Turbulence statistical properties in FELTOR TCV761XX simulation

Are the filaments truly field aligned?

S. Brynjulfsen

Faculty of Physics and Technology
UiT Arctic University of Norway

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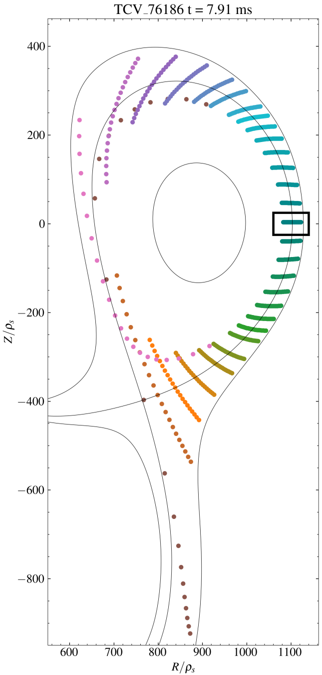
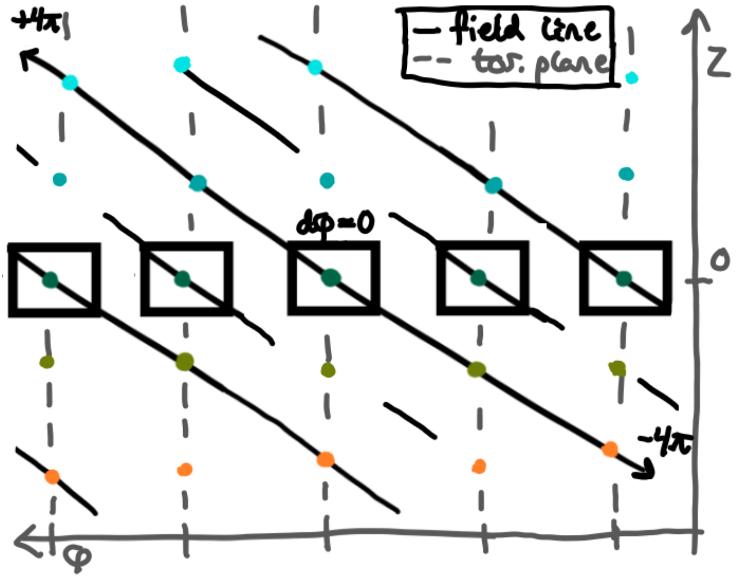
Probe setup

- 32 toroidal planes, axisymmetric
- Field aligned grid of probes $32 \times 29 \times 21 = 19488$
- ≈ 8 ms currently, converged for $\approx$ 3ms (x 32)
- Sampling rate $f = 10$MHz
- Simulation of TCV shots 76186($B_\varphi > 0$) and 76142($B_\varphi < 0$)
- Normalization $n'_e = n_e/n_0 \sim 10^{-1}$ after convergence



Probe grid

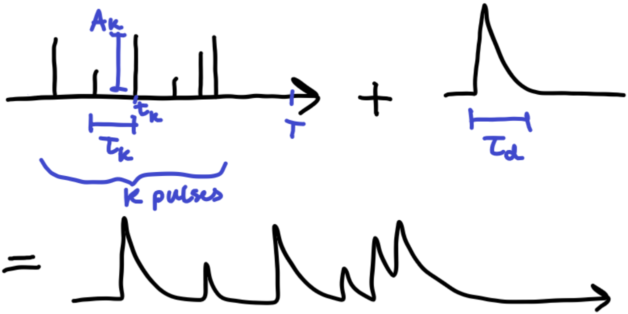


Stochastic model

FPP:

$$\Phi_K(t) = \sum_{k=1}^{K(T)} A_k \phi\left(\frac{t - t_k}{\tau_k}\right), \tag{1}$$

$\gamma = \frac{\tau_d}{\tau_w}$, $\tau_d = \langle \tau_k \rangle$, $\tau_w = T/\langle K \rangle$.



Normalization $\tilde{n}_e = (n_e - \langle n_e \rangle)/n_{e\,\mathrm{rms}}$.

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OMP time series

Signal at various radial positions at the outboard midplane.
Favourable and unfavourable curvature drift direction.

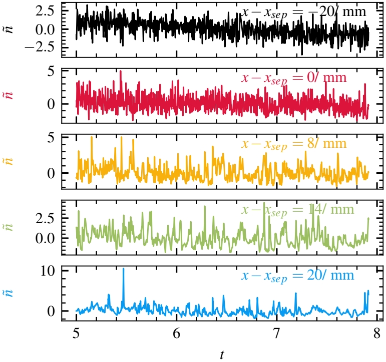

Figure: $B_\varphi > 0$.

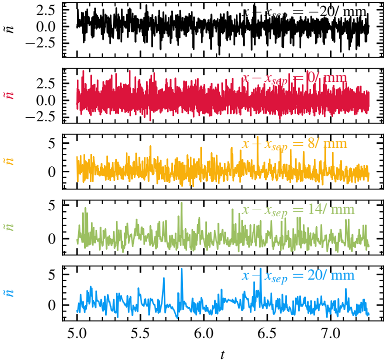

Figure: $B_\varphi < 0$.

OMP density statistics

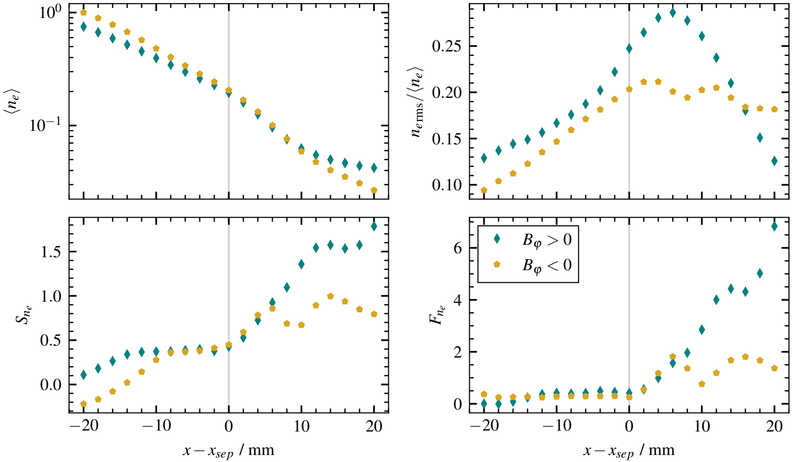

Figure: Density statistics at the outboard midplane for different field directions.

OMP Probability density function

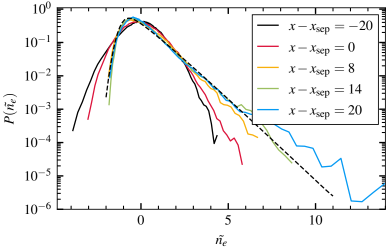

Figure: PDF for $B_\varphi > 0$.

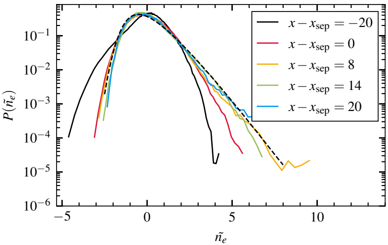

Figure: PDF for $B_\varphi < 0$.

OMP Power spectral density and conditionally averaged pulse shapes

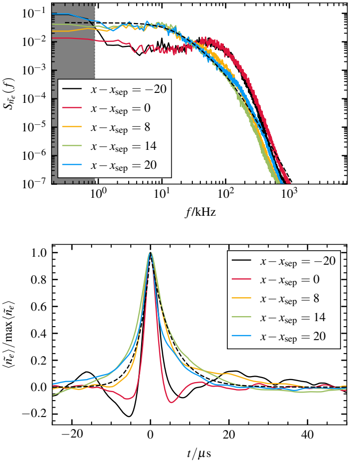

Figure: PSD and CA for $B_\varphi > 0$.

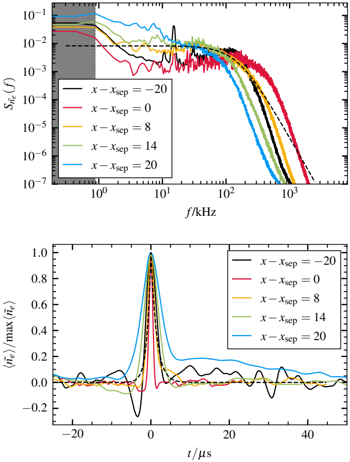

Figure: PSD and CA for $B_\varphi < 0$.

OMP ExB and parallel electron velocity

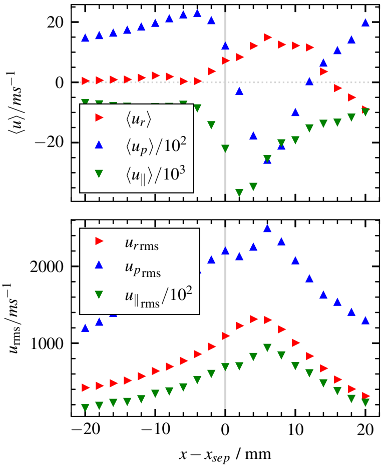

Figure: Velocity mean and rms for $B_\varphi > 0$.

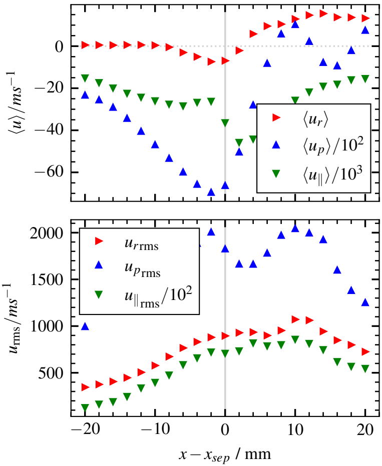

Figure: Velocity mean and rms for $B_\varphi < 0$.

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Timeseries

At position $x - x_{\mathrm{sep}} = 8\mathrm{mm}$.

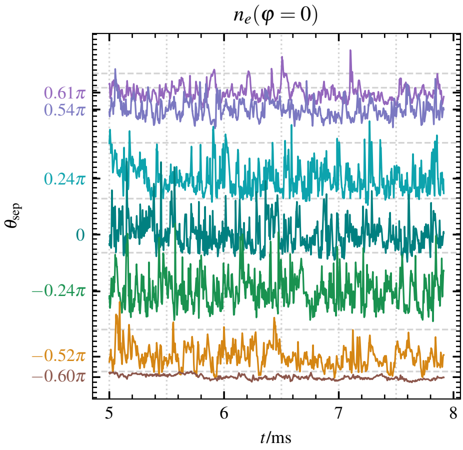
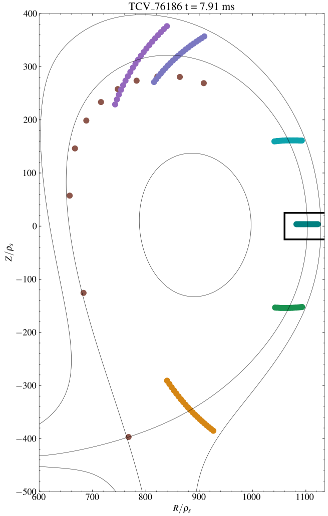


Figure: Timeseries for different poloidal positions for plane $\varphi = 0$.



Separatrix density statistics

At position $x - x_{\mathrm{sep}} = 0\mathrm{mm}$.

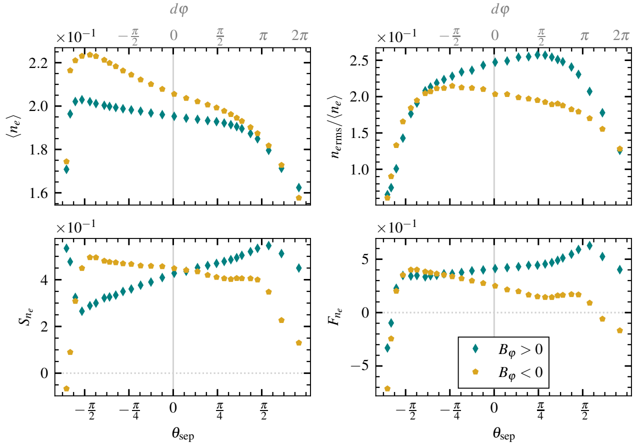


Figure: Poloidal density statistics at the separatrix for different field directions.

Probability density function

At position $x - x_{\text{sep}} = 8\text{mm}$.

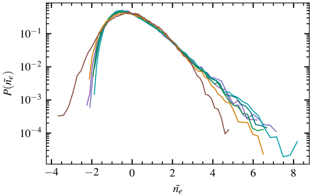
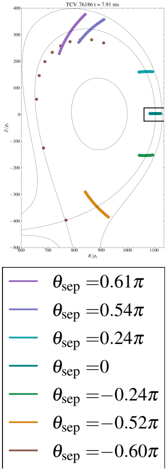


Figure: PDF for $B_\varphi > 0$.



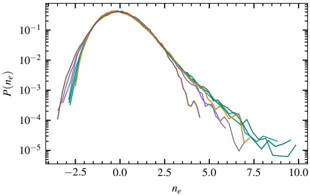
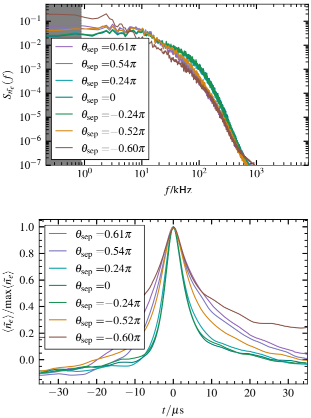
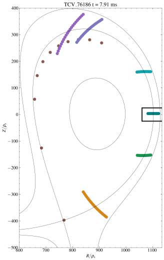


Figure: PDF for $B_\varphi < 0$.

Power spectral density and conditionally averaged pulse shapes

At position $x - x_{\text{sep}} = 8\text{mm}$.





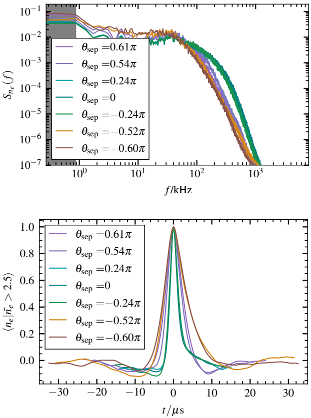


Figure: PSD and CA for $B_\varphi > 0$.

Figure: PSD and CA for $B_\varphi < 0$.

Velocity field

Straightened out field lines.

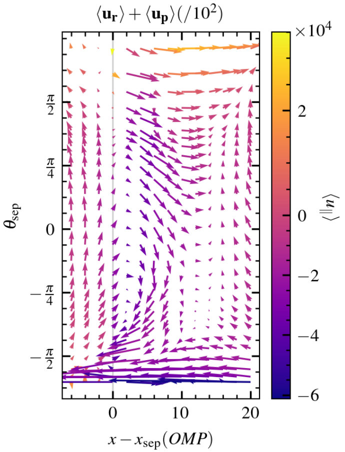


Figure: $B_\varphi > 0$.

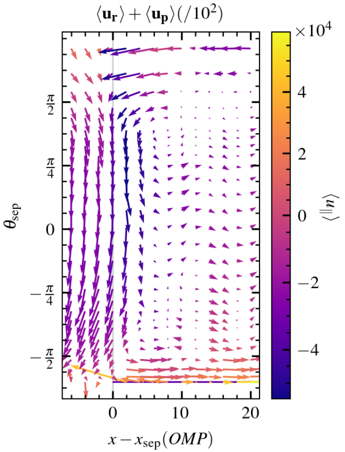


Figure: $B_\varphi < 0$.

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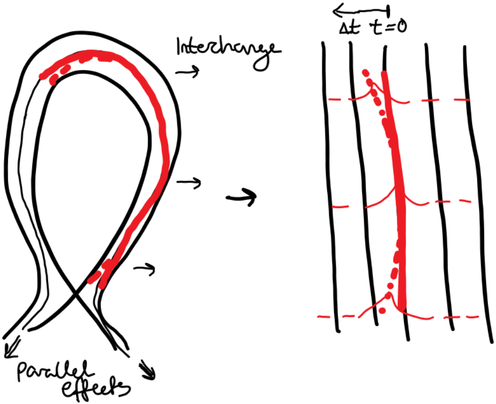
Field line alignment



Time delay estimation from OMP

Condition on OMP: $\tilde{n}_e(d\varphi = 0) > 2.5$

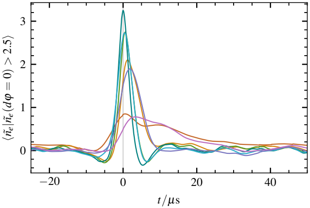
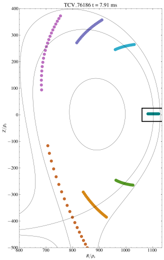


Figure: $x - x_{\mathrm{sep}} = 0$mm.



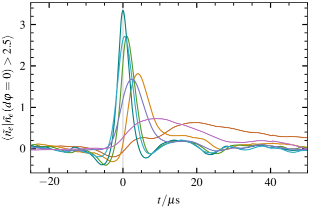


Figure: $x - x_{\mathrm{sep}} = 2$mm.

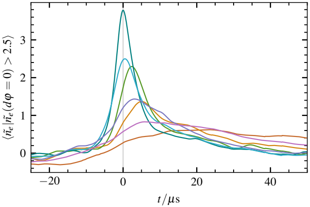
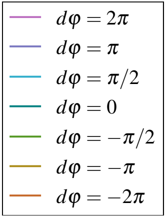


Figure: $x - x_{\mathrm{sep}} = 8$mm.



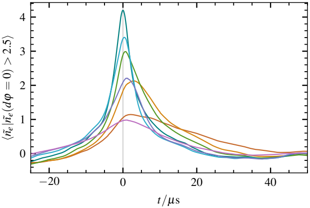


Figure: $x - x_{\mathrm{sep}} = 16$mm.

Time delay estimation from OMP

Time delay estimation using cross conditionally averaging (CCA) with condition $\tilde{n}_e > 2.5$ at $d\phi = 0$. Compared to Cross correlation (CCR) method.

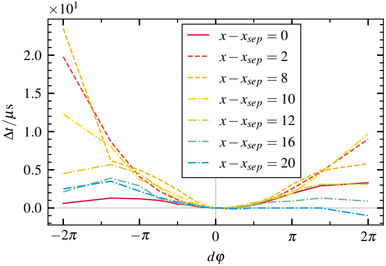


Figure: CCA.

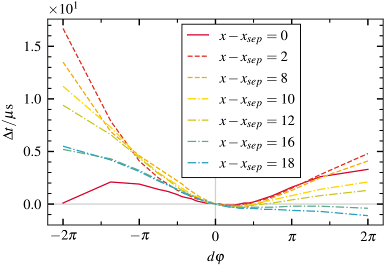


Figure: CCR.

Conditionally averaged amplitudes

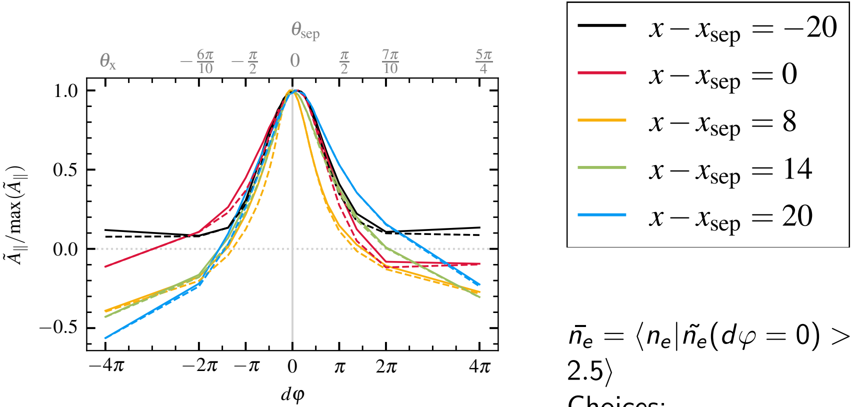


Figure: Amplitude along the field line for various radial positions (OMP values). $\tilde{A}_\parallel = (A - \langle n_e \rangle_{t,\parallel})/n_{e\,\mathrm{rms}(t,\parallel)}$.

$\bar{n_e} = \langle n_e | \tilde{n}_e(d\varphi = 0) > 2.5 \rangle$

Choices:

- $A = \max(\bar{n_e}(t))$
- $A = \bar{n_e}(t = 0)$ (dashed)

Separatrix transition

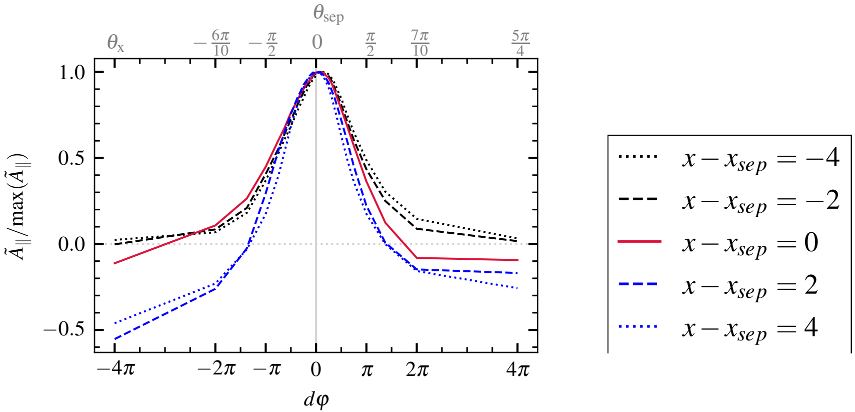


Figure: Filament amplitude change around the separatrix.

Filament amplitude scale length along field line

Gaussian fit to $\exp\left(-\frac{(x-\mu)}{2\sigma_A^2}\right)$

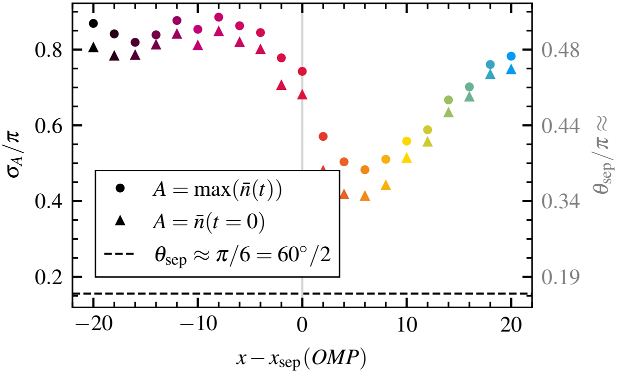


Figure: Scale length of the amplitude along φ from a Gaussian fit for various radial positions.

Filament amplitude scale length along field line

Gaussian fit to $\exp\left(-\frac{(x-\mu)}{2\sigma_A^2}\right)$

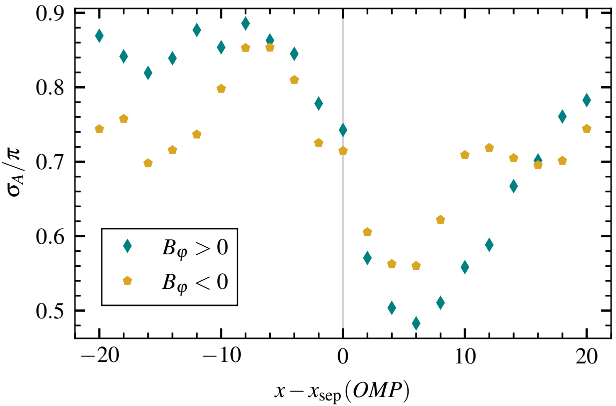


Figure: Scale length of the amplitude along φ for different field directions.

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Conclusion

Validating the simulation

- In agreement with FPP model
- Some behaviours are different than expected, possible simulation limits

Investigating the differences and new opportunities given by 3D simulations compared to 2D

- Large scale background circulations
- Filament alignment to field line varies
- Filament scale length halves when exiting the separatrix

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Radial density profile

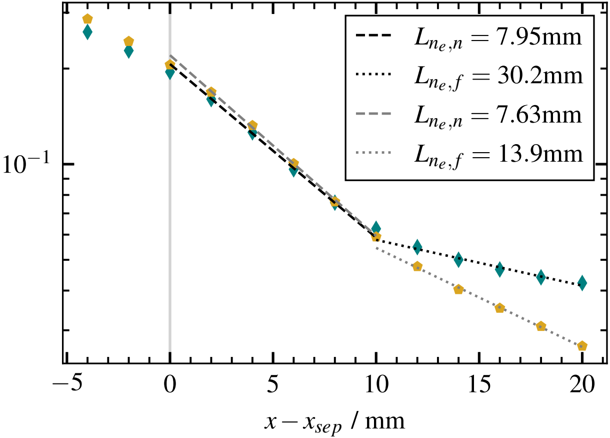


Figure: Density scale lengths from a piece-wise, near and far SOL, exponential fit.

Poloidal change of density profile

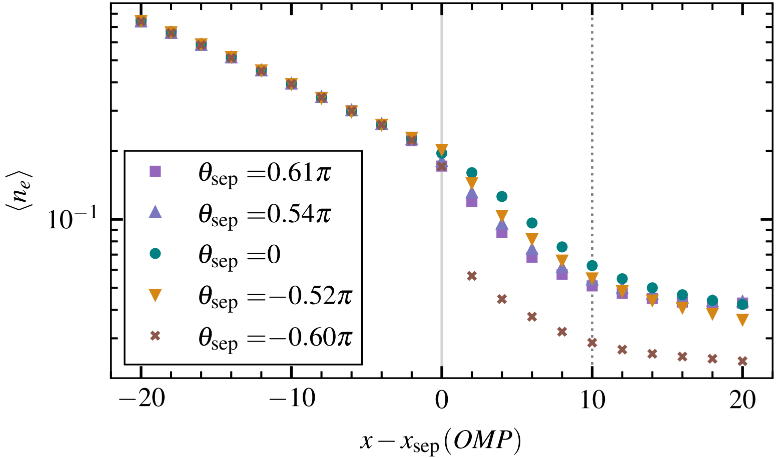


Figure: Radial profiles for different poloidal positions, from X-point to top of torus. Near/far separation relatively constant.

Poloidal change of density scale length

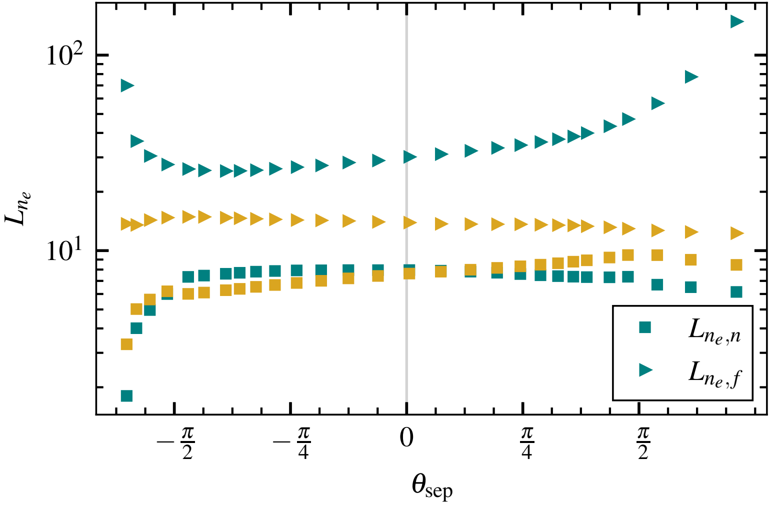


Figure: Density scale lengths from a piece-wise, near and far SOL, exponential fit for varying poloidal positions for each field direction.

8mm density statistics

At position $x - x_{\mathrm{sep}} = 8$mm.

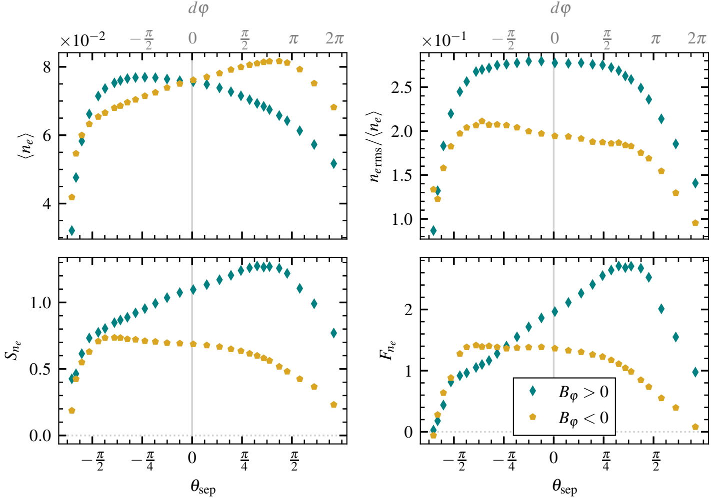


Figure: Poloidal density statistics at $x - x_{\mathrm{sep}} = 8/\mathrm{mm}$ for different field directions

Timeseries

At position $x - x_{\text{sep}} = 0$mm.

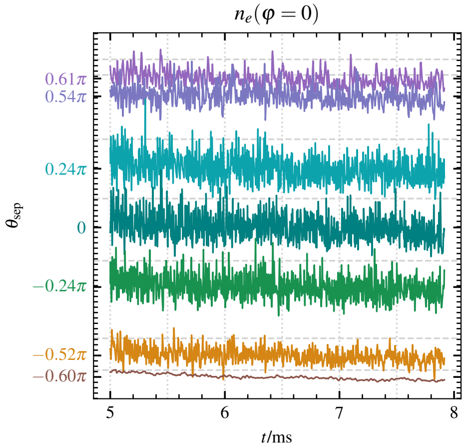


Figure: Timeseries for different poloidal positions for plane $\varphi = 0$.

Flux density field

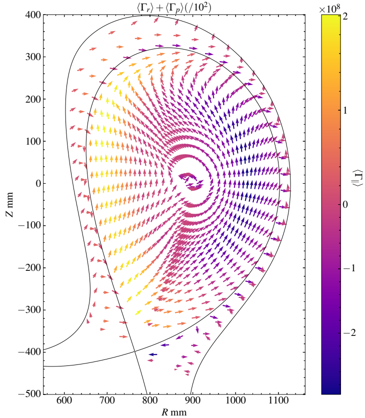


Figure: $B_\varphi > 0$.

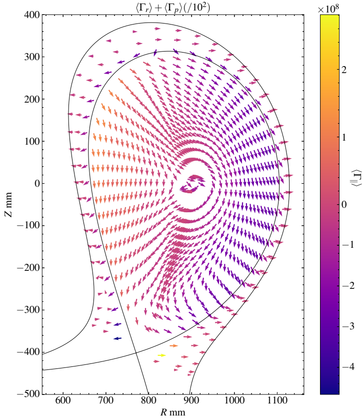


Figure: $B_\varphi < 0$.

Spatial delay estimation from OMP

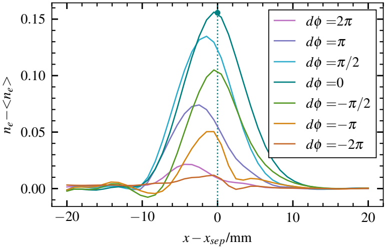


Figure: $x - x_{\mathrm{sep}} = 0$mm.

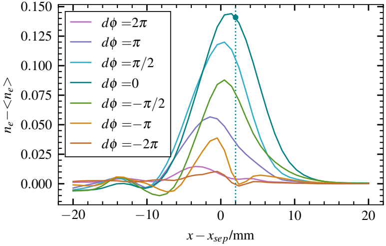


Figure: $x - x_{\mathrm{sep}} = 2$mm.

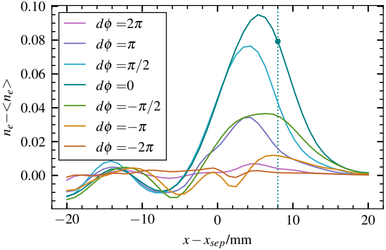


Figure: $x - x_{\mathrm{sep}} = 8$mm.

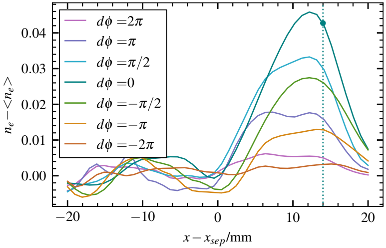


Figure: $x - x_{\mathrm{sep}} = 14$mm.

Time delay estimation from OMP (reverse)

Condition on OMP: $\tilde{n}_e(d\varphi = 0) > 2.5$

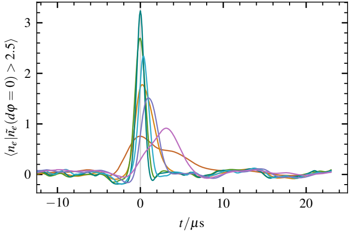


Figure: $x - x_{\mathrm{sep}} = 0$mm.

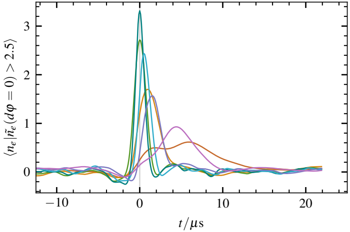


Figure: $x - x_{\mathrm{sep}} = 2$mm.

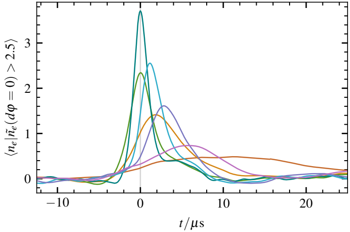


Figure: $x - x_{\mathrm{sep}} = 8$mm.

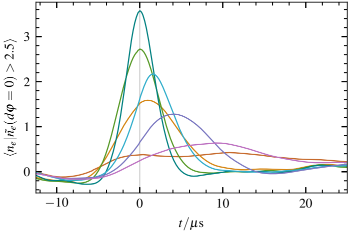


Figure: $x - x_{\mathrm{sep}} = 16$mm.

Time delay estimation from OMP (reverse)

Time delay estimation using cross conditionally averaging (CCA) with condition $\tilde{n}_e > 2.5$ at $d\phi = 0$. Compared to Cross correlation (CCR) method.

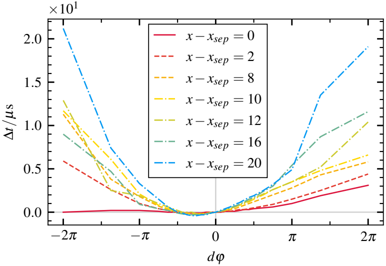


Figure: CCA.

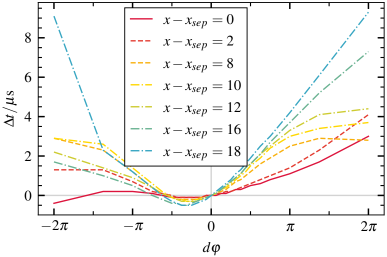


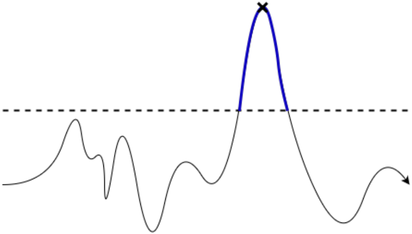
Figure: CCR.

Conditional averaging

Choose an amplitude threshold, and when the signal Φ crosses the threshold (usually $2.5\Phi_{rms}$) record

- Position of peaks
- Amplitude of peaks
- Shape of the signal around peaks

and compute an average shape, ect.
Cross conditional average: take values form one signal using another as reference.



Stochastic model

FPP:

$$\Phi_K(t) = \sum_{k=1}^{K(T)} A_k \phi\left(\frac{t - t_k}{\tau_k}\right), \tag{2}$$

$K(T)$: no. of pulses in T, A_k: pulse amplitude, t_k: pulse arrival time, τ_k: pulse duration

- Shot noise behaviour
- Describes events, excluding origin
- Convolution of a pulse function with a forcing

Intermittency parameter:

$$\gamma = \frac{\tau_d}{\tau_w}, \tag{3}$$

$\tau_d = \langle \tau_k \rangle$ is a constant duration time, and average waiting time between pulses $\tau_w = T/\langle K \rangle$.

Stochastic model

Assuming:

- uncorrelated arrivals
- neglecting end effects
- Amplitude $P_A(A) \sim \exp$
- Exp. pulse shape $\phi(\theta)$, $\theta = (t - t_k)/\tau_d$, with asymmetry λ

The PDF and PSD are:

$$P_{\tilde{\Phi}}(\tilde{\Phi}; \gamma) = \frac{\gamma^{1/2}}{\Gamma(\gamma)} \left(\gamma^{1/2} \tilde{\Phi} + \gamma \right)^{\gamma - 1} \exp \left(-\gamma^{1/2} \tilde{\Phi} - \gamma \right), \qquad (4)$$

$$\Omega_{\tilde{\Phi}}(\omega; \lambda, \tau_d) = \frac{2\tau_d}{[1 + (1-\lambda)^2 \tau_d^2 \omega^2][1 + \lambda^2 \tau_d^2 \omega^2]} \qquad (5)$$

Normalization $\tilde{n}_e = (n_e - \langle n_e \rangle)/n_{e\mathrm{rms}}$