Facility for Fusion Optimization and Validation (FFOV)*

Research to be performed: The FFOV will be dedicated to (1) the optimization of the toroidal magnetic fusion configuration and (2) the validation of toroidal magnetic fusion science. The first of these two synergetic mission elements will be focused on the limit of minimal externally applied magnetic field, embodied by the reversed-field pinch (RFP) configuration. The second mission element will be conducted through the study of RFP, helical-3D, and tokamak magnetic configurations, all produced in the same device.

Many engineering and scientific challenges remain in the development of magnetic fusion, and the optimum magnetic configuration to address these challenges simultaneously is not yet established. This calls for vigorous exploration, in experiment, theory, and computation, of all of the basic variables of toroidal magnetic confinement. These variables include applied toroidal magnetic field strength and the degree of 3D shaping.

Validation of toroidal magnetic fusion science also entails variations, in experiment, theory, and computation, of the same basic variables of magnetic confinement over as wide a parameter space as possible. Such a broad approach is much more likely to lead to predictive fusion science, which is the ultimate goal of validation. Full predictive capability may or may not be an achievable goal for fusion science, but striving for this capability will at a minimum help to reduce uncertainty in extrapolations to fusion devices beyond ITER. Given their expected cost and complexity, empirical scaling may not suffice.

This vision for toroidal magnetic fusion science, with a U.S. focus, is captured in Fig. 1. Optimization and validation need to occur in parallel with and be tightly coupled to the research that is planned for ITER and FNSF, for example, culminating in the design and construction of DEMO. *Note, however, that the FFOV is by no means sufficient to address all of the needs in optimization and validation, but it will contribute substantially*.

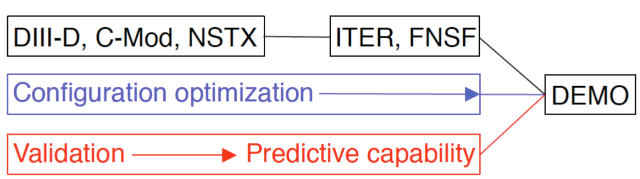

Fig.1. Some of the efforts needed for successful development of toroidal magnetic fusion science.

The Facility for Fusion Optimization and Validation will be the most advanced of its kind. The facility will produce world-leading RFP plasmas along with helical-3D and modest tokamak plasmas. Together, these plasmas comprise a spectrum of magnetic confinement variables. The RFP plasma is formed in the limit of weak externally applied toroidal magnetic field. The helical plasma embodies strong 3D shaping, similar to a stellarator plasma, but arises spontaneously (subject to certain conditions) in the core of otherwise toroidally axisymmetric RFP plasmas [1]. The tokamak plasma is formed with a strong externally applied toroidal magnetic field. The FFOV also requires an advanced and comprehensive diagnostic set, and it requires a very strong, tightly-coupled effort in theory and computation spanning a broad range of physics including magneto-hydrodynamics (MHD) and gyrokinetics. A very simplified rendition of the FFOV is shown in Fig. 2. In the bubbles surrounding the toroidal device are some of the fusion science and plasma physics topics addressed by the facility.

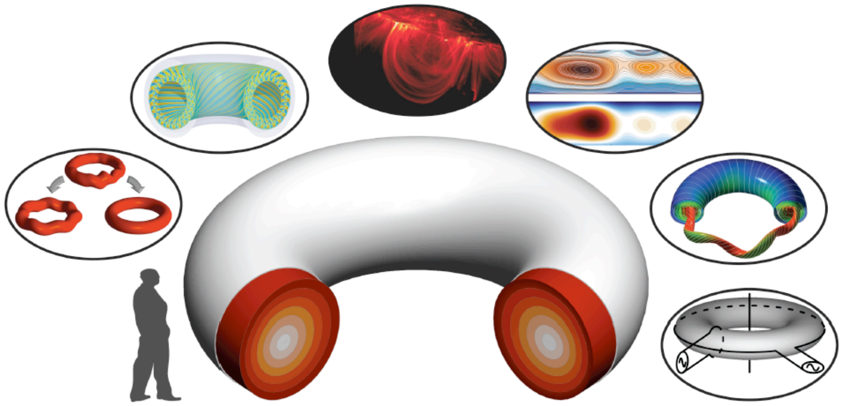

Fig.2. Schematic of the Facility for Fusion Optimization and Validation

The RFP plasmas produced in this facility will be the largest, hottest, and best-controlled RFP plasmas in the world. Most of the confining magnetic field in the RFP is produced by current in the plasma, rather than in coils surrounding the plasma. This provides beneficial engineering attributes, including (1) the possibility that fusion ignition can be reached with Ohmic heating alone, obviating the need for more expensive and complicated means of auxiliary heating and (2) that the magnetic field coils can be copper rather than superconducting. However, this can also lead to larger magnetic turbulence in the plasma, which can degrade fusion performance, and sustainment of the relatively large plasma current presents a challenge for steady-state operation.

A key dimensionless parameter for the RFP is the Lundquist number, $S \sim I_p T_e^{3/2}$, where I_p is the toroidal plasma current, and T_e is the electron temperature. Both the maximum I_p and T_e will be substantially larger in the FFOV than in any present RFP device. Hence, by scanning these parameters in the FFOV, one can attain a large range of $S \sim 10^5$ - 10^9. This will in turn allow one to address key questions for the RFP, one of which is how magnetic turbulence and energy transport scale with S. In present RFP plasmas, as S increases to > 10^7, magnetic turbulence and energy transport are spontaneously reduced, in a self-organized fashion. How this turbulence behaves at even higher S is an important knowledge gap. Another key question for the RFP is whether or not dc sustainment of I_p is possible at high S with purely ac toroidal and poloidal loop voltages. Such ac inductive drive in existing devices has sustained ~ 10% of I_p. The conversion of ac voltages to a dc current involves magnetic self organization, as established in nonlinear MHD modeling. But at low S, the required ac modulation of the equilibrium is substantial and can trigger unacceptably high levels of magnetic turbulence. With larger S as in the FFOV, the required modulation is expected to decrease, and 100% inductive, steady-state sustainment is theoretically possible. But this must be confirmed experimentally.

The variation with S of magnetic turbulence in the RFP will serve as a powerful contributor to validation of nonlinear MHD codes, such as NIMROD, which is already being applied to a variety of magnetic configurations. Electrostatic turbulence, which often governs the behavior of stellarator and tokamak plasmas, can also be studied in RFP plasmas. This is of greatest import in present devices when magnetic turbulence is reduced, either spontaneously as described above, or through advanced inductive control of the plasma. Gyrokinetic codes, such as GENE, are needed to study such plasmas, and this has stimulated the adaptation of such codes to the RFP configuration, incorporating the small toroidal field and large magnetic field shear. The 3D helical plasmas arising in the RFP plasma core become more common and longer-lasting as S increases. For MHD validation purposes, this combines the physics of self organization with 3D shaping. Also important is that the orientation of the helical plasma varies from discharge to discharge, thereby allowing a much more complete view of the helix with each diagnostic. Given the common role of electrostatic turbulence in tokamak plasmas, comparative gyrokinetic modeling of tokamak and RFP plasmas in the FFOV with the same codes will contribute strongly to validation of these codes. Both tokamak and RFP plasmas share commonalities in MHD behavior, e.g., in the occurrence of magnetic reconnection events. Modeling such similarities in the disparate magnetic configurations will further serve the cause of validation.

Note that the validation effort to which we refer here is generally more rigorous than what has been carried out for years in fusion research, i.e., the routine and sometimes qualitative comparison of experimental measurements to theory and computational models [2,3]. One of the fundamental characteristics of validation as it applies here is that it strives to assess quantitatively the degree to which a model accurately represents the real world. Such rigor is now common practice in fluid dynamics, but it is only slowly being adopted in fusion science. This rigor demands experimental data with well-quantified uncertainty, and it demands quantitative comparisons to "verified" computational models [3]. It also benefits from models being able to incorporate parameters as close as possible to experimentally relevant values. In MHD codes, e.g., accommodation of large S is computationally intensive, and this is an area of continuing development.

Facility's impact beyond FES mission: This facility's impact beyond the FES mission lies primarily in its connections to astrophysics, stemming from the many effects of magnetic self organization. Relevant questions in astrophysics abound, including, for example, the physics governing the spatial scales and reconnection rates in stellar coronae. Addressing this and other questions in the laboratory benefits strongly from a plasma with very high S and very low collisionality, mirroring certain astrophysical settings. Given the parameters of the RFP plasmas in the FFOV, it can play an important role in these endeavors world-wide. For example, magnetic reconnection in the FFOV is expected to occur in a regime in which the reconnection layer breaks up into multiple islands, or plasmoids, and this can accelerate the reconnection. Understanding this regime is at the forefront of research on the earth's magnetotail and the solar wind.

The facility: Following the planning in the ReNeW report, the FFOV will be operated in two successive stages. The first stage is described in this white paper. The second stage would entail primarily an upgrade to the facility's power supplies to push I_p and S even closer to the values expected in a burning fusion plasma.

The FFOV is a toroidally axisymmetric device with a circular poloidal cross section, major radius R = 2.4 m, and minor radius a = 0.8 m. Copper magnetic field coils will be driven by fully programmable, feedback-capable, solid-state power supplies. The plasma-facing boundary will be protected by tungsten limiters. A state-of-the-art active feedback system, building on the very sophisticated systems in existing RFP devices, will control otherwise deleterious radial magnetic perturbations. RFP plasma parameters include I_p = 4 MA, T_e ~ 5 keV, S ~ 10^9, and ρ* (the deuteron gyroradius normalized to the plasma minor radius) < 0.01. Since the helical plasmas arise within RFP plasmas, the parameters for these 3D plasmas will be similar to those just listed. As designed for RFP plasmas, the poloidal field system will be more than sufficient for tokamak operation, where the maximum I_p is limited by the applied toroidal magnetic field. As presently conceived, the toroidal field system will allow I_p up to ~ 0.5 MA in tokamak plasmas. The FFOV requires an advanced and comprehensive diagnostic set, not only to measure key parameters, but also to provide multiple independent measurements of these parameters.

Facility context with respect to FES planning documents: The basis for this facility is derived substantially from the Toroidal Alternates Panel and ReNeW reports. These reports describe RFP progress, prospects, and likely contributions to toroidal fusion science. This facility is also motivated by the recent report of the FESAC Subcommittee on the Priorities of the Magnetic Fusion Energy Science Program. This subcommittee prioritized some of the research thrusts described in the ReNeW report. Among the highest priorities were validation, utilization of 3D shaping, and achieving high performance with small applied field. This facility also reflects the planning incorporated in the "Proof of Principle" proposal for RFP research [4], under which the U.S. RFP program has been operating. Based on criteria laid out in that proposal, including progress in RFP fusion performance, a more powerful next-step RFP device is now warranted.

Facility context with respect to world effort in fusion and plasma science research: This facility will produce the largest and hottest RFP plasmas with the highest I_p (4 MA) and S (10^9) in the world, and the range of S will extend over four orders of magnitude. The largest I_p (2 MA) and S (> 10^7) in present devices will not increase substantially for the foreseeable future. The RFP plasmas in the FFOV can be controlled such that magnetic or electrostatic turbulence is dominant, and they can be compared to helical and tokamak plasmas in the same device.

Estimated construction and annual operation cost, and schedule: The final design and construction of the FFOV are estimated to require a minimum of two years and three years, respectively. This is based on past experience with smaller but otherwise comparable facilities. The total initial cost is roughly estimated to be $430M, including $30M for design and $400M for construction. The annual operational cost is estimated to be at least $35M, based on the present operational budgets for the three largest U.S. facilities.

Facility readiness: *This facility is (a) ready to initiate construction*. The mission and technical requirements are well defined, and the basic design of the facility mirrors that of devices already in operation. Certain details of the design will be informed by work ongoing in the world-wide RFP program, including optimal application for inductive control of solid-state, programmable power supplies and the optimal placement of shells and feedback coils surrounding the plasma.

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