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S. Pestchanyi, M Lehnen, A. Huber, S. Gerasimov, Yu. Igitkhanov, I. Landman
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S. Pestchanyi[1], M Lehnen[2], A. Huber[2], S. Gerasimov[3], Yu. Igitkhanov[1], I. Landman[1]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]*Karlsruhe Institute of Technology, 76344, Karlsruhe, Germany*
[2]*Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK*
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ABSTRACT
Analysis of the available data on massive gas injection (MGI) experiments in JET and comparison with simulation results allows developing the MGI scenario for the TOKES code, which describes the sequence of energy and particle transport processes. Understanding the physics of the processes allows extrapolation of the JET results to ITER. The scenario will be used to simulate the ITER wall heat loads and to estimate the wall damage.

1. INTRODUCTION

The physics of disruptions and mitigation of the first wall damage are among the most important issues for ITER performance. Unmitigated disruption in ITER will probably damage the first wall causing significant erosion. In nowadays tokamaks the wall damage is negligible because of moderate energy content. This allows investigation of the disruption processes with the aim of extrapolation of the results to the ITER conditions. Experiments performed in modern tokamaks have proved that fast massive injection of noble gas can effectively mitigate the disruption, transforming both, the plasma energy and the poloidal magnetic field energy into radiation, which loads the first wall more evenly than the direct plasma impact does.

Previous investigations of the tokamak thermal energy irradiation during thermal quench (TQ) of the MGI in JET [1] have revealed open issues in the plasma evolution during the thermal quench of MGI. The most important one is the nature of thermal energy transport.

Main purpose of this paper is to validate and to specify the scenario for TOKES code, developed in previous paper [1], which describes physical processes determining transport of thermal energy and poloidal magnetic field energy during MGI using analysis of experimental data from JET. The scenario is used for simulation of the radiation heat load on the tokamak first wall for assessment of the wall damage. The scenario for MGI is essentially the same as the scenario for disruptions but with some specific features. For example, the disruption caused by MGI started not from inherent plasma evolution, but due to cooling of the plasma edge with injected noble gas (NG). Besides, MGI is used for mitigation of the disruptive wall loads, so it is assumed that a hot plasma touching wall should be avoided.

Physical phenomena in plasma during disruptions have been intensely investigated and the results are summarized in [2,3], but the physics of these events are not fully understood, see for example the discussion in [4-6]. Two distinct physical phenomena have been proposed in [2] as energy and particle transport mechanisms during disruption: (1) the magnetic fluctuations under the non-linear development of helical instabilities (non-linear tearing mode), which effectively enhances conductivity across the magnetic field and (2) the non-linear development of the ideal helical instability in conditions of low magnetic shear. This development results in capturing and macroscopic transportation of ‘bubbles’ (helical flux tubes with cold peripheral plasma) from the boundary into the centre of the plasma column. Contributions of these mechanisms to disruptive energy transport have been discussed there [2].

Analysis of experimental data from JET allows us to specify these contributions for MGI. In following considerations the disruption caused by MGI is divided, as usual, into the pre-TQ, TQ itself and CQ phases.

2. JET DATA ANALYSIS AND SIMULATIONS

2.1 PRE-TQ

In contrast with the disruptions, fast plasma evolution in MGI starts when the front of injected noble gas arrives inside the separatrix and interacts with confined hydrogen plasma. As a result of this interaction, the H plasma is cooled only at the edge of the confinement, see Fig.1. The electron temperature profiles $T_e(r)$ are dropped in the thin layer inside the separatrix, where the injected gas ionized and the NG plasma irradiates the thermal energy of the affected H plasma. It is seen from Fig.1 that the T_e profiles remain unchanged from the magnetic axis till the cooling front, which moves inside from the separatrix. This proves that the thermal energy transport plays negligible role at this phase, so the electron temperature evolution is determined by NG velocity, ionization rate and by the cooling rate of radiation from the ionized NG. The stationary magnetic configuration remains stable at this phase. Experimentally measured time duration of the pre-TQ phase in JET (4-8ms) is determined by injector parameters and by radial distribution of the thermal energy. At this phase the total plasma current I_{tot} is slightly reduced as it is seen in the insert in Fig.2. The pre-TQ phase ends when the electron temperature drastically changes its evolution: the temperature profile abruptly starts to fall down everywhere from the magnetic axis to the separatrix as it is shown in Fig.2.

2.2 TQ ITSELF

Fast drop of the whole electron temperature profile indicates that the radial transport is radically increased. One should note that the measured profile evolution is due to increased thermoconductivity (phenomenon (1) from [2], described above) and not due to large scale convection. From experimental results it is evident that the temperature profile evolves according to the parabolic thermoconductivity equation, without large convective transport of the plasma from the bulk towards the separatrix. Convective energy transport at TQ would assume that hot plasma with characteristic temperature of several kilo-electron-volts crosses the separatrix. This is not the case for all the JET shots under consideration. For all the JET pulses considered one can conclude that convection may play a role in energy redistribution inside the core and does not contribute to the energy transport outside the separatrix. This statement is supported with measurements of the total heat flux to the divertor and the wall, estimated in [7,8] at the level of few percent of the confined energy. Another evidence for the enhanced thermoconductivity is sharp increase of oscillations of the magnetic field B_θ during the TQ, illustrated in Fig.2. These oscillations are typical for TQ of all the disruptions under consideration and they are presumably stochasticizes the magnetic surfaces. Cross magnetic field thermoconductivity with stochastic braiding of magnetic surfaces has been proposed as one of two mechanisms of the radial energy transport during TQ [2]. The effective conductivity coefficient calculated by Rechester and Rosenbluth [9] has already been used for TOKES simulations of JET experiments [1].

3. DISCUSSION

TQ phase of the disruption starts when tearing instability ergodizes the magnetic surfaces and drastically increases the radial thermoconductivity approximately by three orders of the magnitude. It is well known [3] that the tearing modes are developed when sharp negative current gradient arises inside the $q = 2$ magnetic surface. But in JET experiments the transition between pre-TQ and TQ takes place when the electron temperature cooling front penetrates much deeper than the $q = 2$ surface. For example, the $q = 2$ magnetic surfaces are situated at 18cm and 34cm from the separatrix position for JET Pulse No: 76314 and JET Pulse No: 76320 correspondingly, see Fig.1. However, the temperature cooling front positions just before TQ are at the distances 25 cm and 45 cm correspondingly, see Fig.1. This discrepancy may be explained with the fact that the current density gradient delays from the temperature gradient. Unfortunately, the current profile does not measured during the disruptions in JET experiments. Nevertheless, one can easily calculate the current profile from the measured temperature profile. The simulations performed have revealed that the current density diffuses to plasma with better conductivity during pre-TQ when the edge is cooled down. The peak on the current density is due to the current redistribution from the cooled edge to the neighboring well conducted hot plasma. This process obeys the conservation of poloidal magnetic flux $\Phi = \int_0^a B_\theta d$ between the magnetic axis and the metallic wall – both are effectively superconducting at time intervals of few milliseconds. The flux conservation is valid till the plasma at the magnetic axis is hot – of a several keV. The current peak width and height are determined by the magnetic field diffusivity in the transition between the hot bulk plasma and the cooled edge; see the simulation results in Fig.1. Calculated positions for maximum of current gradient correlates better with the calculated $q = 2$ position. At the pre-TQ phase, when the magnetic flux Φ is conserved, the total plasma current is slightly reduced due to increase of the internal inductance of the current profile, as it is seen in the insert in Fig 2 and in Fig. 3.

Effective radial thermoconductivity coefficients $\chi_{eff}^{e,i}(T) = A_{br}\, \chi_{\parallel}^{e,i}(T)$ through the ergodized magnetic surfaces are proportional to the parallel coefficients $\chi_{\parallel}^{e,i}(T)$ with some amplitude, dependent on the degree of the surfaces entanglement, so called braiding coefficient A_{br}. Both coefficients, for electrons and ions should have the same braiding coefficient because it depends of the magnetic field characteristics, not from particle mass. That is, fitting A_{br} from the measured evolution of electron temperature profile would define $\chi_{eff}^{i}(T)$ also. But, $\chi_{\parallel}^{i} << \chi_{\parallel}^{e}$, so ion temperature drop needs much longer time for thermoconductivity through the distance of small plasma radius a. Nevertheless, the measured time dependence for plasma diamagnetic energy W_{dia} shown in Fig.2 indicates that ion cooling time is of the same order as for electrons. Electron-ion equipartition time is also too long to explain ions cooling via electron conductivity.

The only remaining channel for ions cooling is convective mixing of cold NG plasma accumulated at the plasma edge during pre-TQ with hot H plasma from bulk. One can suppose that the phenomenon (2) proposed in [2]: penetration of the ‘bubbles’ filled with dense and cold NG plasma is responsible for this mixing of H and NG plasmas. Analyzing the available data on MGI in JET one can propose the following sequence of events during TQ.

First of all, the tearing modes are developed, when the current density gradient, moving behind the cooling front crosses the $q = 2$ surface. Development of this instability proceeds in cold plasma: $T_e < 100$eV at the $q = 2$ surface, so the time-scale for its growth is $\tau_S = \tau_R^{3/5}/\tau_A^{2/5}$~0.5ms where τ_R is the magnetic diffusion time and τ_A is the Alfven time with respect to the poloidal magnetic field. This estimation is in agreement with the measured magnetic field oscillation growth: approximately 10 times during 1ms, see Fig.2. Ergodization of magnetic surfaces due to the instability increases the electron and the ion thermoconductivities, so T_e drops everywhere down to 50-100eV, or even less, according to the JET measurements (see the last curve in Fig.2). At the same time ions remain hot – even the enhanced thermoconductivity and *i-e* equipartition is not enough to cool them. The resulted highly resistive plasma became unstable for ideal kink mode, so large bubbles with cold NG plasma penetrate inside the bulk plasma. One can find the evidences for this process from the bolometry reconstruction for the radiation source (RS), though the bolometers signal is smeared due to heat transfer delay of 2ms. For example, the sequence of RS for JET PulseNo: 77806 is shown in Fig.3. During pre-TQ RS is situated at the edge of the confinement, highly contaminated with NG plasma. The first part of TQ, when the electron temperature drops almost to zero, the RS is situated at the edge also; there are no evidences for convective mixing at this stage. But later, see the third panel in Fig.3, a clear visible bubble penetrates to the centre. Unfortunately, ECE diagnostics for T_e measurement fails during disruptions of H-mode pulses in JET, but it is available for L-mode pulses. However, for this pulse W_{dia} drops to approximately half of the value at the TQ start. This is indirect evidence that T_e drops to zero and T_i remains unchanged at the start of mixing. The total plasma current reaches its minimum at this time, indicating that the current channel shrinking stops. Simultaneously the flux Φ conservation is no more valid due to electrons cooling down at the magnetic axis. In L-mode pulses, where the diagnostics is available, the T_e drop coincides with the minimum of I_{tot}, indicating the transition from conductive phase of TQ to the convective mixing of H plasma having cold T_e and hot T_i with the cold NG plasma. This mixing of bulk and edge plasmas effectively widens the current channel, producing the increase of I_{tot}, so called current spike [3].

One should mention that apart from the conventional explanation of the current spike with the current profile flattening and widening [2,3] there is an alternative point of view suggested by L. Zakharov [4,6], who proposes surface Hiro current, generated as a result of the m/n = 1/1 kink mode development during VDE disruption and the sharing of Hiro current with the wall [4]. This explanation could be reasonable for unmitigated disruption, when the plasma touches the wall, but for disruptions caused by MGI plasma does not touches wall. Analyzing the comparison of the calculated Hiro current with measurements from JET, shown in Fig.7 of [4] one can notice that the surface current is equal zero at the time of the current spike. The Hiro current mechanism is developed later, at CQ of the disruption.

Another objection in [6] against the current flattening as the cause of the current spike is as follows. If I_{tot} increase is due to the internal inductance L decrease under the flux Φ conservation condition, than the magnetic energy
$E_{mag} = \Phi^2/2L$ should increase during the instability. This energy increase conflicts with the nature

of MHD instabilities, which should be driven by relaxation of magnetic energy. But, this argument, being valid for unmitigated disruption in hot and conducting plasma, is not valid in the case of MGI, when the current flattening proceeds in cold and resistive plasma. For MGI both, the flux Φ and E_{mag} are consumed, so for the current spike one should have the flux and the energy decrease rates fitted in such a way, that the plasma current increases. It is quite simple to fulfill such a condition. As an example one may propose a model with magnetic field diffusion

$$\frac{\partial B_\theta}{\partial t} - \frac{\partial}{\partial r}\frac{D_m}{r}\frac{\partial r B_\theta}{\partial r} = 0, \quad D_m = \frac{c^2}{4\pi\sigma}$$

and simplified convection, which starts at $t > t_c$, (Fig.4):

$$J = \mathrm{rot}\,(B_\theta), \; \frac{\partial J\,(r,t)}{\partial t} = -\frac{J\,(r,t) - J_c\,(t)}{\tau_{conv}},$$

where $J_c(t)$ is flat current density independent of r and calculated from $J(r,t)$, using energy conservation condition; the boundary conditions are $B_\theta = 0$ at the magnetic axis and the flux conservation at the wall. Evolution of B_θ is due to the measured temperature evolution during MGI. The results of such a model are shown in Fig.4. The energy and the flux are decreased monotonically, but the plasma current shows spike.

CONCLUSIONS

JET diagnostics oriented to measurement of plasma parameters in stationary regime. This is why the measurements during disruptions (few ms) are very incomplete. Nevertheless, analysis of the available data combined with simulation results allows developing the MGI scenario, which describes sequence of energy and particles transport processes. Understanding of physics of the processes allows extrapolation of the JET results on ITER. The scenario reads: (i) on pre-TQ phase cross transport of energy is negligible; NG ionization, excitation and radiation are the main contributors for plasma cooling at the edge; current density profile shrunk with increasing negative gradient, which delays from the cooling front. (ii) when the current gradient crosses $q = 2$ surface the tearing modes are developed, ergodizing the magnetic field; as a result TQ starts, enhanced thermoconductivity cools down electrons and remain ions hot. (iii) Cooling of ions is due to convective mixing of cold NG plasma with H plasma, having cold electrons and hot ions. This mixing flattens the current profile and produces the current spike, which indicates the transition from TQ to CQ. Convective energy transport to the divertor and to the vacuum vessel wall is negligible. This scenario will be used for TOKES simulations of the ITER wall damage during MGI.

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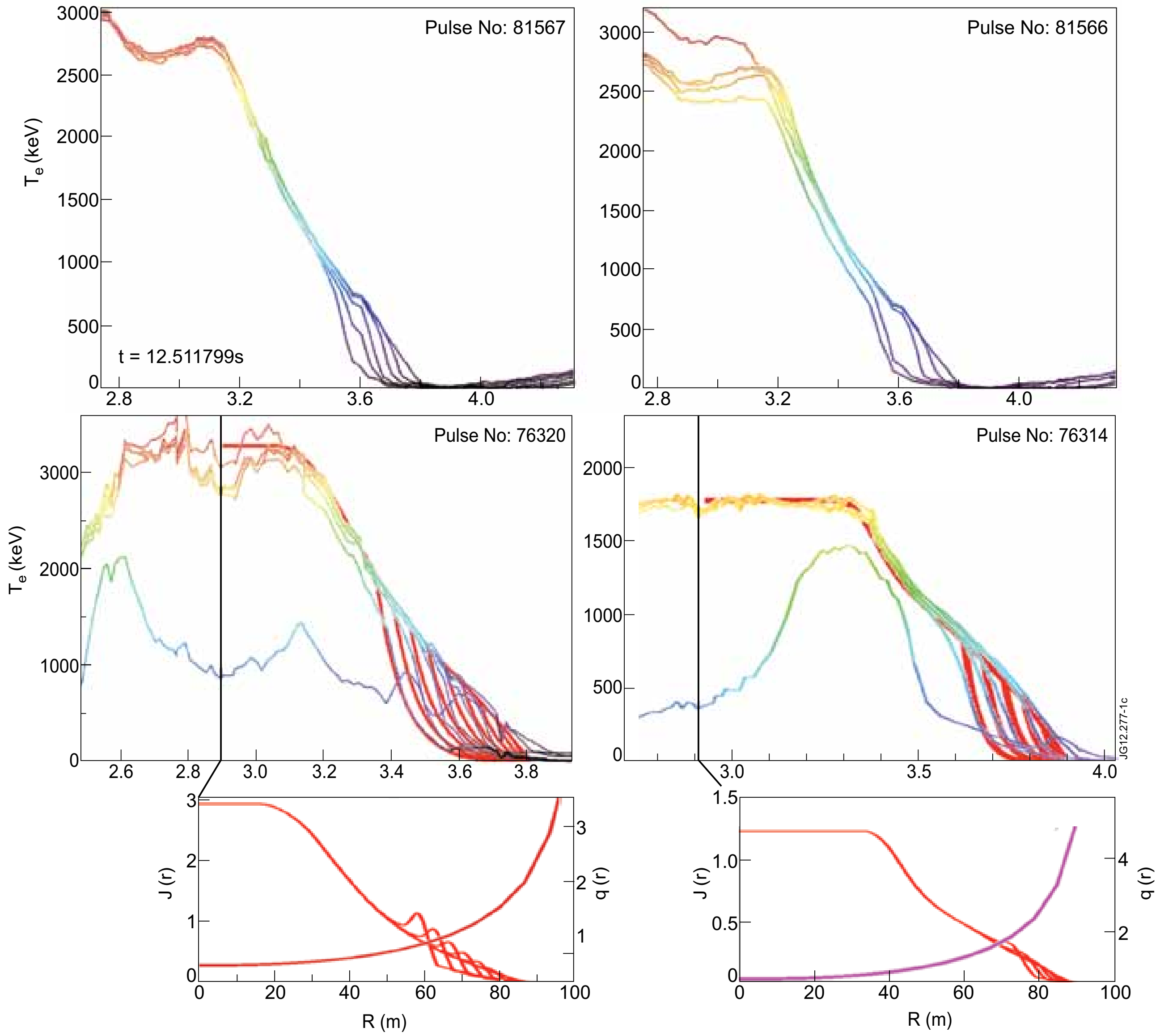

Figure 1: (Color online) Measured electron temperature profiles at consequent time moments with 0.2 ms time step during the pre-TQ phase of the disruption caused by MGI. Shown are 4 pulses: JET PulseNo: 81566, JET PulseNo: 81567 with ILW and JET PulseNo: 76320, JET PulseNo: 76314 with CFC wall. For the last two pulses the simulated temperature, current density and q-profiles (lower panels) are plotted with thick red lines.

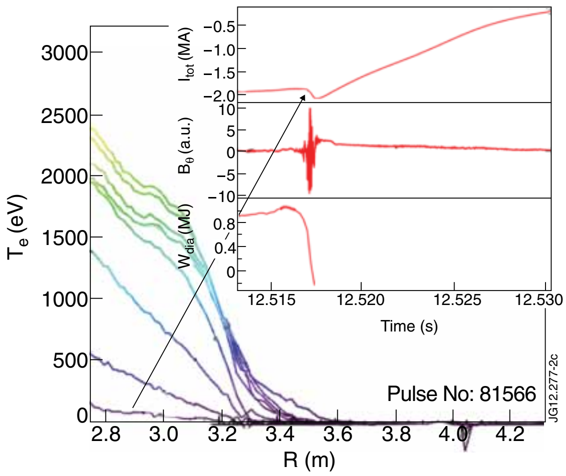

Figure 2: Measured $T_e(r)$ profiles at consequent time moments with 0.2 ms time step during the TQ phase of MGI. In the insert the time dependences for I_{tot}, B_θ and W_{dia} are shown. The current spike corresponds to $T_e(r)$<100 eV.

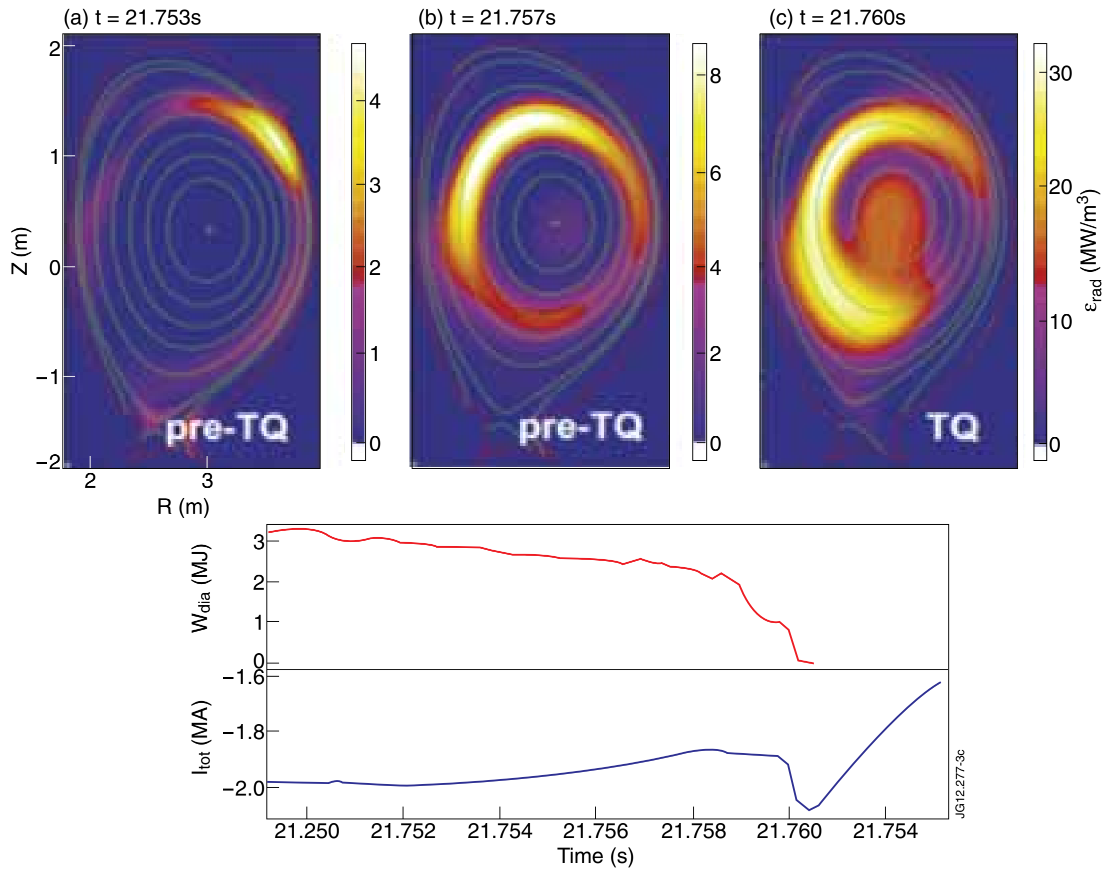

Figure 3: Bolometry reconstruction of the radiation source (upper panel) and time dependences for W_{dia} and I_{tot}. At pre-TQ RS is at the core edge and at the end of TQ radiating bubble penetrates till the magnetic axis.

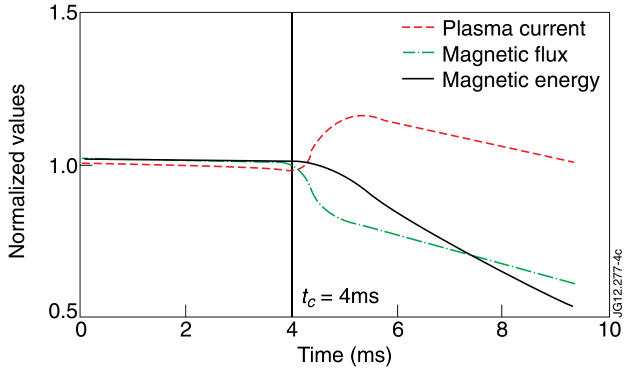

Figure 4: Simulation results for the simplified diffusion-convection model. The plasma current I_{tot} shows spike while the flux Φ and the diamagnetic energy W_{dia} decrease monotonically. Convection starts at $t = t_c$.