GA–A26782

EXPERIMENTS ON GAS PUFFING TO ENHANCE ICRF ANTENNA COUPLING

by

R.I. PINSKER, M.-L. MAYORAL, V. BOBKOV, M.GONICHE, J.C. HOSEA, S.J. WUKITCH, S. MORIYAMA, F.W. BAITY, L. COLAS, F. DURODIE, A. EKEDAHL, G.R. HANSON, P. JACQUET, P. LAMALLE, I. MONAKHOV, M. MURAKAMI, A. NAGY, M. NIGHTINGALE, J.-M. NOTERDAEME, J. ONGENA, M. PORKOLAB, P.M. RYAN, M. VRANCKEN, J.R. WILSON, ASDEX UPGRADE TEAM

MAY 2010

GENERAL ATOMICS

DISCLAIMER

GA–A26782

EXPERIMENTS ON GAS PUFFING TO ENHANCE ICRF ANTENNA COUPLING

by

R.I. PINSKER, M.-L. MAYORAL,* V. BOBKOV,† M.GONICHE,‡ J.C. HOSEA,¶ S.J. WUKITCH,§ S. MORIYAMA,# F.W. BAITY,∆ L. COLAS,‡ F. DURODIE,∞ A. EKEDAHL,‡ G.R. HANSON,∆ P. JACQUET,* P. LAMALLE,ƒ I. MONAKHOV,* M. MURAKAMI,∆ A. NAGY,¶ M. NIGHTINGALE,* J.-M. NOTERDAEME,† J. ONGENA,∞ M. PORKOLAB,§ P.M. RYAN,∆ M. VRANCKEN,∞ J.R. WILSON,¶ ASDEX UPGRADE TEAM

This is a preprint of a paper to be presented at the 37th European Physical Society Conference on Plasma Physics, June 21-25, 2010, Dublin, Ireland and to be published in the *Proceedings.*

*EURATOM/CCFE Association, Culham Science Centre, Abingdon, UK.
†Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany.
‡Euratom-CEA Association, DSM/DRFC, CEA-Cadarache, France.
¶Princeton Plasma Physics Laboratory, Princeton, New Jersey.
§MIT Plasma Science and Fusion Center, Cambridge, Massachusetts.
#Japan Atomic Energy Agency, Naka, Ibaraki ken 31 0193, Japan.
∆Oak Ridge National Laboratory, Oak Ridge, Tennessee.
∞ERM-KMS, Association EURATOM-Belgian State, Brussels, Belgium.
ƒITER Organization, France.

Work supported in part by
the U.S. Department of Energy under
DE-FC02-04ER54698, DE-AC02-09CH11466, and DE-AC05-00OR22725

GENERAL ATOMICS PROJECT 30200
MAY 2010

Experiments on gas puffing to enhance ICRF antenna coupling

R.I. Pinsker[1], M.-L. Mayoral[2], V. Bobkov[3], M. Goniche[4], J.C. Hosea[5], S.J. Wukitch[6], S. Moriyama[7], F.W. Baity[8], L. Colas[4], F. Durodie[9], A. Ekedahl[4], G.R. Hanson[8], P. Jacquet[2], P. Lamalle[10], I. Monakhov[2], M. Murakami[8], A. Nagy[5], M. Nightingale[2], J.-M. Noterdaeme[3], J. Ongena[9], M. Porkolab[6], P.M. Ryan[8], M. Vrancken[9], J.R. Wilson[5], ASDEX Upgrade Team

[1]General Atomics, P.O. Box 85608, San Diego, CA, USA
[2]EURATOM/CCFE Association, Culham Science Centre, Abingdon, Oxon, OX143DB, UK
[3]Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany
[4]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[5]Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ, USA
[6]MIT Plasma Science and Fusion Center, Cambridge, MA, USA
[7]Japan Atomic Energy Agency, 801-1, Mukouyama, Naka, Ibaraki-ken 311-0193, Japan
[8]Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN, USA
[9]ERM-KMS, Association EURATOM-Belgian State, Brussels Belgium
[10]ITER Organization, F-13108, St. Paul lez Durance, France

Plasma heating using compressional Alfven waves [fast waves (FWs)] in the ion cyclotron range of frequencies is a well-established technique in magnetic confinement devices. In almost all cases, the limit on the achievable power density that can be coupled by inductive wave launchers is determined by the maximum sustainable rf voltage in the antenna system. The parameter that determines the peak antenna electric field for a given applied rf power is the antenna load resistance R_L, defined through $P_c = (\frac{1}{2}) I_{ant}^2 R_L$, where the power coupled to the plasma is P_c and the peak antenna current is I_{ant}. Since the peak electric field in the feedline is proportional to I_{ant}, the power limit at a given rf electric field scales directly with R_L. Because the FWs are evanescent in the far scrape-off layer (SOL), only propagating at densities higher than the right-hand cutoff, the loading resistance exponentially decays with radial distance from the antenna to the right-hand cutoff layer [1,2]. Loading resistance may be enhanced by increasing the SOL density, thus reducing the wave evanescence, by decreasing the density gradient within the propagating region, or by the combination of both effects [1]. To facilitate the coupling of the desired FW power to the broad range of SOL densities that are possible in ITER [3], active methods to increase the loading resistance are under study in several tokamak experiments. One promising method is to puff neutral gas into the far SOL during the FW pulse. Here, results on loading enhancement by gas puffing are reported from the DIII-D, JET [4], AUG, and Tore Supra tokamaks.

In ELMy H-modes, the loading is much larger during an ELM than between ELMs [1], so it is the minimum loading between ELMs (MLBE) that determines the power limit (rather than the time-averaged loading). Experiments in JET reported in 2007 [4] showed that puffing deuterium at a level of up to 1.8×10^{22} electrons/s yielded an increase in the MLBE of up to a factor of six, with the antenna strap/separatrix distance of up to 19 cm. This permitted coupling of up to 8 MW of ion cyclotron resonant frequency (ICRF) power using 4 arrays under these challenging conditions. In recent DIII-D experiments, a similar increase in MLBE of up to a factor of six was observed when puffing deuterium at a rate of 1×10^{22} electrons/s from a pair of orifices adjacent to one of the three 4-element antenna arrays (Fig. 1). The MLBE on the antenna with the local puffing increased from $R_L = 0.17\ \Omega$ before the puffing to about 1 Ω between edge localized modes (ELMs) during the puff. The changes in antenna loading caused by the puff are well correlated with changes in the D_α recycling light viewed by photodiodes — higher loading between ELMs during the puff is correlated with higher D_α baseline levels, which in turn indicate higher far SOL density and decreased wave evanescence [5]. Puffing also increases the ELM frequency, from about 38 Hz before the puff to ~100 Hz (somewhat aperiodic ELMs) during the puff. As a result of the reduced edge transport barrier and pedestal height, the global confinement quality H decreases by ~20% during the puffing. Though the puff location in this case was local to, and magnetically connected to only one of the two antenna arrays used, the loading on the other antenna was also significantly increased by the puffing, indicating that the effect is not primarily localized to the puffing orifices, but is due to a more global increase in far-SOL density. A total of 1.3 MW of FW power was coupled with two antenna arrays in this condition, not limited by breakdown in this case. Lower levels of gas puffing have not yet been studied in this configuration; presumably, the optimum level would be that which marginally permits coupling the desired power level consistent with the antenna voltage limit.

Unlike in lower hybrid coupling experiments where significant ionisation is observed to occur in the antenna near-field region [6], ionization of gas by the near fields of FW antennas is probably not playing an important role, at least according to evidence obtained so far. In DIII-D, under conditions in which neutral beam injection (NBI) power is the dominant source of energy input to the plasma, the increase in R_L caused by gas puffing is found to be roughly independent of the FW power level over 4 orders of magnitude, from 1×10^2 W to 1×10^6 W of power applied to the antenna. Both in JET and DIII-D, the magnitude of gas puffing effects on R_L are strongly

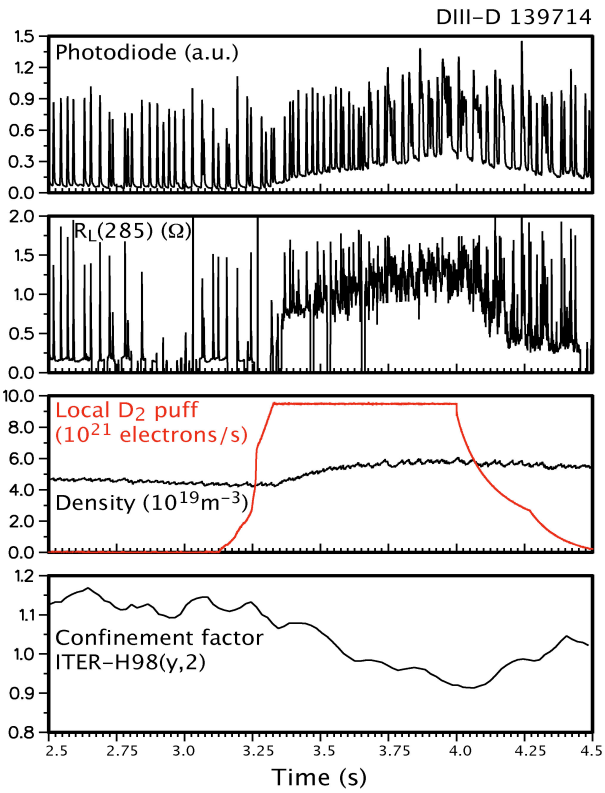

Fig. 1. Gas puffing from orifice adjacent to 285-300 antenna in ELMy H-mode on DIII-D.

dependent on details of the magnetic configuration, while near-field ionisation of the gas would be expected to be relatively constant were it playing an important part in the local ionisation power balance. An example of the sensitivity of the far SOL density profiles to configuration in ELMy H-modes is that high values of the MLBE can be obtained even without gas puffing in DIII-D by adjusting the up/down symmetry of a double-null divertor configuration. Since the cryopumps at the top and bottom of the DIII-D device are not identical, this affects the pumping speed, edge neutral pressure, ELM character and frequency, and hence the far SOL density. In a downwards-biased shape an MLBE of about 1 Ω was obtained on two of the three FW antenna arrays, while maintaining good confinement and an ELM frequency similar to that of the pre-puff period of the case shown in Fig. 1. It may be concluded that in the DIII-D ELMy H-mode case, the predominant factor determining the far SOL density and the FW antenna loading at a fixed antenna/separatrix distance is the balance between particle sources and pumping in that region, and that balance is strongly affected by the ELMs.

An important practical question for ITER is the degree to which puffing local to the antenna is necessary. Studies of this question have been undertaken on JET, DIII-D, AUG and on Tore Supra, in which the effect of gas puffing from an orifice near the powered antenna, or at least magnetically connected to the powered antenna, has been compared with the impact of the same level of gas puffing from a distant orifice. Both JET and DIII-D observe a fairly small difference between near and far puffing in ELMy H-modes, with the near puffing producing a somewhat larger effect. To clarify the part of the effect not dominated by the ELMs, puffing in L-mode plasmas has been studied in AUG and Tore Supra. In Tore Supra a relatively low level of puffing, less than 1×10^{21} electrons/s, from either a magnetically connected location or from a distant location has only a small effect on R_L. The level of puffing from either location was determined by feedback control of the core density, necessary to maintain constant particle recycling. Substantially higher levels of puffing from either puffing location in Tore Supra produced higher core density, higher antenna loading, and higher heat loads on the antennas. For AUG, puffing from an orifice immediately adjacent to one antenna has a substantially larger effect on that antenna's loading than puffing the same amount of deuterium from a distant location (Fig. 2). Puffing at a rate of 5×10^{21} electrons/s from the nearby orifice has roughly the same effect on that antenna's loading as puffing at twice the rate from the distant location. It is concluded from these experiments that the enhancement in loading with gas puffing has a local part and a global part [4], and the relative size of these two contributions is a function of field line geometry relative to the puffing orifice and the antenna, parallel transport, connection lengths, cross-field transport enhancement by turbulence and ELMs, and other factors.

The effect of the puffing on the far SOL density profile has been measured with Li beams, Langmuir probes and microwave reflectometers. In all cases in which density profile measurements local to the antenna have been used, good agreement has been obtained between the antenna loading predicted by three-dimensional EM models such as TOPICA and the experimentally measured values [3]. It may be concluded that the uncertainty in the value of antenna loading expected in ITER is due to the wide possible range of far SOL density profiles.

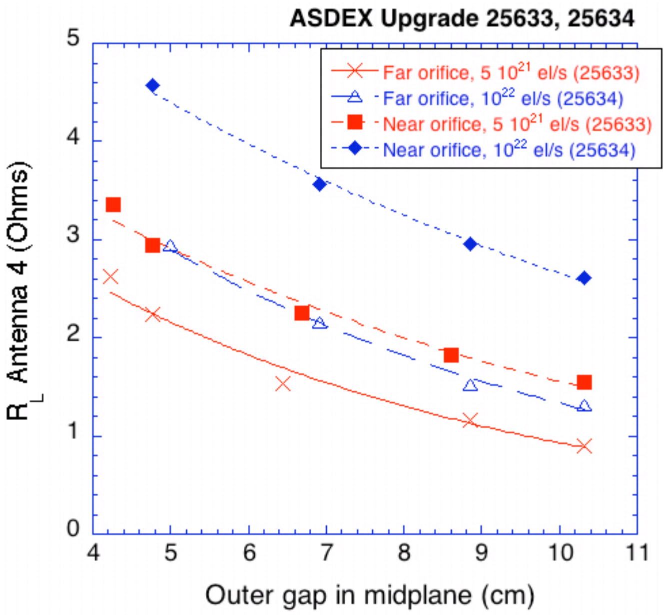

Fig. 2. Effect of puffing on coupling in L-mode discharge on AUG at two levels of puffing from two locations relative to the antenna as a function of outer gap. Lines show exponential fits to the data (symbols).

In conclusion, to the extent that the far SOL density can be increased with an acceptable level of gas puffing, the antenna loading and hence the maximum coupled FW power can be usefully increased. So far, the evidence does not point to an important effect due to ionisation in the rf fields of the antenna, but rather to changes in the balance between particle sources and pumping. In ELMy H-modes, the ELM character and frequency may also have a strong affect on this balance. Due to the negative effects of strong puffing on confinement, as well as negative effects of increased density very close to plasma-facing components (increased heat flux, resulting hot spots, and impurity influx), the puffing should be maintained at the minimum level needed to obtain the necessary antenna loading. Since gas puffing is likely to be an inefficient method of core fueling in ITER, the possibility arises of a gas puffing system as a separate actuator to control the antenna loading without having a significant effect on the core plasma.

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698, DE-AC02-09CH11466, and DE-AC05-00OR22725.

[1] M.J. Mayberry, *et al.*, 1990 Nucl. Fusion **30** 579.
[2] R. Bilato, M. Brambilla, D.A. Hartmann and A. Parisot, 2005 Nucl. Fusion **41** L5.
[3] M.P.S. Nightingale, *et al.*, Radio Frequency Power in Plasmas (Proc. 18th Top. Conf., Gent, Belgium, 2009) (AIP, NY, 2009) 213.
[4] M.-L. Mayoral, *et al.*, Radio Frequency Power in Plasmas (Proc. 17th Top. Conf., Clearwater, FL, 2007) (AIP, NY, 2007) 55.
[5] C.C. Petty, *et al.*, 1999 Nucl. Fusion **39** 1421.
[6] V. Pericoli Ridolfini, *et al.*, 2004 Plasma Phys. Control. Fusion **46** 349.