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Runaway electrons after massive gas injections in TEXTOR: importance of the gas mixing and of the resonant magnetic perturbations.

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Runaway electrons (RE) have to be avoided during an ITER disruption [1]. Two methods of RE suppression are being discussed: (i) massive gas injection (MGI) [1] and (ii) suppression by resonant magnetic perturbations (RMP) [2, 3].

The concept of MGI suppression is to raise the density n_e^* of bound and free electrons above a critical level of $2 \cdot 10^{21} \cdot E$ m^{-3}, determined by the induced field E [V·m^{-1}]. A huge number of atoms has to be delivered into the plasma. We show that depositing atoms into the core can be problematic: the inward mixing turns out to be ineffective for large-Z species.

In the literature experimental data on the RMP suppression are scanty. Previously influence of magnetic perturbations on REs was investigated in TEXTOR during flat top phase of discharge [2]. Only in JT-60U suppression during disruptions was analyzed [3]. Here we present new results on the suppression by RMP in two base modes $m/n = 3/1$ and $6/2$.

Suppression by RMP is achieved due to an increase of RE loss rate in an ergodized magnetic field. It is almost impossible to “turn off” the primary generation mechanism, but the avalanche mechanism being the most critical for ITER can be choked off.

Suppression by massive gas injection

MGI suppression is studied by terminating ohmic TEXTOR discharges with different amounts of He, Ar10% + $D_2$90%, Ne, Ar, Kr, Xe. Gas is injected by a fast valve driven by eddy currents [4]. The number of injected atoms is varied in the range $(2 \div 20) \cdot 10^{21}$, which corresponds to $20 \div 200$ times the particle content of the discharge. Main parameters of discharges are: the major and minor radii are 1.75 m and 0.46 m, toroidal field $B_t = 2.25 \div 2.4$T, plasma current $I_p = 300 \div 350$kA, electron density $< n_e >= 2 \cdot 10^{19}$m $^{-3}$ and thermal energy content $E_{th} \approx 40$kJ.

Increasing the central electron density by MGI is complicated by a phenomenology of this shutdown. In the previous TEXTOR experiments, gas injection was proved to cause a disruption, that seemed to be triggered by cooling of the $q = 2$ flux surface [5]. To confirm the latter a variation of the $q = 2$ radius was performed. Figure 1a presents the time required to destabilize the plasma for different radius of the $q = 2$ surface (the critical radius). The deeper the critical surface lies, the more time it takes to initiate disruption. For two of the discharges given in figure 1a, figure 1b compares emission of singly ionized argon just before the disruption. In the left image the critical radius is by 7 cm larger than in the right one. In both cases, before the thermal quench the injected gas penetrates only up to the position of the $q = 2$ surface. This is also confirmed by measurements of the electron temperature and density with Thomson scattering.

The inward mixing is possible only during the thermal quench. Due to the short timescale of this phase ($\tau_{TQ} < 1$ ms), the mixing is imperfect, which even leads to the generation of REs. It is to be noted that otherwise the RE generation is not typical for natural TEXTOR disruptions.

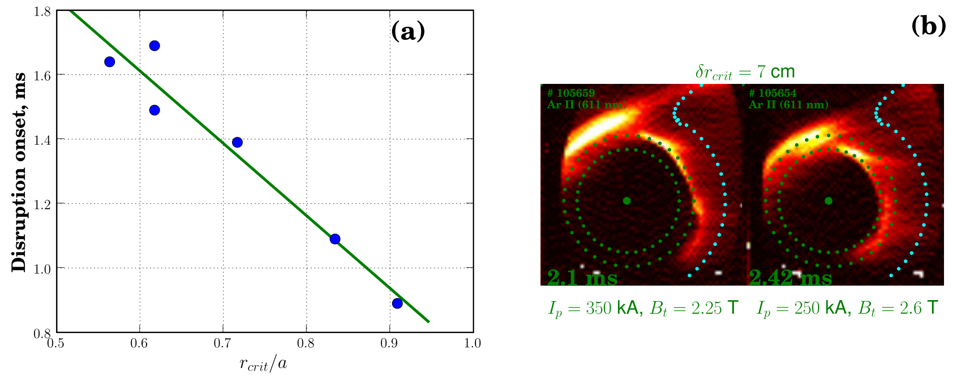

Figure 1: Influence of $q = 2$ position on the disruption onset. Shown discharges were terminated by mixture Ar10%+ $D_2$90%. **a** - dependence of the time required to initiate disruption, i.e. the time from the gas arrival to the plasma edge until the disruption, on the position of $q = 2$. . **b** - emission of ArII before disruption for two cases with different radii of the $q = 2$ flux surface.

REs become apparent as a long lasting current plateau, neutron fluxes and through their synchrotron emission: two of these signals are given in figure 2. Ar, Kr and Xe injections become runaway free only at the highest number of particles, while He, Ar mixture and Ne injections are runaway free in the whole investigated range.

The measurements of runaway current can be conveniently used to estimate the density of injected atoms by applying a simplistic model of current quench:

$$\begin{aligned}
\frac{dn_{RE}}{dt} &= f_{prim} + (\gamma_{RE} - \gamma_{loss})n_{RE} \\
\frac{d}{dt}\left(LI_\Omega + L_{RE}I_{RE} + L_v I_v\right) &= -2\pi R_0 E_{ind} \\
\frac{d}{dt}\left(I_v + I_\Omega + I_{RE}\right) &= -\frac{I_v}{\tau_v} \\
\eta\frac{I^2}{S^2} &= n_e n_{imp} L_{imp}
\end{aligned} \tag{1}$$

The density of injected impurities n_{imp} is essentially a free parameter and is found by fitting the measured current. Discharges without REs (He, mixture, Ne) can be modelled in the same way but with less information available. Ingredients of the model and further details of the procedure

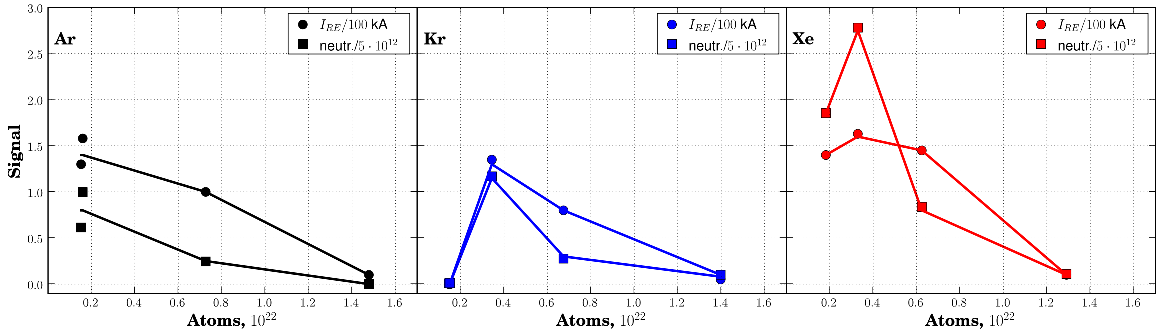

Figure 2: Generation of runaway electrons after massive gas injection. Shown are the runaway plateau current (I_{RE}) and the total number of neutron/γ events.

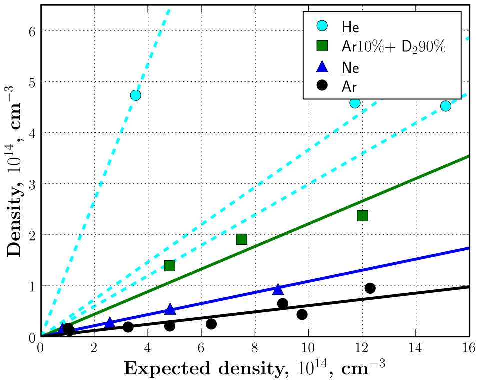

Figure 3: Mixing efficiency for different gases.

are discussed in [6].

Results of modelling are summarized in figure 3 in terms of the mixing efficiency, which is the ratio of impurity density found from the model to the expected density:

$$M.E. = \frac{n_{imp}}{f \cdot N/V} \tag{2}$$

Where N is the number of injected atoms, f is the fraction of atoms injected before the thermal quench and V is the volume. The efficiency is found to be about 20% for the mixture of argon with deuterium, about 10% for Ne and about 5% for Ar. The helium case ($> 40\%$) should be considered only as a preliminary one due to a large influence of intrinsic impurities. The mixing efficiency decreases with Z, but in spite of having a better mixing, light gases possess less electrons, so that the total number of delivered electrons n_e^* remains almost constant. To complete the Z-scaling the analysis of the Kr and Xe experiments should be finalized.

In the Ne experiments, the number of delivered atoms does not differ strongly from the Ar case. However, due to the lower radiative cooling rate the electron temperature is higher for Ne. Hence the induced electric field E is lower and REs are not observed. It is worth noting that in all MGI experiments REs are suppressed only due to a reduction of the primary mechanism. Whether or not light-Z gases are better for the full RE suppression in ITER a more elaborated model taking into account atomic physics of cold plasmas should show.

Poor mixing of high-Z atoms degrades the advantage of having a larger number of electrons. The low mixing efficiency can increase the number of atoms required for RE suppression in ITER to a level being not tolerable by other systems. For this reason, alternative ways of RE suppression like RMP are to be investigated.

Suppression by RMP

In these experiments REs are generated by injection of about $4 \cdot 10^{21}$ atoms of Ar and suppression is achieved by application of RMP. Resonant magnetic perturbations are excited by the dynamic ergodic divertor (DED) located at the high field side of the machine. In this work, an influence of RMP in two base modes m/n = 3/1 and 6/2 is presented, fig. 4. In both modes the runaway population can be significantly reduced (fig. 4a): the amplitude of runaway current drops as the RMP amplitude, which is proportional to the current in the DED coils divided by the toroidal mode number, is increased. In this figure different radial penetration of modes is not taken into account.

Application of RMP has a dramatic effect on the high energy part of the RE population. Above a threshold of about 1.5 kA/n the synchrotron emission disappears, fig. 4b. The synchrotron

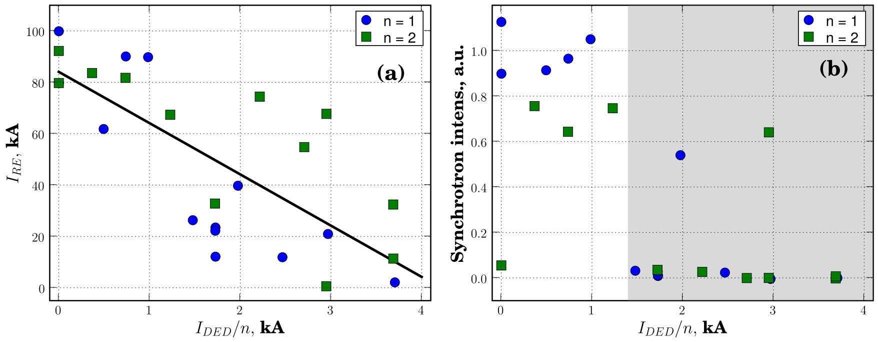

Figure 4: Suppression of runaway electrons by resonant magnetic perturbations. **a** - dependence of the runaway current on the RMP amplitude. **b** - dependence of the synchrotron emission ($\lambda = 3 \div 5$ μm) on the RMP amplitude.

emission is recorded by an IR camera in the spectral range $3 \div 5$ μm and is representative of REs with energy above 25 MeV. That is, with RMP above the threshold a residence time of a runaway electron in the plasma becomes shorter than the time for an electron to reach such high energies. From this we tentatively conclude that the RE avalanche is stopped: the avalanche multiplication being critical for ITER is known to be important only if REs are confined so long that they can gain energy about 20 MeV [7].

Conclusions

The suppression of runaway electrons by electron density increase and by resonant magnetic perturbations were demonstrated in TEXTOR experiments.

With massive gas injection it was possible to suppress the primary mechanism. Because of the disruptive nature of the shutdown, it is not easy to provide a rapid growth of the electron density in the plasma center. The disruption is initiated by cooling of the $q = 2$ flux surface. As a consequence a poor mixing of atoms is typical. To improve the presented analysis further measurements of the runaway and plasma current profiles are required.

Resonant magnetic perturbations is a good candidate for the suppression of runaway electrons. Already at the ergodizing current above 1.5 kA/n, the high energy runaways disappear. This can be interpreted as an evidence for the suppression of the runaway avalanche. However, the present data have a large scatter likely to be related to the position of the beam. This aspect has to be clarified to allow predictions for ITER.

References

[1] T. C. Hender et al., Nuclear Fusion 47 (2007) S128 - S202

[2] K.H. Finken et al., Nuclear Fusion, vol. 46 (2006), S139-S144; K.H. Finken et al., Nuclear Fusion, vol. 47 (2007), 91-102

[3] R. Yoshino, S. Tokuda, Nuclear Fusion, vol. 40 (2000), 1293-1309

[4] Bozhenkov S.A. et al., Rev. of Sci. Instrum., vol. 78 (2007), p. 033503

[5] Bozhenkov S A et al., 34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA 31F, P-5.123 (2007)

[6] Bozhenkov S.A. et al., submitted to Plasma Physics and Controlled Fusion

[7] Jayakumar R. et al., Physics Letters A, vol. 172 (1993), pp. 447 - 451