Studies of Fast Penetration of Impurities into the Core Plasma During the Disruption at T-11M

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Introduction.

Fast penetration of impurities into the plasma core is known to be the most significant result of major disruption in tokamaks. It leads to a number of macro-catastrophic events including plasma current decay and the appearance of runaway electrons. The latter may cause a trouble for the vacuum vessel. These phenomena become the most dangerous problem for reactor-scale large machines. A detailed study of fast penetration of impurities into the plasma core seems to be quite important for this reason.

There are two different models of the nature of penetration process. Following the first[1], plasma disruption is considered as a stochastic spatial overlapping of the magnetic islands. Abnormal diffusion of impurities is a result of magnetic stochastization. The process is opposite to plasma electron cooling, and $\sim(m_i/m_e)^{1/2}$ times slower, i.e. it lasts 1…10 ms approximately depending on the vessel size.

Second model[2] takes into account the capture of "vacuum bubbles" resulting from large-scale fluctuations of peripheral plasma under the low magnetic shear conditions. The process could be described as a nonlinear evolution of ideal kink instability. Therefore its maximum velocity might approach Alfven velocity at the magnetic field of plasma current. Corresponding times of impurity penetration should be of ~1 μs order in this case.

Early experiments[3] gave an evidence of much faster penetration process than predicted by stochastic model, but slower than by "bubble" one. The result does not seem to be definitely proved, however, for it was concluded from the analysis of evolution of separate slightly ionized impurity radiation intensity at the core plasma. There is some uncertainty in this case due to remarkable contribution of background radiation from the peripheral regions.

More definite result had been obtained recently at JET[4]. Fast penetration of Ni ions into the plasma center had been observed during the major internal disruption, comparable to electron cooling time. This makes an evidence of convection-like transport of impurities across the plasma column.

In the present work an attempt was made to trace penetration of C and Li impurities from the periphery into the plasma core during major disruption.

Experimental.

Studies were performed at T-11M tokamak[5] (R = 0.7 m, a = 19…23 cm) under the following general conditions: plasma current - up to 100 kA, shot duration - up to 120 ms, toroidal magnetic field B_t = 1 T, average electron density $n_e \approx (1.5...2)\cdot10^{13}$ cm^{-3}, electron temperature $T_e(0) \approx 0.5…0.8$ keV.

In order to reduce the contribution of slightly ionized impurities at the peripheral regions, total plasma radiation losses profiles evolution had been measured with the use of fast 16-channel Si AXUV photodiode array (2 μs temporal resolution) with wide (visible to soft X-ray) spectral band of sensitivity (MRLMS)[6]. Two ordinary SXR Si detectors were used to monitor core plasma soft X-ray radiation. MRLMS had been installed into T-11M tangential vacuum port (Fig.1) viewing at the cross-section where a graphite limiter is located, the view axis lying at the midplane 60 cm to the tokamak vertical axis (i.e. shifted 10 cm inside from the toroidal axis). Vertical or horizontal (midplane) position of the array view plane could be chosen by proper 90^o rotation of the detector unit. Pinhole geometry provides rectangular 1.25×6.5 cm effective field-of-view (FOV) of each array photodiode at the graphite limiter cross-section (Fig.1). Fast gated data acquisition system (1 MHz sampling rate in transient record mode) had been used to digitize the signals of interest during the disruption. Movable rail-type graphite limiter was located at the bottom of vacuum vessel. It could be replaced, if necessary, by the analogous lithium limiter located at another cross-section of torus outside MRLMS total FOV.

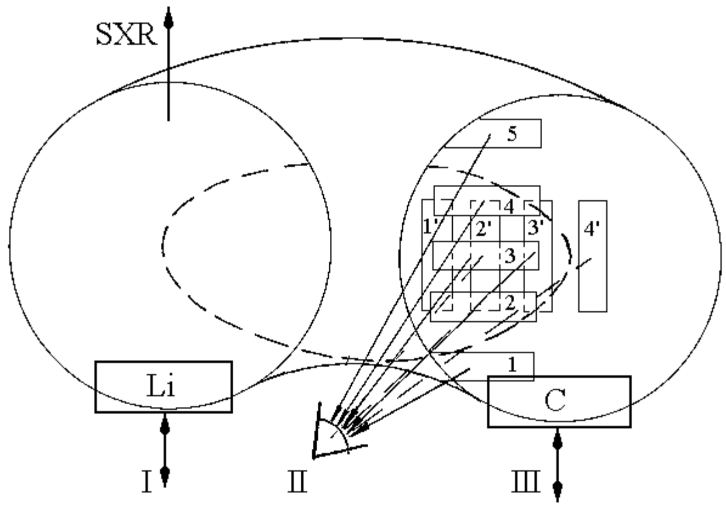

Fig.1. MRLMS view geometry: I – Li-limiter, II – pinhole camera, III – C-limiter, 1-5, 1`-4` – FOVs.

Results.

Typical traces of major disruption evolution at T-11M, apparently caused by locked mode evolution, are shown at Fig.2: positive current spike ΔJp/Jp, its derivative, magnetic probe signal, two central chord SXR detectors and three MRLMS channels oriented in vertical view plane (1 - viewing the graphite limiter located at a = 19 cm, 2 - viewing inter-mediate regions, 3 - viewing plasma core region). The dynamics of radiation front penetration into the core could be clearly seen. Temporal behavior is revealed more explicitly by the derivative of MRLMS signals (lower traces), representing the rate of radiation front movement across the detector FOV. Beginning at the limiter, it expands to the center with the speed $V_p = (0.5\ldots1)\cdot10^6$ cm/s.

Evidently the impurities are extracted from limiter during major disruption. A weak increase of plasma current J_p preceding this event commonly signifies some reduction of internal plasma inductance. Magnetic signals reveal an appearance of helical disturbance (m=2/n=1) at this moment. Perhaps, it caused the first peak of radiation observed by MRLMS channel viewing the limiter. It does not spread into the plasma core, but obviously initiates start-up of MHD activity and consequently, the destruction of plasma center - probably by inducing of MHD instability in the plasma core[7]. The response traces of two adjacent SXR detectors qualitatively confirm this assumption. Note that penetration of impurities into the core (MRLMS traces 2, 3) clearly could not be the reason of SXR radiation decrease, taking into account an earlier response of SXR central channels. It could be concluded therefore, that the origin of this process is related to plasma MHD activity evolution, not a simple sequence of stochastic spatial redistribution of the magnetic configuration. In the latter case impurity penetration time should be 50…100 times longer than electron cooling time, in contradiction to observed almost equal values same as for the internal disruption.

Similar MRLMS traces were obtained during the disruptions when horizontal detector array orientation had been used (Fig.3). At the midplane an impurity source was found to be located at the internal plasma edge. It could be caused by some plasma column shift towards inside, or by breakdown arcs between in-vessel passive elements of T-11M. Some difference in comparison to vertical MRLMS view plane had been observed, however. Response rise-up of an outer channel (trace 2` at fig.3) begins somewhat later than core channels (traces 3`, 4`). That means the process of impurity penetration has no axial symmetry as it could be foreseen assuming an applicability of common abnormal diffusion model. And that is evidently true for "vacuum bubbles" capture model of penetration process[2].

Magnetic shear decrease inside the plasma column is known to be a major condition for this capture. Some reduction of internal inductance just before the disruption (Fig.2) qualitatively confirm an idea, but it should be noted that even a local shear lowering could be enough for the bubble capture. The magnetic islands being present, there are spatial regions of constant or almost constant q(r) located around their separatrixes. Fast migration of "vacuum bubbles" with captured cold impurities along them seems to be quite probable in this case. Deep penetration of separatrixes into the plasma core may occur if non-linear "positive" magnetic islands are grown[8]. Bubble migration along them could explain the phenomena observed. The speed of migration should be limited by the growth rate of magnetic islands, being in agreement with obtained values of impurity penetration time.

Conclusions.

The process of impurity penetration into the plasma core during final (fast) phase of major disruption had been studied in detail with the use of recently developed multichannel plasma radiation losses measuring system (MRLMS) based on fast response AXUV Si photodiodes, installed into tangential vacuum port of T-11M.

Originating at the limiter edge, the impurity source spreads over the whole plasma boundary during the fast phase of disruption. Impurity penetration rate into the plasma core $V_p = (0.5\ldots1)\cdot10^6$ cm/s had been measured by registering of radiation front movement. This value is an order of magnitude lower in comparison to the speed of an ideal kink mode, and >10 times higher than the speed of tearing mode.

Kadomtsev-Pogutse's "vacuum bubble" model had been applied to explain the observed phenomena of fast impurity penetration into the plasma core, combined with an assumption of non-linear "positive" magnetic island growth.

References.

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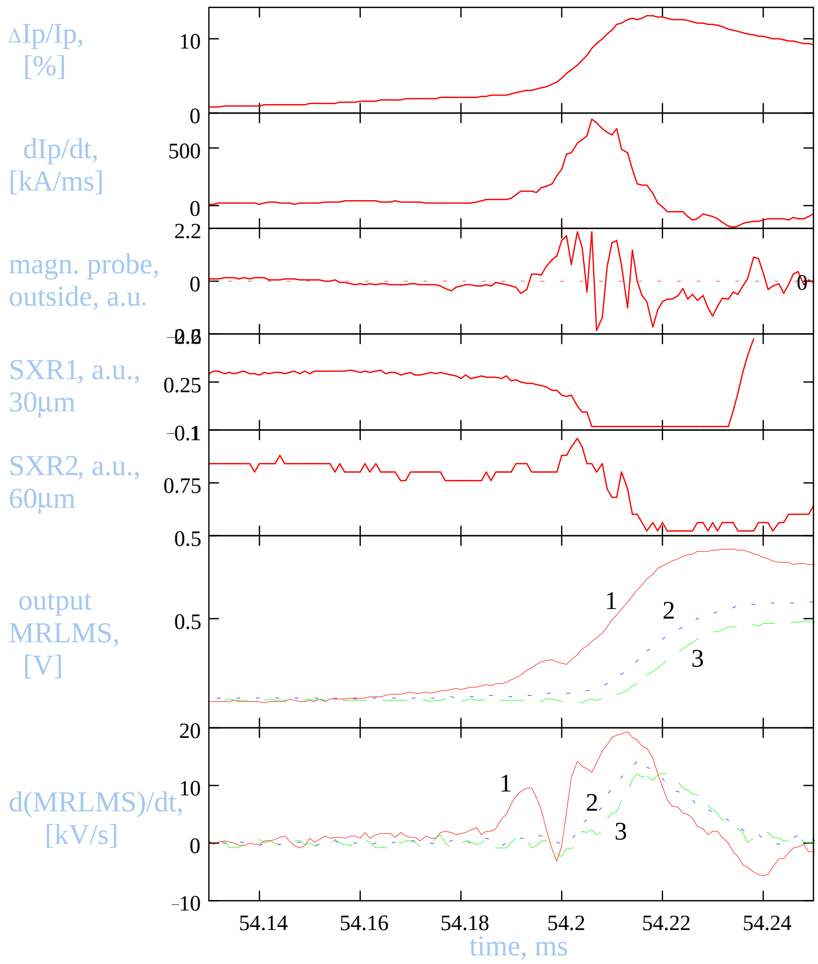

Fig. 2. Major disruption: the positive current spike ΔIp/Ip, its derivative, magnetic probe signal, two SXR signals, three vertical MRLMS traces and their derivatives.

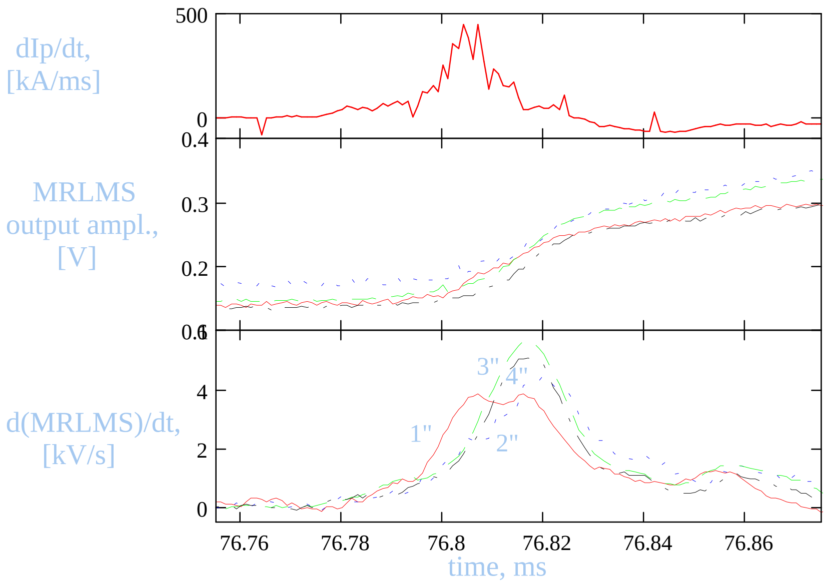

Fig. 3. Plasma current derivative. MRLMS horizontal view traces and their derivatives.