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Improving Plasma Confinement by Controlling Hard X-Ray

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Since runaway electrons and magnetohydrodynamics activity can contribute to serious damage and energy losses in tokamaks, the effect of an external electric field on runaway electrons and hard x-ray spectra is investigated. Parameters such as the plasma current, the hard x-ray photons count and the mean energy of runaway electrons are measured. Positive and negative voltages of 300 V are applied at 10 ms after the plasma initiation (while the plasma is forming), at 15 ms (while the plasma is stable) and at 20 ms (while the plasma is fading away) to attain the most effective time of applying the external electric field. The number of hard x-ray photons has the most changes in the range of 0–200 keV when the external electric fields are applied. Also in the duration of 20–30 ms of plasma the greatest number of hard x-ray spectra is detected. When the external electric fields are applied, the mean energy of runaway electrons reduces significantly, especially at 15 ms (while the plasma is stable).

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The toroidal electric field assists the plasma current and consequently the plasma confinement in a Tokamak. When the toroidal electric field is applied to Tokamak plasma, thermal electrons gain velocity and therefore the friction among them increases rapidly. The speeds of electrons increase without any limitations until they are called runaway electrons. There are three main mechanisms that can give rise to runaway electrons in a Tokamak. Firstly, when the acceleration due to the electric field overcomes the drag force, electrons diffuse through the velocity space towards relativistic velocities. This is called the primary generation. Secondly, a runaway electron can collide with a thermal electron and can transfer so much energy at once to knock it into the runaway region of the velocity space. This mechanism is called the secondary generation (or avalanche) because it requires the presence of existing fast electrons to be active. Thirdly, in a fusion reactor energetic particles (α, β) and gamma rays are present. They can also transfer part of their energy to thermal electrons,[1,2] and produce a small amount of fast electrons.

It is known that the hard x-ray radiation arises when relatively fast electrons strike the limiter or the first wall. In present day tokamaks, runaway electrons are considered to be a serious concern. The final runaway energy can become sufficiently large as to cause serious damage to the Tokamak structures. This issue is of special practical importance in the case of disruption generated runaway electrons.[3] The large electric fields induced during the current quench phase may produce a large number of runaway electrons. The first and the most common goal of hard–x–ray measurement is simple evidence of the presence of runaway electrons in Tokamak plasmas.[4]

It has been proved that when magnetohydrodynamics (MHD) instabilities increase, the runaway electrons decrease. Applying an external field through the biasing electrode at the plasma edge is considered to be a promising technique in reducing the turbulence in the plasma and consequently increases particle confinement. Once the external field is applied, the $E \times B$ shear causes a reduction in radial flow and decreases the possibility of low-energy particles to collide with the Tokamak limiter.[5–7] The appropriate time of applying the external electric field has proven to be of great importance. Thus in this study, great attention is given to applying the appropriate time of the external electric field. Three different times of 10 ms, 15 ms and 20 ms of plasma are selected to apply the external electric field. Also a hard x-ray spectroscopy with a NaI scintillator detector is used to measure, analyze and observe how the hard x-ray radiation is affected after the external electric fields are applied.

IR-T1 Tokamak is an ohmically heated Tokamak with a circular cross section vacuum vessel made of stainless steel. It is also an air center Tokamak with a major and a minor radius of $R = 45$ cm and $a = 12.5$ cm, respectively. In this Tokamak, the toroidal magnetic field is 0.9 T, the maximum plasma current can reach 35 kA. The main parameters of the IR-T1 Tokamak plasma are presented in Table 1. In this study, an external radial electric field is launched at the plasma edge to spin a radial current between limiter biasing and vacuum vessel. The limiter is placed at the plasma edge $(r/a = 0.9)$,[8–10] and the biased voltage of ± 300 V is applied to the plasma at three different times. To reach promising results regarding plasma confinement and plasma energy, three different times of 10 ms, 15 ms and 20 ms are selected to apply the voltages.

In this experiment, the hard x-ray spectra were detected by using a 3×3 NaI-scintillator detector. The detector was placed at a distance of 2 m from

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the vacuum vessel in the equatorial plane. A multichannel analyzer (MCA) was used to obtain the hard x-ray spectrum count with respect to the energy of photons. The schematic diagram of the hard x-ray detector system and the IR-T1 Tokamak are shown in Fig. 1. During one shot, MCA is not able to count enough photons to produce the energy spectrum.

Table 1. The main parameters of the IR-T1Tokamak plasma.

Parameters	Value
Major radius	45 cm
Minor radius	12.5 cm
Toroidal field	<1.0 T
Plasma current	<40 kA
Discharge duration	<35 ms
Electron density	$0.7–1.5\times10^{13}$ cm^{-3}
Toroidal field coils	16

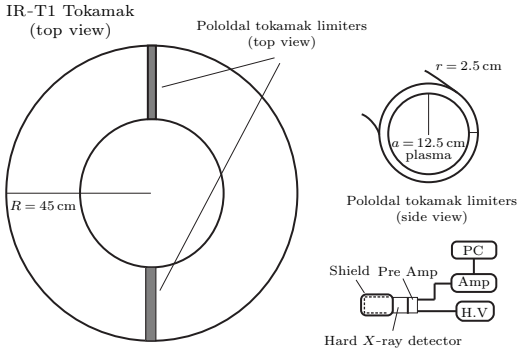

Fig. 1. Schematic diagram of the hard x-ray detector system and the IR-T1 Tokamak.

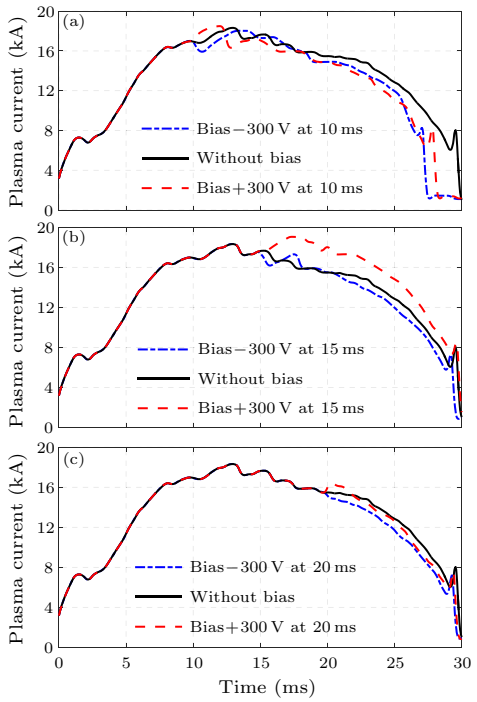

Fig. 2. Time evolution of the plasma current at different times of applying an external electric field: (a) 10 ms, (b) 15 ms and (c) 20 ms.

Therefore, to gain enough spectra, the photons counted in three identical shots were added together. It should be noted that the Am^{241} (59.54 keV) and Na^{22} (511 keV, 1.2 MeV) sources were employed to calibrate MCA in the range of the desire energies of this experiment.

Plasma currents were measured during different times of applying an external electric field on the IR-T1 Tokamak plasma. Figure 2 illustrates plasma currents with and without the limiter biasing system at different times of 10, 15 and 20 ms after starting the plasma. It can be seen from Figs. 2(a) and 2(c) that applying the external electric field of ±300 V at 10 ms (during the ramp up phase of plasma) and 20 ms (during the dying out phase of plasma), caused the plasma to fade away sooner. However, when the external electric field of ±300 V was applied at 15 ms (during the stable phase of plasma), the plasma current shows an improvement and lasts a bit longer (Fig. 2(b)).

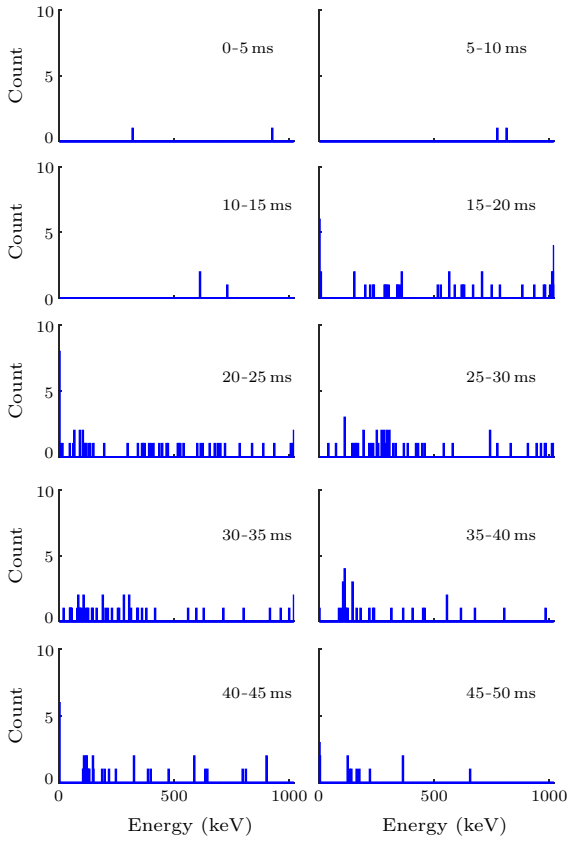

Fig. 3. Comparison of the hard x-ray spectra produced by the IR-T1 Tokamak plasma during a typical shot, without applying the external electric field in 10 different time intervals. Time evolution of hard x-ray radiation emitted by the IR-T1 Tokamak plasma of ten time intervals of 5 ms.

To obtain the mean energy of runaway electrons in shorter time intervals, the discharge time of 50 ms was broken down to 10 equal time intervals of 5 ms each. It can be observed from Fig. 3 that after 15 ms from the plasma initiation, the photons with the energy more than 100 keV are starting to appear. These photons grow longer in count until the plasma fade away. In this investigation the time interval of 50 ms was chosen due to the fact that the hard x-ray spec-

tra could be detected even after the plasma had died out. It can be seen from the hard x-ray count graphs that the number of low energy photons increases as the plasma moves towards the end of its existence.

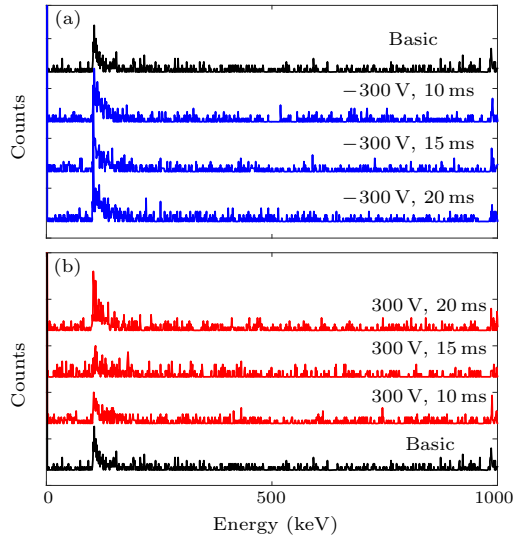

Fig. 4. Applied negative (a) and positive (b) biased voltages on the hard x-ray emission energy.

Figure 4 compares how positive and negative external electric fields were influential on the number of x-ray photons, particularly in the ranges of 100–200 keV. It can be seen from Fig. 4 that applying biased voltages at different times contributed to an overall change in the count axis. Figure 4(b) represents that applying the biased voltage of +300 V at 15 ms after the plasma initiation is to be the most effective timing in reducing the number of x-ray photons in the ranges of 100–200 keV. It can also be seen from Fig. 4 that no significant changes were observed during other times of applying the biased voltage especially at 20 ms. Comparing the biased voltages of +300 V and −300 V, the biased voltage of +300 V contributed to most changes in the count axis. Also, the most significant changes of hard x-ray photons appear in the range of 100–200 keV. The mean energy of runaway electrons is calculated from the MCA spectra, as shown in Fig. 5.

It can be vividly observed that the maximum energy of runaway electrons is in the 0–5 ms time interval. This is completely in agreement with the fact that during the plasma initiation, the loop voltage is high enough that the runaway electrons gain more energy from the electric field and reach their maximum values. Figure 5 altogether implies that when the positive and negative electric fields are applied to the plasma, the mean energy of runaway electrons decreases. This phenomenon happens due to the reduction of runaway electron collision with the limiters and the plasma chamber. It is necessarily noted that the external biasing system provides a force due to the external field to the electrons so that they avoid colliding with the limiters and the wall. Comparing the graphs in Fig. 5, it can be seen from Fig. 5(a) that the external electric fields of ±300 V at 10 ms cause the mean energy of runaway electrons to decrease. However, when the external electric fields are applied at 20 ms (Fig. 5(c)), the mean energy of runaway electrons would not experience a noticeable change in total. On the other hand, the most reduction of runaway electron mean energy can be observed in Fig. 5(b), where the external electric fields of ±300 V are applied at 15 ms.

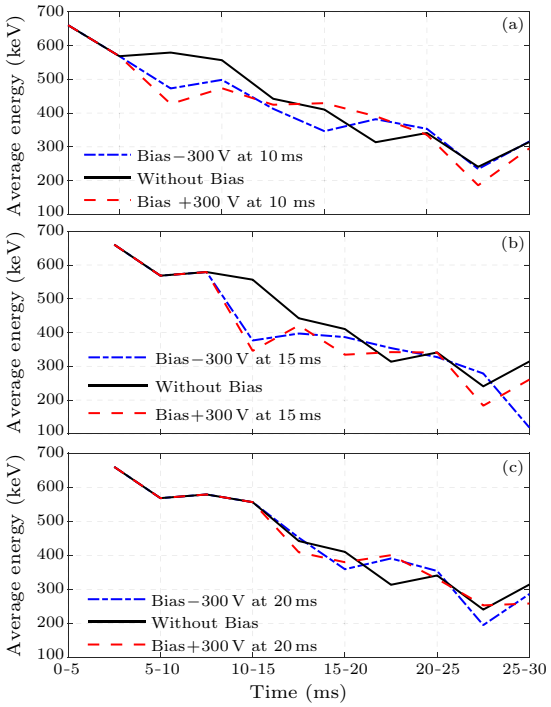

Fig. 5. Time evolution of the mean kinetic energy of runaway electrons during plasma discharge with and without applying biased voltages at different times of (a) 10 ms, (b) 15 ms and (c) 20 ms.

In summary, the effect of the external electric field on hard x-ray spectra due to the runaway electrons has been investigated. Parameters such as plasma current, hard x-ray photons count and runaway electrons mean energy in the presence and in the absence of the limiter biasing system are plotted. The Tokamak plasma is exposed to an external electric field produced by the biasing system of ±300 V in this study. The main purpose of this work is the search for appropriate time of applying the external electric field to the plasma and its effect on the hard x-ray emission rate. To achieve this goal, the voltages of ±300 V are applied at 10 ms after the plasma initiation (ramp up region), at 15 ms (stable region) and at 20 ms (ramp down region). Due to the presence of the external electric field, the runaway electrons experienced less collision with the limiters and the wall. As a direct consequence of this phenomenon, the hard x-ray emission reduced by applying the external electric field. It can be observed from the results that the mean energy of runaway elec-

trons drops the most when the external electric fields are applied at 15 ms after the plasma initiation.

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