Magnetic Configuration Research: A Foundation Element for the Development of Magnetic Fusion Energy

Configuration research is a primary driver of innovation and discovery and must remain a foundational element of any U.S. fusion energy program strategy. Research on the magnetic confinement of fusion plasmas tends to differentiate a handful of named configurations by their separate operating points and relative advantages in solving key challenges toward fusion power. In part, this results from technical differences that make it impractical to study multiple, optimized configurations in a single laboratory setting. There is a strong desire to answer, "What is the best configuration?". However, coordinated configuration research is essential to achieve true predictive fusion science, otherwise our knowledge is limited to the narrow ranges that define the tokamak configuration. Furthermore, the large technological gap between present-day experiments and a commercial fusion reactor implies there are challenges yet to be exposed. The tradeoffs represented in different magnetic configurations offer enormous potential to address these challenges as they arise, increasing the odds to achieve practical fusion power that is competitive in the future energy market. A reduction in the scope of configuration research only reduces the possibility to achieve fusion energy.

The prospects to achieve predictive fusion science are bright, given the combination of mature basic understanding and ever-increasing computational capabilities that help us understand the nonlinear nature of fusion plasma behavior. A suite of well-diagnosed configuration experiments is essential to validate plasma models. Predictive fusion science should embrace multiple configurations as close cousins, not just view them as competitors for fusion, since they represent particular combinations of the fundamental variables that govern magnetic confinement. Importantly, the base plasma models are universal so that the inevitable physics and technological tradeoffs can be understood, increasing the opportunity for innovation and allowing the possibility for optimized configurations yet to be discovered.

Configuration research is also one of the most important risk mitigation strategies for the development of fusion energy. The relative advantages and challenges associated with different configurations inherently broaden the possibilities for achieving a practical fusion power source. The U.S. strategic plan must have a spectrum of risk in its elements, including elements that foster the opportunity for disruptive innovation.

Overview of Magnetic Configuration Research: There are only two magnetic field geometries useful for confining a sustained fusion plasma: the torus and the magnetic mirror. Both geometries rely on fundamental momentum and energy conservation principles, and each takes advantage of the enormous anisotropy for collisional transport in a strong magnetic field. Non-tokamak toroidal configurations are sometimes referred to as "alternates", which reflects the relative degree in development and investment (not alternate fusion power). Stellarator configurations are second in development maturity and are discussed in a separate paper. Here we emphasize other toroidal configurations, mirror configurations, and "magneto-inertial" concepts that fall between sustained fusion plasmas and purely inertial fusion concepts.

The U.S. has been a leader in advancing multiple configurations, but the present funding from DOE-FES supports only the tokamak and stellarator configurations. Sharpened focus on tokamaks and stellarators is occurring worldwide as well. In recent years, the former U.S. Innovative Confinement Concepts (ICC) program on non-tokamak research generated a number of new experiments and innovative scientific results, but it was guided primarily by "is there something better than a tokamak?" and emphasized the distinction in concepts. A broader scientific goal to establish predictive science that spans multiple configurations was not a driving force. Most of these ICC experiments were located at universities, which created visible on-campus leadership opportunities in the highly competitive academic environment. Theory, modeling, and diagnostic capabilities were a modest part of the program, but they fell short of the requirements for a coordinated program with predictive science goals. Looking ahead, multi-configuration research creates a fantastic opportunity for the whole community. Well-diagnosed experiments with predictive science goals are feasible at intermediate scale, which helps create opportunity for multiple institutions. The challenge is greatest for larger facilities that must be constructed to validate fusion science close to burning plasma conditions. It will help greatly if we can say, reliably, what the investment cost needs to be and why.

Planning for toroidal configurations is most developed. The FESAC Priorities, Gaps, and Opportunities study[1] provided a thorough analysis of the technical gaps to fusion power with an emphasis on the tokamak configuration. This was followed by the FESAC Toroidal Alternates Panel[2], which considered the issues and opportunities for the stellarator, reversed field pinch, spheromak, and field-reversed configuration in the ITER era. The sum of these efforts was expanded on in the MFE ReNeW workshop report[3]. Note that mirror configurations and the Levitated Dipole were not included in these exercises. The science for pulsed, magnetized, high-energy-density configurations are discussed in a separate ReNeW workshop report[4].

In terms of gap closure, non-tokamak configurations offer the possibility to eliminate key gaps that occur for the tokamak configuration. All gaps must be addressed, and therefore gap elimination is high leverage in the development of fusion power. Since the elimination of any one gap often comes at the expense of widening other gaps or creating new gaps, there is no way to understand the fundamental tradeoffs inherent to the variables in configuration space unless the fusion program maintains research on multiple magnetic configurations.

Status, Benefits, and Near-Term Opportunities: Prior to the 1990's, the U.S. pursued fusion energy research on a variety of configurations at multiple scales. Experiments were located at national labs, universities, and in industry. Much of this research was terminated in FY 1993 to narrow the program on the tokamak configuration. Following the U.S.'s exit of ITER, there was a rebirth in "alternative concept" research in the late 1990's, which reinvigorated the non-tokamak program with new and under-explored configurations. However, configuration research again declined over the period 2010-2017, and today non-tokamak, non-stellarator support for fusion energy development by the U.S. DoE has all but ceased. The ARPA-E ALPHA program presently supports intermediate-density, magnetized, pulsed fusion concepts through fixed-term funding for technology transfer and collaboration with the private sector.

The non-tokamak, non-stellarator configurations[5] that define this "configuration research" strategic element are identified in Table 1. While this might seem a long list, these configurations derive from a few incontrovertible principles: symmetry, the need for a poloidal field in a torus, and a requirement to pre-heat a burning fusion plasma[6]. Key characteristics that distinguish these configurations from the tokamak are tabulated. Each of these characteristics represents opportunity to simplify and improve the vision for a magnetic fusion reactor. Equally important, the configurations, along with the tokamak and stellarator, provide a basis set needed to validate fusion science. The configurations include (a) those with open magnetic field topologies, e.g. the gas dynamic trap (axisymmetric mirror) and centrifugally confined mirror, (b) those with closed magnetic fields topologies having a moderate toroidal field, i.e., reversed field pinch and spheromak, and with little-to-no toroidal field, e.g. field reversed configuration, levitated dipole, and flow Z-pinch, and (c) pulsed concepts that rely on magnetic insulation and imploding liners, i.e., magneto-inertial fusion (a.k.a. magnetized target fusion).

Configuration	Near-Unity Beta	More Compact	Reduced Field at Magnet	Auxiliary Heating Not Required	Simply- Connected Geometry	Advanced Fusion Fuels	Steady State (S) Pulsed (P)
Gas Dynamic Trap (GDT)	◆				◆		S
Centrifugal Mirror		◆			◆		S
Reversed Field Pinch (RFP)		◆	◆	◆			S
Spheromak		◆	◆	◆	◆		S
Field-Reversed Configuration (FRC)	◆	◆	◆		◆	◆	S
Levitated Dipole	◆				◆	◆	S
Flow Z-pinch	◆	◆	◆	◆	◆	◆	P
Magneto-Inertial Fusion (MIF)	◆	◆	◆	◆	◆	◆	P

Table 1. Advantages of non-tokamak, non-stellarator magnetic fusion configurations. The last column identifies inherently pulsed (P) or a steady-state sustainment scenario is identified (S).

Listed below in a common format are key benefits, fusion science highlights, connections to gaps, world program context, status, and next steps for research on each configuration. Given that the support for non-tokamak, non-stellarator research has been drastically reduced, there is an immediate need to assess and rejuvenate magnetic configuration research. The scope of and coordination between "configuration research" and other strategic elements including tokamak configurations, stellarator configurations, theory, materials, fusion technology, etc. must be formulated in a complete strategic plan for the U.S. fusion energy program.

GAS DYNAMIC TRAP (GDT)[7]: An axisymmetric mirror defined by a long mirror-to-mirror distance (compared to ion mean free path) and high mirror ratio. MHD stability is provided by plasma escaping through the mirror throat into a region of good curvature[8].

Key benefits: Simple engineering; steady state operation; no plasma current

Fusion science highlights: A short-pulse (5 ms) experiment at modest magnetic field and heating beam energy (0.3-15T; 25keV) has demonstrated MHD stability at $\beta \sim 60\%$ with classical fast ion behavior and an electron temperature up to 0.9 keV[9], which meet the requirements of a designed GDT-based fusion neutron source that operates at higher field, beam ENERGY and in steady state.

Connections to gaps: A next-step GDT will press the state of the art in steady state operation, will present the ideal test bed for new high temperature superconducting magnets (simple, small bore, and axisymmetric), and its potential as a fusion neutron source addresses major gaps for materials and component development.

Gap elimination: The axisymmetric mirror has viable reactor scenarios (both tandem[10] and GDT[11] variants) that feature a stable, plasma-current free equilibrium that cannot disrupt. The primary gap elimination is through creation of a fusion neutron source.

World program: Only one GDT experiment has been built to date, in Russia. More broadly, tandem mirrors are used to study fusion science at Gamma10 (Japan) and the new KMAX (China, under construction). There are also several material-plasma interaction experiments in the mirror configuration, including Proto-MPEX/ MPEX (USA), JULE-SIM (Germany) and PLAMIS (South Korea).

Status and next steps (<15 year): The GDT at BINP has a planned upgrade to use a multi-mirror end cell to improve axial confinement and the corresponding reactor scenario. The next step in this path is to create a high flux fusion neutron source[12]. Construction of a proof-of-principle steady state, fully superconducting, high field GDT with pulsed heating systems including 80keV deuterium beam injection can begin immediately (cost estimate $50M). It must confirm low secondary electron emission from the end cells (for electron thermal confinement) and low neutral pressure in the central chamber (for fast ion confinement). Implementation of steady state heating upgrades (totaling 50 MW) and DT operation can commence in about 10 years.

CENTRIFUGAL MIRROR[13]: An axisymmetric magnetic mirror configuration is rotated azimuthally at supersonic speeds. The radial centrifugal force confines plasma along the field, closing out loss cones. Velocity shear suppresses flute interchange instability. Pastukhov loss theory predicts Lawson conditions at Mach 6. 3D MHD simulations show confined toroidal plasma that is MHD stable due to velocity shear (V′). This is an underexplored concept.

Key benefits: Simple geometry, steady state, and no abrupt terminations. The axial length is comparable to toroidal geometry circumference. V′ shear is large enough to also suppress microturbulence, resulting in classical cross-field transport (no neoclassical transport enhancements). Non-conventional, physics-based concept makes a study of this novel system highly attractive academically.

Fusion science highlights: MCX experiment[14,15] (2000-2010) was rotated at supersonic speeds and showed quiescent confinement at Mach 1-3, with a 12-fold drop in density axially. Key parameters: $n \sim 3\times10^{20}/m^3$, $T \sim 40eV$, $\tau \sim 0.4ms$, mirror ratio < 8, peak field 1.2 T. Cost < 0.5M/yr.

Connections to gaps: Broaden predictive understanding of transport and scaling in V′ shear dominated plasmas[16], and develop the plasma-material interface in a poloidal-field geometry, e.g., liquid wall concepts.

Gap elimination: Disruption-free sustained plasma; greatly decreased axial length compared with a static mirror system

World program: Some similarity with the Novosibirsk GDT experiment, which is an elongated mirror rotated subsonic by tailored electrostatic biasing, thus providing V′ shear to stabilize the flute mode.

Status and next steps (<15 year): Currently, there is no centrifugally confined plasma research. The centrifugal concept is in infancy. Next steps after MCX are exploration beyond the neutral-dominated regime (possibly using Li pumping), driving rotation by NBI, test if V′ shear suppresses drift modes and if this implies classical cross-B transport. Scaling studies point to high B operation with high mirror ratio, B^m. Over a 10-year horizon, costs would be <$2M/yr. The centrifugal mirror could possibly be interesting to private venture, but a concept this nascent would require several value-added, high-risk phases. There is synergy with proposals for a GDT-based neutron source. Key challenges: V′ shear must suppress flutes at high Reynolds #s, the atomic speed barrier must be overcome, and insulators must sustain 1-10 MV/m, possibly with flared B fields.

REVERSED FIELD PINCH (RFP)[17]: A toroidal, axisymmetric configuration with a highly sheared magnetic field generated primarily by plasma current rather than external coils

Key benefits: Ohmic ignition[18] and inductive steady-state[19,20] are possible if the tokamak-like confinement achieved in present experiments[21] endures at fusion conditions. Heating and sustainment are provided by robust, reliable, axisymmetric transformers that do not require perforations in vessel materials surrounding the plasma. The magnetic field strength at coils is minimized, and high beta is demonstrated[22].

Fusion science highlights: Seminal development of active MHD control[23,24,25], validation of nonlinear extended MHD models[26] of fusion plasmas[27], magnetic self-organization[28,29], and demonstration of the classical confinement of energetic ions in a toroidal plasma[30].

Connections to gaps: Broaden predictive understanding of transport and scaling associated with microturbulence and multi-scale interactions[31], develop robust mode control[32,33], demonstrate inductive steady-state sustainment (oscillating field current drive[34]), develop the plasma-material interface in a poloidal-field-dominated geometry, e.g., liquid wall concepts.

Gap elimination: Obviate auxiliary heating by rf or neutral beam injection, greatly simplifying a reactor first-wall and enhancing overall maintainability and reliability; minimize the magnetic field at magnets

World program: Five experiments: MST (I_p =0.6 MA, R/a=1.5/0.5, *USA*), RFX-mod (I_p =2MA, R/a=2.0/0.4, *Italy*), KTX (I_p <0.5 MA, R/a=1.4/0.4, *China*), Extrap-T2R (I_p <0.3MA, R/a=1.24/0.18, *Sweden*), RELAX (I_p =0.125MA, R/a=0.51/0.25, *Japan*)

Status and next steps (<15 year): Federal funding for RFP fusion research on MST is being terminated, undermining U.S. leadership in RFP research. An upgrade to the shell, boundary, and control coils on RFX-mod has recently been approved. The KTX program is new, with emphasis on completing power supplies and diagnostics. Resolving key gaps for the RFP requires a larger, high-current device with I_p ≥4MA, as described in the FESAC Toroidal Alternates Panel report. This facility would address understanding transport mechanisms, confinement scaling, and steady-state inductive current drive. It would begin the development of integrated boundary control. The estimated cost is several $100M and could be staged to reduce risk.

SPHEROMAK[35,36]**:** A toroidal, axisymmetric plasma configuration contained within a simply-connected vacuum chamber with no externally applied toroidal magnetic flux[37]

Key benefits: Sufficiently large plasma currents allow for Ohmic ignition provided that sufficient energy confinement quality is achieved at fusion conditions. Reduction of technological complexity due to the elimination of the toroidal field coil set and central solenoid may allow for reductions in fusion reactor costs. Modest peak magnetic field on coil allows for flexibility in superconducting material for the poloidal field coil set which is required for steady-state operation.

Fusion science highlights: Platform for study of plasma self-organization, magnetic relaxation and magnetohydrodynamic (MHD) dynamos, verification and validation (V&V) of nonlinear, non-ideal MHD models for fusion plasmas[38], study of helicity injection current drive[39].

Connections to gaps: Study of advanced, energy-efficient current drive to address gap in magnetic configuration sustainment, greater degrees of plasma current profile control. V&V of nonlinear, non-ideal MHD models on small-scale spheromak experiments to enable predictive modeling of fusion systems. Simpler geometry allows for easier optimization of blanket assemblies and first-wall power loadings for eventual fusion reactor systems.
Gap Elimination: Usage of high plasma current magnetic configuration with energy efficient current drive may allow for Ohmic heating to ignition, eliminating the need for auxiliary heating systems. Reducing overall fusion system complexity to enable easier maintainability and potentially lower capital and maintenance costs to enable economic competitiveness.
World Program: HIT-SI3 (R =0.33 m, R/a =1.4, I_p ~30-90 kA, T <100 eV, B ~30 mT, *U. Washington*), SSX (R =0.25 m, R/a =1.2, I_p ~30 kA, T_i =40 eV, B ~100 mT, *Swarthmore*), FAMU-STPX (I_p ~600 kA, T ~300 eV, *FAMU*), TS-4 (R =0.5 m, R/a =1.5, I_p ~30-100 kA, B ~100 mT, *U. Tokyo*), and the Caltech Spheromak Experiment.
Status and next steps: Federal funding for spheromak experiments is small and insecure across all agencies (DOE OFES, ARPA-E, DOE/NSF Partnership). Investment in a new, upgraded sustained-spheromak facility should be made to enable both mainline and spheromak-specific gaps to be resolved. Transient spheromak experiments (e.g. SSPX at LLNL) have produced transient spheromaks with peak electron temperatures between 500-600 eV[40]. A new sustained-spheromak experiment would help address scaling of advanced, power efficient current drive methods to larger, higher temperature plasmas with sufficient energy confinement quality. Additionally, this facility would provide a greater separation of timescales of plasma dynamics at higher Lundquist number ($S = Lv_A/\eta$). A national sustained spheromak program with $5-15M/yr would greatly improve spheromak R&D progress and gap resolution efforts.

FIELD-REVERSED CONFIGURATION (FRC): A toroidal, axisymmetric, extremely high beta configuration in a simply-connected geometry with poloidal magnetic field generated by plasma current[41,42]
Key benefits: Compact toroidal system with (i) simple axisymmetric geometry that facilitates a translation along a central axis, (ii) extremely high β and associated economic attractiveness, (iii) unrestricted natural divertor system facilitating heat removal and exhaust engineering that could enable direct-energy conversion, and (iv) potential for advanced, aneutronic fuel cycle
Fusion science highlights: Demonstration of various reliable FRC formations such as field-reversed theta pinch (FRTP), rotating magnetic field (RMF) driven, FRC collisional merging, and counter-helicity spheromak merging. Demonstration of macroscopically stable, hot plasma sustainment up to 5+ ms via high-power neutral-beam injection (NBI) whose fast ions are classically confined in an FRC, which also exhibits a favorable energy confinement scaling that is proportional to positive power of electron temperature (unlike Bohm scaling)[43].
Connections to gaps: Study of efficient plasma heating (by NBI, RF, compression, etc.), current drive, and stability / plasma control. Broaden understanding of transport and scaling inside and outside of FRC separatrix. Demonstrate steady-state plasma sustainment or pulsed magnetic/inductive plasma compression for breakeven (magnetized target fusion).
Gap elimination: Eliminate extreme material challenges via aneutronic fuel cycle; eliminate linked-magnet constraints to improve system maintainability and reliability
World program: Ten experiments: C-2U/C-2W (FRTP/FRC merging/NBI, USA), PFRC (RMF, USA), MSX (FRTP, USA), NUCTE/FAT (FRTP/FRC merging, Japan), IPA/Grande (FRTP/FRC merging/MTF, USA), TS-3/TS-4 (Spheromak merging, Japan), MRX/FLARE

(Spheromak merging, USA), SSX (Spheromak merging, USA), KMAX (FRTP/FRC merging, China), Yingguang-I (FRTP/MTF, China)

Status and next steps (<15 year): Two different FRC-based fusion approaches are currently underway in the U.S. and Asia by private/government funding: beam-driven FRC for steady-state operation and pulsed-compressional FRC for MTF. For the beam-driven FRC, near-term objective is to demonstrate steady-state high temperature FRCs by high power NBI and other auxiliary heating; while, for MTF approach, effective high-pulsed compressional magnetic field (up to ~50 T) will be designed and applied to achieve high temperature/density fusion condition. Both of which require device upgrade / scale-up with some R&D; however, experimental span of FRC research can be relatively short / aggressive because of system simplicity.

LEVITATED DIPOLE: Toroidal configuration with a purely poloidal magnetic field generated by a single coil suspended within the plasma by magnetic levitation[44]. The concept was motivated by the understanding gained from satellite observations of magnetospheric plasmas and advances in high-field superconducting magnets.

Key benefits: Provides steady-state, disruption-free, and near-unity beta plasma confinement. It is most relevant for use with aneutronic fusion fuel cycles to accommodate a floating coil within the plasma. The dipole's inherently larger particle transport relative to heat transport bolsters tritium-suppressed D-D fusion, in particular.

Fusion science highlights: Demonstrated robust steady-state operation with good plasma confinement. Observation of inward turbulent pinch[45,46,47]; concept driver for advanced-fuel fusion reactor development[48]; concept driver for fusion space propulsion[49]

Connections to gaps: Broadens understanding of self-organized plasma turbulence, motivates the development of high-field, high-performance magnets, stimulates fusion plasma conditions with advanced fuel cycle

Gap elimination: Simple plasma sustainment that eliminates current disruptions; aneutronic fuel cycle eliminates many fusion material challenges; inherent plasma expansion simplifies the plasma-material interactions, including the interface for auxiliary heating sources

World program: The LDX[50] (MIT) was the largest dipole experiment with a 0.66 m diameter, 1.2 MA superconducting (Nb3Sn) coil. The RT-1 device (U. Tokyo) has a 0.50 m diameter 0.25 MA high-Tc Bi-2223 superconducting coil. Steady-state discharges are maintained with 10-50 kW of ECRH. Recently, low-power ICRH experiments have begun at RT-1.

Status and next steps (<15 year): Laboratory experimental tests of the dipole concept with high-power heating must be conducted to verify confinement properties at fusion-relevant conditions. Several experiments have been proposed but not yet funded. These projects have total project costs ranging between $6M USD and $25M USD. A fusion-performance experiment requires a device that can be built using existing superconducting magnet technology in a scaled experiment, e.g., a 4 m diameter, 15 MA coil coupled with 10 MW of auxiliary heating could achieve Q(DT) $\approx$1. The required containment vessel is large but uses simple, low-cost technology.

FLOW Z-PINCH[51,52]: A linear configuration relying solely on sheared axial flows to provide plasma stability

Key benefits: No external magnetic field coils and purely azimuthal magnetic fields leads to $\langle\beta\rangle = 100\%$ with perpendicular transport towards any material structure. Resulting high energy densities naturally lead to a compact and low-cost device.

Fusion science highlights: Demonstrated high performance sheared-flow-stabilized Z-pinch plasmas[53,54,55] with quiescent lifetimes greater than 1000 V_A and with plasma parameters that are $n_e \approx 2\times10^{23}$ m^{-3}, $\tau \approx 50$ μs, and $T_e \approx 1$ keV[56]. Produced sustained 5-10 μs pulses of DD neutrons, suggesting thermonuclear origin.

Connections to gaps: Investigate sheared-flow stabilization in a simple configuration with potential applications to other configurations. Develop high beta concepts with no magnetic field coils. Study plasma-material interactions, including liquid metal walls.

Gap elimination: High beta operation avails advanced fusion fuels. No external field coil and linear configuration greatly simplify fusion core design.

World program: UW-Seattle/LLNL experiments: ZaP, ZaP-HD, FuZE. Previous experiments of continuous flow pinch and quasi-steady-state plasma accelerator existed at LANL[57] and Kurchatov Institute[58].

Status and next steps (<15 year): Federal funding (ARPA-E) for fusion research on the flow Z-pinch is scheduled to terminate August 2018. Next steps include demonstrating shear flow stabilization of the Z-pinch with increasing plasma current and driving to fusion-grade plasmas, designing plasma-facing electrodes, and researching plasma interactions with liquid metal walls.

MAGNETO-INERTIAL FUSION (MIF), a.k.a. MAGNETIZED TARGET FUSION (MTF)[52]: This is a class[59,60] of pulsed, imploding fusion concepts, i.e., liner compression of a magnetized plasma[61,62,63,64] utilizing magnetic field to reduce thermal transport and enhance alpha-particle deposition in the stagnated fusion plasma.

Key benefits: Intermediate-density MIF optimizes the combination of required stored energy and heating power to achieve Lawson conditions[65], thus potentially offering a lower-cost, faster development path to economical fusion power. Key benefits are (1) use of low-cost pulsed power, (2) heating via compression, and (3) compatibility with a thick liquid blanket.

Fusion science highlights: Simple, low-cost means to access magnetized high-energy-density (HED) regimes[4], enabling advances in fundamental plasma and HED physics.

Connections to gaps: Because MIF has many challenges orthogonal to those of MFE, MIF represents an important piece of a diverse portfolio to mitigate risk in fusion-energy development. MIF also shares common challenges with MFE, e.g., power extraction (G-10, G-11, G-12), predictive modeling (G-1, G-6), measurement (G-3), and RAMI (G-14, G-15).

Gap elimination: MIF, by virtue of its pulsed nature, elimination of auxiliary heating, and likely use of a thick, flowing liquid blanket, strongly mitigates many Greenwald et al.[1] gaps (G-2, G-4, G-5, G-7, G-8, G-13). There are of course new gaps, e.g., robust, repetitive pulsed power.

World program: Z machine (e.g., MagLIF), Russian MAGO, Chinese solid-liner compression of FRC and interest in MagLIF and other MIF concepts, ARPA-E ALPHA program (early-stage development of several MIF variants), and magnetized ICF (LLE/Rochester and NIF).

Status and next steps (<15 year): Continued NNSA funding will allow timely, further studies of crucial physics at fusion-relevant densities and temperatures on the Z machine or other NNSA facilities, benefitting MIF development but not direct support of its fusion energy potential. A combination of ARPA-E follow-on funding and/or reinstatement of support for MIF within FES could allow the most promising CE-level MIF concepts, presently supported by ARPA-E, to possibly progress to POP- and then PE-level performance, which should be a primary objective over the next 10 years. The goal should be to put us on a path to enable DEMO-level performance in 15-20 years. A budget of ~$10M increasing to $20M/year in the next 3-5 years would allow meaningful and timely progress toward POP performance for several of the ongoing CE efforts.

Programmatic Implications: History shows that the strong drive to identify "the best" configuration makes it difficult to coordinate research on different configurations. The loss, rebirth, and subsequent loss of non-tokamak research correlates with the challenge in realizing facilities on the scale of ITER. While it is important to expose the benefits of different configurations, since this may in fact be essential to realize fusion energy, the maturity of fusion science allows the possibility to understand and predict fusion plasma behavior across configuration boundaries. This is a programmatic vision that demands greater coordination and less institutional identity associated with any one configuration. To succeed, theory and computation must be made as universal as possible within the bounds defined by the principles governing fusion plasma confinement and heating. There is an opportunity to organize experimental facilities with greater national ownership. If an appropriate strategy is adopted, the program can support universities, national laboratories, and coordination with the growing private sector's investment in fusion energy development. Given the wide range in relative maturity, experimental facilities at small and intermediate scale are appropriate for many of the next steps described above. New facilities at multiple scales will generate scientific interest and allow rapid progress that complements the inherent longer timescale associated with projects like ITER. The U.S. fusion program needs to regain trust, and successfully completing a number of projects on different scales will help rebuild this trust.

Critics' Concerns and Advocates' Responses:
Concern: The tokamak configuration clearly performs the best. Why do we need to investigate configurations that do not perform as well?
Response: A fusion reactor does not yet exist. It is difficult to prove that any configuration will or will not work. Given fusion's importance, we need risk mitigation strategies, including validated science that reliably determines what is possible or not. Configuration research is fundamental to this science and to overall risk mitigation of fusion energy development.

Concern: We cannot afford research on configurations other than the mainline.
Response: We need arguments that can grow support for fusion energy. Configuration research is a fundamental approach to fusion energy that everyone can embrace for the essential science it provides and for its potential to enable robust, simple, and smaller reactor concepts. The required resources are not large for every element in a balanced portfolio.

Concern: Alternate configurations might help optimize second generation fusion power, but we should concentrate on the tokamak now so that fusion's importance is demonstrated as quickly as possible.
Response: By any metric, the world's fusion programs are already very concentrated on the tokamak and have been for decades. Unless we research alternatives, a second-generation reactor cannot be based on a different configuration. There are legitimate concerns that the present tokamak path will not lead to competitive fusion energy. Developing the scientific and technical understanding that produces economically viable fusion reactors should be a priority, so that a first-generation, non-competitive reactor does not eliminate fusion as a future energy source.

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