

## Runaway electrons in the SINP tokamak

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**Abstract.** The experimental determination of the dependence of confinement time of runaways on various discharge parameters has been presented along with the angular distribution of hard X-rays (HXrays) emitted from the torus in presence and absence of Langmuir probes.

**Keywords.** SINP tokamak; runaway; confinement time; hard X-rays.

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### 1. Introduction

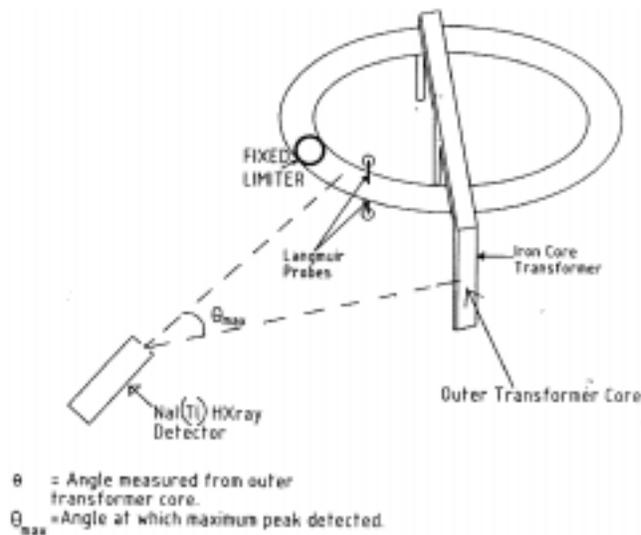
The highly energised runaway electrons ( $W > 100$  keV) is practically inevitable in the presence of an electric field. In tokamak discharges, these, on one hand, are a source of concern causing damages to the limiter and torus walls [1] whereas, on the other hand, it can be used as a diagnostic tool to determine the properties of a non-collisional plasma [2]. The analysis of the effect of various tokamak discharge parameters on the runaways, thus, becomes important.

In the past, theories have been put forward regarding the generation and acceleration of runaway electrons [3]. Efforts have also been made to calculate the production rate of runaways. In lieu of this fact, various forms of the velocity distribution were considered and the flux expression was obtained upto a certain multiplicative constant [4–7]. Kulsrud *et al* [7] in fact solved the Fokker–Planck equation numerically and compared it with the previous results.

The presence of runaways can be detected by measurement of the synchrotron radiation [2,8], cyclotron radiation [9] and hard X-ray measurement [10–12].

The runaway electrons have been studied in the start-up phase [12–14], as well as in the steady phase [15–17]. We have confined ourselves here to the initial rise phase of the discharge mainly because the runaway electrons find the initial low density ( $n_e$ ) and large applied toroidal electric field ( $E_T = V_{loop}/2\pi R$ ), where  $R$  is the major radius, favourable for their production, and the runaway dynamics in the initial start up phase also influences the bulk discharge behaviour [13].

In this paper we report some of the investigations that have been carried out to determine the parametric dependence, viz., toroidal magnetic field ( $\mathbf{B}_T$ ), toroidal electric field ( $\mathbf{E}_T$ ), vertical magnetic field ( $B_v$ ) and minor radius ( $a$ ) on the evolution of ‘RUNAWAY ELECTRONS’ in the SINP tokamak.



**Figure 1.** Detector setup for angular distribution measurement of HXRays.

We then give a plausible explanation of the results in comparison with theoretical predictions and finally give our conclusions.

## 2. Experimental setup

The experiments were carried out in the SINP tokamak [18] by varying the toroidal electric field ( $E_T$ ) between 10.2 V/m to 45.9 V/m, the toroidal magnetic field ( $B_T$ ) from 0.264 Tesla to 0.62 Tesla. The minor radius has been varied from 4.5 cms to 7.5 cms by moving the two vertically placed movable limiters  $180^\circ$  away from the fixed limiter in the toroidal direction. The vertical magnetic field ( $B_v$ ) is varied from 0 Tesla to 0.027 Tesla. The filling pressure has been kept at  $2 \times 10^{-4}$  Torr and  $3.5 \times 10^{-4}$  Torr.

It is a well known fact that when high energy electrons hit a metal target HXRays are emitted. These emitted HXRays gives one a knowledge of the energy of the impinging electrons. Scintillation detector is commonly used to monitor these HXRays. We have mainly performed an analysis of the runaways present in a discharge with the help of the HXRray detector unit. The detector system of the SINP tokamak [19] consists of a NaI(Tl) scintillator placed at the front end of a lead shielded photo-multiplier tube. The detector was calibrated with standard sources such as  $^{57}\text{Co}$  and  $^{133}\text{Ba}$ , as well as X-ray tube, and was found to register X-ray with energies in the range 3 to 150 keV.

Figure 1 shows the exact position of the NaI(Tl) scintillator detector of the SINP tokamak, used for detecting the hard Xrays emitted. This setup also shows the angular base considered for locating the position of maximum detection. The fixed limiter in the SINP tokamak and the Langmuir probes were placed 11 cms apart in the toroidal direction. As seen from figure 3, the maximum in the angular distribution of the hard X-rays is seen within a cone of  $5^\circ$  of the fixed limiter with respect to the detector, i.e., 15 cms in

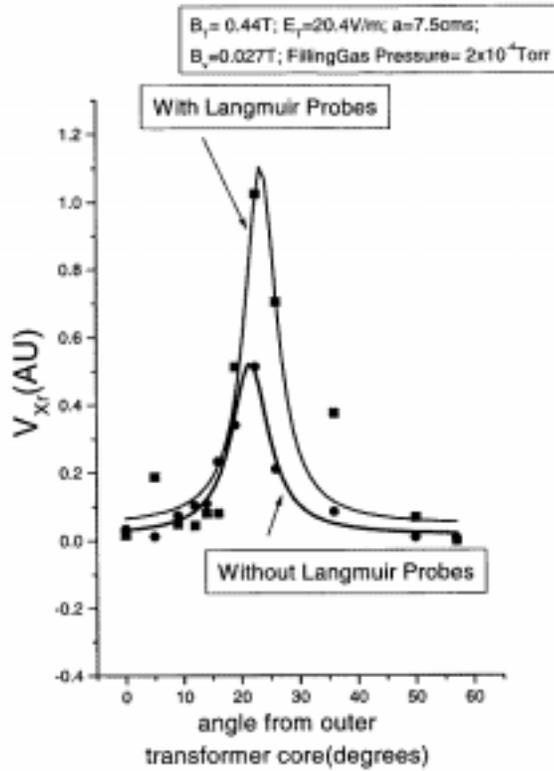


Figure 2. Angular distribution of the HXray detected.

the toroidal direction on either side of the fixed limiter. We felt that the Langmuir probes could also have acted as a target for the runaway electrons. Hence we performed the angular scan once more in the absence of the probes. The decrease in HXray detected intensity by approximately a factor of two (figure 2) confirmed the fact that the probes did act as a target.

In addition to this we have used the loop voltage coil and Rogowskii coil to measure  $E_T$  and the total plasma current respectively. We had also placed two sets of three Langmuir probes each at minor radius = 6.5, 7.0 and 7.5 cms respectively which measured the edge electron density and floating potential.

### 3. Observations and discussions

Figure 3 shows a typical plasma discharge of the SINP tokamak during the rise phase. In this figure, the loop voltage ( $V_{loop}$ ), the total plasma current ( $I_p$ ) and the HXray intensity ( $V_{Xr}$ ) detected is depicted. In this figure,  $I_p$  has been shown till the point it has reached the maximum current value. The HXray signal is seen to rise to a maximum value in about

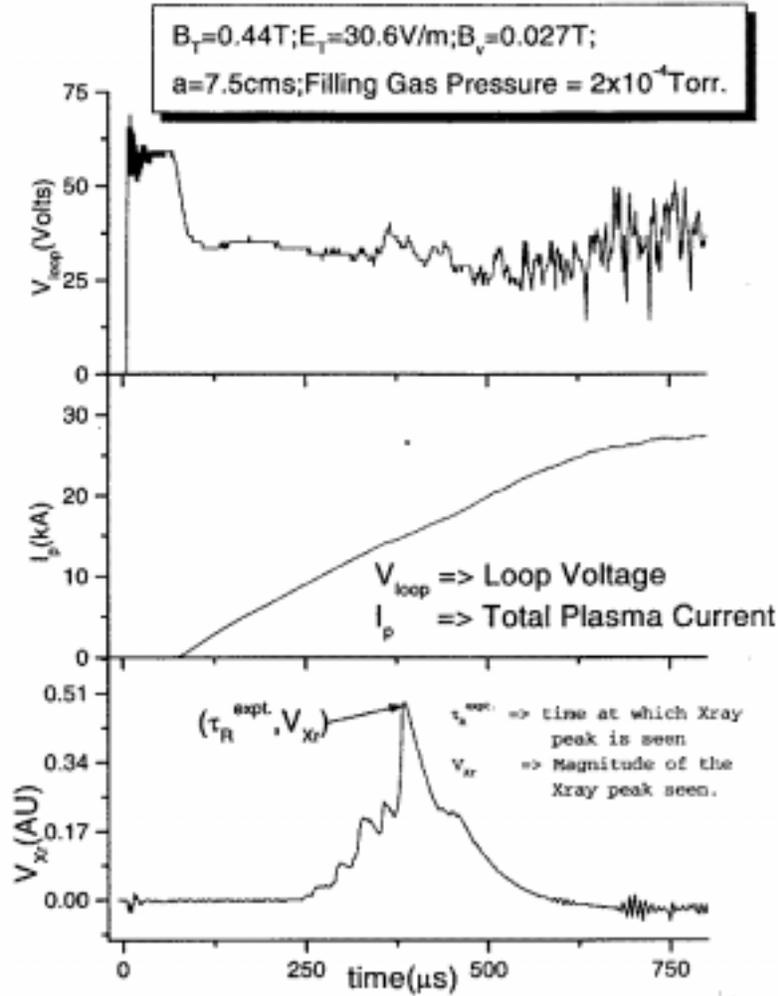
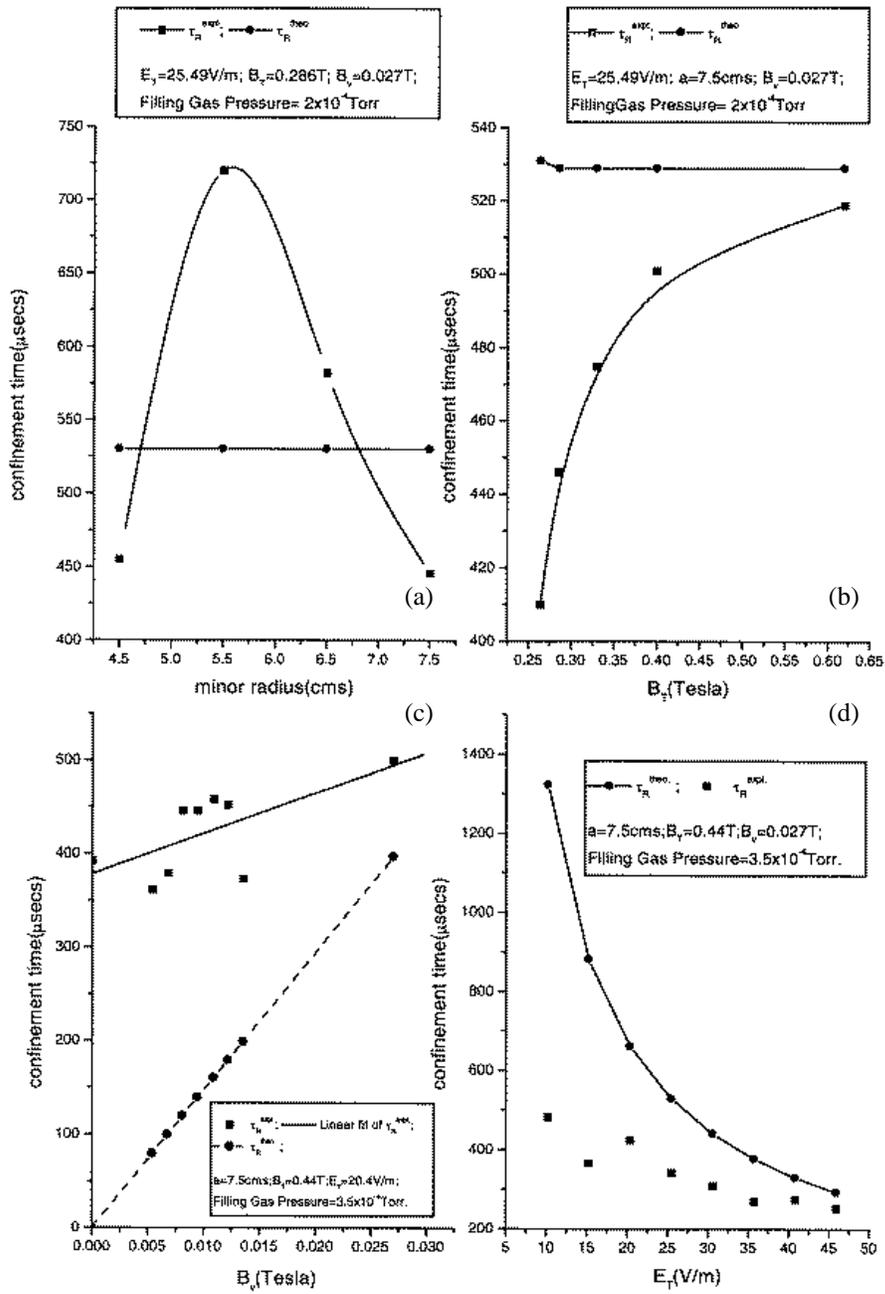


Figure 3. Typical plasma discharge in the SINP tokamak.

125  $\mu$ secs. The signal is seen to decrease thereafter. No X-ray signal are detected in the later phases. The experimental confinement time ( $\tau_R^{\text{expt.}}$ ) has been considered as the time where the HXray signal has reached its peak from the start of the discharge.

In figure 4a the experimental confinement time is seen to have a peak when the minor radius is 5.5 cms. In figure 4b, we see that  $\tau_R^{\text{expt.}}$  is seen to increase with  $B_T$  and tends to saturate at higher values of  $B_T$ . Figure 4c gives the variation of  $\tau_R^{\text{expt.}}$  with  $B_v$  wherein it is seen that the experimental confinement time is linearly increasing with time. Figure 4d gives an inverse variation of  $\tau_R$  with  $E_T$ .

The theoretical confinement time of runaways is given as [14,20]:



**Figure 4.** Comparison of theoretical and experimental results: (a) on variation of minor radius; (b) on variation of toroidal magnetic field; (c) on variation of vertical magnetic field and (d) on variation of applied electric field.

$$\tau_R^{\text{theo}} = \frac{B_v R}{E_T}. \quad (3.1)$$

This expression indicates no dependence of minor radius or  $B_T$  on the confinement time which is quite contrary to what is seen in figures 4a and 4b respectively. The theoretical value with varying  $B_v$  does not seem to follow the experimental results exactly even though there is a general tendency to rise. The theoretical and experimental confinement times with varying  $E_T$  is seen to match within the experimental errors, though the functional behaviour seems to follow eq. (3.1).

The discrepancies seen in the theoretical and experimental values of the confinement time is probably due to the various assumptions made in the derivation of the expression (3.1). The dependance on minor radius and  $B_T$  could be present if one does take into account the large variations in  $E_T$  during the rise phase, as is seen in figure 1.

#### 4. Conclusions

The angular measurement of hard X-ray emission shows that most of the runaway electrons hit the fixed limiter but the Langmuir probes can also act as a target for the runaways. It is seen that  $\tau_R$  increases with  $B_T$  whereas a decrease is seen with increasing  $E_T$ . The confinement time is seen to have a hump at minor radius,  $a = 5.5$  cms. The tendency to increase linearly is seen in  $B_v$  but the slope rate of increase is not the same. As a part of our future plans, we intend carrying out a more detailed modelling of the confinement time taking into account its dependence on other parameters such as  $B_T$ , minor radius etc.

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