

Development of a Synthetic Lithium Beam Diagnostic for the HESEL Turbulence Code and Application to Blob Transport

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Introduction

Filamentary structures in the scrape-off layer (SOL) of fusion devices (so called blobs) are expelled from the main plasma and may lead to enhanced erosion at wall components [1]. In order to measure the blob propagation characteristics, Lithium Beam Emission Spectroscopy (Li-BES) can be used in the plasma edge [2]. An improved understanding of blob dynamics can be obtained by comparing a radiative-collisional Li-BES model (SIMULA) [3] combined with a 2D turbulence code (HESEL) [4] constituting a synthetic Li-BES diagnostic. HESEL is a self-contained, energy conserving model, derived from Braginskii's equations, and covers an area including the last closed flux surface (LCFS) and the SOL. A snapshot of a HESEL density output is shown in Figure 1a (Density Case), where the plane is spanned by the radial (vertical) and the poloidal (horizontal) axis. The other three images show different synthetic 2D-Li-BES emission signals for the density data in Figure 1a. The beam is injected from the top ($x = 0$ cm refers to LCFS).

Figure 1b shows the resulting emission intensity from the Li_{2p} line (Emission Case). The smearing because of the finite lifetime (≈ 27 ns) of the Li_{2p} energy level leads to a larger structure than in the Density Case [2]. Figure 1c averages over $0.5 \times 1.2 \text{ cm}^2$ areas, as this is the approximate covered area by a detector element of the ASDEX Upgrade Li-BES system [5]. Figure 1d (Real SNR Block Case) is the same average, but with artificial noise added. The blob is still visible at $x \approx 5 \text{ cm}$, $y \approx 3 \text{ cm}$.

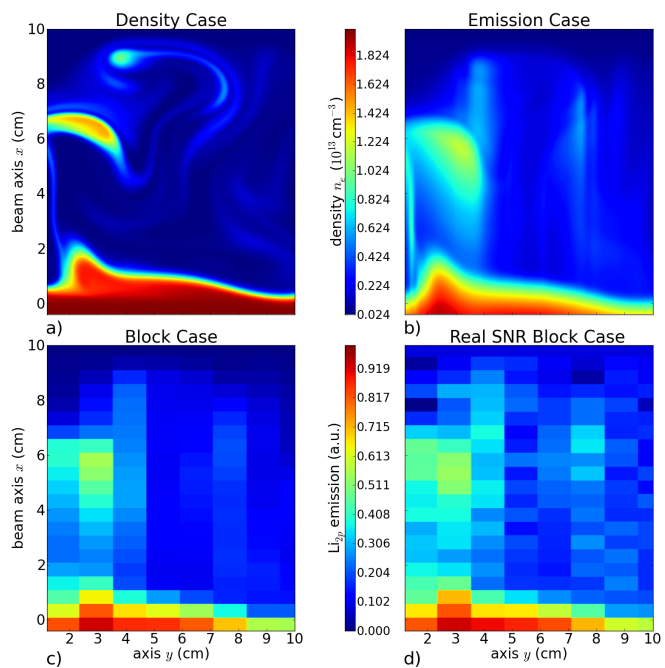


Figure 1: The 2D slab area covered by HESEL and analyzed by SIMULA.

Blob Characterization

The characterization of the blobs in the different cases has been performed via a conditional average technique [6], applied to the synthetic emission output. A threshold of two standard deviations on the time signal has been chosen. The spatial resolution of HESEL was set to 512×512 and a time interval of 7 ms was analyzed. In order to calculate a specific blob property, a reference channel within the SOL is chosen to trigger an event. In Figure 2, the reference channel is at $x = 2.1$ cm outside from the separatrix ($x = 0$ cm). For this channel, a spatio-temporal average $I(x, \Delta t)$ of the synthetic beam emission is obtained after conditional averaging in Figure 2a. The blob velocity is defined by the movement of the center of mass (COM) position X_C

$$X_C = \frac{\int x I(x, \Delta t) dx}{\int I(x, \Delta t) dx}, \quad (1)$$

which is indicated by the vertical lines in Figure 2b for the relative time instances marked in Figure 2a along with the respective profiles $I(x, \Delta t)$. The velocity of the blob is then obtained from a linear fit of the center of mass position and shown in Figure 2c. The maximum blob velocity is defined by the steepest gradient of the COM trajectory. In order to calculate a reliable velocity, the time window for the conditional average should be chosen to be 2–3 times the self correlation time (see Figure 2d), which is the effective time a blob appears in front of a detector element. The blob width ρ_x is then defined as the half width at half maximum of $I(x, \Delta t)$ at $\Delta t = 0$. A further output of the analysis is the fluctuation amplitude $\Delta n/n$ or $\Delta I/I$, respectively. Error estimations are done via statistical analysis of the variation at different poloidal positions.

The blobs can be characterized for different radial positions by changing the position of the reference channel. The density results can now be compared to the synthetic diagnostic results in radial profiles. Figure 3a shows the radial profile of the blob widths. The blob width deduced

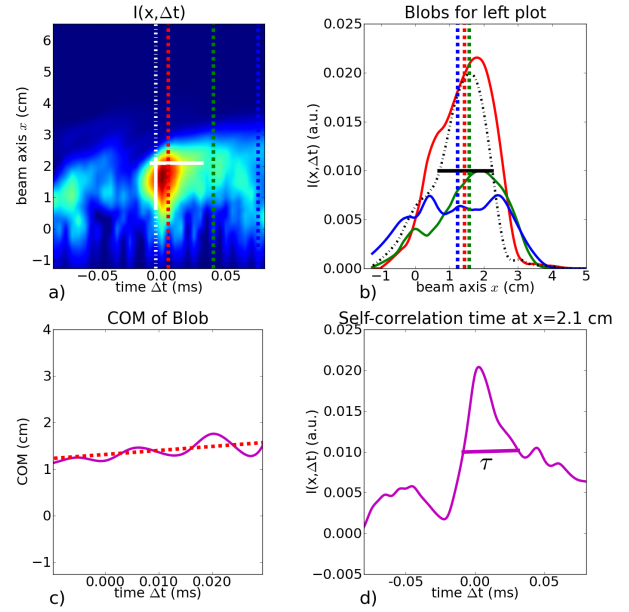


Figure 2: Conditionally averaged emission: a) Averaged blob in time and space, b) blob representatives with COM location, c) COM and average velocity (dashed), d) self-correlation time τ of the blob.

from the emission is about twice the value obtained from the Density Case. This is because of the smearing effect described above. Figure 3b shows, that the blob velocities increase for $x \geq 1$ cm, but start to decrease for $x \geq 2$ cm. Since the velocities in all four cases agree well, it can be assumed, that the velocity estimation from emission data reflects the true blob velocity. The blob frequency in Figure 3c is much higher in the Density Case, as many small blobs are invisible for the synthetic diagnostic. This implies, that the blob frequency is underestimated, if Li-BES is used. The blobs also have higher amplitude

of factor 2 (see Figure 3d) in the Density Case. The reason for this discrepancy may be the path integration effect of the Li_{2p} -state occupation along the beam, which leads to a higher average emission and therefore to a smaller fluctuation amplitude. Figure 3 also shows, that all three emission cases agree well for the radial characteristics. It would thus be sufficient to compare only the Real SNR and the Density Case.

Blob Velocity Scaling

The estimated blob velocity can be compared to the theoretically predicted scaling laws, which predict, that the blob velocity depends on the blob width ρ_x , the relative amplitude $\delta n/n$ or machine parameters like parallel connection length $L_{||}$ and the major radius R . They describe the damping of the blobs via inertial effects due to blob size [7] or sheath-connection with cold ions [8] and warm ions [9]. Theiler et al. [10] combines inertial and sheath-connection effects for cold ions to the formula

$$v_r = \frac{\sqrt{\frac{2\rho_x}{R}}}{1 + \frac{1}{\rho_s^2 L} \sqrt{\frac{R}{2\rho_x}}^{5/2} + \frac{v_{in} \sqrt{R\rho_x}}{\sqrt{2}c_s}} \frac{\delta n}{n} c_s, \quad (2)$$

where the last term in the denominator can be neglected due to low ion-neutral collision frequency v_{in} in the investigated plasma [2]. Here, c_s refers to the ion sound speed $c_s = \sqrt{T_e/m_i}$, with the electron temperature T_e and ion mass m_i and ρ_s corresponds to the Larmor radius. For different magnetic fields and connection lengths the normalized velocity and the blob width was

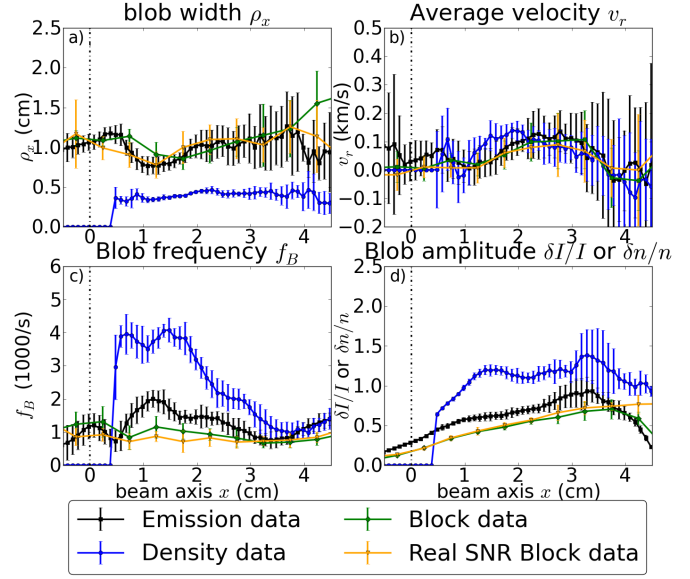


Figure 3: Radial characterization for a simulation with $B_0 = 2.4$ T, $q = 5.5$, $L_{||} = 11.8$ m: a) Blob width, b) Average blob velocity, c) blob frequency, d) relative blob amplitude.

evaluated for a fixed reference position. The result can be seen in Figure 4. Figure 4a shows the Density Case. The scaling predictions (circles) of Krashenninikov are above the maximum and average velocity of the blobs, whereas the maximum blob velocity is predicted well by the Theiler and Manz scaling. Theiler and Manz predict a much smaller velocity in the range of a critical blob size [10] as it is the case here. Since the average blob sizes in the Density Case are much smaller than for the emission cases, the scaling predicts higher

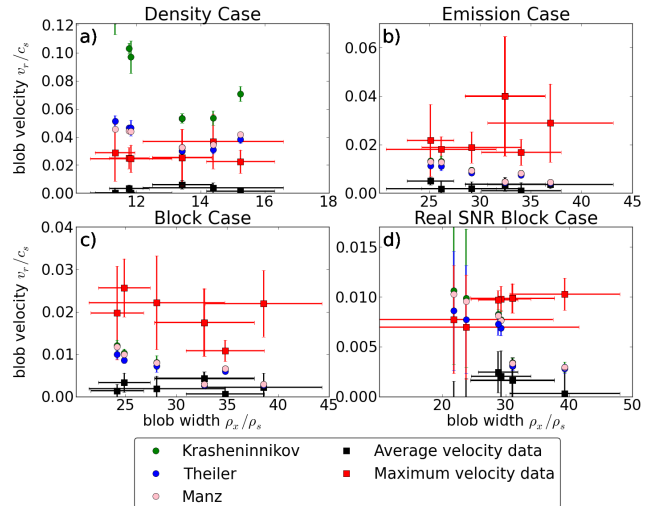


Figure 4: Velocity scaling depending on blob sizes for all four cases. The velocities are normalized by the ion sound speed c_s , the blob sizes by the Larmor radius ρ_s .

velocities. The blobs appear smaller due to a detection limit of the Li-BES system. In the other three cases the scaling laws coincide for larger blobs and the scaling laws predict velocities between the maximum blob velocity (red) and the average velocity (black). This has also been observed by Birkenmeier et al. [2]. In addition, for the overestimated blob size in the emission cases, the scaling laws underestimate the blob velocity if no correction for blob width and amplitude is applied.

Summary and Conclusion

The synthetic Li-BES system included in the first principle model HESEL shows, that it can be used for quantitative analysis of blob characteristics. It is suitable to be compared to experimental Li-BES results. The results of the radial analysis affirm, that the synthetic Li-BES measurements deliver reliable blob velocities. The velocity scaling investigations show a good agreement with the scaling laws, but need to be corrected for a true representation.

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