LOW HYBRID RF HEATING EXPERIMENTS
IN THE MIT AGRICATOR A, C AND VERSAL-11 TOKAMAKS

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ABSTRACT. Experimental results on lower hybrid heating in the Alcator A and the Versator II tokamaks with power levels up to 90 kW are presented. In Alcator A a double waveguide grill, and in Versator II a 4 waveguide grill with arbitrary phasing are used. Also, a 6 waveguide grill experiment in Versator II is described which launches a travelling wave aimed at driving toroidal currents. The forthcoming lower hybrid heating experiment in Alcator C, utilizing four 4 x 4 waveguide arrays with power levels up to 4 MW, is also described.

1. LOWER HYBRID HEATING IN THE ALCATOR A TOKAMAK

In the Alcator A tokamak 90 kW of microwave power at a frequency of 2.45 GHz was injected to test lower hybrid heating and power transmission capabilities [1,2]. A double waveguide array was employed, each waveguide having inner dimensions of 1.275 cm x 0.13 cm and they were separated by a 1 mm septum. Both rf phase and amplitude were independently controlled and measured in each waveguide. The radial position of the waveguide array was adjustable. During this experiment typical Alcator A plasma parameters were \( R = 10 \text{ cm}, \theta = 54 \text{ cm}, B = 0.5 - 4 \times 10^{11} \text{ cm}^{-3}, T_e, T_i \approx 1 \text{ keV}, B_t = 60 - 80 \text{ G}, I_\phi \approx 150 \text{ kA} \) and deuterium or hydrogen filling gas was employed.

Most of the work described below was accomplished with a microwave array having its ceramic vacuum windows outside the toroidal field magnets so that the electron cyclotron resonance layer fell in the vacuum region of the waveguide. Nevertheless, good coupling and the absence of rf breakdown were obtained with up to 90 kW of incident power, which corresponded to 4.5 kW/cm² at the waveguide mouth. Optimum coupling was obtained when the waveguide mouths were positioned at \( r = 12.1 \text{ cm} \) near the vacuum vessel wall \( (r = 12.7 \text{ cm}) \) and with 0, \( \pi \) phasing of the incident electric fields. The measured reflectivity of 1.3% was constant over a range of incident powers \( P_{fg} \) between 5 kW and 90 kW. A second waveguide array with the same dimensions as the first one, but having its vacuum windows biased internally, was also tested so that the \( a = w \) layer was now pressurized. This array also obtained good waveguide plasma coupling and achieved a power density of 8 kW/cm² without breakdown when a single waveguide was excited.

Figure 1a shows the raw data of a typical plasma shot in deuterium where \( B_t = 62 \text{ G}, I_\phi = 150 \text{ kA} \) and the waveguides had a phase difference \( \Delta \psi = 180^\circ \).

\[ \text{No effect on the loop voltage } V_c \text{ or } S \text{ was observed, but the neutron rate sharply increased by a factor of 15 over the thermal level. Peak neutron rates during rf were enhanced by a factor of 50 over the thermal rate and corresponded to a net rate of } 2 \times 10^{11} \text{ neutrons/sec.} \]

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Figure 1a shows the variation of the neutron enhancement with $\phi$ during the rf pulse. The neutron rate is found to increase during the rf pulse within a relatively narrow band in $\phi$, centered near $\phi = 1.7 \times 10^{14}$ cm$^{-3}$. This neutron rate enhancement does not change as $\phi$ varies from 0° to 180°. During this neutron enhancement, no clear increase in bulk ion $T_e$ is observed within the 100 eV experimental uncertainty, which indicates a bulk plasma heating efficiency of less than 40%. These neutrons were emitted near the plasma center, as evidenced by the appearance of sawteeth on the neutron rate and measurements by a collimated neutron detector. In Figure 2 we show the spatially resolved neutron emission data.

This neutron rate increase correlated well to the observation of an energetic tail at $E > 10$ keV on the fast neutrals emitted by the plasma. The plasma heating efficiency in the neutron enhancement mode is probably affected by the imperfect confinement of energetic ions in Alcator A. The neutron rate during rf and its 1/e decay time of $\sim 1.5$ msec after rf shutdown are consistent with the production of ion tails having tail temperatures $T_e > 10$ keV and extending out to $E > 50$ keV. Such ion tails would be strongly influenced by banana orbit ion losses, which are a function of plasma current. Scattering of ions into these unconfined orbits can occur in Alcator A at $I = 150$ kA for $E > 30$ keV at $r = 0$ and $E > 10$ keV at $r = 5$ cm. Furthermore, when $I$ is lowered to 75 kA a perpendicular ion tail would be cut off at $E > 37$ keV for $r = 3$ cm, which would then sharply reduce the neutron rate and tail times. Experimentally, no neutron enhancement is obtained during the rf pulse when $I < 100$ kA. Figure 3 shows the observed 1/e decay time of the neutron rate after rf shutdown vs. $I_p$. As expected, a factor of 2 increase is obtained as $I_p$ is increased from 120 kA to 200 kA.

Another important loss mechanism is due to trapping of energetic ions in the 7% toroidal field ripple in Alcator A. Above $E = 5$ keV such ripple trapped ions drift out of the plasma before being scattered into better confined orbits; the resulting depletion has been experimentally observed by charge exchange measurements [3].
It has been estimated that the resulting hole in velocity could reduce rf heating efficiencies by more than a factor of 2 as nearly perpendicular ion tail rapidly scatters into this loss region [4].

As the plasma density is further lowered to $n_e \approx 1 \times 10^{15} \text{cm}^{-3}$ electron heating is indicated by both the electron cyclotron emission and Thomson scattering. This 10% increase in $T_e$ would result from a bulk plasma heating efficiency of at least 35% (and perhaps as high as 60%). In Figure 4 we show $T_e(T)$ as measured by the 2nd detector with and without rf power. Thomson scattering also confirmed this data.

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**Fig. 2.** Neutron rate vs. plasma minor radius. $B = 6.0 T$, $R = 1.7 \times 10^{16} \text{cm}^{-3}$.

**Fig. 3.** RF enhanced neutron rate 1/e decay time vs. $I_p$ for $R = 1.5 \times 10^{16} \text{cm}^{-3}$, $P_{rf} = 85 \text{kw}$, deuterium; dots are at $B = 6.2 T$, open circles are at $B = 8.0 T$.

**Fig. 4.** $T_e$ vs. $r$ as measured by the 2nd detector. $R = 1 \times 10^{16} \text{cm}^{-3}$, $B = 6.2 T$.

**Fig. 5.** RF probe measurements at $B = 6.2 T$, deuterium, $I_p = 150 \text{ka}$ and $P_{rf} = 80 \text{kw}$.
In these experiments we have also observed nonlinear effects. Figure 5a shows a typical high frequency spectrum taken by an rf probe located in the shadow of the limiter 90° away toroidally from the waveguide array. The spectrum is broadened and downshifted in frequency. Figure 5b shows the low frequency spectrum obtained during rf injection and indicates an enhancement in the low frequency fluctuations during rf. The high frequency probe signal sharply drops as the density increases past \( n_e \approx 1.5 \times 10^{14} \text{cm}^{-3} \) which correlates with the appearance of rf neutron production and indicates the onset of strong wave absorption in the plasma interior. The frequency width of the high frequency spectrum increases from 0.5 to 6 MHz as \( n_e \) is raised from \( 1 \times 10^{14} \text{cm}^{-3} \) to \( 3 \times 10^{15} \text{cm}^{-3} \). Similar waveguide phase-independent frequency spectra are obtained in the plasma interior by CO\(_2\) laser scattering [5].

The observed fast ion production at the plasma center at \( n_e \approx 1.7 \times 10^{14} \text{cm}^{-3} \) and the electron heating are consistent with the absorption of lower hybrid waves having \( n_m = 2 \), \( c/w_0 = 5 \) by Landau damping on thermal particles near the plasma center. Furthermore, the independence of the neutron rate on \( \Delta \phi \) indicates that this wave power spectrum is not dependent on waveguide phasing. This is not consistent with conventional, slab-plasma linear waveguide-plasma coupling theory, which predicts that the injected lower hybrid waves should be characterized by \( n_m \gamma 3 \) when \( \Delta \phi = 180° \), and \( n_m \gamma 1.6 \) when \( \Delta \phi = 0 \). Since accessibility is attained only for waves with \( n_m \gamma 1.5 \), we would not expect wave penetration (and central heating) when \( \Delta \phi = 0 \). Thus, these heating results indicate a modification in the lower hybrid \( k_m \) spectrum near the plasma edge.

One possible cause of this modification is parametric decay of the pump wave into other lower hybrid waves which possess higher \( n_m \) in the plasma periphery. Such a decay is indicated by the broadened and downshifted rf probe frequency spectra of Figure 5a. Experimentally we find no clear threshold or nonlinear variation of these spectra on the probe, even when the pump power is lowered down to \( P_f = 100 \text{ W} \). Unfortunately, a measurement of the wavenumber spectrum near the waveguide mouth was not feasible in these experiments. Another process which would cause modification of the wavenumber spectrum is the scattering of the injected lower hybrid waves off the ambient level of density fluctuations near the plasma edge. These fluctuations (having \( \Delta n/n \gamma 1 \) ) have a long wavelength along \( B \) and would not change the \( k_m \) of the wave locally. However, magnetic shear would increase \( k_m \) as the wave penetrated toward the plasma center as follows [2,6]:

\[
k_m (r) = k_m (a) \left[ 1 + \frac{\sin \theta}{w_0} \left( \frac{1}{q(a)} - \frac{1}{q(r)} \right) \right]
\]

where we assume the wave has undergone a scattering of its radial \( E_R (E_r \ B = 0) \) at \( r = a \) by an angle \( \theta = \sin^{-1} \left( \frac{w_0}{w_0} \right) \) at \( r = a \). In principle, this enhancement can increase \( k_m \) by a factor of 3 and allow waves having \( n_m < 1.5 \) near the plasma edge to penetrate to the plasma center after a scattering.

Further detailed ray tracing calculations, including scattering by low frequency (drift) waves will be published elsewhere [7]. Here we wish to summarize some of the relevant results. It is found that rays launched at the plasma periphery with \( 1.3 < n_m < 6 \) find their way into the plasma interior. This is due to the combined effects of scattering of the waves on low frequency fluctuations, and modification of their wave numbers by magnetic shear and toroidal effects. At \( B = 6.0 \text{ T} \), and proper q-profiles, there is a transition from electron to ion heating at densities \( n_e = 1.4 \times 10^{14} \text{cm}^{-3} \), in good agreement with the experimental observations. The electron heating is relatively independent of the density below \( n_e = 1.4 \times 10^{14} \text{cm}^{-3} \), and it occurs due to a toroidal upshift of \( n_m \) near the plasma center where \( \rho_0 (r) \) is maximum. As the density is increased above \( n_e = 1.5 \times 10^{14} \), absorption on ions takes place due to "perpendicular" ion Landau damping. Again, there is a toroidal upshift of \( n_m \) and \( n_x \) just before

\[

\text{(Equation continued...)}
\]
strong absorption occurs, particularly for the initially low \( n_e \)'s. As the density is increased, or as \( n_e \) is increased above 5, the ion heating shifts to radii \( r/a \approx 0.5 \) where we expect strong ion banana orbit losses, especially for energetic ions. Thus, we expect a high density cut-off of neutron production, again in approximate agreement with the experimental results. Further studies will be needed to decide whether this scattering by density fluctuations, followed by toroidal transformations of the ray trajectories and wavenumbers is sufficient to explain the observed phase independent heating, or whether the initial parametric decay of the incident wave at the waveguide mouth is also essential. Nevertheless, it seems clear that in designing future experiments ray-tracing calculations with toroidal effects will be essential to determine wave penetration and absorption.

**ALCATOR C LOWER HYBRID HEATING**

We are in the process of building a 6 MW lower hybrid heating system for Alcator C. After transmission losses, we plan to inject up to 75% of this power via 4 grills, each consisting of a 4 x 4 waveguide array. The BeO vacuum windows will be brazed into each waveguide so that the guide will be pressurized by the electron cyclotron resonance layer. The total width of the grill is approximately 4.0 cm (each guide is 0.8 cm wide) so that the grill can just fit through the narrow ports of Alcator C. The complete grill unit can be moved radially by bellows so as to optimize coupling. The rf pulse length can be increased to 0.5 sec, and the frequency of the source is chosen to be at 4.6 GHz. Thus, we can heat either hydrogen or deuterium at densities \( n = (0.4-1) \times 10^{15} \text{ cm}^{-3} \) at a magnetic field of \( B > 10 \text{ T} \). Depending on the plasma parameters, the absorption of the incident wave is shared between electrons and/or ions. However, above \( T_e = 2 \text{ keV} \) electron heating tends to dominate for a relative phasing of \( 180^\circ \) between adjacent waveguides (which will produce a spectrum peaked at \( n_e = 3 \)). The phasing can be varied electronically even during the rf pulse (which can be made 0.5 sec long if so desired) so as to optimize heating. Initial experiments at the \( P = 0.20 \text{ MW} \) level will commence in the fall of 1980, and the power will be raised to 1 MW by the end of 1980. Then, as additional grill units will be fabricated, the rf power will be raised to the full power capability during 1981. Our transport code studies predict that at \( n_e = 6 \times 10^{13} \), maximum electron and ion temperatures of \( T_e = T_i = 3.5 \text{ keV} \) may be achieved [8].

**VERSATOR II EXPERIMENTS**

In the Versator II tokamak we are studying (1) the physics of ion heating and (2) the physics of electron heating and rf current drive [9,10]. For the ion heating studies we use a four-waveguide coupler with a guide width of 2.5 cm and wall thickness of 0.6 cm. The relative phasing between adjacent waveguides is typically \( 180^\circ \). For the electron heating studies we use a six-waveguide coupler with a guide width of 0.85 cm and wall thickness of 0.19 cm. The relative phasing between adjacent guides is typically \( 90^\circ \) or \( 120^\circ \) so as to launch a travelling wave. The Versator II plasma parameters are as follows: major radius \( R = 40 \text{ cm} \), minor radius \( a = 13 \text{ cm} \), toroidal magnetic field \( B = 1.2-1.5 \text{ T} \), discharge current \( I < 40 \text{ kA} \), \( T_e < 600 \text{ eV} \), \( T_i < 200 \text{ eV} \), \( n = 5 \times 10^{12} - 5 \times 10^{13} \text{ cm}^{-3} \). The rf system consists of a 180 kW output, 800 MHz klystron which can provide 10 usec pulses [11]. The power is split four (or six) ways and fed into the waveguide array through commercial coaxial vacuum feed-throughs as shown in Fig. 6.
Fig. 6. Power splitter arrangement for the Versator II 800 MHz rf system.
With the help of the high power phase shifters, the phase of each guide can be adjusted to any value desired. The waveguide array is vacuum pumped through a pumping manifold connected to each waveguide. Isolation between adjacent waveguides is 30 dB or better. We note that the electron cyclotron resonance is on the vacuum side of the rf windows. The relative position of the grill and plasma can be adjusted by means of a bellows-arrangement. A shutter is installed in front of the mouth of the grill which can be closed during discharge cleaning so as to prevent contamination of the grill walls.

A. LOW POWER PLASMA-WAVEGUIDE COUPLING MEASUREMENTS

We have carried out coupling measurements at low power level (P = 0.5 - 10 kW, or P/A = 1 - 20 W/cm²) to test prediction of the Brambilla Theory [12]. We found that the reflected power is strongly dependent on the relative phases Δφ between adjacent waveguides, as well as on the radial position of the grill. The results for the four-waveguide grill phased 0, π, 0, π are shown in Fig. 7. For the theoretical curves (based on the Brambilla code [12]) we used the density gradients measured by Langmuir probes at the plasma edge in the absence of the rf power. The measured values of V_n were found to be 10^{10} - 10^{11} cm^{-1}, and there was no sudden jump in V_n as the probe was retracted into the waveguide. We see that there are considerable discrepancies between the experimentally measured reflection coefficients and the theoretical predictions. If we assume a density gradient 50—100 times larger than the measured values, we get a reasonable agreement with the average reflection coefficient. However, the relative magnitude of the reflection coefficients between inner and outer waveguides is still reversed from that predicted by theory. Similar disagreement is found in low power experiments utilizing the six-waveguide grill. In that case, a typical overall reflection coefficient for 90—180° phasing is ~ 30%. In Fig. 8 we show reflection coefficient measurements as the function of relative phasing between adjacent guides for the four-waveguide coupler. The three curves shown correspond to different positions of the waveguide array relative to the limiter edge. We see that the low rf reflection is obtained for a grill position X_c = 3.3 cm, which corresponds to the grill mouth retracted 1 cm into the port. We see the strong phase dependence of the reflection coefficients at these low power levels. When the grill is pushed into the edge plasma too far (X_c = 2.1 cm) the reflection coefficient rises to high values for any phasing due to the overdense plasma.

A possible explanation of the discrepancy between theory and experiment is the presence of gaps between the grill and the port walls (one cm wide). We have made calculations with the Brambilla code where we included open waveguides outside the grill, with variable depths. Although the disagreement was reduced somewhat, we could still not get satisfactory agreement between the observed "inverted" reflection coefficients between inner and outer guides. Furthermore, the large discrepancy in the measured density gradients and theoretical values needed could not be resolved. It appears that one may have to consider extended density profiles (not just local values at the grill-plasma interface) in future theoretical works.

B. HIGH POWER EXPERIMENT

To achieve high power operation of the grill assembly (P > 10 kW) it is necessary to rf pulse-clean ("process") the system. In the absence of special treatment, such as baking the system, it can take several weeks of processing to be able to inject 100 kW of rf power into the vacuum chamber in the absence of the plasma. However, when the complete grill assembly was baked at 400°C in
a vacuum oven for 10 hours, the processing took only a few days. In Fig.9 we show the effectiveness of baking the grill.

During the first day of operation (7-2-80) the power could be raised to 50 kW after 3 hours of processing. After the second day of operation (7-22-80), the power was raised to 90 kW, and after two more days the full 110 kW was transmitted for pulse lengths up to 10 usec without any evidence of arcing or rf breakdown (a comparator circuit was built into the system which shut down the rf system within 10 usec in the case of an arc, or sudden jump in the reflected power). In the absence of baking we see evidence of possible plasma formation in the waveguide, resulting in phase independent reflection coefficients. In Fig. 10 we show results from the 6-waveguide coupler which was not baked or well processed initially. As the power is raised above 20 kW, (or P/A = 400 W/cm²) the overall reflection coefficient becomes phase independent, and is reduced to the low level of R = 20%. In Fig. 11, we show, in more detail, what happens at Δφ = 0°. In particular, η is the curve which corresponds to the phase shift observed in the reflected rf signal and Γ is the reflected power. As we see, above 10 kW of total incident power a phase shift occurs in the reflected signal which we interpret as evidence of possible plasma formation in the waveguide. This phase shift, which shows a smooth variation with incident power occurs typically within 300 micro-seconds after the start of the rf pulse. Meanwhile, above 30 kW a sudden decrease in the reflected power is observed. Above 70 kW many complete 2π radiant phase shifts in the reflected signal may be observed, indicating a potential loss of phase control. We note, however, that plasma formation in the guides is not the only possible explanation of this phenomenon; for example, ponderomotive forces at the plasma surface may play a role here. Clearly, further studies will be required.
Fig. 9. RF power handling capability in vacuum vs. processing time after 400°C baking of the grill. (No processing between 7/2/80 and 7/22/80).

Fig. 10. Reflection coefficient vs. power in the six-guide array. $S = P/A$.

Fig. 11. Reflection coefficient ($\Gamma$) and the phase shift ($\xi$) in waveguide No. 4 vs. rf power. The relative phasing between adjacent guides was 0°.

We have recently begun ion heating studies using a baked and processed four-waveguide phase-array. We find that while in vacuum such a system can handle $P > 100$ kW without any phase shifts in the reflected signal, when the waveguide is in contact with the plasma renewed evidence of phase shifts and/or minor jumps in the reflected power can occur. Nevertheless, we now carried out a
set of high power heating experiments (P = 80 kW, At pulse = 5 msec) and used perpendicular charge exchange diagnostics of the fast neutrals to detect any evidence of heating and/or ion tail production. The charge exchange system is located at 180° from the grill. In addition, a VUV spectrometer is used to monitor impurity lines. During the injection of the high power rf pulse, often a 15% increase in the density is observed. In addition, during rf injection, increased MHD activity is also observed which is manifested by irregular bursts on the B_0 loops on microsecond time-scales. Parametric decay spectrum consisting of several ion-cyclotron harmonics is also often observed on a probe placed in the shadow of the limiter. The VUV monochrometer often shows an increase in the intensity of the OIV line. Thus, it may be that the result of rf injection is recycling accompanied by possible plasma edge cooling [13]. Similar results have been also observed on the earlier JFT-2 experiments [14].

During the ion heating experiments  n = 2.1 x 10^{13} cm^{-3} in hydrogen gas. During a 5 msec long 80 kW rf pulse the density raised to  n = 2.4 x 10^{13} cm^{-3}. We have also observed an apparent rise in the ion temperature as measured by the perpendicular charge exchange detector from an initial value of  T_i = 215 eV to a final value of 275 eV. However, we found that a similar apparent temperature rise could be obtained even in the absence of the rf power just by raising the density to  n = 2.4 x 10^{13} cm^{-3}. Furthermore, monitoring the NVI line by the VUV spectrometer did not show any significant change in the bulk ion temperature (within a ± 20 eV uncertainty). In our plasma the NVI line is located well within the bulk of the plasma column (0 < r/a < 0.4). Thus, we conclude that in this first series of runs no clear evidence of bulk ion heating was found. We did find, however, that when conditions were such that a strong parametric decay was observed, an ion tail was detected by the charge exchange system. At present, we do not understand these results. We note, however, that at the high power levels there were sudden reductions in the reflected power, as discussed earlier. These problems will be investigated in future experiments.

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