# Understanding the Physical Processes Prevailing in the Edge Plasma Region of ADITYA-U Tokamak using Spectroscopic Measurements

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**Abstract**

The edge region of any tokamak plasma controls both the core plasma confinement as well as the particle and heat flux to the plasma facing components and vessel wall. The ADITYA-U tokamak edge plasma has been extensively explored using spectroscopy diagnostic to understand the prevailing physical phenomena in this region. While deducing the ion and neutral temperatures, an anomaly arising due to Zeeman effect has been removed and real temperature are estimated. As the tokamak plasma is suspended in high-magnetic fields, Zeeman effects are important to be included in the line-shape profile analysis. By including the Zeeman effect in the line shape analysis of $H_\alpha (656.28\,nm)$ fuel neutral and $C^{1+}$ $(657.8\,nm)$, $O^{4+}$ $(650.02\,nm)$ impurity ions it has observed that there exists a poloidal asymmetry in neutral temperature, which is reported for very first time. The anomaly has been resolved through modelling of spectral line shape profile with by incorporating the Zeeman influenced components in simulation. The analysis also showed that there exists two components of neutral temperature (warm and hot) in ADITYA-U tokamak plasma, corresponding to different atomic and molecular processes. The corrected temperatures of $\mathrm{C}^{1+}$and $\mathrm{O}^{4+}$ions and their radial profiles indicated that presence of magnetic islands significantly influence the impurity temperatures. *In the novel $Li_2TiO_3$ Inductive Pellet Injection (IPI) experiments, self-absorption phenomenon in $Li_\alpha$ spectral line emission has been identified and thoroughly analysed.* For recycling and influx estimations emissions from stainless-stell wall and graphite limiter with and without Li coating are collected and analysed. Using this the temporal evolution of $H_\alpha$, $O^{1+}$ $(441.6\,nm)$ and $C^{2+}(464.7\,nm)$ emissions, the recycling from these surfaces is quantified. To further decipher the edge plasma physical processes, The Diffusion coefficient is estimated for C, O, Ne, Ar, and Fe with an in-house developed SITA code (Study of Impurity Transport in ADITYA-U tokamak). Using the code, it has been observed that with increasing Z value the diffusion coefficient decreases. The observed mass dependency of diffusivity coefficient throws a new light towards understanding the impurity transport in tokamaks. Due to very low plasma temperatures near the wall, molecular processes become very important. The presence of different impurities in this region further complicates the molecular band identification. The overlapping of bands is studied in a RF produced plasma and correct impurity ion temperatures are estimated. A elaborated edge plasma diagnosis through spectroscopic technique and understanding of physics basis for the events occurring there will be presented in this paper.

## 1. Introduction

The primary challenge associated to large scale tokamak ITER like machine is power exhaust handling which is hard to combat to the existing plasma facing components. To regulate this, it is important to understand the edge plasma as it acts as a preliminary region in modifying the power exhaust through the Plasma Wall Interaction (PWI) and external gas injections into the edge. The spectroscopic diagnostic is the suitable tool to acquire and investigate plasma emissions from edge region. This region of tokamak plasma is dominated by the neutral particle and low-Z impurities ions [4,5]. The neutral and impurity behaviour through estimation of neutral and impurity ion temperatures through incorporating Zeeman broadening and respectively denoted by $T_n$ and $T_{imp}$. It is helful in understanding the atomic and molecular processes dominated in plasmas There have been multiple previous attempts to measure the neutral and ion temperatures in tokamak edge region. In Alcator C-Mod, TRIAM-1M, TEXTOR tokamak extensive studies on ion and neutral temperatures have been carried out through incorporating the Zeeman broadening into experimental measurement [8, 9, 10, 11]. Along with the neutral and ion temperature measurements, the study particle sources are important to understand interaction between plasma particles with PFCs. In ASDEX, ISX-B, TRIAM-1M tokamaks extensive studies related to recycling and particle influx measurements have been carried out [12, 13, 14,15, 16]. It is seen in detached divertor condition H-mode plasma line emissions from fuel neutrals have the significant amount of direct contribution from charge exchange and molecular pathways in addition to atomic one [17]. Also effect of molecular assisted

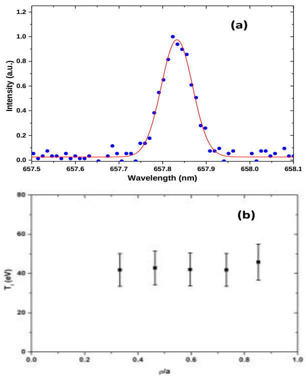


*Figure 1: $C^{1+}$ temperature estimation without Zeeman (a) fitting of experimental data through considering doppler broadening (b) Space resolved $C^{1+}$ ion temperature*

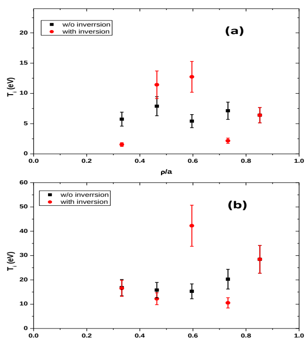


*Figure 2: Spatial profile of neutral and impurity ion temperatures, (a) $C^{1+}$ ion temperature with incorporating Zeeman broadening (b) $O^{4+}$ ion temperature with incorporating Zeeman broadening*

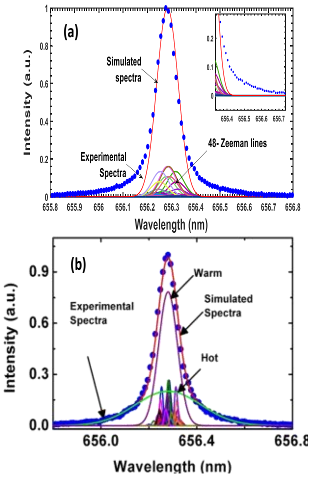


Figure 3: incorporating Zeeman (a) $H_{\alpha}$ fitting with single component (b) $H_{\alpha}$ fitting with warm and hot temperature components

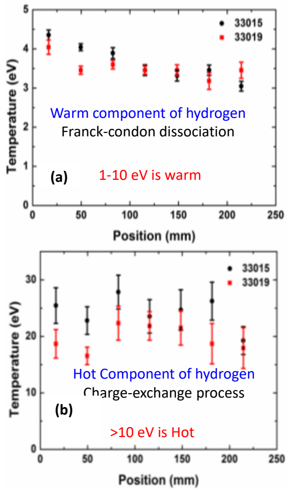


Figure 4: Spatial profile of neutral (a) warm and (b) hot temperature component

recombination on ionisation per photon is studied through DEGAS2 neutral transport code [16]. Contribution from molecular pathway in the neutral hydrogen emission as the measurement of $H_2$ Fulcher band from tokamak plasma is extremely challenging as the molecules are ro-vibronically excited and the population densities are small [15]. Similarly, the impurities penetration in the plasma are happened through the quite complex processes and their perpendicular transports are not only governed by plasma (collision and turbulence), but also on their atomic number (Z). However, not much work has been done on the Z-dependency of the impurity transport. Not only that, contradictory outcomes obtained when classical and Pfirsch-Schlüter regimes of neo-classical transport do not depend on the impurity charge state Z, however the Banana-Plateau regime of neo-classical theory is predicted to decreasing function of charge state Z [17,18]. In experimental scenario the Z-dependence of the impurity diffusion coefficient have been found to vary machine to machine. Then, along with neutral transport, impurity transport studies are needed to be explored to understand its effect on the plasma properties.

## 2. Experimental setup

The Aditya-U tokamak is upgraded varient of Aditya tokamak, the machine is upgraded to have operations in both limiter as well as divertor configurations. The Aditya-U tokamak has a SS304L torus shaped vacuum vessel having circular cross-section, with major radius, R = 0.75 m and minor radius, a = 0.25 m. The machine can be operated with toroidal magnetic field $B_T$ = 0.75-1.5 T [19]. In the initial phase of operations, the machine is performed operations in the limiter configuration. It is equipped with many diagnostics. In this paper spectroscopic disgnostic on ADITYA-U tokamak will be discussed. The

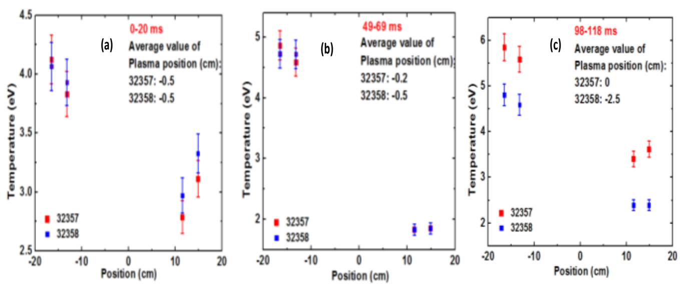


Figure 5: Poloidal asymmetry measurement in neutral temperature

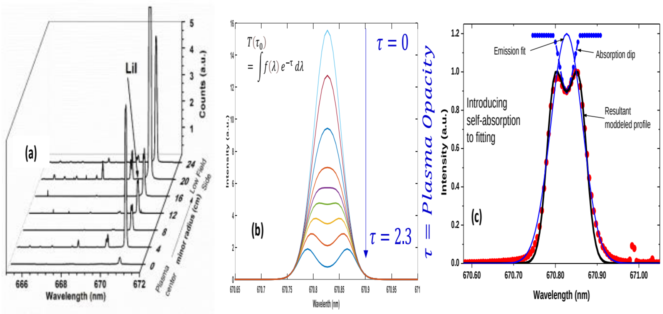


Figure 6: $Li_2TiO_3$ inductive pellet injection experiment (a) space resolved measurement of Lithium emission, (b) Emission and absorption profile and opacity effect and (c) opacity estimation in experimenatlly observed data

observations and studies have been done for wide variety of discharges starting from plasma current $I_P \sim 80-150\ kA$ and plasma duration $\sim 70-300\ ms$. The cord average densities and electron temperatures for analyzed plasma are $n_e \sim 1.5-3.5\ \times 10^{19}\ m^{-3}$ and $T_e \sim 300-550\ eV$, respectively.

Along with Aditya-U tokamak, another low temperature plasma device is used to develop the technique for characterization of tokamak divertor plasma having low electron temperature and relatively high electron density. This device is mainly developed to coat the divertor graphite (C) tiles with tungsten (W) keeping in mind the use of it as the future PFC material of tokamak [20]. This is a cylindrical shaped stainless steel vacuum vessel having diameter 360 mm and height 300 mm. It is well equipped with ports (35 and 63 CF) to accommodate different diagnostic, pumping system, gauge, probe, etc. The RF plasma is produced with RF power 13.6 MHz and power 600 W.

(a) spectrometer-based setup: In the presented studies for line shape profile modelling, the multi-track spectrometer (MTS) system has been used. It is setup to capture the radiation from total seven Line of Sights (LoS) covering almost entire plasma radius. The spatial resolution is ~ 25 mm using lens and optical fiber setup. Here, the optical arrangements are made on the top-rectangular view-port of the machine, the viewing LoS configurations are also varies with the requirement of the study. Case I: Space resolved measurement LoS: 1.65, 4.95, 8.25, 11.60, 14.90, 18.20 and 21.44 cm (center to LFS edge). Case II: estimation of poloidal asymmetries in plasma, LoS: outboard

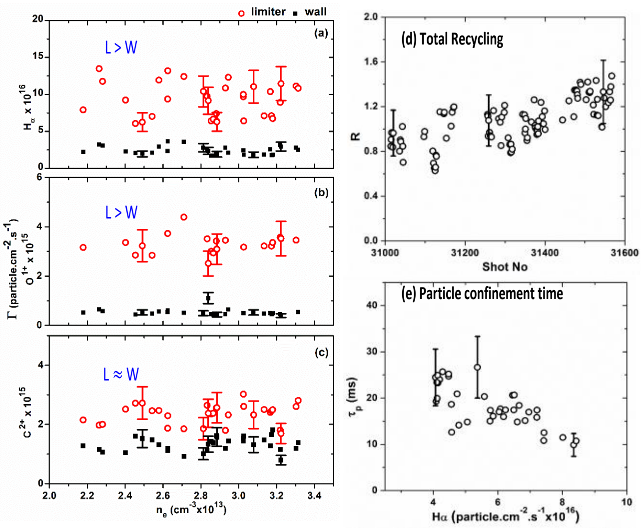


Figure 7: (a),(b) and (c) measured influx from graphite limiter and SS wall for $H_{\alpha}$, $O^{1+}$ and $C^{2+}$, (d) recycling estimation and (e) particle confinement time estimation

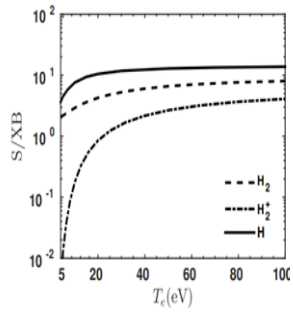


*Figure 8: Molecular influence in S/XB*

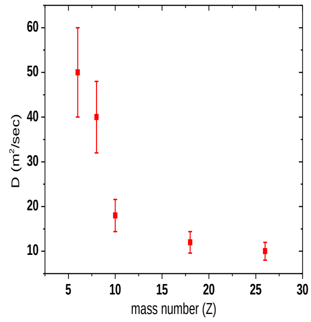


*Figure 9: Mass dependency of diffusivity on charge state Z*

(LFS) at 11.50 cm, 14.85 cm and inboard (high field side, HFS) at −16.5 cm and −13.2 cm.

(b) PMT based optical set up: This setup is used in particle influx, recycling and particle balance estimations for $H_\alpha, O^{1+}, C^{2+}$: measurement using LoS terminating on the graphite limiter and stainless-steel wall. These all unit are having the collimating lens for light collection, optical fiber for transporting the light, narrow band interference filter (bandwidth = 1 nm) for wavelength selection and PMT for detection.

(c) Spectroscopic instrumentation for low temperature and high-density plasma related study: A simple spectroscopic setup using lens and optical fiber were arranged on a 63CF optical view-port for viewing the discharge. The spectrometer used during this experiment is a compact miniature spectrometer (USB4000; make: ocean optics).

All the optical systems are calibrated in-situ for quantitative analysis to get the exact wavelength, relative intensity between the channels and absolute intensity. The spatial profile measurement was converted using Abel-line matrix inversion to obtain the radial profiles. Array of Langmuir probes are also placed inside machine for getting electron density and temperature at the plasma edge region. This system is used to obtain the plasma outflow required to estimate recycling coefficient. A set of sine-cosine coils is developed for plasma position measurement. However, to control the plasma position movement using the position feedback control system signals of $\boldsymbol{H_\alpha}$ radiations measured using two photodiode-based unit is utilized.

## 3. Result and discussion

*3.1. Investigation of plasma properties through spectral line shape profiles and their modelling:*

In tokamak plasma where magnetic field strength is higher it produces the extra broadening effect in experimentally measured spectrum due to Zeeman effect along with Doppler broadening which is responsible for temperature estimation of neutral and impurity ions. If Zeeman broadened components are not considered into the measurement through modelling, then temperature estimation can be erroneous. As seen in fig. 1(a) the space resolved $C^{1+}$ impurity ion present at 657.8 nm is estimated to be $\sim 40 - 60\ eV$ as shown in fig. 1(b) through only doppler broadened FWHM measurement (fitting in fig. 1(a)). However, the $C^{1+}$has ionization potential of $\sim 24\ eV$, such high temperature attained by $C^{1+}$ ion is not possible also in the edge region electron temperature measurement through Langmuir probe is $\sim 10\ eV$. The discrepancy present in the estimation is answered through incorporating Zeeman components in the measurement. For $C^{1+}$(657.8 nm) and $O^{4+}$ (650 $nm$) is investigated and it is found that it contributes 7 and 21 Zeeman components respectively. The same is included in the modelling through simulation, a group of MATLAB functions are developed to do so. Through this corrected impurity ion and neutral temperature can be estimated. As shown in fig. 2a and 2b for shot no #33015 estimated $T_{imp}$ $C^{1+}$ and $O^{4+}$ respectively. The it is seen that $C^{1+}$ ion temperature without inversion (black data points) are withing range $< 10\ eV$, with inversion it is $<$ 15 $eV$ and peaking at ∼0.6 radial location. Similarly, for $O^{4+}$ the corrected temperature estimated $< 30\ eV$. With Abel inversion the temperature is $\sim 10 - 50\ eV$ with peak at $\sim 0.6$ radial location, this represents 15 cm of plasma radii al low field side. Because of magnetic island the electron temperature profile remains flat inside the island also there is no turbulance, no flow shear inside the island because flat profile of electron temperature. In contradiction it is observed in JT-60U tokamak that the ion temperature becomes peaked inside the magnetic island [1]. The turbulance inside the island is then driven by the ion temperature gradient. The similar observation is made at ADITYA-U tokamak for ion temperature gradient.

With the same approach theoretical spectral line shape of $H_\alpha$ present at 656.28 nm were developed by considering total 48-Zeeman components into the measurement which adds up the overall broadening of the line shape [2]. The experimentally acquired $H_\alpha$ line is modelled with simulated to get the neutral temperature using single Gaussian profile as shown in fig. 3a. It was found out that the simulated line-shape profile is best fitted with the experimental spectrum when two temperature components of neutral hydrogen are considered. One is the warm component (1-10 eV) and other is the hot component (>10 eV), the same have been fitted fig. 3b. The space resolved profile measurement of neutral temperature gives Aditya-U neutral temperature 3-5 eV for warm component and 15-30 eV for hot temperature components of the neutral as shown in fig. 4a and 4b respectively. Here, the hot components are existed due to the charge exchange produced neutral.

The poloidal asymmetry in neutral temperatures have been measured for the first time in tokamak history. In this setup is arranged in the both LFH and HFS of the plasma. In fig 5., it is seen that neutral temperature measurement is having values ~2.5 eV in LFS and 4-6 eV in HFS side. The neutral temperatures from HFS are always at higher than that of LFS. It is then confirmed that there is a poloidal asymmetry in the neutral temperature, which is most likely a first time observed in the tokamak. It is well known that plasma parameters usually vary strongly across the magnetic field lines rather than parallel to them due to the freely moving nature of the charge particles along the field lines in toroidally confined plasmas. Hence, in tokamaks, the plasma parameters including neutral/ion temperatures are considered to be symmetric along the toroidal and poloidal directions [21]. In tokamak neutral may acquire temperature through the collision with plasma ions. Then there must be an asymmetry in the ion temperature, which has been seen in many tokamaks.

The absorption is also modelled along with emission line-shape profiles. During $Li_2TiO_3$ inductively driven pellet injection experiments produce *self-absorption* phenomenon in the spectral line shape profile of $Li$ (670.8 $nm$) is observed for the first time. Analysing this the plasma opacity is estimated as shown in fig. 6. Fig 6a. space resolved measurement of $Li$ emissions, fig. 6b shows how spectrum can evolve if self-absorption occurs. Fig. 6c is the modelled line shape profile along with experimental measurement gives the estimated opacity 0.55 [22].

*3.2. Investigation of particle influx, recycling, and particle confinement time:*

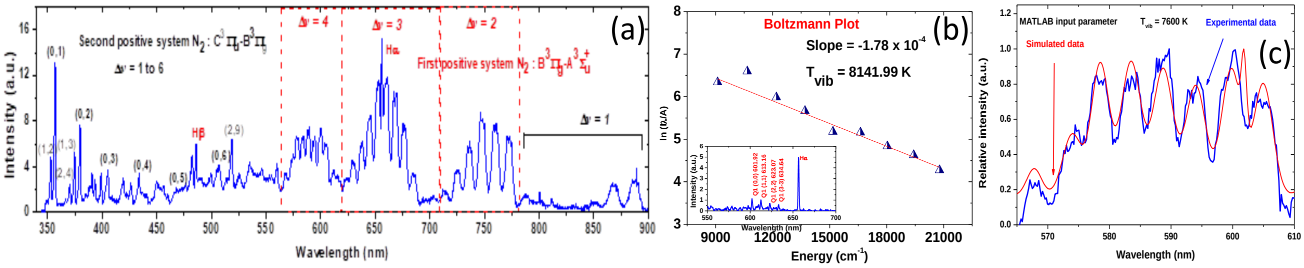

*Figure 10: Experiments in linear device (a) visible survey spectrum of $N_2$ spectrum, (b) Boltzmann plot and (c) simulated and modelled*

Particle and impurity influxes from various surfaces (graphite limiter and SS wall) exposed to plasma has been estimated using the PMT based diagnostics. For these purposes, $H_\alpha, O^{1+}$ and $C^{2+}$ emissions were collected in GDC and GDC with Lithiumization wall conditioning. It is observed in fig. 7a, 7b and 7c, oxygen and hydrogen influx are more on graphite limiter compare to SS walls. However, the contribution of carbon influx is more from SS wall ($9.2 \times 10^{19}$ $particles/sec$) than from graphite limiter surfaces ($3.8 \times 10^{19}$ $particles/sec$). The all these finding is explained by considering the edge plasma dynamic. The particle recycling and impurity influxes has been estimated to understand the effect of Lithium coating on the PFC and wall. The measured results suggest that for oxygen and hydrogen the reduced by 83% and 60% respectively from the graphite limiter surface, from SS wall surface also the oxygen and hydrogen shows reduction of influx by 50% and 30% respectively. However, for carbon emission did not change much after lithium coating, it is suspected that it is due to carbon is coating on all over wall during plasma discharges. Recycling coefficient is also estimated fig. 7d, it is related to particle source and sink. Particle confinement time is measured and given in fig. 7e.

*3.2. Investigation of molecular hydrogen on S/XB:*

Previously estimated influx measurement includes only atomic S/XB. However, when the edge or divertor regions electron temperature becomes ~ 10 eV, the molecular contribution in Hα emissivity and subsequently in the particle influx becomes significant. To understand the contribution from molecule in the particle influx estimation, neutral transport code, DEGAS2 has been used. It modelled the experimental radial profile of Hα emissivity to find the contribution from molecule in total emissivity. Then influxes from molecule, molecular ion and atom have been calculated to get the total influx. The importance of molecule in influx study is revealed through this study for the tokamak plasma region having very low $T_e$. The estimated S/XB for atomic and molecular hydrogen is shown in fig. 8.

*3.3. Impurity transport investigation:*

The Radial Impurity Transport Equation (RITE) equation is then solved by implicit Crack-Nicolson by minimized step. The von Neumann Stability analysis to determine the time step size. Based on this the code is developed indigenously and verified for oxygen impurity ion. In this study several subroutines have been introduce in the code for Low-Z, medium-Z, i.e., C, O, Ne, Ar, and Fe impurity ions. The experimental emissivity is estimated through the MTS spectroscopic system. Through this code it is observed that the diffusivity changes with impurity species, i.e., to say with atomic number, Z. As the atomic mass number increases, the diffusivity decreases as shown in fig. 9. Although, the value of diffusion coefficient is quite larger than the estimation using neo-classical theory, but the change is same to the predicted by the neo-classical theory of impurity transport.

*3.4. Influence of hydrogen Fulcher band on temperature estimation:*

plasma will be produced in the Aditya-U. Then the divertor region plasma, especially plasma with detached divertor, will have very low temperature $T_e$ <10 eV [23]. In this plasma, there will be substantial amount of neutral present and they will give molecular emission, either of hydrogen or from the seeded nitrogen used for the radiative cooling. In this low temperature region molecular volume recombination seeks attention. Not only that, neutral gas will play important role in this plasma through their interaction with plasma particle via various atomic and molecular processes. Yet the spectroscopic studies related to detached divertor condition has not been performed in great detail. Here, the experiments were performed on Lab experimental device to develop the characterization technique. The experiments were performed with $H_2$ and $H_2$+$N_2$, considering the effect of nitrogen gas seeding experiments will be performed to get radiative diverter. As shown in fig. 10 a, the three nitrogen bands $\Delta v$ =2 (710 - 790 nm), $\Delta v$ =3 (620 - 690 nm) and $\Delta v$ =4 (560 to 620 nm) of 1st positive system (1PS) are simulated to obtain the gas temperature by considering excited state population follow the Boltzmann distribution (fig. 10b. It was found that temperatures obtained from three band are different experimental data are matching very well fig 10c. However, when the correction made using $H_2$ Fulcher band, all three band gives same gas temperature ~0.68 eV.

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