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Comparison of carbon and main ion radiation profiles in matched helium and deuterium plasmas in JET

M.E. Fenstermacher [a,*], K.D. Lawson [b], G.D. Porter [a], S.K. Erents [b], C. Ingesson [c], G.F. Matthews [b], G.M. McCracken [b], V. Philipps [d], R.A. Pitts [e], M.F. Stamp [b], Contributors to the EFDA-JET Workprogramme

[a] *Lawrence Livermore National Laboratory, DIII-D National Fusion Facility, Livermore, 94550 CA, USA*
[b] *EFDA-JET, UKAEA Fusion, Culham Science Centre, Abingdon, Oxfordshire OX14 3EA, UK*
[c] *FOM Instituut voor Plasmafysica Rijnhuizen, EURATOM Association, Postbus 1207, NL-3430 BE Nieuwegein, Netherlands*
[d] *FZJ – Forschungszentrum Julich, Association Euratom-FZJ, D-52425 Julich, Germany*
[e] *CRPP – Ecole Polytechnique Federale de Lausanne, Association Euratom-Confederation Suisse, CH-1015 Lausanne, Switzerland*

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Abstract

This paper examines the radiation profiles and corresponding ionization source profiles of carbon and main plasma ions in matched helium and deuterium L-mode plasmas in JET. The radiation intensities from C^{1+}, C^{2+} and C^{3+} in the helium plasmas showed reduction by factors of 8, 10 and 25, respectively along the inner SOL and divertor leg compared with the deuterium cases. However, the emission in the outer divertor leg was less than a factor of 2 lower in helium. Using photon efficiencies calculated by the UEDGE code for the spectrometer lines of sight, the calculated source rates of C^{1+} and C^{3+} along the inner SOL and inner divertor were reduced by factors of 4 and 20, respectively in the helium plasmas. In the outer divertor leg the source rate of C^{3+} was reduced by a factor of 10 but the C^{1+} source rate did not change in helium. These measurements are consistent with a model that chemical sputtering of carbon dominates the source from the inner wall and inner divertor in deuterium L-mode plasmas while physical sputtering appears to dominate the source from the outer divertor.

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1. Introduction

In tokamaks operated with graphite walls and deuterium plasmas, carbon impurities play a significant role in the radiation distribution and power balance for the scrape-off-layer (SOL) and divertor plasmas. One way to substantially change the carbon effects in the divertor, for comparison against predictive theories, is to change the working gas from deuterium (D) to helium (He). In helium plasmas the source of carbon due to chemical sputtering is expected to be small and the cross sections for charge exchange and ionization are different so the divertor conditions should change substantially, thereby testing the models.

This paper focuses on a comparison of radiation profiles and implied carbon source rates in matched L-mode deuterium and helium plasmas in a JET high clearance equilibrium shape. Carbon and helium emission data from fixed visible and scanning VUV views of

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[*] Corresponding author. Address: General Atomics, P.O. Box, 85608, San Diego, CA 92186-5608, USA. Tel.: +1-858 455 4159/858 455 4155; fax: +1-858 455 4156/858 455 4190.

E-mail addresses: max.fenstermacher@gat.com, fenstermacher@fusion.gat.com (M.E. Fenstermacher).

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the divertor and SOL show significant differences by region between helium and deuterium plasma operation. The responses of the source rates in helium plasmas as functions of injected power and plasma density are also examined.

2. Description of experiments

The matched helium and deuterium plasmas for this study used a JET equilibrium shape with large plasma-wall gaps (high clearance) and vertical sweeps of the divertor strikepoints to provide detailed profiles in the divertor from target Langmuir probes, IRTV and bolometers. Basic operational parameters were: major radius, $R = 2.9$ m, minor radius, $a = 0.9$ m, elongation, $\kappa = 1.7$, plasma current, $I_p = 2.4$ MA, toroidal field, $B_T = 2.4$ T, and safety factor, $q_{95} = 2.7$.

Time histories of operational parameters are shown in Fig. 1 for the L-mode discharges used in this paper. In the matched helium and deuterium plasmas, $P_{SOL} \sim 4.0$ MW and $n_e = 3.6 \times 10^{20}$ m^{-3}. One of the other helium discharges had higher power, $P_{SOL} = 6.2$ MW at comparable density and the final helium discharge had higher density, $n_e = 7.0 \times 10^{20}$ m^{-3} at comparable power. The helium plasmas using He neutral beam injection (NBI) contained approximately 4% deuterium. The deuterium plasma with deuterium NBI contained 2% helium.

The primary measurements used for the poloidal profile analysis were VUV CIV and HeII from a vertically viewing scanning VUV spectrometer (KT1) and visible CII from a vertically viewing camera (KL2C). Both of these diagnostics view the plasma from the top with wide views of the divertor and part of the SOL regions. For the helium discharges the two detectors of the KT1 instrument were set to the 31.2 nm CIV line and the 3rd order (91.1 nm) of the 30.3 nm HeII line. In the deuterium plasma KT1 also gives information on CIV. The KL2C camera measures intensity of the 658 nm visible CII line for all of the discharges considered here. Finally, calibrated measurements of 465 nm CIII emission from wide angle chords viewing horizontally at the midplane and vertically into the inner and outer divertor regions are available from the KS3 spectrometer for all of the discharges.

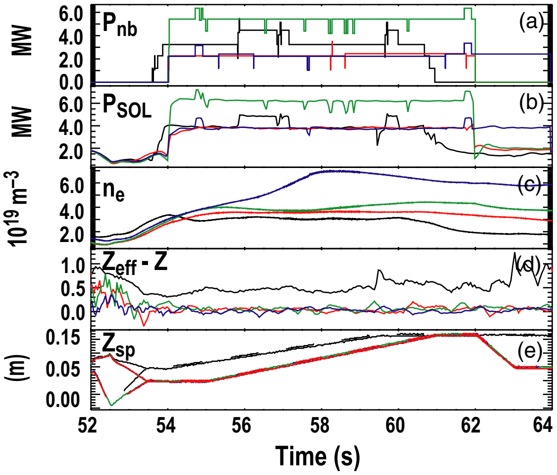

Fig. 1. Time histories of (a) neutral beam injected power, P_{nb} (MW), (b) power entering the SOL, P_{SOL} (MW), (c) line averaged electron density, n_e (10^{19} m^{-3}), (d) plasma effective charge, Z_{eff}, and (e) inner (dashed) and outer (solid) strike point vertical position for the deuterium discharge (50414 – black), the matched helium plasma (53981 – red), and helium pulses at higher power (53982 – green) and high density (53984 – blue).

3. Analysis

The spectroscopy data showed significant reductions in carbon emission in the inner divertor and SOL in helium compared with deuterium plasma operation but less change in the outer divertor (Fig. 2). For the matched discharges at 57.5 s when the densities are comparable, the carbon emission in He plasma in the outer divertor leg is only about a factor of 2 lower than in the D plasma. However the emission is significantly lower in helium for the inner leg (factor of 10) and the midplane SOL (factor of 12) than in deuterium. At higher power in helium the CIII emission in the outer leg increased to the level in the deuterium plasma but the emission in the inner leg and at the midplane was still much lower (factors of 3 and 5, respectively) than in deuterium. Finally at comparable power but higher

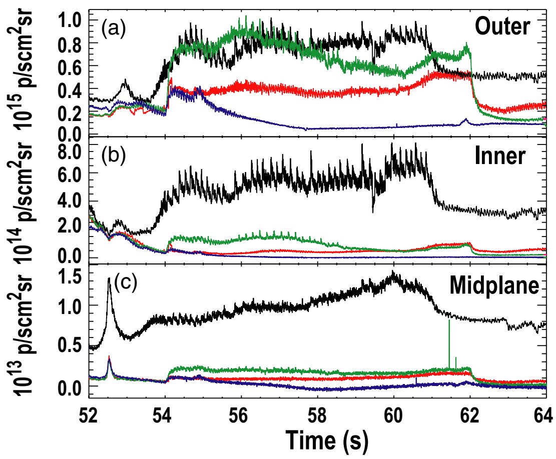

Fig. 2. Time histories of CIII (465 nm) emission from the wide angle views of the KS3 spectrometer at (a) the outer divertor, (b) the inner divertor and (c) the horizontal midplane. The plasmas and color scheme are the same as in Fig. 1.

density in helium the CIII decreased to low values in all views.

3.1. UEDGE modeling

To quantify the differences in carbon behavior between helium and deuterium plasmas in terms of sources the UEDGE fluid plasma code [1] was used to calculate an average photon efficiency, S/XB, for the measured wavelengths and lines of sight of several of the diagnostics. In each UEDGE simulation the plasma consisted of a combination of neutrals and all ion charge states of deuterium, helium and carbon. A diffusive fluid model was used for the neutrals. For deuterium the full set of fluid equations was solved including ion continuity and parallel momentum equations with classical parallel and anomalous perpendicular viscosities. For the helium and carbon ions only a simplified equation balancing pressure gradient, friction, electrostatic and temperature gradient forces was solved [2]. Deuterium charge exchange effects were included but no model of helium charge exchange was available. Models for both physical and chemical sputtering of carbon by deuterium and helium were used [3]. Poloidally and radially uniform transport coefficients were $D = 0.35$ and $\chi = 0.70$ m^2/s for particles and energy, respectively. Simulations with these coefficients produced good matches with measured upstream radial profiles of density and temperature (e.g., deviations of <20% from reciprocating probe SOL T_e data).

Since the primary goal of the modeling was to calculate S/XB for the diagnostic measurements, the local recycling coefficients for ions and neutrals were adjusted independently at the inner and outer target plates to obtain reasonably good matches between the probe target profiles of J_{sat}, n_e and T_e and the simulation profiles (Fig. 3). The largest difference was in the helium cases where the simulation tended to overestimate the temperature near the inner target plate by up to a factor of 2 (Fig. 3(b)). This will tend to overestimate the S/XB value in the inner divertor by comparable factors so the inner divertor source rates inferred from the emission measurements are upper limits. Finally, since the plates should be saturated, a better model would be to use unity recycling on all targets. There are indications that combining this with the UEDGE model for poloidal particle drifts due to ion ∇B and $E \times B$ effects [4] may help the simulations match the in–out asymmetry of the measurements. Although the present deuterium simulations show similar peaks in the chemical sputtering sources along both the inner and outer SOL just above the divertor region and no corresponding source in the helium simulations, strong conclusions about the poloidal distribution of these sources cannot be drawn from the modeling until the poloidal drifts are included; work on these simulations is in progress.

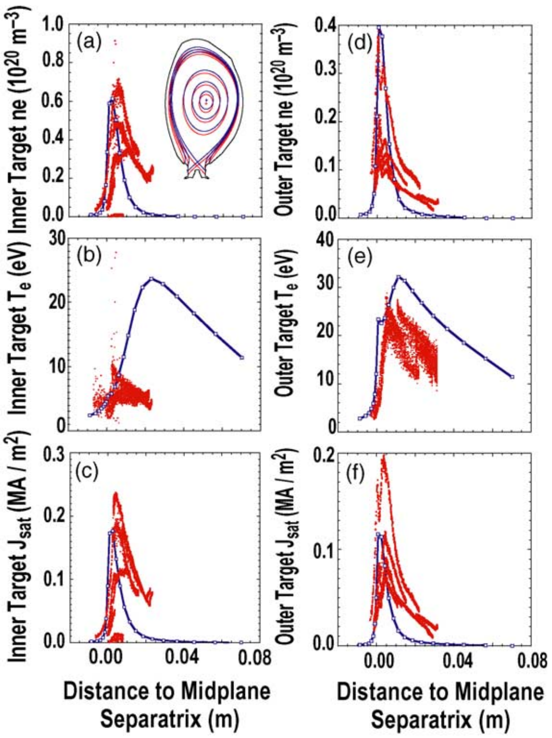

Fig. 3. Comparison of inner (a–c) and outer (d–f) target plate profiles of electron density n_e (10^{20} m^{-3}) (a,d), electron temperature T_e (eV) (b,e) and ion saturation current J_{sat} (MA/m^2) (c,f) measured by fixed Langmuir probes (red dots) and calculated by UEDGE (blue line with open squares) for helium discharge 53981. All of the probe data from the vertical X-point sweep (see equilibria inset) are shown.

3.2. Comparison of carbon source rates

Comparison of poloidal profiles of CII visible and CIV UV emission show that helium operation has a significant effect on the source of low charge states of carbon in the inner divertor region and on the level of higher charge states of carbon throughout the divertor (Fig. 4). The radiation profiles (Fig. 4(a) and (c)) show a factor of 8 reduction in the CII emission and a factor of 25 reduction of CIV from the inner divertor region in helium, and a factor of 10 reduction of CIV from the outer divertor. These reduction factors are very similar to those seen in helium plasmas in DIII-D [5]. However the CII emission in the outer divertor region is comparable with that in deuterium plasmas. Converting to sources (Fig. 4(b) and (d)) using the S/XB values calculated by UEDGE, the data show the reduction in C^{1+} source in the inner divertor is a factor of 4 and the reduction in the source of C^{3+} is more than a factor of 10 throughout the divertor region. The C^{1+} source in the outer divertor region is comparable in helium and deuterium. These data indicate that the carbon sources from

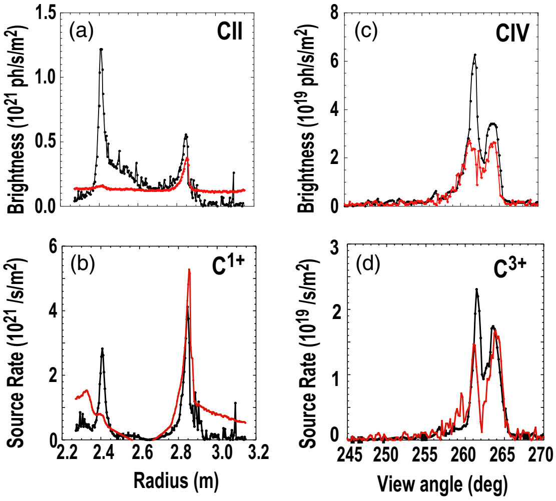

Fig. 4. Comparison of profiles of (a) visible CII (658 nm) and (c) UV CIV (31.2 nm) intensities and the inferred source rates of (b) C^{1+} and (d) C^{3+} from the KL2C and KT1 spectrometers, respectively in helium plasma 53981 (red) versus deuterium plasma 50414 (black). For clarity CIV intensity and C^{3+} rate displayed for the helium plasma are 10× actual values. The abscissa for the CII data is the major radius of the view chord at a vertical location of $Z = -1.9$ m from the midplane. For CIV the abscissa is the poloidal angle of the view chord from the spectrometer collection mirror at $R = 3.35$ and $Z = 3.69$ m. In (a) and (b) the ISP and OSP are at 2.35 and 2.85 m, respectively. In (c) and (d) the ISP and OSP are at 259° and 267°, respectively.

the inner divertor region, or perhaps the main chamber wall outside the spectrometer views, are more important for determining the source of the high charge states of carbon that get into the core plasma than the source in the outer divertor leg.

Comparisons of the emission profiles in helium plasmas as functions of injected power and density show that increasing the power increased the carbon and helium source rates in the divertor; in contrast, increasing the density decreased the carbon production in the divertor and increased the helium sources in the SOL outside the divertor (Figs. 5 and 6). When the injected power was increased at constant density the emission of CII increased in both divertor legs and the inferred source rate of C^{1+} increased in the outer divertor (Fig. 5(a) and (b)). The CIV radiation increased in both divertors and the C^{3+} source increased, primarily in the outer divertor (Fig. 5(c) and (d)). The He^{1+} emission and source increased slightly in the divertors (Fig. 6). However, when the density of the plasma was increased at constant power the CII emission decreased in both divertors and the inferred source of C^{1+} decreased dramatically in the outer divertor. The CIV emission actually increased slightly in this case and the inferred C^{3+} source rate was comparable with the lower density discharge. Again, these data show that the source rate of low charge states of carbon in the outer divertor was not the dominant source for setting the source level of high charge states of carbon that may get into the core.

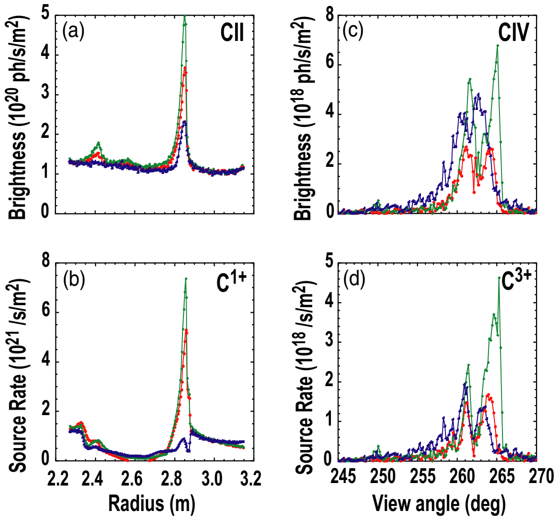

Fig. 5. Comparison of profiles of (a) visible CII (658 nm) and (c) UV CIV (31.2 nm) intensities and the inferred source rates of (b) C^{1+} and (d) C^{3+} from KL2C and KT1, respectively in helium plasmas for the baseline case 53981 (red), the higher power discharge 53982 (green) and the higher density discharge 53984 (blue). ISP and OSP at same locations indicated in Fig. 4.

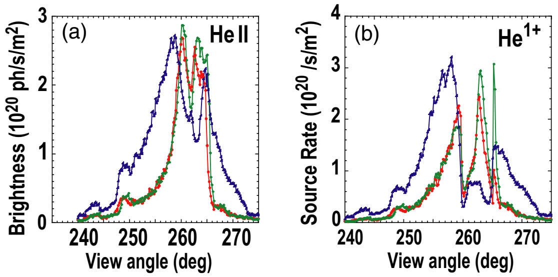

Fig. 6. Comparison of profiles of (a) HeII UV (30.3 nm) intensities and (b) inferred source rates of He^{1+} from KT1 for the same helium plasmas and color scheme as in Fig. 5. ISP and OSP at same locations indicated in Fig. 4.

The responses of HeII emission and inferred He^{1+} source rates to power and density variations indicated that the baseline and higher power cases had effective helium recycling in the divertor but the helium ionization source moved outside the divertor in the higher density discharge. The HeII emission and He^{1+} source increased slightly in the divertors for the higher power discharge (Fig. 6) with little change seen in the inner or outer SOL. At higher density, the HeII emission and He^{1+} source decreased in the divertors but increased by factors of 3 in both the inner and outer SOL regions outside the divertors. This indicates that substantial escape of helium neutrals occurred in the high density case compared with the two discharges at lower density.

4. Discussion

Taken together the differences in carbon emission between helium and deuterium plasmas are consistent with a model of carbon production in which: (1) the dominant source in helium plasmas is ion physical sputtering, and (2) multiple sources (e.g., ion and neutral physical sputtering, chemical sputtering) all play a role in deuterium plasmas with the dominant source mechanism and location depending on the divertor operating conditions. Comparable C^{1+} source rates in the outer divertor for the matched helium and deuterium discharges is consistent with the expected ion physical sputtering at the attached outer divertor target. The variation of C^{1+} source with power in helium plasmas is also consistent with this model. Helium emission and source rates as a function of power confirm that the outer divertor is in an attached, high recycling condition for the baseline helium discharge. The large reduction of C^{1+} source in the inner divertor and the insensitivity of this source to power or density variations is consistent with a chemical sputtering mechanism for this source in deuterium that is eliminated in helium. Since the inner divertor is likely detached in these moderate power L-mode plasmas the plasma conditions would not be expected to produce much physical sputtering but would be expected to produce large chemical sputtering yields in deuterium. Finally, the reduction of C^{1+} source in the outer divertor when density is increased in helium is consistent with the expected reduction in outer divertor plasma temperature and ion physical sputtering as detachment is approached. The HeII emission and He^{1+} source response to density increase also indicated loss of the attached, high recycling condition for the high density plasma.

Finally, the comparisons in this study indicate that the carbon source in the hot attached outer divertor is not the source that determines the source of high ionization states of carbon which eventually increase the impurity level of the core plasma. Instead, carbon sources from the inner divertor or the main chamber may dominate the source to the core. In deuterium these sources can be large due to chemical sputtering mechanisms. In helium the chemistry is eliminated and the ionization source of the C^{3+} charge state is significantly reduced.

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