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Highly Radiative Plasmas for Local Transport Studies and Power and Particle Handling in Reactor Regimes*

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ABSTRACT

To study the applicability of artificially enhanced impurity radiation for mitigation of the plasma-limiter interaction in reactor regimes, krypton and xenon gases were injected into TFTR supershots and high-l_i plasmas. At neutral beam injection (NBI) powers $P_B \geq 30$ MW, carbon influxes (blooms) were suppressed, leading to improved energy confinement and neutron production in both D and DT plasmas, and the highest DT fusion energy production (7.6 MJ) in a TFTR pulse. Comparisons of the measured radiated power profiles with predictions of the MIST impurity transport code have guided studies of highly-radiative plasmas in ITER. The response of the electron and ion temperatures to greatly increased radiative losses from the electrons was used to study thermal transport mechanisms.

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1. INTRODUCTION

In a tokamak reactor such as ITER more than 200 MW of fusion alpha heating power must be dispersed. [1] Heat removal by radiation from controlled injection of impurity gases, either in the main chamber or in the divertor, is a promising technique for mitigating the severe problem of concentrated power loading of the divertor. [2] Experiments have shown that a large fraction of the heating power can be removed by impurity radiation without deleterious effects on plasma performance. [3,4] In TFTR [5], this technique has been extended to reactor regime plasmas (T_e = 5-9 keV, T_i = 20-40 keV) and to higher-Z impurities, krypton and xenon, by injection of these gases [6] into supershot [7,8] and high internal inductance [9] plasmas. At the high electron temperatures in reactors, higher-Z impurities are more appropriate because the lower-Z impurities ionize to high charge states which produce little radiation. Furthermore, much lower concentrations of high-Z ions can be used because of the very high specific radiation per ion ($P_{rad} \sim Z^3$), resulting in lower fuel dilution ($\Delta n_H/n_e \sim \langle Z\rangle\, n_Z/n_e$), where n_H and n_Z, respectively, are the density of the hydrogenic fuel and impurity, and $\langle Z\rangle$ is the average charge state of the ions.

Two distinct experiments were performed in TFTR. These were (1) high neutral beam heating power ($P_b \geq 30$ MW) discharges for reduction of deleterious influxes of wall impurities (carbon "blooms") [10] and deuterium, and improved energy confinement and fusion power production; and (2) thermal transport studies at moderate power (P_b = 16 MW).

These plasmas are distinctly different from the "Z-mode" of ISX-B [11] or "RI-mode" of TEXTOR [3] plasmas, which were performed at much lower temperatures and with lower-Z gases. The RI mode plasmas **require** injection of both neon and deuterium gas to achieve high density ($n_e \sim n_e^{GW}$, where n_e^{GW} is the Greenwald density [12]) and improved confinement (relative to L-mode), whereas in the TFTR experiments, high-Z gases were injected parasitically into steady-state supershots to reduce the power flow to the edge, and were not required for enhanced confinement.

2. THERMAL TRANSPORT EXPERIMENTS

The highly radiative plasmas provided a convenient tool for local transport studies, because the distribution of power loss between radiation and conduction plus convection was greatly changed (*e. g.*, from 25:75% to 75:25% globally) in a locally measurable way, while the NB deposition profile was relatively unchanged. Krypton and xenon gases were puffed into TFTR supershots with P_b = 16 MW, a plasma current I_p of 2 MA, and a toroidal magnetic field of 4.8 T. Feedback control of the gas puff rate was used to maintain a constant radiated power fraction, $f_r = P_{rad} / P_{heat}$, where P_{rad} and P_{heat} are the measured radiated power and neutral beam heating power. At radiated fractions as high as 80% the energy confinement time was not reduced. The electron temperature $T_e(r)$ was hardly changed, while the ion temperature $T_i(r)$ increased significantly in the radiative plasmas, by about 35% in the center and 10% near the edge.

Transport analysis for the Xe-puffing shot coupled the invariance of $T_e(r)$ to increased heating from ion-electron equipartition energy as both the electron density $n_e(r)$ and ion temperature $T_i(r)$ increased. The transport analysis indicated that χ_e did not change in the core with the increased radiation from Xe, while χ_i and χ_ϕ decreased, as shown in Fig. 1. The Dα and CII line emission decreased by 40 and 15%, respectively. The reduced Dα emission would correlate with a confinement improvement of 10% under the normal supershot scaling. [13]

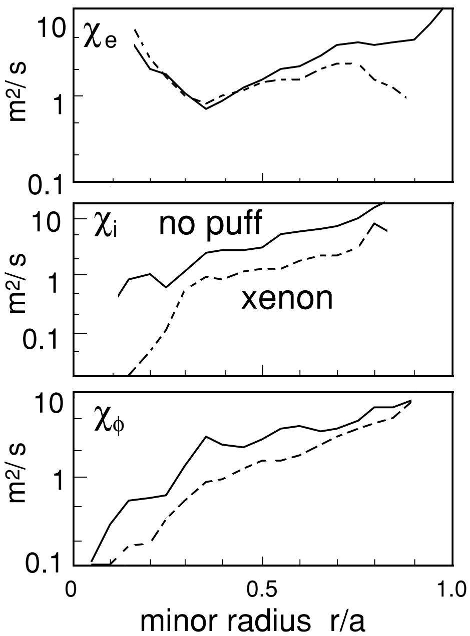

Fig. 1 Radial Profiles of the electron and ion thermal diffusivity and the momentum diffusivity with intrinsic (fr ≈ 0.25, solid curves) and xenon-enhanced radiation (fr ≈ 0.75, dashed curves)

Improvements in energy confinement in tokamaks have recently been associated with the formation of flow shear layers which suppress the turbulence responsible for anomalous transport [14]. In this context, it should be noted that the poloidal velocity v_θ of carbon impurities about 15 cm inside the last closed flux surface increased from 1 km/s to 5 km/s just after the Xe puff. The poloidal rotation profile, expressed in terms of its contribution, $v_\theta B_\phi$, to the radial electric field E_r, is shown in Fig. 2a. Coupled with changes in the toroidal rotation, there is a factor of three increase in the total radial electric field E_r to ~50 kV/m at this location. The evolution of the components of the equilibrium radial field E_r at the radius of its maximum excursion are shown in Fig. 2b. Changes in E_r of similar magnitude have been associated with the formation of transport barriers in TFTR ERS plasmas [15].

3. POWER AND PARTICLE HANDLING

At heating powers above 30 MW in TFTR, the fusion neutron production and energy confinement time were often limited by large influxes of carbon and hydrogenic species from the limiter. The radiative-regime experiments successfully suppressed the carbon "blooms" by reducing the power flowing to the edge. These experiments were done at I_p = 2.2-2.6 MA and B_T = 5.1-5.5 T. In D plasmas with $P_B \geq 30$ MW, increasing the radiated power fraction from the normal ~25% to levels of 45 - 70% by injection of either Kr or Xe suppressed carbon blooms and

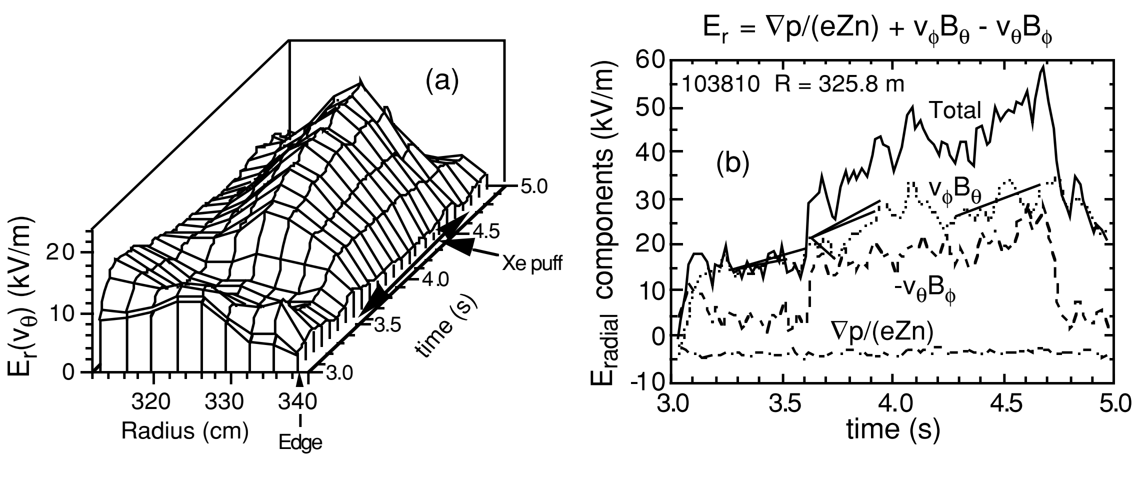

Fig. 2 (a) Radial electric field E_r resulting from the poloidal velocity v_θ, showing peaking during Xe puff. (b) E_r components and total E_r at the location of peaking in (a).

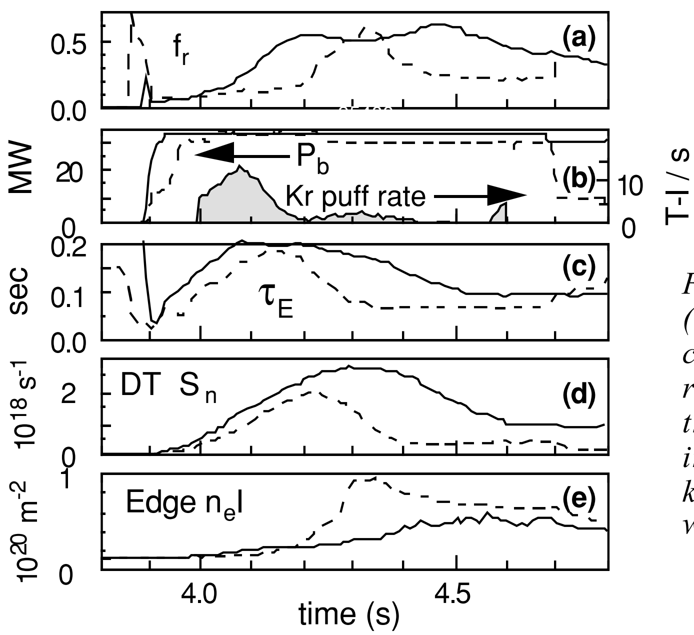

Fig. 3 (a) Radiated power fraction, (b) heating power, (c) energy confinement time, (d) DT neutron rate, and (e) electron density near the edge for two high internal inductance discharges, one with krypton puffing (solid) and one without krypton (dashed).

resulted in significantly improved τ_E and neutron production, relative to that in similar shots without impurity gas puffing. A DT shot with Kr injection to maintain f_r = 70% produced 7.6 MJ of fusion energy, a record for TFTR.

The enhanced impurity radiation was successfully combined with the technique of lithium wall conditioning [16,17] to further reduce wall impurity influxes. Figure 3 illustrates the effect of puffing Kr into a high-l_i shot (solid curve) with 32 MW of NB heating, while continuously injecting lithium globules into the plasma edge via laser ablation ("DOLLOP" technique [17]). In the reference discharge without Kr puffing (dashed curve) a large influx of carbon and hydrogenic species (not shown) results in a large increase in edge density (e) as the energy confinement (c) and neutron rate (d) drop sharply. With Kr injection the confinement and neutron rate are maintained higher for a longer time before rolling over, and the edge density is maintained lower.

4. IMPLICATIONS FOR REACTORS

This demonstration of the successful removal of a large fraction of the heating power as radiation under reactor conditions without degrading confinement or significantly diluting the fuel ions creates the possibility of improving power handling in fusion reactors. Reduction of the power flowing to the edge may substantially ameliorate the divertor heat load problem. [1,2] The high specific radiative power of Kr and Xe at reactor temperatures permits additional radiation power of ~10 MW in TFTR with minimal fuel dilution ($|\Delta n_H/n_e| < 10\%$, $n_Z/n_e \sim 10^{-3}$). The power was radiated across the entire plasma; the power profile from Kr was slightly hollow and that from Xe slightly peaked in the center.

Comparison of the TFTR radiated power with simulations by the MIST code [18] enabled a "calibration" of the code to provide more confidence in extending MIST modeling to reactor plasmas. For both Kr and Xe the measured radiated power profile shapes were reasonably predicted by the code with the assumptions of a diffusion rate $D(r) = 1\ m^2s^{-1}$, a radially uniform impurity concentration, and Lotz ionization rates. The total radiated power measured by bolometer arrays, however, was higher than that calculated by MIST by a factor 3.0 ± 0.4, where the "error" bar is strictly the statistical variation of the data. This difference suggests a deficiency in the magnitude of the radiated power cross sections of the different charge states. The required high-Z impurity gas concentrations were determined from spectroscopic line intensities or from the measured increase in Z_{eff}. This difference between the measured and MIST predictions is a favorable finding for modeling reactor radiative plasmas, because it means that the required high-Z impurity concentrations to produce a requested radiated power level are smaller by a factor of 3 than those predicted by the uncalibrated MIST.

MIST simulations were done for production of 150 MW of radiated power in ITER. ITER profiles having a central T_e of 21 keV and a flattish density profile with a central value of 1.33×10^{20} m^{-3} were used. Other parameters were R = 8.0 m and a = 2.8 m. For these scoping studies a circular cross section was assumed for ITER. For elongated cross sections, the radiated power should scale roughly as the plasma volume. Using the calibration factor from the TFTR data, the required concentrations of Kr and Xe were 18 and 3.9, respectively, in units of 10-5, resulting in a reduction of the hydrogenic density of 0.63% and 0.2%.

5. SUMMARY AND CONCLUSIONS

High-Z gas puffing enabled reduction of the power flowing to the edge by a factor of 3 in TFTR supershot discharges. Wall influxes were significantly reduced at high power, resulting in higher confinement times and fusion neutron production. At modest power, χ_i and χ_ϕ decreased significantly. A localized increase in poloidal rotation near the edge lead to a tripling of E_r. The significance of this change in E_r shear is being investigated. [19] MIST modeling, using the results from the TFTR data, suggest that nonperturbing concentrations of order 10^{-4} of Kr or Xe can radiatively dissipate 150 MW, which is a significant fraction of the fusion alpha heating power in ITER, and thus greatly reduce the power flowing to the divertor.

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