Particle transport studies using gas-puff modulation in WEST

A. Salmi[1], T. Tala[1], P. Maget[2], F. Clairet[2], H. Yang[3], C. Orrico[4], the WEST Team* and the EUROfusion Tokamak Exploitation Team**

[1]VTT Technical Research Centre of Finland; [2]CEA, IRFM, F-13108 Saint Paul-lez-Durance, France; [3]M2P2 Aix-Marseille Univ, CNRS, Centrale Mediterranee, Marseille, France; [4]DIFFER, Eindhoven, The Netherlands. *See author list in J. Bucalossi 2026 to appear in Nucl. Fusion **See author list in N. Vianello et al, Nucl. Fusion 66 (2026) 116010

Gas-puff modulation provides a dynamic test of particle transport because the radial amplitude and phase of the density response depend on source localization, diffusion, convection and modulation frequency. WEST long-pulse Ohmic and L-mode LHCD discharges were used to apply small feed-forward deuterium gas modulations while slow density feedback maintained the operating point. Burst-mode mid-plane reflectometry, supported by interferometry, resolves sub-percent perturbations and gives repeatable local modulation profiles. Frequency, gas-rate and LH-power scans show a coherent response: phase steepens with modulation frequency, the gas scan mainly changes the SOL/pedestal response, and LH heating flattens the phase at similar density. First predictive HFPS-TGLF simulations reproduce some global density constraints but generally transmit or amplify the modulation inward more strongly than observed, making the data a sensitive constraint on pedestal-top profile reproduction, source localization and outer-core particle transport.

1. Motivation and experiment

Predictive density control in reactor-relevant plasmas requires particle transport models constrained by more than time-averaged density profiles. In gas-puff modulation the source is driven at a known frequency and the plasma response is measured as a complex density perturbation. The radial amplitude and phase then provide a frequency-domain constraint on effective diffusion and convection [1-3], provided the perturbation remains small enough that the background plasma is not strongly changed.

The WEST campaign exploited long steady phases at about 400 kA and 3.55 T, with LH power up to 4 MW. Figure 1 shows the discharge we model in this contribution with its 5 Hz and 2.5 Hz gas modulation phases. The sinusoidal feed-forward deuterium gas waveform was superposed on density control whose bandwidth was slow enough not to cancel the modulation. The data set includes a five-point LH-power scan, a density/gas-rate scan, a frequency scan and back-to-back repeat pulses. The perturbations were small, typically of order 10^{17} m^{-3} and in some cases

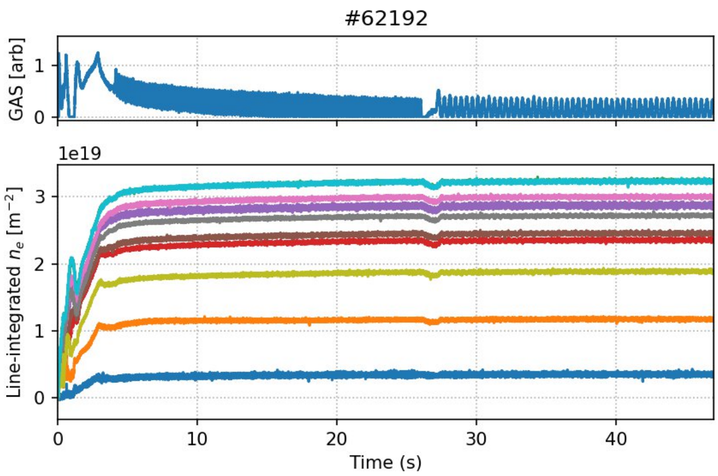

Figure 1 3 MW LHCD-heated WEST discharge modulated with a small feed-forward gas puff while slow density feedback maintained the operating point. Here 5 Hz and 2.5 Hz phases are used.

below 0.3% locally, to avoid density runaway and preserve stationary conditions over many cycles.

Temperature information is an important limitation. LHCD raises the central electron temperature and enables long discharges, but reliable ECE profile measurements are limited outside mid-radius in the present analysis. For this reason the comparison presented here is driven mainly by the density response.

2. Density-response measurements

The central experimental advance is the quality of the density-response measurement. The newly commissioned WEST mid-plane profile reflectometer [4,5] was operated in burst mode, giving more than 100,000 sweeps per pulse. Stacked spectral analysis of the profile time series was used before extracting the response at the imposed frequency. This is essential because the coherent harmonic amplitude is small compared with density fluctuations in the 0.5-15 Hz range. The modulation peak remains resolved even in demanding frequency-scan cases.

Reflectometry provides the local mid-plane profile needed to distinguish SOL, pedestal and confined-region response. Interferometry supplies an independent line-integrated density check. Synthetic line densities from the reflectometer reconstruction agree well enough with measured interferometer trends to support the radial interpretation. A back-to-back 2.5 Hz, 3 MW LH repeat pair gives a practical uncertainty scale: both pulses reproduce the same amplitude and phase structure (Fig. 2).

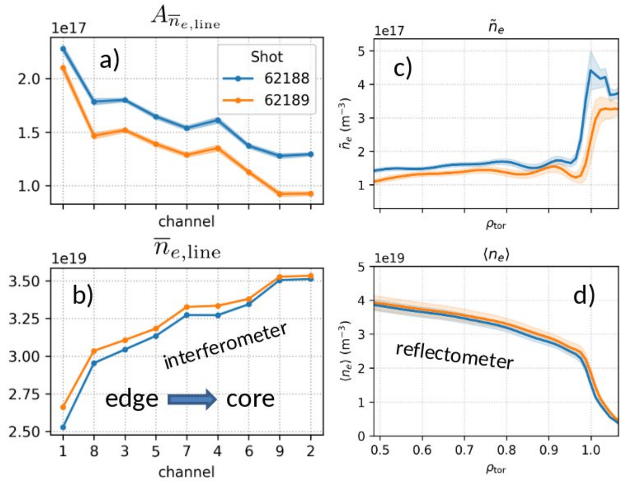

Figure 2 2.5 Hz, 3 MW LH repeat pair gives nearly identical amplitude and phase trends for both line-integrated (a,b) and reflectometer (c,d) giving insight into statistical and plasma noise.

3. Experimental trends

The three scans provide complementary constraints on the density response. Only the frequency scan is shown here; the main trends from the gas-rate and LH-power scans are summarized below.

The frequency scan (Fig. 3) provides the clearest timescale test. During the 3 MW LH-heated phases, the response evolves smoothly from 1 to 4 Hz: the phase gradient increases approximately in proportion to frequency, while the normalized core amplitude decreases roughly as (1/f).

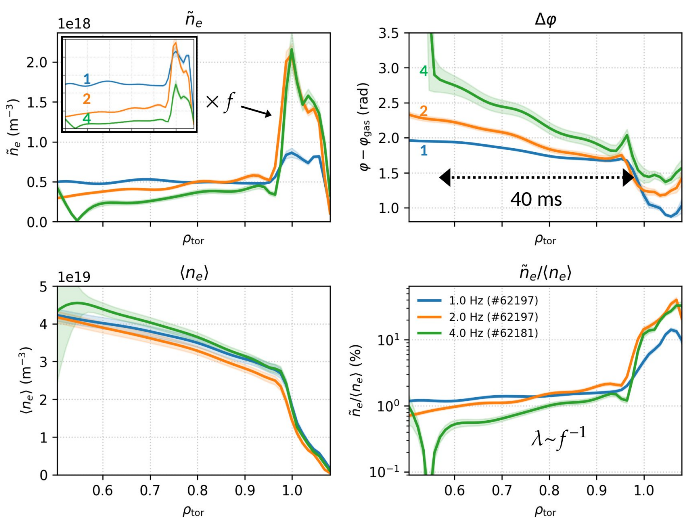

Figure 3 Increasing frequency steepens the phase and reduces core amplitude.

In the gas-rate scan, increased fuelling raises the mean density. After normalization to the gas drive, the confined-region response changes only weakly, with most of the variation concentrated near the SOL and pedestal top. This identifies source localization, recycling, detachment state and possibly radial electric-field effects as important edge sensitivities, but does not by itself indicate a large change in outer-core transport.

The LH-power scan acts more directly as a transport perturbation. At similar mean density, additional LH heating flattens the phase profile, most clearly between the Ohmic and 1 MW cases, consistent with faster effective particle transport.

Together, the frequency, fuelling and heating scans form a coherent dynamic constraint on the particle-response model.The three scans give complementary information on the density response:.

4. Predictive HFPS-TGLF comparison

The modelling comparison uses integrated HFPS simulations with TGLF turbulent transport and NCLASS neoclassical transport for a D, N and W ion mix [6]. Separatrix boundary conditions are taken to be:

$$n_{\mathrm{sep}} \approx 3\left(\frac{P_{\mathrm{SOL}}}{100}\right)^{0.55}\left(\frac{q_{95}}{3}\right)^{-0.5} \text{ and } T_{\mathrm{sep}} \approx 0.25\left(\frac{P_{\mathrm{SOL}}}{100}\right)^{0.32-0.36}\left(\frac{q_{95}}{3}\right)^{0.5},$$

with multiplicative factors used to explore consistency with experimental values. The particle source is treated with FRANTIC. Electron density is driven by a feed-forward deuterium gas puff at the experimental frequency, with waveform values tuned to match the line-integrated density evolution. Nitrogen and tungsten sources are feedback-controlled to match effective charge and bulk radiated power in the SANCO workflow. The set includes SAT1/SAT2 saturation-rule variations, boundary scans and neutral-energy assumptions.

The first target is not perfect profile agreement, but whether the model transmits the perturbation inward with the right normalized amplitude and phase. In the present predictive set, simulations generally amplify the modulation inward and produce phase profiles that are too flat (Fig. 4). The experiment instead remains flat or weakly damped after pedestal-top normalization. This dynamic discrepancy is not captured by matching only mean line density or a steady profile. Cases with larger simulated particle diffusivity tend to show stronger inward amplitude peaking, while lower-diffusivity boundary-adjusted cases are closer to the measured response. This is a modelling clue for the present predictive setup, not a validation or falsification of TGLF in general.

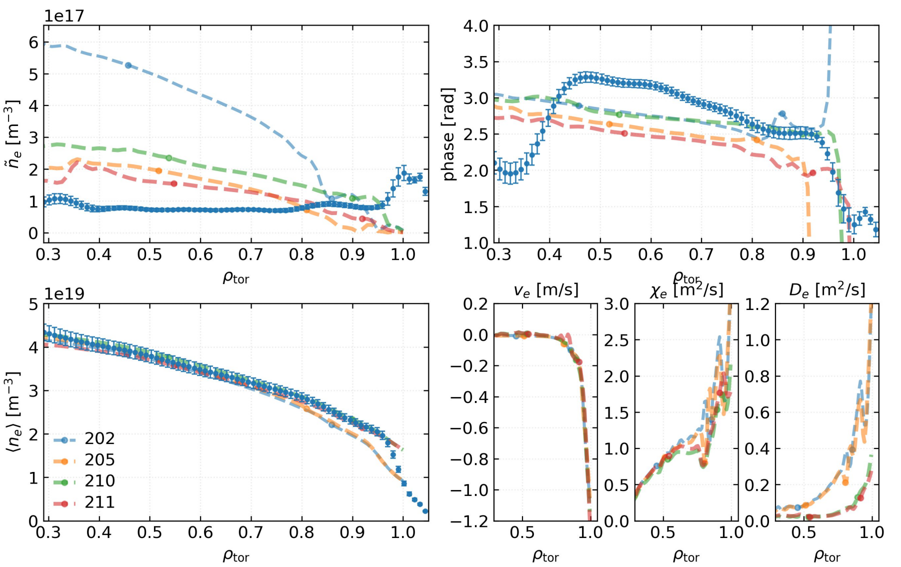

Figure 4 Representative integrated HFPS-TGLF simulations with FRANTIC particle sources. Experiment #62192 is shown in blue with error bars. The lower-right panels show the electron heat and particle transport coefficients. In these simulations, particle diffusion is turbulence-dominated, whereas the inward pinch is almost entirely neoclassical.

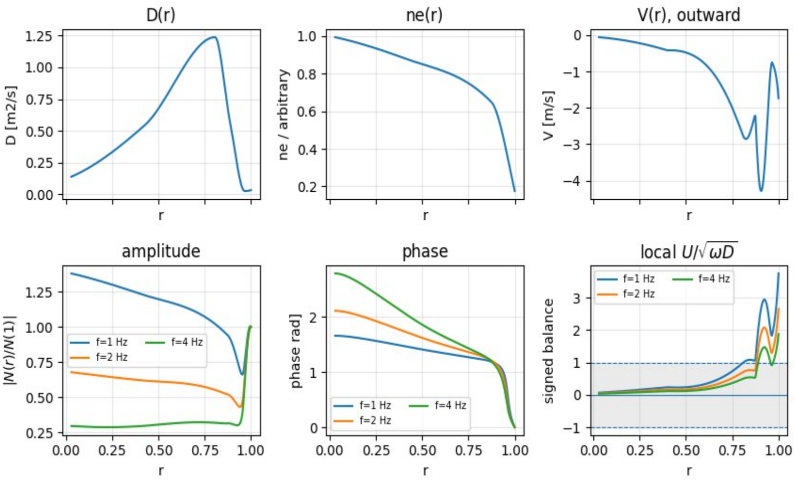

Figure 5 With experiment and HFPS-inspired D, V and n_e data (top row) the bottom row shows the linear perturbation response at 1, 2 and 4 Hz and the convection to diffusion ratio ($U = |V|$ with $\omega = 2\pi f$). Smaller values of the ratio lead to more dominant diffusion influence on the response.

A simple linearized source-free cylindrical modulation model:

$$i\omega\tilde{n} + \frac{1}{r}\frac{d}{dr}\left[r\left(-D\frac{d\tilde{n}}{dr} + V\tilde{n}\right)\right] = 0$$

helps interpret the result (Fig. 5). After normalization near the pedestal top, the inward amplitude and phase evolution are mainly a transport constraint: higher frequency damps the perturbation, while larger diffusion or inward convection lets it penetrate and can make the amplitude rise inward. HFPS-TGLF cases peak inward and have too-flat phase profiles contradicting observations (see also Fig. 3). This points primarily to the simulated outer-core transport response, with pedestal matching and source localization setting important boundary conditions.

5. Conclusions and outlook

WEST gas-puff modulation now provides repeatable local density-response profiles that are strong enough to challenge predictive particle-transport modelling. The strength of the dataset is its consistency across scans: modulation frequency changes the phase slope, gas fuelling mainly changes the edge/SOL response, LH heating flattens the phase, and repeat discharges reproduce the same structure. First HFPS-TGLF comparisons meet some global density constraints but often over-amplify the inward modulation and flatten the phase, showing that dynamic response data add information beyond steady density profiles. The most likely levers are pedestal-top density reproduction, neutral source localization, and the balance of outer-core diffusion and pinch. Next steps are to extend the constraint with new experiments without LHCD with validated electron-temperature profiles from ECE and Thomson scattering, optimize gas waveforms for q95 and temperature scans aimed at varying pinch strength, test time-dependent boundary and pedestal matching in HFPS-TGLF, and compare absolute fuelling and SOL response against matched SOLEDGE [7] calculations.

References

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