GA–A25331

COMPATIBLITY OF THE RADIATING DIVERTOR WITH HIGH PERFORMANCE PLASMAS IN DIII-D

by
T.W. PETRIE, M.R. WADE, S.L. ALLEN, N.H. BROOKS, M.E. FENSTERMACHER,
M. GROTH, A.W. HYATT, A.W. LEONARD, C.J. LASNIER, M.A. MAHDAVI,
M. MURAKAMI, G.D. PORTER, M.J. SCHAFFER, J.G. WATKINS, W.P. WEST,
and the DIII-D TEAM

JUNE 2006

GENERAL ATOMICS

DISCLAIMER

GA–A25331

COMPATIBLITY OF THE RADIATING DIVERTOR WITH HIGH PERFORMANCE PLASMAS IN DIII-D

by

T.W. PETRIE, M.R. WADE, S.L. ALLEN,* N.H. BROOKS, M.E. FENSTERMACHER,* M. GROTH,* A.W. HYATT, A.W. LEONARD, C.J. LASNIER,* M.A. MAHDAVI, M. MURAKAMI,† G.D. PORTER,* M.J. SCHAFFER, J.G. WATKINS,‡ W.P. WEST, and the DIII-D TEAM

This is a preprint of a synopsis of a paper to be presented at the 21st IAEA Fusion Energy Conference, October 16-21, 2006, in Chengdu, China, and to be published in the *Proceedings.*

*Lawrence Livermore National Laboratory, Livermore, California.
†Oak Ridge National Laboratory, Oak Ridge, Tennessee.
‡Sandia National Laboratories, Albuquerque, New Mexico.

Work supported by
the U.S. Department of Energy
under DE-FC02-04ER54698, W-7405-ENG-48,
DE-AC05-00OR22725, and DE-AC04-94AL85000

GENERAL ATOMICS PROJECT 30200
JUNE 2006

GENERAL ATOMICS

Compatiblity of the Radiating Divertor With High Performance Plasmas in DIII-D* EX-D

T.W. Petrie,[1] M.R. Wade,[1] S.L. Allen,[2] N.H. Brooks,[1] M.E. Fenstermacher,[2] M. Groth,[2] A.W. Hyatt,[1] A.W. Leonard,[1] C.J. Lasnier,[2] M.A. Mahdavi,[1] M. Murakami,[3] G.D. Porter,[2] M.J. Schaffer,[1] J.G. Watkins,[4] W.P. West,[1] and the DIII-D Team

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608
email: petrie@fusion.gat.com

[2]Lawrence Livermore National Laboratory, Livermore, California
[3]Oak Ridge National Laboratory, Oak Ridge, Tennessee
[4]Sandia National Laboratories, Albuquerque, New Mexico

We report on recent DIII-D experiments that successfully applied a radiating divertor scenario to high performance "hybrid" plasmas [1]. Good hybrid conditions were maintained (e.g. $\tau_E/\tau_{ITER\_89P} \geq 2$, $\bar{n}_e/n_{GW} \approx 0.65$, β and $\beta_N \cong 2.4$), while the peak heat flux at the outer divertor target was reduced by a factor of 2.5. Values of exhaust enrichment $\eta_{exh} \approx 64$ were obtained using argon as the seeded impurity, so that a radiated power fraction $P_{RAD}/P_{INPUT} > 0.6$ could be maintained with only a modest contamination of the main plasma by the argon ($n_{AR}/n_e < 0.003$). (Exhaust enrichment is defined as the ratio of the neutral argon pressure in the baffle plenum to the atomic-equivalent pressure of deuterium in the baffle plenum, divided by the ratio of argon density to electron density in the main plasma.)

Hybrid plasmas are characterized by good confinement and the absence of central sawteeth activity, which is suppressed by an internal tearing mode that maintains the central safety factor >1. Thus, the hybrid removes the sawtooth trigger for the deleterious 2/1 neoclassical tearing mode, allowing operation at higher β. In the *puff-and-pump* approach [2] used here, argon was injected near the outer divertor target. Plasma flows into both the inner and outer divertors were enhanced by a combination of particle pumping near both divertor targets and deuterium gas puffing upstream of the divertor targets. A "dome" structure divided the private flux region (PFR) between the inner and outer divertors (Fig. 1).

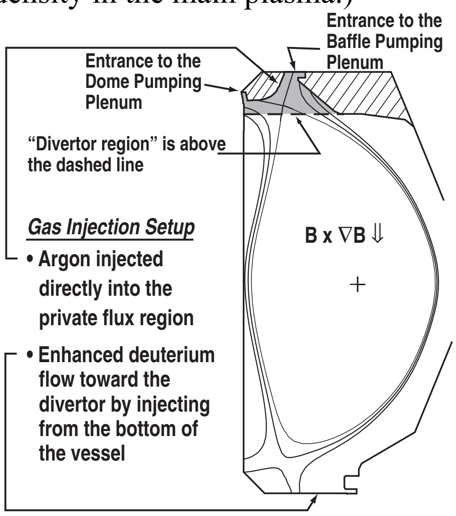

Fig. 1. The poloidal locations of the particle pumping and gas injection, along with the poloidal cross-section of the plasma, are superimposed on the vessel geometry.

The table summarizes the response of hybrid H-mode plasmas to three argon injection rates, Γ_{AR}: "trace", "moderate", and "high". The deuterium gas injection rate, Γ_{D2}, was unchanged for these cases. In general, good hybrid conditions were maintained at each level of Γ_{AR}. When comparing the high Γ_{AR} (Case 3) with the trace Γ_{AR} (Case 1), we find that between Case 1 and Case 3: (1) The total radiated power fraction $P_{RAD,TOT}/P_{INPUT}$ increased from 0.45 to 0.63, with approximately 50% of this *increase* from the main plasma and ≈40% from the divertor plasma; (2) The peak heat flux at the *outer* divertor target, $q_{P,OUT}$, normalized to Case 1, fell by a factor of 2.5, while the normalized peak heat flux at the *inner* target, $q_{P,IN}$, decreased only ≈20%; (3) The average electron temperature at the *outer* divertor target, $T_{e,OUT}$, decreased from ≈22 eV to ≈10 eV, while the average electron temperature at the *inner* divertor target, $T_{e,IN}$, was unchanged at ≈10 eV for all three cases; and (4) The Type-1 ELM frequency ν_{ELM} decreased from ≈80 Hz (Case 1) to ≈70 Hz (Case 3). Both inner and outer divertor legs were "attached" at all times. Exhaust enrichment depended weakly on

*Work supported by U.S. Department of Energy under DE-FC02-04ER54698, W-7405-ENG-48, DE-AC05-00OR22725, and DE-AC04-94AL85000.

Note: $\beta_N \approx 2.4$ in All Cases	D_2 + Argon (Case 1)	D_2 + Argon (Case 2)	D_2 + Argon (Case 3)
Γ_{D2} (torr liter/s)	108	108	108
Γ_{Ar} (torr liter/s)	0.4	3.4	6.4
$\overline{n}_e$ (10^{20} m^{-3})	0.61	0.64	0.67
$H_{ITER89P}$	2.0	2.0	2.0
P_{IN} (MW)	6.9	6.8	6.6
$P_{RAD,TOT}/P_{IN}$	0.45	0.52	0.63
$P_{RAD,MAIN}/P_{IN}$	0.17	0.21	0.24
$P_{RAD,DIV}/P_{IN}$	0.16	0.18	0.22
$\hat{q}_{P,IN}$	1.0	0.94	0.81
$\hat{q}_{P,OUT}$	1.0	0.60	0.40
$T_{e,IN}$ (eV)	10	10	10
$T_{e,OUT}$ (eV)	22	14	9
ν_{ELM} (Hz)	≈ 80	≈ 75	≈ 70
n_c/n_e (ρ = 0.7) (%)	2.1	2.1	2.2
n_{Ar+16}/n_e (ρ = 0.7) (%)	0.007	0.06	0.13
Z_{eff} (ρ = 0.7)	1.6	1.8	2.0
η_{exh}	64	62	56

Γ_{AR} in the three cases considered. While argon-induced carbon sputtering in the divertor increased with Γ_{AR}, the increase in the carbon density in the main plasma, n_C, was <10% between Case 1 and Case 3, and the increase in Z_{eff} was predominantly from argon.

The differences in the heat flux reduction between inner and outer diveror targets was largely due to a much higher argon concentration near the outer divertor target than near the inner divertor target (≈6-9 times). Several factors may have contributed to the asymmetric distribution of argon. First, the argon source was located in the PFR near the *outer* separatrix target. Direct access of injected argon neutrals to the inner divertor target was not possible, because the "dome" obstructed the direct flight of the injected neutral argon from reaching the inner divertor target. Second, the leakage of argon out of this *closed* outer divertor was reduced by the enhanced deuterium flow toward this divertor by upstream deuterium gas injection. Finally, the E_RxB-induced ion particle flow across the PFR was directed *away* from the inner divertor target toward the outer divertor target. These results suggest the possibility of independent control over the radiating properties of the inner and outer divertors under prescribed operating conditions and, by implication, the possibility of independent control over their respective target heat fluxes. UEDGE [3] modeling will be used to explore this possibility.

Exhaust enrichment was found to be linear with Γ_{D2}, and η_{exh} values of ≈60 were measured at the highest level of Γ_{D2}. However, η_{exh} was >10, even for Γ_{D2} near zero. This suggests that other considerations(s), in addition to enhanced plasma flow, also contributed to the η_{exh}. If we compare these results with those from a previous DIII-D puff and pump experiment where argon was also injected into the PFR of ELMing H-mode plasmas, the maximum η_{exh} of the latter [4] was less than half of η_{exh} reported here. Possible explanations may be related to the differences between these two experiments, such as the direction of the E_RxB-induced ion particle flow across the PFR and the presence of a "dome" structure bisecting the PFR.

This puff and pump approach with argon produced tradeoffs between the desired reductions in heat flux and an unacceptable fuel dilution by argon ($\approx Z_{AR}\, n_{AR}/n_e$). For the hybrid plasmas discussed here, this tradeoff was favorable, i.e., modest dilution (e.g., ≈2%-4% for the "high" Γ_{AR} case) and a sharply reduced peak heat flux at the outer divertor target. The argon accumulation inside the main plasma was nearly linear with Γ_{AR} for fixed Γ_{D2}. While the argon density profile was more peaked than the electron density profile, the radiated power emissivity was still strongly peaked toward the edge of the plasma, even in the high Γ_{AR} case. The m=3, n=2 neoclassical tearing mode may play a role in limiting more pronounced accumulation of argon near the plasma center.

The response of the hybrid plasma to a radiating divertor environment, as described here, is particularly relevant, should the hybrid regime be considered as one of the "high performance" scenarios for ITER. Our results also provide data on the usefulness of physically dividing the inner from the outer divertor during radiating divertor operation.

[1] T.C. Luce, et al., Nucl. Fusion **43** (2003) 321.
[2] M.J. Schaffer, et al., Nucl. Mater. **241-243** (1997) 585.
[3] T.D. Rognlien, et al., Plasma Phys. **34** (1994) 362.
[4] M.R. Wade, et al., Nucl. Fusion **38**, 1839 (1998).