

DRAFT: Detachment dynamics and disturbance rejection in the TCV X-Point Target divertor

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Abstract. The X-Point Target divertor is an alternative divertor configuration with a secondary X-point in its divertor volume. In this work, we investigate the dynamic response and disturbance rejection capacity of the XPT configuration on the TCV tokamak, comparing it to a single null (SN) divertor. We employ a system identification approach using multi-sine perturbations to measure the dynamic response of the detached state in both Ohmic and auxiliary-heated L-mode scenarios upon D₂ fuelling, N₂ seeding and Electron Resonance Cyclotron Heating (ECRH) power modulations. We demonstrate an inherent disturbance rejection capacity of the XPT at its secondary X-point compared to a SN configuration for all perturbation scenarios. Upstream of its secondary X-point, the dynamic response of the detached state between the XPT and SN appears similar. The disturbance rejection capacity of the XPT could be highly beneficial for passively buffering disturbances that cannot be effectively managed by power exhaust controllers. At the same time, it presents a challenge for monitoring the detached state close to the secondary x-point.

Keywords: X-Point Target, Divertor, Detachment, Dynamics

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1. Introduction

Power exhaust remains one of the key challenges on the path to reactor-grade tokamaks. Without mitigation, the projected target heat loads and temperatures in reactor-class devices like EU-DEMO [1] and especially compact devices like STEP [2], SPARC [3], and ARC [4, 5] can largely exceed the material limits of the divertor targets, posing a risk to structural machine damage.

To stay within the wall material limits, detached operation of the divertor plasma is required. In the detached state, the plasma flowing from the core into the scrape-off layer (SOL) first cools through radiative interactions with impurity species, often actively injected, promoting volumetric power dissipation [6, 7]. Secondly, plasma-neutral interactions further remove power, momentum and particles (ions) from the plasma [8–11], which can be enhanced via the injection of additional hydrogenic species in the divertor chamber. This causes the ionisation source (*detachment front*) to ‘detach’ from the target as a neutral particle buffer builds in front of the target surface in the divertor. Consequently, the heat and particle fluxes to the target are significantly reduced. To ensure divertor wall protection, the front must therefore remain detached from the target, yet not approach the core close enough to reduce fusion performance [12–14], trigger core instabilities (e.g. ELMs, sawteeth instabilities [15]) and potentially violent disruptions [16–18]. Maintaining the detachment front within these two hard limits throughout a discharge cycle is rendered challenging by transient events occurring across multiple timescales, such as plasma core instabilities [15], low (L) to high (H) confinement mode transitions [19] (or vice versa), core pellet fuelling [20] or failing heating systems [21]. The situation is further complicated by the limited actuation possibilities for fast disturbances due to the slow actuation of gas valves, as well as significant injection delays caused by long transportation times via gas pipes [22].

With regard to the described exhaust challenges, recent studies of Alternative Divertor Configurations (ADCs) in TCV and MAST-U show key exhaust benefits compared to conventional divertor geometries in quasi-steady state. Experiments on the Super-X Divertor (SXD) at MAST-U demonstrate reduced target heat fluxes, improved detachment access (i.e. reduced *detachment onset*), an enlarged operational

parameter space for which the detachment front is located in between the target and X-point (*detachment window*), and a reduction of the *detachment sensitivity* to core conditions [23]. Although the geometry of the TCV X-Point Target (XPT) divertor, which includes a secondary X-Point, differs substantially from the SXD, it features similar benefits. Reduced target heat loads, an enlarged detachment window, and indications of reduced detachment front sensitivity near the secondary X point were all observed [24].

While these recent ADC results show promise for mitigating stationary power exhaust, reactor-relevant solutions must also address *dynamic* behaviour of the detached state throughout a discharge, requiring an understanding of how it responds to constant disturbances, arising from transients with different timescales.

To study this behaviour, a system identification method can be used to identify detachment dynamics, which has been demonstrated in multiple tokamaks [25–29]. Using system identification, experiments with sinusoidal gas puff modulations on the SXD at MAST-U confirm that the observed detachment sensitivity reduction in quasi-steady-state extrapolate towards control-relevant timescales [27]. This built-in buffer provides actuators with more time to respond to disturbances and is thus favourable for maintaining the detached state throughout a discharge.

Building on the TCV X-Point Target and MAST-U results, this work addresses the disturbance rejection capacity of the TCV X-Point-Target and its overall detachment behaviour from a dynamics perspective. We systematically introduce sinusoidal perturbations in the XPT configuration for three different scenarios:

- (i) D₂ fuelling gas valve modulations, raising the core density
- (ii) N₂ impurity seeding via gas valve modulations in high power conditions while keeping the core density constant
- (iii) Heating perturbations via electron cyclotron resonance heating (ECRH) in the core plasma at high power conditions, whilst keeping the core density and impurity injection constant

These experiments are benchmarked to a long-legged conventional divertor (Single Null - SN) configuration with similar core shape, plasma scenarios, and perturbations. It is demonstrated that the XPT divertor features an inherent disturbance rejection

capacity to fuelling, seeding and ECRH heating modulations at its secondary X-point. In the region upstream of the secondary X-point, the dynamic response of the XPT and SN divertor is similar.

This work starts with an overview of the experimental setup and system identification method in section 2. Section 3 provides an overview of the D₂ fuelling perturbation experiments, followed by the results from perturbative N₂ seeding and ECRH power modulations experiments in section 4. Section 5 provides a discussion on the presented results and its implications for future reactors, and exhaust control in an XPT configuration.

2. Experimental setup and methods

All experiments presented in this work were conducted at the Tokamak à Configuration Variable (TCV) [30], which is a medium sized tokamak with major radius $R_0 = 0.88$ m, minor radius $a = 0.25$ m, and a carbon first wall. TCV is equipped with independent control over its poloidal field coils, allowing for precise core and divertor shape control [31]. This capability not only allows the formation of the XPT divertor, but also facilitates the design of a core shape and plasma scenario that is similar for both XPT and SN divertors. Thereby, a comparison of the detachment dynamics in both divertors is enabled while they operate in similar scenarios, as described in Section 2.1. An overview of the diagnostics that were employed to measure the evolution of the detached state is provided in Section 2.2. Section 2.3 details the system identification approach that combines outputs from the diagnostics with inputs from the actuators to identify detachment dynamics.

2.1. Plasma scenarios

Figures 1(a) and 1(b) highlight the operational scenarios and different magnetic geometries that were employed in this study. The XPT configuration in red is formed by introducing a secondary poloidal magnetic null in the outer divertor leg of a single null configuration. This results in a split of the outer leg into two distinct active branches and multiple strike points (SP in the figure). Here, SP3 is magnetically disconnected, whereas the division of heat and particle fluxes between SP2 and SP4 primarily depends on the radial distance between the separatrices at the outboard midplane in the direction of the far-SOL, denoted as $dR_{u,x2}$, and the toroidal field direction that determines $\vec{E} \times \vec{B}$ behaviour close to the secondary X-point [35, 36]. The larger $dR_{u,x2}$, the more connected SP2 will be compared to SP4. In the presented experiments $dR_{u,x2} = 1.0 \pm 0.5$ mm, which is small relative to the e-folding heat flux width ($\lambda_q \approx 4$ mm

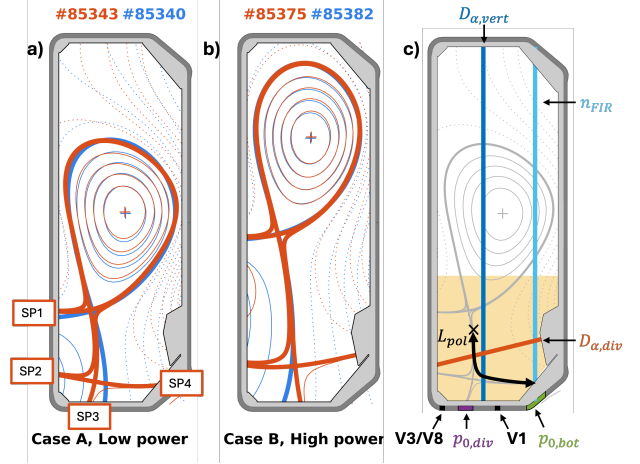


Figure 1. Magnetic equilibria and diagnostic locations. a) and b) show the magnetic equilibrium reconstructions at $t = 1.2$ s for the SN (blue) and XPT (red) configurations used in this study for two different plasma scenarios; Case A: Ohmic heating, and Case B: Ohmic + ECRH. c) Provides an overview of all the diagnostics that were used in the analysis, including CIII front tracking (L_{pol}) with the Multispectral Advanced Narrowband Tokamak Imaging System [32] (MANTIS, approximate field of view in transparent orange), $D_{\alpha,vert}$ and $D_{\alpha,div}$ for line-integrated Balmer- α emission intensity via filterscopes (Photodiodes), a core density proxy n_{core} via interferometer chord two (FIR [33]), neutral pressure measurements $p_{0,div}$ and $p_{0,bot}$ via pressure gauges (APG [34]).

[24]) of the SOL. As a result, the majority of the heat flux is expected to be guided to SP4.

The different divertor configurations in this work solely operate in a L-mode plasma in two different scenarios. Case A shows the equilibria for both SN (blue, 85340)) and XPT (red, 85343) in an Ohmic scenario, operating with $I_p = 300$ kA, a toroidal field strength of $B_t = 1.4$ T in reversed toroidal field configuration, which is unfavourable for H-mode [19] access. This scenario is equivalent to the one described in [24], except for the baffling configuration. D₂ fuelling perturbations were introduced in the XPT and SN configurations via Valve 1 (V1 in Figure 1), without gas injection from other valves. An overview of the relevant discharges, including parameters of the perturbation signals is provided in Table B1. Note that in this scenario, no auxiliary ECRH is added, as core density fluctuations induced by fuelling perturbations impact the ECRH coupling, thus complicating the analysis of fuelling impact on the detached state.

Case B shows the equilibria of the high power scenarios, in which the scenarios of Case A were modified by using long-legged SN (blue, 85382) and XPT (red, 85375) configurations and auxiliary ECRH power [36]. N₂ gas was injected via either valves 3 and 8 (V3/V8 in the figure), which have the same poloidal, but different toroidal position. In SN discharges, $P_{ECRH} = 520$ kW, whereas for XPT discharges, a

total of $P_{ECRH} = 2570$ kW is injected. All gyrotrons heat on-axis via the second harmonic X-Mode (X2). To obtain a similar level of detachment between the SN and XPT configurations, ECRH power and N₂ seeding were scaled according to the Detachment Location Sensitivity model [37, 38]. In this model, the magnetic geometry of the divertor is linked to a detachment driver D which combines upstream density $n_{e,u}$, impurity fraction $f_z = n_z/n_e$ and upstream parallel heat flux $q_{||,u}$ as $D = n_{e,u} f_z^{1/2} / q_{||,u}^{5/7}$. The scenarios in Case B are employed for ECRH and N₂ seeding perturbations.

2.2. Diagnostic setup

Figure 1(c) shows the employed diagnostics to study detachment dynamics. This work relies heavily on MANTIS [32] to study detachment dynamics. The lower divertor MANTIS system provides bandpass filtered images of selected radiating spectral lines with an approximate view that corresponds to the transparent orange region in Figure 1. After tomographic inversion [40], a poloidal (2D) map of this emission is obtained. Together with magnetic reconstruction via LIUQE [41], the inverted emission can be overlaid with magnetic field lines in the divertor. We combine inverted images with LIUQE magnetic reconstruction to track the emission front of the CIII (465 nm) transition along the divertor leg, representing a cold ($T_e = 5 - 8$ eV [25, 42, 43]) plasma region. A version of the tracking algorithm described in [44] is used, adjusted to be compatible with the curved divertor legs of the XPT divertor. The CIII front is defined as the position along the divertor leg where CIII emission has dropped by 50 percent of its maximum value [13, 14]. Although the CIII front is located upstream of the detachment front ($T_e < 5$ eV [12, 45, 46]), its movement along the divertor leg is commonly used as a proxy for detachment evolution and sensitivity [14, 24, 47]. The position of the CIII front along the divertor leg is defined as L_{pol} , which represents the poloidal distance between the front and target along the magnetic field, as shown in Figure 1.c.

Additionally, far infrared (FIR [33]) interferometer chord number 2, shown in light blue in Figure 1, provides a measure for the line-integrated core density. This chord was selected, because it provides a line-integrated core density measurement that is comparable between SN and XPT configurations, whereas other FIR chords include significant contributions of the plasma density in the divertor region for the XPT case. Furthermore, a measurement of the core density by FIR was preferred over measurements via Thomson scattering as the acquisition frequency of the latter (60 Hz) is insufficient to resolve the dynamics investigated

in this study. The neutral pressure p_0 in the divertor is monitored by two fast ion gauges (green and purple coloured APG [34] in Figure 1), located at different positions in the divertor region. Furthermore, two photodiodes (PD) with vertical (top-down, in dark blue) and divertor (in red) sight lines measure the Balmer- α emission (656 nm) intensity D_α , which results from the de-excitation of neutral deuterium atoms [48]. The D_α emission is commonly used as a proxy for plasma-neutral interactions.

2.3. System identification method

The given set of diagnostics is used to identify detachment dynamics using a system identification method, which has been applied to study various dynamical processes in multiple tokamaks [22]. With this method, we perturb the divertor plasma (the system, described by non-linear physics) around an operational point to obtain a measurement of the local linearized dynamics of the detached state. That is, assuming the divertor plasma behaves linear close to the operational point. In this work, the operational point constitutes the CIII front position at the divertor leg as a measure for the status of the detached state. Figure 2 provides an overview of the method, which is detailed in this section.

After detaching the CIII front from the target, an input perturbation $u(t)$ is introduced via different actuators, i.e. D₂ gas fuelling, N₂ gas impurity seeding or ECRH power modulations (Figure 2(a)). The gas valves are feedback controlled and contain a flow meter near the vessel wall, such that dynamical effects from neutral transport in the gas system can be separated from the identified detachment dynamics. The perturbation in the input signal is chosen to be a multi-sine opposed to e.g. a block-wave or step function, as it enables the excitation of a specific set of frequencies (timescales), provides a good signal-to-noise ratio (SNR), and facilitates the differentiation between linear or non-linear behaviour [22]. A detailed description of the multi-sine signal design is given in Appendix A.

Upon actuation with carefully chosen excited frequencies f_{exc} in the multi-sine signal, the detached state evolves, which can be measured as an output $y(t)$ (Figure 2(c)). Here, $y(t)$ is a measurement of one of the diagnostics described in Section 2.2. To characterize the dynamics that determines the input-output relation, both input and output signals are transformed from the time domain, to frequency domain via a Discrete Fourier Transform (DFT), yielding $U(f) = \mathcal{F}\{u(t)\}$ and $Y(f) = \mathcal{F}\{y(t)\}$ (Figure 2.d,f). To correct for distortions in the DFT caused by slow transients (originating from e.g. pump dynamics or wall effects) and drifts of the operational point,

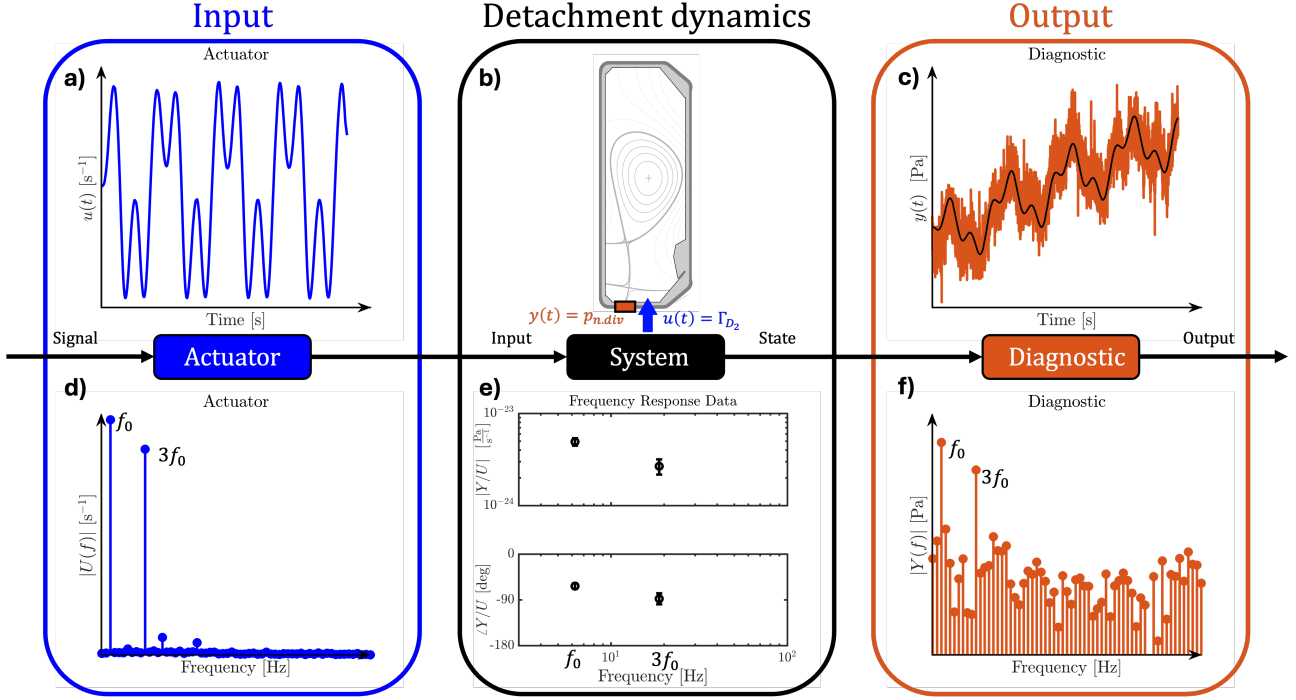


Figure 2. Example of the system identification method to obtain Frequency Response Data (FRD) for TCV discharge #85343. The actuator (D_2 gas puff) introduces a multi-sine perturbation input signal $u(t) = \Gamma_{D_2}(t)$ (a) to the divertor plasma in (b) with excited frequencies $f_{exc} = f_0 \cdot [1, 3]$, as shown by the Discrete Fourier Transform (DFT) $U(f) = \mathcal{F}\{u(t)\}$ in (d). As a result, the divertor state evolves, which is measured with various diagnostics. The resulting output (divertor neutral pressure in this case) is shown in (c) with $y(t) = p_{n,div}(t)$ in red, and LPM [39] reconstructed response in black. (f) shows the DFT of the output signal $Y(f) = \mathcal{F}\{y(t)\}$. As a result, the linearized dynamics can be identified via the FRD $H(f_{exc}) = Y(f_{exc})/U(f_{exc})$ in (e) with error bars determined via the LPM [39].

the local polynomial method (LPM) [39] is used. Slow drifts of the operational point can be caused by the accumulation of gas throughout the perturbative phase, which increases the neutral pressure in the divertor, causing the CIII front to move upstream.

By combining the input and output with the LPM correction in the frequency domain, a measurement of the local linear dynamics at the excited frequencies can be extracted as Frequency Response Data (FRD, Figure 2(e)) $H(f_{exc})$, defined as

$$H(f_{exc}) = \frac{Y(f_{exc})}{U(f_{exc})}. \quad (1)$$

Two criteria have to be met for the FRD to be a reliable measurement of the linearized dynamics that relates input to output. First of all, the system has to respond dominantly linear upon excitation, which can be identified through the output spectrum $Y(f)$. Linear systems show a response only at the excited frequencies f_{exc} . Contrary, dominant non-linear systems also generate a response at (low-order) integer multiples of f_{exc} [39]. Therefore, to facilitate the detection of dominant nonlinearities, all excitation signals in this work utilize excitation frequencies with odd-order harmonics (e.g. $f_{exc} = f_0 \cdot [1, 3, 5, \dots]$). This

choice ensures that any resulting dominant even-order harmonics in $Y(f)$ can be attributed to even-order nonlinearities.

Secondly, the SNR of the excited frequencies in the output $Y(f_{exc})$ should be sufficiently high to exceed the noise floor. The SNR of the output signal is defined as $SNR = |Y(f_{exc})|/\sigma_{noise}$, where σ_{noise} is a measure for the noise contribution in the excited frequency bin, determined with the LPM for each excited frequency individually. Taking the average of the noise for all excited frequencies defines an average noise floor $\bar{\sigma}_{noise}$. Measurements with an $SNR \geq 5$ are considered to represent a reliable FRD point [49]. The FRD is typically visualized in a Bode plot, which displays the amplitude gain $|H(f_{exc})|$ and phase lag $\angle H(f_{exc})$ as a function of frequency. The gain quantifies the magnitude by which the system's output responds to the input across excited frequencies, whereas the phase lag characterizes the time delay of the output relative to the input.

Altogether, the FRD provide a measurement of linearized dynamics that does not require an *a priori* physics model, which we use to compare detachment dynamics between SN and XPT discharges.

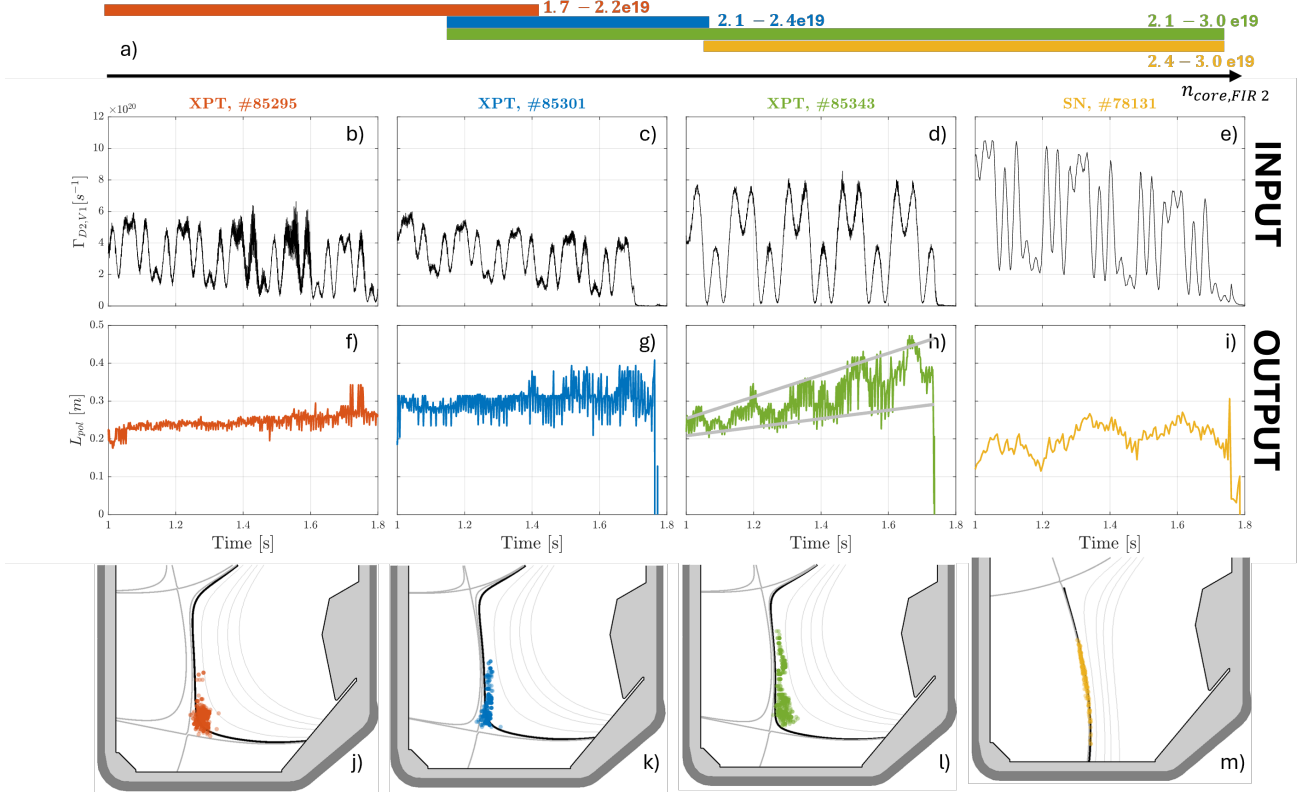


Figure 3. Comparison of the CIII front response in time domain at different operational points in discharges 78131 (SN) and 85295, 85301, 85343 (XPT). (a) shows the line-integrated core density $n_{e,FIR2}$ of these discharges at the begin and end of the perturbative phase. Multi-sine gas inputs (b-e) and the resulting CIII front movement outputs (f-i) are shown for all discharges. (j-m) shows the poloidal projection of the detected CIII fronts. The black curves represent the flux tube along which the fronts are tracked. The grey lines in (i) indicate an increasing amplitude of the output response for constant input amplitude, suggesting changing sensitivity.

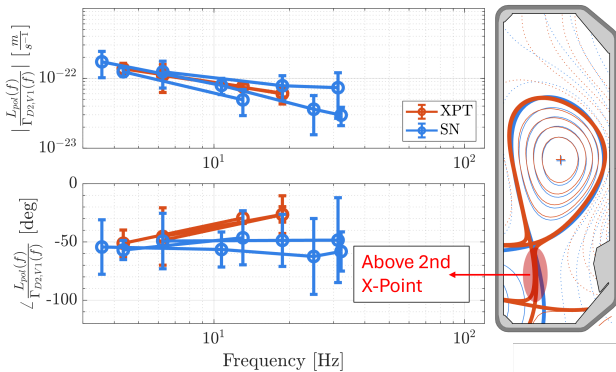


Figure 4. FRD of SN discharges 78131, 85340, and 85347 (blue) and XPT discharges 85343, 85350, and 85353 (red). The CIII front in all XPT discharges drifts from the secondary X-Point towards the first X-Point, indicated with the red transparent region. FRD from the same shot are connected with a line.

3. Detachment front dynamics under D2 fuelling perturbations

In this section we consider the results of the D2 fuelling perturbative experiments in both XPT and

SN configurations. The scenarios described by case A in Section 2.1 were used for this study. We first analyse and compare CIII front dynamics in both SN and XPT discharges. This is followed by a comparison of the overall dynamics between the SN and XPT, as measured by multiple diagnostics.

3.1. XPT and SN front dynamics comparison

Figure 3 provides an overview of the CIII front evolution (f-i) in a selection of three XPT discharges and one SN discharge upon multi-sine D₂ fuelling perturbations (b-e). The poloidal projection of the detected CIII fronts in the given time interval are shown in (j-m). The range of line-integrated core densities in which they operate is shown in (a).

Focussing on the first three columns with XPT discharges in Figure 3, the CIII front appears insensitive to the fuelling perturbations when it is close to the secondary X point in (f). In contrast, the response becomes more pronounced as the front drifts from the secondary towards primary X-point in (g) and (h), as the fuelling levels and core density are raised prior to the perturbative phase, shown in

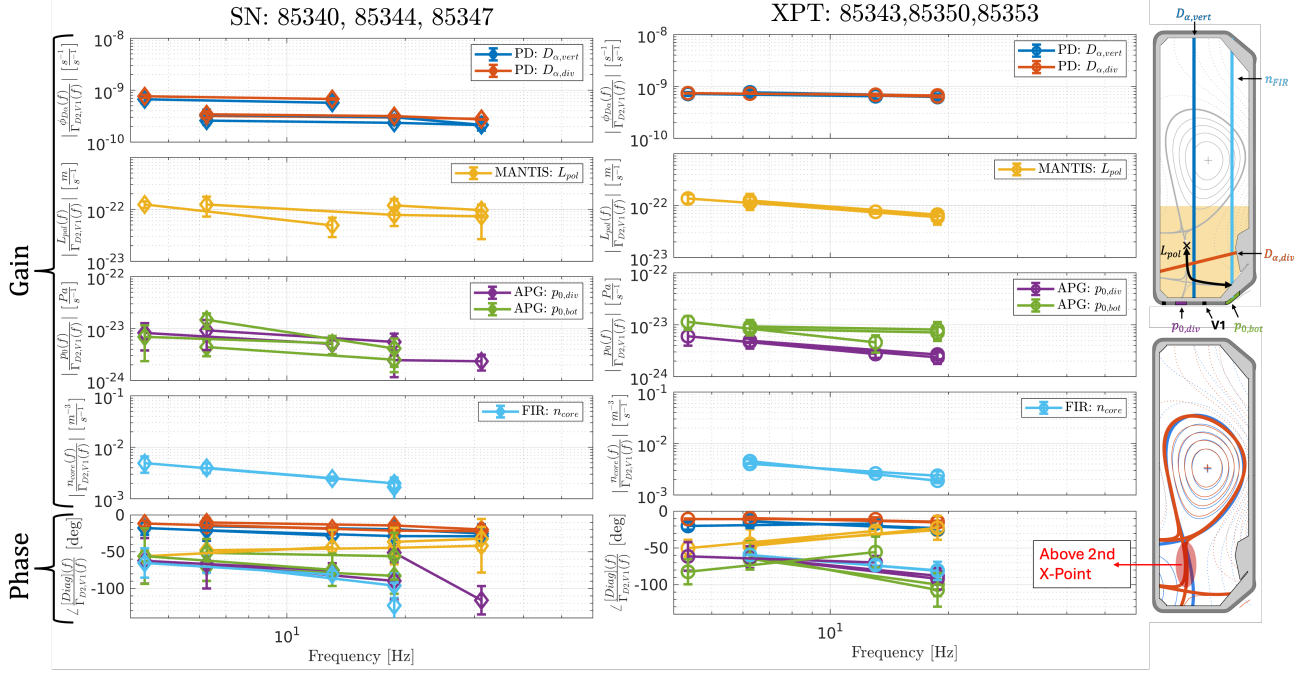


Figure 5. FRD of SN discharges 85340 and 85347 on the left, and XPT discharges 85343, 85350, 85353 on the right. The top four plots for both SN and XPT represent the FRD points of different diagnostic outputs D_2 fuelling perturbation input with varying multi-sine signals. The CIII front is located above the secondary X-point in all XPT discharges.

(a). This is especially evident in discharge 85343, where the amplitude of the CIII front output increases upon constant input amplitude fuelling perturbations, indicated with the grey lines in (h). Here, the response of the CIII front in the region upstream of the secondary X-point appears similar compared to the response of a SN divertor (e,i,m). The reduced sensitivity of the CIII front at the secondary X-point of the XPT divertor is considered highly beneficial for maintaining the detached state, as the secondary X-point could function as a passive buffer to mitigate fast transients that cannot be actively controlled with slow actuators in the divertor region.

Due to the reduced front sensitivity of the CIII front at the secondary X-point, the quality of the FRD points in that region for XPT discharges is poor as evidenced by the low SNR ($\text{SNR} < 5$) listed in Table B4. Nevertheless, we can estimate a factor 3 sensitivity reduction in the region of the secondary X-point compared to the upstream region and SN discharges as shown in Appendix C.1.

In the region upstream of the secondary null, the pronounced response of the CIII front can be compared with SN discharges. The resulting FRD points are visualized in a Bode plot in Figure 4. First, consider the gain in the top part of the bode plot. The overlapping FRD points for SN and XPT discharges indicate a similar gain of the CIII front evolution upon D_2 gas puff perturbations. Similarly,

the phase response in the bottom of the figure is comparable for all excited frequencies in SN and XPT configurations in a range of phase lags between 20 and 50 degrees. Note that the decreasing phase lag towards higher frequencies in the XPT FRD is unphysical behaviour, since a system with pure time delay only shows a constant or increasing phase lag towards higher frequencies [50]. The phase response of the CIII front around 50 degrees is consistent with prior system identification experiments at TCV as shown in Appendix C3, and previous observations across multiple devices [22].

3.2. XPT and SN multi-output comparison

We further characterize the dynamical behaviour of the divertor in both SN and XPT configurations, by extending the system identification analysis to multiple sensors that were introduced in Section 2.2. This allows for a comparison in the phase response between different sensors to identify the chronological order in which they respond. The gain is compared primarily between SN and XPT to identify differences in response imposed by their different magnetic geometries. All data presented in this section was observed to have a dominantly linear response, as shown in Appendix C.3.

The results are shown in Figure 5 for SN and XPT discharges separately. The phase response of all sensors is plotted collectively in the bottom figures, whereas the gain is shown in the top four rows.

Examining the phase response in Figure 5, a consistent trend is observed for both the SN and XPT scenarios for all perturbed frequencies. First, a response is observed in the D_α emission by the photodiodes with a top-down ($D_{\alpha,vert}$), and divertor ($D_{\alpha,div}$) line of sight. The phase lag of both photodiodes is between 10° at low frequencies and 30° at higher frequencies. This indicates that D_2 neutrals start to interact with the plasma almost instantly upon injection. This is followed by a response of the CIII front. Finally, the neutral pressure, measured at two divertor locations, responds simultaneously with the core density, as measured by FIR chord two. In both configurations, the neutral pressure at the two divertor locations responds nearly in phase. The chronological order of all these processes are consistent with observations at MAST-U and DIII-D [22]. Furthermore, the similar phase response across multiple sensors in SN and XPT discharges indicates that the magnetic geometry of the divertor in TCV does not affect the chronological ordering of the underlying processes. Being unaffected by the magnetic field, this suggests a dominant role of neutral particle dynamics as a driver for detachment dynamics.

Next, we compare the gain of the different diagnostics between the SN and XPT discharges, as shown in the top four subplots of Figure 5. Starting at the top, an almost identical response is observed for the photodiodes with different lines of sight. A minimal gain attenuation towards higher frequencies is observed, indicating that the plasma responds almost instantly to the injected D_2 neutrals, consistent with the observations in phase response. The lower gain in two SN discharges differs from the gain response of SN 85347 and all XPT discharges. This may be attributed to the lower amplitude of the perturbation signals in these discharges, although a clear cause has not been identified.

Moving on to the neutral pressure at two divertor locations in the SN and XPT, a difference in gain response is observed between the configurations. In the SN case, the neutral pressure at both locations has an identical gain, evidenced by the green and purple FRD points that overlap for all discharges. In contrast, the neutral pressure in the XPT shows a consistently higher gain for $p_{0,bot}$ compared to $p_{0,div}$. This indicates that the neutral particle buildup in the secondary PFR is reduced compared to the region close to the sensor at SP4.

The gain response of the core density measured by FIR chord 2 is similar and almost identical for both SN and XPT geometries. This indicates that the magnetic equilibrium does not seem to influence the transport of neutral D_2 into the core plasma.

For all diagnostics, the gain attenuation (i.e.

the slope of the gain across frequencies) is similar between the XPT and SN configurations, suggesting a comparable underlying physical mechanism. Taking both phase and gain responses into account, the dynamic behaviour of the SN and XPT divertors is similar upon D_2 perturbations, excluding the different response in neutral pressures at different divertor locations in the XPT discharges. Despite this similarity, the XPT demonstrates the capacity to buffer fuelling perturbations at its secondary X-point, diverging from the front behaviour observed in SN discharges. Thus, the magnetic equilibrium of the divertor seems to affect the front sensitivity.

4. High power scenarios

In this section we consider the results of N_2 seeding and ECRH perturbations, employing the plasma scenarios described by case B in Section 2.1. An overview of all presented discharges in this section is provided in Table B2 and B3.

Before proceeding to the results of these experiments, it must be noted that the high power L-mode XPT [36] scenario has a CIII emission pattern that differs significantly from the experiments presented in Section 3. As shown in Figure 6, two regions of emission can be distinguished in the outer divertor leg of the XPT, with a contribution along the separatrix to the secondary X-Point, and a contribution at a flux surface in the far-SOL close to $dR_{us} = 5$ mm. The origin and implications of these two distinct regions are discussed in further detail in Section 5.2. Throughout the discharges, the front position at the secondary X-point is mostly stationary. Therefore, the emission front was tracked along a flux surface closest to the region of maximum CIII emission close to $dR_{us} = 5$ mm towards SP4.

4.1. N_2 seeding perturbations

To further investigate the resilience of the XPT at the secondary X-point, N_2 seeding perturbations were introduced in a XPT and SN configuration. Figure 7 shows an overview of the actuator input (a), power conditions (b), line integrated core density as measured via Thomson Scattering (c) and the resulting CIII front evolution output (d) of perturbative N_2 seeding experiments in SN discharge 85388 and XPT 85380. The N_2 seeding perturbations were introduced from Valve 3, and are shown in respectively blue and red for the SN and XPT scenarios in Figure 7(a). The light colored blue and red curves in the same Figure correspond to the D_2 gas puff from Valve 1. To facilitate the absorption of ECRH power, core density control was enabled during both discharges, in which Valve 1 was used as an actuator. The perturbative

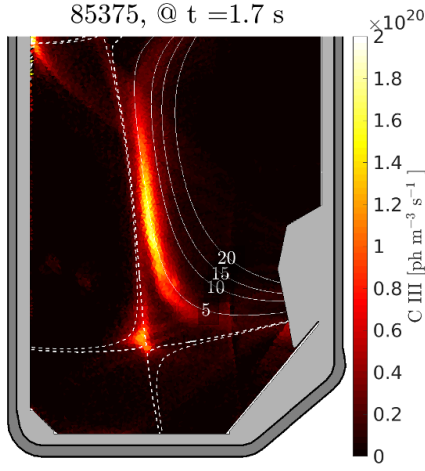


Figure 6. Tomographic inverted image [40] of CIII emission obtained via MANTIS [32] with LIUQE [41] reconstructed equilibrium in white, showing two distinct regions with CIII emission in the divertor leg for the XPT. The dotted lines represent the separatrix, whereas the solid white lines represent flux surfaces starting at $dR_{us} = [5, 10, 15, 20]$ mm.

phase in these scenarios starts at $t = 1.2$ s. The excitation signal is identical in both scenarios, with $f_{exc} = [6.25, 18.75]$ Hz.

Both discharges have a baseload of ECRH power P_{ECRH} starting at $t = 0.8$ s, that differs between the configurations. 520 kW of ECRH power is injected in the SN discharge 85388. According to ray-tracing calculations with TORAY-GA [51], the absorbed fraction of ECRH power temporarily drops at $t = 1.38$ s, and $t = 1.6$ s, as shown in Figure 7(c). A total of 2570 kW ECRH power is injected in the XPT discharge. Due to the auxiliary ECRH power, the temperature in the plasma increases, which results in a lower plasma resistivity. Consequently, the coupled ohmic power in the plasma is reduced for the XPT compared to SN, as shown in Figure 7(b). On the contrary, the penetration of N_2 in the core plasma throughout the perturbative phase increases the coupled Ohmic power, as $P_{Ohm} \sim Z_{eff}$. Altogether, the total amount of power coupled into the plasma is larger for the XPT (2687 kW on average) compared to the SN (888 kW on average) during the perturbative phase.

Despite nearly three times higher coupled power and comparable seeding levels in the XPT compared to the SN, the CIII front in the XPT discharge remains detached and nearly stationary at the secondary X-point throughout the entire perturbative phase. In contrast, the CIII front in the SN is attached in the first part of the perturbative phase, after which it moves back and forth from the target to the first X-point, as shown in Figure 7(d). The response of the front in the SN discharge may be significantly

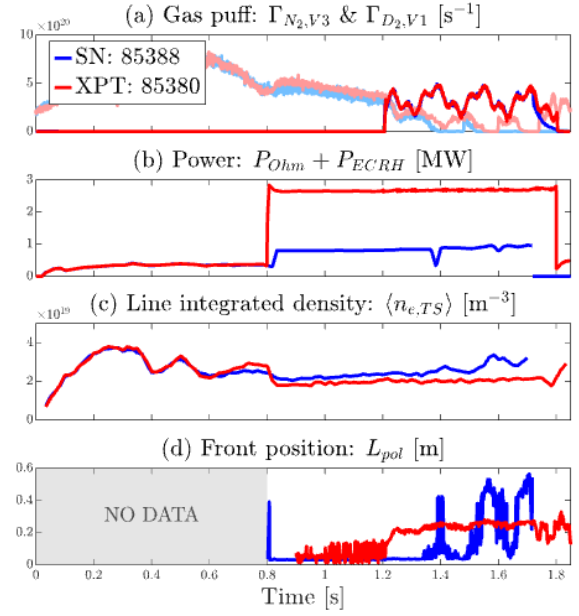


Figure 7. Comparison of N_2 seeding perturbations in SN discharge 85388 and XPT 85380 in respectively blue and red. Time traces of (a) identical N_2 gas puff modulations from Valve 3 with $f_{exc} = [6.25, 18.75]$ Hz and background D_2 gas puff from Valve 1 (light coloured), (b) Ohmic + absorbed ECRH (via TORAY-GA [51]) power provided to the plasma, (c) Line-integrated core density with FIR chord 2, (d) evolution of the CIII front position.

affected by the temporary ECRH power cut-off, which could exaggerate the front movement throughout the discharge. Due to these cut-offs, a comparison between the FRD of both discharges is considered to be unreliable.

Nevertheless, the disturbance rejection capacity of the XPT observed in the perturbative fueling experiments is also observed in a high power scenario for seeding perturbations.

4.2. ECRH power perturbations

ECRH power modulations were introduced in similar scenarios as the previous section. Figure 8 shows a comparison of XPT 85375 and SN 89544 experiments, displaying the total absorbed ECRH power P_{ECRH} as actuator input (a) along with the coupled Ohmic power, D_2 fueling (light coloured) and N_2 seeding gas puffs via respectively Valve 1 and Valve 8 (b), the line integrated core density as measured by Thomson Scattering in (c), and the resulting CIII front motion L_{pol} in (d), for SN discharge 89544 (blue) and XPT 85375 (red). Here too, core density control was enabled to facilitate the absorption of ECRH. Power modulations via ECRH are introduced at $t = 1.2$ s via SN and XPT scenarios, with $f_{exc,SN} = [7.69, 38.46]$ Hz, and $f_{exc,XPT} = [25.7, 44.6]$ Hz. The amplitude of

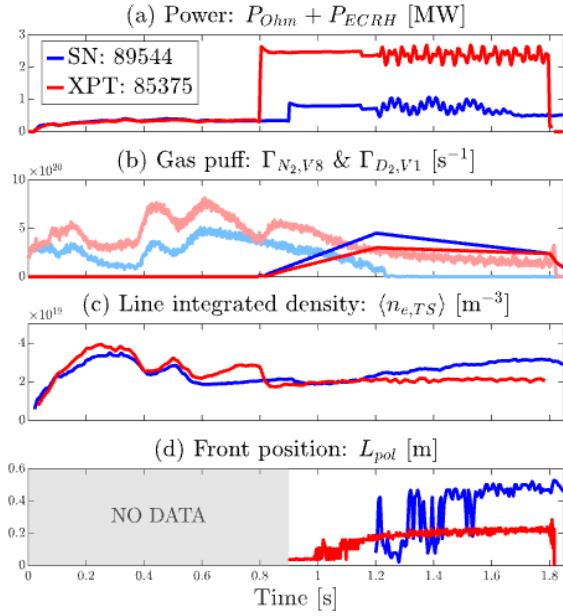


Figure 8. Comparison of ECRH power perturbations in SN discharge 85377 and XPT 85375 in respectively blue and red. Time traces of (a) absorbed ECRH power modulations (according to TORAY-GA [51] from G1/L1, with $f_{exc} = [25.65, 46.17]$ Hz, and additional baseload power in the XPT discharge, (b) Ohmic power coupled into the plasma, (c) identical N_2 seeding and variable D_2 fuelling (light coloured) (d) evolution of the CIII front position.

the power oscillations is 300 kW, along with 1850 kW ECRH baseload ECRH power for the XPT case. To detach the divertor plasma, N_2 seeding gas is injected for both XPT and SN scenarios, where the seeding levels in the SN scenario had to be increased to detach the CIII front from the target. The resulting CIII front evolution is shown in Figure 8(d). The CIII front is detached at the start of the perturbative phase in the XPT discharge, in contrast to the SN in which the front is initially attached. The SN configuration exhibits a pronounced response of the front to the applied power modulations, whereas the CIII front along $dR_{us} = 5$ mm in the XPT discharge remains remarkably stable throughout the perturbative phase. Due to the limited response in the XPT discharge, the FRD analysis could not be performed as the response of the CIII front at the excited frequencies in the XPT discharge does not exceed the noise floor. Again, this demonstrates the reduced sensitivity of the CIII front near the secondary X-point, which extends the disturbance-rejection capacity of the XPT to power fluctuations.

5. Discussion

In this discussion section, we address the observed front dynamics in the presented discharges and try to understand the disturbance rejection of the XPT at its secondary X-point. The implications of these observations for the application and control of an X-Point Target divertor in a reactor class device are subsequently explored.

5.1. Position dependent front dynamics XPT

In the perturbative fueling experiments D_2 , we characterized the dynamics of the CIII front in the XPT at several operational points, demonstrating the disturbance rejection capacity of the secondary X-point. Due to the limited response of the CIII front at the secondary X-point, quantification of this disturbance rejection by means of comparing the gain in CIII front to fueling perturbations was challenging due to the poor SNR, yet it provides an estimate of a factor 3 reduction in CIII front sensitivity at the secondary null, as shown in Appendix C. Since we show that the dynamic response of the core plasma and divertor neutral pressure are nearly identical between the SN and XPT divertor, we fully attribute the reduced sensitivity of the CIII front to the magnetic geometry of the XPT divertor, which correlates strongly with a local increase in total connection length and poloidal flux expansion.

Interestingly, similar reductions in sensitivity are found when comparing the two magnetic geometries with the Detachment Location Sensitivity (DLS) model [37, 38]. The DLS model is a reduced model that provides a prediction for the detachment onset, window and sensitivity. Most importantly however, it is a *static* model, not taking anything *dynamical* effects into account. Taking the DLS model as described in Appendix D, we can compare the SN and XPT geometry by evaluating the detachment front location L_{pol} as a function of the detachment driver defined in the model as $n_{e,u} f_z^{1/2} q_{||}^{5/7}$, as shown in Figure 9. Although the DLS model considers a static situation, the slope of the DLS curve may inform on the local front sensitivity of that region. As seen from the figure, the slope of the XPT and SN geometry are similar for the region upstream of the secondary X point, suggesting similar sensitivity to changes in the detachment driver. Furthermore, it demonstrates a reduced sensitivity of the front at the secondary X-point. Both are consistent with the findings in Section 3. Altogether we find that the reduction of front sensitivity at the secondary X-point extrapolates from a *static* (DLS and the work in [24]) to a *dynamic* regime (this work).

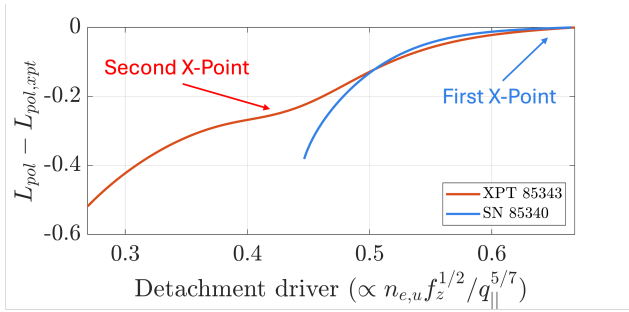


Figure 9. Operational space of the XPT and SN as predicted by the DLS model. The poloidal front position is indicated as the difference between the primary X-point $L_{pol,xpt}$ and front position L_{pol} , such that the minimum and maximum of the curve correspond to respectively target and primary X-point for both XPT and SN curves. All poloidal locations of the X-points are indicated. The slope of the DLS predicted curves informs on the front sensitivity. As such, the slope of the SN is similar to the slope of the XPT above the secondary X-point, indicating similar sensitivity in that region, consistent with experimental observations. Similarly, the reduced slope at the secondary X-point of the XPT also agrees with experimental observations.

5.2. Dynamic analysis high power scenarios

Scenarios with heating and seeding perturbations in both SN and XPT were presented in Sections 4.1 and 4.2. In both scenarios, the CIII front in the XPT is shown to be highly resilient to heating and seeding perturbations compared to a SN divertor. However, the interpretation of these results warrants further discussion.

First of all, two regions of CIII emission were observed in the outer divertor leg, with a contribution along the separatrix close to the secondary X-point and contribution along the far-SOL.

Thomson scattering [52] measurements in Figure 10(b) reveal that the gap between the emission regions is likely the result of a density shift to the far SOL. First, the electron temperature near the separatrix approaches relatively high electron temperatures of $T_e \approx 30$ eV. At these temperatures the ionization balance of the carbon impurity shifts towards higher charge states, thereby depleting the population of emitters responsible for the CIII line. Consequently, the CIII emission in this region of elevated temperatures is reduced.

Secondly, the electron density in Figure 10(b) peaks at the $z = -0.47$ m chord location, which is in the far-SOL as shown in Figure 10(a). Due to a lower electron density close to the separatrix, the excitation and subsequent emission of carbon impurities is reduced in this region compared to the far-SOL.

The origin of this cross-field transport can be found in strong $\vec{E} \times \vec{B}$ drifts close to the secondary X-point, as discussed in detail in [36] and [35]. Please

note that this behavior could change significantly in a forward toroidal field scenario, opposed to the reversed field scenarios that were employed in this study, also shown in [36] and [35]. An assessment of forward field XPT scenarios with perturbative experiments would therefore be an important next step in quantifying detachment dynamics in the XPT configuration. This is especially relevant for reactor designs that plan to operate with a double-null XPT configuration, such as ARC [5], where the drift effects will be opposite for the upper and lower divertor.

All summed up, the CIII front tracking in the far-SOL does capture the dynamics of the bulk plasma throughout the evolution of the detached state, although a fraction of hot electrons and ions at the separatrix seems to channel SP4. Hence, standalone emission fronts (such as CIII in this work) are unlikely a suitable proxy for detecting the primary heat flux channel and assessing the detached state in these high power scenarios.

Furthermore, a quantitative comparison of the front dynamics in the SN compared to the XPT using an FRD, could not be carried out in both seeding and power modulation scenarios, due to multiple factors. First of all, both scenarios required core density control to facilitate the absorption of ECRH. Valve 1 in the divertor region was used to inject D_2 gas to maintain a constant core density throughout the discharge, as shown in Figures 7 and 8. As a result, the controller reacts on the multi-sine input signals that were introduced via either N_2 gas or ECRH. As the fuelling also affects the evolution of the CIII front, the output spectrum contains a component that is introduced by fuelling rather than the intended response upon a single actuator, which also differs between the SN and XPT discharges. Consequently, a comparison of FRD would be carried out on non-equivalent experimental conditions.

Secondly, in the SN scenario with N_2 seeding perturbations, ECRH cut-offs may exaggerate the front motion throughout the discharge, resulting in an unequal basis for comparison with the XPT, as shown in Section 4.1.

Lastly, during power modulations, a clear response is measured for the SN scenario, whereas no front response is observed for the XPT, thereby also precluding a quantitative (FRD) analysis of the dynamics as the response at excited frequencies does not exceed the noise floor. Again, this lack of measurable response in the XPT configuration indicates strong disturbance rejection in the region of the secondary X-point, although the high temperatures of the underdense separatrix could still result in damage to the targets. The following section discusses

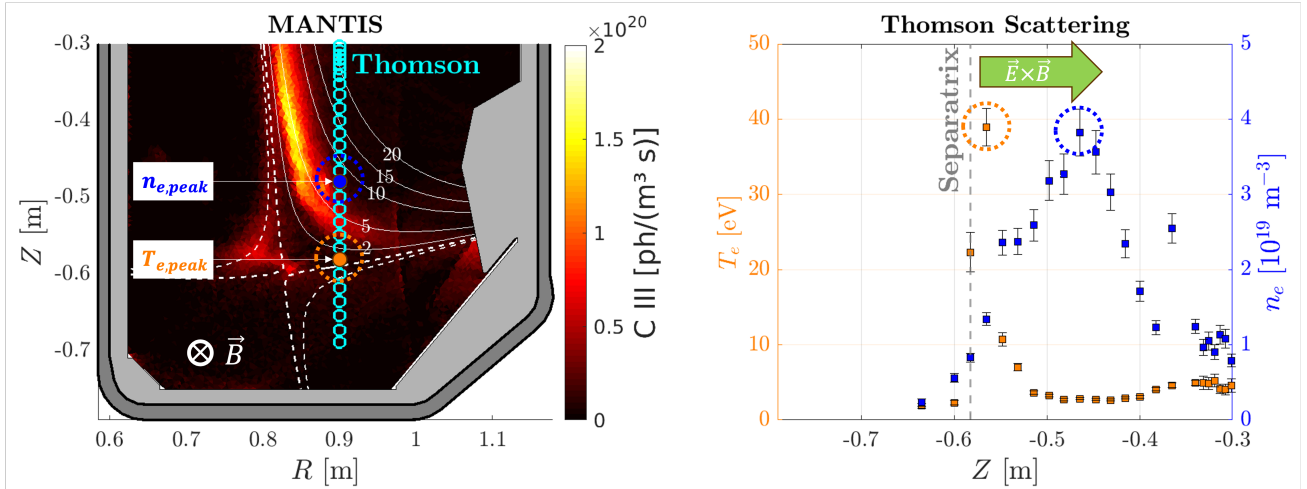


Figure 10. TCV discharge 85375 with an XPT divertor during ECRH modulations in a high power L-mode scenario at $t = 1.4$ s. (a) Two regions of CIII emission are observed in the tomographic inverted image [40] obtained via MANTIS [32] with LIUQE [41] reconstructed separatrix (dashed) in white, along with magnetic field lines (line) starting at $dR_{us} = [2, 5, 10, 15, 20]$ mm. Thomson scattering [52] measurement chords are shown in cyan. (b) Thomson Scattering measurements of the electron temperature T_e and density n_e . The electron temperature peaks close to the separatrix whereas the density peaks in the far-SOL, indicative of cross-field plasma transport into the far-SOL.

the implications of these observations for future reactors.

5.3. Implications for future reactors

This work demonstrates the resilience of the detached state in the XPT to perturbations in D_2 fuelling, N_2 seeding, and ECRH power. The secondary X-point could function as a virtual target, providing a passive buffer that mitigates the effect of upstream disturbances on the divertor plasma. This intrinsic buffer mechanism could be highly beneficial for future reactors, where the response of actuators (gas valves) in the divertor to fast disturbances is limited. Although these are promising results, the exact limits on the disturbance magnitude the XPT could buffer is not specified in this work, and is part of future research.

At the same time, the limited response of the CIII emission front as well as strong $\vec{E} \times \vec{B}$ drifts close to the secondary null presents a challenge for future exhaust control systems, as observables based on emission fronts may not be a good enough proxy to assess the detached state. Hence, an alternative observer would have to be developed compared to demonstrated radiative front control [13, 53]. The requirement of developing a new sensor setup does align with the necessary evolution of power exhaust control systems. These future systems will look inherently different due to restrictions on sensors that can withstand the conditions of a reactor. As such, they employ a different sensor setup (no 2D emission profile that a camera system such as MANTIS provides) to monitor the detached state, mostly relying on a sparse sensor

setup providing 1D line-integrated measurements, such as spectroscopic systems [27, 54] or bolometers. Given the limited response of observables close to the secondary X-point, as well as the 2D emission structure of this region that must be diagnosed with 1D measurements, it will be challenging to design observers that can monitor the detached state in an XPT divertor robustly.

As an additional layer of complexity, it will likely be challenging to maintain the precise XPT shape (specifically $dR_{u,x2}$) in a future reactor. Consequently, fluctuations in the magnetic equilibrium may affect the power sharing between SP2 and SP4 in the outer divertor leg [35]. This sensitivity could be further increased by the fact that the heat flux e-folding width λ_q for future reactors is predicted to be significantly smaller compared to the presented experiments [55], thereby providing uncertainty in the strikepoint that receives the majority of upstream heat and particle fluxes. This too must be taken into account in designing observers for exhaust controllers.

6. Conclusions

In this work we present a dynamic analysis and comparison of experiments with a XPT and SN divertor subjected to perturbations with D_2 fuelling, N_2 seeding and ECRH power. The XPT configuration demonstrates an inherent disturbance rejection capacity near its secondary X-point, observed in both Ohmic and auxiliary ECRH-powered experiments. This not only confirms that the observed benefits of reduced detachment sensitivity in quasi steady-state operations per-

sist on control relevant timescales, but also extends towards high power scenarios. The reduced sensitivity is highly advantageous, as it could provide a passive buffer to mitigate fast disturbances that would be too rapid for gas actuators to control. As such, the reduced sensitivity at the secondary X-point could be highly beneficial for maintaining the detached state. In the region above the secondary X-point, the dynamic response of the XPT is similar to a SN divertor, as verified by the dynamic response of multiple diagnostics. The varying detachment sensitivity is qualitatively captured by the DLS model, which demonstrates that the observed change in dynamic gain of the CIII front, is correlated with the steady state gain predicted by this static model at different front positions.

7. Acknowledgements

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

Appendix A. Signal design

The multi-sine actuation signals utilised for system identification were designed to be compatible with the different plasma scenarios described in Section 2.1 as well as the operational constraints of TCV. The main design objective is to obtain reliable FRD while remaining within actuator limits and preserving an operating point (CIII front location) in the detached state. The multi-sine signals of the input signals $u(t)$ were designed using Crest factor ($C = |u_{max}|/u_{rms}$) minimization [56]. By reducing this peak-to-RMS ratio, we generate a signal with maximized average power for a fixed peak amplitude, thereby improving the SNR. Each excited frequency should complete at least three full periods within the available perturbation time to enable the estimation of a standard deviation σ on the response via the LPM [39]. The typical perturbation time in the presented TCV experiments is $T_{pert} = 0.8$ s, which defines a lower frequency limit of $f_{exc} = 3/T_{pert} = 3.75$ Hz. In the perturbative scenarios that include D2 and N2 gas puff modulations, a high frequency limit is set by the available gas valve that cannot follow gas flow request above 50 Hz [57].

The total amount of injected gas in the fuelling and seeding experiments further constraints the excitation amplitude. Excess fuelling and impurity seeding cool the divertor throughout the perturbative phase, which shifts the CIII front upstream from its original position. This drift alters the operational point of the detached state and leads to non-local measurements. Contrary, input signals with smaller amplitudes result in a worse SNR, compromising the FRD quality. Within these bounds the selected frequencies match those used in previous system identification studies [13, 50, 53, 57] at TCV on SN configurations. This consistency facilitates comparison across plasma regimes, machine configurations, and actuators. The experiments using ECRH actuation similarly utilizes excitation frequencies that match previous studies [22]. In this scenario, the hardware permits excitation frequencies exceeding 50 Hz.

Appendix B. Shot overview

Appendix B.1. D₂ fuelling perturbations

Table B1. Overview of discharges with D₂ gas fuelling perturbations. Excitation frequencies f_{exc} , amplitude A of the designed signal, start time of the perturbations t_{start} , and amount of completed periods P are given.

Shot	Configuration	f_{exc} [Hz]	A [10^{20} part./s]	t_{start} [s]	P
85295	XPT, Case A	$6.25 \cdot [1, 3, 5]$	2	1	5
85301	XPT, Case A	$6.25 \cdot [1, 3, 5]$	2	1	4
85340	SN, Case A	$6.25 \cdot [1, 3, 5]$	2	1	4
85343	XPT, Case A	$6.25 \cdot [1, 3]$	4	1	4
85344	SN, Case A	$6.25 \cdot [1, 3, 5]$	2	1	3
85347	SN, Case A	$4.35 \cdot [1, 3]$	4	1	5
85350	XPT, Case A	$6.25 \cdot [1, 3]$	4	1	4
85353	XPT, Case A	$4.35 \cdot [1, 3]$	4	1	4

Appendix B.2. N₂ seeding perturbations

Table B2. Overview of discharges with N₂ gas seeding perturbations. Excitation frequencies f_{exc} , amplitude A of the designed signal, start time of the perturbations t_{start} , and amount of completed periods P are given.

Shot	Configuration	f_{exc} [Hz]	A [10^{20} part./s]	t_{start} [s]	P
85380	XPT, Case B	$6.25 \cdot [1, 3]$	2.75	1.2	3
85388	SN, Case B	$6.25 \cdot [1, 3]$	2.75	1.2	3

Appendix B.3. ECRH power perturbations

Table B3. Overview of discharges with ECRH power modulations. Excitation frequencies f_{exc} , amplitude A of the designed signal, start time of the perturbations t_{start} , and amount of completed periods P are given.

Shot	Configuration	f_{exc} [Hz]	A [kW]	t_{start} [s]	P
85375	XPT, Case B	[25.7, 44.6]	300	1.2	3
85377	SN, Case B	[25.7, 44.6]	300	1.2	3
89544	SN, Case B	[7.69, 38.46]	300	1.2	3

Table B4. SNR values of the FRD determined via system identification in discharges with fuelling perturbations. A $SNR > 5$ is considered to be a good measurement and is coloured green. Points with $3 < SNR < 5$ are coloured orange are less accurate but could still be used. Points with $SNR < 3$ are considered to be an unreliable measurement. For entries with an 'x' the diagnostic was not available during that discharge.

SNR overview								
Shotnumbers	#85295	#85301	#85340	#85343	#85344	#85347	#85350	#85353
Configuration	XPT	XPT	SN	XPT	SN	SN	XPT	XPT
f_0	6.25	6.25	6.25	6.25	6.25	4.35	6.25	4.35
f_{exc}	[1,3,5]	[1,3,5]	[1,3,5]	[1,3]	[1,3,5]	[1,3]	[1,3]	[1,3]
MANTIS: L_{pol}								
[1]	2.8	5.7	4.8	5.8	1.9	13.7	20.5	10.1
[3]	8.7	8.6	5.1	30.8	6.0	5.1	7.1	24.0
[5]	1.1	1.5	3.1		7.2			
PD: $D_{\alpha, top}$								
[1]	13.4	20.7	12.2	29.4	8.0	12.3	12.5	22.8
[3]	20.8	15.2	22.0	23.9	45.9	28.3	16.1	19.1
[5]	8.3	28.5	9.2		15.0			
PD: $D_{\alpha, div}$								
[1]	50.1	192.9	18.8	40.6	13.4	28.6	61.0	171.1
[3]	62.2	28.6	35.9	162.8	41.4	66.4	50.8	41.4
[5]	52.3	51.2	22.3		127.6			
APG: $p_{0, div}$								
[1]	x	x	2.4	21.5	3.4	3.7	7.7	5.9
[3]	x	x	3.8	10.6	4.5	11.5	7.9	12.9
[5]	x	x	5.9		2.0			
APG: $p_{0, bot}$								
[1]	x	x	6.0	7.8	6.1	3.0	6.0	6.7
[3]	x	x	4.7	7.2	3.6	5.2	5.0	5.5
[5]	x	x	1.0		1.9			
FIR: n_{core}								
[1]	6.3	26.1	9.4	25.1	2.4	5.7	358.9	2.6
[3]	8.2	9.8	6.9	19.3	3.7	21.8	9.2	17.9
[5]	4.2	1.9	1.2		1.1			

Appendix C. Extended FRD analysis

Appendix C.1. XPT FRD analysis per region

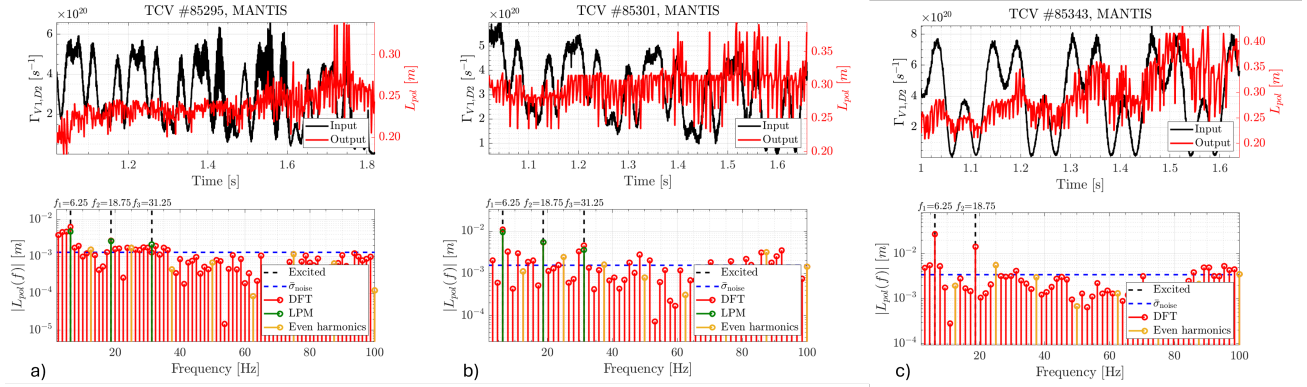


Figure C1. Response in time (top) and frequency (bottom) domain of the CIII front to D₂ fuelling perturbations in discharges XPT 85295, 85301 and 85343. The excited frequencies (black, dashed), average noise floor (blue, dashed), DFT (red), LPM correction of the DFT (green) and even multiples of the excited ground frequency $f_0 = 6.25$ Hz (orange) are shown. No dominant even non-linearities are detected in this frequency range for all discharges, indicating a dominantly linear response. A minimal response to the excited frequencies is observed in (a), whereas the excited frequencies in (b) and (c) do show a response.

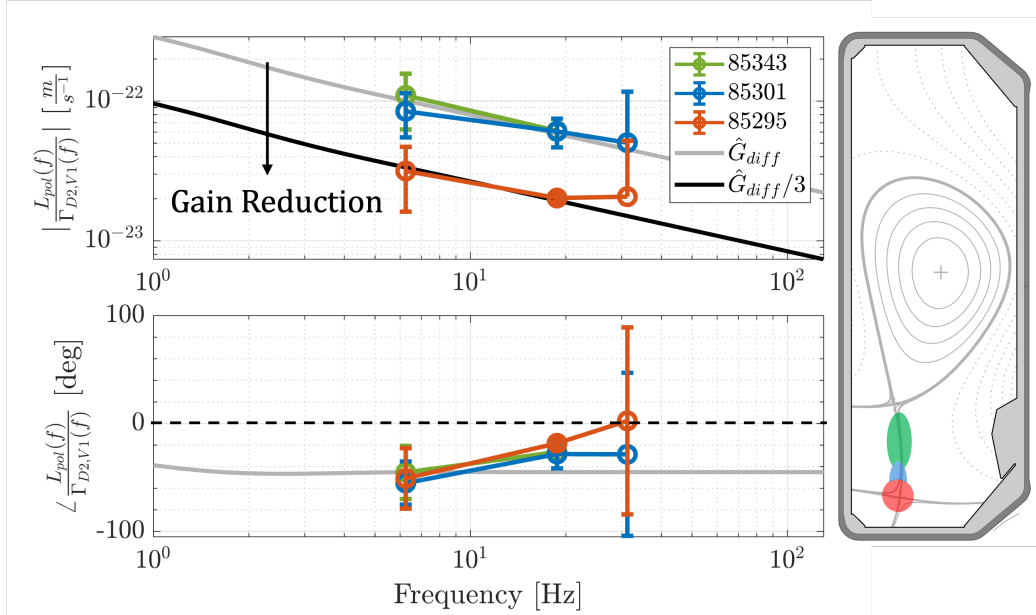


Figure C2. FRD for XPT discharges 85295, 85301 and 85343, with D₂ gas puff input and CIII front L_{pol} output. As the CIII front approaches the secondary X point in 85295, a significant reduction in gain is observed compared to the upstream region in 85301 and 85343. Fitting the diffusion based model G_{diff} defined by Koenders et al. [25], a gain reduction of 3 is measured at the secondary X-point. Since the model G_{diff} is based on SN discharges, it is indirectly a way to compare the SN and XPT geometries, showing that the region upstream of the secondary null (e.g. 85301, 85343) show identical behaviour compared to the SN geometry. The SNR of the datapoints in discharge 85295 is poor as shown in Table B4. Please note that a phase response larger than 0 is considered non-physical as that would implicate a response in L_{pol} before D₂ gas is injected.

Appendix C.2. Extended FRD analysis XPT and SN comparison

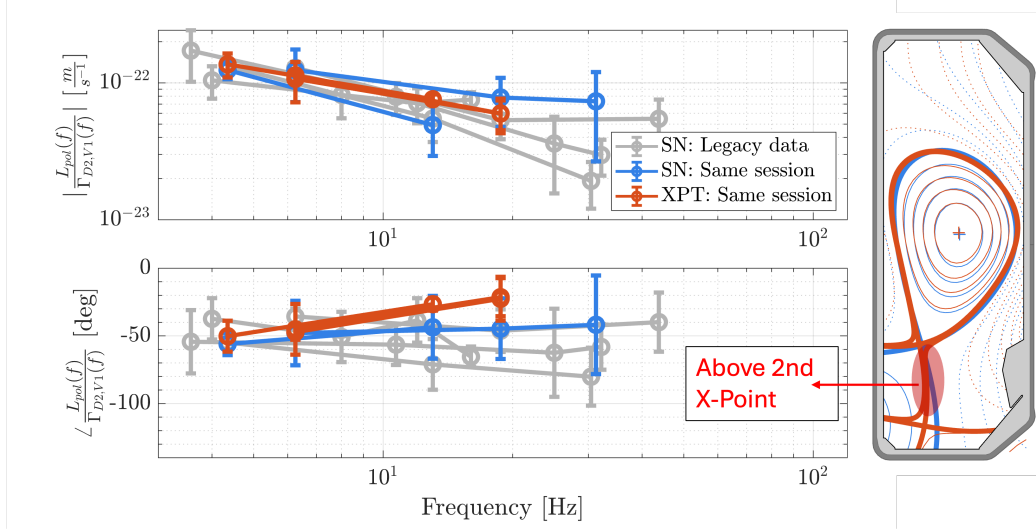


Figure C3. FRD data for experiments with a D₂ gas puff input and front L_{pol} output. The figure includes measurements from discharges 63163, 63135, 78131, 78142 (SN: Legacy data, in gray), 85340, 85344, 85347 (SN: Same session, in blue), and 85343, 85350, 85353 (XPT: Same session, in red). The dynamic response of the SN and XPT (above secondary X-Point) are comparable.

Appendix C.3. Multi-output analysis

TCV #85340, SN

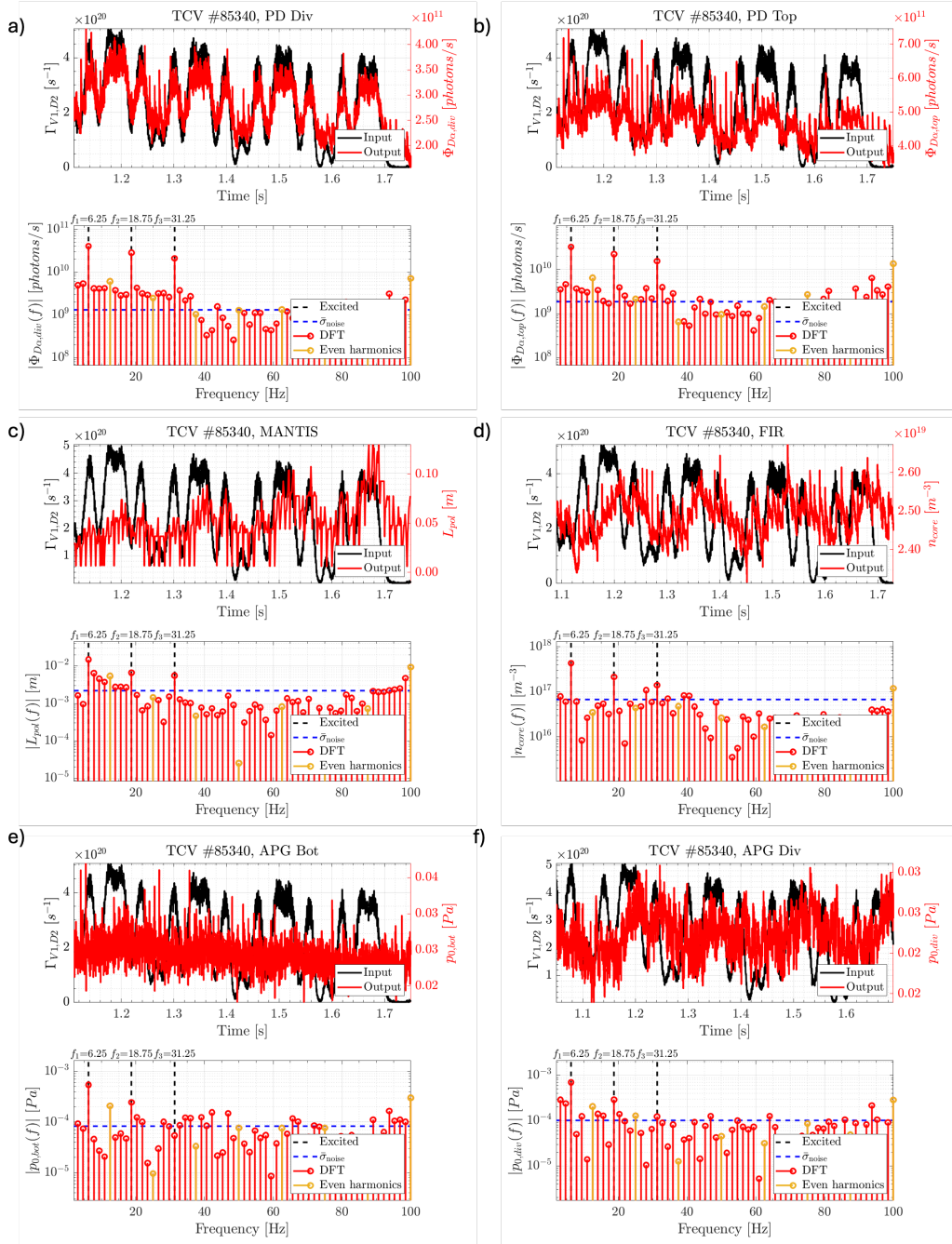


Figure C4. Response in time and frequency domain of various diagnostics to D_2 gas perturbations via Valve 1 in TCV discharge 85340, with a SN divertor. a) and b) show the response of the D_α by photodiodes with respectively divertor, and top-bottom viewlines. c) Shows the response of the CHII front L_{pol} measured by MANTIS, d) the response of the core density n_{core} measured by FIR, e) and f) the neutral pressures $p_{0,bot}$ and $p_{0,div}$ of APG at 2 locations.

TCV #85343, XPT

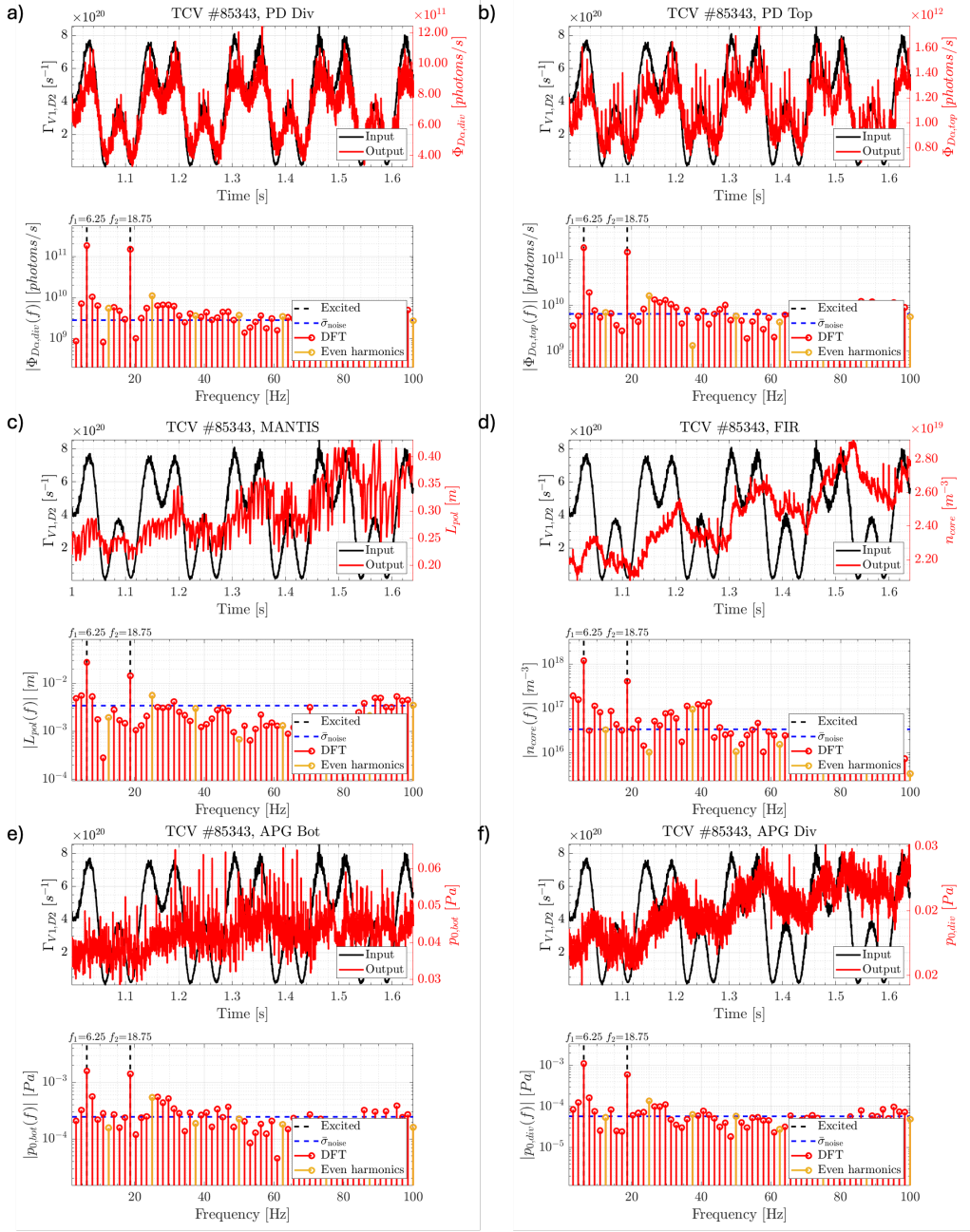


Figure C5. Response in time and frequency domain of various diagnostics to D_2 gas perturbations via Valve 1 in TCV discharge 85343, with a XPT divertor. a) and b) show the response of the D_{α} by photodiodes with respectively divertor, and top-bottom viewlines. c) Shows the response of the CIII front L_{pol} measured by MANTIS, d) the response of the core density n_{core} measured by FIR, e) and f) the neutral pressures $p_{0,bot}$ and $p_{0,div}$ of APG at 2 locations.

TCV #85344, SN

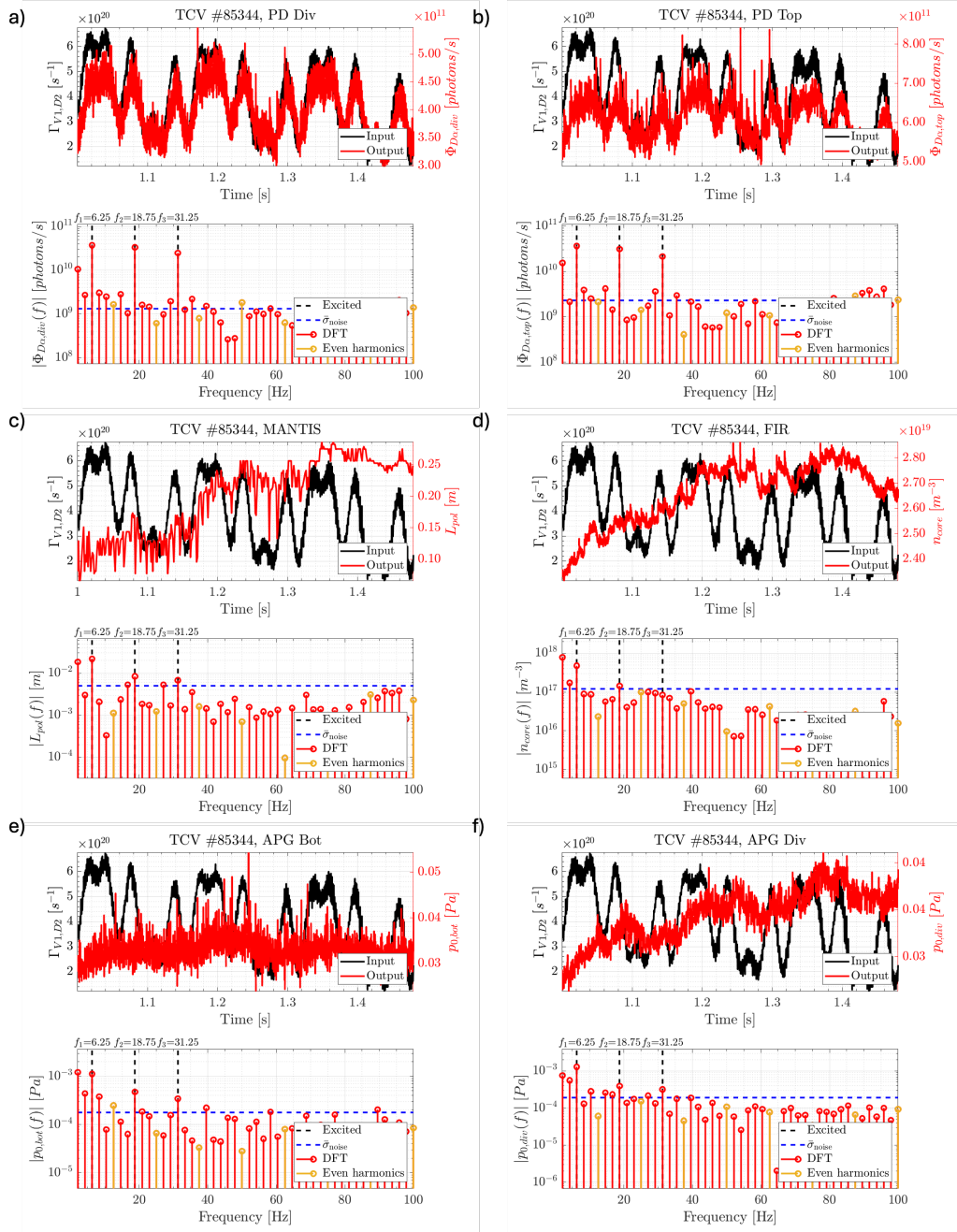


Figure C6. Response in time and frequency domain of various diagnostics to D_2 gas perturbations via Valve 1 in TCV discharge 85344, with a SN divertor. a) and b) show the response of the D_{α} by photodiodes with respectively divertor, and top-bottom viewlines. c) Shows the response of the CIII front L_{pol} measured by MANTIS, d) the response of the core density n_{core} measured by FIR, e) and f) the neutral pressures $p_{0,bot}$ and $p_{0,div}$ of APG at 2 locations.

TCV #85347, SN

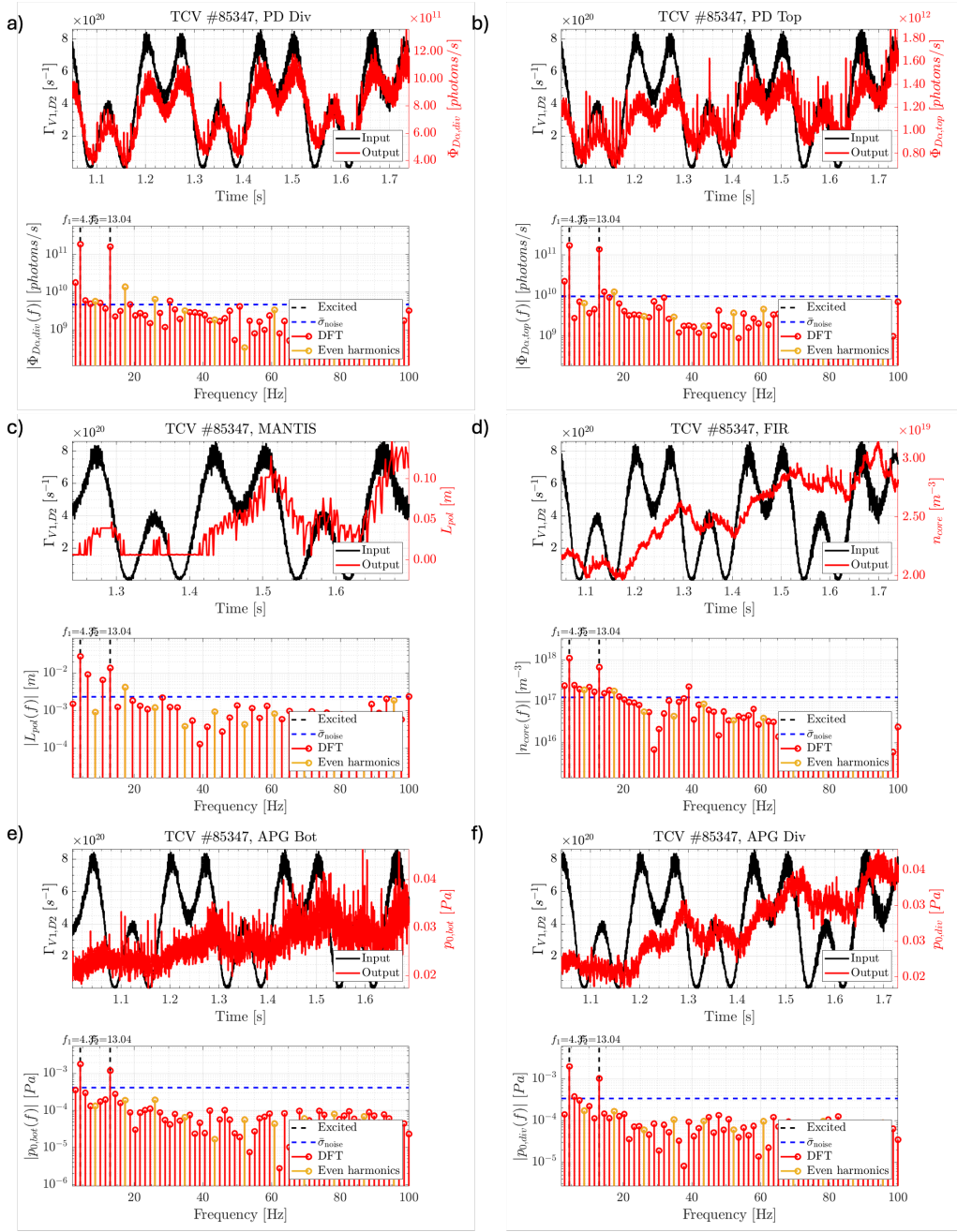


Figure C7. Response in time and frequency domain of various diagnostics to D₂ gas perturbations via Valve 1 in TCV discharge 85343, with a SN divertor. a) and b) show the response of the D_α by photodiodes with respectively divertor, and top-bottom viewlines. c) Shows the response of the CIII front L_{pol} measured by MANTIS, d) the response of the core density n_{core} measured by FIR, e) and f) the neutral pressures $p_{0,bot}$ and $p_{0,div}$ of APG at 2 locations.

TCV #85350, XPT

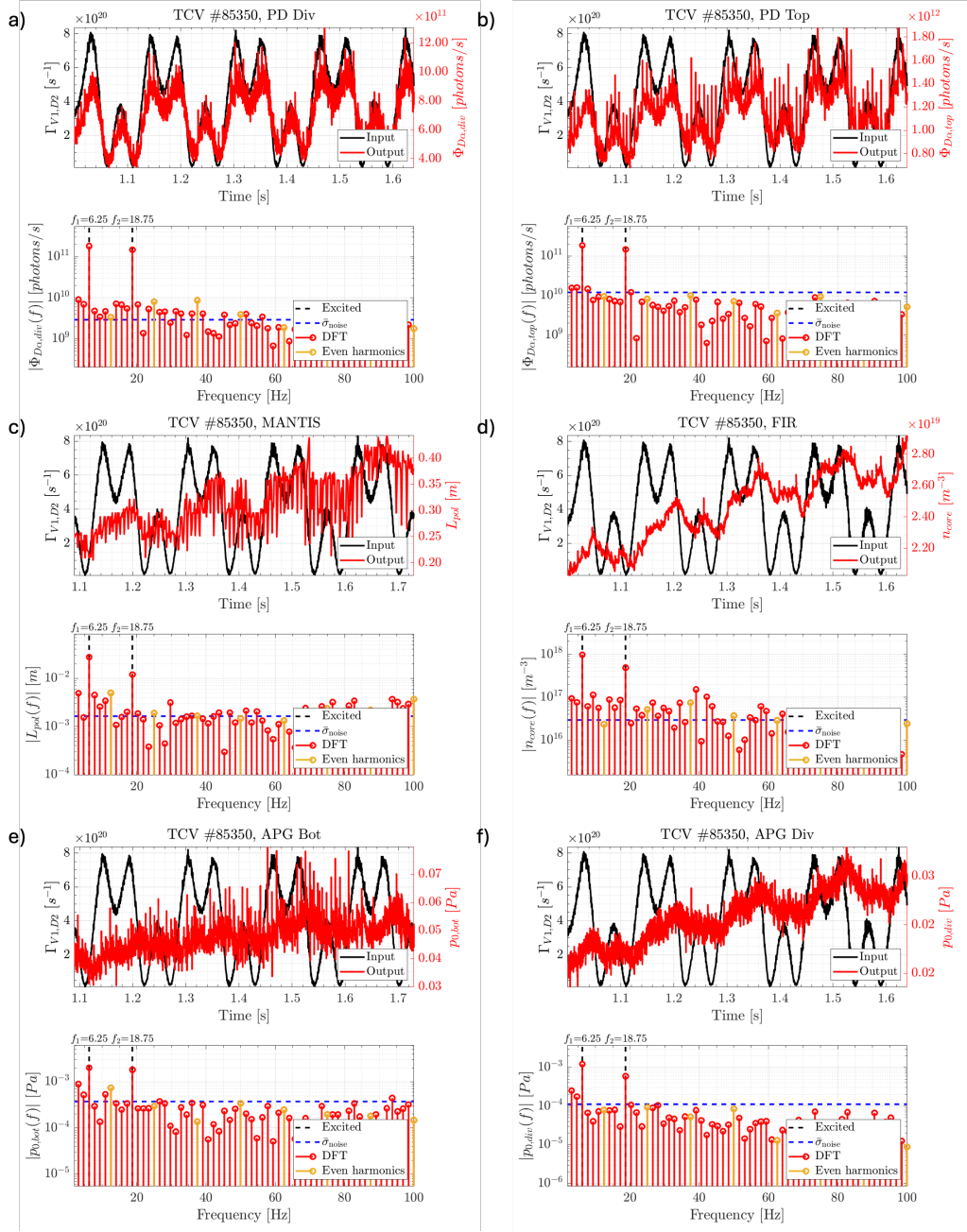


Figure C8. Response in time and frequency domain of various diagnostics to D_2 gas perturbations via Valve 1 in TCV discharge 85350, with a XPT divertor. a) and b) show the response of the D_{α} by photodiodes with respectively divertor, and top-bottom viewlines. c) Shows the response of the CHII front L_{pol} measured by MANTIS, d) the response of the core density n_{core} measured by FIR, e) and f) the neutral pressures $p_{0,bot}$ and $p_{0,div}$ of APG at 2 locations.

TCV #85353, XPT

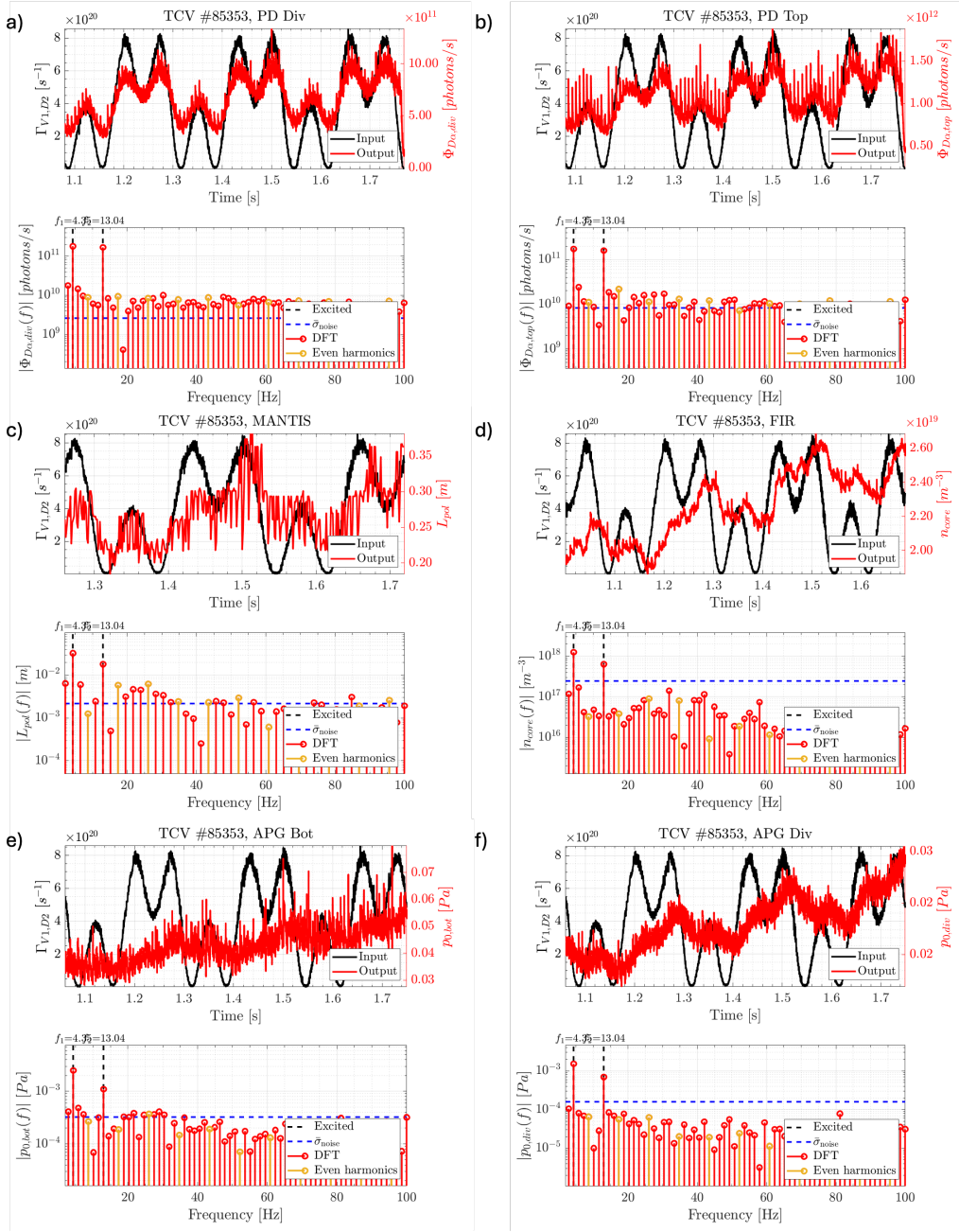


Figure C9. Response in time and frequency domain of various diagnostics to D₂ gas perturbations via Valve 1 in TCV discharge 85353, with a XPT divertor. a) and b) show the response of the D_α by photodiodes with respectively divertor, and top-bottom viewlines. c) Shows the response of the CIII front L_{pol} measured by MANTIS, d) the response of the core density n_{core} measured by FIR, e) and f) the neutral pressures $p_{0,bot}$ and $p_{0,div}$ of APG at 2 locations.

Appendix D. DLS

The Detachment Location Sensitivity (DLS) model [37, 38], defines an infinitely thin impurity radiation front along a flux tube in the SOL that spans the outboard midplane to the outer divertor target. Along the fluxtube, a parallel coordinate z is defined as

$$dz = \frac{B_{\times}}{B(L)} dL = \frac{B_x}{B_{pol}(L)} dL_{pol}, \quad (D.1)$$

Here $B_{\times}$ is the magnetic field at the primary X-point, B_{pol} the poloidal component of the magnetic field along the fluxtube, L the non-scaled parallel coordinate along the flux tube, and L_{pol} the poloidal projection of the parallel coordinate.

Within the fluxtube that represents the entire divertor leg, the impurity front is assumed to be responsible for all power dissipation via impurity radiation with a single impurity specie. Hence, momentum, particle and power losses via ionization and plasma-neutral interactions are ignored. According to the DLS model, the location of the front is determined by three factors.

- (i) A set of three plasma parameters. The plasma parameters are lumped together in a driver parameter $D = \frac{n_u f_z^{1/2}}{q_{\parallel,u}^{5/7}}$, with n_u the upstream electron density at the outboard midplane, f_z the impurity fraction, and $q_{\parallel,u}$ the upstream parallel heat flux.
- (ii) The magnetic geometry upstream of the front. A single magnetic field line from the outboard midplane to the front location along the divertor leg is chosen. This is a limitation for configurations with multiple strike points such as the XPT. There, heat and particle fluxes are guided to multiple strike points in different spatial regions (e.g. SP2 and SP4 in Figure 1), with varying magnetic geometries. Therefore, this work only considers the magnetic field line that carries the dominant heat flux contribution, e.g. a field line towards SP4.
- (iii) A 'cooling function' which is assumed to be constant and invariant of the chosen magnetic geometry. Therefore, the analysis in this Section only considers the first two points as a function of the front position L_{pol} .

This is combined in a single equation given by:

$$\frac{n_u \sqrt{f_z}}{q_{\parallel,u}^{5/7}} = \frac{1}{U} \frac{B(z_f)}{B_{\times}^{3/7}} \times \left[\int_{z_f}^{z_{\times}} B^2(z) dz + \int_{z_{\times}}^L \frac{B^2(z)(L-z)}{L-z_{\times}} dz \right]^{-2/7} \quad (D.2)$$

Here U is assumed to be a constant cooling function that originates from the Lengyel integral [58], given by

$$U = 7^{2/7} (2\kappa_0)^{3/14} \sqrt{\int T^{1/2} Q(T) dT}, \quad (D.3)$$

with a cooling curve of the radiating specie $Q(T)$, T the temperature, and κ_0 the heat conduction coefficient of the plasma.

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