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Feedback control systems for plasma operation at Wendelstein 7-X

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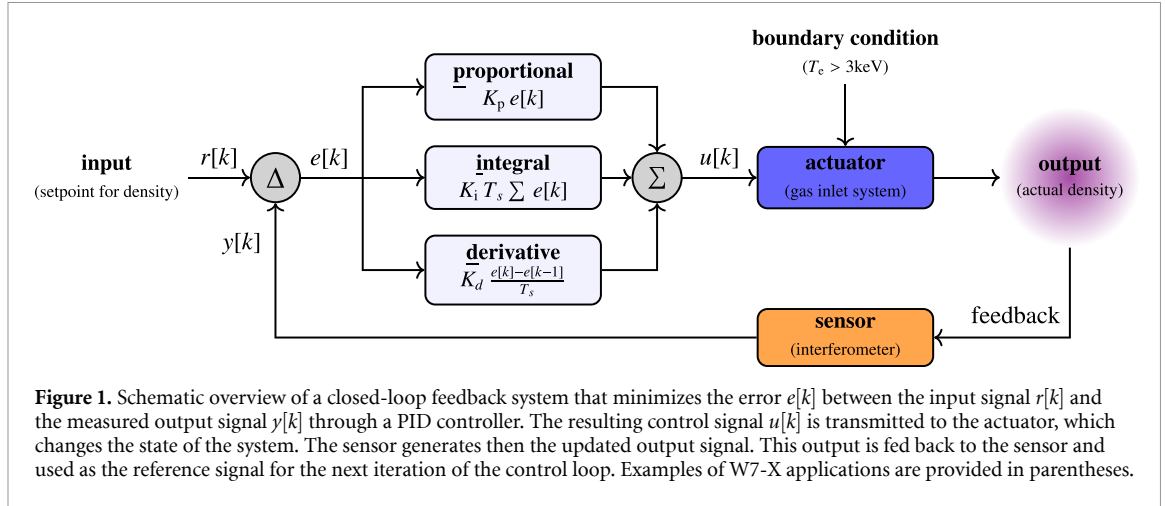
Abstract

Real-time feedback control is essential for meeting the physics and operational demands of Wendelstein 7-X (W7-X), particularly the need to respond effectively to transient events, maintain stationary high-performance phases and operate reliably across a wide range of magnetic configurations and plasma regimes. This work provides an overview of the feedback systems implemented and validated in recent campaigns, including the control of key plasma parameters such as density, radiation and heating power under varying conditions. These systems rely on the W7-X segment control architecture and its millisecond-scale real-time network, which enable precise and deterministic coordination of sensors and actuators. Representative experiments highlight robust performance, including long stationary discharges and integrated multi-parameter control. Additional boundary conditions such as core electron temperature limits ensure protection against radiative collapse and other failure modes. Looking forward, planned developments include advanced actuators, neural-network-assisted control strategies and long-term efforts toward full profile control of electron density and temperature. Overall, these developments establish real-time feedback control as an essential element of W7-X operation and a robust basis for advanced control concepts in future steady-state fusion devices.

1. Introduction

Feedback control systems have become an integral part of fusion devices, enabling the precise control and stable maintenance of key operating parameters (e.g. electron temperature and density, plasma position, toroidal current and radiation) in real-time [1]. These systems rely on sensors to continuously monitor relevant plasma parameters and on actuators to adjust the system behavior accordingly. By processing the measured input and applying targeted corrections, the system can achieve and maintain pre-defined values. In addition, it can respond to transient or unintended events, which constitutes in combination with the aforementioned features a prerequisite for e.g. steady-state operation. Although the control parameters are very similar across different fusion devices, the features and technical implementation of the feedback systems vary significantly between machines. In particular, feedback control systems in tokamaks are required to actively mitigate instabilities and prevent disruptions, which is generally not relevant for stellarator feedback control systems [2–7].

This work summarizes the development and implementation of feedback control systems at the Wendelstein 7-X (W7-X) stellarator and assesses their performance in representative plasma scenarios. Specifically, this work focuses on feedback control systems that regulate plasma parameters (e.g. electron density, radiation and heating power), as opposed to other feedback systems operated at W7-X such as magnet current control or control of plasma vessel pressure. Special focus is placed on their importance for reliable steady-state operation, integrated plasma control and future reactor-relevant operation schemes.



The first plasma feedback control system of W7-X was implemented during the second operational campaign OP1.2a in 2017. The number of feedback systems has steadily increased over the years, driven by the growing demand for sophisticated program scenarios. As a result, new systems have been progressively tested and fully integrated into the W7-X control system. The technical realization of this is described in section 2. An overview of their functionalities, along with application examples and performance evaluations, is provided in section 3, including aspects of integrated multi-parameter control and implications for steady-state operation. Planned feedback systems and preliminary considerations for their implementation are outlined in section 4. A complete list of all feedback systems of W7-X is given in the [appendix](#).

2. Implementation of feedback control systems

A closed feedback loop is necessary to achieve desired control of parameters in changing conditions. One of the most applied closed-loop control system is the Proportional-Integral-Derivative (PID) controller which is versatile, cost effective and easy to implement [8, 9]. Because of that, they are employed in industrial automation, various aspects of everyday life and also in more advanced research fields such as in fusion devices. The fundamental role of a PID controller is to dynamically minimize the error between the measured system output (e.g. actual electron density) and the desired setpoint (e.g. pre-defined electron density).

A schematic overview of a closed feedback loop with a digital (discrete) PID controller is given in figure 1. The output signal $y[k]$ is measured with the sensor (e.g. microwave interferometer) at each discrete time index k and fed back into the loop. The difference between this signal and the input signal $r[k]$ defines the error signal $e[k] = r[k] - y[k]$ which is minimized by the PID controller resulting in the control function

$$u[k] = K_p e[k] + K_i T_s \sum_{i=0}^k e[i] + K_d \frac{e[k] - e[k-1]}{T_s}, \quad (1)$$

where K_p , K_i , K_d and T_s are the tuning parameters of the proportional, integral (discrete summation), derivative (discrete differentiation) terms and the sampling time, respectively. This control function drives the actuator (e.g. gas inlet system) and thereby sets the output of the system. These steps are repeated at each sampling time $t = k T_s$ to continuously minimize the error signal, accounting for the current error (proportional term), its accumulation over discrete samples (summation term) and predicted error trends based on discrete differences (difference term). An additional boundary condition (e.g. a minimum electron temperature limit) can restrict the actuator if it is not fulfilled, see section 3.6.

Feedback control systems in fusion devices critically rely on low-latency, millisecond-scale data synchronization among all interconnected units. Achieving rapid and precise data exchange in a deterministic and reproducible manner represents a significant technical challenge for the practical implementation of any distributed real-time control system. At W7-X, these requirements are met by the segment control system [10, 11], which forms the underlying architecture for real-time plasma control. The segment

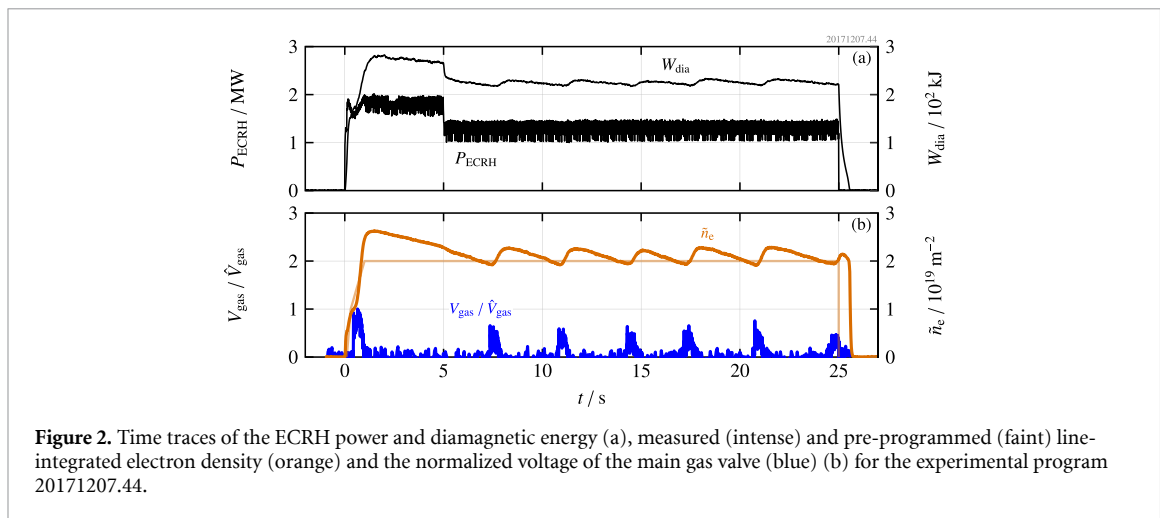


Figure 2. Time traces of the ECRH power and diamagnetic energy (a), measured (intense) and pre-programmed (faint) line-integrated electron density (orange) and the normalized voltage of the main gas valve (blue) (b) for the experimental program 20171207.44.

control system divides a plasma program into consecutive segments of arbitrary duration, allowing programs of variable length and complexity to be executed. The technical and diagnostic systems involved in a given segment, such as gas valves, heating systems or invasive diagnostics, are represented as software components that perform pre-defined tasks according to parameters specified for that segment. For actuator components, these parameters include a selectable control mode, allowing operation either in feed-forward mode, where a pre-programmed trajectory is applied directly, or in feedback mode, where the actuator is instead driven by a PID controller whose gains (K_p , K_i , K_d) and setpoint are likewise specified as components parameters. Communication between these actuators and the corresponding sensors is realized via a dedicated Ethernet-based real-time data bus utilizing advanced switching techniques [12], in which signals are distributed as User Datagram Protocol multicast packets, thereby enabling the required deterministic, millisecond-scale data synchronization. This architecture allows individual feedback loops to be activated, reconfigured or replaced from one segment to the next, providing the flexibility required to integrate new sensors, actuators and control strategies into evolving plasma scenarios.

3. Functionality of feedback control systems

The following sections offer a more detailed exploration of the feedback control systems outlined in table 1 (see [appendix](#)). All of these systems are based on the digital PID control scheme introduced in section 2, differing mainly in the choice of sensor, actuator and controller tuning. While the descriptions are not exhaustive, a comprehensive overview is provided being sufficient for understanding the core mechanisms. For detailed information, references to relevant publications are cited where available.

3.1. Control of electron density via gas injection

Feedback control of electron density is particularly important in order to meet the requirements for scenario development. This is especially crucial for realizing pre-defined electron density time traces, achieving steady-state conditions over several seconds or reacting to changing boundary conditions such as variations in electron cyclotron resonance heating (ECRH) and the associated pump-out effects. In the operational campaign OP1.2a in 2017, the first implementation and experimental validation of electron density feedback control were successfully carried out [6]. In this demonstration, the main gas injection system [13] is used as actuator, delivering gas injections into the plasma vessel that is subsequently ionized to adjust the electron density. The line-integrated density $\tilde{n}_e$ (simplified to electron density in the following text), measured with a dispersion interferometer, is used as a sensor signal for the feedback control system. This signal is distributed over the real-time network with a repetition rate of 1 kHz.

A representative example (experiment program number (XP) 20171207.44) is shown in figure 2. The electron density is pre-programmed to reach a target of $2 \times 10^{19} \text{ m}^{-2}$. To start with an initial density at the beginning of the program, gas (He) is injected via pre-puffs (not shown in figure 2). Additionally, gas is introduced into the plasma vessel through the feedback loop, which is clearly visible at the time $t = 0.1 \text{ s}$. The piezo valves used for injection through the diagnostic port are located approximately 3 m away from the plasma facing components, resulting in an effective reaction time of the gas injection in the order of 100 ms. Because of this comparatively slow response, the density significantly overshoots

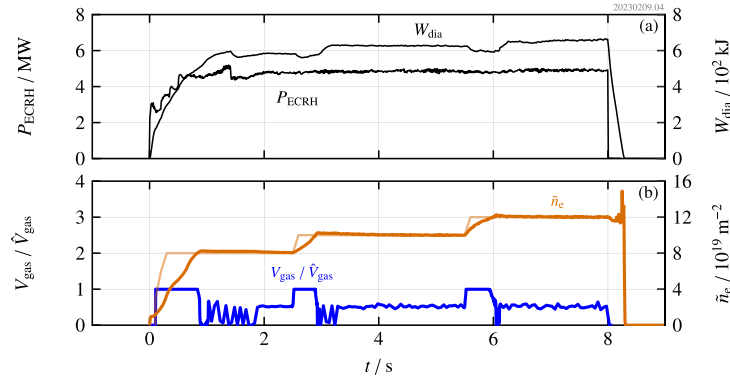


Figure 3. Time traces of the ECRH power and diamagnetic energy (a), measured (intense) and pre-programmed (faint) line-integrated electron density (orange) and the normalized voltage of the divertor gas valve (blue) (b) for the experimental program 20230209.04.

the target value. For systems with substantial dead time, the achievable closed-loop bandwidth is fundamentally limited by the delay itself, so that faster tuning of a standard PID controller increases the risk of overcorrection, overshoot and sustained oscillations. In practice, this trade-off requires either conservatively tuned controller gains or a dedicated dead-time compensation scheme, such as a Smith predictor [9]. This is indeed reflected in the present case, where the feedback-controlled density consistently exceeds the setpoint by approximately 12.5% each time gas is injected. These oscillations are also evident in other signals, such as the diamagnetic energy W_{dia} , indicating that the discharges are not fully stationary which poses a challenge for long-term, high-precision analysis. Despite that, the program lasts over 24 s, which was a significant achievement given the early stage of the experiment.

To achieve more stable, steady-state conditions, a similar feedback control scheme was implemented and applied in several stabilized detachment experiments in the subsequent campaign OP1.2b in 2018 where gas is now injected via the divertor gas valves to regulate the electron density with a precision of less than 1% [7]. This level of precision is achieved because the gas valves are installed directly behind the divertor, resulting in short response times (less than 10 ms) between the control voltage V_{gas} and the gas flow [13]. This system was fully integrated into the segment control of W7-X in the operational campaign OP2.1 in 2023. An example of this improved control is presented in figure 3.

The experimental program (XP 20230209.04) shown in figure 3 demonstrates the planned increase of electron density from $8 \times 10^{19} \text{ m}^{-2}$ to $10 \times 10^{19} \text{ m}^{-2}$ and finally to $12 \times 10^{19} \text{ m}^{-2}$, with the density held constant at each plateau between steps (indicated by the faint orange line). To achieve these pre-defined target values, the PID controller drives the control voltage for the divertor valve to its maximum during startup and between plateaus, thereby fully opening the valve to allow maximum gas flow. The resulting electron density increases at a rate limited by the reservoir gas pressure (set to 1 bar for this program) and is subsequently maintained at the desired level by varying the gas flow. The delay in the density rise is further minimized by increasing the reservoir pressure to 1.5 bar (see for example figure 7). Crucially, the overshoot observed in figure 2, which was common with the main gas inlet system, was avoided due to the fast reaction times of the gas flow resulting from the short distance between the gas valve and the plasma. As a result, this strategy has become the standard for precise electron density feedback control and has been successfully used in all subsequent campaigns.

3.2. Control of plasma radiation via gas injection

Feedback control of the total plasma radiation enables the achievement of stable intrinsic and impurity-seeded detachment, reaction on radiation drifts due to changes in wall out-gassing and effective mitigation of thermal loads on the divertor which is a prerequisite for long-pulse operation. In the operational campaign OP1.2b in 2018, the resistive two-camera core bolometer system of W7-X [14] acted as sensor and provided a real-time proxy for the total radiated power P_{rad} to the controller, operating at a cycle time of approximately 10 ms. However, the effective response of this signal exhibits a typical delay of approximately 100 ms with respect to the valve actuation, arising partly from the intrinsic reaction time of the plasma radiation to changes in fueling or seeding and partly from the processing time of the bolometer electronics [7]. The divertor gas valves are selected as the actuator for this control scheme.

Since precise determination of the actual radiated power is computationally expensive, simplifications must currently be employed to allow real-time operation within the constraints of the presently

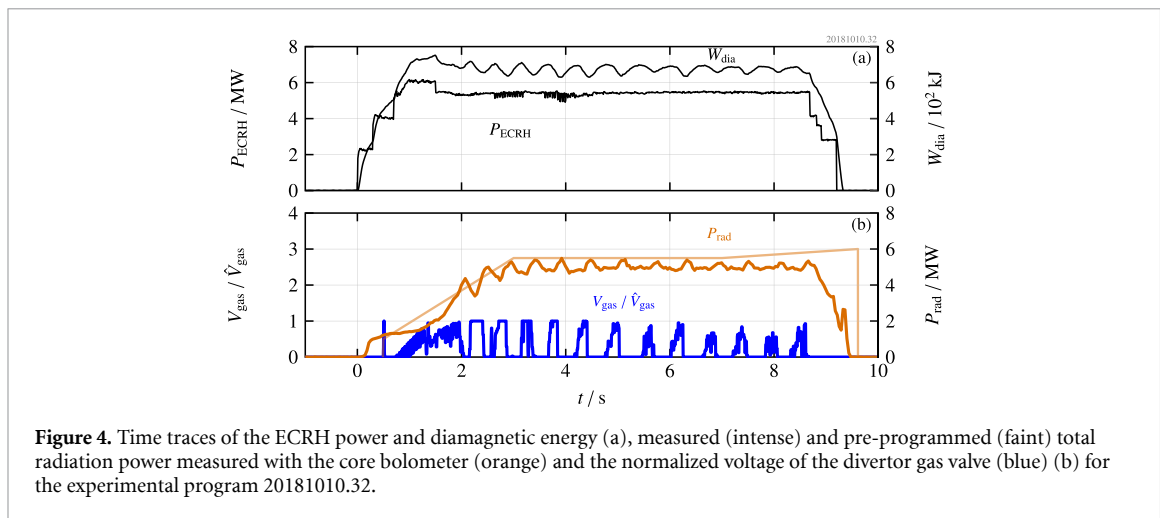


Figure 4. Time traces of the ECRH power and diamagnetic energy (a), measured (intense) and pre-programmed (faint) total radiation power measured with the core bolometer (orange) and the normalized voltage of the divertor gas valve (blue) (b) for the experimental program 20181010.32.

used hardware and computational resources. More advanced approaches, for instance based on machine learning, may reduce the need for such simplifications in the future (see section 4). The applied simplifications include, among others, the use of a subset of lines of sight and specific assumptions about the radiation distribution [15].

A representative example of a discharge exhibiting stable detachment conditions, maintained at a radiation fraction (radiation power over total input power) of approximately 80% – 90% is shown in figure 4. Here, the plasma radiation is successfully maintained at the target level for 6s via gas (H) injection through the divertor valves and reaches the desired setpoint with an uncertainty of about 10%. The gas valve was closed automatically at approximately 8.6s to avoid radiation collapse, as the electron temperature fell below a pre-defined threshold caused by the drop in ECRH power P_{ECRH} . This additional boundary condition is described in detail in section 3.6. However, oscillations are clearly visible in the radiated power and also diamagnetic energy and can largely be attributed to the delayed bolometer signal and the attempts of controlling the radiated power on too fast time scales given the delayed input signal.

In another experimental program (e.g. XP 20181009.41), this control scheme also reduces heat loads on the divertor via controlled seeding of low-Z impurities in the edge [7]. The induced radiation at the plasma edge leads to power dissipation and thus reduces the peak heat fluxes on plasma-facing components. This capability proved particularly significant for subsequent campaigns and drove further development on systems for radiation feedback control. The initial control scheme based on the core bolometer system remained a standalone setup and was never fully integrated into the W7-X segment control. Motivated by the oscillations arising from the substantial delay of the core bolometer signal, a diagnostic with significantly reduced response time was pursued for subsequent campaigns, together with a systematic, model-based controller design, in order to enable a more robust and fully integrated radiation feedback control system [16].

This further developed feedback control concept was tested and fully implemented into the W7-X segment control during the operational campaign OP2.3 in 2025 [16]. Newly installed compact bolometer cameras are now used as the sensor [17]. They provide a proxy for the total radiated power via four lines of sight covering a triangular cross-section. This cross-section is equivalent to the core bolometer view mentioned above, but with a substantially reduced total delay of approximately 25ms, compared to 100ms for the previous system. The actuator remains the divertor gas inlet, as in the previous feedback concept. For initial testing, preparatory programs were run to identify the frequency response of the system (i.e. its transfer function) via perturbative gas-seeding experiments, which allowed for a systematic, model-based design of the controller gains, rather than relying solely on empirical tuning [16]. Thanks to this optimization and the short response time of the overall system, the oscillations mentioned above are almost avoided and the deviation from the pre-defined setpoint is less than 5%. Nitrogen, neon, argon and ethane are used as seeding gases and feedback-controlled gas injection in different plasma scenarios. The discharge shown in figure 5 for example uses neon seeding.

The radiated power in the experimental program shown in figure 5 is stepwise increased from 3.5MW to 6.3MW by the end of the discharge. The desired radiation power levels are reached due to gas puffs from the divertor. Consequently, steady-state phases with different radiation fractions are established. The comparatively slow approach to each new setpoint is a deliberate choice of conservative PID

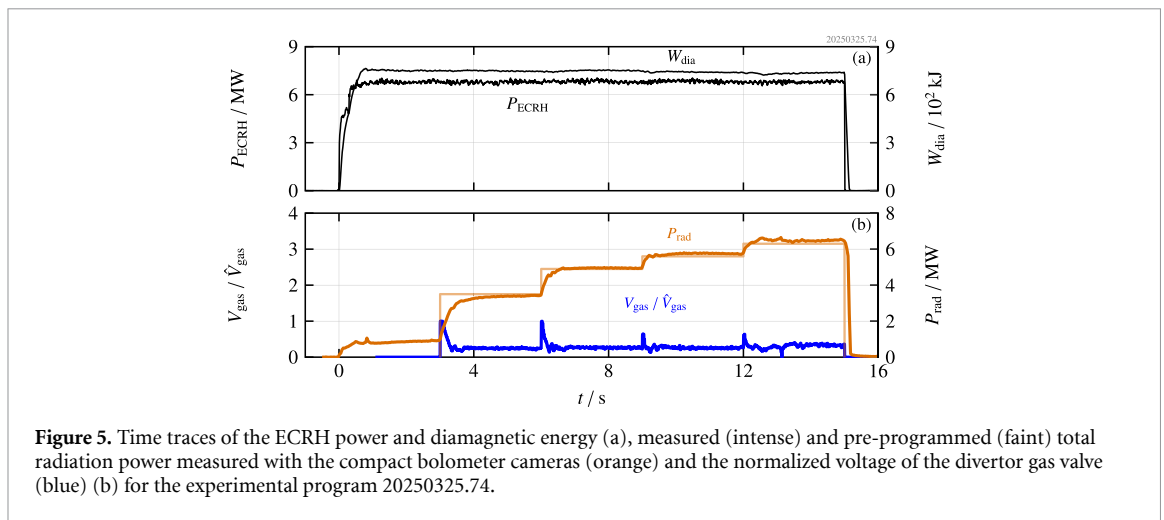


Figure 5. Time traces of the ECRH power and diamagnetic energy (a), measured (intense) and pre-programmed (faint) total radiation power measured with the compact bolometer cameras (orange) and the normalized voltage of the divertor gas valve (blue) (b) for the experimental program 20250325.74.

gains, rather than a limitation of the actuator or sensor. This choice reflects a trade-off intrinsic to the system, since the radiated power responds to impurity seeding with a finite equilibration time, arising from the redistribution of the injected impurities within the plasma and their subsequent exhaust [16]. Attempting to track setpoint changes faster than this intrinsic response time would drive the controller into a regime of overshoot and sustained oscillations, similar to the behavior discussed in section 3.2. Since such oscillations would compromise the stationarity of the discharge and complicate the intended physics analysis of the steady-state radiation phases, the controller gains were instead conservatively tuned to prioritize a smooth, oscillation-free approach to each setpoint over minimizing the rise time.

3.3. Control of neutral pressure via gas injection

Efficient particle exhaust is crucial for maintaining density control and especially in a future reactor to assure the helium ash removal. Within the concept of the island divertor in W7-X, the particles neutralized at the divertor surfaces are compressed and exhausted through closed sub-divertor chambers which are pumped out by several turbo molecular and cryopumps. The particle removal rate is proportional to the sub-divertor pressures which are used as a metric of the total pumping rate [18].

In order to protect the divertors from thermal overloads, detachment conditions are the most promising scenario for future stellarator-type reactors. Experiments at W7-X [7] as well as simulations with the 3D edge plasma simulation code EMC3-EIRENE [19] show increasing neutral sub-divertor pressure with increasing radiation fraction in transitions from attached to detached conditions while a roll-over of the pressure occurs at excessively high radiation fractions. Therefore in the quest for optimum plasma conditions, the detachment state needs a stabilization at the maximum value of the sub-divertor pressure. With this purpose, the neutral pressures in the sub-divertor chambers were implemented as input values in the gas injection feedback control scheme at W7-X. The system was fully implemented into the segment control architecture and tested during the operational phase OP2.2 in 2024. Neutral pressure gauges [20] are employed as sensors of the neutral pressure. To achieve a pre-defined neutral pressure, gas fueling is applied via the divertor gas injection system. The deviation between the requested neutral gas pressure setpoint and the achieved pressure is less than 3% despite the fact that the gas fueling actuator and pressure measurement are located in different machine modules. This enables precise program execution while maintaining the neutral gas pressure setpoint, as demonstrated in figure 6.

The experimental program shown in figure 6 was conducted in the high-iota magnetic field configuration as it is known to have the highest neutral pressure. The ion current from the neutral gas pressure gauges serves as a proxy for neutral gas pressure, which is programmed to increase steadily over 6 s before remaining constant for 13 s. The pressure change is achieved via divertor gas injection. As a result of this feedback control scheme, the measured neutral gas pressure closely follows the target values with minimal deviation. Additionally, the electron density remains also constant during the steady state phase since it is closely related to the neutral particles build-up in the divertors, though this is not shown in figure 6 for simplicity.

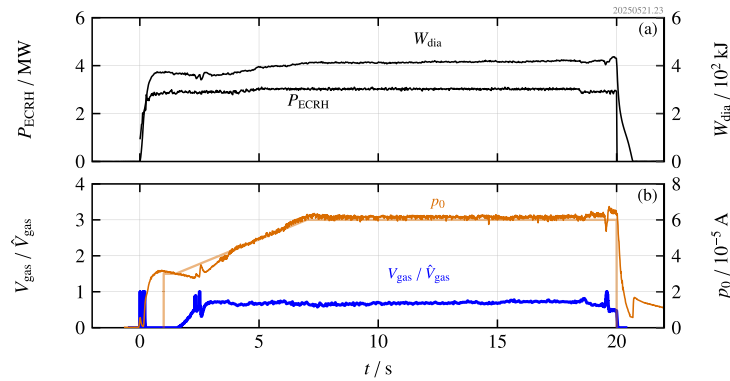


Figure 6. Time traces of the ECRH power and diamagnetic energy (a), measured (intense) and pre-programmed (faint) neutral pressure measured with the neutral pressure gauge (orange) and the normalized voltage of the divertor gas valve (blue) (b) for the experimental program 20 250 521.23.

3.4. Stabilization of ECRH power

The main heating system of W7-X is ECRH being designed to deliver 10 MW of steady-state heating power for up to 30 min [21, 22]. Hence, stabilizing the ECRH power is a critical tool for compensating potential gyrotron failures and therewith maintain stationary discharges. This is particularly important when radiation feedback (please see section 3.2) is set to a radiation fraction close to 1 where fluctuations of the ECRH power might lead to premature discharge termination. In practice, the feedback control of the ECRH power has primarily been applied to long-pulse discharges (also with radiation feedback control). This is because gyrotron interlock events, triggered for instance by arcing, mode loss or excessive body current, occur stochastically, so that the cumulative probability of at least one such event increases with discharge duration [23]. In addition, gyrotron reliability itself depends on time-dependent factors such as cooling and beam path conditions, which can progressively change over the course of long discharges. Such failures are particularly critical in long-pulse, high-performance scenarios, where the radiated power is deliberately kept close the absorbed ECRH power to minimize divertor heat loads, leaving little margin before a brief power deficit can trigger a radiative collapse of the plasma.

For the operational campaign OP2.2 in 2024, this feedback system was fully implemented and successfully tested [23]. The achieved total ECRH power is determined from individual measurements of each gyrotron. The individual power is measured with an RF diode [24] which serves as the sensor in this feedback control system. The output power of each gyrotron depends on the accelerating voltage (set by high-voltage power supplies) and the beam current, with the latter kept constant. If the total power deviates from the planned value (for example due to a gyrotron failure), the power output of the remaining available gyrotrons is adjusted accordingly by high-voltage power supplies acting as actuator. Since the maximum power of each gyrotron is individually limited, a sufficient number of gyrotrons must be operating at medium power level in order to compensate, for instance, for the complete loss of a single gyrotron. This feedback control system operates with a cycle time of 1 ms. For power deviations of up to 550 kW, corresponding to the loss of a single gyrotron, the total ECRH power is conservatively restored to its setpoint within less than 50 ms, enabling a rapid reaction to total power fluctuations. This is significantly faster than the plasma energy confinement time (typically of the order of 100 ms), ensuring that a transient gyrotron dropout does not lead to a significant drop in stored plasma energy and thereby preventing a radiative collapse or premature discharge termination.

A representative example is shown in figure 7. The program maintains stationary conditions for more than 70 s, even though one of the gyrotrons (A5) completely fails three times during this period (see the solid orange line at the bottom of subplot b). The power output of the A5 gyrotron, approximately $P_{\text{A5}} \approx 0.55$ MW, is compensated within less than 50 ms by redistributing the load among the remaining seven gyrotrons P_{act} , whose power levels are correspondingly increased. Consequently, the pre-defined total ECRH power P_{ECRH} stays constant over the whole program length. Under certain conditions, dropped-out gyrotrons can be reactivated which happens at approximately $t = 30$ s. This is preferred over indefinitely operating the remaining gyrotrons at increased power, since it restores the reserve power needed to compensate for potential subsequent gyrotron failures. As a result, the power of the compensating gyrotrons must be reduced accordingly to re-balance the system. The gyrotron dropout recurs at around $t = 58$ s and can again be successfully compensated which improves the overall system reliability.

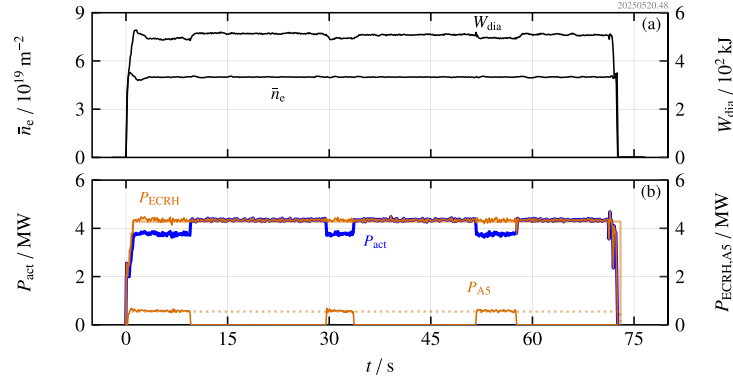


Figure 7. Time traces of the line-integrated electron density and diamagnetic energy (a), measured (intense) and pre-programmed (faint) total ECRH power (orange). Additionally, the measured (intense, orange) and planned (dotted, orange) A5 gyrotron power as well as the ECRH power of the remaining gyrotrons (blue) that compensate the drop of the A5 gyrotron (b) for the experimental program 20250520.48.

The discharge shown above also achieves the excellent performance of both the density control and the radiated power control (the latter omitted from figure 7 for simplicity). With the combined feedback control of the electron density, the radiated power and the stabilization of the total ECRH power, a stationary discharge (XP 20250520.11) was sustained for more than 360 s [25].

3.5. Control of electron density via ECRH power

Electron density control via ECRH power was successfully demonstrated in first proof-of-principle experiments in the operational campaign OP2.3 in 2025. In this preliminary scheme, the electron density is measured by the dispersion interferometer, which serves as the sensor and is propagated via the real-time network to the local gyrotron control system [23]. As in section 3.4, the high-voltage power supplies act as the actuator, adjusting the accelerating voltage and thereby the ECRH gyrotron power. The approach exploits the pump-out effect [26–28] of centrally deposited ECRH power, which leads to a reduction of the electron density in the plasma center. In contrast to the gas-injection-based density control described in section 3.1, which increases the electron density via fueling, the ECRH-based density feedback control described here reduces the electron density through the pump-out effect. It therefore provides an important complement to gas or pellet injection-based density control, particularly for controlled reductions of the electron density. This capability is especially valuable when the density overshoots due to gas or cryogenic pellet injection, or when a deliberate density decrease is required. Furthermore, density control via additional ECRH power remains effective alongside neutral beam injection (NBI) [29], provided the ECRH power is sufficiently large relative to the NBI power to counteract the centrally peaked density profiles resulting from NBI core fueling [30].

A representative example is shown in figure 8. First, a constant density of $5 \times 10^{19} \text{ m}^{-2}$ is achieved by means of gas-injection feedback control. After approximately 4.3 s, three cryogenic pellets are injected (indicated as vertical lines). As a consequence, the electron density increases dramatically to $1.8 \times 10^{20} \text{ m}^{-2}$. The density then decays slowly with its characteristic time constant until, at about 5.6 s, NBI heating is applied, which increases the electron density again due to its core particle fueling effect. At 6 s, the ECRH power, as planned, is increased from 2 to 2.5 MW. The feedback control is activated shortly after at $t = 6.5$ s and remains active until the end of the discharge. The planned ECRH power increase subsequently reduces the density below the setpoint of $1.4 \times 10^{20} \text{ m}^{-2}$ (at around 7.3 s). In response, the ECRH power is reduced by the feedback controller, thereby bringing the electron density back toward the pre-defined value. To compensate for the ensuing overshoot, the feedback controller increases the ECRH power to about 3.3 MW until the setpoint is reached again. The actual density deviates by less than 10% from the target density, which can be attributed, among other factors, to the early developmental stage of the feedback system and the resulting lack of experience and controller optimization. Full integration into the segment control of W7-X, along with system improvements, is planned for the upcoming operational campaign OP2.4 (expected in 2026) and has already been partially implemented.

3.6. Core electron temperature boundary condition

As mentioned in section 2, additional operational constraints can be assigned to an actuator such that the actuator is restricted whenever a specified limit is violated. In the W7-X segment control system, a boundary condition of this type has been implemented to prevent the core electron temperature at a

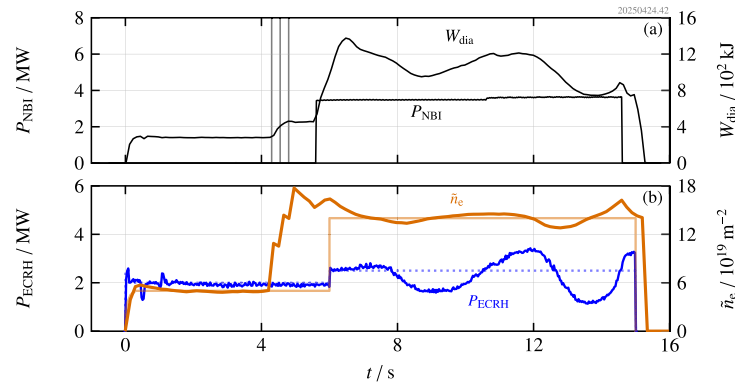


Figure 8. Time traces of the NBI power and diamagnetic energy (a), measured (intense) and pre-programmed (faint) line-integrated electron density (orange) as well as the measured (intense) and pre-planned (faint dotted) total ECRH power (blue) (b) for the experimental program 20250424.42. Vertical lines indicating the times of pellet injection (a).

selected effective radius from falling below a critical value. The temperature is monitored via a proxy signal from the electron cyclotron emission [31, 32] diagnostic, which is streamed to the real-time network at 10Hz.

In operation, this constraint has been employed in the feedback control of the electron density using the divertor gas inlet (see section 3.1). When the measured electron temperature drops below a preset threshold, the gas flow is automatically interrupted by closing the valve and the integral part of the PID controller is set to zero until the temperature exceeds the threshold value when the controller resumes its normal operation. This mechanism mitigates premature discharge termination caused by radiative collapse, which can occur, for example, when insufficient absorption of the ECRH arises as a consequence of too low electron temperature (especially at O_2 heating). This is particularly relevant for the second-harmonic ordinary-mode (O_2) ECRH heating scenario, which is employed at W7-X to access electron densities above the cutoff density of the more commonly used X2-mode, but which is only partially absorbed in a single pass through the plasma and therefore relies on sufficiently high electron temperatures to achieve adequate overall absorption [33]. This is illustrated in figure 4, where the gas valves were closed at approximately 8.6s because the ECRH power dropped out, leading to a reduction of the electron temperature below the pre-defined threshold. In the upcoming operational campaign OP2.4 (expected in 2026), this boundary condition will also be applicable to all established feedback control systems using gas injection as actuator.

3.7. Multiple feedback control for steady-state operation

The interaction between different actuators and plasma parameters represents a major challenge for integrated plasma control. Gas injection affects not only the electron density but also the radiation level, neutral particle balance and plasma confinement. Likewise, variations in ECRH power influence the electron temperature, density pump-out and radiation stability. As a consequence, the individual feedback systems cannot be considered fully independent, especially in high-performance scenarios close to operational limits.

A representative example of multiple feedback control system in operation was demonstrated in a steady-state scenario with detached divertor conditions and feedback-controlled impurity seeding. In this scenario, the plasma density is maintained constant by gas injection feedback control while the total ECRH power is stabilized despite repeated gyrotron dropouts by redistributing the heating power among the remaining gyrotrons. The resulting discharge reached a pulse length of 363s and a total heating energy of 1.8GJ while maintaining low divertor heat loads below 3.5MWm^{-2} [25]. Throughout the stationary phase, the diamagnetic energy and plasma density remained nearly constant, demonstrating the robustness of the combined feedback approach.

It should be noted that the density and radiation feedback loops applied in this scenario are not explicitly coordinated with one another. Each PID controller operates independently without knowledge of the setpoint or action of the other. Since both loops act via gas injection through different divertor valves supplied with different gas species, an interaction between the two loops cannot be excluded in general. In practice, this potential cross-coupling is mitigated empirically by selecting distinct injection locations and gas species for fueling and impurity seeding. A more systematic treatment of such actuator and control-loop interactions, e.g. through a coordinated or decoupled multi-input multi-output control

design, remains an important goal for future work. These experiments nonetheless demonstrate that reliable long-pulse operation critically depends on sufficiently robust coordination between the individual diagnostics, actuators and supervisory boundary conditions employed at W7-X.

4. Planned feedback control systems

The broad spectrum of feedback control systems implemented on W7-X clearly demonstrates their crucial role in both establishing and enabling the required plasma scenarios. The comparatively simple infrastructure of the segment control system together with the real-time network provides a flexible framework for extending the feedback capabilities with new sensors and actuators. These extensions are primarily driven by evolving physics requirements and aim to enhance the stability of existing plasma scenarios while also enabling new, more challenging operational regimes.

One feedback system currently under development is the control of the electron density via hydrogenic pellet injection. In contrast to the continuous PID control schemes discussed above, this system will be based on a two-point (on/off) controller with hysteresis. Rather than continuously adjusting an analog control signal, a two-point controller switches the actuator between only two discrete states, e.g. ‘inject’ and ‘do not inject’, depending on whether the measured value lies below a lower or above an upper threshold, respectively. This scheme is particularly suited to actuators that cannot be modulated continuously, such as the steady-state pellet injector [34], which delivers discrete pellets rather than a continuously viable fueling rate. In the planned scheme, the lower threshold, which triggers injection of a pellet, is determined from the requested electron density (measured using the dispersion interferometer as sensor) minus half of the expected density increase produced by a typical pellet. Once the density exceeds the requested setpoint itself (the upper threshold), the controller becomes inactive and no further pellets are injected until the density again falls below the lower threshold. This hysteresis behavior ensures that the electron density fluctuates around and on average meets the target value. Due to hardware limitations, a subsequent pellet injection can occur only after a minimum interval of 250 ms, which has so far provided a sufficient average fueling rate in the experiments.

Neural-network-based control of fueling or impurity gas injection valve voltages is in preparation as first demonstration of this type of control of a stellarator plasma and will be tested in the following two schemes. Firstly, the neutral pressure in the sub-divertor chambers under detached plasma conditions shall be maximized and kept constant at the maximum value. Secondly, the total plasma radiation shall be controlled in a variety of plasma parameter regimes especially including high heating powers (also by combined ECRH and NBI heating) and high radiation fractions. The planned set of input diagnostic signals comprises the line-integrated electron density, total plasma radiation, total ECRH power, stored plasma energy and neutral gas pressures in the sub-divertor chambers.

Extending the radiation feedback system (see section 3.2) to use the radiation fraction, i.e. the ratio of the total radiated power to the total heating power, as the sensor signal instead of the absolute radiated power appears to be a promising approach for improving the ability of the system to respond to unforeseen variations in heating power, such as an unplanned drop in ECRH power (see section 3.4) or an unforeseen change in the radiated power itself. Additionally, the radiated power setpoint must be manually adjusted in the current implementation whenever the heating power changes during a discharge, since a constant absolute radiated power corresponds to a different radiation fraction at each heating power level. Controlling the radiation fraction directly would instead allow the feedback loop to react self-consistently to the actual heating conditions, without requiring pre-programmed setpoint adjustment at each planned change in heating power. Such an implementation appears feasible for the upcoming campaign, as all required signals are already available and capable of real-time operation.

A particular strength of W7-X is the flexibility of its magnetic field configuration [35, 36]. The trim and control coils can already be adjusted on a program basis, whereas the non-planar and planar main field coils are typically fixed for an entire session. Starting with OP2.4 (planned end of 2026), modifications will allow to slightly adjust the main field configuration on a program basis. In either case, however, real-time feedback control of the magnetic field configuration is not yet realized. Depending on the chosen configuration, the resulting absolute toroidal plasma current varies and can range from approximately 1 to 20 kA. A significant toroidal current modifies the plasma edge topology and consequently the interaction patterns with the divertor components, which is referred to as the strike-line position [37]. Strike-line control is especially important for long-pulse operation, as it enables mitigation of divertor heat loads. In addition, control of the rotational transform, which also depends on the toroidal current, is of considerable relevance for edge physics. A further requirement is the control of the magnetic field strength, for example to optimize ECRH absorption and adapt heating conditions to different plasma

scenarios. The range of potential applications is broad, driven by both physical and operational demands. Work toward realizing such control capabilities is already underway, although the technical implementation and the associated safety considerations remain challenging. Nevertheless, the real-time algorithm for strike-line position determination has already been successfully implemented as part of the divertor protection system [38]. This existing real-time computation is expected to serve as the sensor input for a future strike-line position controller.

A longer-term development effort aims at achieving full profile control of both the electron density and temperature using multiple actuators. At present, only the electron density is employed as a sensor signal. The planned upgrade, however, is intended to enable direct influence on the radial profiles in order to artificially and controllably generate gradients that modify transport properties and confinement. It is anticipated that several actuators will be required to accomplish this, although a detailed understanding of the underlying physical processes needs to be further investigated in the future.

5. Conclusion

A broad range of feedback control systems has been successfully developed, implemented and experimentally validated at W7-X during recent operational campaigns. These systems enable reliable control of key plasma parameters such as electron density, plasma radiation, neutral pressure and heating power under varying operational conditions. Together with the millisecond-scale real-time network and segment control architecture, they provide the basis for stable long-pulse and high-performance plasma operation. In particular, the combination of density, radiation and ECRH power control enabled long-pulse discharges with stable detached divertor conditions. Future developments will focus on advanced actuators, neural-network-assisted control strategies and profile control capabilities.

In contrast to tokamaks, where feedback control commonly targets quantities such as plasma shape, vertical position and plasma current, which are not required in the same way for the externally imposed magnetic equilibrium of a stellarator, feedback control at W7-X places a stronger emphasis on long-term actuator coordination, drift compensation and stable control during stationary conditions. The operational experience gained at W7-X therefore provides an important basis for the development of integrated and advanced control concepts for future reactor-scale stellarators and steady-state fusion devices.

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Data availability statement

The data cannot be made publicly available upon publication due to legal restrictions preventing unrestricted public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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Appendix. History of implemented plasma feedback control systems

The tested and implemented feedback control systems of W7-X are summarized in table 1. Specifically, the table lists the control parameters, actuators and sensors as well as the name of the campaign during each system was initially implemented and tested.

Table 1. List of feedback control systems that were tested and fully implemented in the segment control of W7-X.

Control of (sensor)	Via (actuator)	Remarks	Sections
electron density (interferometer)	gas injection (main gas system)	implemented in OP1.2a (2017)	3.1
electron density (interferometer)	gas injection (divertor gas system)	tested in OP1.2b (2018), fully implemented in OP2.1 (2023)	3.1
total plasma radiation (core bolometer)	gas injection (divertor gas system)	only in OP1.2b (2018)	3.2
total plasma radiation (compact bolometer cameras)	gas injection (divertor gas system)	implemented in OP2.3 (2025)	3.2
neutral pressure in sub-divertor chamber (neutral pressure gauges)	gas injection (divertor gas system)	implemented in OP2.2 (2024)	3.3
ECRH power (ECRH power measurement)	ECRH power (high-voltage supply)	implemented in OP2.2 (2024)	3.4
electron density (interferometer)	ECRH power (high-voltage supply)	first tests in OP2.3 (2025), not yet in segment control	3.5

References

- [1] Kurihara K, Lister J, Humphreys D, Ferron J, Treutterer W, Sartori F, Felton R, Brémond S and Moreau P 2008 *Fusion Eng. Des.* **83** 959
- [2] Ringler H, Gasparino U, Kuhner G, Maassberg H, Renner H and Sardei F 1990 *Plasma Phys. Control. Fusion* **32** 933
- [3] Sudo S *et al* (LHD Team) 2006 *Fusion Eng. Des.* **81** 1713
- [4] Kamio S, Kasahara H, Seki T, Saito K, Seki R, Nomura G and Mutoh T 2015 *Fusion Eng. Des.* **101** 226
- [5] de la Peña A, Pacios L, Carrasco R and Lapayese F 2009 *Fusion Eng. Des.* **84** 676
- [6] Brunner K J, Akiyama T, Hirsch M, Knauer J, Kornejew P, Kursinski B, Laqua H, Meineke J, Trimiño Mora H and Wolf R C (the W7-X Team) 2018 *J. Instrum.* **13** 09002
- [7] Krychowiak M *et al* (the W7-X Team) 2023 *Nucl. Mater. Energy* **34** 101363
- [8] Bennett S 2001 *Annu. Rev. Control* **25** 43
- [9] Aström K and Hägglund T 2001 *Control Eng. Pract.* **9** 1163
- [10] Laqua H, Niedermeyer H and Schacht J 2003 *Fusion Eng. Des.* **66–68** 669
- [11] Laqua H, Niedermeyer H, Schacht J and Spring A 2006 *Fusion Eng. Des.* **81** 1807
- [12] Laqua H, Niedermeyer H and Willmann I 2002 *IEEE Trans. Nucl. Sci.* **49** 478
- [13] Schacht J, Brakel R, Viebke H, Pingel S, Wölk A, Laqua H, Schmidt F and Müller I (the W7-X Team) 2018 *Fusion Eng. Des.* **129** 6
- [14] Zhang D *et al* 2010 *Rev. Sci. Instrum.* **81** 10E134
- [15] Scholl P 2025 Impurity Transport and Radiation at the Stellarator Wendelstein 7-X *PhD Thesis* (University of Greifswald, Germany)
- [16] Tsikouras A, Reimold F, Partesotti G, Krychowiak M, Schröder T and van Berkel M (the W7-X Team) 2026 *Plasma Phys. Control. Fusion* **68** 085004
- [17] Partesotti G, Reimold F, Ruhnau J, Tsikouras A, Kubeneck D, Zhang D and Geißler P (the W7-X Team) 2024 *Rev. Sci. Instrum.* **95** 103503
- [18] Eich T H *et al* 2026 *J. Plasma Phys.* **92** E66
- [19] Feng Y, Beidler C, Geiger J, Helander P, Hölbe H, Maassberg H, Turkin Y and Reiter D (the W7-X Team) 2016 *Nucl. Fusion* **56** 126011
- [20] Wenzel U, Schlisio G, Mulsow M, Pedersen T S, Singer M, Marquardt M, Pilopp D and Rüter N 2019 *Rev. Sci. Instrum.* **90** 123507
- [21] Erckmann V *et al* (W7-X ECRH Team at IPP Greifswald, W7-X ECRH Team at FZK Karlsruhe and W7-X ECRH Team at IPF Stuttgart) 2007 *Fusion Sci. Technol.* **52** 291
- [22] Wolf R C *et al* (the W7-X Team) 2018 *Plasma Phys. Control. Fusion* **61** 014037
- [23] Krier L *et al* 2026 *Nucl. Fusion* **66** 106038

- [24] Erckmann V, Braune H, Laqua H P, Michel G, Dammertz G, Thumm M, Gantenbein G, Kasperek W and Mueller G A (W7-X ECRH Teams) 2003 *AIP Conf. Proc.* **691** 213
- [25] Grulke O (the W7-X Team) 2026 *Nucl. Fusion* **66** 116003
- [26] Zushi H *et al* 1988 *Nucl. Fusion* **28** 1801
- [27] Maaßberg H, Beidler C D, Gasparino U, Romé M, Team W-A, Dyabilin K S, Marushchenko N B and Murakami S 2000 *Phys. Plasmas* **7** 295
- [28] Castejón F, Eguilior S, Calvo I, López-Bruna D and García-Regaña J M 2008 *Phys. Plasmas* **15** 012504
- [29] Lazerson S A *et al* (the W7-X Team) 2021 *Nucl. Fusion* **61** 096008
- [30] Bannmann S *et al* (the W7-X Team) 2023 *J. Instrum.* **18** 10029
- [31] Schmuck S, Hartfuss H-J, Hirsch M and Stange T 2009 *Fusion Eng. Des.* **84** 1739
- [32] Hirsch M *et al* (the W7-X Team) 2019 *EPJ Web Conf.* **203** 03007
- [33] Laqua H *et al* (the W7-X Team) 2021 *Nucl. Fusion* **61** 106005
- [34] Meitner S J, Baylor L R, Gebhart T E, Harris J H, McGinnis W D, Bjorholm T P and Logan K G 2020 *IEEE Trans. Plasma Sci.* **48** 1585
- [35] Geiger J, Beidler C D, Feng Y, Maaßberg H, Marushchenko N B and Turkin Y 2014 *Plasma Phys. Control. Fusion* **57** 014004
- [36] Riße K, Rummel T, Bosch H-S, Bykov V, Carls A, Füllenbach F, Mönnich T, Nagel M and Schneider M 2018 *Fusion Eng. Des.* **136** 12
- [37] Gao Y *et al* (the W7-X Team) 2019 *Nucl. Fusion* **59** 106015
- [38] Jabłoński B, Puig Sitjes A, Makowski D, Jakubowski M, Gao Y, Fischer S and Winter A (the W7-X Team) 2023 *Fusion Eng. Des.* **190** 113524