Behavior of Non-Thermal Electrons during ECR Pre-Ionization at Aditya Tokamak*)

Shishir PUROHIT, Shankara JOISA, Malay Bikas CHOWDHURI, Brajkishore SHUKLA, Jayesh RAVAL, Ranjana MANCHANDA, Nilam RAMAIYA, Umesh NAGORA, Parveen ATREY, Rakesh TANNA, Kumarpalsinh JADEJA, Shailesh BHATT, Chetnarayan GUPTA, Ajai KUMAR, Joydeep GHOSH and Aditya Team

Institute for Plasma Research, Bhat, Gandhinagar, 382 428, India

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The non-thermal electrons (NTE) in tokamak plasma have a strong effect over the plasma properties and on the plasma facing components. This establishes an importance of NTE to be studied in both flux and energy space. The NTE was studied for Aditya tokamak by monitoring X-ray spectrum using a Silicon Drift Detector (SDD) based X-ray spectroscopic diagnostic for the ECR pre-ionization experiments. The spectra shows X-ray line radiation band on top of the bremsstrahlung. Line radiation is primarily the combination of multiple characteristics lines existed between 5 keV to 7 keV and mostly associated with multiple ionized states of iron, tokamak wall material. This is likely due to the interaction between the NTE, generated during ECR pre-ionization experiment, with the stainless steel vessel wall of the Aditya Tokamak. The behavior of NTE was studied as a function of vertical field and pre-filled pressure. With the application of vertical field, energy carried by the NTE is reduced due to higher vertical drift velocity in comparison to the case of without one. Significant reduction of the X-ray line radiation strength with higher pre-filled pressure also indicates the reduction of NTE due to the enhanced electron neutral collision.

Keywords: non-thermal electron, X-ray spectra, SDD, ECR pre-ionization, Aditya tokamak

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1. Introduction

Electron populations associated with the tail of electron energy distribution for tokamak plasma are referred as non-thermal electrons (NTE). They hold higher energies and are potential enough to migrate into the runaway regime causing the plasma to lose its energy [1]. Moreover interaction of NTE with the plasma facing components (PFC) and other inner structures of the tokamak are potential enough to damage them and tokamak vessel, which is a matter of great concern [2]. These distinctive features offer a strong candidature of NTE to be studied in depth, both in energy and flux space. NTE are mostly observed during the plasma startup and current collapse/disruption. However a finite population of NTE is always present over the plasma discharge.

The NTE are also prominently observed during the Electron Cyclotron Resonance (ECR) pre-ionization assisted tokamak plasma breakdown [3]. It serves as a useful tool for discharge initiation which reduces the consumption of Ohmic power at initial phase of discharge, thus widely employed for tokamak plasma startup [4, 5]. NTE has been studied by monitoring the X-ray spectrum [6, 7] generated during the plasma experiments. Our previous work has reported the X-ray spectra associated with NTE for the ECR pre-ionization experiments in Aditya tokamak [7].

Figure 1 shows the characteristic X-ray radiation band on top of the bremsstruhlang, which seems to be a combination of multiple characteristics lines colonized within 5 to 7 keV. The band is primarily associated with the multiple ionized states of Fe, which is main constituent of stainless steel, wall material of vacuum vessel of Aditya tokamak.

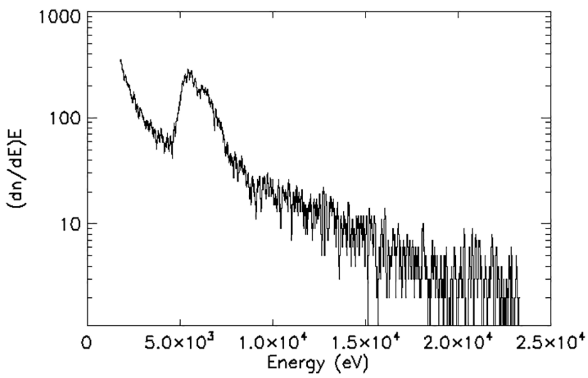

Fig. 1 X-ray spectrum, integrated over few discharges for ECR pre-ionization experiment for Aditya tokamak plasma.

author's e-mail: pshishir@ipr.res.in & malay@ipr.res.in

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It can be inferred that there exist a strong NTE and vessel interaction. This strong interaction is mostly attributed to the drift of NTE particle across the field lines in the absence of any compensating mechanism. This drift of NTE is observed due to different reasons namely; drift due to the presence of error field, grad B and curvature drift [8–10]. The drifting of NTE takes away considerable energy from the plasma which would have been consumed in for better ionization of the fuel particles. A study has been done to understand the behavior of NTE of Aditya tokamak during ECR based pre-ionization startup and to understand the effect of different parameters like pre-filled pressure and applied vertical field, over the NTE behavior.

The experimental results from Electron Cyclotron Resonance based pre-ionization startup are presented in this article. It was observed that vertical field and higher pre-filled pressure reduces that NTE particle and wall interaction. The experimental setup is described in Sec. II. Result and Discussion of behavior of NTE with different experimental conditions are discussed in Sec. III which is followed by a summary.

2. Experimental Setup

ADITYA tokamak is a mid-sized device (R = 0.75 m, a = 0.25 m), with two breaks in vacuum vessel toroidally 180° apart, carrying about 80 - 150 kA of plasma current with a graphite poloidal limiter [11]. Equally spaced 20 coils offers 0.75 T - 1.35 T toroidal field. The cross-section view of Aditya tokamak is shown in Fig. 2. The TF coils are square in shape. The BV1 and BV2 are the major coils by which the vertical field is configured for the Aditya tokamak. The typical Aditya core plasma temperature resides within 300 to 500 eV and the line averaged electron density ranges in between 1.0 to 2.5×10^{19} m^{-3}. Aditya Tokamak is having a verity of diagnostics for measuring different plasma parameters, namely Rogowski coils for plasma current, and magnetic diagnostic and Mirnov coils for the MHD studies, Soft X-ray detector array for chord average plasma temperature and MHD studies. The microwave diagnostic measures the plasma electron density [11, 12]. Visible spectroscopy systems [13] provides information about the temporal behavior of H_α, H_β emissions and spectral line emissions, such as OII, CII, and CIII of different impurities, from the Aditya tokamak plasma. The Silicon Drift Detector (SDD) X-ray spectroscopic diagnostic records the NTE X-ray spectrum in the energy range of 1.5 - 26 keV [7]. The system is mounted on a radial mid plane port with 35CF opening on the Aditya tokamak (see Fig. 3). This geometry allows the detector to view 20 cm plasma cross-section around the center of plasma.

The ECR system [14] coupled with Aditya tokamak is having a 42 GHz, 0.5 MW configurations. Its pulse length for this experiment was kept ~ 70 - 100 ms and powers 130 - 150 kW, respectively. ECR power was launched from the low field side of the Aditya tokamak with 0.75 T toroidal field.

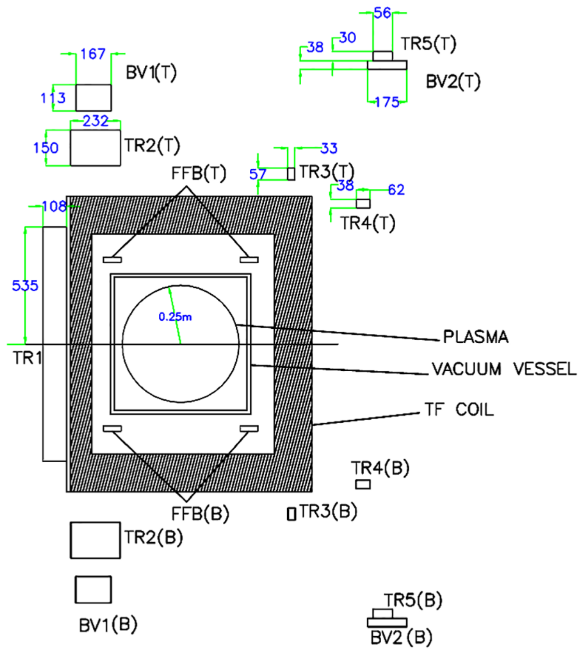

Fig. 2 Cross-section view of the Aditya tokamak. Coils TR1-TR5 are part of the OT connected in series, BV1 and BV2 are the vertical field coils and FF coils are the fast feedback coils.

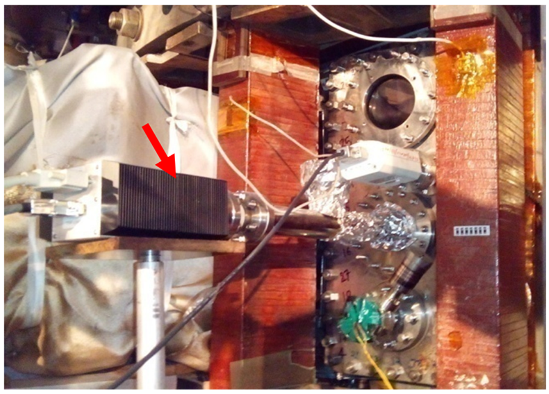

Fig. 3 SDD spectrometer coupled with the Aditya Tokamak by a 35CF connection on a radial mid plane.

3. Results and Discussion

The experiments were divided in to two sets. First set was to understand the NTE drift behavior under the vertical field and second set for the dependence of the collisions over NTE as a function of pre-filled pressure.

3.1 Effect of the vertical field

The first set of experiment was performed at fixed plasma and operational parameters and by altering applied vertical field. The result from two representative discharges 26953 (blue) and 28163 (red) are shown in Fig. 4. The time evolution of the plasma current (A), ECR power

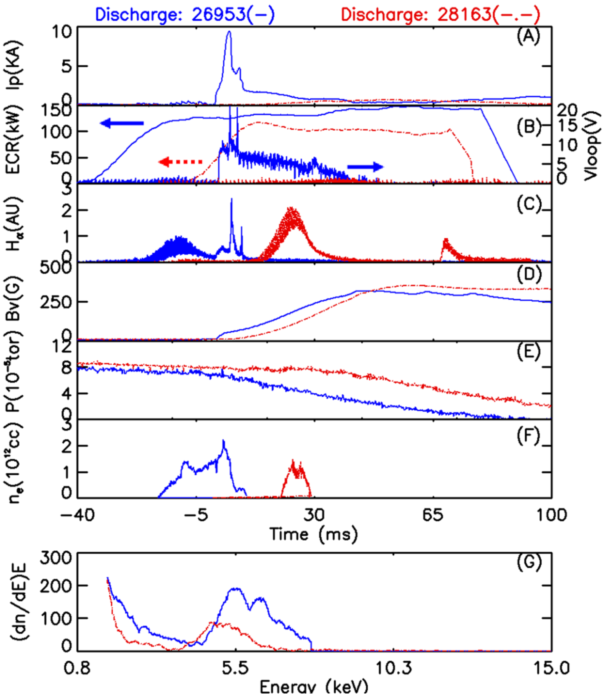

Fig. 4 The time evolution of the Plasma current (A) ECR power & loop voltage (B), H_α signal (C) applied vertical field (D), pre-filled pressure (E) , line averaged density (F) and time integrated NTE spectrum (G) for two Aditya discharges.

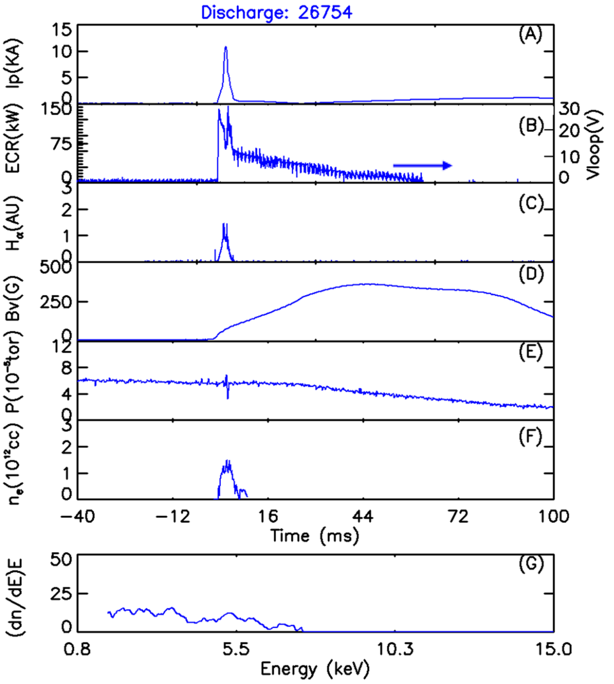

Fig. 5 The time evolution of the Plasma current (A) ECR power & loop voltage (B), H_α (C) applied vertical field (D), pre-filled pressure (E), line averaged density (F) and time integrated NTE spectrum (G) of pure Ohmic Aditya breakdown for discharges 26754.

& loop voltage (B), H_α signal (C), applied vertical field (D), pre-filled pressure (E), and line averaged electron density (F) are shown. The NTE spectra for the respective discharges integrated over the discharge life time are shown in Fig. 4 (G).

The ECR pulse was launched when the vertical field was almost zero for discharge 26953 (blue). The H_α signal for this discharge is low indicating less ionization within the tokamak. However, one can see that it has also a second peak, corresponding to the application of loop voltage. The affect of loop voltage on the generation of NTE is explained later. The X-ray spectrum shows a considerable line radiation sitting above the continuum (see Fig. 4 (G)), within the energy band of 5 - 7 keV for this discharge. This line radiation is mostly correlated with the stronger NTE and wall material interaction resulting from the particle drift. On the other hand the ECR power for discharge 28163 (red) launched at the ramping up phase of the vertical field. The H_α signal for this discharge has increased, almost twice from the 26953 (blue), indicating higher ionization with this vertical field configuration and offers a better plasma start-up condition. The NTE X-ray spectrum shape is also different for the discharge, 28163. The X-ray line radiation contribution within the X-ray spectrum is observed to be less prominent, pointing towards the change in the energy of the NTE reaching to the wall under the presence of vertical field.

To evaluate the possible contribute of loop voltage in the production of NTE during the breakdown phase data were collected from many discharges with plasma startup initiated by Ohmic power only without any ECR assisted pre-ionization. A typical Ohmic Aditya discharge 26754 is shown in Fig. 5. This discharge, as like of 26953, is having almost similar current and the vertical field at the time when H_α is peaked. The Loop voltage is also higher than the discharge 26953 (blue). The NTE spectrum for this discharge can be seen in the Fig. 5 (G). The spectrum do not exhibit any line radiation and the flux is also very less in comparison to the discharge 26953 (blue). Then, it can be inferred that ECR pulse becomes the dominant contributor to the generation of NTE as indicated by the strong X-ray spectrum as shown in Fig. 4 (G).

During tokamak breakdown phase, charged particle intensely drift vertically due to the error field in toroidal field, gradient and curvature drift under zero or the non application of appropriate vertical field. During the pre-ionization phase, equilibrium is mainly provided by the vertical field. In the presence of vertical field, the field lines are helical in nature which allows the particles flow toroidally [15], which reduces the loss of particles on the wall due to the drift [10, 16]. That is to say that vertical field acts as a compensatory field.

The X-ray spectrum, at higher vertical field, of the discharge 28163 (red) shows a shift in the line radiation peak. One can figure out that the centroid of the line radiation has shifted towards the lower energy side on the energy axis. This clearly shows that the energy carried by the NTE has reduced. This can be understood by following equation of electron velocity in Z direction and the connection length [7, 10].

$$v_z \cong -\frac{m\gamma(v_\parallel^2 + v_\perp^2/2)}{eRB_\varphi} + \frac{B_v}{B_\varphi}v_\parallel, \tag{1}$$

$$L = H\frac{B_\varphi}{B_V}. \tag{2}$$

Here $v_\parallel$ and $v_\perp$ denote parallel and perpendicular component of velocity to the field and γ is the relativistic factor. The first term represents the vertical drift due to the gradient and curvature in the B_φ. H is the particle drifted distance, which is equal to the minor radii of the vessel. Then to avoid the drifting of the particle along the vertical direction proper compensating vertical field is needed to be applied. However, in our experimental condition second term is dominating than the first term, as for example, for the electron having an energy of 3 keV and a pitch angle of 80 degree, the second term becomes $\sim 1 \times 10^5$ m/s while the first term $\sim -1.4 \times 10^4$ m/s for $R = 0.75$ m, $B_v = 100$ Gauss and $B_\varphi = 0.75$ T. It is basically over compensating situation due to the application of vertical field B_v of ~ 100 G. That is to say the experimental data shown here exhibit two discharges; one is without compensation and other is the case of over compensation. When B_v was not applied (discharge no - 26953) the magnitude of the vertical drift velocity was lower than that of during the over compensating case having shot no of 28163. In the over compensating case, the electron reaches the wall quickly without gaining much energy and they are therefore producing the X-ray spectrum having peak shifted towards relatively lower energy as reflected in the spectrum shown in Fig. 4 (G) in red colour. Increasing vertical field will reduce the connection length. It causes the particle drift quickly towards the wall. And therefore NTE is likely going to carry lower energy while interacting with the wall. Along with that the electron having $v_z = 0$ will be confined, gain energy and may convert to the runway electron and will not contribute in x-ray line radiation until they reach the wall, but predominantly contribute in continuum X-ray spectrum. This can be seen in the Fig. 5 (G), here characteristics peak is not considerably apparent but continuum radiation is present.

3.2 Effect of the pre-filled pressure

The effect of the collisions within the plasma over the NTE was investigated as a function of pre-filled pressure. The desired pre-filled pressure has been created for the hydrogen gas, by a piezoelectric valve, prior the ECR power applied into the Aditya tokamak.

The results from two representative discharges 28392 (red) and 29213 (blue) for these experiments are shown in the Fig. 6. Here, the discharge 28392 (red) and 29213 (blue) are operated with low and high pre-filled pressures, respectively, The ECR power, ~ 150 kW, was launched for

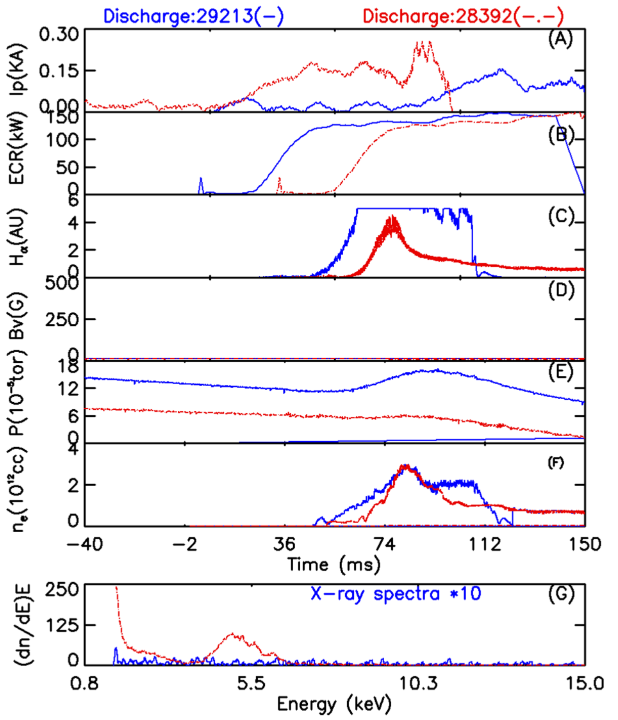

Fig. 6 The time evolution of the Plasma current (A) ECR power (B), H_α (C) applied vertical field (D), pre-filled pressure (E) , line averaged density (F) and time integrated NTE spectrum (G) for two Aditya discharges.

both of the discharges. During the experiment Ohmic power was switched off and vertical fields were kept zero as shown in Fig. 6 (D). Both discharges are having similar plasma current as shown in Fig. 6 (A).The H_α signal for the discharges with low pressure 28392 (red) shows lower signal. The high pre-filled pressure discharge 29213 (blue) exhibiting higher H_α signal, which is almost saturating for most of the discharge life time is indicative of improved ionization for this discharge.

The line radiation shown in Fig. 6 (G) (blue in color), indicative of interaction of NTE and wall, has completely disappeared and the total X-ray counts have also reduced in comparison from the low pressure discharge. Peak electron densities are similar in both cases although H_α signal is lower in low pre-filled pressure discharge. This might be related to the contribution of electrons coming from higher amount of impurities entering into the plasma because of higher NTE-wall interaction in the low pressure discharges.

The high pre-filled pressure offer higher neutral density which is directly affects the electron–neutral collision frequency, ν_{en}, given by equation 3 [16, 17], where σ_{en} (T_e), effective electron–neutral scattering cross section given by equation 4 n_n is the neutral density and T_e is electron temperature.

$$\nu_{en} = \sigma_{en}(T_e)n_n\sqrt{\frac{eT_e}{m_e}}, \tag{3}$$

$$\sigma_{\mathrm{en}} = 6.6 \times 10^{-1} \left[\frac{\left(\frac{T_{\mathrm{e}}}{4} - 0.1 \right)}{\left(1 + \left(\frac{T_{\mathrm{e}}}{4} \right)^{1.6} \right)} \right]. \quad (4)$$

The loss time are defined as follows

$$\tau = \frac{d}{v_{\mathrm{z}}}. \quad (5)$$

Where d is the half height of the vacuum vessel, v_{z} is the drift velocity as defined in the first term of the equation no. 1 since B_{v} was not applied. For 10 eV electrons, i.e., one can say thermal electron in ECR produced pre-ionization plasma; typical life time becomes ~ 5 ms, which is one order higher than the electron-neutral collision times. Estimated collision times are 34 and 103 μs for the discharge with high and low pressures, respectively. However in the case of ECR produced non thermal electron having T_{e} of 3 keV, the life time reduces to ~ 50 μs, which is comparable to the electron-neutral collision time (~ 60 μs) at higher fill pressure, on the other hand, electron neutral collision times becomes ~ 170 μs in the case lower fill pressure case. That is why NTE losses its energy in higher pressure case before reaching the wall and did not produced any significant X-ray photon which is apparent from the Fig. 6 (G) (in blue color & solid line). Whereas NTE did not suffer any energy losses due to collision in lower pressure case and produces prominent X-ray spectrum as shown in the Fig. 6 (G) with red color and dotted dash line. Thus the weak X-ray spectrum and disappearance of the line radiation from the X-ray spectrum for discharge 29213 (blue) is most likely attributed to the increase in the collision frequency at high pre-filled pressure suggesting the reduction of the NTE.

4. Summary

To understand the behavior of the NTE during the ECR pre-ionization assisted startup in the Aditya tokamak X-ray spectrum were recorded by SDD based spectroscopic system. It was seen that with the increase in the vertical field and the pre-filled pressure the energy of NTE reaching to the wall is reduced as indicated by the X-ray spectrum and the improvement of ionization is occurred. With the application of vertical field energy carried by the NTE is reduced due to higher vertical drift velocity enabling the electron to reach the wall quickly without gaining much energy in comparison to the case in which the vertical field is not applied In high pre-filled pressure, NTE is suppressed due to the higher electron-neutral collision frequency.

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