A Two-photon Absorption Laser Induced Fluorescence diagnostic for atomic H in a helicon plasma device

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Introduction

Atomic H neutrals play an important role in several areas of fusion research, such as negative ion production for Neutral Beam Heating, or the achievement of a detached divertor regime required for next-generation fusion devices such as ITER [1, 2]. Many of the diagnostics widely used to investigate neutrals, such as Optical Emission Spectroscopy, require extensive modeling efforts to measure the neutral density.

The Two-photon Absorption Laser Induced Fluorescence (TALIF) technique allows highly localized measurements of the atomic H absolute density and temperature[3, 4] without the need for detailed collisional-radiative modeling. It uses an intense laser pulse tuned to 205.1nm to excite ground state H atoms to the $n = 3$ states through the absorption of two photons. These excited states decay to the $n = 2$ energy levels by emitting fluorescence at 656 nm. The intensity of the emitted fluorescence across the entire absorption spectrum is proportional to the atomic H density, while the width of the absorption spectrum is related to the temperature of atomic H. The Resonant Antenna Ion Device (RAID)[5], Fig. 1 is a linear helicon plasma device capable of producing steady-state plasmas with electron densities and temperatures similar to those found in the divertor region of tokamaks. A set of six copper coils produces an axial magnetic field between 100-800 G on-axis and two 'birdcage' helicon antennas located on the ends of the vessel are each capable of injecting up to 10 kW of RF power at 13.56 MHz.

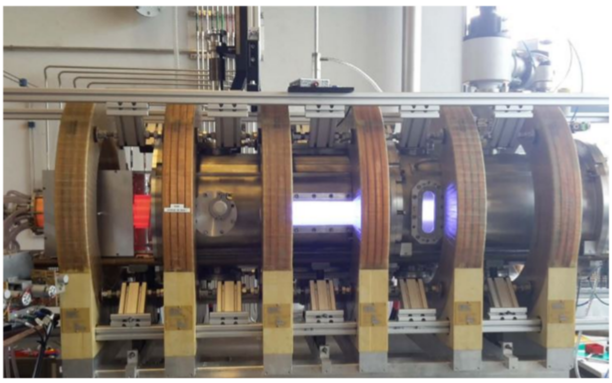

Figure 1: *A plasma generated in the Resonant Antenna Ion Device (RAID).*

Experimental setup

We are currently developing a TALIF diagnostic on RAID in order to perform local measurements of the atomic H density and temperature. A diagram of the experimental setup is shown on Fig. (2).

The EKSPLA PL2231 laser system produces the ultrashort UV pulses used for the TALIF experiments. At the required 205.1 nm wavelength, it emits 28 ps duration pulses with an energy of about 100 μJ, at a 50 Hz repetition rate. The laser beam is guided by a set of mirrors and injected vertically through the plasma column. UV fused silica lenses are used to focus the beam to a diameter of 200 μm at the center of the vessel. Ground state H atoms that absorb the laser light are excited to the 3S and 3D states, then decay by spontaneous emission to the 2P state. The fluorescence is detected by a Princeton Instruments PI-MAX 4 ICCD camera, capable of acquiring the fluorescence emission over very short gating times, down to 3 ns. A set of collection optics are used to focus the emitted fluorescence onto the camera. Depending on the level of TALIF signal we observe, we can choose to image a small region of emission to maximize the signal-to-noise ratio, or instead image a large portion of the laser beam in order to perform 1D measurements.

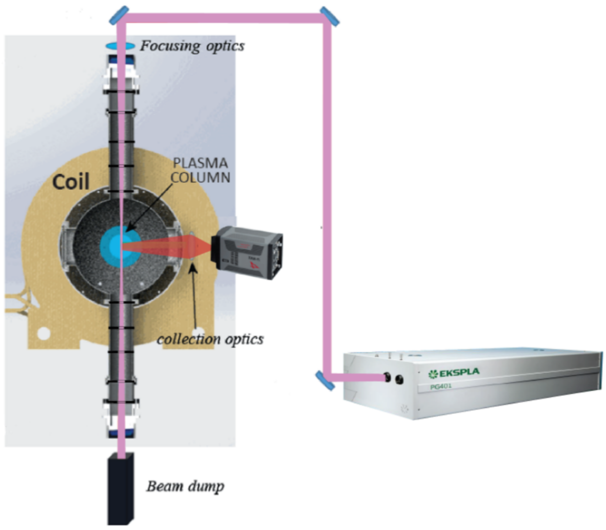

Figure 2: *The TALIF setup.*

Neutral density and temperature measurements

The TALIF diagnostic will allow performing highly localized absolute density and temperature measurements in H_2 and D_2 plasmas. By tuning the wavelength of the laser emission around the 205.1 nm two-photon absorption line, we will trace out the absorption spectrum of the ground state neutrals.

The shape of the measured absorption spectrum is expected to be determined mainly by Doppler broadening which is associated with the thermal motion of the neutrals. However, the lineshape can be influenced by additional factors, such as the applied magnetic field leading to Zeeman broadening, collisions between electrons and neutrals leading to Stark broadening or saturation broadening due to too large laser intensity. For typical plasma parameters in RAID, we expect all broadening mechanisms apart from Doppler broadening to be negligible. In this case, the width of the absorption spectrum can be related in a simple way to the neutral temperature.

The neutral density n_H is determined from the total area under the absorption spectrum and is proportional to the number of fluorescence photons N_F detected upon the injection of each laser pulse, as shown in eq. (1). The level of signal will also depend on the parameters of the laser beam such as the pulse energy E_{pulse}, the radius of the beam at the focal point w_0 and on the two-photon cross-section σ_H. The emitted signal also depends on the branching ratio a_{23} of the TALIF scheme. Our collection optics will be adjusted to cover a certain portion of length L_C of the laser beam. By increasing L_C we increase the level of signal but reduce the spatial resolution of the diagnostic.

$$N_F \propto n_H a_{23} \sigma_H L_C \frac{E_{pulse}^2}{w_0^2} \tag{1}$$

The two-photon cross-section σ_H is not accurately known, therefore eq. 1 was only used to estimate the level of signal we would expect in given plasma conditions. In order to obtain absolute density results, a calibration procedure will be performed in Kr gas. By performing TALIF measurements in a known density n_{Kr} of room-temperature Kr gas in RAID and recording the level of fluorescence emission, we are able to relate the signal obtained in H plasmas to the absolute density of atomic H, n_H. As Kr has a two-photon absorption line at a wavelength very close to the one we use in H, the behavior of the laser system and the injection optics remain approximately unchanged between Kr and H measurements. However, the change in some parameters such as the transmission factors T through the collection optics, the quantum efficiency η of the ICCD camera or the branching ratio a must be taken into account, as summarized in eq. (2). The main source of uncertainty in the calibration process is in the ratio of two-photon absorption cross-sections σ between Kr and H. The ratio of the cross-sections was measured by [6] and later by [7], with the authors claiming an uncertainty of about 30% on the reported value.

$$\frac{S_{Kr}}{S_H} \propto \frac{n_{Kr}}{n_H} \frac{\sigma_{Kr}}{\sigma_H} \frac{a_{Kr}}{a_H} \frac{T_{Kr}}{T_H} \frac{\eta_{Kr}}{\eta_H} \tag{2}$$

As shown in eqs. (1) and (2), absolute density measurements require the determination of the branching ratio a_{23}. An H atom that absorbs the laser and is excited to the $n = 3$ states does not necessarily decay by emitting fluorescence. Other processes, in our case mainly electron impact excitation, can deplete the excited states before they decay by spontaneous emission to the 2P state. These additional processes are collectively named "quenching" and their presence will reduce the level of emitted fluorescence. Eq. 3 describes the relation between the quenching rate Q and the branching ratio. It is a simple and general expression that does not depend on the details of the underlying collisional-radiative processes. An additional effect of quenching is the reduction of the decay time τ of the fluorescence signal after absorption of the laser pulse. Therefore, by measuring τ we are able to calculate the branching ratio using the known spontaneous emission rate of the fluorescence A_{32}, without explicit knowledge of the quenching processes. By acquiring the TALIF signal at various delays with respect to the laser emission, we are able to measure the time evolution of the signal and determine the branching ratio a_{23}.

$$a_{23} = \frac{A_{32}}{A_{32} + Q} = A_{32} \cdot \tau \tag{3}$$

As the background 656 nm line emission from the plasma is expected to be strong, we must take steps to reject as much of it as possible. Fortunately, the TALIF signal is emitted over a very short period of time, $\tau \leq 18ns$, which is reduced in the presence of quenching. The ICCD camera will be set to acquire the signal over a gating time of at most a few τ, reducing the impact of the background emission. Additionally, the camera will acquire the 656 nm line intensity shortly before the laser pulse injection, allowing us to subtract it from the TALIF signal. The fluctuations of the background emission over the nanosecond timescale will not be rejected, however they are expected to be small compared to the signal.

Conclusions and outlook

A new Two-photon Absorption Laser-Induced Fluorescence diagnostic is currently being installed on the RAID linear helicon plasma device, which will enable us to perform direct and localized measurements of absolute density and temperature of atomic hydrogen and deuterium in plasma conditions similar to those found in the divertor and scrape-off layer of tokamaks. Determination of the absolute density will require an absolute calibration using Kr gas. Additionally, time-resolved measurements will be used to determine the decay rate of the fluorescence in order to account for possible quenching processes. The studies performed in RAID will also help us determine the applicability of the TALIF technique in studies of neutral particles in tokamaks such as TCV.

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