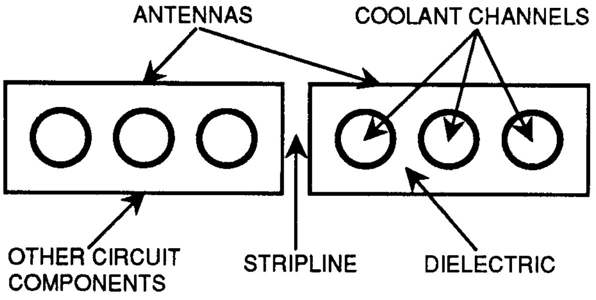

Figure 2. *One potential rectenna geometry.*

to large production runs of similarly sized integrated circuits. A preliminary estimate, based on Turner, et al. [8], is that \$0.375/We is reasonable.

4. Conclusions

Synchrotron radiation conversion by rectennas is intrinsically a D-^{3}He mode of operation because of the leverage gained by a high ratio of synchrotron radiation power to fusion power. The presumed benefits in power plant simplicity, reliability, and cost must be balanced against the more difficult physics requirements and the need to demonstrate rectenna technology at the high frequencies of interest. Because the extension of plasma parameters is less than that required to go from D-T to D-^{3}He, and because the technology extrapolation appears to be straightforward, rectenna conversion of synchrotron radiation is an attractive option for D-^{3}He tokamak reactors.

Acknowledgement

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