Influence of Recycling on the Density Limit in TEXTOR-94

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(Received 20 January 1998)

An experimental investigation into density limits has been performed in the TEXTOR-94 limiter tokamak. In discharges close to the Greenwald limit, generally, a high-radiation-zone (Multifaceted Asymmetric Radiation from the Edge, or MARFE) precursor developed at the high-field side of the tokamak, which led to the destabilization of the plasma. In this Letter it is shown that recycling properties contribute to the development of the MARFE and hence the density limiting process. Reduction of the recycling yielded an increase of the achievable density of a factor of 2 above the Greenwald limit. Stationary discharges, operated at densities of 1.6× the Greenwald limit, have been obtained. [S0031-9007(98)05916-X]

PACS numbers: 52.55.Fa, 52.40.Hf

In tokamak devices a plasma can be confined by means of large magnetic fields. The aim of thermonuclear fusion is to achieve the thermonuclear burn conditions for a self-sustaining tokamak plasma. For this, very high densities will be required. However, scaling of empirical data has shown that a maximum achievable density exists. Generally, operation of a tokamak reactor near, or at, this density limit will result in a degradation of plasma confinement or a disruption of the tokamak discharge [1]. Density limits form a major problem in tokamak physics.

Two types of density limits can be distinguished. In Ohmic and auxiliary heated discharges, contaminated with low-Z impurities, the density is limited by a radiative collapse. In these cases the density can be increased until the radiation power equals the total input power. This radiative collapse leads to a symmetric radiation belt around the plasma and a shrinking of the plasma column, which triggers large scale instabilities in the plasma. The physical mechanism which causes this limit are rather well understood [1,2].

However, for tokamak discharges with a low impurity content and strong auxiliary heating another limit is found. Greenwald *et al.* concluded that the maximum achievable line-integrated density, $\bar{n}_e^{\mathrm{GW}}$, scales with the averaged current density in the plasma [3]. In a circular tokamak plasma, like that in TEXTOR-94, one finds

$$\bar{n}_e^{\mathrm{GW}}(\mathrm{m}^{-3}) = 1 \times 10^{17}\ (\mathrm{kA}^{-1}\,\mathrm{m}^{-1})\,\frac{I_p}{\pi a^2}\,, \qquad (1)$$

where I_p is the total plasma current and a is the radius of the plasma column. The cause of the destabilizing mechanism is still not well known. ITER, the first tokamak which aims to achieve a self-sustaining plasma, is planned to operate at, or near, the Greenwald limit [4]. In the limiter plasmas of TEXTOR-94 the processes at the Greenwald limit might deviate from that in ITER. In recent experiments transitions from a high to a low confinement mode have been observed when the Greenwald limit was approached in an ITER-like plasma [5]. It is, however, still important to study the underlying physics processes leading to this limit in order to ensure safe high-density operation.

Over the past years many experimental investigations about density limits in tokamak plasmas have been presented [6–9]. Important results are that the central density is limited due to destabilizing processes at the edge and that a relation exists between the edge density and the central density. A specific edge phenomenon has been observed preceding disruptions at the Greenwald limit [5,10]. A so-called MARFE (multifaceted asymmetric radiation from the edge), which is a zone of high radiation, develops [11]. The MARFE is usually located at the inner side of the torus which is referred to as the high magnetic field side (HFS). The MARFE is thought to play a role in the destabilizing process of the discharge operated near the Greenwald limit [6]. Also in standard TEXTOR-94 discharges large MARFEs develop when the density approaches the Greenwald limit. The MARFE phase starts generally as early as 100 ms prior to the actual disruption.

The destabilization of the edge is caused by a thermal instability. The radiative power density P_{rad} is determined by the electron density, the impurity density n_Z, and the cooling rate L_Z, i.e., the radiation rate for the impurity; hence, $P_{\mathrm{rad}} = n_e n_Z L_Z$. An increase of density will enhance the radiation power and consequentially cool the plasma boundary. Furthermore, for most intrinsic low-Z impurities in the edge a reduction in the local temperature yields an increase in the cooling rate L_z and, thus, additional radiation losses and a further decrease of the temperature. This radiation instability is triggered when the edge temperature is decreased to a specific value. Additional heating will therefore provide the possibility to increase the density limit to higher values, as it is generally observed, in tokamaks [1]. For the first type of density limiting process, the radiative collapse, it results in a cooling of the whole outer boundary, poloidally symmetric around the plasma column. In Ohmic discharges this may even lead to a detachment of the plasma from its limiting surface [2].

In the case of a MARFE the thermal instability is localized, mostly at the HFS of the torus. A MARFE is not poloidally, but toroidally, symmetric. The preference of the MARFE position might be explained by an asymmetric heat and particle flux which is mainly directed towards the outer or low-field side (LFS) of the torus. The MARFE develops if the transport parallel to the magnetic field lines is not sufficient to heat the HFS. Since the pressure is constant along a magnetic field line in a tokamak, the drop in temperature in the MARFE yields an increase in density. Hence, a MARFE is characterized by a high radiative power and an extremely high internal density [11].

The edge temperature, prior to the development of the MARFE, is, however, expected still to be too large in order to start the radiative cooling instability. In this case a different mechanism for triggering the MARFE could be more relevant, as proposed in Ref. [12]. The local cooling of the edge, required for the onset of the thermal instability, occurs by localized recycling of particles between the plasma edge and the first wall in the position of preference at the HFS. The energy losses are caused by charge exchange processes, ionization of the neutral influx, and heating of the generated charged particles. The increase of the density in the MARFE even enhances the particle recycling, yielding again a nonlinear cooling mechanism.

Stabilization techniques can be proposed in order to prevent the further development of the MARFE and a disruption of the discharge. Knowledge about the development of MARFEs may provide ways to exceed the empirical Greenwald limit in tokamaks. The Greenwald limit can be exceeded by breaking the relation between the edge and central densities. For example, after injection of a hydrogen pellet, the central density peaks with respect to the edge density [8]. However, the profile peaking is transient and does not clarify the destabilizing process behind the density limit. This paper is dedicated to experiments in the TEXTOR-94 tokamak which show the importance of particle recycling on the density limit. TEXTOR-94 has a main magnetic field of $B_0 = 2.25$ T and a major radius of $R_0 = 1.75$ m.

In our recent experiments the recycling properties have been modified by repositioning the plasma such that its contact with the HFS wall is diminished. Experiments in TEXTOR have already shown that the development of a MARFE can be suppressed only by small changes in the plasma position [13].

The plasma was diagnosed by several diagnostics. Relevant for these experiments are a 9-channel interferometer, providing information on the density profile, and a CCD camera for the observation of the H_α radiation. The H_α radiation gives the neutral flux and is indirectly an indication for the recycling [14]. Hence, the radiation intensity provides information on the global neutral particle flux and localized recycling effects. In order to determine the local recycling at the bumper limiter the radiation is integrated over a small volume, shown in Fig. 1. Additionally, the brightness of Carbon (C II) line radiation in the vicinity of the MARFE has been monitored. A four camera bolometric diagnostic measured the total radiation from the plasma, enabling a tomographic reconstruction of the radiation profile. Spectroscopic measurements of charge exchange processes between the plasma particles and those from neutral beam injection were used to determine the impurity densities. Furthermore, usual plasma core and edge diagnostics were used.

The position control was performed magnetically and the plasma column was limited, solely by a top and bottom limiter, to a minor radius of $a = 0.42$ m. In this case it was possible to change the horizontal plasma position (see Fig. 1). The toroidal plasma current was $I_p = 270$ kA, which gives a Greenwald limit of $\bar{n}_e^{\mathrm{GW}} = 4.9 \times 10^{19}\ \mathrm{m}^{-3}$. The neutral beam injectors provided an auxiliary power of $P_{\mathrm{aux}} = 0.9$–1.0 MW. The horizontal plasma position was changed from discharge to discharge. The density was increased each time, by normal gas puffing, up to a disruption. For a specific plasma position the time traces of the density and H_α intensity are shown in Fig. 2. The H_α intensity is found to increase until $t = 1.5$ s, when a small MARFE appears which leads to the disruption. It can be seen that the density exceeds the predicted Greenwald limit considerably.

In Fig. 3(a) it is shown that a higher density could be reached if the plasma is moved several cm towards the LFS. The Greenwald number is shown for each discharge, which is the density normalized to the Greenwald density. For this set of discharges a maximum Greenwald number, $N^{\mathrm{GW}} \approx 1.3$, was found, if the plasma column was repositioned more than 4.5 cm outwards. The discharges, which had been moved towards the HFS, disrupted near the

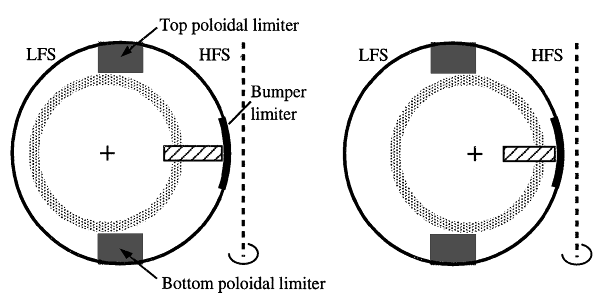

FIG. 1. Two schematic views of the plasma poloidal cross section for an outwards (left) and inwards (right) shifted discharge. The plasma boundary is determined by the two limiters. The bumper limiter, located at the HFS, is indicated. The measured H_α intensities, given in this paper, are integrated over the hatched area.

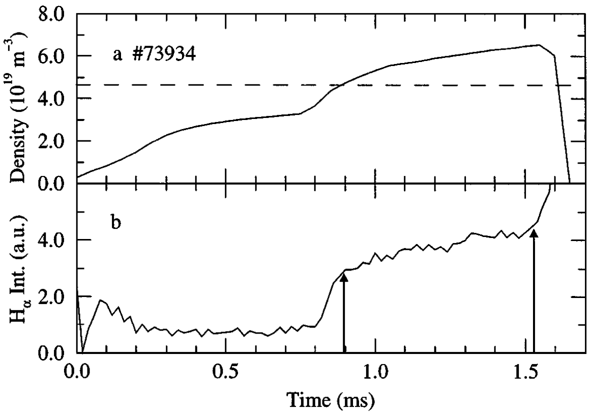

FIG. 2. Time traces of the central line-averaged density and the H_α intensity from the HFS for a discharge which is positioned 3.5 cm outwards. The times at which the Greenwald limit (horizontal line) is reached and the MARFE appears are indicated. The H_α intensities measured at these successive times are represented by, respectively, circles and triangles in Fig. 3(b).

predicted Greenwald limit. A different development of the events preceding the disruption has been observed for different position settings. The discharges, located near the HFS wall, showed large MARFEs, which all had a duration of almost 100 ms, while in the LFS shifted discharges only a small MARFE appeared.

The shift in the horizontal plasma position, shown schematically in Fig. 1, changed the particle recycling at the inside of the torus. This has been determined for each discharge at a time just prior to the MARFE development (see Fig. 2). In Fig. 3(b) it can be seen that the H_α radiation and, hence, the particle flux are approximately equal for all discharges at these specific times. Therefore,

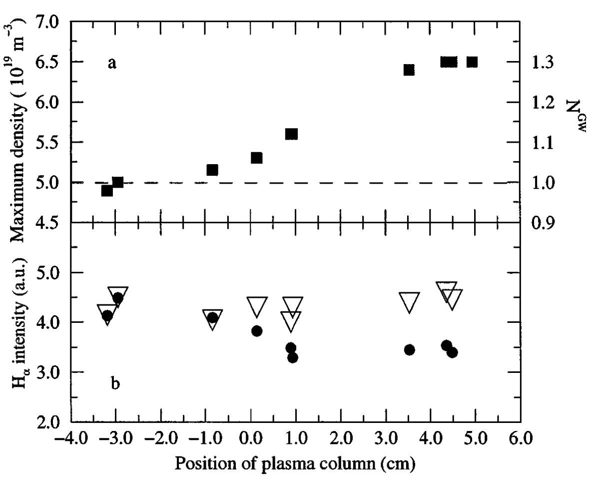

FIG. 3. (a) In the top graph it is shown that the maximum density or Greenwald number scales with the position of the plasma column. An inward shift is represented by a negative plasma position. (b) The recycling properties, deduced from the H_α intensity, measured for each discharge at separate times are given. The triangles have been measured just prior to the MARFE development. The circles represent the recycling in case the Greenwald limit has been reached.

it can be concluded that a threshold exists for the triggering of a MARFE and the disruption.

In Fig. 2 it can be seen that, for this discharge, the H_α intensity is lower than the threshold, at the time the Greenwald limit has been reached. A significant difference is observed, as shown in Fig. 3(b), if one compares the H fluxes, for each separate discharge, measured at the time the Greenwald limit is reached. When the discharge has a position near the inner bumper limiter the localized recycling enhances the H flux in the observed volume, such that the threshold is already reached if the density equals the Greenwald limit. In the outward shifted discharges the H flux is approximately 25% lower for the same density. Also a reduction in the C II line radiation was observed in these plasmas. Thus, the lower particle recycling at the bumper limiter affects the development of the MARFE, and the central density can be increased to higher values.

The conditions of the previous set of discharges were optimized by increasing the auxiliary power. The plasma position was shifted 5 cm towards the LFS. An example is shown in Fig. 4. The plasma current for this discharge was reduced to $I_p = 228$ kA, which gives a Greenwald limit of $\bar{n}_e^{\mathrm{GW}} = 4.1 \times 10^{19}$ m^{-3}. Two neutral beam injectors were switched on at $t = 0.8$ and 1.0 s, respectively, and provided together a total power of $P_{\mathrm{aux}} = 1.8$ MW. Figure 4(a) shows that the central line-averaged density could be increased up to $\bar{n}_e^{\max} = 8 \times 10^{19}$ m^{-3} just prior to the disruption. This is a factor of 2 beyond the predicted Greenwald limit. A central density of $n_e(0) = 9.8 \times 10^{19}$ m^{-3} could be determined, and the central electron temperature has been found to be $T_e(0) = 800$ eV.

No clear indication of the appearance of a MARFE was found during this discharge. However, the total radiated power from the plasma is shown to increase in Fig. 4(b). It equals the total input power just before the disruption. Furthermore, a fast decrease of the edge temperature, measured at the outer side of the torus, below 35 eV has been observed. This all might be an indication that a

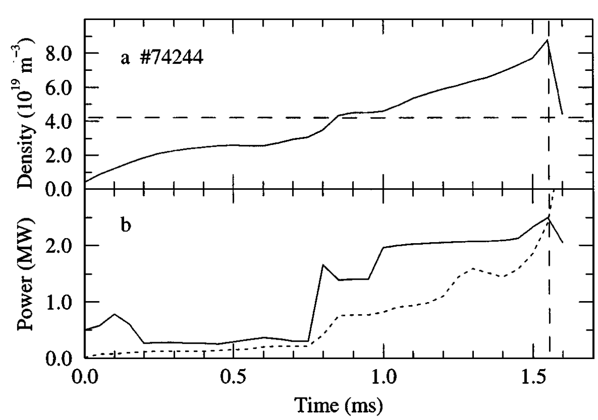

FIG. 4. (a) The time trace of the line-averaged central density. The horizontal dashed line shows the Greenwald limit. At the $t = 1.57$ s the discharge disrupts indicated by the vertical line. (b) The balance between the total input power (full line) and the radiative power (dotted line).

poloidally symmetric radiative collapse is the cause of this high-density disruption.

The high densities, obtained in TEXTOR-94 discharges, are not a transient effect. During a discharge, with $I_p = 228$ kA, $a = 0.42$ m, the plasma position was shifted outwards for about 2 s. The two neutral beams, switched on at $t = 0.8$ and 1.0 s, provided a total power of $P_{\mathrm{aux}} = 1.9$ MW. The density was increased, during this period, up to a constant level far above the Greenwald limit but below that of a radiative collapse. In Fig. 5 it is shown that a stationary density, which is a factor of 1.6 above the Greenwald limit, can be maintained for 800 ms. After this period the plasma position is moved back and the density is decreased below the Greenwald limit in order to have a safe ending of the discharge.

The high-density operation did not affect the confinement of the plasma; hence, the energy content was constant during the discharge. No significant change in the density profile was observed. The radiative power was kept below the total input power for the whole high-density phase. However, it slightly increased up to a fraction of the total power of $\gamma = 80\%$ due to an increase in the impurity density.

The control of the impurities, the radiative power, and the particle recycling in the edge of a tokamak plasma is important for a stable operation. The density limit is thought to be caused by a nonlinear cooling of the plasma edge at high-density operation leading to violent instabilities and a loss of the discharge.

It has been shown in this Letter that a relation exists between the empirical Greenwald limit and the occurrence of MARFEs in TEXTOR-94. It reveals the physical processes underlying this limit. Regarding ITER, it should be emphasized that our experiments have been performed in a circular limiter tokamak, while MARFE develop differently in an elongated divertor plasma. Nevertheless it has been shown that the local recycling properties at the HFS play a dominant role in the destabilization of the plasma. The Greenwald limit can easily be overcome by suppressing this localized recycling. A repositioning towards the LFS can accomplish this. A much higher central density, and consequently edge density, is needed to obtain a MARFE and a subsequent disruption. Densities which are a factor of 2 above the Greenwald limit have been obtained in this way.

The density limit cannot be described by the simple empirical scaling given in Eq. (1). An accurate description of the plasma edge, which includes particle recycling and the degree of poloidal asymmetry in a tokamak, is required. Future experiments in TEXTOR-94 have been planned which involve the study of density limits in high confinement discharges.

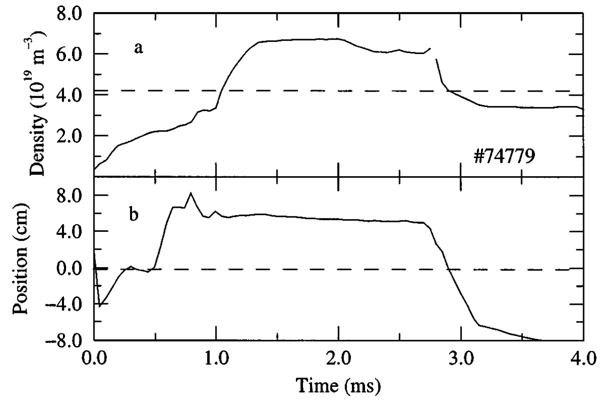

FIG. 5. (a) The time trace of the line-averaged central density. The Greenwald limit is given by the dashed line. (b) The position of the plasma column is given as a function of time.

The authors thank Dr. A. Pospieszczyk and Dr. H. R. Koslowski for their helpful comments. This work has been performed in the framework of the Trilateral Euregio Cluster under the EURATOM-FOM and EURATOM-KFA association agreements with financial support from NWO, Forschungszentrum Jülich GmbH, and EURATOM.

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