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Journal of Nuclear Materials 313–316 (2003) 904–908

journal of nuclear materials

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Scrape-off layer features of the QH-mode

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Abstract

The quiescent high confinement (QH-mode) and quiescent double barrier (QDB) modes in DIII-D have long-duration H-mode confinement without ELMs, possibly an alternative operating mode in future tokamaks for avoiding damage by ELMs. Instead of ELMs, there is an edge harmonic oscillation (EHO), which is a continuous electromagnetic mode with associated density fluctuations. The edge pedestal is similar to ELMing H-mode, but at very low density to date. We see C^{6+} ion temperatures of 3–7 keV in scrape-off layer (SOL), 100 kV/m radial electric fields just inside the separatrix, and a hot area on the divertor baffle whose heating correlates with the presence of the EHO. We attribute the baffle heating to perturbation of trapped ion orbits by the EHO, allowing particles to strike the baffle. The outboard SOL is wider than the inboard, probably for lack of trapped ions on the inside.

PACS: 32.40.Hf; 52.55.Fa; 52.65.Cc; 52.25.Gj
Keywords: SOL; Divertor; QH; QDB; EHO; ELM; Trapped particle orbits

1. Description of QH- and QDB-modes

Future large high-power tokamaks may operate in ELMing H-mode, but need to avoid ELMs energetic enough to damage the plasma facing components in the divertors [1,2]. It would be desirable to operate such a device in a regime having confinement characteristics equivalent to H-mode but without ELMS.

In this paper, we examine the scrape-off layer (SOL) plasma of the quiescent high confinement mode (QH-mode) in DIII-D. The QH-mode is a regime of long-duration stationary H-mode performance without ELMs [3–5], so far observed only at low pedestal density with counter neutral beam injection (NBI), strong pumping, and a large outer gap of 10 cm or more between the separatrix and the wall. QH-mode has been sustained until neutral beams were shut off, for 3.5 s or about 25 energy confinement times. The edge profiles of the QH plasma strongly resemble ELMing H-mode profiles. The edge density pedestal is low ($\sim$0.2 n_{GW}, where n_{GW} is the Greenwald density) due to strong pumping [3].

In place of ELMs, there is an edge MHD mode that ejects particles and allows pumping for density control. This is usually the edge harmonic oscillation (EHO), a steadily oscillating (not bursting) mode near the separatrix. The EHO prevents the uncontrolled density increase found in standard ELM-free H-modes.

The QDB adds to the QH profiles an inner transport barrier at $\rho \sim 0.4$–0.5 [3]. Most QH-modes in DIII-D contain this inner barrier. In the QDB-mode, we see peaked density profiles and an accumulation of nickel and copper impurities in the core. The density peaking and impurity accumulation are much weaker in

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PII: S0022-3115(02)01474-5

QH-mode without a strong inner transport barrier ($Z_{eff} = 3$ rather than $Z_{eff} = 6$) [6]. Z_{eff} must be reduced for a reactor.

Magnetic sensors show that the EHO has toroidal mode numbers of $n = 1$ up to $n = 7$ simultaneously. The fundamental frequency is often near 9 kHz but varies with plasma conditions. The edge pedestal electron density and temperature are hardly changed by the transition from ELMing H-mode to QH-mode.

The QH-mode occurred with ion ∇B drift toward and away from the divertor, and in both lower and upper single-null. All the data shown in this paper are for counter NBI, upper single-null diverted discharges with ion ∇B drift away from the divertor, where most of the DIII-D EHO and QH-mode operation has occurred to date. Descriptions of QH and QDB modes are found in Refs. [3–5].

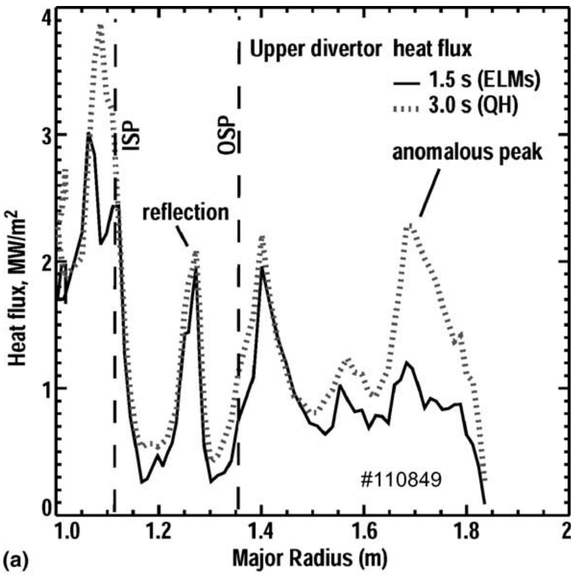
2. Scrape-off layer features

The EHO is detectable by most edge diagnostics with high enough time resolution and sampling rate. It has been seen on fixed and reciprocating Langmuir probes, reflectometry, beam emission spectroscopy, millimeter wave scattering, phase contrast imaging, D_α emission, and magnetics. Several of these diagnostics show the associated density oscillation is strongly localized near the separatrix. Infrared thermography (IRTV) shows a wide distribution of deposited heat flux (q_{div}) in the divertor and on the baffle structure (Fig. 1). This heat flux extends to areas that connect via flux surfaces to the outer midplane more than 6 cm from the separatrix.

In the q_{div} profiles on the flat part of the upper outer baffle ('shelf'), we find an extra peak, 4–5 cm outside the separatrix when mapped to the outer midplane ($\Psi_N \sim 1.04$). This peak is clearly distinct from the outer strike point heat flux peak. The anomalous q_{div} peak becomes significant only after the EHO begins.

A divertor Langmuir probe shows an increase in particle flux during the EHO at the same radial location as the anomalous q_{div} peak, including ions more energetic than the 200 V maximum probe bias. If the particles are assumed to have an average energy of 5 keV, which is consistent with the edge ion energy measured by charge exchange recombination spectroscopy (CER), the resulting heat flux is within a factor of two of the thermographic heat flux. This shows the peak is not a reflection or other camera artifact, and proves the presence of charged particle flux.

The CER shows a 3–7 keV population of C^{6+} ions extending deep into the SOL (Fig. 2), as well as an edge pedestal C^{6+} temperature of $\sim$5 keV. The line emission from these SOL ions is Maxwellian, indicating a thermal population. These hot ions are present in the earlier ELMing phase of the discharge (at about one-half the later temperature) and persist during the EHO. We deduce a hot population of deuterium ions to account for the particle flux measured by the Langmuir probe. We believe it is these D ions heating the divertor shelf, probably because trapped ion orbits are perturbed by the EHO (see Section 3).



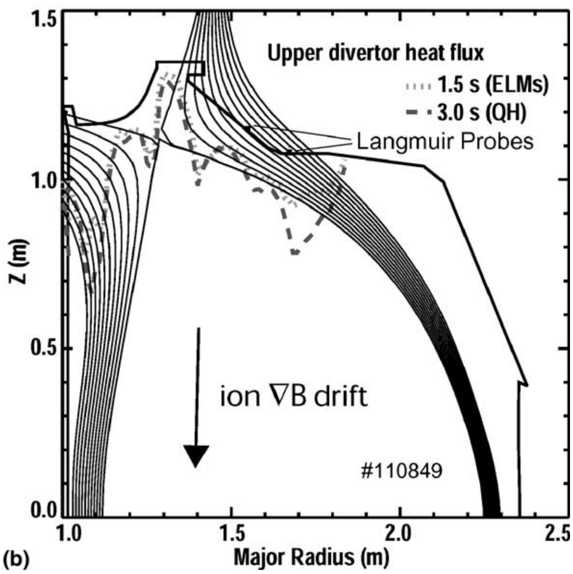


Fig. 1. (a) Upper divertor Heat flux vs. major radius. The peak in the private flux area is a reflection of the outer strike point. The profile at 1.5 s is during the ELMing phase (time-averaged over ELMs); 3 s is during the EHO. Two of the divertor Langmuir probes are shown. (b) The same heat flux profile overlaid on the baffle structure.

There is an apparent dip in the ion temperature just outside the separatrix, probably due to a cold ion

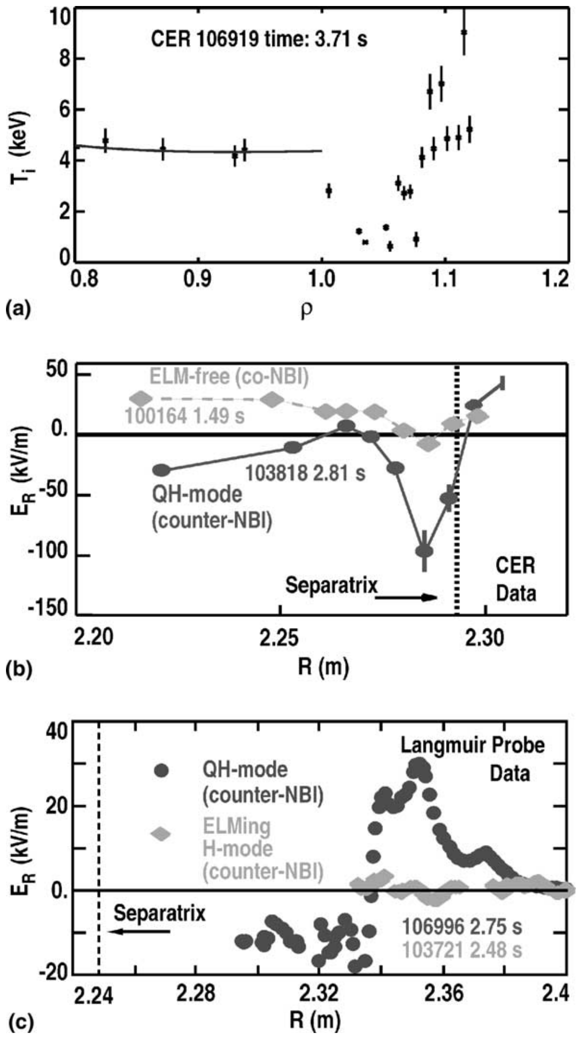


Fig. 2. (a) Ion temperature profile for C^{6+}. The ions in the far SOL are 3–7 keV. The low temperatures just outside the separatrix indicate a localized cold population. (b) E_R from CER, for QH-mode and for co-injected ELM-free H-mode. There is a large negative electric field just inside the separatrix. (c) E_R from reciprocating Langmuir probe, for QH-mode and counter-injected ELMing H-mode. The probe shows a large positive electric field in the far SOL and a zero crossing further in.

population there, which overwhelms the emission of the hot ions. SOL electrons have temperatures of less than 200 eV with a radial density profile nearly flat at $3-4\times10^{18}$ m^{-3}.

A large radial electric field is detected by both CER (from plasma rotation) and the reciprocating Langmuir probe. The CER shows a large negative field localized just inside the separatrix, roughly five times larger than the corresponding field for ELM-free H-mode (Fig. 2). The reciprocating probe shows a large positive electric field in the deep SOL and a zero crossing in the near SOL. These electric fields will have a strong effect on the trapped ion orbits mentioned above.

There is a much larger q_{div} peak at the inner strike point ($R=105$ cm). The sharpness of this peak shows that the inboard SOL is narrower than the outboard. If the outboard SOL is being broadened by the action of the EHO, it may be that the effect of the EHO is strongest at the outside, as has been suggested for ELMs [7] although with a different mechanism. The magnetic measurements do not show a significant decrease in amplitude of the EHO on the inboard side. However, there are few trapped particles on the inboard side to interact with the mode. This difference in the trapped population provides a mechanism for affecting primarily the outboard SOL.

Substantial heat flux also appears at $R\sim155$ cm where the flux surfaces are nearly tangential to the sloping baffle surface. If a parallel heat flux $q_\parallel$ is calculated, it is more than an order of magnitude larger than on surrounding flux surfaces. However, a divertor Langmuir probe at this location sees very little particle flux, so this heating cannot be due to charged particles. A bolometer inversion reveals a concentrated source of radiation in the nearby SOL, which would contribute to heating of this surface (Fig. 3).

Some of the signal detected by bolometers is ascribed to neutral particles striking the detector, demonstrated by signal differences between detectors that view directly and those viewing through the main plasma. The direct view measures higher power, due to neutrals striking the detectors. The inverted 2-D power profile shown in Fig. 3 does not consider neutral power, but the effect is small for this discharge. For other discharges, the effect can be large enough to prevent an acceptable inversion. From this we conclude that neutral particles can carry significant heat to the baffle, although the amount is difficult to quantify.

3. Ion orbit calculations

Radiant heating does not adequately account for the heat flux peak seen near $R=170$ on the shelf, particularly since a charged particle flux is measured there. Fixed Langmuir probe data suggests hot ions present in the SOL, perhaps banana-trapped, flow to the divertor only during the EHO (or in one case core tearing modes instead of EHO). However, the particle flux at the location of the anomalous heat flux peak is only weakly modulated at the EHO frequency. There is a strong modulation at 800 Hz not seen near the separatrix.

Fast ions in the periphery are clearly present in the QH-mode of operation. Counter NBI results in promptly lost orbits for those beam particles ionized within 20–30 cm of the outboard separatrix. Additionally, the high measured ion temperature and low density

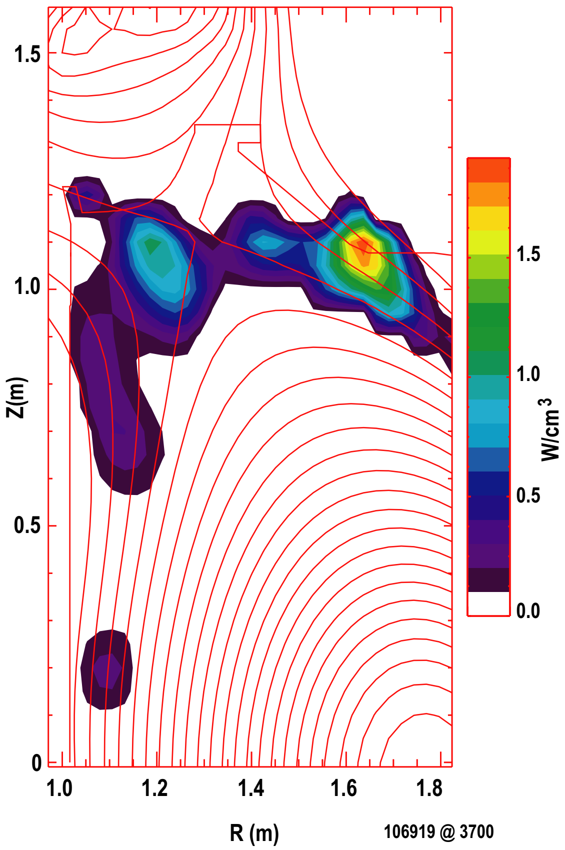


Fig. 3. Bolometer inversion, showing a 2-D profile of radiated power.

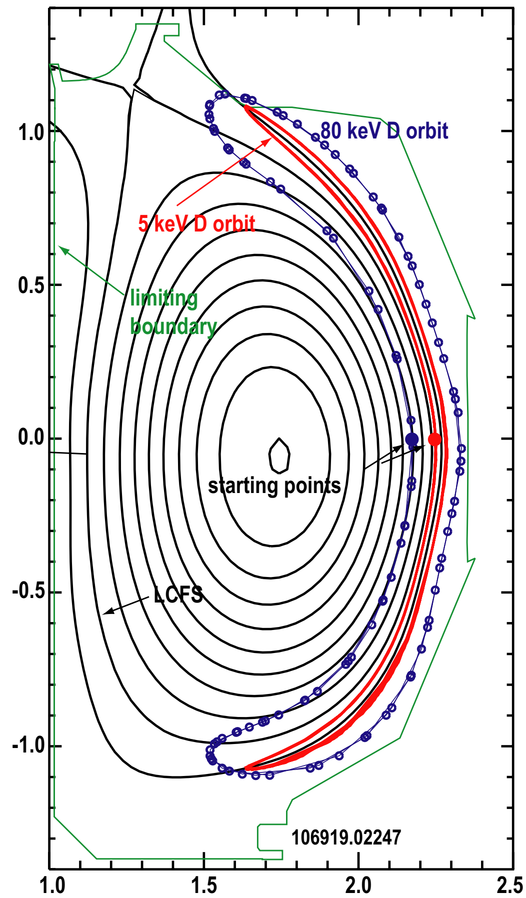


Fig. 4. Trapped ion orbits for 80 and 5 keV deuterium ions.

in the edge indicates that fast thermal ions can execute collisionless trapped orbits. Ion orbit computations were performed with a guiding center code that assumes constant magnetic moment. In Fig. 4, we show the resulting guiding center orbits. A counter-injected 80 keV D ion is launched 6.5 cm inside the last closed flux surface (LCFS) on the midplane at the pitch angle of the injected neutral and initially will move downward for DIII-D topology. This beam ion then strikes the shelf on the first swing outward (the full orbit is shown as if the boundary did not stop it). This class of ions will clearly deliver heat to the upper baffle near $R = 170$ cm but since this heating feature correlates with the EHO we suspect that these beam ions orbits are not the cause of the increased baffle heating during the EHO. Full computations are yet to be done on prompt beam loss to the baffle, taking into account the vertical extent of the NB source.

Also shown in Fig. 4 is a 5 keV D ion started 1 cm beyond the LCFS and with the banana tip just contacting the baffle. This energy was chosen to correspond to the CER measurements. The interesting feature of this orbit is that the banana precession frequency is 1.2 kHz, very similar to the modulation frequency of the particle flux mentioned above. It is possible that these orbits are being bunched toroidally, perhaps by interaction with the EHO, and thus giving rise to a modulation in the lost orbit flux at the precession frequency. Indeed, the bounce frequency of this orbit is $f_b \sim 6.3$ kHz, which is not too different from the fundamental EHO frequency. We are in the process of doing extensive orbit surveys including the edge electric field, which modifies the toroidal precession velocity of the thermal ions, and seeing if there can be resonances between f_b and the EHO frequency, or the harmonics.

4. Summary and conclusions

The QH and QDB exhibit H-mode confinement for a duration of many energy confinement times without ELMs and therefore without divertor heat pulses. This is a desirable characteristic for an operating mode in future large tokamaks, in which energetic ELM heat pulses would damage the divertor surfaces. The QH- and QDB-modes have an H-mode edge, and the ELMs are replaced by an EHO. The EHO serves a function similar to ELMs in that it continuously ejects particles from the separatrix, which allows the plasma to be pumped effectively. This is unlike transient standard ELM-free modes, which at this stage in their research sustain runaway density due to uncontrolled particle confinement, suffer a large ELM, and then revert to standard ELMing H-mode.

We see a q_{div} peak on the shelf that we ascribe to fast ions hitting the surface. A diffuse population of 3–7 keV ions is found in the SOL, present in the ELMing phase of the discharges and remaining in the QH phase. The measurements by CER are of carbon ions, but we deduce a population of hot deuterium ions. The measured carbon ions appear to be a Maxwellian population but the density is too low to be collisional. This is born out by the low temperatures measured for electrons in the SOL.

From the global behavior, we know that the EHO throws particles into the SOL, which allows pumping for density control. This is similar to the time-averaged behavior of ELMs. We propose that the EHO also acts on trapped particles near the separatrix, to put some of them on orbits that collide with the divertor baffle.

Both CER and the reciprocating Langmuir probe show much larger E_R in the boundary than in other confinement modes. The large E_R will be important in determining the trapped particle orbits.

Beam ion orbit losses may contribute to baffle heating, but only a weak effect is seen from outer gap sweeps. No effect is measured from changing to different beam locations, or a different mix of left and right beams. We believe it is more likely the baffle heating is due to a class of lower-energy trapped thermal ions, whose orbits are perturbed by the EHO enough to hit the baffle. We plan more detailed orbit calculations including the effect of electric fields.

There is a localized high q_{div} at the inner strike point. If the EHO is playing a role in the broadening of the outer SOL, this indication of a narrow SOL could indicate that the EHO is primarily effective on the outboard side. This is similar to behavior ascribed to ELMs, but for the EHO it could be caused by a lack of trapped particles on the inside.

If the trapped ion orbits are important in producing the EHO and QH-mode, as well as being acted on by the mode, it is likely to be collisionality of the edge that is important rather than density. If the collisionality is too high, the banana orbits or bunching mechanism could be disrupted. At higher powers and temperatures, the QH-mode may appear at higher densities. There may not be sufficient input power to test this in present devices.

Acknowledgements

Work supported by US Department of Energy under Contracts W-7405-ENG-48, DE-AC03-99ER54463, DE-AC04-94AL85000, and Grant DE-FG03-95ER54294.

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