GA–A23171

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JULY 1999

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M.R. WADE,* W.P. WEST, D.N. HILL,† S.L. ALLEN,† J.A. BOEDO,‡ N.H. BROOKS,
M.E. FENSTERMACHER,† J.T. HOGAN,* R.C. ISLER,* R.J. JAYAKUMAR,†
C.J. LASNIER,† R. LEHMER,‡ A.W. LEONARD, R. MAINGI,* R.A. MOYER,‡
T.W. PETRIE, M.J. SCHAFFER, J.G. WATKINS,△ D.G. WHYTE,‡ and R.D. WOOD†

This is a preprint of a paper presented at the Twenty-Sixth European Physical Society Conference on Controlled Fusion and Plasma Physics, June 14–18, 1999 in Maastricht, The Netherlands, and to be published in *The Proceedings.*

*Oak Ridge National Laboratory, Oak Ridge, Tennessee.
†Lawrence Livermore National Laboratory, Livermore, California.
‡University of California, San Diego, California.
△Sandia National Laboratories, Albuquerque, New Mexico.

Work supported by
the U.S. Department of Energy
under Contract Nos. DE-AC03-99ER54463, DE-AC05-96OR22464,
W-7405-ENG-48, DE-AC03-94AL85000 and Grant No. DE-FG03-95ER54294

GA PROJECT 30033
JULY 1999

Demonstration of the ITER Power Exhaust Solution Using the "Puff and Pump" Technique on DIII-D

M.R. Wade,[1] W.P. West, D.N. Hill,[2] S.L. Allen,[2] J.A. Boedo,[3] N.H. Brooks,
M.E. Fenstermacher,[2] J.T. Hogan,[1] R.C. Isler,[1] R.J. Jayakumar,[2] C.J. Lasnier,[2]
R. Lehmer,[3] A.W. Leonard, R. Maingi,[1] R.A. Moyer,[3] T.W. Petrie,
M.J. Schaffer, J.G. Watkins,[4] D.G. Whyte,[3] and R.D. Wood[2]

General Atomics, P.O. Box 85608, San Diego, California 92186-5608

[1]Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[2]Lawrence Livermore National Laboratory, Livermore, California.
[3]University of California, San Diego, California..
[4]Sandia National Laboratory, Albuquerque, New Mexico..

In future, high power density fusion devices, the need to prevent excssive local deposition of the plasma energy efflux on the first-wall surfaces is a critical design consideration in order to maintain the integrity of such surfaces. This requirement must be met without significant impact on plasma purity or overall plasma confinement. For the International Thermonuclear Experimental Reactor (ITER), these constraints have led to the following design criteria [1] $P_{rad}/(P_{input}+ P_{\alpha}) = 83\%$, $P_{rad,core}/(P_{input}+ P_{\alpha}) = 33\%$, $P_{target}/P_{loss} = 17\%$, $Z_{eff} < 1.8$, and $\tau_E/\tau_{E,ITER93H} > 0.85$. Here, P_{loss} is the power flowing out of the core (i.e., $P_{input} + P_{\alpha} - P_{rad,core}$) and P_{target} is the power conducted to the target plate. These criteria represent a compromise between obtaining sufficient radiation to reduce the target heat load to a tolerable level, minimizing core fuel dilution, and maintaining sufficient power flow through the edge plasma to maintain H–mode confinement. Past experiments have had difficulty achieving these conditions simultaneously when using seeded impurities, and therefore there has been some concern regarding the viability of the ITER design. However, recent experiments in DIII–D using the "puff and pump" technique with argon as the seeded impurity have demonstrated the compatibility of these design constraints. In particular, steady-state plasma conditions have been achieved with $P_{rad}/P_{input} = 72\%$, $P_{rad,core}/P_{input} = 16\%$, $P_{target}/P_{loss} = 17\%$, $Z_{eff} = 1.85$, and $\tau_E/\tau_{E,ITER93H} = 1.05$.

The "puff and pump" technique, pioneered on DIII–D [2], combines deuterium gas injection near the symmetry point combined with divertor exhaust to produce a strong frictional drag force on the impurities in the SOL. The premise of this technique is to augment the frictional drag on the impurities in the SOL imposed by the main ion flow sufficiently to overcome the thermal gradient force, which acts to drive impurities toward the core plasma [3,4]. Additional benefit may be gained through lowering of the SOL and divertor ion temperature, which increases the frictional force and reduces the thermal gradient force. The tailoring of the main ion flow using this technique has been an integral part of the DIII–D program since 1994 [2,5–7]. These studies have concluded that such a technique is effective in increasing the enrichment of impurities in both the open and closed divertor configurations [5,7] The improvement has been found to be substantial for higher Z impurities [6] with argon enrichment values as high as 17 obtained in the highest flow cases.

These studies were conducted in a lower-single-null configuration with $I_p = 1.3$ MA, $B_T = -2.1$ T, $q_{95} = 4.1$, $\kappa = 1.75$ and $\langle\delta\rangle = 0.28$. The outer strike point (OSP) is positioned within 5 cm of the baffle entrance to the pumping plenum to insure strong exhaust of both deuterium and argon (Fig. 1). In these discharges, neutral beam injection (NBI) begins shortly after the plasma current has reached flat-top. A SOL flow is then induced by increasing D_2 gas injection near the symmetry point of DIII–D to the desired level and then maintaining a constant fueling rate until the end of the discharge while simultaneously exhausting gas at the same rate Approximately 500 ms later, argon injection directly into the divertor plasma begins and is maintained for approximately 2 s.

To determine the optimum set of input parameters for obtaining radiative divertor conditions, systematic scans in the D_2 flow rate, Ar flow rate, and input power were conducted. The best radiative divertor conditions were found with a D_2 injection rate of 2.5×10^{22} D°/s, a Ar injection rate of 1.3×10^{21}Ar°/s, and an input power of 11.9 MW. At this D_2 fueling rate, radiation levels are higher than normally found in ELMing H–mode plasmas with the total radiated power representing approximately 50% (~6.0 MW) of the total input power. Fueling rates up to 3.5×10^{22} D°/s were attempted but did not show measurable improvement over the 2.45×10^{22} D°/s, case.

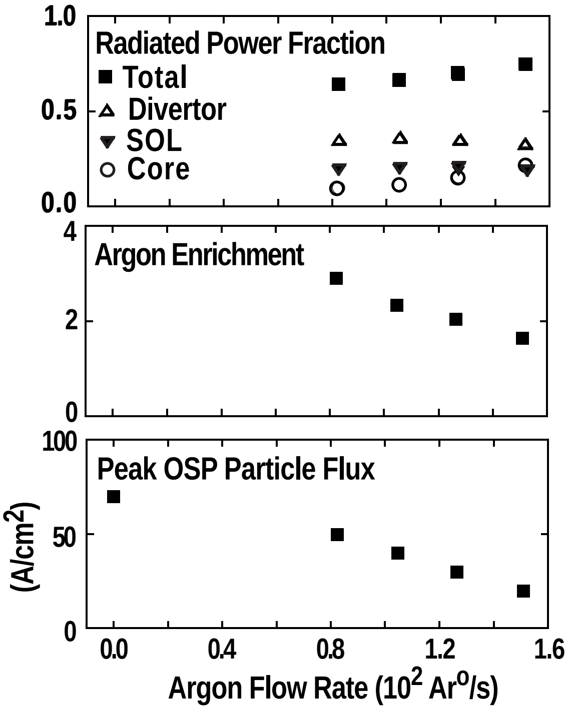

Fig. 1. Variation of the (a) total, divertor, SOL, and core radiated power fractions; (b) argon exhaust enrichment, and (c) peak particle flux at the outer strike point with argon injection rate. D_2 flow rate = 2.45×10^{22} D°/s and P_{NBI} = 11.9 MW in all cases.

In terms of achieving optimized radiative divertor plasma conditions, the best results have been obtained at the highest power levels attempted ($P_{NBI} \approx 12$ MW). In these cases, β_N approaches 2.3 and plasma energy confinement is limited by the appearance of n=3, m=2 neoclassical tearing modes. At lower input power levels, the ability to maintain radiative divertor conditions was complicated by spontaneous transitions to radiative mantle conditions. After this transition occurs, the plasma density increases uncontrollably, likely due to cooling of the SOL by the increased radiation and better penetration of the fueled D_2 and Ar to the plasma core. Although reasonable energy confinement is maintained for an extended duration following this transition (~500 ms in the best cases), the continuous rise in electron density and plasma radiation eventually lead to thermal collapse of the core plasma.

Over a wide range in total radiated power fraction, key plasma parameters in these radiative discharges are found to vary roughly linearly with the argon injection rate. As expected, the radiation power balance was found to be dependent on the argon injection rate. Figure 1(a) shows the fraction of radiation from various plasma regions during an argon injection rate scan. The radiated power in the core, SOL, and divertor increases with argon injection rate with the majority of the increase in radiated power being core radiation. This data suggests that we have not reached the point at which the response of core radiation and plasma confinement becomes non-linear with the argon level as has been seen in previous neon experiments on DIII–D. Furthermore, the linear dependence of all these parameters on argon injection rate over the wide range in radiating power suggests that feedback control of the radiated power should be possible. Of some concern is that fact that argon enrichment (ratio of divertor argon concentration to core concentration) decreases steadily as the argon injection rate (or total radiated power) increases with enrichment decreasing from ~3.0 at the lowest argon injection rate to 1.6 at the maximum argon injection rate [Fig. 1(b)]. This decrease is most likely due to the increased level of detachment (i.e., reduced particle flux) at the outer strike point as argon injection is increased [Fig. 1(c)].

The plasma solution produced as part of these studies has many features embodied in the ITER power exhaust solution. In terms of power exhaust, significant radiation is obtained from both the core and divertor plasmas with $P_{rad,div}$: $P_{rad,SOL}$: $P_{rad,core}$ (MW) = 4.3:2.4:1.8. The radiation from the core plasma is localized in the last 10% of the plasma volume while the radiation in the divertor plasma is distributed fairly evenly over the entire divertor volume. Argon line radiation provides the preponderance of the core radiation while carbon line radiation provides the bulk of radiation from the divertor region with a small fraction (~20%) coming from argon. This is consistent with the ITER design in which it is anticipated that the majority of radiation in the divertor region will come from lower Z impurities (beryllium or carbon) with necessary core radiation being provided by the seeding of a higher Z impurity (probably argon). The argon radiation from the core plasma is found to be consistent with argon concentrations (~0.20 %) inferred from CER measurements. This level of argon concentration (along with ~1% carbon concentration) leads to $Z_{eff} = 1.85$. This level of fuel dilution is consistent with the ITER requirement that $Z_{eff} < 1.8$ and is significantly below the Z_{eff} (~2.25) predicted by the multi-machine scaling law developed by Matthews et al. [8]. In fact, the measured incremental Z_{eff} (i.e., $Z_{eff} - 1$) in these "puff and pump" discharges is consistently lower than the predicted scaling value, regardless of the level of argon (Fig. 2). This is consistent with the fact that the radiation in the DIII–D radiative discharges comes primarily from the divertor plasma; therefore, one might expect that P_{rad} is not a linear function of Z_{eff} as suggested by the Matthews scaling law. At present, it is not clear whether this result is particular to the "puff and pump" discharges on DIII–D or represents a generic problem when using the proposed scaling for DIII–D data.

Even though the biggest increase in total radiation is observed to come from the core plasma, it is important to note that the divertor radiative efficiency (defined as the ratio of the power radiated in the divertor to the power conducted to the divertor) actually increases substantially during the argon injection phase from 40% up to 55%. As a result of the high level of radiation, partial detachment of the outer divertor leg (i.e., particle flux is negligible at the outer strike point locations but still measurable further out in the SOL) is achieved with the peak heat flux values reduced by a factor of 4 from that expected in non-radiative conditions. It is important to note that partial detachment of the divertor is a key ingredient in the ITER design as it is required to simultaneously achieve tolerable heat flux levels and adequate helium exhaust. Typical of partially detached divertor conditions, the peak in the heat flux shifts ~5 cm away from the separatrix. The particle flux at the separatrix is also reduced substantially but there is appreciable particle flux in the outer SOL region. Furthermore, there is spectroscopic evidence for volumetric recombination with the ratio Lyβ/Lyδ as measured by the divertor SPRED instrument. The local divertor plasma conditions are consistent with the presence of recombination with the divertor electron temperature and density as measured by Thomson scattering being ~2 eV and 1×10^{20} m^{-3}, respectively.

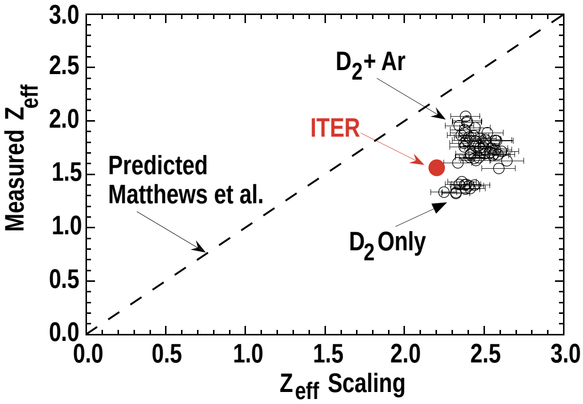

Fig. 2. Measured Z_{eff} versus the predicted scaling $Z_{eff} = 1 + 4.5\ P_{rad}\ Z^{0.12} / \left(S^{0.94}\bar{n}_e^{1.89}\right)$ where P_{rad} is the total radiation power, Z is the charge of the primary impurity, S is the plasma surface area, and $\bar{n}_e$ is the line-averaged density. The horizontal error bars depicted here represent the uncertainty related to the impurity charge to use in the scaling expression (ranging from Z = 6 (carbon) to Z = 18 (argon). The ITER data point is calculated using P_{rad} = 150 MW, S = 1250 m^2, $n_e = 0.96\times10^{20}$ m^{-3}, and Z = 18 (argon).

Energy confinement is not grossly affected by the increased radiation with $\tau_E/\tau_{E,ITER93H}$ ~ 1.0. In fact, Fig. 3 shows that over the entire ensemble of data from these studies, energy confinement is not grossly affected even as the density approaches the Greenwald density (i.e., n_e/n_{GW} ~ 1) or the radiation limit (i.e., P_{rad}/P_{input} ~ 1.0). Note that multiple data points from a single discharge are included in this figure. The robustness in overall energy confinement is correlated with an invariance of the edge pressure, which remains typical of the edge pressure in non-radiative ELMing H–mode plasmas. Even though the pedestal pressure remains constant, the ELM energy loss during the argon injection phase of these discharges is approximately a factor of 4 lower than typically observed in similar plasma conditions. This is believed to be due to the external gas puffing increasing the ELM frequency and thereby reducing the energy loss per ELM. Although this reduction in ELM energy loss is favorable for ITER, it should be pointed out that the ELM energy loss in this case is still ~8% of the edge pedestal energy, which is well above the design value of 2% for ITER.

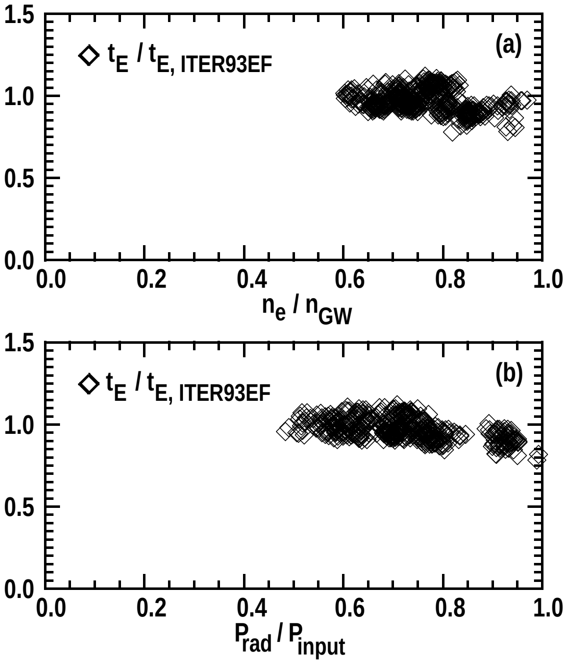

Fig. 3. Variation of energy confinement relative to the ITER93 ELM-free H–mode scaling with (a) density normalized to the Greenwald density and (b) total radiated power fraction for an ensemble of “puff and pump” discharges with D_2 flow rate = 2.45×10^{22} D°/s and P_{NBI} = 11.9 MW. Multiple points are included from a single discharge.

In conclusion, a radiative plasma which meets all of the relevant criteria embodied in the ITER design has been produced on DIII–D using induced SOL flow in combination with argon injection. Conditions have been produced in which high radiation losses ($P_{rad}/P_{input} > 70\%$), low core fuel dilution ($Z_{eff} < 1.9$), and good core confinement ($\tau_E > 1.0\ \tau_{E,ITER93H}$) have been achieved simultaneous with partial detachment of the divertor plasma. The argon fraction obtained here (~ 0.20%) is consistent with the maximum fraction allowed in ITER as estimated by computational simulations [9]. Finally, it is worth noting that the “solution” described here embodies many of the favorable aspects of a “hybrid” radiative solution in which low-Z impurity radiation predominates in the divertor and radiation from a high-Z impurity embellishes this divertor radiation while providing additional radiation in the core plasma.

This is a report of work supported by the U.S. Department of Energy under Contract Nos. DE-AC03-99ER54463, DE-AC05-96OR22464, W-7405-ENG-48, DE-AC04-94AL85000, and Grant No. DE-FG03-95ER54294.

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