GA–A27859

IMPURITY CONFINEMENT TIMES IN QH-MODE PLASMAS ARE SHORTER THAN ELMing PLASMAS ON DIII-D

by
B.A. GRIERSON, K.H. BURRELL, A.M. GAROFALO, W.M. SOLOMON,
A. DIALLO, AND M. O'MULLANE

AUGUST 2014

GENERAL ATOMICS

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

GA–A27859

IMPURITY CONFINEMENT TIMES IN QH-MODE PLASMAS ARE SHORTER THAN ELMing PLASMAS ON DIII-D

by
B.A. GRIERSON,* K.H. BURRELL, A.M. GAROFALO, W.M. SOLOMOM,*
A. DIALLO,* and M. O'MULLANE†

This is a preprint of a paper to be presented at the Forty-First European Physical Society Conf. on Plasma Physics, June 23–27, 2014 in Berlin, Germany and to be published in the *Proceedings.*

*Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA.
†Department of Physics, University of Strathclyde, Glasgow, UK.

Work supported in part by
the U.S. Department of Energy under
DE-AC02-09CH11466 and DE-FC02-04ER54698

GENERAL ATOMICS PROJECT 30200
AUGUST 2014

GENERAL ATOMICS

Impurity Confinement Times in QH-mode Plasmas are Shorter than ELMing Plasmas on DIII-D

B.A. Grierson[1], K.H. Burrell[2], A.M. Garofalo[2], W.M. Solomon[1], A. Diallo[1], M. O'Mullane[3]

[1] Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA
[2] General Atomics, P.O. Box 85608, San Diego, CA 92186-5608, USA
[3] Department of Physics, University of Strathclyde, 107 Rottenrow, Glasgow G4 0NG, UK

Introduction

Sufficient outward radial transport of low-Z particles such as fusion product helium "ash" and medium to high-Z impurities is essential for maintaining a high fuel-ion ratio and low levels of core contaminating impurities and associated radiation in fusion reactors [1, 2]. Impurity concentrations in the tokamak core during stationary H-mode operation are typically regulated by naturally occurring edge localized modes (ELMs). However, the energy released from ELMs can have significant consequences by decreasing the lifetime of plasma-facing components subject to the large localized heat flux that may be unacceptable in ITER. Quiescent H-mode (QH-mode) is an operational regime maintained without ELMs and with constant density and radiated power that presents and attractive alternative to other ELM-control techniques [3]. Density control in the QH-mode is established by the onset of a benign magnetohydrodynamic (MHD) oscillation with a clear magnetic signature, known as the edge harmonic oscillation (EHO). Onset of the EHO produces a clear increase in the total particle flux across the H-mode pedestal [4]. The EHO can appear with either a coherent or broadband character, with corresponding different rates of particle transport. As seen in Fig. 1(a), the density evolution is smoothly varying and controlled and there are no ELMs, however excursions are seen during periods where the EHO changes character and the baseline D_α increases. In Figs. 1(b,c) the periods of relatively abrupt particle pumpout (negative dn_e/dt) are well correlated in time and magnitude with the increase of

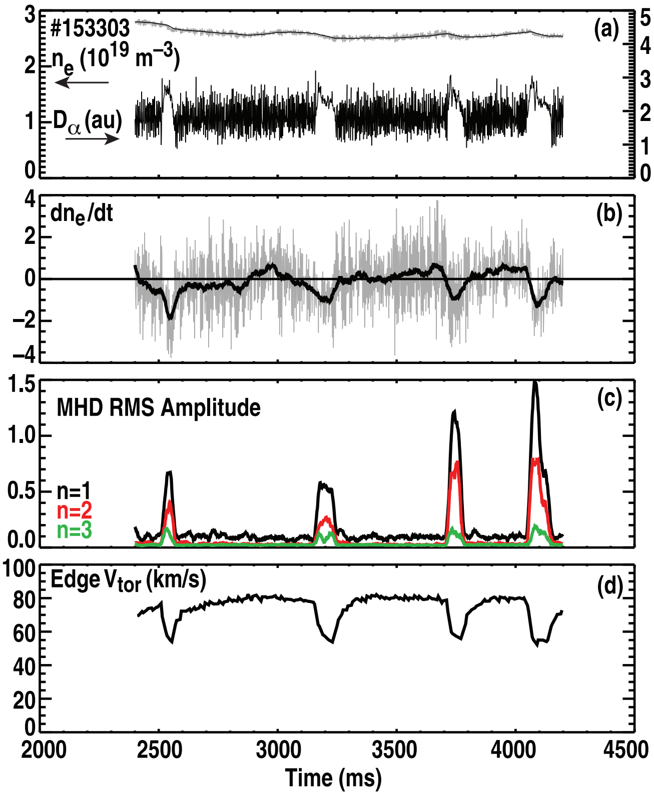

Figure 1: *Time history of (a) line-averaged density and filterscope, (b) time-derivative of line-averaged density, (c) MHD RMS amplitude and (d) edge toroidal velocity*

coherent EHO activity. Also correlated with the increase in coherence of the EHO is a drag of the (impurity) toroidal rotation [Fig. 1(d)]. Radial localization of the EHO has been determined from beam-emission spectroscopy (BES) measurements near the H-mode edge pedestal in the steep gradient region [4].

Impurity Confinement

While the EHO is known to effectively increase the electron particle transport, a question remains regarding the rate of impurity transport by the EHO. In this paper we investigate the efficacy of the EHO as the particle transport mechanism for expelling impurities from the plasma, while the central impurity profiles will be determined by neoclassical and turbulent transport. We compare with ELMing conditions, and over a range of toroidal rotation known to modify the energy confinement time. To investigate the impurity particle confinement time we inject a non-intrinsic, non-recycling impurity and monitor the uptake and expulsion of the ion from charge-exchange recombination (CER) spectroscopy to deduce the impurity ion confinement time. The confinement time is revealed by the exponential time-decay of the photoemission after its peak intensity in time-stationary conditions. A mixture of 90% deuterium and 10% carbon-tetrafluoride was used to introduce fluorine into the tokamak. Fluorine was chosen due to its unique characteristics. Fluorine is non-intrinsic, and monitoring of the fluorine line emission in discharges prior to deliberately introducing fluorine revealed negligible emission. Fluorine is highly reactive and electronegative which minimizes the recycling of this impurity. In each discharge the fluorine emission is negligible prior to the the gas puff, and decays monotonically to noise levels after each gas injection. Fluorine is fully stripped in the core of fusion-grade plasmas with beam-induced charge-exchange emission from the F-IX (10-9) transition at 4796 Å, and complex atomic modeling to determine charge-state ionization balance is unnecessary.

A critical requirement for any operational scenario with mitigated or absent ELMs is rapid impurity exhaust. In order to assess the impurity expulsion rate induced by the EHO and compare with the impurity expulsion by ELMs, two discharges are compared with approximately equal plasma density. In the ELMing discharge the EHO amplitude decays during the early ELM-free phase and disappears, replaced by large and infrequent ELMs. Figure 2 displays the time history of the two discharges. Here the timebase is with respect to the first discharge number. Density in the QH-mode is held relatively constant, while the ELMing discharge displays the repeated cycle of density rise followed by a rapid drop at the ELM crash, indicated by the large excursions in the D_α time history. Central fluorine emission in these two discharges displayed in Fig. 2(c) decays smoothly for both QH-mode and ELMing conditions. However the decay constant τ_p is equal to, or smaller, in the QH-mode discharge than the low-frequency ELMing discharge. This displays equal or more rapid expulsion of the impurity by the continuous transport provided by the EHO than low-frequency periodic ELMs. A database of discharges that are QH-mode or ELMing during this experimental campaign on impurity transport has been compiled to assess the general scaling of impurity confinement time for QH-mode and ELMing discharges during steady periods.

In these discharges with the neutral beam torque and toroidal rotation directed oppositely to the plasma current the impurity confinement times can be significatly longer than co-injection resulting in relatively high τ_p/τ_e [5, 6, 7]. Figure 2(d) displays the fluorine particle confinement as a function of line averaged density from the CO_2 interferometer. Fluorine impurity confinement scales directly with total plasma density for the QH-mode, while the density scaling of the ELMing conditions in this database is not readily apparent due to the lack of large density variation. As can be seen in Fig. 2, the impurity confinement times are smaller for all QH-modes in this study compared to ELMing conditions. It is well known that the impurity flushing by ELMs is proportional to the ELM frequency, and high frequency ELMs will display reduced impurity confinement times lower than those reported in this study.

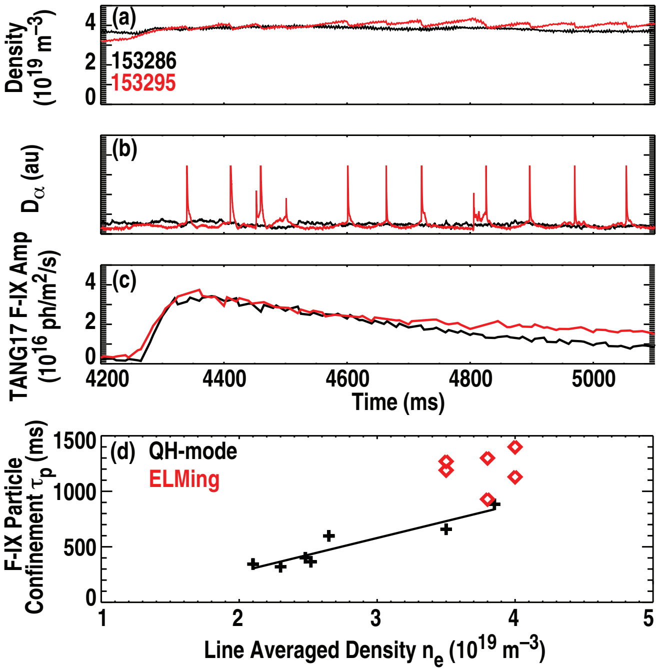

Figure 2: *Time history of (a) line-averaged density (b) filterscope monitoring D_α, (c) central fluorine emission and (d) scaling of fluorine confinement time with line-averaged density for QH-mode and ELMing plasmas*

One important control parameter that has clear effects on energy confinement in QH-mode plasmas is the applied neutral beam injection (NBI) torque. QH-mode is a regime where the the energy confinement can be maximized at low NBI torque and low toroidal rotation across much of the plasma minor radius, while maintaining strong $\mathbf{E}\times\mathbf{B}$ rotation shear at the pedestal. The strong edge rotation shear arises either naturally, or with the assistance of non-resonant magnetic field (NRMF) torque through neoclassical toroidal viscosity (NTV) [8]. Therefore a critical question is whether the confinement time of impurities also increases with energy confinement, or if the mechanism for increased energy confinement permits rapid cross-field impurity exhaust while retaining thermal energy. In order to test the particle confinement at low NBI torque, a sequence of discharges was executed at fixed density, while the NBI torque was systematically lowered after the initial startup phase. Figure 3 displays a torque scan with the plasma density held at $\langle n_e\rangle \approx 2\times10^{19}$ m^{-3}. Here $\langle n_e\rangle$ denotes line-averaged density from the CO_2 interferometer. Torque from NBI was reduced from $T_{inj} \approx 4.7$ N-m to 0.6 N-m, with a corresponding central toroidal velocity decrease from $V_{tor} \approx 310$ km/s to $V_{tor} \approx -20$ km/s. Despite the reduction in toroidal rotation and $\mathbf{E} \times \mathbf{B}$ rotation shear across most of the plasma minor radius, the overall thermal energy confinement determined from TRANSP increases from 100-150 ms. This increase in confinement is contrary to observations in advanced scenarios [9, 10], which suffer a degradation in confinement as mean $\mathbf{E} \times \mathbf{B}$ shear is reduced by lowering the toroidal rotation. For all discharges in the torque scan, the decay time of the fluorine emission is seen to be approximately constant, with $\tau_p \approx 375-425$ ms with no systematic change with torque or rotation. Thus while the energy confinement increases, the impurity particle confinement time does not increase.

Demonstration of rapid impurity exhaust in ELM-controlled discharges is critical for assessing reactor relevance. The QH-mode displays a lower impurity confinement time than a comparable ELMing discharge, and we find that this is a general feature revealed from a database of QH and ELMing discharges obtained during this campaign. At low neutral beam torque and low toroidal rotation, the energy confinement is maximized in the QH-mode, while the impurity confinement does not display any measurable increase. Impurity confinement characteristics of QH-mode plasmas with an EHO present an attractive option for reactor operation without ELMs.

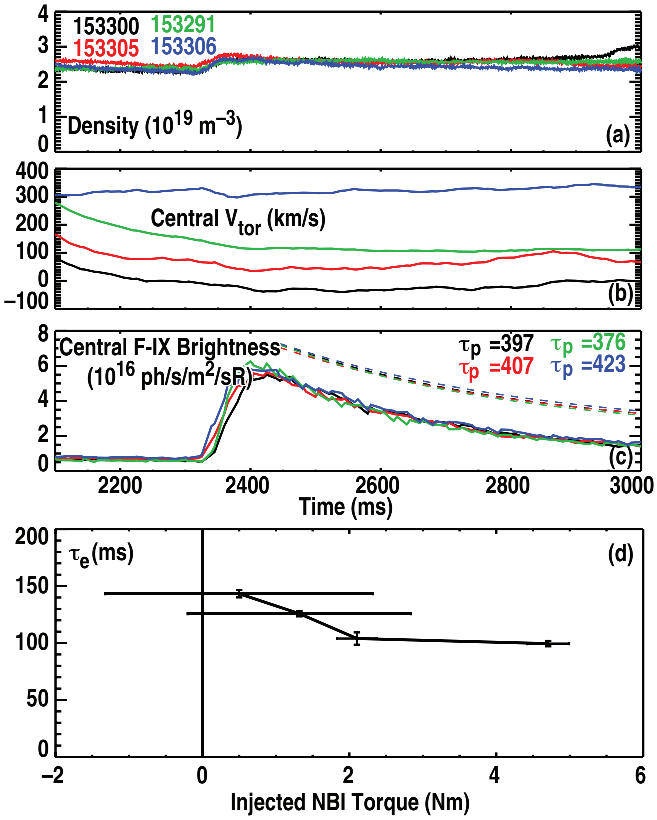

Figure 3: *Time history of (a) line-averaged density, (b) central toroidal rotation, (c) fluorine emission and (d) scaling of energy confinement with injected torque. Overlaid in (c) are exponential fits and decay time constants.*

This work supported in part by the U.S. Department of Energy under DE-AC02-09CH11466 and DE-FC02-04ER54698. The originating developer of ADAS is the JET Joint Undertaking.

References

[1] D. Reiter, *et al.*, Plasma Phys. Controlled Fusion **33**, 1579 (1991)
[2] M.R. Wade, *et al.*, J. Nucl. Mater. **290**, 773 (2001)
[3] P.T. Lang, *et al.*, Nucl. Fusion **53**, 043004 (2013)
[4] K.H. Burrell, *et al.*, Phys. Plasmas **8**, 2153 (2001)
[5] K.H. Burrell, *et al.*, Phys. Rev. Lett. **47**, 511 (1981)
[6] K. Wong, *et al.*, Phys. Fluids B **1**, 545 (1989)
[7] K. Hoshino, *et al.*, Nucl. Fusion **51**, 083027 (2011)
[8] A.M. Garofalo, *et al.*, Nucl. Fusion **51**, 083018 (2011)
[9] P.A. Politzer, *et al.*, Nucl. Fusion **48** 075001 (2008)
[10] W.M. Solomon, *et al.*, Nucl. Fusion **53**, 09303 (2013)