Appendix C. Quasi-Poloidal Stellarators as Reactors

C.1. Introduction

A low-aspect-ratio (compact) stellarator could combine the best features of tokamaks (moderate A_p, good confinement, and high $\langle\beta\rangle$) and currentless stellarators (steady-state operation without external current drive or disruptions, stability against external kinks and vertical displacement events without a close conducting wall or active feedback systems, and low recirculating power in a reactor). The benefits of lower A_p are larger plasma size for a given cost for an experiment and lower cost for a given fusion power in a reactor. The ARIES-RS reactor [1], an "advanced tokamak" with reverse (stellarator-like) shear in the inner part of the plasma, is relatively compact (R = 5.5 m) and should have good plasma performance, but would have a relatively low engineering Q (the ratio of the net electric power produced to the total electric power required for operation of the power plant) because of the power that must be returned to the plasma for current drive and control of the plasma. The Stellarator Power Plant Study (SPPS) reactor [2] had relatively high engineering Q because it did not need power recirculated to the plasma for current drive or plasma control, but its relatively large size (R = 14 m) and high plasma aspect ratio (A_p = 8) led to a relatively low wall power loading. In spite of this, the projected cost of electricity was essentially the same for both because the larger size of SPPS was offset by the reduction in the power needed for the total plant operation. A compact stellarator reactor aims at preserving the low recirculating power advantage of SPPS while attaining the smaller size (low aspect ratio) advantage of tokamaks. This combination could lead to a reactor with a lower cost of electricity than either SPPS or ARIES-RS without feedback stabilization, current drive, rotation drive, or a serious risk of disruptions. A compact stellarator reactor could retain the cost savings associated with the low recirculated power of the SPPS reactor, but with smaller size and higher wall power density (hence lower cost of electricity) than the SPPS reactor.

C.2. QPS Reactor Configurations

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 beta and are robust against current-driven modes (external kinks), vertical instabilities, and disruptions.

Figures C.1 and C.2 show two possible high-β quasi-poloidally-symmetric (QPS#1 and 2) reactor configurations. The characteristics of these configurations are discussed in Chapter 2. The coils that create these configurations are characterized by $A_\Delta = R/\Delta$ and B_{max}/B_0 where Δ is the minimum distance between the plasma edge and the centerline of the coils for a given R, and B_{max} is the maximum field on the coils. These ratios depend on the specific coil design and are important because the minimum reactor size is set by $R_{min} = A_\Delta(d + ct/2)$ where d is the limiting (inboard) space needed for the plasma-wall distance, first wall, blanket, shield, vacuum vessel, and assembly gaps. The half radial depth of the modular coils is given by

$$ct/2 = A_\Delta B_0/(16N_{coil}\, j_{coil} k)[1 + \{1 + 32\, N_{coil}\, j_{coil} kd/(A_\Delta B_0)\}^{1/2}]$$

where N_{coil} is the number of coils, j_{coil} is the current density averaged over the coil cross section in kA cm^{-2}, and k is the ratio of toroidal width to radial depth of the coils. A 20-cm thick cryostat surrounds the reactor core. The value assumed for d is 1.12 m, similar to that for ARIES-AT [3]; the value on the outboard side is 1.30 m. The other reference reactor

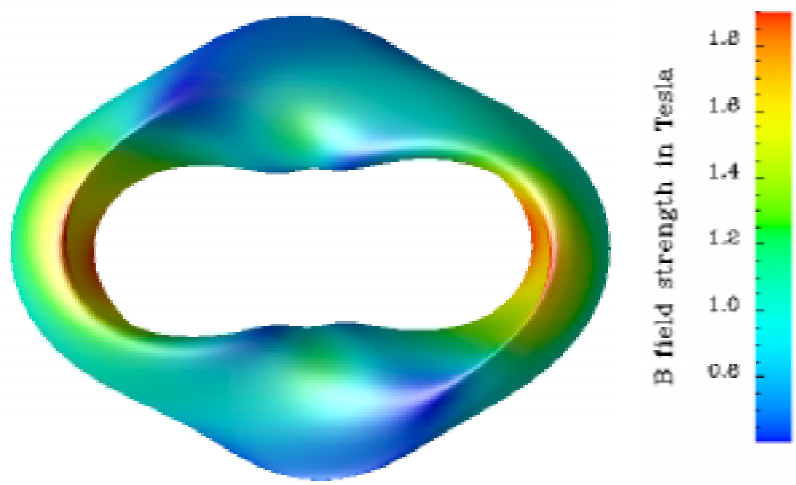

Figure C.1. |B| values and shape of the LCFS for an R/a = 2.6 QPS configuration (QPS#1) at $\langle\beta\rangle$ = 10%.

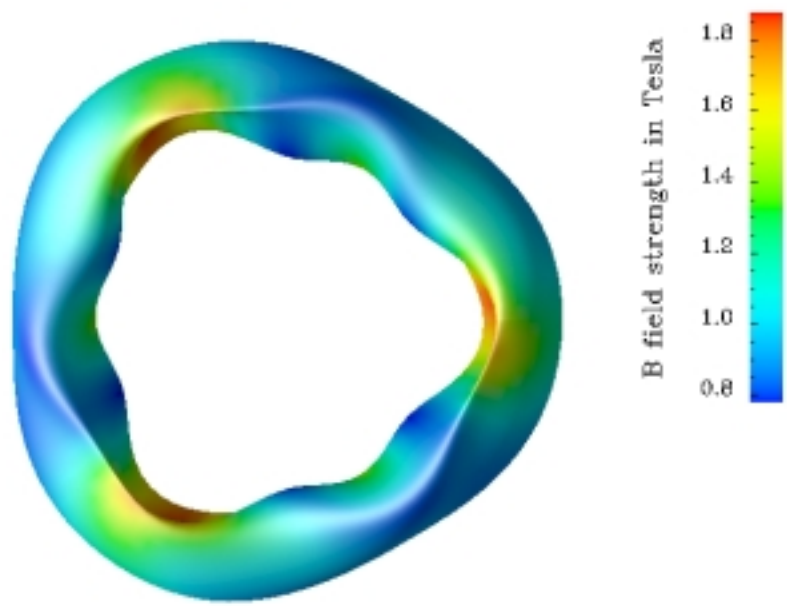

Figure C.2. |B| values and shape of the LCFS for an R/a = 3.7 QPS configuration (QPS#2) at $\langle\beta\rangle$ = 15%.

cryostat surrounds the reactor core. The value assumed for d is 1.12 m, similar to that for ARIES-AT [3]; the value on the outboard side is 1.30 m. The other reference reactor assumptions are also similar to those for ARIES-AT; e.g., a thermal conversion efficiency η = 59% and B_{max} = 12 T whereas the SPPS reactor had η = 46% and B_{max} = 16 T.

Rather than calculating actual coils for a large number of possible coil-plasma distances and coil cross sections, an approximate model developed for the corresponding QA reactor scoping study was used for a scaling study. The NESCOIL code [4] was used to calculate B_{max}/B_0 at a distance ct/2 radially in from a current sheet (at a distance Δ from the plasma edge) that reproduced the last closed flux surface. The value of B_{max}/B_0 was increased by 15% to simulate effects due to a smaller number of coils from experience in the SPPS study. There is a tradeoff between minimizing B_{max}/B_0, which increases the field in the plasma for a given B_{max} on the coils, and maximizing Δ to allow a smaller R for a reactor with a given d. Because the fusion power P_{fusion} (and hence the net electric power generated, $P_{electric}$) $\propto \beta^2 B_0^4 V_{plasma}$, the value of B_{max}/B_0 needed for a given $P_{electric}$ and d is proportional to $(R/\Delta)^{3/4}$.

Using this model, the minimum value for R was calculated for the two QPS reactors subject to several constraints: $P_{electric}$ = 1 GW, $\Gamma_n \leq 4$ MW m^{-2}, a plasma-coil distance $\geq$ 1.11 m, $j_{coil} \leq 3$ kA cm^{-2}, H-95 $\leq$ 3.5, $\langle n\rangle/n_{Sudo} \leq 1$, and $\langle\beta\rangle \leq 5\%$. Here H-95 = τ_E/τ_E^{ISS95} where $\tau_E^{ISS95} = 0.79 a_p^{2.21} R^{0.65} P^{-0.59} n^{0.51} B^{0.83} \iota^{-0.4}$ [5] and $n_{Sudo} = (1/4)[PB/Ra^2]^{1/2}$ [6] with R and a_p in m, B in T, n in 10^{20} m^{-3}, and P in MW. The value for Γ_n is an important figure of merit for reactor economics because it relates to the power generated per unit wall area and the costs of the main reactor core elements (blankets, shield, and coils) are proportional to the wall area. Table C.1 shows the results for the two QPS cases. The minimum values for R and H-95 are obtained with $\langle n\rangle/n_{Sudo}$ = 1.

Table C.1. Scaled 1-GW QPS Reactors with B_{max} = 12 T, $\langle\beta\rangle \leq \beta_{limit}$, H-95 $\leq$ 5.

	QPS#1	**QPS#2**
Plasma aspect ratio R/a_p	2.70	3.70
Volume average β limit $\langle\beta\rangle_{limit}$ (%)	10	15
Average major radius R (m)	**7.34**	**7.84**
Average plasma radius a_p (m)	2.72	2.12
Plasma volume V_{plasma} (m^3)	1040	690
On-axis field B_0 (T)	**5.23**	**5.03**
τ_E/τ_E^{ISS95} multiplier H-95	**3.61**	**4.42**
Volume average beta $\langle\beta\rangle$ (%)	**4.6**	**6.2**
Energy confinement time τ_E (s)	2.49	2.01
Vol.-average density $\langle n\rangle$ (10^{20} m^{-3})	1.40	1.70
Density-aver. temperature $\langle T\rangle$ (keV)	11.3	11.5
Neutron wall load Γ_n (MW/m^2)	**1.54**	**1.85**

The higher $\langle\beta\rangle$ allowed for the QPS configurations requires higher values for H-95. The higher $\langle\beta\rangle$ also allows reducing B_{max}, which leads to smaller R and higher Γ_n. For the QPS#1 case, reducing B_{max} from 12 T to 8.5 T reduced R from 7.34 m (with H-95 = 3.6 and $\langle\beta\rangle$ = 4.6%) to R = 7.09 m (with H-95 = 5.4 and $\langle\beta\rangle$ = 9.7%) and increased Γ_n from 1.37 MW/m^2 to 1.65 MW/m^2.

Table C.2 shows the same analysis for $P_{electric}$ = 2 GW. The values for B_0 are unchanged because B_{max} was assumed to be 12 T at 1 GW and 2 GW. For the QPS cases, the beta limit is not reached at 2 GW, so the reactor size is unchanged; β increases by a factor $2^{1/2}$ to produce twice the power, Γ_n doubles, and τ_E decreases by a factor $2^{1/2}$ because $\tau_E \propto \beta/P_{electric}$. The value for $n_{Sudo} \propto P_{electric}^{1/2}$ increases by $2^{1/2}$ and $\langle T\rangle \propto P_{electric}\tau_E/\langle n\rangle$, so $\langle n\rangle$ should increase by a factor of $2^{1/2}$ and $\langle T\rangle$ should not change. This occurs for the QPS#2 case where $\langle n\rangle/n_{Sudo}$ = 1, but not for the QPS#1 case where $\langle n\rangle/n_{Sudo}$ is only 0.82. The value needed for H-95 only decreases by 1.4% for the QPS#1 case and by 10.9% for the QPS#2 case. Increasing the allowed value for $\langle n\rangle$ to 2 x n_{Sudo} (as in LHD) did not decrease R_{min} for B_{max} = 12 T, but decreased the required H-95 multiplier by a factor of ~1.3. Increasing B_{max} to 16 T, as for ARIES-IV, increased R_{min} for the QPS reactors by only 25 cm, but decreased $\langle\beta\rangle$ by a factor of 1.86 and H-95 to 2.41 for QPS#1 and 2.96 for QPS#2.

Table C.2. Scaled 2-GW QPS Reactors with B_{max} = 12 T, $\langle\beta\rangle \le \beta_{limit}$, H-95 ≤ 4.

	QPS#1	**QPS#2**
Average major radius *R* (m)	**7.34**	**7.85**
Average plasma radius a_p (m)	2.72	2.12
Plasma volume V_{plasma} (m^3)	1070	700
τ_E/τ_E^{ISS95} multiplier H-95	**3.56**	**3.94**
Volume average beta $\langle\beta\rangle$ (%)	**6.5**	**8.75**
Energy confinement time τ_E (s)	1.76	1.42
Vol.-average density $\langle n\rangle$ (10^{20} m^{-3})	1.62	2.40
Density-aver. temperature $\langle T\rangle$ (keV)	13.7	11.5
Neutron wall load Γ_n (MW m^{-2})	**3.07**	**3.68**

The same assumptions were used with the plasma and coil configurations corresponding to the W7-X based HSR [7], the LHD based MHR-S [8], and SPPS reactors for comparison with these reactor studies. The modified HSR* had R = 17.4 m (instead of 22 m because B_{max} was increased from 10.6 T to 12 T), H-95 = 3.06, $\langle\beta\rangle$ = 4.9%, and Γ_n = 1.24 MW m^{-2}. The modified MHR-S* had R = 18.6 m (instead of 16.5 m because of the ARIES-AT blanket and shield assumptions), H-95 = 2.87, $\langle\beta\rangle$ = 5%, and Γ_n = 0.62 MW m^{-2}. The modified SPPS* had R = 20.8 m (instead of 14.0 m because B_{max} was decreased from 16 T to 12 T), H-95 = 3.13, $\langle\beta\rangle$ = 5%, and Γ_n = 0.60 MW m^{-2}. For the same modeling assumptions, the compact stellarator configurations lead to reactors with a factor of 2 to 3 smaller major radius and a factor of 1.4 to 3 higher wall power loading.

C.3. Results for Two Reference Compact Stellarator Reactor Cases

Figure C.3a shows a POPCON plot of the operating space ($\langle n \rangle$ and $\langle T \rangle$) for a 1-GW QPS#1 reactor with R = 7.3 m and B_0 = 5.2 T. The numbers label contours of constant auxiliary heating power in MW, "0" indicates ignition, and the curves indicate constant levels of $\langle \beta \rangle$, $P_{electric}$, and the Sudo density "limit". The dot marks the thermally stable 1-$GW_{electric}$ operating point. The reference reactor assumptions are B_{max} = 12 T, ARIES-AT inboard blanket and shield, and P_{fusion} = 1.69 GW [$P_{electric}$ = 1 GW (net)]. The reference plasma assumptions are broad ARIES-AT density profiles with $n_e \leq n_{Sudo}$, peaked ARIES-AT temperature profiles, $\tau_{He}/\tau_E = 6$, and an alpha-particle energy loss fraction = 0.1. The plasma parameters at the operating point are $\langle n \rangle = 1.5 \times 10^{20}$ m^{-3}, $\langle T \rangle$ = 9.1 keV, $\langle \beta \rangle$ = 3.74%, H-95 = 2.95, n_{DT}/n_e = 0.82, n_{He}/n_e = 5.8%, and Z_{eff} = 1.48. The saddle point in Figure C.3 determines the startup power required to reach ignition. Plasma parameters at the saddle point are $\langle n \rangle = 1.1 \times 10^{20}$ m^{-3}, $\langle T \rangle$ = 5.4 keV, $\langle \beta \rangle$ = 1.5 %, and P_{aux} = 20 MW. The H-95 confinement improvement required increases if the alpha-particle power lost increases.

The same reactor could produce 2 GW as shown in Figure C.3b where the plasma parameters at the operating point have increased to $\langle n \rangle = 2.0 \times 10^{20}$ m^{-3}, $\langle T \rangle$ = 9.3 keV, $\langle \beta \rangle$ = 5.28%, for H-95 = 2.65. The plasma parameters at the saddle point are $\langle n \rangle = 1.3 \times 10^{20}$ m^{-3}, $\langle T \rangle$ = 5.4 keV, $\langle \beta \rangle$ = 1.4 %, and P_{aux} = 39 MW. The higher beta limit also allows decreasing the magnetic field on the coils. Reducing B_{max} from 12 T to 8.5 T requires increasing H-95 from 2.95 to 4.1 for 1-GW operation. The values of $\langle n \rangle$ and $\langle T \rangle$ at the saddle point and the operating point are unchanged, but $\langle \beta \rangle$ increases to 3.1% at the saddle point and 8.4% at the operating point.

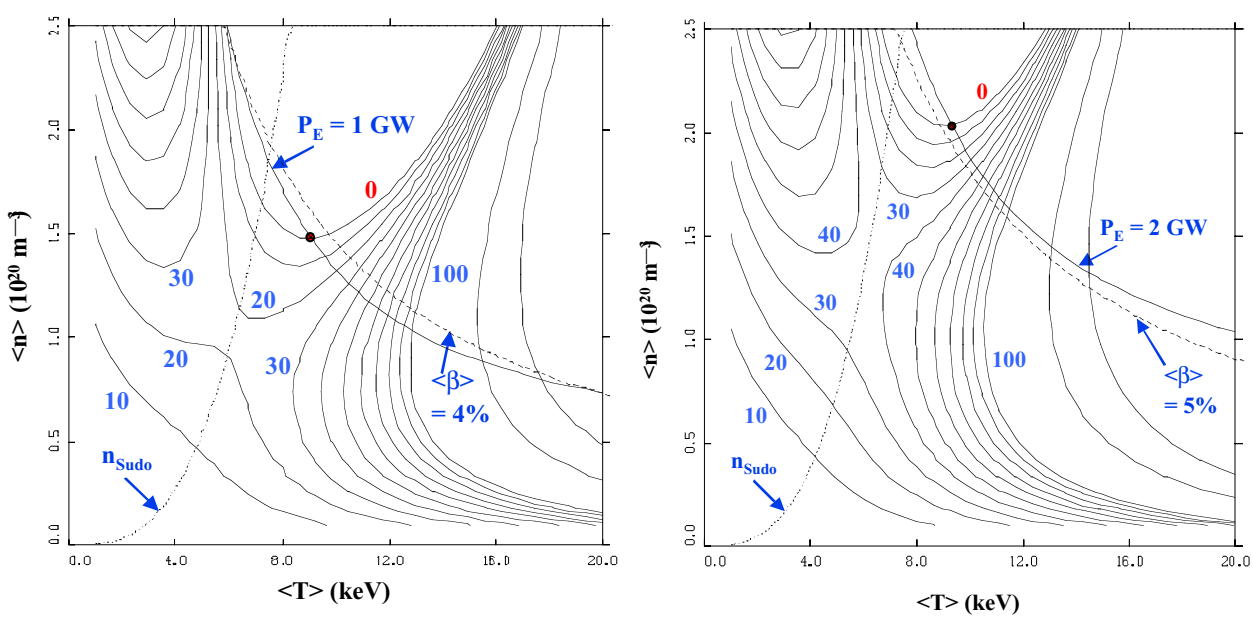

Figure C.3. Operating space for a QPS#1 reactor (a, left) at 1 GW and (b, right) at 2 GW.

C.4. Conclusions

Both quasi-poloidally-symmetric configurations have the potential for a more attractive stellarator reactor compared with SPPS. Using the ARIES-AT model with B_{max} = 12 T on the coils gives compact stellarator reactors with R = 7.3-8.2 m, a factor of 2-3 smaller in R than other stellarator reactors for the same assumptions. The two-field-period configuration leads to smaller reactors because of its lower plasma aspect ratio and smaller values for R/Δ. The QPS configurations are better suited for higher power reactors or lower magnetic field on the coils.

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