GA-A14881

MASTER

# LOWER HYBRID WAVE HEATING IN DOUBLET IIA

by

CHARLES P. MOELLER, NEIL H. BROOKS, V. S. CHAN, R. L. FREEMAN, E. J. HECKMAN, T. H. JENSEN, JOHN LOHR, J. L. LUXON, T. OHKAWA, JOHN C. RIORDAN, J. F. TOOKER, and D. F. VASLOW

This is a preprint of a paper to be presented at the Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas, July 3-7, 1978, Grenoble, France.

Work supported by
Department of Energy
Contract EY-76-C-03-0167, Project Agreement No. 38

GENERAL ATOMIC PROJECT 3235
FEBRUARY 1978

GENERAL ATOMIC COMPANY

# LOWER HYBRID WAVE HEATING IN DOUBLET IIA*

by

Charles P. Moeller, Neil H. Brooks, V. S. Chan, R. L. Freeman,
E. J. Heckman, T. H. Jensen, John Lohr, J. L. Luxon,
T. Ohkawa, John C. Riordan, J. F. Tooker, and D. F. Vaslow
General Atomic Company, San Diego, California 92138

ABSTRACT

Doublet IIA electron heating experiments utilize lower hybrid waves launched by slow wave structures with various $n_{\parallel} = ck_{\parallel}/\omega$ (11, 14, 16) to achieve spatially localized heating by electron Landau damping. Radiofrequency power of 350 kW at 800 MHz and 200 kW at 915 MHz is available to heat circular discharges with ohmic input power of 100 kW. Significant increases in the electrical conductivity have been observed, but plasma response to the rf power is sensitive to the impurity level of the discharge. Power absorption mechanisms and energy balance will be discussed.

Experiments are presently being conducted in Doublet IIA on electron heating by Landau damping of the lower hybrid wave at frequencies above $\omega_{LH}$. These experiments were preceded and stimulated by observation of efficient electron heating in the dc Octopole by the lower hybrid wave (Ref. 1).

Slow wave antennas are being used for wave launching in these experiments. They were chosen in preference to the multiwaveguide grill both because of limited access and because of the large $n_{\parallel} = k_{\parallel}c/\omega$ values required for Landau damping. The slow wave antennas being used in Doublet IIA are all of the design shown in Fig. 1. They basically consist of a balanced transmission line loaded by resonant radiating elements alternately connected to the two conductors of the transmission line and separated by metallic limiters. This results in a structure which is self-supporting and therefore requires no insulators. The electric field presented to the plasma is very similar to that of the waveguide grill structure.

The self-consistent calculations of the plasma loading and radiated power spectrum are given in Ref. 2. The main results are that the plasma loading has a broad maximum as a function of the plasma density gradient, so that the voltage along the antenna and the resulting radiated spectrum do not vary greatly with the density gradient at the antenna. Three pairs of antennas are located symmetrically on the top and bottom of the machine with $n_{\parallel}$'s of 11, 14, and 16. The experimental data on the antenna loading is rather qualitative and is typified by Fig. 2. The upper pair of traces are the forward and reflected power for the $n_{\parallel} = 11$ antenna while the lower inverted traces are for the $n_{\parallel} = 14$ antenna. All traces are 50 kW/div vertical and 5 msec/div horizontal. At 20 msec, the plasma began to shift radially, reducing its effective diameter and the density at the antenna. The increase in reflected power shows that the antennas are not over coupled at the normal density. Note that the $n_{\parallel} = 14$ is more strongly affected than the $n_{\parallel} = 11$. The $n_{\parallel} = 11$ and 14 antennas are being operated routinely at 80 kW each and the $n_{\parallel} = 16$ antennas at 60 kW each. The $n_{\parallel} = 11$ antenna has been tested at powers as high as 150 kW without breakdown occurring.

*Work supported by Department of Energy Contract EY-76-C-03-0167, Project Agreement 38.

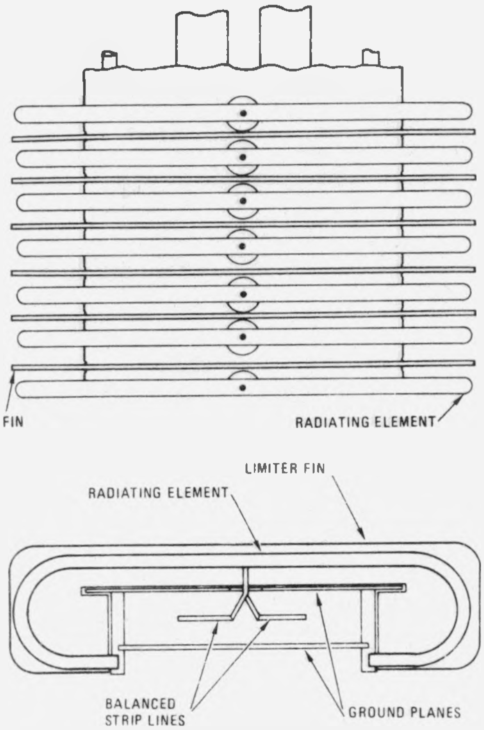


Fig. 1. Doublet IIA slow wave antenna

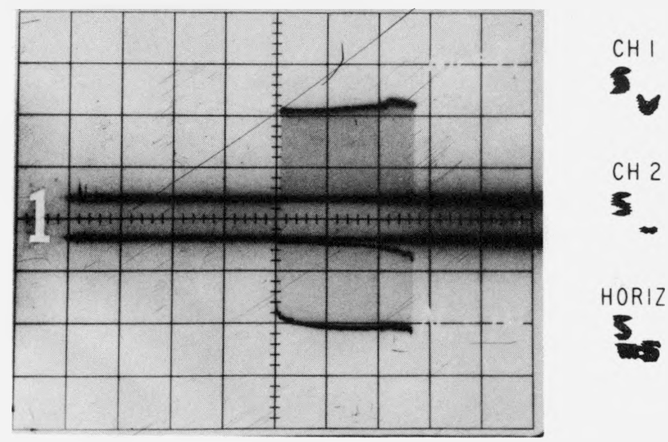


Fig. 2. Forward and reflected power, 100 kW/div
Upper pair of traces $n_{||} = 11$
Lower pair of traces $n_{||} = 14$

Our experiments, which have been performed in two phases, have all been with circular discharges and hydrogen filling gas.

In the first phase, during which two 800 MHz sources from Princeton Plasma Physics Laboratory were used to give a total of 100 kW with antennas of $n_{||} = 11$ and 14, the parameters were ultimately as indicated in the left-hand column of Table 1. The early discharges did not have as low $Z_{eff}$ as indicated in the table. The application of 100 kW of rf produced no observable macroscopic effect in that case. The use of a pulsed discharge cleaning technique (Ref. 3) produced a much cleaner discharge, which showed the behavior indicated in Fig. 3 upon application of the rf. The current increase and voltage drop give an average conductivity temperature increase of 50% from 140 eV to 210 eV if $Z_{eff} = 1$ is assumed. There is no evidence that this behavior is due to runaways based on the hard and soft X-ray detector signals and decay of the conductivity in approximately 1 msec after

TABLE 1
TYPICAL DOUBLET IIA OPERATING PARAMETERS

| | 100 kW | 500 kW |
|---|---|---|
| Operating gas | Hydrogen | Hydrogen |
| Toroidal magnetic field (kG) | 6.4 | 7.6 |
| Plasma current (kA) | 30 | 35 |
| Ohmic power (kW) | 70 | 100 |
| Central electron temperature | 150 | 300 |
| Average electron density ($cm^{-3}$) | $0.7 \times 10^{13}$ | $1.2 \times 10^{13}$ |
| $Z_{eff}$ | 1-2 | 3-5 |

the rf ceases. It remains possible, however, that this effect involves only tail electrons with collision times too long to be thermalized in comparison with the energy confinement time. The Thomson scattering was not working reliably at that time so that it was not possible to determine if there was in fact a real temperature increase. A spectrometer looking radially 10 cm above the plasma midplane showed an increase of $O^{3+}$ light with rf which did not occur with $O^{1+}$ light, suggesting no influx of oxygen during the rf pulse and no density increase. Lacking a similar measurement through the plasma center, we can only conclude that energy was being absorbed at least part way into the plasma.

In the second and current phase of the experiment, we have available 350 kW at 800 MHz from the upgraded Princeton Plasma Physics Laboratory system plus 200 kW at 915 MHz, the latter presently driving antennas with $n_{||} = 16$. The plasmas, with the typical parameters shown in the right-hand column of Table 1, have had higher $Z_{eff}$ than in the first phase. This has resulted in higher initial $T_e$ which is more in the range for Landau damping than in the first phase. We have added a radiometer at 2 $\omega_{ce}$, moved the spectroscopy to observe the plasma center, added a soft X-ray array, and improved the Thomson scattering.

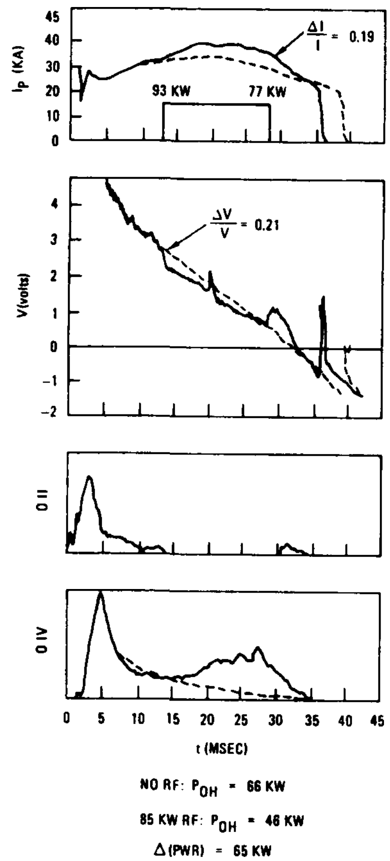


Fig. 3. An increase in the electrical conductivity of a circular plasma due to the application of rf power is illustrated by the solid curves showing the temporal dependence of the plasma current and voltage. The behavior of the oxygen line radiation is shown in the last two traces.

Although we have not recovered the low $T_e$ of the first phase, the machine is sufficiently clean so that gas puffing is required to maintain the density during the discharge, and there is only a slight density increase during rf. The conductivity increase is very small under these conditions.

A typical shot is shown in Fig. 4, in which the radiometer increase is shown with an expanded sweep. The rise and fall times are of the order of 1 msec so that the electrons contributing to the signal are neither very poorly confined nor are they runaway. The $O^{5+}$ and $Fe^{14+}$ show increases during rf, while the low states do not. The soft X-ray shows a consistent substantial increase in the plasma interior and not on the edge. The Thomson scattering shows no increase in central $T_e$, but a small density increase. The time for isotropization of the electrons at the phase velocity is much shorter than the thermalization time or energy confinement time, however, so that the radiometer could easily show such an effect independent of the Thomson scattering.

The most recent observations are that the conductivity increase can be partially recovered by operating at lower density ($\sim 5 \times 10^{12}$ cc).

CONCLUSION

Excellent coupling has been observed with the slow wave structures along with evidence that the antennas are not over coupled.

Evidence exists (spectroscopy, soft X-rays) that wave energy is being absorbed in the plasma interior. The Thomson scattering measurements in the central region show no significant electron temperature increase with the application of rf power, yet the radiometer and soft X-ray signals show sizable increases.

Our interpretation of these results is that wave energy is being absorbed in the tail of the electron distribution as intended, but that either these electrons are poorly confined in comparison with the Maxwellianization time, their energy is lost through impurity radiation, or the energy transferred is small. Diagnostics are currently being added to test these possibilities, while we are preparing to operate at a higher density which should both shorten the thermalization time and lengthen the energy confinement time. Preparations are also under way to launch waves of higher $n_{\|}$ so that the phase velocity will not be so far in the tail of the electron distribution.

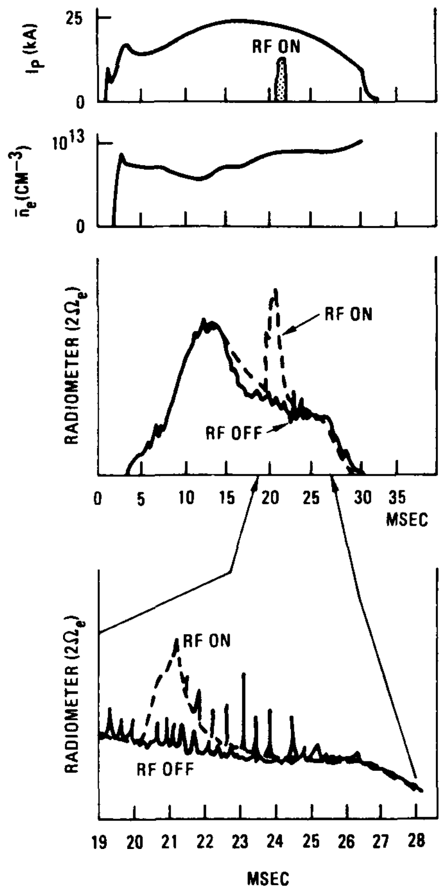


Fig. 4. The application of a 1 msec pulse of rf power at the 150 kW level to a circular discharge results in a large increase in the radiation at the second harmonic of the electron cyclotron frequency. The last trace shows the radiometer signal with a faster time sweep at the time of the heating pulse.

REFERENCES


1. Wesley, J. C., *et al.*, "RF Heating of Electrons by Slow Lower Hybrid Waves in the dc Octopole," General Atomic Report GA-A14461, June 1977.

2. Moeller, Charles P., and Vincent S. Chan, "A Slow Wave Structure for Launching Lower Hybrid Waves of Short Parallel Wavelength," General Atomic Report GA-A14836, January 1978, to be published.

3. Oren, L., and R. J. Taylor, Nucl. Fusion 17, 1143 (1977).