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**Final Report
for
Beat wave Current Drive Experiment
on
the Davis Diverted Tokamak (DDT)
DOE Contract # DE-FG03-89ER53289**

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I. Introduction

The beatwave current drive experiment, which had received funding from the Applied Plasma Physics Branch of the Office of Energy Research of DOE over the period between 1989 and 1991, can be summarized as divided into three phases. The first phase of the experiment, approximately covered the first year, was the construction of the microwave sources and the diagnostics needed to demonstrate the beat wave effects, i. e. the measurement of the electrostatic plasma wave produced by the beating of two high intensity electromagnetic waves. In order to keep the cost of the experiments to a minimum, a low density filament plasma source (10^8 to 10^{10} particles cm^{-3}) was employed and the magnetic field in the toroidal plasma was produced by a dc power supply. The geometry of the experimental apparatus is shown in figure 1. The results from the field measurement are described in the enclosed Physics of Fluids B article¹.

II. Phase I

During the first year operation, the electrostatic waves were measured by small cylindrical probes in the plasma. Much time and care was taken to verify the validity of such measurements, i.e. the signal being measured was not the result of the probe sheath nonlinearly mixing the two microwave signals. The strongest evidence of the validity of these measurements is the comparison between the time evolution of the wave amplitude with the microwave driving force (fig. 2). The driving force is measured by mixing the microwave signals received by a small dipole antenna in the interaction region and passing the signal through a low pass filter to isolate the $\omega = \omega_0 - \omega_1$ signal. The beat wave is observed to grow much slower (linear growth in time, in agreement with theory) and the beat wave signal persists long after the microwave pulse is off.

The wave vector of the wave was measured by a pair of probes mounted on the same shaft which could rotate so that the line between the probes could be at an arbitrary angle to the magnetic field. Figure 3 shows the waveforms as recorded by a fast digital oscilloscope. The waves are seen to be in phase when the probes are perpendicular to the magnetic field and have a maximum phase

¹ J. H. Rogers, D. Q. Hwang, J. C. Thomas, R. Horton, J. Killeen, and G. Dimonte
Physics of Fluids B 4, 1920(1992)

difference when the probes are along the field lines, indicating that $\vec{K}$ is parallel to $\vec{B}$. The magnitude of the phase difference when the probes are aligned with $\vec{B}$ gives k , since w and the distance between the probes is known. The dispersion relation measured in this way is consistent with what is expected.¹ It was found that when $w_{ce} > w$, numerous electrostatic modes could be driven when $w_{pe} > w$. However, only the lowest density mode, where $\vec{K} = \vec{K}_0 - \vec{K}_1$, is observed to accelerate electrons (this is because the other modes have too high a phase velocity¹). Also, the power dependence of the beat wave was found to agree with theory, i.e. $P \propto P_0 P_1$.

III. Phase II

The second phase of the experiment is the study of the interaction of the electron population with the electrostatic plasma wave. This work roughly covers the second year, and the results were reported in the enclosed Physical Review Letter.² We had to develop an electrostatic energy analyzer which was placed outside of the microwave interaction zone (see Fig. 1).

When the target plasma has the appropriate density, an energetic electron tail is observed, using the electrostatic energy analyzer, to develop after an appropriate propagation delay time (usually, the electron tail is measured after the microwave pulse is over). The propagation delay is due to the finite group velocity of the plasma wave and the time required to couple the energy to the electrons (approximately the Landau damping time). The accelerated electrons are found to be spatially localized to dimensions similar to the microwave spot size (which is an important characteristic for current profile modification applications).

The modified electron distribution was found to extend from velocities somewhat below the phase velocity of the plasma wave to well above the phase velocity of the plasma wave. Figure 4 shows two typical energy analyzer traces along with the corresponding distribution functions (the derivative of the analyzer data). The extent of the high energy electron tail in velocity space was estimated by where the distribution differs from the unperturbed distribution at the low velocity side (circle), and where the

² J. H. Rogers, and D. Q. Hwang, Phys. Rev. Lett. 68, 3877 (1992)

magnitude is approximately one e-fold smaller than the maximum on the high velocity side (square). Figure 5 shows the dependence of this range in velocity space on the phase velocity of the wave. As expected, when the phase velocity of the wave is increased, the electrons are accelerated to higher energies. However, because the coupling is decreasing, the number of electrons which are accelerated decreases as phase velocity increases, so that the total current carried by the accelerated electrons is a weak function of phase velocity. It was also verified that the current in this energetic electron tail is proportional to $(P_0 P_1)^{1/2}$, as expected by theory, however the observed magnitude was lower than expected.²

IV. Phase III

The estimated L/R time for our toroidal plasma is approximately 100 μ sec. Therefore, in order to observe finite current generation, we need to develop a long pulse length microwave source ($t > 100$ msec). This represents the work carried out over the third year. The most significant upgrade is that of the microwave power system (magnetron supply). The original military-surplus magnetron power supplies used on DDT permitted only uniformly-spaced 1 msec microwave pulses at 1 kHz rate, a pulse interval much greater than the plasma L/R time ($\sim 100 \mu$ sec). These have been replaced by a commercially available semiconductor-based switching system (DEI, Inc.) which allows great flexibility in burst-mode operation; viz., pulse length .1 - 2 msec, repetition rates ≤ 1 MHz, peak power ≤ 960 kWatt (Fig. 6). Pulse power trains of sufficient length and amplitude for long-pulse current drive have been delivered using the new modulator, through a pulse transformer, into a dummy load which simulates magnetron characteristics. Using the improved long pulse sources, we should be able to overcome the L/R or back-EMF effect from the bulk plasma.

The most relevant long-pulse experiment is that of the measurement of the wave generated plasma current. This effect should be detectable with both internal magnetic loops and external Rogowski coils. Moreover, the details of the beat wave modes, especially across the magnetic field, will be useful in understanding the difference between the theoretical efficiency and the experimentally measurements². In order to determine both the spatial and temporal structures of the wave modes, we are using a computer

controlled probe scanner (Fig. 7) which was developed for the compact toroid injection experiments. Various magnetic and electrical probes can be installed on the scanner, and data from the probes will be analyzed using LabView data acquisition programs.

In order to make the full use of the developed microwave and diagnostic hardwares, we have converted some remaining third year funds into a fourth year no-cost contract so that the long-pulse burst-mode experiment can be performed. As the experiment progresses, we expect that new physics issues relevant to this current drive method for future uses will come to light.

The Beat Wave Experiment on DD⁺

Fig. 1

Figure 2

Figure 3

Figure 4

v/v_e range of accelerated electrons

Figure 5

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