ON ANALYSIS OF CHARGE EXCHANGE NEUTRAL PARTICLE ANALYZER MEASUREMENTS IN THE ADITYA TOKAMAK

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ABSTRACT

Core-ion temperature, T_{i0}, measurements have routinely been carried out by the energy analysis of passive Charge Exchange (CX) neutrals escaping out of the ADITYA-tokamak (R/a=75cm/25cm) plasma using a 45° parallel plate electrostatic energy analyzer. The temporal evolutions of peak ion temperature in the core regime typically found to be T_{i0}~80 eV to 150 eV as estimated by analyzing the energetic CX-neutral counts obtained on four energy cannels using *Channeltrons* of multi-channel data acquisition system for circular limiter *ohmically* heated plasma discharges. The maximum error in the T_{i0} measurements comes out to be $\Delta T_{i0}/T_{i0}\sim 0.25$. Ratio of ion temperature to the electron temperature (Ti/Te) is found to be in the range of~0.3 to 0.4 for set of plasma discharges investigated herein. Several plasma discharges having similar plasma parameters are investigated for the Aditya tokamak, which provides an estimate for the neutral hydrogen (H^0) density in the core regime and its evolution with time. Effect of Ion cyclotron radio frequency heating (ICRH) on T_{i0} is observed and reported here, which shows additional increase of T_{i0} by ~50 to 60 % (maximum) for the set of plasma discharges investigated herein. Experimental observations of the CX-neutral counts at each energy channels are compared with the calculated CX-neutral energy spectrum using a simple slab model. Using the modelling results, local energy loss rate profile for the CX-particle flux leaking out of plasma has also been reported and compared with total CX-neutral power loss from the plasma based on experimental results. Temporal evolution of the total CX-power loss from the tokamak plasma during current flattop is also estimated and typically found to be around 3% of input ohmic power.

1. INTRODUCTION

The flux of fast neutral atoms emitted by the plasma in tokamak machines reveals useful information about the ion component of the plasma. It makes possible the measurements of core-ion temperature (T_{i0}) and the density of neutral atoms (n^0) in plasma. Thus the role of fast atoms in the plasma energy balance and information on the presence and drift of trapped particles can be realized.

The neutral atom density estimations in plasma usually involves rigorous numerical calculations correlating the magnitude and spectrum of the emitted flux of atoms along with the density distribution of charged and neutral particles, their reaction cross-sections, with the temperature distribution of ions and electrons in the plasma, as well as with the magnitude of the atomic flux entering into the plasma volume [1].

In the present work, however, an estimate of the neutral atom density in the centre has been done based on the experimental observations of passive charge exchange (CX) neutral particle analyzer (NPA). The NPA provides time and energy (E_H^0) resolved CX-neutral counts. By taking the reasonable assumption that sufficiently high energetic atoms ($E_H^0 >> T_{i0}$) are only emitted and contributed by the central region of the observed line of sight (this is justified by taking the neutral counts in region where the energies of CX-neutrals detected by the NPA channel is $\geq 3\ T_{i0}$), while the outer layers of the chord only has the role of attenuating this flux because of various ionization and charge exchange processes reducing their mean free path $\lambda_{cx} \leq a$ (plasma minor radius) by eq.(1).

$$\lambda_{cx} = \frac{1}{n_e \sum_N \sigma_N(E)} \quad (1)$$

Where, n_e is the plasma density and σ_N is the various reaction cross-sections responsible for the attenuation of CX-neutrals.

Scope of the present paper is to provide direct approach to estimate various quantities associated with the CX-neutrals by analyzing CX-NPA measurements. The paper is arranged in the following way, in Section-2 parameters of the ADITYA tokamak and analysis of experimental data for estimation of neutral hydrogen density ($n_H^0(0)$) in core-regime are described. Section-3 covers CX-NPA specifications, experimental observations for the typical plasma discharges, method for the analysis of energy resolved CX-Neutral counts and estimation of core-ion temperature, comparison of electron and ion temperature as well as their typical ratio, estimation of $n_H^0(0)$. Effect on core ion-temperature during application of ion cyclotron radio frequency heating (ICRH) is reported in Section-4. In Section-5, using simple slab model, CX-neutral energy spectrum is calculated and compared with the experimental observations. Temporal evolution of total CX-neutral power loss is also estimated in this section and compared with the power loss predicted by the modelling results and then the article is summarized.

2. ESTIMATION OF CORE NEUTRAL HYDROGEN ATOM DENSITY

Core Ion temperature of hydrogen plasma has been estimated on the ADITYA tokamak using 45° parallel plate electrostatic analyzer with hydrogen gas cell configuration to ionize the fast charge exchange neutrals escaping out of the magnetic confinement. The detailed system description of the NPA deployed on the ADITYA tokamak has been reported in earlier work [2, 3]. Typical machine parameters of the ADITYA tokamak are listed in Table-1. The fast charge exchange neutral counts, as obtained on four energy channels of charge exchange neutral particle Analyzer (CX-NPA), gives a measurement of the highest ion temperature along the line of sight of analyzer situated at radial port 10 of the tokamak. With the values of the core ion temperature estimated for several ohmic plasma discharges, attempted have been made to get information on core neutral hydrogen density n_H^0 and its evolution with the time of plasma discharges.

Table-1: *Typical machine and plasma parameters of the ADITYA tokamak*

Machine and plasma parameters	Values
Major radius (R)	75 cm
Minor radius (a)	25 cm
Number of toroidal coils	20
Toroidal magnetic field at R	0.75-0.80 Tesla
Plasma Current (I_p)	70-150 kA
Central plasma density (n_{e0})	1E+13 to 3E+13 cm^{-3}
Edge electron density (n_{ea})	1E+12 to 2E+12 cm^{-3}
Core electron temperature (T_{e0})	200 to 700 eV
Edge electron temperature (T_{ea})	5 to 20 eV
Core ion temperature (T_{i0})	~80 eV to 250 eV
Edge ion temperature (T_{ia})	5-10 eV
q* (cylindrical q)	~2 to 3.5
Z_{eff}	~2 to 4
Density spatial profile shaping power factor (α_n)	1.00 to 1.25
Temperature spatial profile shaping power factor (α_T)	1.50 to 1.75
Plasma discharge duration	80 ms to 200 ms
Plasma discharge gas	Hydrogen

The number of counts recorded at the exit of the analyzer corresponding to the energy E of ions can be given by eq. (2)

$$C(E) = \frac{\Omega}{4\pi} \eta_s \eta_t \eta_c N(E) \Delta E \Delta t \quad (2)$$

Where, Δt is the interval over which counts are collected, Ω is the solid angle subtended by the stripping gas cell at the plasma centre, η_s is the stripping cell efficiency, η_t is the net transmission efficiency of NPA-system, η_c is the detection efficiency of the CEMs, ΔE is the energy resolution of the analyzer and N (E).ΔE is the number of neutrals in the energy range E and E+ΔE emitted per second from the plasma volume ΔV sampled by the analyzer given by eq. (3)

$$N(E) = \Delta V n_0 n_+ f \sigma_{cx} v \tag{3}$$

Where n_0 and n_+ are the neutral and ion densities respectively, σ_{cx} is the cross-section for charge exchange reaction at ion energy E, *v* is the relative velocity between neutrals and ion undergoing charge exchange and *f(E)* is the Maxwellian energy distribution plasma ion given by eq.(4):

$$f(E) = \frac{2}{T}\sqrt{\frac{E}{\pi T_i}}\exp\left(-\frac{E}{T_i}\right) \tag{4}$$

T_i being the ion temperature, substituting eq.(3) and (4) in eq.(2), one can get the expression for the counts CX neutral counts C(E) detected by NPA at a channel with energy E as eq.(5):

$$C(E) = \frac{\Omega}{4\pi}\Delta \mathrm{V}\, \eta_s \eta_t \eta_c n_0 n_+ \frac{2}{T_i}\sqrt{\frac{E}{\pi T_i}}\exp\left(-\frac{E}{T_i}\right)\Delta E\, \sigma_{cx} v \Delta t \tag{5}$$

Factoring out the energy dependent terms one can get,

$$\ln F = \ln K - \frac{E}{T_i} \tag{6}$$

Where,

$$F = \frac{C(E)}{\eta_s \sigma_{cx} v \sqrt{E}\,\Delta E} \tag{7a}$$

$$K = \frac{\Omega}{4\pi}\Delta \mathrm{V}\, \eta_s \eta_t \eta_c n_0 n_+ \frac{2}{T_i}\sqrt{\frac{1}{\pi T_i}}\Delta t \tag{7b}$$

Therefore by knowing the energy dependent quantities in F (i.e. η_s, $<\sigma_{cx}v>$, ΔE and C(E) at different E) one can obtain the inverse of the slope given by the eq.(6), as an estimate of the ion temperature (T_i). For a given temperature (T_{i0}) value and known energies of calibrated channels (E), one can have the values of $n_H{}^0$ (using other experimentally known parameters involved in the term K) given by eq. (8):

$$n_{H^0} = \frac{F(E)}{\frac{\Omega}{4\pi}\Delta \mathrm{V}\, \eta_s \eta_t \eta_c n_{H^+} \frac{2}{T_i}\sqrt{\frac{1}{\pi T_i}}\exp\left(-\frac{E}{T_i}\right)\Delta t} \tag{8}$$

In next section, based on experimental parameters, T_{i0} and $n_H{}^0$ are estimated.

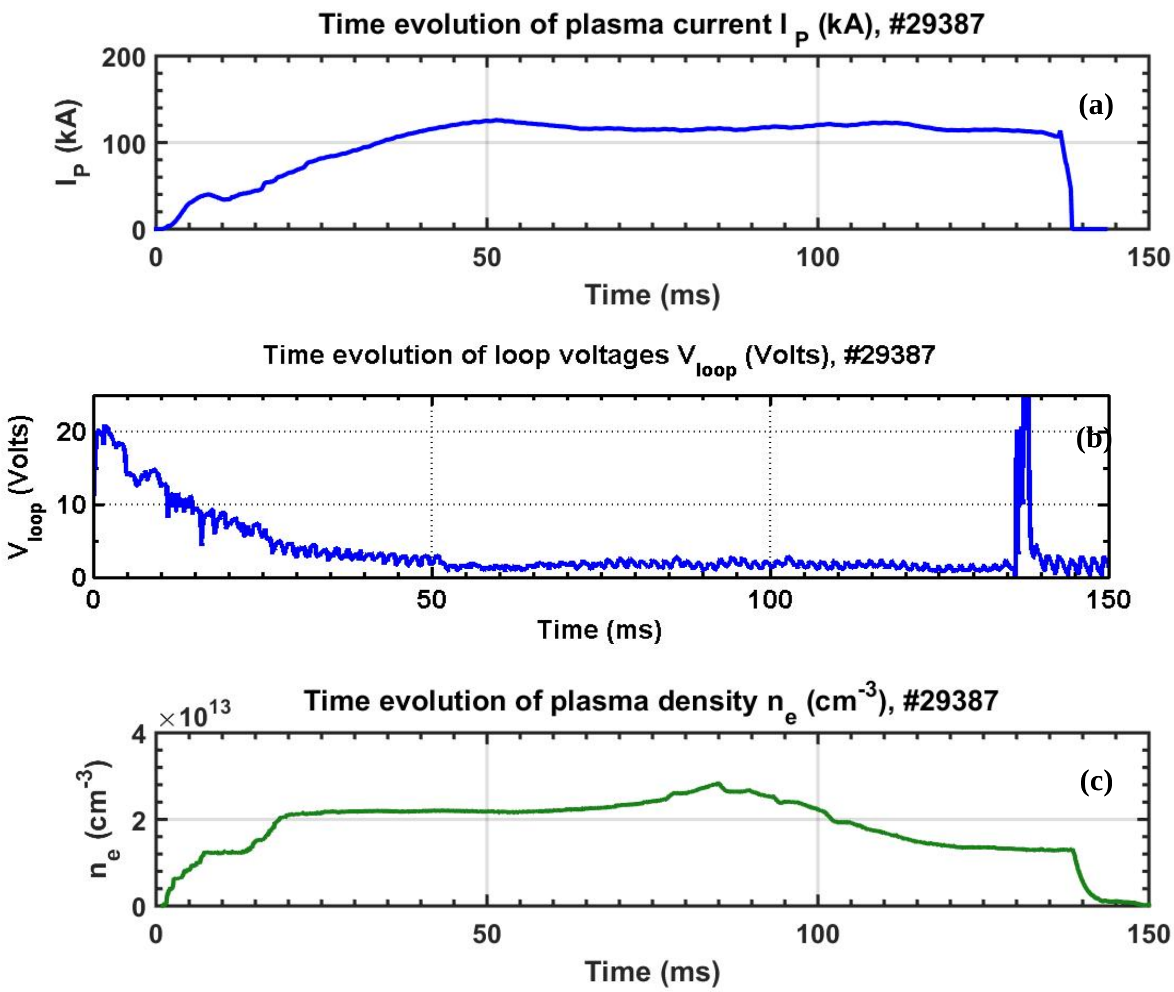
3. ION TEMPERATURE MEASUREMENTS AND ESTIMATION OF NEUTRAL HYDROGEN DENSITY

The core ion temperature of plasma in the absence of auxiliary heating has been estimated for several plasma discharges of the ADITYA tokamak using CX-NPA. Technical specification of the CX-NPA is given in Table-2. It is observed that the ion temperature in the core region consistently remains 80 eV to 150 eV for most of the ohmic plasma discharges in the ADITYA.

Table-2: *Specification of CX-NPA for the ADITYA tokamak* [2, 3]

CX-NPA specification / technical parameters	**Values**
Analyzer type	45° Electrostatic Energy Analyzer
Static retarding electric field	5 to 15 kV/m
Number of energy channels	4
Detector	Channel Electron Multiplier (CEM)
Energy detection range E_{min} to E_{max}	100 eV to 3000 eV
Energy resolution ΔE/E	10% to 50%
Time resolution of DAQ system $\mathbf{\Delta t}_{NPA}$ (sampling time)	10 ms
Mode of operation	Counting mode
Type of gas in gas-cell for stripping reaction	Hydrogen
DAQ	Stand alone

A representative plasma discharge #29387 of the ADITYA tokamak is shown in Fig.1 where temporal evolutions of various plasma parameters are depicted.



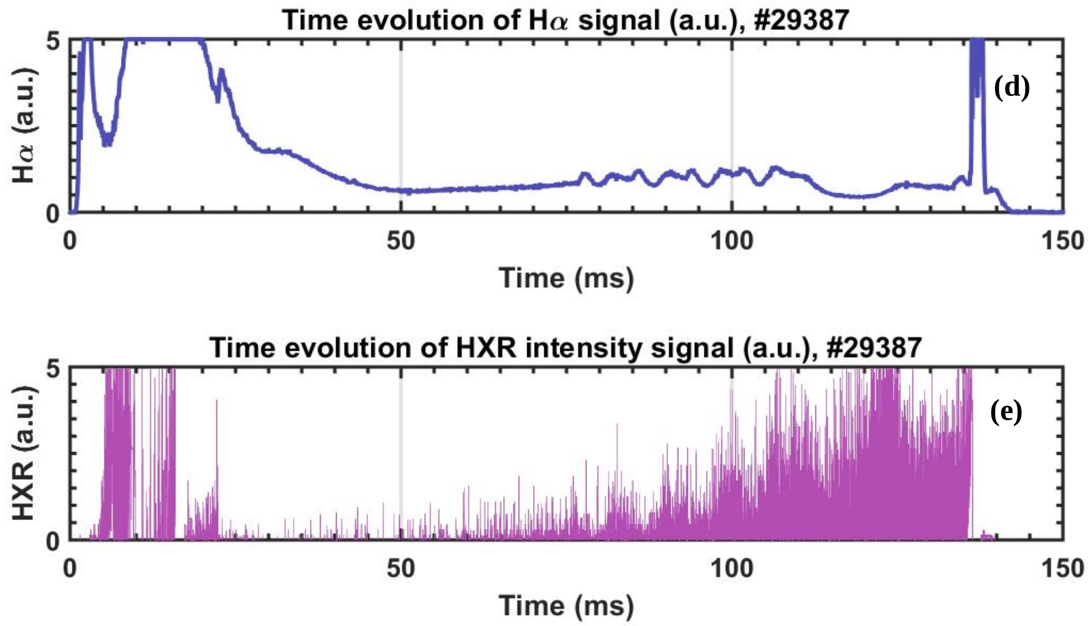


Figure-1: Time evolution of various plasma parameters for Plasma Shot#29387: (a) Plasma current (b) loop voltage (c) density (d) Ha intensity (e) Hard X-ray intensity

Time evolution of CX-Counts recorded by the NPA on 4 energy channels during the plasma discharge #29387 is shown in Fig.2 (a) and estimation of temperature is shown in Fig.2 (b) by least square fitting on 4 channel data points. Sources of error in the measured core ion temperature are the energy resolution of the channels, stripping cell pressure variations, statistical error in registering the counts etc. [2].

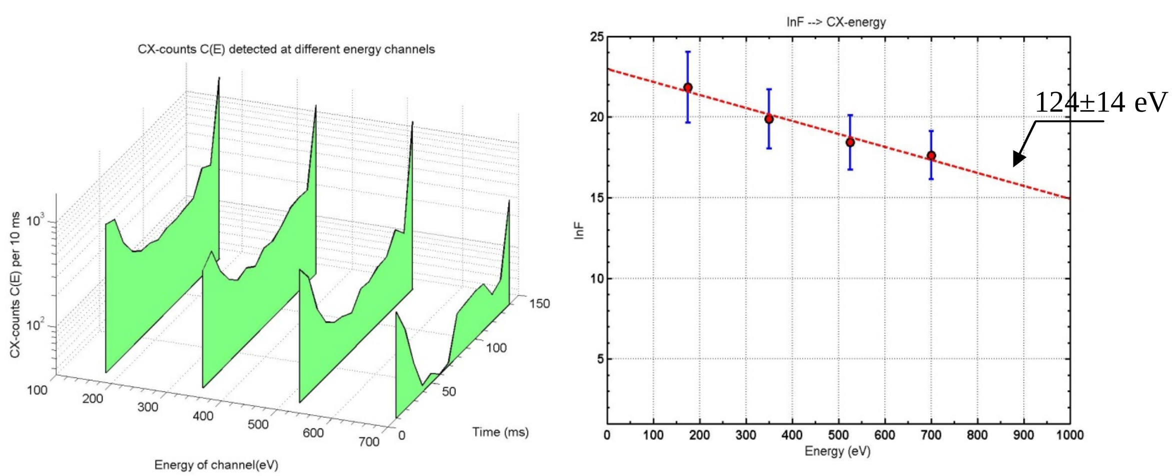


Figure-2: (a) Plot shows CX-neutrals counts at 4 different energy channels with time and (b) Plot of lnF vs. Energy for Plasma Shot#29387 at time t=100ms

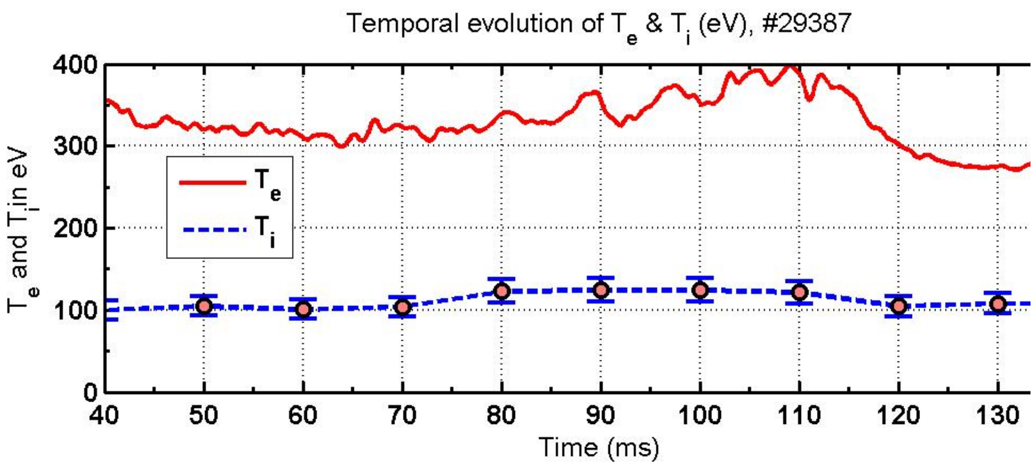


Figure-3: Temporal evolution of temporal evolution of core-ion temperature T_{i0} and T_{e0} for Plasma Shot#29387 during plasma current flattop

Temporal evolution of T_{i0} is presented in Fig.3 along with temporal evolution of electron temperature (T_{e0}). Here the T_{e0} measurements are carried out using double foil ratio method. Likewise various plasma discharges were analyzed having similar plasma parameters in which auxiliary heating was absent. It has been found that during plasma current flattop, ion temperature remains typically in the range ~80eV to 150 eV for the set of plasma discharges analyzed.

The cold atom densities of ohmic plasmas can be obtained from the charge-exchange NPA measurement analysis [1]. The evaluation of core neutral density in the central region of the observed plasma column for the ADITYA tokamak, as estimated on the basis of the fast charge exchange spectrum observed at CX-NPA channels and using eq.(8). Fig.6 (a) depicted a representative shot where temporal evolution of core-neutral density is evaluated. Fig.6 (b) shows histogram of neutral density of core regime estimated for of 23 plasma discharges having similar plasma parameters. It can be concluded that n_H^0 (0) ranges between ~$8x10^7$ to $5x10^8$ cm^{-3}. This value is greater in several orders of magnitude than the value of $n_H^0(0)$ which is expected by considering the known atomic flux entering the plasma column and the penetration of such atoms to the core region with the accountability of the ionization and charge exchange processes taking place [4]. However, the n_H^0 (0) density estimated here are in close agreement with experimental investigation made before in the ADITYA tokamak using spectroscopic observations of H-alpha line [5].

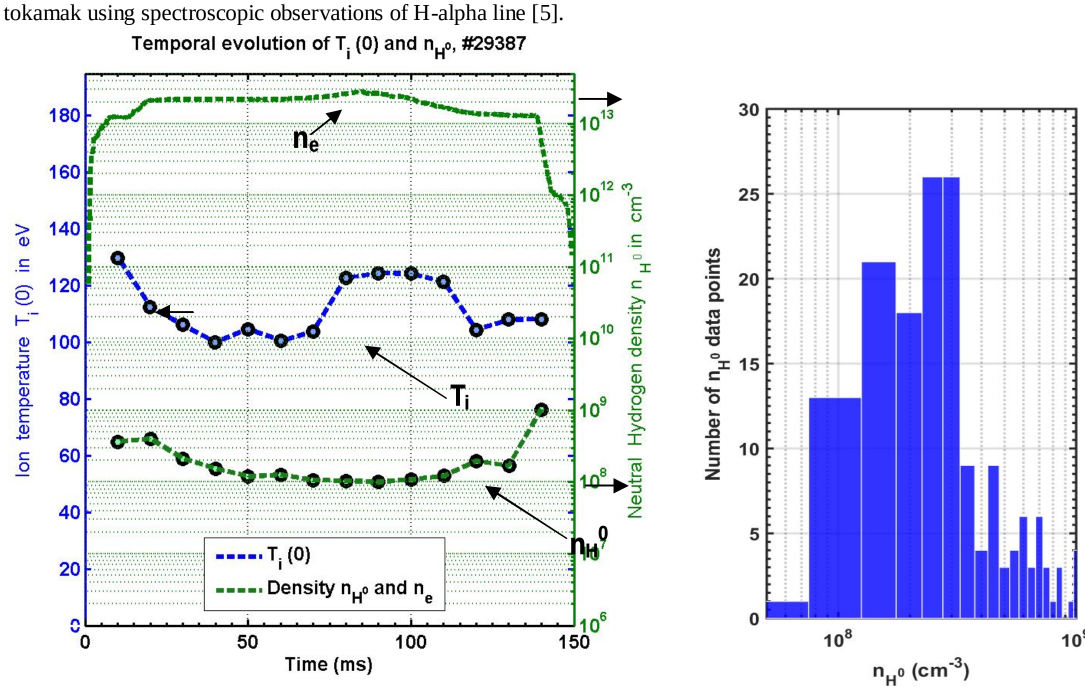


Figure-6: (a) Temporal evolution of neutral density in core regime for representative plasma discharge #29387 and (b) histogram of core hydrogen neutral density data points for 23 similar plasma discharges having Ip~80±10kA

4. EFFECT ON ION TEMPERATURE DURING ICRH HEATING

The CX-NPA system has recorded time and energy resolved fast CX-neutral counts for several discharges when ICRH auxiliary heating was operational and in several plasma discharges effective rise in T_i was observed just after the application of ICRH pulse and continue to rise during the pulse. A representative two discharges with and without ICRH pulse are presented in Fig.7.

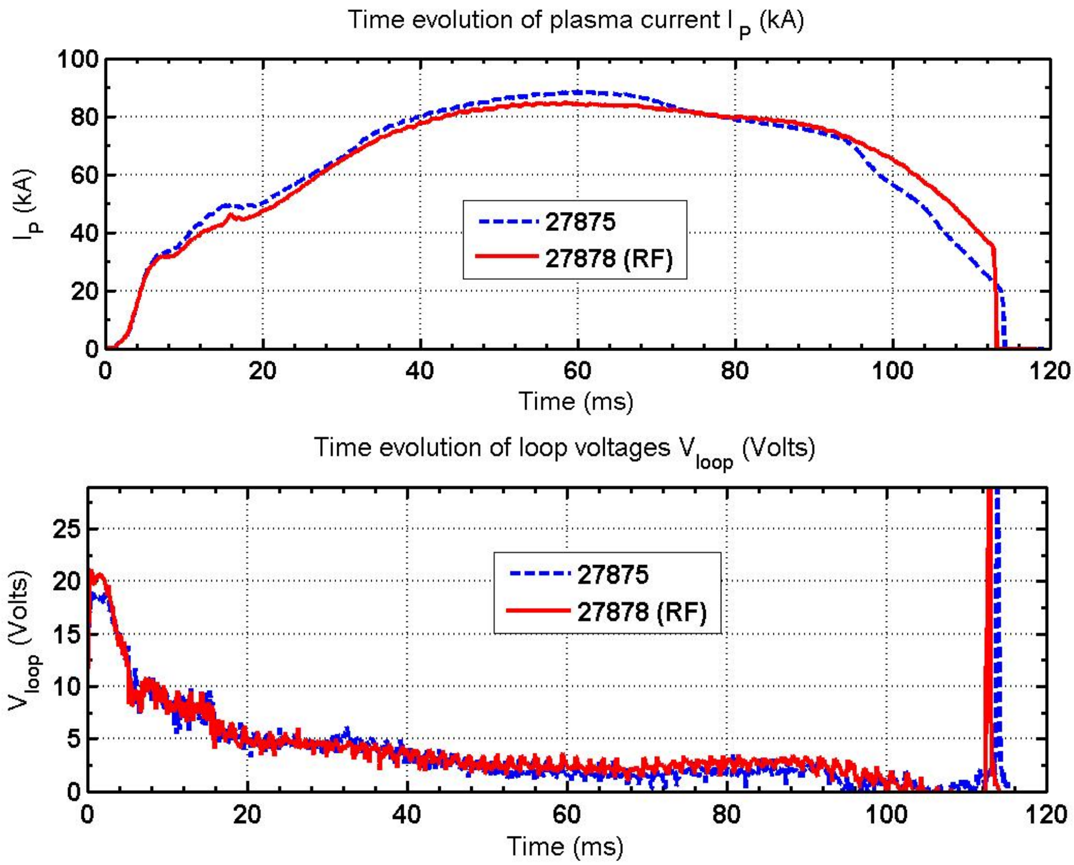


Figure-7: (a) Temporal evolution of plasma current profiles and its comparison for the discharge #27875 and #27878 (RF)

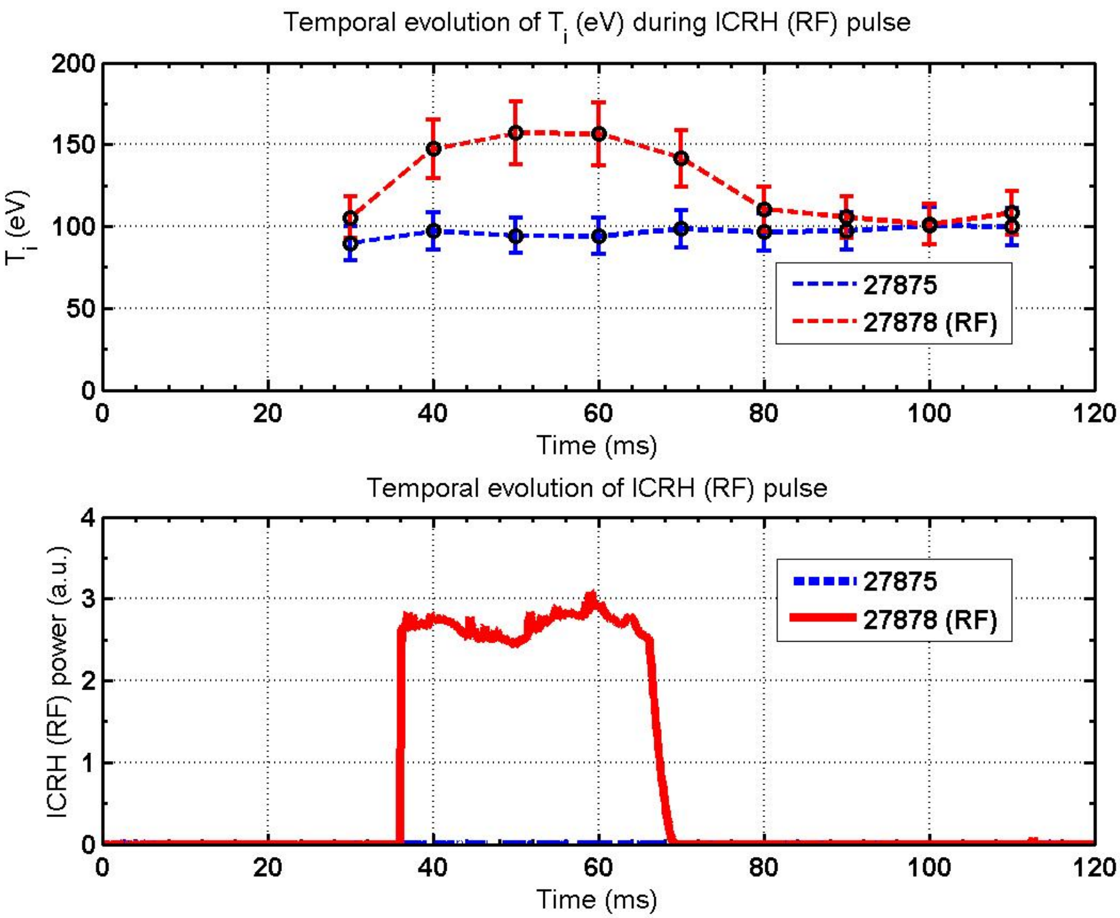


Figure-7: (b) temporal evolution of Ti0 with and without ICRH heating and (d) Temporal profile of ICRH pulse showing after application of ICRH pulse, plasma ion temperature is increased.

CONCLUSIONS & SUMMARY

Several plasma discharges, having similar plasma parameters are investigated for the Aditya tokamak and various parameters associated with CX-neutrals generation & dynamics were estimated by quick analysis of CX-NPA measurements. Core-ion temperature estimated in the range of 80 eV to 150 eV and compared with the electron temperature. The ratio T_{i0}/T_{e0} is found to be ~ 30% to 40%. Neutral hydrogen density found of the order of 10^8 to 10^9 in the core regime and its evolution with time. Effect of Ion cyclotron radio frequency heating (ICRH) on T_{i0} is observed and reported here, which shows increase of ΔT_{i0} by ~ 50 to 100 eV after application of ICRH pulse. Experimental observations of the CX-neutral counts at each energy channels are compared with calculated counts by means of simple slab model. Using the modeling results, local energy loss profile for CX-particle flux leaking out of plasma has also been reported and compared with total CX-neutral power loss from the plasma based on experimental results. The total CX-power loss found to be in the range of ~1 to 3% of input ohmic power which is negligible compare to the other power loss channels i.e. radiation power loss and power loss due to the limiter-plasma surface interaction in case of the ADITYA tokamak.

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REFERENCES

[1]. Hiroshi Takeeuchi, Teruaki Shoji, Akimasa Funahashi and Koki Takahashi, *"Study on Proton Behavior in JFT-2 Tokamak from analyses of Charge-Exchanged fast atoms*", Journal of the physical society of Japan, Vol. 44, No. 4, April 1978, p1363.

[2]. Santosh P. Pandya, Kumar Ajay, Priyanka Mishra, Rajani D. Dhingra and J. Govindarajan, *"Core-Ion Temperature Measurement using Passive Charge Exchange Neutral Particle Energy Analyzer for the ADITYA tokamak"*, Review of Scientific Instrument, Vol. 84, Issue 2, p023503, (2013).

[3]. T. A. Santosh Kumar, L. M. Awasthi, Chavda Chhaya, H. D. Pujara, B. N. Buch, H. R. Prabhakara and S. K. Mattoo, "*ADITYA Charge Exchange Diagnostics*", Technical Report: Aditya Charge Exchange Diagnostics, Institute for Plasma Research Library, IPR/TR-56/96, February 1996.

[4]. M. P. J. Gaudrean, A.I. Kislyakov, Yu. A. Sokolov, "*Investigation of fast-atom fluxes in the high-density plasma in Alcator*", Nuclear Fusion Vol.18, No.12 (1978)-letters, p1725.

[5]. Santanu Banerjee, J. Ghosh, R. Manchanda, R. Dey, N. Ramasubramanian, M.B. Chowdhuri, Ketan M. Patel, Vinay Kumar, P. Vasu, P. K. Chattopadhyay, P.K. Atrey and Aditya Team, *"Observations of Hα emission profiles in Aditya tokamak"*, J. Plasma Fusion Res. SERIES, Vol. 9 (2010).