High Performance H–mode Plasmas at Densities Above the Greenwald Limit* **EX**

M.A. Mahdavi,[1] T.H. Osborne,[1] R.J. La haye,[1] M.E. Fenstermacher,[2] A.W. Leonard,[1] R. Maingi,[3] T.W. Petrie,[1] M.S. Chu,[1] J.G. Watkins,[4] S.L. Allen,[2] J.A. Boedo,[5] N.H. Brooks,[1] R.J. Colchin,[3] T.E. Evans,[1] R.C. Isler,[3] C.J. Lasnier,[2] R.A. Moyer,[5] M.J. Schaffer,[1] P. Stangeby,[6] M.R. Wade,[3] W.P. West,[1] and D.G. Whyte[5]

A critical fusion reactor issue is understanding the density limit and density effects on plasma confinement and stability. While the ignition criteria and effective radiative heat dispersal require minimum operating densities, the well known but poorly understood Hugill and Greenwald density limit scaling laws indicate that in reactor grade devices access to the desired operating densities would be problematic. Another area of concern is observations made on several tokamaks, notably JET and JT60-U, that confinement in H–mode plasmas degrades at densities even below the Greenwald "limit"; $n_{GW} = I_p(MA)/\pi a^2(m)\times 10^{19}\ m^{-3}$. In this paper we will present results and interpretation of experiments on the DIII–D tokamak where densities up to $1.4 \times n_{GW}$ were reproducibly obtained with combined gas fueling and divertor pumping in H–mode plasmas, without confinement degradation ($H_{ITER89p} = 2$). A remarkable feature of these discharges is that the amplitude of type-I ELMs is a factor of 5 lower than that indicated by a recent multi-device study at lower densities [1].

Density and confinement traces from a high density discharge(I_p=1.2 MA, q_{95}=3.1, triangularity $\delta = 0$) are shown in Fig. 1. In this discharge density was ramped up with fueling at the rate of ~ 14 Pa m^3/s (~100 Torrℓ/s). Since nearly an equal amount of gas is exhausted at the divertor pump, the rate of density rise corresponds to a small fraction of the gas injection rate. In this discharge, the pedestal density saturates at ~ 90% of the Greenwald limit, while the line average density reaches $1.4 \times n_{GW}$. The density peaking factor, defined as the ratio of peak to line average density was <1.5, compared to ~ 1.3 in the reference low density discharges. Initially, due to thermalization of fast particles, the H-factor decreases with density. However, later in the discharge, due to increased thermal component, confinement is restored to its initial value. Confinement data from this series of DIII–D discharges are shown in Fig. 2.

All high density discharges were sawtoothing and displayed type-I ELMs. However, the amplitude of both modes decreased with increasing density. In the high density discharges, as shown in Fig. 3, energy loss per ELM is typically a factor of 5 lower than that of the low density reference discharges and in comparison with the expected value from a recent multi-device study at low density [1]. The reduction in energy loss per ELM is of great importance for design of the next generation devices. According to the multi-device scaling at low

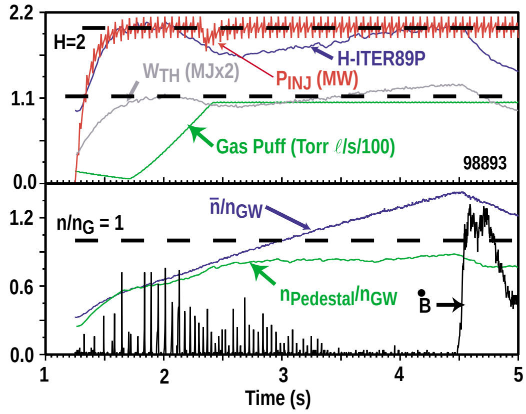

Fig. 1. Density and confinement traces from a high density H–mode discharge. W_{TH} is the plasma thermal energy.

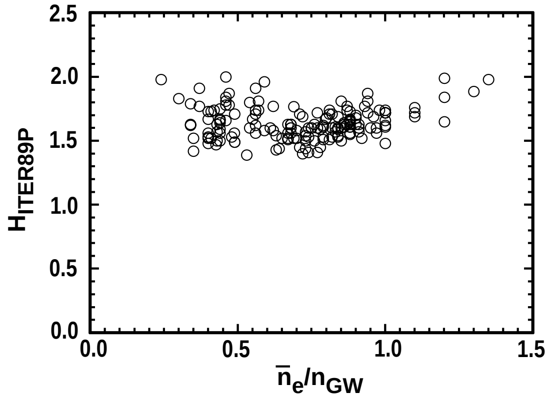

Fig. 2. Normalized confinement versus normalized density from a series of shots with simultaneous gas fueling and divertor pumping.

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[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA email: mahdavi@fusion.gat.com
[2]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[3]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37381, USA
[4]Sandia National Laboratories, P.O. Box 5800, Albuquerque, New Mexico
[5]University of California, San Diego, California, USA
[6]University of Toronto Institute for Aerospace Studies, Toronto, Canada.

density, the expected erosion rate of the proposed graphite target plates of ITER due to type-I ELMs would be a factor of five too large for an acceptable divertor lifetime.

The key to access to high densities in high confinement H–mode is preventing the formation of a cold radiative plasma at the X–point. This was demonstrated in our earlier work [2,3] where densities up to $1.5 \times n_{GW}$ were obtained in ELM free H–mode plasmas ($H_{ITER89p} \sim 1.9$) by controlling the Scrape-Off-Layer through divertor pumping while increasing the core density by pellet fueling. The approach in the experiments reported here was to prevent the formation of a cold radiative zone by increasing the convected component of the parallel heat flux in the SOL by simultaneous gas puffing and divertor pumping. Thus, in contrast to the pellet experiments where the separatrix density was maintained at ~ 0.1 n_{GW}, in the gas fueled discharges the separatrix density was allowed to rise to ~ 0.5 n_{GW}. With the aid of a simple 1-D model it is shown that for a given separatrix density, convection reduces the density and increases the temperature in the vicinity of the X–point, and reduces the recycling neutral source. These changes reduce radiation and conduction heat losses in the vicinity of the X–point. Although in all high density discharges represented in Fig. 2 a low temperature (T_e~2 eV) radiative zone developed in the inner leg of the divertor plasma, in no case the intense radiative zone crossed the separatrix into the main body of the plasma.

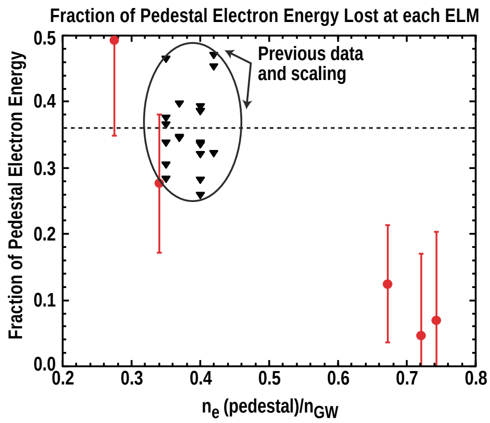

Fig. 3. Energy loss per ELM is typically a factor of 5 lower in high density discharges compared to low density reference discharges and in comparison with a recent multi-device scaling at low density.

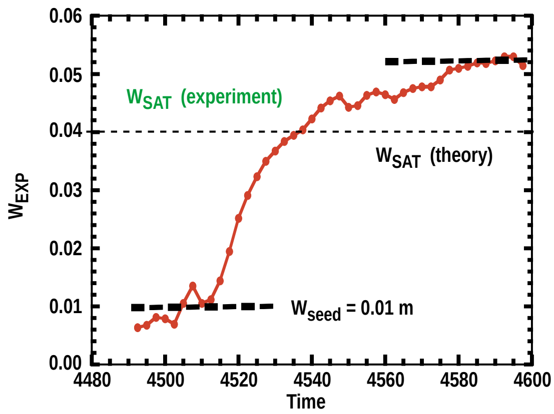

Fig. 4. The saturated island width, deduced from the magnetic measurements, is in good agreement with predictions of NTM theory.

In the highest density discharges, the density rise and improvement in confinement were ultimately terminated by the onset of the 3/2 tearing mode (Fig. 1). In a sequence of discharges where the neutral heating power was varied shot to shot, with increasing power the onset of the tearing mode occurred at an earlier time in the discharge and consequently at a lower density. However the onset of the mode was nearly at the same β_p in all the discharges with similar I_p and B_T, suggesting that the mode is of neoclassical origin. In discharges where the heating power was sustained at a constant level, the mode ultimately saturated, with both density and stored energy reduced to a lower steady-state value. Other evidence that points to the neoclassical nature of the mode are: (1) Δ’, calculated with the aid of PEST3 code, is negative, (2) the mode amplitude initially increases linearly with time, and (3) the saturated island width, deduced from magnetic measurements, is in good agreement with predictions of theory (Fig. 4).

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