Plasma Edge Cooling during rf Heating

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A new approach to prevent the influx of high-Z impurities into the core of a tokamak discharge by using rf power to modify the edge plasma temperature profile is discussed. This concept is based on spectroscopic measurements on PLT (Princeton Large Torus) during ohmic heating and ATC (Adiabatic Toroidal Compressor) during rf heating.

The deleterious effects of impurities in present tokamak operation, as well as in possible reactor designs, are well recognized. When the ST,[1] ATC,[2] ORMAK,[3] TFR,[4] and PLT[5] are compared, it appears that in larger devices a smaller fraction of the input power is deposited on the limiter. The remaining power is radiated either in the central core typically by high-Z impurities or in the edge region by low-Z impurities or the working gas. PLT[6] and DITE[7] results indicate that if a sufficiently strong mechanism, such as low-Z impurity radiation, does not exist in the edge region to dissipate the input power more or less uniformly on the walls and decrease the plasma edge temperature, there is a substantial power loss by high-Z radiation in the core. To avoid this potential serious problem, Gibson and Watkins have recently proposed using a cold plasma blanket to control the edge temperature.[8]

In this paper, a new approach to prevent the influx of high-Z impurities into the core of the discharge will be presented using rf waves. rf power appears to affect the plasma transport in the plasma periphery in such a way as to decrease the edge plasma temperature and increase the power radiated by low-Z impurities in the edge region. This concept has evolved from an analysis of spectroscopic measurements conducted on both the Princeton Large Torus[6] (PLT) and the Adiabatic Toroidal Compressor[9] (ATC).

Recently in PLT, the concentration of low-Z impurities (in particular oxygen and carbon) has been substantially reduced ($n_0/n_e \lesssim 0.01$ and $n_c/n_e \lesssim 0.004$). In these discharges with $I_p \approx 400$–500 kA, $B_T \approx$kG, $\bar{n}_e \sim (2-4)\times 10^{13}$ cm^{-3}, the power radiated by high-Z impurities (in particular tungsten) was found to dramatically affect the power balance.[5] Typically, the temperature profiles were hollow and the energy confinement time relatively short. As in experiments on ST[10] and TFR,[11] the power radiated by high-Z impurities was found to be inversely correlated with the presence of low-Z impurities. Recently, we also found a strong correlation between ion edge temperature T_i(edge) and the density of high-Z and low-Z impurities.[6] Namely, when low-Z impurity concentrations were low, T_i(edge) was relatively high and tungsten radiation was high, as shown in Fig. 1. The edge ion temperature was determined from Doppler broadening of the C IV 1548-Å and C III 2297-Å lines using 1-m Ebert-Fastie monochromator with a fast vibrating LiF plate. Furthermore, simultaneous measurements of the edge ion temperature and edge electron temperature from cyclotron emissions were well correlated.[6]

The advantages of plasma edge cooling were also demonstrated in helium and very recently deuterium experiments on PLT. By suitably programming a large gas influx, it was possible to achieve a low edge temperature, low tungsten

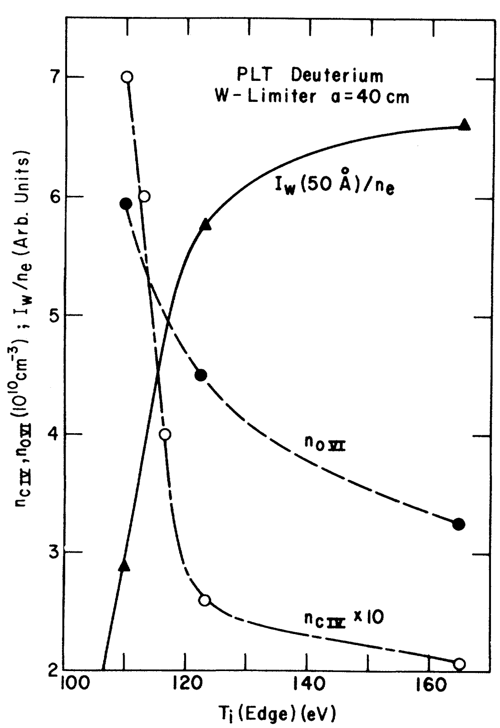

FIG. 1. Correlation between the ion edge temperature (from Doppler broadening of the C IV 1548 Å line), oxygen and carbon density and the tungsten band intensity at 50 Å.

radiation and also high densities. Spectroscopic and bolometric measurements showed that a large fraction of the ohmic input power was radiated from the edge, similar to experiments with a substantial contamination of low-Z impurities.

Using rf waves one may enhance the radiation by low-Z impurities in the plasma edge without substantially increasing their concentration in the center and decrease the plasma temperature in the plasma periphery. The feasibility of this approach is based on extensive spectroscopic measurements on the ATC tokamak made during rf heating experiments, both lower hybrid (LH) and ion cyclotron range frequency (ICRF), conducted over a wide range of operating parameters. In the LH experiments,[12] a wave-guide array coupled the rf power (at 800 MHz) to the plasma. The maximum rf power into the plasma was 160–180 kW for ~5 msec. In ICRF experiments,[13] a 25-MHz generator was used corresponding to the second-harmonic deuterium frequency at $B_T \approx 16.4$ kG. The maximum rf power was $P \approx 200$ kW and pulse length typically ≈ 10 msec.

In both experiments, the impurity concentration and Doppler broadening of various impurity lines were measured. For rf heating of 60–100 kW, the intensity of C IV and O VI lines increased by a factor of 2–3 and the enhancement increased with increasing power. The enhancement of the emission occurred only during rf heating and in 2–3 msec after the rf pulse decreased to the level of a discharge without rf. Emission of C III, C II, and O II lines increased by a similar factor (1.5–2.5) while background plasma lines (D or H) changed by a much smaller factor (< 50%). At the same time, the intensity of C V 2271-Å and O VII 1623-Å lines did not change as shown in Fig. 2. The ionization and excitation energy of these lines is much higher than that of the C IV and O VI lines. Thus, the C V and O VII lines radiated nearer the center[9] ($r/a \sim 0.3$–0.5) while the emission of the C IV and O VI lines were located not far from the plasma edge ($r/a \sim 0.7$–0.9).

The enhanced radiation by the lower ionization states cannot be explained by a change in the electron density, for during rf heating the line average electron density increased by only (20–30)%. Also the edge density as determined from Thomson scattering measurements did not change while the edge electron temperature decreased during this time. More accurate measurements of the edge ion temperature from the broadening of the C IV 1548-Å line showed a significant decrease in T_i as a function of rf power (Fig. 3). At the same time the ion temperature near the center from measurements of C V and O VII lines increased substantially[9,12,13] (Fig. 4). Thus, during rf heating (especially ICRF), plasma-edge cooling was quite evident, as was the increase in power radiated, based on spectroscopic measurements, also shown in Fig. 4. Nonresonant line radiation is not included in estimating the radiation losses. Recent calculations indicate that including these additional transitions may increase the power radiated by a factor of ~2.[6] The uncertainty in the absolute value of the radiated power

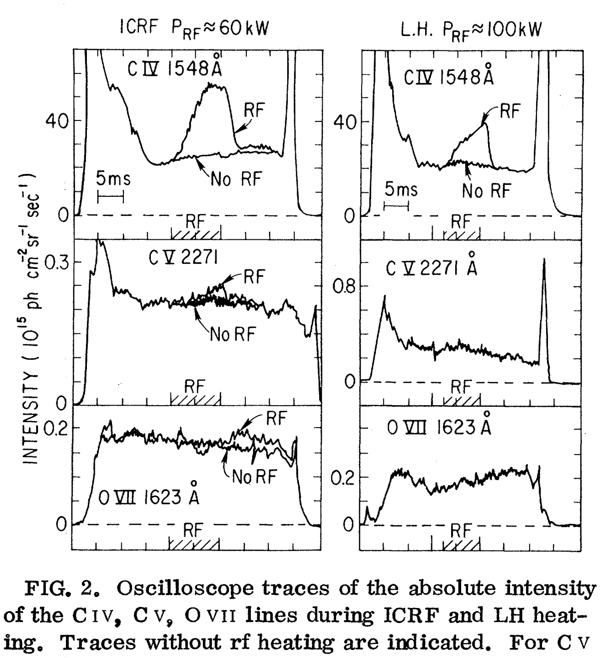

FIG. 2. Oscilloscope traces of the absolute intensity of the C IV, C V, O VII lines during ICRF and LH heating. Traces without rf heating are indicated. For C V and O VII lines (LH case) the trace without rf heating was indistinguishable and hence not shown.

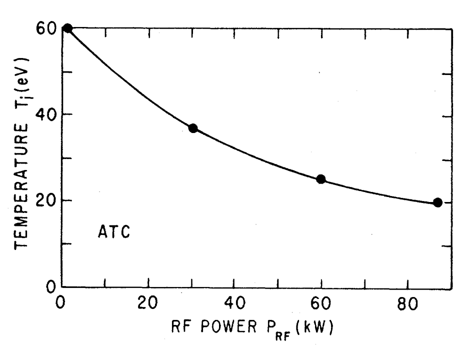

FIG. 3. Ion edge temperature at the end of the ICRF pulse from Doppler-broadening measurements of C IV 1548 Å.

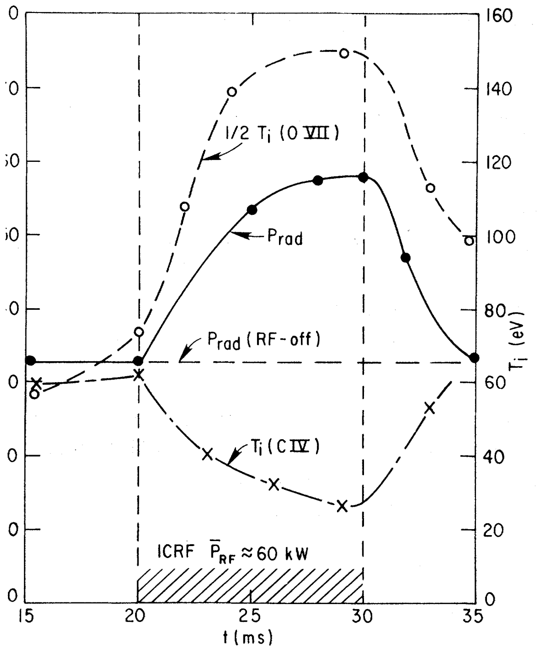

FIG. 4. Spectroscopic measurements of power radiated and ion temperature (from C IV lines in the edge and O VII lines in the core) during the ICRF heating.

is a factor of 2, though the uncertainty in the relative change during rf is considerably less (~ 20%). From the behavior of the C V and O VII lines, it appears that the concentration of low-Z impurities in the plasma core did not increase during rf heating. Nonetheless, if the rf power was too large, resulting in perhaps excessive edge cooling, the plasma would become disruptive and then all of the impurity lines increased.

rf heating also appears to modify the plasma transport in the plasma periphery. Probe measurements[14] showed an increase in the density decay length during rf heating in the plasma periphery, thus, indicating an increased particle diffusion coefficient. An increase in the diffusion coefficient is also suggested by the CO_2-laser measurements of the low-frequency turbulence by Surko and Slusher.[15] In these measurements, the low-frequency turbulence increased during rf heating with a temporal evolution similar to that of the C IV line radiation. Furthermore, the the increase was localized in the edge region ($r/a \sim 0.7-1$).

In conclusion, in ATC the edge temperature was decreased by the application of rf power. The decrease in edge temperature may be associated with the modification in the transport coefficients (both particle transport and possibly heat conduction) in the plasma periphery and the increase in power radiated by low-Z impurities. By decreasing the edge temperature due to a combination of increased transport as well as increased radiation it should be possible, as in PLT, to decrease the high-Z radiation.

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