1. PROGRAMMATIC RATIONALE AND OBJECTIVES

This chapter discusses the programmatic role of QPS, quasi-symmetry, the relationship of QPS to the U.S. and world stellarator program, and to NCSX and the Compact Stellarator PoP Program in particular.

1.1. Programmatic Role of QPS

The most developed magnetic confinement approaches for fusion research are based on the tokamak or the currentless stellarator. The tokamak has low plasma aspect ratio ($R/a_p \sim 3$), good neoclassical confinement, and the potential for a high volume-average beta limit ($\langle\beta\rangle$ ~5-10%). But all of the rotational transform is provided by an internal plasma current, which leads to certain disadvantages – the potential for disruptions and the need for a close conducting wall and active feedback systems for stability against external kink instabilities and vertical instability. Even advanced tokamak (AT) concepts which derive most of the rotational transform from a plasma-generated bootstrap current require some external current drive resulting in high recirculating power in a reactor. Currentless stellarators avoid this problem by creating the poloidal field with currents flowing solely in external windings. But they have large plasma aspect ratios (R/a_p = 6-11), leading to very large reactor sizes (R = 22 m for the W 7-X-based HSR compared to R = 5.5 m for an AT reactor), and have lower beta limits ($\langle\beta\rangle$ ~ 5%).

Figure 1.1 shows the locations of major tokamak and stellarator experiments in a space $\iota_{ext}/\iota_{total}$

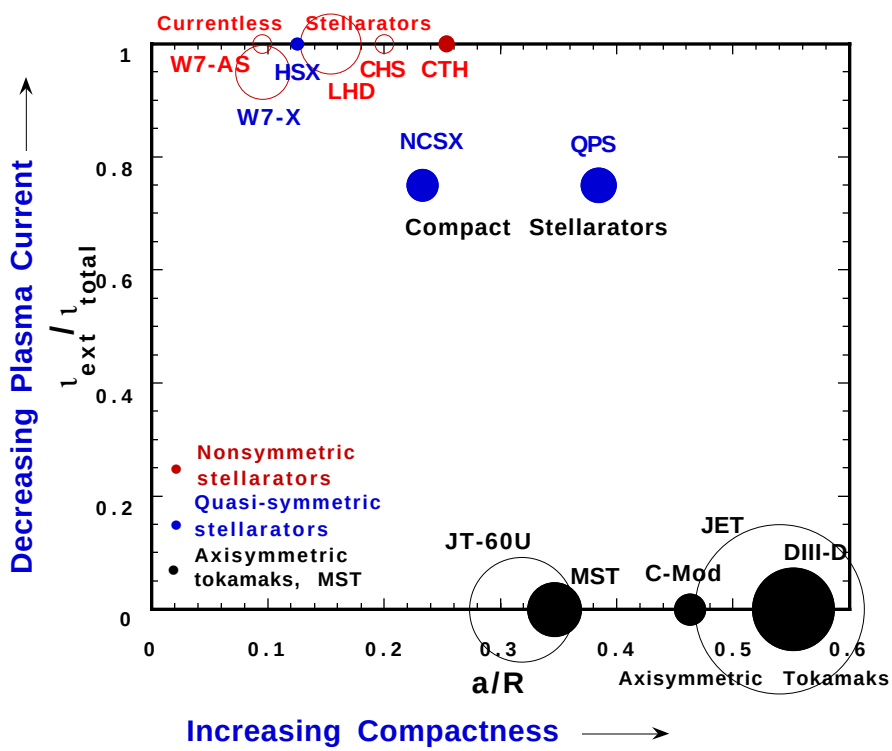

Figure 1.1. Configuration space for toroidal experiments

(the fraction of the rotational transform supplied by coils) versus a/R (the inverse plasma aspect ratio). The size (radius) of the points is proportional to the average plasma radius a for each experiment with U.S. experiments shown as solid circles and foreign experiments shown as open circles. We see that existing experiments leave a large unexplored area in this parameter space.

Figure 1.2 shows the "engineering Q" (the ratio of the net electric power produced to the total electric power required for operation of the power plant) versus the neutron wall power density. Reactor realizations of currentless stellarators, such as HSR or SPPS, achieve low recirculating power, which translates into high engineering Q, but their large size and high plasma aspect ratio (R/a = 8-11) and moderate plasma β result in low wall fusion power densities. Tokamak reactor studies based on AT physics, such as ARIES-RS and ARIES-AT, achieve high wall power densities because of their compactness, but the large recirculating power needed for current drive and control of the plasma reduces the engineering Q. The ARIES reactor studies have shown that the projected cost of electricity for these two approaches are comparable. There is a clear reactor advantage if high power density and low recirculating power can be combined with a high β.

The reduced bootstrap current in a QPS configuration, typically ~1/4 that in a comparable tokamak, should lead to reactor configurations that are relatively insensitive to β and are robust against current-driven modes (external kinks), vertical instabilities, and disruptions. The QPS experiment would test this approach at the concept-exploration level as part of an integrated compact stellarator proof-of-principle program with emphasis on key physics issues: reduction of neoclassical transport, scaling of the bootstrap current, and configuration invariance with increasing β, up to $\langle\beta\rangle$ ~ 2.5%. The larger NCSX would demonstrate disruption-free operation near $\langle\beta\rangle$ ~ 4% and test

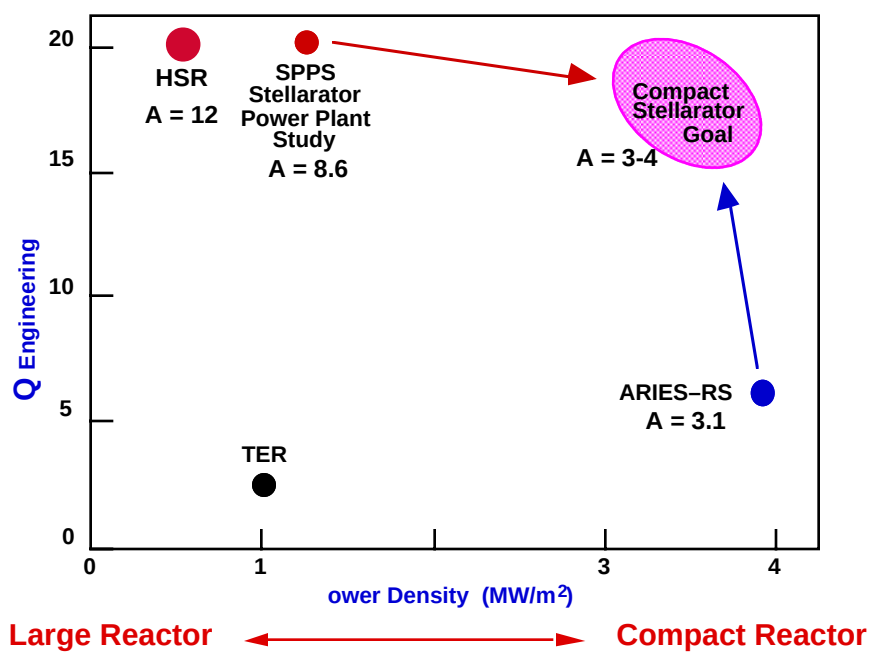

Figure 1.2. A Compact Stellarator reactor could combine the best features of stellarators and tokamaks.

the physics of the quasi-axisymmetric approach with substantial plasma current. Both facilities are needed to develop the knowledge base to choose the best configuration for a possible next step in the development of the stellarator concept.

Two scientific advances have occurred in recent years making it possible to find magnetic configurations with the potential for an improved reactor concept. The first is the advance in understanding particle orbits in highly complex magnetic fields when expressed in Boozer coordinates, and the recognition of possible symmetries that are not apparent in the usual configuration space. In these coordinates the drift motion is determined by a Hamiltonian that depends only on the spatial structure of the magnitude of the magnetic field |B|. In a stellarator, |B| can be expressed in a Fourier spectrum as

$$|B| = \Sigma\, B_{mn}(\psi) \cos\,(m\theta - n\phi)$$

where θ and ϕ are poloidal and toroidal angle variables in "Boozer" coordinates [1] and ψ is the toroidal flux. In this coordinate system the magnetic flux surfaces are concentric toroids (ψ = constant) and the magnetic field lines are straight lines in a θ–ϕ plane. If the Boozer spectrum consists of only a single helicity (m, n), then the drift Hamiltonian admits a constant of motion that limits the radial orbit excursion and in turn yields favorable neoclassical transport. This is the three-dimensional (3-D) analogue of the constant of motion P_ϕ in axisymmetric devices that accounts for the good neoclassical transport in those devices. Although it is not possible in 3-D to have a single helicity in the Boozer spectrum, configurations are possible in which a single helicity dominates. In this case we speak of quasi-symmetry. Section 1.2 gives a more detailed discussion of the different quasi-symmetries.

The second advance is the combination of computational power and numerically efficient algorithms. It is now possible to carry out the extremely computationally intensive calculations needed to evaluate the physics of low aspect ratio 3-D systems. The physics properties of stellarators (Boozer spectrum, equilibrium, transport, and stability) are determined by the shape of the last closed flux surface, the pressure profile, and the rotational transform profile. With modern computers we are able to use these parameters as variables in order to obtain optimum configurations at low aspect ratio that simultaneously have good quasi-symmetry, good neoclassical transport, good stability, bootstrap current consistent with the MHD equilibrium, and good engineering properties.

The U.S. stellarator community has recognized the opportunity to make a major advance in toroidal reactor attractiveness through the investigation of compact stellarators with significant bootstrap current. This approach would complement the much larger foreign program in large-R/a, current-free stellarators and allow the U.S. to make an important contribution to the international stellarator program. In effect this would fill in some of the blank area in Figure 1.1. In May 1998 the U.S. stellarator community issued a plan for a Compact Stellarator Proof of Principle Program having the objective to develop the knowledge base needed to make a decision on a Compact Stellarator performance extension step. This has subsequently been adopted as a programmatic goal of the

DOE Integrated Program Planning Activity (IPPA) – within ten years to "determine the attractiveness of the compact stellarator".

Analysis and design efforts since 1998 have yielded two complementary lines of investigation for low-R/a stellarator research based on different physics approaches – (1) quasi-poloidal symmetry and (2) quasi-axisymmetry. If successful, either has the potential for attractive, but very different, compact reactor realizations.

(1) quasi-poloidal symmetry – very low aspect ratio (A = R/a ~ 2.7), good neoclassical and alpha-particle confinement due to quasi-poloidal symmetry, very high β (stable to all modes at $\langle\beta\rangle$ to at least 11%), confinement improvement with increasing β, ι increasing with radius (tokamak-like shear), ~1/4 the bootstrap current compared to a similar tokamak due to strong toroidal field variation, and reduced poloidal viscosity affecting poloidal flow and transport barrier formation.

(2) quasi-axisymmetry – low aspect ratio (A ~ 4), achieves good neoclassical confinement due to quasi-axisymmetry, high β ($\langle\beta\rangle$ = 4% to 6%), ι decreasing with radius (stellarator shear), ~1/4 the bootstrap current compared to a similar tokamak due to larger ι than in a tokamak, and low toroidal viscosity due to quasi-axisymmetry.

Although reactor studies at the level of the ARIES tokamaks or the SPPS stellarator have not yet been performed for compact stellarators, simple scaling studies of existing quasi-poloidally-symmetric configurations and coil concepts using the same rules as the ARIES studies have been carried out (see Appendix C). This study shows that quasi-poloidally-symmetric configurations have the potential for a more attractive stellarator reactor than SPPS, which was already economically competitive with ARIES-RS. Using the ARIES-AT model with B_{max} = 12 T on the coils gives compact stellarator reactors a factor of 2-3 smaller in R than other stellarator reactors for the same assumptions.

To develop the knowledge base needed for a next step in compact stellarators requires that both lines be investigated. Quasi-axisymmetry, drawing as it does on advanced tokamak physics and being a more modest decrease in aspect ratio, is a more conservative step and has been judged as appropriate for Proof-of-Principle (PoP) level exploration as embodied in the proposed NCSX device. The high-β, quasi-poloidally symmetric configuration envisioned for a reactor is very different from any previous device. Compared to W 7-X (under construction in Germany), to which it bears some resemblance, it represents a factor of 4 decrease in aspect ratio, has more than twice the β limit, has the opposite shear, has significant plasma current, and employs a very different spectrum of helicities in order to achieve confinement, stability, and bootstrap current control in the face of a much larger $1/R$ (B_{01}) field variation. As a first-of-a-kind device, the basic physics is appropriately investigated first at the Concept Exploration (CE) level. We propose to investigate the physics of quasi-symmetric stellarator configurations in a two-field-period device called QPS having R = 0.9 m, a = 0.35 m, and on-axis magnetic field B = 1 T.

A concept-exploration-level QPS will: (1) broaden our understanding of toroidal magnetic configurations through exploration of quasi-poloidal symmetry; (2) allow exploration of very low aspect ratio (~2.6) 3-D stellarator physics; (3) lay the physics foundation for QPS configurations having β limits that are high relative to conventional stellarators, and (4) complement NCSX in completing the knowledge base needed for advancing the development of the compact stellarator concept to the next stage.

Role of the CE-scale device in the development of QPS physics. The proposed CE-level device is designed to have sufficient flexibility to change the controlling magnetic configuration properties: ι, shear, magnetic well, helical axis excursion, mirror ratio, and plasma current. It is the logical first step in understanding the key physics issues important for optimizing and accessing high-β QPS configurations.

(1) It is critical to understand quasi-poloidal symmetry and its effect on neoclassical and anomalous transport improvement. In order to access the high-β quasi-poloidally-symmetric configurations it is particularly important to understand how to obtain enhanced confinement regimes, the dependence of energy confinement on quasi-poloidal-symmetry features, and the role (and control) of the ambipolar electric field in confinement improvement at moderate β values ($\langle\beta\rangle$ = 2-3%).

(2) Understanding the configuration dependence and β dependence of the bootstrap current at very low aspect ratio is important for understanding the high-β quasi-poloidally-symmetric devices, which derive a significant fraction of their rotational transform from bootstrap current. W 7-X achieves very low bootstrap current throughout its operating range by cancellation of the contribution from different magnetic helicities.

(3) The plasma equilibrium changes from a first stability regime to a second stability regime as β increases. By optimizing the plasma shape (outer flux surface), rotational transform profile, and pressure profile for a target β, ballooning stable configurations with good bootstrap alignment in the range 2% < $\langle\beta\rangle$ < 23% were obtained. Understanding MHD stability at $\langle\beta\rangle$ < 2-3% is expected to begin to develop an understanding of this transition and the importance of ballooning modes on confinement.

(4) The high-β QPS configurations have a high shear, tokamak-like transform profile (ι *decreasing* radially) which could increase the size of magnetic islands and destabilize neoclassical tearing modes. Mitigating this is the absence of the ι = 1/2 resonance (internal disruptions are suppressed) and other low-order resonances. Changing (and reversing) the shear in QPS would allow a careful study of the impact of stabilizing and destabilizing magnetic islands and neoclassical tearing modes on confinement and equilibrium quality.

In addition to the information that the proposed experiment will provide that is specifically of importance to understanding quasi-poloidal symmetry and its implementation in high-β configurations, QPS will broaden our basic understanding of toroidal confinement physics. It will

also support the NCSX program and the world stellarator program by extending the data base to much lower aspect ratio.

(1) 3-D equilibrium at low aspect ratio. There are a number of basic questions related to the existence of highly shaped equilibria at low R/a, and to our ability to predict them numerically. It was shown by Grad in the early 1970's that there is no mathematical guarantee of existence of MHD equilibria in 3D. The most sophisticated MHD equilibrium codes used to predict β show good magnetic surfaces exist. Understanding neoclassical healing effects is important, but present-day codes are not capable of simulating this. Stellarator experiments give practical (if not mathematical) demonstration of existence at moderate and high R/a. QPS will extend this data base to very low aspect ratio, $R/a = 2.6$, less than half that of existing stellarators. QPS can study equilibrium quality, islands and ergodic regions, through external coil variations which effect the plasma shaping (and hence the |B| spectrum), ι profile , and magnetic shear.

(2) Physics of the bootstrap current. QPS can extend the study to very low aspect ratio of the configuration dependence of the bootstrap current in stellarators. QPS also has the interesting property that the number of trapped particles in the toroidal ripples does not vanish near the magnetic axis, thereby permitting finite bootstrap current at the plasma center. While this is not so important for configurations – such as NCSX – which have a large rotational transform contribution at the magnetic axis from external coils – it mitigates the need for seed current and on-axis current drive in the high-β QPS. In addition, the direction of bootstrap current and the sign of shear should decrease the size of magnetic islands as β increases.

(3) Anomalous transport. There is no information on anomalous transport in stellarators at aspect ratio <5. QPS can test the validity of transport scaling laws such as ISS95 and extend the database upon which such scalings are based.

(4) Neoclassical transport. QPS will extends the understanding of neoclassical transport and the role of quasi-symmetry in transport reduction to quasi-poloidal systems and to very low aspect ratio.

(5) Poloidal flow and transport barrier formation. The direction of symmetry in a QPS is nearly perpendicular to the magnetic field (far enough from the edge of the plasma), so damping of the toroidal flow will be much stronger than in an axisymmetric system and for the *same* radial electric field the parallel flow in QPS should be much smaller. On the other hand, damping in the poloidal (symmetry) direction is expected to be much weaker in QPS, thus allowing the possibility of both self-generated and externally-driven poloidal flow. QPS can study the impact of poloidal flows on electric fields and enhanced confinement as well as the level of helical ripple than can be tolerated while achieving significant control of the electric field (and its shear) through external momentum input.

These objectives respond to the key scientific issues of fusion science that were identified in the DOE Integrated Program Planning Activity as those that carry particular leverage for the progress of fusion research.

1. Transport and Turbulence -- *What are the fundamental causes of heat loss in magnetically confined plasmas, and how can heat losses be controlled?*

2. Plasma Fluid Behavior and Macrostability -- *What are the fundamental causes and nonlinear consequences of plasma pressure limits in magnetically confined plasma systems?*

The October 2000 report of the Fusion Science Assessment Committee (FuSAC) of the National Research Council described four major physics questions motivating research with various configurations. Two of the issues were the need to (1) understand the stability limits to plasma pressure and (2) understand classical plasma behavior and magnetic field symmetry. The study of MHD instabilities and β limits in QPS at low aspect ratio in a stellarator addresses the first issue, and the study of equilibrium quality and the configuration dependence of the bootstrap current at low aspect ratio in addition to the unique physics associated with quasi-poloidal symmetry address the second issue.

1.2. Quasi-Symmetry

The shape of the last closed flux surface (LCFS), together with the plasma current (or transform) and pressure profiles, completely determines the equilibrium, stability, and neoclassical confinement properties of a magnetic configuration with nested (or approximately nested) flux surfaces. The magnitude of the magnetic field, |B|, plays an important role in determining the properties of the configuration.

Three types of symmetry are possible in a toroidal configuration:

(a) helical symmetry, as in an infinite aspect ratio (cylindrical) stellarator where only the $ml = nk$ terms in the above equation are non-zero, for pairs of integers (l, k) corresponding to a fixed helical pitch l/k;

(b) toroidal symmetry, as in ideal tokamaks, reverse field pinches, and spherical tori where only the $n = 0$ terms are non-zero (this is a special case of helical symmetry with zero "pitch"; and

(c) poloidal symmetry where only the $m = 0$ terms are non-zero (infinite "pitch"). Since the drift-Hamiltonian depends only on |B|, in such systems there is an ignorable coordinate and a corresponding constant of motion, which leads to no viscosity in the symmetry direction and low neoclassical transport. In a real toroidal system the nonsymmetric terms can be made small, but not zero (except at one magnetic surface inside the plasma).

Figure 1.3 shows the B_{mn} spectrum for a low aspect ratio quasi-helical stellarator configuration which exemplifies the first (and most general) type of quasi-symmetry. The nonsymmetric terms can be made much smaller by going to larger A, as in the HSX (Helically Symmetric Experiment) currentless stellarator. Physically HSX has $A_p = 8$, but has an effective magnetic aspect ratio of 400

based on the ratio |B|(m = 1, n = 0)/|B|(m = 0, n = 0) due to the 1/*R* field departure from helical symmetry. The additional non-helically symmetric terms in the example shown in Figure 1.3 were necessary to reduce A_p to 3.6 and increase the ballooning MHD stability limit.

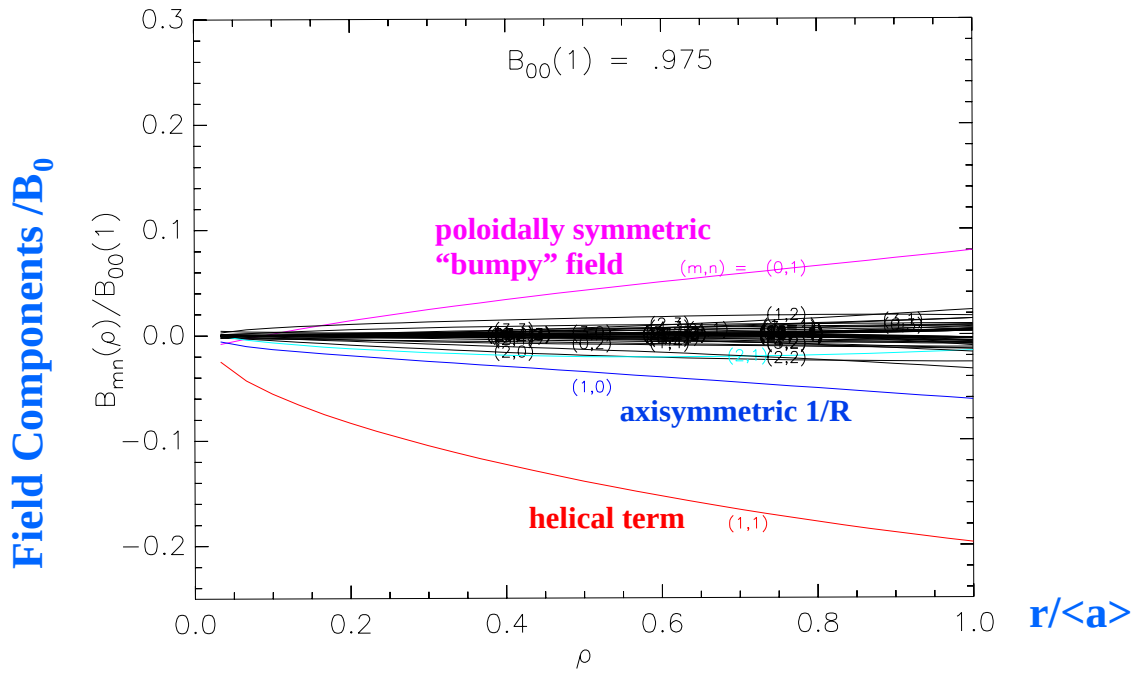

Figure 1.3. B_{mn} spectrum for a low-aspect-ratio quasi-helical stellarator.

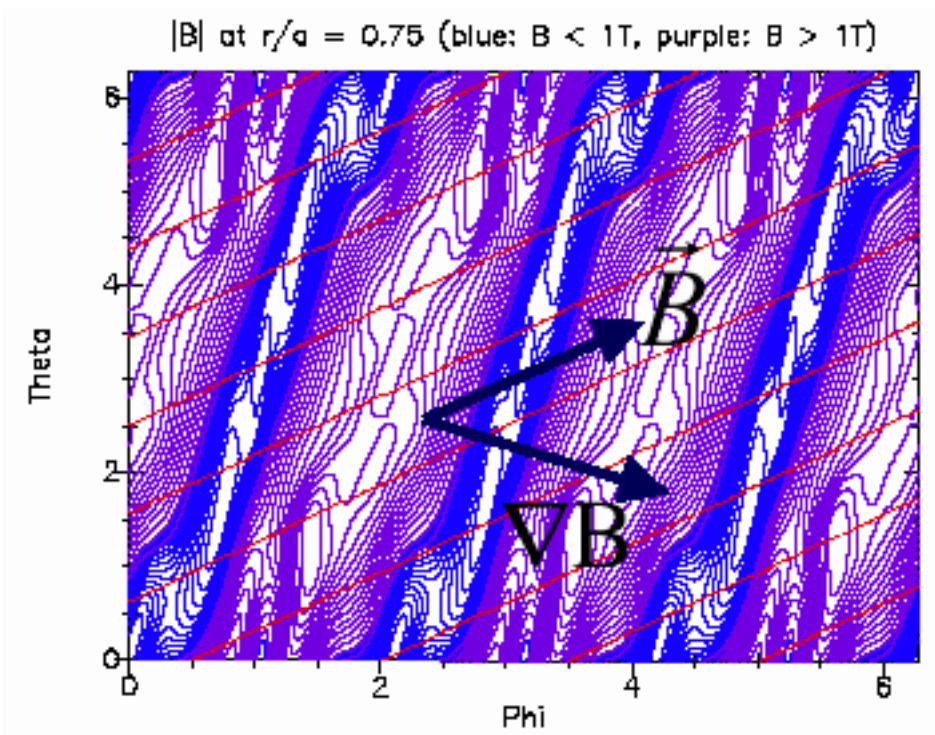

Figure 1.4. |B| structure for a quasi-helical stellarator.

Figure 1.4 shows contours of |B| at r/<a> = 0.75 for the quasi-helical stellarator example in Figure 1.3, a three-field-period (M = 3) compact stellarator with A_p = 3.6 [2], a volume-average $\langle\beta\rangle$ = 2%, and a small bootstrap current. The pitch of the helical structure differs from that of the field lines, indicating a variation of |B| (ripple) along the field lines. The variation of |B| along the dominant helical structure indicates that this system is not purely helical (in contrast to a very large A_p stellarator), as indicated by significant energy in components of the |B| spectrum with different helical pitch. In general, a compromise is necessary between conflicting requirements in optimizing a magnetic configuration. The purpose of an experiment is to clarify these compromises and the role of the various optimization criteria.

Figure 1.5 shows an example of a quasi-axisymmetric stellarator, the magnetic configuration chosen for NCSX (the National Compact Stellarator experiment) with A_p = 4.4 and $\langle\beta\rangle$ = 4%. In this case the |B| structure is oriented in the toroidal direction and the pitch of the field lines is closer to that of the |B| contours. The $n = 0$ terms in the |B| spectrum are dominant and the $n \neq 0$ terms are very small (but non-zero). Magnetically (at least as far as neoclassical transport is concerned), this configuration is therefore similar to a tokamak and should have tokamak-like transport properties, including a sizeable bootstrap current. In the case of NCSX, about 1/4 of the net rotational transform is produced by the bootstrap current. Because the edge transform in NCSX is much larger than it would be in a tokamak, the bootstrap current is much smaller than what would be necessary to produce the same edge transform in a tokamak.

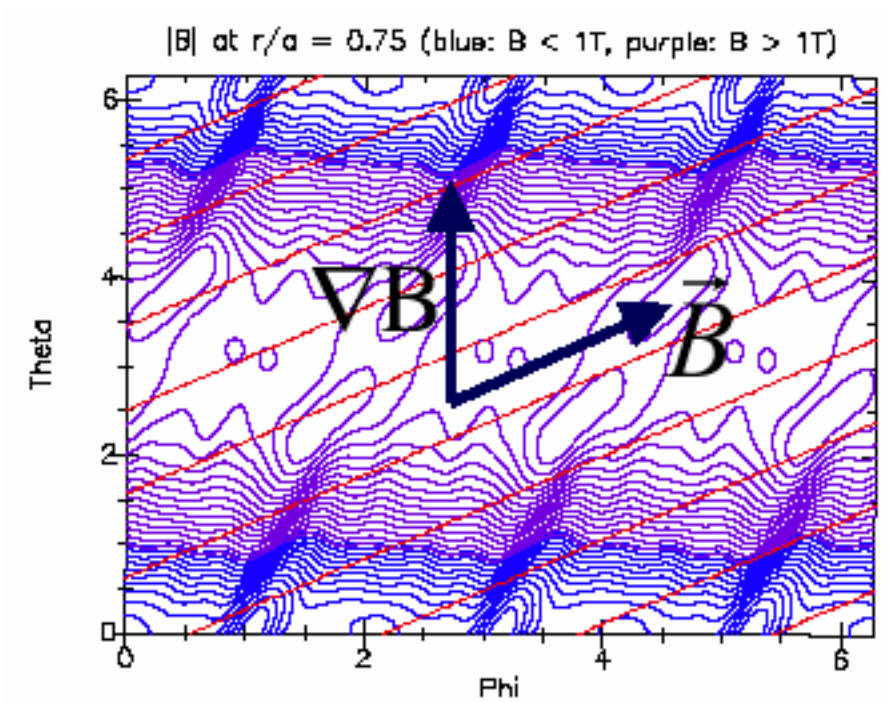

Figure 1.5. |B| structure for a quasi-axisymmetric stellarator.

The third type of magnetic symmetry is quasi-poloidal symmetry, which is the basis for the QPS concept-exploration experiment being proposed here. Figure 1.6 shows an example of a quasi-poloidal stellarator with N = 2 field periods, $A_p = 2.6$, $\langle\beta\rangle = 2\%$, and a modest bootstrap current (57 kA for $R = 1$ m, $B = 1$ T) [3]. This magnetic configuration has a |B| spectrum with the $m = 0$ terms dominant and the $m \neq 0$ terms small. Magnetically, it looks like toroidally linked mirrors with rotational transform.

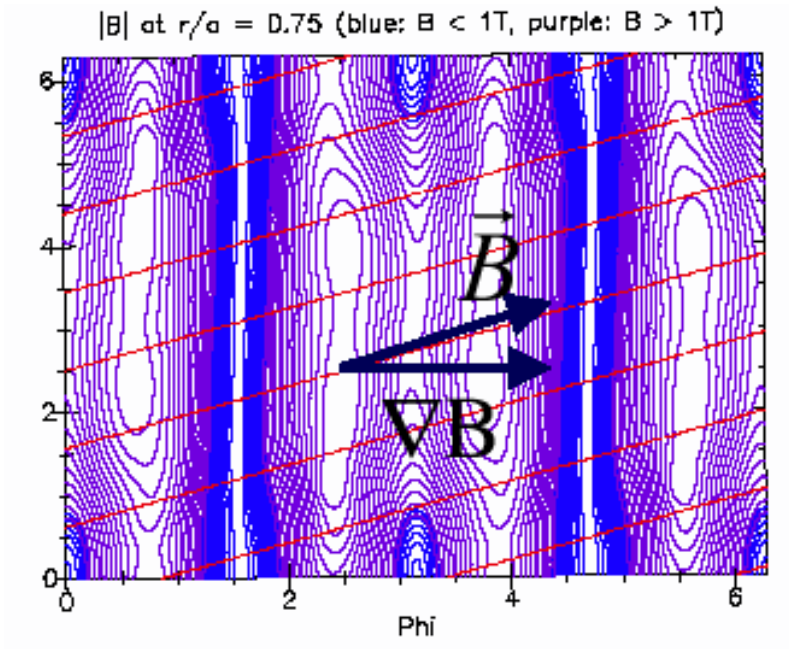

Figure 1.6. |B| structure for a quasi-poloidally symmetric stellarator.

1.3. Relation to the U.S. and World Stellarator Program

Categorization of the main experiments in the world stellarator program according to type of symmetry and plasma aspect ratio is illustrated in Figure 1.7. The size of the circles is proportional to their average plasma radius, red denotes the new proposed U.S. compact stellarators, blue the existing U.S. stellarators, and green the foreign stellarators. The main emphasis of the U.S. stellarator program is on exploring different types of quasi-symmetry over a range of plasma aspect ratios, a unique niche in the larger world stellarator program.

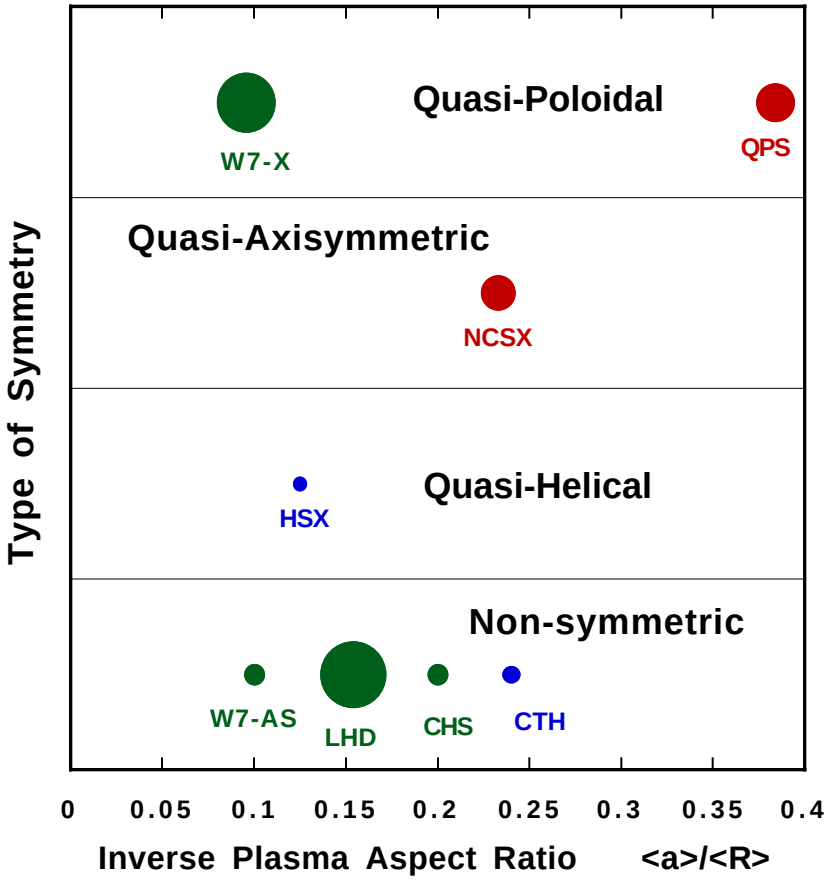

Figure 1.7. Characterization of stellarators by type of symmetry and plasma aspect ratio.

The main experiments in the world stellarator program are listed in Table 1.1. The U.S. stellarator program now consists of two CE-level experiments while the foreign program has facilities ranging from the high-end CE to the Performance Extension level. The Helically Symmetric Experiment (HSX) is now operating at the University of Wisconsin and the Compact Toroidal Hybrid (CTH) is now under construction at Auburn University. HSX will test the predicted benefits of quasi-helical symmetry on neoclassical transport and the role of high effective rotational transform on reduction and control of direct loss orbits. QPS would play a complementary role in testing the predicted reduction of neoclassical transport through reduced poloidal ripple. Shear in the ambipolar electric field should lead to reduced anomalous transport. The CTH stellarator will

Table 1.1. World Stellarator Experiments

Device	Location	Type	R (m)	a (m)	R/a	V_{pl} (m^3)	B (T)	P (MW)
QPS	U.S. (2006)	quasi-poloidal, bootstrap current	0.9	0.35	2.6	2.1	1	1-3
NCSX	U.S. (2006)	quasi-axisym., bootstrap current	1.4	0.33	4.3	3.0	1.7	6-12
W 7-X	Germany (2006)	quasi-poloidal, currentless	5.5	0.52	10.6	30	3	30
LHD	Japan	helical torsatron, currentless	3.9	0.60	6.5	28	4	30
HSX	U.S.	quasi-helical, currentless	1.2	0.15	8.0	0.5	1.3	0.2
CHS	Japan	helical torsatron, currentless	1.0	0.20	5.0	0.8	2	2
W 7-AS	Germany	reduced I P-S, currentless	2.0	0.20	10.0	1.6	2.5	2
CTH	U.S. (2003)	helical torsatron, plasma current	0.75	0.18	4.2	0.5	0.5	0.1

study passive stabilization of current-driven MHD instabilities and contribute to our understanding of kink and tearing modes in stellarators. QPS will use an Ohmic current to approximate the optimized $\langle\beta\rangle = 2\%$ configuration at low collisionality, augment the bootstrap current in modifying the rotational transform and shear for study of modified QPS configurations and neoclassical tearing modes, and simulate (at $\langle\beta\rangle$ up to 2%) the very-high-β QPS magnetic configurations of reactor interest.

W 7-X has the closest magnetic configuration to that of QPS, but at a factor of 4 higher plasma aspect ratio. The similarities are that each has a dominant quasi-poloidal component in |B|. The |B| contours on the r/a = 0.75 surface for the two-field-period, $R/a = 2.6$ QPS and the five-field-period, R/a = 10.6 W 7-X are compared in Figure 1.8. The |B| spectra $B_{mn}(r/a)$ normalized to the average magnetic field on the LCFS ($\psi/\psi_{max} = 1$) are compared in Figure 1.9. The B_{00} term, the average magnetic field, is suppressed in these figures. The magnitude of B_{00} on axis is 0.88 for the QPS reference configuration gb4 and 0.99 for W 7-X; it is 1 for both on the LCFS. The dashed curves in Figure 1.9 indicate the quasi-poloidally-symmetric ($m = 0$) components of |B|. The degree of quasi-poloidal symmetry varies with radius for both. The dominant $m = 0$ term is 1.65 to 2.07 times larger in QPS. However, the toroidal coupling is much stronger at the very low aspect ratio of

QPS: the 1/*R* component in QPS is 3.75 times larger than in W 7-X, comparable to the ratio of geometric aspect ratios (4.1). The helical components B_{11} for both configurations are of comparable magnitudes across the plasma cross-section.

Our studies indicate that minimizing the non-quasi-poloidal components of the |B| spectrum does not necessarily give the lowest transport at the low aspect ratio characterizing QPS. There are also significant differences in the QPS and W 7-X optimizations arising from the large difference in aspect ratios. The cancellation of the bootstrap current in W 7-X which occurs over the entire plasma cross-section is not present in the QPS design (due to the different ratio of B_{11}/B_{10} in the two devices). In fact, the bootstrap current is an important component of the QPS optimization, and although it is reduced by a large factor compared to an equivalent tokamak, it is not possible (nor desirable) to entirely eliminate it and still retain good plasma properties. The reduction of neoclassical transport in QPS is associated with the near alignment of B and grad |B|, while in W 7-X it is associated with quasi-omnigenity, the approximate alignment of drift surfaces and flux surfaces. This is indicated in Fig. 1.7 where the magnetic field lines more nearly cut, on average, the |B| contours at 90° for QPS compared with W 7-X.

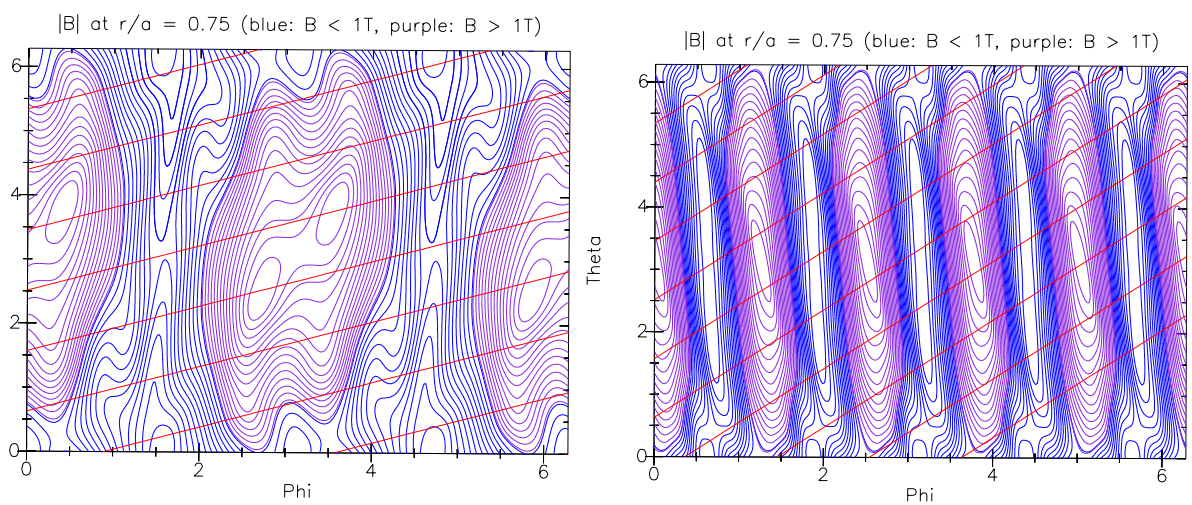

Figure 1.7. |B| contours at r/a = 0.75 for QPS (left) and W 7-X (right).

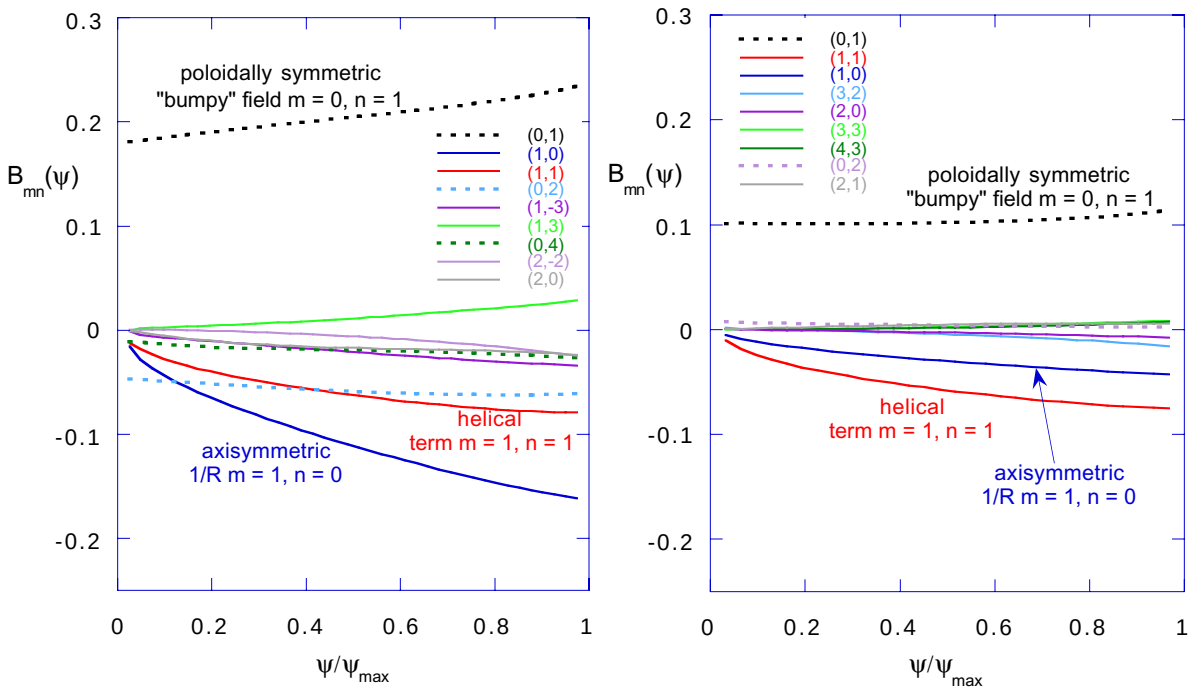

Figure 1.8. |B| spectra for QPS (left) and W 7-X (right).

1.4. Relation to NCSX and the Compact Stellarator PoP Program

As a high-end CE-level compact stellarator, QPS both complements and supports NCSX, the main element in the proposed U.S. compact stellarator program. Compact stellarators are hybrid devices that rely on both 3-D shaping of the plasma (as in conventional stellarators) and the plasma-generated bootstrap current (as in tokamaks) to generate the required rotational transform. The flexibility inherent in having both 3-D shaping and plasma current allows exploration of a wider range of toroidal magnetic configurations than possible in tokamaks and conventional stellarators.

QPS complements NCSX by exploring the quasi-poloidally-symmetric approach to compact stellarator optimization, which could lead to a high-β ($\langle\beta\rangle$ = 10-15%) attractive compact stellarator reactor, while NCSX will explore the quasi-axisymmetric (QA) approach aimed at an attractive compact stellarator reactor in the $\langle\beta\rangle$ = 4-6% range. For the reactor configuration, the quasi-poloidal nature becomes stronger as β increases and the thermal and alpha-particle confinement improve with β. Programmatically, the QA NCSX connects to the axisymmetric advanced tokamak (AT) approach while QPS connects to the currentless high-aspect-ratio (R/a = 10.6) W 7-X approach, but at a factor of 4 lower aspect ratio.

At the experimental level, the distinguishing characteristics of QPS and NCSX allow each to complement the other in extending our understanding of toroidal configurations. Table 1.2 lists some of these features. NCSX achieves reduction of neoclassical transport by quasi-axisymmetry, so NCSX should have similar transport behavior as a tokamak. On the other hand, QPS achieves reduction of neoclassical transport by quasi-poloidal symmetry which produces approximate alignment of the B and grad |B| directions. Since the radial motion of particles *normal* to the

magnetic surfaces is given by the radial component of the *B* x grad |B| drift, this approximate alignment reduces these drifts. This has the potential to significantly reduce both neoclassical energy and particle losses as well as the parallel bootstrap current arising from density and temperature gradients. In the limit of *exact* poloidal symmetry, the canonical angular momentum $p_{\theta_} = mv_{\theta_} + eA_{\theta_}$ is conserved. Particle orbit excursions would then be limited to the gyroradius in the *toroidal* field, which is usually much smaller than the *poloidal* gyroradius (banana width) characteristic of orbit widths in axisymmetric or quasi-axisymmetric devices.

Table 1.2. Features of QPS and NCSX

Feature	NCSX	QOS
Scope of Experiment	PoP-level	CE-level
R, ⟨a⟩, B, $P_{heating}$	1.4 m, 0.33 m, 2 T, 6-12 MW	0.9 m, 0.35 m, 1 T, 1-3 MW
Magnetic Symmetry	Quasi-Axial	Quasi-Poloidal
R/⟨a⟩	4.3	2.6
Key physics issue	High-β stability and disruption immunity	Low-R/⟨a⟩: toroidal mode coupling effects on equilibrium, stability & transport
Enhanced Confinement Route	Tokamak-like drift orbits, flow-shear stabilization	Small *B* x ∇B radial drift, reduced poloidal viscosity

In addition, QPS supports NCSX in exploring the low-aspect-ratio end of compact stellarator optimization. With an R/a = 2.6, QPS has a significantly lower aspect ratio than NCSX. The toroidal and helical coupling effects are much stronger at the lower aspect ratio. Initial reactor scoping studies for the quasi-axisymmetric approach [4] examined both a three-field-period R/a = 4.4 configuration based on li383, the NCSX configuration, and a two-field-period R/a = 2.7 configuration, 2101, with good physics properties but for which an attractive modular coil set had not been developed at the time that the NCSX configuration was chosen. While the two-field-period R/a = 2.7 configuration led to a smaller reactor, the programmatic risk associated with this configuration was deemed too high for a PoP-level experiment. The CE-level QPS is the correct level to address the issues associated with the lower value of aspect ratio in a compact stellarator experiment. The understanding gained should allow us to have more confidence in a lower aspect ratio extension of the QA concept, should that be deemed a desirable route for future exploration. The combination of the PoP-level NCSX and the CE-level QPS would establish the knowledge base needed for decisions on the next (post-PoP) stage in the compact stellarator program.

1.5. Summary

There is a large world stellarator program focused on the high-aspect-ratio currentless approach to stellarator optimization and a concept-exploration level stellarator program in the U.S. exploring

unique aspects of stellarators research: quasi-helical symmetry at high aspect ratio in HSX and the effect of ohmic current in a stellarator in CTH. The critical missing component is optimization of stellarators at low plasma aspect ratio that could lead to a more attractive reactor than either the advanced tokamak or conventional currentless stellarator. The proposed NCSX will explore the tokamak-stellarator-hybrid quasi-axisymmetric approach at R/a = 4.3 that could lead to a reactor with $\langle\beta\rangle$ = 4-6%. The unique contributions that a concept-exploration-level QPS would make are (1) establishing the basis for a high-β ($\langle\beta\rangle$ > 10%) low-aspect-ratio (R/a = 2.7) compact stellarator reactor and (2) exploration of very low aspect ratio (R/a = 2.6) and quasi-poloidal symmetry in optimization of compact stellarators. This information is needed in the 10-year time frame both to meet the objectives laid out by FESAC for the compact stellarator and as input for decisions on the next step in the world stellarator program after LHD and W 7-X.

QPS is needed because there is no existing experimental database that would allow one to reasonably extrapolate to this high-β configuration. A CE-level experiment is also the optimum vehicle for studying the physics of quasi-poloidal symmetry and very low aspect ratio in a stellarator with bootstrap current. QPS could make unique contributions relating to some of the key fusion science areas outlined by the IPPA: the physics of neoclassical confinement improvement at very low aspect ratios, flux surface robustness at $\langle\beta\rangle$ up to 2-3% in the presence of strong toroidal/helical coupling, the dependence of bootstrap current on configuration properties at low aspect ratio, and the electric potential and its influence on enhanced confinement regimes.

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