

# The Updated Case for a National Stellarator Program

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The stellarator concept provides a compelling path to a Fusion Pilot Plant that features steady state, disruption free operation with low recirculating power. The need for a national stellarator program and a new stellarator experiment have been highlighted previously in the FESAC Long-Range Plan (LRP) [1] and the APS Community Planning Process (CPP) [2]. There have been many advances in the stellarator field since those reports were drafted, both theoretically and experimentally, that provide an even stronger motivation for an expanded stellarator program within the US. In addition, in recent years a number of private companies have been founded (and funded) to pursue the stellarator concept, two of which are FES Milestone Program award recipients. An expanded stellarator program is needed to fully support these companies and their goals. This whitepaper aims to briefly provide an updated outlook on the need for a national stellarator program including benefits to private industry and opportunities for Public Private Partnerships (PPP).

**Experimental Advances:** Perhaps the single most important advancement made in the last five years (since the FESAC LRP) is the experimental demonstration of reduced neoclassical transport in the optimized Wendelstein 7-X (W7-X) stellarator [3][4]. Also of great importance is the experimental demonstration of complete energy detachment in long-pulse high power plasmas at W7-X [20]. These advancements have proven the concept of the optimized stellarator and retired the most significant risks along the stellarator path. In addition, the successes (and challenges) from the W7-X and HSX [19] programs highlight opportunities for the US stellarator program to take a leading role in improving stellarator performance and our understanding of stellarator physics.

**Theoretical Advances:** Key findings and developments over the last 5-10 years in theory and modeling have enabled the design of experiments with superior optimization compared to existing devices, including: **(a)** the identification of quasi-symmetric configurations with excellent neoclassical and fast-ion confinement [5][6], **(b)** the introduction of new gyrokinetic codes capable of incorporating turbulent transport as an optimization objective (GX [7]), **(c)** enhanced stellarator MHD modeling capabilities (M3D-C1 [8]), **(d)** validated understanding and modeling of neoclassical transport (SFINCS [9]), **(e)** tools for simplifying coils and reducing engineering tolerances, **(f)** further development of US stellarator optimization tools such as SIMSOPT [10] and DESC [11], **(g)** improved equilibrium codes like DESC and SPEC, and **(h)** the utilization of dipole coils and permanent magnets. In addition, new techniques that utilize machine learning and artificial intelligence combined with high performance computing are poised to accelerate and enable improved performance prediction and optimization strategies [12].

**Private Companies:** There are now three private companies in the US pursuing the stellarator concept: *Thea Energy* [13], *Type One Energy* [14] and *Stellarex* [15]. There are also five international stellarator companies, several of which have US subsidiaries. Two of the US companies, Thea and Type One, have received FES Milestone Program awards. Both of these companies have received substantial private funding, have large scientific and engineering teams, and have aggressively started working on machine design and hardware prototyping. More information on these private companies can be found in Refs. [16] and [17].

A strong publicly funded national stellarator program is important in supporting these companies in further developing the stellarator concept, innovating towards improved stellarator performance, and developing strong public-private partnerships to accelerate pilot plant development. The private companies necessarily need to pursue highly focused research and development on aggressive schedules with utilization of the most mature technical solutions; this approach may limit the ability for these companies to pursue more innovative research activities, or to develop the kind of deep experimental and theoretical understanding that can be accomplished at Universities or National Laboratories. There are several ways in which a publicly funded program can provide benefits to these private endeavors: **(a)** Scientific Innovation **(b)** Deep Physics Understanding **(c)** Theoretical Validation **(d)** Comprehensive Diagnostics **(e)** Flexibility in Experiments **(f)** Experimental Access **(g)** Workforce Development. A longer description of each of these areas of benefit can be found in Ref. [18]. The development of effective and productive Private Public Partnerships requires a vibrant well funded public program that develops expertise and provides added value to the company's pursuits.

**Conclusion:** The US program currently consists of three parts: Theory and Modeling, International Collaboration at W7-X and LHD, and small domestic stellarator experiments such as HSX, CTH, MUSE, CSX and STAR\_Lite (primarily operated at universities). We advocate for expansion of US research activity in all of these areas, as well as construction of a new publicly funded mid-scale stellarator user-facility. The motivation and mission for a mid-scale stellarator was recently laid out in a series of stellarator whitepapers as part of the call from the FESAC Subcommittee on Facilities, See Refs. [18], [19], [16] and [17]. The mission called for in these papers is entirely in line with the outstanding gaps outlined in the CPP and LRP reports, but has been updated to take into account advances in recent years. An expanded national stellarator program will also greatly benefit all confinement concepts; stellarator research necessitates the development of validated 3D tools and exhaust solutions, which can be applied to many other configurations for higher fidelity modeling and prediction.

Now, more than ever before, an expanded national stellarator program in the US is needed to take advantage of the theoretical and experimental progress, and to support the thriving private stellarator endeavors.

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