INTERNATIONAL ATOMIC ENERGY AGENCY
18th IAEA Fusion Energy Conference
Sorrento, Italy, 4 to 10 October 2000

IAEA-CN-77/ EXP3/08

Origin of Rapid Impurity Penetration to Plasma Center During the Disruption in Tokamak T-11M

S.V. Mirnov 1), A.M. Belov 1), D.Yu. Prokhorov 2), A.G. Alekseyev 1), I.N. Makashin 1)

1) TRINITI, Troitsk, Moscow reg. 142190 RUSSIA
2) Institute of Nuclear Fusion, RSC “Kurchatov Institute”, Moscow, 123182 RUSSIA
e-mail contact of main author: mirnov@triniti.ru

Abstract. The results of impurity penetration studies at T-11M tokamak just before and during the disruption are presented. Two scenarios of the process are considered: (i) initiated by the major disruption, the latter being the main source of impurity, and (ii) minor disruption or Locked Mode (LM) provide preliminary impurity penetration into the periphery followed by deep internal disruption. Well-known “vacuum bubble” capture model is proposed for the explanation of rapid impurity penetration.

1. Introduction

The phenomena of rapid ($v_{\perp}\approx 10$ km/sec) impurity penetration and pellet-injected hydrogen into the plasma core during operations in tokamak are currently well known [1-6]. Simple reconnection of magnetic islands with fast equalization of electron temperature in the region of overlapped magnetic surfaces could not cause the observed phenomena. Ion movements along the magnetic field lines to plasma center are 2 orders of magnitude slower then electrons. It contradicts to the fact that ion penetration process is as fast as electron cooling one. That is the main evidence of convective nature of rapid ion transport.

Rapid penetration of ions into the core always is related to plasma MHD activities. During the minor disruptions impurities fill peripheral plasma only, and hard major disruptions result to the filling of central core [6]. An analysis of the magnetic perturbations and rapid impurity penetration leads us to the conclusion that well-known “vacuum bubble” model [7] could explain the rapid inward transport of ions both during the disruptions and pellet injection.

2. Experimental.

Experiments were performed on the tokamak T-11M [6]. Multichannel radiation losses measuring system (MRLMS) have been used for indication of rapid impurity penetration into the plasma core [8]. An absolute extreme UV (AXUV) photodetectors used in this system could be regarded as electromagnetic radiation bolometers in 1…5000 eV photon energy range, with high temporal resolution (~ 2 μs). The tangential direction (touching toroidal axis) of the detector field-of-view (FOV) with vertical orientation of FOV plane have been chosen, contrary to traditional poloidal directions of view chords. It provides an opportunity to watch the vertical diameter chord of poloidal plane (toroidal angle $\varphi=0^0$), in the vicinity of Li limiter installed at the bottom of the vessel, being the main source of impurities during the disruptions. This view geometry eliminates the necessity of Abel inversion procedure, being the main source of errors in the absence of cylinder symmetry of UV-radiation.

According to coronal model for the Li limiter case, the main component of penetrating impurity should be in the form of Li^{+1} and Li^{+2} ions. First ~200 μsec after the penetration their emission should be almost constant with slow increase versus the increase of electron temperature T_e = 50…400 eV. Further Li become totally ionized resulting to the decrease of emission intensity and the shift of spectrum from UV to the soft X-ray region. Two operating gases - D_2 and He were used. Common graphite limiter was installed at the opposite toroidal side ($\varphi = 180^0$), providing an opportunity to substitute the Li one for comparison.

3. Major and minor disruptions

Typical example of plasma major disruption at T-11M with the graphite limiter is shown at Fig.1 representing in grayscale the evolution of magnetic perturbations over the poloidal angle θ, plasma current variation (positive current pulse ΔI_p), Shafranov shift, soft X-ray (SXR) emission and output signals of 2 MRLMS channels corresponding to central and bottom view chords. Over 70 major and minor disruptions were analyzed. It was noticed that impurity emission from the limiter increases if the maximum of magnetic perturbation (perhaps, an X-point of magnetic islands) is located near the limiter.

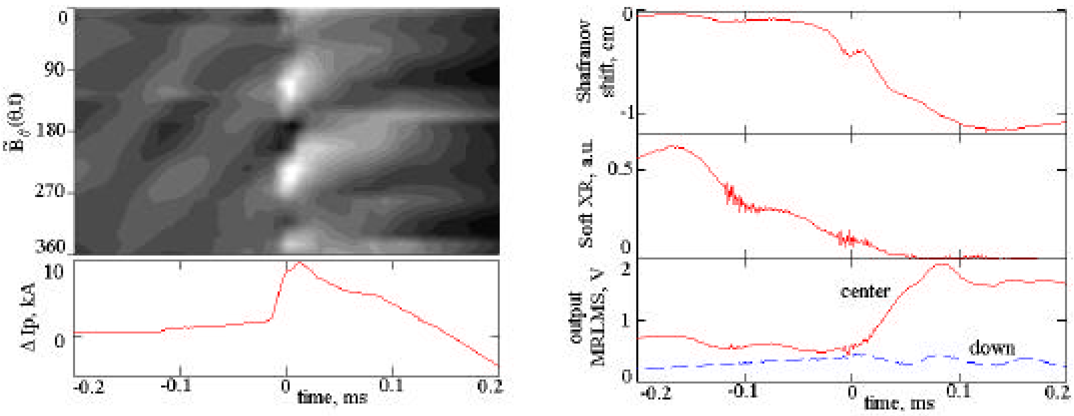

FIG. 1. $\tilde{B}_q(q,t)$ - evolution of magnetic perturbations over the poloidal angle, inside 0° and 360°, outside 180°. DIp – plasma current variation (positive current pulse), Shafranov shift, soft X-ray emission from center, and two MRLMS channels with middle and lower view chords.

The disruption represented at Fig.1 is typical for tokamaks operating closely to the current limit q(a)<3. In fact, it follows deep internal disruption (revealed by falling of SXR emission from the center), being widely spread internal event m=1/n=1 expanding to the neighbor resonant regions up to $q(r_s) \approx 2$. Remarkable signs of such events – slow increase of current I_p and some shift of plasma column inside. It occur to be enough to start m=2/n=1 perturbation transferring abruptly to m=3/n=1 one followed by positive current pulse ΔI_p and drop of Shafranov shift. The loss of stability by m=2/n=1 perturbation along minor radius is the essential phase of major disruption. It results to plasma throw out to the wall or limiter, and flattening of current profile (signed by positive current pulse ΔI_p). That means the lowering of magnetic shear inside the plasma column. Graphite limiter (perhaps, covered by Li layer) seems to be naturally the main source of impurities to the plasma core during the disruption in the case under consideration. Relatively low UV signals from the bottom MRLMS channel confirm this assumption since they correspond to the yield of impurities from the wall in this case. Thus simple chain of events seems to be clear: (i) major disruption followed by decrease of plasma shear, (ii) intensification of plasma-limiter interaction resulting to the increased yield of impurities and then (iii) their rapid penetration into the plasma core. Many disruptions observed at T-11M provide rapid impurity penetration by this scenario (variant I).

Another frequently observed process of major disruption at T-11M (variant II) is represented at Fig.2. Lithium limiter had been used in this case. The disruption initiated by the evolution of lock mode (LM) and two preceding minor disruptions. Notice, that this scenario had been accepted for ITER. An analysis of MRLMS signals revealed the penetration of impurities approximately to the radius $r \sim 0.5a$ during the minor disruptions. It resulted to the start of instability and deep internal disruption, similar to shown at Fig.1. During this internal disruption the impurities penetrate plasma core initiating the major disruption. Similar process had been observed at JET after the Ni injection [5]. In this case the following chain of events occur: (i) first the outer circular region is filled by impurities due to the evolution of LM mode or minor disruptions, then (ii) deep internal disruption, followed by the decrease of magnetic shear in the plasma core, and finally – (iii) penetration of impurities into the core and major disruption. The mechanism of primary filling of plasma outer circular region by the impurities in minor disruption still remains unclear.

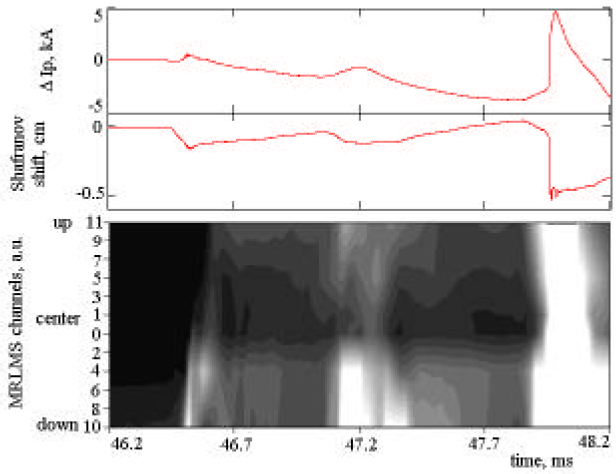

FIG. 2. The impurity penetration if major disruption has been initiated by the two minor disruptions. MRLMS channels - UV-signal from down (limiter) to up

Fig.3 represents in grayscale the evolution of UV emission profile during the first minor disruption shown at Fig.2. It is clear that impurities penetrate into the peripheral plasma from the bottom edge (Li limiter). The process is quite complicated. At first the impurities move directly along minor radius. According to the magnetic measurements, it starts when high frequency (HF) bursts appear (see B_θ map at Fig.3a), and supposed X-point of magnetic island passes the limiter. Then some weakening of plasma-limiter interaction occur inside MRLMS FOV, and impurities localize at r=0.6…0.7a as if they move in poloidal direction only along the separatrix of peripheral magnetic island. It seems to be quite probable taking into account lowering of the magnetic shear in the vicinity of separarix.

4. Model of local decrease of magnetic shear.

Cold “vacuum bubble” capture model had been proposed by B.Kadomtsev and O.Pogutse, as mechanism for rapid penetration of cold peripheral plasma into the core [7]. Low magnetic shear along the trajectory of such a “bubble” is known to be the main requirement for this event. It is generally accepted that it could occur in the case of the flat current profile only. So strong restriction commonly is realized during major disruptions, and perhaps results in the rapid penetration of impurities into the plasma core, similar to the case represented at Fig.1. To the other hand, it could be shown, that the local flattening of q(r) profile with corresponding lowering of magnetic shear (even up to the creation of the “positive” magnetic islands) are possible in the vicinity of X-points of the magnetic islands, if strong helical current disturbance would occur during the disruptions [9]. Let us estimate the level of current disturbance required for the local q(r) profile flattening and migration of “vacuum bubbles”. Fig.4 represents an example of model calculation for the creation of such region in the vicinity of $q(r_s)\approx 2$ resonant surface in the case of the most probable situation of major disruption: (q(0)=1.5, q(a)=3). It was supposed that m=2 current disturbance could be described by helical tube with radius $\delta r=0.17a$ with the current density required for the local disappear of magnetic shear at $q(r_s)=2$ [9]. It is clear that low shear region ($q(r)\approx 2\pm 0.1$) could expand to the radius ~0.5a thus providing the conditions for deep penetration of peripheral "vacuum bubbles" into the plasma core along separatrix with no crash of general current profile. The required value of current disturbance is ~10% of I_p. Corresponding magnetic field disturbance at the location of measuring magnetic coils inside the vessel would be ~5% of $\hat{A}_\theta$.

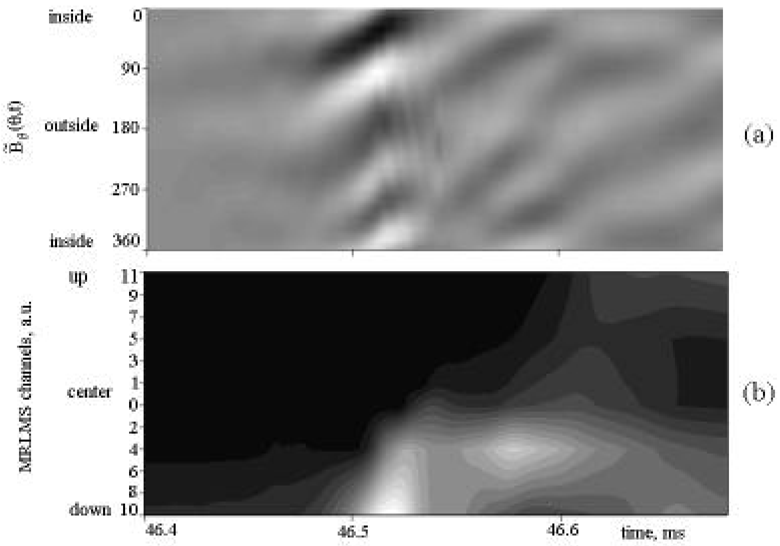

FIG. 3. Minor disruption. (a) Magnetic perturbations over the poloidal angle, $\tilde{B}_q(q,t)$. It is clearly visible m=3 mode and HF-burst. (b) UV-signal from down (limiter) to up.

During the real disruptions it frequently reaches 10…20% value, i.e. the convective mechanism of rapid impurity transport from X-pint along the separatrix of magnetic island could take place. In particular, it could be responsible for the penetration of impurities into the plasma core during the minor disruption. In addition it could play an essential role for the evolution of internal disruptions. Finally, an evolution of plasma turbulence during the disruptions could promote the convective movements of cold impurities. The signs of its presence could be clearly seen, for example, at Figs.1 and 2 in the form of HF bursts. Dissipation of the magnetic fluxes could also be promoted by the turbulence since it leads to reduction of plasma conductivity. I.e. it acts in the same direction – enhance the movement of cold magnetic tubes towards the decrease of their magnetic energy [7].

5. Consequences of rapid impurities penetration and pellet injection.

It is fairly accepted that the main results of impurity penetration into the plasma core would be its cooling and current decay. These consequences were actually observed in our experiments though Li is not effective energy re-radiator and hence, the level of its influence on the current decay is lower than for carbon impurity. Total current decay had been observed only in variant II disruptions, or when the graphite limiter had been used. After some major disruptions plasma current did not change. Such events were commonly related to reduced number of impurities reaching the center. During the major disruption in variant I, the reduction of plasma current was 10…20%, electron density n_e increased 2…3 times. Few milliseconds after the event, lithium plasma was heated up to $T_e\approx 300$eV and radiation losses spectra was shifted into soft X-ray region with following ~10-fold increase of SXR emission. We have not observed runaway electrons, but their generation could be assumed in this phase.

During the experiments with Li limiter we succeeded to observe few events of direct injection of liquid Li droplets (~0.5 mm^3) into the plasma with the velocity 100…200 m/sec, similarly to common pellet injection. The analysis of MHD activity revealed that the process in this case follows variant II scenario with the only difference that asymmetric filling of peripheral regions results from the vapor of droplet. After reaching the core (r≈0.5*a*), an internal disruption and abrupt filling of the center by Li were observed, as reported earlier [2,3].

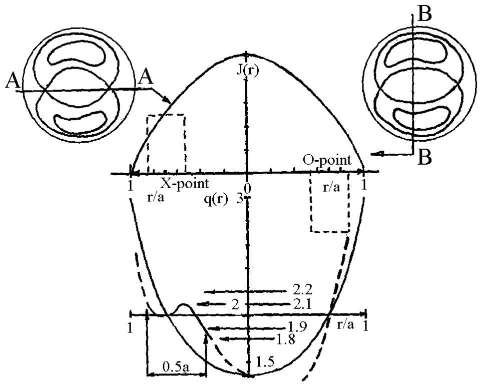

FIG. 4. Perturbed q(r) distribution (left) near x-point of magnetic island m=2/n=1.

6. Conclusions

1. Two different variants of rapid impurity penetration into the core were revealed:

I - the most frequent event, - major disruption generates the impurities penetrating plasma core after the generation of positive current pulse ΔI_p and loss of magnetic shear;

II - two-stage process including the slow phase, when the impurities generated by LM mode, or minor disruption, or pellet injection, fill at first peripheral circular regions (r>0.5*a*), and the fast phase of impurity penetration into the plasma core after the internal disruption with m=1/n=1 instability, finally resulting to generation of positive ΔI_p.

2. Rapid impurity penetration could be explained by the migration of "vacuum bubbles" into the core after the local decay of magnetic shear before and during major disruption.

3. The event of fast fulfillment of plasma periphery by cold impurities could be used in large tokamaks and ITER as an indication of approaching major disruption.

References

[1] VLASENKOV,V.S. et al. "Plasma column perturbation preceding to disruption in T-6 Tokamak" Proc. 6 EPPC Conf. Contr. Fus. & Plasma Phys. (1973), V1 p.55. KADOMTSEV,B.B. "Progress in tokamak research" ibid.V2 p.1.

[2] GOMEZ,C.et al."H_2-pellet fueling in ALCATOR" Bull. Am. Phys. Soc.**29** (1984) p.1320.

[3] CHEETHAM,A.D. et al. "Profile effects associated with pellet fueling of JET" Proc.14 EPS Conf. Contr. Fus. & Plasma Phys., V1 1D P1 (1987) p.205.

[4] WHYTE,D.G. et al."Rapid Inward Impurity Transport" Phys.Rev.Lett.,V81(1998) p.4392.

[5] WESSON,J.A. et al. "Transport in the Sawtooth Crash" Phys. Rev. Lett., V79 N25 (1997).

[6] ALEKSEEV,A.G. et al."A Fast Penetration of Impurities into the Core Plasma during the Disruption in T-11M" Proc. 26 EPS Conf.Contr.Fus.&Plasma Phys, V.23J (1999) p.833.

[7] KADOMTSEV,B.B., POGUTSE, O.P. "Nonlinear helical perturbations in tokamak plasma" Journ. Exp. & Theor. Phys., V65 (1973) p.575 (rus.).

[8] ALEKSEYEV,A.G. et al. "Fast multichannel plasma radiation losses measuring system" Plasma Devices & Operations, V7 (1999) p.139.

[9] MIRNOV,S.V. "A Possible Nonlinear Scenario for the Magnetic Island Formation in Tokamaks" Plasma Phys.Reports, V24 N10 (1998) p.813.