Influence of the plasma background on the critical size of 3D scrape-off layer filaments

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Abstract

This paper presents the effect of self-consistent plasma backgrounds, on the dynamics of filament propagation. The critical size δ^*, is an important scaling parameter for filaments. It is here defined as the perpendicular size, where filaments are fastest and is shifted to larger sizes for higher densities, due to the plasma viscosity. If the density dependency of the plasma viscosity is included, δ^* does not show a temperature dependency, but instead a density dependency is observed.

Introduction

Filaments are field-aligned non-linear pressure perturbations that have been observed in many magnetized plasmas [1]. These pressure perturbations can carry a significant fraction of particles and density in the scrape-off layer (SOL) [2]. An increased understanding of filaments is therefore of general interest, not only for the design of future fusion devices.

Scaling laws have been derived for the dependency of the critical perpendicular size δ^* of filaments [3, 4]. δ^* is often defined as where parallel currents and polarization currents balance. Here further currents are included, therefore the critical size is defined as where filaments are fastest. The study presented here extends the study of δ^* by looking at filaments that have been seeded on self consistent background plasmas. The model used here is the STORM [4, 5, 6] code for BOUT++ [7, 8] and also includes neutrals [9]. A more detailed description of the physics module is given in [9].

Modelling setup

The STORM physics module is a cold ion, drift ordered fluid model. The simulations presented here are run in a simplified 3D straight field line SOL geometry. The filaments are seeded on background profiles as Gaussian in the perpendicular direction, and with a tanh profile in the parallel direction, i.e. along the magnetic field line. The background profiles are an extension of the two point model [10].This means there are no gradients in the radial direction, only in

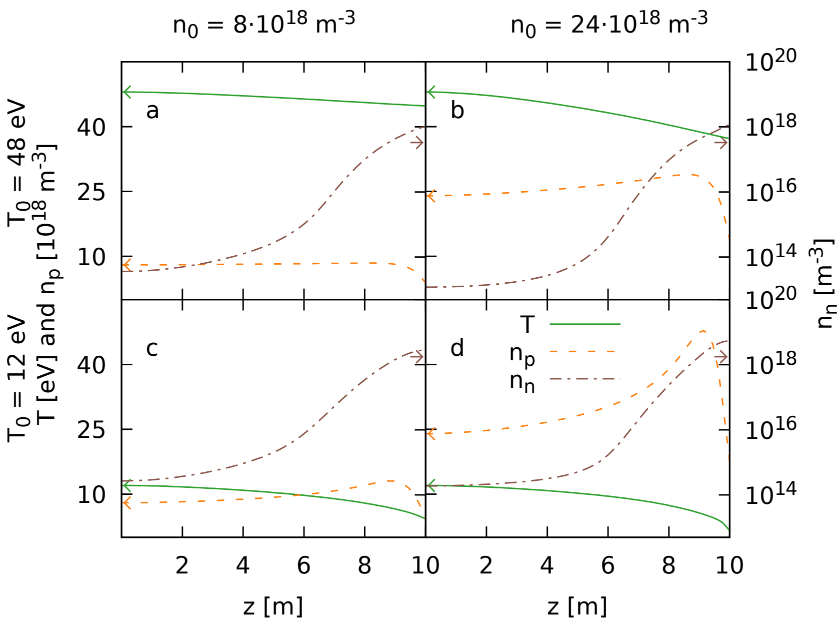

Figure 1: Background plasma profiles, run to steady-state for a set upstream electron temperature T_0 and density n_0. The target is at $z = 10$ m and the mid-plane is at $z = 0$ m. The linear scale gives the plasma density and the electron temperature, while the log scale gives the neutral density.

the parallel direction. The parallel connection length $L_{\|}$ used here of 10 m is a typical value for MAST [4].

Here four cases are considered, varying upstream density and upstream electron temperature. The two quantities are prescibed, and the system is allowed to evolve. The background profiles are shown in figure 1. The shown profiles range from low recycling regimes, in the 48 eV cases (a and b), to a high recycling regime for the 12 eV cases (c and d). In the later cases the temperature drops significantly towards the target. Note that these conditions do not include detachment. At $z = 0$ m is the mid-plane, which acts as a symmetry plane.

In the self consistent case, the viscosity is proportional to $\frac{n}{\sqrt{T}}$. In the case of the viscosity without density dependency, this is reduced to $\propto \frac{1}{\sqrt{T}}$. Easy et al. give a more detailed description of the used viscosity term.

Filament evolution

The filament is seeded as a perturbation in density and temperature on top of the background profiles in figure 1. The Gaussian width $\delta_\perp$ was scanned from 5 mm to 80 mm. In MAST observed filaments have typically a size of around 20 mm. In parallel directions the filaments have a tanh profile.

Theoretical scaling for the radial velocity v_r of filaments is given by $v_r^s = \frac{g L_{\|} \delta_p \sqrt{T_0 + \delta_T}}{(n_0 + \delta_n)\delta_\perp^2}$ for the sheath limited regime and by $v_r^i = \sqrt{\delta_\perp g \frac{\delta_p}{n_0 + \delta_n}}$ for the inertial limited regime [4]. The per-

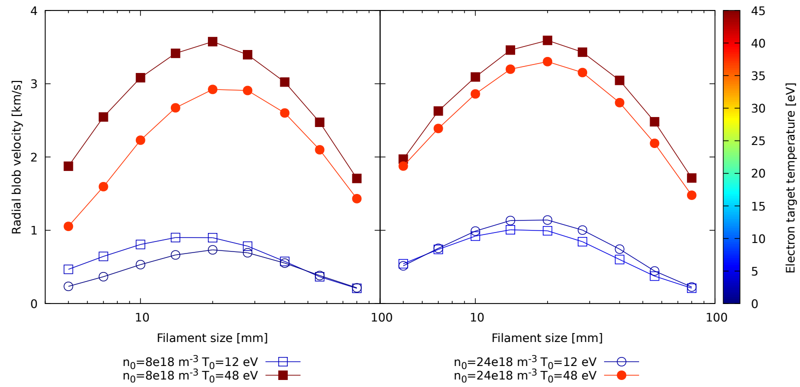

Figure 2: Radial velocity of different sized filaments. Shown is the peak velocity for the four backgrounds from figure 1. On the left are simulation with the self consistent plasma viscosity, on the right hand side for the plasma viscosity without density dependency.

turbation $\delta_{n,T,p}$ are above the background of density n_0, electron temperature T_0 and pressure $p_0 = n_0 T_0$. $g = \frac{2}{R_c}$ is dependent on the radius of curvature R_c. For filaments of the critical size both contributions should balance each other, resulting in the critical size δ^*

$$\delta^* = \left(g L_\parallel^2 \delta_p \frac{T_0 + \delta_T}{n_0 + \delta_n} \right)^{\frac{1}{5}} \overset{\delta_\alpha = \alpha_0}{\propto} \left(6 g L_\parallel^2 T_0^2 \right)^{\frac{1}{5}} \tag{1}$$

This assume a perturbation δ_α above the background value α_0 equal to the background value, for $\alpha \in n, T$. The pressure perturbation δ_p is a sum of density and temperature perturbation $\delta_p = \delta_n T_0 + \delta_T n_0 + \delta_T \delta_n = 3 n_0 T_0$. Note that there is no density dependency for δ^* remaining, with the chosen filament amplitude.

From the filament simulations the centre of mass was calculated in the radial direction. As the initial amplitude near the target is very small, the shown results are measured near the mid-plane. For each filament simulation, the maximum of the centre-of-mass velocity is computed and compared.

Filament size

To study the influence of the size of the filament on its dynamic, different sized filaments have been seeded, and their motion analysed. Figure 2 (a) presents the scan in filament size. The critical filament size is where the filament are fastest, and can be extracted from the graph as the maximum of the graphs. It can be seen that the critical filament size δ^* is in the low density cases between 14 and 20 mm, and for the high density cases between 20 and 28 mm. The position of δ^* does seem to be only influenced by the upstream density n_0, and not by the electron upstream temperature T_0.

A scan with fixed plasma viscosity was performed. This is shown in figure 2 (b). In this case the fastest filaments are around $\delta_\perp \approx 20$ mm for the 48 eV cases, and between 14 and

20 mm for the 12 eV case. This shows that the density dependency of δ^* is due to the density dependency of the plasma viscosity, which hasn't been included in past studies. Further, the temperature dependency of δ^* disappears. From the simple scaling derived, a temperature but no density dependency is expected. This suggests that future derivations of δ^* should include a self consistent plasma viscosity, and its effect on the vorticity.

Summary

Filament radial velocities in the scrape-off layer for different background profiles have been studied. Thereby the upstream temperature and density have been varied, resulting in self consistent parallel profiles. The backgrounds don't include gradients in the radial direction. Filaments were seeded on the background profiles, and the radial velocity was measured.

The critical size δ^* showed a density dependency. This was not expected from scaling laws, but can be explained by the density dependency of the plasma viscosity. Further the expected temperature dependency of δ^* was only observed if the viscosity wasn't included self consistently, which suggests that the plasma viscosity should be included if scalings for δ^* are derived.

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References

[1] D. D'Ippolito, et al., *Physics of Plasmas (1994-present)*, vol. 18, no. 6, p. 060501, 2011.

[2] J. A. Boedo, et al., *Physics of Plasmas*, vol. 8, no. 11, pp. 4826–4833, 2001.

[3] C. Theiler, et al., *Phys. Rev. Lett.*, vol. 103, p. 065001, Aug 2009.

[4] N. R. Walkden, et al., *Plasma Physics and Controlled Fusion*, vol. 58, no. 11, p. 115010, 2016.

[5] L. Easy, et al., *Physics of Plasmas*, vol. 21, no. 12, 2014.

[6] L. Easy, *Three Dimensional Simulations of Scrape-Off Layer Filaments*. PhD thesis, University of York, 2016.

[7] B. Dudson, et al., *Computer Physics Communications*, vol. 180, no. 9, pp. 1467 – 1480, 2009.

[8] B. D. Dudson, et al., *Journal of Plasma Physics*, vol. 81, 1 2015.

[9] D. Schwörer, et al., *Nuclear Materials and Energy*, pp. –, 2017.

[10] P. C. Stangeby, et al.,, *The plasma boundary of magnetic fusion devices*, vol. 224. Institute of Physics Publishing Bristol, 2000.