Long-Pulse Suprathermal Discharges in the ASDEX Tokamak

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Use of the ASDEX divertor permits the production of stable low-density discharges ($n_e \gtrsim 10^{12}$ cm^{-3}) with extremely low resistivity lasting for more than 10 s. While the distribution functions of electrons and ions show suprathermal tails, runaway electrons in the megaelectronvolt range are found to disappear with decreasing density. There are indications that in these discharges the energy confinement is improved compared with ALCATOR scaling.

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Recently discharges with a pulse length up to 12 s have been produced in the ASDEX divertor tokamak (Keilhacker *et al.*,[1] $R_0 = 1.65$ m, $a = 0.04$ m, $B_{\text{tor}} = 2.2$ T). In normal discharges the pulse duration is limited to approximately 3 s by the available transformer flux swing. This limitation is overcome in clean, extremely low-density discharges where increased plasma conductivity leads to a reduction of the loop voltage by an order of magnitude. The divertor is found to play an important role in these experiments: it prevents plasma pollution and enables very-low-density operation by reducing the recycling from the walls. In these discharges limitations in the toroidal-field power supply determine the discharge duration.

In Fig. 1 is shown the time dependence of six essential parameters for a typical long-pulse discharge. For the time interval 0.6–0.78 s a density plateau of $\bar{n}_e = 2.5 \times 10^{13}$ cm^{-3} is set by feedback control. Thereafter the hydrogen-gas inlet valve is closed. The density then decays to 5×10^{12} cm^{-3} within 100 ms and reaches a lower limit of $(1\text{–}2) \times 10^{12}$ cm^{-3} after a few seconds. This asymptotic limit is probably sustained by hydrogen outgassing from the walls. Also shown in Fig. 1 are the traces of the electron temperature according to electron cyclotron emission (ECE, second harmonic), the plasma current (~250 kA), the loop voltage (U_L, falling from 1.2 to 0.12 V), the soft-x-ray intensity emitted by the plasma (70 eV $< h\nu <$ 30 keV), and the hard x rays released by impact of runaway electrons at a stainless-steel limiter 7 cm beyond the magnetic separatrix at the outer side of the torus.

Thomson scattering, soft-x-ray pulse-height analysis (PHA), and ECE measurements yield equal electron temperatures of 0.7 keV [Fig. 2(a)] during the density plateau from 0.6–0.78 s in Fig. 1. Thereafter Thomson scattering fails because the density is too low, but the ECE indicates—in agreement with PHA measurements—a rapid increase in T_e to 1.5–1.6 keV at 0.96 s [Fig. 2(b)]. At this time an electron energy confinement time of about 25 ms is obtained. After that time the development of a weak suprathermal tail in the electron distribution function is inferred from soft-x-ray PHA measurements. This is also indicated by a steep increase in the ECE (dotted part of T_e in Fig. 1) to intensities which, for a thermal and optically thick plasma, would correspond to electron temperatures above 10 keV at 1.2 s. [Figure 2(c): The experimental

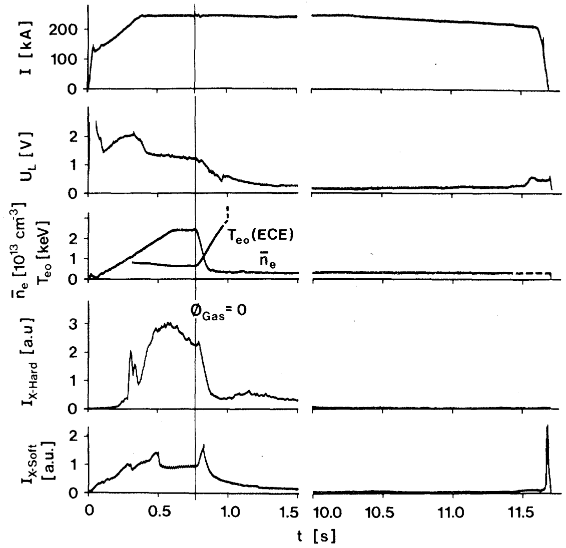

FIG. 1. Time dependence of various plasma parameters in a long-pulse discharge (notice the break of time scale).

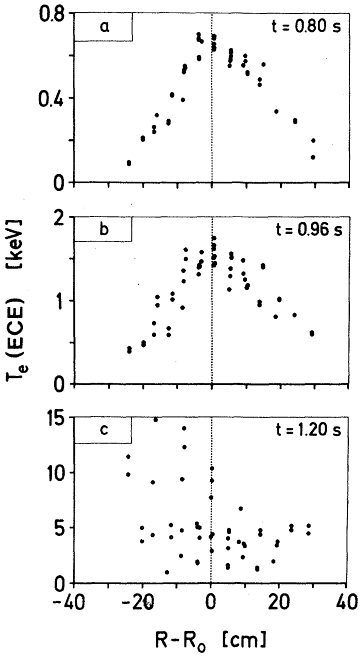

FIG. 2. T_e profiles according to ECE measurements for three different times in discharges similar to that of Fig. 1.

points at identical radii were obtained shot by shot and the large degree of scatter observed strongly reflects minor variations in the temporal decay of the density after 0.78 s]. From the slope of the PHA spectra (available only for $t \leq 1.4$ s) an electron temperature of approximately 2.0 keV and a corresponding confinement time of 50 ms are obtained at $t = 1.4$ s. Th initial increase of the electron temperature is consistent with the increase in the soft x rays (Fig. 1), the bolometer signal, and the impurity-line radiation (O VIII, Fe XVII) from the plasma center which shows a considerable enhancement for about 50 ms.

It has also been observed that this type of suprathermal discharge can be returned to the normal state by hydrogen addition through gas puffing. However, the ECE and soft-x-ray PHA measurements indicate a relatively slow relaxation process. Thus, a Maxwellian distribution is not restored until the density $\bar{n}_e$ is again above 2×10^{13} cm^{-3} after 0.6 s of gas puffing, in contrast to the rapid-decay phase where measurements imply the existence of a Maxwellian distribution down to densities below 5×10^{12} cm^{-3}.

In contrast to what is generally expected, the hard-x-ray flux from the limiter is seen in Fig. 1 to decrease with decreasing density and to disappear almost completely after a few seconds. Furthermore, for discharge durations $\gtrsim 5$ s no final burst of hard x rays is observed, neither from the limiter nor from other parts of the torus. Whereas the initial rapid decrease of the hard-x-ray signal is probably enhanced by an inward shift of the runaway drift surfaces resulting from a decrease in pressure ($\beta_{\rm pol}$) and a peaking of the current profile, a deceleration of the runaway electrons must also be assumed to explain these observations. The minimum value of their original kinetic energy, E_k, is known to be 10 MeV. This value is obtained by calculating (using a standard particle trajectory code) the radial outward shift $\Delta R(E_k)$ of the runaway drift separatrix which, in our case, must exceed $\Delta R = 7$ cm if the runaway electrons diffusing across this separatrix are to strike the limiter rather than enter the divertor. This value is in agreement with results from hard-x-ray pulse-height analysis, and analysis of the limiter activation produced by (γ, n) and (γ, np) processes, from which energies in the range of $10 \lesssim E_k \lesssim 25$ MeV are also deduced. Since the transparency of the torus vessel is greater than 10% for photon energies above 300 keV, the decrease in the hard-x-ray signal implies that the runaway electrons are slowed down from 10 MeV to less than a few hundred kiloelectronvolts. Such deceleration cannot be attributed to Coulomb friction, as is demonstrated by calculating the slowing down time for the relativistic electrons: even neglecting the accelerating electric field, it amounts to 7.5 s for 10-MeV particles at $n_e = 5\times10^{12}$ cm^{-3}.[2] Moreover, it is observed that the electron density decays more rapidly than the loop voltage. Hence, the accelerating field decreases more slowly than the Coulomb drag force and no slowing down is to be expected. For this reason an additional loss mechanism such as particle-wave interaction must be postulated to explain the observed deceleration. While the theory of beam-wave interactions suggests that the deceleration of nonrelativistic runaway electrons may take the form of the Cherenkov effect,[3] for relativistic electrons cyclotron radiation losses following particle pitch-angle scattering by these waves might be more effective.

Information on the behavior of the ion distribution is obtained from charge-exchange measurements. During the density plateau of $\bar{n}_e \sim 2.5\times10^{13}$ cm^{-3} a peaked ion temperature profile with $T_{i0} = 0.6$ keV $\lesssim T_{e0}$ is found. With decreasing density the bulk ion temperature decreases to approximately 0.1 keV over most of the plasma cross section except for a small central part ($r \lesssim 10$ cm) where about 0.3 keV is measured. Moreover, a weak suprathermal ion tail is observed: the charge-exchange flux for particle energies > 5 keV is increased for the lower densities. The peaking of the ion temperature at the plasma axis could indicate the existence of a suprathermal beam as has been reported from ORMAK and TFR tokamaks in the case of runaway discharges.[4,5] However, in contrast to ORMAK we do not observe a noticeable horizontal displacement of the plasma column. There seems to be only a marginal increase in the internal inductance ($l_i \sim 1.5$, $\Delta l_i / l_i \leqslant +30\%$) correlated with the decrease of density, in contradiction with the hypothesis of a strongly constricted current beam.

During the stationary low-density phase ($t > 2$ s) of the discharge the total power input is only 30 kW. According to bolometer measurements the radiation losses amount to a few kilowatts. If, for this period, the suprathermal character of the discharge is neglected, an electron temperature of $T_{e0} = 3.7$ keV may be deduced from Spitzer conductivity, assuming no temporal variations in the effective charge number $\overline{Z}$ and in the shape of the temperature profile. Furthermore, with the reasonable assumption of a parabolic profile for n_e and a squared parabola for T_e, an electron energy confinement time of 120 ms—which is larger than the maximum confinement time of 60 ms at high densities—is inferred. Taking into account trapped-particle effects and a slight increase of $\overline{Z}$ would yield even higher values for the electron energy confinement time. Note, however, that in these considerations the relation between conductivity and electron energy content for a thermal plasma is implicit, and for a suprathermal discharge this may lead to an overestimation of the confinement time, since in such a case a larger fraction of the current can be carried by a beamlike tail of the distribution function. In this context it is necessary to distinguish between the integral energy confinement time (bulk plus beam) and the partial confinement time of the bulk electrons. In the case of a pronounced beam the confinement of the bulk may be very poor. The integral confinement time, however, can still be rather high and not much different from the value obtained by the thermal conductivity relation. Thus, even under the extreme assumption that during the low-density phase the total current is carried by a homogeneous beam distribution $[f_b(v) = \text{const}, \ 0 \leqslant V \leqslant V_{\max}]$ with a maximum energy of 100 keV and a corresponding density in the beam of $n_b / n_e \sim 5\%$, the integral confinement time would be 26 ms, still remarkably high. To obtain a criterion for the suprathermal contribution to conductivity we determine the runaway parameter E/E_{D}, i.e., the ratio of the induced electric field to the Dreicer field $E_{\text{D}} = 3.60 \times 10^{-17} n_e \ln\Lambda / T_e$, where $\ln\Lambda$ is the Coulomb logarithm (T_e in electron-volts, other quantities in mks units). In addition an estimate on $\overline{Z}$ is obtained by assuming $q(0) = 1$, where $q(r)$ is the safety factor. Combining the latter condition—which for $t \leqslant 0.8$ s could be substantiated by the observation of soft-x-ray sawtooth activity—with Spitzer's conductivity, we obtain the relations $T_e(0) = 45.2[B_{\text{tor}} \ln\Lambda g(\overline{Z})/U_L]^{2/3}$ and $E/E_{\text{D}}(0) = 2.77 \times 10^{17}[B_{\text{tor}}\, g(\overline{Z})]^{2/3} \times (U_L \ln\Lambda)^{1/3} R_0^{-1} n_e(0)^{-1}$, with $g(\overline{Z}) = \overline{Z}(2.67 + \overline{Z})/(1.13 + \overline{Z})$. Thus, by comparison with measured temperatures, we get at $t = 0.8$ s, $\overline{Z} = 1.4$ and $E/E_{\text{D}} = 0.006$. At $t = 0.96$ s, $\overline{Z}$ is found to have increased to 1.7 and E/E_{D} has reached its maximum of 0.03 ± 0.01. According to theory,[6] however, there should still be only a marginal suprathermal enhancement of the conductivity ($\lesssim 10\%$) for this value of the runaway parameter. Furthermore, the runaway production rate,[7] which increases exponentially with E/E_{D}, is very small: $\dot{n}_{\text{run}}/n_e \lesssim 5 \times 10^{-3}\ \text{s}^{-1}$ at $t = 0.9$ s.

Comparing our experiments with low-density discharges in other (smaller) tokamaks (Refs. 5 and 8; for a review see Knoepfel and Spong[9]), it is found that—because of higher current densities and larger $\overline{Z}$—those have typically been performed at $E/E_{\text{D}} \gtrsim 0.1$, where, in agreement with theory, appreciable runaway activity is observed and about 50% of the current is carried by suprathermal electrons. In particular, in cases where the ratio of the plasma to cyclotron frequency, ω_{pe}/ω_{ce}, is less than 1, strong relaxations in the loop voltage, cyclotron emission, and other signals appear which are explained by energy transfer from parallel to perpendicular motion due to particle-wave interaction.[3] In ASDEX ω_{pe}/ω_{ce} decreases from 0.9 to 0.3, but the only indication for such relaxations is a small modulation in the ECE signal with a frequency of ~ 100 Hz. The smallness (or nonoccurrence) of these effects, as well as the fact that the soft-x-ray PHA spectra show only weak tails for photon energies $\gtrsim 6$ keV, supports the interpretation that in the case of ASDEX the deviations from a Maxwellian distribution are actually very small ($n_b/n_e \lesssim 1\%$), so that the decrease of the loop voltage with density should indeed be due primarily to an increase in temperature resulting from improved confinement conditions for the bulk electrons. However, when the beam is weak, as we have assumed here, it is uncertain whether the cited beam-wave interactions can quantitatively explain the observed steep increase of the ECE signal, the occurrence of suprathermal ion tails, and the deceleration of the relativistic runaway electrons.

Apart from the technological achievement —tokamak discharges with a duration of 12 s have been obtained without difficulty—there are a number of physical aspects of these low-density discharges which are of interest. In particular, we have found indications that the energy confinement is much better than predicted by ALCATOR scaling ($\tau_E \propto n_e a^2$) which, for the lowest densities, yields $\tau_E \sim 2$ ms. Although we cannot completely exclude the possibility of a cold-electron bulk with temperatures much less than 1 keV, in general our findings are consistent with a bulk temperature in the range of 1.5–3.7 keV. These electron temperatures and the very low power input result in an electron energy confinement time of $\tau_E > 50$ ms. Furthermore, additional heating or current drive studies by rf or neutral injection appear rather attractive in this regime in view of the small number of particles. A further point is the possibility of beam formation in stronger runaway discharges which has been found to yield improved magnetohydrodynamics and tearing-mode stability,[4] and which possibly could be used to penetrate the $q(a) = 2$ barrier.

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