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Correlation of neutral beam injection parameters and core β with anomalous first-wall heating during QH-mode

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Abstract. Anomalous first-wall heating has been observed far from the divertor strike point during QH-mode in DIII-D, with measured heat flux comparable to that at the outer strike point. The data are consistent with deuterium ions of approximately the pedestal energy carrying the anomalous heat flux. Although an instability has not been identified that is correlated with the anomalous heat flux, two classes of behavior have been observed: one in which the anomalous heat flux depends linearly on core β, and another class with no β-dependence. The anomalous heat flux depends strongly on the injected beam energy of the non-tangentially-injected neutral beams but not that of the tangential beams.

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PSI-17 keywords: DIII-D, divertor, Edge pedestal, SOL Plasma boundary

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1. Introduction

QH-mode is a regime of sustained H-mode confinement without edge localized modes (ELMs), and is of interest for future high-power tokamaks because it avoids divertor damage by the pulsed heat loads of ELMs [1-4]. In certain conditions during DIII-D QH-mode upper-single-null discharges, we detected localized heating of the upper outer baffle far outside the strike point. The heat flux there calculated from infrared camera measurements is in many cases comparable to the heat flux at the outer strike point. This could be a significant cause of first-wall damage in a higher-power machine, particularly if this heat flux occurs in a location not designed to accept high power.

Based on measurements from charge exchange recombination (CER) and fixed Langmuir probes, we attribute this heating to impact by moderate energy (~5 keV) ions lost from the core plasma. We find a class of QH discharges in which the power deposited in this area of the upper outer baffle depends linearly on core β, and another class in which the baffle heating is lower by more than a factor of three and does not depend on core β. The β-dependent case occurred in discharges in which less-tangential neutral beams were injected at 75 keV for the full-energy component. The beta-independent case had the less-tangential beams at 71 keV. Variation of the energy of more-tangential beams did not have an observable effect on the ion loss.

The dependence of the anomalous power loss on core β and beam energy, and a lack of correlation with edge parameters, suggests that a core instability is responsible for the ion loss. The strong effect of less-tangential beams may be an indication of the importance of trapped particles in the loss mechanism. There is as yet no obvious reason the anomalous particle loss should be specific to QH-mode, but it has not been observed in other high-performance regimes such as weak or reversed central shear, hybrid, ELM-free, or VH modes.

II. Analysis

For this paper we analyzed a large group of QH-mode discharges [5], with toroidal field of 2 T, plasma current 1.3 MA, and all upper single null. Figure 1 shows heat flux profiles on the upper divertor for a QH and ELMing phase of a discharge, overlaid on the divertor structure. The heat flux peak in the QH profile at $R = 1.7$ m corresponds to field lines 4 cm from the separatrix when mapped to the outer midplane. The power deposited on the upper outer baffle (UOB) was calculated from divertor tile surface temperature data obtained with an infrared camera, by assuming toroidal symmetry and integrating the heat flux from major radius $R =$ 1.60 m to 1.72 m (the end of the data).

By comparing QH- and ELMing H-mode phases of the discharges, we found a class of QH-modes in which the power deposited on the UOB depends linearly on core β, and another class in which the deposited power is approximately three to four times lower, and independent of core β (Fig. 2) The β-dependent points are plotted as circles. A few outlying points were discarded for this plot. A comparable correlation was not found for pedestal β.

On further investigation of this surprising result, we found the two classes of points occurred in discharges on three separate days. Two of the days produced the β-dependent result, with an intervening day containing the β-independent data. The significant difference between these days was the accelerating voltage at which certain neutral beam heating sources were run for injection into the plasma. The geometry for more- and less-tangential sources at the time of these experiments is shown in Fig. 3. The less-tangential beams intersected the magnetic axis at 47 degrees, and the more-tangential at 63 degrees. In Figs. 4, 5, and 6 are shown histogram plots of neutral beam source voltage for different beam sources. For each source the β-dependent (red) and β-independent cases (blue) are plotted on separate graphs.

For almost all cases in the β-dependent set, the less-tangential neutral beams were operated at 75 keV. Operation near 70 keV was associated predominantly with UOB power that was β-independent. This very strong dependence on the energy of the injected deuterons points to an effect of ion orbit geometry.

During QH-mode, charge exchange recombination (CER) measurements reveal unusually energetic carbon ions in the scrape-off layer (SOL), around 5 keV, which is similar to the carbon ion temperature in the pedestal [1,2]. There is also a cold population of carbon ions in the SOL near the separatrix that dominates the density as well as the CER spectra in that region. Tangentially- and vertically-viewing CER chords show different effective temperatures of the hot SOL carbon population, indicating a non-Maxwellian ion distribution. The vertical view spectra are fit in most of the SOL by ion temperatures similar to the pedestal temperature, but the tangential view shows higher energy. The deuteron energies are not measured directly.

To further examine the nature of particles striking the UOB, we analyzed data from a Langmuir probe located nearly at the peak of the anomalous heat flux on the UOB for a similar QH discharge. These data showed evidence of ions at higher energy than the probe could discriminate. Using the Langmuir probe-measured particle flux and assuming a deuteron energy equal to a 5 keV CER-measured SOL carbon-ion energy to calculate a heat flux, the result was similar to the heat flux derived from IR camera data. In addition, the inversion of bolometer data shows a localized zone of radiation near the UOB heat flux peak.

III. Interpretation

The measurements lead us to conclude that ions of energy approximately equal to those in the pedestal struck the UOB preferentially at the location of the heat flux peak. The distance at the outer midplane from the separatrix to the flux surface of the UOB intersection point is about 5 times the width of the strike point. Some particle orbit calculations show a possibility of 5 keV particles on banana orbits striking the upper outer baffle (ref) as shown in Fig. 4 of Ref. [6].

The question remains as to what causes the ions to be pushed out of the plasma preferentially when a particular beam energy is injected. We believe this is associated with an instability that is yet to be identified. Interestingly, we see from far infrared scattering (FIR) a multitude of core-localized reversed shear Alfvén eigenmodes (RSAE) (also known as Alfvén Cascades) in the majority of these discharges [7]. However, after examination, we do not find these modes correlate directly with the two different UOB power trends.

Core tearing modes are present in many of these discharges. However, there is at that time a change in magnetic geometry shifting the plasma closer to the upper baffle, so that the effect of the tearing modes on baffle heat flux cannot be determined unambiguously. Evidence of numerous other instabilities manifests in these discharges, but we have not yet shown any to correlate with the UOB power. We plan to continue the search for signatures of instabilities that correlate with and may be the cause of the UOB power deposition. It will be important in future QH mode operation to understand, predict, and control the location of heat deposition.

Acknowledgment

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Captions

Fig. 1. Divertor tile heat flux vs major radius. The solid curve is during an ELMing phase and the dotted curve during a QH phase of the same discharge. The divertor geometry is superimposed. ISP is the inner strike point position, OSP is the outer strike point.

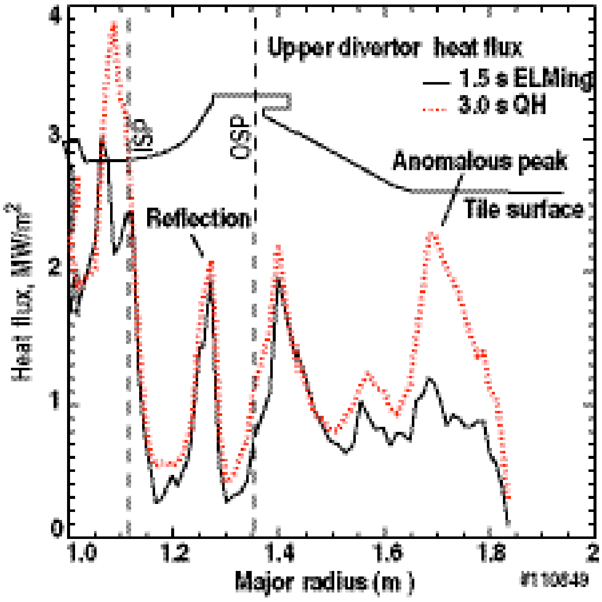
Fig. 2. UOB power vs β. Circles form the β-dependent group, and the squares make up the β-independent group.

Fig. 3. Neutral beam geometry for DIII-D at the time of these experiments. The beam sources are labeled by the toroidal angle of the injection port. Less-tangential beams intersect the inner wall but more-tangential beams do not.

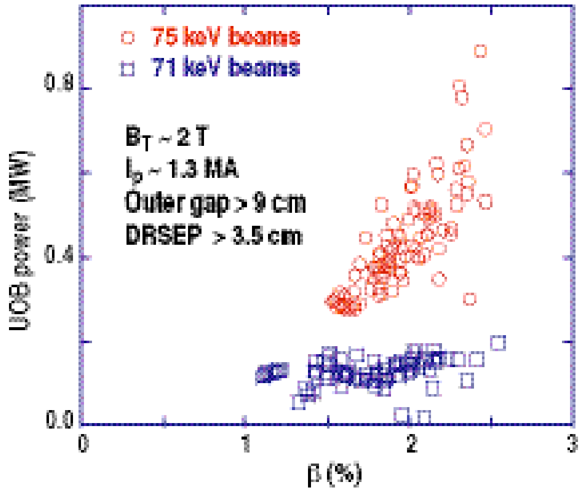
Fig. 4. Neutral beam 150 degree accelerating voltage for (a) β-dependent group and (b) β-independent group.

Fig. 5. Neutral beam 210 degree accelerating voltage for (a) β-dependent group and (b) β-independent group.

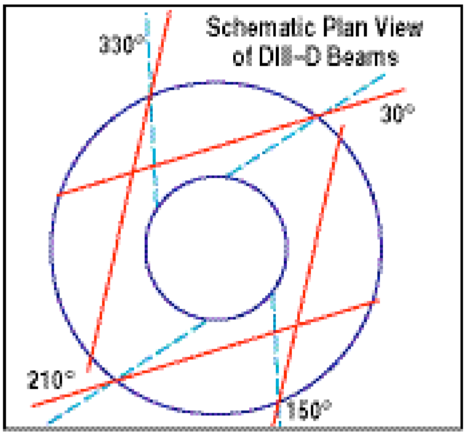
Fig. 6. Neutral beam 330 degree accelerating voltage for (a) β-dependent group and (b) β-independent group.



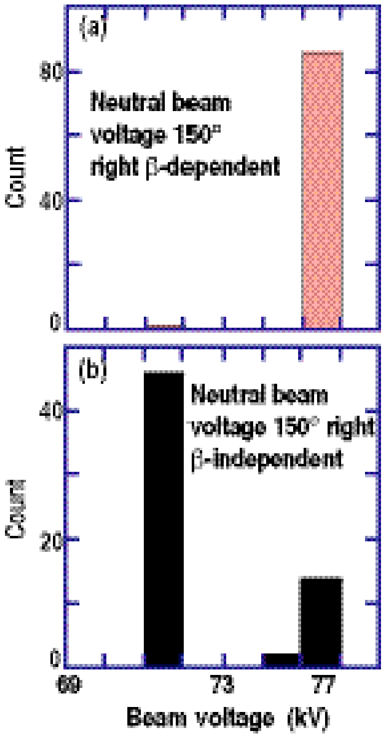
C.J. Lasnier Figure 1



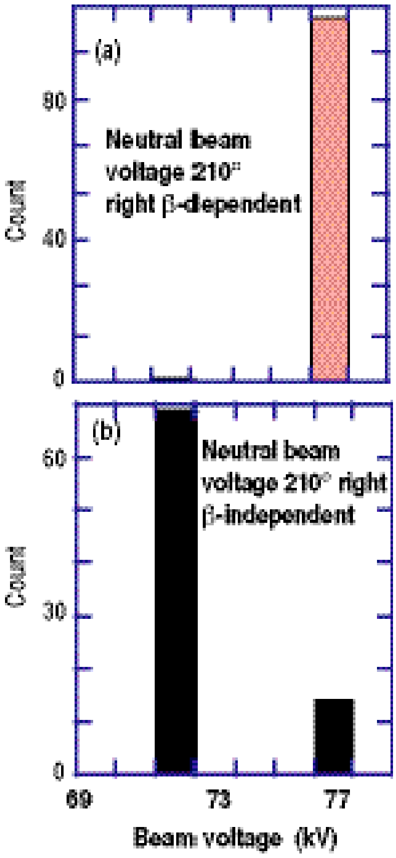
C.J. Lasnier Figure 2



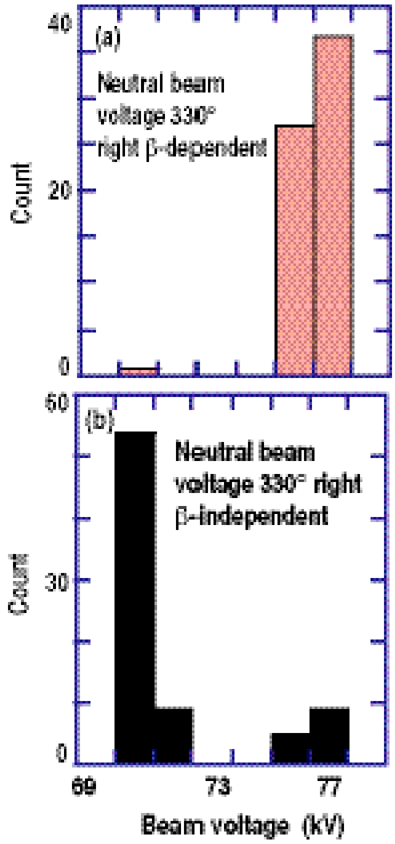
C.J. Lasnier   Figure 3



C.J. Lasnier Figure 4



C.J. Lasnier Figure 5



C.J. Lasnier Figure 6