Real-time total ECRH power control for reliable long-pulse operation and density feedback at Wendelstein 7-X

To cite this article: L. Krier *et al* 2026 *Nucl. Fusion* **66** 106038

OPEN ACCESS
IOP Publishing | International Atomic Energy Agency
Nuclear Fusion
Nucl. Fusion **66** (2026) 106038 (8pp)
https://doi.org/10.1088/1741-4326/ae9cc9

Real-time total ECRH power control for reliable long-pulse operation and density feedback at Wendelstein 7-X

L. Krier*, S. Marsen, H. Laqua, H.P. Laqua, D. Moseev, F. Noke, J.W. Oosterbeek, N. Polei, S. Ponomarenko, T. Reichert, T. Stange, L. Versemann, R.C. Wolf, J. Zimmermann and W7–X Team[a]

Max-Planck-Institute for Plasma Physics (IPP), Wendelsteinstr. 1, D-17491 Greifswald, Germany

E-mail: laurent.krier@ipp.mpg.de

Received 8 April 2026, revised 24 July 2026
Accepted for publication 21 August 2026
Published 8 September 2026

CrossMark

Abstract

The electron cyclotron resonance heating (ECRH) system at the Wendelstein 7-X (W7–X) stellarator is equipped with eleven megawatt-class gyrotrons that operate at a frequency of 140 GHz, designed for pulse durations of up to thirty minutes. For long-pulse detached-divertor plasma experiments at W7–X, a stable total ECRH power delivered to the plasma is crucial, because the radiated power at the plasma edge is preferably close to the heating power. Consequently, the unexpected shutdown of only one gyrotron can cause a premature end of the experiment due to radiation collapse of the plasma. This paper introduces a system-level controller that dynamically redistributes power among gyrotrons to maintain total ECRH power, improving reliability and enabling feedback control. The controller maintains a specified total ECRH power output by adjusting the accelerating voltage of all gyrotrons. First implemented in the operational phase (OP) 2.2, the system contributed to two major milestones of W7–X during OP 2.3: highest long-pulse triple product for 43 s and highest energy turnover of 1.8 GJ during 360 s. In addition to reliability improvements, the controller enables the adjustment of the total ECRH power for other control objectives, such as maintaining a desired line-integrated plasma density to counteract the ECRH pump-out effect in high-performance scenarios. This paper also presents the first proof-of-principle experiments demonstrating an ECRH-based density feedback system.

Keywords: gyrotron, stellarator, electron cyclotron resonance heating (ECRH), real-time control, Wendelstein 7-X, long-pulse operation

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

[a] See Grulke *et al* 2024 (https://doi.org/10.1088/1741-4326/ad2f4d) for the W7-X Team.
* Author to whom any correspondence should be addressed.

1. Introduction

The Wendelstein 7-X (W7–X) stellarator is designed to demonstrate the capabilities of optimized stellarator configurations for steady-state plasma operation

with reactor-relevant performance [1, 2]. Achieving long-pulse, high-performance plasmas requires reliable and precisely controlled heating systems. The heating systems at W7–X are electron cyclotron resonance heating (ECRH) [3, 4], neutral beam injection (NBI) [5] and ion cyclotron resonance heating (ICRH) [6]. The ECRH system is the only continuous-wave (CW) heating system and is designed to deliver 10 MW of millimeter-wave power at 140 GHz for a pulse duration of up to thirty minutes.

For steady-state operation, the total ECRH power delivered to the plasma must remain stable. In particular, during detached-divertor plasma operation [7], the radiated power at the plasma edge is typically adjusted slightly below the absorbed power to minimize the heat flux onto the divertor. For this purpose, a feedback control system keeps the radiated power at a specified level with impurity seeding [8]. Fluctuations in ECRH power can therefore directly affect plasma power balance and even lead to premature discharge termination.

Real-time control of ECRH systems has been extensively studied in various fusion devices. Early demonstrations of deposition control in helical devices include the work by Tsujimura *et al* on LHD [9]. Multi-beam ECRH/ECCD control for MHD stability was achieved on TCV by Felici *et al* [10], while Galpertiet *et al* demonstrated a multinode ECRH real-time control system on FTU [11]. Model-based observers for density profile control were explored by Pastore *et al* [12], and Blanken *et al* presented a real-time plasma state monitoring and supervisory control system for TCV [13]. For reactor-scale applications, Carannante *et al* outlined the status of ITER's ECRH&CD control system development [14]. While these studies focused on specific physics objectives (e.g. deposition control, MHD stability, or density profiling), this work introduces a system-level total power controller to ensure reliability during long-pulse operation, a critical requirement for steady-state fusion devices like W7–X.

The ECRH system at W7–X currently comprises eleven gyrotrons with a total heating power of up to 8.5 MW. Occasionally, interlocks are triggered by potential damaging events such as arcing in the atmospheric transmission line, mode loss, or excessive body current in the gyrotron [15] leading to an immediate shutdown of the gyrotron. Even brief interruptions of a single gyrotron can cause a noticeable drop in total heating power.

To address these challenges, several local recovery measures have been introduced in recent years to reduce the frequency and duration of interlock events for individual gyrotrons [16, 17]. While these developments have improved the reliability of each gyrotron, maintaining stable total ECRH power at the system-level remained an open issue. Crucially, due to the cathode current boosting scheme required for stable long-pulse operation, each gyrotron requires a five second warm-up period before it generates millimeter-wave power. Even with a spare unit available, the replacement of an interlocked gyrotron inevitably leads to a transient power loss of at least five seconds. This inherent delay limits the effectiveness of hardware redundancy alone. Ensuring uninterrupted power delivery requires a control approach capable of dynamically redistributing power among the remaining gyrotrons whenever one experiences a temporary shutdown.

This work presents the design, implementation, and experimental validation of a total ECRH power controller that actively regulates the combined output of all gyrotrons at W7–X. The controller adjusts the accelerating voltage of each gyrotron to maintain a specified total power level, thereby improving overall system reliability and plasma stability. First implemented during operational phase (OP) 2.2, this control scheme supported key milestones in OP 2.3, including record plasma performance and energy turnover.

Beyond enhancing reliability, total power control enables new applications of ECRH in high-performance plasmas. Since ECRH power influences plasma density through the pump-out effect in NBI-fueled experiment programs [18, 19], it can be used to stabilize plasma density. A feedback controller using total ECRH power to regulate the line-integrated plasma density has been developed and demonstrated in first proof-of-principle experiments.

This paper is organized as follows: section 2 describes the ECRH system at W7–X and its operational characteristics. Section 3 details the design and implementation of the total power controller. Section 4 presents experimental results demonstrating power stabilization during long-pulse operation. Section 5 discusses the first experiments of ECRH-based density feedback control. Finally, section 6 summarizes the results and outlines perspectives for future OPs.

2. ECRH system at W7–X

The ECRH system at W7–X comprises eleven megawatt-class gyrotrons operating at a frequency of 140 GHz, corresponding to the second harmonic of the electron cyclotron resonance in a magnetic field of 2.5 T. The ECRH system is designed for continuous operation of at least thirty minutes, and currently delivers up to 8.5 MW of millimeter-wave power to the plasma [20].

Figure 1 shows an overview of the ECRH system. The gyrotrons are installed in two dedicated halls, Hall 1 and Hall 5, adjacent to W7–X modules 1 and 5. Each hall accommodates up to six gyrotrons, with individual positions labeled alphabetically from A to F, combined with the hall number (e.g. A1, B1 … F5).

Of the eleven gyrotrons, ten were manufactured by Thales (France) company and are designated TH1507, developed by the Institute for Pulsed Power and Microwave Technology (IHM) at the Karlsruhe Institute of Technology (KIT) [21]. The remaining gyrotron is a VGT8141A produced

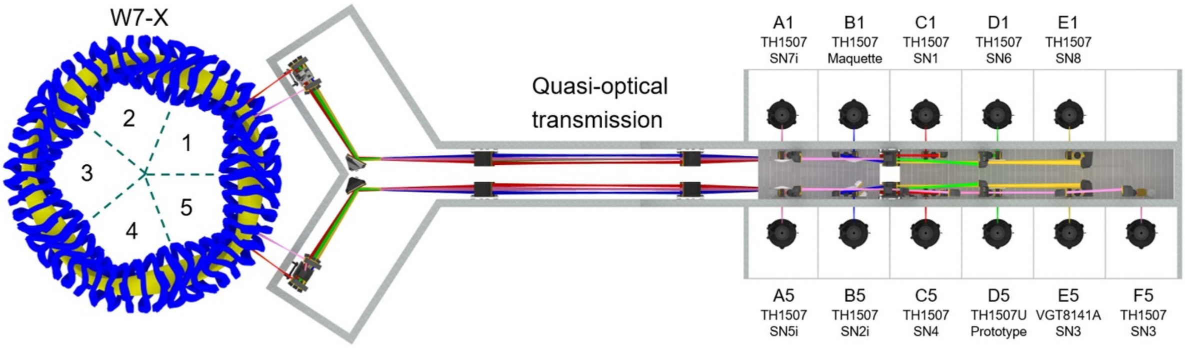


Figure 1. Overview of the ECRH system at W7–X. The gyrotrons labeled with their serial number are located in two gyrotron halls. Each mm-wave beam is represented with a different color. The mm-wave beams are transmitted fully quasi-optical to the plasma vessel.

by Communications & Power Industries (CPI, USA) [22]. The gyrotrons are all designed for an output power of 1 MW, except for the TH1507U (D5) gyrotron, which is designed for an output power of 1.5 MW [23].

The millimeter-wave power from each gyrotron is transmitted to the plasma via a fully quasi-optical system [24], including beam-shaping optics, polarizers, and multi-beam combining sections, which deliver the power to the plasma through front-steering launchers.

The mm-wave power from each gyrotron is measured at the first mirror, where a small fraction of the Gaussian beam is directed either through coupling holes or via a diffractive grating surface to a millimeter-wave Schottky diode power detector. The diode detectors are cross-validated against calorimetric measurements. The calibration uses a second-order polynomial to model the nonlinear relationship between the diode signal and the actual power, ensuring accurate power measurements within the operational range. This calibration is performed before each operational campaign to account for drift or aging effects in the diodes.

Each gyrotron is powered by a high-voltage system providing both the accelerating voltage (up to $\sim$83 kV) and the beam current (up to $\sim$50 A) [25]. Together, these determine the gyrotron output power. The gyrotrons are operated in a single-depressed collector scheme, where the collector is at ground potential. The high-voltage system comprises two main components:

- Cathode-voltage supply: implemented as a pulse-step modulator (PSM), delivering up to -64 kV and providing the electron beam current.
- Body-voltage supply: provides up to 30 kV to the gyrotron body.

The output voltage of both power supplies is controlled by a digital input signal allowing arbitrary waveforms at a bandwidth in the order of several kHz. A dedicated field programmable gate array (FPGA) based controller of each gyrotron transmits the setpoints for cathode and body voltages to the respective power supplies. Accelerating voltage setpoints can be updated on the sub-millisecond timescale, enabling rapid adjustments of the gyrotron output power.

In addition to the high-voltage and high-power operating conditions, the gyrotrons at W7–X employ a cathode current boosting scheme to maintain stable beam current during long-pulse operation. This scheme compensates the cathode cooling at the start of a pulse, ensuring consistent output power. However, this stabilization mechanism requires a five second warm-up period before the gyrotron generates millimeter-wave power. As a result, when a gyrotron is interlocked and must be replaced by a spare unit, the system experiences a minimum five second power outage, even if the spare gyrotron is ready to operate. Consequently, direct replacement of an interlocked gyrotron cannot restore full ECRH power instantaneously. This inherent limitation underscores the need for a system-level control strategy capable of dynamically redistributing power among the remaining active gyrotrons in real time, thereby minimizing the impact of individual gyrotron failures and enabling seamless long-pulse operation.

The total power controller presented in this work exploits the rapid control of the accelerating voltage. By adjusting the setpoints of all active gyrotrons in real time, the controller maintains a specified total ECRH power injected into the plasma. In this context, the high-voltage power supplies operate as the actuators of the control loop and are central to achieving reliable, system-level regulation of the ECRH output power.

3. Design and implementation of the total power controller

The output power of a gyrotron depends primarily on its accelerating voltage and electron beam current. For the gyrotrons at W7–X, the beam current is typically held constant during long-pulse operation and can only be adjusted on a timescale of tens of seconds. Therefore, the fastest control parameter is the accelerating voltage.

The typical output power P_{gyro} increases monotonically with the accelerating voltage U_{acc} until the gyrotron enters the mode-cutoff regime, where it loses the mode excitation and thus its output power. To characterize this relationship, a dedicated calibration is performed before each operational campaign, where P_{gyro} is measured at discrete U_{acc} setpoints (typically from 70 kV to 82 kV). As shown in figure 2 for the

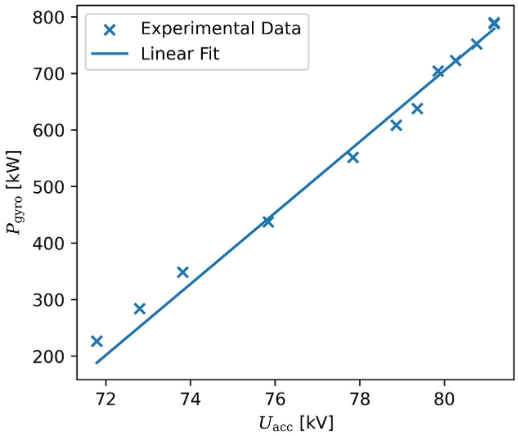


Figure 2. Measured output power (crosses) vs accelerating voltage for the B5 gyrotron. The line shows the linear approximation used for control design, with slope K_{gyro}. The linear approximation is performed before each operational campaign.

B5 gyrotron, the P_{gyro} vs U_{acc} curve is approximately linear in the operational range. This relationship is linearized around a nominal operating point using a first-order Taylor expansion:

$$P_{\mathrm{gyro}} \approx P_0 + K_{\mathrm{gyro}} \left(U_{\mathrm{acc}} - U_0\right),$$

where P_0 is the nominal output power at the nominal voltage U_0 and K_{gyro} is the local slope of the power-voltage curve (gain of the gyrotron).

This linearization is used to calculate the required accelerating voltage for a requested power. Moreover, for the total power controller, it allows to treat each gyrotron as a controllable gain section in the system-level control loop.

In long-pulse operation, the main objective is to maintain a specified total ECRH power injected into the plasma. The total power is the sum of the powers of all individual gyrotrons $P_{\mathrm{gyro},n}$:

$$P_{\mathrm{tot}} = \sum_{n=0}^{N} P_{\mathrm{gyro},n}.$$

Fluctuations of an individual gyrotron output, e.g. due to interlocks, can cause deviations of P_{tot} from the total power setpoint $P_{\mathrm{tot,set}}$. To compensate, a system-level feedback controller calculates a correction factor based on the total power error:

$$\Delta P = P_{\mathrm{tot,set}} - P_{\mathrm{tot}}.$$

The total power error ΔP serves as the input to a Proportional-Integral (PI) controller, which computes a correction factor C_{corr}. This factor is a dynamic control signal that scales the nominal accelerating voltage setpoints of all active gyrotrons:

$$U_{\mathrm{acc},n} = U_{\mathrm{acc},n}^{\mathrm{nom}} \left(1 + C_{\mathrm{corr}}\right),$$

where $U_{\mathrm{acc},n}^{\mathrm{nom}}$ is the nominal operating voltage of gyrotron n. The PI controller adjusts C_{corr} in real-time to minimize ΔP,

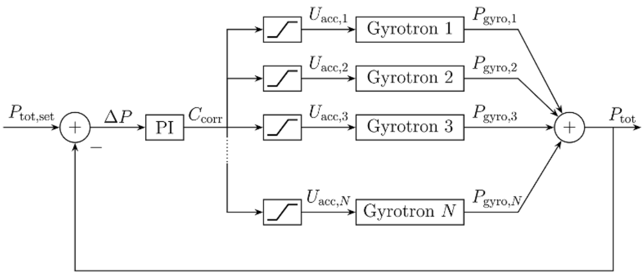


Figure 3. Control diagram for the total power feedback system. The correction factor C_{corr} is the output of the PI controller and is applied to the accelerating voltage setpoints of all gyrotrons.

thereby maintaining the total ECRH power at the desired setpoint. Due to the feedback loop, the total power controller effectively redistributes power among all active gyrotrons by scaling their accelerating voltage with C_{corr}. The corresponding control diagram is shown in figure 3.

An important consideration in the control design is the dynamic nature of the ECRH system's total gain, which depends on the individual gains $K_{\mathrm{gyro},n}$ of each gyrotron and thus, on the number of active gyrotrons N. For example, when a gyrotron unexpectedly shuts down (e.g. due to an interlock), N decreases, and the total gain drops accordingly. This reduction in total gain affects the system response to the correction factor, as fewer gyrotrons are available to compensate for power deviations. To ensure stable control performance, the PI controller gain is scaled in real-time by the ratio of the initial total gain to the current total gain, accounting for changes in the number of active gyrotrons and their individual gains $K_{\mathrm{gyro},n}$. This allows robust performance across all operational scenarios, including transient failures.

Furthermore, to ensure safe operation, the accelerating voltage of each gyrotron is limited to an individual maximum value, preventing it from entering the mode-cutoff regime.

One drawback of this control scheme is that gyrotrons cannot operate at their maximum output power. To ensure that the controller can compensate for gyrotron failures, each gyrotron must operate below its maximum power to provide headroom for redistribution. If i out of N gyrotrons fail simultaneously, the remaining gyrotrons must increase their output to maintain the total power P_{tot}. For simplicity, it is assumed that all gyrotrons have the same the maximum output power P_{max}. Under this assumption, the nominal operating power P_{nom} for each gyrotron is derived from the requirement that the total power remains constant:

$$P_{\mathrm{tot}} = N P_{\mathrm{nom}} = \left(N - i\right) P_{\mathrm{max}} .$$

Solving for P_{nom} results in

$$P_{\mathrm{nom}} = \frac{(N-i)}{N} P_{\mathrm{max}}.$$

The reserve power per gyrotron is then

$$P_{\mathrm{res}} = \frac{i}{N} P_{\mathrm{max}}.$$

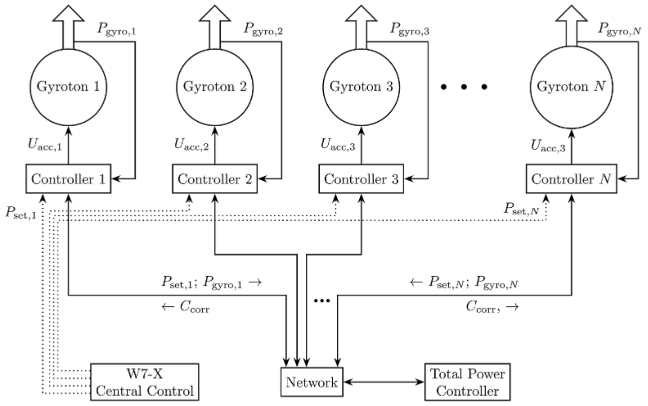


Figure 4. Implementation of the total power controller.

This reserve ensures that the system can maintain P_{tot} even if up to i gyrotrons fail simultaneously. This trade-off reduces the maximum available total ECRH power but improves reliability, which is critical for long-pulse operation.

The implementation of the total power control system is shown in figure 4. The total power controller is implemented as a distributed control system with the following architecture:

- Gyrotron-level controllers 'Controller 1… N': each gyrotron is controlled by a dedicated FPGA, which handles the setpoints for the cathode and body voltages (summing up to $U_{\text{acc},1,\ldots N}$), monitors interlocks, and reads the actual gyrotron power $P_{\text{gyro},1,\ldots N}$. The gyrotron millimeter-wave power is measured using a calibrated diode detector. The 'W7–X central control' sends the respective power setpoint $P_{\text{set},1,\ldots N}$. to the corresponding gyrotron controller. Each gyrotron controller multiplies the nominal accelerating voltage setpoint of its gyrotron by the received correction factor to update the applied accelerating voltage.
- 'Total power controller': the system-level control loop runs on a Raspberry Pi with a real-time Linux operating system. The power controller calculates the correction factor C_{corr} based on the total power error ΔP. The control loop operates with a 1 ms update rate, enabling rapid compensation for fluctuations in total power while keeping each gyrotron within its safe operating regime
- Data communication: Control data (including the set and actual power of each gyrotron $P_{\text{gyro},1,\ldots N}$, and the computed correction factor C_{corr}) are transmitted via local area network (LAN) between the Raspberry Pi and the gyrotron controllers.

The total power controller is integrated into the W7-X segment control system [26]. Within this system, power control can be activated for each gyrotron, and the respective power setpoint can be specified. Furthermore, the time window during which the controller should be enabled can also be specified.

This distributed implementation allows real-time control of the total ECRH power, fast response to individual gyrotron disturbances, and flexibility for future extensions, such as ECRH-based density feedback control.

4. Experimental results

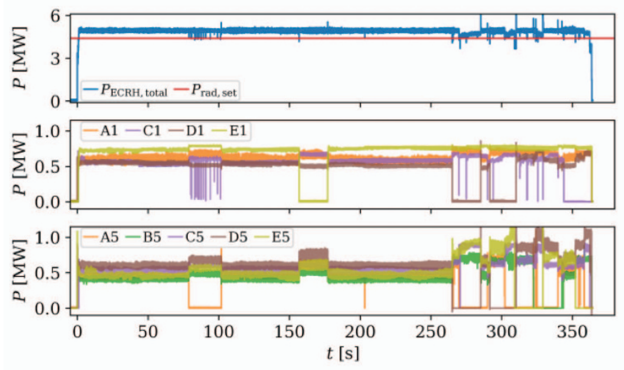
The total ECRH power controller was successfully used in OP 2.2. and OP 2.3 for plasma pulses longer than 15 s. Its capability was demonstrated in a 360 s detached-divertor experimental program (ID 20 250 520.011). Detached plasma operation minimizes heat loads on the divertor through enhanced radiation at the plasma edge. Nine gyrotrons were used in the program with a set total power of 4.9 MW. Accordingly, the total radiated power was feedback controlled at a level of $P_{\text{rad,set}} = 4.5$ MW using the divertor gas inlet as actuator. To prevent a radiative plasma collapse, the absorbed ECRH power must be higher than the radiated power. Since the radiated power is only slightly below the set total ECRH power, the shutdown of a single gyrotron longer than the plasma energy confinement time (in the range of hundreds of milliseconds [27]) will lead to a premature end of the plasma program. During the experiment, multiple gyrotrons had a temporary shutdown for durations longer than ten seconds.

Figure 5 shows the output power of the individual gyrotrons and the resulting total ECRH power during the 360 s plasma program. Despite the shutdown of multiple gyrotrons, the total power remained stable and above the set radiated power.

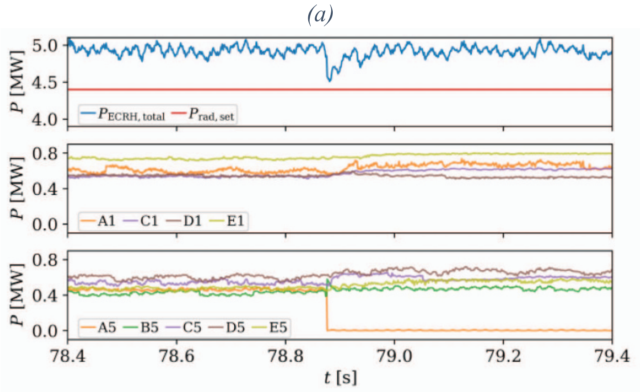
The first shutdown occurred for gyrotron A5 after 78 s, triggered by an interlock due to cathode overcurrent. The controller reacted and increased the output power of the other gyrotrons. The total power reaches its nominal power within 100 ms, which is faster than the energy confinement time as shown in figure 5(*b*). After the interlock was manually checked and resolved, the A5 gyrotron was restarted after 35 s and emitted at its nominal power. The controller noticed the increased total power and decreased the output power of the other gyrotrons. A similar event occurred at 160 s, where gyrotron E1 experienced an interlock due to body overcurrent.

After 265 s, multiple gyrotrons had to shutdown due to mode loss, overcurrent and arcing in the transmission line. The gyrotrons were manually restarted after several tens of seconds. Figure 5(*c*) shows how many gyrotrons were down simultaneously. The controller managed to keep the requested total power for up to two simultaneous gyrotron shutdowns. For three simultaneous shutdowns, the total power could be kept above the set radiation power. A drop in total power is noticeable, since the remaining gyrotrons are running at their maximum output power. With four simultaneous shutdowns, the total power drops below the set radiated power. Up until 365 s, the total power controller prevented plasma decay and the plasma program was not interrupted. At 365 s, all gyrotrons were shutdown, because the maximum allowed temperature of the gyrotron cooling water inlet was reached.

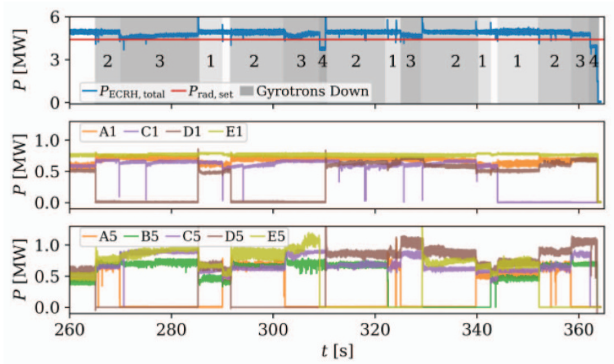
The experiment demonstrates the ability of the controller to redistribute power among active gyrotrons while respecting individual operating limits. Each gyrotron accelerating voltage was automatically adjusted, and saturation at the predefined maximum accelerating voltage prevented operation beyond safe voltages.



(a)



(b)



(c)

Figure 5. Total ECRH power and individual gyrotron output power during experiment ID 20 250 520.011. (*a*) Full 360 s discharge, (*b*) zoom on gyrotron A5 failure at 78 s, (*c*) zoom on multiple gyrotron failures after 265 s. The total power (black line) remains stable despite individual gyrotron shutdowns.

The experiment demonstrates that system-level total power control is essential for reliable, high-performance, long-pulse operation at W7-X, particularly under conditions where multiple gyrotrons may be unavailable for extended periods. The reliability of the total power controller was validated in multiple long-pulse experiments. Key observations include:

- Stability: the controller maintained the total ECRH power at its setpoint during steady-state operation, even with transient gyrotron failures.

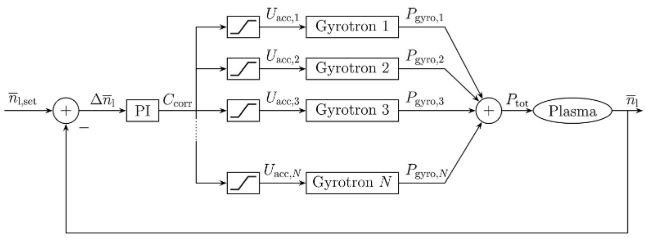


Figure 6. Control diagram for the ECRH density feedback system.

- Robustness: the chosen PI gains prevented closed-loop instability, resulting in stable, oscillation-free operation.
- Actuator limits: the controller respected the maximum accelerating voltage limits for each gyrotron, preventing operation in the mode-cutoff regime. When a gyrotron reached its limit (e.g. during compensation for a gyrotron failure), the remaining gyrotrons continued to redistribute power until the reserve was exhausted.
- Failure handling: the system gracefully handled hardware interlocks (e.g. arcing, mode loss) by excluding failed gyrotrons from the control loop and redistributing their power among the remaining units.

5. ECRH density feedback

Beyond stabilizing the total injected power, the system-level controller enables new applications in plasma-performance optimization. One promising application is the regulation of the plasma density using the ECRH pump-out effect. In high-performance plasma scenarios at W7-X with a combination of NBI and ECRH [28], the central fueling capabilities of NBI allows generating peaked density profiles which can be controlled or even destroyed by central ECR heating. Within a specific ratio of NBI and ECRH power [29], the line-integrated density follows the central density and can be used as control parameter for the ECRH power to keep the plasma in the optimal operation regime. If the ECRH power is too high, the plasma loses density over time; conversely, if the ECRH power is too low, the plasma density increases further due to the continuous NBI fueling. For each plasma scenario with a different NBI power or different magnetic field configuration, there exists a specific ECRH power level that maintains a constant density. Until now, the ECRH power has been set feedforward, but even small mismatches between the prescribed and required power lead to a slow drift of the plasma density. A feedback system can compensate such drifts by continuously adjusting the ECRH power in response to the measured density.

Figure 6 shows the new control diagram, where the feedback variable is the line-integrated density $\bar{n}_l$, which is available as a real-time measurement. Apart from this new input, the overall control architecture is identical to the one shown in figure 3, with the total power controller operating as the actuator for the density-feedback loop.

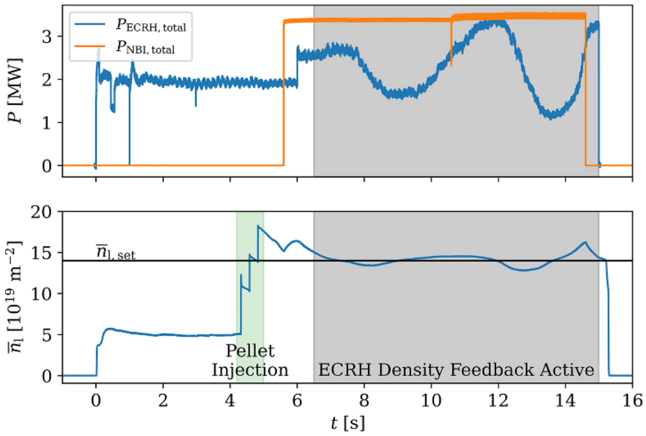


Figure 7. Experiment ID 20 250 424.042 with ECRH density feedback.

A dedicated proof-of-principle experiment (ID 20 250 424.042) was carried out in OP 2.3 to evaluate whether the total ECRH power could serve as an effective actuator for controlling the line-integrated plasma density. In this experimental program, both NBI and ECRH were applied simultaneously. Figure 7 shows the behavior of the controller. During the first 4 s, the target plasma is initialized and stabilized at an ECRH power of 2 MW. Between 4.3 s and 4.9 s three cryogenic hydrogen pellets are injected to rapidly generate a peaked density profile which is maintained afterwards by NBI fueling starting at 5.5 s. At 6.0 s, the ECRH power was set feedforward to 2.5 MW, which is a predefined level aimed to achieve the set density of $\bar{n}_{\mathrm{l}} = 14 \cdot 10^{19}\ \mathrm{m}^{-2}$.

The ECRH density feedback is enabled at 6.5 s. Upon activation, the actual density was higher than the setpoint, and the controller slightly increased the ECRH power to decrease the density. By $t = 7.0$ s, the density reached the setpoint, but continued to decrease because of finite plasma response time, prompting the controller to correspondingly reduce the ECRH power after 7.5 s. At 8 s, the actual density increases and crosses the set density at 9 s, where the controller increases the ECRH power again to keep the density at its setpoint, and the cycle repeats itself. The feedback system consistently attempts to steer the line-integrated density toward the prescribed setpoint. However, due to the delay of the density response, the system does not converge to a steady equilibrium but instead produces bounded oscillations around the target value. For safety reasons, the maximum ECRH power was set to 3.2 MW.

This experiment demonstrates that the controller reacts correctly to deviations in line-integrated density and that the plasma responds to the commanded changes in total ECRH power with the expected sign and timescale. While the present controller gains and operational constraints do not yet yield stable regulation, these initial results confirm that total ECRH power is a viable actuator for density control. Future experiments will focus on optimizing controller parameters to achieve fully stable density regulation.

6. Conclusion and outlook

In this work, a new system-level controller for the W7-X ECRH system was developed and successfully deployed during OP 2.2 and OP 2.3. The controller provides a framework for regulating the total injected ECRH power while respecting actuator limits, interlocks, and operational constraints. By coordinating all gyrotrons through a common control law, the system ensures stable power delivery even during transient events such as gyrotron failures. During OP 2.2 and OP 2.3, the controller successfully maintained a constant total power output, even when two gyrotrons experienced interlocks simultaneously. When three gyrotrons failed simultaneously, a noticeable drop in total power occurred, but the output power still remained above the radiated power. These capabilities significantly improve the robustness and flexibility of ECRH operation and form the basis for more advanced plasma-performance control.

A key implication of this control scheme is the trade-off between reliability and maximum power output. To compensate for up to i simultaneous gyrotron failures, each gyrotron must operate below its maximum power, holding a fraction of its capacity in reserve. While this reduces the total available power, it ensures uninterrupted operation during transient failures, which is a critical requirement for long-pulse experiments. In future devices like ITER or DEMO, where N is larger, the fractional reserve could be reduced, depending on how many simultaneous gyrotron failures need to be compensated.

Beyond power stabilization, the new controller enables the use of the total ECRH power as an actuator for higher-level physics objectives. As a first demonstration of this capability, a proof-of-principle experiment was conducted in which the line-integrated plasma density was regulated using the ECRH pump-out effect. The experiment confirmed that the plasma density responds reliably and with the expected sign to modulation of the total ECRH power commanded by the feedback system. Although the initial controller parameters did not yet permit stable regulation, the experiment validates the fundamental principle and establishes the feasibility of density control using ECRH.

Acknowledgment

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

ORCID iDs

L. Krier 0000-0003-0627-1074
D. Moseev 0000-0001-7955-8565
J.W. Oosterbeek 0009-0000-1775-4501
S. Ponomarenko 0000-0002-6993-9329
T. Reichert 0009-0004-8778-6700
T. Stange 0000-0003-4154-1455
L. Versemann 0009-0006-9585-3859
R.C. Wolf 0000-0002-2606-5289

References

[1] Beidler C. *et al* 1990 Physics and engineering design for Wendelstein VII–X *Fusion Technol.* **17** 148–68
[2] Endler M. *et al* 2021 Wendelstein 7-X on the path to long-pulse high-performance operation *Fusion Eng. Des.* **167** 112381
[3] Erckmann V. *et al* 2007 Electron cyclotron heating for W7-X: physics and technology *Fusion Sci. Technol.* **52** 291–312
[4] Wolf R.C. *et al* 2018 Electron-cyclotron-resonance heating in Wendelstein 7-X: a versatile heating and current-drive method and a tool for in-depth physics studies *Plasma Phys. Control. Fusion* **61** 014037
[5] Lazerson S.A. *et al* 2021 First neutral beam experiments on Wendelstein 7-X *Nucl. Fusion* **61** 096008
[6] Ongena J. *et al* 2023 Physics design, construction and commissioning of the ICRH system for the stellarator Wendelstein 7-X *Fusion Eng. Des.* **192** 113627
[7] Feng Y., Beidler C.D., Geiger J., Helander P., Hölbe H., Maassberg H., Turkin Y. and Reiter D. 2016 On the W7-X divertor performance under detached conditions *Nucl. Fusion* **56** 126011
[8] Krychowiak M. *et al* 2023 First feedback-controlled divertor detachment in W7-X: experience from TDU operation and prospects for operation with actively cooled divertor *Nucl. Mater. Energy* **34** 101363
[9] Tsujimura T. *et al* 2020 Real-time control of the deposition location of ECRH in the LHD *Fusion Eng. Des.* **153** 111480
[10] Felici F., Goodman T.P., Sauter O., Canal G., Coda S., Duval B.P. and Rossel J.X. 2012 Integrated real-time control of MHD instabilities using multi-beam ECRH/ECCD systems on TCV *Nucl. Fusion* **52** 074001
[11] Galperti C., Boncagni L., Alessi E., Sozzi C., Nowak S., Granucci G., Minelli D. and Marchetto C. 2014 Testing and commissioning the multinode ECRH realtime control system on the FTU tokamak *Fusion Eng. Des.* **89** 214–23
[12] Pastore F. *et al* 2026 Applications of a novel model-based real-time observer for electron density profile control experiments in TCV (arXiv:2603.26310)
[13] Blanken T.C., Felici F., Galperti C., Vu N.M.T., Kong M., Sauter O. and de Baar M.R. 2019 Real-time plasma state monitoring and supervisory control on TCV *Nucl. Fusion* **59** 026017
[14] Carannante G., Cavinato M., Cindric K., Ferrari M., Ferrò G., Cabrita Neto A. and Sartori F. 2023 Status of the ITER ECRH&CD control system development *EPJ Web Conf.* **277** 04005
[15] Braune H. *et al* 2007 Architecture of central control system for the 10 MW ECRH-plant at W7-X *Fusion Eng. Des.* **82** 677–85
[16] Wilde F. *et al* 2019 Automated mode recovery for gyrotrons demonstrated at Wendelstein 7-X *Fusion Eng. Des.* **148** 111258
[17] Krier L. *et al* 2025 Overview on active measures to increase the reliability of megawatt-class gyrotrons at Wendelstein 7-X *50th Int. Conf. on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)* (*Helsinki, Finland*, *17–22 August 2025*) (https://doi.org/10.1109/IRMMW-THz61557.2025.11319875)
[18] Erckmann V. and Gasparino U. 1994 Electron cyclotron resonance heating and current drive in toroidal fusion plasmas *Plasma Phys. Control. Fusion* **36** 1869
[19] Lloyd B. 1998 Overview of ECRH experimental results *Plasma Phys. Control. Fusion* **40** A119
[20] Ponomarenko S. *et al* 2024 Experimental results of the novel 1.5-MW-Class 140-GHz continuous-wave gyrotron for the Wendelstein 7-X Stellarator *IEEE Electron Device Lett.* **45** 2550–3
[21] Thumm M. *et al* 2007 EU megawatt-class 140-GHz CW gyrotron *IEEE Trans. Plasma Sci.* **35** 143–53
[22] Blank M., Felch K., Borchard P., Cahalan P., Cauffman S.R., Chu T.S. and Jory H. 2004 Demonstration of a high-power long-pulse 140-GHz gyrotron oscillator *IEEE Trans. Plasma Sci.* **32** 867–76
[23] Leggieri A. *et al* 2025 Breaking the megawatt barrier in the millimeter wave band for continuous wave devices: test results of the THALES TH1507U 140 GHz 1.5 MW CW industrial gyrotron *2025 26th Int. Vacuum Electronics Conf. (IVEC)* (*Rotterdam, Netherlands*, *14–17 April 2025*) pp 1–2
[24] Kasparek W. *et al* 2005 Status of the 140GHz, 10MW CW transmission system for ECRH on the stellarator W7-X *Fusion Eng. Des.* **74** 243–8
[25] Braune H. *et al* 2005 HV-system for CW-gyrotrons at W7-X and the relevance for ITER *J. Phys.: Conf. Ser.* **25** 56
[26] Laqua H. *et al* 2017 Experiences with the segment control system at Wendelstein 7-X operation *Fusion Eng. Des.* **123** 588–92
[27] Yamada H. *et al* 2005 Characterization of energy confinement in net-current free plasmas using the extended International Stellarator Database *Nucl. Fusion* **45** 1684
[28] Langenberg A. *et al* 2024 Achieving stationary high performance plasmas at Wendelstein 7-X *Phys. Plasmas* **31** 052502
[29] Ford O.P. *et al* 2024 Turbulence-reduced high-performance scenarios in Wendelstein 7-X *Nucl. Fusion* **64** 086067