Journal of Theoretical and Applied Physics (2020) 14:307–314
https://doi.org/10.1007/s40094-020-00386-1

RESEARCH

Mitigation of disruption on IR-T1 tokamak by means of low-energy neutral beam injection to control runaway electron generation

M. Kafi[1] · **M. Ghoranneviss**[1] · **M. R. Ghanbari**[2] · **M. K. Salem**[1]

Received: 23 June 2020 / Accepted: 26 July 2020 / Published online: 9 August 2020

Abstract

In a tokamak, the poloidal magnetic field provided by the toroidal plasma current forms an essential part of the magnetic field confining the plasma. However, instabilities of magnetohydrodynamic equilibrium can lead to an uncontrolled sudden loss of plasma current and energy, which is called a disruption. Disruptions are of significant concern to future devices due to the large amount of energy released during the rapid quenching of the plasma. One important consequence of disruption is the generation of significant current carried in multi-MeV runaway electrons that are eventually lost into plasma components. They can damage the tokamak walls and its structure if they are not controlled. Disruption control by neutral beam injection has been performed on IR-T1 to study the effect on runaway electron generated by plasma disruptions. Noble gases are used for injection, pure Hydrogen, Helium and Argon. The use of these non-reactive gases for disruption control ensures they fast removed from the vessel after the termination of a tokamak discharge. A piezo-valve is used for injection which has the precision of 1 ms. The effect of runaway electron generation control during disruption is studied using a comparison between reference disruptive discharge and a discharge into which different impurity species are injected. The data collected can then be used to optimize the performance of these energetic electrons control generated in disruption.

Keywords Tokamak · Runaway electrons · Hard X-ray

Introduction

The tokamak is one of several types of magnetic confinement devices being developed to produce controlled thermonuclear fusion power. In magnetically confined plasmas, the optimization of the plasma density and temperature for fusion energy production has led to a wide range of plasma instabilities. One of the most serious threats to tokamak operation is disruption [1], which is a global instability that results in the loss of plasma confinement and a rapid release of the thermal and magnetic energies stored in it [2]. Disruption has two phases: thermal quench (TQ) and current quench (CQ). In the first phase, a large fraction of the thermal energy is lost to plasma-facing components, and in the second one, all the magnetic energies are dissipated. The evolution of characteristic quantities during a typical disruption is shown in Fig. 1.

A disruption has several consequences which can damage the device in different ways. When the major disruption occurs, plasma current shuts down suddenly and plasma energy collapses at the high temperature to the walls and causes the melting or evaporation of its components. If the plasma touches the wall after the loss of confinement, then the high and localized heat flux can also damage the device. Furthermore, electromagnetic forces could be produced during the CQ which are harmful for device. Also, currents flowing in the tokamak structure can result in $j \times B$ forces which can damage vessel components [3]. Another severe consequence of disruption, which is the main purpose of our experiments on IR-T1, is runaway electron generation.

During a disruption, the loop voltage multiplies several times and increasing in that can lead to generation of several MeV electron beams or runaway electrons. Actually, when the toroidal electric field is applied to the plasma, thermal electrons accelerate. With increasing the velocity of electrons, the friction force decreases in front of them. If the electrons velocity exceeds the critical value of V_{cr}, they

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✉ M. Ghoranneviss
m_ghoranneviss29@yahoo.com

[1] Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

[2] Department of Basic Sciences, Garmsar Branch, Islamic Azad University, Garmsar, Iran

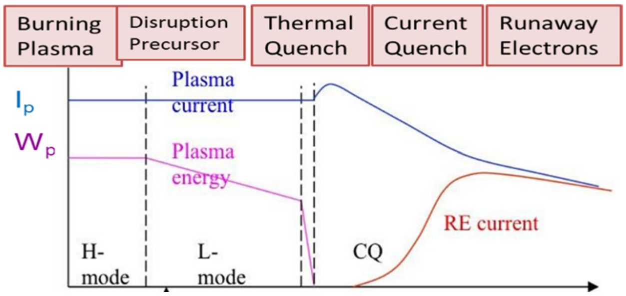


Fig. 1 Disruption phases: the thermal quench (TQ) and the current quench (CQ)

can accelerate continuously and their velocity will increase without any restrictions, so they will run away. This is a one mechanism of RE generation [4, 5]. Capable of a high penetration in the wall, they can cause erosion damage even behind the first shielding of the vacuum vessel. So, we conclude that disruption is a huge obstacle to the successful development of tokamak, because it limits the current density and creates large mechanical shock and severe damages. Thus, we need some skills to control or maybe restrain it to avoid its consequences. For this purpose, we experimented gas injection method in IR-T1 tokamak.

The specific characteristic of IR-T1 tokamak which is categorized as a small-size tokamak is that an ohmically heated air core tokamak with a major radius of $R=0.45$ and a minor radius of $a=0.125$ m is defined by two poloidal stainless-steel limiters. The vacuum chamber has a circular cross section with two toroidal breaks and a minor radius of $b=0.15$ m. Toroidal magnetic field is equal to $B_{\mathrm{t}} \sim 0.6-0.8T$, plasma current is $I_{\mathrm{P}} \sim 25-30$ KA, plasma discharge duration is $t_{\mathrm{d}} \sim 35$ ms, averaged electron density in Hydrogen is 0.7–1.5×10^{19} m^{-3}, and electron temperature is $T_{\mathrm{e}}(0) \sim 150-180$ eV.

The IR-T1, as a small-size tokamak, and having a low-density plasma make a good situation for producing runaway electrons. Therefore, we tried neutral beam injection to examine how it decrease them which is discussed in details in the next sections.

Gas injection

A lot of ongoing work is devoted to understand disruptions and to try to prevent them and their consequences such as runaway electrons generation. In order to avoid disruption dangers, there is one way to try to shut down the plasma before the instability occurs. There are several ideas about how to achieve this, among which a common element is to induce an artificial disruption that would deposit the energy in a safe and controlled way. This artificial disruption can be induced by injecting impurities into the plasma [6]. The impurities would radiate a way the thermal energy in a uniform manner, which would be beneficial for the device. Several tokamaks have studied the behavior of runaway electrons during disruptions caused for example by Argon or other noble gas puff [7–9].

On IR-T1 tokamak, two methods of plasma termination have been investigated: using high-*Z* atoms (Argon) only and low-*Z* atoms (Helium) and (Hydrogen) separately. The neutral beam injections were performed by means of a piezo-valve. Hard X-ray spectrometer was used to determine the runaway electrons energies. Plasma parameters were investigated before and after injections.

Experimental background and setup

Runaway electrons used to be observed on a regular basis during disruptions on IR-T1 tokamak. Their mean energy has been investigated in the past [10]. Furthermore, flexibility of various plasma parameters and having low-density plasma make good situation for RE generation, and runaway population makes IR-T1 suitable for runaway models validation and scaling toward ITER.

In order to perform runaway beam mitigation experiments, a reliable scenario has been developed at IR-T1 tokamak. The disruption is triggered by injection of pure Argon, Helium and Hydrogen using a piezo-valve. The piezo-valve used for injection is connected to the vessel through stainless-steel tube. This tube length implies a delay between the time of valve opening and the time at which the

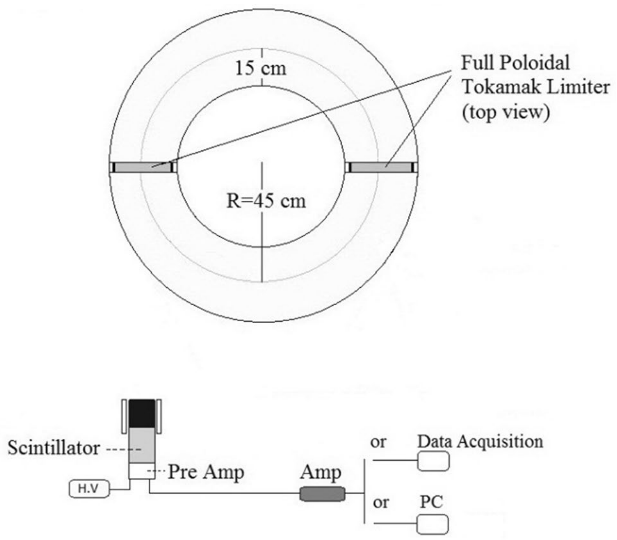


Fig. 2 Schematic illustration of IR-T1 (top view) showing the hard X-ray detector system. HV, high-voltage–power supply for the scintillator; pre-Amp and Amp, preamplifier and amplifier, respectively [11]

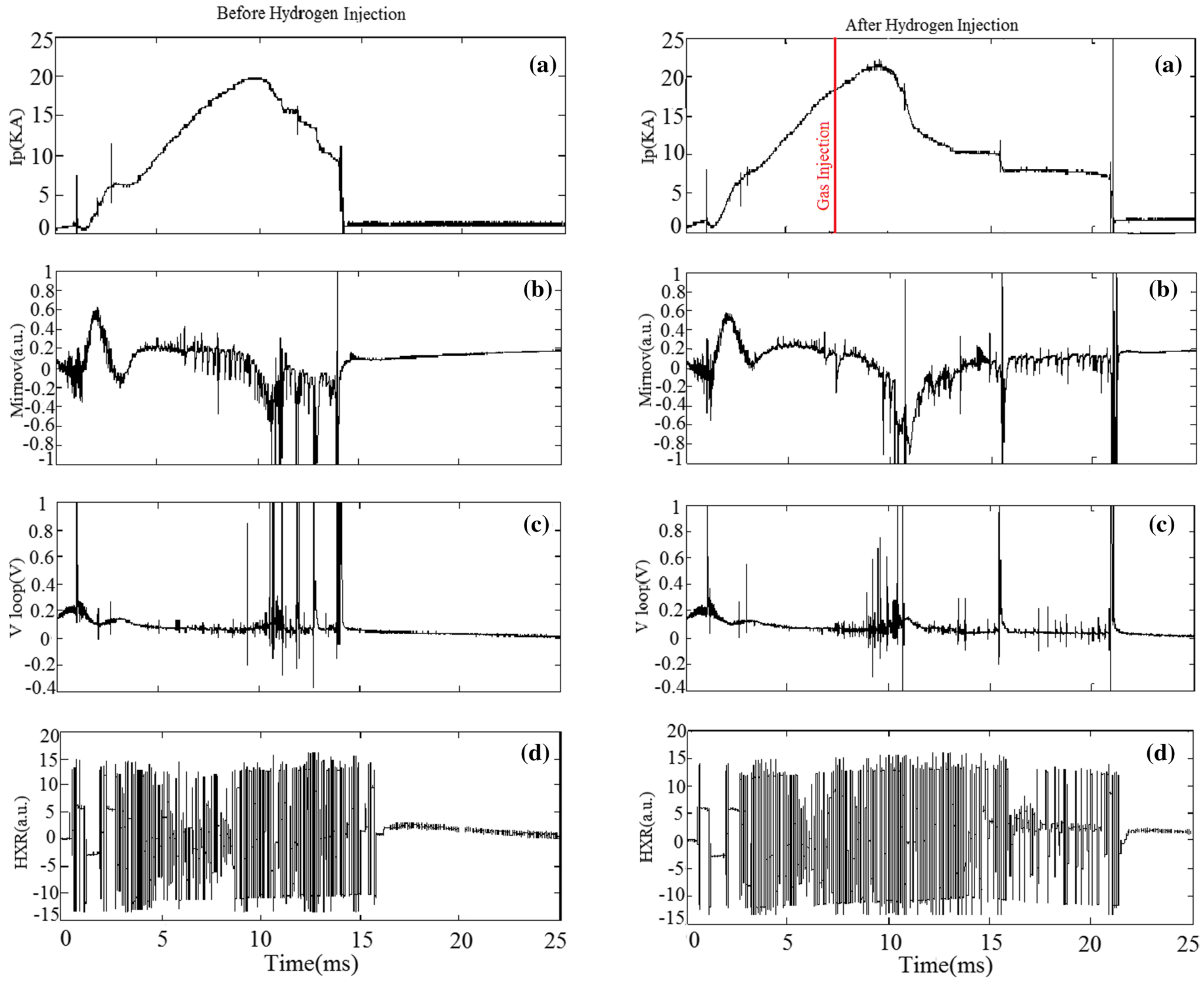


Fig. 3 **a** Plasma current, **b** Mirnov oscillations, **c** loop voltage and **d** hard X-ray with respect to the time before and after Hydrogen injection

gas puff starts to interact with the plasma. To our knowledge, this valve has response time of 1 ms. For the first time, a mass flow controller solenoid valve was used for entering primary gas, which is Hydrogen, in IR-T1 tokamak.

In order to detect and analyze the hard X-ray spectrum, a 2 inch × 2 inch NaI scintillator has been used (Fig. 2).

The detector is located at distance of 3–4 m from a vacuum vessel in the equatorial plane. The voltage applied to the photomultiplier was 930 V, and the hard X-ray intensity in the detector can be identified on data acquisition after preamplifier and amplifier. In order to obtain a hard X-ray spectrum (counts with respect to energy of photons), a multichannel analyzer (MCA) was used. The output signal from the detector was analyzed by the MCA, and this spectrum was observed via computer. Two standard Cs^{137} (0.66 MeV) and Am^{241} (59.54 MeV) sources were employed in order to calibrate the MCA. By making changes in vertical field and doing different shots, artificial disruptions were occurred and reproducible situations were created.

Results and discussion

In this section, the effect of runaway electron generation control during disruption is presented using a comparison between reference disruptive discharge and a discharge into which different impurity species are injected. Figures 3, 4 and 5 show plasma parameters comparison before and after injection of Hydrogen, Helium and Argon, respectively. Also, Fig. 6 shows plasma currents in different discharges with different gas injection and no gas injection.

According to these comparisons, after impurity injection and a growth of plasma density, hard X-ray intensity

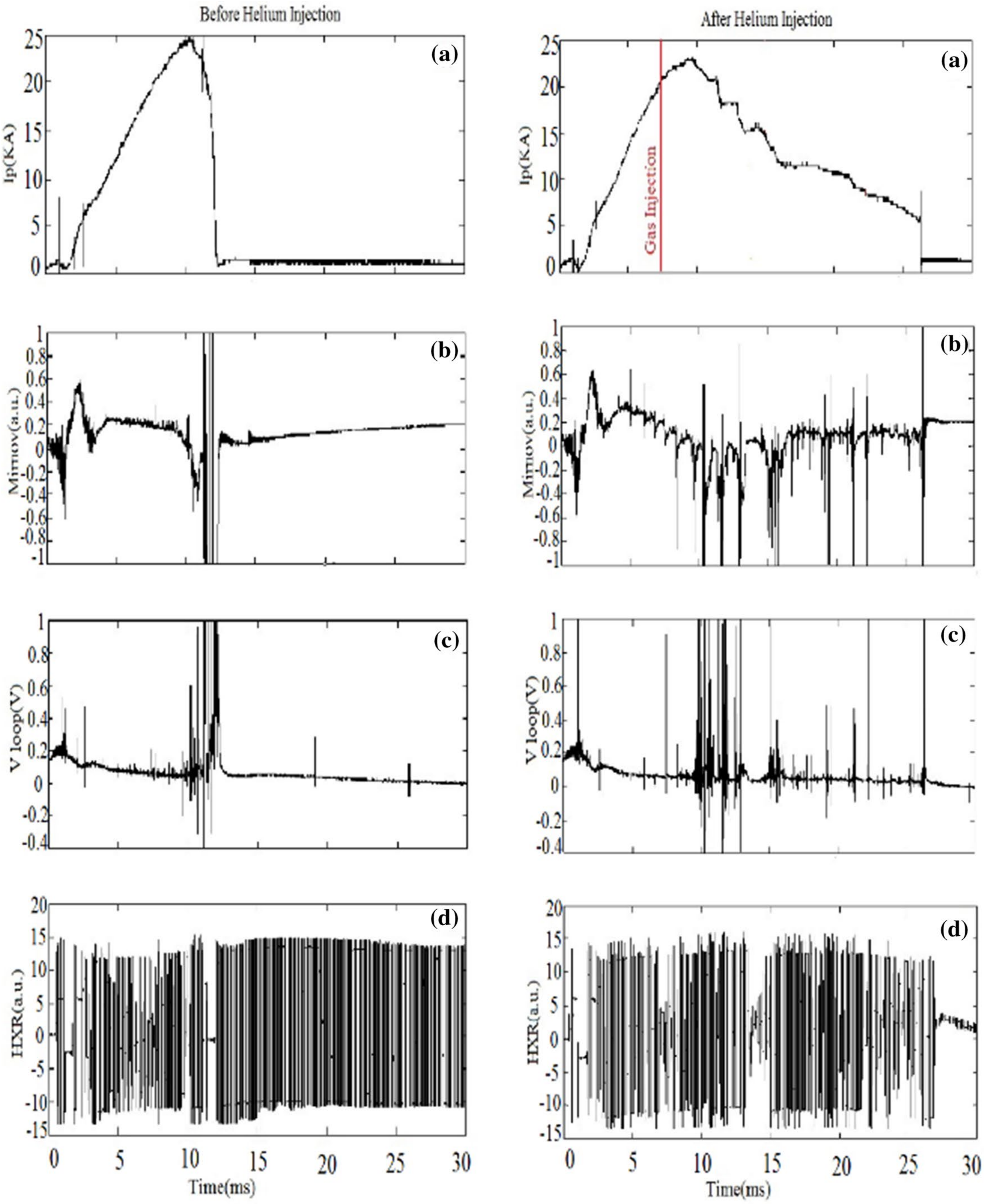


Fig. 4 (a) Plasma current (b) Mirnov oscillations, (c) loop voltage and (d) hard X-ray with respect to the time before and after Helium injection

and consequently runaway electron generation have been decreased. In fact, after penetration of impurity species into the plasma it causes the fast temperature drop and ceases the plasma current. As it is shown in the diagrams, injection of Hydrogen, Helium and Argon, respectively, has better ability to control disruption and prevent runaway electron generation. Because when the heavy Argon is injected into the vessel, it does not penetrate deep into the plasma and in contrary, injection of the lighter noble gases Hydrogen or Helium does not generate runaways because they penetrate deeper into the plasma and with more particles penetration into the plasma, density growth and with distribution of temperature in more particles, plasma cools quickly and shuts down before generation of these high-energy electrons at current quench phase.

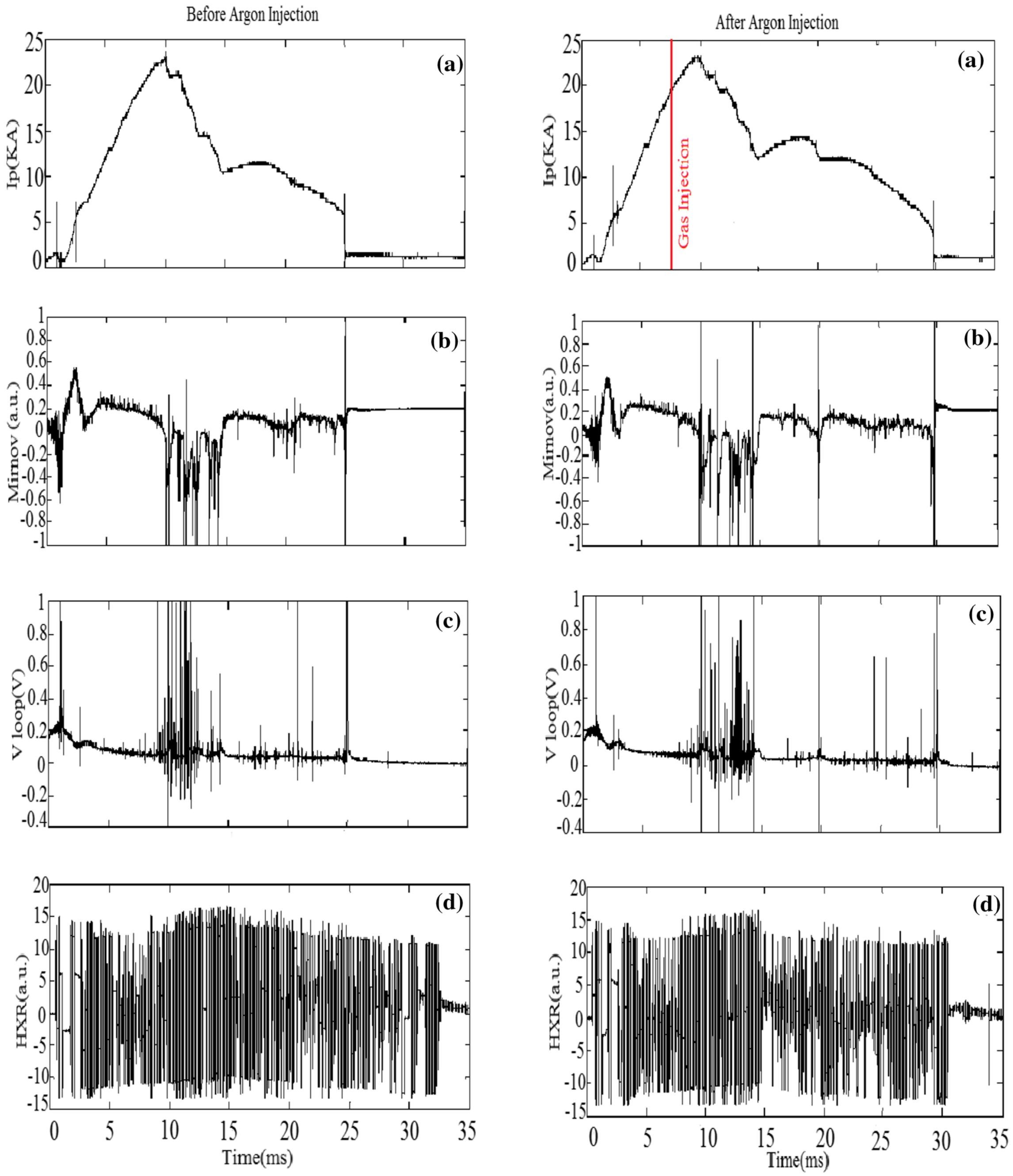


Fig. 5 **a** Plasma current, **b** Mirnov oscillations, **c** loop voltage and **d** hard X-ray with respect to the time before and after Argon injection

Figures 7, 8 and 9 shows the comparison between the photon number respect to energy, before and after gas injection.

According to Dreicer electric field $E_D = \frac{n_e e^3 (\ln \Lambda) Z_{\mathrm{eff}}}{4\pi \epsilon_0 m_e v_{\mathrm{th}}^2}$ (where n_e is the electron density, m_e is the electron mass, e is the elementary charge, ln is the Coulomb logarithm and v_{th} is super thermal electrons velocity), E_D is proportional to $\frac{n_e Z_{\mathrm{eff}}}{T_e}$; furthermore, the rate of primary runaway electron generation in tokamak is [12]

$$\frac{dn_r}{dt} = \lambda(\epsilon, Z_{\mathrm{eff}}) \vartheta_e(v_{\mathrm{th}}) n_e \tag{1}$$

And $\lambda(\epsilon, Z_{\mathrm{eff}})$ is

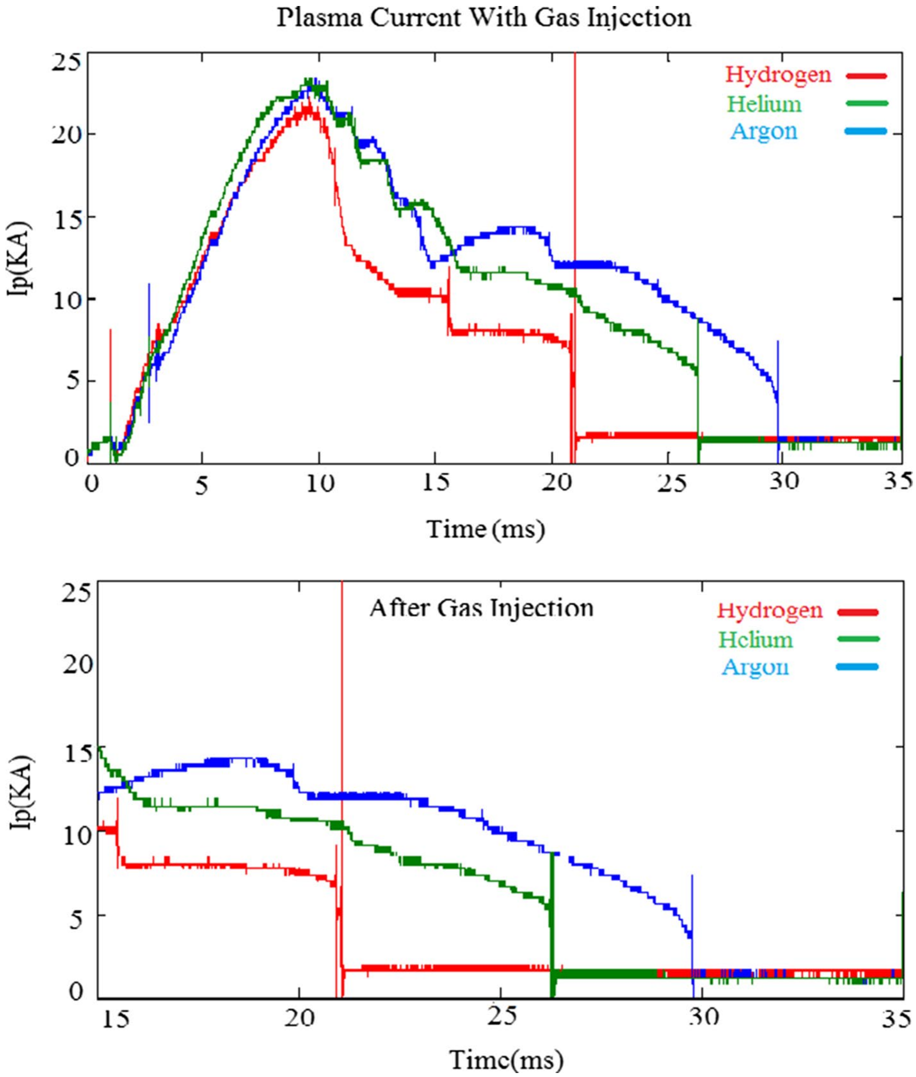


Fig. 6 The comparison of plasma currents in different discharges with different gas injection and no gas injection

$$\lambda(\epsilon, Z_{\mathrm{eff}}) = K(Z_{\mathrm{eff}})\epsilon^{-3(Z_{\mathrm{eff}}+1)/16} \exp\left(-\frac{1}{4\epsilon} - \sqrt{\frac{Z_{\mathrm{eff}}+1}{\epsilon}}\right) \tag{2}$$

where $\epsilon = \frac{E_{\mathrm{tor}}}{E_{\mathrm{D}}}$ and E_{tor} is toroidal electric field. The function $\lambda(\epsilon, Z_{\mathrm{eff}})$ shows that increment in toroidal electric field could cause increasing in the primary runaway electron generation [12]. If we consider $E_{\mathrm{tor}} = \boldsymbol{\eta j}$ (j for current density and $\boldsymbol{\eta}$ the Spitzer resistivity), toroidal electric field is proportional to $Z_{\mathrm{eff}}T_{\mathrm{e}}^{-3/2}$; therefore, the ratio of $\epsilon = \frac{E_{\mathrm{tor}}}{E_{\mathrm{D}}}$

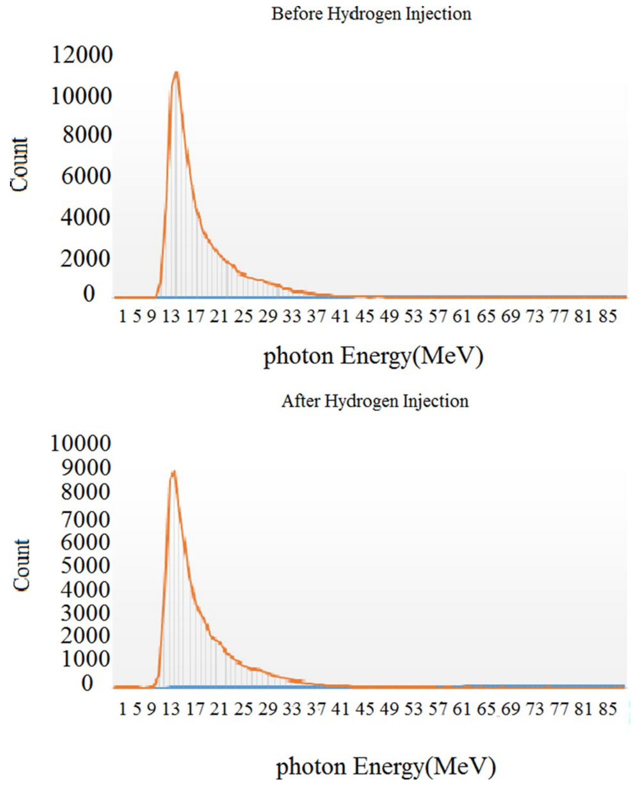
$$\epsilon \alpha n_{\mathrm{e}}^{-1} T_{\mathrm{e}}^{-1/2} \tag{3}$$

so we conclude that increment in density or temperature leads to decrease in ϵ and consequently $\lambda(\epsilon, Z_{\mathrm{eff}})$ reduction which means less runaway electron generation. While we have lower RE's generation, the hard X-ray spectrum and photon number would decrease.

As it is observed, after injection the graphs have a shorter stretch than before injection which means the reduction of hard X-ray photon number and consequently decrement in RE's generation.

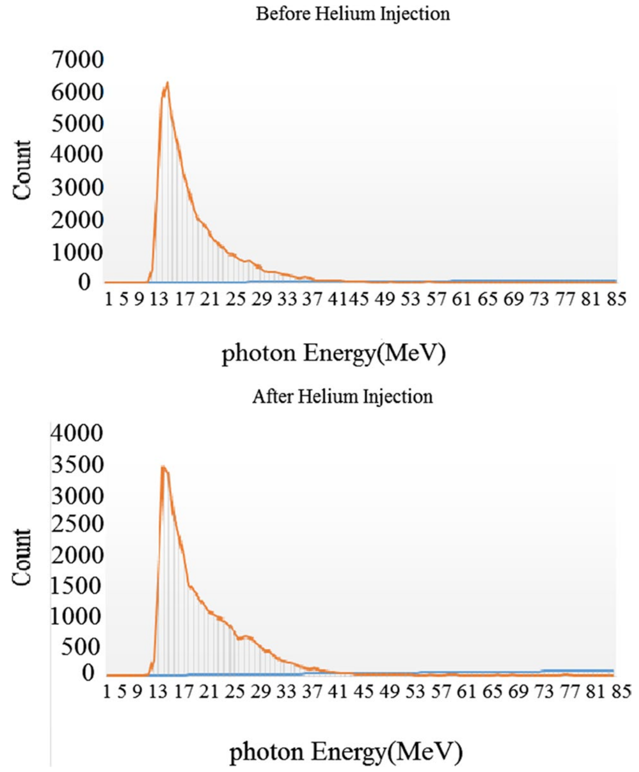
Summary

Disruptions are dangerous instabilities in tokamaks that should be mitigated to avoid its consequences such as runaway electrons generation. One possible disruption mitigation method is to inject impurities into the plasma to shut it down in a controlled way. This method was performed on IR-T1 with injection of noble gases: pure Hydrogen, Helium and Argon. The use of these non-reactive gases for disruption control ensures they fast removed from the vessel after the termination of a tokamak discharge. A piezo-valve was used for injection which has the precision


Before Hydrogen Injection

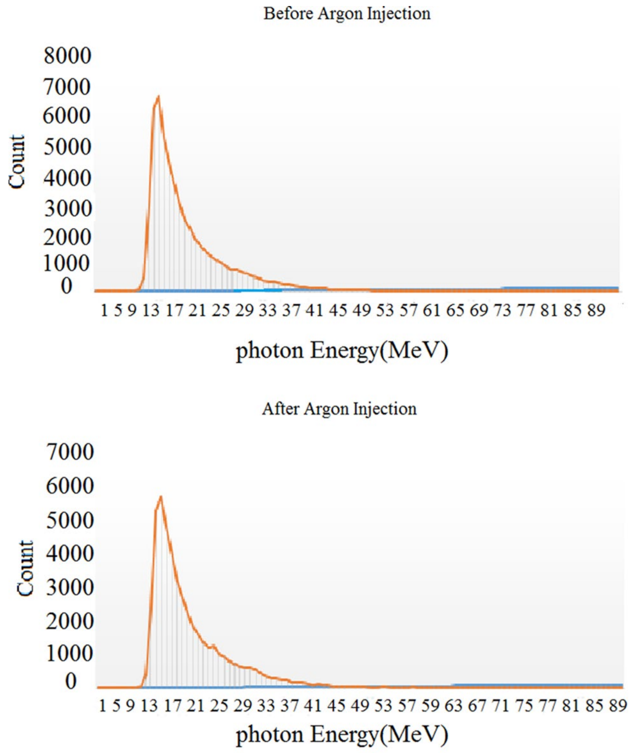
After Hydrogen Injection

Fig. 7 Hard X-ray photon number respect to photon energy before and after Hydrogen injection


Before Helium Injection

After Helium Injection

Fig. 8 Hard X-ray photon number respect to photon energy before and after Helium injection


Before Argon Injection

After Argon Injection

Fig. 9 Hard X-ray photon number respect to photon energy before and after Argon injection

of 1 ms. The plasma current, loop voltage, Mirnov oscillation and hard X-ray intensity were measured before and after injection. The comparison between these parameters indicates that after gas injection and increment in density, hard X-ray intensity and consequently runaway electron generation were decreased. Furthermore, noble gases with low-*Z* have more effect on disruption and runaway electrons control. Because, in the case of low-*Z*, gas particles can penetrate easily into the plasma, therefore, with density growth and distribution of temperature in a large number of particles, plasma cools rapidly before generation of runaway electrons.

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