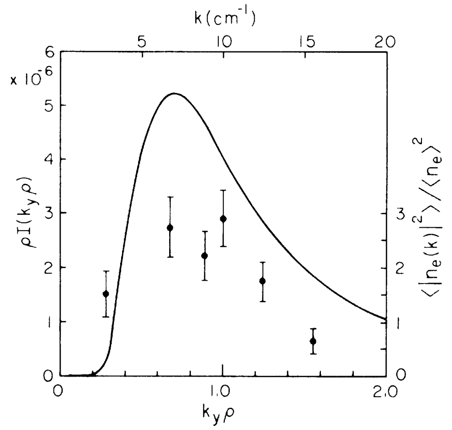

FIG. 1. Comparison of the theoretical spectral distribution $I(k_y\rho)$ given by the solid curve, with the previously reported data (Ref. 1) for the electron density fluctuation spectrum obtained from microwave scattering in the ATC experiment.

and 11.2 cm assuming that the current density $j_\parallel(r)$ varies at $T_e^{3/2}(r)$. Similar evaluations for other tokamak experiments are being performed and will be reported in a later article.

In conclusion, the theory appears to explain several features of both the spectral distribution and the total mean density fluctuation observed in the experiment. We observe that the theory is a first-principles calculation in that, although numerous conventional approximations are made, there are no free parameters available.

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[1] E. Mazzucato, Phys. Rev. Lett. 36, 792 (1976).

[2] V. N. Oraevskii, H. Tasso, and H. Wobig, in *Proceedings of the Third International Conference on Plasmas Physics and Controlled Nuclear Fusion Research, Novosibirsk, U. S. S. R., 1968* (International Atomic Energy Agency, Vienna, 1969), Vol. I, p. 671; H. Tasso, Phys. Lett. 24A, 618 (1967); E. Ott, W. M. Manheimer, D. L. Book, and J. P. Boris, Phys. Fluids 16, 855 (1973).

[3] T. H. Dupree, Phys. Fluids 10, 1049 (1967).

[4] D. Choi and W. Horton, Jr., Phys. Fluids 17, 2048 (1974).

[5] W. Horton, Jr., Phys. Fluids 19, 711 (1976).

[6] N. T. Gladd and W. Horton, Jr., Phys. Fluids 16, 879 (1973).

[7] R. Z. Sagdeev and A. A. Galeev, *Nonlinear Plasma Theory* (Benjamin, New York, 1969), pp. 103–110.

Alfvén-Wave Heating in the Proto-Cleo Stellarator*

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Global excitation of Alfvén waves in the Proto-Cleo $l = 3$ stellarator was accomplished by exciting a helical winding corresponding to a $q = 3$ rational surface with a pulsed, high-power rf source. A doubling of both the electron and ion temperatures was observed, and a slight increase in the ratio of the temperatures with and without rf heating occurred at the predicted resonance locations. Enhanced loss also occurred during heating, with 2.5-kHz oscillations observable in a microwave interferometer signal after heating.

Alfvén-wave heating of toroidally confined plasmas has been proposed by several authors.[1-3] Recent experimental work at Kyoto University[4] and at Kharkov[5] apparently show that *local* excitation of Alfvén waves leads to heating of both ions and electrons, when the resonant condition $\omega = k_\parallel V_A$ was satisfied. V_A is the Alfvén speed and $k_\parallel$ is the wave number in the direction parallel to the dc magnetic field. $k_\parallel$ was always greater than $2\pi L$ where L is the distance around the torus. It is the purpose of this Letter to report successful Alfvén-wave heating of plasma contained

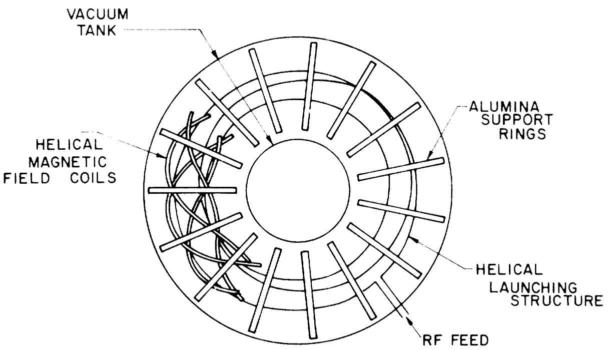

FIG. 1. The experimental configuration for the Proto-Cleo stellarator,

in the Proto-Cleo stellarator,[6] where the excitation is *global*, rather local, and where the excitation condition has been modified to provide an infinite series of *both* poloidal and toroidal wave numbers.

The experiment was performed in the Proto-Cleo stellarator operated in its $l = 3$, seven-field-period configuration. Hydrogen plasma is produced by an accelerated Bostick gun and injected radially from a point just outside of the separatrix. The particle containment time is approximately 2.0 msec. The toroidal field is 3.0 kG. Proto-Cleo has a major radius, R_0, of 40 cm and an average minor radius to the separatrix of 4.5 cm.

Alfvén-wave heating is produced with a separate, electrostatically shielded, helical winding shown in Fig. 1. The pitch of the winding was designed to approximate a $q = 3$ rational magnetic surface. The current in this winding may be represented by toroidal and poloidal wave numbers, if the torus is approximated by a cylinder,[7] viz.,

$$\vec{J} = \delta(r - r_c)\frac{3}{\pi}J_0\cos(\omega t) \times(\hat{\theta}\cos\alpha + \hat{z}\sin\alpha)\sum_{p=1}^{\infty}\cos\left[p\left(\theta - \frac{z}{3R_0}\right)\right], \qquad (1)$$

where r_c is the radius of the helical winding, J_0 is the current amplitude, and α is the pitch angle of the helix.

In Proto-Cleo, the resonant condition $\omega = k_{\parallel}V_A$ cannot be satisfied at frequencies below the ion-cyclotron frequency. However the more general resonance, including both toroidal and poloidal wave numbers, given by

$$\omega_A{}^2 = [(m/r)B_\theta + kB_z]^2/\mu_0\rho_m, \qquad (2)$$

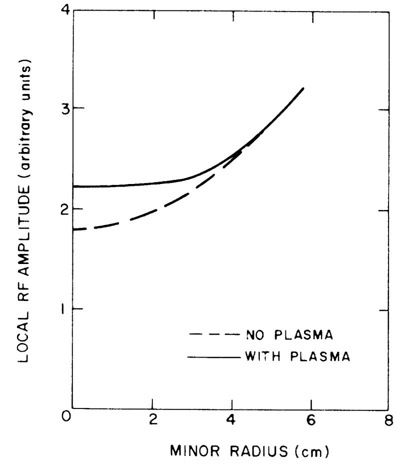

FIG. 2. Local rf field amplitude versus radius with and without plasma present.

can easily be satisfied in Proto-Cleo. In Eq. (2), B_θ and B_z are the dc poloidal and toroidal magnetic fields, m and k are the poloidal and toroidal wave numbers, μ_0 is the permeability of free space, and ρ_m is the mass density. B_θ, B_z, and ρ_m are functions of minor radius. Note that if the mode numbers are of opposite sign it is possible for the resonant frequency to go to zero. According to measured magnetic-field and density profiles for Proto-Cleo, for a constant frequency, two regions of resonance will exist at minor radii of approximately 1.5 and 3.5 cm. The resonant regions shift in position somewhat as plasma density varies.

Figure 2 shows a plot of local rf field amplitude produced by the coil, as measured by a shielded magnetic probe, versus minor radius with and without plasma present. Note that the field amplitude does not decrease in the plasma region,

TABLE I. Profile of the ratio of the electron temperature with rf to that without rf.

Minor radius	T_e with rf / T_e without rf
0	1.0
0.5	1.5
1.0	1.25
1.5	1.75
2.0	1.25
2.5	1.75
3.0	2.0
3.5	1.5
4.0	1.25
4.5	1.0

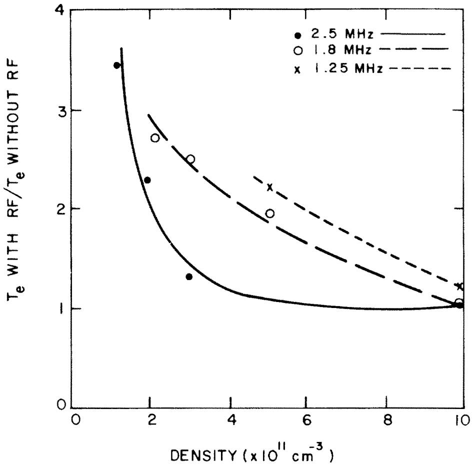

FIG. 3. Ratio of electron temperature with rf to electron temperature without rf versus density at three frequencies.

which implies that the wave penetrates into the plasma.

Electron temperature T_e was measured with a swept floating double probe. With 10 kW of rf at a frequency of 1.8 MHz pulsed for 0.4 msec, the electron temperature doubled throughout the plasma volume, from 8 to 16 eV. Very slight peaking of the ratio of T_e with rf to T_e without rf occurred near the region of expected resonance, as shown in Table I. Similar results were observed at other frequencies all well below the ion cylcotron frequency of 4.5 MHz.

Ion temperature was measured with a multigridded probe[8] and showed a similar doubling of the temperature, in this case from 10 to 20 eV. Figure 3 shows a plot of the ratio of T_e with rf to T_e without rf versus density as measured with the double probe and a microwave interferometer for three different excitation frequencies. Note that at a given density, the increase was greater at lower frequencies. This is consistent with calculations of heating efficiency for Proto-Cleo utilizing the theoretical model of Tataronis and Grossmann.[2]

In conjunction with the heating, it was noted that increased loss of plasma occurred during heating. The loss was greatest at the lowest heating frequencies. After heating, the electron temperature decreased (in about 2 msec) to the value it would have had had there been no rf heating. This may imply that the energy containment time in Proto-Cleo is bounded.

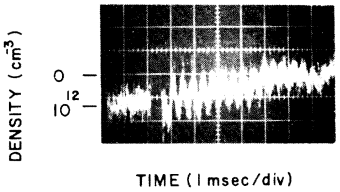

FIG. 4. Microwave interferometer trace showing rf pulse and 2.5-kHz oscillation after the rf pulse.

An alternative explanation for the loss might be inferred from the fact that the microwave interferometer signal showed oscillations in density, at a frequency of approximately 2.5 kHz, after heating. These may be indicative of an instability or other mechanism producing enhanced transport. These oscillations are displayed in Fig. 4.

In summary, global Alfvên-wave heating has shown effective penetration of the wave into the entire plasma, resulting in a doubling of both the ion and electron temperatures. The authors wish to express their thanks to W. Grossmann for helpful conversations and to B. H. Kolner for assistance with the experimental apparatus.

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[1] J. A. Tataronis and W. Grossmann, Z. Phys. 261, 203, 217 (1973).

[2] J. A. Tataronis and W. Grossmann, in *Proceedings of the Second Conference on rf Heating of Plasmas, Lubbock, Texas, 1974*, (Texas Tech. Univ., Lubbock, Tex., 1974), paper A 6, and Nucl. Fusion 16, 4 (1976).

[3] A. Hasegawa and L. Chen, Phys. Rev. Lett. 32, 454 (1974).

[4] A. Hirano, private communication.

[5] F. W. Perkins, private communication.

[6] R. A. E. Bolton, C. R. J. Hoffman, D. J. Lees, S. S. Medley, P. Reynolds, P. H. Shatford, and B. M. White, Phys. Fluids 14, 1566 (1971).

[7] S. N. Golovato, J. L. Shohet, and J. A. Tataronis, University of Wisconsin Report No. ECE-76-8, 1976 (unpublished).

[8] S. S. Medley and D. R. A. Webb, J. Phys. D 4, 658 (1971).

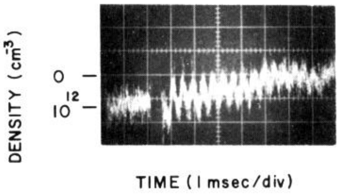

FIG. 4. Microwave interferometer trace showing rf pulse and 2.5-kHz oscillation after the rf pulse.