Active spectroscopy for atomic H and D measurements in fusion EX

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Introduction — Atomic hydrogen (H) and deuterium (D) play a fundamental role in fusion plasmas, particularly in ionization, line radiation, and recombination processes, which significantly influence the particle, momentum, and energy balance in divertors of fusion devices. Additionally, H and D interact with wall surfaces, affecting adsorption, desorption, and recycling, which in turn shape divertor and scrape-off layer dynamics. Despite their importance, quantitative measurements of H and D in tokamak scrape-off layer (SOL) and divertors remain scarce, partly due to the operational constraints of tokamaks. To address this, we have used the flexibility and diagnostic accessibility of the RAID device at the Swiss Plasma Center (SPC) to develop and operate a two-photon absorption laser-induced fluorescence (TALIF) system using a ps laser. This system has enabled high-resolution 1D-resolved measurements of H density in hydrogen plasmas that could previously only be performed using indirect spectroscopic methods and modeling. Our experiments have demonstrated the usefulness of the technique in fusion-relevant studies and opened the door to investigations of its applicability in high power devices through the use a fs laser system.

The Resonant Antenna Ion Device (RAID) — RAID [1] is a linear (1.5 m total length and 0.4 m diameter) basic plasma physics device in operation at SPC. In RAID, steady-state helicon plasmas in various gases, including H_2 and D_2, are produced by two radio frequency (RF) birdcage resonant antennas delivering a maximum power of 10 kW per antenna at 13.56 MHz. The cylindrical vacuum vessel is water-cooled and allows for long-time (up to days) continuous operation with stable and reproducible plasma conditions. Seven magnetic field coils, surrounding the vacuum chamber, generate an axial magnetic field up to 660 G on axis. Typical electron density in H_2 and D_2 can be as high as $7\text{x}10^{18}$ m^{-3} on the axis of the column with good homogeneity along the axial direction. Typical on-axis electron temperatures are ~5-7 eV. Parameters such as the neutral gas pressure, the RF injected power and the background magnetic field can be varied to control plasma profiles and access a variety of plasma conditions of relevance for tokamak divertor studies.

TALIF diagnostics — TALIF [2] is a technique that allows measurement of H or D densities by laser-pumping ground state (n = 1) atoms into the n = 3 states and subsequently detecting the radiative decay (fluorescence) to n = 2 which occurs in the visible (656 nm) and has a natural lifetime of ~15.5 ns. An advantage of TALIF is that an absolute calibration procedure is possible using Kr gas at a known pressure and temperature. In that widely-used method, the laser is tuned at a nearby wavelength to achieve two-photon absorption in Kr and a subsequent fluorescence at 826 nm. Comparison of the fluorescence signal to the one obtain with TALIF on H (or D) yields the desired value of density.

On RAID, two systems are presently installed to perform TALIF measurements. In a first scheme [3], the UV pulses used for the TALIF experiments are generated by an EKSPLA ps-laser tunable system with 50 Hz repetition rate and a pulse energy up to 100μJ in the 204−205 nm range used for the present studies. The ~28 ps pulse duration is much shorter than the ∼ns timescale of the collisional and radiative processes in the plasma. The fluorescence generated after two-photon absorption of the laser beam is collected by a set of lenses into a Princeton

PI-MAX 4 ICCD camera mounted perpendicularly to the laser beam. The measured, spatially resolved, decay times for H are shown in Fig. 1-Left. The spatial, 1D-resolved, profile is consistent with a uniform decay time across the measured region, for both H and Kr (not shown, for details, see [3]). In the case of H, the profile has a mean of 9.7ns ± 0.2 ns, which is significantly lower than the purely optical decay time of the 3d state, 15.5 ns. Our measurements of the absolute atomic density are consistent with a flat profile of H density across the cylindrical plasma column of RAID, up to a radius of 4 cm, a region over which n_e and T_e show a significant variation. The average density across the measured region is 2.3 ± 0.1×10^{19} m^{-3}. This corresponds to a mean dissociation degree of ~2.9%.

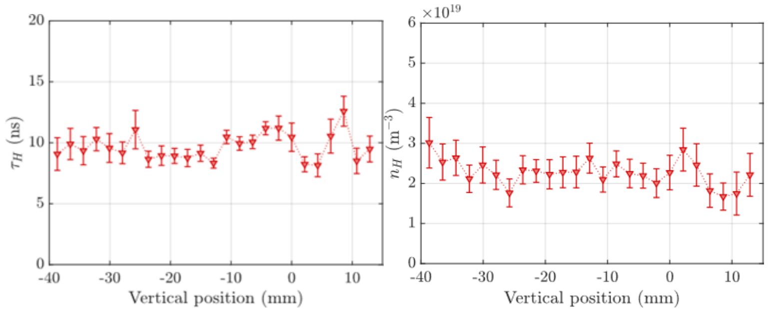

Fig 1: Left – Profile of fluorescence decay times of H across the dense hydrogen plasma column of RAID (axis of device at 0 mm). Right - H absolute density profile.

The second TALIF system, currently under development as part of a EUROfusion ENR project [4] led by Baquero-Ruiz, is designed for single-pulse, 1D-resolved measurements of H and D density using an fs-laser.

The use of fs pulses overcomes a critical limitation of earlier TALIF methods for tokamak applications. Traditional ns- or ps-laser pulses have a narrower bandwidth than the expected absorption broadening of H and D in the SOL or divertor. This broadening arises from factors such as Doppler shifts of atoms with kinetic energies up to ~10 eV, Zeeman splitting at ~1 T magnetic fields, and possible Stark broadening. As a result, ns- and ps-laser-based systems require scanning the laser wavelength across the entire absorption line to obtain the spectrally integrated fluorescence signal needed for density calculations. In contrast, fs laser pulses have very large bandwidths in the order of 0.1‑1.0 nm, capable of exciting in each pulse the local H and/or D ground-state populations independent of the expected laser absorption broadening mechanisms. fs laser pulses can therefore enable single laser pulse measurements of density, eliminating the constraint of performing scans and allowing to capture the rapidly changing conditions of fusion plasmas.

Ongoing investigations of fs TALIF in RAID will allow determining the feasibility of the technique in fusion devices.

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References

[1] I. Furno et al., EPJ Web Conf. 157 (2017) 03014.
[2] Bokor J, Freeman R R, White J C and Storz R H 1981 Phys. Rev. A 24 612(R) [3] H. Reimerdes et al 2021 Nucl. Fusion 61 024002.
[3] L. Kadi et al., Plasma Phys. Control. Fusion 66 (204) 125007.
[4] EUROfusion Enabling Research project ENR-TEC.02.EPFL