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Possible mechanism for filament motion in the SOL of a tokamak

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1. Introduction

Filaments have been observed both in L-mode and during ELMs [1]-[2]. The structures observed in L-mode are thought to result from the interchange instability and move towards the wall due to $\vec{E}\times\vec{B}$ drifts [3]. In the case of ELMs the ballooning mode evolves into several filamentary structures that are highly elongated along $\vec{B}$ [4]. These filaments with density and temperatures significantly larger than those in the SOL detach from the LFS of the plasma edge and travel away from the separatrix [1]-[2]. Their size perpendicular to $\vec{B}$ is of the order of a few cm, while they are extended along $\vec{B}$ by several metres. We consider the evolution of such a filament once it has detached from the core and moves towards the wall.

In the absence of the ambient plasma the filaments are expected to accelerate, similar to the case of a pellet cloud [3]. The vertical ∇B driven current is balanced by the polarization current, which flows inside the filament in the opposite direction. This current is proportional to the temporal derivative of the vertical electric field $\partial E/\partial t$, which causes an acceleration in the LFS direction : $g = 2(T_{ef} + T_{if})/(m_i R)$, ($T_{e,if}$ are filament temperatures). The acceleration of filaments in the SOL during ELMs has been observed [1-2], however, it was an order of magnitude smaller than predicted by this expression. The ∇B driven current might be short-circuited by currents in the divertor plates. Such models were considered for blobs [3], [6]-[7]. The change in the sheath potential drop at the plates produces parallel currents, which short-circuit the ∇B driven current of the filament. However, this mechanism is not applicable to strongly non-linear filaments. For parameters associated with ELMs, the parallel currents, which are required to compensate the ∇B driven current of the filament, are larger than the ion saturation current at the plates. Hence only the perpendicular polarization current of the ambient plasma can contribute to the short-circuiting. The effect is amplified by the fact that the field lines come close to each other, especially near to the X-point, and a strong perpendicular electric field is created. This effect has been discussed in [8] with the assumption that short-circuiting takes place at scales smaller than the ion gyroradius, so electron perpendicular conductivity has been invoked. However, flux expansion near the X-point is not that strong for the case of ELMs. The short-circuiting of the ∇B driven current of the strongly non-linear filament by the plasma of the SOL is discussed below in an MHD approximation. It is shown that the filament is accelerated towards the LFS but that the acceleration is order of magnitude smaller than that in the absence of the ambient plasma.

2. Model

The ∇B driven current of the filament is (the subscript *f* corresponds to filament parameters):

$$j_{\nabla B} = \frac{2n_f(T_{ef}+T_{if})}{B_f R}. \tag{1}$$

The integral along $\vec{B}$ (half of the net current) is defined as $I_{\nabla B} = \int_0^\infty j_{\nabla B} ds = j_{\nabla B} l_{\parallel}$, where $l_{\parallel}$ is the filament parallel size. This current is partially balanced by the polarization current inside the filament flowing in the opposite direction:

$$I_p^f = \int_0^\infty j_p^f ds = \frac{n_f m_i}{B_f^2}\frac{\partial E_f}{\partial t} l_{\parallel}. \tag{2}$$

In the absence of parallel currents in the ambient plasma, from $I^{\nabla B} = I_p^f$, one obtains $E_f = gB_f t;\ :\ g = 2(T_{ef}+T_{if})/(m_i R)$. This field corresponds to the acceleration in the LFS (*x*) direction in Fig.1. Taking into account the SOL, the parallel current, which is necessary to compensate the ∇B driven current of the filament, is

$$j_{\parallel}^f = \frac{2n_f(T_{ef}+T_{if})}{B_f R}\frac{l_{\parallel}}{l_{\perp}}. \tag{3}$$

If the ∇B driven current is short-circuited by the plates, then the parallel current Eq.(3) would flow through the sheath. On the other hand, the maximal parallel current is restricted by the ion saturation current: $j_{\parallel}^{sat} = en_{pl}[(T_{epl}+T_{ipl})/m_i)]^{1/2}$, (subscript *pl* corresponds to plate parameters). Hence the ∇B driven current could be short-circuited by the plates only if:

$$j_{\parallel}^{sat} > j_{\parallel}^f = \frac{2n_f(T_{ef}+T_{if})}{B_f R}\frac{l_{\parallel}}{l_{\perp}}. \tag{4}$$

In the following we assume that this condition is not satisfied, which as will be shown later is the typical case for ELMs. Therefore we will neglect the current through the plates. In this case the parallel current in Eq. (4) should be equal to the divergence of the polarization current in the ambient plasma integrated along the magnetic field $div_{\perp} I_p^b = j_{\parallel}^f$. The electric field in the filament is determined by current balance $I_{\nabla B} = I_p^f + I_p^b$. Due to the distortion of the magnetic flux tube near the X-point, at a given distance *s*, a strong electric field arises almost in the radial direction, Fig.1. This electric field $E_b = \varphi/\delta_\perp$ is significantly larger than the electric field in the filament $E_f = \varphi/l_\perp$. Here $\delta_\perp(s)$ is the smaller size of the distorted cross section of a flux tube which at $s = 0$ has a circular cross section with radius $l_\perp$. The polarization current is flowing in the ambient plasma across the magnetic field mainly in the direction of the maximal potential gradient (x' direction in Fig.1). The direction of the ambient polarization current projected along $\vec{B}$ to the filament is slightly tilted inside the filament forming an angle $\delta_\perp/l_\perp$ with the *y*-axis. The closing of the circuit might be completed by a small additional electric field in the *x*-direction inside the filament. The current density at a given distance *s* is $j_p = n_b m_i B^{-2}\delta_\perp^{-1}\partial\varphi/\partial t$. This current density projected to the plane $s = 0$ should be $\delta_{pol}/l_\perp$ times larger due to the divergence of the magnetic field lines. The net polarization current of the ambient plasma ($\delta_\perp\delta_{pol} = l_\perp^2$) is

$$I_p^b = m_i \frac{\partial E_f}{\partial t} \int_0^{s_{plate}} \frac{n_b}{B^2}\frac{l_\perp^2}{\delta_\perp^2} ds. \qquad (5)$$

Finally, the acceleration of the filament is ($\alpha < 1$).

$$g = 2\alpha(T_{ef} + T_{if})/(m_i R),\ \alpha = \left(1 + \frac{B_f^2}{n_f l_\parallel} \int_0^{s_{plate}} \frac{n_b}{B^2}\frac{l_\perp^2}{\delta_\perp^2} ds\right)^{-1} \qquad (6)$$

3. Comparison with experiment

Typical parameters for filaments observed during ELMs in MAST [1]-[2] are: $n_f = 2\cdot10^{19}m^{-3}, T_{ef} = T_{if} = 80eV, l_\parallel = 8m, l_\perp = 4cm, B = 0.25T, R = 1.5m$, and at the plates $n_{pl} = 2\cdot10^{18}m^{-3} = 0.1n_f$, $T_{epl} = 20eV$ and $T_{ipl} = T_{epl}$. This corresponds to $j_\parallel^{sat} = 15kA/m^2$. For the parameters chosen $j_\parallel^f \approx 600kA/m^2$ and $j_\parallel^f / j_\parallel^{sat} \approx 40$, so the current could not be short circuited through the plates. On MAST the acceleration of the filaments was reported to be $g = 1.8\cdot10^8 m/s^2$ [2], (in vacuum $g = 10^{10} m/s^2$). To calculate α we take parameters near the *X*-point: the ratio $l_\perp/\delta_\perp = 16$ and $B_{Xpo\mathrm{int}}/B_f = 2.67$. Assuming that the effective parallel length of the SOL plasma coincides with $l_\parallel$, we obtain $\alpha = 2.5\cdot10^{-2}$. From Eq. (6) the predicted value of the filament acceleration is $g = 2.5\cdot10^8 m/s^2$, which is in good agreement with the measured acceleration of $1.8\cdot10^8 m/s^2$ [2], Fig.2. During MAST – AUG similarity experiments [9] it was reported that the acceleration of the filaments is lower in AUG than in MAST in spite of the higher filament temperature in AUG. From the above analysis it can be shown that the current inside the filament can be more effectively short-circuited in AUG than in MAST. Indeed, for AUG the ratio $B_{Xpo\mathrm{int}}/B_f = 1.43$ is smaller than for MAST and according to Eq. (6) the impact of the ambient plasma is determined by $(B_{Xpo\mathrm{int}}/B_f)^2$. The distortion of the magnetic tube for AUG is also slightly larger than for MAST: $l_\perp/\delta_\perp = 26.6$. As a result for AUG $\alpha = 2.5\cdot 10^{-3}$, which is smaller than in MAST and hence the corresponding acceleration will be also smaller in spite of the larger filament pressure.

4. Conclusions

It is demonstrated that high density and temperature detached filaments, typical for ELMs, in the SOL are accelerated outwards. The acceleration is determined by the balance between the ∇B drift current inside the filament and the polarization current in the SOL plasma. The impact of the polarization current is amplified by the distortion of the magnetic flux tube, especially near the X-point. The short-circuiting through the divertor plates does not play a significant role for such strongly non-linear filaments. The predicted acceleration values are in reasonable agreement with the filament accelerations observed on MAST and AUG.

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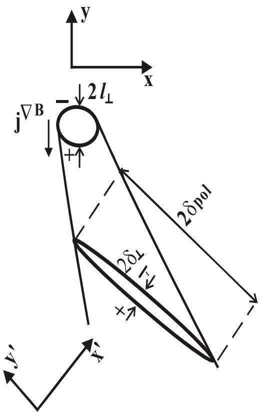

Fig.1. Scheme of magnetic tube distortion.

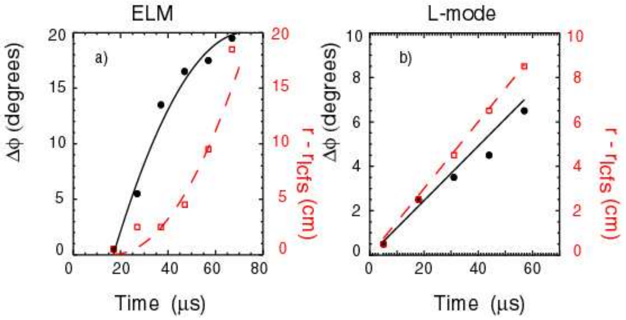

Fig.2. The change in toroidal and radial location of one filament as a function of time during a) an ELM and b) in L-mode.