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Published in:
Plasma Physics and Controlled Fusion

DOI:
10.1088/1361-6587/acc425

Published: 01/05/2023

Document Version
Publisher's final version

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Please cite the original version:
Electron density pedestal behaviour in strike-point sweeping experiment on JET

To cite this article: A Salmi et al 2023 Plasma Phys. Control. Fusion 65 055025

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Electron density pedestal behaviour in strike-point sweeping experiment on JET

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Received 9 November 2022, revised 1 March 2023
Accepted for publication 14 March 2023
Published 12 April 2023

Abstract
Strike-point sweeping, a technique often used to spread heat loads on divertor targets, was employed in JET experiments for the first time to generate an edge-localized modulated particle source for investigating plasma fuelling and particle transport in the edge region. This approach was motivated by the possibility of achieving higher modulation frequencies than those available from traditional gas puff modulation at JET. Higher frequencies would enable the collection of more edge-localized information from the electron density response to the modulated particle source. Various sweeping frequencies, up to 18.5 Hz, were commissioned and utilized in the experiments. Both strong and weak electron density responses were observed in H-mode plasmas, depending on the strike-point configuration and the distance the strike-points moved during the sweep cycle. The electron density response exhibited complex and unconventional behaviour (compared to gas puff modulation), which presented challenges for interpretation. In this study, we analyse one experiment in detail using an optimization framework in which transport and particle source parameters are determined by fitting our forward model parameters to the experimental electron density measurements. We demonstrate that a consistent picture emerges and that our approach can provide new insights into these complex data. However, we note that while strike-point sweeping generates the desired modulated edge-localized particle source, it also modifies the properties of the edge transport barrier. Therefore, the strike-point sweeping methodology is a promising but challenging way to study edge particle transport and edge fuelling properties, requiring very precise measurements.

5 See Mailloux et al 2022 (https://doi.org/10.1088/1741-4326/ac47b4) for JET contributors.
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Keywords: tokamak, fusion, particle transport, strike-point sweeping

(Some figures may appear in colour only in the online journal)

1. Introduction

Strike-point sweeping at JET is a technique often used to spread the heat load in high-power discharges for machine protection [1, 2] or to allow high-radial resolution measurements of target temperature and heat flux profiles with Langmuir probe arrays mounted on the divertor tiles [3–5]. In this work, we utilise this technique for the first time to study the particle source and transport near the plasma edge by creating periodic variations in the divertor conditions and thus in the recycled particle sources. Conventionally, gas puff modulations [6–10] or supersonic molecular beam injection (SMBI) [11] are used for these studies. However, one typical downside of gas puff modulation is that frequencies can be limited by the valve opening times, the long distance from the gas tanks to the vacuum vessel, or both. At JET, the main limiting factors are the long gas pipes with tight bends that effectively act as low-pass filters on the gas waveform. Our previous gas modulation experiments found that a 6 Hz modulation frequency could still yield sufficient amplitude, but at 10 Hz the gas flow into the vessel becomes too flat, and thus high modulation frequencies are not available. The strike-point sweeping experiments were motivated by the prospect that significantly higher frequencies could be achieved than those available from gas puff modulation. With sufficiently high perturbation frequency, one could essentially directly measure the particle source from the density perturbation, as the convoluted transport effects could be ignored [12]. Furthermore, combining high and low frequencies in the same discharge conditions could potentially significantly constrain the possible combinations of particle source and transport properties that together determine the electron density evolution.

A priori, we do not expect the sweeping technique to uncover new physics investigation possibilities for the confined plasma region compared to, for example, gas puff modulations if they operate at the same frequency. In both cases, the modulated particle source is expected to be similarly edge-localized with the dominant contribution coming from recycling. It is possible, of course, to place the gas reservoirs close to the vessel and install fast valves to obtain fast gas modulations or to utilise SMBI systems with fast modulations. However, these options are not available on JET and here we attempt to access a higher frequency actuator for perturbative studies using the sweeps.

After the necessary commissioning efforts and machine safety considerations, we managed to achieve a sweeping frequency of up to 18.5 Hz (previously, frequencies of 1–4 Hz were routinely used, see [1–5]). This is less than we had hoped for, but a fair achievement given the available time and significantly more than what is available from gas puffs. The primary concern during the commissioning was the potential for mechanical resonances due to the magnetic forces arising from fast current ramps in the divertor coils. Since our goal is to apply the modulations for several seconds, it is paramount to avoid such resonances in the vessel in order to avoid damage. Vibration monitoring and careful ramp-up of the divertor coil currents were used to ensure safe operation.

The paper is organised as follows: first, we provide an overview of the experimental data and the strike-point sweeping geometry, along with our key measurements of electron density evolution based on profile reflectometry diagnostics. We then describe our modelling framework, where an optimization approach is used to find parameters that allow the best fit between the simulated electron density evolution and the reflectometer measurements. This is followed by section 4, where we present our key results and point out the limitations of the present modelling. Finally, we summarise our findings and elaborate on ongoing work that can further improve the present results.

2. Experiment overview

The Deuterium H-mode discharge #92347 we analyse in this work is heated with neutral beam injection (NBI) and is characterised by $P_{\text{NBI}} \approx 12$ MW, $B_z \approx 2.3$ T, $I_p \approx 1.7$ MA, $\Gamma_D \approx 3 \times 10^{22} \text{s}^{-1}$ and $q_95 \approx 4$. Furthermore, in the Greenwald density limit $n_{GW} = 6.7 \times 10^{19} \text{m}^{-3}$, the line averaged density $n_{\text{core}} \approx 4.8 \times 10^{19} \text{m}^{-3}$ and the expected H-mode power threshold $P^*_{\text{HTL}} \approx 6.2$ MW [13]. With these parameters, the discharge is in H-mode with $H_{98} \approx 0.7$ (typical for JET ITER-like Wall baseline [14]) and has a relatively high type-I edge localised mode (ELM) frequency $f_{\text{ELM}} \approx 100$ Hz. The steady-state phase lasts for $\sim 10$ s and contains three separate $\sim 3$ s periods each with a different strike-point sweep frequency (18.5 Hz, 7.7 Hz and 3.9 Hz). Figure 1 shows the experimental overview of this discharge. The different strike-point sweeping frequency phases can be seen in the top panel where the major radius location of the X-point $R_{xp}$ is plotted. X-point and strike-point move in tandem allowing the X-point movement to be used as a proxy for the strike-point (for illustrative purposes, see figure 2). The discharge runs very stably with no signs of impurity accumulation, magnetohydrodynamic (MHD) instabilities (besides ELMs and sawteeth) or confinement-time changes. The steady-state kinetic profiles for the different sweeping phases are within 1% from each other and thus well within the experimental uncertainties. Subsequent analysis assumes that the time averaged transport profiles are identical between the different sweeping frequencies. Subsequent analysis assumes that the time averaged transport profiles are identical between the different sweeping frequencies.

Figure 2 shows the magnetic geometry comparison between the strike-point extreme locations. During the strike-point sweeping of the main chamber the plasma shape is kept as constant as possible. The maximum radial variation in the outer midplane separatrix position is a modest $\pm 5$ mm. The optimal strike-point sweep range that we ended up using in this discharge ($\sim 8$ cm) was found after multiple trials.

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Some figures may appear in colour only in the online journal.
Figure 1. (Left) Experimental time traces of some of the key quantities for discharge 92347. The discharge has three phases each with different sweeping frequencies illustrated by the movement of the X-point radial location $R_{xp}$ (top panel). Line integrated electron densities in the core and through the pedestal are stable with clear signatures of density modulation. The NBI heating and plasma diamagnetic energies are also nearly stationary allowing comparisons between the three frequencies (18.5 Hz, 7.7 Hz, 3.9 Hz). (Right) Time averaged electron temperature and density profiles. Temperature is based on electron cyclotron emission measured with the heterodyne radiometer and density based on X-mode profile reflectometry.

Figure 2. During the sweeping, strike-points are periodically moved along the target plates while keeping the main plasma shape as constant as possible. The sweep range on the horizontal tile (Tile 5) is roughly 8 cm and the sweeping frequency is either 18.5 Hz, 7.7 Hz or 3.9 Hz. The blue equilibrium is referred to subsequently as the ‘inner’ equilibrium and the orange one as the ‘outer’ equilibrium. Dashed horizontal line shows the profile reflectometer line-of-sight. Smaller sweep ranges did not yield robustly measurable density perturbations, while more extended ranges tended to induce $LH$ transitions, especially when near or crossing the pumping corners, leading to violent pedestal movements.

For the purposes of core/pedestal transport studies, it does not matter which physics mechanisms are responsible for the induced density modulation. However, we expect that the changes in the divertor configuration during the sweep influence at least the leakage of neutrals from the divertor to the main chamber (more leakage with innermost strike-point location, see section 4.1) and pumping efficiency (better pumping with strike-point nearer to the pumping ducts) [15]. Both of these effects tend to favour higher SOL densities with innermost strike-point location. These appear consistent with figure 3, which shows the outboard midplane electron density at the normalised square root of the poloidal flux $\rho_{pol} \sim 1.03$ from profile reflectometry [16] coherently averaged over one sweep period for each of the three frequencies. One can see that the midplane density is highest when the X-point (i.e. strike-point) is radially inward. In fact, the SOL density seems to follow the strike-point movement with a very small delay. Only at the highest frequency, 18.5 Hz, one might observe some slight delay $\sim 5$ ms between the two. This magnitude of delay could be consistent with the time it takes for the SOL to adjust to the new recycling conditions caused by the strike-point geometry changes [17].

Figure 4(a) shows time traces of the ELM behaviour during a few sweep cycles and figure 4(b) shows the ELM frequency variation due to the sweeping. The quantitative estimation of how the ELM frequency varies during the sweeping cycles is
Figure 3. The outboard midplane electron density at $\rho_{\text{pol}} \sim 1.03$ versus X-point (strike-point) major radius coordinates for one coherently averaged sweep cycle.

Figure 4. (a) Representative ELM behaviour during the 7.7 Hz phase. Shown are the Be II line from the inner divertor apron region, the electron density in SOL at $\rho_{\text{pol}} = 1.03$ and at the pedestal top $\rho_{\text{pol}} \sim 0.9$ (reflectometer) and the electron temperature at the pedestal top (ECE). The dashed overlaid lines show the major radius value of the X-point (proxy for the strike-point position). (b) ELM frequency variation (coherent average) during the sweeping cycle.

somewhat limited by the fact that only $\sim 3$ s ($\sim 300$ ELMs) are observed for each sweep frequency. Despite the statistics, the coherent binning shows that the type-I ELM frequency is $\sim 100$ Hz and varies fairly moderately $\pm 5$ Hz during the sweeping. We observe that the ELM frequency increases with the strike-point moving inboard. This behaviour can be understood by realising two earlier observations. First, previous experiments with stationary strike-point locations have shown that for typical type-I ELM conditions the $L-H$ transition the power threshold increases with increasing strike-point major radius for H, D and helium plasmas in JET ($P_{LH,\text{outer}} > P_{LH,\text{inner}}$) [18, 19]. Second, as per definition, the type-I ELM frequency increases with increasing heating power [20]. We maintain a constant heating power during the sweep cycles.
and we expect higher frequency type-I ELMs when $P_{LH}$ is smallest, i.e. when strike-point radius is at its smallest. Our focus is not, however, on the pedestal stability, and therefore a more detailed MHD stability analysis is left out of this analysis. Still, it is worth noting that the sweep modulation measurements and our subsequent simulations include the average ELM effects. It is not obvious how this effect influences the observations and is good to keep in mind. Unfortunately, we do not have similar data in the absence of ELMs (i.e. in L-mode) due to the limited available experimental time. However, ELMs appear to be influenced similarly across our three modulation frequencies and thus we assume that any trends we see are not dominated by ELMs.

Figure 5 shows the main interest of this work, electron density response to the perturbation caused by the periodic strike-point sweeping. The measurements are provided by profile reflectometry diagnostics yielding high spatial and temporal resolution data from the scrape-off layer (SOL) to $\rho_{pol} \sim 0.2$ for this discharge. Group-delay oscillations due to spurious reflections in the measurement are reduced by an averaging procedure together with a number of other analysis improvements [21] and are a prerequisite for obtaining reliable data for this work. The error bars are derived from two non-overlapping 1.5 s time windows and are found to be relatively small, especially when considering that the density perturbation is well below 1% in amplitude in a large part of the plasma volume. The smallness of the error bars gives us fair confidence that even the fine structure of the modulation amplitude in the SOL region (outboard midplane measurements) is not just noise. Our neutral and SOL transport (discussed later) models are presently very simple and we do not attempt to reproduce those details. In fact, we limit our radial region of interest in $\rho_{pol}$ between 0.2 and 1.01.

One can observe that both the amplitude and phase profiles have a set of features that are not trivial to reconcile. In a naïve picture, which can be largely true for the gas puff modulation data [6, 7], edge localised particle source would cause a simple radially decaying amplitude profile, which has a peak at the source maximum and a monotonically increasing phase profile that has a minimum near the source maximum. Here, however, both the phase and the amplitude profiles are non-monotonic and at first seem to even suggest regions of outward propagating perturbations. Even with the baffling data, the small error bars and trends in profile features between the frequencies motivated us to try to explain them. We find, e.g., that the amplitude minimum and the step-like change in phase around $\rho_{pol} \in [0.6, 0.8]$ move outwards with increasing frequency, which seems intuitive as higher frequency perturbations generally decay faster. Outside the separatrix, where the source effect is suspected to be higher, the density modulation amplitude becomes smaller with increasing frequency. In addition, for all frequencies, the phase outside the separatrix is nearly the same and synchronous with the strike-point movement, which seems consistent with a fast SOL equilibration time. The next sections of this paper describe the framework we use to simulate the data and to fit parameters that allow reproduction of the experimental data.

Anecdotally, in some low-density Ohmic plasmas with higher sweeping frequencies, we observed peculiar anomalies in interferometer measurements (line averaged electron density). These were identified to be due to the spurious reference signal caused by the inductive coupling of the oscillating divertor coil current and the diagnostic ground loop. The manifestation was an unphysical, wild, line integrated density variation if this effect was not specifically removed by...
non-standard analysis. We did not observe similar problems in H-mode plasmas and, furthermore, reflectometer diagnostics did not suffer from such anomalies even in Ohmic plasmas.

3. Optimisation framework

We have set out to reproduce numerically the experimental, ELM averaged, electron density dynamics shown in the previous section where the electron density modulation was seen to feature a complex set of phase and amplitude profiles, see figure 5. It is quite clear that such profiles cannot be reproduced with time-independent transport profiles when the perturbed source is edge localised using the diffusion-convection paradigm. It turns out, as expected; that by allowing time-dependent diffusion and convection profiles together with a modulated source, it is possible to create a rich variety of density responses. In this section, we describe the equation used for electron density evolution, the chosen parameterisation and the optimisation approach in our simulation framework.

3.1. Electron density evolution

Electron density evolution is governed by the continuity equation

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma = S - \frac{n_e}{\tau_{||}},$$

which in the usual 1.5D cylindrical form, with the geometrical terms included and the flux composed of diffusion and convection can be written as

$$\frac{\partial \nabla n_e}{\partial \rho} \frac{\partial \nabla}{\partial \rho} = \frac{\partial \nabla}{\partial \rho} \left( \langle \nabla \rho \rangle^2 D \frac{\partial n_e}{\partial \rho} - \langle \nabla \rho \rangle \nabla n_e \right) + \frac{\partial \nabla}{\partial \rho} \left( S - \frac{n_e}{\tau_{||}} \right),$$

where $\rho$ is the radial coordinate (here normalised square root of poloidal flux), $D$ is the electron diffusion coefficient, $V$ is the convection velocity (positive is outwards), $S$ is the particle source, $V$ is the plasma volume, $\tau_{||}$ is the parallel confinement-time and $\langle \rangle$ denotes flux surface averaging. The geometrical terms $\nabla \langle \nabla \rho \rangle^2$ and $\langle \nabla \rho \rangle$ are based on EFIT [22, 23] equilibrium reconstruction and provide the extra 0.5D information for the geometry enabling direct comparison against the experiment. The parallel confinement time $\tau_{||}$ is set to infinity inside the separatrix and to a small value (1–5 ms) outside. This allows extension of the simulations to the scrape-off layer (SOL) where the fixed value boundary condition $n_e(t, \rho = \rho_{max}) \sim 0$ is a good approximation. This way we can avoid setting the boundary conditions at separatrix which can have a big influence even at the pedestal top and thus can reduce any interpretations made from the simulations. At the magnetic axis, zero flux condition $\Gamma(t, \rho = 0) = 0$ is used. $D, V, S$ and $n_e$ in our model are time-dependent while $\tau_{||}$ we take to be constant.

It should be noted that in the experiment, one can expect a finite $\tau_{||}$ modulation due to the change in particle recycling near the divertor plate. Higher recycling for the inner equilibrium can increase $\tau_{||}$, while lower recycling for the outer equilibrium can decrease $\tau_{||}$. The variation in the connection length between the inner and outer configurations is small (approximately 1%) and is not expected to play a significant role. We adopt the constant $\tau_{||}$ approximation for practical reasons, as disentangling $\tau_{||}$ modulations from the source and transport modulations is not possible with our current constraints. The same overall effect on particle flux can be achieved with multiple combinations of $\tau_{||}$, source and transport. The consequence of the lack of an accurate experimental $\tau_{||}$ modulation in our model can lead to spurious transport modulations, mostly in the SOL region but potentially extending up to the pedestal top.

Our simple model for the electron density evolution can capture quite complex phenomena through its time dependent transport coefficients and source. It cannot, however, explain the underlying physics, and it is limited to local transport. Possible non-local effects [24–28] are obviously not included. However, it has also been reported that several phenomena that have been thought to be non-local can be explained with local transport when allowing coupling between transport channels [29, 30]. In a plasma experiment, it is practically impossible to generate perturbations in just a single transport channel and instead several quantities tend to be simultaneously modulated. This is why transport problems are typically solved as a coupled system [31, 32]. In our model, we do not explicitly solve either electron/ion temperature or rotation evolution. Their variations, however, influence the turbulence that causes time evolution also in the particle transport channel. We do not have a physics based approach for solving this time evolution but use an optimiser to fit it against experimental measurements as explained in the following sections. It is clear that our simple model does not have predictive capabilities and that it is useful only for interpretative analysis.

The electron density evolution, equation (1), is solved with a simple but fast purpose built FORTRAN routine using an explicit, centred, first order finite difference scheme as part of a larger Python workflow. This routine was successfully checked against equations like $\partial n_e/\partial t = \partial^2 n_e/\partial x^2$ in slab geometry that have analytical solutions, e.g. $n(x) = (4\pi \tau)^{-0.5} e^{-x^2/4\tau}$ and against JETTO [32] transport code in a realistic EFIT geometry to validate the implementation.

3.2. Parameterisation of $D, V$ and $S$

In order to find the transport ($D, V$) and particle source ($S$) that are consistent with experimental density measurements a parameterisation is needed. For robust optimisation with a unique global minimum, a small number of parameters is preferred. On the other hand, very rigid profile shapes cannot reproduce the experimental measurements. After a few iterations, the parameterisation that was found to be a good compromise fulfilling both requirements is shown in figure 6. The steady-state part of the diffusion profile is described by three parameters given at predetermined locations $\rho = 0.9$ and $\rho_{max} \sim 1$. The time evolution of the diffusion profile is controlled by six extra parameters (three for phase and three for amplitude), at the same radial locations. The convection profile is controlled
similarly but only at two locations $\rho = 0.6, 1$ with a total of six parameters for the steady-state, amplitude and phase. The convection on-axis is taken to be zero (valid physics constraint).

The mathematical representation of the chosen parameterisation is shown in equation (2) where the variables in bold are controlled by the optimiser. The edge particle source, $S_0$, is also optimised to some extent, but on a higher level, and its role will be elaborated in section 4.

$$D(t, \rho) = D_0(\rho) + D_1(\rho) \sin(\omega t - \varphi_D(\rho))$$
$$V(t, \rho) = V_0(\rho) - V_1(\rho) \sin(\omega t - \varphi_V(\rho))$$
$$S(t, \rho) = S_{\text{NBI}}(\rho) + [S_0 + S_1 \sin(\omega t - \varphi_S)] e^{-\frac{(\rho - \rho_0)^2}{w_0^2}},$$

where $D_0(\rho) = d_1 + d_2 \rho - d_3 e^{-\frac{(\rho - \rho_0)}{w_0^2}}$ and $V_0(\rho)$ is simply obtained from a three-point cubic spline. The minus sign for $V_1$ is chosen to avoid $\pi$ shift between $\varphi_D$ and $\varphi_V$ that arises from the fact that $D_0$ is positive while $V_0$ is negative. The width $w_{\text{ETB}}$ and the location $\rho_{\text{ETB}}$ of the Gaussian shaped edge transport barrier (ETB) are fixed during the optimisations. It turns out that the ability to fit the experiment is not particularly sensitive to the barrier width, so a range $w_{\text{ETB}} \in (0.02 - 0.06)$ is reasonable. We chose $w_{\text{ETB}} = 0.05$ to avoid numerical problems arising from abrupt radial changes in $D$ while still being rather localised. The location of the edge transport barrier $\rho_{\text{ETB}}$ is easily found manually in just a couple of iterations by aligning pedestal gradients between simulations and measurements. For the simulations in this work $\rho_{\text{ETB}} \approx 0.98$ is used. Particle source from NBI, $S_{\text{NBI}}$, is calculated with PENCIL [33] and the edge particle source is simply centred at the separatrix ($\rho_s = 1$) and the source width $w_s$ is set to 0.05 to imitate roughly the expected ionisation profile. These values are fixed during the optimisation and are found to allow good fits. Obviously, altered values for the edge transport barrier and source shape parameters result in quantitatively different optimised transport. However, we expect that the edge transport barrier and the particle source shapes should be identical for all three phases in the discharge, thus creating similar bias for all. The trends found should nevertheless be reasonable even if these parameters may not precisely reflect the experiment. In future work, described elsewhere, more consideration for these variables are planned.

3.3. Optimisation procedure

We use the scipy.optimize module from Python for optimisation. After experimenting with a few different algorithms, we converged to Nelder–Mead that is a gradient free optimiser and appears to be well suited for our case with up to 18 degrees of freedom. The objective function $\chi^2$ to minimise is taken to be

$$\chi^2 = \sum_i \left[ \tilde{n}_{\text{exp}}(\rho_i) - \tilde{n}_{\text{sim}}(\rho_i) \right]^2 + wgt \sum_{ij} \left[ \tilde{n}_{\text{exp}}(\rho_j, \rho_i) - \tilde{n}_{\text{sim}}(\rho_j, \rho_i) \right]^2,$$

where the first term accounts for the steady-state difference and the second term covers the perturbation part alone and the electron density is normalised with $10^{19}$ m$^{-3}$. The separation is added to allow an increased emphasis on reproducing the phase and amplitude profiles of the electron density modulation. In order to fit noiseless synthetic data, separation is not needed but our simplified parameterisation (see section 3.2) leads to a non-negligible steady-state contribution in $\chi^2$ due to the inability to reproduce the fine details in the steady-state profile. Without the second term, this imperfection would dominate the small perturbative contribution leading to poor overall fitting. The scalar multiplier $wgt$ is chosen such that the second term in $\chi^2$ is about a factor $\sim 2$ larger than the first term near the optimum. The absolute value of $wgt$ depends on the case and the spatio-temporal grid resolution ($j, i$, respectively) and is manually set after iterating the optimisations a few times. Depending on the experimental data quality, the objective function may exclude some radial regions. For our discharge, we only include the radial range $\rho_{\text{pol}} \in (0.2 - 1.01)$.

For the given set of parameters describing the spatio-temporal evolution of $D, V$ and $S$ and the given initial
condition \( n_{\text{sim}}(t = 0, \rho) = n_0(\rho) \) the electron density equation, equation (1), is evolved until a quasi steady-state is reached. We use the relative profile variation of \(<10^{-4}\) between the periodic times as the termination criterion. Near the convergence, when parameter changes are small, a single modulation cycle may be sufficient, while with large optimiser steps, tens of cycles may be needed to reach steady-state. The quasi steady-state detection criterion is found to speed up the whole optimisation procedure considerably. The objective function \( \chi^2 \) is evaluated for the last simulated modulation cycle (stationary state), and the procedure is repeated until an optimum is found.

The higher the number of free parameters, the more local optima exist in the optimisation space. This makes it necessary to run multiple optimisations from varying starting positions to ensure the global optimum is found. Our problem typically requires \( \sim 1000 \) iterations of convergence with the Nelder–Mead algorithm. Fortunately, equation (1) is a relatively fast way to evolve until steady-state, it usually takes 10–500 ms with one CPU and a radial grid size of 115, mostly depending on how far the initial value is from the convergence. This makes it feasible to utilise a Monte Carlo approach for the optimisation starting point to increase the coverage of the optimisation space. In noise-free synthetic simulations, Nelder–Mead algorithm is found to converge robustly to the known solution, when the starting point is remotely sensible. However, with the rich set of features in the experimental profiles (see figure 5) and with a relatively large number of parameters, human interaction can occasionally help to nudge the optimiser for further improvement. At times, a temporary reduction in the optimisation space dimensionality can also guide the optimiser to a better optimum than using the full set of variables. Thus, the results here are typically obtained by some iterations between human and automated optimisation to ensure a global optimum is reached.

### 4. Results

In this section, we first briefly show how EDGE2D/EIRENE simulations can help to understand the strike-point geometry’s influence on neutrals. We then move on to the results and insights that we get from our optimisation approach and point out some expected deficiencies in our present modelling and potential ways for future improvements.

#### 4.1. EDGE2D/EIRENE simulations

To gain some insight into the strike-point/divertor geometry influence on neutrals, we performed EDGE2D/EIRENE (steady-state) simulations for discharge \#92347. Using the conventional approach, simulated kinetic profiles in the midplane were fitted against experimental profiles by tuning the effective radial heat and particle diffusivities together with a pumping albedo [15]. This iterative procedure was performed only for the inner equilibrium (see figure 2). Then, a second simulation was made for the outer equilibrium while keeping these adjustable parameters fixed. The right panel in figure 7 shows the poloidally resolved EDGE2D/EIRENE calculations of the ionisation rate inside the separatrix for the two equilibria. It is shown how, especially on the low field side, ionisation increases with the inner equilibrium. The left hand side frames show the calculated \( D_\alpha \) radiation (rough proxy for neutral density) for the two configurations in steady state. This suggests that the higher neutral densities and ionisation through the separatrix in the midplane region are largely due to the more open geometry of the inner configuration allowing increased neutral leakage from the divertor into the main chamber. Since neutrals penetrate the SOL in the main chamber more easily, due to flux compression, total fuelling across the separatrix increases. These simulations also successfully reproduce the experimental trend: higher SOL electron density for the inboard side strike-point location, as seen in figure 3.

On the other hand, as shown by others through EDGE2D/EIRENE simulations [34, 35]: strike-point geometry influences the recycling process, which influences the temperature profile at the target, which through force balance modifies the radial electric field near the separatrix and thus the quality of the edge transport barrier. We thus expect that strike-point sweeping can modify both the transport (barrier) and the ionisation source, making them both time-dependent in this experiment.

#### 4.2. Interference between source and transport perturbations

As already briefly discussed, the measured electron density modulation amplitudes and phase profiles, see figure 5, are quite complex and cannot be reproduced with modulated edge sources and time-independent diffusive and convective transport profiles. We gain some insight into how time-dependent transport allows for more complex density responses by comparing simulations with and without time-dependency. Figure 8 shows the experimental data (blue), a best fitting simulated density response with time-evolving transport (orange), and two partial simulations. In the partial simulations, either the transport modulation or the particle source modulation have been turned off while keeping the other parameters the same as in the optimised case. One can observe a strong qualitative difference in both the amplitude and phase profiles between the fully time-dependent simulations (that match the experiment) and the partial simulations. In the red case, where only the particle source is modulated, we observe a phase minimum near the source location\(^6\) and a monotonically increasing phase towards the plasma centre. The amplitude maximum is slightly shifted inward from the source maximum (at separatrix) due to the inward convection, and its radial decay is monotonic. This behaviour is close to what is seen in gas modulation experiments [6, 7] where the transport perturbation caused by the puff tends to be much smaller than that of the strike-point sweeping in JET plasmas. The green case, where the particle source is time-independent and only the transport is modulated, shows similar but vitally

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\(^6\) Recall the edge source parameterisation in figure 6.
Figure 7. (Left) EDGE2D/EIRENE calculated $D_\alpha$ radiation (∝ neutral density) for the sweep extremes showing increased neutral leakage from the divertor with the ‘inner’ configuration. The dashed line shows an example of radial summation direction for each poloidal index. (Right) Total source rate inside the separatrix from summing over the radial grid index (dashed line). Due to the high similarity of the two grids, this crude measure gives a fair comparison and shows that the increased fuelling comes mostly from the low field side (poloidal angle increases counter clockwise and is zero at the outboard midplane).

Figure 8. Interference between the modulated source and the modulated transport for the 7.7 Hz phase. Experimental data (blue), optimal solution (orange), simulation with gas modulation turned off with other parameters being identical to the optimal solution (green) and simulation with gas modulation on but transport modulations off (red). In all simulations, the steady-state density profiles are well reproduced. See equation (2) for the meaning of the symbols.

different behaviour: the amplitude peak and phase minimum are located just inside the maximum density gradient and are shifted w.r.t. the gas modulation case. Both partial profiles are qualitatively far from the experimental profile, but their combination, or interference, can reproduce the observations where neither the phase nor the amplitude are monotonic but feature double peaks. While such interference is easy to imagine, it is still quite reassuring to see that with relatively simple but plausible transport profiles one can obtain a pattern that matches the observations this well. We will later show more details of the inferred transport and the resulting density perturbation. First, certain ambiguities need to be discussed.

4.3. Ambiguity due to unknown source strength $S_0$

In section 3.2 we discussed all other parameters except the magnitude of the edge particle source $S_0$. There are no direct measurements available to determine it from the experiment at JET which leads us to an obvious problem in the fitting procedure that we have not yet discussed. The problem is illustrated in figure 9 where we show two optimisation results for the 7.7 Hz phase of the discharge. For clarity, we plot only the amplitude and phase plots together with the steady-state diffusion and convection profiles since in all our converged cases the simulated and measured steady-state density profiles are practically on top of each other (e.g. figure 11). The difference between the simulations is that they have different edge particle source $S_0$. In the blue simulation, the source inside the separatrix corresponds to about 36% of the total experimental gas fuelling rate while in the orange simulation it is doubled. One can see that in both cases the fitted profiles match the experiment relatively well (optimisation is limited to the radial range 0.2–1.01). While this is shown here for only two source magnitudes, it is obvious that with any reasonable source (say 10%–100% of the experimental gas rate), the experimental data can be reproduced with similar accuracy. This is a sign
that there are too many variables, i.e. underdetermination of the problem and a well-known limitation. The amplitude and phase responses and the steady-state profiles are all convoluted between the source and the transport effects and cannot be simultaneously unambiguously determined without extra information.

It is possible to constrain the particle source at JET, e.g. with an indirect scheme using visible spectral Balmer I line radiation ($D_{\alpha}$) measurements [36]. In this scheme, the simulated neutral source parameters, such as recycling coefficients and the plasma radial transport properties are iteratively adjusted to match both the measured kinetic upstream profiles and the $D_{\alpha}$ measurements with simulation tools such as EDGE2D/EIRENE [37]. Another way to limit the degrees of freedom in the fitting is to inject physics information for transport. For example, one could use time resolved temperature measurements as in [6] to fix the transport dynamics (phase profile) and allow the optimiser to only find the amplitude response coefficients. Advanced transport models are yet another approach, but here they are not particularly attractive due to their considerable CPU time requirements. For the moment, the inclusion of some of these additional constraints is left to future improvements. Nevertheless, even without these constraints for the source or transport, we can still learn some dynamical insights from the present optimisation approach as already seen in figure 8 and further shown later.

4.4. Ambiguity due to source modulation $S_1$

Similar to what was seen in section 4.3 there is an ambiguity between the modulated transport and the modulated source. Increased source modulation can be compensated by increased transport modulation to the extent that disentangling them simultaneously is impossible outside the experimental error bars, even if the error bars are relatively small. This is demonstrated in figure 10 where one fully optimised solution for a given steady-state source magnitude was further optimised by forcing a non-ideal source modulation amplitude. A scan with $S_i/S_0$ from zero to 0.4 was made and even the worst solutions were found to be only about 20\% worse than the optimal one. Furthermore, a large part of the increase in $\chi^2$ comes from the radial region 1–1.01 where experimental uncertainty is higher; see the right hand side frames.

Again, in order to obtain quantitative results, extra information is needed for either the transport side or the source side. Regardless of the fluidity of some aspects of our results, the temporal order of the source and the transport barrier modulations are relatively consistent, as also seen in the above frame (top row, second from left). For essentially all our optimised cases, the source phase is quite robustly $\varphi_S \approx \pi$ which corresponds to the maximum source for the inner equilibrium (i.e. $R_{xy}$ is smallest). Similarly, the quality of the transport barrier always starts to degrade before the source. $\varphi_D (petb) - \varphi_S$ converted to time delay corresponds to roughly $2$–$4$ ms for all frequencies when the experiment fits the experiment well.

4.5. Fitting three frequencies with shared quantities

One additional piece of information that we can use to constrain the optimisation space are the shared properties between the three modulation frequencies. It seems fair to assume that for all modulation frequencies: (1) the steady-state transport profiles ($D_{0i}, V_{0i}$) are identical and (2) the steady-state gas fueling profiles are the same. Furthermore, given the fast SOL adjustment time to the strike-point geometry changes (consistent with figure 3) one might further expect the source modulation amplitude $S_1$ to be similar across the frequencies.

Figure 11 shows the optimal fits together with transport profiles under these constraints. The fits were obtained by first fitting the 7.7 Hz phase with 17 free parameters by only fixing the steady-state gas rate such that fuelling across the separatrix is about $\sim 50\%$ of the experimental gas puff rate (a reasonable but somewhat arbitrary choice). Optimisations for the 3.9 Hz and 18.5 Hz phases are then performed with $D_{0i}, V_{0i}, S_0$ and $S_1$ (see equation (2)) fixed to those of the 7.7 Hz phase. The remaining properties left to optimise are thus $D_1, V_1, \varphi_D, \varphi_V$ and $\varphi_S$. It turns out that with these constraints, the experimental density dynamics are well reproduced for all three sweep frequencies. We find that there is a trend of increasing transport modulation with increasing modulation frequency, roughly following the scaling $V_1 \sim f$ and $D_1 \sim \sqrt{f}$. It is, however, not clear, whether this trend can be attributed solely to physics or whether, e.g. the simplicity of our neutral source model requires spurious extra transport modulations to compensate. Future work is planned with a neutral source calculated by FRANCTIC [38] to assess the sensitivity of these results against more realistic neutral dynamics. Interestingly, no good fits for all three phases are found if instead of fixing the $S_1/S_0$ ratio for the three frequencies we fix the transport modulation amplitude and allow the optimiser to choose the best $S_i/S_0$ and transport timing ($\varphi_D, \varphi_V$) for each frequency separately.

It appears that while we cannot be confident that the transport modulation is not affected by possible spurious
Figure 10. Optimisations for the 7.7 Hz case for a source modulation amplitude scan ($S_0$ is the same for all). For clarity, the phase and modulation amplitude of the transport are shown only for the edge points: $\tilde{v}_{sep} = V_1 (1)$, $\tilde{D}_{ETB} = D_1 (\rho_{ETB})$. Deviations from the optimum at $S_1/S_0 \sim 0.23$ increase $\chi^2$ only weakly. On the right hand side, electron density amplitudes and phases are shown to illustrate the similarity of the simulated profiles throughout the scan.

Figure 11. Optimised transport and fits to experimental data with $S_0 = 3 \times 10^{21} \text{m}^{-3} \text{s}^{-1} (\sim 0.5 \Gamma_D)$ and $S_1/S_0 \approx 0.1$. The green vertical lines indicate the modulation range of the transport. The top row is for 3.9 Hz, the middle row for 7.7 Hz, and the bottom row for 18.5 Hz case.

contributions, the assumptions about the shared properties ($D_0, V_0, S_0$ and $S_1$) seem to be the only set that gives consistent results. Even though this set appears to be the most natural one, it is a positive result for the optimisation scheme, showing that there are limitations to what can be assumed and it is not possible to get good fits with just any assumptions with the remaining degrees of freedom.

4.6. Source-transport dynamics

One of the most robust and thus interesting outcomes with the present capabilities of our optimisation approach is how the timing between the transport barrier quality and the source ($\phi_D (\rho_{ETB})$ and $\phi_S$) are linked. It turns out that, with any reasonable source modulation magnitude in $\sim 5\%–35\%$ range ($\sim 15\%$ can be crudely estimated from midplane $D_\alpha$ measurements), the diffusion at the barrier location starts to increase (i.e. barrier quality decreases) some $2–4 \text{ ms}$ before the ionisation source increases. Roughly, the same absolute time difference is observed across the three frequencies (3.9 Hz, 7.7 Hz and 18.5 Hz). Figure 12 illustrates the high sensitivity between the timing of the source and the barrier evolution. The best fitting simulation (orange) is repeated with identical optimised parameter set except for the source phase $\phi_S$, which is either delayed (green) or advanced (red) by just $2 \text{ ms}$. The high sensitivity of the amplitude and phase to the small changes in the source and transport timing increases our confidence in the sequence of occurrences. This seems consistent with the picture where the target conditions rapidly alter the ETB quality through the radial electric field, and the particle source adjusts to the new geometry and recycling conditions shortly thereafter.
5. Summary and discussion

We have presented the first strike-point sweeping experiments at JET aimed at shedding more light on particle transport and source phenomena and our interpretation of the various mechanisms at play. To understand the complex response of the electron density to the sweeping, we implemented a 1.5D forward model, extending into the SOL, for the electron density evolution. The model uses parameterised particle transport and source properties ($D$, $V$ and $S$) whose optimal values are determined via an optimisation procedure by fitting the simulated electron density response to the experimental measurements. We found that experimental matching is only possible if we allow temporal evolution of transport in addition to the modulated edge particle source. We point out that the results from our current model, without additional experimental or theoretical constraints for the transport or the source, are ambiguous in terms of absolute magnitudes. Utilising the three different sweep frequencies simultaneously with their shared properties, this ambiguity could be mitigated but not sufficiently to allow unique solutions with small uncertainties. Potential remedies, such as additional information for transport from temperature measurements, or neutral source magnitude derivation from visible light spectroscopy were discussed but are left for future work. We expect them to help narrow down the feasible solution space. Further uncertainties arise from the fact that our SOL is treated in 1D with time-independent parallel transport. The impact of these approximations is not trivially assessed with our present tools but remains of interest for future considerations.

Despite the current limitations, our modelling clearly demonstrates that strike-point sweeping perturbs the edge transport significantly. This is not a desirable effect for particle source studies near the edge and has a clear downside compared to the conventional gas puff modulation where the edge transport barrier is generally much less influenced by the perturbation. Therefore, it seems that sweeping cannot be viewed simply as a higher frequency replacement for gas puffs. It might be more appropriate to use it as a tool for examining divertor geometry effects in general. A related finding in our simulations was the robust temporal sequence between the increase in the particle source and the degradation of the edge transport barrier. It turned out that when strike-point moves to a smaller major radius, the main chamber neutral source increases (via increased divertor leakage, supported by EDGE2D/EIRENE) and is led by the edge transport barrier degradation by about 2–4 ms. This sequence could be consistent with the picture, where (1), the radial electric field modification due to strike-point geometry [34] nearly instantaneously influences the edge transport barrier, and (2), SOL and divertor conditions adjust to the new geometry, with a small delay causing increased neutral densities and ionisation across the separatrix around the midplane. Our present model is not able to confirm this in more detail as it likely requires more comprehensive 2D/3D codes that are capable of self-consistent neutral/plasma simulations.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant No. 101052200 EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.
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