

Optimizing particle transport for enhanced confinement in quasi-isodynamic stellarators

A. Bañón Navarro ^{*,†}, A. Di Siena ^{*,‡} and F. Jenko 

Max Planck Institute for Plasma Physics, Boltzmannstraße 2, 85748 Garching, Germany

A. Merlo  and E. Laude

Proxima Fusion, Flößergasse 2, 81369 Munich, Germany



(Received 30 July 2025; accepted 13 November 2025; published 21 April 2026)

Despite substantial advances in mitigating turbulent heat losses, including those achieved in the stable quasi-isodynamic design family [J. Plasma Phys. **89**, 905890504 (2023); PRX Energy **3**, 023010 (2024)], particle confinement remains a principal performance bottleneck in modern quasi-isodynamic stellarators, a challenge not fully addressed in previous optimization efforts. Using gyrokinetic simulations within the GENE-Tango framework, we identify suppressed inward thermodiffusion, caused by unfavorable magnetic geometry, as the primary cause. To overcome this limitation, we design a new configuration with a reduced mirror ratio, which enhances the contribution of passing electrons to the inward particle flux. This facilitates the formation of strongly peaked density profiles, suppresses turbulence, and leads to a substantial improvement in confinement. Our optimized configuration achieves nearly a twofold increase in energy confinement compared to Stellaris, highlighting the crucial role of optimizing particle transport in next-generation stellarator designs.

DOI: [10.1103/fbbl-ps5l](https://doi.org/10.1103/fbbl-ps5l)

Introduction. Understanding turbulent transport in stellarators has become increasingly important, especially in light of the substantial progress made over the past decades in optimizing neoclassical transport. Wendelstein 7-X (W7-X) exemplifies this advancement, having achieved significant reductions in neoclassical transport through careful magnetic configuration optimization, with turbulent transport now limiting overall confinement [1–3]. This success has led to a paradigm shift in stellarator design, where turbulent transport, previously neglected in optimization metrics, is now being actively included. Consequently, various optimization strategies have emerged, including minimizing flux compression in regions of unfavorable magnetic curvature [4,5], increasing the critical gradient for turbulence stabilization [6,7], reducing magnetic curvature itself [8–10], optimizing max- J configurations that confine trapped particles to regions of favorable curvature [11–14], and other approaches aimed at mitigating turbulent transport [15–17]. These turbulence optimization methods also require retaining essential features necessary for stellarator reactors, such as strong neoclassical and energetic particle confinement and reduced bootstrap current [12,18–21], MHD stability [22,23], favorable max- J

properties [24–26], and manageable coil complexity [21,27]. An example of this approach is the development of the stable quasi-isodynamic design (SQUID) stellarator configurations [5,18]. Their optimized magnetic geometry ensures excellent fast ion and neoclassical confinement, along with MHD stability, while simultaneously reducing turbulent transport.

These stellarator configurations, including the latest design for Stellaris, a fusion power plant concept by Proxima Fusion, the Max Planck Institute for Plasma Physics, and other academic partners, exhibit reduced turbulent transport, particularly in terms of heat fluxes [28]. However, a detailed understanding of particle transport in these highly optimized geometries remains an open question. Accurately predicting particle transport is essential for evaluating plasma performance, as it is closely coupled to heat fluxes through the plasma density profile, for example, via density gradient stabilization of ion temperature gradient (ITG) turbulence. To address this, we present the high-fidelity turbulence simulations of Stellaris with self-consistent density profiles, utilizing gyrokinetic flux-matching simulations performed with the GENE code [29] coupled to the Tango transport solver [30]. The GENE-Tango framework has been extensively validated in tokamak geometries across a variety of scenarios at ASDEX Upgrade [31,32] and JET [33], consistently demonstrating excellent agreement with experimental measurements. More recently, it has also been validated against four experimental scenarios on W7-X [34], establishing it as one of the most reliable tools currently available for predictive performance studies in stellarator configurations.

To benchmark Stellaris, we compare its performance to a reference W7-X plasma from the GENE-Tango validation study [34] of an electron cyclotron resonance heating discharge (1 MW) fueled by gas puffing (with a particle source

*These authors contributed equally to this work.

†Contact author: alejandro.banon.navarro@ipp.mpg.de

‡Contact author: alessandro.di.siena@ipp.mpg.de

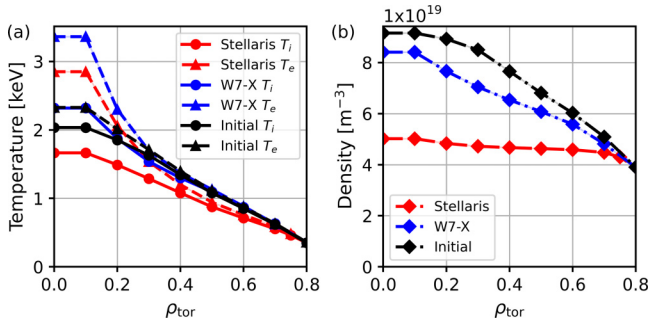


FIG. 1. (a) Ion and electron temperature profiles T_i and T_e , respectively. (b) Corresponding density profiles, all plotted as a function of the normalized radius ρ_{tor} . GENE flux-tube simulations are performed along the magnetic field line defined by $\alpha = q\theta^* - \phi = 0$, with ρ_{tor} ranging from 0.1 to 0.8 in steps of 0.1 for W7-X. For Stellaris, an additional point at $\rho_{\text{tor}} = 0.75$ is added to improve convergence near the boundary. Here q is the safety factor, θ^* is the PEST poloidal angle, and ϕ is the toroidal angle. The other stellarator-symmetric field line at the middle of the period was also tested, yielding similar results. Simulations use a resolution of $(128, 64, 192, 32, 12)$ in $(k_x, k_y, z, v_{\parallel}, \mu)$, where k_x and k_y are the radial and binormal wave numbers, z is the coordinate along the field line, $v_{\parallel}$ is the parallel velocity, and μ is the magnetic moment. The radial box size is $l_x \approx 128\rho_s$ and the minimum binormal wave number is $k_{y,\text{min}}\rho_s = 0.05$. We use generalized twist-and-shift boundary conditions [35] in the parallel direction with $n_{\text{pol}} \approx 1$ –1.5, depending on radius and configuration. The parallel velocity box size is $l_{v_{\parallel}} = 3\sqrt{2}v_i$ and for the magnetic moment $l_{\mu} = 9T_i/B_0$. We note that the local approach used here, which is much less computationally expensive than a global one, is justified by the small value of $\rho^* = \rho_s/a \approx 1/300$ – $1/700$ in these simulations, so radially global effects are expected to be minimal, as shown by previous studies [36,37], which demonstrate very good agreement with global results for similar ρ^* values in optimized stellarators, including W7-X.

of $4.5 \times 10^{20} \text{ s}^{-1}$) plus neutral beam injection (3 MW). The boundary conditions for ion and electron temperatures and density are fixed at the normalized toroidal flux radius $\rho_{\text{tor}} = 0.8$, where $\rho_{\text{tor}} = \sqrt{\Phi/\Phi_{\text{edge}}}$ is defined as the square root of the ratio of enclosed toroidal magnetic flux Φ to the total edge flux Φ_{edge} . From this location, plasma profiles are evolved inward to the magnetic axis until a steady state is reached, wherein turbulent transport matches the integrated external sources across all modeled channels and radii. For a fair comparison, we retain the plasma size and magnetic field strength from W7-X in both geometries, with a minor radius of $a = 0.5 \text{ m}$ and an on-axis magnetic field strength of $B_0 = 2.6 \text{ T}$. The resulting steady-state temperature and density profiles are shown in Fig. 1.

Surprisingly, despite Stellaris being specifically optimized to reduce turbulent transport, it achieves significantly lower central plasma pressure than W7-X. This reduction is primarily due to a significant degradation in particle confinement. As a result, while W7-X maintains a strong density gradient across the radial domain, Stellaris exhibits a pronounced collapse in plasma density. This density collapse also impacts the temperature profiles: With the density gradient largely vanishing, Stellaris loses the stabilizing effect that finite density gradients exert on ITG turbulence. Consequently, the temperature profiles in Stellaris become broader and less peaked compared to those in W7-X.

These results indicate that the prevailing focus on minimizing turbulent heat transport in optimization strategies neglects a key factor: effective control of the plasma density profile. As highlighted in recent W7-X experimental campaigns [38–40], maintaining a high core density is essential for achieving improved overall performance. This consideration becomes even more important for future stellarator reactors, where α particle heating scales with the core density. Devices capable of sustaining higher densities at similar temperatures may enter a positive feedback loop, where increased α heating further boosts central plasma pressure, ultimately enabling higher fusion performance.

Optimizing particle transport for enhanced confinement. In the following, we present a design strategy for stellarator configurations that simultaneously achieve exceptional particle and heat confinement. This is accomplished by combining established turbulence optimization methods with new insights into the physics of particle transport. In particular, we enhance the contribution of the mechanism responsible for the inward particle flux, enabling the formation of more peaked density profiles.

The underlying optimization strategy can be understood by analyzing the key dependences of the particle flux, assuming turbulence locality. This assumption is well supported by current experimental evidence and is expected to hold even more robustly in reactor-relevant regimes. Under this approximation, the electron particle flux Γ_e can be decomposed into diffusive, thermodiffusive, and convective components as follows:

$$\Gamma_e = D_e \frac{a}{L_{n,e}} + D_{T,e} \frac{a}{L_{T,e}} + aV_{p,e}. \quad (1)$$

Here D_e , $D_{T,e}$, and $V_{p,e}$ denote the diffusion, thermodiffusion, and convective transport coefficients, respectively, as defined in Refs. [41,42], and $a/L_{n,e}$ and $a/L_{T,e}$ are the normalized electron density and temperature gradients, defined as $a/L_X \equiv -a d \ln X / dr$, with X representing either n_e or T_e . For completeness, and given the central role of the thermodiffusion coefficient, we provide its definition explicitly:

$$D_{T,e} = \frac{k_y c_s^2}{\Omega_{ci}} \left\langle \int d^3v F_M \frac{(\gamma_k + \hat{v}_k)(\frac{v^2}{T_e} - \frac{3}{2})}{(\omega_k + \hat{\omega}_d)^2 + (\gamma_k + \hat{v}_k)^2} J_0^2(k_{\perp} \rho_s) |\hat{\phi}_k|^2 \right\rangle. \quad (2)$$

Here γ_k and ω_k are the normalized growth rate and real frequency of the unstable linear mode, respectively. The normal-

ized electrostatic potential is $\hat{\phi}_k = e\phi_k/T_e$ and the normalized magnetic drift frequency is $\hat{\omega}_d = (v_{\parallel}^2 + v_{\perp}^2/2)/v_{\text{the}}^2 \hat{\omega}_{Dk}$, where

$v_{the} = \sqrt{2T_e/m_e}$ is the electron thermal speed. The magnetic drift frequency is defined as $\omega_{Dk} = k_y \mathcal{K}_y c_s / a$, where k_y is the binormal wave number, $\mathcal{K}_y$ is the binormal curvature, and $c_s = \sqrt{T_e/m_i}$ is the ion sound speed, with T_e the electron temperature and m_i the ion mass. The normalized collision frequency is $\hat{\nu}_k = \nu_{ei} v_{the}^3 / v^3 \omega_{Dk}$, with ν_{ei} the electron-ion collision frequency. The (squared) total particle speed is defined as $v^2 = v_{\parallel}^2 + \mu B_0$. In addition, F_M denotes the Maxwellian distribution function, J_0 is the zeroth-order Bessel function of the first kind, and $k_{\perp} \rho_s$ is the normalized perpendicular wave number, with $\rho_s = c_s / \Omega_{ci}$ the ion sound gyroradius and $\Omega_{ci} = eB_0 / m_i$ the ion gyrofrequency. This expression neglects parallel motion and assumes a simple Krook collision operator, whereas the GENE simulations retain the full dynamics and employ a Landau-Boltzmann collision operator.

The diffusion term is always positive, representing outward transport. The thermodiffusive term is proportional to $v^2/T_e - 3/2$, leading to a larger outward flux of particles with large velocities and a compensating inward flux of slower particles. The resulting net thermodiffusive flux is determined by the balance of these contributions. Finally, the convective term is a purely geometric effect, arising from magnetic field curvature and inhomogeneities, and is often referred to as the curvature pinch. It can be directed either inward or outward depending on the microinstability and magnetic geometry in question.

Our strategy aims to enhance the inward thermodiffusive transport by increasing the contribution of slow electrons, those with normalized velocities $v^2/T_e < 3/2$, which preferentially drive the inward flux. This is achieved by combining two elements: increasing collisionality to suppress the trapped-particle population via detrapping and tailoring the magnetic geometry to reduce the mirror ratio, thereby increasing the passing-particle fraction. Together, these effects amplify the role of passing electrons in driving inward transport. This mechanism is clearly reflected in our numerical results.

Figure 2(a) shows how increasing collisionality influences particle transport in both W7-X and the Stellaris configuration. A clear trend emerges: The total particle flux decreases with collisionality. However, while W7-X exhibits a robust particle pinch, Stellaris saturates near zero flux and does not enter the pinch regime. To understand this difference, we decompose the total flux into contributions from passing and trapped particles. As is shown in Fig. 2(b), the inward flux in W7-X is predominantly carried by passing electrons, whose contribution is significantly larger than in Stellaris. This difference is directly linked to the magnetic geometry: W7-X's low mirror ratio (about 3.5% on axis) yields a larger passing-particle fraction, while Stellaris's much higher mirror ratio (about 25% on axis) results in a larger trapped population that contributes less effectively to inward transport. Thus, reducing the mirror ratio and increasing collisionality act in synergy to enhance inward thermodiffusion via passing electrons.

This trend is further illustrated in Fig. 2(c), which shows the particle flux for a set of magnetic configurations generated by systematically modifying the magnetic geometry to reduce the mirror ratio, from approximately 25% to 10%, while keeping other parameters fixed. For each configuration, the figure also displays the fraction of the total particle flux carried by passing electrons. The results clearly demonstrate that lowering the mirror ratio significantly strengthens the

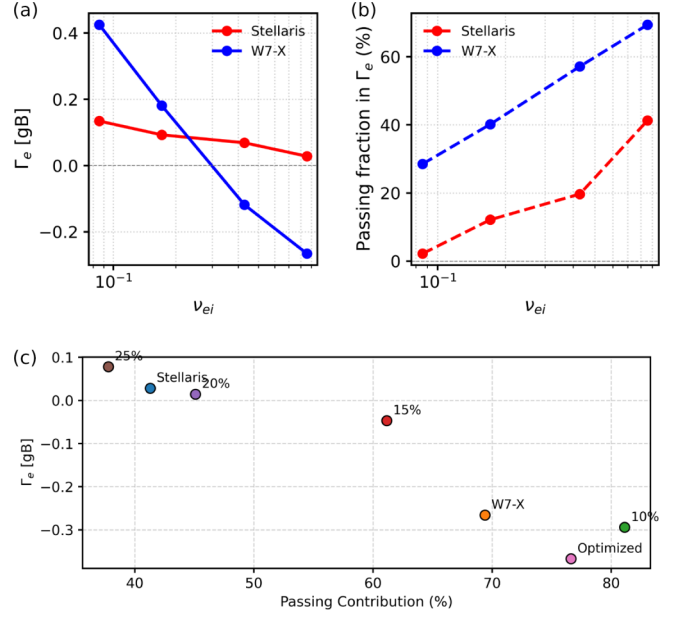


FIG. 2. (a) Total electron particle flux expressed in gyro-Bohm units $[gB] = n_e c_s \rho_s^2 / a^2$ as a function of collisionality ν_{ei} for values representative of the profiles shown in Fig. 1, comparing W7-X (blue) and Stellaris (red). (b) Decomposition of the particle flux into passing- and trapped-electron contributions for the same configurations and collisionalities, within the range obtained from the previously presented Tango simulations. (c) Inward particle flux versus mirror ratio across a series of configurations with varying on-axis mirror ratios (expressed in percent). The optimized configuration is designed to follow the radial mirror ratio profile of W7-X. A strong correlation is observed: Reducing the mirror ratio increases the passing-particle contribution and enhances the inward pinch. GENE flux-tube simulations were performed at $\rho_{tor} = 0.8$ using the same resolution as in the GENE-Tango simulations, but with profile parameters such as $a/L_{T,e} = a/L_{T,i} = 2.2$, $a/L_n = 0.5$, and $T_e/T_i = 1$.

inward particle pinch, with a growing share of the flux attributed to passing electrons. This behavior is robust: It holds across different radial positions and persists over the full range of collisionalities considered.

Density-optimized configuration. Building on these insights, we propose a density-optimized magnetic configuration designed to enhance inward thermodiffusion. This configuration has a significant lower overall mirror ratio compared to Stellaris. Consequently, it increases the population of slow passing electrons and maximizes the inward particle flux, particularly at the higher collisionalities relevant for future fusion devices.

This corresponds to the case shown in Fig. 2(c) (optimized), which exhibits the strongest negative particle flux. Our design aims to improve particle confinement and consequently suppress heat transport by producing strongly peaked density profiles. These profiles stabilize ITG turbulence through density gradient stabilization, leading to significantly enhanced overall performance. The optimized configuration is shown in Fig. 3. The optimization targets a configuration with aspect ratio $A^* = 11.5$, on-axis magnetic mirror ratio $\Delta^* = 5\%$, a vacuum magnetic well $W_{vacuum}^* = 1\%$. The rotational transform is constrained within $\iota \in [0.8, 1.0]$, and the flux

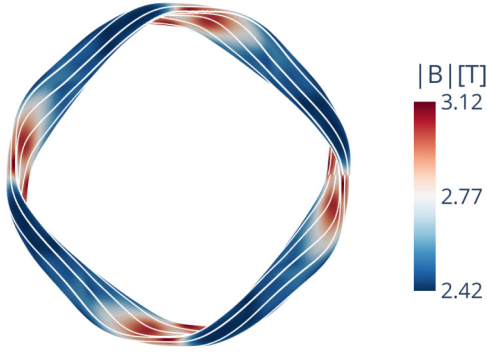


FIG. 3. Magnetic field strength at the plasma boundary of the optimized configuration. White lines represent magnetic field lines.

surface compression in regions of unfavorable curvature is kept below a reference value. Moreover, we minimize the deviation from a quasi-isodynamic field at midradius and at the plasma boundary following Ref. [5]. We use the ideal-MHD solver vmec++ [43] and solve the constrained optimization problem using an augmented Lagrangian method, employing covariance matrix adaptation evolution strategy as the inner oracle [44,45].

We assess neoclassical transport in the $1/\nu$ regime using the neo code [46] to compute the effective ripple ϵ_{eff} , which ranges from 0.1% at the magnetic axis to 1.2% at the plasma boundary. The configuration is stable according to the Mercier criterion and it possesses negative infinite- n ballooning growth rates up to a volume-averaged beta of $\langle\beta\rangle_V \simeq 2.0\%$. The α -particle confinement is evaluated using the SIMPLE code [47]. We simulate the trajectories of 5000 fusion-born α particles with a kinetic energy of 3.5 MeV, uniformly distributed in pitch angle and isotropically launched at midradius. Each trajectory is followed for 0.1 s. As is standard practice for this assessment, the configuration is scaled to the ARIES-CS design point [48]. Confinement improves with increasing plasma β : The loss fraction decreases from 20% at $\langle\beta\rangle_V = 2\%$ to 15% at $\langle\beta\rangle_V = 4\%$.

The performance of our density-optimized configuration is evaluated using GENE-Tango with the same setup employed for Stellaris. This ensures a fair comparison by matching the minor radius and magnetic field on axis. The results are presented in Fig. 4, demonstrating a substantial improvement across all modeled plasma profiles. In particular, the

optimized configuration achieves nearly a twofold increase in calculated energy confinement time compared to Stellaris. Ongoing work indicates that plasma performance can be retained or even improved while significantly enhancing MHD stability and fast-ion confinement.

Summary and discussion. In the present Letter we have identified particle confinement as a key performance bottleneck in modern turbulence-optimized stellarators, in particular within the SQUID family [5,18], a factor largely overlooked in previous optimization efforts. Using advanced gyrokinetic simulations within the GENE-Tango framework, we have demonstrated that this limitation can be overcome by maximizing the inward particle flux driven by thermodiffusion. We have designed a magnetic configuration with a significantly reduced mirror ratio compared to existing turbulence-optimized designs, thereby increasing the fraction of passing electrons responsible for the inward particle pinch. This enables the formation of strongly peaked density profiles.

The resulting density gradient stabilizes ITG turbulence, leading to substantial improvements in both particle and heat confinement. Our density-optimized configuration achieves nearly a twofold increase in energy confinement relative to Stellaris, for identical edge plasma parameters and heating conditions. These results highlight the critical role of particle transport optimization as a necessary complement to traditional approaches focused solely on turbulent heat flux reduction.

Future stellarator designs should incorporate particle transport optimization as a central objective, alongside heat transport reduction, to achieve the high core densities and robust confinement required for reactor-relevant performance. The optimization strategy proposed in this Letter offers a promising route toward this goal, enabling simultaneous control of heat and particle transport to surpass current performance limits. Our results strongly motivate continued theoretical and experimental investigations into particle flux control and the development of magnetic geometries that exploit key physical mechanisms for improved confinement and enhanced fusion performance.

Beyond the strategy presented in this Letter, additional pathways might be explored to further improve particle transport. For instance, the convective particle flux, strongly influenced by magnetic geometry, can be engineered to enhance the inward pinch [49]. Another promising direction

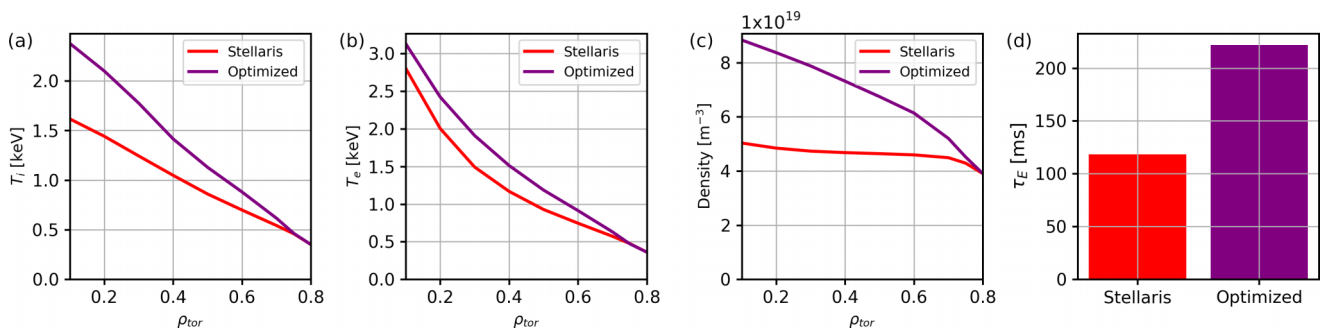


FIG. 4. Comparison of plasma profiles for the density-optimized configuration (purple) and Stellaris (red): the (a) ion temperature T_i , (b) electron temperature T_e , and (c) density n profiles. Also shown are (d) the calculated energy confinement times in milliseconds, demonstrating the performance improvement of the optimized configuration.

involves optimizing the denominator of the thermodiffusive term, which depends on the mode frequency, on the drift frequency, and, when including parallel dynamics, also on parallel streaming, which is proportional to the parallel wave number $k_{\parallel}$ [50]. In particular, increasing $k_{\parallel}$ to resonate with the frequency of the slow-passing electron population may further enhance inward transport. This can be achieved by increasing the local magnetic shear or by increasing the connection length through varying the number of field periods [51,52]. Together, these strategies define a broader class of stellarator optimization approaches, grounded in the physics of particle transport.

Acknowledgments. The authors would like to thank A. Zocco, F. Wilms, G. Merlo, D. Fernando, and R. Ramasamy

for useful discussions. The *Stellaris* magnetic equilibrium was authored by Alan Goodman and colleagues in the Stellarator Concepts Group; the data was obtained as part of the collaboration for Ref. [28]. Numerical simulations were performed on the Marconi Fusion supercomputer at CINECA (Italy), the Viper cluster at the Max Planck Computing and Data Facility (Germany), and the LUMI supercomputer at CSC (Finland).

Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

-
- [1] R. Wolf, A. Ali, A. Alonso, J. Baldzuhn, C. Beidler, M. Beurskens, C. Biedermann, H.-S. Bosch, S. Bozhnikov, R. Brakel, A. Dinklage, Y. Feng, G. Fuchert, J. Geiger, O. Grulke, P. Helander, *et al.*, Major results from the first plasma campaign of the Wendelstein 7-X stellarator, *Nucl. Fusion* **57**, 102020 (2017).
 - [2] T. Klinger, T. Andreeva, S. Bozhnikov, C. Brandt, R. Burhenn, B. Buttenschön, G. Fuchert, B. Geiger, O. Grulke, H. Laqua, *et al.*, Overview of first Wendelstein 7-X high-performance operation, *Nucl. Fusion* **59**, 112004 (2019).
 - [3] C. D. Beidler, H. M. Smith, A. Alonso, T. Andreeva, J. Baldzuhn, M. N. A. Beurskens, M. Borchardt, S. A. Bozhnikov, K. J. Brunner, H. Damm, M. Drevlak, O. P. Ford, G. Fuchert, J. Geiger, P. Helander, U. Hergenbahn, M. Hirsch, U. Höfel, Y. O. Kazakov, R. Kleiber, *et al.*, Demonstration of reduced neo-classical energy transport in Wendelstein 7-X, *Nature (London)* **596**, 221 (2021).
 - [4] S. Stroteich, P. Xanthopoulos, G. Plunk, and R. Schneider, Seeking turbulence optimized configurations for the Wendelstein 7-X stellarator: Ion temperature gradient and electron temperature gradient turbulence, *J. Plasma Phys.* **88**, 175880501 (2022).
 - [5] A. G. Goodman, P. Xanthopoulos, G. G. Plunk, H. Smith, C. Nührenberg, C. D. Beidler, S. A. Henneberg, G. Roberg-Clark, M. Drevlak, and P. Helander, Quasi-isodynamic stellarators with low turbulence as fusion reactor candidates, *PRX Energy* **3**, 023010 (2024).
 - [6] G. T. Roberg-Clark, G. G. Plunk, P. Xanthopoulos, C. Nührenberg, S. A. Henneberg, and H. M. Smith, Critical gradient turbulence optimization toward a compact stellarator reactor concept, *Phys. Rev. Res.* **5**, L032030 (2023).
 - [7] G. Roberg-Clark, P. Xanthopoulos, and G. Plunk, Reduction of electrostatic turbulence in a quasi-helically symmetric stellarator via critical gradient optimization, *J. Plasma Phys.* **90**, 175900301 (2024).
 - [8] H. E. Mynick, N. Pomphrey, and P. Xanthopoulos, Optimizing stellarators for turbulent transport, *Phys. Rev. Lett.* **105**, 095004 (2010).
 - [9] H. E. Mynick, N. Pomphrey, and P. Xanthopoulos, Reducing turbulent transport in toroidal configurations via shaping, *Phys. Plasmas* **18**, 056101 (2011).
 - [10] H. Mynick, P. Xanthopoulos, B. Faber, M. Lucia, M. Rorvig, and J. N. Talmadge, Turbulent optimization of toroidal configurations, *Plasma Phys. Controlled Fusion* **56**, 094001 (2014).
 - [11] J. Velasco, I. Calvo, E. Sánchez, and F. Parra, Robust stellarator optimization via flat mirror magnetic fields, *Nucl. Fusion* **63**, 126038 (2023).
 - [12] E. Sánchez, J. Velasco, I. Calvo, and S. Mulas, A quasi-isodynamic configuration with good confinement of fast ions at low plasma β , *Nucl. Fusion* **63**, 066037 (2023).
 - [13] J. García-Regaña, I. Calvo, E. Sánchez, H. Thienpondt, J. Velasco, and J. Capitán, Reduced electrostatic turbulence in the quasi-isodynamic stellarator configuration CIEMAT-QI4, *Nucl. Fusion* **65**, 016036 (2024).
 - [14] J. L. Velasco, I. Calvo, F. J. Escoto, E. Sánchez, H. Thienpondt, and F. I. Parra, Piecewise omnigenous stellarators, *Phys. Rev. Lett.* **133**, 185101 (2024).
 - [15] P. Kim, S. Buller, R. Conlin, W. Dorland, D. Dudt, R. Gaur, R. Jorge, E. Kolemen, M. Landreman, N. Mandell, *et al.*, Optimization of nonlinear turbulence in stellarators, *J. Plasma Phys.* **90**, 905900210 (2024).
 - [16] R. Jorge, W. Dorland, P. Kim, M. Landreman, N. R. Mandell, G. Merlo, and T. Qian, Direct microstability optimization of stellarator devices, *Phys. Rev. E* **110**, 035201 (2024).
 - [17] W. Guttenfelder, N. Mandell, G. Le Bars, L. Singh, A. Bader, K. Camacho Mata, J. Canik, L. Carbajal, A. Cerfon, N. Davila, *et al.*, Predictions of core plasma performance for the infinity two fusion pilot plant, *J. Plasma Phys.* **91**, E83 (2025).
 - [18] A. Goodman, K. Camacho Mata, S. Henneberg, R. Jorge, M. Landreman, G. Plunk, H. Smith, R. Mackenbach, C. Beidler, and P. Helander, Constructing precisely quasi-isodynamic magnetic fields, *J. Plasma Phys.* **89**, 905890504 (2023).
 - [19] P. Helander and J. Nührenberg, Bootstrap current and neoclassical transport in quasi-isodynamic stellarators, *Plasma Phys. Controlled Fusion* **51**, 055004 (2009).
 - [20] M. Landreman and E. Paul, Magnetic fields with precise quasisymmetry for plasma confinement, *Phys. Rev. Lett.* **128**, 035001 (2022).
 - [21] F. Wechsung, M. Landreman, A. Giuliani, A. Cerfon, and G. Stadler, Precise stellarator quasi-symmetry can be achieved with electromagnetic coils, *Proc. Natl. Acad. Sci. USA* **119**, e2202084119 (2022).
 - [22] P. Helander, Theory of plasma confinement in non-axisymmetric magnetic fields, *Rep. Prog. Phys.* **77**, 087001 (2014).

- [23] E. Rodríguez and R. Mackenbach, Trapped-particle precession and modes in quasisymmetric stellarators and tokamaks: A near-axis perspective, *J. Plasma Phys.* **89**, 905890521 (2023).
- [24] J. H. E. Proll, P. Helander, J. W. Connor, and G. G. Plunk, Resilience of quasi-isodynamic stellarators against trapped-particle instabilities, *Phys. Rev. Lett.* **108**, 245002 (2012).
- [25] J. Proll, G. Plunk, B. Faber, T. Görler, P. Helander, I. McKinney, M. Pueschel, H. Smith, and P. Xanthopoulos, Turbulence mitigation in maximum-J stellarators with electron-density gradient, *J. Plasma Phys.* **88**, 905880112 (2022).
- [26] E. Rodríguez, P. Helander, and A. Goodman, The maximum-J property in quasi-isodynamic stellarators, *J. Plasma Phys.* **90**, 905900212 (2024).
- [27] J. Kappel, M. Landreman, and D. Malhotra, The magnetic gradient scale length explains why certain plasmas require close external magnetic coils, *Plasma Phys. Controlled Fusion* **66**, 025018 (2024).
- [28] J. Lion, J.-C. Anglès, L. Bonauer, A. Bañón Navarro, S. Cadena Ceron, R. Davies, M. Drevlak, N. Foppiani, J. Geiger, A. Goodman, W. Guo, E. Guiraud, F. Hernández, S. Henneberg, R. Herrero, C. Hintze, H. Höchster, J. Jelonnek, F. Jenko, R. Jorge, *et al.*, Stellaris: A high-field quasi-isodynamic stellarator for a prototypical fusion power plant, *Fusion Eng. Des.* **214**, 114868 (2025).
- [29] F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers, Electron temperature gradient driven turbulence, *Phys. Plasmas* **7**, 1904 (2000).
- [30] J. B. Parker, L. L. LoDestro, D. Told, G. Merlo, L. F. Ricketson, A. Campos, F. Jenko, and J. A. Hittinger, Bringing global gyrokinetic turbulence simulations to the transport timescale using a multiscale approach, *Nucl. Fusion* **58**, 054004 (2018).
- [31] A. Di Siena, A. Bañón Navarro, T. Luda, G. Merlo, M. Bergmann, L. Leppin, T. Görler, J. Parker, L. LoDestro, T. Dannert, K. Germaschewski, B. Allen, J. Hittinger, B. Dorland, G. Hammett, F. Jenko, the ASDEX Upgrade Team, and the EUROfusion MST1 Team, Global gyrokinetic simulations of asdex upgrade up to the transport timescale with GENE-Tango, *Nucl. Fusion* **62**, 106025 (2022).
- [32] A. Di Siena, R. Bilato, A. Bañón Navarro, M. Bergmann, L. Leppin, T. Görler, E. Poli, M. Weiland, G. Tardini, F. Jenko, the ASDEX Upgrade Team, and the EUROfusion MST1 Team, Impact of supra-thermal particles on plasma performance at asdex upgrade with GENE-Tango simulations, *Nucl. Fusion* **64**, 066020 (2024).
- [33] A. Di Siena, J. Garcia, R. Bilato, K. Kirov, J. Varela, A. Bañón Navarro, H.-T. Kim, C. Challis, J. Hobirk, A. Kappatou, E. Lerche, D. Spong, C. Angioni, T. Görler, E. Poli, M. Bergmann, F. Jenko, and JET contributors, Assessing the impact of alpha particles on thermal confinement in jet D-T plasmas through global GENE-Tango simulations, *Nucl. Fusion* **65**, 016050 (2025).
- [34] D. L. C. Agapito Fernando, A. Bañón Navarro, D. Carralero, A. Alonso, A. Di Siena, J. L. Velasco, F. Wilms, G. Merlo, F. Jenko, S. A. Bozhnikov, E. Pasch, G. Fuchert, K. J. Brunner, J. Knauer, A. Langenberg, N. A. Pablant, T. Gonda, O. P. Ford, L. Vanó, T. Windisch, *et al.*, Validation of a comprehensive first-principles-based framework for predicting the performance of future stellarators, *Phys. Plasmas* **32**, 073904 (2025).
- [35] M. F. Martin, M. Landreman, P. Xanthopoulos, N. R. Mandell, and W. Dorland, The parallel boundary condition for turbulence simulations in low magnetic shear devices, *Plasma Phys. Controlled Fusion* **60**, 095008 (2018).
- [36] F. Wilms, A. Bañón Navarro, T. Windisch, S. Bozhnikov, F. Warmer, G. Fuchert, O. Ford, D. Zhang, T. Stange, F. Jenko, and the W7-X Team, Global gyrokinetic analysis of Wendelstein 7-X discharge: Unveiling the importance of trapped-electron-mode and electron-temperature-gradient turbulence, *Nucl. Fusion* **64**, 096040 (2024).
- [37] A. Bañón Navarro, G. T. Roberg-Clark, G. G. Plunk, D. Fernando, A. Di Siena, F. Wilms, and F. Jenko, Assessing core ion thermal confinement in critical-gradient-optimized stellarators, *Phys. Plasmas* **31**, 062508 (2024).
- [38] P. Xanthopoulos, S. A. Bozhnikov, M. N. Beurskens, H. M. Smith, G. G. Plunk, P. Helander, C. D. Beidler, J. A. Alcúsn, A. Alonso, A. Dinklage, O. Ford, G. Fuchert, J. Geiger, J. H. E. Proll, M. J. Pueschel, Y. Turkin, F. Warmer, and the W7-X Team, Turbulence mechanisms of enhanced performance stellarator plasmas, *Phys. Rev. Lett.* **125**, 075001 (2020).
- [39] H. Laqua, J. Baldzuhn, H. Braune, S. Bozhnikov, K. Brunner, M. Hirsch, U. Hoefel, J. Knauer, A. Langenberg, S. Marsen, D. Moseev, E. Pasch, K. Rahbarnia, T. Stange, R. Wolf, N. Pablant, O. Grulke, and the W7-X Team, High-performance ECRH at W7-X: Experience and perspectives, *Nucl. Fusion* **61**, 106005 (2021).
- [40] O. Ford, M. Beurskens, S. Bozhnikov, S. Lazerson, L. Vanó, A. Alonso, J. Baldzuhn, C. Beidler, C. Biedermann, R. Burhenn, G. Fuchert, D. Hartmann, M. Hirsch, A. Langenberg, H. Laqua, P. McNeely, N. Pablant, E. Pasch, F. Reimold, T. Romba, *et al.*, Turbulence-reduced high-performance scenarios in Wendelstein 7-X, *Nucl. Fusion* **64**, 086067 (2024).
- [41] C. Angioni, J. Candy, E. Fable, M. Maslov, A. G. Peeters, R. E. Waltz, and H. Weisen, Particle pinch and collisionality in gyrokinetic simulations of tokamak plasma turbulence, *Phys. Plasmas* **16**, 060702 (2009).
- [42] E. Fable, C. Angioni, and O. Sauter, The role of ion and electron electrostatic turbulence in characterizing stationary particle transport in the core of tokamak plasmas, *Plasma Phys. Controlled Fusion* **52**, 015007 (2010).
- [43] J. Schilling, The numerics of VMEC++, [arXiv:2502.04374](https://arxiv.org/abs/2502.04374).
- [44] N. Hansen and A. Ostermeier, Completely derandomized self-adaptation in evolution strategies, *Evol. Comput.* **9**, 159 (2001).
- [45] S. A. Cadena, A. Merlo, E. Laude, A. Bauer, A. Agrawal, M. Pascu, M. Savtchouk, E. Guiraud, L. Bonauer, S. Hudson, *et al.*, ConStellation: A dataset of QI-like stellarator plasma boundaries and optimization benchmarks, [arXiv:2506.19583](https://arxiv.org/abs/2506.19583).
- [46] V. Nemov, S. Kasilov, W. Kernbichler, and M. Heyn, Evaluation of $1/\nu$ neoclassical transport in stellarators, *Phys. Plasmas* **6**, 4622 (1999).
- [47] C. G. Albert, S. V. Kasilov, and W. Kernbichler, Accelerated methods for direct computation of fusion alpha particle losses within stellarator optimization, *J. Plasma Phys.* **86**, 815860201 (2020).
- [48] F. Najmabadi, A. Raffray, S. Abdel-Khalik, L. Bromberg, L. Crosatti, L. El-Guebaly, P. Garabedian, A. Grossman, D.

- Henderson, A. Ibrahim, *et al.*, The ARIES-CS compact stellarator fusion power plant, [Fusion Sci. Technol. **54**, 655 \(2008\)](#).
- [49] A. Mishchenko, P. Helander, and Y. Turkin, Curvature particle pinch in tokamak and stellarator geometry, [Phys. Plasmas **14**, 102308 \(2007\)](#).
- [50] C. Angioni, E. Fable, M. Greenwald, M. Maslov, A. G. Peeters, H. Takenaga, and H. Weisen, Particle transport in tokamak plasmas, theory and experiment, [Plasma Phys. Controlled Fusion **51**, 124017 \(2009\)](#).
- [51] G. G. Plunk, P. Helander, P. Xanthopoulos, and J. W. Connor, Collisionless microinstabilities in stellarators. III. The ion-temperature-gradient mode, [Phys. Plasmas **21**, 032112 \(2014\)](#).
- [52] G. G. Plunk, P. Xanthopoulos, G. M. Weir, S. A. Bozhakov, A. Dinklage, G. Fuchert, J. Geiger, M. Hirsch, U. Hoefel, M. Jakubowski, A. Langenberg, N. Pablant, E. Pasch, T. Stange, D. Zhang, and the W7-X Team, Stellarators resist turbulent transport on the electron Larmor scale, [Phys. Rev. Lett. **122**, 035002 \(2019\)](#).