LA-UR 91-4080

LA-UR--91-4080

DE92 005053

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE ITER EDGE-PLASMA CONDITIONS VERSUS PUMP CONFIGURATION

AUTHOR(S) K. A. Werley and S. A. Cohen

SUBMITTED TO 10th International Conference on Plasma Surface Interactions
in Controlled Fusion Devices Monterey March 30, 1992

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.

In acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ITER Edge-Plasma Conditions versus Pump Configuration

K.A. Werley and S.A. Cohen

Los Alamos National Laboratory, Los Alamos, NM 87545
Princeton University, Plasma Physics Laboratory, Princeton, NJ 08543

December 11, 1991

Abstract

Two-dimensional fluid simulations of ITER double-null divertor scrape-off-layer plasma conditions have been restricted to examining a single outboard divertor plate with up/down symmetry assumed. The present work evaluates the effect of pumping at only one plate on particle flow patterns and other parameters of interest. Pumping only at one plate results in reduced sheath temperatures at both plates but an increased heat flux at the pumped plate.

The physics assumptions for separatrix density ($n_{SEP} = \langle n \rangle / 3.5$) and for radial particle diffusivity ($D = 0.66 \text{ m}^2/\text{s}$) used in the simulation of ITER edge plasma result in particle throughputs two orders of magnitude greater than that required for acceptable fusion-product ash removal rates. The particle confinement time, however, is an order of magnitude shorter than the transport energy confinement time, τ_E . Plasmas ($D = 0.04 \text{ m}^2/\text{s}$) which would have $\tau_p \sim \tau_E$ are evaluated and found to have unacceptably high plasma temperatures and heat flux at the plate. Ash removal rates are still acceptable. A plasma recycle coefficient (at the divertor plate) of $R = 0.965$ reduces the particle throughput by a factor of 2.8 below the no-recycle case.

I. INTRODUCTION

Two-dimensional (2D) fluid simulations of ITER¹ double-null (DN) divertor scrape-off-layer (SOL) plasma conditions have been restricted to examining a single outboard divertor plate with up/down symmetry assumed.² The ITER vacuum design, however, calls for pumping at only the lower of the two outboard divertor plates.¹ The present work evaluates the effect of pumping at only one plate on particle flow patterns and other parameters of interest. Pumping only at one plate results in reduced sheath temperatures at both plates but an increased heat flux at the pumped plate. Physics-phase High Aspect Ratio Device (HARD)³ ignition conditions are examined.

The physics assumptions¹ for separatrix density ($n_{sep} = \langle n \rangle / 3.5$) and for radial particle diffusivity ($D = 0.66 \text{ m}^2/\text{s}$) used in the 2D simulation of ITER SOL plasma result in particle throughputs two orders of magnitude greater than that required for acceptable fusion-product ash removal rates. The particle confinement time, however, is an order of magnitude shorter than the transport energy confinement time, τ_E . Such a situation, with $\tau_p < \tau_E$, is physically unlikely, and has not been observed experimentally (especially in a diverted device such as ITER where neutral particles do not penetrate across the magnetic separatrix into the main plasma). To study this issue, first, the effect that plasma recycle (at the divertor plate) has on particle throughput and confinement time is evaluated for ITER Conceptual Design Activity (CDA) physics-phase conditions. Secondly, plasma conditions for plasmas ($D = 0.04 \text{ m}^2/\text{s}$) which would have $\tau_p \sim \tau_E$ are evaluated.

II. EDGE-PLASMA MODEL

The model description summarizes the B2 code of Braams.⁴ Steady-state, 2D, two-fluid energy, particle, and parallel momentum continuity equations are enforced. Classical⁵ collisional parallel transport is assumed, although heat and momentum flux limits are imposed to prevent collisional processes from allowing transport more rapid than particle free-streaming limits. Perpendicular (cross-field) transport diffusivities are specified and are assumed constant in space. Impurity line radiation is neglected. The 2D geometry describes magnetic field-line and normal to flux-surface directions, and is generated⁶ from TEQ⁷ equilibrium code results⁸.

The interaction of the plasma particles with material surfaces and vacuum pumps are modelled by specification of a local plasma recycle coefficient along the wall, plate, and pump port. The recycle coefficient along the wall is set to a value of 1. The plate and pump recycle coefficient profile was set through iteration of plasma and neutral-particle conditions between the plasma model and the DEGAS⁹ 2D neutral-particle transport code.¹⁰ Recycled particles are redeposited in the plasma based upon the ionization mean free path of 10eV neutrals in the local plasma environment. Neutral-particle transport both along and across flux surfaces is allowed.

Boundary conditions applied at the plasma electric sheath which exists just in front of the divertor plate include Mach flow and electron and ion energy transmission coefficients of 4 and 2.5, respectively (not including the kinetic energy). For the case that only one divertor plate is considered, symmetry (zero flux conditions) is applied at the upstream

boundary. At the first wall, extrapolation-endpoint conditions are applied on density and temperature. These wall constraints affect the plasma conditions away from the wall very weakly. Boundary conditions on the inner boundary are iterated on until the total power through the separatrix, P_{SEP} , and the electron density at the upstream midplane separatrix position, n_{SEP} , match the design values.

The physics assumptions for n_{SEP} and for the perpendicular diffusivities were recommended by the ITER Physics Group¹ and are based upon present experimental divertor conditions. These assumptions include $n_{SEP}=n/3.5$ and the particle diffusivity is $D=0.66m^2/s$. Both ITER and commercial tokamak reactors are expected to operate in regimes of higher magnetic field strength and higher edge plasma pressure than present devices achieve.

III. OUTBOARD DN DIVERTOR: 1 Pump versus 2

In order to examine the effect of particle pumping at only one of the two outboard divertor plates, the full outboard divertor geometry is used and is shown in Fig. 1. A zero-flux boundary condition was applied to the inner boundary of the private-flux region. This condition isolates the inboard SOL plasma from the outboard. The HARD physics-phase ignition parameters are examined.

First a 2-plate, 2-pump basecase was calculated to verify up/down symmetry of the solution and to compare to the 1-plate, symmetry-assumed basecase. Excellent agreement and symmetry was obtained and is demonstrated in the first two columns of TABLE I.

Second, a 2-plate, 1-pump case was run using the exact same boundary

Fig. 1. Computational mesh representing the outboard DN SOL geometry.

TABLE I.
ITER HARD Ignition DN Outboard Divertor Plate Conditions
1-Plate vs. 2-Plates; 1-Pump vs. 2-Pumps

CASE	I	II	III	IV
Comments	1-plate basecase	2-plate symmetric	2-plate (pump @ plate 1 only) (same BC as CASE II)	2-plate (pump @ plate 1 only) (same P_{SEP} & n_{SEP} as CASE II)
P_{SEP} (MW)	39.22	78.33	73.05	78.33
n_{SEP} (m^{-3})	4.029	4.034	4.156	4.032
$Z_{eff-SEP}$	1.496	1.496	1.496	1.496
SEP part thrupt ($10^{22}/s$)	7.21	14.31	9.45	9.27
UPPER PLATE:				
T_e (eV)	-----	19.50	2.58	6.50
T_i (eV)	-----	8.99	3.52	8.81
q (MW/m ²)	-----	13.70	5.68	10.19
LOWER (Pumped) PLATE:				
T_e (eV)	19.64	19.49	13.06	16.83
T_i (eV)	8.98	8.99	9.84	9.68
q (MW/m ²)	13.73	13.70	12.75	14.65

Note: (1) All calculations were done for a fixed plate/wall recycle model.
(2) The plate heat flux q is directed poloidally along flux surfaces.

conditions as in CASE II. While the P_{SEP} and n_{SEP} values differ from the design values, this CASE III demonstrates the magnitude that pumping plays in affecting sheath plasma conditions. Case IV is also a 2-plate, 1-pump configuration, but has the design P_{SEP} and n_{SEP} values.

Cases IV and II can be directly compared to show the difference between one and two pump operation. The 1-pump case has lower electron and ion temperatures than the symmetric case at both plates. The unpumped plate has a 30% lower peak sheath heat flux, while the pumped plate has a 7% increase in the peak heat flux. Also of note, the net particle throughput for the 1-pump case is 65% of the symmetric case.

The lower temperature and heat flux at the unpumped plate results from higher plasma recycling and a reduced convective power flow to the

plate. The symmetric and 1-pump particle velocity flow fields are shown in Figs. 2 and 3. High recycling at the unpumped plate causes particle flow along the separatrix from the unpumped plate to the pumped divertor. The figures only show the velocity field rather than the particle flux field. The particle fluxes are much greater near the separatrix than they are away from the separatrix. There is zero net particle flow into the unpumped divertor.

Figure 4 shows the components of the poloidal heat flux along the separatrix for the 1-pump case. Note that the convective flux is asymmetric in that particles near the unpumped plate ($x > 1.4\text{m}$) are carried to the pumped plate ($x = 12\text{m}$). The "extra" convective energy that is carried to the pumped divertor increases the peak heat flux only slightly because of a longer connection length (now plate-to-plate) for radial transport, and because of a 29% increased particle load and the resulting stronger local recycling at the separatrix of the pumped plate. Figure 5 illustrates the resulting asymmetry of the poloidal heat flux on the two plates. Note that for the unpumped plate, the ions and electrons carry similar heat fluxes to the sheath.

IV. PARTICLE THROUGHPUT AND CONFINEMENT TIME

In addition to the effect of pumping on particle flow patterns and sheath plasma conditions, the effect on particle throughput, fusion-product ash removal, and pump requirements are also important issues. The CDA fusion power is 1080MW and the maximum acceptable ash fraction is 0.1. Assuming that the ash leaves the main plasma in proportion to the ash fraction, a total particle throughput of at least

Fig. 2. Particle flow velocity field for the 2-plate symmetric case.

Fig. 3. Particle flow velocity field for the 2-plate, 1-pump case.

FLOW VELOCITIES

Fig. 4. Poloidal heat flux along the separatrix from the unpumped plate ($x=0$) to the pumped plate ($x=11.056$) for CASE IV. The heat flux components shown include the total, q_{TOT} , the ion, q_i , the electron, q_e , the ion and electron thermal conduction, q_{Ki} and q_{Ke} , convection, q_{Ci} and q_{Ce} , and the ion viscous flux, q_{VISC} .

SEPARATRIX THETA FLUX vs. LENGTH

Fig. 5. Poloidal heat flux along both divertor plates for the 1-pump CASE IV. The ion, electron, and total heat fluxes are shown.

$3.8 \times 10^{21}/s$ is required. For a main plasma density of $8.9 \times 10^{19}/m^3$ and an approximate plasma volume of $1100/m^3$, the particle confinement time is required to be less than 26s. By comparison, the ITER CDA ignition-device energy confinement time is $\tau_E = 3.82s$.¹ The assumptions on separatrix density, particle diffusivity, and plate (pump) recycle primarily determine the particle throughput. The most recent 2D plasma and 2D neutral (DEGAS) iteration for the ITER CDA physics-phase conditions resulted in an average plate recycle coefficient of $R_p = 0.990$.¹⁰ Since then, the local plate recycle model was held fixed, however, changes in the magnetic equilibrium, a more accurate representation of the equilibrium, a new spacing of the non-uniform mesh, and the addition of a parallel momentum flux limit have led to a reduced average $R_p = 0.965$, which will serve as a basis for the present discussion. For the above assumptions, the present B2-code prediction of the throughput for a single symmetric plate is $9.84 \times 10^{22}/s$. Using a (1-plate, symmetric) to a (2-plate, 1-pump) throughput conversion factor of 1.3 (as calculated in Sec. III) gives a particle confinement time of only 0.76s, which is much smaller than the energy confinement time of 3.8s.

A zero recycling case was calculated to evaluate the magnitude of recycling on the particle throughput. A $\tau_p = 0.23s$ resulted, which corresponds to a factor of 2.8 reduction in throughput compared to the $R_p = 0.965$ case. The plate recycle affects throughput much more weakly than the $1/(1-R)$ scaling that would be expected if the neutrals penetrated directly into the main plasma. The zero-recycle τ_p value is 17 times smaller than τ_E .

One can imagine a variety of plasma transport conditions ranging from

the extreme of no plasma conduction for which $\tau_p = \tau_E$ to the situation which has no convection or which has $R_p = 1$ for which $\tau_p = \infty$ and thus $\tau_p \gg \tau_E$. While not mathematically impossible, it is difficult to imagine a regime where very little energy is transported from the plasma (large τ_E), but there is rapid particle loss (small τ_p), especially in the case where neutrals do not penetrate across the separatrix into the main plasma. Thus, the situation with $\tau_p < \tau_E$ is physically unlikely, and has not been observed experimentally.

It would seem prudent to consider a zero recycling case that would have $\tau_p = \tau_E$. Then, recycling could be added in to obtain acceptable plasma sheath conditions and $\tau_p = 4\tau_E$. Such a plasma would still have $\tau_p = 13s$ and should remove ash at a sufficient rate to maintain a 5% ash fraction. In order to achieve $\tau_p = \tau_E$ for the zero-recycle case, either the edge density or the edge particle diffusivity must be lowered. Experience has shown the peak sheath heat flux and temperature to be very sensitive to the separatrix density. Any reduction in n_{SEP} would very quickly lead to unacceptable sheath conditions. The present work examines the case of reducing the particle diffusivity from $0.66m^2/s$ to a value 17 times lower of $0.04m^2/s$. The recycling model was left on, resulting in an average value of $R_p = 0.993$. The resultant particle confinement time was $\tau_p = 6s$, which is greater than τ_E , but the peak sheath temperature and heat flux were 210eV and $51.6MW/m^2$ - both unacceptably high from a heat removal and an erosion viewpoint. The small diffusivity shortens the radial power e-folding length which results in high peak sheath temperatures and heat flux. The poloidal heat flux along the plate is shown in Fig. 6 for both the $D=0.66$

Fig. 6. Poloidal heat flux along the divertor plate for both $D=0.066\text{m}^2/\text{s}$ (solid; CDA A.1 basecase) and $D=0.04\text{m}^2/\text{s}$ (dashed; $\tau_p > \tau_g$ case).

PLATE HEAT FLUX vs. PLATE LENGTH

(Werley B2 11/91)

and the $D=0.04\text{m}^2/\text{s}$ cases. Clearly, this issue of having a consistent n_{SEP} , D , R_p , τ_p , and τ_E will affect crucially divertor performance.

V. SUMMARY AND CONCLUSIONS

The double-null two-outboard-plate divertor plasma conditions were evaluated for a 2-pump (up/down symmetric) and a 1-pump configuration. The 1-pump case had lower sheath temperatures at both plates, a 30% lower peak heat flux at the unpumped plate, and only a 7% higher peak flux at the unpumped case. The total particle throughput dropped to 65% for the 1-pump case. Basically the 1-pump case acts like a SOL plasma with an overall higher system plasma recycle coefficient.

The effect of recycling on particle throughput was also examined. Increasing the average R_p from 0 to 0.965 increases the τ_p (decreases the throughput) by a factor of 2.8 .

Given the recommended physics assumptions for separatrix density and particle diffusivity, the particle throughput calculated by the B2 code for the CDA ignition baseline is two orders of magnitude higher than that needed to remove the ash, resulting in τ_p values much smaller than τ_E . If one requires $\tau_p > \tau_E$, then the present physics assumptions recommended by the ITER physics group are inconsistent. To obtain $\tau_p > \tau_E$ in the B2 simulations, either n_{SEP} or D must be reduced significantly. If made consistent, then the plasma sheath conditions lead to unacceptable erosion and heat flux loads even for the ITER CDA physics-phase device which has reduced power handling requirements than the technology-phase device. Raising plate recycling will help somewhat.

In conclusion, it would seem appropriate to ask the ITER physics

group to modify their recommendations for D and n_{SEP} so that $\tau_p = \tau_E$ for the no recycle case. Subsequently, using the 2-plate, 1-pump configuration, the B2 code should add in recycling, and the results should be iterated with the 2D DEGAS neutral transport results. Care should be taken to account for vacuum pump constraints and to have a throughput that adequately removes the fusion ash. This, then, would be a proper starting place for evaluating the sheath peak temperature and heat flux.

ACKNOWLEDGEMENTS

The authors would like to acknowledge R. Bulmer of Lawrence Livermore National Laboratory (LLNL) for supplying the ITER equilibria. Also, M. Rensink and T. Rognlien, both from LLNL, provided the mesh generation routines and advice on how to use them. Thanks also to D. Ruzic of the University of Illinois for useful physics discussions.

REFERENCES

1. "The ITER Conceptual Design Report", IAEA/ITER/DS/18, ITER Documentation Series, IAEA, Vienna(1991).
2. S.A. Cohen, K.A. Verley, D.E. Post, B.J. Braams, J.L. Perkins and D. Pearlstein, "Two-Dimensional Fluid Simulations of ITER SOL Plasma", J. Nucl. Mat., 176&177(1990)909.
3. hard
4. B.J. Braams, "A Multi-Fluid Code for Simulation of the Edge Plasma in Tokamaks", NET Report Nr. 68, EUR-FU/XII-80/87/68 (January, 1987).
5. M. Petravic, J. Comp. Phys., 73(1987)125.
6. teq
7. bulmer
8. S.I. Braginskii, in Reviews of Plasma Physics, edited by M.A. Leontovich (Consultants Bureau, New York, 1965), Vol. I, 205.
9. D.B. Hefetz et al., J. Comp. Phys., 46(1982)309.
10. D.N. Ruzic, K.A. Verley and S.A. Cohen, "Neutral Gas Temperature and Densities in the Divertor Region and Pump Duct of ITER", J. Nucl. Mat., 176&177(1990)926.