EIRENE interpretation of divertor deuterium emission in DIII-D constrained by 2D Divertor Thomson Scattering and Langmuir probe measurements

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Abstract: Standalone EIRENE simulations constrained with 2D Divertor Thomson Scattering electron temperature (T_e) and density (n_e), and target Langmuir probe ion saturation current measurements are consistent with the measured low principal quantum number Lyman and Balmer hydrogenic neutral, and Fulcher hydrogenic molecular band emissions in detached plasma conditions in DIII-D ohmically heated plasmas. Such agreement implies that the EIRENE physics models and tabulated reaction rates are sufficiently accurate to predict the neutral densities and hydrogenic emissions in steady state, low power conditions.

Introduction

Accurately predicting power and momentum dissipation in the edge region of fusion devices is one of the most critical tasks in designing future fusion power plants [1]. Experiments in the DIII-D tokamak were carried out to characterize the primary neutral hydrogenic radiation as a benchmark for the atomic and molecular densities for simulations with the coupled edge fluid, neutral Monte-Carlo code EDGE2D-EIRENE [2], [3]. These studies indicated that agreement of the measured and predicted emission within 50% is obtained for attached conditions (T_e at the low-field side (LFS) strike point, $T_{e,LFS-sp} > 5$ eV) when constraining the simulations with the measured conditions at the LFS midplane [4]. However, disagreement of factors 2-5 between the predictions and measurements were reported for detached divertor conditions, $T_{e,LFS-sp} < 2$ eV . Previous studies [5] demonstrated agreement within 20% between the measured and predicted Balmer emissions also for detached conditions, using reaction rate and photon emissivity coefficients from the ADAS [6] and AMJUEL formatted dataset collected from different sources [7] when imposing the measured target ion fluxes and background plasma conditions in OEDGE simulations [8] for similar divertor conditions as in these studies.

Constraining EIRENE simulations with 2D DTS and Langmuir probe data

Density scans in purely Ohmic-heated plasmas in deuterium were performed in DIII-D to characterize the plasma conditions in 2D for T_e and n_e with the Divertor Thomson Scattering (DTS) system, j_{sat} across the LFS divertor plate with Langmuir probes (LPs), the Lyman-α 121.534 nm emission with Divertor SPRED (DivSPRED), the Balmer-α 656.1 nm, Balmer- β 486.0 nm, and Balmer-γ 433.9 nm emission with the Multichord Divertor Spectrometer (MDS) and a wavelength-filtered photomultiplier array (filterscope, FS), and the Fulcher band spectrum in the range of 600-640 nm with the MDS [4]. The Fulcher band spectra were fitted and integrated to yield total intensity [9]. To increase the extent and spatial resolution of these measurements the divertor strike points were swept across the LFS plate and data mapped to a single equilibrium. The core plasma density was raised discharge-wise from low densities (Greenwald fraction, $n/n_{GW} \sim 0.2$) to the highest attainable densities ($n/n_{GW} \sim 0.6$) yielding detached plasma conditions of $T_e \sim 0.7$ eV at the LFS strike point. In these conditions T_e was measured below 5 eV across the entire LFS leg, and n_e peaked poloidally halfway between the divertor plate and the X-point (Figs. 1b and 1d).
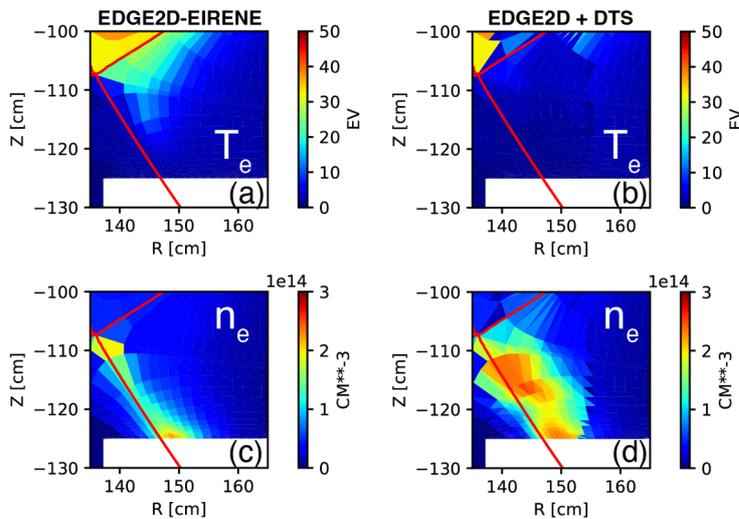

Fig. 1. 2D profiles of EDGE2D-EIRENE predicted (a,c) and measured (b,d) electron temperature (a,b) and density (c,d).
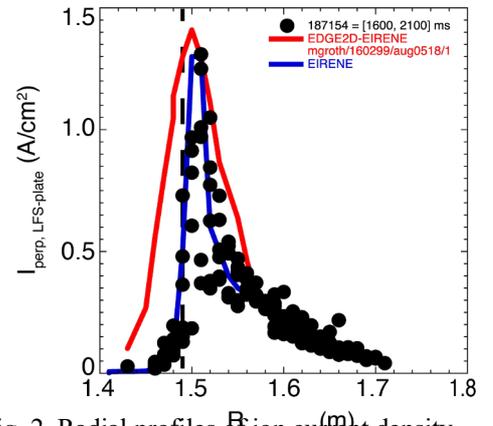

Fig. 2. Radial profiles of ion current density (perpendicular to surface) as measured (black circles, DIII-D 187154, 1600-2100 ms), predicted by EDGE2D-EIRENE (red line, mgroth/160299/aug0518/1) and imposed in EIRENE (blue line).

EDGE2D-EIRENE simulations predict the Lyman-α and Balmer-α emission in low ($T_{e,LFS-sp} \sim$ 30-40 eV) and high-recycling conditions ($T_{e,LFS-sp} \sim$ 2-3 eV) within the uncertainty of the measurements and the two codes' input parameters, e.g., imposed radial transport reproducing the measured profiles of T_e and n_e at the LFS midplane, and radiated power at the core boundary [4]. In partially detached conditions the simulations consistently show $T_e < 1$ eV at the LFS strike point (Fig. 1a) and LP j_{sat} (Fig. 2). However, they do not predict T_e below 2-3 eV across the entire divertor leg up the LFS X-point region as measured (Fig. 1a). Furthermore, none of the simulations conducted in these studies accurately predict the measured 2D n_e profile (Fig. 1c). The resulting EIRENE predictions for hydrogenic emission is a factor-of-five higher for Lyman-

α, a factor-of-three lower for Balmer-α, a factor of eight lower Balmer-γ, and significantly higher Fulcher band emission in the LFS divertor leg than measured (Fig. 3).

To isolate the discrepancy in the measured and predicted emissions to the EIRENE physics models (e.g., transport, ionization and recombination), and the applied reaction rates for photonic emission using AMJUEL and ADAS, the measured 2D DTS T_e and n_e profiles, and the measured LP j_{sat}, representing the surface neutral source, were imposed in standalone EIRENE simulations. In addition, the impact of Lyman-α and Lyman-β photon opacity on the measured Lyman-α and Balmer-α emission was assessed (c.f., [10] for JET-ILW). Significantly improved agreement between the measured and predicted emission profiles were obtained: (a) redistribution of Lyman-α emission peaking at the target plate due to recombination and ionization near the LFS X-point (Fig. 3b) resulting in a flat vertically integrated radial emission profile consistent with the DivSPRED measurement. (b) Significantly increased Balmer-γ emission (Fig 3h) consistent with the FS measurements (Fig. 3i). As anticipated, introducing Lyman-α and Lyman-β photon opacity reduces the vertically integrated Lyman-α emission by 50-100%, and increases the Balmer-α emission by 10-20%, further reducing the discrepancy between the measurements and predictions. The reduction of T_e below 2-3 eV across the entire LFS divertor leg results negligible Fulcher band emission inside the LFS divertor, consistent with the MDS measurements.

Consistent with [5], these studies highlight that the models for ion recycling, transport of molecules and atoms, and the ion-atom and ion-molecule interaction rates are sufficient to describe hydrogenic emission in the DIII-D divertor when EIRENE is constrained ad-hoc by the plasma (T_e and n_e only) and ion current to the target plate. When constrained, recombination is more dominant than in EDGE2D-EIRENE, indicating a potential root cause for the low reduction in j_{sat} with increasing density at the LFS midplane as observed previously [4]. Concomitantly, the molecular and atomic densities extend further into the divertor leg, the molecular and atomic contents are up to ten times higher, resulting in stronger plasma momentum losses and thus a higher degree of detachment than predicted by EDGE2D-EIRENE.

Acknowledgement / Disclaimer
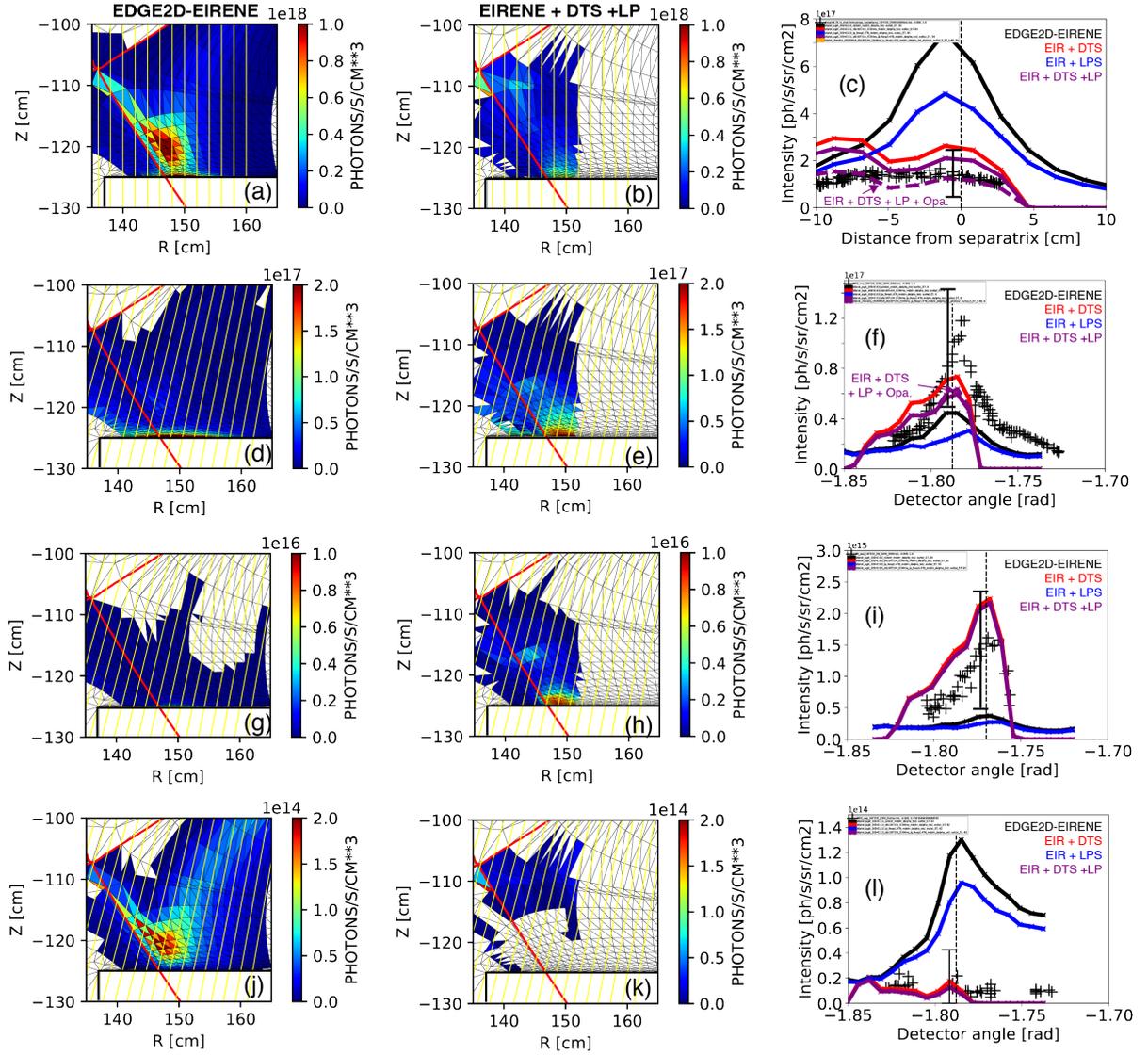
Fig. 3. 2D profiles of the EIRENE predicted Lyman-α (a,b), Balmer-α (d,e) Balmer-γ (g,h) and Fulcher band emission (j,k). The predicted 2D emission profiles based on EDGE2D-EIRENE (a,d,g,j) and EIRENE constrained by DTS and LPs measurements are shown in (b,e,h,k). The line-integrated Lyman-α (c), Balmer-α (f), Balmer-γ (i) and Fulcher band emissions (l) are integrated along synthetic view chords shown in the 2D plots replicating the experimental setup. The colors correspond to integration through the EDGE2D-EIRENE plasma solution (black), EIRENE constrained by DTS only (red), LPs only (blue) and constrained by both DTS and LPs (purple). The dashed purple line includes Lyman-α and Lyman-β opacity in EIRENE for the case constrained by the DTS and LPs. The measured Lyman, Balmer and Fulcher band emissions are show as black symbols, respectively. The systematic uncertainties of the measurements are indicated by the error bars.

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