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Novel approaches for mitigating runaway electrons and plasma disruptions in ADITYA tokamak

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Abstract

This paper summarizes the results of recent dedicated experiments on disruption control and runaway mitigation carried out in ADITYA, which are of the utmost importance for the successful operation of large size tokamaks, such as ITER. It is quite a well-known fact that disruptions in tokamaks must be avoided. Disruptions, induced by hydrogen gas puffing, are successfully avoided by two innovative techniques in ADITYA using a bias electrode placed inside the last closed flux surface and applying an ion cyclotron resonance pulse with a power of ~50 to 70 kW. These experiments led to better understanding of the disruption avoidance mechanisms and also can be thought of as one of the options for disruption avoidance in ITER. In both cases, the physical mechanism seems to be the control of magnetohydrodynamic modes due to increased poloidal rotation of edge plasma generated by induced radial electric fields. Real time avoidance of disruption with identifying proper precursors in both the mechanisms is successfully attempted. Further, analysing thoroughly the huge database of different types of spontaneous and deliberately-triggered disruptions from ADITYA, a significant contribution has been made to the international disruption database (ITPA). Furthermore, the mitigation of the runaway electron generated mainly during disruptions remains a challenging topic in present tokamak research as these high-energy electrons can cause severe damage to in-vessel components and the vacuum vessel. A simple technique has been implemented in ADITYA to mitigate the runaway electrons before they can gain high energies using a localized vertical magnetic field perturbation applied at one toroidal location to extract runaway electrons.

Keywords: runaway, disruption, control, electrode biasing, ICRH

(Some figures may appear in colour only in the online journal)

1. Introduction

Disruption avoidance and runaway mitigation are subjects of the utmost importance for the successful and safe operation of large size tokamaks including ITER. Disruptions are rapid events in which large fractions of the plasma thermal energy are lost suddenly and must be avoided for successful operation of large devices including ITER. The heat and particles are released from a confined region on a short timescale and get dumped on the plasma facing components, causing damage in proportion to the stored energy [1, 2]. Therefore, it is essential to prevent or mitigate the disruptions. There exist several techniques tested in tokamaks round the world to stabilize magnetohydrodynamic (MHD) modes and avoid disruptions, such as static helical magnetic field perturbation technique for magnetic islands suppression (COMPASS C) [3], large increase of plasma density by massive gas injection of noble gas, significantly reducing the disruption forces and heat loads on the first wall or divertor (JET, ASDEX-U, DIII-D, MAST) [4–7], and the avoidance of spontaneous disruptions by electrode biasing in a small tokamak (SINP) [8] is also reported. Depending upon the device and the disruption mechanism, successful avoidance of disruption using ECRH has also been obtained in many tokamaks such as JFT-2M [9], RTP [10], T-10 [11] and FTU [12]. In FTU it has been shown that MHD mode coupling plays an important role during disruptions, which can be exploited for disruption avoidance through localized ECRH injection. Other than ECRH, electron-cyclotron current drive (ECCD) [13], and neutral beam heating (NBI) [14] has also been successfully attempted to avoid disruptions in DIII-D and TEXTOR respectively through MHD mode stabilization.

Disruption also generates a large amount of runaway electrons (REs) as the plasma temperature decreases suddenly making the plasma resistive and hence increasing the toroidal loop voltage. REs can also damage the first wall components severely. In ITER, fast electrons with energies of tens or hundreds of MeV are estimated which can carry a significant fraction of plasma energy and be locally deposited leading to extensive damage to the first wall components. Further, the generation of a large population of REs also limits the use of massive gas injection of noble gas for disruption control. Therefore suppression and/or extraction of REs are a prerequisite for reliable tokamak operation. There exist several techniques for suppressing the REs in tokamaks. Magnetic perturbation (JT-60U, Versator I) [15], resonant magnetic perturbation (TEXTOR) [16], massive gas injection (DIII-D, TEXTOR), suppression of REs during disruption has been achieved by non-axisymmetric magnetic perturbations to deconfine seed REs before the avalanche process could amplify the RE beam (DIII-D, JT-60U [17]), argon killer pellets (DIII-D), ECH heating and LHCD (FTU) [18], and additional gas puff (JET, ASDEX, TCABR and ADITYA [19]).

Recent experiments in the ohmically heated circular limiter tokamak ADITYA [20] have addressed disruption avoidance and runaway mitigation and obtained a few innovative techniques. The outcomes of these innovative experiments are very encouraging and may play a significant role in future tokamak operations. Analysing thoroughly the database of different types of disruptions in ADITYA, it is observed that unstable MHD modes grow prior to the disruptions [21] leading to the sudden loss of confinement and subsequent transfer of plasma energy to the surrounding structural components. Based on this analysis a significant contribution has been made to the ITPA international disruption database (IDDB) after identifying and categorizing many disruptive discharges of ADITYA. Disruptions caused by destabilizing MHD modes can be caused by puffing hydrogen gas in a sufficient amount in ADITYA. These gas puff induced disruptions are successfully avoided in ADITYA by two simple techniques: (1) by the application of a bias electrode placed inside the last closed flux surface (LCFS) and (2) by launching ion cyclotron resonance (ICR) of suitable power. Further, the REs are successfully extracted by applying a local vertical magnetic field (LVF) in ADITYA. The LVF perturbation pulse of magnitude ~3–4% of the toroidal magnetic field (B_T) and of pulse width ~7–15 ms is applied during the start-up, ramp-up and current quench phases causing a significant reduction in limiter hard-x-ray emissions indicating RE mitigation in all the phases. Application of LVF pulse during the ramp-up phase showed a considerable reduction in RE dominated plasma current leading to a significant improvement in discharge consistency. The experimental set-up is presented in section 2, results and discussion in section 3 and the paper is summarized in section 4.

2. Experimental set-up

The experiments reported in this paper have been carried out in ADITYA, which is a medium size air-core tokamak with a circular limiter having major radius, $R = 75$ cm, and minor radius, $a = 25$ cm. Typical plasma parameters for the discharges presented in this article are $B_\phi \sim 0.75 - 0.84$ T, plasma current ~70–80 kA, discharge duration ~80–100 ms, chord averaged central electron density $n_e \sim (1 - 2) \times 10^{19}\,\mathrm{m}^{-3}$, central electron temperature $T_e \sim 300 - 450$ eV, and edge safety factor $q \sim 3 - 4$.

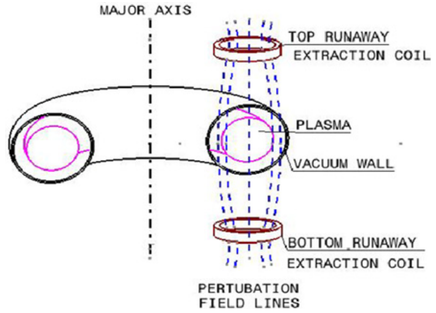

Figure 1. The LVF perturbation using Helmholtz like coils for magnetic extraction of REs in ADITYA.

For the disruption avoidance experiments using the biased electrode technique [22], a movable cylindrical molybdenum electrode of 0.5 cm diameter and 2.0 cm exposed length is placed 3.0 cm inside the LCFS ($r_{\mathrm{elec}} = 22.0$ cm) from the top port of the machine. The electrode is powered by a capacitor-bank based pulsed power supply (PPS) using a semiconductor controlled rectifier (SCR) as a switch with forced commutation [23]. For controlling the disruptions by ICR technique, an ICR pulse of ~50–70 kW is launched through a fast wave poloidal type antenna with a Faraday shield placed outside the LCFS. For real time control, a special comparator trigger circuit [23] based on MHD signals and H_α emissions as precursors is used to trigger the electrode biasing and ICR pulses during disruptions.

The RE mitigation experiment in ADITYA is performed by applying a LVF at one toroidal location using two Helmholtz like coils placed at the top and the bottom of the machine. The coils are connected in series to produce LVF perturbation in the direction opposite to the actual equilibrium field and are powered by a capacitor bank power supply. The current in the coils is monitored with a Pearson current transformer (CT) of calibration factor of 10 mV/1 A. The schematic of the LVF application is shown in figure 1.

The main set of diagnostics used in these experiments includes external magnetic sensors to measure loop voltage (V_{loop}), plasma current (I_P) and plasma position. The MHD oscillations are measured by a garland of 16 Mirnov coils distributed at equal angular separations in the poloidal direction at a single toroidal location [24]. Eight-channel microwave interferometer is used for line average electron density (n_e) measurements. Neutral (H_α) and impurity line radiation (O-I, C-III, visible continuum) are measured using visible spectrometer and photomultiplier tubes (PMTs) with wavelength filters. The central electron temperature is measured using soft x-ray detectors. The hard x-ray flux measurement is carried out by using two NaI (Tl) scintillator detectors with diameters of 1.5 and 3 inch working in a current mode with PMT readout. The lead shielded scintillator is located at the equatorial plane of the machine and collimated to see the limiter radiation.

3. Results and discussion

3.1. Disruption avoidance

Several hundreds of spontaneously disrupted discharges in ADITYA are analysed thoroughly before attempting the disruption avoidance experiments [25]. This analysis showed that maximum numbers of discharges are spontaneously disrupted due to the onset of MHD modes in ADITYA. Experimentation with gas puffing of fuel gas during the discharges in ADITYA has shown that when a sufficient amount of gas is fed at the plasma current flat-top it leads to the growth of MHD modes causing disruptions and termination of plasma current. Hence, for disruption avoidance experiments, the discharges are purposefully disrupted by puffing a sufficient amount of hydrogen gas during the I_P plateau at different times (40–45 ms for biased electrode and 55–60 ms for ICR experiment) to obtain successive repetitive disruptive discharges after obtaining normal repetitive discharges of 70–100 ms durations. These potentially disrupting discharges in ADITYA are completely revived by applying a bias voltage above a threshold of $\sim +200$ V to the electrode before the gas puff and also with the application of ICR pulse.

Complete restorations of plasma current along with electron density and electron temperature in discharges have been observed with the application of a bias voltage to the electrode prior to the gas puff. The influx of H_2 gas causes the abrupt growth of MHD oscillations, which leads to current quench and termination of the discharge. These modes clearly subside in the discharge with bias and thereby avoid disruption. The application of positive bias voltage builds up positive plasma potential leading to an increase in the radial electric field (E_r) and its shear in the region between the electrode and the limiter. Consequently, the $E_r \times B_\phi$ rotation of the plasma and its shear increases compared to the corresponding value in without bias. As plasma rotation shear is known to stabilize MHD modes [26, 27], when the rotation shear becomes equal to magnetic shear in our experiments at a particular bias voltage ($\geqslant$180 V), the tearing modes generated due to gas puff are stabilized and the disruptions caused by these modes are avoided. A detailed description of disruption avoidance can be found in [22, 23].

As a biased electrode cannot be put in a large tokamak, plasma biasing by non-resonant ponderomotive forces of radio-frequency waves for generating sheared rotation to curb disruptions have been attempted. Simulations showed stationary radial electric fields (E_r) can be typically of the order of several hundred volts per centimetre when the wave frequency is 1% lower or higher than the ion-cyclotron frequency [28]. Therefore, an ICR pulse of 50–70 kW has been successfully attempted to avoid disruptions in ADITYA. As the application of the ICR pulse is possible in large size tokamaks, this method of avoiding the disruption can be feasible in larger tokamaks.

Similar to biasing experiments, after obtaining repetitive disruptive discharges using gas puff injection, the ICR pulse is applied prior to gas puff to avoid disruptions. The disruptions are also avoided in real time by detecting the increase in H_α emission signal due to gas puff and used it as a precursor for triggering the ICR pulse to avoid disruptions. When the H_α emission amplitude increases due to gas puffing (figure 2(*b*)) and crosses a certain threshold value (figure 2(*d*)), a trigger pulse is automatically generated to trigger the ICR system (figure 2(*c*)). The current quench due to gas puffing is clearly avoided with the application of the ICR pulse, as shown in figure 2(*a*).

In resemblance to the biasing results, the H_2 gas puff induced uncontrolled growth of MHD modes, as shown in figure 3, gets subsided with the application of the ICR pulse. The comparison of time–frequency analysis of Mirnov probe signals using fast Fourier transform (FFT) between discharges with and without ICR pulse clearly indicates suppression of MHD modes with ICR application. The disruption avoidance

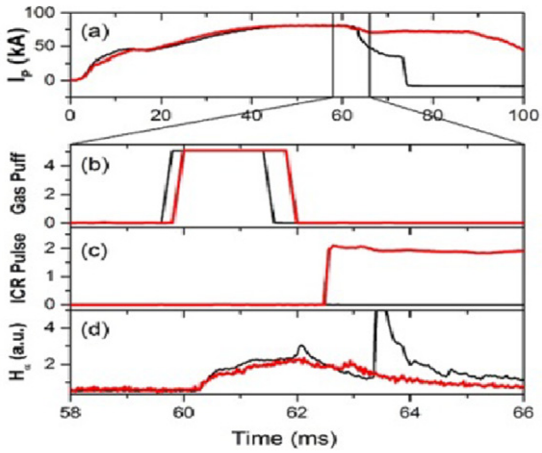

Figure 2. Typical gas puff induced disruptive discharge (#27700) and discharge (#27715) with disruption avoidance in the presence of ICR pulse. (*a*) Plasma current (I_P), (*b*) H_2 gas pulse, (*c*) ICR pulse and (*d*) H_α line intensity.

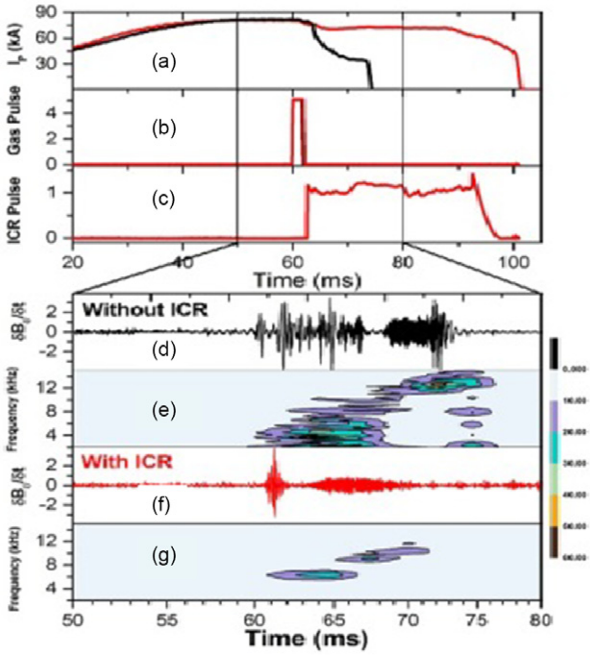

Figure 3. Comparison of without ICR (#27700 black) and with ICR (#27715 red) with H_2 gas injection and ICR pulse. (*a*) Plasma current (I_P), (*b*) H_2 gas pulse, (*c*) ICR pulse, (*d*), (*f*) $\dot{B}_\theta$ measured at the midplane low field side, and (*e*), (*g*) FFT analysis of $\dot{B}_\theta$.

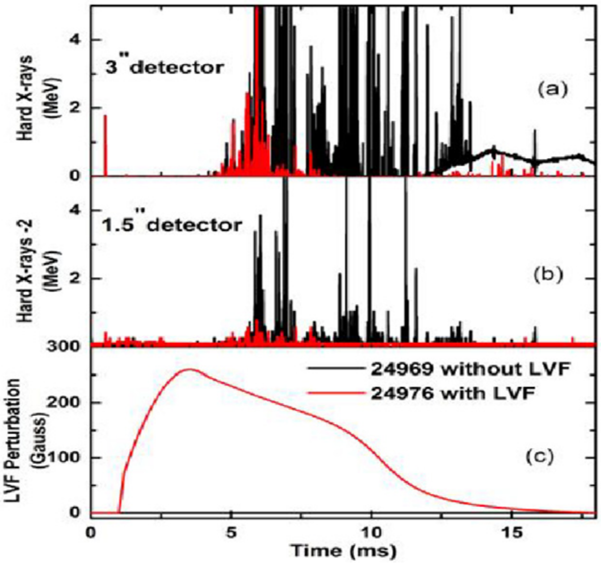

Figure 4. Discharge comparison with LVF (shot #24976 red) and without LVF (shot #24969 black) showed temporal evolution of (*a*) hard x-rays (3 inch detector), (*b*) hard x-rays (1.5 inch detector) and (*c*) LVF perturbations (gauss) for magnetic extractions of initial REs.

is observed with ICR power in the range of ∼50–70 kW in typical gas puff induced disruptive discharges of ADITYA. However, increasing the power beyond 70 kW does not lead to disruption avoidance in these set of discharges in ADITYA. Therefore, the disruption avoidance in the case of the ICR pulse does not seem to be due to heating near the Islands as ICR heating for the reported discharges in ADITYA is observed for ICR power more than ∼100 kW. Most likely the disruptions are avoided due to induced radial electric fields by ponderomotive forces of ICR waves, which in turn generate sheared poloidal rotation, quenching the growth of MHD modes as observed in the case of electrode biasing.

3.2. Runaway mitigation

The runaway mitigation experiments with application of LVF perturbations in ADITYA is carried out in different phases of plasma pulse namely, initial phase, current ramp-up phase and disruption phase. The experiment is carried out in the initial phase (during the first 15 ms of discharge time) of breakdown as well as in the current ramp-up phase by applying the LVF perturbation with varying its magnitude from 150 260 G at plasma centre. The field is directed anti-parallel to the actual equilibrium field. The pulse width of the LVF is also varied from 7–15 ms.

The time evolution of hard x-rays measurements (including 3 nd 1.5 inch detectors) during the first 15 ms time of the discharge length with and without LVF perturbation is shown in figure 4. Significant reduction (∼5 times) in initial hard x-rays is observed in both the detector signals in discharges in which the LVF perturbation is applied. Similarly when the LVF perturbation is applied at the plasma current ramp-up phase, a reduction in HXR counts is observed as well as the runaway current contribution in the main current, which leads to improvement in discharges in terms of their repeatability as well as plasma temperature. The time evolution of ADITYA discharges comparison for LVF perturbation applied at 30 ms with LVF perturbation (shot #28020 red) and without LVF perturbation (shot #28030 black) is shown in figure 5.

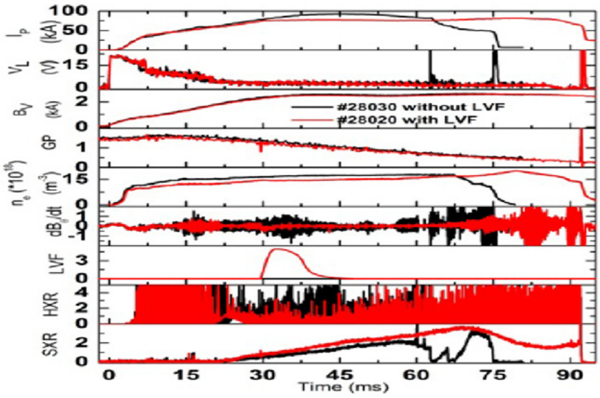

Figure 5. Discharge comparison with LVF (shot #28020 red) and without LVF (shot #28030 black) showed temporal evolution of (*a*) plasma current, (*b*) loop voltage, (*c*) vertical field, (*d*) pre-filled gas pressure, (*e*) electron density, (*f*) B_θ measured at midplane, low field side, (*g*) LVF perturbations, (*h*) hard x-rays (3 inch detector) and (*i*) SXR emission.

By keeping the operating parameters exactly similar in both the discharges, the discharge condition improved in comparison to without LVF discharges in many respects with LVF application. The RE mitigation during the disruption phase with the application of LVF perturbation is carried out in real time feedback mode. The LVF perturbation is applied in real time by detecting and using the increase in the hard x-rays flux amplitude signal as the precursor for triggering the LVF pulse. The time evolution of ADITYA discharges comparison for LVF perturbation (shot #28459 red) applied in real time feedback mode and without LVF perturbation (shot #28458 black) is shown in figure 6.

With the application of the LVF pulse, the hard x-ray emission duration during the disruption gets reduced along with reduction in positive loop voltage spike as shown in figure 6(*c*). The reduction in H_α and C-III line emissions (figures 6(*d*) and (*e*) respectively) also observed indicating less interaction of REs with the wall. Therefore, application of a local vertical perturbation field of magnitude ∼3–4% of the toroidal magnetic field reduces the hard x-rays considerably, which means that the REs are thrown out of the main plasma before gaining higher energies without affecting the thermal component of the plasma in typical discharges of ADITYA. The mechanism of runaway extraction is very simple. The perturbation leads to a radial diffusion governed by the expression

$$D_\perp \approx \left[(B_p/B)L\right]^2 v_\parallel/2\pi R \qquad (1)$$

where $v_\parallel$ is the particle velocity along magnetic field, B, B_p is the perturbation magnetic field and L is the scale length of the perturbation field gradient. Due to the LVF perturbation, the particle moves in the vertical direction in the region of the perturbation field. This leads to a radial diffusion, which will be proportional to the particle velocity parallel to the total magnetic field. As the REs have higher parallel velocity, the RE

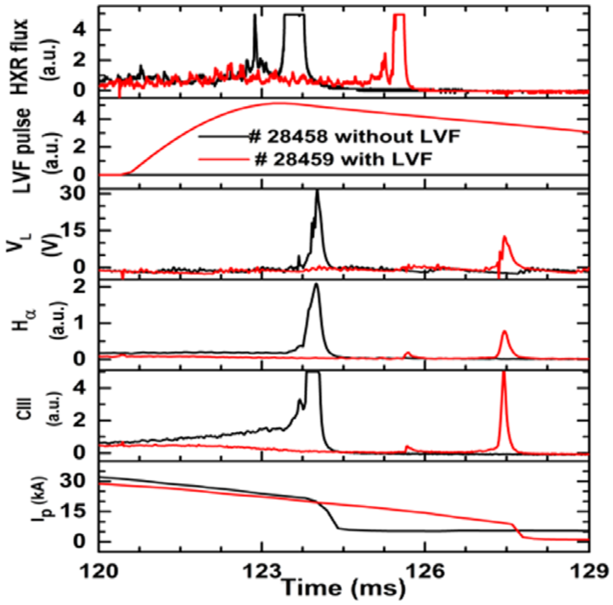

Figure 6. Discharge comparison with LVF (shot #28459 red) in real time feedback mode and without LVF (shot #28458 black) showed the temporal evolution of (*a*) hard x-rays flux, (*b*) LVF perturbations, (*c*) loop voltage, (*d*) H_α emission, (*e*) C-III emission and (*f*) plasma current.

diffusion is 10 times larger than that of the thermal particles in typical ADITYA discharges with the application of LVF perturbation field of ~260 G.

4. Summary

In summary, disruptions, induced by hydrogen gas puffing are successfully avoided using biased electrode and ICR pulse techniques. The complete avoidance of the disruptions in discharges with $I_P \sim 65 - 70$ kA has been obtained with a biasing voltage of more than ~180–190 V to an electrode placed inside the last closed flux surface. Sheared poloidal plasma rotation in the vicinity of $m/n = 3/1$ island through a radial electric field generated by biased electrode reduces the growth of the magnetic islands corresponding to $m/n = 3/1$ and 2/1 MHD modes and hence avoids the disruptions. As a biased electrode cannot be put in the very edge region of a reactor, the disruptions are successfully avoided with applying an ICR pulse with power of 50–70 kW to the disruptive discharges in ADITYA. The physical mechanism seems to be the control of MHD modes with induced poloidal rotation of edge plasma due to induced radial electric fields by the non-resonant ponderomotive force of ICR waves. Runaway electrons are also successfully removed from the main plasma by applying a short local vertical field pulse of magnitude 3–4% of the toroidal magnetic field and a pulse width of 7–15 ms in the opposite direction of the equilibrium magnetic field at one toroidal location. The REs are mitigated during plasma current start-up, plasma current flat-top and discharge termination phases.

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