

Stable Small Plasmas at the Density Limit in the W7-X Stellarator

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Experiments in the Wendelstein 7-X (W7-X) stellarator with plasma density beyond the established density limit in stellarators [Scalings of energy confinement and density limit in stellarator/heliotron devices, *Nucl. Fusion* **30**, 11 (1990).] resulted in unusual, reduced size, fully radiative plasmas lasting stably for many confinement times [Small, stable plasmas, fully decoupled from the plasma-facing components in W7-X, *Stellarator News* **175**, 1 (2021).]. In these experiments, the plasma had shrunk to a significantly smaller minor radius due to intense edge radiation from a radiating mantle and had no contact with material components, yet it remained relatively well confined for many confinement times with electron temperatures on the order of 1 keV. To our knowledge, this is the first definitive experimental long-time stability demonstration of such high-temperature contactless plasmas in the laboratory. It is shown that the onset and extent of this fully radiative small plasma state is predictable. The stability of the plasma size is elucidated with a simple power-balance model. In other helical devices such as the Large Helical Device (LHD) and the Wendelstein 7-AS (W7-AS), plasmas that start shrinking suffered from core impurity accumulation leading to a collapse whereas this was generally not observed for these W7-X plasmas.

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Introduction—Sustained fusion process in a laboratory deuterium-tritium plasma requires that the plasma meets the Lawson criterion [2], which sets a threshold on the product of plasma density (n_e), ion temperature (T_i), and energy confinement time (τ_E) for self-heating by fusion-born alpha particles. While reaching the required T_i is essential, increasing n_e is especially attractive, as it boosts the triple product without reducing τ_E [3] and minimizes plasma-wall interactions [4]. Unfortunately, n_e in magnetic confinement devices is limited by stability constraints. In tokamaks, exceeding this limit often leads to disruptive terminations [5–7], while in stellarators it typically results in radiative collapses [8,9]. In the W7-X stellarator, however, we observe a different outcome: the plasma shrinks and enters a fully radiative regime, which is fully detached

from the walls while remaining stably sustained by external heating. In this context, a simple model for detachment in stellarators by Itoh *et al.* showed that the plasma radius is proportional to the ratio of input power and line averaged density [10].

In the experiments exploring the density limit in the Large Helical Device (LHD), edge impurity radiation increased with plasma density, leading to an initial plasma shrinkage followed by a collapse [8]. As reported in Ref. [11] “The radiation is also enhanced as the hot plasma column shrinks leaving an increasingly larger volume of low temperature plasma in which the light impurities radiate strongly.” This drove the plasma into power starvation, shrinking, and collapse. Impurity accumulation in the core of these discharges, potentially caused by a negative radial electric field, may have played a role in the terminations of these discharges [12]. Similar observations were reported from W7-AS, where the centrally peaked impurity profile caused by inward pinching led to peaked radiation profiles. This led to rapid discharge termination from radiation instability once a density threshold was exceeded. Some plasma contraction was also reported prior to collapse [9,13].

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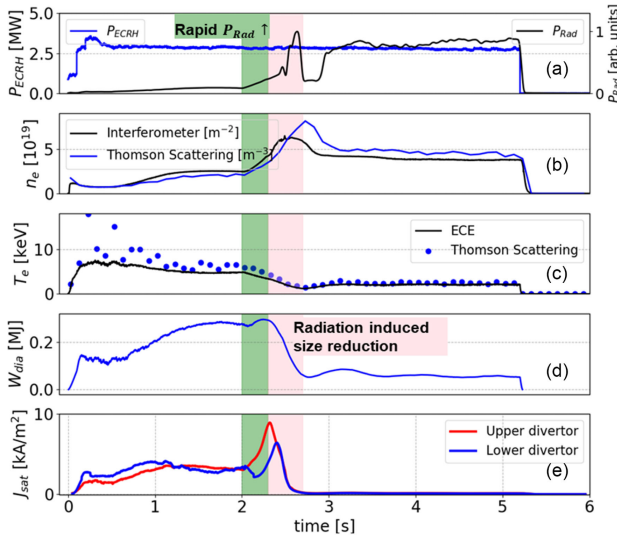


FIG. 1. Overview of the plasma discharge 20171207.021. The temporal evolution of (a) input power and radiated power, (b) n_e from Thomson scattering (TS) and interferometer, (c) central T_e from TS and ECE diagnostic, (d) diamagnetic energy in the plasma are shown, and (e) averaged ion saturation current measured by the lower and upper divertor LPs.

Electron cyclotron resonance heated (ECRH) plasmas in the W7-X stellarator can exceed both the Sudo limit and the W7-X-specific density limit [14]. Rather than undergoing a radiation collapse, the plasma contracts and enters a fully radiative regime. In this contracted state, it can remain stable for hundreds of confinement times, as first described in Ref. [15]. This small plasma maintains high central electron temperatures (T_e) and n_e while the plasma minor radius shrinks to values ranging between 62% and 82% of the original. In some cases, as the plasma shrinks, core T_e drops due to enhanced radial transport driven by gradients and the low- T_e radiating mantle (5–50 eV). When central T_e drops below ~ 500 eV and n_e below $\sim 5 \times 10^{19} \text{ m}^{-3}$, ECRH absorption becomes inefficient, initiating a cooling-feedback loop that leads to collapse.

We highlight the key experimental characteristics of small plasmas, present a simplified power balance to elucidate the underlying physics, and compare the results with a density-limit scaling law [14]. Finally, we discuss the broader implications and applications in future stellarator scenarios.

Observations—The time evolution of discharge 20171207.021 is shown in Figs. 1 and 2. Figure 1 provides an overview of the plasma parameters, while Fig. 2 shows snapshots from the video camera diagnostic (VCD), with field lines corresponding to the nominal vacuum last closed flux surface (LCFS) overlaid on the plasma images. Initially, the plasma has a full-sized minor radius of ~ 0.51 m. A gas puff starts at $t = 2$ s, leading to increased edge radiation [Fig. 2(a)]. This results in radiated power rising more rapidly than the plasma density [Figs. 1(a) and

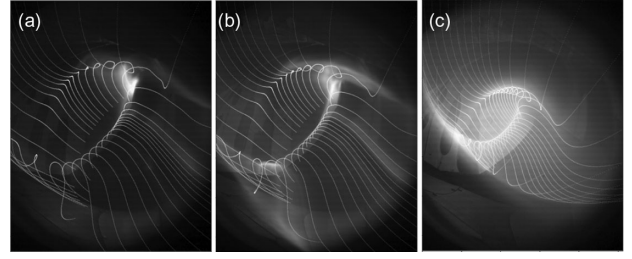


FIG. 2. Snapshots of the plasma cross section captured by the VCD at different time instances. (a) $t = 2$ s. (b) $t = 2.3$ s. (c) $t = 2.7$ s.

1(b)], indicating radiation instability [8]. At $t = 2.3$ s, as the line-averaged density approaches the Sudo limit [$5.5 \times 10^{19} \text{ m}^{-3}$; Fig. 1(b)], the edge radiation intensifies [Fig. 2(b)], triggering a contraction of the plasma. This is marked by a decline in W_{dia} [Fig. 1(d)], indicating that the plasma radius has receded inside the LCFS. Although the gas puff is stopped, the density continues to rise, and plasma reaches its minimum radius at $t = 2.7$ s [Fig. 2(c)].

The plasma is effectively contactless at this point. This is evident from the time trace of the ion saturation current, representing the ion flux on the divertor, averaged across all Langmuir probes in the upper and lower divertors [Fig. 1(e)]. The ion flux initially increases sharply following the strong gas puff at $t = 2.3$ s but subsequently decreases rapidly, approaching nearly zero in the small plasma phase.

Before W_{dia} begins to drop, $\tau_E \approx 104$ ms. The plasma radius goes down from ~ 0.51 m at $t = 2$ s to ~ 0.29 m at $t = 2.7$ s. Afterwards, the plasma attains more or less a stable radius with $\tau_E \approx 28$ ms. τ_E is reduced to 27% of its full sized plasma value. From ISS04 scaling, the dependence of confinement time on the minor radius (a) of the plasma is $\tau_{E,\text{small}}/\tau_{E,\text{full}} = (a_{\text{small}}/a_{\text{full}})^{2.28} = (0.3/0.51)^{2.28}$. The subscripts “full” and “small” represent full-sized and small plasma phases, respectively. The reduction in τ_E expected from this scaling is about 30%. Thus, the observed reduction in τ_E is only 10% lower than expected from the ISS04 scaling. This indicates that the small plasmas in the W7-X stellarator are not poorly confined but are simply reduced in size. The plasma has a central $n_e = 6 \times 10^{19} \text{ m}^{-3}$ and a central $T_e \sim 2.5$ keV. T_e and n_e profiles from Thomson scattering (TS) are shown in Fig. 3 for the full-sized, the smallest, and stable small plasma phases. The central T_e drops below 2 keV in the smallest phase, while the central n_e remains high. During the transition to the small plasma phase, the density profile becomes centrally peaked at $t = 2.7$ s but flattens again after the transition ($t = 4.2$ s), accompanied by a slight increase in central T_e . The mechanism behind this profile shape change remains an open question.

Radiating mantle, power balance, and stability—When the plasma is full sized but detached, it extends to (and

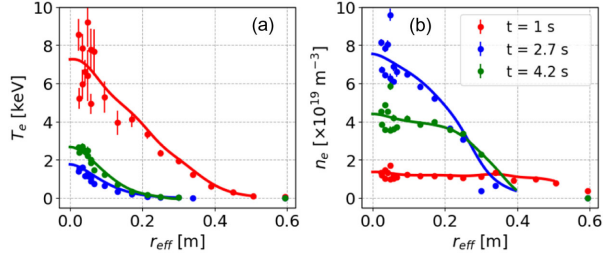


FIG. 3. Radial profiles of (a) plasma temperature and (b) plasma density in the plasma core plotted at three time instances. Because of the low signal-to-noise at very low densities, unreliable measurements for $r_{\text{eff}} > 0.35$ m are not plotted.

slightly beyond) the LCFS and the radiation zones (RZs) reside near the X points [4]. Figure 4 shows the 2D inversion of the plasma radiation measured by the bolometers at $t = 3.2$ s. The plasma has a continuous fully surrounding radiating mantle around it, far away from any X point as shown in Fig. 4.

To understand plasma stability at a specific minor radius, we construct a simple power-balance model. We assume that all the radiation originates from the surrounding radiating mantle postshrinkage, and neglect core radiation losses. This is corroborated by data from the coherence imaging spectroscopy (CIS) shown in Fig. 5 (the CIS camera PoV is rotated 45° clockwise). The dashed vertical lines on the left and right sides of the subfigures, indicate the approximate locations of the lower (labeled LD) and upper divertors (UD), respectively. Figure 5 shows CIII emissions moving inward at 2.4 s [Fig. 5(a)], forming an intense radiating mantle from 2.6 to 2.7 s [Fig. 5(b)], then weakening by 2.7 s [Fig. 5(c)] as the plasma regains volume (see the W_{dia} signal in Fig. 1). Figure 6 shows radial radiation profiles at different times. At $t = 1$ s, there is some radiation beyond the LCFS ($r = 0.51$ m), while by $t = 3.2$ s, the peak is well inside the LCFS. The FWHM of a Gaussian fit on the radiation profile at $t = 3.2$ s yields the radiating mantle thickness, $t_{\text{rad}} \approx 0.05$ m, which remains stable once the plasma reaches a steady radius.

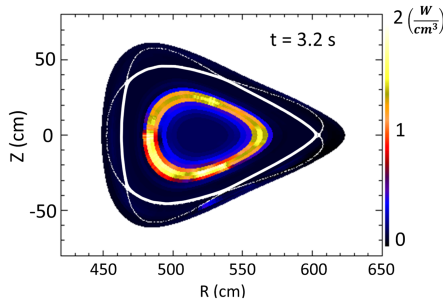


FIG. 4. 2D inversion of plasma radiated power from bolometer measurements at 3.2 s, showing a radiating mantle well inside the LCFS (thick white line).

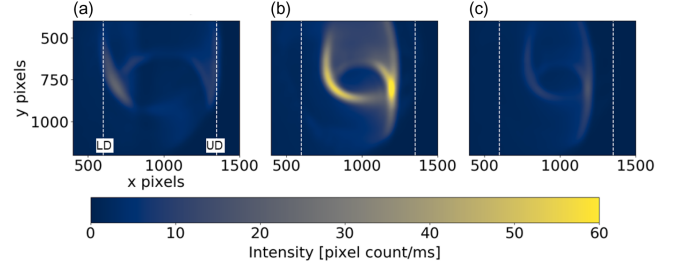


FIG. 5. Radiating mantle with CIII emissions, measured by coherence imaging spectroscopy. (a) $t = 2.4$ s. (b) $t = 2.6$ s. (c) $t = 2.7$ s.

Impurity accumulation is not observed in the small plasma phase. This likely results from a combination of limited plasma-wall contact, which reduces impurity sources, and core transport mechanisms that prevent impurity accumulation. While turbulent transport may play a significant role, a dedicated transport analysis is needed to confirm this. Low- Z impurities radiating from the edge may still enter the core, but their concentrations appear to remain low. This is supported by previous W7-X observations that in ECRH plasmas, impurity transport is dominated by turbulence [16–18].

The input power to the electrons in the RZ comes from perpendicular transport of heat flux from the center of the plasma. This can be modeled with the following simplified expression [4,19,20]:

$$Q_{\perp}(r) = \chi_{\perp} n_e(r) \frac{dT_e(r)}{dr} A_{\text{surf}}(r) = Q_{\perp}^*(r) n_e(r). \quad (1)$$

$\chi_{\perp}$ is the perpendicular heat diffusivity, $n_e(r)$ and $T_e(r)$ are the plasma density and the electron temperature, respectively, at radius r , and $A_{\text{surf}}(r)$ is the surface area of the magnetic surface at radius r . We estimate $\chi_{\perp}$, using the method used in the W7-AS [21] and W7-X stellarator [14], as $\chi_{\perp} = r_p^2 / \tau_E$, where r_p is the plasma minor radius. The plasma pressure and T_e are assumed uniform on a magnetic

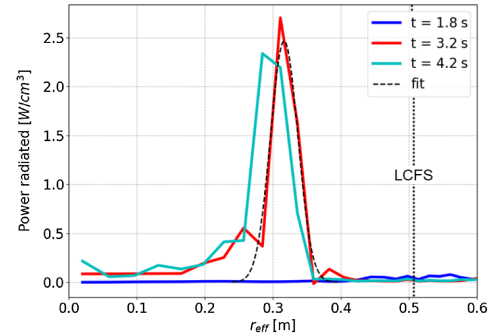


FIG. 6. Radial profile of plasma radiation at different time instances. In the small plasma phase, the radiation peak is inside the LCFS (shown in dotted vertical line). Black dashed curve shows the Gaussian fit on the radiation profile at $t = 3.2$ s.

surface inside the LCFS and therefore with that assumption, we do not need to resolve the parallel convection and conduction but need only concentrate on the perpendicular direction. The main energy loss channels in the RZ are radiation losses (Q_{rad}), ionization losses (Q_{ion}), and charge exchange losses (Q_{CX}) [22].

$$Q_{\text{loss}}(r) = Q_{\text{rad}}(r) + Q_{\text{ion}}(r) + Q_{\text{CX}}(r) \quad (2)$$

The individual loss terms in Eq. (2) are calculated using Eqs. (3)–(5).

$$\begin{aligned} Q_{\text{rad}}(r) &= n_e^2(r) f_{\text{imp}} L_z(T_e(r)) V(r) \\ &= Q_{\text{rad}}^*(r) n_e^2(r) \end{aligned} \quad (3)$$

where, f_{imp} is the impurity fraction calculated from the Z_{eff} value [14]: $f_{\text{imp}} = (Z_{\text{eff}} - 1)/[Z_{\text{imp}}(Z_{\text{imp}} - 1)]$. Z_{imp} is the average charge of the radiating impurities, which is a function of T_e [23]. Z_{eff} at different radial positions is obtained from Bayesian inference of Z_{eff} profiles from line integrated bremsstrahlung spectra [24], except for the discharge 20171207.021, for which the radial profile was not available but a mean Z_{eff} value is used. $L_z(T_e(r))$ is the radiation cooling intensity, which is a function of T_e at radius r . $V(r)$ is the volume of RZ at r , $V(r) = 2\pi R_0 A_{\text{rad}}(r)$ where, $R_0 = 5.5$ m is the major radius of the W7-X stellarator and $A_{\text{rad}}(r) = \pi[(r + t_{\text{rad}})^2 - r^2]$.

$$\begin{aligned} Q_{\text{ion}}(r) &= en_e^2(r) \langle \sigma_{\text{ion}} v \rangle f_n V(r) (E_{\text{ion}} \\ &\quad + T_i(r) + T_e(r) - 2T_n) = Q_{\text{ion}}^*(r) n_e^2(r) \end{aligned} \quad (4)$$

where, $\langle \sigma_{\text{ion}} v \rangle$ = ionization reaction rate obtained from the ADAS database [25]. In the RZ, it is assumed that $T_i = T_e$ and the neutral temperature, $T_n = 3$ eV [22]. Ionization and charge-exchange losses are small compared to radiation losses in detached plasmas [26], but are calculated for completeness. The neutral fraction, f_n , is the ratio of neutral particle density to plasma density. Neutral density is obtained from the neutral pressure measurements. Even though the neutral pressure measured near the walls does not represent the neutral pressure in the RZ exactly, we use it to get an estimate of the order of magnitude of the neutral particle density in the radiating mantle.

$$\begin{aligned} Q_{\text{CX}}(r) &= en_e^2(r) \langle \sigma_{\text{CX}} v \rangle (T_i(r) - T_n) f_n V(r) \\ &= Q_{\text{CX}}^*(r) n_e^2(r) \end{aligned} \quad (5)$$

Equating the sources with the losses yields a relation for the maximum plasma density which would be allowed for a given radius r .

$$n_{e,\text{max}}(r) = Q_{\perp}^*(r) [Q_{\text{rad}}^*(r) + Q_{\text{ion}}^*(r) + Q_{\text{CX}}^*(r)]^{-1} \quad (6)$$

To obtain $L_z(T_e(r))$, T_e inside RZ is needed, where TS measurements are uncertain. Shortly before the radiation

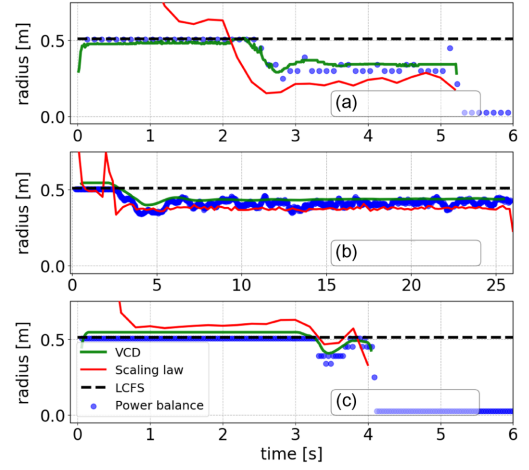


FIG. 7. Time evolution of the plasma radius from the VCD alongside the calculated plasma radius from the power balance model and density scaling for three plasma discharges. (a) 20171207.021. (b) 20180828.024. (c) 20180829.027.

zone reaches a given radial location, causing the TS measurement uncertainty to increase, the measured T_e there is ~ 10 eV. Moreover, given the radiated power's nonlinear dependence on plasma density, the T_e inside the RZ is in the “unstable” part of the radiation cooling curve [23]. In this discharge, oxygen and carbon are the primary impurities. As T_e falls, carbon, with its radiation peak at a lower T_e , is likely to become the dominant radiator. Using Eq. (6), we calculate the maximum allowable density, $n_{e,\text{max}}(r)$ at a particular r at this temperature. If the measured density is below this threshold, the radius is stable; otherwise, it contracts. Figure 7 shows these calculations for several small plasma experiments, along with plasma radius evolution from VCD and density limit scaling calculations, which will be discussed shortly. The VCD method measures the effective radius of the visible radiation belt at the plasma edge. It compares EDICAM images with synthetic images that represent the hypothetical radiation patterns of different flux surfaces. The method is described in detail in Ref. [27].

The radii calculated from power balance calculations align well with measurements from the VCD (Fig. 7). For three discharges, the plasma radius behavior is as follows: (a) it shrinks to ~ 0.3 m and stabilizes, (b) it shrinks slightly from 0.51 to ~ 0.42 m (82% of the full radius) and remains stable for over 20 s, and (c) it shrinks at ~ 3.5 s but recovers after fueling stops. The simple power balance model accurately identifies the onset of plasma shrinkage. However, its validity is restricted to nearly flat density profiles, and it may not accurately determine the plasma's final stable radius, since Eq. (1) is an approximation, which ignores the density gradient term [19].

Scaling law for small plasma radius—The power balance description in the last section is very similar to those used to derive stellarator density limit scaling laws [10,28].

In these models, for a given heating power, the density at which the plasma temperature falls to zero before reaching the actual minor radius of the vessel is identified as the density limit. Following this argument, the density of the small plasma should be identical to the critical density of a plasma with the minor radius equal to the radius of the small plasma (in the following referred to as the radiation radius, r_{rad}). It should, hence, be possible to take the scaling law for the density limit in the W7-X stellarator [14] and solve it for the minor radius. When applying this scaling, heat transport ($\chi \sim a^2/\tau_{E,\text{ISS04}}$ [14]) is estimated via the ISS04 scaling, which uses the device minor radius a (not the minor radius in the critical density model [10]). This is justified, as the actual plasma radius is not known *a priori*, and the overall transport remains similar in both full-size and contracted phases. This can be seen from the renormalization factor $f_{\text{ren}} = \tau_E/\tau_{E,\text{ISS04}}$, which is ~ 0.7 before contraction, and drops to ~ 0.2 after contraction (if device minor radius is used), mainly due to reduced plasma volume. Using the contracted plasma radius instead yields $f_{\text{ren}} \approx 0.6$, which is close to the initial value. Solving for r_{rad} then leads to the following scaling law:

$$r_{\text{rad}} = 0.25(P[\text{MW}])^{0.7}(\bar{n}_{e,19})^{-1.25}(f_{\text{imp}})^{-0.5}, \quad (7)$$

where $\bar{n}_{e,19}$ = line averaged density in the units of 10^{19} m^{-3} and $P[\text{MW}]$ = input power in MW. For the W7-X stellarator, it is found that $f_{\text{imp}} = 5\%$ is a good approximation for unboronized walls [Fig. 7(a)] and for boronized walls $f_{\text{imp}} = 2.5\%$ is used [Figs. 7(b) and 7(c)] for calculating r_{rad} . The exact value should be interpreted with caution, as it also compensates for potential simplifications in the radiation model used in deriving the density limit scaling (see Ref. [14]). Figure 7 compares the results from the scaling law with the power balance model and VCD observations. While the match is not perfect, the scaling law provides a quick and practical estimate of the transition onset and small plasma size. It reframes the density limit as a controllable power balance issue and shows that the transition is reversible rather than a termination event [see Fig. 7(c)], making it a useful tool for experiment planning.

Discussion—In the W7-X stellarator, remarkably, some discharges avoid collapse and remain stable due to the absence of significant impurity radiation in the core, which enables high central T_e and efficient ECRH power absorption. This behavior is attributed to the W7-X stellarator's optimization for reduced neoclassical transport [29] and turbulence-dominated impurity transport [16–18] preventing impurity accumulation. In contrast, in the devices like LHD and W7-AS the influx of impurities is believed to have caused core power losses and eventual radiation collapse. These plasmas in the W7-X stellarator are novel, being the first laboratory examples of stably confined plasmas with negligible contact with material objects.

They reduce plasma-wall interactions and mitigate lifetime issues [30,31] by uniformly distributing heat via photons and charge-exchange neutrals, lowering peak fluxes on plasma-facing components. The plasma minor radius is set by a power balance within nested flux surfaces. Such plasmas offer a promising platform for studying core behavior under varying magnetic field configurations without excessive heat loads, though this requires further investigation.

Power balance calculations indicate that during shrinkage, the plasma boundary becomes unstable when radiated power exceeds the power entering the radiation zone due to excessive edge density. This aligns with findings for the LHD [32], showing that edge plasma parameters are crucial for boundary stability in extreme detachment cases. A peaked density profile with lower edge density can stabilize the plasma boundary, beyond the density limit, as demonstrated by pellet injection in LHD [32] and the W7-X stellarator [33]. Therefore, plasma stability can, in principle, be controlled by adjusting parameters like heating power or neutral fueling to adjust the minor radius. The stability of these plasmas, along with their tunability and scalability as inferred from the scaling law, makes them promising for addressing the heat-flux exhaust challenge in stellarators, including at reactor scale, where economic constraints may not allow for a large radial gap between the plasma and the first wall. As shown in this Letter, these plasmas can operate predictably in a fully radiative regime, achieving stable configurations with only a modest contraction relative to the LCFS. This enables near-complete utilization of the plasma volume and outlines a clear research path toward addressing the power exhaust problem. However, a significant drawback exists: these plasmas, being fully decoupled from the divertor, lack efficient neutral compression. As a result, much larger pumping capacities or absorbing areas are needed to exhaust particles, such as helium, effectively. Additional research is also required to evaluate impurity screening and their potential for achieving high triple products at elevated core ion temperatures.

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from T. S. P. and G. F., and with data contributions from all co-authors. Review and editing were led by A. P., with contributions from T. S. P., F. R., and V. P.

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.

Data availability—The data that support the findings of this article are openly available [34].

- [1] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/cfg9-v8hf> for the members of the W7-X team.
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