PHENOMENOLOGICAL MODELING OF THE SUPRATHERMAL ELECTRON GENERATION DURING MAGNETIC FIELD LINE RECONNECTIONS IN EXPERIMENTAL ADVANCED SUPERCONDUCTING TOKAMAK

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The strong suprathermal electron generation is modeled in conditions of bursts of the strong MHD plasma activity in the Experimental Advanced Superconducting Tokamak (EAST) when magnetic field line reconnections took place. Because of the fast changes in the magnetic flux during these magnetic field line reconnections the instant bursts of the induced electric field occur. The instant changes in suprathermal electron density during these bursts of the induced electric field have been analyzed.

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INTRODUCTION

Runaway electron generation is a fundamental physical phenomenon. At the same time the runaway electrons during major disruptions can cause a serious damage of plasma-facing-component surfaces in large tokamaks like ITER [1, 2].

The strong electric fields induced during the tokamak disruption can generate a lot of these runaways. The energy of runaway electrons can reach as high as tens of Megaelektronvolt.

1. RUNAWAY GENERATION

Runaway electrons are generated when the electron energy exceeds a critical energy at which the electric field driving force is equal to the minimum frictional drag force in the plasma. There are primary runaway generation ($p_{\|0} >> p_{\perp 0}$, Dreicer generation [3]) and secondary runaway generation ($p_{\|0} << p_{\perp 0}$, avalanche generation [4]). The inequality

$$p_{//0} > p_{cr}(2+Z_{eff})^{0.25} \quad (1)$$

determines the runaway region of primary generation process [5] and the inequality

$$p_{\perp 0} > \sqrt[4]{12}\, p_{cr}(2+Z_{eff})^{0.5} / 3 \quad (2)$$

determines the runaway region of secondary generation process [6], where $p_{//0}$ and $p_{\perp 0}$ are the initial values of the electron longitudinal and transverse (with respect to magnetic field) momenta, respectively, and

$$p_{cr}^2 = e^3 m_e n_e L / 4\pi\varepsilon_0^2 E_{//} . \quad (3)$$

Here, e and m_e are the charge and the resting mass of the electron, n_e is the plasma density L is the Coulomb logarithm, Z_{eff} is the effective ion charge number, $E_{//}$ is the tokamak toroidal induced electric field and c is the velocity of light. The avalanche formed as a result of the secondary generation with avalanche time t_{av} [7]:

$$t_{av} \approx \sqrt{12} m_e c L (2+Z_{eff}) / 9eE_{//} . \quad (4)$$

2. RUNAWAY EAST DISCHARGE

The runaway ohmic discharge #28957 in EAST was performed in the limiter configuration with the toroidal magnetic field B_0 = 2 T, the plasma current I_p = 250 kA, the central line-averaged density $<n_e>$ = 2.2×10^{19} m^{-3}, the plasma major radius R = 1.86 m and the minor radius a = 0.45 m (see, e.g. [8]). At the plasma center, the electron temperature $T_e \approx 0.55$ keV was obtained using a soft x-ray pulse height analysis (PHA) system during the plasma current flat-top phase (duration of impulse was 5 s). MHD modes m/n=1/1 (the soft x-ray signal) and m/n=2/1 (the Mirnov coil signals) existed in the plasma, where m and n are the poloidal and toroidal mode numbers.

Runaway electrons were created by the ohmic coil during the start-up phase of the discharge. The runaway electrons were located around the q = 2 rational magnetic surface (ring-like runaway electron beam (see, e.g., [8]).

In shot #28957 three types of events were observed during the stepwise increases in the non-thermal ECE signal [9]:

1. The MHD (*m/n*=2/1) small amplitude spikes (type I events, small non-thermal ECE jumps) emerged approximately every 0.02 s and coincided with sawtooth *m/n=1/1* peaks.
2. Huge MHD spikes (type II events) emerged approximately every 0.5 s.
3. Larger amplitude MHD (*m/n*=2/1) spikes (type III events) were observed approximately every 0.3 s after each huge MHD spike (type II events).

In cases II-III types events the MHD (*m/n=2/1*) spikes were not correlated with the *m/n=1/1* sawtooth oscillations peaks.

Due to the local runaway generation processes, local changes in the plasma current density profile should occur (around the q = 2 rational magnetic surface, where the runaway electrons are located). The tearing mode stability depends rather sensitively on the current-density gradient in the vicinity of the resonant surface

[10]. These local changes in the plasma current density profile near the q = 2 rational magnetic may be the trigger for the strong enhancement of the MHD activity (m/n=2/1 spikes).

The generation of suprathermal electrons should be enhanced during these MHD spikes because of the fast changes in the magnetic flux (squeezing and reconnection of the magnetic field lines). As result of these changes in magnetic flux the bursts of induced electric fields occurred [10]. During these bursts of the induced electric field $E_{//}$, electron runaway region increased because the value of p_{cr} dropped (see Eqs. (1)-(3)). The abrupt growth in the suprathermal electron population occurred during these bursts of $E_{//}$. In Ref. [9] conclusion was made that the step-like non-thermal ECE jumps may be explained by the abrupt growth in the suprathermal electron generation (number of runaways) during MHD m/n=2/1 spikes.

In Ref. 8 the runaway energy $E \approx 30$ MeV was deduced for EAST shot #28957 and conclusion was made that the secondary runaway generation process should take place with avalanche time $t_{av} \approx 0.5$s (EAST #28957 parameters: $E_{//} \approx 0.1$ V/m, $Z_{eff} \approx 3$, and $L \approx 15$). The value of $t_{av} \approx 0.5$ s is of the same order as the value of the time of strong MHD activity (0.3 s or 0.5 s intervals).

The time behavior of runaway electron density n_r is described by the following well-known equation (see, e.g., [11-13]):

$$\frac{dn_r}{dt} = n_e(t)\nu_e(t)\lambda(t) + \frac{n_r(t)}{t_{av}(E_\parallel)} - \frac{n_r(t)}{t_l}, \qquad (5)$$

where

$$\nu_e = \frac{e^4 n_e(t) L}{4\pi\varepsilon_0^2 m^2 v^3}, \quad \varepsilon = \frac{E_\parallel}{E_D}, \quad E_D = \frac{e^3 n_e L}{4\pi\varepsilon_0^2 T_e}, \qquad (6)$$

$$\lambda(t) = K(Z_{eff})\,\varepsilon^{-\frac{(Z_{eff}+1)}{16}}\, e^{-\frac{1}{4\varepsilon} - \sqrt{\frac{(Z_{eff}+1)}{\varepsilon}}}. \qquad (7)$$

The first term in right part of Eq. (5) describes primary generation, second term describes secondary generation and last term describes the runaway loss. Solution of Eq. (5) has the next form:

$$n_r(t) = \exp\left(\int_{t_0}^{t} dt'\left(\frac{1}{\tau_{av}(E_\parallel)} - \frac{1}{t_l}\right)\right)\times$$
$$\times\left[n_r(t_0) + \int_{t_0}^{t} dt' n_e \nu_e \lambda_e \exp\left(-\int_{t_0}^{t} dt''\left(\frac{1}{\tau_{av}(E_\parallel)} - \frac{1}{t_l}\right)\right)\right]. \qquad (8)$$

Because of a very short time of the MHD m/n=2/1 spikes, the linear time dependence of changes of the bursting electric field was taken for modeling (Fig.1):

$$E_\parallel(t) = \begin{cases} E_0, & t_0 \le t \le t_1; \\ E_0 + E_m \dfrac{t - t_1}{\tau_{br}}, & t_1 \le t \le t_1 + \tau_{br}; \\ E_0 + E_m \dfrac{t_2 - t}{\tau_{br}}, & t_1 + \tau_{br} \le t \le t_2; \\ E_0, & t \ge t_2. \end{cases} \qquad (9)$$

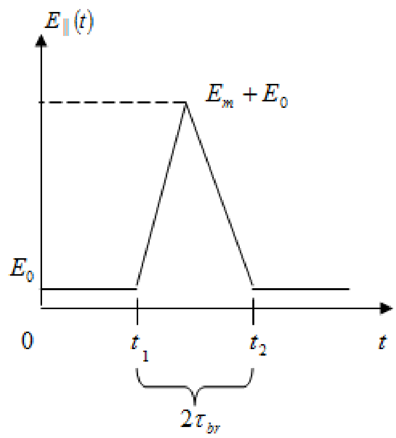

Fig. 1. Model for bursting electric field

The instant change in suprathermal electron density during the burst of induced electric field is given by:

$$\Delta n_r = \frac{E_m^{\frac{3}{2}}\varepsilon_0\sqrt{4\pi n_e}}{\sqrt{e m_e L}} \frac{K(Z_{eff})}{(2+Z_{eff})^{\frac{3}{4}}} \bar{\varepsilon}^{-\frac{3(Z_{eff}+1)}{16}} \tau_{br}\left\{\exp\left(\tau_{br}\left(\frac{1}{t_{av}(E_m)} + \frac{2}{t_{av}(E_0)}\right) - \frac{2\tau_{br}}{t_l}\right)\times\right.$$

$$\left.\times\int_0^1 dI(t)\exp\left(-\frac{\tau_{br}}{2t_{av}(E_m)}t^2 - \frac{\tau_{br}}{t_{av}(E_0)}t + \frac{\tau_{br}}{t_l}t\right) + \int_0^1 dI(t)\exp\left(\frac{\tau_{br}}{2t_{av}(E_m)}t^2 + \frac{\tau_{br}}{t_{av}(E_0)}t - \frac{\tau_{br}}{t_l}t\right)\right\}, \qquad (10)$$

where

$$I(t) = \left(t + \frac{E_0}{E_m}\right)^{\frac{3}{2} - \frac{3(Z_{eff}+1)}{16}} \exp\left(-\frac{1}{4\bar{\varepsilon}\left(t + \frac{E_0}{E_m}\right)} - \sqrt{\frac{(Z_{eff}+1)}{\bar{\varepsilon}\left(t + \frac{E_0}{E_m}\right)}}\right), \qquad \bar{\varepsilon} = \frac{E_m}{E_D}. \qquad (11)$$

Eq. (10) describes of instant change in suprathermal electron density at the time of the fast reconnection of magnetic field lines that was accompanied by the burst of induced electric field. Reconnections of magnetic field lines leads to the stochastization of magnetic field lines. Rapid changes of synchrotron spot structure and intensity during EAST experiments were result of changes in the runaway beam structure owing this stochastization. Recall, the synchrotron radiation is used for the direct observation of the runaway beam image. The loss term in Eq (10) describes the radial drift of suprathermal electrons due to this magnetic turbulence. This equation is used for modeling of experiments in tokamak EAST.

Note, in Refs. [12, 13] the equation (5) was used for modeling of disruption generated runaways in JET by including secondary runaway generation with the value of avalanche time, t_{av} , which was obtained in Ref. [7] (see Eq. (4)). This modeling of a JET disruption showed that here the secondary runaway generation plays a dominant role.

3. MODELLING OF THE SUPRATHERMAL ELECTRON GENERATION DURING HUGE MHD SPIKES

In modeling the same plasma parameters were used that were in the EAST shot #28957 (see Table).

Plasma parameters for modeling of #28957

The plasma parameters	Value
E_0 in Eq. (9)	0.1 V/m
E_m in Eq. (9)	(0.9…5) V/m
E_D	16 V/m
Plasma density, n_e	2.2×10^{19} m^{-3}
Effective ion charge, Z_{eff}	3
Coulomb logarithm, L	15
Electron temperature, T_e	550 eV
$K(Z_{eff})$	0.5

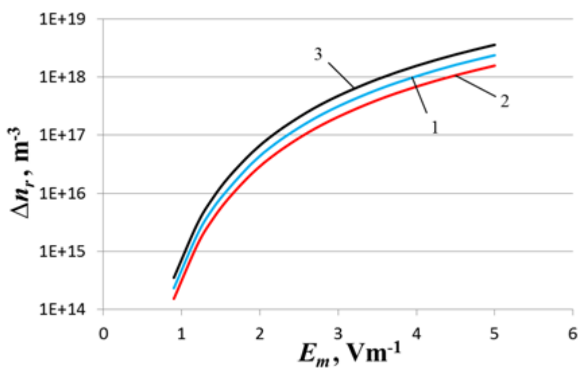

Fig. 2. Instant changes in the suprathermal electron density on amplitude of bursting electric field

Huge MHD spike (type II events) was modeled for assumed range of the induced electric field from 0.9 to 5 V/m. The calculation was performed by a standard program Microsoft Excel which realized Simpson method for numerical integration. In Fig. 2 the phenomenological modeling result of instant changes in suprathermal electron density is presented (curve 1 corresponds to 2.5 ms of burst duration ($2\tau_{br}$), curve 3 for 3.75 ms, curve 2 for 1.7 ms). These three values of burst durations are result of data analysis from Ref. 9. They are in good agreement with EAST experiments. Note, the value E_m=12 V/m of induced electric field was found during a series of minor disruptions in the T-10 tokamak [14].

CONCLUSIONS

The dependence of instant changes in suprathermal electron density from amplitude of bursting electric field during the strong MHD plasma activity in EAST has been investigated. We plan to use obtained results for further comparison with EAST experiments.

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ФЕНОМЕНОЛОГИЧЕСКОЕ МОДЕЛИРОВАНИЕ ГЕНЕРАЦИИ НАДТЕПЛОВЫХ ЭЛЕКТРОНОВ ПРИ ПЕРЕЗАМЫКАНИИ МАГНИТНЫХ СИЛОВЫХ ЛИНИЙ В EXPERIMENTAL ADVANCED SUPERCONDUCTING TOKAMAK

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Моделируется сильная генерация надтепловых электронов в условиях коротких вспышек сильной МГД-активности плазмы при перезамыкании магнитных силовых линий в Experimental Advanced Superconducting Tokamak (EAST). В результате быстрых изменений магнитного потока во время таких перезамыканий магнитных силовых линий индуцируются короткие вспышки электрического поля. Проанализированы мгновенные изменения плотности надтепловых электронов при этих вспышках индуцированного электрического поля.

ФЕНОМЕНОЛОГІЧНЕ МОДЕЛЮВАННЯ ГЕНЕРАЦІЇ НАДТЕПЛОВИХ ЕЛЕКТРОНІВ ПРИ ПЕРЕМИКАННІ МАГНІТНИХ СИЛОВИХ ЛІНІЙ В EXPERIMENTAL ADVANCED SUPERCONDUCTING TOKAMAK

Ю.М. Марчук, І.М. Панкратов

Моделюється сильна генерація надтеплових електронів в умовах коротких сплесків сильної МГД-активності плазми при перемиканні магнітних силових ліній в Experimental Advanced Superconducting Tokamak (EAST). В результаті швидких змін магнітного потоку під час таких перемикань магнітних силових ліній індукуються короткі сплески електричного поля. Проаналізовані миттєві зміни густини надтеплових електронів під час цих сплесків індукованого електричного поля.