11. EXPERIMENTAL PROGRAM

This chapter describes the experimental program to achieve the QPS objectives and discusses the diagnostics needed to carry it out.

QPS is a high-end CE-level experiment that explores a compact stellarator concept. This concept is both complementary and supportive of the NCSX, the main element in the proposed Compact Stellarator proof-of-principle program. QPS is complementary to NCSX in that it explores the low-aspect-ratio, quasi-poloidally-symmetric approach to compact stellarator optimization. This aspect of the program requires understanding of the properties (equilibrium, confinement, stability) of low-aspect-ratio quasi-poloidally-symmetric configurations and their relation to the low-aspect-ratio quasi-poloidally-symmetric high-β reactor vision. The QPS is supportive of the NCSX program in that it provides knowledge needed to extend the NCSX quasi-axisymmetric (QA) approach to lower aspect ratio for a more attractive QA reactor [1].

As a high-end CE-level experiment exploring a new approach, QPS needs to address the range of physics issues outlined by FESAC and the IPPA: MHD equilibrium and stability, confinement and transport, plasma heating, and particle and power handling. However, the funding constraints of a CE-level experiment dictate that these studies cannot be conducted at the same depth or to as high parameters as for a PoP experiment, so a CE experiment must select a few areas for in-depth physics studies. For QPS these areas are equilibrium quality and energy confinement at very low aspect ratio. The difference between a PoP mission and a CE mission is not in the concept being explored but in the experiment capability: the device size and plasma heating power (and hence the plasma parameters), the suite of diagnostics available for in-depth studies, and the size of the staff to carry out the experimental program. The plans presented in this chapter are preliminary, and will evolve as a better understanding of costs (potential budgets) and of detailed physics issues is developed. They will also evolve through the expected contributions of the broader stellarator community as a result of direct experimental participation in the program and through expected advisory committees.

11.1 Phase 0 — QPS Commissioning

The purpose of the device-commissioning phase is to confirm that the capability needed to carry out the QPS experimental program is as designed, to correct any problems that are uncovered, and to ready QPS for the experimental physics program. The testing would include: (1) checkout of the coils, power supplies, and associated controls; (2) checkout of the vacuum conditions including the pumping system, controls, and bakeout and wall conditioning systems; (3) checkout of the machine controls and safety systems; and (4) "first plasma" with low-power ECH to demonstrate that all systems are functional and to uncover any problems that need correction before routine operation. This phase only requires basic machine diagnostics (vacuum system readouts, coil currents, power supply signals, interlock signals, low level ECH power) and a minimal set of diagnostics to verify

attainment of first plasma. These include, e.g., a CCD camera, diamagnetic loops, 2-mm single-channel interferometer, and hard X-ray detector. The same diagnostics would also allow initial tests of the Ohmic heating system including coils, power supplies and controls.

After commissioning the QPS facility, five phases are envisioned for the QPS experimental program:

- characterization of the vacuum flux surfaces for the range of magnetic configurations to be studied
- initial low-power ECH plasma studies at $B = 0.5$ T
- plasma heating and confinement studies at $B = 1$ T
- plasma edge and divertor studies
- MHD equilibrium and stability limit studies at higher β.

The length of each phase and of the experimental program is uncertain and depends on operations funding. With nominal funding, a four to five year program is likely. Table 11.1 outlines the diagnostics and physics issues that will be emphasized in each phase. The diagnostics needed to take full advantage of the QPS capabilities are listed in Table 11.2 along with the phase of the physics issues for which they are first needed. The diagnostics in blue require more effort and would be in the later stages of the program. Diagnostics in red will be important in taking advantage of the physics opportunities that QPS allows but will require resources that may be outside of the scope of the proposed program. Collaboration will be a key component of the diagnostic strategy.

11.2. Phase 1 — Characterization of Vacuum Configurations

Study of equilibrium quality at very low aspect ratio and the flexibility to vary the magnetic configuration properties is essential to the QPS experimental program. The first experimental phase will be devoted to characterization of the quality of the vacuum magnetic surfaces for the magnetic configurations previously identified in the pre-operational physics modeling studies as configurations of the most interest for the experimental program. This will also allow experimental verification of the accuracy of the coil systems. An electron beam and fluorescent mesh (as has been used by Auburn and ORNL on the Auburn Torsatron, Uragan-3, and ATF, and, more recently, by the TJ-II and HSX teams) or fluorescent rods (as was used on W 7-AS) and CCD camera will be used to obtain pictures of the flux surfaces at the two symmetry planes. This technique can also be used to determine drift orbit deviations from flux surfaces (as on HSX) and infer the largest components of the |B| spectrum. The measurements will be carried out with different magnetic field strengths and compared with the vacuum-field flux surface calculations from AVAC. These measurements will be used to verify the absence of significant field perturbations from the coil leads, from coil misalignments or fabrication errors, or from any magnetic structures outside the vacuum tank.

Table 11.1 QPS Experimental Plan

Resource/Phase	**Phase 0**	**Phase 1**	**Phase2**	**Phase 3**	**Phase 4**	**Phase 5**
Objective	**Commissioning**	**Vacuum configurations**	**Configuration characterization**	**Heating, confinement**	**Power, particle control**	**MHD limits**
Heating			**ECH 500 kW B = 0.5 T**	**ECH 1 MW B = 1.0 T**		**ECH + ICH 2 MW total**
CCD camera, H-alpha filter Fast diamagnetic loop 2 mm interferometer Fluorescent screen/rods						
Soft X-ray arrays Spectroscopy Rogowski coils/magnetic loops Bolometers Probes						
Charge exchange YAG Thomson scattering Reflectometer						
Filtered CCD cameras Divertor probes IR camera Divertor bias plates						
Edge interferometer Heavy ion beam probe High frequency magnetic probes Fast X-ray array						
Vacuum surface quality Equilibrium, flux surface robustness Bootstrap current Power balance Transport MHD stability Plasma edge, divertor geometry						

Under discussion
Planned
Primary issue emphasis

Table 11.2. Physics Areas and Diagnostic Needs

PROGRAM AREA	PHYSICS ISSUES	DIAGNOSTIC
VACUUM MAGNETIC GEOMETRY, FLEXIBILITY	startup/low beta geometry: dominant |B| components, ergodic regions, islands, aspect ratio, ellipticity, triangularity, helical axis, etc.	electron beam with fluorescent screen or rods and CCD camera: low energy -- flux surfaces; high energy — lowest |B| components and energetic orbits.
MHD EQUILIBRIUM, ROBUSTNESS OF FLUX SURFACES	finite-beta geometry: flux surfaces, magnetic axis shift, interior ergodic regions and magnetic islands	soft X-ray diode arrays YAG Thomson scattering
BOOTSTRAP CURRENT	variation (reduction) with coil currents, effect on magnetic islands, ergodization of flux surfaces, and tearing modes	Rogowski coils, magnetic loops
POWER BALANCE	power deposition power losses	fast diamagnetic loop, YAG Thomson scattering, reflectometer bolometers, spectroscopy fast ion loss cups
TRANSPORT	electron density profile electron temperature profile ion temperature profile electric field	2-mm/FIR multi-channel interferometer ECE, Thomson scattering spectroscopy, charge-exchange probes, spectroscopy, HIBP
MHD INSTABILITY	frequency spectrum, mode structure, correlations	high frequency magnetic probes soft X-ray array
PLASMA EDGE, DIVERTOR GEOMETRY	limiting aspect ratio, edge magnetic structure and islands, diverted flux bundle	Langmuir probes, filtered CCD cameras, edge interferometer, IR camera, bias on divertor plates

11.3. Phase 2 — Initial Low-Power ECH Plasma Studies

Initial plasma investigations will be at low power (<500 kW) 28-GHz ECH, at B = 0.5 T, and a preliminary set of diagnostics to gain experience with different magnetic configurations and to characterize the global plasma parameters for the reference configuration. The first objective will be obtaining good vacuum conditions for the initial plasma studies through a combination of baking, glow discharge cleaning, and titanium gettering. The second experimental emphasis will be on studying the effects of small, but finite, beta ($\langle\beta\rangle < 0.3\%$) on the equilibrium and surface quality. Thirdly, the configuration dependence of transport scaling, and bootstrap current at these betas will be examined.

Breakdown characteristics with ECH and ECH combined with OH will be studied in order to compare different wall conditioning and plasma startup scenarios. Initial hydrogen and impurity ionization rates will provide an understanding of hydrogen and impurity recycling and wall conditions.

The initial affects of finite beta will be examined. Magnetic configurations with good surfaces that were identified in the mapping of the vacuum flux surfaces will be studied for deterioration at finite β as indicated, e.g., by smaller plasma volumes. At these beta levels, bootstrap currents should be in the 10 kA range and can be measured with external poloidal and saddle Rogowski coils. The magnitude of the bootstrap current and its dependence on magnetic configuration parameters will be compared with low-collisionality bootstrap current calculations from the DKES and BOOTSJ to begin the development of an understanding of finite beta plasma currents. A long-term effort to integrate diagnostic measurements with 3-D VMEC calculations for equilibrium reconstructions will be initiated.

Global confinement studies will be conducted with low-density ($n_e < 5 \times 10^{18}$ m^{-3}) low-collisionality ($\nu_e^* \sim 0.1$ and $\nu_i^* \sim 1$) plasmas with $T_e < 1$ keV and $T_i << T_e$. Comparisons with global scaling models such as ISS95 will be made. Ohmic heating currents in the 50 kA range will be possible and the influence of transform magnitude and profile (OH tends to reverse the shear as shown in Chapter 7) on confinement in this regime can be examined.

This phase of the experimental program requires a basic set of plasma diagnostics: the visible camera (with different filters), diamagnetic loops, 2-mm interferometer (upgraded to a multi-channel system), and hard X-ray detector used in the commissioning phase plus diagnostics needed to characterize the global plasma parameters: Rogowski coils for measurement of the bootstrap current, an array of magnetic loops for characterizing the moments of the plasma current distribution, a wide-angle bolometer and visible spectrometer for impurity investigations, and a few single-channel soft X-ray detectors with Be filters for determination of the electron temperature and low-frequency fluctuations. Boronization to supplement the large-area titanium getter pumping and installation of divertor plates would occur in this phase of the program if needed.

11.4. Phase 3 -- Plasma Heating and Confinement Studies at *B* = 1 T

After experience is gained in Phase 2 on basic plasma operation at $B = 0.5$ T with low power ECH, the experimental program will focus on plasma heating and confinement studies at low aspect ratio. For these studies, QPS will be brought to full magnetic field and heating capability and an expanded set of diagnostics will be installed. The plasma performance in this stage is limited by ECH density cutoffs than by the heating power. The ECH power will be increased to 1 MW by installing the remaining gyrotrons. The best mix of 28-GHz and 53.2-GHz gyrotrons will be decided during or before the second phase of the experimental program.

This phase of the program allows extending study of anomalous transport, internal transport barriers, and the possible impact of poloidal flows on electric fields and enhanced confinement to low-aspect-ratio QPS configurations. The low electron collisionalities obtained with high-power ECH will allow a comparison of observed transport levels and their scaling with equilibrium parameters (shear, transform) with neoclassical electron confinement. The additional plasma diagnostics needed in this stage of the program are measurements of the electron temperature (ECE and soft X-ray) and Thomson scattering, and the electric field (edge probes, spectroscopy).

Preparation for the next phase of the program will require increasing the density with Ohmic heating and pellet injection so EBW heating can be explored and ICRF heating demonstrated.

11.5. Phase 4 -- Plasma Edge and Divertor Studies

Characterization of the plasma edge is important for understanding the equilibrium flux surfaces and the size (aspect ratio) of the plasma. While this issue will be examined to some level in earlier phases of the experimental program, the control of plasma energy and particle transport needed to optimize confinement is particularly sensitive to this set of physics.

Edge islands or ergodic regions can determine the plasma radius and lead to further flux surface deterioration as β increases. The sign of the shear in QPS is in the direction theoretically to reduce magnetic island and stabilize tearing modes. The Ohmic current capability should cause the reverse to occur. Edge magnetic islands and ergodization of the boundary can be studied using edge Langmuir probes, H_α measurements, edge interferometer measurements, and an IR camera to map the footprint of the edge islands on limiters inserted into the plasma. The open viewing geometry is an advantage for these studies.

Optimization of the size and location of the divertor plates under the modular coils is needed for the higher-power phase of the experimental program. The pattern of the flux bundles that strike the divertor plates can be measured using an IR camera, and the current and power density in the exiting flux bundles can be measured with probes. The power flow along different flux bundles can be influenced by biasing the divertor plates as in the IMS experiment. The biased plates can also be used to increase the particle confinement time, as in the ATF experiment.

11.6. Phase 5 -- MHD Equilibrium and Stability Studies

This phase of the program requires operation at full power and high density. An improved divertor, depending on the results of the divertor/edge plasma program, may be necessary during these 2-MW experiments in order to effectively handle the power with optimum confinement. EBW and ICRF heating will be used at the ~2 MW level for these studies based on the experience gained in Phase 3. Higher power is in principle available (1.2 MW at 28 GHz, 0.6 MW at 53.2 GHz, 2 MW at 6-20 MHz, and 1.5 MW at 40-80 MHz), but may needed for presently anticipated beta-limits and confinement.

Equilibrium studies of the magnetic surfaces at low β and low bootstrap current would be examined in earlier phases of the experimental program. However, breakup of magnetic surfaces is more probable at the higher β values and larger bootstrap currents, and more important to separate from instability limits. Higher bootstrap current and Ohmic current will allow

- comparing the effects of different current profiles on equilibrium quality (islands, ergodic regions) and on its repair
- study of the configuration dependence of the bootstrap current at low aspect ratios
- changing the magnetic transform and shear to study stabilizing and destabilizing magnetic islands and neoclassical tearing modes
- changing the magnetic transform and shear with OH vary stability boundaries.

Study of large islands or ergodic regions in the plasma interior will require a YAG 50-Hz multi-chord Thomson scattering system for point measurements with fine spatial resolution at many times during the evolution of the discharge and soft X-ray diode arrays to tomographically reconstruct the interior flux surfaces with lower spatial resolution but with high temporal resolution ($<<$ 1 ms). The higher-β capability allows study of β limits and instability characteristics at $\langle\beta\rangle < 2$-3% for different magnetic configurations at very low aspect ratio using arrays of high-frequency magnetic loops and soft X-ray diodes.

References

[1] Lyon, J. F., et al., "Compact Stellarators as Reactors", 18th IAEA Fusion Energy Conference, Sorrento, Italy, October 4-10, 2000.