Filament propagation in abrupt parallel connection length transitions

B Shanahan[1], P Huslage[2]

[1]*Max-Planck Institut für Plasmaphysik, Teilinstitut Greifswald, Germany,*

[2] *Fakultät für Physik und Astronomie, Am Hubland, 97074 Würzburg, Deutschland*

Introduction

Filament physics in stellarators is only starting to be investigated numerically, primarily due to the difficulties incorporating the complex geometry. The BSTING project [1] has provided a framework for global edge and SOL turbulence simulations in Wendelstein 7-X, but filament physics often benefits from simplifications. Simulations of blobs in simplified geometries are common [2, 3] since these geometries are much faster than global edge simulations, allowing thorough investigations of the primary mechanisms in filament dynamics. These methods have already been applied to non-uniform drive scenarios [4], a feature which is prominent in – but not exclusive to – stellarators. Here we extend previous work by simulating filaments in areas of abrupt parallel connection length ($L_{\parallel}$) transitions.

Isothermal model

The effects of $L_{\parallel}$ transitions are investigated here using the `blob2d` example available in the `BOUT++` examples [5, 6, 7] which includes an approximated parallel closure term. This model evolves plasma density n and vorticity ω, and the governing equations in SI units are:

$$\frac{dn}{dt} = 2c_s\rho_s\xi \cdot (\nabla n - n\nabla\phi) + n\gamma \tag{1}$$

$$\rho_s^2 n_0 \frac{d\omega}{dt} = 2c_s\rho_s\xi \cdot \nabla n + \gamma \tag{2}$$

where $\gamma = \phi\left(\frac{\rho_s}{L_{\parallel}}\right)$ is an approximation for the parallel current gradient ($\nabla_{\parallel}J_{\parallel}$) and provides a parallel sheath closure. The vorticity is given by $\omega \equiv \nabla_{\perp}^2\phi$, total derivatives are split via $\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{u_E}\cdot\nabla$ where $\mathbf{u_E}$ is the **ExB** velocity.

Blob scaling in different connection length regimes

A filament where the current is dissipated through the sheath is considered to propagate in the sheath-limited regime. In this regime, the velocity of the filament scales as $\delta_{\perp}^{-2}$, where $\delta_{\perp}$ is the perpendicular blob size. If, however, a filament is in closed-field-line regimes, it scales as $\delta_{\perp}^{1/2}$, and is said to be inertially-limited. A thorough discussion of these regimes, and derivations of the scaling with perpendicular size can be found in References [8, 9]. Of particular interest here is how the parallel connection length alters the filament scaling.

Figure 1 illustrates the scaling of filament velocity vs the perpendicular filament size, $\delta_\perp$, for various $L_\parallel$. For this scaling, filaments were initialized as a 10% Gaussian perturbation above a background with parameters chosen to be W7-X-relevant: $T_{e0} = 100$eV, $n_0 = 2\times10^{19}\text{m}^{-3}$, R = 6m, $B_0 = 2.5$T.

From Figure 1 it appears that filaments of sufficient size will be sheath limited, even in the case of a very long connection length region such those found in Wendelstein 7-X.

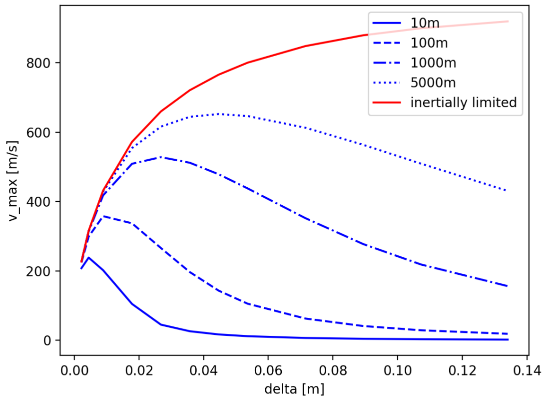

Figure 1: Filament velocity scaling in various connection length regimes

Seeding location relative to transition

The scrape-off-layer of Wendelstein 7-X exhibits a patchwork $L_\parallel$ structure, where neighboring field lines can have completely different connection lengths – up to an order of magnitude [10]. Here, we determine how such a transition can affect the dynamics of a seeded filament. The trajectory of a filament is altered when it crosses a transition in parallel connection length, as shown in Figure 2 which depicts the radial position of a filament vs time for various locations of the parallel connection length transition relative to the filament seeding location.

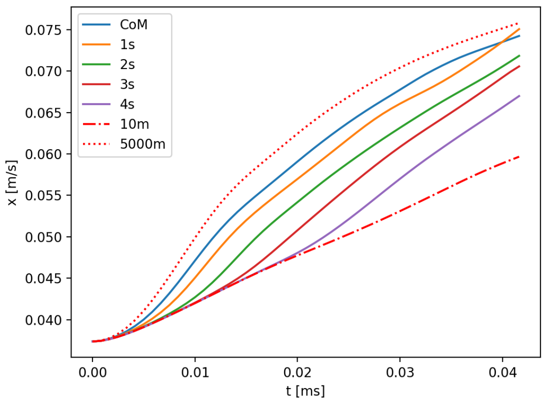

Figure 2: The effect of a transition: filaments encountering a transition to higher $L_\parallel$ are accelerated. This is consistent for various distances between filament seeding location and the $L_\parallel$ transition

A filament entering a different $L_\parallel$ regime will jump to the other propagation regime – blobs which enter regions of longer $L_\parallel$ are accelerated relative to the case without a transition (as shown in Figure 2), while the opposite transition causes a deceleration. In some cases, a filament can even be accelerated such that it travels farther than if it had encountered no transition at all.

The effects of transition magnitude

Having established that filament trajectory is altered by a transition in $L_\parallel$, it is natural to try and determine if the strength of the transition – how large the step in $L_\parallel$ is – drastically affects the blob propagation. Figure 3 indicates the radial position of a filament as a function of time in cases with varying transition strength.

From Figure 3 it appears that even small transitions (by W7-X standards) significantly alter propagation. Furthermore, there is very little difference between a filament which has encountered a transition from 10m to 50m than that which has seen a transition from 10m to 1km, despite there being a factor of twenty in the 'step size'.

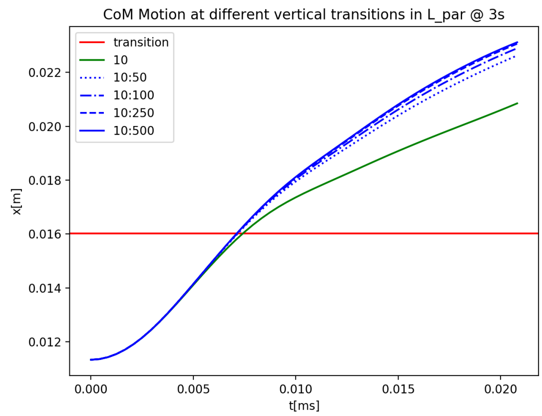

Figure 3: Transitions in $L_{\parallel}$ always affect propagation, even when the change in $L_{\parallel}$ is small

Horizontal transition

A filament will not always encounter a transition which is perpendicular to the propagation trajectory. Therefore, a filament was seeded with an $L_{\parallel}$ transition which divides the density perturbation exactly in half such that the lobes of the associated potential dipole evolve in two separate $L_{\parallel}$ regimes. Figure 4 indicates the vertical position of various sized filaments which are initialized across transition in $L_{\parallel}$.

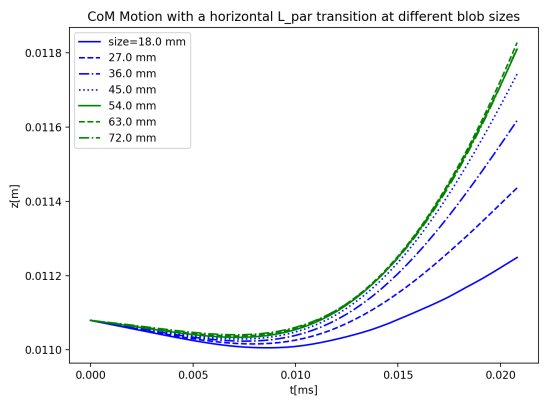

Figure 4: A filament is steered into regions of higher $L_{\parallel}$, but this effect is reduced for smaller filaments

Filaments whose potential dipole evolves in two separate $L_{\parallel}$ regimes are steered into the region of higher $L_{\parallel}$. At higher $L_{\parallel}$, the potential difference cannot be resolved and the vorticity steers the filament into this region. This effect is less drastic for a small transition in $L_{\parallel}$, and for small filaments – as illustrated in Figure 4. Smaller filaments tend to be inertially-limited, and the parallel currents (and therefore parallel connection length) are sub dominant.

Conclusion

Transitions in parallel connection length ($L_{\parallel}$) can alter filament propagation. Filaments entering regions of higher $L_{\parallel}$ are accelerated, whereas filaments encountering a shorter connection length are decelerated. This effect is present for differently-sized transition magnitudes, although to differing degree. If a filament has a dipole which exists in two separate $L_{\parallel}$ regimes, the filament can be steered into the region of higher $L_{\parallel}$. These results indicate that filaments in devices such as Wendelstein 7-X could have a more complicated trajectory due to the strong variation on parallel connection length present in the scrape off layer.

Acknowledgments

The authors would like to acknowledge the work of the BOUT++ development team. BOUT++ is an open-source framework available at boutproject.github.io. The input files used in this work are available upon request.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] B Shanahan, B Dudson, and P Hill. Fluid simulations of plasma filaments in stellarator geometries with BSTING. *Plasma Physics and Controlled Fusion*, 61(2):025007, 2018.

[2] N R Walkden, L Easy, F Militello, and J T Omotani. Dynamics of 3d isolated thermal filaments. *Plasma Physics and Controlled Fusion*, 58(11):115010, 2016.

[3] B W Shanahan and B D Dudson. Blob dynamics in torpex poloidal null configurations. *Plasma Physics and Controlled Fusion*, 58(12):125003, 2016.

[4] Brendan Shanahan, Ben Dudson, and Peter Hill. The effects of non-uniform drive on plasma filaments. *Journal of Physics: Conference Series*, 1125:012018, 2018.

[5] B D Dudson, M V Umansky, X Q Xu, P B Snyder, and H R Wilson. BOUT++: A framework for parallel plasma fluid simulations. *Computer Physics Communications*, 180:1467–1480, 2009.

[6] Benjamin Daniel Dudson, Jens Madsen, John Omotani, Peter Hill, Luke Easy, and Michael Løiten. Verification of bout++ by the method of manufactured solutions. *Physics of Plasmas*, 23(6):062303, 2016.

[7] Ben Dudson et al. Bout++ v4.2.2, March 2019.

[8] D A D´ Ippolito, J R Myra, and S J Zweben. Convective transport by intermittent blob-filaments: Comparison of theory and experiment. *Physics of Plasmas*, 18:060501, 2011.

[9] Sergei I Krasheninnikov. On scrape off layer plasma transport. *Physics Letters A*, 283(5):368–370, 2001.

[10] F. Effenberg et al. Investigation of 3d effects on heat fluxes in performance-optimized island divertor configurations at wendelstein 7-x. *Nuclear Materials and Energy*, 18:262 – 267, 2019.