Modeling of RA Generation in JET Disruption

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Abstract

To define initial conditions of RA generation in disruption modeling of current flattening in the second thermal quench was made. It is shown that at special shape of the total current spike with current growing to the end of spike at least two current flattening events have to take place. During the second current density redistribution a great amount of impurity ions penetrated in plasma volume and cool plasma down to temperature of several ev. As a result electric field rises and electrons run away. A model of disruption RA generation at presence of great amount of not fully ionized impurity ions is described. Calculation results are compared with results of RA current measurements on JET.

Introduction

It is known that observed on JET RA generation in discharge disruptions is quite irregular [1] and emission of hard X-rays and neutrons in the process can have different intensity in discharges with very similar parameters [2]. Therefore coincidence of modeling result with experiment for one select shot may be occasional and doesn't demonstrate that used model is sufficient to predict generation of RAs in other regimes and in other machines. Comparison of modeling and experimental results for wide set of shots with different parameters can give more reliable information about validity of accepted model. We used this approach in our analysis of published by JET team RA generation data [1,2,3].

Modeling of Current Flattening

For correct calculation of RA generation it is necessary to know initial distributions of plasma density, electron temperature, Z_{eff} and ohmic current density. Some of them (n_e, Z_{eff}, T_e) are measured in experiment only before the second thermal quench. Therefore to trace their evolution later we were forced to make modeling of different physical processes during current flattening in the second thermal quench using measured data as initial conditions. The model includes a) equations for current density based on energy conservation, b) enhanced thermal conductivity due to magnetic (input parameter) and electrostatic turbulence for electrons, c) free move of particles along magnetic field in a contact layer with effective thickness 'h' (the second input parameter), d) radiation cooling of plasma by impurities (a total flux of impurity is the third input parameter) and e) strongly enhanced move (mixing with different time of mix including $\tau_m \approx 0$ what is equivalent to homogeneous injection of impurity ions) of all particles in plasma cross-section during current redistribution stage. In a modeling process we found out that an only event of current flattening in a start of the second thermal quench can not give a shape of current spike characteristic for some disruptions. A typical example is shown on fig. 1 (a, JET shot № 13340 [1]). We divided the picture in three different stages: 1.the first current density redistribution, 2.relatively quiescent phase and 3. the second current flattening event (CFE). Usual shapes with one CFE with different final electron temperature (T_f) obtained with the model are shown also. Increase of a total current in the second stage of spike occurs due to decay of opposite current in outer shell and some growing of electron temperature in a vicinity of axis together with some decrease of magnetic turbulence. It is possible to obtain following current grow (in stage 3) and low electron temperature in the end of spike only if a second flattening event takes place before a total

current decay. Appearance in plasma of great amount of impurities during this event leads to lowering of electron temperature and fast decay of a total current consequently. A range of admissible input parameters at which modeling results coincide with experiment is quite narrow. An amplitude of current spike in any case depends only on current flattening in outer shells of current (at r>0.7a). Despite of some unclear points in the modeling described above (mixing description, time behavior of magnetic turbulence and so on) the main modeling results important for RA-generation stay unchanged at different approaches. They are following. 1. At least two events of current flattening should take place at the specific shape of current spike. 2. The near axis temperature of electrons before second current flattening is about 100 ev. 3. Amplitude of current spike depends only on current redistribution in outer part of plasma column. Central current density (where RA generation is maximal) can be unchanged or transformed arbitrary.

Model of RA Generation

1. In our calculations we assumed that hydrogen ion density is constant in time, homogeneous everywhere in plasma cross-section and its value is equal to 0.6-0.7 of a critical density for all regimes.

2. We assumed that initial Z_{eff} is defined by carbon ions C^{+6} and for each was taken according to [4]. After beginning of the second thermal quench concentration of C^{+6} is homogeneous also. Consequent value of Z_{eff} depends on amount of impurities appearing in plasma. Ionization and recombination of them and losses at the edge were included in calculations.

3. We believe that the second current flattening as the first one is accompanied by deep and fast penetration of weakly ionized impurity ions inside plasma column. We considered the penetration as a some kind of homogeneous injection of ions C^{+1} (or C^{+2} and C^{+3}) everywhere in plasma volume (what is a limit case of mixing with $\tau_m = 0$). Their ionization and radiation cool plasma electrons down to several ev. For calculation of this process we used 'cooling rates' [5] for every ion separately. A total number of injected ions was a main input parameter of the modeling.

4. Distribution of current density is very important parameter in calculations of RA generation. As shown in [6] one can make a rather accurate estimation of RA current by means of the following expression

$$j_{RA} = j_\Omega - 15\, C\, n_e\, \sqrt{T_e}/Z_{eff}$$

where ohmic and RA current densities in A/cm^2, T_e in ev and n_e in 10^{13}cm^{-3}. All plasma parameters have to be taken for a moment of RA generation. Multiplier C equals 1 for hydrogen plasma with completely ionized impurities and only Dreicer acceleration, $C = 1+k$ for plasma with great amount of not fully ionized impurities (k is a ratio of an additional drag force with bounded electrons to the drag force with free electrons ≈ 0.1) and $C = T_e/mc^2$ for a case of avalanche action. As it was mentioned above the current density redistribution in central part of plasma column can not be defined by modeling of current flattening. Therefore the ohmic current density in the beginning of current decay is really the second free parameter of the task.

5. Presence of great amount of not fully ionized impurity ions in plasma leads to appearance of additional friction between accelerating and bounded electrons of impurity ions or atoms. Well known formula for this force gives too high value of it in a range of low electron energy. Therefore we accepted a new expression for the force:

$$F_{eC0} = 4\pi e^3 n_{C0}(2\ln mv^2/2I_1 + 2\ln mv^2/2I_3 + 2\ln mv^2/2I_5)/mv^2.$$

where n_{C0}- concentration of carbon atoms, $mv^2/2$ - electron kinetic energy, I_1, I_3 and I_5- ionization potentials of electrons on outer, intermediate and inner shells of carbon atom. For ions C^{+1} the first term in brackets will be $1 \cdot \ln mv^2/2I_2$ and so on. Moreover if a critical energy of electrons ($W_{cr} \approx T_e E_{cr}/E$) is lower I_5 then the last term in brackets has to be omitted. Validity of this expression was verified by the following procedure. The suggested formula can be used for calculations of 'cooling rates' being integrated for electrons with maxwellian energy distribution at some temperature. Results of such procedure (made for C^{+1},C^{+2}.C^{+3},C^{+4} and $T_e=$ 100..500 ev) give a power of energy losses in almost all points slightly above (<10%) of the data presented in [5]. (Cooling rates of [5] don't consider kinetic energy of secondary electrons as energy losses) It is quite good coincidence for our purposes. Presence of not fully ionized impurity ions changes Dreicer source of RA. New critical field is now $E_{cr} = E_{crD}(1+k)$ ($k=\Sigma F_{eCi}/F_{ee}$). Therefore

$$S_D \approx \exp(- (1+k)(1+k_m)E_{crD}/4E - ((Z+1+k)(1+k)E_{crD}/E)^{1/2})$$

where k_m - mean value of k in energy interval 0 - W_{cr} ($k_m \approx 0.5k$). Avalanche multiplication changes too due to ionization of bounded electrons by RAs with transfer of energy equal to $W_{cr}+ I_i$.

In accordance with mentioned above considered processes are the following. Ions C^{+1} are injected in plasma with known (variable) distribution of current density, homogeneous plasma density, and $T_e=T_i=100ev$. There is no any heat or particles transport what leads to small overestimation of needed flux of impurities. Injection of ions was increased step by step with calculation of RA generation what is shown in fig2a. In a case of only Dreicer acceleration a time of RA current formation is less of 1 msec. If avalanche is included this time becomes longer (≈ 5 msec) and we stopped our calculations after 10 msec. We used circular cross-section for plasma and accordingly reduced value of total current ($I_{mod}=I_{real}1 /\varepsilon$). For calculations of central current density we assumed that elongation (ε) of near axis magnetic surfaces was about 1.3 and $q(a) \approx 3$.

Results

Growing of RA-current with increase of carbon ions flux is shown in fig2a. It is seen that transition to RA generation occurs very quickly in narrow range of carbon flux. Regimes denoted by different letters are explained below. Dependence of RA current on current density distribution is shown in fig2b. We present several different cases. A) only Dreicer acceleration for pure hydrogen plasma at peaked current density distribution ($q(0)=1$). The RA current in the case is significantly lower than measured at low total currents. B) The same case for slightly expanded current density ($q(0)=1.2$). C) The same conditions that in B) but with taking into account the influence of not fully ionized carbon ions. D) The same as C) with avalanche multiplication. Two other curves relate to very flat current density distribution: $j_\Omega=j_0(1-0.95r^2/a^2)^{0.4}$. E) Dreicer acceleration with impurities. F) Dreicer acceleration with impurities and avalanche. It is worth to notice that final value of RA current can increase up to 25% at plasma move along the major radius ($I'_{RA}= I_{RA}R/(R-\Delta R)$).

We modeled also possible influence of magnetic turbulence and current filamentation on the value of RA current. In the main both factors are able to increase it. But really the RA current formation takes place at very low electron temperature when all magnetic disturbances dissipate very quickly (in several mksec).Therefore its influence have to be very small. We modeled also behavior of warm electrons at lowering of electron temperature and growing of electric field as a result [7]. It was shown that in all regimes with different n_e, T_e, Z_{eff} and j_Ω there is a critical energy dividing electron population in two parts. Electrons with energy higher then critical value are accelerated by electric field. But number of such electrons is very

low and their contribution to RA current is negligible. The acceleration of these electrons begins much earlier of the main bulk of RAs. In this time magnetic turbulence is quite intensive and accelerated electrons can diffuse to plasma edge. Therefore they could be responsible for an early pulse of hard X-rays observed in experiment.

Conclusion

1. It is shown that the suggested model can explain results obtained on JET if assume that current flattening grows with the total current. Decreasing of Dreicer born RAs with a total current growing correlates with measured neutron yield ($Y \approx I^{2.6}$) though such estimations have to be made with caution since in short time considered a part of magnetic flux is frozen in metall structures of device.

2. Two factors – flux of impurities and current density distribution after current flattening – could be a reason of measurements scattering
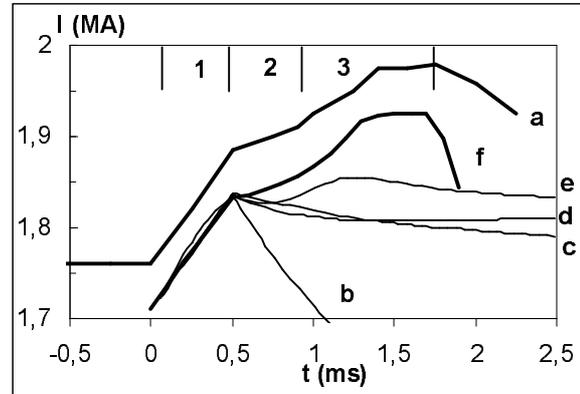

Fig1.Shapes of current spikes: a - JET №13440, b- only CFE with T_f=5 ev, c- T_f=50 ev, d - T_f=100 ev, e - T_f=100 ev with slow decrease of edge T_e, f - two CFE in the first and third stages of current spike.
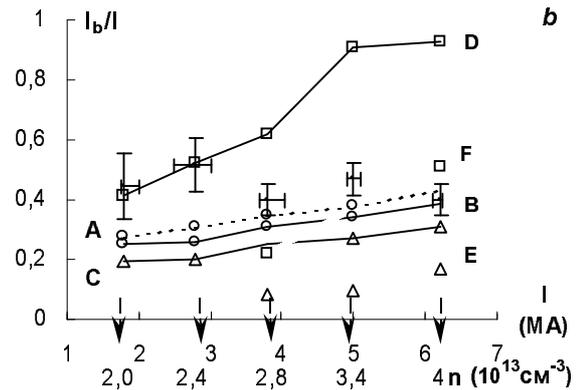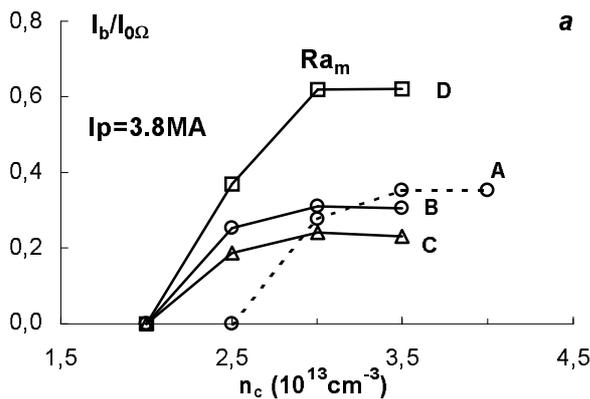

Fig2a - RA current at various density of injected carbon ions, fig2b - RA currents in JET disruptions - experimental + [3] and modeling results (RA_m) for different total currents: A)- only Dreicer acceleration in pure hydrogen plasma at peaked current density (q(0)=1). B) The same for slightly expanded current density (q(0)=1.2). C) The same conditions as in B) but with influence of not fully ionized carbon ions. D) The same as C) with avalanche multiplication. E) Dreicer acceleration with impurities at $j_\Omega = j_0(1-0.95r^2/a^2)^{0.4}$. F) The same with avalanche.

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