*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-2.162 (2006)*

Observation of disruption mitigation experiments by an ultra fast framing camera

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Disruptions constitute a major problem for a tokamak operation on a reactor scale. The loss of the stored energy on a short time scale being typical for disruptions can cause a severe damage to the machine in several ways [1]: (i) excessive thermal loads on the plasma facing components; (ii) electromagnetic loads caused by induced currents; (iii) electromagnetic loads caused by halo currents (plasma currents having a part of their path in the wall); (iv) localized energy deposition by runaway electrons (electrons accelerated to MeV energies). For these reasons elaborated techniques of softening of the disruption negative consequences are under development. The simplest and the most promising technique of disruption mitigation is a massive gas injection. The present work is focused on the initial stage dynamics of disruption mitigation experiments. For this analysis an ultra fast framing CCD camera is used [3]. The main parameters of the camera are: framing rates up to 500 kHz, sensor dimensions 64×64 pixels, dynamic range of 13 bits, memory for 300 frames. The view of the camera covers the whole poloidal cross section at the valve position and provides a spatial resolution of 1.5 cm/pix.

The experiments are conducted at the tokamak TEXTOR with major and minor radii $R = 1.75$ m and $a = 0.46$ m. Gas is puffed into a stable plasma, the parameters of the target plasma are: toroidal field $B_t = 2.25$ T, plasma current $I_p = 350$ kA, central line averaged electron density $< n_e >= 2 \cdot 10^{19}$ m $^{-3}$, stored energy before the disruption: $E_{th} \sim 30$ kJ, $E_{mag} \sim 300$ kJ. The injections are performed with a fast valve activated by eddy currents [2].This valve combines fast reaction time, high flow rate and the ability to be operated in a high magnetic field environment. The mitigation valve is situated at a distance of 1.3 m from plasma edge. The internal volume of the valve is about 25 ml, the operating pressure is up to 5 bar. Following gases and mixtures are used in the experiment: D_2, He, Ar, D_2 + 10% Ar.

In general in the disruption mitigation experiments four successive stages can be distinguished, fig. 1: 1 - the gas flow in the vacuum duct; 2 - the spreading of the gas around the plasma and cooling of the edge plasma, this period being sometimes called "propagation of cold front"; 3 - thermal quench (TQ); 4 - current quench (CQ).In the present paper the attention is drawn to the stage 2. During this stage the injected gas cools the plasma and leads to an instability initiating TQ. The stage starts at the moment when the gas jet is detected at the edge

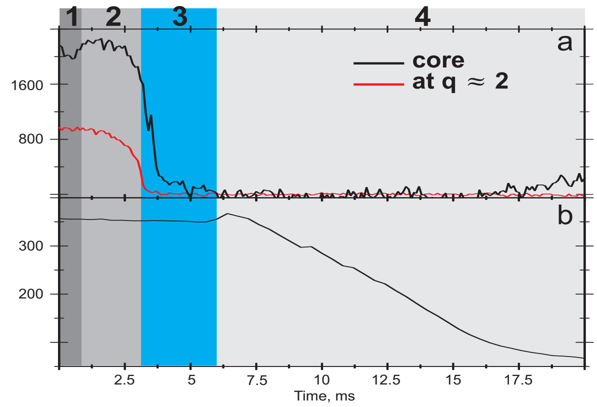

Figure 1: *Time traces of the main plasma parameters for the TEXTOR shot* 99685*, an He injection.* ***a*** *- ECE measurements of the electron temperature at the* $q \approx 2$ *(red curve) and in the center (black curve), eV;* ***b*** *- plasma current, kA. The time is given in ms relative to mitigation valve trigger signal.*

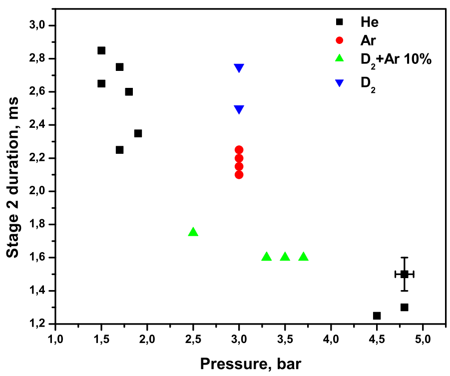

Figure 2: *The duration of stage 2 for different gasses and initial pressures.*

of the plasma and lasts until the time moment of the maximum of the central temperature decay rate ($\partial T_e(r = 0)/\partial t$), i. e. until the thermal quench. Figure 2 summarizes the dependence of the stage 2 duration on the type of the injected gas and on the initial pressure of the gas. There are two main mechanisms responsible for the change of the shown duration: the first one is the variation of the cooling capability and the second one is the variation of the gas penetration and deposition. Both of these mechanisms can be traced in the presented results. In the experiments with the injection of He at different pressures the cooling capability is varied by the total amount of the gas, while the deposition is defined by the density of the jet. In the experiments at the same initial pressure but with different gases the first mechanism is involved via the atomic physics of the element and the second via both the atomic physics and sound velocity.

The neutral density about 10^{23} m^{-3} on entering the plasma does not allow the jet to penetrate

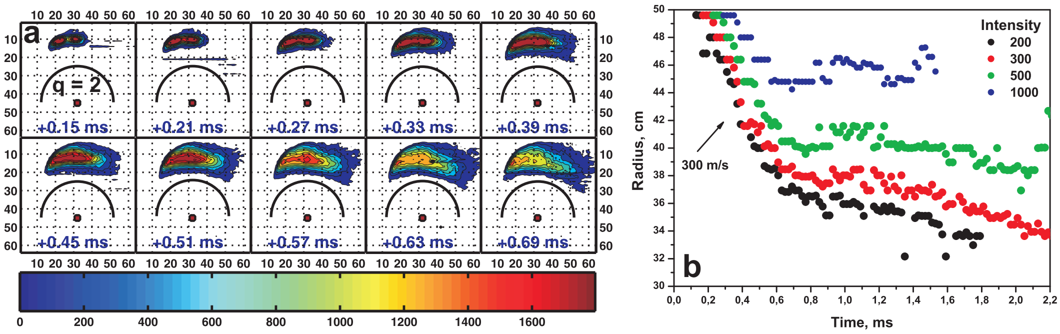

Figure 3: ***a*** *- contour plots of initial gas penetration into plasma. TEXTOR shot 99685, He 1.5 bar injection, He I filter.Axes are in pixels, 1.5 cm/pix. Point at the position* $x = 32, y = 45$ *is the center of the discharge. The semicircle represents the position of the* $q = 2$ *surface. Not all frames are shown. Time is given relative to the detection of the jet at the edge of the plasma.* ***b*** *- the shortest distance from different intensity contours to the plasma center as a function of time.*

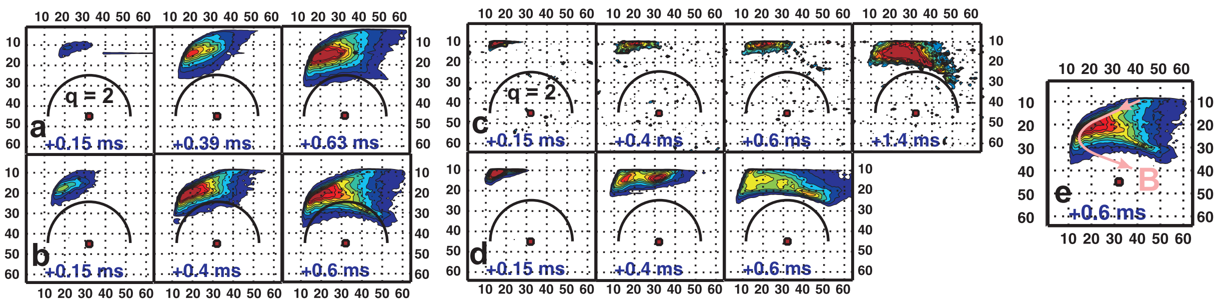

Figure 4: *Contour plots of initial gas penetration into plasma.* ***a*** *- TEXTOR shot 99688, He 1.5 bar injection, He II filter.* ***b*** *- TEXTOR shot 100168, He 4.5 bar injection, He II filter.* ***c*** *- TEXTOR shot 100934, Ar 3 bar injection, Ar II filter. The noise is produced by RE induced neutrons or X-rays.* ***d*** *- TEXTOR shot 100936,* D_2 *+ 10 % Ar 3 bar injection, Ar II filter. For further explanations see fig. 3.* ***e*** *- Magnetic geometry illustrated on the last frame of sequence* ***b*** *. The toroidal magnetic field goes through the paper. The major axis of the tokamak is to the right.*

to the center of the discharge at sound velocity. The neutral atoms are ionized and the ions are bound to the magnetic lines. The full ionization is probably not required for the jet stopping because of the high collisionality in the cold dense cloud. A sequence of frames of neutral helium emission ($\lambda = 706.5$ nm) recorded with 20μs time resolution in the 1.5 bar He injection experiment is shown in the figure 3a. The gas moves from the top of the plasma column towards the center of the discharge and at the same time spreads poloidally. At the beginning the emission front moves towards the center with a velocity ≈ 300 m/s, but at $t \approx 0.6$ ms and $r \approx 37$ cm the velocity is changed indicating a change in the propagation mechanism, the process is illustrated in the figure 3b where the dependencies of the radial position of the certain intensity levels on time are shown. In the first 600μs the gas is expected to move at sound velocity but after that the gas progresses with the cooling front. To convert the emission front velocity into the gas flow velocity the knowledge of the parameters of the cloud is required. The frame sequence of ionized He emission ($\lambda = 468$ nm) under the same experimental conditions is shown in the figure 4a. The maximum of the He II emission lies approximately at the same radial position, however the form of the cloud is different due to the free spreading of the ions along magnetic field lines. The projection of the magnetic field line onto the used view is illustrated in figure 4e. This geometry creates a misleading impression of longer radial extension of the intensity contours of ionized elements. An increase of the initial He gas pressure from 1.5 to 4.5 bar and hence a 3 times higher jet density leads to a deeper penetration of the gas, compare figures 4a and 4b. The difference in the positions of maximum light emission between low and high pressure injections is about 8 cm, in the last case the jet penetrating almost to the $q = 2$ surface. An energy sink in the vicinity of $q = 2$ is known to quickly destabilize the plasma [4], and this is in fact observed in the experiment: the injection of 4.5 bar He leads to the disruption about 2 times faster than injection of 1.5 bar He, fig.2. It should be also noted that at the same time the total amount of injected particles is increased. Similarly the faster and deeper deposition of the cooling impurity is observed in the case of D_2 + 10% Ar mixture injection as compared to the injection of the pure Ar, fig. 4c and 4d correspondingly, where a comparison of Ar II emission ($\lambda = 611.5$ nm) is shown. This provokes the thermal quench earlier by 0.5 ms. However to some extent the high cooling capability of Ar compensates its low sound velocity and the shallow initial deposition as it is illustrated in the figure 4c: the Ar II emission front moves radially with an average velocity of about 130 m/s by the progressive plasma cooling.

To summarize, the main presented results are: (i) the time required to trigger a disruption is a strong function of the gas type and the working gas pressure, the dependence is defined by penetration depth of the gas and by its cooling capability; (ii) the strong correlation between shorter stage 2 duration and deeper gas deposition is demonstrated however the effect of the higher amount of injected gas could not be fully excluded.

References

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