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Fueling of QH-mode plasmas on DIII-D with pellets and gas

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Abstract

The quiescent high confinement mode (QH-mode) discovered on DIII-D [K.H. Burrell et al. Phys. Plasmas 8 (2001) 2153; C.M. Greenfield et al. Phys. Rev. Lett. 86 (2001) 4544] has the promising features of stationary good H-mode plasma confinement with an H-mode edge, but without the periodic edge localized modes (ELMs) common in H-mode that produce a divertor pulsed heat load. Experiments have been carried out with pellet and gas fueling to determine if the QH-mode is robust to theses edge perturbations. Pellets of different sizes were injected from several different locations [L.R. Baylor, T.C. Jernigan et al. J. Nucl. Mater. 290 (2001) 398] and gas puffs were introduced to study core fueling in QH-mode plasmas. The QH-mode is generally a low density operating regime and so there is interest in developing a fueling scheme that can lead to high density to make the QH-mode attractive as a burning plasma scenario. Results indicate that the QH-mode is maintained with small perturbations in density, however large pellet perturbations and gas puffs lead to an almost instantaneous transition to ELMing H-mode.

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1. Introduction

The ideal burning plasma scenario has good thermal confinement with high density and robust edge plasma without periodic pulsed heat loads that can limit the lifetime of the divertor material. The QH-mode discovered on DIII-D is a potential regime that could lead to a burning plasma operating mode due to its high confinement and ELM free H-mode edge. Research in this regime has been performed to determine if the QH-mode can be extended to higher operating density by fueling the plasma with pellets or gas. In this paper we review the QH-mode operating regime on DIII-D and give the results of experiments with pellet injection from different injection locations and from gas fueling introduced from the outside above the midplane.

The QH-mode on DIII-D is obtained in single and double-null divertor plasma configurations [4] with deuterium neutral beam injection (NBI) directed counter to the plasma current direction as the dominant heating method which also provides a strong angular momentum source that drives toroidal rotation.

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A unique characteristic of this operating mode is an edge harmonic oscillation (EHO) that enhances the edge particle flux exiting the plasma without significantly affecting the thermal transport [1,2]. For these experiments the QH-mode was obtained at plasma currents of 1.3–1.6 MA and a toroidal field of 1.9–2 T with line average electron density near $2 \times 10^{19}\,m^{-3}$ and a pedestal density of $\sim 1 \times 10^{19}\,m^{-3}$. A similar operating regime has been seen on ASDEX-U [5] which is also found in a relatively low density operational window.

Fueling fusion plasmas with the injection of frozen pellets of hydrogenic isotopes has been a successful method to raise the operating plasma density in many confinement devices [6]. Recently the research in this area has concentrated on comparison of pellet fueling from different injection locations to optimize the fueling efficiency and minimize the interaction with ELMs. In general pellets injected from the inner wall or high field side (HFS) has been shown to lead to deeper, more efficient fueling of tokamak plasmas than from other locations and has been found to trigger ELMs that are similar to the naturally occurring ELMs while other injection locations can lead to large ELMs that significantly reduce confinement [7,8]. In this study on DIII-D, we examine the effectiveness of gas and pellet fueling to raise the density in QH-mode while avoiding the triggering of ELMs.

The pellet injector on DIII-D [9] produces 1.8-mm and 2.7-mm diameter and length cylindrical deuterium pellets ($\sim 2 \times 10^{20}$ atoms and $\sim 6 \times 10^{20}$ atoms respectively) with speeds of 100–1000 m/s. Curved guide tubes have been installed to connect the three barrels of the injector to vertical ports ($V+1$ and $V+3$) and to two inner wall locations (HFS 45 and HFS mid) as shown in Ref. [3]. Gas fueling in these experiments was provided from the GASA port, which is located in an upper port above the outside midplane also shown in Ref. [3].

2. Pellet and gas fueling results

Deuterium gas was injected from the GASA valve during the QH-mode phase of several discharges at different flow rates from 2–50 torr-L/s. An example where $\sim$40 torr-L/s (5 Pa-m^3/s) of deuterium is puffed in using feedback control is shown in Fig. 1. Here it is observed that the gas puff leads to an increase in line average and pedestal electron density with an efficiency of $\sim$10% over the duration of the puff, however after 200 ms of fueling, the edge harmonic oscillation is observed to disappear and periodic ELMs begin to appear while the density continues to increase. The line average density increased by 25% and pedestal by 30% before the ELMing occurs and the EHO frequency and edge toroidal rotation velocity of carbon decreases while the density rises. At larger flow rates the delay to start ELMing is reduced

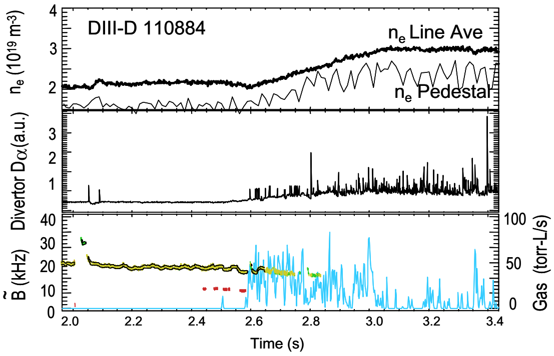

Fig. 1. Temporal evolution of the line average and pedestal electron density, divertor D_α emission, gas fueling rate, and edge magnetic fluctuation frequency in a gas fuelled QH-mode discharge. ELMs are observed to occur shortly after the gas puff begins and EHO ends.

to essentially zero. At very low gas flow rates of a few torr-L/s the density is not observed to increase and the QH-mode persists during the gas flow period.

Deuterium pellets of both 1.8-mm and 2.7-mm diameter cylinders of equal length were injected into QH-mode discharges from all of the available injection locations to examine the response of the plasma. An example of multiple pellets injected from the $V+3$ port is shown in Fig. 2. The initial pellet raises the density by 30% and initially the $n = 2$ dominated EHO from magnetic probe measurements is observed to disappear for about 50 ms while an ELM like event occurs. The EHO then reappears but at a reduced frequency while the increased line average and pedestal density both persist. A reduction in the toroidal rotation speed of carbon near the edge is

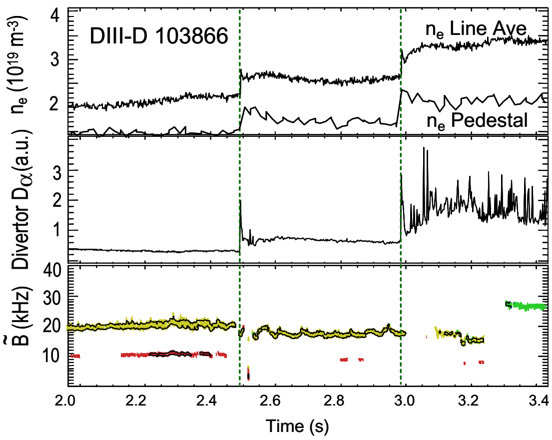

Fig. 2. Temporal evolution of the line average and pedestal electron density, divertor D_α emission, and edge magnetic fluctuation frequency in a pellet fueled QH-mode. The pellets are 2.7 mm size injected from the $V+3$ vertical port outside the magnetic axis.

also observed after the pellet. A second pellet increases the density by an equal amount of the first and several ELMs begin within a few ms followed by constant ELMing behavior with the increased density. The EHO disappears for nearly 100 ms after the pellet, but reappears for a short time before ending completely after 200 ms.

From these experiments it was observed that the smaller the pellet perturbation the less likely was constant ELMing to occur. Very large density perturbations from the 2.7 mm pellets with deep penetration were found to cause the plasma to enter a continuous ELMing state immediately after injection. Smaller 1.8 mm pellets led to fewer ELMs being generated after injection. The $V+3$ injection location was found to produce the fewest ELMs and in fact did not generate any ELMs in one case at high NBI power.

3. Fueling profiles and efficiency

The density perturbation size and depth from these pellets was very much dependent on the injection location and pellet size. In the case shown in Fig. 2, the density perturbation was localized to the outer ~1/3 of the plasma radius as shown in the density profile plots in Fig. 3. The observed localized outer perturbation is expected from this vertical pellet trajectory as the tangency radius for this injection line is at $\rho = 0.65$. The pedestal density is observed to nearly double from the pellet event in this case, which does not instigate continuous ELMing (see Fig. 4).

The gas fueling efficiency in these experiments defined as the percentage of fuel introduced that is retained in the core plasma after the gas puff is completed is fairly low but higher than in other ELMing H-mode experiments [3]. Efficiencies of up to ~10% were observed with

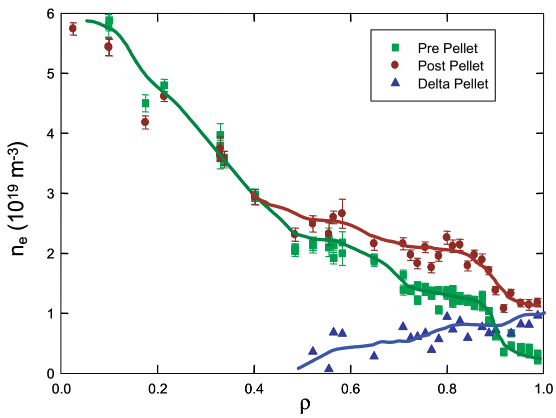

Fig. 3. The fueling source profile from the pellet injected in the core plasma in the discharge from Fig. 1.

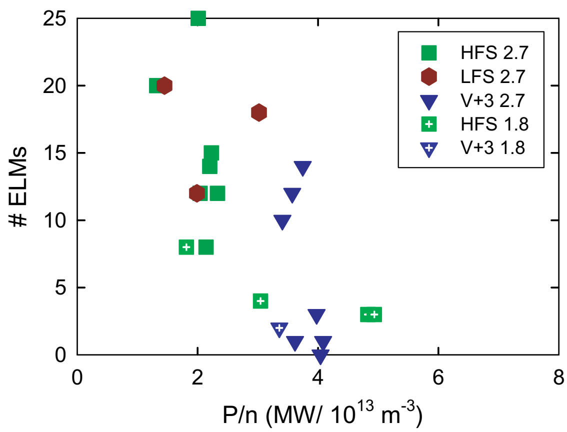

Fig. 4. The number of ELMs that occur in 500 ms after pellet injection as a function of the NBI power divided by the line average density.

the higher gas flow rates attempted. The pellet fueling efficiency was similar to previous reported results in H-mode plasmas [3] with the $V+3$ injection line leading to relatively low efficiency due to the edge localized perturbation and ExB drift effect hypothesized to eject mass out of the plasma [8].

4. Discussion

In order to compare the ELM generation from the fueling in these experiments we have plotted the number of ELMs that occur in the 500 ms period after beginning the fueling as a function of the power injected in the plasma divided by the line average density. We find that at high power per plasma particle the number of ELMs generated is smaller and can indeed be zero with a small enough density perturbation. However we found that with multiple pellet injection the second pellet in a sequence would raise the density to a high enough level that a significant number of ELMs would occur. In no cases did we find a multiple injection scenario where the plasma could withstand the density rise without starting to generate ELMs. From these results it appears that smaller higher repetition rate pellets may lead to a way to better optimize the QH-mode density without leading to ELMs.

In conclusion, gas and pellet fueling experiments on DIII-D in the standard QH-mode shape have been used to examine the fueling from different fuel injection locations in QH-mode. Gas fueling efficiency in QH-mode is fairly low and when strong puffing is used the plasma quickly responds with a higher pedestal density and strong ELMs. Pellet injection in QH-mode has much higher fueling efficiency than gas fueling due to deeper mass penetration and can lead to ~30% higher line average density without ELMs. However attempts to increase the density with multiple pellets in this plasma configuration led to ELMing conditions once the pedestal density reaches $\sim 2 \times 10^{19}\,\mathrm{m}^{-3}$. Further studies to investigate both gas and small pellet fueling in the QH-mode plasma regime at higher triangularity where higher pedestal electron densities above $6 \times 10^{19}\,\mathrm{m}^{-3}$ have been observed [4,10] are planned for the future. The physics of the QH-mode edge remains to be fully understood, but clearly the pedestal density plays a key role in the EHO, which appears to be necessary to remain in the QH-mode regime [4]. The effect of fueling on the EHO and toroidal rotation and associated radial electric field structure may lead to a deeper understanding of this regime. The question remains whether the QH-mode can be extended to a high density operating regime that would be more attractive for a burning plasma experiment.

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