

Stellarator Coils for Future Fusion Reactors via an Augmented Lagrangian Approach

Pedro F. Gil¹, Weiping Li^{2,3}, Julianne Stratton³, Alan A. Kaptanoglu³, and Eve V. Stenson¹

¹*Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany*

²*BASIS Independent Silicon Valley, San Jose, California 95126, USA*

³*Courant Institute of Mathematical Sciences, New York University, New York, New York 10012, USA*



(Received 10 October 2025; accepted 10 July 2026; published 7 August 2026)

A long-standing issue for fusion reactors based on 3D magnetic confinement (stellarators) has been finding suitable coils. Traditional optimization methods struggle to balance multiple physics and engineering constraints, requiring significant computing resources and input tuning, yet still resulting in suboptimal or infeasible configurations. We present a new optimization method based on an augmented Lagrangian scheme and show that it efficiently generates stellarator coils that exhibit enhanced physics performance and meet essential design requirements. This will accelerate progress toward commercially viable stellarator fusion reactors.

DOI: [10.1103/n7gk-922h](https://doi.org/10.1103/n7gk-922h)

Introduction—Nuclear fusion stands as a promising approach to deliver energy to the grid with low carbon emissions. Magnetic confinement fusion (MCF) stands as one of the main branches of fusion research, to which belong both tokamaks and stellarators. After decades of development and progress of the Wendelstein 7-X device [1–3], the stellarator is considered a front-runner for a viable fusion power plant. Unlike axisymmetric MCF devices like tokamaks, stellarators rely on complex, often numerically optimized, three-dimensional magnetic fields to confine the plasma, allowing for stable, steady-state operation. The stellarator concept therefore does not require pulsed induced currents in the plasma for confinement; it instead fully delegates the magnetic field generation to external magnetic coils. This should help to avoid disruption events and large magnetohydrodynamic instabilities, which can present major obstacles to achieving commercial nuclear fusion [4–8]. The pursuit of steady-state controlled magnetic fusion has led to the establishment of multiple fusion stellarator startups around the world [9–14].

The design of a stellarator is, in practice, typically subdivided into two optimization problems. First, an equilibrium for the plasma is found by solving the magnetohydrodynamic (MHD) force balance equations while simultaneously targeting specific plasma properties, such as reduced transport or MHD stability; this is

commonly known as stage I [15–20]. Then, using the boundary of the stage-I plasma equilibrium as a target, we find the coils generating a magnetic field everywhere tangential to it through solving an inverse magnetostatics problem; this is stage II [21–29].

The vast majority of modern stellarator designs use modular coils. These are nonplanar, current-carrying curves that surround the plasma. Compared to previous helical coil designs [30–32], they allow for softer manufacturing requirements, namely smaller, easier to handle, individual coils with fewer electrical joints, possibly enabling better scalability. However, having modular nonplanar coils has historically come at a price: their shapes can become extraordinarily complex and still require very tight manufacturing and assembly tolerances [33–35]. Finding cost-effective, buildable, and accurate coil sets for a given stellarator is currently a bottleneck for the viability of the stellarator designs, as coil complexity challenges have been responsible for considerable cost overruns, the cancellation of the NCSX project [36], and the delay of the decade-long, million-hour construction of the magnets for Wendelstein 7-X [37]. The physics and engineering characteristics of the coils can ultimately determine the cost of a stellarator fusion power plant [38].

Coil design is known to be an ill-posed inverse problem; any one equilibrium has an infinite number of coil sets that reproduce its physical properties. Nearly all of these coil sets are infeasible to manufacture or assemble, so additional engineering constraints are added to the design problem. Current state-of-the-art methods in coil optimization incorporate these engineering-related constraints by converting the problem into a multi-objective optimization, which requires users to manually tune 10–15 *ad hoc* numerical weights to balance physics accuracy against engineering feasibility [28,39–41]. This process can be heuristic and

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Open access publication funded by the Max Planck Society.

slow, and it often fails to find optimal solutions, resulting in the allocation of considerable computing power to scan numerous possibilities [26,27,42–45].

In this Letter, we introduce a new approach that recasts coil design as a highly nonconvex equality-constrained optimization problem using an augmented Lagrangian method [46]. This eliminates nonintuitive weight amplitudes that are not computable *a priori* and greatly improves physical and engineering-related constraint satisfaction. By applying this method, we have discovered a suite of stellarator coil designs that are demonstrably superior to previously published configurations across key physics and engineering metrics. These optimal coils can be found much more regularly than with previous methods, as we illustrate in our companion paper [46] by showing a variety of Pareto-optimal coil sets for several different stellarator designs. This method can shortcut the path toward simpler designs that facilitate the manufacturing, and ensure built conformity. Overall, our Letter removes a long-standing roadblock, providing a robust and systematic method for designing feasible, high-performance magnets required for a stellarator power plant.

Methods—Traditional stellarator coil optimization strategies either use “winding surface” optimization, where coils are represented as a sheet current on a prescribed toroidal surface surrounding the plasma, or filamentary methods, where coils are represented as 3D infinitely thin curves in space. Winding-surface methods were used in the past to design, for example, W7-X and HSX [47,48]. However, this method suffers from the disadvantages that it constrains the coil sets to lie on a single surface and introduces errors when more discrete curves are “cut” from the surface [49–51]. Filamentary methods require solving a very nonconvex, highly constrained optimization problem, so that solutions are often found that are suboptimal or infeasible, as mentioned previously.

We propose a new approach that reformulates the filamentary coil optimization problem with an augmented Lagrangian method [41,52,53]:

$$\mathcal{L}_A(\mathbf{x}, \boldsymbol{\lambda}, \boldsymbol{\mu}) = f(\mathbf{x}) - \boldsymbol{\lambda}^\top \mathbf{c}(\mathbf{x}) + \frac{1}{2} \|\sqrt{\boldsymbol{\mu}} \circ \mathbf{c}(\mathbf{x})\|_2^2, \quad (1)$$

where (1) f is the objective function. (2) $\boldsymbol{\lambda} \in \mathbb{R}^{N_c}$ is the vector of Lagrange multipliers. (3) $\boldsymbol{\mu} \in \mathbb{R}^{N_c}$ and $\mu_l > 0$ for all l are the penalty parameters. (4) $\mathbf{c} : \mathbb{R}^n \rightarrow \mathbb{R}^{N_c}$ is a vector of equality constraints. If there are inequality constraints $c_l(\mathbf{x}) \leq c_{\text{target}}$, these are recast to equality constraints by using $\max_{\mathbf{x}}(c_l(\mathbf{x}) - c_{\text{target}}, 0) = 0$. $\frac{1}{2} \|\sqrt{\boldsymbol{\mu}} \circ \mathbf{c}(\mathbf{x})\|_2^2$ is the penalty term defining the Hadamard product between $\boldsymbol{\mu}$ and $\mathbf{c}(\mathbf{x})$ and penalizes constraint violations. What previously were user-determined hyperparameters w_l are now Lagrange multipliers that are automatically updated throughout the optimization. Another advantage over previous coil optimization methods [54–57] lies in the

self-adjustment of the magnitudes of w_l , avoiding very large weight magnitudes for constraint satisfaction, which can destabilize the optimization algorithm. This algorithm also goes beyond what has previously been implemented by Wechsung *et al.* [58]. There, the optimization function consists of an unconstrained problem with a linear sum of all the constraints, each with an individual hyperparameter that is updated by a given factor depending on whether the corresponding constraint is still violated. Our approach categorizes hyperparameters into two distinct roles, Lagrange multipliers and penalty parameters, each of which gets a dedicated update rule, while simultaneously tuning tolerance and convergence thresholds throughout the optimization. This is similar to the penalty method shown in the companion manuscript to often give sub-optimal results. One main distinction of the augmented Lagrangian targeted at coil optimization, as opposed to the stellarator equilibrium boundary optimization presented in Conlin *et al.* [41], is that the algorithm is not hampered by the question of MHD convergence of the equilibrium during the optimization. Their problem takes as a constraint the MHD force residual, which can exhibit singularities. Moreover, it can directly affect all other constraints, since their values are dependent on the convergence degree of the force residual. However, coil optimization does not suffer from this sensitivity issue, since their parametrization and objectives/constraints values do not depend on solving a nested equilibrium to some tolerance. We have a slightly different problem; it is essential in our problem to adaptively choose weights such that coil-coil and coil-surface intersections never occur (or are quickly recovered from, e.g., by using the linking number contribution to the line search but not the gradient calculation), since this can cause blowup and early optimization exit. Moreover, we use different update rules and adaptive refinement of both the Lagrange multipliers, penalty parameters, and optimization convergence and tolerance targets.

What drives the shaping of stellarator coils during stage-II optimization is the minimization of the squared flux metric, also understood as the magnetic field error metric. This is expressed as

$$f_{\text{SF}} = \frac{1}{2} \frac{\int_S |\mathbf{B} \cdot \mathbf{n}|^2 dS}{\int_S |\mathbf{B}|^2 dS}, \quad (2)$$

where S is the target surface coming from a stage-I plasma design, $\mathbf{B}$ is the magnetic field generated by the coils and obtained via the Biot-Savart law, and $\mathbf{n}$ is the target surface normal. It can be shown that if this metric is close enough to zero, the magnetic coils successfully reproduce the entirety of the target magnetic field [59,60]. However, minimizing f_{SF} is not sufficient to obtain reactor-relevant stellarator coils. This is typically achieved by adding multiple additional terms/constraints that aim at regularizing the design of the stellarator coils. Typical reactor-compatible constraints used in stellarator design are shown in Table I.

TABLE I. Rough estimates of upper and lower bounds for engineering metrics of a reactor-scale stellarator design.

Objective	Motivation
Normalized f_{SF}	Sufficient magnetic field accuracy to ensure important plasma properties.
Min coil-to-surface distance	Sufficient distance for neutron- absorbing blanket.
Min coil-to-coil distance	Sufficient distance for avoiding coil intersections and assembly difficulties from finite coil build.
Total coil length	Must balance costs of purchasing superconducting material, and high field accuracy.
Max curvature κ	Low local curvature to simplify geometry and manufacturing costs.
Max mean-squared-curvature (MSC)	Similar to the curvature κ , the MSC should stay low to reduce extensive manufacturing costs.
Coil linking avoidance	Interlinking coils could greatly increase the complexity of assembly.
Max force	Must stay within force tolerances of estimated industrial REBCO-based HTS cables [61–63]

Each constraint is translated into a single component of $\mathbf{c}(\mathbf{x})$ in Eq. (1) with corresponding thresholds $\mathbf{c}_{\text{target}}$. The expression of each term and how it is integrated into the optimization is further explained in the companion paper [46]. Traditionally, f_{SF} is set as the primary objective in the optimization, but it is used here as an inequality constraint possessing an upper threshold and relocated as another component of $\mathbf{c}(\mathbf{x})$. Additionally, a dummy function always equal to zero and returning zero for its gradient is used as the objective function. We believe this reformulation of f_{SF} as a constraint is in part responsible for the effectiveness of our approach.

Our Letter is fully implemented and reproducible using the open-source SIMSOPT code [56]; all the runs were performed on a single laptop.

Pareto-optimal configurations—We now demonstrate the effectiveness of the augmented Lagrangian method by comparing it to previous state-of-the-art work found in literature and industry. To start, we choose a quasi-axisymmetric (QA) stellarator as a target for the optimization. Quasisymmetry is a magnetic field property essential for the confinement of α -particles (born from deuterium-tritium reactions) and effective redistribution of their energy back into the fusion plasma. A stellarator with sufficiently low departure from quasisymmetry across its volume reaches neoclassical transport levels comparable to a tokamak [15]. Thea Energy is an example of a fusion start-up company hoping to leverage this together with dipole coil arrays to design a quasi-axisymmetric neutron source [12].

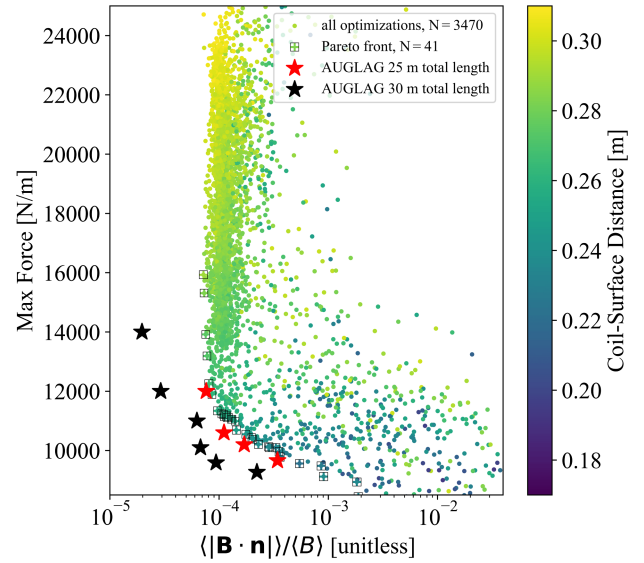


FIG. 1. Comparison between 3470 traditional coil optimizations (already filtered from a total of 8500) and the augmented Lagrangian method for two different coil length thresholds: 25 m (red), 30 m (black). The augmented Lagrangian method manages to outline two Pareto-fronts, where there is a direct trade-off between field accuracy and maximum force on the conductor.

We optimize here coils for the QA configuration shown in Ref. [15] and compare our results with the coil optimization scans performed in Kaptanoglu *et al.* [26], where 8500 different coil sets were optimized with randomly picked *ad hoc* weights in order to map a region of the optimization space. The equilibrium was scaled to 1 m major radius and the field to ~ 300 mT on axis. The results are plotted in Fig. 1, with each coil set having 20 coils in total, and circular coils as initial conditions. Using an identical setup, targeting the constraints shown in Table I, where the upper boundary for coil length is 25 m, we perform four different optimizations by varying successively the linear coil force threshold to 9, 10, 10.5, and 12 kN/m (red stars following the Pareto-front), further fast-particle simulations and information about the optimization can be found in the companion paper [46]. Moreover, by relaxing the coil length constraint to 30 m in total, the coils now have additional room to compensate for coil ripple effects due to their modular nature. This results in a decrease in field error, and in the outline of a new Pareto-front, all the while fulfilling the same filtering criteria as the scan. This shows the consistent reaching of optimal coil sets by the augmented Lagrangian method.

Quasi-axisymmetric configuration—By improving the balance between physics and engineering properties, this new method allows for the exploration of new coil configurations. As an example, we take the same QA equilibrium as previously from Landreman and Paul [15], but optimize for 12 coils instead of 20 in order to demonstrate comparable performance but greatly improved

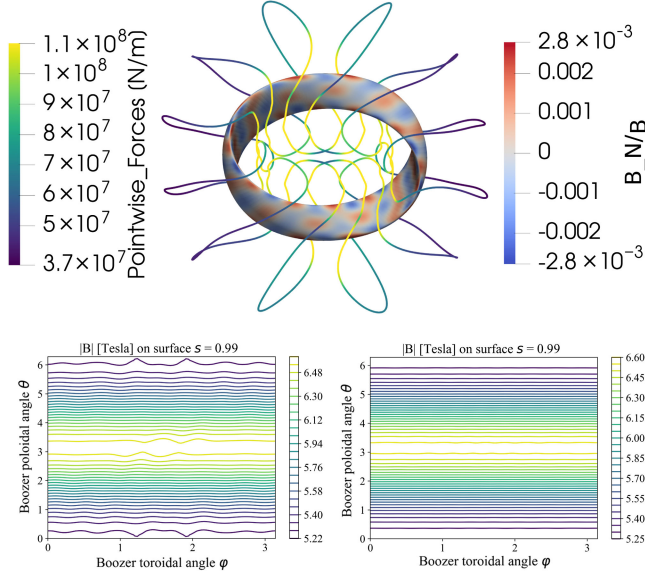


FIG. 2. A highly accurate 12-coil QA configuration with improved plasma access. Top: the maximum $\mathbf{J} \times \mathbf{B}$ linear forces on the coils and field errors on the surface are displayed. Bottom: Boozer plots at the equilibrium edge of the 12-coil (left) Landreman and Paul configuration versus the target (right) field presented in this Letter showing the quality of the quasisymmetric field generated by the coils.

plasma access. The equilibrium is now scaled to an ARIES-CS fusion reactor with a minor radius of 1.7 m and an averaged on-axis field of 5.7 T [64]. The coil set together with the outmost plasma surface and magnetic field strength plots (in the Boozer transformed coordinate system) displaying the degree of quasisymmetry are shown in Fig. 2. The straight lines on the right Boozer plot at the outmost surface of the equilibrium correspond to the target field and denote a high degree of quasisymmetry. On the left is shown the Boozer plot for the 12-coil configuration; while some degradation of quasisymmetry can be seen, this quality of quasisymmetry is actually quite remarkable, as a stellarator with only 12 coils is expected to have considerable amounts of coil ripple, preventing it from having good neoclassical confinement properties.

Next, the optimized configuration is compared to a 16-coil QA stellarator optimized by Wechsung *et al.* [58], with the same total coil length. To our knowledge, there is no other Landreman and Paul QA configuration that has been optimized with 12 coils. The overview of the properties of both stellarators is shown in Table II. This configuration is able to improve on the field accuracy, coil forces, and quasisymmetric errors while maintaining equal coil length, a lower amount of coils, and increased spacing in between coils. The required HTS length is, however, larger: a lower number of coils requires higher currents per coil to keep the average magnetic field amplitude equal.

Quasi-isodynamic configuration—We present a second example of an optimized configuration, this time for a

TABLE II. Comparison of magnetic field and coil properties for our 12-coil solution and the corresponding 16-coil Wechsung solution scaled to the ARIES-CS [64] reactor with 5.7 T on axis and a 1.7 m minor radius. Properties that should ideally be lowered (increased) in the design are indicated by $\downarrow$ ($\uparrow$). Here, we assume a fixed total current per plasma field period, taking 200 HTS turns per coil for the 4-coil solution as reference, explaining the difference in the max force between the table values and Fig. 2.

Property	Goal	3-coil L18	Wechsung L18
No. of coils per hfp	$\downarrow$	3	4
$\langle \mathbf{B} \cdot \mathbf{n} \rangle / \langle B \rangle \times 10^{-5}$	$\downarrow$	85.5	91.1
Max $(\mathbf{B} \cdot \mathbf{n} / B) \times 10^{-4}$	$\downarrow$	28	34
Max force [MN/m]	$\downarrow$	0.41	0.44
Coil length per hfp [m]	$\downarrow$	182	182
Min CC distance [m]	$\uparrow$	1.49	1.34
Min CS distance [m]	$\uparrow$	2.74	2.75
Max κ [m^{-1}]	$\downarrow$	0.53	0.44
Max MSC [m^{-1}]	$\downarrow$	0.05	0.05
Quasisymmetry error $\times 10^{-3}$	$\downarrow$	2.0	2.1
HTS length [km]	$\downarrow$	194	146

^aTop-performing metrics are highlighted in bold.

different magnetic field topology: a quasi-isodynamic stellarator. It differs from the previous QA configuration by having contours of constant magnetic field strength closing poloidally instead of toroidally, but it conserves equivalent α -particle confinement properties [17,65]. There has been recent progress regarding quasi-isodynamic (QI) configurations [18,66], where plasma equilibrium optimization has resulted in reduced turbulence, with MHD stability allowing for higher beta operation, and reduced bootstrap current stabilizing island-divertor operation, all while keeping neoclassical transport levels low. This has motivated private fusion start-ups such as Proxima Fusion and Type One Energy [9,11] to consider similar designs for their demonstrator power plants. In this Letter, we compare our designs with the Stellaris power plant coil set presented in Ref. [9] by Proxima Fusion and targeted to deliver a peak fusion power of ~ 2700 MW to achieve commercial fusion energy. Stellaris is a QI device with 12.7 m major radius, aspect ratio 9.8, and an axis averaged magnetic field strength of 9 T.

Here, we target two improved configurations: the first (no. 1) improves the physics properties while keeping the engineering constraints similar, and the second (no. 2) is able to substantially improve *all* the engineering constraints considered while maintaining agreeable physics properties. The second configuration is shown in Fig. 3, and the results are summarized in Table III.

Notably, configuration no. 2 reduces the maximum force on the conductor by 29%, increases the minimum coil-to-coil distance by 22 cm, reduces the maximum curvature by 39% and the maximum mean squared curvature by 35%, and decreases the required total HTS length by 6%

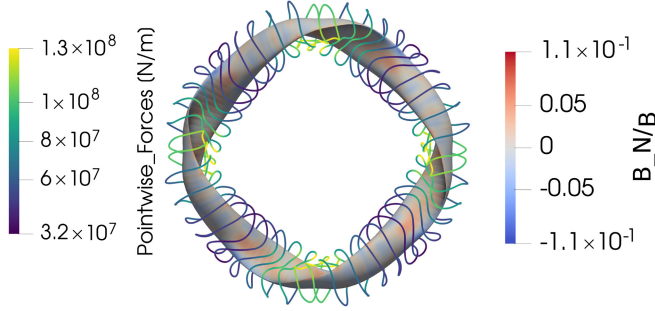


FIG. 3. Improved Stellaris configuration no. 2 with maximum $\mathbf{J} \times \mathbf{B}$ linear forces on the coils and field errors on the surface.

while increasing slightly the coil-to-surface distance. These features mean the following: a direct 6% cost reduction by needing less superconducting tape, a likely reduction in the required structural support to counteract electromagnetic forces, and ease of coil manufacturing and assembly by providing simplified coil shapes and spacing. While this comes at a cost of field accuracy, we show in Fig. 4 that quasi-isodynamicity at both the plasma core and edge still closely match the target. This does not allow us, however, to draw extended conclusions on the confinement properties; further studies are necessary to assess the viability of such a reactor. Nevertheless, fast-particle simulations for the configurations can be found in the companion paper [46]. Configuration no. 1 serves as a complementary configuration, showing that depending on what the user targets, it is possible to improve on physics accuracy by 54% by letting the length increase and keeping the remaining engineering targets similar. Nevertheless, these are *unperturbed* configurations; it is yet unknown if reactor scale manufacturing and assembly errors manage to achieve the targeted field errors.

TABLE III. Comparison of magnetic field and coil properties for the three different Stellaris configurations. No. 1 and no. 2 are results from this Letter, while the Proxima configuration was optimized by the start-up Proxima Fusion. Forces were scaled by assuming 200 turns per coil in the 48 solution and fixed total coil current.

Property	Goal	No. 1	No. 2	Proxima
No. of coils per hfp	↓	6	6	6
$\langle \mathbf{B} \cdot \mathbf{n} \rangle / \langle B \rangle \times 10^{-3}$	↓	2.3	14.7	4.0
Max $(\mathbf{B} \cdot \mathbf{n}) / B \times 10^{-2}$	↓	1.6	11.4	3.5
Max force [MN/m]	↓	0.64	0.64	0.9
Coil length per hfp [m]	↓	145	130	138
Min CC distance [m]	↑	0.7	0.89	0.67
Min CS distance [m]	↑	1.3	1.40	1.37
Max κ [m^{-1}]	↓	1.6	0.96	1.57
Max MSC [m^{-1}]	↓	0.35	0.22	0.34
HTS length [km]	↓	232	208	221

^aTop-performing metrics are highlighted in bold.

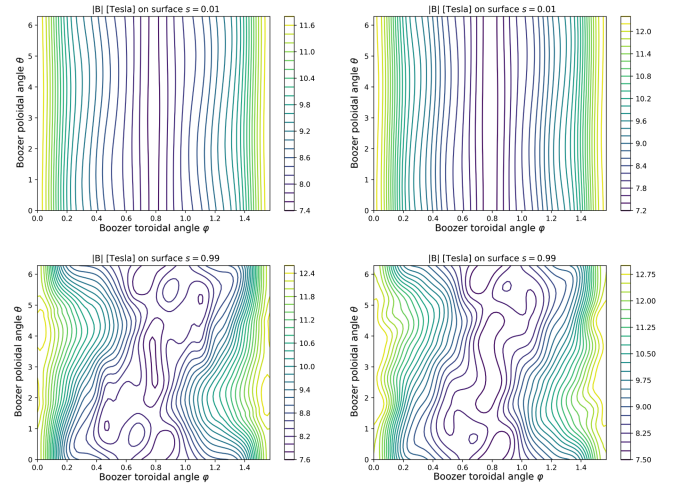


FIG. 4. Boozer plots of the improved Stellaris no. 2 (left) configuration versus the target field (right) presented in this Letter, showing the quality of the omnigenous field generated by the coils at the core (top) and edge of the plasma (bottom).

Conclusion—A new method for coil optimization has been employed to show that it is possible to consistently reach Pareto-optimal configurations. This is done by turning an ill-posed problem into an augmented Lagrangian formulation and recasting target functions as inequality constraints. It is found that among 8500 different coil optimizations, about 41 draw out the Pareto-front, which is repeatedly met by our method, and relaxing the constraints proves to outline even new Pareto-fronts. This method is then applied to find coils for two different plasma configurations. The first optimization illustrates a 12-coil configuration for a precise quasi-axisymmetric stellarator [15], yielding considerable improvements for plasma access while having fewer field errors than a 16-coil configuration which has served as a standard reference in the stellarator literature of field accuracy so far [58]. The second is a stable quasi-isodynamic design [18] presented by Proxima Fusion and is currently one of the most promising contenders for a fusion power plant [9]. Compared to Proxima’s design, it is shown that it is possible to achieve improved engineering metrics while conserving target physics. Conversely, we demonstrate another solution that improves field error by 50% while conserving engineering properties. Along with the additional evidence of the strength of our approach in the companion paper [46], we can conclude that this method can be effectively used for finding improved coil designs for fusion power plants.

Acknowledgments—This work was supported through grants from the Simons Foundation under Award No. 560651 and from the Helmholtz Association Young Investigators Group program as Project No. VH-NG-1430. We thank Jorrit Lion, Gabriel Plunk, Alan Goodman, Matt

Landreman, and Benedikt Geiger for sharing plasma boundary configuration files, and Rory Conlin, Paul Huslage, David Bindel, and Tom Simpson for useful discussions.

Data availability—The data that support the findings of this article are openly available [67].

- [1] A. H. Boozer, Stellarators as a fast path to fusion, *Nucl. Fusion* **61**, 096024 (2021).
- [2] T. Klinger, C. Baylard, C. Beidler, J. Boscary, H. Bosch, A. Dinklage, D. Hartmann, P. Helander, H. Maßberg, A. Peacock, T. Pedersen, T. Rummel, F. Schauer, L. Wegener, and R. Wolf, Towards assembly completion and preparation of experimental campaigns of Wendelstein 7-X in the perspective of a path to a stellarator fusion power plant, *Fusion Eng. Des.* **88**, 461 (2013).
- [3] C. Beidler, G. Grieger, F. Hermegger, E. Harmeyer, J. Kisslinger, W. Lotz, H. Maassberg, P. Merkel, J. Nührenberg, F. Rau *et al.*, Physics and engineering design for Wendelstein VII-X, *Fusion Technol.* **17**, 1 (1990).
- [4] A. Murari *et al.*, A control oriented strategy of disruption prediction to avoid the configuration collapse of tokamak reactors, *Nat. Commun.* **15**, 2424 (2024).
- [5] E. Strait *et al.*, Progress in disruption prevention for ITER, *Nucl. Fusion* **59**, 112012 (2019).
- [6] P. Rodriguez-Fernandez *et al.*, Overview of the SPARC physics basis towards the exploration of burning-plasma regimes in high-field, compact tokamaks, *Nucl. Fusion* **62**, 042003 (2022).
- [7] P. Helander, C. D. Beidler, T. M. Bird, M. Drevlak, Y. Feng, R. Hatzky, F. Jenko, R. Kleiber, J. H. E. Proll, Y. Turkin, and P. Xanthopoulos, Stellarator and tokamak plasmas: A comparison, *Plasma Phys. Controlled Fusion* **54**, 124009 (2012).
- [8] W. Zheng *et al.*, Disruption prediction for future tokamaks using parameter-based transfer learning, *Commun. Phys.* **6**, 181 (2023).
- [9] J. Lion *et al.*, Stellaris: A high-field quasi-isodynamic stellarator for a prototypical fusion power plant, *Fusion Eng. Des.* **214**, 114868 (2025).
- [10] J. Miyazawa and T. Goto, Development of steady-state fusion reactor by Helical Fusion, *Phys. Plasmas* **30**, 050601 (2023).
- [11] D. T. Anderson, J. M. Canik, C. C. Hegna, and C. M. Mowry, A comprehensive, unified baseline physics design for the type one energy stellarator fusion pilot power plant, “infinity two”, *J. Plasma Phys.* **91**, e65 (2025).
- [12] D. Gates, S. Aslam, B. Berzin, P. Bonfiglio, A. Cote, D. Dudt, E. Flom, D. Fort, A. Koen, T. Kruger, S. Kumar, M. Martin, A. Ottaviano, S. Pasmann, P. Romano, C. Swanson, L. Tang, E. Winkler, and R. Wu, Stellarator fusion systems enabled by arrays of planar coils, *Nucl. Fusion* **65**, 026052 (2025).
- [13] F. Volpe, Renaissance fusion technologies, <https://renfusion.eu/technology> (2023), accessed: October 1, 2023.
- [14] M. Zarnstorff, A. Bhattacharjee, and R. Carty (Stellarex Team), The stellarex path to a stellarator fusion pilot plant, in *APS Division of Plasma Physics Meeting Abstracts*, APS Meeting Abstracts Vol. 2023 (American Physical Society, College Park, Maryland, 2023), p. CM06.009.
- [15] M. Landreman and E. Paul, Magnetic fields with precise quasisymmetry for plasma confinement, *Phys. Rev. Lett.* **128**, 035001 (2022).
- [16] M. Drevlak, C. Beidler, J. Geiger, P. Helander, and Y. Turkin, Optimisation of stellarator equilibria with ROSE, *Nucl. Fusion* **59**, 016010 (2018).
- [17] 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).
- [18] 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).
- [19] 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).
- [20] 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).
- [21] K. Hammond, A framework for discrete optimization of stellarator coils, *Nucl. Fusion* **65**, 046012 (2025).
- [22] J.-F. Lobsien, M. Drevlak, and T. Sunn Pedersen (Working at X-Team), Stellarator coil optimization towards higher engineering tolerances, *Nucl. Fusion* **58**, 106013 (2018).
- [23] B. F. Lee, E. J. Paul, G. Stadler, and M. Landreman, Stellarator coil optimization supporting multiple magnetic configurations, *Nucl. Fusion* **63**, 014002 (2022).
- [24] A. A. Kaptanoglu, M. Landreman, and M. C. Zarnstorff, Optimization of passive superconductors for shaping stellarator magnetic fields, *Phys. Rev. E* **111**, 065202 (2025).
- [25] A. Wiedman, S. Buller, and M. Landreman, Coil optimization for quasi-helically symmetric stellarator configurations, *J. Plasma Phys.* **90**, 905900307 (2024).
- [26] A. A. Kaptanoglu, A. Wiedman, J. Halpern, S. Hurwitz, E. J. Paul, and M. Landreman, Reactor-scale stellarators with force and torque minimized dipole coils, *Nucl. Fusion* **65**, 046029 (2025).
- [27] A. Baillod, E. Paul, T. Elder, and J. Halpern, Enhancing stellarator accessibility through port size optimization, *Nucl. Fusion* **65**, 086040 (2025).
- [28] L. Fu, E. J. Paul, A. A. Kaptanoglu, and A. Bhattacharjee, Global stellarator coil optimization with quadratic constraints and objectives, *Nucl. Fusion* **65**, 026045 (2025).
- [29] L. Singh, T. G. Kruger, A. Bader, C. Zhu, S. R. Hudson, and D. T. Anderson, Optimization of finite-build stellarator coils, *J. Plasma Phys.* **86**, 905860404 (2020).
- [30] A. Iiyoshi *et al.*, Overview of the large helical device project, *Nucl. Fusion* **39**, 1245 (1999).
- [31] M. Wakatani and S. Sudo, Overview of Heliotron E results, *Plasma Phys. Controlled Fusion* **38**, 937 (1996).
- [32] T. Obiki *et al.*, First plasmas in Heliotron J, *Nucl. Fusion* **41**, 833 (2001).

- [33] T. Andreeva, T. Bräuer, M. Endler, J. Kießlinger, and Y. Igitchanov, Analysis of the magnetic field perturbations during the assembly of Wendelstein 7-X, *Fusion Sci. Technol.* **46**, 388 (2004).
- [34] T. Andreeva, T. Bräuer, V. Bykov, K. Egorov, M. Endler, J. Fellingner, J. Kießlinger, M. Köppen, and F. Schauer, Tracking of the magnet system geometry during Wendelstein 7-X construction to achieve the designed magnetic field, *Nucl. Fusion* **55**, 063025 (2015).
- [35] L. E. Dudek, J. H. Chrzanowski, P. J. Heitzenroeder, S. Raftopoulos, M. E. Viola, G. H. Neilson, D. Rej, M. J. Cole, P. Goranson, and K. Freudenberg, Status of the NCSX construction, *Fusion Eng. Des.* **84**, 351 (2009).
- [36] R. Strykowski, T. Brown, J. Chrzanowski, M. Cole, P. Heitzenroeder, G. Neilson, D. Rej, and M. Viol, Engineering cost & schedule lessons learned on NCSX, in *Proceedings of the 23rd IEEE/NPSS Symposium on Fusion Engineering* (IEEE, New York, NY, 2009), pp. 1–4.
- [37] H.-S. Bosch *et al.* (Working at X-Team), Final integration, commissioning and start of the Wendelstein 7-X stellarator operation, *Nucl. Fusion* **57**, 116015 (2017).
- [38] L. M. Waganer, K. T. Slattery, and J. C. W. I. and, ARIES-CS coil structure advanced fabrication approach, *Fusion Sci. Technol.* **54**, 878 (2008).
- [39] M. Landreman, Mapping the space of quasisymmetric stellarators using optimized near-axis expansion, *J. Plasma Phys.* **88**, 905880616 (2022).
- [40] Z. Feng, D. A. Gates, S. A. Lazerson, M. Landreman, N. Pomphrey, and G. Fu, Optimization of quasi-axisymmetric stellarators with varied elongation, *Phys. Plasmas* **27**, 022502 (2020).
- [41] R. Conlin, P. Kim, D. W. Dudt, D. Panici, and E. Kolemen, Stellarator optimization with constraints, *J. Plasma Phys.* **90**, 905900501 (2024).
- [42] A. Giuliani, Direct stellarator coil design using global optimization: Application to a comprehensive exploration of quasi-axisymmetric devices, *J. Plasma Phys.* **90**, 905900303 (2024).
- [43] S. Hurwitz, M. Landreman, P. Huslage, and A. Kaptanoglu, Electromagnetic coil optimization for reduced Lorentz forces, *Nucl. Fusion* **65**, 056044 (2025).
- [44] F. Wechsung, A. Giuliani, M. Landreman, A. Cerfon, and G. Stadler, Single-stage gradient-based stellarator coil design: Stochastic optimization, *Nucl. Fusion* **62**, 076034 (2022).
- [45] S. Glas, M. Padidar, A. Kellison, and D. Bindel, Global stochastic optimization of stellarator coil configurations, *J. Plasma Phys.* **88**, 905880208 (2022).
- [46] P. F. Gil, W. Li, J. Stratton, A. A. Kaptanoglu, and E. V. Stenson, companion paper, Augmented Lagrangian methods produce cutting-edge magnetic coils for stellarator fusion reactors, *Phys. Rev. E* **114**, 025202 (2026).
- [47] J. Nührenberg and R. Zille, Quasi-helically symmetric toroidal stellarators, *Phys. Lett. A* **129**, 113 (1988).
- [48] F. Anderson, A. Almagri, D. Anderson, P. Matthews, J. Talmadge, and J. Shohet, Helically symmetric experiment, (HSX) goals, design and status, *Fusion Technol.* **27**, 273 (1995).
- [49] P. Merkel, Solution of stellarator boundary value problems with external currents, *Nucl. Fusion* **27**, 867 (1987).
- [50] M. Landreman, An improved current potential method for fast computation of stellarator coil shapes, *Nucl. Fusion* **57**, 046003 (2017).
- [51] M. Drevlak, Optimization of heterogeneous magnet systems, in *Proceedings of the 12th International Stellarator Workshop, Madison, WI* (1999), pp. P1–17.
- [52] A. R. Conn, N. I. M. Gould, and P. L. Toint, *Trust-Region Methods*, MPS/SIAM Series on Optimization (Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA, 2000).
- [53] J. Nocedal and S. J. Wright, *Numerical Optimization*, 2nd ed. (Springer Science & Business Media, New York, NY, 2006).
- [54] C. Zhu, S. R. Hudson, Y. Song, and Y. Wan, New method to design stellarator coils without the winding surface, *Nucl. Fusion* **58**, 016008 (2017).
- [55] T. Brown, J. Breslau, D. Gates, N. Pomphrey, and A. Zolfaghari, Engineering optimization of stellarator coils lead to improvements in device maintenance, in *2015 IEEE 26th Symposium on Fusion Engineering (SOFE)* (IEEE, Piscataway, NJ, 2015), pp. 1–6.
- [56] M. Landreman, B. Medasani, F. Wechsung, A. Giuliani, R. Jorge, and C. Zhu, SIMSOPT: A flexible framework for stellarator optimization, *J. Open Source Software* **6**, 3525 (2021).
- [57] D. W. Dudt and E. Kolemen, DESC: A stellarator equilibrium solver, *Phys. Plasmas* **27**, 102513 (2020).
- [58] 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. U.S.A.* **119**, e2202084119 (2022).
- [59] R. Dewar, S. Hudson, and P. Price, Almost invariant manifolds for divergence-free fields, *Phys. Lett. A* **194**, 49 (1994).
- [60] R. Dewar and J. Meiss, Flux-minimizing curves for reversible area-preserving maps, *Physica (Amsterdam)* **57D**, 476 (1992).
- [61] Z. S. Hartwig, R. F. Vieira, B. N. Sorbom, R. A. Badcock, M. Bajko, W. K. Beck, B. Castaldo, C. L. Craighill, M. Davies, J. Estrada *et al.*, VIPER: An industrially scalable high-current high-temperature superconductor cable, *Supercond. Sci. Technol.* **33**, 11LT01 (2020).
- [62] Z. Zhao, P. Moore, and L. Chiesa, Structural modeling of REBCO VIPER cable for high-field magnet applications, *IEEE Trans. Appl. Supercond.* **32**, 1 (2022).
- [63] N. Riva, R. Granetz, R. Vieira, A. Hubbard, A. Pfeiffer, P. Harris, C. Chamberlain, Z. Hartwig, A. Watterson, D. Anderson *et al.*, Development of the first non-planar REBCO stellarator coil using VIPER cable, *Supercond. Sci. Technol.* **36**, 105001 (2023).
- [64] F. Najmabadi *et al.*, The ARIES-CS compact stellarator fusion power plant, *Fusion Sci. Technol.* **54**, 655 (2008).
- [65] P. Helander, Theory of plasma confinement in non-axisymmetric magnetic fields, *Rep. Prog. Phys.* **77**, 087001 (2014).
- [66] 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).
- [67] P. F. Gil, W. Li, J. Stratton, A. Kaptanoglu, and E. V. Stenson, Coilsets and scripts from augmented Lagrangian methods for stellarator coils, Zenodo, 10.5281/zenodo.18497939 (2026).