

Observations of fast ion loss to the plasma facing wall during quiescent H-modes on DIII-D

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Abstract

The Quiescent H-mode exhibits H-mode levels of confinement and edge pedestal pressures, but does not exhibit ELMs. To date this mode has only been observed in tokamaks during beam heating with some or all of the beams injected counter to the direction of plasma current. During QH-mode, fast ion loss to the low field side plasma facing surfaces has been observed. Some of the fast ion loss is calculated to be the result of outwardly directed banana orbits of the energetic beam ions created in the edge region. Other fast ion loss has been observed to be associated with bursts or oscillations in broadband, high-frequency, magnetic fluctuations. The relationship of the fast ion loss to the ELM stabilization or edge particle transport during QH-mode is not yet understood.

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1. Introduction

The quiescent high confinement mode (QH-mode) represents a clear demonstration that an edge transport barrier producing good global confinement, equal to that in standard H-mode, can be achieved in a quasi-stationary plasma with no edge localized modes (ELMs) [1–3]. This mode of operation is of interest for future burning plasma experiments, where H-mode level of

confinement is required for high fusion gain, but where ELMs that typically accompany H-mode confinement are predicted to be very destructive to plasma facing surfaces. During QH-mode operation the edge barrier remains stable and provides a high pedestal pressure as required for high core confinement, yet allows good particle and impurity control without the deleterious effects of ELMs.

QH-modes are a valuable tool for pedestal stability research [4–6], as well as core plasma profile control [2,7,8]. Long duration QH-modes have been observed in DIII-D, ASDEX-Upgrade [6], and JT-60U [9]. QH-modes are always accompanied by continuous MHD

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activity, usually in the form of a saturated, coherent multi-harmonic mode with toroidal mode numbers ranging from 1 to 10. The nature of this mode, called the edge harmonic oscillation (EHO) and located near the region of the pedestal, has not yet been identified.

In all cases QH-modes are observed only in neutral beam heated discharges with some beams injected counter to the direction of plasma current. Usually the beam heating is dominantly counter. Counter injection is known to be prone to fast ion loss to the wall, and previous work has shown that the resulting wall heating can be significant [10], equal to about half of the total heat flux to the divertor region. In this paper we will focus on fast ion loss to the wall. Past work recognized the importance of prompt fast ion loss to the main wall due to the banana orbits of energetic ions born through ionization of the beam neutrals in the edge region. Recently, QH-mode has been observed in counter injected discharges designed to avoid prompt fast ion loss due to these banana excursions to the wall [5,6]. In this paper we will report on the observation of new fast ion loss mechanisms during these counter injected discharges that are associated with high frequency, broadband magnetic fluctuations.

2. Fast ion loss in QH-mode

In counter-injected, beam-heated discharges on DIII-D, some fast ions created by ionization of beam neutrals in the region of the pedestal are lost to the outer wall in a single banana orbit [10]. To minimize outer wall heating by the beam ions, these discharges are typically operated with a large (>10 cm) gap between the separatrix location at the midplane and the closest limiting surface. However, as shown in Fig. 1, orbits from the four beams on DIII-D that are injected nearly tangentially (Tang-beams) are still lost at the entrance to the upper divertor in a single banana orbit. Promptly lost ions may contribute to localized heating of the baffle, as reported in [10]. The beam ion losses may also contribute to a very deep (~ 100 kV/m) and narrow radial electric field well in the region of the pedestal [1,5]. Another indirect indicator that prompt fast ion loss may be important to QH is the fact that a database of QH-mode operation on DIII-D showed a relationship to QH-mode duration and the injection of Tang-beams [11]. With the large outer gap, the three beams on DIII-D that are injected at a more perpendicular angle (Perp-beams) are not promptly lost to the wall. Motivated by these observations, QH-modes were attempted with only Tang-beams and only Perp-beams. Time traces from two of these QH-mode discharges are shown in Fig. 2. The plasma shapes are very similar to that shown in Fig. 1. As discussed in [4,5] QH-mode is initiated and sustained for a significant duration

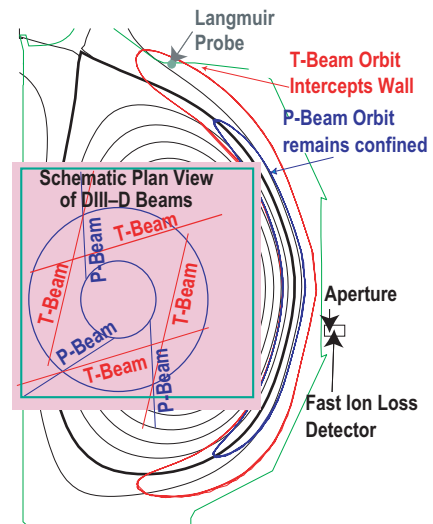


Fig. 1. Calculated orbits of fast ions created by ionization of heating beam neutrals at the midplane near the top of the pedestal are shown for both directions of beam injection on DIII-D. The inset shows a schematic of the beam injection angles. Orbit squeezing effects by the large edge E_r well are included, but are not significant for beams ions. The locations of the Langmuir probe on the upper baffle and the midplane fast ion detector are also shown.

with Perp-beams only, indicating that prompt beam ion loss is not essential.

Recent analysis has indicated that another fast ion loss mechanism exists in the Perp-beam only discharge that is not present in the Tang-beam shot. Shown in Fig. 2(e)–(f) are the time traces from a fast ion detector [12] located just outside the limiting surface at the midplane of DIII-D (Fig. 1). The signal is very quiet in the Tang-beam discharge, as might be expected since ion orbit calculations indicate that the edge beam ions are scraped off by the upper baffle (Fig. 1) before they reach the midplane wall. However in the Perp-beam shot, there is significant bursty ion loss activity seen by the midplane detector. Ion orbit calculations indicate these lost ions may originate in the outer part of the plasma, near the lower turning point of the banana orbit for the Perp-beam ions shown in Fig. 1. The lost ion bursts are highly correlated in time with broadband high-frequency magnetic fluctuations seen on \dot{B} probes located on the outboard side, just below the outer midplane (the magnetic signal is much quieter in the Tang-beam discharge). Fig. 3 shows the \dot{B} signal over a brief period of time during a Perp-beam only QH phase. A high frequency burst is clearly visible at 3230.6 s, imposed over the EHO (dominantly $n=2$) oscillation at 15 kHz. The time locations of the magnetic bursts are easily seen in the absolute value of the time derivative of the \dot{B} signal, shown in Fig. 4 and compared to the fast

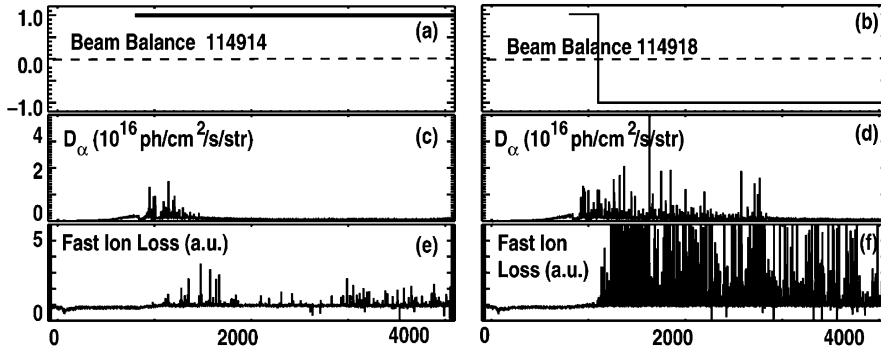


Fig. 2. Time dependence of the Tang- and Perp-beam balance, divertor recycling, and the fast ion loss signal are shown for two discharges, 114914 with injection of three Tang-beams and 114918 with injection of three Perp-beams. Injected beam power is 7 MW and plasma current is 1.3 MA in both discharges.

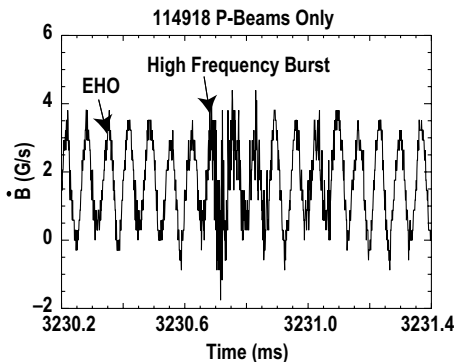


Fig. 3. The \dot{B} signal is shown over a brief period during QH-mode. The EHO oscillation at about 15 kHz is easily visible. A high frequency magnetic burst is apparent near 3230.6 ms.

ion loss detector signal. There is an apparent correlation of the timing of the magnetic and fast ion bursts. Unfortunately, the digitization rate (10 kHz) of the fast ion signal was insufficient to completely characterize the bursts, and some bursts might have been missed. It is clear the majority of the bursts have a duration of $<100 \mu\text{s}$. The red stars in Fig. 4 represent the time locations where the integrated power above 200 kHz in FFTs of the \dot{B} signal, taken on a $100 \mu\text{s}$ time step, exceed ~ 2 times the average value. Over the period of time from 2900 to 3100 ms, approximately 272 lost ion bursts were observed, i.e. an average appearance rate of 1.4 kHz. Of those, 212 fell within $100 \mu\text{s}$ of a high-frequency magnetic burst, whereas if they had been randomly distributed in time, on average only 90 would be expected to correlate. These bursts have not been identified in any other fluctuation diagnostic, and their spatial location in the plasma has not been established. During the QH period from 2900 to 3100 ms of the Tang-beam only discharge shown in Fig. 2, only 43 lost ion bursts are observed; many of which are correlated with magnetic bursts.

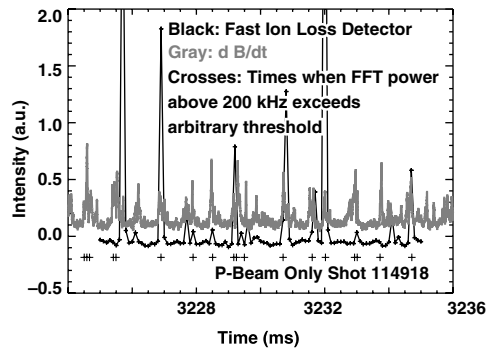


Fig. 4. The signal from the midplane fast ion loss detector (black) is compared to the absolute value of time derivative of the \dot{B} signal (gray), which emphasizes the high frequency bursts. The black crosses show the time location where the integrated spectral power above 200 kHz, obtained from FFTs taken on a $100 \mu\text{s}$ time step, exceeds twice the average value.

The edge radial electric field profiles measured during the QH phase in these two discharges are very similar, [5].

The bursts are present during both the QH phase and the ELMing phase. During the ELMing phase, the ELMs are a source of intense high-frequency magnetic bursts as well as fast ion loss. Bursts similar to those seen during the QH phase are seen between ELMs, but are not present for a few ms after each ELM.

Examination of Langmuir probe ion saturation current at the upper baffle (Fig. 1) during a mixed beam discharge, 106999, discussed in [10] reveals a slightly different relationship of ion loss to magnetic activity. The observed time behavior of the ion saturation current over a 20 ms period of the QH phase in this discharge is shown in Fig. 5. The ion current shows intermittency, with bursts of longer duration of about 0.5 ms, a variable amplitude, and a more regular but slower appearance rate of about 800 Hz compared to the fast ion

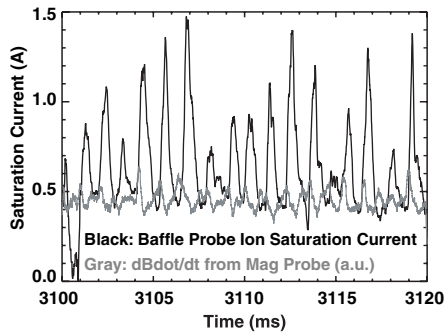


Fig. 5. The ion saturation current to the Langmuir probe (black) in the upper baffle is compared to the absolute value of the time derivative of the \dot{B} signal (gray).

loss in the Perp-beam only shot in Fig. 4. These bursts are also associated with high-frequency MHD activity. Shown in Fig. 5 is the time derivative of the \dot{B} signal, averaged over 200 μ s. It is clear, without any statistical analysis, that there is a strong correlation in the frequency and phase of the oscillatory behavior of fast ion loss amplitude and the amplitude of the high frequency MHD activity. Unfortunately, the Langmuir probe was not functional during the discharges in Fig. 2, and the fast ion loss detector was not functional during 106999.

Fast Fourier transforms of the \dot{B} signals indicate the bursty, high-frequency MHD activity is broadband, extending from 150 to 500 kHz (the Nyquist limit). In DIII-D no evidence has been found of the 400 kHz coherent magnetic mode seen in ASDEX-Upgrade [6].

3. Discussion

The radial electric field well, which exists just inside the pedestal in most discharges, increases in depth going from L-mode to H-mode, and in counter injection it increases again in going to QH-mode. In QH-mode the well can extend to a depth of -100 kV/m, $\sim 2X$ deeper than in ELMy H-mode, and is very narrow with a width of ~ 1 cm. While the details of the E_r structure are likely determined primarily by the sharp gradients of the plasma profiles in the pedestal [13], the fast ion loss would tend to enhance the depth over that found in co-injected discharges.

Beam ion orbit modeling indicated that the Tang-beams on DIII-D produce prompt beam ion loss in QH-mode, while the Perp beams do not. A database of QH-mode performance over a period of three years indicated a dependence of the duration of QH-mode phases on the power of the Tang-beams, but no data was available in discharges with only Perp-beams. To test the hypothesis, discharges were carried out in coun-

ter injection with three Perp-beams, and with three Tang-beams. QH-modes were obtained in both cases, indicating that prompt beam ion loss is not required for QH formation. It was noticed that QH-mode forms more quickly and lasts longer with Tang-beam injection. E_r measurements showed the well width, depth, and location are very similar in these two cases. Recent analysis has revealed that a new mechanism for fast ion loss is active in the Perp-beam discharges. This mechanism is observed to eject ions in bursts to the midplane fast ion detector, rather than the upper divertor baffle. The bursts are strongly correlated with high frequency, broadband magnetic fluctuation activity. The observed bursty ion loss is about an order of magnitude more active in the Perp-beam discharges than in the Tang-beam discharges. Even though the Perp-beam discharges do not suffer prompt beam ion loss, this new fast ion loss mechanism may be making some contribution to the edge E_r well. A reexamination of QH discharges with mixed beam injection has revealed that a similar mechanism, correlated with high-frequency, broadband magnetic activity, is making some contribution to ion loss to the upper baffle as well.

More data is needed to draw stronger conclusions concerning the role of fast ion loss and the E_r well in QH-mode. Simultaneous data from the midplane fast ion loss detector, the Langmuir probe on the upper baffle, and the local heat flux measurement do not exist on a set of Perp vs. Tang beam discharges. More QH-mode experiments will be conducted this year to investigate the fast ion loss in more detail. We will also attempt to localize the position of the high frequency mode inside the plasma using the extensive spatially resolving fluctuation diagnostics on DIII-D. A better characterization of the fast ion loss mechanisms, intensity, and wall interaction is needed for the first wall design for future devices based on the QH-mode.

Acknowledgments

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