

## Measurement of Molecular Deuterium Fluxes in the DIII-D Edge

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In hydrogen-fueled tokamak discharges, the distribution of molecular hydrogen (or deuterium) in the plasma edge region plays a central role in edge fueling, affecting pedestal shape and core density control [1]. In addition to its role in edge fueling, molecular hydrogen is important for plasma edge atomic physics. An example of this is the enhancement of plasma volume recombination known to occur in the presence of vibrationally-excited hydrogen molecules via conversion of  $H^+$  ions into molecular ions such as  $H_2^+$  and  $H_3^+$  [2].

Here, measurements of the  $D_2$  molecule flux into the far edge/scrape-off layer (SOL) of the DIII-D tokamak are made using passive visible spectroscopy of the  $D_2$  diagonal Fulcher band ( $3p-2s$  triplet  $Q$ -branch) line emission over the range  $\lambda = 600-640$  nm [3]. L-mode, lower-single-null discharges are studied. A multi-chord visible spectrometer with views of both lower divertor legs and the main chamber is used [4]. A schematic of the spectrometer view chords used here, as well as typical magnetic flux surfaces, midplane probe location, and Thomson scattering view locations, are shown in Fig. 1. As a convenient variable to describe the location of each view chord, the poloidal angle  $\theta$  of the corresponding emission volume is used (Fig. 1). Each view chord crosses the SOL twice; in the case of the upper view chords and lower view chords, the emission from the SOL closer to the lower divertor is expected to dominate the measured signal. In the case of the midplane view chord, lineshape (Zeeman splitting) analysis of the  $D_\alpha$  line indicates that the received emission is typically dominated by the inner wall SOL (over the outer wall SOL by  $\approx 2-8\times$ ).

A sample survey of the Fulcher band is shown in Fig. 2 with some of the strongest lines labeled, e.g.  $Q6(1-1)$  refers to the ( $3p, V'=1, J'=6$ )  $\rightarrow$  ( $2s, V''=1, J''=6$ ) transition, where  $V$  and  $J$  are the vibrational and rotational quantum numbers. Measured Fulcher band line brightnesses are converted into edge  $D_2$  fluxes by summing over

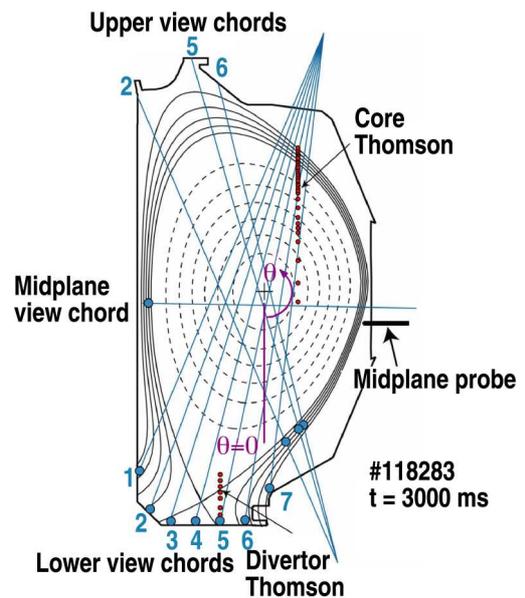


Fig. 1. Schematic of visible spectrometer view chords, midplane probe, and divertor Thomson scattering. Dots indicate approximate emission region locations.

lines to estimate the total band brightness and then multiplying the total band brightness by a  $D/XB$  (dissociation events per Fulcher photon) conversion factor. Summing over line brightnesses is typically done by fitting to a different rotational temperature for each vibrational level in the excited ( $3p$ ) electronic state and then to a single vibrational temperature to describe the (rotationally summed) level densities in the ground ( $1s$ ) electronic state [5]. The ground electronic state vibrational level densities are mapped to the  $3p$  state in the coronal approximation using the vibrationally-resolved Franck-Condon matrix for electron-impact excitation [6]. Typically, these functional forms are found to describe the measured line brightnesses reasonably well. Sample fits are shown in Fig. 3(a) for the  $3p$  state rotational temperature for the first two  $3p$  state vibrational levels; and in Fig. 3(b) for the  $1s$  state vibrational temperature for first 4 vibrational levels ( $V=0$  to  $V=3$ ). Off-diagonal ( $P$  and  $R$ ) branches are not fit explicitly, but are accounted for using a factor 2 correction. In some cases, particularly in detached divertor measurements, a two rotational temperature (bi-Boltzmann) fit is found to better match the  $3p(V=0)$  brightness data, with the “knee” in the distribution typically occurring around  $Q7$ .

In DIII-D, measurable line emission has been observed up to the 6th vibrational level ( $V=5$ ) of the Fulcher band. Often, however, it is not practical to measure the entire band, so only the first ( $V=0$ ) branch is measured. In this case, the empirical scaling for  $T_{rot}^{1s}$  vs  $T_{rot}^{3p}(V=0)$  found in TEXTOR hot edge plasmas with  $T_e > 30$  eV can be used to estimate the entire band brightness [7]. In DIII-D, this empirical scaling has been extrapolated to higher  $n_e$  and lower  $T_e$  conditions, and is typically found to estimate the total band brightness within  $\pm 50\%$  for normal (attached) conditions and within  $\approx 2 \times$  for detached divertor conditions.

Figure 4 shows the measured Fulcher band brightnesses (estimated from the  $V=0$  branch) as a function of emission volume poloidal angle  $\theta$  (with  $\theta = 0$  roughly corresponding to the divertor floor,  $\theta = \pm 1.5$  to the outer/inner midplane, see Fig. 1). The three cases shown differ

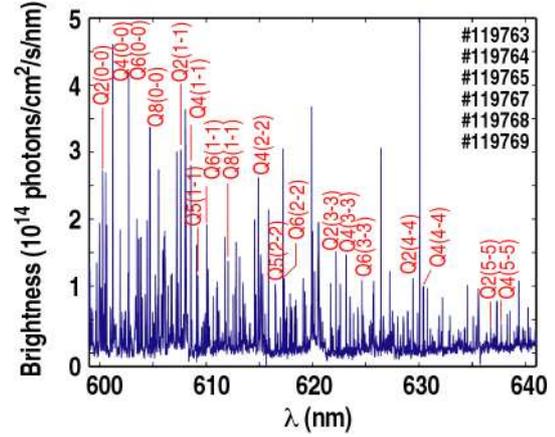


Fig. 2. Survey of  $D_2$  Fulcher band (composite of six spectra using divertor view chord 6).

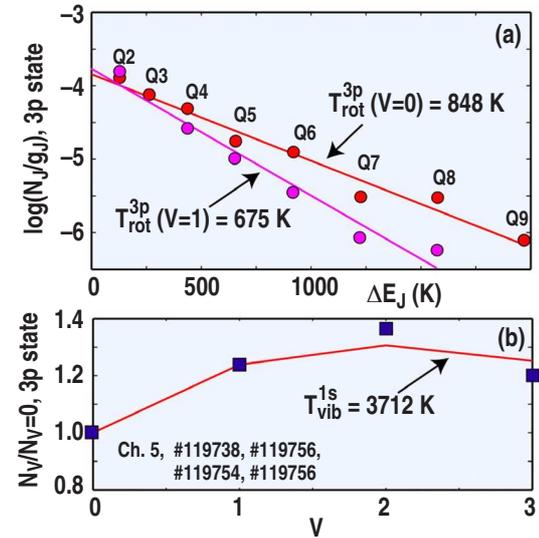


Fig. 3. (a) Single rotational temperature fits to first two vibrational levels of Fulcher band and (b) single-vibrational temperature fit to relative densities of first four vibrational levels.

primarily in plasma density, the magnetic geometry being nearly identical. As expected, the Fulcher brightness is largest near the divertor strike points, although some signal is still observed in the outer and inner main chamber regions. Blue circles in Fig. 4 are  $D_\alpha$  brightness measured during the same discharges using  $D_\alpha$  filterscopes. The filterscope view chord geometries are similar to the spectrometer view chords shown in Fig. 1.

Green diamonds in Fig. 4 show the  $D_\alpha$  brightnesses predicted to result from  $D_2$  breakup processes. In the midplane view chord ( $\theta = -1.5$ ), where there is almost certainly no recombination, the atomic deuterium in the SOL can be reasonably well accounted for from  $D_2$  breakup. In the divertor region, however, atomic deuterons appear to be  $\approx 2 - 3 \times$  more abundant than predicted. This divertor  $D$  flux could arise from thermal release of  $D$  from hot spots in the divertor floor. However, IR thermography indicates that the divertor remains fairly cold ( $T_{\text{wall}} < 500$  K) in these L-mode discharges and measurements made in front of a graphite test limiter indicate that, for cold ( $T_{\text{wall}} < 1000$  K) wall conditions, deuterons released from graphite are dominantly ( $>90\%$ ) in the form of  $D_2$  neutrals (as opposed to thermal release  $D$  or reflection of  $D^+$ ) [8]. Alternately, at least in Fig. 3(b) and 3(c), the excess  $D_\alpha$  emission could be arising from volume recombination processes in the divertor, as DIII-D L-mode plasmas with  $n_{e,0} > 2 \times 10^{13} \text{ cm}^{-3}$  are typically expected to begin detaching in at least one divertor leg.

The  $D/XB$  factor used to convert measured Fulcher brightnesses into  $D_2$  fluxes is obtained from an experimentally verified [5] collisional-radiative model [9] and increases with both electron density  $n_e$  (roughly logarithmically) and with electron temperature  $T_e$  (with a minimum at 5 eV and then increasing roughly linearly above 10 eV). Both experiments [7] and simulations [10] indicate that the rotational temperature of the neutral molecules depends dominantly on the electron density, and only weakly on the electron temperature. Here, we use the roughly linear scaling observed in the experiments to estimate the electron density in the Fulcher band emission region from the measured value of  $T_{rot}^{3p}(V=0)$ . Subsequently, the electron temperature in the emission region is interpolated from the measured edge probe and main chamber Thomson ( $n_e, T_e$ ) profile (or from the divertor Thomson ( $n_e, T_e$ ) profile for divertor views). Typically, values of  $T_{rot}^{3p}(V=0) \approx 600-900$  K are measured in the main chamber; corresponding emission region parameters are estimated to be in the range  $n_e \approx 0.2-1.0 \times 10^{13} \text{ cm}^{-3}$  and  $T_e \approx 20-60$  eV. The local deuteron fueling resulting from  $D_2$  influx can now be estimated as being:  $\Gamma_D(D_2) \approx I_{D_2}(D/XB)$ , where  $I_{D_2}$  is the

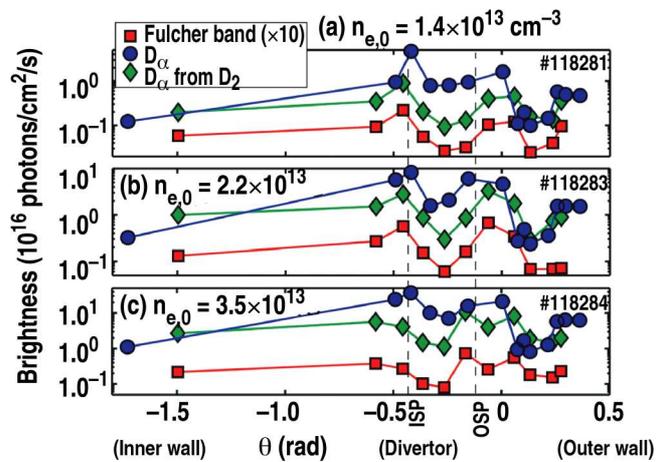


Fig. 4. Fulcher band brightness,  $D_\alpha$  brightness, and  $D_\alpha$  brightness predicted from  $D_2$  breakup as a function of poloidal angle  $\theta$  for three different discharge densities.

total Fulcher band brightness. Note that only half of the incident deuterons from each  $D_2$  molecule are assumed to contribute to the fueling flux, *i.e.* we assume that half the deuterons from  $D_2$  result in  $D$  atoms which are not ionized but return directly to the chamber wall. Similarly, the local deuteron fueling estimated from  $D_\alpha$  emission can be estimated as being:  $\Gamma_D(D_\alpha) \approx I_{D_\alpha}(S/XB)$ , where  $I_{D_\alpha}$  is the measured  $D_\alpha$  brightness and  $S/XB \approx 10 - 20$  is the  $D$  ionizations per  $D_\alpha$  photon ratio [11]. For the purposes of evaluating  $S/XB$ , the  $D_\alpha$  emission is assumed to be localized to the same  $(n_e, T_e)$  region as the  $D_2$  emission in the same view chord.

In Fig. 5, red squares show fueling (deuteron) flux calculated from the Fulcher band brightnesses of Fig. 4. It can be seen that the recycling flux increases strongly with increasing plasma density, with the maximum flux in the highest central density ( $n_{e,0} = 3.5 \times 10^{13} \text{ cm}^{-3}$ ) case being  $\approx 15 \times$  larger than the maximum in the lowest density case ( $n_{e,0} = 1.4 \times 10^{13} \text{ cm}^{-3}$ ), consistent with a  $n_{e,0}^3$  scaling.

The blue circles of Fig. 5 show the apparent deuteron flux resulting from  $D_\alpha$ . It can be seen that the main chamber fueling is, on average, underestimated by a factor of roughly 2-3 by measuring  $D_\alpha$  only. This is consistent with previous measurements in JET which found that estimates of the deuteron flux from the wall using only the  $D_\alpha$  brightness can lead to significant ( $\approx 2 \times$ ) underestimates [12].

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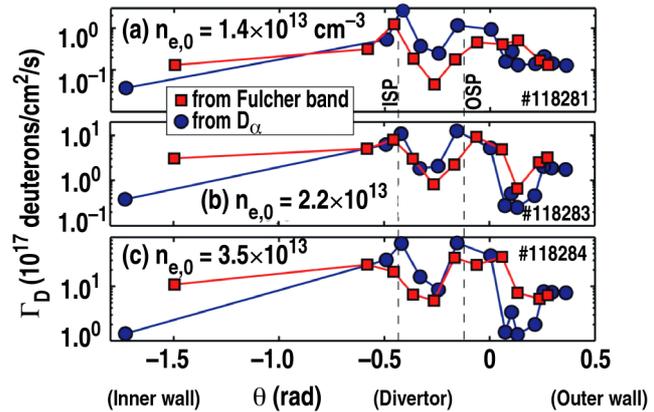


Fig. 5. Deuteron fueling flux from Fulcher band and from  $D_\alpha$  vs poloidal angle  $\theta$  for data of Fig. 4.

- [1] B. Unterberg, S. Brezinsek, G. Sergienko, *et al.*, J. Nucl. Mater. **337**, 515 (2005).
- [2] A. Yu. Pigarov, Phys. Scripta **T96**, 16 (2002).
- [3] D.K. Otorbae, M.J. de Graaf, M.C. van de Sanden, *et al.*, Contr. Plasma Phys. **35**, 195 (1995).
- [4] N. Brooks, D. Fehling, D. Hillis, *et al.*, Rev. Sci. Instrum. **68**, 978 (1997).
- [5] S. Brezinsek, P.T. Greenland, P. Mertens, *et al.*, J. Nucl. Mater. **313**, 967 (2003).
- [6] U. Fantz and B. Heger, Plasma Phys. Control. Fusion **40**, 2023 (1998).
- [7] S. Brezinsek, "Study of atomic and molecular hydrogen in front of a graphite surface in a high-temperature edge plasma," PhD thesis (Forschungszentrum Juelich, 2002).
- [8] S. Brezinsek, G. Sergienko, A. Pospieszczyk, *et al.*, to appear in Plasma Phys. Control. Fusion (2005).
- [9] P.T. Greenland, Contrib. Plasma Phys. **42**, 608 (2002).
- [10] E.M. Hollmann, A.Yu. Pigarov, and K. Taylor, J. Nucl. Mater. **337**, 451 (2005).
- [11] H.P. Summers, Atomic Data and Analysis Structure – User's Manual, JET Joint Undertaking Report JET-IR94, 1994.
- [12] A. Pospieszczyk, S. Brezinsek, G. Sergienko, *et al.*, J. Nucl. Mater. **337**, 500 (2005).