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Disruptions – a proposal for their mitigation by runaway suppression

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Abstract

The avoidance of disruptions is essential for the next generation tokamaks. The dangerous consequences of disruptions are excessive heat loads, high forces, creation of high-energy runaway electrons, and a bad conditioning for the start of the following discharge. In order to mitigate these effects, a fast valve has been developed on TEXTOR with a response time to full opening of 1 ms after a trigger pulse. The fast injection of helium by such a valve suppresses runaway electron production and even removes them if present. The reaction time of the valve is fast enough to apply it even after the start of a disruption. The fast gas injection has been applied to a nearly stationary runaway discharge and it was successfully shown that the energetic electrons are quickly expelled.

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1. Introduction

Disruptions are considered as dangerous events for tokamak devices. The threat for the machine integrity after a disruption increases with the size of the machine [1–6]. For the Next Step Device, ITER, the potential damage is so large that the number of disruptions has to be kept to an absolute minimum. Critical issues are the induced currents (halo currents) in the structural materials and the resulting forces, the excessive heating of exposed surfaces by the instantaneous power release, the initiation of high-energy runaway electrons in the decay phase of the plasma current where the loop voltage is high, and, finally, the modification of the wall by impurity redistribution and an excessive loading of the wall by the discharge gas such that the start of the following discharge is disturbed.

In previous papers [7–9] the power release and heat deposition during disruptions have been analysed. If the limit of stable plasma operation is reached slowly, disruptions start with a pre-disruptive phase. In this phase internal modes start growing and initiate a deterioration of the confinement in the plasma core. The plasma energy is transported from the core to the edge of the plasma where an intermediate temperature rise is observed just prior to the observation of the power quench. The following actual energy quench can consist of a single heat pulse or of a series of heat pulses. The time duration of the individual power deposition pulses is very short: only a few ten microseconds. This duration is given by the MHD time scale, i.e. some 10–100 Alfvén transit times for the growth of the underlying instability. Even though the instantaneous power density is extremely high, the spatial pattern of the disruptive power deposition resembles in many aspects the 'normal convective' power deposition on the limiter surface.

These observations have shown that the power flux to the wall during a disruption cannot be described by a diffusive process. For a purely diffusive process and the high heat flux observed for the disruption, the power

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e-folding length should be very large which is inconsistent with the experimental data. On the other hand, the ergodic [10] – diffusive model is sometimes assumed for explaining the internal plasma transport in the pre-disruptive and disruptive phases. This picture bases also on the presence of magnetic islands prior and during disruptions [11–16]. Other models base on the development of ballooning modes [17]. In this contribution we describe at first the possible effect on the mitigation of a disruption by fast gas injection. This includes a fast valve for injecting gases at the onset of a disruption. In the second part, we will sketch a new model for explaining the disruptive quench.

2. The mitigation

In order to mitigate effects of disruptions we propose the use of fast gas injection. However, due to the very fast development of the power quench state the mitigation during the first energy quench phase is rather limited: Even with the fastest valves, the injection time is large compared to the MHD time scale. Therefore, by puffing large amounts of gas, the disruption will always reach the density limit or radiation limit; at that instance the thermal energy stored in the plasma will be released in the energy quench. Impurity pellets may radiate more efficiently because this source emits from the hot plasma core. However, our experience with killer pellets on runaway discharges is that energetic electrons may survive the pellet injection on flux surfaces which are not destroyed [18]. Thus killer pellets may be unreliable with respect to runaway removal. Nevertheless, even for this quickly developing phase, the gas injection can

(1) dilute the plasma and distribute its energy over more particles until the density or radiation limit is reached; the energy of the impinging particles thus becomes lower even though the total energy remains unchanged,
(2) establish a 'cushion' of gas or cold plasma at sensitive areas e.g. the top of the vessel in case of vertical displacements. However, in order to achieve a gas shielding, the gas has to be injected at the right place and at a sufficiently large rate, i.e. the gas flow rate has to be of the order of the rate on which the gas is ionised and transported away convectively. The gas density is increased by convective flows in the SOL towards areas of the wall which are in contact with the plasma forming there a very dense recycling cloud. If the cloud is dense enough, charge exchange processes may distribute the power to a larger area,
(3) establish a high density state in the divertor leading to high recycling cloud also there.

The mitigation effect due to gas puffing is more important during the current decay phase. The dangerous effects in this phase are forces due to halo currents and the production of runaway electrons. These two aims of the mitigation concept may be conflicting: For the minimisation of the forces, one wants to shorten the current decay phase as much as possible. This shortening of the decay phase, however, results in an increase of the loop voltage; by the enhanced loop voltage the critical electric field for the onset of runaway generation may be exceeded. In our opinion the creation of runaways is a higher potential risk to a fusion reactor than the forces, because the force problem can be taken care of by an appropriate design. Runaway electrons on the other hand penetrate easily low Z-materials (graphite) and deposit their energy in a short distance at the transition to a high Z-material (e.g. at the braze of graphite to copper) [19].

Recently it has been shown by Bakhtiari et al. [20] that injection of high Z-gases leaves only a very small margin for the mitigation without runaway production. In addition, all gases with the exception of helium will be deposited into the walls during the disruption; during the start of the next discharges those particles are released again and endanger the successful ramping up of the discharge current. We therefore have concentrated on the use of helium for the mitigation of the disruption.

3. The valve development

In the IPP-Juelich, two fast valves for the mitigation of disruptions have been built, a small prototype and a bigger one. The smaller valve releases the gas from a reservoir of about 10 mm^3 only while the reservoir of the final one can contain between 5 and 250 ml. The filling pressure can be varied between 1 and 30 bar. In contrast to other fast valves, the one of the IPP-Juelich does not contain any ferromagnetic material; therefore the valve can be flanged directly on the vessel and be operated with the full magnetic field. The moving part of the valve is an aluminium stem which is activated by eddy currents induced from a pan-cake coil. Fig. 1(a) and (b) shows the opening characteristics of the valve where the top sub-figure represents the full opening characteristic and the lower part only the initial phase. One can see that the valve starts to open 0.4 ms after a trigger signal and is fully open 1 ms after the trigger signal. After 18 ms the valve is closed again.

4. Interaction of injected helium with runaway electrons

In order to show the fast reaction of the valve on the plasma, the first version of the fast valve has been applied to a runaway discharge on TEXTOR. The runaway electrons are recorded by synchrotron radiation emitted in the infra-red spectral region [21,22]. This

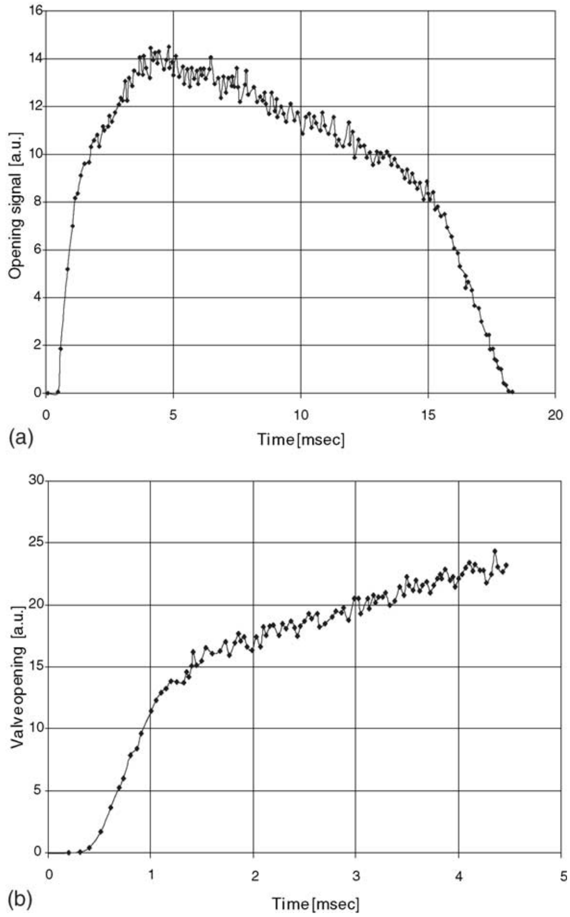

Fig. 1. Opening curve of the valve developed at the IPP-Juelich. In order to obtain the opening curve, a glass fibre has been inserted through the whole which feeds the gas to the reservoir. The glass fibre is illuminated and the light passing the – normally sealing – stem is recorded by a photomultiplier. The top figure shows the whole opening characteristic of the valve and the lower part the only the initial phase. One sees that the stem starts to move 0.5 ms after the trigger signal and is open after 1 ms. Then, after 18 ms it is closed again.

method allows the detection of the runaway electrons inside the plasma while many other methods measure runaways only when they are leaving the plasma. The synchrotron radiation is detected by an IR scanner in the wavelength range of $2\ \mu\mathrm{m} \leqslant \lambda \leqslant 8\ \mu\mathrm{m}$ and the method is sensitive to electrons above energies of 20 MeV. The scanner consists of a detector and two mirrors which create an image in the TV-standard. This means that the image contains both local and temporal information; the image is swept from top to bottom within 20 ms.

The synchrotron radiation is continuum radiation which is proportional to the number of energetic electron N_{run}, to their instantaneous radius of curvature R and to the electron energy W:

$$P_{\mathrm{syn}} \propto N_{\mathrm{run}} \frac{W^4}{R^2}.$$

In a series of stationary, well reproducible runaway discharges the different quantities of the equation has been studied. The energy W has been derived from the spectrum of the radiation, in particular from the exponential slope in the short wavelength part and amounts typically to 25–30 MeV. The radius of curvature has been derived from the pitch angle in forward direction of the emitted radiation which has been measured to about 100 mrad. Using these input data, the absolutely measured IR radiation provides a runaway electron number corresponding to a runaway current of 5–10 kA which is a few percent of the total plasma current.

The only serious uncertainty of the analysis is the assumption about the distribution function of the runaway electrons because the synchrotron radiation is sensitive in particular to the high energy particles. The data given here assume a peaked distribution function at highest energy. Unfortunately we do not have reliable data on the number of runaways at lower energies. If one assumes a flat distribution function of the runaways, the runaway current increases easily by an order of magnitude.

Typical discharge conditions for obtaining reproducible runaway conditions are line averaged electron densities of about $6 \times 10^{18}\ \mathrm{m}^{-3}$. The synchrotron radiation develops about 1 s after the start of the discharge, consistent with the required time for the acceleration of the energetic electrons by the loop voltage. When keeping the electron density constant, the synchrotron radiation increases gradually until the end of the discharge. Fig. 2(a) shows an image of the IR scanner of such a runaway discharge containing the synchrotron radiation as the bright object from the top of the image to the middle. Shortly before the time marked by the top arrow, the fast valve is triggered. One sees that the runaway electrons start to react within half a millisecond and are quickly slowed down; the hard X-ray detectors show, that the runaways are not expelled to the walls keeping their initial energy but they have to loose most of their energy before hitting the wall. The proper disruption due to the massive helium influx occurs about 2 ms after the trigger signal.

Fig. 2(b) gives – from top to bottom – the traces of the loop voltage, of the plasma current, of the line averaged density and of a separate IR detector for this discharge. Unfortunately, the installed IR detector has a time resolution of 3 ms only such that less details than from the IR scanner can be seen. In addition, the IR detector is not oriented towards the limiter surface but

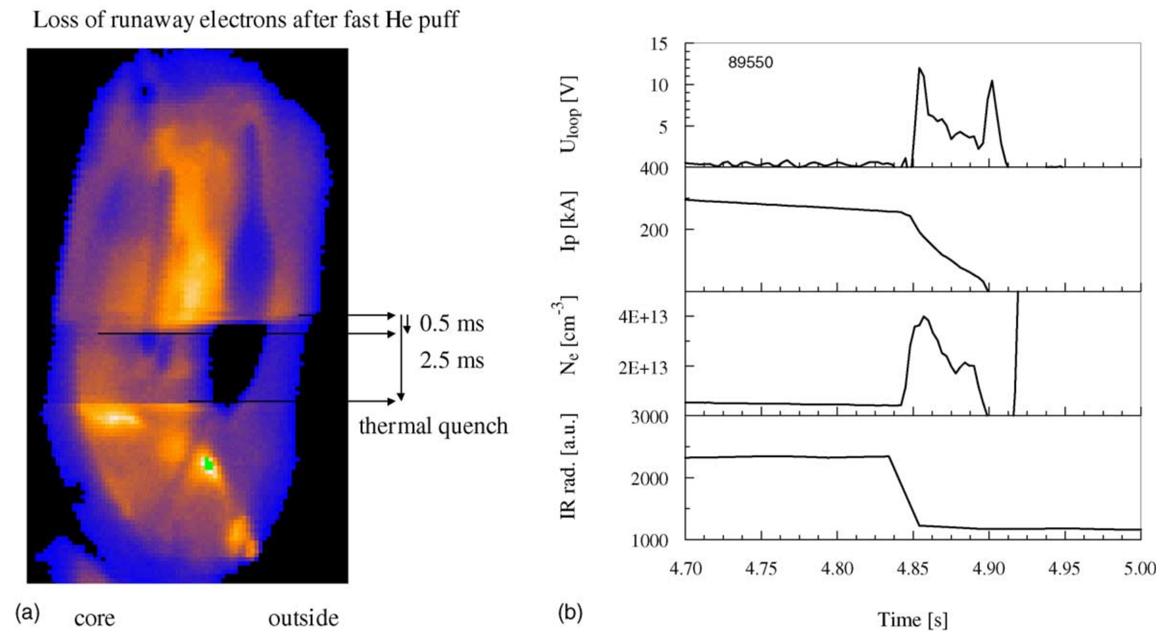

Fig. 2. (a) The figure shows a recording of an IR scanner taken in the line scan mode. The scanner sensitive at a wavelength of $2\ \mu\text{m} \leqslant \lambda \leqslant 8\ \mu\text{m}$ detects both thermal IR radiation and synchrotron radiation. The top part of the image is dominated by the synchrotron radiation. About 0.5 ms after the fast injection of helium, the runaway electron radiation stops and after another 2 ms the energy quench of the disruption shows up as short intense heat pulse. (b) Characteristic signals for the discharge of (a). The traces from top to bottom are: loop voltage, plasma current, line averaged electron density and IR signal. The data are displayed for 0.3 s around the time of the disruption provoked by gas injection. The lower trace has a time resolution of 3 ms only.

horizontally towards the liner such that the power flux from the energy quench is not detected.

Fig. 2(b) shows the sudden increase of the electron density after the valve activation. Most likely, the density is higher than indicated because the interferometer 'lost fringes' during the fast puffing phase. At the density maximum, the loop voltage first shows the negative voltage spike and then the characteristic increase, characteristic for the energy quench phase and the start of the current decay phase. The IR signal decays at the very beginning of the gas injection which is consistent with the observations in Fig. 2(a). Even though the IR scanner has an internal quartz clock, the times-values of the data logger signal of Fig. 2(b) and of the scanner may be slightly shifted with respect to each other. Therefore an exact time correlation within milliseconds of Fig. 2(a) and (b) cannot be given.

The plasma current decays in about 50 ms as the second trace of Fig. 2(b) shows. The decay is at first rapid, then slows down for a transient period and increases again at the end. The flatter part of the current decay is often attributed to a production of runaway electrons. In principle, this may also be true on TEXTOR. However, the energy of the runaways remains too low that we could detect them by synchrotron radiation. In general, during the current decay phase we do not find synchrotron radiation (perhaps with the exception of a very few cases, less than 5), probably because the TEXTOR device is too small and cannot provide sufficient stored energy for the acceleration.

One feature in Fig. 2(a) may be remarkable: It may be expected that the collision of the runaway electrons with the injected helium background (nuclei, bound or free electrons) would increase the perpendicular momentum of the runaway electrons. If this would happen, one expects an increase pitch angle of the electrons and connected with this a decrease of the instantaneous radius of curvature of the runaways. This again should lead to a transiently enhanced emission of the synchrotron radiation before it decays; this is not observed. Therefore it must be concluded that either the decay of the energetic runaways is too fast the transient increase due to the change of the curvature or that the fast electron loose so much energy by the collision that they do no longer contribute to the synchrotron radiation.

Even though the runaway electrons in this example are not created in a disruption – TEXTOR is to small to produce multi-MeV energy electrons during a disruption – it is expected that the fast injection of helium by the valve prevents the creation of runaway electrons also. Initial tests on JET – however with helium injection using a 'normal' valve – support this supposition.

5. Estimates

From the data obtained from the gas injection experiments one can obtain some consistency checks whether the runaway loss is only related to Coulomb scattering. Here we are interested in order of magnitude estimations because a detailed analysis requires the analysis of collisions with nuclei. We assume that the helium density amounts to $n_{\mathrm{HE}} = 1 \times 10^{19}\ \mathrm{m}^{-3}$, and the collision time to $t_{\mathrm{c}} = 1$ ms. The collision length then becomes $L_{\mathrm{c}} = ct_{\mathrm{c}} = 3 \times 10^{5}$ m. and correspondingly the collision cross section

$$\sigma = \frac{1}{nl_{\mathrm{c}}} = 3 \times 10^{-25} \quad \mathrm{m}^2.$$

The radius r_{c} of the collision cross section results therefore in

$$r_{\mathrm{c}} = \sqrt{\frac{1}{\pi\sigma}} \approx 3 \times 10^{-13} \quad \mathrm{m}.$$

This collision radius is very short for plasma physics standards, it is even short as compared to the Bohr radius and nearly reaches nuclear distances. Therefore it does not matter whether the target electrons of the helium are bound or free.

In order to relate the observed loss rate with the theoretically expected value we consider t first the slowing down time for runaway electrons neglecting the creation effects. This value amounts according to formula (1) in [23] to

$$t_{\mathrm{c}} = 18.5 \Big/ \frac{n_{\mathrm{e}}}{10^{20}},$$

where the slowing down time t_{c} is given is seconds and n_{e} in m^{-3}. For our experimental conditions, this value is more than an order of magnitude larger than the observed one. However, the formula contains only the slowing down time for collisions of the runaways with electrons. Since the impact parameter is much lower than the atomic radius of the helium, the enlarged value Z_{eff} of the helium nucleus may reduce the above given value of t_{c} by a factor of two, leaving still a factor which is still to large by an order of magnitude.

If we take into account also the generation processes of the runaways, e.g. the secondary generation of runaways due to the collisions of primary runaways with thermal background electrons, we obtain still larger discrepancies to the experimental data. For the given loop voltage of 5 V during the current decay phase of the disruption (higher even in the initial phase where the runaway decay is observed), the electric field normalised to the critical field of formula (1) again in [23] amounts to about $\widehat{E} = 5$ resulting in positive gain factor C (formula (2) and Fig. 4) for the runaway creation of about $C \approx 3$: The runaways should not decay but grow. Even though this finding is not consistent with the observations and not understood, the result is favourable for the elimination of runaway electrons from a disrupting discharge because the required pressure for the mitigation of runaways can be reduced by about an order of magnitude. A topic of future research will be the measurement of the runaway loss as a function of the species of injected gases.

6. Conclusions

A valve has been developed which injects which opens about half a millisecond after a trigger signal and allows to vary the amount of injected gas from 5 mbarl to 7.5 barl. This value should be sufficient to mitigate several negative effects of disruptions even if they are detected only by the energy quench. In order to study the loss of the high energetic electrons, such a valve has been applied to runaway discharges. As injection species, helium has been applied. It has been found that runaway electrons are expelled out of the high energy part of the distribution function within 0.5 ms. Since the synchrotron radiation in the given IR range is sensitive only to electrons above 20 MeV it remains unclear whether the runaways are slowed down or expelled. The loss process in not linked with increased hard X-ray or neutron radiation which occurs if the runaways hit the wall without braking. Estimates show that the experimentally observed slowing down time is shorter than the one due to classical Coulomb collisions. It will be a task of future research whether the enhanced loss of runaways can be utilised for the mitigation of disruptions.

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