Comparison of anomalous Doppler resonance effects with molybdenum and graphite limiters on HT-7

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(Received 8 September 2011; accepted 29 February 2012; published online 28 March 2012)

The material of limiter in HT-7 tokamak was changed from graphite to molybdenum in the last experimental campaign. The pitch angle scattering of runaway electrons due to anomalous Doppler resonance effects was observed. The experimental results agree very well with the stable boundary condition expected from the linear resistive theory but only agree with that from the nonlinear evolutionary of runaway-electron distribution theory in low electric field region. The current carried by runaway electrons is the same under different limiter conditions. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.3695093>]

I. INTRODUCTION

Relativistic runaway electrons in tokamaks have been studied consistently since the middle fifties.¹ In the initial startup phase of a tokamak plasma discharge, the electric field is strong and the plasma density is low, and these conditions are favorable for runaway electrons generation.² The critical velocity and energy can be obtained by the balance of the electron drag force and the collision friction when an electric field is applied.³ In this case, a runaway tail will develop in the distribution function. The distribution becomes unstable in a strong magnetic field due to the anomalous Doppler resonance (ADR) effects, which can be explained by the interaction between the runaway electrons and plasma waves.⁴ The ADR effects occurs when the condition $v_{\parallel} = (\omega_k + \omega_{ce})/k_{\parallel}$ is satisfied, where $v_{\parallel}$ and $k_{\parallel}$ represent the velocity and wave number of runaway electrons parallel to the magnetic field, respectively, ω_k denotes the frequency of the plasma waves, and ω_{ce} is the electron cyclotron frequency.

The turbulent pitch angle scattering (PAS) of the runaway electrons by unstable waves then enhances their perpendicular energy at the expense of the parallel energy,^{5,6} due to the ADR effects. The ADR effects have been studied in HT-7 from various aspects.^{7–12} It was concluded from the nonlinear of runaway electrons distribution theory that the stability of the runaway electrons is mainly determined by the density critical value, $\eta = \omega_{pe}/\omega_{ce}$, and electric field critical value, E/E_0 .⁵

In this paper, the difference of the ADR effects between two different limiter conditions is studied, and the statistical results are given. It is found that the experimental results agree with the nonlinear evolution of runaway electrons distribution theory only in the low electric field while the data agree with the linear resistive theory in all the electric field region. Besides, the current carried by runaway electrons is estimated.

II. EXPERIMENTAL SETUP

A. Alteration of limiter materials

HT-7 is a circular poloidal limiter superconducting tokamak with a major radius $R = 1.22$ m and minor radius $a = 0.27$ m.¹³ Figure 1 shows the position of all the limiters placed in the vacuum vessel. The water cooling belt limiter is placed in the mid-plane at the high field side and the toroidal limiter is placed at the bottom, and the superconducting poloidal limiter is also presented.

At the beginning of the 2011 HT-7 campaign, the material of the limiters have been altered from graphite to molybdenum, and the photos of the limiters are shown in Figure 2.

B. Diagnostics for runaway electrons measurements

During the experiment, three diagnostics are mainly used to study the ADR effects; a 16-channel heterodyne radiometer¹⁴ detects the electron cyclotron emission (ECE) in the frequency range of 98.5–126 GHz; two channels of runaway electrons diagnostics using BGO detector,¹⁵ measuring

FIG. 1. All the limiters used in the vacuum vessel in HT-7.

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FIG. 2. The photos of the limiters inside HT-7 tokamak. The left picture is molybdenum limiter after the alteration of limiter materials, and the picture in the right hand side is the photo of graphite limiter.

the thick target bremsstrahlung with the energy range of 0–10 MeV; a 12-channel hard x-ray detecting system using cadmium telluride (CdTe) semiconducting detector, monitoring the hard x-ray intensity within the energy range of 20–300 keV.¹⁶

The real 3D position of these diagnostics is shown in Figure 3. In Figure 4, each channel of the diagnostics is presented. The two channels of the runaway electron diagnostics, channel 3 and channel 4, detect the runaway electrons near to the magnetic axis. The 12-channel hard x-ray detecting system is placed vertically, and the detecting location of each channel of ECE diagnostics is calculated under the given experimental magnetic field.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The waveform of a typical low density discharge shot 110738 in HT-7 is shown in Figure 5. In this discharge, the central magnetic field is $B_0 = 1.8$ T. As shown in this figure, the ECE signals performed a rapid rise at time 0.616 s, and there is a disturbance in hard x-ray and runaway electrons signals at the same time. After that time, the ECE signals keep rising (or a step rise) while the other signals going down. This behavior of the signals indicate the parallel energy of the runaway electrons transports to the perpendicular energy, and the disturbance on hard x-ray and runaway electrons signals is attributed to the fact that some kinds of electrostatic wave was excited in the plasma. Since this shot is an Ohmic discharge, the runaway electrons can only resonance with the exited waves.

FIG. 3. The real 3D position of the diagnostics.

FIG. 4. Chord view of each channel of the diagnostics: The circle at the center is the detect position of runaway electrons diagnostics channel 3 and channel 4. The black line is each channel of vertically placed hard x-ray diagnostics, and from left to right is the channel 1 to channel 12. The small circles represent the detecting position of 16-channel ECE diagnostic system calculated at the experimental magnetic field.

FIG. 5. Waveform of the typical runaway discharge shot No. 110738 in HT-7 tokamak. The sub-panels from up to the bottom are (a) plasma current, (b) central density, (c) and (d) ECE06 and ECE07 signals, (e) hard x-ray signal, (f) and (g) runaway electrons diagnostics channel 3 and channel 4.

FIG. 6. The experimental data of ADR effects under both molybdenum and graphite limiters condition. The solid line is calculated from the nonlinear evolution of runaway electrons distribution theory and the dashed line is given by the linear resistive theory. The triangles denote the experimental data with molybdenum limiter and the circles are experimental data with graphite limiter.

Figure 6 illustrates the density critical value and the electric field critical value for the discharges with ADR effects under both molybdenum and graphite limiters condition. Comparing with the stable boundary calculated from the nonlinear evolution of runaway electrons distribution theory (solid line in Figure 6) and linear resistive theory (dash line in Figure 6),⁵ we find that all the experimental data are coincident with the linear resistive theory while few data in relatively higher electric field region ($0.8 < E/E_0 < 0.9$) violate the nonlinear distribution theory. At the same electric field critical value, the ADR effects happens at a higher critical density value.

The current I_r carried by runaway electrons can be presented in the following way:

$$I_r = -en_e v_{||} S_r, \quad (1)$$

where n_e , $v_{||}$, and S_r are the density, critical velocity, and the poloidal surface of the runaway electrons, respectively. Since the critical density of the runaway electrons can be derived from the balance between electron force and the collision friction, we notice that $I_r \propto n_e^{3/2}$ while the factor $\eta B \propto \sqrt{n_e}$.

After some derivation, we find

$$k = \frac{I_r}{(\eta B)^3} = \frac{1}{2} \sqrt{\frac{e^5 (\pi a_r^2)^2 \epsilon_0 \ln \Lambda}{4\pi (\gamma_e m_e)^4}} \sqrt{\frac{2 + Z_{eff}}{E}}, \quad (2)$$

where a_r is the radius of runaway electrons, $\ln \Lambda$ is the Coulomb logarithm, Z_{eff} and E are the effective particle charge and loop electric field, respectively.

TABLE I. The value of variables used in the calculation.

	Graphite	Molybdenum
Z_{eff}	3	10
E	0.2	0.33
a_r	0.034	0.023

Then the total plasma current can be represented

$$I_p = I_r + I_{thermal} = k(\eta B)^3 + I_{thermal}. \quad (3)$$

From Eq. (3), the plasma current is composed of two parts. One part of the current is carried by the runaway electrons and the other is carried by normal thermal electrons.

A calculation is done using variables listed in Table I.

The value of the Z_{eff} is estimated from previous HT-7 database because the lack of diagnostics in this experimental campaign, and the E_r are typical loop electric field in the experiment. The radius of the runaway electrons with graphite limiter is about 1/8 of the minor radius of HT-7 tokamak⁸ at the onset of ADR effects. In tokamak plasma, high-Z impurities lead to a stronger central accumulation,^{17,18} then the concentration of the high-Z impurities is higher near the center. The behavior of high-Z impurities leads to a higher concentration of electrons near the center due to the plasma electrical neutrality. So the radius of runaway electrons is reduced. The calculation result fits the experimental data fairly well. The value of k with the graphite limiter is about three times larger than with the molybdenum limiter while the current carried by normal thermal electrons are almost the same, which can be seen in Figure 7. These results need

FIG. 7. The calculation of current carried by the runaway electrons compared with the experimental data. The crosses are experimental data with graphite limiter and the data with molybdenum limiter are presented with stars. The dash line and the solid line shown in the figure are calculated with graphite and molybdenum limiters condition, respectively, using value of variables listed in Table I.

further investigation since many variables are assumed due to the lack of diagnostics.

IV. CONCLUSIONS

The pitch angle scattering of runaway electrons due to the ADR effects was observed after the alteration of the limiter materials from graphite to molybdenum in HT-7. After an investigation of ADR effects during Ohmic discharge in HT-7, the two critical values, the density critical value $\eta = \omega_{pe}/\omega_{ce}$ and the electric field critical value E/E_0 , are compared with both the nonlinear evolution theory and the linear resistivity theory of runaway electrons. We find that all the experimental data are coincident with the linear resistivity theory, and the data are coincident with the nonlinear evolution theory at relatively low electric field region while a violation can be found in a relatively high electric field region. The data also show that the ADR effects happen in a higher density critical value at the same electric field value with molybdenum limiter than with the graphite limiter.

The current carried by the runaway electrons is estimated. The result turns out that the ratio of current I_r to the factor $(\eta B)^3$ is about three times larger with graphite limiter than with molybdenum limiter, while the current carried by the normal thermal electrons are nearly the same, although the results need detailed research in the future.

ACKNOWLEDGMENTS

The authors like to thank Dr. Shiyao Lin for a fruitful discussion with the hard x-ray diagnostics. We also thank Dr. Ping Xu for a useful discussion about impurity behaviors. This work is supported by the National Magnetic Confinement

Fusion Research Program of China (Nos. 2010GB106000, 2010GB106001, and 2011GB107003), and the National Natural Science Foundation of China (Nos. 11021565 and 11175209).

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