PPPL- 4889

PPPL- 4889

Facilities for Quasi-Axisymmetric Stellarator Research

G.H. Neilson, et. al.

June, 2013

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

Princeton Plasma Physics Laboratory
Report Disclaimers

Full Legal Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Trademark Disclaimer

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

PPPL Report Availability

Princeton Plasma Physics Laboratory:

http://www.pppl.gov/techreports.cfm

Office of Scientific and Technical Information (OSTI):

http://www.osti.gov/bridge

Related Links:

U.S. Department of Energy

Office of Scientific and Technical Information

Fusion Links

Facilities for Quasi-Axisymmetric Stellarator Research

G. H. Neilson, D. A. Gates, P. J. Heitzenroeder, S. C. Prager, T. Stevenson, P. Titus, M. D. Williams,
and M. C. Zarnstorff
Princeton Plasma Physics Laboratory, Princeton, NJ 08543 U.S.A.
Corresponding author e-mail: hneilson@pppl.gov.

***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, with operation starting in 2027.**

Keywords—stellarator, quasi-symmetric, quasi-axisymmetric, roadmap.

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 is developing the Heliotron line, leading to 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. These advantages provide solutions to key problems facing MFE development-disruption-free steady-state operation and more favorable plasma conditions for steady-state divertor operation. The investment in stellarator research significantly reduces 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 or D plasmas with a minor radius of ~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. The W7-X projects to a modular-coil DEMO device, HELIAS, in which the geometry of the coils is chosen to optimize plasma physics properties.

Researchers in the United States have proposed an innovative stellarator optimization strategy called *quasi-axisymmetry (QA)*, in which the configuration is three-dimensional (3D) but the *magnitude* of the magnetic field exhibits tokamak-like dependence along magnetic field lines [5, 6]. In a QA stellarator the effective helical ripple [7] along magnetic field lines, the parameter that drives neoclassical transport in stellarators, can be the lowest of any stellarator ever built, making the magnitude of the magnetic field be 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, as predicted by the same neoclassical theory that underpins both the QA and HSX optiizations.

The QA-based ARIES-CS power plant design [8] is, like the HELIAS, a physics-optimized modular-coil device but more compact (major radius of ~8 m *vs.* 22 m) and higher power density (2.6 $\mathrm{MW/m^2}$ average neutron wall load *vs.* 1.0 $\mathrm{MW/m^2}$). The advantages of the QA approach, and its complementarity with the LHD and W7-X approaches, motivate taking the next step in QA development, 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.

III. QUASAR

A new experimental facility, QUASAR, is proposed to support the next step in QA stellarator research. 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.

Recently, the U.S. Department of Energy identified QUASAR as an option for the U.S. fusion program as part of a planning activity to identify critical science user facilities for the next decade. A report of the Fusion Energy Sciences Advisory Committee gave quasi-symmetric stellarators (of which QA stellarators are a subset) its highest ranking for enabling world-leading science and said that “the time is ripe to pursue a comprehensive approach to quasi-symmetric stellarators.” Motivated by this renewed interest, we have re-examined the implementation plans that existed for NCSX, identified new issues and opportunities, and have developed an implementation scenario for QUASAR.

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, and QUASAR experiments will validate the extensive numerical models and optimization methods used in that design. Recent physics optimization studies [9] indicate that it may also be possible to use plasma shaping to minimize small-scale turbulence in QA configurations. Shaping flexibility may make it possible to experimentally test these predictions of micro-turbulence theory in QUASAR, potentially leading to reduced turbulent transport of plasma energy. 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 [10] and is predicted to be resilient to disruptions. This will be validated experimentally

B. Design

The QUASAR design is based on a three-period stellarator configuration that was optimized to provide stable, high-beta QA plasmas with good magnetic surfaces. The magnet system consists of 18 modular coils (six each of three different shapes), plus various planar coil sets. The modular 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.

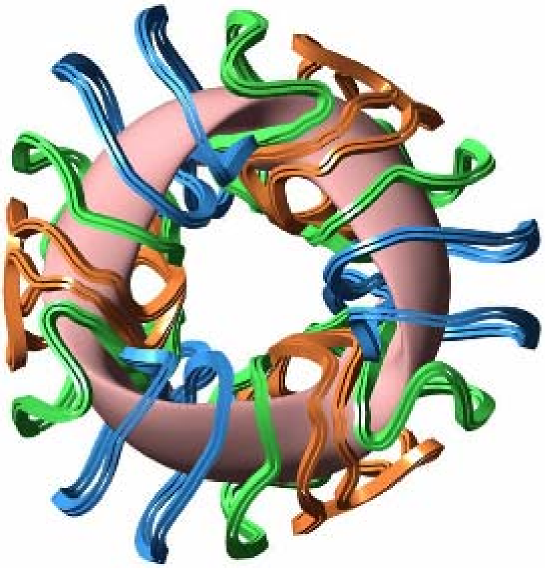

Fig. 1. Modular coils and plasma configuration.

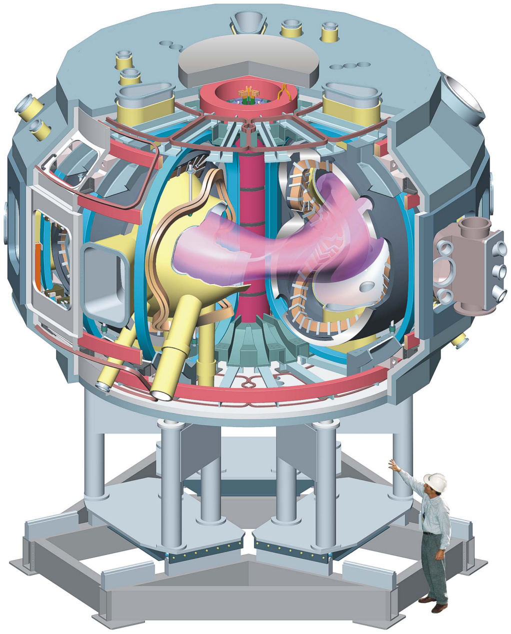

Fig. 2. QUASAR stellarator device design (CAD

The engineering design of QUASAR is depicted in Fig. 2. The most critical subsystem, and the structural "backbone" of the device, is the modular 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. 3). The modular coil shell is divided into eighteen sectors, one per coil, each subtending twenty degrees of toroidal angle between planar flanges. Cutouts accommodate port penetrations into the vacuum vessel. The coil conductors were wound directly onto accurately machined support features on the shell sectors, and epoxy-impregnated in place for strength and stability. The magnet system is designed to be pre-cooled to cryogenic temperature (80 K); the temperature rise in a pulse is ≤ 40 K and heat is removed between pulses by liquid nitrogen coolant flowing through tubes on the outside of the coil winding pack.

The QUASAR device also includes several systems of planar coils– toroidal field (TF) coils, poloidal field (PF) coils, central solenoid (CS), and trim coils– which provide the plasma configuration flexibility required for physics experiments. The 18 TF coils surround the modular coils and mainly serve to vary the rotational transform. The 3 pairs of PF coils, arranged similarly to those of a D-shaped tokamak, provide the axisymmetric field shaping needed to control the average plasma shape and position. The CS provides the flexibility for inductive startup and for varying the toroidal current. The trim coil system, consisting of 48 coils arranged in a saddle-like orientation just outside the modular coil shell, was a design improvement added during NCSX construction to provide additional physics flexibility, including the capability to control equilibrium islands at important plasma resonances.

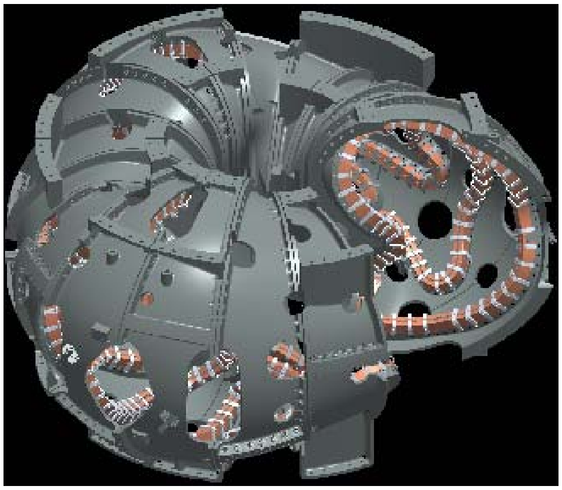

Fig. 3. Modular coil system engineering design.

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

C. Construction Status and Assembly Plan

Construction of QUASAR will take advantage of equipment and assembly plans produced by the NCSX project [11]. All 18 modular coils and all 18 TF coils were fabricated, with modular coil winding centers falling within a ±0.5 mm tolerance band over ~90% of their circumference. A completed modular coil is shown in Fig. 4. In addition, all vacuum vessel components, consisting of three toroidal sectors and dozens of port extensions, were fabricated. A vacuum vessel sector, with installed services including heating and cooling tubes, magnetic diagnostics, and temperature sensors, is pictured in Fig. 5.

The device assembly process starts with the construction of six modular coil half-period assemblies (HPAs), each consisting of three coils, one of each type. Two HPAs, one of

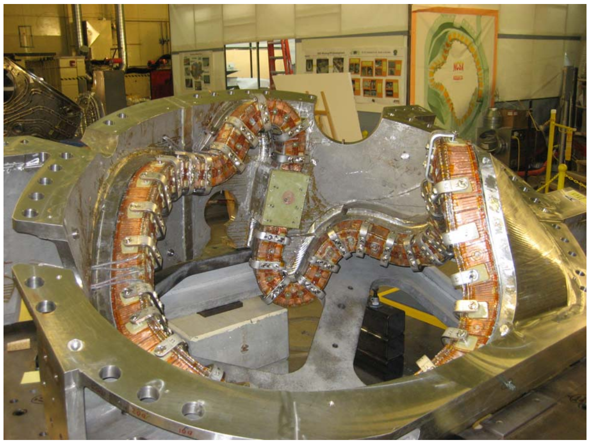

Fig. 4. Completed modular coil.

Fig. 5. Vacuum vessel sector with installed services.

which is pictured in Fig. 6, 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 (Fig. 7), 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 installed on movable sleds and translated simultaneously along radial paths to their final position. After installation of poloidal field coils and trim coils, the temporary sleds will be replaced by permanent machine supports and finally the FPAs will be joined at their modular coil and vacuum vessel interfaces.

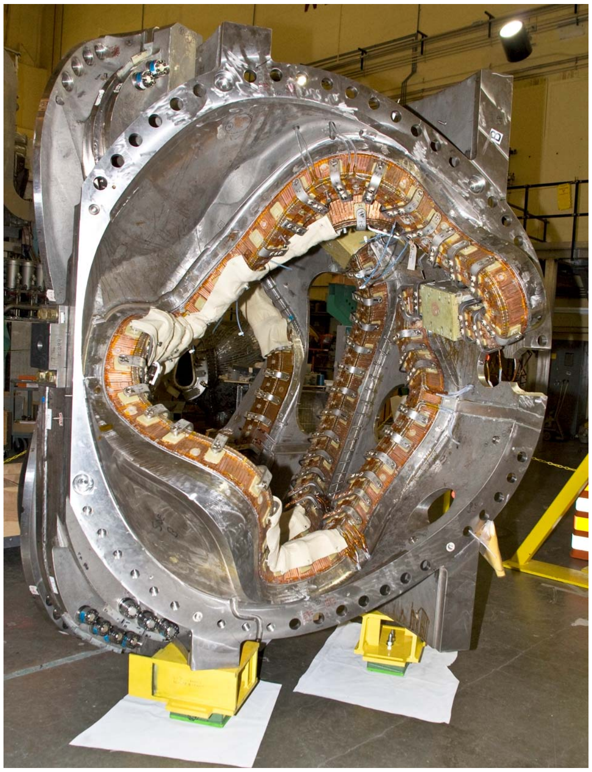

Fig. 6. Completed modular coil half-period assembly.

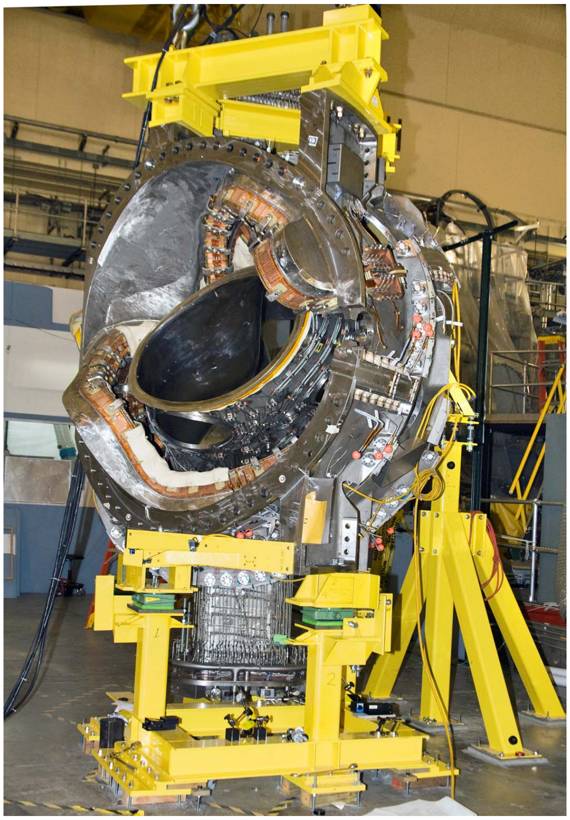

Fig. 7. Trial installation of half-period assembly over vacuum vessel sector

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 planning would 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 clearly 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 pre-cooled to 80 K 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 modular 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 obsolescence of key components. A concern is that repair or replacement of some high-voltage power supply components may be difficult due to their age. Beam line costs would include new accel supplies and a new stand-alone liquid helium system (commercially available) to avoid the high operating costs and losses of the formerly planned liquid helium batch-transfer system. New, commercially-available JET-type sources will be considered in lieu of refurbishing the PBX sources. 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 offsettiong cost reductions.

4) A faster schedule.

The continued advances in the world stellarator program in the years since NCSX termination, the decrease of U.S. fusion capability resulting from the termination of Alcator C-Mod, 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 with temporary facility connections 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 due to funding limitations. For QUASAR, we would integrate these research preparations with the device construction schedule, 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. The successful completion of critical assembly operations, described in Sect. III.C, may also justify a shortened schedule and/or reduced schedule contingency requirements for the remaining critical-path assembly steps leading to first plasma, although 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, with research equipment being implemented in parallel instead of in series, then the QUASAR research program could begin in FY-2019.

IV. NEXT-STEP QA STELLARATOR FACILITY OPTIONS

While QUASAR will provide the first integrated physics test of QA shaping, a new facility will be needed to extend the understanding of QA stellarators to high temperature, high pressure sustained plasmas at approximately the JET scale, with the magnetic field sustained by external coils alone. This facility would 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.
- Extension and integration of simplified-coil strategies with a large scale experiment.

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 [12], 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. A stellarator facility of this scale, 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. Thus the range of possible capabilities and missions for the next-step QA stellarator facility 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.

Design studies, initially emphasizing simplification of coil designs to improve construction and maintenance characteristics, will continue in parallel with initial operation of W7-X and QUASAR. Mission decisions would be made during the facility design process, based on tradeoffs among schedule urgency, technical risk, and cost. 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. In a proposed scenario, the QUASAR project would be planned in Fiscal Year (FY) 2014, constructed in 48 months starting in FY-2015, and be ready to support physics research operations starting in FY-2019. 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 (plasma minor radius ~1 m), designed for steady-state operation. For a moderate aspect ratio, similar to QUASAR, this would imply a major radius in the range of 3 - 4.5 m. Operating in DD, such a facility would investigate the scale-up in size and pulse length from QUASAR. 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

Research supported by the U.S. Department of Energy under Contract No. DE AC02 09CH11466 with Princeton University

REFERENCES

[1] F. Romanelli, *et al.*, “Fusion Electricity: A roadmap to the realisation of fusion energy,” European Fusion Development Agreement (EFDA) Report, November 2012 (
[2] Y. X. Wan, “Design and Strategy for CFETR,” this conference.
[3] G.-S. Lee, “Korean Fusion Roadmap: K-Demo Design and R&D Plan,” this conference.
[4] F. Najmabadi, *et al.*, “The Starlite Study: Assessment of Options for Tokamak Power Plants -- Final Report,” UC San Diego Report UCSD-ENG-005 (1997). mailto:http://aries.ucsd.edu/LIB/REPORT/-STARLITE/final.shtml.
[5] A. H. Boozer, Phys. Fluids **26** 496 (1984)
[6] L. P. Ku and A. H. Boozer, Phys. Plasmas **16**, 082506 (2009)
[7] W. Dommaschk, W. Lotz, J. Nührenberg, Nucl. Fusion **24**, 794 (1984)
[8] F. Najmabadi and A. R. Raffray, Fusion Sci. and Technol. **54** (2008) 655.
[9] H. Mynick, N. Pomphrey, P. Xanthopoulos, Phys. Rev. Letters **105** 095004 (2010)
[10] M. Zarnstorff, et al., Plasma Phys. Control. Fusion, **43** A237 (2001)
[11] G. H. Neilson, *et al.,* Fusion Sci. and Technol. **56** (2009) 485.
[12] J.E. Menard *et al.*, Nucl. Fusion **51** (2011) 103014.