EFDA–JET–CP(12)02/05

C. Guillemaut, R.A. Pitts, J. Bucalossi, G. Corrigan, A.S. Kukushkin, D. Harting,
A. Huber, M. Wischmeier, G. Arnoux, S. Brezinsek, S. Devaux, J. Flanagan,
M. Groth, S. Jachmich, U. Kruezi, S. Marsen, J. Strachan, S. Wiesen
and JET EFDA contributors

EDGE2D-EIRENE Modelling of Divertor Detachment in JET High Triangularity L-mode Plasmas in Carbon and Be/W Environment

EDGE2D-EIRENE Modelling of Divertor Detachment in JET High Triangularity L-mode Plasmas in Carbon and Be/W Environment

C. Guillemaut[1], R.A. Pitts[2], J. Bucalossi[1], G. Corrigan[3], A.S. Kukushkin[2], D. Harting[4], A. Huber[4], M. Wischmeier[5], G. Arnoux[3], S. Brezinsek[4], S. Devaux[3], J. Flanagan[3], M. Groth[6], S. Jachmich[7], U. Kruezi[4], S. Marsen[8], J. Strachan[9], S. Wiesen[4]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Association Euratom CEA, CEA/DSM/IRFM, Cadarache, 13108 Saint-Paul-lez-Durance, France
[2]ITER Organization, Route de Vinon sur Verdon, 13115 Saint-Paul-Lez-Durance, France
[3]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[4]Institut fur Plasmaphysik, Forschungszentrum Juelich GmbH, EURATOM Association, Trilateral Euregio Cluster, D-52425 Juelich, Germany
[5]Max-Planck-Institut für Plasmaphysik, EURATOM-Association, Boltzmannstr. 2, D-85748 Garching, Germany
[6]Aalto University, Association EURATOM-Tekes, Otakaari 4, 02015 Espoo, Finland
[7]Laboratory for Plasma Physics, ERM/KMS, Association EURATOM-Belgian State, B-1000 Brussels, Belgium
[8]Max-Planck-Institut für Plasmaphysik, Teilinsitut Greifswald, EURATOM-Assoziation, D-17491 Greifswald, Germany
[9]PPPL, Princeton University, Princeton, NJ 08540, USA
** See annex of F. Romanelli et al, "Overview of JET Results", (23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).*

Preprint of Paper to be submitted for publication in Proceedings of the
20th International Conference on Plasma Surface Interactions , Eurogress, Aachen, Germany
21st May 2012 - 25th May 2012

ABSTRACT
The EDGE2D-EIRENE code is applied for simulation of divertor detachment during density ramp experiments in high triangularity, L-mode plasmas in both the carbon and Be/W environments in JET. Emphasis is placed on matching experimental data (upstream and in the divertor) as far as possible. The code runs without drifts and includes either C or Be as impurity, but not W, assuming that the divertor plasma is always cold enough for the W target source to be negligible and that the W targets have to some extent been coated with Be via main chamber migration. The simulations reproduce the observed particle flux detachment as density is raised in both C and Be/W, but not the experimental in/out asymmetry. The main difference between detachment in carbon and Be/W environments is a higher upstream density required in the Be/W case to obtain similar divertor conditions to those when carbon dominates.

1. INTRODUCTION
Partially detached divertor operation is mandatory on ITER to maintain the target power loading at a manageable level during burning plasma operation [1]. Such regimes are found on essentially all divertor tokamaks, but are still not straightforward to reproduce in modelling. Here, the EDGE2D-EIRENE code (2D fluid plasma + 3D kinetic Monte-Carlo neutrals) [2,3] is used to simulate the detachment during JET L-mode density ramp experiments in high triangularity plasmas with either carbon (C) or beryllium/tungsten (Be/W) Plasma-Facing Components (PFC), but essentially identical divertor geometry.

These discharges, which have the primary X-point close to the inner target (HT3L configuration – see Fig.1) were performed for detachment characterization with hydrogen as working gas and with carbon PFCs just before the change-out of materials to the ITER-Like Wall (ILW) configuration. The plasmas were run with 2MA plasma current, 3T toroidal magnetic field and 3 MW input power and then repeated (but with deuterium as working gas) in the Be/W environment early on in the first JET-ILW campaign. Gas fuelling was applied in the divertor to produce a controlled density ramp, driving the divertor plasma from low recycling through conduction-limited to detached regimes. This paper presents the results from EDGE2D-EIRENE modelling of these shots with emphasis on matching experimental observations as closely as possible. The modelling runs are performed without drifts, using upstream separatrix density control and including either C or Be as the impurity. Cross-field transport coefficients are held constant throughout the simulated density ramp, allowing a reasonable match to the experimental upstream n_e and T_e profiles (Fig.2). One of the key ingredients in providing a reasonable description of the detachment behavior seems to be the use of an improved neutral model in EIRENE [4,5] (see next Section and Table 2).

2. DETACHMENT MODELING WITH CARBON PFCS
JET Pulse No: 79315 with 3MW total heating power (ohmic plus Neutral Beam Injection (NBI), the latter assumed not to contribute to the discharge fuelling) was selected as the reference for

detachment modelling in the carbon dominated environment, prior to the ILW changeout. In this particular experiment, hydrogen is used as the working gas. This study is focused on the evolution of the downstream Scrape-Off Layer (SOL) conditions during the density ramp and makes use of the experimental signals provided by the diagnostics shown in Fig.1.

The magnetic equilibrium used to build code simulation grid is taken from an EFIT reconstruction at t = 20s, at the centre of the density ramp, in which the line average density increases from 2.5×10^{19} m^{-3} at the start of the ramp to 4.5×10^{19} m^{-3} at the end. Within experimental error, the equilibrium reconstruction is identical at all times through the ramp. The vessel wall at the top of the main chamber was modified slightly in the calculation to accommodate a wider SOL in the 2D grid. Following [4], the albedo of the vessel wall is adjusted for both default and improved neutral models (see Table 1) to allow the puffing and pumping rate to match the experimental values in the simulation. The puffing rate varies from 2.2×10^{22} s^{-1} to 2.7×10^{22} s^{-1} during the density ramp. The pumping rate is deduced from the Penning gauges in the divertor pumping duct, assuming a temperature of 300K for the sub-divertor region and a pumping speed of 150 $m^3.s^{-1}$ for the divertor cryo-pump. It increases from 1×10^{21} s^{-1} to 1.7×10^{22} s^{-1} during the density ramp. The dynamic retention [6] is a transient phenomena acting like a pump during the shot and can be responsible for the mismatch between pumping and puffing rates in experiment.

The gas puff in the code is introduced in the private flux region, as in experiment and the density is controlled at the outer midplane separatrix. The separatrix position is estimated using a two-point model [7] to compute the separatrix temperature in the lowest density (low recycling) case. It appears that the EFIT separatrix must be shifted by ~1cm towards the high field side to provide a match between the analytic prediction and the experimental data. This 1 cm separatrix shift has been applied to all upstream experimental profiles throughout the density ramp. In EDGE2D-EIRENE, the perpendicular transport is assumed to be diffusive and in this particular case, the shifted experimental n_e and T_e profiles provided respectively by the Li-beam and HRTS diagnostics, are matched by adjustment of constant cross-field transport coefficients that do not vary during the density ramp, Fig. 2. The perpendicular particle and heat diffusivities are thus fixed at $D_\perp = 0.5 m^2.s^{-1}$ and $\chi_\perp = 1.5\ m^2\ s^{-1}$ for hydrogen and carbon impurity ions. The 3MW input power is split equally between electrons and ions, poloidal drifts are not activated, Bohm conditions is applied at the target (M = 1) and electron and ion flux limiters are respectively set at 0.2 and 10. The carbon impurity is released by physical and chemical sputtering with the latter estimated according to the Haasz/Davis Model [7].

Two different neutral models are compared in this study: the default model used in most EDGE2D-EIRENE simulations to date and an improved model [4,5] including more atomic physics processes, Table 2. The inclusion of collisions between ions and hydrogen molecules enhances the momentum transfer from ions to neutrals, promoting detachment. The use of the CRM model for electron and hydrogen molecule collision rates is important because of the low temperatures and high densities associated with detachment. Finally, the improved model includes the basic reactions involving H_2^+ ions which may effectively enhance the volumetric recombination. In all cases, EIRENE is run with 64000 neutral histories to reduce the statistical noise.

Simulations with the improved neutral model provide reasonable agreement with the magnitude (factor 2) and especially the trend of the particle flux evolution measured with Langmuir probes at the targets and the deposited power obtained with IR thermography (see Fig. 3, where the simulated particle flux values have been multiplied by a factor 2). Only the improved model allows EDGE2D-EIRENE to reproduce clearly the experimentally observed partial detachment phase (solid blue and red curves on Fig. 3) with a progressive decrease of J_{sat} and n_e at both targets. The upstream separatrix density limit is also well predicted with the code stopping where a disruption is observed in experiment.

As usual in these kinds of simulation, the code fails to match the observed Langmuir probe outer target electron temperature evolution through the early phases of the density ramp, when the experimental measurements indicate a strongly attached, low recycling divertor plasma. In contrast, the code target T_e has already collapsed to very low values (< 10eV) at the beginning of the ramp, even though, as discussed above, the particle flux is matched within a factor of 2 at these lowest densities. At the inner target, there are no IR thermographic measurements the Langmuir probe T_e data is very widely scattered and of insufficient quality to provide any benchmark for the code. There is clearly a strong experimental in-out asymmetry in both the profile shape and evolution of the target particle fluxes. The shape variation is due largely to the divertor geometry, with a vertical (IT) versus horizontal (OT) target configuration and with the X-point very close to the IT. The earlier experimental inner detachment in comparison with the outer is commonly observed and difficult to reproduce in simulations, even with drift terms active [5].

One possible explanation for the discrepancy between the simulated and measured target temperatures is the influence of kinetic effects in the parallel electron transport to the target. As described in [9], depending on the collisionality in flux tubes in the X-point to divertor region (where strong parallel temperature gradients develop), electrons may reach the targets collisionlessly, carrying with them memory of the value of T_e at the location of the last collision. Since Langmuir probes are sensitive only to the high energy tail of the electron velocity distribution, it is thus possible that values much higher than those characteristic of the actual target temperature may be registered by embedded target probes at the lower density range of the density ramp. As the density increases, collisionality increases strongly in the divertor and it would thus be expected that for the high recycling and detaching regimes, the probes would provide a more realistic measure of the local T_e.

In simulations run with the default neutral model in EDGE2D-EIRENE (see dashed curves in Fig.3) the code is able to match the low and high recycling phases, but runs into difficulty (crashes) before showing a significant decrease of J_{sat} and n_e. The atomic processes included in the improved neutral model therefore appear to be mandatory for modelling the partially detached phase in JET with EDGE2D-EIRENE.

During this phase, the total radiation power predicted by EDGE2D-EIRENE is around 1.5MW

(1.1MW from C and 0.4MW from H) with about 0.5MW distributed around the X-point. In experiment, the bolometers measure 1.8MW of total radiated power and 0.6 MW (calculated from tomographic inversion) coming from the X-point region during the same phase.

3. DETACHMENT MODELING WITH BE/W PFCS

The same density ramp experiment in HT3L configuration described for carbon in Section 2 was repeated in the JET-ILW, but on this occasion with deuterium as working gas (compared with hydrogen in the carbon case). In this case, JET Pulse No: 82342 is chosen as the reference for EDGE2D-EIRENE. Figure 5 presents the same compilation of signals (code and experiment) from this more recent experiment as for the C case in Fig.3. Comparing the two, the experimental detachment behavior is essentially the same in both the C-dominated and Be/W environments. The same in/out asymmetry is observed, with much earlier detachment at the IT. The only notable difference is the higher (by ~20%) experimental upstream density required in the Be/W case to obtain divertor conditions similar to the carbon case.

The EDGE2D-EIRENE model for Pulse No:82342 is the same as for Pulse No: 79315, with the hydrogen replaced by deuterium and C replaced by Be for the entire wall, including the divertor. It is therefore assumed that the W targets are essentially entirely coated with beryllium as a result of main chamber migration [10] and that in any case the divertor plasma is cold enough, especially at the higher densities, that W sputtering is effectively absent and so the concentration of tungsten is sufficiently low to be ignored in the simulation. Slightly different vessel wall albedos are required to adjust the code to the experimental puffing and pumping rates, Table 3. The puffing rate increases from 2×10^{22} s^{-1} to 5.8×10^{22} s^{-1} whereas the pumping rate increases from 1×10^{21} s^{-1} to 4.2×10^{22} s^{-1} during the density ramp. The default and improved neutral models were also compared in this case.

Similarly to the carbon case, the low and high recycling regimes are reasonably well reproduced with both neutral models (Fig.5). As before, the partial detachment phase can be well reproduced in the simulations only if the improved neutral model is used in EIRENE. The earlier detachment observed experimentally at the IT in comparison with the OT is also again not matched by the simulations. It would thus appear that impurity type (and hence the radiation levels for example) are not the main driver for this in-out asymmetry.

An important difference in the Be/W case in comparison with C is the less abrupt collapse of the outer target temperature at relatively low density, possibly related to lower levels of divertor radiation in the Be/W plasmas. The behavior is quite well reproduced, within an approximate factor of 2, by the code. The predicted upstream separatrix density limit also matches well the Be/W experiment and appears to be also 20% higher than calculated for the carbon case. As in the experiment, this is the only notable difference between the carbon and beryllium environments.

During the partial detachment phase, the total radiated power predicted by EDGE2D-EIRENE is around 1 MW, equaly splited between deuterium and beryllium impurities, with ~0.2MW distributed around the X-point. In experiment, the bolometers measure 2MW of total radiative power during the same phase. Unfortunately, tomographic inversions has not been possible in these Be/W density ramps due to the poor quality of the bolometry signals and so the contribution from the X-point region cannot be reliably estimated.

CONCLUSIONS

Results from EDGE2D-EIRENE modelling of detachment experiments in high triangularity L-mode JET plasmas are presented for both carbon and Be/W environments. In both cases, the code can produce a clear stable partial detachment phase as in experiment, provided that a more complete set of atomic processes is used in EIRENE. The key points distinguishing the improved model are:

(a) collisions between ions and hydrogen molecules (both elastic and inelastic) which enhance the momentum transfer from ions to neutrals at low temperature and high density;

(b) CRM rates for the reactions involving electrons and hydrogen molecules, which have strong density dependence at low temperature, and;

(c) reactions involving H_2^+ ions which may facilitate volume recombination.

The experiments show a strong in/out asymmetry during the detachment for both carbon and Be/W environments – a feature still missing in the simulation results. The in/out asymmetry cannot therefore be attributed to the wall material (and hence, for example, the level of impurity radiation in the divertor plasma). During the detachment, a notable difference between carbon and Be/W environments is the ~20% higher upstream density required to produce to produce similar divertor conditions in Be/W to the case of carbon only.

ACKNOWLEDGMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]. R.A. Pitts et al. Journal of Nuclear Materials 415 (2011) S957–S964

[2]. R. Simonini et al. Contribution Plasma Physics **34**, 368 (1994)

[3]. www.eirene.de/e2deir_report_30jun06.pdf

[4]. V.Kotov et al. Plasma Physics and Controlled Fusion **50** (2008) 105012

[5]. M. Wischmeier et al. Journal of Nuclear Materials **523–529** (2011) 415

[6]. J. Bucalossi et al. 28nd EPS Conf. on Plasma Physics (2001) vol 25A (ECA) P4.082

[7]. P. Stangeby, The plasma boundary of magnetic fusion devices, IOP publishing (2000)

[8]. J.W. Davis et al. Journal of Nuclear Materials **241–243** (1997) 37

[9]. J. Horacek et al. Journal of Nuclear Materials **313–316** (2003) 931

[10]. K. Krieger et al. 20th PSI Conference (2012)

Upstream n_e (10^{19} m^{-3})	1.3	1.5	1.7	> 2
Default neutral model	0.86	0.90	0.94	0.97
Improved neutral model	0.88	0.93	0.95	0.98

Table 1: Wall albedos used along the density ramp in the simulation with C impurities

Default EIRENE model:	**Improved EIRENE model**
(1) $e + H^0 \rightarrow 2e + H^+$	Same reactions as default plus:
(2) $H+ + H^0 \rightarrow H^0 + H^+$	(9) $H_2 + H^+ \rightarrow H^+ + H_2$
(3) $e + C^0 \rightarrow 2e + C^+$	(10) $H_2 + H^+ \rightarrow H_2+ + H^0$
(4) $e + H_2 \rightarrow 3e + 2H^+$	(11) $e + H_2 \rightarrow 2e- + H_2^+$
(5) $e + H_2 \rightarrow e + 2H^0$	(replacing (4))
(6) $e + H_2 \rightarrow 2e + H^+ + H^0$	(12) $e + H_2^+ \rightarrow e + H^0 + H^+$
(7) $e + H^+ \rightarrow H^0$	(13) $e + H_2^+ \rightarrow 2e + 2H^+$
(8) $2e + H^+ \rightarrow e + H^0$	(14) $e + H_2^+ \rightarrow 2H^0$
No CRM for (4), (5) and (6)	CRM for (11), (5) and (6)

Table 2: Default and improved set of atomic reactions used in EIRENE

Upstream n_e (10^{19} m^{-3})	1	1.5	2.1	> 2.4
Default neutral model	0.76	0.93	0.98	0.98
Improved neutral model	0.79	0.95	0.98	0.98

Table 3: Wall albedos used along the density ramp in the simulation with Be impurities

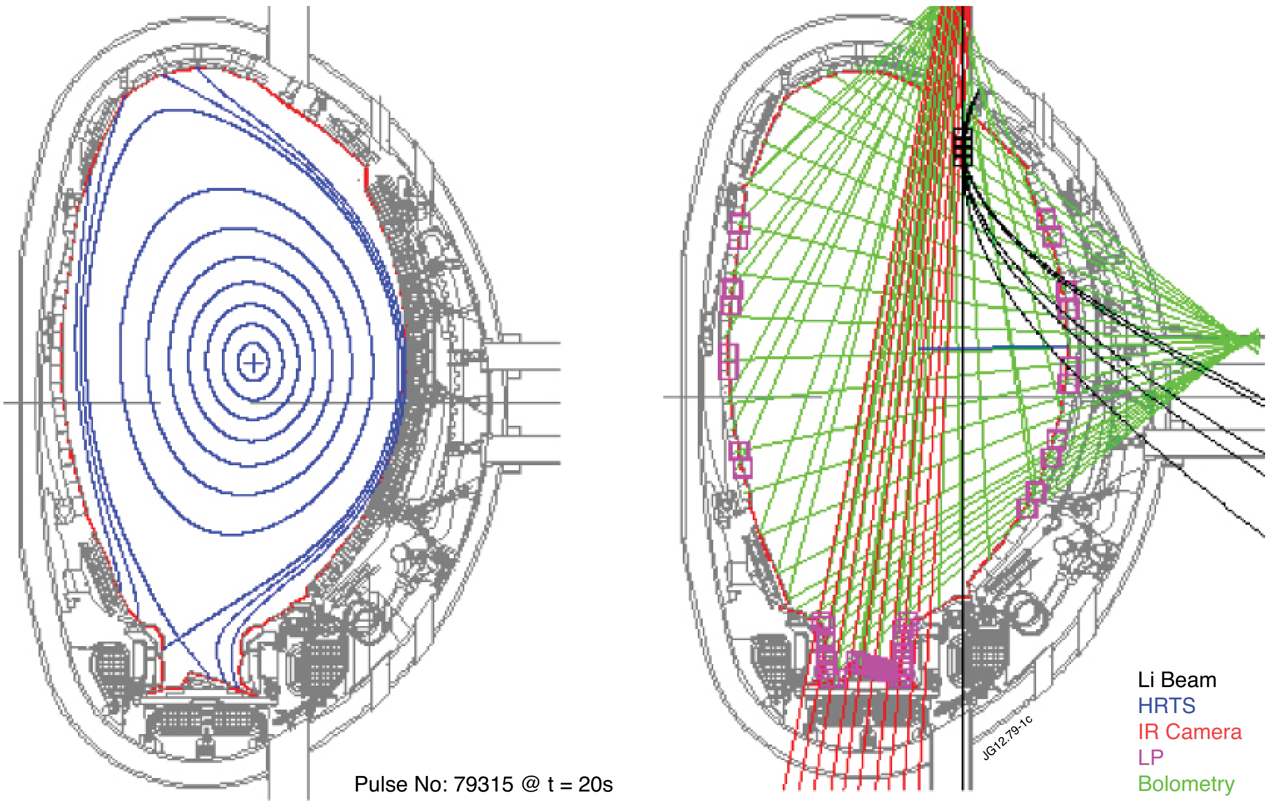

Figure 1: Left: HT3L magnetic equilibrium for JET pulse #79315 at t = 20 s. Right: main diagnostics used for comparison of code and experiment: Lithium Beam (Li-beam), High Resolution Thomson Scattering (HRTS), infra-red (IR) camera, Langmuir Probes (LP) and bolometers.

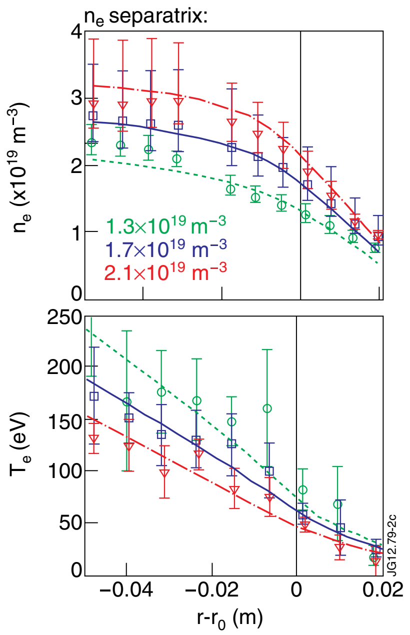

Figure 2: Left: upstream density match between the EDGE2D-EIRENE model (lines) and experimentally measured with Li-beam (error bars) at 3 different points in the density ramp. Right: upstream temperature match between EDGE2D-EIRENE (lines) and experimental measurements from HRTS (error bars). Intermediate cases with 1.5 and 2x10^{19} m^{-3} midplane separatrix densities are omitted for clarity.

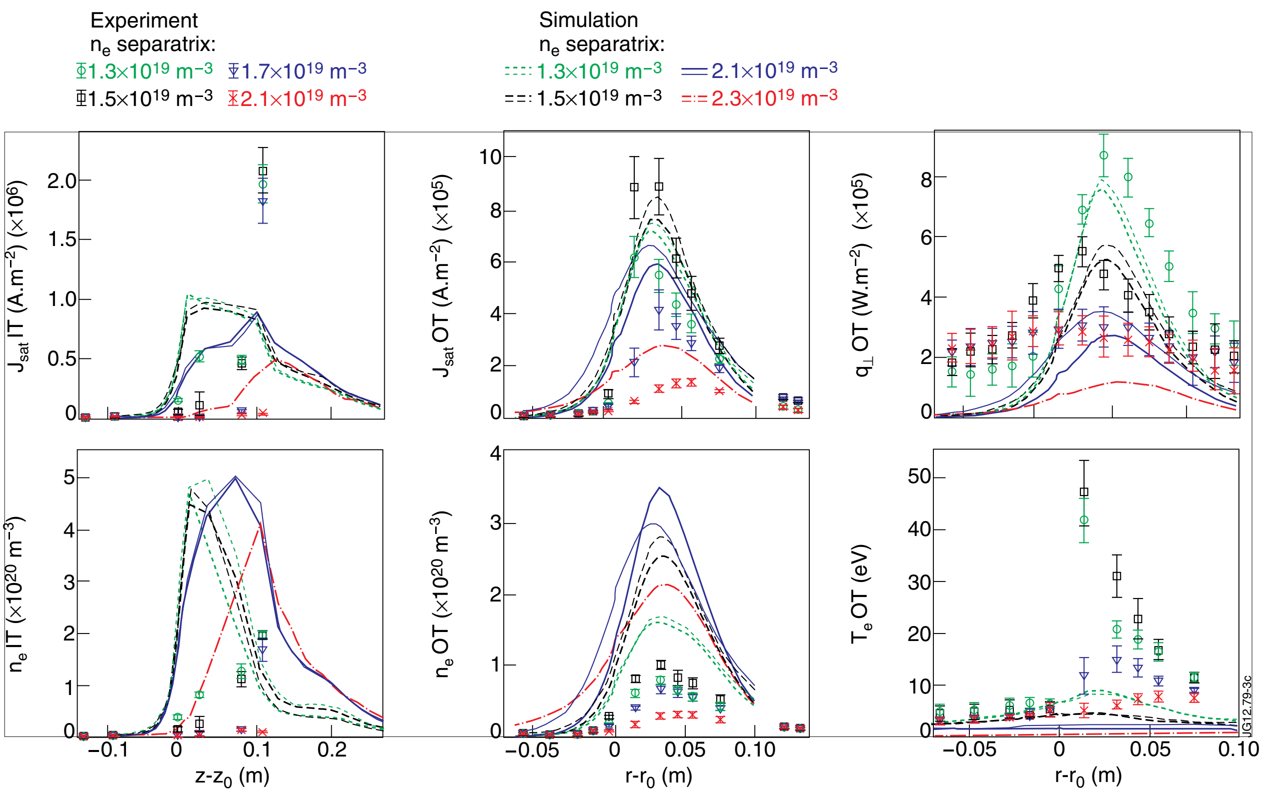

Figure 3: Comparison between EDGE2D-EIRENE simulations (solid lines for improved neutral model and dashed for default) and experimental data during the density ramp for carbon PFCs. From left to right and top to bottom: IT and OT ion saturation current density, OT power deposition profile, IT and OT electron density and OT electron temperature. All calculated values are doubled.

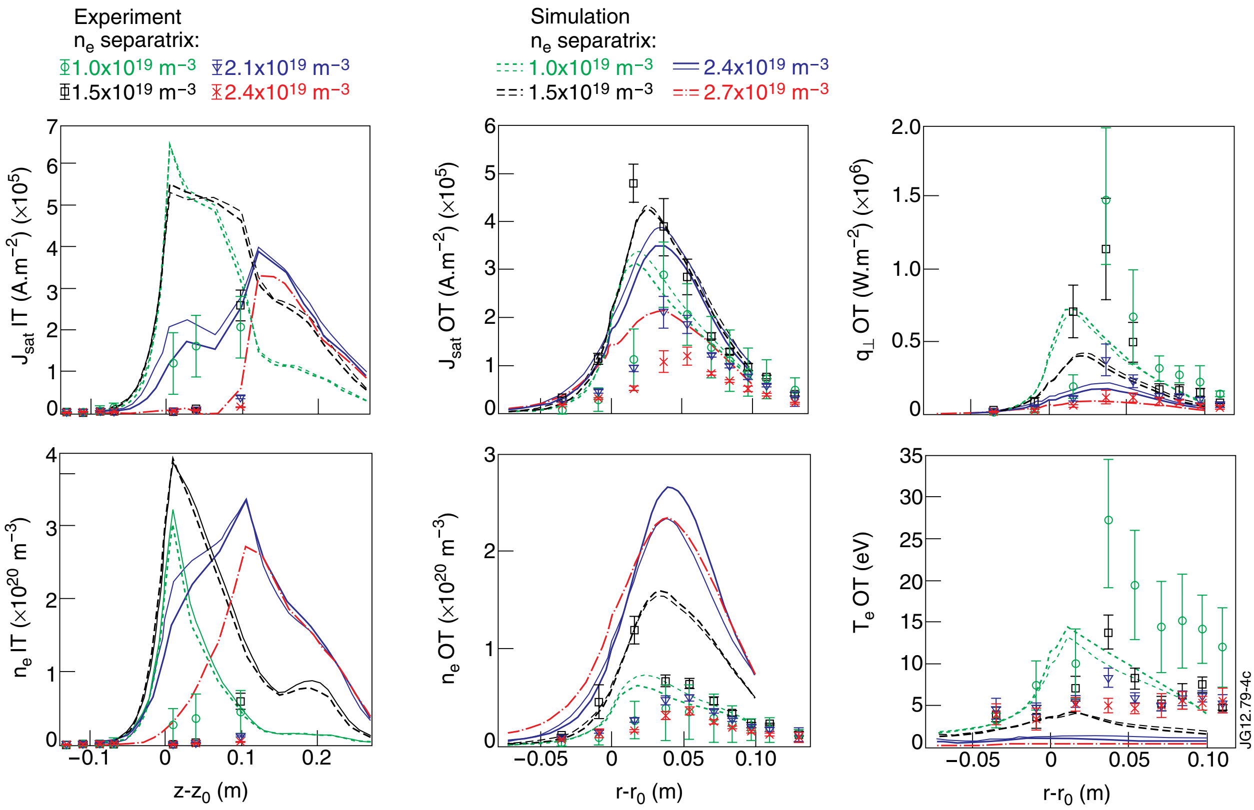

Figure 4: As in Fig. 3 but for the Be/W environment. No multiplicative factor has been applied to the simulation data.