Chapter 14 -- Reactor Potential of Compact Stellarators

14.1 Quasi-Axisymmetric Compact Stellarator Reactor Configurations

Compact stellarators [1] may 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 earlier Stellarator Power Plant Study (SPPS) reactor [2] with average major radius R = 14 m was calculated to be cost competitive with the R = 6 m ARIES-IV and R = 5.5 m ARIES-RS tokamak reactors with higher wall power densities largely due to SPPS's low recirculated power [3]. A more compact stellarator reactor could retain the cost savings associated with the low recirculated power of the SPPS reactor, and benefit from smaller size and higher wall power density (hence lower cost of electricity) than was possible in the SPPS reactor.

Although the NCSX configuration was not optimized as a reactor configuration, it is instructive to explore the potential of QA configurations as reactors. The analysis discussed here is only a preliminary examination of the possibilities that compact stellarators offer as reactors to see if a more detailed study is warranted. Two types of low-A_p QA compact stellarators [4] with volume-average beta $\langle\beta\rangle$ = 4-6% were examined. Figure 14-1 shows the last closed flux surface and the $|B|$ contours on that surface for these cases; here magenta indicates the lowest $|B|$ value and red the highest. The configuration in Figure 14-1(a) is the li383 configuration chosen for NCSX and that in Figure 14-1 (b) is 2101 configuration.

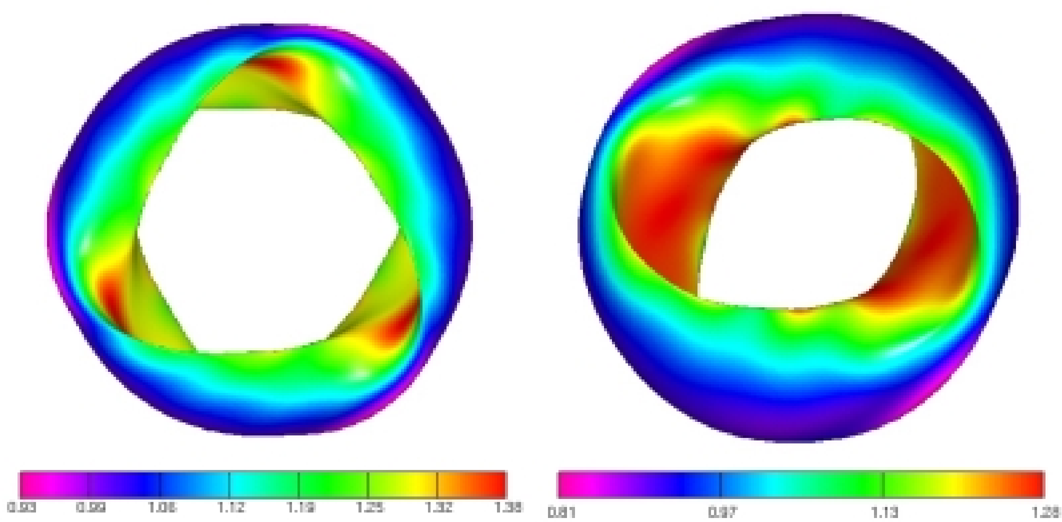

Figure 14-1

(a) QA#1: M = 3, A_p = 4.4. ***(b) QA#2: M = 2, A_p = 2.96.***

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, B_{max} is the maximum field on the coils, and B_0 is the average on-axis magnetic field. 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 thickness, blanket, shield, vacuum vessel, structure, and assembly

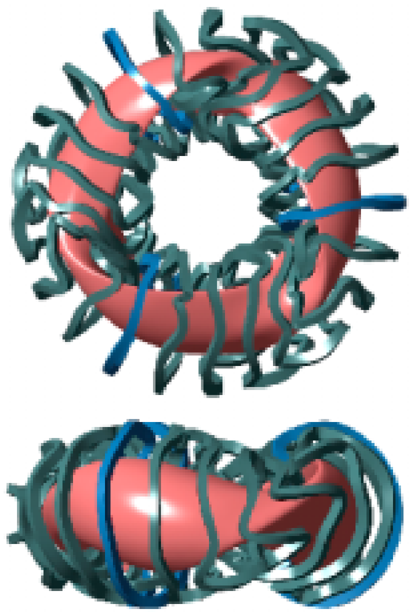

Figure 14-2. A modular coil set for the QA plasma configuration shown in Figure 14.1(a).

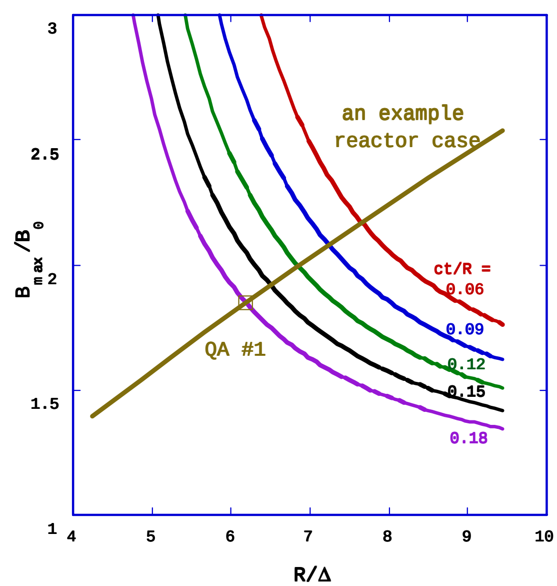

Figure 14-3 Variation of B_{max}/B_0 with R/Δ for the QA plasma configuration shown in Figure. 14-1(a).

gaps. From Ampere's law and the definitions of R_{min} and the average current density over the modular coil cross section, the half radial depth of the modular coils is given by

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

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. For these studies, j_{coil} = 3 kA cm^{-2}, k = 2, and d = 1.12 m (similar to that for ARIES-AT [5]); the value corresponding to d 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%. A 16-T value is assumed for B_{max} (as was used for the ARIES-IV, ARIES-RS, and SPPS reactor studies), which may be more relevant for a QA reactor than the 12-T value for B_{max} used in the ARIES-AT study.

14.2 Results for the Scaling Model

The parameters that characterize a particular coil configuration in the expression for ct/2 are A_Δ, B_{max}/B_0, and N_{coil}. Figure 14-2 shows a particular modular coil set for the QA#1 plasma configuration shown in Figure 14-1(a). Rather than calculating actual coils for a large number of possible coil-plasma distances and coil cross sections, an approximate model was used for a scaling study. The NESCOIL code [6] 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. Figure 14-3 shows the 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, for the QA#1 case shown in Figure 14-1(a). Similar calculations were done for the QA#2 case in Figure 14-1(b). 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 $(R/\Delta)^{3/4}$, as indicated by the "example reactor" line in Figure 14-3.

Using this model, the minimum value for R was calculated for $M = 2$ and $M = 3$ QA reactors for each ct/R value subject to several constraints: $P_{electric} = 1$ GW, Γ_n 4 MW m^{-2}, a plasma-coil distance 1.11 m, j_{coil} 3 kA cm^{-2}, H-95 3.5, $\langle n \rangle / n_{Sudo}$ 1, and $\langle \beta \rangle$ β_{limit} (4.2% for QA#1 and 4% for QA#2). Here $n_{Sudo} = 2.5[PB/Ra^2]^{1/2}$ [7] and H-95 = τ_E/τ_E^{ISS95} where $\tau_E^{ISS95} = 0.079 a_p^{2.21} R^{0.65} P^{-0.59} n^{0.51} B^{0.83} \iota^{-0.4}$ [8] with R and a_p in m, B in T, n in 10^{19} 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. The coil parameters obtained in this way are $A_\Delta = 6.18$, $B_{max}/B_0 = 1.85$, and $N_{coil} = 21$ for the three-field-period QA#1 configuration and $A_\Delta = 4.84$, $B_{max}/B_0 = 1.93$, and $N_{coil} = 14$ for the two-field-period QA#2 configuration .

Table 14-1. Scaled 1-GW QA Compact Stellarator Reactors with $\langle \beta \rangle$ β_{limit}, H-95 3

	B_{max} = 12 T		B_{max} = 16 T	
	QA#1	**QA#2**	**QA#1**	**QA#2**
Average major radius R (m)	**9.77**	**8.22**	**9.15**	**7.28**
Average plasma radius a_p (m)	2.22	2.78	2.08	2.46
Plasma volume V_{plasma} (m^3)	950	1250	780	870
On-axis field B_0 (T)	**5.65**	**5.41**	**7.53**	**7.21**
Energy confinement time τ_E (s)	2.35	2.69	2.13	2.25
τ_E/τ_E^{ISS95} multiplier H-95	**2.65**	**2.65**	**2.27**	**2.45**
ITER-89P confinement multiplier	1.50	1.44	1.17	1.18
Volume average beta $\langle \beta \rangle$ (%)	**4.20**	**4.00**	**2.61**	**2.70**
Vol.-average density $\langle n \rangle$ (10^{20} m^{-3})	1.54	1.31	1.55	1.33
$\langle n \rangle / \langle n \rangle_{Sudo}$	1.00	1.00	0.79	0.73
Density-aver. temperature $\langle T \rangle$ (keV)	10.9	11.1	11.9	13.1
Neutron wall load Γ_n (MW m^{-2})	**1.41**	**1.34**	**1.61**	**1.71**

Table 14-1 shows the results for the two QA cases for $\langle \beta \rangle$ the nominal β_{limit} (4.2% for QA#1 and 4% for QA#2) and B_{max} = 12 T value, and the result if B_{max} is increased to 16 T. The values for R range from 7.28 m to 9.77 m, considerably smaller than the R = 14 m value obtained in the SPPS study or the R = 18-22 m values obtained in the HSR studies [9]. The required multiplier on the ISS-95 confinement time is modest; H-95 ranges from 2.27 to 2.65. The minimum values for R and H-95 are obtained with $\langle n \rangle / n_{Sudo} = 1$ and $\langle \beta \rangle = \beta_{limit}$ for

B_{max} = 12 T. However, the $P_{electric}$ = 1 GW limit is reached for $\langle n \rangle / n_{Sudo} < 1$ and $\langle \beta \rangle < \beta_{limit}$ when B_{max} is increased to 16 T; $P_{electric} \propto \beta^2 B_0^4 V_{plasma}$ and the factor 3.16 increase in B_0^4 does not allow taking advantage of the β_{limit}. The value of V_{plasma} can not decrease enough to allow $\langle \beta \rangle = \beta_{limit}$ because the value of R is constrained by $R_{min} = A_\Delta(d + ct/2)$. Operation at the β limit in these cases would produce substantially more than 1 $GW_{electric}$.

Table 14-2 shows the result if the β_{limit} is increased to 5% or 6% with B_{max} = 12 T. This leads to smaller values for R as shown in Table 14.2. The higher $\langle \beta \rangle$ values allow reducing R to R_{min}, R = 8.80 m for QA#1 and R = 6.99 m for QA#2 versus R = 9.77 m for QA#1 and R = 8.22 m for QA#2 in Table 14-1. The ISS-95 confinement multipliers H-95 have had to increase to keep $P_{electric}$ = 1 GW to compensate for the smaller plasma volumes. Table 14-3 shows the same analysis with $P_{electric}$ = 2 GW. Higher values of $\langle \beta \rangle$ are now useful; a value of 6% can be accommodated with B_{max} = 12 T but not with B_{max} = 16 T. The value for Γ_n is approximately double that for the $P_{electric}$ = 1 GW cases in Table 14-1 because there is little change in R.

Table 14-2. 1-GW QA Reactors with B_{max} = 12 T, β_{limit} = 5% and 6%, H-95 3

	β_{limit} = 5%		β_{limit} = 6%
	QA#1	**QA#2**	**QA#2**
Average major radius *R* (m)	**8.80**	**7.08**	**6.99**
Average plasma radius a_p (m)	2.00	2.39	2.36
Plasma volume V_{plasma} (m^3)	700	800	770
On-axis field B_0 (T)	**5.65**	**5.41**	**5.41**
Energy confinement time τ_E (s)	2.01	2.16	2.11
τ_E/τ_E^{ISS95} multiplier H-95	**2.82**	**2.90**	**2.95**
ITER-89P confinement multiplier	1.61	1.61	1.62
Volume average beta $\langle \beta \rangle$ (%)	**4.91**	**5**	**5.1**
Vol.-average density $\langle n \rangle$ (10^{20} m^{-3})	1.80	1.64	1.65
$\langle n \rangle / \langle n \rangle_{Sudo}$	1.00	1.00	0.98
Density-aver. temperature $\langle T \rangle$ (keV)	10.8	11.1	11.3
Neutron wall load Γ_n (MW m^{-2})	**1.74**	**1.81**	**1.86**

Table 14-3. Scaled 2-GW Compact Stellarator Reactors with ⟨β⟩ 6%, H-95 3

	B_{max} = 12 T		B_{max} = 16 T	
	QA#1	**QA#2**	**QA#1**	**QA#2**
Average major radius *R* (m)	**9.71**	**7.90**	**9.15**	**7.28**
Average plasma radius a_p (m)	2.21	2.67	2.08	2.46
Plasma volume V_{plasma} (m^3)	930	1110	780	870
Energy confinement time τ_E (s)	1.65	1.80	1.51	1.59
τ_E/τ_E^{ISS95} multiplier H-95	**2.80**	**2.65**	**2.38**	**2.34**
ITER-89P confinement multiplier	1.50	1.46	1.17	1.16
Volume average beta ⟨β⟩ (%)	**6.00**	**6.00**	**3.69**	**3.82**
Vol.-ave. density ⟨*n*⟩ (10^{20} m^{-3})	1.59	1.65	1.61	1.65
$\langle n\rangle/\langle n\rangle_{Sudo}$	0.72	0.84	0.58	0.64
Density-aver. temperature ⟨*T*⟩ (keV)	15.0	13.2	16.2	15.0
Neutron wall load Γ_n (MW m^{-2})	**2.86**	**2.91**	**3.23**	**3.43**

The same assumptions were used with the plasma and coil configurations corresponding to the W7-X based HSR, the LHD based MHR-S [10], 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, ⟨β⟩ = 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, ⟨β⟩ = 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, ⟨β⟩ = 5%, and Γ_n = 0.60 MW m^{-2}. Thus, 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.

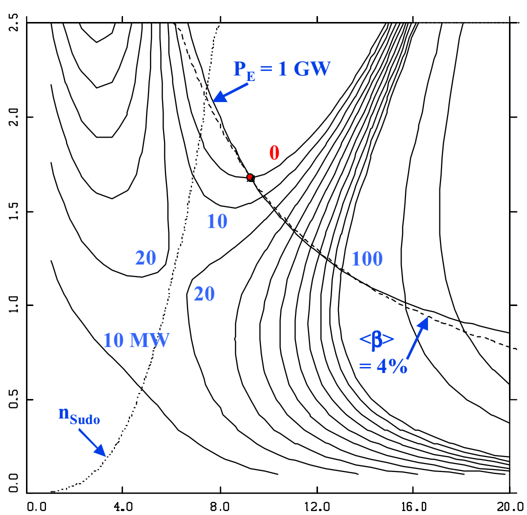

Figure 14-4. Operating space for a QA#2 reactor.

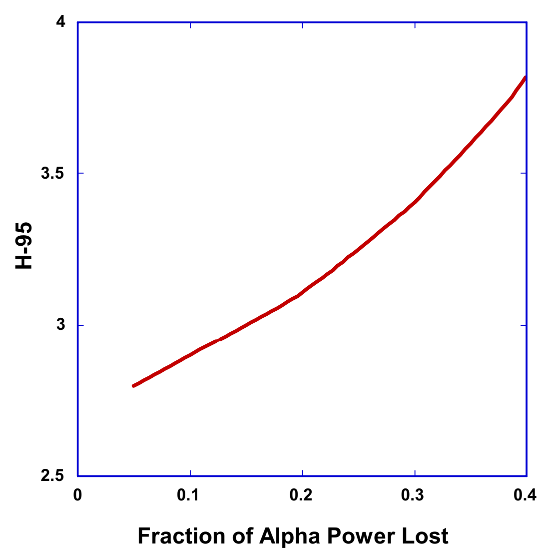

Figure 14-5. Effect of alpha-particle power loss

14.3 Results for a Reference Compact Stellarator Reactor Case

Figure 14-4 shows a POPCON plot of the operating space ($\langle n \rangle$ and $\langle T \rangle$) for a QA#2 reactor with R = 7.1 m and B_0 = 5.4 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 red dot marks the thermally stable 1-$GW_{electric}$ operating point. The reference reactor assumptions are A_Δ = 4.84, 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 n_{Sudo}, peaked ARIES-AT temperature profiles, τ_{He}/τ_E = 6, and an alpha-particle energy loss fraction = 0.1. The plasma parameters at the operating point are $<n>$ = 1.7 x 10^{20} m^{-3}, $<T>$ = 9.3 keV, $<\beta>$ = 4.04%, H-95 = 2.90, n_{DT}/n_e = 0.82, n_{He}/n_e = 5.9%, and Z_{eff} = 1.48. The saddle point in Fig. 14.4 determines the startup power required to reach ignition. Plasma parameters at the saddle point are $<n>$ = 1.1 x 10^{20} m^{-3}, $<T>$ = 5.4 keV, $<\beta>$ = 1.5 %, and P_{aux} = 20 MW. The confinement improvement required increases if the alpha particle power lost increases. Figure 14-5 indicates the effect of alpha-particle losses on the confinement required. The allowable alpha-particle energy loss varies from 5% at H-95 = 2.8 to 40 % at H-95 = 3.8.

14.4. Conclusions

QA configurations have the potential for a more attractive stellarator reactor. Using the ARIES-AT model with B_{max} = 12 T on the coils gives compact stellarator reactors with R = 7-8.8 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 their lower plasma aspect ratios and smaller values for R/Δ. For either configuration, only modest values of H-95 are required. Further study, e.g. by the ARIES group, is warranted to fully assess the reactor potential of these configurations.

References

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