Radial measurements of core hydrogen isotope ratios in ASDEX Upgrade

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1. Introduction. For a plasma fuelled with separate ion species in the core and edge, the ratio between the fuel-ion densities at a given plasma location is set by the radial transport coefficients of each species. While these cannot be measured directly, the ability to measure fuel-ion ratios in the plasma core, and potentially control them via different fuelling schemes [1], remains important for optimizing the power output of future fusion reactors. Few diagnostics are able to provide core-localized measurements of hydrogen isotope ratios under reactor-relevant conditions, but collective Thomson scattering (CTS) represents an exception [2]. This technique relies on injecting a powerful probe beam into the plasma and collecting part of the resulting scattered radiation. This was used to infer an approximately uniform radial profile of $n_{\mathrm{H}}/n_{\mathrm{D}}$ in TEXTOR [3], qualitatively similar to later results from DIII-D [4] and LHD [5] based on charge exchange spectroscopy, and from JET based on edge spectroscopy only [6]. However, these results relied on either L-mode plasmas [3], the use of neutral beam injection [4, 5] (not foreseen in future power plants), or model predictions for the plasma core [6]. Hence, it seems prudent to extend the above works to radial core measurements in H-mode plasmas subject to reactor-relevant heating schemes. Here we present the first such proof-of-principle measurements of radially resolved H/D ratios in the core of ASDEX Upgrade (AUG) using CTS. Furthermore, we show preliminary results from exploring the use of artificial neural networks for rapidly and robustly estimating H/D ratios from the measured CTS spectra. This represents a first step towards making such measurements relevant for future real-time reactor control.

2. Experimental measurements. Our H/D measurements were conducted in pure Ohmic/ECRH-heated H-mode discharges at AUG at a toroidal field $B_t = -2.65$ T and plasma current $I_p = 0.8$ MA. Plasma heating was achieved using 2 MW of central ECRH at 140 GHz, while the CTS probe gyrotron operated at 105 GHz. Here we focus on discharge #42099, with timetrace
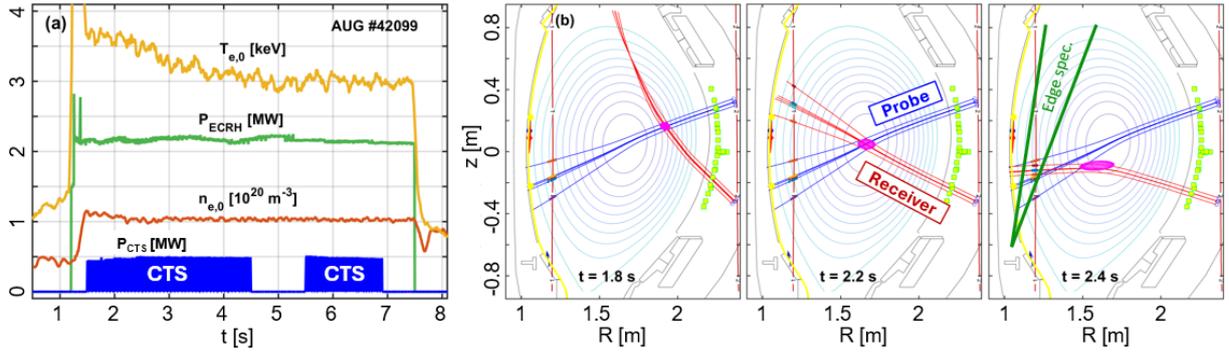
Figure 1: *(a) Timetrace of discharge #42099, showing central electron temperature $T_{e,0}$ and density $n_{e,0}$, auxiliary heating power P_{ECRH}, and power P_{CTS} of the CTS probe gyrotron. (b) Example of a radial sweep of the CTS measurement volume, showing the CTS probe beam (blue), receiver view (red), and the resulting scattering volume (magenta ellipsoid) at different times in a poloidal cross section of AUG. Green lines mark the inner– and outermost of the 15 edge spectrometer sight lines discussed in Sec 3.*

shown in Fig. 1(a). The discharge was fuelled using edge puffing of H into D plasma, with core electron densities measured by Thomson scattering of $n_{e,0} \approx 1 \times 10^{20}$ m^{-3} and H content $R_i = n_H/(n_H + n_D)$ reaching $\approx 50\%$ as estimated from edge optical spectroscopy.

We acquired CTS data throughout the flattop phase using a combination of 8-bit [7] and 14-bit fast digitizers, for a total of 340 acquisition pulses of 1.0–1.4 ms each. By sweeping the CTS receiver view, the measurement volume was moved across the plasma core three times from $t = 1.5$ s, with each sweep lasting $\Delta t = 1.0$ s. From $t = 5.5$–7.0 s, the CTS volume was fixed close to the plasma core at a poloidal flux coordinate $\rho_p \approx 0.2$. An example sweep is illustrated in Fig. 1(b) based on raytracing for the relevant plasma equilibrium. The high core density induces strong refraction of the diagnostic beams on the high-field side, where the measurement volume becomes poorly defined, so here we focus on data taken on the low-field side.

3. Analysis and results. The CTS digitizer data were calibrated, background-subtracted, and corrected for small drifts in probe gyrotron frequency within the acquisition periods. Fig. 2(a) presents the resulting spectrogram from the 8-bit digitizer. The variation in CTS signal strength with time is clearly seen as the measurement volume is swept through the core three times. Fig. 2(b) shows example spectra at different ρ_p. For the estimated measurement angles relative to **B** of $\phi = 87°$–$95°$, the CTS data are sensitive to the H/D ratio through the presence of characteristic spectral peaks – also clearly visible in Fig. 2 – that are separated by roughly the ion cyclotron frequency $\omega_{c,i} = qB/m_i$ of the different ion species in the measurement volume.

To infer R_i from these data, we are currently exploring the use of a multilayer perceptron neural network (NN [8]; to be described in detail elsewhere), trained on synthetic, noisy CTS
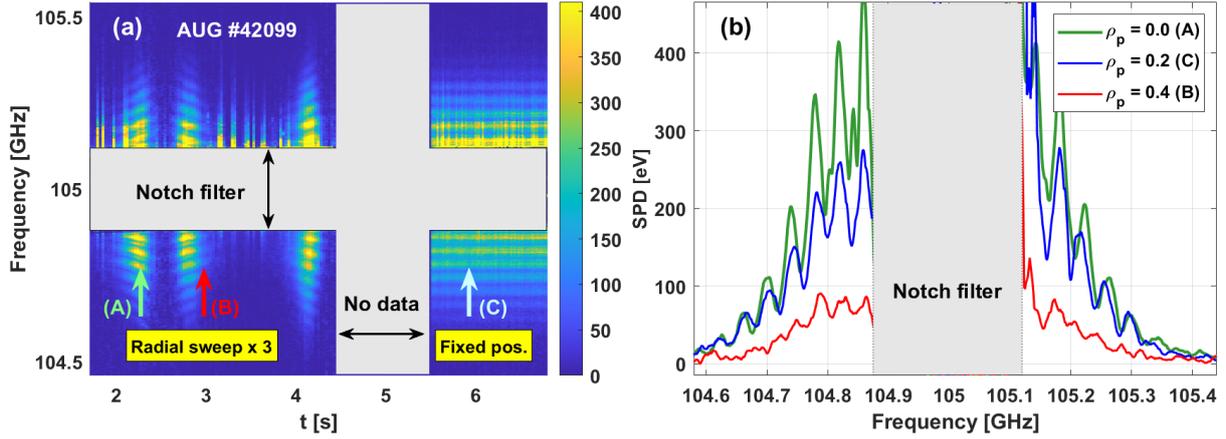
Figure 2: *(a) CTS spectrogram of AUG #42099. Labelled arrows mark the times represented in panel (b), which shows example spectra at $t = 2.20\,s$ ($\rho \approx 0.0$), $t = 5.90\,s$ ($\rho \approx 0.2$), and $t = 2.97\,s$ ($\rho \approx 0.4$).*

spectra resembling the experimental data. For comparison, we consider line-integrated estimates of R_i based on edge Balmer β spectroscopy of neutrals along 15 different sightlines (of which the inner– and outermost are marked in Fig. 1, here intercepting values of $\rho_p \geq 0.65$). Fig. 3 presents these edge results and compares them to our NN-based core estimates from CTS. For the latter, evaluation of the uncertainty on individual estimates is still ongoing, so here we simply show average values based on combining results associated with specific intervals in ρ from all the radial scans. The NN-based estimates display substantial variance, but we caution that these results are still preliminary and will later be compared to those from more refined NN architectures and to results from our standard (but computationally intensive) Bayesian inversion scheme [9]. If taken at face value, our CTS results from the core to mid-radius suggest broad agreement with the edge measurements, albeit with slightly elevated values except in the very core/early in the flattop phase. However, the current variance of our results precludes any robust conclusions on this or on any temporal evolution in measured R_i at a given ρ.

4. Discussion and conclusions. We have successfully demonstrated proof-of-principle radial measurements of the H/D ratio in AUG H-mode plasmas. To our knowledge, these represent the first localized estimates of H/D content obtained from the core of a purely wave-heated H-mode plasma. Our preliminary results indicate a high H content in AUG #42099 of $R_i \approx$ 0.5, with no strong evidence for a radial trend in R_i for this edge-fuelled discharge, nor for any clear systematic variation between CTS-based core measurements and line-integrated edge spectroscopy. A radially uniform value of R_i would be expected in case of, e.g., strong ion-temperature-gradient driven turbulence [10], but we emphasize that our results are preliminary, relying on a subset of the acquired CTS data for a single discharge and on NN-based inference
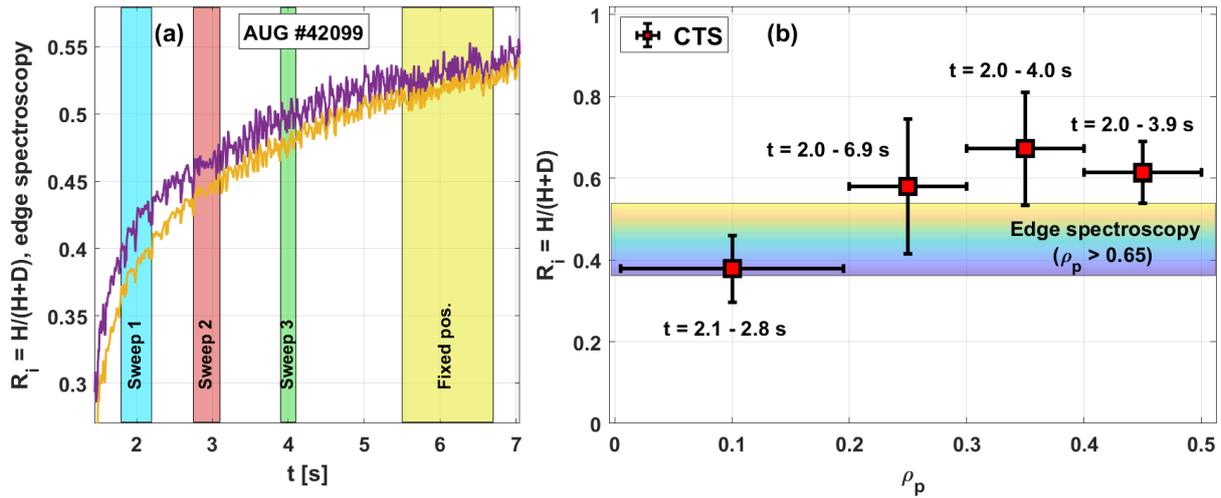
Figure 3: *(a) Isotope ratios from edge spectroscopy in AUG #42099, based on the two sightlines illustrated in Fig. 1(b). The various CTS measurement phases are indicated. (b) Isotope ratios inferred from CTS as a function of ρ_p, shown as the mean and standard deviation for different radial ranges, each based on acquisition pulses within the labelled time ranges. For reference, horizontal bar represents the range in R_i from edge spectroscopy ($\rho_p \geq 0.65$) across all 15 sightlines and all CTS phases.*

of R_i that is still being refined as part of ongoing work. Optimization of our analysis on the full data set, including averaging of neighbouring acquisition pulses, should be able to suppress both systematic and statistical scatter seen in Fig. 3. Experimentally, we also plan to extend this work to plasmas involving core fuelling (NBI/pellets), direct ion heating (ICRH), low collisionality, and H/He mixed plasmas. Ultimately, the results could shed light on the possible benefits of a dedicated CTS-based fuel-ion diagnostic on future burning-plasma devices.

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