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RADIO FREQUENCY PLASMA HEATING IN LARGE TOKAMAK SYSTEMS NEAR THE LOWER HYBRID RESONANCE

A. Deitz, W. M. Hooke

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Summary

Recent experimental results with lower hybrid heating on the Adiabatic Toroidal Compression (ATC) machine at PPPL have indicated a need to look into larger RF heating systems. This paper is intended to project to the reader the state of the art of existing equipment which could be used for lower hybrid heating of a plasma as well as some of the physics restraints which establish the requirements for this equipment. At the present time the frequency range around 1-5 GHZ looks attractive because of two aspects: First, physics requirements select this frequency range as being optimal to produce the best heating results for existing and proposed experimental machines. Second, the engineering prospects appear favorable in that the equipment required does not need extensive development in this frequency range, and the coupling systems require waveguides rather than an antenna system internal to the vacuum vessel.

The frequency range, power, efficiency, and pulse length of a high power rf system are discussed as they might be applied to the TFTR Tokamak facility as well as on a full scale reactor. Comparisons are made of the size, power output, and costs to obtain microwave power sufficient to satisfy the physics requirements.

A new microwave feed concept is discussed which will improve the coupling of the microwave energy into the plasma. The unique advantages of waveguide feed systems is apparent when one considers the practical problems associated with coupling supplementary heating energy into a reactor.

Requirement for Auxiliary Heating

Auxiliary heating in tokamaks is being explored from three aspects; Neutral Injection, Ion Cyclotron Resonance Heating (ICRH), and Lower Hybrid Heating (LHH). This paper concentrates on Lower Hybrid heating as it presents some attractive features for present as well as future tokamak devices.

Some type of auxiliary heating must be used to supplement Ohmic Heating in Tokamaks. Ohmic Heating will not be adequate to raise the plasma temperature to reaction levels for two basic reasons. First, the plasma resistivity is inversely proportional to the temperature so as we heat the plasma the resis-

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q in practice is generally greater than 2 or 3. However, if the current is increased to the point where q decreases to less than 2, the plasma becomes unstable. Thus, ohmic heating can only take us so far as we must rely on other or auxiliary methods for heating the plasma.

The use of Lower Hybrid heating appears attractive from several aspects. The most fundamental advantage is the availability of power sources.

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$$- \quad B_p \quad R$$

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In tokamaks

$$\frac{\omega_{ep}^2}{\omega_{ec}^2} \simeq 1$$

$$\therefore \omega_{LH} \simeq 0.7 \; \omega_{ip}$$

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Since $n_e \sim 2 \times 10^{13}$ (typical) the Lower Hybrid frequency works out to be in the low GHZ frequency range.

In large microwave heating systems for tokamaks, three fundamental engineering problems must be solved.

1. Generation of the microwave power.
2. Transmission to the tokamak device.
3. Coupling of the energy to the plasma.

Microwave Power Generation

To a large extent, microwave power generation has evolved as a result of the broadcast industry and Department of Defense effort. High power (50 kW) CW klystrons were developed for commercial UHF TV, while multimegawatt klystrons were developed for high power radar tracking facilities. Unfortunately, there appeared to be a large gap in power/pulse width performance between a 50 kW klystron and a 5 MW klystron capable of pulse widths on the order of tens of usec's. The deep space program helped fill this gap as the requirement for long pulse or CW high power microwave tubes became necessary for long range tracking, satellite communication and radar mapping of terrestial bodies. Klystrons capable of 1/2 MW CW in the S band region are now available.

Proposals have been received from vendors to build 1 MW long pulse klystrons and the feasibility of 2 MW klystrons is now being explored.

As experiments progress in the Lower Hybrid regime, we continue to look into large microwave systems to determine their feasibility, costs and space requirements. Table 1.0 shows the basic specifications for LH systems which now exist or are being proposed at PPPL.

Table 1.0

Existing and Proposed PPL LH Systems

	Freq.	Power	Pulse Width
H1	155 MHz	15 kW	3 msec
ATC	800 MHz	200 kW	20 msec
PDX	1.1 GHz	5 MW	0.3 sec
TFTR	1-2 GHz	50 MW	0.5 sec

Transmission System

Transmission of the rf power from the power source to the tokamak is relatively easy at these low microwave frequencies. The transmission losses do not become serious until the transport distance starts to exceed 100 to 200 ft. Power density in the wave guide is not a limiting factor. Some component development is necessary, however, it does not appear to be a major stumbling block. In particular, large high power isolators or circulators will be required to effectively isolate klystrons from the plasma load. Dependent on machine parameters, the plasma coupling can vary widely, causing severe mismatch conditions which must not be reflected back to the output klystrons. Since, how-

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Coupling System

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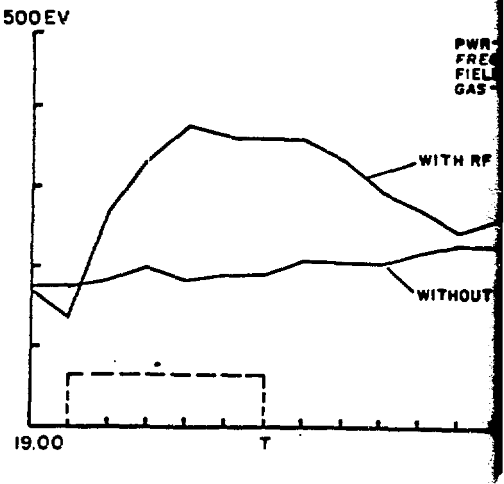

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Coupling System

One of the most critical elements of the rf system is the coupling system -- the point where the hardware and the plasma are in close proximity. LH coupling systems and feeds present one of the most difficult and yet attractive features of an rf heating system. Initial experiments utilized an open ended waveguide as the feed mechanism for the microwave energy. Experiments with this feed gave promising results (see Figure 1). This shows the rf induced temperature as a function of time. The number of eV per watt is very encouraging. If the entire plasma were heated by this amount, the heating efficiency would be on the order of 40%. It should be pointed out, however, that heating throughout the plasma volume has not been demonstrated as of yet.

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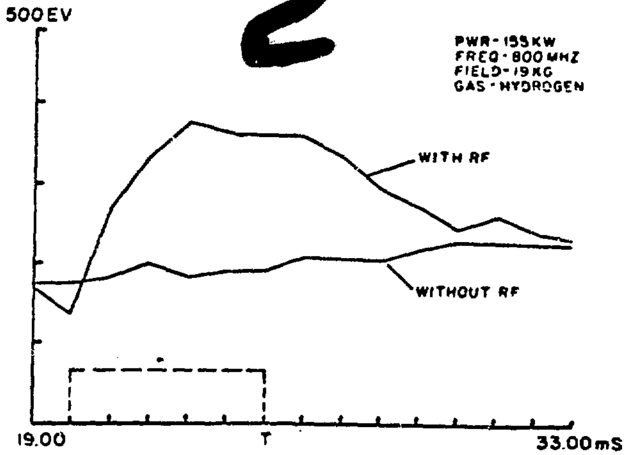

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Experiments are now being conducted for multiple waveguide feeds, i.e. a phased array scheme. This type of feed system seems to hold the promise of better coupling and deeper penetration of the rf energy into the plasma.

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Of some concern also is the development of high power ceramic windows which can efficiently transmit the microwave energy while providing a reliable vacuum break where the waveguide interfaces with the tokamak device. Again, the task does not appear formidable, as windows have already

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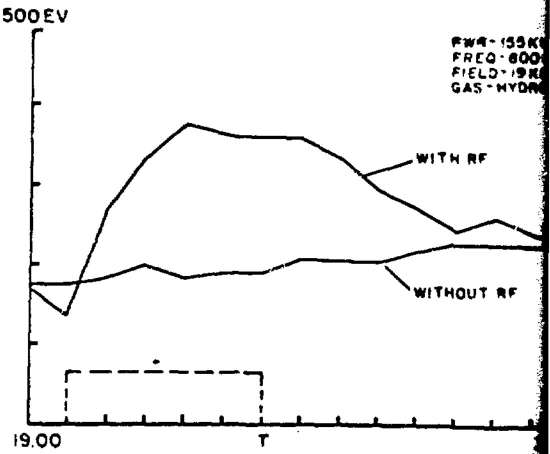

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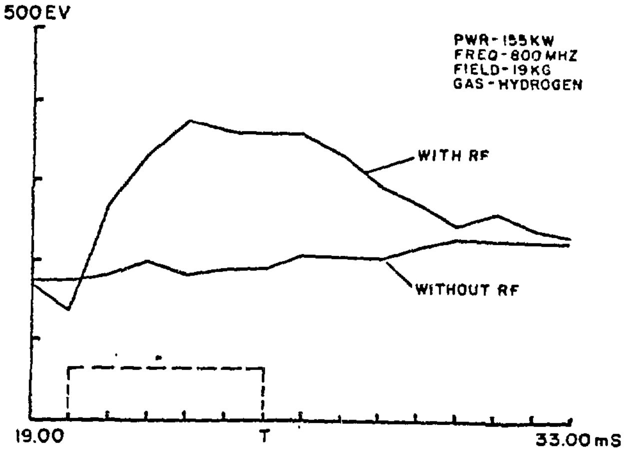

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Future Systems

To date, the microwave systems built for LH heating have been relatively small. We are presently planning larger systems for use on the tokamaks which are in the building or planning stages. One such system is a 5 MW, 1.1 GHz system being considered for use on the PDX machine. Figure 2 is a simplified block diagram depicting the major components.

You will note that there are 6 - 1 MW klystrons shown. (We've allowed for 1 dB of loss.)

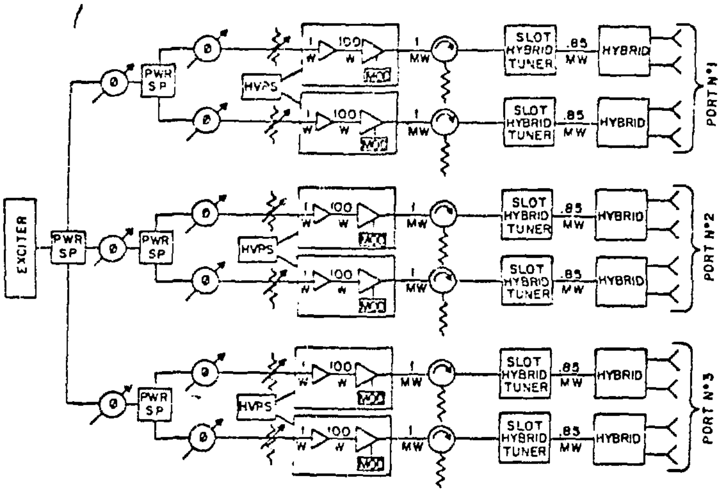

Figure 2 - Proposed 5 MW L Band System for PDX Lower Hybrid Heating

These tubes are an extrapolation of the existing 1/2 MW klystrons. A system such as this would be approximately 50% efficient, i.e. rf output/dc power input, and would operate at a voltage of about 80 kV.

It will take approximately 2-1/2 years to design and build this system and will require about 55 man years of labor. The overall program cost by the time of completion (considering escalation, contingencies, etc.) will be on the order of $7M.

Considering this system as a stepping stone to a larger one for TFTR machine, we project that the size of an rf system would be on the order of 30 to 50 MW. To generate this power we would envision the development of a 2 MW klystron. This system would be comparable in size to the presently proposed TFTR Neutral Injection system.

A concept in simplified form is shown in Figure 3.

In this system we would use 30 - 2 MW klystrons and 15 high voltage power supplies. It's possible, for a slight cost increase, to be able to design the presently proposed TFTR Neutral Injection power supplies so they can be shared by this rf system.

A system this size would probably cost on the order of $30M. This considers escalation, contingencies, and development. This cost is somewhat the same as that of the TFTR Neutral Beam system costs. A building about 160' X 160' would be required to house this system (this includes everything from the AC breakers to the waveguide outputs of the klystrons).

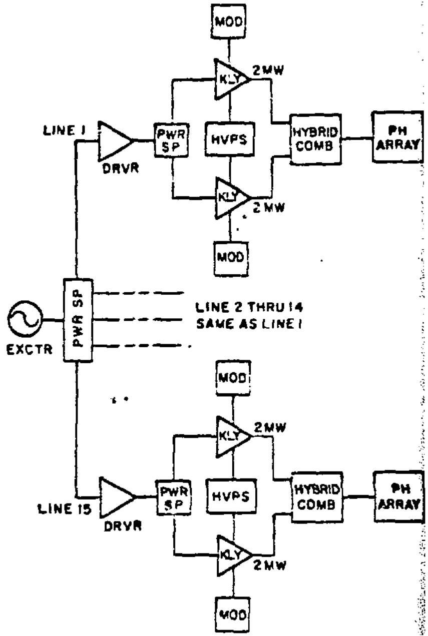

Figure 3 - Conceptual Lower H
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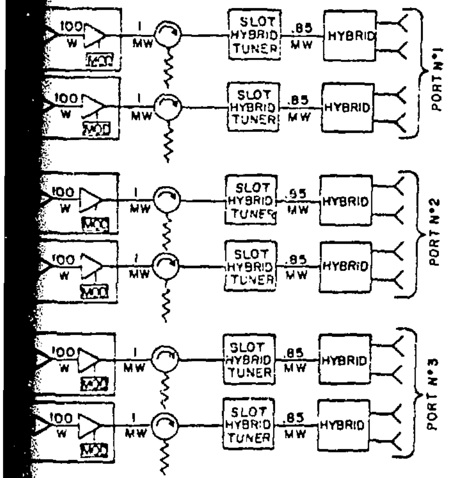

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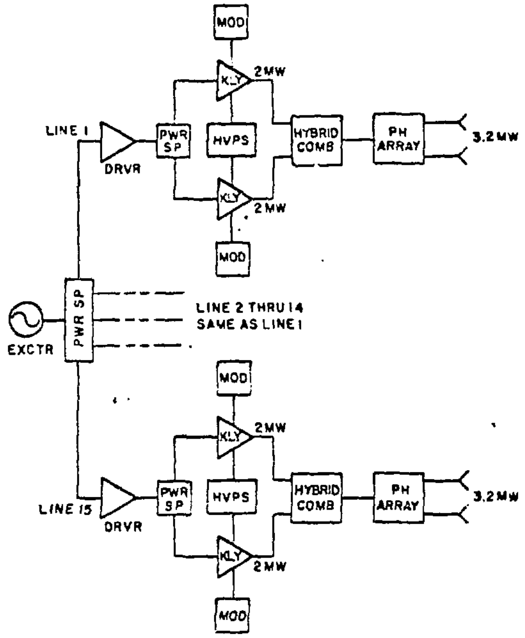

Figure 3 - Conceptual Lower Hybrid Heating System for the TFTR Machine

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