Mitigation of disruptions by fast helium gas puffs

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Abstract. In order to mitigate the effect of disruptions in tokamaks, it is proposed to inject quickly a relatively large amount of helium; first experiments on this topic have been performed on TEXTOR. For this purpose, a fast valve has been developed which releases 10 mbar L of helium gas within 1 ms; the valve is located at a vessel flange such that a fast response is guaranteed even if it is triggered at the onset of the disruption. The amount of gas is sufficient to exceed the density limit even with low density discharges. The intention of the proposal is to shorten the plasma current decay phase, to reduce halo currents, to suppress runaway electrons and to provide good conditions for the start of the following discharge. In particular, for achieving the last goal, helium is the optimum choice of all the elements. The experiments performed on TEXTOR have proven various of these mitigation aspects: the current decay time is shortened, runaway electrons are expelled by the gas puff and the conditions for the start of the next discharge have neither deteriorated with respect to gas release from wall components nor with respect to excessive impurity production.

1. Introduction

The possible occurrence of disruptions is a serious threat to tokamak based fusion reactors. Only a few hundred disruptions at full plasma current are tolerable for ITER; otherwise the integrity of the device will be endangered. The threat stems from the large amount of free plasma energy carried by the plasma current. A review about disruptions, their causes, their effects and schemes for the mitigation of these effects is the subject of a special issue of *Nucl. Fusion* entitled ITER Physics Basis [1].

Disruptions can be divided into two classes: the first class occurs when a boundary of stable plasma operation is passed and the second class is due to control circuit failures. With regard to the contents, these two classes are finally identical because a failure may lead to a loss of plasma position such that finally the last closed flux surface possesses a safety factor $q < 2$, which is normally an unstable condition. Nevertheless, a distinction between the two classes is meaningful because in the first class the disruptions have time to 'develop' while in the second class no time is left for a warning prior to a disruption.

Heuristically found approaches to stable operation boundaries and different kinds of modes are typical warning signals for naturally developing disruptions. Systems based on neural networks [2, 3], have been trained to find stable and unstable operation conditions and are used to warn of coming disruptions. An alternative method is the detection of dangerous modes: neoclassical tearing modes [4, 5] typically precede β limit disruptions; mixtures of modes [6], in particular the $m/n = 3/2$ and 2/1 modes are observed before most other disruptions. If the modes lock or exceed a certain level, the disruption can no longer be avoided. The critical level may be of such an order that a major part of the plasma is ergodized by the underlying perturbation fields. A vessel wall closely located to the plasma may delay the onset of disruptions; this process is described by resistive wall mode theory. The warning time prior to the disruption can amount to several hundred milliseconds. Proposals have been put forward to start countermeasures during this time which avoid disruptions or destroy the plasma intentionally, for example, by killer pellets [7], liquid jets [8], gas puffs, external helical fields [9] and external negative loop voltages.

For the healing of plasma modes, experiments with additional heating [10, 11] (ECH for tearing modes [4], NBI and ICRH otherwise) have been performed. This heating is of particular interest for plasma states which are close to a radiative collapse, for example near the density limit or at increased impurity levels. Heating methods which transfer a toroidal force to the plasma, such as tangential NBI, have the additional advantage that dangerous mode locking is avoided. The mode locking due to error fields becomes an increasingly serious problem with the increase in size of fusion devices [12, 13]. Only very small error fields are tolerable for a reactor without additional means.

Vertical displacement instabilities of highly elongated plasmas (vertical displacement events (VDEs)) belong to the class of sudden events. These disruptions naturally do not leave enough time to prepare specific actions before the onset of a disruption. Since these disruptions often occur at full plasma current and under the best confinement conditions, they are particularly dangerous and it is highly desirable to find ways to mitigate the effects of these.

After a discussion of the character of the disruptions, their detrimental effects and the techniques used and proposed to mitigate these negative effects, ideas about, and experimental results obtained by, fast injection of helium gas are discussed. Gas injection has a positive influence on the current decay phase, it suppresses runaway electrons and is very favourable for the next discharge.

2. Characteristic features during disruptions

The development of a disruption [14–16] is most completely seen in disruptions preceded by modes [17]: the development of a mode is a manifestation of the internal MHD instability of the confined plasma. The mode activity ends in one crash (a major disruption) or a series of crashes (minor disruptions followed by the final disruption). During this crash or series of crashes, one observes nearly instantaneously a loss of plasma energy, a negative loop voltage spike, power pulses to the plasma facing components and a high recycling and release of hydrogen (deuterium) and impurities from the wall [18]. The negative voltage spike is attributed to a flattening of the plasma current profile resulting in a reduction of the internal inductance. At the same instant, the plasma current starts to decay with a decay time of 20–50 ms on TEXTOR. During the plasma current decay phase, the energy stored in the magnetic field is dissipated when the energy has to be transferred to the walls. This dissipation is connected with a high loop voltage, halo currents, a partial recovery of the plasma column such that the creation of runaway electrons is sometimes observed (e.g., in JET [19] and JT-60 [20]) and power is released again in the form of short pulses towards plasma facing components. However, a large fraction of the power is also radiated in this phase due to the increased impurity level.

The power pulses to plasma facing components have been investigated at TEXTOR [21]. The pulse lengths of individual pulses amount to about 100 μs and could correspond to the transit time of a sonic plasma flow along opened magnetic field lines. During this short time most of the stored energy is lost to the wall components. Even though the power flux density is enormous, the radial decay length of the power pulses is nearly the same as those of normal discharges. This excludes any diffusive process as the underlying mechanism for heat transport. Therefore, the picture of a laminar magnetic structure opening up due to plasma ergodization has been proposed as a mechanism for the plasma edge [22].

In our view, the collapsing plasma creates the power flow to the wall and this flow again releases hydrogen and impurities from the wall which then enhance the disruptive process via radiation. The TEXTOR data on disruptions would not fit well with a model in which the impurity influx is the primary cause of the disruption.

3. Detrimental effects

The effects which are critical for a device during a disruption are:

(a) The enormous power flux density falling on the plasma facing components.

(b) The halo currents observed during the current decay phase; this halo current can carry a substantial fraction of the plasma current. The halo current has been successfully reduced by massive helium injection at DIII-D [23, 24]; on the circular TEXTOR plasma the halo currents are less harmful.

(c) The creation of runaway electrons during the current decay phase. On JET it is observed that the runaway electrons are preferentially created in discharges with a transient current plateau [25]. For present day machines the runaway electrons are in most cases no danger for the machines; however, there are exceptions [26]. For ITER the situation is expected to be different. In detail, much depends on the question of how dominant will be the secondary generation of runaways in comparison with the classical Dreicer mechanism and how important will be the transient healing of the flux surfaces during this phase.

(d) The start of the following discharge. This difficulty in there being a successful start after a disruption may be related to two possible effects: (i) During the disruption, impurities are released and deposited in an uncontrolled way. During the next current ramp-up phase, the impurities are released and generate an excessive plasma cooling by radiation. (ii) During the end phase of the disruption the hydrogen (deuterium) hits the wall rather hard and is stored there in abundance. This gas is then released again in the following start-up, leading to too high a density in the initial phase and therefore to an unsuccessful start.

The aim of this proposal is to mitigate as far as possible the effects (a) to (d) by a fast injection of helium gas.

4. Other mitigation studies

Before we come to the advantages of this proposal, other efforts should first be discussed. These efforts are based on killer pellet injection or (heavy) gas injection. Both methods tend to terminate the discharge in a more controlled way than is possible during an unprogrammed disruption. The underlying mechanism of the mitigation is the attempt to transform as much of the stored plasma energy into radiation and thus to avoid excessive erosion of wall facing materials by the incoming heat pulse. Without any doubt, the warning time delivered by the mode activity or other signs of coming disruptions is very valuable in preparing for pellet or gas injection.

The mitigation schemes discussed so far tend to influence primarily the effect (a), the power flux distribution on the plasma facing components. On TEXTOR some trials with carbon, aluminium and iron killer pellets have been performed; the aim of these discharges was termination of runaway electron discharges. We wanted to see whether pre-existing energetic electrons — electrons with energies in the range 20–30 MeV have been studied by the synchrotron radiation detection method — are a favourable seed for runaway creation during the high loop voltage phase of disruptions. It was observed that the injected pellets also interact strongly with the runaway electrons and that a fraction of the runaways is indeed quickly lost. However, the loss was not complete and we found that the runaway electrons remained inside one or several large magnetic islands, i.e. a runaway snake was observed. The loss of the runaways from a large fraction of the plasma was interpreted as due to the creation of a transient magnetic field line ergodization due to the injection. The persistence of the runaways was attributed to large internal islands embedded in the ergodic sea.

In our opinion, pellet injection starts with a local and temporally short interaction and it is not guaranteed that a killer pellet will influence the whole plasma cross-section in a way such that no runaway electrons will be created in the later current decay phase. In addition, we suspect that the magnetic structure of the disrupting plasma column may be rather complicated; even if one assumes ergodization as the prime cause of a disruption, it is not guaranteed that the column will remain completely ergodized during the whole decay phase. From the creation of runaways and from the existence of short heat pulses it is assumed that transiently intact flux surfaces are re-established even during the current decay phase. A mitigation scheme which avoids the creation of runaway electrons should therefore take this effect into account.

Gas instead of pellet injection is favourable for removing the runaways in so far as the gas is more diffuse and therefore acts more easily on the whole plasma column. Since runaway production depends both on the loop voltage and on the electron density (which is typically quickly decaying together with the plasma current), it is advantageous to use a highly recycling gas which persists long enough in the discharge and is not deposited in the walls. In this respect helium is the best gas; it is implanted the least of all elements; all other gases, including the noble ones, recycle less and stick to the walls.

For distributing the power by radiation, high Z materials initially seem most promising, leading to a radiative collapse disruption [27]. However, a close examination indicates that the radiation potential of highly ionized atoms can only be utilized until the onset of the proper disruption. This limit is most likely reached if the radiation has cooled the boundary such that near the $q = 2$ surface the plasma current is suppressed. From then on the disruptive mechanism discussed above sets in. It is doubtful whether the high radiation potential can then be utilized further because the critical heat fluxes occur close to the plasma edge with rather reduced electron temperatures and low impurity ionization states. A mitigation of the power flux to the wall may require a careful optimization of the impurity composition, its injection timing and amount.

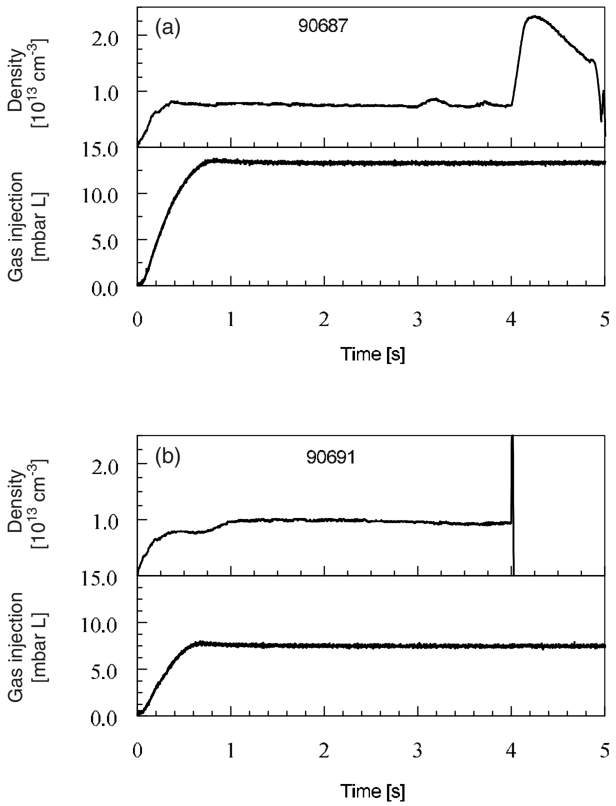

Figure 1. Density evolution and the trace of injected fuelling gas (D_2) for two low density (runaway) discharges. (a) This discharge belongs to a series of similar discharges; at the end of these discharges a moderate amount of helium was applied in order to stop the energetic runaway electrons. (b) This series is characterized by the helium puff at about 4 s. The discharges do not show an overshoot in density as compared with the top trace. The overshoot is always observed if D_2 was injected instead of helium.

5. Advantage of helium

The main advantage of using helium for the mitigation of disruptions is its low Z number combined with its low probability to be implanted in walls. This results in two positive effects: the electron density remains high to the end of the disruption (in particular at those locations where T_e is still higher than 10–20 eV) and the start of the next disruption is not inhibited. It is well known that small amounts of helium are trapped during discharges and are released in the following ones [28]. However, the observations on TEXTOR have shown that the amount of liberated helium is never critical to the start of the following discharge. If the turbopumps of the pump limiter ALT-II are open, the helium pressure in the subsequent discharge is near the detection limit (about 2%) while without turbopumping the helium concentration can reach about 5%. In addition, the helium also seems to block the sites for deuterium in the wall facing components; there is no overshoot of the electron density during the buildup phase of the following discharge.

Figure 1 shows traces of the density and of the injected D_2 gas for two low density discharges (runaway discharges). The discharge shown in Fig. 1(a) belongs to a sequence where a moderate amount of helium is injected at 4 s in order to reduce the number of runaway electrons. The discharge shown in Fig. 1(b) shows the same initial density evolution now for a discharge of a sequence where fast helium injection is applied to trigger a disruption; the required fuelling gas is rather similar for both discharges.

The observed evolution of the synchrotron radiation is the same for the whole sequence. This is a rather sensitive test because, if we had added additional deuterium at the end of the first discharge, the initial density would have overshot and the synchrotron emission would have been delayed. Experimentally, on TEXTOR we have never observed deteriorated conditions for the next discharge after the termination of a discharge with a helium puff.

Helium as compared with hydrogen isotopes shows, in addition, the favourable feature that it undergoes no resonant charge exchange with the majority gas. Therefore the bombardment of the wall with highly energetic charge exchange particles is strongly reduced. This feature is favourable for the wall integrity; it also may be one of the reasons for the low sticking probability of helium at the walls.

6. Injection valve

In order to mitigate disruptions by a gas puff it is required to inject it at a sufficiently large rate. If the gas is injected, for example, by a conventional piezovalve, the discharge gradually reaches the density or radiation limit and then the disruption proceeds in the normal way. In particular it is also not possible to react to ‘fast’ events.

The valves used for pellet injection are fast and provide a high throughput. However, the valves known to us have a ferromagnetic stem, which is accelerated if a coil is activated. The ferromagnetic material prevents their use close to the vessel in the high toroidal magnetic field environment. For the

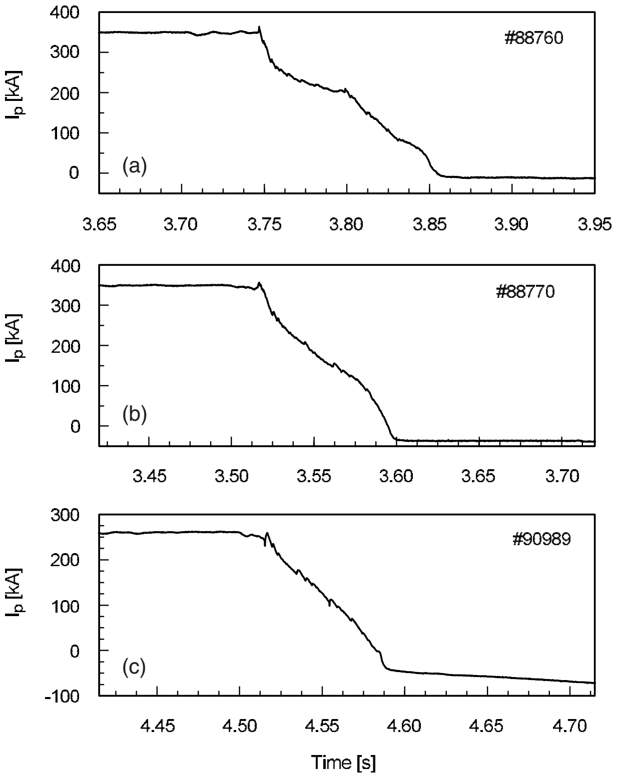

Figure 2. Decay of the plasma current during disruptions. In the first discharge (a), the disruption was caused by the density limit. In the second discharge (b) a similar density was programmed; however, if a helium puff was injected just before the disruption would have occurred naturally. The third discharge (c) is a moderately heated discharge with a plasma shift towards the HFS prior to the disruption. Obviously, the plasma current decays faster with the addition of helium, probably because of the enhanced cooling. The decay curve is smoother and less noise developed during the disruption.

acceleration of our valve we use an eddy current scheme where a pancake coil is adjacent to an aluminium stem. The pancake coil is activated by a capacitor discharge; in this way a gas reservoir of less than 1 cm^3 and of a pressure up to 50 bar is released in less than a millisecond (time counted from the trigger signal). The first effect of helium injection is seen as a fast cooling of the outer ECE channels measuring T_e; the onset of the cooling starts within less than a millisecond after the triggering and the cold front propagates from the edge into the core plasma. The injected amount of helium gas has been measured to be 10 mbar L. Assuming the propagation velocity to be the speed of sound, the released gas reaches the plasma within one millisecond.

7. Observations

It has already been mentioned above that the injected helium has no negative effects for the following discharge as compared with a discharge which has ended smoothly. This by itself is a very favourable result.

7.1. Halo current

As a further point for mitigation the reduction of the halo currents was mentioned. The halo currents are reduced if the current decay phase is shortened. In addition a cooling of the outer plasma boundary (increased electrical resistance) is essential for the reduction of the halo current. Therefore the first test was the recording of the plasma current decay. In Figs 2(a)–(c) (discharges 88760, 88770 and 90989) the development of the plasma current is shown for three discharges; the first discharge disrupted at the density limit and the disruption of the second and third discharges was triggered by fast helium injection. Without helium puff, the plasma current decays in about 100 ms. Discharge 88760 is not the fastest disruption observed on TEXTOR; it was, however, typical for the conditioning of the device (old boronization, high density). In the case of Fig. 2(b), the plasma was close to the density limit before the injection of the helium. In Fig. 2(c) the density was lower and the plasma was positioned more towards the high field side (HFS) before helium injection. The current decay rate with the helium puff is shorter than that without a puff. However, the maximum current decay rate is not increased, the decay is smoother.

The noise development during the mitigated disruption is less than that of a normal disruption; this may also indicate that the force acting on the structural components may be reduced. It is expected that the decay rate will be influenced by the amount of injected helium. An optimization of the decay rate needs still more experiments and may be machine dependent. Owing to the circular cross-section of TEXTOR the halo currents are not a problem; for critical tests a device with an elongated plasma is better suited.

7.2. Runaway electrons

The idea of mitigation of disruptions arose during experiments on runaway electrons using a synchrotron radiation detection system [29–36]. Until

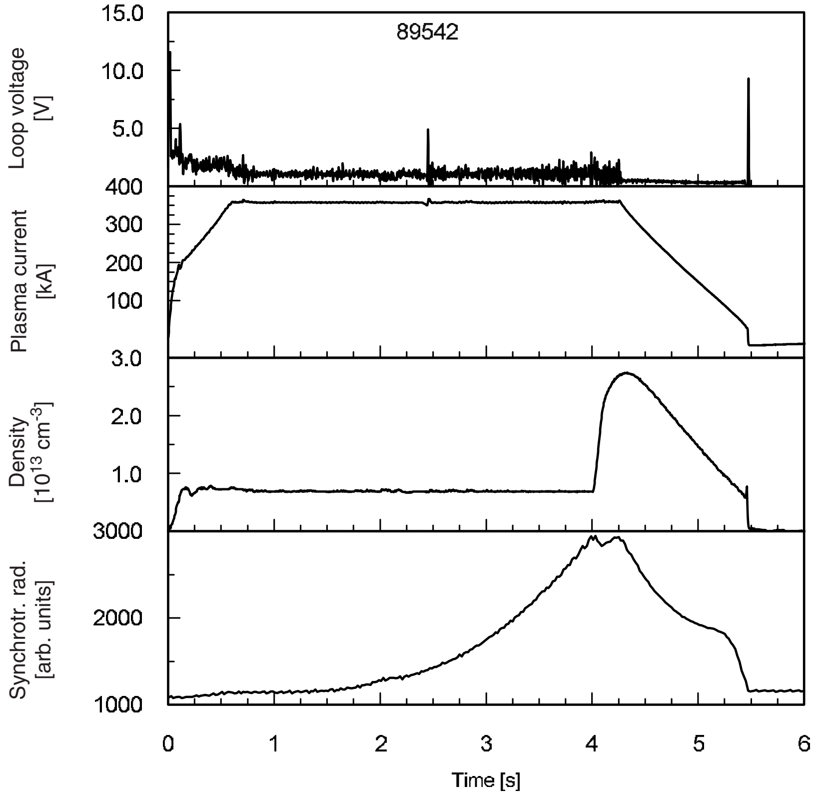

Figure 3. Traces of the loop voltage, plasma current, density trace and synchrotron radiation. A moderate amount of helium is introduced at 4 s. Before helium injection the runaway signal increases nearly exponentially; after the injection, the runaways are lost with a time constant of 0.6 s. This decay time is consistent with the classical (relativistic) collision rate of the runaways with the background electrons.

two years ago, in our extensive investigations on runaways we never had any problems with induced radiation from energetic electrons. For about two years this has changed for a reason which is still unknown to us. Now a typical runaway discharge produced about 15 μSv of radiation, a level which would be intolerable for our yearly radiation budget. We therefore started to inject a moderate amount of helium with a piezovalve at the end of a runaway discharge and by this means we could reduce the radiation level by more than an order of magnitude. Figure 3 shows a sequence of traces for a runaway discharge with an addition of helium at 4.0 s. The traces are from top to bottom the loop voltage, the plasma current, the density and the synchrotron radiation of the runaway electrons. The decay time of the synchrotron radiation amounts to about 0.6 s and corresponds well to the collision time of runaways with the background electrons (Section 8.2). As already stated before, the helium had no negative effects on the discharge prior to the injection.

In order to check the runaway suppression option after the fast puff of helium, we operated the fast valve during a runaway discharge. Figure 4 shows similar traces to the previous figure. With the injection of the helium, the discharge disrupts and the runaways are quickly lost. The positive action of the helium remains preserved, namely the radiation level remains as low as we found with moderate helium injection.

In high time resolution, the loss of the synchrotron radiation is shown in Fig. 5 as an IR scanner image of the disruption. The scanner consists of two sweeping mirrors (horizontal fast, vertical slower) and an IR detector; these three constituents generate a picture in TV-CCIR norm. However, in

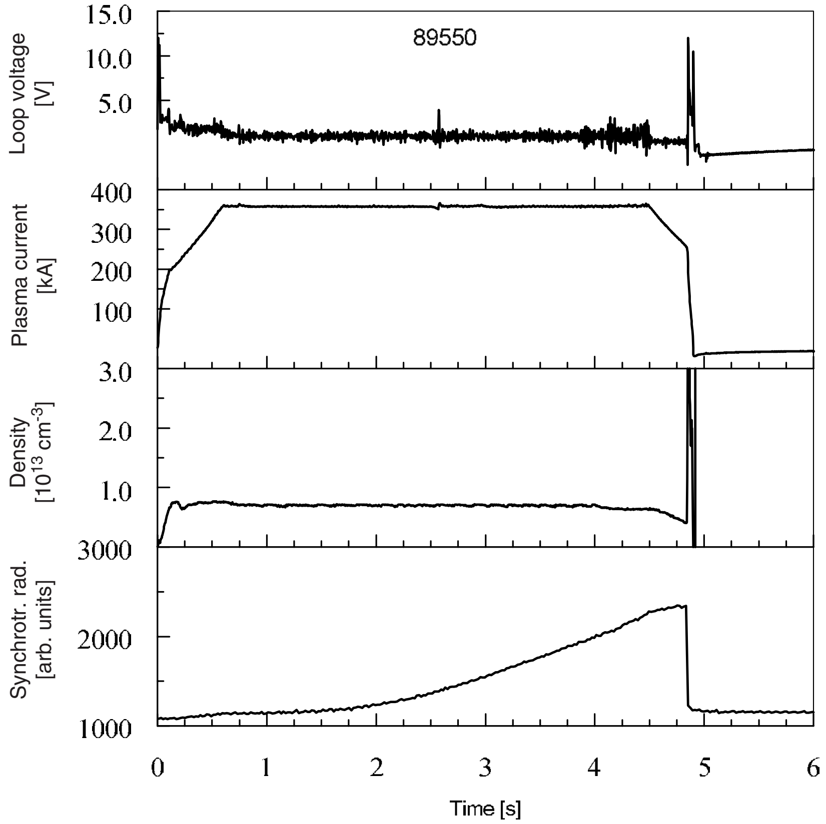

Figure 4. Similar traces to those in Fig. 3. The discharge is terminated by fast helium injection and the synchrotron radiation stops immediately.

contrast to a CCD image, this picture also contains time information from the sweeping mirrors. The time runs from top to bottom, spanning about 20 ms.

At the top of Fig. 5 well developed synchrotron radiation is observed which suddenly stops, namely after the injection of helium. The runaways decay first at the low field side and about 0.5 ms later in the core. This time span is consistent with the propagation time of helium, at least in vacuum. A more detailed comparison with the ECE channels shows that the helium at first cools the plasma edge. The loss of the runaway electrons even at the edge does not occur immediately at the arrival time of the cooling helium front, but with a delay of about 2 ms. The collision cross-section of the helium enriched plasma is also not large enough to explain the rapid runaway loss. Therefore, our assumption for the rapid loss is that together with the propagating helium front a transient ergodic magnetic structure has to be formed which opens a path for the fast electrons to the edge. This mechanism has already been proposed in conjunction with pellet injection experiments.

Two milliseconds after the loss of the runaways the heat pulse of the disruption occurs which shows up in the heating of the limiter ALT-II. Fast helium injection is obviously a powerful tool with which to destroy the pre-existing runaways and avoid their creation. It is expected that the creation of the runaways takes place on flux surfaces which are (transiently) intact during the current decay phase. These areas of higher confinement would then also possess hotter electrons than the rest of the column and therefore it should be expected that the injected helium should be preferentially ionized and confined in these channels. Therefore, conditions which are favourable for the creation of runaway electrons are also favourable for the attraction of helium, thus forming locally enhanced density regions. This mechanism then suppresses a further growth of the runaway electrons. The

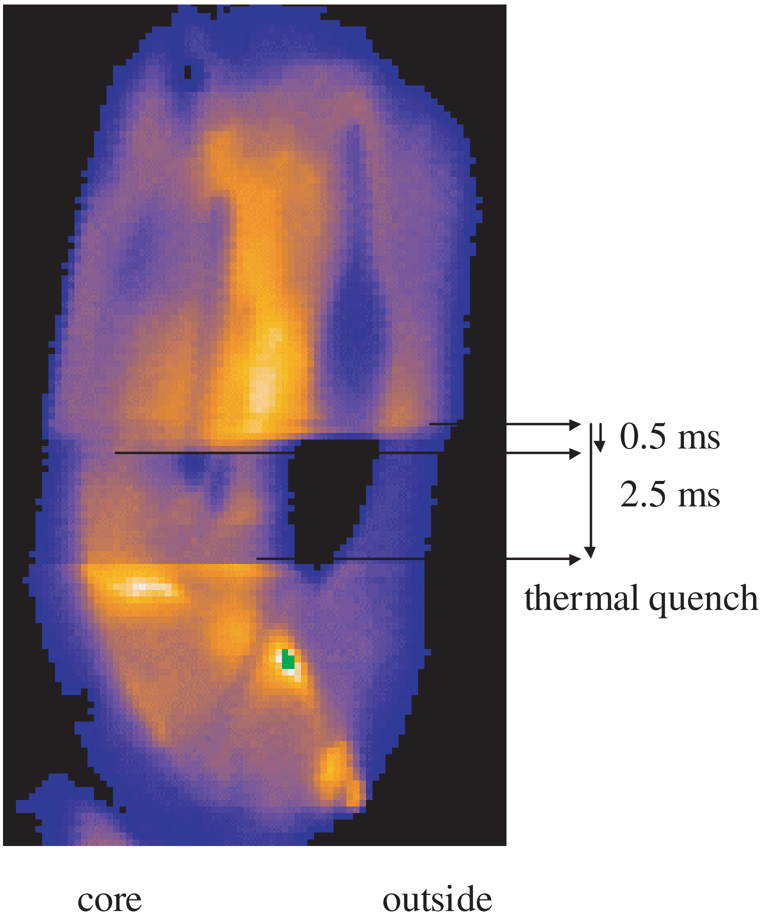

Figure 5. Infrared radiation for the same discharge as in Fig. 4. Because of the construction of the IR scanner, the IR image also contains time information (about 20 ms from the top of the image to the bottom). In the IR region one sees a superposition of thermal radiation and synchrotron radiation from the energetic runaways. The colours are 'false', where the lowest intensity is coded black and purple while the brighter ones vary from red via yellow to white. At the top one observes a considerable contribution of synchrotron radiation, which is suddenly lost. The loss 'propagates' from the outside to the centre of the discharge within half a millisecond. Since the loss occurs only about 2 ms after the injection, we attribute the loss more to a transient ergodization of the plasma than to the direct effect of the helium puff.

avoidance of runaways alone would already be sufficient reason to continue the work on fast helium injection.

8. Some estimates

Here we want to give some estimates on the processes occurring during disruptions. These estimates have only a generic character and cannot replace a later more thorough modelling.

8.1. Heat flux

Heat pulses can be mitigated by the proposed method only if sufficient warning time is provided, which we estimate to be about 5–10 ms depending on the size of the device.

Just as has been observed in the example of runaway discharges, fast injection of helium will not immediately lead to a disruption. Before the power quench a transient phase is observed where the plasma accepts the helium and — parallel to this process — cools down. The cooling is both due to a power distribution to more particles and due to enhanced radiation. In this 'preparation phase' of the disruption, the plasma conditions are already mitigated with respect to the coming event. However, all other mitigation schemes would have the same favourable effect.

As mentioned before, the proper heat pulse occurring after the 'preparation phase' is very fast. We cannot imagine a realistic scenario in which the stored plasma energy could be radiated quickly enough or in which the temperature could be lowered by the addition of particles. If at the end of the preparation phase the plasma were to have a temperature of 500 eV on TEXTOR or, for example, 1 keV on a larger device, and if we were to reduce the plasma temperature instantly to 25 eV, it would be required to enhance the plasma content by a factor of 20–40. In addition, this number of particles would have to be delivered into the plasma volume within about 100 μs. Even pellets with the required particle number would probably not be sufficient because the ablation process requires time and these size pellets would probably cross the plasma column before being sufficiently ablated.

In order to estimate the possible energy loss from the plasma to helium, EIRENE code calculations have been performed taking into account the relevant processes of excitation, radiation, ionization, charge exchange and scattering. The plasma is assumed as a slab of 1 m thickness assuming a density of 10^{19} m^{-3} and a temperature of 5 eV, which may be more typical of the current decay phase. The helium is assumed to start at the walls with an energy of 0.04 eV (wall temperature). If a helium flow corresponding to 1 A is assumed, the loss rate of the electrons in the plasma amounts to 14.8 W and that of the ions to 1.66 W. Forty-seven per cent of the helium flux will be ionized and the rest will be elastically backscattered. These data mean that about 35 eV are needed per ionization process of helium. This value is very close to that of hydrogen; the difference in the ionization energy of the two species is obviously compensated by the different radiation characteristics. Therefore the mitigation effect of hydrogen isotopes and helium on power exhaust are similar in a first order approximation.

If one considers the heat transfer not during the quench phase but during the current decay phase where the stored magnetic energy has to be dissipated, then the injected helium particles can play an important role. The particle confinement time during the current decay time is probably very low. The measured H$_\alpha$ and helium line intensities usually saturate the detector; the line intensities are for at least 2 orders of magnitude larger than those in the non-disruptive phase, resulting in a particle confinement of 0.1 ms $\leq \tau_p \leq$ 1 ms. The lower, minimum, value is given by the transit time for a thermal particle for a path between the recycling zone and the wall. The 10 mbar L of injected helium corresponds then to a flux of $2.7 \times 10^{23} \leq N_{He}/\tau_p \leq 2.7 \times 10^{24}$ particles/s. This helium flux provides a cooling rate to the plasma electrons of 43 kW $\leq P_{cool} \leq$ 430 kW and removes a considerable fraction of the stored magnetic energy over the current decay time.

Even though the injected helium cannot remove the power during an energy quench, the high density low temperature edge plasma may be very favourable for transferring the power in a less harmful way towards the wall elements: the conditions may be favourable to achieving a higher recycling condition. The collision lengths for encounters between helium and electrons or protons are important parameters. According to the EIRENE code, the collision rate for helium ions with electrons is $\langle \sigma v_e \rangle = 10^{-10}$ cm^3/s and that with protons is $\langle \sigma v_p \rangle = 2 \times 10^{-9}$ cm^3/s. For an electron density of 10^{20} m^{-3} and $T_e = 5$ eV, this leads to a collision length of 80 m for electrons and 0.1 m for ions. In particular, the ions are collisional and can reduce their energy before hitting the wall. However, this aspect in particular, requires intensive modelling.

8.2. Runaway electrons

As discussed before, the effect of helium on the runaway electrons is twofold: the existing runaway electrons are lost and no new runaway electrons are created in the current decay phase. The loss of runaway electrons during the slow helium pulse is mainly due to their deceleration. The observed synchrotron radiation — emitted by electrons with energy $W_r =$ 20–30 MeV — decays on a timescale of about 0.6 s for a density increase up to $\langle n_e \rangle = 2.5 \times 10^{19}$ m^{-3}. Since the synchrotron radiation P_{syn} is proportional to W_r^4, a collisional decrease is expected on a timescale τ_{syn} of

$$\tau_{syn} = \frac{P_{syn}}{dP_{syn}/dt} = \frac{1}{4}\,\frac{W_r}{dW_r/dt} \approx \frac{1}{4}\,\frac{p_\parallel}{F_{drag}}$$

where $p_\parallel$ is the parallel momentum and F_{drag} is the collisional drag force, which in the relativistic case amounts to [37]

$$F_{drag} = \frac{e^4 n_e \ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2}\left(1 + \frac{Z_{\mathit{eff}} + 1}{\gamma}\right).$$

Here e is the elementary charge, m_e the electron rest mass, $\ln\Lambda$ the Coulomb logarithm and γ the relativistic mass factor. For $W_r = 25$ MeV and $n_e = 2.5 \times 10^{19}$ m^{-3}, this leads to

$$\tau_{syn}\ [\mathrm{s}] \approx 0.1\,\frac{W_r\ [\mathrm{MeV}]}{n_e\ [10^{19}\ \mathrm{m}^{-3}]} \approx 1.0$$

which is close to the observed decay time of 0.6 s.

For fast helium puff, the density increase is larger (about a factor of 2), but the time for deceleration is much shorter (of the order of 2 ms), leading to a negligible change in runaway energy of $\Delta W_r < 0.1$ MeV. However, for fast helium puff the dominant effect is the loss of runaway electrons due to the stochastization of the field lines. This provides a direct channel for the runaway electrons to reach the limiter very quickly and deposit their energy on its surface. Direct evidence for this process is seen in the signal of the fast IR diode, observing the limiter, which shows a steep rise coinciding with the loss of synchrotron radiation from the plasma. For this signal it is estimated that a total energy of about 4 kJ is deposited. This corresponds to a 4 kA runaway current of 25 MeV electrons. From the intensity of the synchrotron radiation a similar value was found.

The generation of new runaway electrons is prohibited in the phase after the fast helium pulse, since

(a) The existing runaway electrons are lost and therefore the secondary generation process cannot start,

(b) The rate for primary generation is drastically reduced at the anticipated conditions of $T_e = 100$ eV, $n_e = 5 \times 10^{19}$ m^{-3}, $Z_{\mathit{eff}} = 2$ and the electric field in the centre estimated from $E_\parallel = \eta j_0$ (where η is the resistivity and j_0 the central current density, assumed to be unchanged immediately after the crash).

The primary generation is a strong function of the parameter $\varepsilon = E_\parallel / E_{crit} \sim E_\parallel T_e / n_e \sim Z_{\mathit{eff}} / (n_e \sqrt{T_e})$. Therefore, compared with the predisruptive case ($T_e = 1500$ eV, $n_e = 0.7 \times 10^{19}$ m^{-3}, $Z_{\mathit{eff}} = 2.0$) this parameter is decreased by about a factor of 2, making runaway production almost negligible.

9. Conclusions

Initial experiments have been performed aimed at mitigation of the detrimental effects resulting from disruptions. For this purpose a fast valve with a response time of 1 ms and a gas content of 10 mbar L has been developed (the time is measured from the trigger to the time when the gas has been fully released). The injected amount of gas leads to an electron density of about twice the density limit such that even for low density discharges a disruption is guaranteed.

Helium gas has been selected because it is the gas with the least influence on the next discharge: the injection of large amounts of hydrogen isotopes generally loads the wall such that special measures need to be taken for the release of the gas stored in the wall (this is not possible in a routine way for all devices). Heavier impurities may be deposited on the walls and reappear in the startup phase of the coming discharge. This may also lead to a poor performance of the next discharges. Helium is the gas which is least stored in the walls and which generally would not prevent a successful startup even if smaller amounts are released.

The experiments have shown that the injection of helium is very promising for the mitigation of the disruptions:

(a) The plasma current decay time is reduced and it is expected that the lower edge temperature plasma should produce lower halo currents.

(b) The runaway electrons are successfully and quickly extracted from a discharge and — as we have discussed in detail — it is expected that they would not further develop during the current decay phase.

(c) It has finally also been demonstrated that the wall conditions remain very favourable after a helium puff induced disruption.

A possible problem of the injected helium may develop for devices with cryopumps (TEXTOR has only turbopumps). The injected helium gas is normally not pumped by the cryopump and causes enhanced heat conduction between the walls and the cooled cryopanels. Since the heat conduction is active in between discharges, the heating of the pumps may limit the amount of injected gas for these devices. Nevertheless, there remains an interesting margin such that JET would most likely allow an injection of a few bar litres, which might be sufficient to achieve sufficient mitigation.

The long range aim of this work is the development of a mitigation scheme for the next generation tokamak device. Since several detrimental disruption effects have to be considered the optimization of gas injection is not straightforward; therefore, there may not be a unique solution for the different aspects. The optimization will require additional investigations including larger devices than TEXTOR. Therefore, at present another fast valve with a larger gas reservoir is under construction and may be applied elsewhere.

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