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# Next Steps in Quasi-Axisymmetric Stellarator Research

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***Abstract*— The quasi-axisymmetric (QA) stellarator, a three-dimensional magnetic configuration with close connections to tokamaks, offers solutions for a steady-state, disruption-free fusion system. A new experimental facility, QUASAR, provides a rapid approach to the next step in QA development, an integrated experimental test of its physics properties, taking advantage of the designs, fabricated components, and detailed assembly plans developed for the NCSX project. A scenario is presented for constructing the QUASAR facility for physics research operations starting in 2019. A facility for the step beyond QUASAR, performance extension to high temperature, high pressure sustained plasmas, is described. Operating in DD, such a facility would investigate the scale-up in size and pulse length from QUASAR, while a suitably equipped version operating in DT could address fusion nuclear missions. New QA optimization strategies, aimed at improved engineering attractiveness, would also be tested.**

***Keywords—stellarator, quasi-symmetric, quasi-axisymmetric, NCSX, QUASAR.***

## I. Introduction

The establishment of the ITER project marks a transition in the world magnetic fusion energy (MFE) program to one increasingly focused on the facilities and programs needed, in addition to ITER, to demonstrate electricity generation from fusion. The European community has recently published a roadmap [1] that includes plans for construction of a fusion demonstration plant (DEMO) starting around 2030. China [2] and South Korea [3] are developing designs for next-step fusion nuclear facilities intended for construction starting in the 2020s and net electricity generation as their ultimate goal. These plans all rely on the tokamak for the demonstration step but, significantly, the European plan includes a mission to develop the HELIAS stellarator line as a long-term alternative and Japan continues to develop the Heliotron line, aiming toward a helical-coil stellarator DEMO.

Steady-state plasma operation is generally considered to be a requirement for fusion power plants; see, for example, Ref. [4]. This fact motivates the interest in stellarators, three-dimensional devices which have the advantage of an intrinsically steady-state magnetic configuration that relies on currents in coils, not in the plasma, to satisfy basic conditions for confinement. Since there is no need for external current drive to sustain the configuration, recirculating power requirements are low. In addition, stellarators generally do not exhibit disruptions and, unlike tokamaks, are not limited to low densities by the Greenwald limit or current drive requirements. Stellarators can thus provide solutions to key problems facing MFE development-disruption-free steady-state operation and more favorable plasma conditions for steady-state divertor operation, but continued concept development and experimental tests at high performance and long pulse are needed if fusion is to take advantage of these benefits. Increased investment in stellarator research can significantly reduce fusion development risks compared to a program that is limited mainly to tokamaks.

## II. Quasi-Axisymmetric Stellarators- Role in MFE Development

Currently there are two major stellarator development programs in the world: Japan's Large Helical Device (LHD) and Germany's Wendelstein 7-X (W7-X) experiment, the latter currently under construction. These programs are advancing stellarator physics in H and D plasmas at a minor radius around 0.5 m. Both use superconducting magnet technology to facilitate long-pulse (30 min. or more) operation for testing of control strategies and divertor concepts. The LHD projects to a continuous helical-coil DEMO device, FFHR-d1 [5]. The W7-X projects to a non-planar coil DEMO device, HELIAS [6], in which the geometry of the coils is chosen to optimize plasma physics properties.

In an innovative stellarator optimization strategy called *quasi-axisymmetry (QA)*, the configuration is three-dimensional (3D) but the *magnitude* of the magnetic field exhibits tokamak-like dependence along magnetic field lines [7, 8]. In a QA stellarator the effective helical ripple [9] along magnetic field lines, the parameter that drives neoclassical losses in stellarators, can be the lowest of any stellarator ever built, making the magnitude of the magnetic field approximately constant in the toroidal direction. This property allows a QA stellarator to exhibit the attractive confinement properties of tokamaks, such as well-confined charged particle orbits and support of plasma flows, while retaining the stability and steady-state properties of stellarators. In contrast to LHD and W7-X, which target zero net toroidal current operation, the QA design uses the self-generated bootstrap current to produce a fraction of the poloidal magnetic field. While the QA stellarator awaits experimental testing, the closely related quasi-*helically* symmetric HSX stellarator in Wisconsin has been demonstrated to have good orbit and neoclassical confinement, and plasma flows [10] in accordance with the same neoclassical theory that underpins both the QA and HSX optimizations.

The advantages of the QA approach, and its complementarity with the LHD and W7-X approaches, motivate implementation of a long-range QA development program. A recent report of the U.S. Fusion Energy Sciences Advisory Committee, charged by the Department of Energy to identify critical facilities for the next decade, said that "the time is ripe to pursue a comprehensive approach to quasi-symmetric stellarators to exploit their projected benefits and deal with their presently-understood challenges in more integrated, high-performance plasma experiments." [ 11 ] While a comprehensive program would include multiple elements such as theory, design optimization, and reactor studies, the key element is experimental research using large-scale facilities. Motivated by the need and the renewed interest, as well as an issue, geometrical complexity, that currently detracts from the advantages, this paper describes a path forward for the next facility steps in QA stellarator research.

## III. Integrated QA Physics Test: QUASAR

A new experimental facility, QUASAR, would support an integrated experimental test of QA physics properties at the minimum scale and pulse length needed to evaluate its potential and risks in comparison with other approaches. The cost and schedule for QUASAR implementation would be minimized by using the design and the components that were fabricated for the planned NCSX facility before its construction was terminated in 2009.

### A. *Mission*

QUASAR's mission, like that of NCSX, is to assess the physics benefits and risks of using QA shaping as a strategy for controlling high-beta stability and confinement in future steady-state fusion devices. The original NCSX design was optimized for low ripple, motivated by neoclassical transport considerations, as well as good magnetic surfaces and stability at high beta [12-16]. QUASAR experiments will validate the optimization methods used in that design. Recent studies [17] indicate that it may also be possible to use plasma shaping to minimize small-scale turbulence in QA configurations. QUASAR's shaping flexibility may make it possible to experimentally test these predictions of micro-turbulence theory. The similarity between QA and true axisymmetry means that the 3D science studied on QUASAR will inform tokamak research in critical areas such as edge localized mode (ELM) control, divertor heat control, and error field penetration.

The physics questions that motivated the NCSX program over ten years ago have not been addressed in the intervening years and are still in need of answers. QUASAR will support research to provide answers to those questions; specifically, how does QA shaping affect:

- Pressure limits and limiting mechanisms?
- Disruptions and operating limits?
- Transport and confinement with low QA ripple?
- Turbulence and turbulent transport?
- Relationship between QA and tokamak transport?
- Equilibrium islands and tearing-modes?
- Divertor operation, compatibility with good core performance?
- Energetic-ion stability and confinement?

Research on QUASAR will improve understanding of the relationship between tokamaks and QA stellarators and the extent to which future QA developments can build on tokamak results, particularly burning plasma physics results from ITER. While only 25% of the rotational transform is provided by self-generated currents in QUASAR high-beta scenarios, experiments on low-beta current-carrying stellarators (e.g., CLEO, Wendelstein 7A) showed that disruption-free operation was possible with as much as 85% of the transform provided by plasma currents. QUASAR has been designed to eliminate all known large-scale plasma instabilities and is predicted to be resilient to disruptions. This will be tested experimentally

### B. *Design*

The QUASAR design is based on a three-period QA stellarator configuration. The magnet system consists of 18 non-planar coils (six each of three different shapes), plus various planar coil sets. The non-planar coils and plasma are depicted in Fig. 1. The major radius R is 1.4 m, the magnetic field on axis $B_0$ is $\leqslant 2$ T, and the pulse length is 0.5 to 2 s depending on the magnetic field strength. In order to limit the size of islands due to field errors, a magnet system tolerance of ±1.5 mm, magnetic permeability $<1.02\mu_0$, and material choices to limit eddy currents were specified. An array of trim coils provides capability to compensate for construction errors. The magnet system is designed to provide plasma shape flexibility in order to test the effects on plasma stability and transport.

The engineering design of QUASAR is depicted in

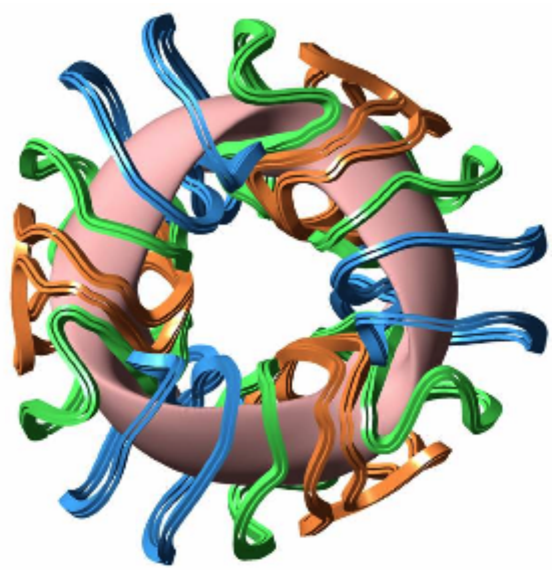

Fig. 1. Non-planar coils and plasma configuration.

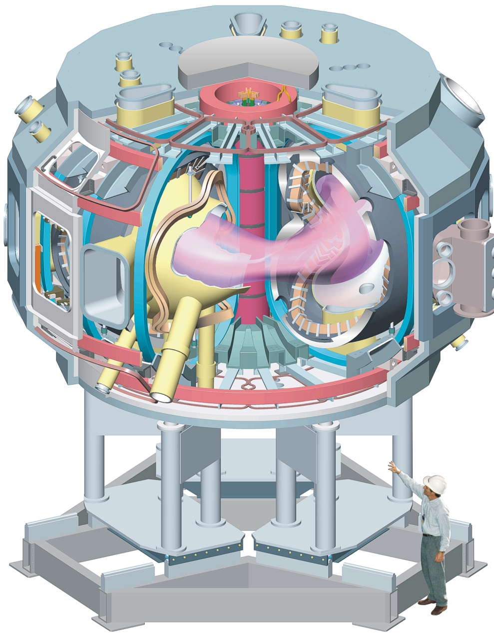

Fig. 3. QUASAR stellarator device design (CAD model).

Fig. 3. The most critical subsystem, and the structural "back-bone" of the device, is the non-planar coil array. A shell-type structure, with the coils supported on the inside surface, was adopted as a robust solution to the problem of minimizing deflections under a wide range of operating conditions (Fig. 2). The magnet system is designed to be pre-cooled to cryogenic temperature (80 K) and heat is removed between pulses by liquid nitrogen coolant flowing through tubes on the outside of the coil winding pack.

The QUASAR vacuum vessel design features about one hundred ports, providing access for diagnostics, vacuum pumping, fueling, and plasma heating. It can support up to 100% coverage of the interior wall with either carbon or tungsten plasma-facing components and has capability for heating to 350 C for bakeout purposes, as well cooling for between-shots heat removal compatible with up to 12 MW of auxiliary heating. A concept for a pumped divertor compatible with the QUASAR plasma geometry exists and provides a basis for detailed design development

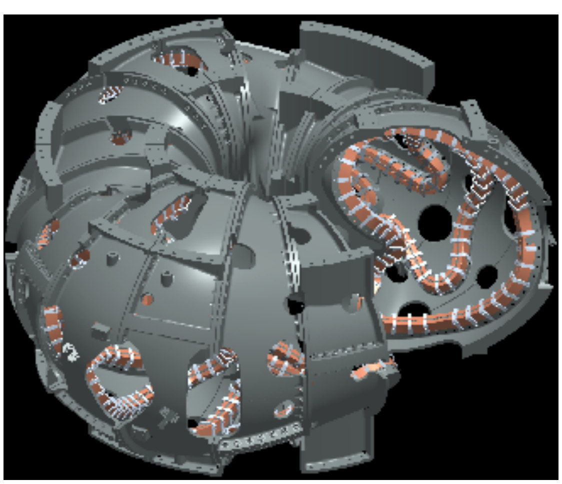

Fig. 2. Non-planar coil system engineering design.

*C. Construction Status and Assembly Plan*

Construction of QUASAR will take advantage of equipment and assembly plans produced by the NCSX project [18]. All 18 non-planar coils and all 18 TF coils were fabricated, with non-planar coil winding centers falling within a ±0.5 mm tolerance band over ~90% of their circumference. In addition, all vacuum vessel components, consisting of three toroidal sectors and dozens of port extensions, were fabricated, and services including heating and cooling tubes, magnetic diagnostics, and temperature sensors were installed.

The planned device assembly process starts with the construction of six non-planar coil half-period assemblies (HPAs), each consisting of three coils. Two HPAs, one of which is pictured in Fig. 4, have been constructed, both within the ±0.5 mm coil positioning tolerance allocated to the HPA step. The next step will be the construction of three field period assemblies (FPA), starting with the installation of two HPAs over the ends of a vacuum vessel sector and joining them together. No FPAs have been constructed but a trial installation of a HPA over a vacuum vessel sector was performed, validating the tooling and procedures for that step.

In subsequent assembly steps, the TF coils and port extensions will be added to complete the FPA. During final assembly, the FPAs will be translated simultaneously along

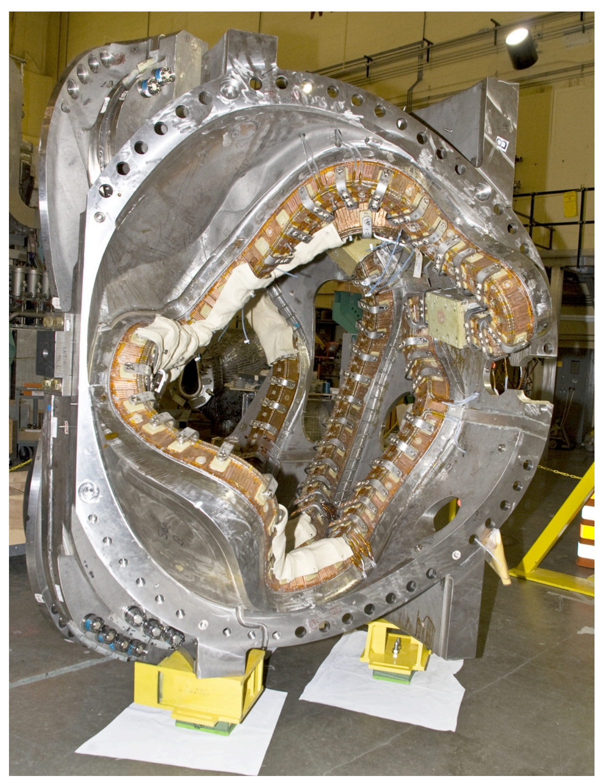

Fig. 4. Completed coil half-period assembly.

radial paths to their final position, after which the FPAs will be joined at their coil and vacuum vessel interfaces, and finally the poloidal field coils and trim coils will be installed.

The QUASAR device can be installed in the C-Site test cell at Princeton Plasma Physics Laboratory (PPPL), utilizing the site that was prepared for NCSX as well as magnet power and plasma heating systems available at PPPL. Other sites, both at PPPL and elsewhere, are being examined as possible sites for QUASAR.

### *D. Implementation Plan*

QUASAR implementation will build on the detailed technical plans and estimates for completing NCSX construction, reviewed multiple times in the course of the NCSX project, which are available and are still valid. A 2007 engineering review by an international panel concluded, based on the work completed and assembly plans in place at that time, that the stellarator could be successfully constructed and maintained. After such a long hiatus, a new planning and estimating activity, concluding with the establishment of a project baseline, is needed. While the technical plans and logic for completing the NCSX project are directly applicable to QUASAR, changes in circumstances over time motivate updating the implementation plan.

*1) An optimized cryogenic system design.*

Planning for QUASAR will include a re-examination and optimization of the cryogenic systems design, taking into account the successful experience from the Alcator C-Mod experiment which, like QUASAR, operates with coils at cryogenic temperature. The QUASAR design includes a liquid nitrogen (LN) supply, delivery, and distribution system; a cryostat enclosing the entire magnet system; and thermal insulation. Coil cooling between pulses is accomplished with a closed high-pressure manifolded system. For initial cooldown, a dry gaseous system was originally chosen for the interspace around the coil shell. However, an alternative based on LN tubing connections to the outer surface of the shell was under consideration at the time of NCSX closeout. Another alternative is exemplified by Alcator C-Mod, which uses a tube-fed drip system with pumped recirculation of liquid from a sump at the bottom of the cryostat and which performed successfully over 20 years of operation of that facility. In summary, opportunities to optimize the QUASAR cooldown design for simplicity, space conservation, and reduced risk are available without impacts to existing construction, and will be considered. Similarly, opportunities to optimize thermal insulation and cryostat interfaces are also available.

*2) Re-evaluation of plans for use of legacy equipment.*

The NCSX plans, established in the early 2000s, for re-use of existing legacy equipment will be re-visited to ensure that QUASAR can be a fully-utilized facility with a high level of availability. In the case of the neutral beam injection (NBI) heating system, the NCSX plan was to refurbish the system of four beams that were originally built around 1978 for the PBX experiment; however, the cost of this solution has risen due to the need to replace obsolete components with new equipment for efficient and reliable operation. An alternative is to procure an entirely new NBI system, which would provide options for pulse lengths longer than the 0.3 - 0.5 second limit of the PBX beams, and would likely offer higher availability. A key task for the QUASAR planning phase will be the careful quantitative evaluation of the costs and risks of these options. Similarly, other NCSX legacy equipment choices to be examined include vacuum pumping equipment, magnet power supplies, and diagnostic equipment. It is expected that the original choices will be validated in some cases, while new or partially new solutions may be needed in others.

*3) An updated cost estimate*

The cost to complete the NCSX project through first plasma was estimated at the time of closeout (2009) at \$73.4M, including \$18.3M of contingency. This estimate covered construction of the stellarator and achievement of first plasma with temporary facility services, i.e. magnet power supplies, vacuum pumping, and controls. The estimated cost to install the heating, diagnostics, and permanent facility services needed to support the start of physics research was an additional \$27.8M, for a total of \$101.2M in 2009 dollars. A key task for the QUASAR planning phase will be to update the cost estimate, taking into account inflation and planning changes such as those described in this section. While inflation and the expiration of legacy equipment would lead to increases, the opportunities to optimize machine assembly and the cryogenic systems and to avoid temporary facility services provide the potential for offsetting cost reductions.

*4) A faster schedule.*

The continued advances in the world stellarator program in the years since NCSX termination and the urgency of finding solutions for steady-state operation motivate a faster implementation schedule for QUASAR than was planned for NCSX. The time to complete construction of the stellarator device and achieve first plasma was estimated at 55 months, including 15 months of schedule contingency, at the time of NCSX closeout. Implementation of systems needed to begin physics research was foreseen to require an additional year; this serial approach was dicated by funding limitations. For QUASAR, we would integrate research preparations with the device construction schedule and perform them in parallel, thereby avoiding the extra year of schedule and the cost of temporary solutions, and making the facility ready to start its research mission immediately upon achievement of first plasma. A reassessment of the assembly schedule based on the successful completion of critical assembly operations, described in Sect. III.C, may also lead to a shortened schedule and/or reduced schedule contingency requirements for the remaining critical-path assembly steps leading to first plasma. This remains to be checked in detail.

In a target scenario that has been proposed to DOE, the QUASAR project would be planned in Fiscal Year (FY) 2014, leading to DOE approval of a performance baseline. Assuming a FY-2015 project start, if the construction schedule can be optimized for completion in 48 months, instead of the previously planned 55 months, then the QUASAR research program could begin in FY-2019.

## IV. Next-Step: QA Performance Extension

While QUASAR will provide the first integrated physics test of QA shaping, a second facility will be needed to extend the understanding of QA stellarators to high temperature, high pressure sustained plasmas. This facility will address scientific questions requiring high performance, specifically:

- Plasma confinement in optimized QA configurations at reactor-like temperature and pressure.
- Variation of QA confinement properties with system size and pulse length.
- Integration of 3D divertor and plasma-facing component designs with a steady-state core plasma at near-burning performance.
- Validation of fusion reactivity and control using DT fuel.

The envisioned facility would be approximately JET scale (plasma minor radius ~1 m). For a moderate aspect ratio, similar to QUASAR, this would imply a major radius in the range of 3 - 4.5 m, similar to LHD and somewhat smaller than W7-X. From a recent study of pilot plant concepts [19], a DT facility on this scale with magnetic field strengths in the range 5-6 T would be expected to produce plasmas with fusion gain Q in the range of 4-20. Additional mission elements could be incorporated, if desired, with the inclusion of breeding blankets. The facility, so equipped, could operate as a low power (100 – 200 MW) pilot plant, due to the low recirculating power, or as a component test facility with 300 – 500 MW of fusion power and up to 2 MW/m$^2$ neutron wall loading. Such a facility could provide a path for these fusion nuclear missions that would avoid the need for efficient current drive, active instability controls, or comprehensive diagnostic systems in a burning environment. The range of possible capabilities and missions for the next-step QA stellarator facility thus extends from size and pulse length scale-up in DD plasmas, to inclusion of DT for burning plasma studies, to inclusion of blankets for fusion nuclear missions.

Another possible mission for the next step is the integration of simplified-coil design strategies in a large scale experiment. The need for coil simplification was highlighted by the ARIES-CS QA stellarator power plant design [20] which, like the HELIAS, was a physics-optimized non-planar coil device, but more compact (major radius of ~8 m *vs.* 22 m) and higher power density (2.6 MW/m$^2$ average neutron wall load *vs.* 1.0 MW/m$^2$). The ARIES-CS design featured very large toroidal excursions in its non-planar coils, which would strongly restrict maintenance access and limit removal and replacement of limited-life in-vessel components to small modules. In response, we have continued to explore configuration design strategies aimed at improving the engineering characteristics of QA stellarators while preserving attractive plasma properties [21]. Recently, we have developed a new coil optimization code that dramatically increases the design freedom available to meet coil design objectives. It removes the restriction of having only Fourier-representable coils allowing, for example, the imposition of straight sections in non-planar coils, a basic feasibility requirement for large-sector maintenance of in-vessel equipment. The code also allows the addition of local saddle coils to recover plasma shaping capability. As shown in Fig. 5, the code is able to produce solutions targeting maintenance feasibility issues for the first time, though further work is needed to optimize the trade-off between

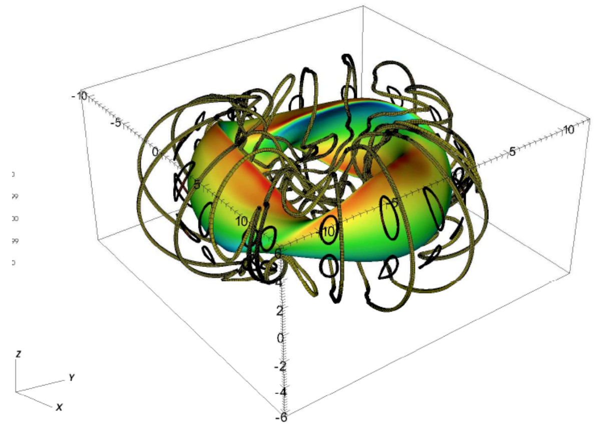

Fig. 5. Modified ARIES-CS coil design with straight, parallel sections on the non-planar coils and local saddle coils that can be removed as part of a large sector during maintenance.

physics and engineering objectives, possibly entailing modest increases in the aspect ratio of future devices. While this work is aimed at power plant attractiveness, available advances would be incorporated into the design of a next-step QA experiment as a test of improved optimization strategies.

Mission and design studies for the next step need not await QUASAR results and thus could start immediately. The schedule and mission choices would depend on tradeoffs among urgency, technical risk, and cost. In a moderately aggressive scenario, construction could start around 2022 and operation could start in ~2027. Initially DD plasmas would be used explore and validate confinement predictions. This would be followed by a transition to DT operation and associated mission elements. This plan would provide timely results, contemporaneous with results from W7-X and ITER, informing a possible path to steady-state fusion energy systems based on 3D shaping.

## V. Summary

The quasi-axisymmetric (QA) stellarator is an innovation that offers solutions to key problems facing MFE development- disruption-free steady-state operation, and more favorable plasma conditions for steady-state divertor operation- in a 3D configuration closely connected to tokamaks. Its advantages, its complementarity with LHD and W7-X, and the success of the closely-related HSX experiment motivate taking the next step, an integrated experimental test of its physics properties at the minimum scale and pulse length needed to evaluate its physics potential and risks in comparison with other approaches. A new experimental facility, QUASAR, provides a rapid approach to that step by taking advantage of the designs, fabricated components, and detailed assembly plans developed for NCSX. Beyond QUASAR, the next step in QA stellarator development would extend performance to high temperature, high pressure sustained plasmas. That mission would involve a facility of approximately JET scale designed for steady-state operation. Operating in DD, such a facility would investigate the scale-up in size and pulse length from QUASAR and would test advances in configuration optimization strategy. A suitably equipped facility of the same scale, operating in DT, could address fusion nuclear missions. Such a facility could be constructed starting in 2022 and operated starting in 2027, providing results contemporaneous with results from W7-X and ITER.

## ACKNOWLEDGMENT

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