RUNAWAY ELECTRON (RE) MITIGATION USING SUPersonic MOuler BEAM INJECTION IN THE ADITYA-U TOKAMAK


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Abstract

Generation of runaway electrons (REs) during the operation sequence in a fusion device is a potent threat to the plasma facing components and the interface of actively cooled parts. REs may be generated at the initial phase of a discharge due to a high E/p start-up in a tokamak and also during disruptions due to the loop voltage surge during the current quench (CQ) phase. Mitigation of REs is of prime importance for safe operation and machine health of a fusion device. A supersonic molecular beam injection (SMBI) system is installed in the Aditya-U tokamak to explore the effects of the high Mach number molecular beam on the REs and ways to mitigate them. It has been observed that SMBI can mitigate the initial REs successfully and a good correlation of this mitigation efficiency has been observed with the interaction of the SMBI with the MHD activities (tearing modes). A sharp downshift of the tearing mode frequency is observed in shots with substantial mitigation of the REs.

1. INTRODUCTION

Runaway electrons (REs) with energies >=1-10 MeV are generated in fusion devices both during the start-up phase and during plasma disruptions. These REs can penetrate through the low-Z (viz. Carbon, Beryllium) first wall and pose serious threat to the plasma facing components and the interface of actively cooled parts. During the plasma start-up, electric field E is induced by the Ohmic solenoid and the fuel gas (in this case it is hydrogen) is filled at a suitable pressure p (fill pressure) in the vacuum chamber. According to the Townsend avalanche theory [1], mean velocity of the electrons is a function of E/p. As long as E/p < 2 x 10^4 V m^-1 Torr^-1, one is within the safe limit of RE production. Aditya-U is operated with a peak loop voltage during start-up of 3.8 - 4.2 V m^-1 and a fill pressure of 1.2 – 2 x 10^4 Torr. This makes E/p ~ 2.5 – 3 x 10^4 V m^-1 Torr^-1. Thus the start-up phase is susceptible to RE generation and spikes of hard X-ray (HXR) are often seen in abundance. Hence, efficient means need to be explored to reduce the RE population after the burn-through and plasma current (I_p) ramp-up phases are complete.

The other concern is the generation of REs during plasma disruptions and remains as an outstanding challenge for future fusion reactors [2]. Majority of disruptions in tokamaks [3,4] display MHD modes, as precursors. Radiation cool-off at the edge is seen to trigger abrupt growth of MHD modes, mode locking and thereby disruptions [5,6]. The REs are generated due to increase in plasma resistivity following the thermal quench (TQ) and the large surge in loop voltage as the current quench (CQ) phase starts. Interestingly, the magnetic fluctuations die down substantially during the RE generation phase. This has also been seen in Aditya tokamak [7,8] and later in Aditya-U tokamak. Several RE mitigation techniques have been tried out in different machines, such as massive gas injection [9], and application of resonant magnetic perturbations (RMP) [10]. However, the effect of both these mechanisms are restricted to the very edge of the tokamak plasma and the REs primarily generated inside the plasma following the TQ, are not completely affected by these mitigation techniques, especially in large tokamaks. It has been estimated that a large plasma density is required to suppress the avalanche amplification of REs through Coulomb collisions in tokamaks during the CQ phase [11]. Enhancing the magnetic fluctuations during the disruptions is an alternate method to suppress the REs and a more penetrative fuelling technique is required to achieve that. At times, significant RE flux has been found to suppress magnetic fluctuations and a considerable RE current is generated during the disruptions. There is a recent experimental observation of the suppression of the RE current during disruptions by magnetic perturbations, excited by the supersonic molecular beam injection (SMBI) [12]. However, a detailed understanding of the underlying dynamics of such a suppression is far from being completely understood.

A SMBI system, to enable deep penetration inside the plasma, is installed on the low field side (LFS) of the Aditya-U tokamak and RE mitigation experiments are carried out. In this paper we present the successful mitigation of the REs generated during the start-up phase and also the attempts to mitigate the REs generated during disruptions. Interaction of the SMBI with the REs and the magnetic fluctuations (magneto-hydro dynamics, MHD activity) is reported.
2. EXPERIMENTAL SETUP

Aditya-U [13] is a medium-sized air-core tokamak with a maximum toroidal magnetic field, \( B_T \leq 1.5 \) T, major \( (R) \) and minor \( (a) \) radii 0.75m and 0.25 m, respectively. Core electron density \( (n_e) \) and core electron temperature \( (T_e^{core}) \) in the discharges are typically \( n_e \sim (4-5) \times 10^{19} \) m\(^{-3} \) and \( T_e \sim 450-500 \) eV, respectively, and the discharge duration \( \sim 150–180 \) ms. Plasma current \( I_p \sim 130-150 \) kA is achieved routinely during the higher parameter space circular cross-section limiter plasma operation. The vacuum vessel has a circular cross-section fitted with a toroidal inboard limiter and two circular poloidal limiters at two toroidal locations 180° apart. There are electrical insulations between the two halves of the toroidal vacuum vessel making it discontinuous. Hence, eddy currents, generated due to the gradients of coil currents or plasma currents itself, can be neglected.

A supersonic molecular beam injection (SMBI) system, to enable deep penetration inside the plasma, has been installed on the low field side of the Aditya-U tokamak. Front end of the system consists of a Laval nozzle of throat diameter 0.5 mm and a fast response solenoid valve. Schematic of the Laval nozzle is shown in Fig. 1. Theoretically, gas injection speed of Mach 10 is achievable with this nozzle design. The plenum gas pressure can be varied to adjust the throughput of the beam. A particle flux of \( 2.6 \times 10^{22} \) particles/s is achievable at a plenum pressure of 1 MPa. The SMBI system on Aditya-U is developed in three stages. This system is first designed to deliver voltages \( <30 \) V to the solenoid valve. The next upgrade allows us to deliver voltages up to \( 200 \) V to the valve. This provides the flexibility in the SMBI pulse width and hence the particle input. It enables us to deliver short intense pulse at a pre-decided time instant of the plasma shot. The final upgrade is implemented recently to operate the SMBI system in a feedback mode. We attempt here to fire the SMBI pulse during the disruption phase such that the disruption REs can be mitigated. This, however, requires a robust disruption prediction system. Such a system is being developed for Aditya-U and will take a while to get operational. On the other hand, we tried to work around the problem with an easier alternative. As seen earlier [8], a TQ always precedes the CQ phase and one or more spikes can be seen in the soft X-ray (SXR) signal as a signature of the TQ. We intend to use the first spike in the SXR signal to trigger the SMBI pulse.

![Schematic of the Laval nozzle and the SMBI system with two options such as: Option I: Pre-programmed mode to fire the SMBI pulse at a pre-determined time instance during the shot and Option II: feedback mode to fire the SMBI pulse right after the TQ phase; Photograph shows the Laval nozzle (yellow arrow) and the SMBI front end assembly on the Aditya-U tokamak.](image)

Chord averaged \( T_e \) is monitored at 50 kHz sampling frequency with SXR detectors. Chord averaged \( n_e \) at the core is monitored with a homodyne microwave interferometry system. A garland of 16 Mirnov coils are installed poloidally to measure the \( \hat{B}_\theta \) signals. The volume hard X-rays (HXR) are monitored along a line of sight passing through the plasma center. A Phantom v7.1 fast camera is installed using an imaging fiber bundle on a view-port slightly above the mid-plane to acquire images of plasma evolution at 26 kHz frame rate. The camera has a tangential view covering a quarter of the tokamak on the side of the SMBI injection system. The SMBI port is
just beyond the field of view (FOV) of the camera and hence, direct imaging of the injection cannot be achieved. However, the effect of SMBI, like the change in overall intensity of an image frame, any transient effect on the plasma column or radiation collapse etc. can be monitored by the imaging system.

3. RE MITIGATION AT THE CURRENT FLAT-TOP PHASE

As a first step towards RE mitigation SMBI is fired at 40 ms. Two shots are shown in Fig. 2 with and without SMBI. Copious HXR spikes can be seen without SMBI and the detectors are even rendered saturated at ~58 ms. The shot with SMBI has a similar \(I_p\) and loop voltage waveform. With the application of SMBI, a sudden jump in SXR signal can be seen indicating a sharp rise in density. It can be noted here that the sharp jump occurs after 4-5 ms after the SMBI is fired. A distinct increase in intensity in the fast visible images is also observed after the same time delay from the SMBI pulse. This is concomitant with the resistive diffusion time scale of the Aditya-U plasma. With the rise in density, significant reduction in the RE population is also evident from the HXR signals. Further, a ~5% decrease in \(I_p\) can be seen following the SMBI pulse. This is mostly due to the reduction in RE population and resultant loss of the fraction of \(I_p\) carried by them. It is noteworthy here that there is no surge in impurities with the SMBI pulse.

![Fig. 2. 2 shots showing the effect with and without SMBI](image)

Two sets of shots are shown in Fig. 3. In the left panel two shots (#31271 and #31263) are shown to achieve substantial mitigation of the REs following the SMBI pulse, while in the right panel there are two shots (#31266 and #31264) with no appreciable reduction of the HXR spikes. However, in the shots of the right panel, a similar reduction of the \(I_p\) is seen following the SMBI pulse. This could still be due to the loss of RE population. Sharp rise in SXR signal is also seen for the right panel shots indicating density rise comparable to the left panel shots.
Fig. 3. Left panel: 2 shots showing substantial reduction in HXR flux and hence mitigation of the RE population with SMBI; right panel: 2 shots showing negligible effect of SMBI on the RE population, even though the increase in density is comparable in both these two sets.

4. EFFECT OF SMBI ON MHD ACTIVITY

As evident from the SXR and density signals SMBI penetrates from the LFS and takes a while (~4-5 ms) to increase the core density. During this interval, the beam injects neutrals along its path and alters the density gradient. This alteration is seen to have profound effect on the diamagnetic rotation frequency of the tearing mode islands. The \( m/n = 2/1 \) and \( 3/1 \) island rotation frequency indeed responds to the SMBI and shows a sharp reduction as shown in Fig. 4. This reduction in rotation frequency varies from shot to shot. The rotation frequency again starts resuming the general mode frequency ~12-14 kHz value, seen in Aditya-U after the sharp reduction phase is over. By this time the SMBI neutrals have penetrated to the core and the core density starts increasing, thereby resuming the original density gradient again. This downshift in mode frequency can also be explained from the drift wave turbulence. Diamagnetic drift frequency is defined by \( \omega_\ast = k_y T_e/eB L_{pe} \) (where \( k_y \) is poloidal wave number, \( T_e \) is electron temperature, \( e \) is electron charge, and \( L_{pe} \) is electron pressure gradient scale-length). As \( T_e \) decreases and \( L_{pe} \) increases by the neutral gas penetration, \( \omega_\ast \) is expected to decrease with the SMBI penetration.

A significant increase in the MHD fluctuation amplitude has been observed in most of the cases. This increase is most likely due to the radiation cooling towards the edge due to the injected neutrals by SMBI. It has also been seen that if the SMBI throughput is not tailored as per the discharge parameters, the sudden radiation cooling and abrupt increase in the MHD fluctuations can lead to disruptions.
As seen earlier, SMBI can mitigate the REs successfully in most of the occasions, while there are some clear examples where the REs are affected less to none and HXR bursts are not reduced appreciably after the SMBI pulse (refer Fig. 3). This has a direct correlation with the amount of reduction that can be imparted by SMBI on the mode rotation frequency of the tearing modes. It has been seen that more drastic the reduction in frequency, the better the RE mitigation achieved in a given shot. Fig. 5 shows two consecutive shots as shown in the panels of Fig. 3. In shot #31263, the frequency reduction is much sharper compared to that in shot #31264. Likewise, RE mitigation is substantial in #31263 while there is comparatively less effect of SMBI on the REs for #31264. Interestingly, increase in the fluctuation amplitude, following the SMBI pulse, does not seem to have direct correlation with the extent of RE mitigation in Aditya-U.

As stated in section 2, in option II, SMBI is operated in feedback mode with the SXR signal. With the initiation of the operation sequence, the comparator circuit detects the TQ spike in the SXR signal and generates trigger for the SMBI pulse. This up-grading is still under progress and trigger has been generated successfully at the disruption phase. Fig. 6 shows the trigger as generated with the TQ spike prior to the loop voltage spike during disruption. Throughput optimization is underway and effect of the pulse on the disruption REs will be reported shortly.

5. SMBI IN FEEDBACK MODE AT THE PLASMA DISRUPTION PHASE

As stated in section 2, in option II, SMBI is operated in feedback mode with the SXR signal. With the initiation of the operation sequence, the comparator circuit detects the TQ spike in the SXR signal and generates trigger for the SMBI pulse. This up-grading is still under progress and trigger has been generated successfully at the disruption phase. Fig. 6 shows the trigger as generated with the TQ spike prior to the loop voltage spike during disruption. Throughput optimization is underway and effect of the pulse on the disruption REs will be reported shortly.
Fig. 6. Trigger for the SMBI pulse generated at the SXR spike during the plasma disruption phase. Red broken line denotes the time instant where the threshold criterion of the comparator circuit is met with and SMBI trigger is generated.

6. SUMMARY AND DISCUSSIONS

A SMBI system has been developed and installed in the Aditya-U tokamak. Major goal of this system is to mitigate the REs generated during plasma initiation and also during the loop voltage spike following the TQ phase during disruptions. REs generated during start-up and burn-through phase, due to higher \( E/p \) ratio, has been mitigated successfully while avoiding radiation collapse in several shots. It has been seen that for the same throughput of neutrals with the SMBI pulse, substantial RE mitigation can be achieved in several shots, while it is not the case for some other shots. This is the case even though a sharp rise in density has been observed with the SMBI pulse in all the shots. Hence, for these shots, either the physical criteria for RE mitigation is not met with or the RE production was still higher and mitigation is not sufficient for the fixed throughput of neutrals delivered by the SMBI pulse. Efficiency of the SMBI pulse in RE mitigation has been seen to be linked with the level of frequency downshift achieved for the tearing modes. The next logical step will be to vary the neutral throughput by changing the input voltage to the solenoid valve and/or the width of the SMBI pulse or the plenum pressure. However, the throughput optimization is crucial for the discharge to carry forward smoothly or else a radiation collapse and disruption may occur.

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REFERENCES