Studying ELM filaments with Doppler reflectometry in ASDEX Upgrade

E. Trier$^{1,2}$, P. Hennequin$^2$, J.R Pinzón$^{1,3}$, M. Hoelzl$^1$, G.D. Conway$^1$, T. Happel$^1$, G.F. Harrer$^4$, F. Mink$^{1,3}$, F. Orain$^{1,5}$, E. Wolfrum$^1$, the ASDEX Upgrade Team and the EUROfusion MST1 Team$^*$

$^1$ Max Planck Institute for Plasma Physics, D-85748 Garching, Germany
$^2$ LPP, Ecole Polytechnique, CNRS, F-91128 Palaiseau Cedex, France
$^3$ Physik-Department E28, Technische Universität München, 85747 Garching, Germany
$^4$ Institute of Applied Physics, TU Wien, Austria, Fusion@ÖAW
$^5$ CPHT, Ecole Polytechnique, CNRS, Université Paris-Saclay, 91128 Palaiseau, France

During edge localized modes (ELMs), filaments are expelled from the edge of H-mode plasmas [1]. Shear flows have been shown to be an important ingredient, and are now included in the models [2]. It is therefore essential to investigate experimentally the dynamics of the filaments during an ELM crash. In this contribution, the observation by Doppler reflectometry (DR) of an acceleration, followed by a reversal of the filament velocity during type-I ELMs is reported.

Methodology

In ASDEX Upgrade, the Doppler reflectometers are operated in the V (50-75 GHz) and W (75-110 GHz) bands. The received signal has a Doppler-shift in frequency, $f_D = k \cdot v / 2\pi$, where $k$ is the scattering wave-vector defining the spatial scale of the probed density fluctuations and $v$ their velocity. In H-mode, ‘burst-like’ events of backscattered signal, with a typical duration of $\sim 10\,\mu$s are observed [3, 4], either during the inter-ELM phase or the ELM crashes (fig. 1). The Doppler frequency (fig. 1b) is usually well-defined and can be associated to a single event. Some of the strongest of these events can be observed in the inter-ELM phase with other diagnostics (Bolometers, divertor currents), which allows an identification with the filaments. In this study, the filaments and the associated time interval are detected automatically via a threshold in the signal modulus amplitude. The Doppler frequency $f_D$ associated with an event is evaluated in the corresponding time interval. The series of filaments detected during a stationary phase of an H-mode plasma (at the same probing frequency) are ELM-synchronized (the ELM onset $t_{ELM}$ is chosen as the start of the rise in divertor current).

Evolution of the filament motion during ELMs

The observed dynamics of the $f_D$ evolution is (fig. 2): an acceleration in the electron direction during the first $\sim 0.2\,\text{ms}$ of an ELM, then a reversal in the ion direction for $\sim 1\,\text{ms}$, and a recovery for $\Delta t_{ELM} \gtrsim 1\,\text{ms}$. This is observed for most of the frequencies probing the pedestal, and for both polarizations. Ray-tracing using the TORBEAM code [5], on ELM-synchronized $n_e$ profiles (fig. 2c) was used to evaluate the

*See author list of "H. Meyer et al 2017 Nucl. Fusion 57 102014"
normalized poloidal radius at the turning point $\langle \rho_{pol} \rangle$ (mapped on a pre-ELM equilibrium) without taking into account the perturbations due to filaments. Above $\sim 95$ GHz, the turning point is inside the pedestal top $\langle \rho_{pol} \rangle < 0.96$ where the radial electric field is positive. The small value of the pre-ELM Doppler shift ($\sim 1$ km/s) was reported in [4].

Radial or poloidal propagation During an ELM, some filaments are expelled with a radial velocity $v_r$ [1], which could induce a Doppler shift $f_D = k_r v_r / 2\pi$ (originating from the regions where $k$ has a radial component). This possibility is addressed by comparing measurements with different DR poloidal launching angles, in a way that the perpendicular component of $k$ at the turning point changes sign. The compared H-mode plasmas with type-I ELMs are #34347 $t = 2 - 4.5$ s (beam launched upwards, angle to the horizontal direction $+4^\circ$), and #34978 $t = 2 - 4.5$ s (downwards, angle $-21^\circ$). The change of polarity of $f_D$ between these two shots (fig. 3) shows that it is caused by a motion in the perpendicular (rather than radial) direction: indeed, the radial component of the wave-vector along the two probing beams are not of opposite signs.

2D ray tracing using JOREK density maps 2D ray tracing was applied to the $n_e$ fields resulting from a JOREK ELM simulation for a case similar to #34347 [6]. Typical $n_e$ perturba-
Figure 3: ELM-synchronized Doppler frequency shift of the filament events for two plasmas with reversed direction of the perpendicular component of the wave-vector at the turning point. X-mode polarization is used, at frequencies probing the pedestal ($\rho_{\text{pol}} \sim 0.99$).

The beam is 'modelled' by a series of 5 rays (fig. 4a), with ray equations similar to [7]. The $n_e$ perturbation size in the poloidal direction (typical range is 15 – 40 cm) is larger than the beam dimensions $\sim 4$ cm. The calculated evolution of $\rho_{\text{pol}}$ and the poloidal wave-vector component $k_\theta$ at the turning points are represented in figs. 4b and c. It is found that: (i) $\rho_{\text{pol}}$ is varying but remains inside the pre-ELM separatrix (ii) $k_\theta$ experiences significant variation, with $k_{\theta \text{max}}/k_{\theta \text{min}} \geq 2$ for all frequencies (iii) $\rho_{\text{pol}}$ and $k_\theta$ are almost in quadrature: the minimum of $k_\theta$ is reached when $\rho_{\text{pol}}$ is close to its mean value. Because the backscattered signal is stronger at lower $k$ (see next section), it results that the localization of the bursts should be well represented by $\langle \rho_{\text{pol}} \rangle$, calculated with a $n_e$ profile unperturbed by filaments (like in fig. 2c).

Figure 4: (a) Example of ray-tracing superimposed on ELM $n_e$ perturbations from JOREK calculations. Evolution of averaged quantities at the turning point, for a series of X-mode probing frequencies (76-100 GHz): $\rho_{\text{pol}}$ (b) and the poloidal wave-vector $k_\theta$ (c). Note the quasi-quadrature between $\rho_{\text{pol}}$ and $k_\theta$.

Full wave study in a slab geometry   The effect of a $n_e$ perturbation between the antenna and the cut-off is investigated using a full wave code [8]. A perturbation moving in the y–
direction $\delta n_e = \delta n_{e0} \cos(2\pi y/\lambda_b) \exp\left(-\frac{(x-x_b)^2}{\Delta x_b^2}\right)$ is added to a density background profile (fig. 5a) with a Gaussian turbulence (fluctuation level: 0.1%). A beam is simulated, with an unperturbed wave-vector $k_y = 6\,\text{cm}^{-1}$ if $\delta n_{e0} = 0$. The perturbation amplitude $\delta n_{e0}$ is varied from 0 to $2 \times 10^{19} \,\text{m}^{-3}$, and its distance to the cut-off from 3 to 1.5 cm. Significant changes of the backscattered signal amplitude are observed (fig. 5b). The main determining parameter is the wave-vector $k_y$, which can change significantly because the perturbation modulates the beam incidence angle close to the turning point. This results in a stronger signal at low $k_{\perp}$, qualitatively consistent with the turbulence spectrum shown in fig. 5b.

**Conclusion** 'Bursts' of backscattered signal associated with filaments have been studied during ELMs. The corresponding Doppler shift was found to be due to a motion in the perpendicular direction. After an acceleration in the electron direction for $\sim 0.2$ ms, rotation in the ion direction is measured during $\sim 1$ ms. The modulation of the wave-vector due to the $n_e$ perturbations is one possible cause for the increase in signal amplitude, because of the generally stronger turbulence at lower $k$. The observed qualitative properties of the filament motion during an ELM should be compared with the radial electric field evolution in the future.

**Figure 5:** (a) Geometry of the full wave simulation, and background $n_e$ profile. Simulation default parameters are $\Delta x_b = 1 \,\text{cm}$, $\lambda_b = 35 \,\text{cm}$ (b) RMS values of backscattered amplitude in a moving short-window for several runs, as a function of the $k_y$ wave vector.

**References**
[6] M. Hötzl et al., Contributions to Plasma Physics (accepted)

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