Stochastization and pump-out in edge plasma caused by ELMs

V Rozhansky[1], E Kaveeva[1] and M Tendler[2]

[1]*Peter the Great St.Petersburg Polytechnic University, St.Petersburg, Russia*

[2] *Alfven Laboratory Royal Institute of Technology, Stockholm, Sweden*

1. Introduction

Filaments have been observed in the H-mode during onset of edge localized modes (ELMs) [1-2]. There is experimental evidence that rather strong bipolar [3-4] or monopolar [5-6] currents of the order of 200-400A flow in the filaments. In [7-8] an idea was put forward that such large currents could create a stochastic layer in the pedestal region leading to the pedestal density and temperature reduction [1-2]. We propose a model for pump out during onset of ELMs type I. The key element of the model is increase of the radial outward particle and heat convective fluxes due to the deviation of radial electric field from the neoclassical value in the stochastic layer during life time of current carrying filaments.

2. Currents in the filaments

In the SOL the filament is getting polarized by vertical ∇B and curvature current. The radial acceleration of filament measured in the experiments is not big enough to provide the closure of major part of those currents by the polarization current inside the filament. Therefore the external currents perpendicular to the magnetic field should arise. The bipolar parallel currents in the filament connecting these external currents and filament can be estimated as:

$$j_{\parallel}^{f} \approx \frac{2n_f (T_{ef} + T_{if})}{BR} \frac{l_{\parallel f}}{l_{\perp f}}, \qquad (1)$$

where n_f, T_{ef}, T_{if} are the filament density and temperatures and $l_{\parallel f}, l_{\perp f}$ are the filament sizes along and across magnetic field. For the typical parameters of filaments during ELMs in MAST ($n_f = 2 \cdot 10^{19} m^{-3}$, $T_{ef} = T_{if} = 80eV$, $l_{\parallel f} = 8m$, $l_{\perp f} = 4cm$, $B = 0.3T$, $R = 1.5m$ [2,4]) $j_{\parallel}^{f} \approx 400kA/m^2$. Partially the parallel currents can be short-circuited through the divertor plates, still in many discharges these currents are bigger than ion saturation current at the plates and therefore are closed through the ambient plasma. In [4] the distortion of the magnetic flux tube near the *X*-point leading to the big polarization currents in this region is discussed as a mechanism of filament current closure. The polarization current in the divertor plasma can also contribute to the closing of bipolar parallel currents.

Current density at the plasma edge inside the separatrix could be estimated as $1000kA/m^2$ [9]. This current can be inherited by the filament when it detaches. Such monopolar current density is too large to be short-circuited through the divertor. The life times of monopolar current can be estimated for typical MAST parameters as $\tau_I^{vis} \approx 10^{-8} \div 10^{-9} s$ if it is closed by the current associated with perpendicular viscosity and $\tau_I^{n} \approx 10^{-6} \div 10^{-7} s$ if it is closed by the current associated with ion-neutral collisions in the divertor region. They are much smaller than the life-time of the filament, therefore the evolution of the filament current can be described by MHD equations assuming only perpendicular polarization currents. The solution is an Alfven standing wave localized inside the filament. The magnetic signal at the Alfven frequency was indeed detected in [2]. The steady-state currents exceeding the ion saturation current to the divertor plates observed in experiments most probably are the part of the system of dipole currents. At the same time the monopolar current in the filament contributes to the plasma edge ergodisation while it is still attached to the core plasma for the time of about $50\mu s$ [2].

3. Penetration of magnetic perturbations

Magnetic perturbations produced by the filaments currents start penetrating into the ETB. The estimate for the characteristic time of the linear growth of the separate island in the theory of forced reconnection [10] is $\tau_{B1} = \tau_A^{2/5}\tau_R^{3/5}$ for the magnetic perturbation with poloidal wave vector $\vec{k}$, $\tau_A = (\mu_0 m_i n_e / B_\theta^2)^{1/2} q/q'$, $\tau_R = \mu_0 \sigma_\parallel / k^2$. Further penetration is determined by the characteristic time for nonlinear island growth $\tau_{B2} = \tau_R k\delta$, where δ is the saturated island width. For the typical parameters of MAST plasma boundary ($n_e = 2\cdot 10^{19} m^{-3}$, $T_e = 200 eV$, $q/q' \approx 0.1m$ [11], $\vec{k} \approx 40 m^{-1}$ for ELM filaments, $\delta \approx 0.5cm$) $\tau_{B1} \approx 10 \div 100\mu s$ and $\tau_{B2} \approx 100\mu s \div 1ms$. From the experiments with RMPs it is known that stochastisation starts at the level of the RMPs about $b_{y\vec{k}}^{stoch} = B_{y\vec{k}}^{stoch} / B \approx 10^{-4}$ [11]. The magnetic field perturbation which is produced by the current 1 kA flowing inside the filament at the distance of few centimeters from resonant layer is of the order of $b_{y\vec{k}}^{sat} \approx 10^{-3}$. Therefore a stochastic layer should arise in the ETB region before the islands reach full saturation, the corresponding time could be estimated as $\tau_{stoch} \approx \tau_{B2} b_{y\vec{k}}^{stoch} / b_{y\vec{k}}^{sat} \approx 10 \div 100\mu s$.

After the stochastisation the characteristic time for the further resonant magnetic field penetration can be estimated as $\tau_s = (q/nq')(\mu_0 / k_x)\sigma_{pen}$ with the effective conductivity $\sigma_{pen} = i_\delta \sqrt{\pi} R n_e e^2 / \sqrt{2 m_e T_e}$. This estimate is based on the approach on integration of electron kinetic equation [12] and the evaluation of toroidal currents [13]. For MAST $\tau_s \approx 10 \div 100 \mu s$ and the perturbation can fully penetrate during the life time of a filament $\tau_f \approx 200 \mu s$ [2].

4. Dynamics of radial electric field and pump-out

Radial electric field in a steady state $E_r^{Eq} = (\sigma_{St} E_r^{St} + \sigma_{NEO} E_r^{NEO})/(\sigma_{St} + \sigma_{NEO})$ is determined by the condition of ambipolarity $j_r^e = -j_r^i$ where the ion radial current $j_r^i = \sigma_{NEO}(E_r - E_r^{NEO})$ is a neoclassical current caused by the deviation of the radial electric field from the neoclassical value and the radial current of electrons $j_r^e = \sigma_{St}(E_r - E_r^{St})$ is a radial projection of a parallel current in the stochastic magnetic field [13-14]. Here

$$E_r^{St} = -(T_e / e) d \ln n_e / dr - \alpha (T_e / e) d \ln T_e / dr . \qquad (2)$$

In the collisionless limit ($\lambda_e / \tilde{L}_k >> 1$, where λ_e is the electron mean free path, $\tilde{L}_k$ is a correlation length, of the order of Kolmogorov length; for the tokamak $\tilde{L}_k \sim qR$), $\sigma_{St} = i_\sigma e^2 n_e D_{St} \sqrt{2} / \sqrt{\pi m_e T_e}$, with i_σ being a numerical factor of the order of unity, $\alpha = 0.5$.

$$E_r^{NEO} = T_i / e(d \ln n_e / dr + k_T d \ln T_i / dr) + B_p U_T , \qquad (3)$$

where U_T is a toroidal velocity, $\sigma_{NEO} = 3\mu_{i1} / (2R^2 B^2)$. The viscosity coefficient [15] in the low collisionality regime is $\mu_{i1} = \varepsilon^{3/2} \nu_*^2 n_e T_i / \nu_i$, where $\nu_* = qR \nu_i \varepsilon^{-3/2} / \sqrt{2T_i / m_i}$.

For time-dependent radial electric field the additional radial current of ions exists associated with the toroidal inertia, see e.g. [16]:

$$j_r^i = \sigma_{NEO}(E_r - E_r^{NEO}) + n_e m_i (1 + 2q^2) / B^2 \partial E_r / \partial t . \qquad (4)$$

The equation describing the relaxation of the radial electric field to the stationary value is

$$\partial E_r / \partial t = -(E_\mathrm{r} - E_r^{Eq}) / \tau_E , \qquad (5)$$

where $\tau_E = n_e m_i (1 + 2q^2) B^{-2} / (\sigma_{St} + \sigma_{NEO})$. When $\sigma_{St} = 0$, $\tau_E = \tau_E^{NEO}$ [16]. In the low collisionality regime $\tau_E^{NEO} \approx \nu_i^{-1}$. The stochastic conductivity reduces the relaxation time.

Let us consider two limits of slow $\tau_s >> \tau_E$ and fast $\tau_s << \tau_E$ time of the magnetic field penetration. In the first case the radial electric field is always close to the equilibrium one for the given level of perturbed magnetic field. The outward radial flux arises:

$$\Gamma = \sigma_{NEO}(E_r^{Eq} - E_r^{NEO}) / e = \sigma_{St}(E_r^{St} - E_r^{Eq}) / e . \qquad (6)$$

In the opposite case $\tau_s << \tau_E$ the period of the order of τ_E exists when the electric field is not an equilibrium one and the dynamic pump-out effect can be important. The loss of particles with steady-state electric field is $\delta N^{static} \approx \tau_f \Gamma$. The loss of particles during τ_E while the electric field is changing and stays of the order of E_r^{NEO} is $\delta N^{dynamic} \approx \tau_E \sigma_{St}(E_r^{St} - E_r^{NEO})/e$, if this time is smaller than τ_f. For low collisionality this mechanism can be the main one.

Let us make estimates for parameters of the MAST pedestal. The neoclassical relaxation time $\tau_E^{NEO} \approx \nu_i^{-1} \approx 300\mu s$. It is of the order of the filament life-time and therefore the dynamic and static losses of particles are of the same order. The neoclassical conductivity estimate is $\sigma_{NEO} \approx (5 \div 7)\cdot 10^{-3} S \cdot m^{-1}$, $E_r^{St} - E_r^{NEO} \approx 40 kV/m$. The particle loss per ELMs event is $\delta N \approx S \tau_f \sigma_{NEO}(E_r^{St} - E_r^{NEO})/e \approx 5\cdot 10^{18}$ particles, where S – the flux surface area. According to experiments [11] the particle loss in the ELM event is 2-3% of the particles in the discharge while full amount of the particles is $(1 \div 2)\cdot 10^{20}$. The estimate shows that the pump-out particle loss is of the same order as experimental one.

5. Conclusions

The ETB region is getting stochastized during ELMs events by the magnetic field perturbations produced by currents flowing in the filaments. The radial electric field in the edge is getting positive or less negative and the convective particle flux arises for the period of filaments life time. This leads to the reduction of the pedestal density and temperature.

Acknowledgements

The work was supported by grant of Russian Ministry of Education and Science “Filaments and stochastization”

References

[1] Kirk A *et al* 2006 *Phys. Rev. Lett.* **96** 185001

[2] Kirk A *et al* 2006 *Plasma Phys. Control. Fusion* **48** B433

[3] Rozhansky V and Kirk A 2008 *Plasma Phys. Control. Fusion* **50** 025008

[4] Furno I *et al* 2011 *Phys. Rev. Lett.* **106** 245001

[5] Vianello N *et al* 2011 *Phys. Rev. Lett.* **106** 125002

[6] Muller H W *et al* 2011 *Nucl. Fusion.* **51** 073023

[7] Aladio F *et al* 2008 *Plasma Phys. Control. Fusion* **50** 124019

[8] Evans T *et al* 2009 *J. Nucl. Mater.* **390–391** 789

[9] Koh S, Chang C S, Ku S, Menard J E, Weitzner H and Choe W 2012 *Phys. Plasmas* **19** 072505

[10] Hahm T S and Kulsrud R M 1985 *Phys. Fluids* **23**(8) 2412

[11] Kirk A. *et al* 2010 *Nucl. Fusion* **50** 034008

[12] Kaganovich I and Rozhansky V 1998 *Phys. Plasmas* **5** 3901

[13] Kaveeva E and Rozhansky V 2012 *Nucl. Fusion* **52** 054011

[14] Rozhansky V *et al* 2011 *Nucl. Fusion* **51** 083009

[15] Hirshman S P and Sigmar D J 1981 *Nucl. Fusion* **21** 1079

[16] Rozhansky V and Tendler M 1996 *Reviews of Plasma Phys*. vol 19, ed. B.B. Kadomtsev, (New-York – London: Consultants Bureau) p 147