

EDGE AND BULK VARIATIONS OF PLASMA INDUCED BY Kr AND Ar INJECTION IN FTU

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1. Introduction

The requirements of decreasing the power load on the divertor plates has increased interest in the injection of impurities into Tokamak plasmas. In this context small but variable amounts of Kr and Ar were injected into the FTU tokamak and the effects on the edge and bulk plasma properties were studied. Most experiments were made by injecting the impurities on a stationary plasma with a line average density of $5 \times 10^{19} \text{ m}^{-3}$ and a plasma current of 0.5 MA, with some results at higher densities ($7-9 \times 10^{19} \text{ m}^{-3}$) and greater currents (0.9 MA). Three distinct plasma regimes were identified.

2. Experimental Results

A variety of diagnostic techniques were employed: bolometry, visible Bremsstrahlung, a polychromator in the visible, VUV (SPRED and GRITS) and soft X-rays (rotating and curved crystal spectrometers) and Langmuir probes. The intrinsic impurities were mainly molybdenum from the limiter, with small quantities of nickel, iron, chromium, oxygen and carbon from the chamber walls. The measured radiated power can be adequately explained using the Mo impurity alone. The three observed regimes depend on the quantity of injected gas.

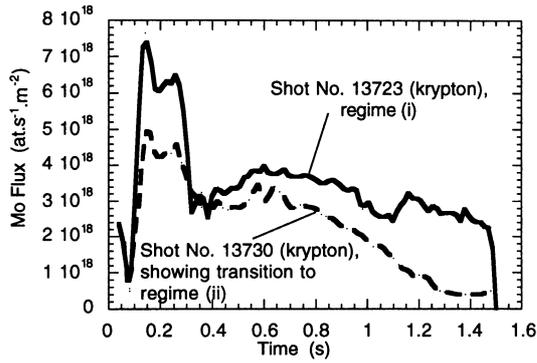


Fig. 1. Two Kr shots showing the change in Mo flux between regimes I) and II)

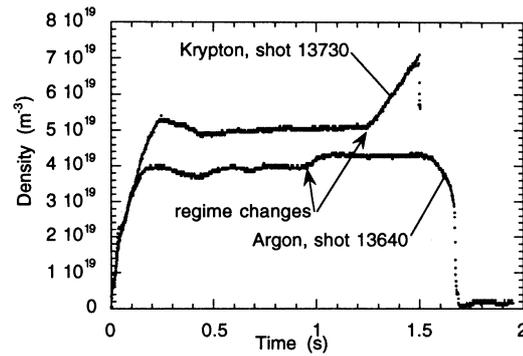


Fig. 2. Electron density (central chord) for Ar (regime I) and Kr (regime II and III)

i) Weak perturbation. Although clear evidence of the injected impurity can be seen using spectroscopy (visible, VUV and soft X-ray), there is no perturbation of the global plasma parameters (density, temperature, intrinsic impurities, bolometry and Bremsstrahlung), with the minor exception of a slight increase of radiated power in the outer bolometry chords.

ii) Significant perturbation. A $\sim 20\%$ increase in the bolometry and Bremsstrahlung signals occurs in the core. In the SOL, Langmuir probes show a decrease at the LCFS of about half for n_e ($0.75 \rightarrow 0.35 \times 10^{19} \text{ m}^{-3}$) (Fig.3) and about 25 % for T_e ($20 \rightarrow 15 \text{ eV}$), and an overall tendency toward poloidal uniformity. This is accompanied by a major reduction of the Mo flux (Fig. 1) and the other metal impurities in the SOL (as seen with the polychromator). This transition occurs suddenly and simultaneously for all signals (at times $\approx 300 \text{ ms}$ after injection for Ar and $\approx 400 \text{ ms}$ for Kr). Almost always in this regime the Ar discharges reach a stationary state, while those with Kr mainly disrupt but can survive depending on the quantity of injected gas. The radiated power increases in the centre of the discharge and decreases slightly at the edge, while the core electron density and temperature remain unchanged.

iii) Major perturbation. This regime starts like the second, but is followed by a sudden change in what we interpret to be particle transport. At this point the central electron density increases while the central temperature falls. The effect of the cooling in the region $r/a > 0.6$ causes an increase in the gradient of T_e . The L-shell emission from Ne-like Mo and its satellites increases somewhat while that from Kr increases markedly. There is a substantial increase in the electron density, especially within the inversion radius of sawteeth. A few discharges of this kind disrupt (central thermal instability). This scenario only occurs with Kr. The time histories (Ar,Kr) of the $n_e(0)$ are shown in Fig. 2 and illustrate the rapid for Kr and the steady state obtained for Ar.

3. Model

The observations which have been made can be explained by a simple model which illustrates the dependence on the quantity of injected gas. The following model provides an estimate of the threshold value of $n_G Q_G$ (the product of gas density and cooling rate) which can be compared to experiment.

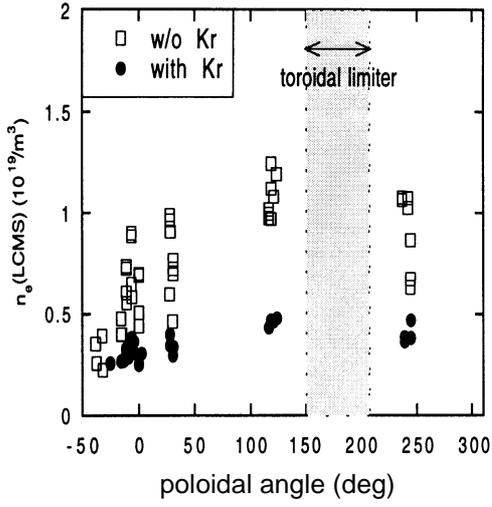


Fig. 3. Electron density at LCMS with Langmuir probes for shots with and without Kr

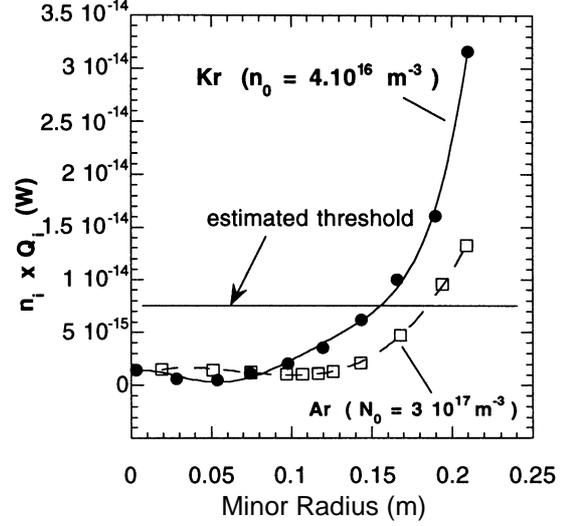


Fig. 4. $n_{imp}Q_{imp}$ profiles for Ar and Kr, showing threshold

The energy equation for electrons, using standard notation, is

$$\frac{3}{2}n_e \frac{\partial T_e}{\partial t} + \nabla \cdot \mathbf{q} = P_{OH} - P_r \quad \text{with} \quad \mathbf{q} = -\mathbf{u}_r n_e \chi_e \frac{\partial T_e}{\partial r} \quad (1)$$

Supposing that the only time variations are due to the injection of impurity gas, $\Delta P(t) = \Delta P_{OH} - P_r^G$, and neglecting conduction

$$\frac{3}{2}n_e \frac{\Delta T_e}{\Delta t} = \Delta P_{OH} - P_r^G = \left[\frac{\Delta \langle Z_{eff} \rangle}{\langle Z_{eff} \rangle} - \frac{3}{2} \frac{\Delta T_e}{T_e} \right] P_{OH} - n_G n_e Q_G \quad (2)$$

where the first term on the RHS is due to the change in resistivity since the plasma current is kept constant; the second term is the radiated power due to the injected gas. We look for effects which cause at least a change ΔT_e of 20 % in the equilibrium T_e^0 ($\Delta T_e = -0.2 T_e^0$)

$$\left[\frac{\Delta \langle Z_{eff} \rangle}{\langle Z_{eff} \rangle} - \frac{3}{2} \frac{\Delta T_e}{T_e} \right] P_{OH} - n_G n_e Q_G = \frac{3}{2} n_e \frac{\Delta T_e}{\Delta t} = -\frac{3}{2} n_e \frac{0.2 T_e^0}{\Delta t} \quad (3)$$

To neglect conduction, the conduction time, $\tau_c > \Delta t$, implying $L^2/\chi > \Delta t$. Putting these results together

$$n_G n_e Q_G > \frac{0.3 n_e T_e^0 \chi_e}{L^2} + \left[\frac{\Delta \langle Z_{eff} \rangle}{\langle Z_{eff} \rangle} - \frac{3}{2} \frac{\Delta T_e}{T_e} \right] P_{OH} \quad (4)$$

Taking $T_e^0 = 800$ eV, $T_e = 600$ eV, $\langle Z_{eff}^0 \rangle = 5$, $J = 10^6$ A/m², $\sigma = 6 \times 10^6$ $\Omega^{-1} \cdot m^{-1}$ ($P_{OH} = 2 \times 10^5$ W/m³), $\delta Z_{eff} = 1.5$ (Kr), 1.8 (Ar), $n_e = 6 \times 10^{19}$ m⁻³, $\chi_e = 0.5$ m²/s, $L = 0.05$ m, gives $n_G Q_G > 1 \times 10^{-4}$ W.

Figure 4 gives the measured $n_G Q_G$ values for Kr and Ar at a particular time. These profiles can increase with time depending on the injected quantity of impurity. Regime i) is where $n_G Q_G$ is everywhere below the threshold, $\tau_c \ll \Delta t$ and $P_r^G \ll P_r^I$ (I = intrinsic impurities). Regime ii) is where the threshold is reached at about mid radius; the gas produces a measurable (20 %) increase in P_r and the Bremsstrahlung emission, but not sufficient to modify T_e and n_e in the core, nor the other global parameters ($\tau_c \approx \Delta t$ and $P_r^G \approx P_r^I$). The effects in this regime occur only at the edge (reduced P_r^I , reduced Mo and metals fluxes) and lower SOL (probe results) parameters. Regime iii) is when the threshold is surpassed even within the mid radius. The gas cools the plasma everywhere and modifies the T_e profile ($\tau_c \gg \Delta t$, $P_r^G \geq P_r^I$). Consequently, the increase of ∇T_e in the outer 2/3 of the plasma, confirmed by the GRITS and the ECE measurements, induces a change in particle transport leading to increased electron density, as well as krypton and Mo densities, in the core. This creates a situation in the centre where $P_r > P_{in}$ which causes a major disruption. This third situation only occurs for Kr, which has an order of magnitude higher radiation properties than Ar. The expression for the threshold also explains why the higher current discharges are more resistant to the mode change (higher T_e , lower P_r) whereas higher density discharges at the same current witness the mode changes at earlier times (lower T_e , higher radiation losses towards centre).

4. Conclusions

The phenomena illustrated here depend on the product $n_G Q_G$ and therefore on the particle transport [$n_G(r,t)$] as well as the radiative properties of the gas [$Q_G(T_e)$]. As we have seen in other measurements [1] during the evolution of gas throughout the discharge, the profile of n_G is fairly constant within about 0.1 m increasing towards the outside where the gas is introduced. In time the density profiles increase driven by the pressure gradient from the outside and leading to the different regimes discussed above. Ar usually reaches an equilibrium when the gradient vanishes. The Kr, because of its transport and its high radiative power, is able to modify strongly the outer region of the confined plasma ($r/a > 0.6$) and produce an enhanced particle confinement regime. This transition will be studied in greater detail in the next future.

Acknowledgement

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Reference

- [1] D. Pacella, B.C. Gregory, L. Gabellieri, G. Mazzitelli, M. Leigheb, G. Pizzicaroli, K.B. Fournier, W.H. Goldstein, M. May, M. Finkenthal: "Measurement of the Radiative Cooling Rate for Krypton and Argon and their Profiles in the FTU Plasma." *Proc. 1998 ICPP&25th EPS Conference, Praha, June 29 – July 3, 1998.*