TRANSPORT STUDIES OF COMPACT TORSATRON REACTORS*

S. L. Painter**, J. F. Lyon

CONF-891007--13

Fusion Energy Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee, USA

DE90 001353

ABSTRACT An efficient transport survey code utilizing the spectral collocation method was developed and is being used to study ignition in low-aspect-ratio torsatron reactors. Using a transport model dominated by helical-ripple-induced neoclassical heat fluxes, it is shown that ignition is possible for a range of radial electric fields and plasma aspect ratios even when the loss of trapped alpha particles is considered. However, control of the density profile near the plasma boundary is necessary. The sensitivity of the results to anomalous electron transport is also considered. Some initial investigations on the role played by "off-diagonal" terms in the neoclassical transport matrix in determining reactor performance are also presented, and a potentially attractive operating regime is found when these additional terms are considered.

I. INTRODUCTION

Stellarator reactors offer the possibility of steady-state high-beta operation without the need for recirculating power to drive a net toroidal plasma current. The compact torsatron variants of stellarators have the additional advantages of compact size, relatively open coil geometry, and natural divertors. These compact torsatron reactors¹ have major radii of 8 - 12 m as opposed to 20 - 25 m for conventional designs. However, the combination of low-aspect ratio and large helical modulation in the magnetic field strength raises some concerns for the compact torsatron. A relatively large fraction ($\approx 1/3$) of particles are trapped in the helical modulation of the magnetic field strength in these devices. In the absence of radial electric fields, essentially all of these helically trapped particles are lost from the plasma region. Radial electric fields develop naturally in these devices to insure quasineutrality of the plasma and prevent helically trapped thermal particles from leaving the plasma region through $E \times B$ poloidal orbit rotation. However, alpha particles have energies above those for which the electric field can provide confinement. The loss of these energetic particles and the heat flux associated with the helically trapped thermal particles combine to decrease the ignition potential of compact torsatron reactors.

The sensitivity of torsatron reactor performance to various transport assumptions is addressed in this paper. Houlberg² *et al.* studied reactors based on the Advanced Toroidal Facility³ (ATF) configuration and concluded that ignition is possible with moderate electric fields. Startup requirements with self-consistent determination of the radial electric field were also addressed, and low density startup was found to be advantageous. Lyon¹ *et al.* addressed similar issues for low-aspect-ratio devices having magnetic properties similar to ATF and found that ignition is also possible in these devices provided the density profiles near the plasma boundary can be controlled. The present study considers similar low-aspect-ratio torsatron configurations, but places a greater emphasis on indentifying parameteric dependences and sensitivities to modeling assumptions. The ATF was used as the reference configuration, but a range of aspect ratios (4 - 8) and helical ripples ($\epsilon_h = 0.125$ to 0.25) were considered. A new approach to transport survey studies was developed so that the large parameter space could be

scanned in an efficient manner. This approach is described in section II. Results are given in section III using a diagonal model for the heat fluxes. A more complete transport model using the full transport matrix is considered in section IV, and a new operating regime having more optimistic confinement is identified.

II. TRANSPORT CALCULATIONS

A transport survey code capable of making rapid parameter scans without the need for restrictive assumptions about temperature profile shapes was developed. This code solves the steady-state radial 1-D power balance equations for electrons and ions in integral form using the spectral collocation method. The survey code was checked both by numerical convergence studies⁴ and by comparisons with the WHIST⁵ transport code. Since the entire operating space of average temperature $\langle T \rangle$ and density $\langle n \rangle$ must be considered, and since steady-state conditions do not exist for all values of $\langle n \rangle$ and $\langle T \rangle$, it is necessary to modify the power balance equations to force equilibrium solutions. This is accomplished in either of two ways. In the plasma-operating-contour or POPCON⁵ mode, an external heating term P_e with a prescribed radial profile is added to the power balance. The magnitude of P_e is adjusted to give the desired average temperature. When P_e is positive it simply represents the amount of external heating power required to maintain thermal equilibrium for a given $\langle n \rangle$ and $\langle T \rangle$. Zero or negative values of P_e indicate ignition. For comparing reactor designs, the ignition margin M is a useful quantity. In this approach, no external heating term is included, but the alpha heating term is divided by M which is the quantity solved for to give the desired average temperature. The ignition margin M measures the departure of the reactor plasma from the steady-state ignited condition; $M = 1$ indicates ignition, and larger values of M indicate that additional power losses can be tolerated.

Because the particle fluxes and the radial electric fields are determined by transport processes which are not well understood, the density and electric potential profiles were fixed while the power balance equations were solved. Sensitivities to the assumed profiles were addressed. The density profile was parameterized by

$$n(\rho) = n_0 [(1 - P)(1 - \rho^2)^3 + P(1 - f\rho^2)^{1/2}], \quad (1)$$

where the parameter f controls the edge density and the parameter P controls the peaking of the density profile. $P \approx 1$ yields broad density profiles, $P < 1$ yields peaked profiles, and $P > 1$ results in hollow density profiles. $P = 1$ and $P = 1/3$ are used here. The electric potential was taken in the form $\phi = \Phi_0(1 - \gamma\rho^\alpha)^\beta$ where α , β , and γ are parameters. Here ρ is the normalized radius.

With these assumptions the transport equations are essentially the same as those used in tokamak modeling except for differences in the radial heat flux terms. Alpha particle heating, classical electron-ion heat flow due to Coulomb collisions, and radiation losses are accounted for. All alpha particles with birth orbits trapped by the toroidal and helical modulation of the magnetic field strength are assumed to be lost from the plasma region (direct loss), and an additional loss of 15% of the total alpha power is added to account for particles scattering into the loss region⁶. The radiation loss term combines hydrogenic Bremsstrahlung; impurity radiation using Post's coronal model⁷ assuming

* Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

** Research partially fulfills degree requirements for PhD in Nuclear Engineering, University of Tennessee.

impurity fractions of 0.01 for carbon and 10^{-5} for iron; and synchrotron radiation using Trubnikov's formulation⁸ with 90% wall reflectivity.

At reactor relevant temperatures and densities the radial heat fluxes are expected to be dominated by the neoclassical heat fluxes due to helical-ripple trapped electrons and ions.

$$Q^{ncr} = -n\chi^T dT/dr - T\chi^n dn/dr - Zen\chi^* d\Phi/dr \quad (2)$$

Shaing's integral formulation⁹ is used for the transport coefficients. The radial electric field $d\Phi/d\rho$ enters in two places, through the transport coefficients and in the off-diagonal third term above. In Fig. 1 the thermal diffusivity χ^T is plotted versus the collision frequency ν for two values of the radial electric field. The radial heat flux is maximum when $\nu \approx \omega_B$, where ω_B is the $E \times B$ poloidal drift frequency. The heat flux is independent of the radial electric field in the $\chi \propto \frac{1}{\nu}$ regime. In the $\chi \propto \nu$ regime the heat flux is independent of the magnetic field strength. Two additional terms are included in the heat flux model: a neoclassical axisymmetric term, and an anomalous term of the form

$$\chi^{an} = \chi_0 / (1.0 - 0.9\rho^2) \quad (3)$$

to simulate the effect of edge turbulence for the electrons.

Fig. 1. Helical-ripple-induced thermal diffusivity χ for the ATF reference reactor for two values of the normalized electric potential $\xi = e\Phi_0/kT_0$. χ is evaluated at the normalized radius $\rho = 0.67$.

III. RESULTS WITH A DIAGONAL TRANSPORT MODEL

The heat flux model Eq. 2 contains terms that are not proportional to the temperature gradient. Neoclassical theory predicts these off-diagonal terms to make a significant contribution to the total heat flux. However, some of the predicted effects of these terms have not been observed experimentally, suggesting that perhaps anomalous processes are also playing a role. In this section, only the diagonal $dT/d\rho$ term is included in the heat flux model.

Radial profiles of electron and ion temperature are shown in Fig. 2 for an ATF-like torsatron reactor having $\epsilon_A=0.2$, aspect ratio of 8, 2m plasma radius, and magnetic field of 5T. The density profile is peaked and the edge density is 1% of the central density. The electric potential profile is

Fig. 2. Radial profiles of electron temperature (dashed curve) and ion temperature (solid curve) for an ignited ATF reactor.

parabolic with $\xi = e\Phi_0/kT_0 = +3$. POPCON contours are shown in Fig. 3 for this reactor. Ignition occurs at ≈ 8 keV at high densities and at ≈ 12 keV at lower densities. The minimum power required for ignition is ≈ 50 MW. Low density startup is advantageous because of the need to keep plasma ions in the low collisionality regime where electric fields improve confinement. Electrons are more collisional and stay in the $1/\nu$ regime where electric fields do not improve confinement significantly.

Fig. 3. POPCON plot for the ATF reference reactor assuming a diagonal transport model and a normalized potential ξ of +3. Contours are shown every 10 MW up to 100 MW and every 100 MW thereafter.

In Fig. 4 the maximum ignition margin along a curve of fixed fusion power (4 GW) denoted by M_* is used to characterize the ignition potential of a given configuration as the normalized electric potential ξ is varied. Four combinations of helical and toroidal ripple are considered. Other assumptions are the same as for the ATF reactor discussed previously. The value of ξ necessary for ignition depends sensitively on the aspect ratio and to a lesser extent on the magnitude of the helical modulation. $\xi = +2$ is sufficient for ignition at aspect ratio of 8, but larger values $\xi = +3$ are required for ignition at aspect ratio of 4.

The sensitivities of the reference reactor to the density and electric field profile assumptions were also studied. Changing the density profile from peaked ($P = 1/3$) to broad ($P = 1$) reduced M_* from 1.8 to 0.5. An edge density of 10% also reduced the ignition margin (1.5). Low densities in the plasma edge region are advantageous because the collisionality is reduced there which drives the ions deep into the ν regime and allows the electrons to approach the $\nu-1/\nu$ transition where electric fields reduce the thermal conductivity. A thermally insulating layer thus forms in the plasma edge region. The reactor plasma performance is better when the electric fields are larger in this low-collisionality region. A parabolic squared profile for the electric potential decreased the ignition margin to 1.2, and a square-root parabolic profile increased M_* to 2.5. This is because the broader potential profiles result in larger electric fields in the outer regions of the plasma. M_* is insensitive to B_0 (1.8 for $B_0 = 7.5T$ and 1.7 for $B_0 = 10T$). Although χ in the $1/\nu$ regime is reduced by increasing the magnetic field strength, the effect is compensated for by increases in the synchrotron losses.

Fig. 5. Sensitivity of the maximum ignition margin I_* to anomalous electron transport in the plasma edge region. See text for assumptions.

The sensitivity of the reactor performance to anomalous electron heat transport at the plasma edge is illustrated in Fig. 5. Anomalous heat diffusivities in the form of Eq. 3 were used. Relatively large values of χ^{an} can be tolerated before the reactor plasma performance is degraded. This insensitivity comes from the fact that the electron thermal diffusivity is already large neoclassically.

IV. RESULTS WITH THE FULL NEOCLASSICAL TRANSPORT MATRIX

When the full neoclassical transport model given by Eq. 2 is considered, two operating regimes appear. This can be seen by examining the $\text{grad-}\Phi$ component of the heat flux summed for electrons and ions $en(\chi_i - \chi_e)d\Phi/d\rho$. This term is negative indicating a radially inward-directed heat flux which partially compensates for the large outward-directed grad-T term when $\chi_e > \chi_i$ and $d\Phi/d\rho > 0$ or when $\chi_e < \chi_i$ and $d\Phi/d\rho < 0$. Having $\chi_e > \chi_i$ requires the ions to be well into the ν regime with the more collisional electrons near the $\nu-1/\nu$ transition, i.e. high temperatures and low densities to minimize the collisionality. This operating regime (not shown) is similar to the one obtained with the diagonal transport model. The second operating regime is characterized by high density, moderate temperatures, and negative electric fields with the electrons just entering the $1/\nu$ regime and the ions near the $\nu-1/\nu$ transition. A PUP-CON plot illustrating this operating regime is shown in Fig. 6 for the ATF reference reactor with a broad density profile and $\xi = -3$. The sensitivities in this operating regime are being investigated.

Fig. 4. Maximum ignition margin at fixed fusion power (4 GW) versus normalized electric potential for four combinations of helical and toroidal ripples. Squares are for aspect ratio of 4 and helical ripple of 0.25. Circles are for aspect ratio of 4 and helical ripple of 0.125. Upward pointing triangles are for aspect ratio of 8 and helical ripple of 0.25 and downward pointing triangles are for aspect ratio of 8 and helical ripple of 0.125.

Fig. 6. POPCON plot for the ATF reference reactor using the full neoclassical transport matrix and a normalized potential ξ of -3. Contours are shown every 10 MW up to 100 MW and every 100 MW up to 1 GW. Contours above 1 GW are not shown.

V. CONCLUSIONS

The neoclassical heat flux associated with helically trapped particles does not by itself prevent ignition in low-aspect-ratio torsatron reactors. Even when the loss of trapped alpha particles is taken into account, ignition is possible at moderate values of the radial electric field provided the density profile in the plasma edge region can be controlled. Under conditions where neoclassical transport will allow ignition, the results are relatively insensitive to the level of anomalous electron transport in the plasma edge region.

When the complete neoclassical transport matrix is considered, a second operating regime characterized by moderate temperatures, high densities, and negative electric fields appears. This operating regime offers several advantages including ignition with smaller fusion power output and the possibility for decreased anomalous transport because of the negative electric field. The fact that different results are obtained with and without the non-diagonal heat fluxes emphasizes the need for a better understanding of the physics associated with these terms including the anomalous contributions. This increased understanding will follow from the study of experimental results from larger stellarators which have more heating power to reach the low collisionality regime.

REFERENCES

1. J. F. LYON, B. A. CARRERAS, V. E. LYNCH, J. S. TOLLIVER, and I. N. SVIATOSLAVSKY, "Compact Torsatron Reactors," *Fusion Technol.*, **15**, 1401 (1989).
2. W. A. HOULBERG, J. T. LACATSKI, and N. A. UCKAN, "Assessment of a Compact Torsatron Reactor, ATSR," *Fusion Technology*, **10**, 227-235 (1986).
3. J. F. LYON, B. A. CARRERAS, K. K. CHIPLEY, M. J. COLE, J. H. HARRIS, T. C. JERNIGAN, R. L. JOHNSON, V. E. LYNCH, B. E. NELSON, J. A. ROME, J. SHEFFIELD, and P. B. THOMPSON, "The Advanced Toroidal Facility," *Fusion Technol.*, **10**, 179 (1986).
4. S. L. PAINTER and J. F. LYON, "Transport Studies Using the Spectral Collocation Method," *Proceedings of the 7th International Stellarator Workshop (IAEA)*, in press.
5. W. A. HOULBERG, S. E. ATTENBERGER, and L. M. HIVEY, "Contour Analysis of Fusion Reactor Plasma Performance," *Nucl. Fusion*, **22**, 935 (1982).
6. S. L. PAINTER and J. F. LYON, "Alpha Particle Losses in Compact Torsatron Reactors," *Fusion Technol.*, **16**, 157 (1988).
7. D. E. POST, R. V. JENSON, C. B. TARTER, W. H. GRASBERGER, and W. A. LOKKE, "Steady-State Radiative Cooling Rates For Low-Density, High-Temperature Plasmas," *Atomic Data and Nuclear Data Tables*, **20**, 397-439 (1977).
8. B. A. TRUBNIKOV, "Universal Coefficients for Synchrotron Emission from Plasma Configurations," *Reviews of Plasma Physics*, Vol. 7, M. A. Leontovitch, ed., Consultants Bureau, New York, 1979, pp. 345-379.
9. K. C. SHAIN, "Stability of the Radial Electric Field in a Nonaxisymmetric Torus," *Phys. Fluids*, **27**, 1567 (1984).