Blob shapes the scrape-off layer: Comparison of measurements to simulations

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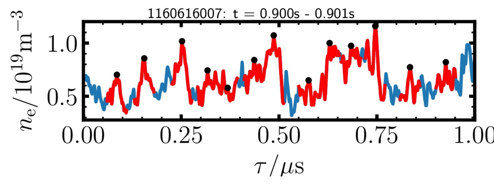
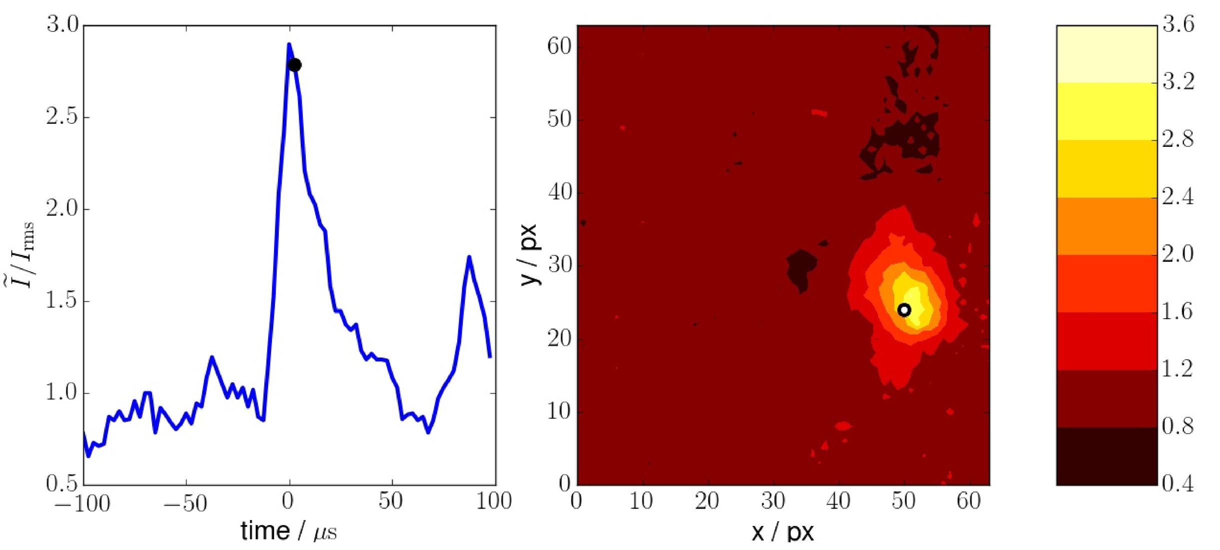
Introduction

- Data time series in scrape-off layer plasmas feature intermittent, large amplitude bursts. [1]
- Large amplitude bursts are due to blob propagating through the SOL towards the vessel wall [2]





Right: C-Mod GPI data (phantom camera, SOL view in radial-poloidal domain)
Left: Intensity time series of a single pixel

- Time series normalized to vanishing mean and unity root mean square $\widetilde{\Phi} = \frac{\Phi - \overline{\Phi}}{\Phi_{\mathrm{rms}}}$
- Time series analysis: Conditional average gives the average wave form of the pulses: $\langle \Phi(\tau) | \Phi(\tau = 0) > 2.5 \times \Phi_{\mathrm{rms}} \rangle$

Stochastic model describes these time series as superposition of uncorrelated pulses:

- Pulse arrival time $0 < t_k < T$
- Pulses arrive uncorrelated $P_t(t) = T^{-1}$
- Pulse amplitudes A_k exponentially distributed
- Pulse shape $\phi(\tau)$

$$\Phi_K(t) = \sum_{k=1}^{K} A_k \phi(t - t_k)$$

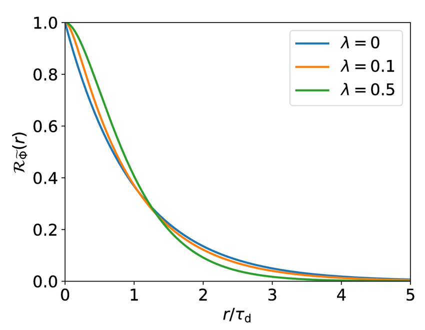
- Two-sided exponential pulse shape
- Pulse asymmetry parameter: λ
- Normalized time $\theta = \tau / \tau_d$
- Rise / Fall time: $\tau_r = \lambda \tau_d$, $\tau_f = (1-\lambda)\tau_d$,

$$\phi(\theta) = \Theta(-\theta)\exp\left(\frac{\theta}{\lambda}\right) + \Theta(\theta)\exp\left(-\frac{\theta}{1-\lambda}\right)$$

- Autocorrelation function of the pulse shape gives the signals autocorrelation function: $\mathcal{R}_{\widetilde{\Phi}}(\tau) = \rho_\phi(\tau / \tau_d)$

$$\mathcal{R}_{\widetilde{\Phi}}(\tau) = \frac{1}{1 - 2\lambda}\left[(1-\lambda)\exp\left(-\frac{|\tau|}{(1-\lambda)\tau_d}\right) - \lambda \exp\left(-\frac{|\tau|}{\lambda \tau_d}\right)\right]$$

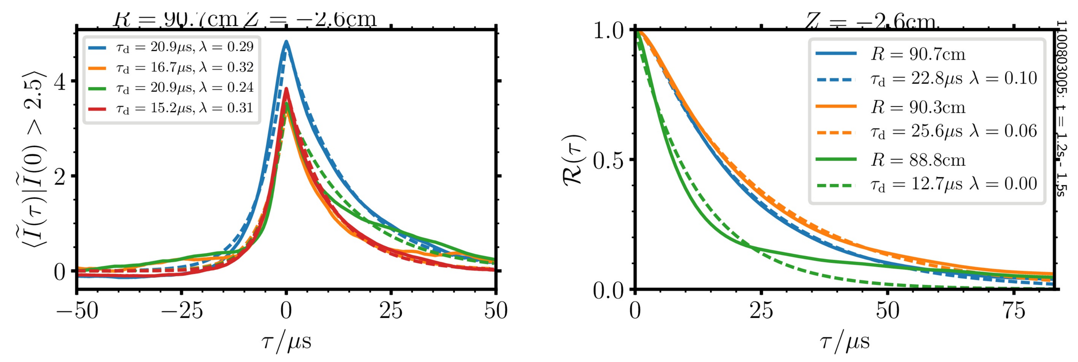
- Pulse asymmetry parameter λ governs autocorrelation function
- Exponential decay for $\lambda = 0$
- Parabolic shape at $\tau = 0$ for $\lambda = 1/2$



How do conditionally averaged wave forms vary across different diagnostics?
How do blob pulses look like in simulations?
Which physics governs the blob shape?

Gas Puff Imaging measurements

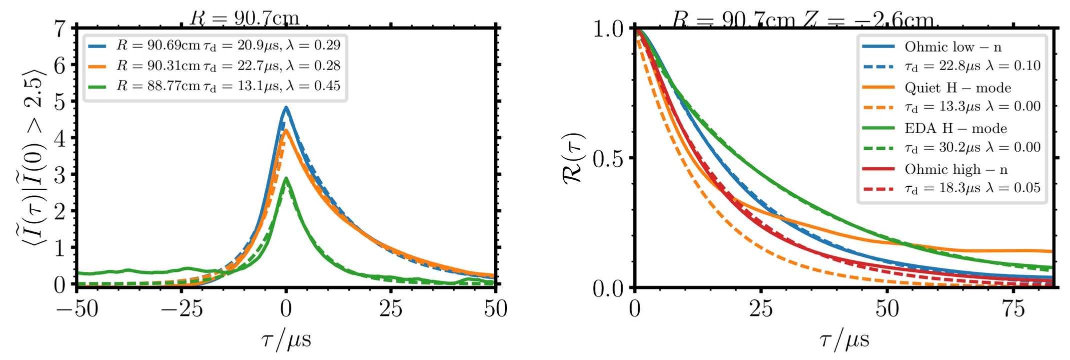
Ohmic L-mode, n_e/n_G=0.2, different radial positions



Low density L-Mode:
- Average waveform show steep rise and slow decay.
- Both waveforms yield similar fit parameters
- Autocorrelation function at R=88.8cm does not decay to 0.

Comparison among confinement modes

Ohmic L-mode (high- and low-density), EDA H-mode, quiescent H-mode

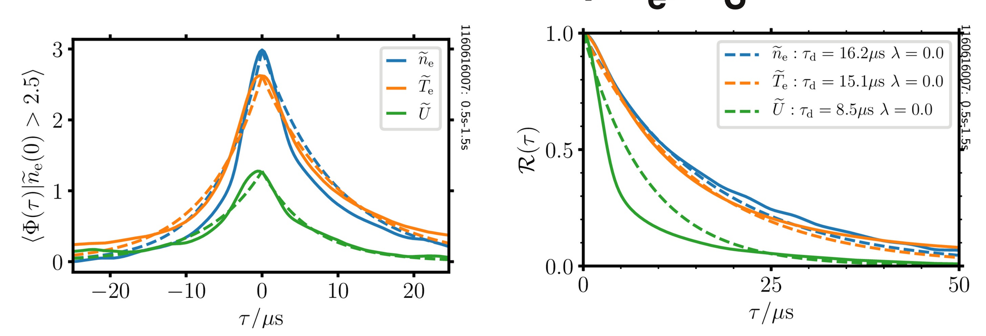


- Conditionally averaged wave form well described by two-sided exponential function
- τ_c agrees from fit on waveform similar to parameter fit on autocorrelation function

Mirror Langmuir Probe measurements

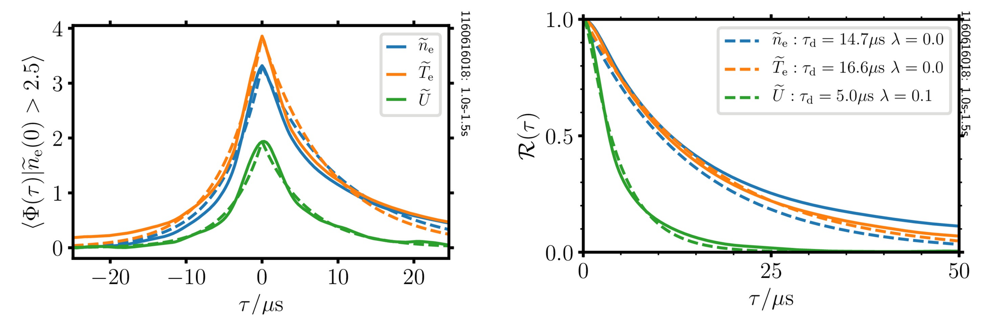
Probe dwelled at limiter radius at outboard mid-plane, sampled 0.8-1.0s long data time series

Ohmic L-mode, n_e/n_G=0.12



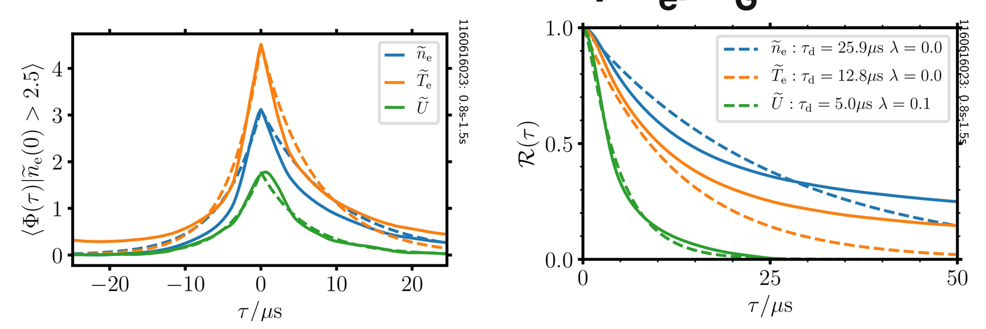
- Density and temperature wave forms rise and decay approximately exponentially
- Parabolic shape at $\tau = 0$
- Symmetric wave form
- Autocorrelation function decays exponentially
- Little asymmetry from least squares fit on wave form

Ohmic L-mode, n_e/n_G=0.4



- Conditional averaged wave form:Similar duration times and asymmetry as in low-density discharge
- Fit on autocorrelation function yields similar duration time and asymmetry as in low-density discharge

Ohmic L-mode, n_e/n_G=0.6



- Conditional averaged wave form: Similar duration times and asymmetry as in low-density discharge
- Autocorrelation function for density and temperature do not decay to zero

Numerical simulations

Simplified interchange model

- Blob motion due to interchange mechanism [5]
- Constant electron temperature, T_i=0
- Time normalized to interchange rate

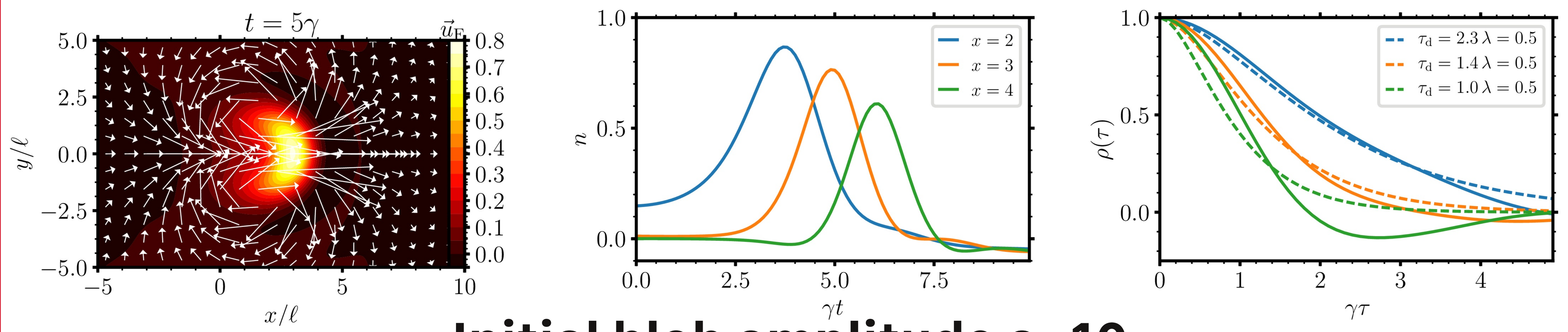
$$\gamma = \sqrt{\frac{C_s^2}{R_0 \ell}}$$

$$\left(\frac{\partial}{\partial t} + \frac{\mathbf{b}\times\nabla\phi}{B_0}\cdot\nabla\right)\frac{\widetilde{n}}{N} + \mathcal{K}(\phi) - \frac{T_e}{e}\mathcal{K}\left(\frac{\widetilde{n}}{N}\right) = \nu\nabla_\perp^2 \widetilde{n} N$$

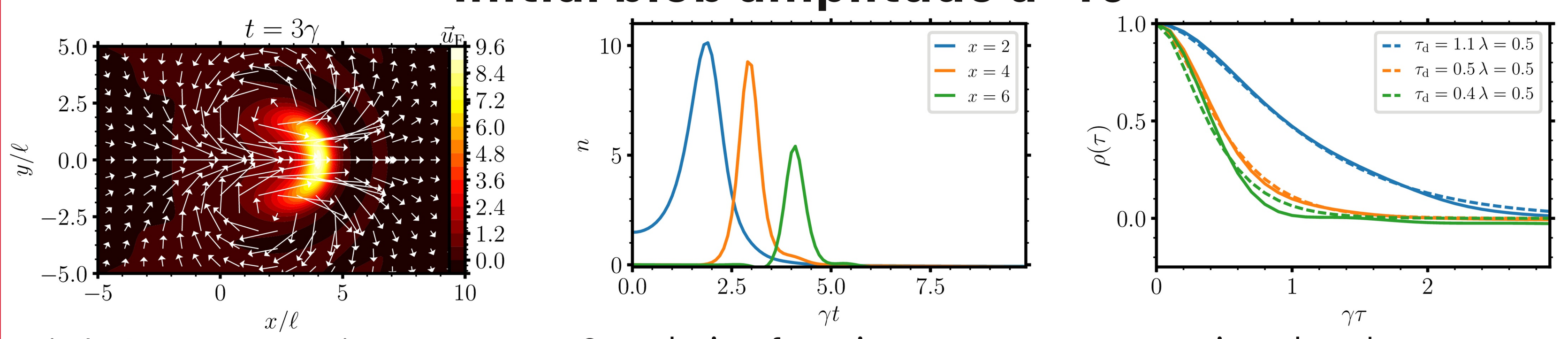
$$\left(\frac{\partial}{\partial t} + \frac{\mathbf{b}\times\nabla\phi}{B_0}\cdot\nabla\right)\Omega - \Omega_{ci}\frac{T_e}{e}\mathcal{K}(\widetilde{n}) = \nu\nabla_\perp^2\Omega$$

$$\Omega = \nabla_\perp^2\phi$$

Initial blob amplitude a=1



Initial blob amplitude a=10



- Little front steepening
- Correlation function suggests symmetric pulse shape

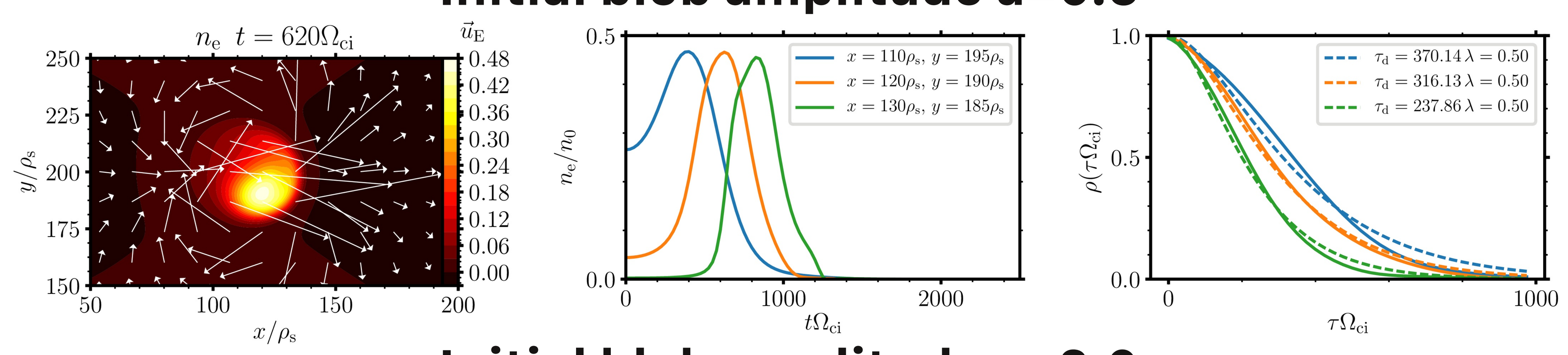
Gyro-fluid model

- 4 field model: dynamic n_e N_i T_e T_i [6]
- Self-consistent, dynamic FLR effects
- Gyro-Bohm normalization

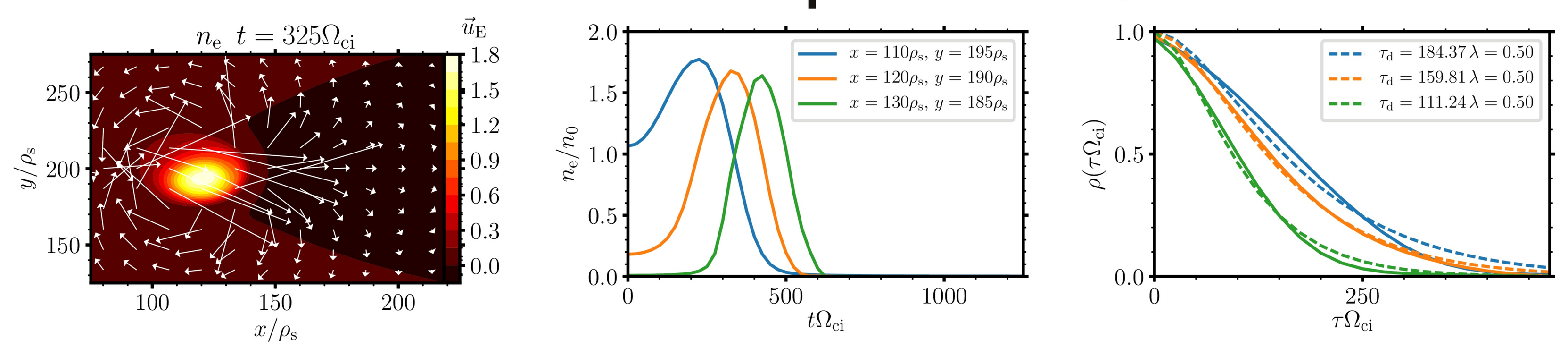
Non-linear polarization:

$$\nabla \cdot \left(\frac{n_e}{B\Omega_{ci}}\frac{\mathrm{d}}{\mathrm{d}t}\nabla_\perp \phi^*\right) \approx \frac{1}{e}\mathcal{K}(p_e + p_i)$$

Initial blob amplitude a=0.5



Initial blob amplitude a=2.0



- Blob develops increasingly strong poloidal momentum with initial amplitude
- Density and temperature fields strongly correlated, i.e. similar wave forms
- Pulse shapes present little asymmetry
- Auto-correlation functions well approximated by expression for two-sided exponential
- Least squares fit suggests

Conclusions and future work

Conditionally averaged waveforms of the plasma density and temperature, as sampled by the Mirror Langmuir Probes in ohmically heated L-mode plasmas, are well approximated by symmetric, two-sided exponential functions. Auto-correlation functions the low- and medium density discharge agree well with the auto-correlation function of a two-sided exponential pulse shape, but suggest a vanishing pulse asymmetry. A similar analysis on GPI data on the other hand suggests that the conditionally averaged wave form presents a faster rise and a slower decay. This agrees with parameters estimated from a fit on the auto-correlation function. Numerical simulations of seeded plasma blobs in the ideal interchange regime suggest however an almost symmetric pulse shape. Auto-correlation functions of single point data time series confirm this. Least squares fit on the data time series yield lambda = 1/2. Future work will focus on identifying additional functions to describe the pulse shape observed in seeded blob simulations, as well as in SOL turbulence simulations. This may elucidate the observed similarity in auto-correlation functions for pulse shapes which are not well approximated by two-sided exponential functions.

References

[1] G.Y. Antar et al. Phys. Plasmas **10** 419 (2003)
[2] D.A. D'Ippolito et al. Phys. Plasmas **18** 060501 (2011)
[3] O.E. Garcia, Phys. Rev. Letters **108** 265001 (2012);
O.E. Garcia et al. Phys. Plasmas 24 032309 (2017)
[4] A. Theodorsen et al. Nucl. Fusion **57** 114004 (2017)
[5] R. Kube et al. Phys. Plasmas **23** 122302 (2016);
O.E. Garcia et al. Phys. Plasmas **12** 090701 (2005);
[6] M. Held et al. Nucl. Fusion **56** 126005 (2016)