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PLASMA PARAMETERS IN RUNAWAY DISCHARGES IN TCABR TOKAMAK

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1. Introduction. A new regime of runaway discharges (RAD) has been observed in the TCABR tokamak [1,2]. The distinctive features of this regime are weakly ionized low-temperature plasma detached from the limiter due to the recombination, and relaxation instability with strong spikes of H_α emission correlated with sowtooth relaxation of the plasma line density. In the present work, the plasma density distribution has been measured by multi-chord microwave interferometer. The plasma electron temperature less 1 eV is estimated from analysis of spikes of loop voltage, plasma density and H_α emission caused by the beam-plasma instability.

2. Plasma density and H_α emission profiles. The tokamak discharges are generated in TCABR (R = 0.615 m, a = 18 m, B = 1.1 T) using programmed control of the loop voltage and neutral gas (hydrogen) puffing. The relaxation instability is a characteristic feature of RAD. Each cycle of relaxation instability has two phases. The first one is a short, ~ 10 μs, instability process which manifests itself in spikes of H_α-emission, plasma density and signals of other diagnostics. These effects indicate plasma heating caused by the instability. Increase of plasma electron temperature leads to ionization of the neutral gas. Then the instability is quenched, the electron temperature drops, and the density decays due to recombination. An example of a RAD with high neutral density is presented in Fig. 1. The neutral density increases linearly with time due to gas puffing. The plasma line density is measured along 7 vertical chords by a two-channel microwave interferometer. Because only two chords can be used simultaneously, the density profile is determined on a shot- by

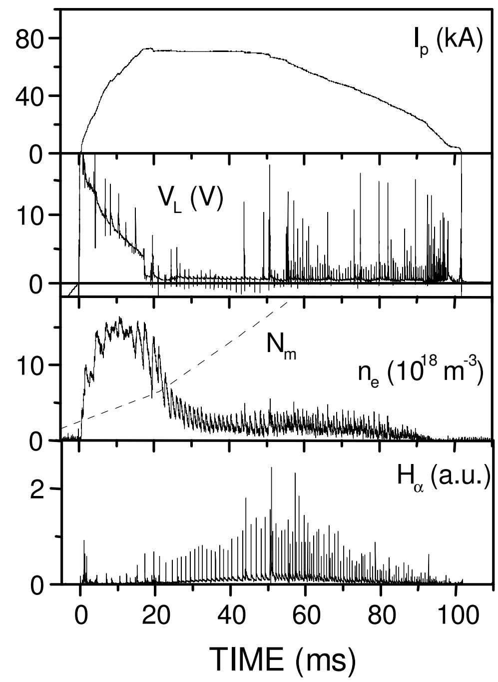

Fig. 1. Runaway discharge with high neutral density; N is neutral density due to gas puffing.

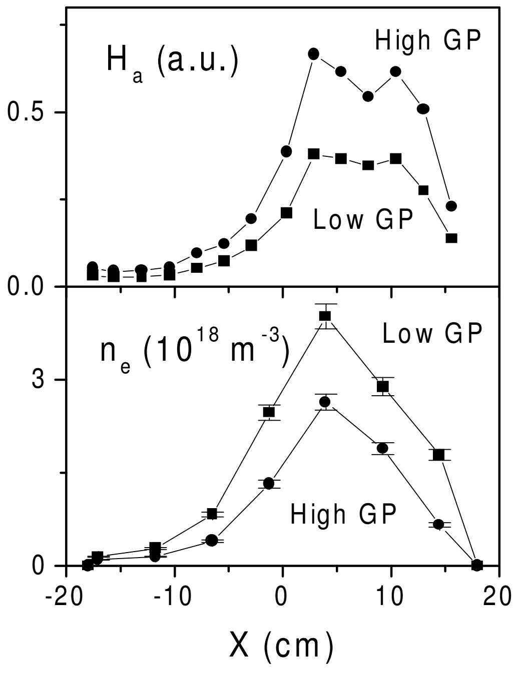

Fig. 2. Radial profiles of plasma density and H_α emission.

shot basis, keeping one chord fixed for checking discharge reproducibility. The H_α emission profiles are measured simultaneously along 14 vertical chords by a set of photodiodes with optical filters. The results are presented in Fig. 2 for two RAD with different neutral densities. The H_α profiles are similar to the density profiles and both density and H_α profiles at the spike are similar to those at the relaxation phase. The measured profiles are rather peaked. The peak of the density has a large shift outward, 4-6 cm. With the neutral density increase, the plasma density decreases and the H_α emission intensity increases. In the case of high neutral density, the plasma in SOL is absent within the sensitivity of the measurements, i.e. ~ 10^{17} m^{-3}.

3. Electron temperature. The electron temperature in RAD can be estimated from the decay time of positive voltage spikes (VS) frequently observed in this discharge as one can see in Fig. 1. This method is discussed in detail in [3]. In our model, the plasma current is generated inductively due to the fast runaway losses and then decays due to resistive damping with a time constant determined by the plasma inductance and resistance. The plasma resistance and thus the electron temperature can be estimated from the measured value of the time constant. Two types of the VS are observed in our

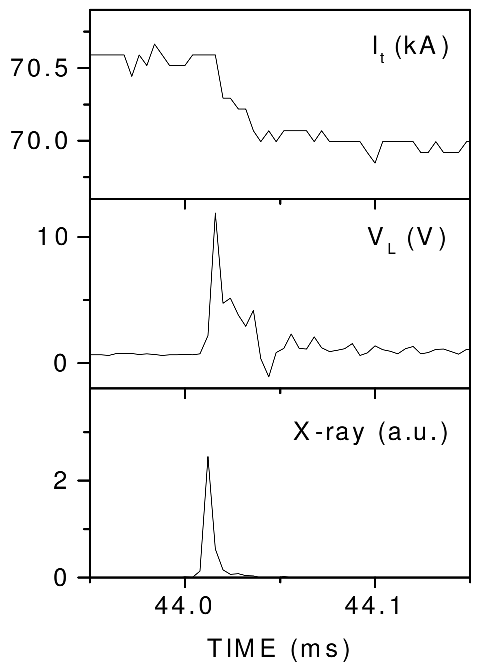

Fig. 3. Spikes in toroidal current and loop voltage caused by runaway losses.

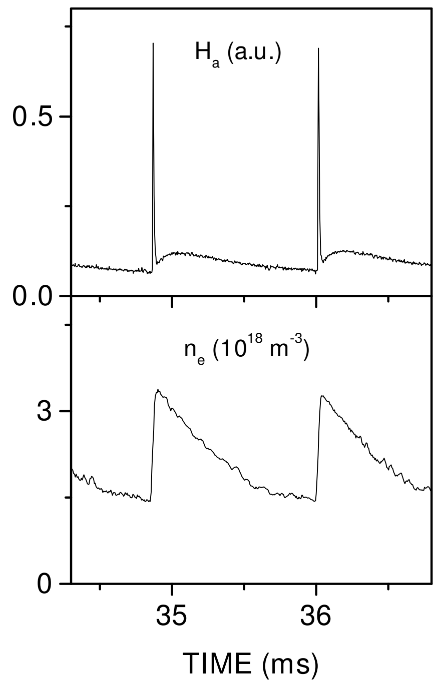

Fig. 4. Expanded spikes in H_α emission and plasma density correlated with relaxation instability.

experiments. The low-amplitude VS, ~ 0.1 V, correlated with the relaxation instability, have rather large decay time of 300-600 μs; this gives T_e = 3-5 eV. However, as discussed in [4], these spikes can be caused by small inward plasma shifts also always correlated with the relaxation instability. In the second type, the spikes are not associated with the relaxation instability. They have rather high amplitude, so that spikes in the toroidal current are measurable showing agreement with the VS as one can see in Fig. 3. The short burst in hard X-ray emission always occurs in this case indicating to the runaway losses to the limiter. The decay times of these spikes are less 20 μs, i.e. corresponding electron temperatures are around 1 eV; T_e decreases with the neutral density increase. As one can see in Fig. 3, the method accuracy is limited at low decay time by oscillation in the loop voltage caused by parasitic capacitances of ohmic heating winding.

Another possibility to estimate the plasma electron temperature is an analysis of the plasma density and H_α emission. Expanded spikes caused by the relaxation instability are shown in Fig. 4. The simplified equations for the plasma density and H_α intensity have the form

$$\frac{dn_e}{dt} = K_p n_e N + K_b n_b N - K_r n_e^2 \tag{1}$$

$$I = A\left(S_p n_e N + S_b n_b N + S_r n_e^2\right) \tag{2}$$

where we take into account effects of ionization and excitation by plasma and runaway electrons and recombination, A is the instrumentation factor. At spikes, ionization by plasma electrons dominates. From measured value of density rate, Eq. (1) gives $K_p \approx (0.5\text{-}1.0)\times 10^{-14}$ m^{3}s^{-1}, i.e., $T_e \approx$ 10-15 eV in spike. Supposing that recombination dominates at the relaxation phase, we estimate the value of recombination rate constant from the measured rate of density decay as $K_r \sim 10^{-16}$ m^{3}s^{-1}, i.e. T_e = 0.4 - 0.2 eV at plasma densities 10^{18}-10^{19} m^{-3}. Excitation by plasma electrons dominates at spikes. This allows determination of the instrumentation factor in Eq. (2). Then H_α intensity measured at the relaxation phase can be used for estimations of the electron temperature. This approach gives also electron temperatures less 1 eV. Note that conclusion about dominating role of the recombination in H_α generation at the relaxation phase follows already from the experimental fact that emission intensity monotonically increases with the increase of neutral density in spite of the decrease of the electron temperature. In the case of excitation by plasma electrons, one has expect the opposite dependence due to the strong exponential decay of $S_p(T_e)$ at $T_e < 10$ eV.

4. Conclusion. The bulk plasma in the RAD has electron temperature around 1 eV at the relaxation phase of the instability. This conclusion agrees with the energy balance calculations [5]. At low temperatures, the gas ionization and plasma heating are mainly provided by collisions of runaway electrons with neutrals and plasma electrons. Plasma particle losses are mainly due to the recombination, and thermal losses due to the electron-ion and ion-neutral collisions. The effects of particle and heat diffusion are relatively weak. In this situation, one has to expect a local connection between runaway density and plasma parameters. This explains measured profiles of the plasma density and H_α intensity and effect of plasma detachment from the limiter.

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