

Deuterium Fulcher Band measurements in WEST tokamak

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Study of the behavior of neutrals and molecules, especially of the hydrogenic species, in the regions outside the scrape-off layer of the MCF plasma is an important part of understanding the plasma-surface interactions and also energy and momentum loss in the region [1]. Molecular participation is frequently inferred from the observation of excited atoms produced during dissociation, but there is also a possibility of direct observation of the optical emission of the molecular bands – singlet bands in VUV region with direct connection to the molecular ground level, and triplet bands in the visible, of which the most prominent and well-known are the $d^3\Pi_u$ to a $^3\Sigma_g^+$ transition called Fulcher band [2, 3, 4].

The $d^3\Pi_u$ level excitation energy is relatively large (over 14 eV), so the band is of high intensity in very particular regions, where both energetic particles and molecular gas (from gas puff or wall recycling) are in abundance. This effect makes FB parameters useful as an indication of so-called ionization front [4]. Both the intensity and the internal energy of the molecules depend on plasma parameters in the studied region – temperature and density of electrons, particle flux, neutral and of course molecular density, so for constant plasma conditions it can be also used as a measure of molecular outgassing [5].

Obtaining both the intensity and the internal energy of the hydrogenic molecules from the molecular radiation is challenging, because the band covers the relatively broad region of 590 to 630 nm with several vibrational transitions and the dense rotational spectrum requires high resolution spectrometers for determination of the rotational temperature. Therefore in many cases [2,4], the estimations are based on the most intense and easiest to analyze region 600-610 nm, where the behavior of the Q-branch of the strongest 0-0 vibrational transition is used as a proxy of the whole band. This is also true for this contribution, because in WEST the high-resolution spectrometer has a roughly 10 nm spectral region, so the full band measurement would need 4 exactly reproducible pulses, which is difficult to do in the framework of the first-test piggyback experiment.

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The measurements were performed during two plasma pulses: #60658 test long-time pulse (19.7 s length, disrupted) with attached divertor, $I_p = 230$ kA, line-averaged central density $3 \cdot 10^{19} \text{ m}^{-2}$, lower hybrid heating from both antennas 0.9 to 1.5 MW (slowly increasing during the pulse), and #61568 nitrogen-seeded high-fluence test pulse (37 s), $I_p = 400$ kA, density $4 \cdot 10^{19} \text{ m}^{-2}$, LH heating 2/2 MW. Both were diverted pulses with the x-point in the lower divertor, with high-field side inner strike point (ISP) around $R = 2.1$ m and low-field outer strike point (OSP) at 2.23 m. In the first pulse case the 11 spectrometer lines of sight were evenly divided between the lower and upper divertor, in the second all the l-o-s were directed toward lower divertor, giving much more detailed information about the different observed spatial regions there. In the nitrogen-seeded case the seeding was switched on few seconds after the LH heating was online and stopped before the end of the pulse (~ 8 -26 s).

The example of the pure deuterium molecular spectrum, with the identification of the FB rotational transitions and overlapped with JET divertor example is presented in Fig 1a. The Q-branch 0-0 and 1-1 transition lines can be relatively easily identified. In Fig 1b, the spectrum is compared with the spectrum from nitrogen-seeded pulse during the seeding, which helps to identify the lines from the FB spectrum. There are not many new lines in N_2 seeded spectrum, the D_2 lines mostly disappear.

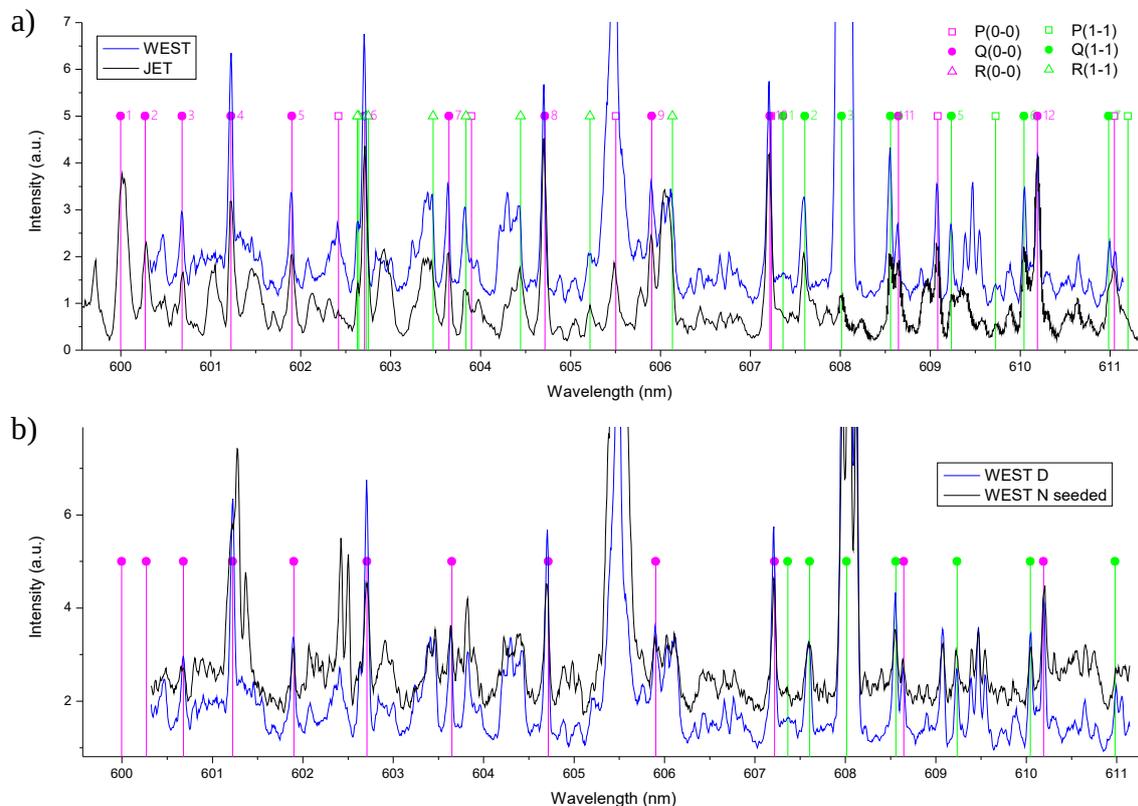


Fig. 1. Examples of a) the pure D_2 spectrum from WEST divertor compared with the spectrum from the JET outer divertor and b) D_2 and D_2+N_2 spectra from the WEST divertor.

The WEST high-resolution spectra allow to estimate the intensity of Q(0-0) 2 to 12 rotational lines, and Q(1-1) 2 to 7 lines, with Q(1-1) 3 line overlapping an atomic line. This allows for estimating the rotational temperature and total intensity of the vibrational transition. Previously published [2-5] data suggest the rotational temperature decreasing with vibrational quantum number, and the WEST data support this finding, with $T_{\text{rot}}(1-1)$ consistently 30-70% lower than $T_{\text{rot}}(0-0)$. The spatial dependence of the rotational temperature for both vibrational levels in attached case is mostly below the accuracy, apart from the increase in the inner strike point region during last few seconds of the attached 60658 pulse, which may be connected with increasing density in the region. This would be supported by presented in [2] the multimachine dependence of the rotational temperature on the plasma density.

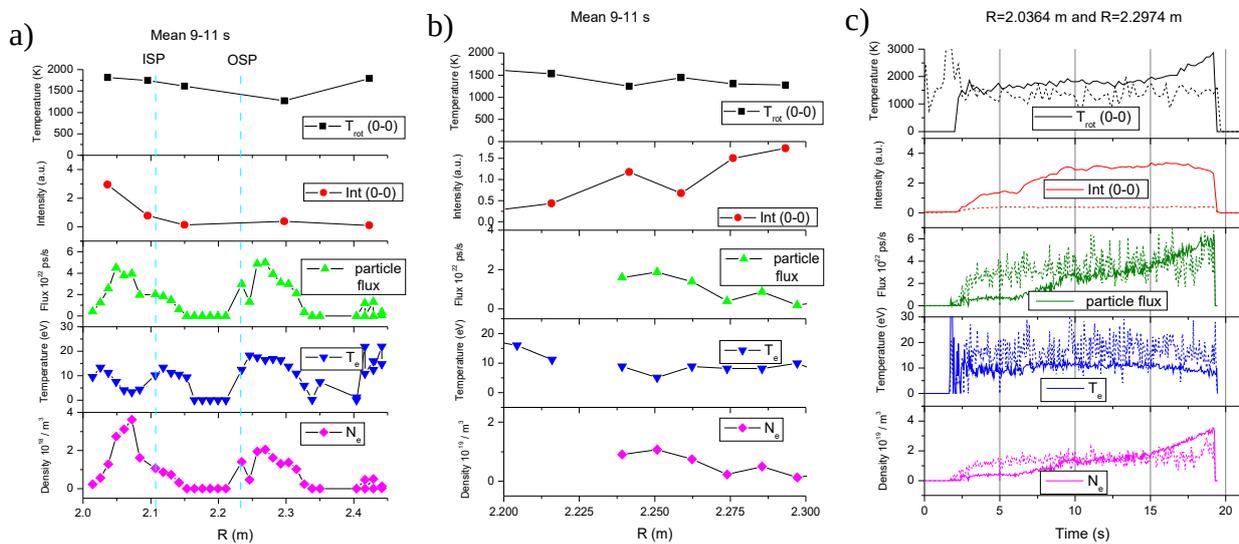


Fig. 2. Comparison of the results of Fulcher band 0-0 parameters and probe-measured plasma parameters for a) lower divertor (including baffle) and b) upper vessel region. On c) are shown the time dependencies of the signals in low (dashed line) and high (solid line) field side in the lower divertor at FB intensity maxima.

The FB parameters (intensity and rotational temperature) measured during WEST pulses follow roughly the same pattern as the results from the other machines [2-5] (Fig. 2). During attached conditions with high and constant electron temperature the FB intensity is correlated with particle flux reaching the surface. The intensity is highest outside the strike point positions ([2] for both ISP and OSP, [5] for OSP only), though the open ISP in WEST case makes the radiating region much broader than the one in the much more closed DIII-D case.

The nitrogen-seeded partially detached pulse #61568 (Fig. 3) has very similar probe-measured plasma parameters, but the total flux to the divertor surface is higher, even if the maximum of the flux is similar, due to the profile being broader. The FB intensity has similar profile to the previous pulse during the attached conditions, but the maximum intensity is significantly

higher (some of the D₂ lines were even saturated). The rotational 0-0 temperature is also similar, close to 1500 K and relatively uniform over the whole divertor. During seeding, the intensity of FB on the low field side does not change, whereas the high field side drops nearly to zero. During this phase the 0-0 rotational temperature seems to rise significantly, but as the intensity is very low, the error bars are very large. This is a first indication that the rotational temperature of the D₂ molecule can rise also in detached conditions which are not obtained via seeding, not via density increase, though it may also result from N_e increase on ISP.

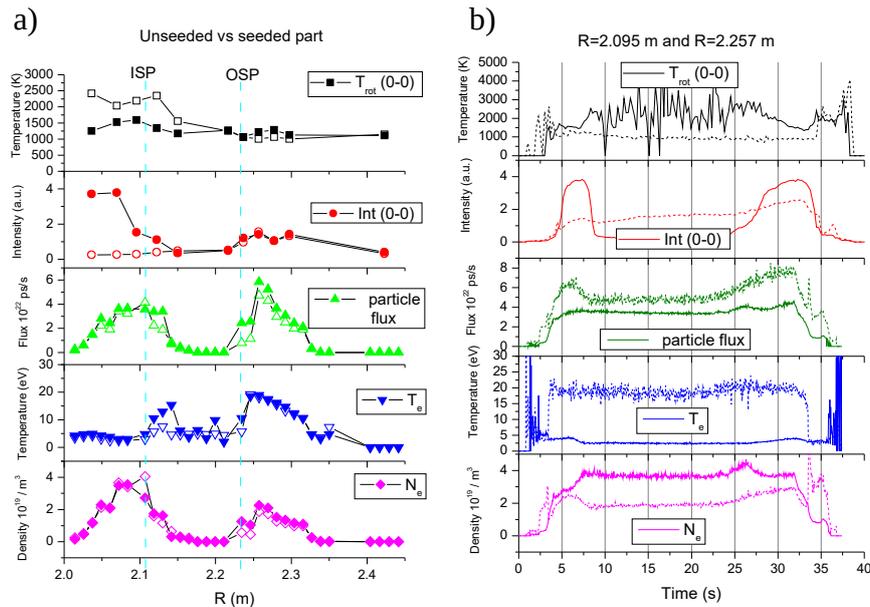


Fig. 3. a) Comparison of the averaged results of Fulcher band 0-0 and plasma parameters for lower divertor in unseeded (solid markers, 7s) and seeded (open markers, 15s) conditions. b) The complete time dependence of the high field side (solid line) and low field side (dashed line) parameters at FB intensity maximum.

Summarizing, the results of Fulcher band measurements in WEST support the use of the molecular band intensity and rotational temperature as the indication of a plasma state in different wall-adjacent regions, and as the check for results of plasma modeling of detachment and plasma-surface interactions. This contribution shows also, that in WEST a significant signal from this molecular band can be obtained from the regions where the separatrix is far from the wall (upper vessel region) and that the data can be useful also in cases of nitrogen seeded pulses, showing sharply the dependence of the band intensity on detachment status.

[1] Verhaegh et al, NME **26** (2021) 100922. [2] Hollmann et al, PPCF **48** (2006) 1165–1180 [3] Sergienko et al, JNM **438** (2013) S1100–S1103 [4] Osborne et al. PPCF **66** (2024) 025008 [5] Brezinsek et al, NF **54** (2014) 103001 [6] Pawelec et al, EPS 2022 ECA, O2.J501

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