Quantitative prediction of the blob generation rate

G. Fuchert[1], D. Carralero[1], P. Manz[2], U. Stroth[1,2], E. Wolfrum[1], ASDEX Upgrade team

[1] Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany

[2] Physik-Department E28, Technische Universität München, 85748 Garching, Germany

Introduction

Filaments of increased pressure (“blobs”) that transport particles and energy towards the wall are commonly observed in the scrape-off layer (SOL) of magnetically confined fusion experiments. They can lead to an enhanced perpendicular energy and particle transport, wall deterioration, and increased impurity densities. However, there is still no model to predict the generation rate of blobs, which would be of major interest for understanding and modeling the SOL physics and to ensure the safe and reliable operation of future fusion power plants.

In this novel approach, the generation rate of blobs is related to the dispersion of the underlying turbulence and the stability of the blobs themselves. Predictions from this model are compared to experimental values from ASDEX Upgrade.

Prediction

In many fusion experiments it is observed that blobs are generated around a specific radial position ("generation region"). Inside of this region, usually a micro instability is present. According to many experimental observations (e. g. from Alcator C-Mod [1]), blobs detach from quasi-coherent structures of this instability (*seed fluctuations*). In ASDEX Upgrade this region is observed close to the separatrix. Probe measurements in L-mode plasmas indicate that the plasma turbulence in this generation region is dominated by a drift-wave-like instability. Hence, it is assumed that the generation rate is given by the frequency of this dominant edge instability. Since the frequency is linked to the spatial structure size by the dispersion relation it is necessary to know on which size scale the blob generation takes place. In ASDEX Upgrade the characteristic size of coherent structures remains constant when crossing the separatrix [2]. Hence, the blob size can be used as a proxy for the scale of the generating instability.

For a fixed observer the characteristic rate of seed fluctuations is then given by the background $\mathbf{E}\times\mathbf{B}$-drift velocity $v_{\mathrm{E}_r\times\mathrm{B}}$ and the phase velocity v_{ph} of the instability:

$$f_{\mathrm{g}} = (v_{\mathrm{ph}} + v_{\mathrm{E}_r\times\mathrm{B}})/\lambda_\perp\,. \tag{1}$$

For ASDEX Upgrade L-mode discharges it is assumed that in the SOL $E_r = -3\nabla T_{\mathrm{e}}/e$ [3] and, as discussed above, that the seed instability is drift-wave-like. Hence, v_{ph} is approximated by the diamagnetic velocity v_{dia} and it follows:

$$f_{\mathrm{g}} = \left| \frac{1}{3\delta_\theta} \cdot \left(\frac{\nabla p_{\mathrm{e}}}{e n_{\mathrm{e}} B} - 3 \frac{\nabla T_{\mathrm{e}}}{eB} \right) \right| , \tag{2}$$

with the electron density n_{e}, pressure p_{e} and temperature T_{e}, the elementary charge e and magnetic field strength B. Here, the conversion between the poloidal blob size δ_θ, defined as the full (poloidal) width at half maximum (FWHM) of the density perturbation, and the poloidal wave length $\lambda_\perp$ of the dominant edge instability $\lambda_\perp = 3\delta_\theta$ has been used, since the FWHM of the positive part of a sine wave is approximately $\lambda/3$.

Due to the small fraction of large amplitude events and the experimental focus on these, most of the generated structures are not detected. The detection rate f_{d} can be predicted as follows: The seed instability generates blobs at a rate f_{g}. They propagate radially outward, where a fraction γ_{d} of them is detected, depending on the blob amplitude distribution function and threshold amplitude a_{thresh}:

$$f_{\mathrm{d}} = f_{\mathrm{g}} \gamma_{\mathrm{d}} \, . \tag{3}$$

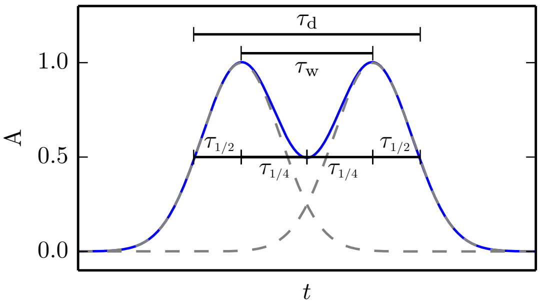

Figure 1: *In a pressure sensitive quantity A, single blobs are not properly resolved for* $\tau_{\mathrm{d}} \geq 1.7\tau_{\mathrm{w}}$. *A characteristic structure (closed line) is a compilation of* $(\tau_{\mathrm{d}}/\tau_{\mathrm{w}}) + 0.3$ *single events (dashed lines).*

In principle γ_{d} could be calculated from a given amplitude distribution. Since this distribution is not yet known, γ_{d} will be determined from experimental data below.

This line of argument is only valid as long as the blob transit time at a given position τ_{d} is small compared to the characteristic waiting time $\tau_{\mathrm{w}} = 1/f_{\mathrm{g}}$. In a simple model, for $\tau_{\mathrm{d}} \geq 1.7\tau_{\mathrm{w}}$, a typical blob is a compilation of $(\tau_{\mathrm{d}}/\tau_{\mathrm{w}}) + 0.3$ single events (these relations can be derived from Fig. 1, the calculations are not shown here). This reduces the number of clearly distinguishable blobs. In this case f_{d} is predicted as

$$f_{\mathrm{d}} = \frac{f_{\mathrm{g}}}{\tau_{\mathrm{d}}/\tau_{\mathrm{w}} + 0.3} \gamma_{\mathrm{d}} = \frac{1}{\tau_{\mathrm{d}} + 0.3\tau_{\mathrm{w}}} \gamma_{\mathrm{d}} \, . \tag{4}$$

For the comparison with experimental data, a circular blob shape is assumed, i. e. the radial size is equal to the poloidal one ($\delta_r = \delta_\theta$).

Comparison with experimental data

Blob detection rates were measured in L-mode discharges at ASDEX Upgrade (#29321-#29326 and #29887, toroidal magnetic field $B_{\mathrm{t}} = -2.5\,\mathrm{T}$, safety factor $q_{95} = 5.32$, plasma current $I_\mathrm{p} = 800\,\mathrm{kA}$, and ECRH power of $600\,\mathrm{kW}$) for different fueling levels. Using probes, the detection rate f_d was measured at the radial position $\rho_\mathrm{pol} = 1.025$. The kinetic profiles required for evaluating the model equations are deduced from the standard edge diagnostics [4].

From these data and Eqs. (3) and (4), the unknown γ_d can be estimated. For the evaluation, τ_d is identified with the radial auto-correlation time of the probe signal. A good agreement is obtained for $\gamma_\mathrm{d} = 0.035$, as is shown in Fig. 2, where the circles correspond to the predictions of Eq. (3) for $\tau_\mathrm{d}/\tau_\mathrm{w} < 1.7$ and the squares to $\tau_\mathrm{d}/\tau_\mathrm{w} \geq 1.7$, Eq. (4) (evaluated at the separatrix). The observed detection rate scales linearly with the prediction. However, the slope is smaller than one. Hence, the aforementioned assumptions should be revised in future experiments. Nevertheless, the majority of points is predicted correctly within a factor of two.

The successful prediction of f_d included experimental data for δ_θ and τ_d from probe measurements. A predictive model, however, should only depend on either measured or simulated density and temperature profiles. Now, the model equations can be evaluated by taking the most stable blob size δ_b as the poloidal blob size and estimating $\tau_\mathrm{d} \approx \delta_\mathrm{b}/v_\mathrm{b,r}$ (assumption of a circular blob shape).

At ASDEX Upgrade, the identification of the relevant blob regimes is subject of present research [5]. There are at least two different regimes relevant for typical L-mode discharges depending on the connection of the plasma to the target plates. For low edge densities the size and velocity of blobs seem to scale as predicted by the well-studied sheath limited regime, probably influenced by a finite ion temperature T_i.

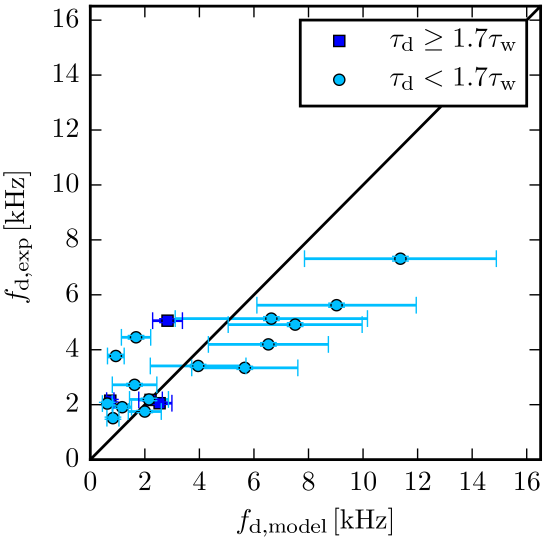

Figure 2: *Experimental blob detection rate* $f_\mathrm{d,exp}$ *around* $\rho_\mathrm{pol} = 1.025$ *compared to a prediction from Eq.* (3) *for* $\tau_\mathrm{d} < 1.7\tau_\mathrm{w}$ *and Eq.* (4) *for* $\tau_\mathrm{d} \geq 1.7\tau_\mathrm{w}$*, respectively with* $\gamma_\mathrm{d} = 0.035$.

Following Ref. [6] and assuming that in the SOL $T_\mathrm{i} \approx 3T_\mathrm{e}$, $l_\| = 70\,\mathrm{m}$ (parallel connection length) and $R = 2.155\,\mathrm{m}$ (major radius of the separatrix), the following scaling laws are obtained:

$$\delta_b = 4\rho_\mathrm{s}\left(\frac{l_\|^2}{\rho_\mathrm{s} R}\right)^{1/5}, \quad v_{\mathrm{b},r} = 4c_\mathrm{s}\left(\frac{\rho_\mathrm{s}}{\delta_\mathrm{b}/2}\right)^2 \frac{l_\|}{R}. \tag{5}$$

Above a threshold line-integrated edge density of about $2.5 \cdot 10^{19}\,\mathrm{m}^{-3}$ the blob size is observed to scale linearly with the density. The identification of this regime with one of the cases described in the literature is ongoing. Therefore, in this regime a constant blob velocity of $v_{\mathrm{b},r} \approx 600\,\mathrm{m/s}$ and an empirical scaling for the blob size

$$\delta_b[\mathrm{m}] = 0.047 \cdot (\langle n_{\mathrm{edge}} \rangle [10^{19}\,\mathrm{m}^{-3}] - 2.5) + 0.030 \tag{6}$$

are assumed in accordance with the experimental values reported in Ref. [5]. Using these equations and $\gamma_\mathrm{d} = 0.035$ the prediction of f_d is repeated (shown in Fig. 3).

The absolute values are again predicted correctly within a factor of two for most data points. Improving the scaling laws for δ_b and $v_{\mathrm{b},r}$ in the high-density regime may improve this agreement further.

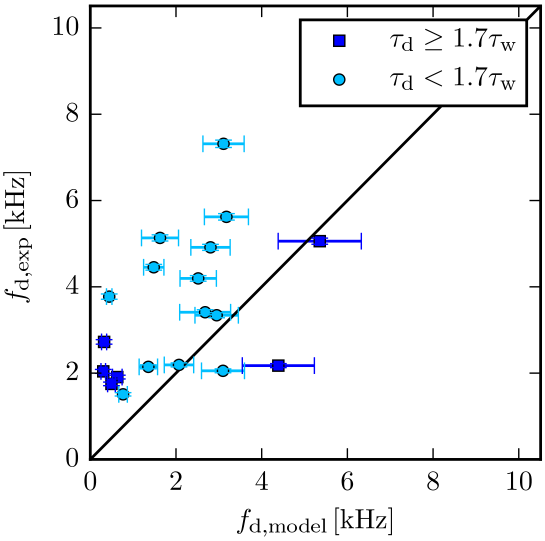

Figure 3: *Same representation as Fig. 2, but using analytical scaling laws for* δ_b *and* τ_d.

Summary and conclusion

A phenomenological model has been derived from the experimental findings that blobs are generated in a distinct region close to the separatrix by a dominant edge instability and that there seems to be a relation between this instability and the blobs in terms of detection frequency and size.

A comparison with experimental detection rates has been done for ASDEX Upgrade L-mode discharges. A good overall agreement was achieved, using the kinetic profiles as only input.

References

[1] J. L. Terry *et al*, Phys. Plasmas **10**, 1739 (2003)
[2] B. Nold *et al*, Plasma Phys. Control. Fusion **52**, 065005 (2010)
[3] P. C. Stangeby, The Plasma Boundary of Magnetic Fusion Devices, Taylor and Francis Group, NY (2000)
[4] R. Fischer *et al*, Fus. Sci. Techn. **58**, 675 (2010)
[5] D. Carralero *et al*, Nucl. Fusion **54**, (2014)
[6] P. Manz *et al*, Phys. Plasmas **20**, 102307 (2013)

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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Furthermore, this work is supported by Agence Nationale pour la Recherche, contract ANR-11-BS09-023-03 (SEDIBA).