CONFINEMENT PHYSICS AND FLOW DAMPING IN QUASI-POLOIDAL STELLARATORS

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1. Introduction

Very low aspect ratio (R_0/<a> = 2.7) two-field period (racetrack-shaped) devices with quasi-poloidal (QP) stellarator symmetry have been designed that generate their rotational transform both from internal plasma currents and external shaping. Neoclassical transport in QP stellarators has been minimized so as to be negligible in comparison with the expected anomalous levels. QP systems also possess an anisotropy in their viscous flow damping coefficients (poloidal viscosity < toroidal viscosity) that is opposite to that of tokamaks. This feature is expected to help maintain sheared radial electric fields and may facilitate access to enhanced confinement regimes. Independent control over modular coil currents, vertical coil currents and a background toroidal (i.e., 1/R) field allows substantial physics flexibility in our QPS design.

2. 1-D Performance Modeling and Global Monte Carlo lifetimes

A 1-D transport model that includes both neoclassical and anomalous energy transport components has been constructed for QPS plasma performance predictions. The neoclassical fluxes are modeled using an integral[1] formulation for the electric field dependence and the NEO[2] $e_{eff}^{3/2}$ coefficient to scale the overall level of the transport flux. Fixed density and power deposition profiles are used. Anomalous levels are varied to result in targeted global confinement improvement (H-ISS95) factors. The resulting neoclassical and total power flows vs. radial location are shown in Figure 1(a) for a low density ECR heated case for H-ISS95 = 1, 2, and 4.

(a) (b)

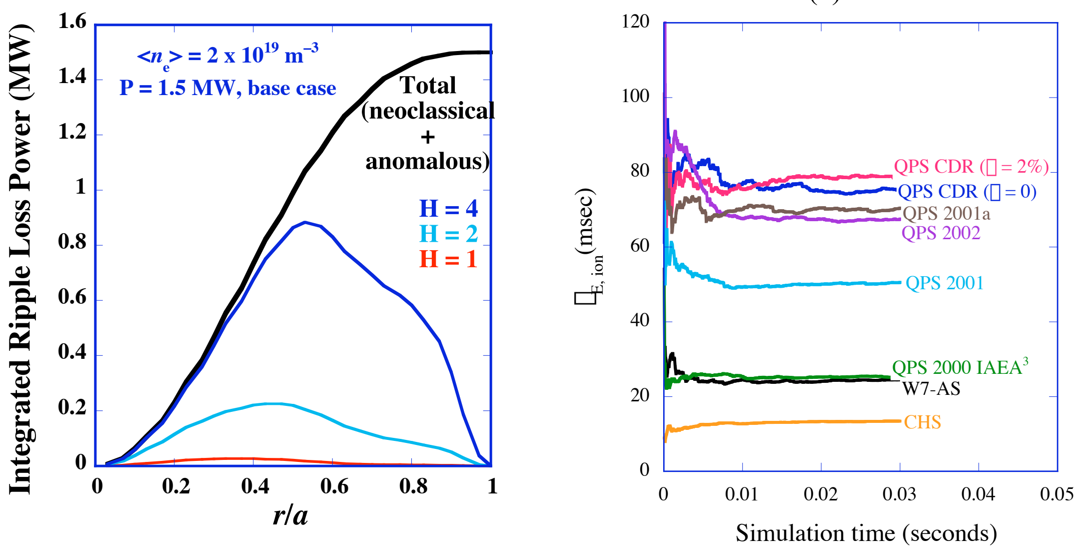

Figure 1 – (a) Integrated power flows vs. radius for 1.5 Mw ECH case, and (b) Monte Carlo ion energy lifetimes of different configurations for the ICH case.

As can be seen, for H-ISS95 = 1 and 2 the neoclassical power flows are small relative to anomalous flows. In Figure 1(b) we plot neoclassical ion energy lifetimes as obtained for an ion cyclotron heated regime [$n(0) = 8.3 \times 10^{19}$ m^{-3}, $T_i(0) = T_e(0) = 0.5$ keV] using Monte Carlo methods with $E_r = 0$ for our latest configuration (QPS CDR), several previous QPS[3] versions, and for the existing CHS and W7-AS devices. In all cases, the average magnetic field was set at 1 Tesla. As indicated, the confinement of QPS configurations has been improved by optimization in recent years.

3. Neoclassical Viscosities, Flow Damping

Recent methods developed by Sugama, et al.[4] have allowed calculation of the neoclassical viscosity tensor for a stellarator based upon the transport coefficients obtained from the DKES[5] code. The applicability of this procedure is currently limited at low collisionalities by the convergence criteria of DKES and at high collisionalities/finite electric fields by differences in the treatment of the $\mathbf{v_E}\cdot\nabla n_1$ term between the DKES model[5] and the analysis of Sugama.[4] However, the range of applicability between these limits is generally sufficient to provide us with at least qualitative indications of the different flow damping physics present in a QP device as compared to the equivalent toroidally symmetric device. In a QP device with perfect symmetry, it would be expected that toroidal flow components would be nulled out, leading to the relation $E_r = (B_t/B_p)BV_{||}$ between the parallel flow and the electric field (B_p, B_t = poloidal/toroidal magnetic field components). This provides an enhancement factor of $\sim(B_t/B_p)^2$ in the radial electric field over the equivalent relation in a perfectly symmetric tokamak $E_r = B_pV_{||}$, where the poloidal flow components must cancel. In a realistic QP system there will be somewhat larger damping of the parallel flows due to the higher level of parallel viscosity [see Figure 2(b)], but not by a large enough factor in the plateau regime: $\nu/v \sim 0.01$ (relevant to ion flows) to negate the $(B_t/B_p)^2$ enhancement factor.

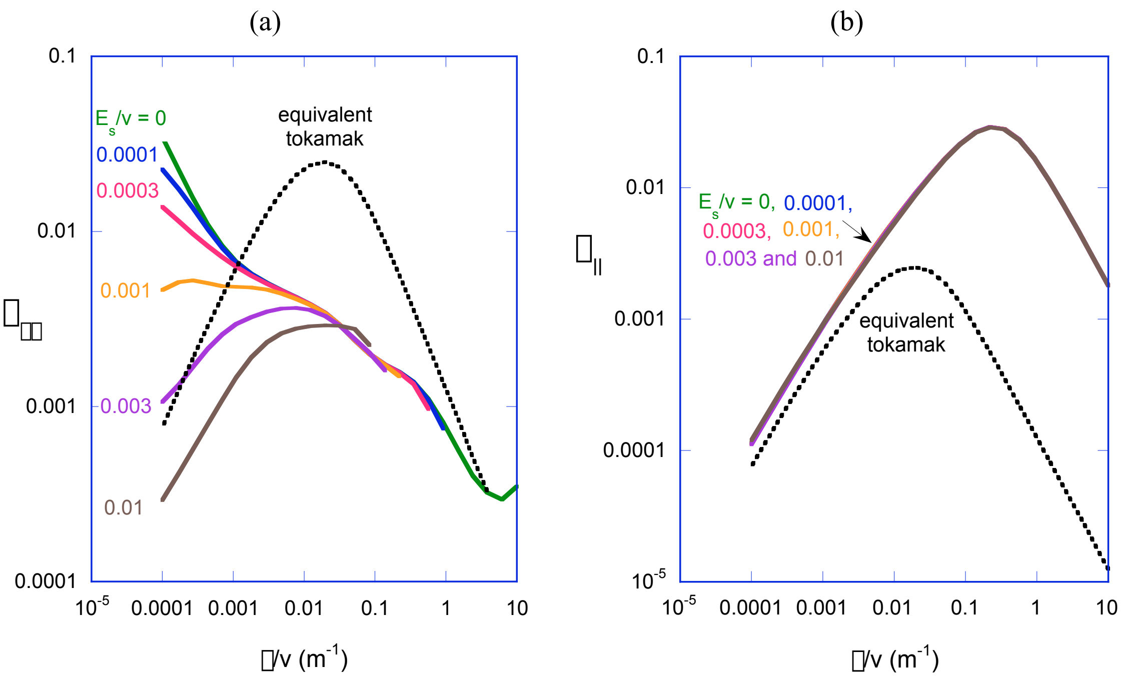

Figure 2 – Monoenergetic (a) poloidal and (b) parallel neoclassical viscosities vs. collisionality and ambipolar electric field for the QPS configuration. These are obtained using the DKES code[5] coupled with the analysis of Sugama, et al.[4]

The basis for the dominance of poloidal flows in QPS is also seen in Figure 2(a) where the poloidal viscosity coefficient is reduced by up to a factor of 10 in the plateau regime from that for the equivalent tokamak (i.e., the tokamak with the same iota profile and toroidally averaged shape as QPS). The coefficients plotted in Figure 2 are related to those of ref. 4 by: $\square_{\square\square} = M_{aPP}(K)/\mathrm{mv_T}K^{3/2}$, $\square_{\parallel} = M^* = M_a(K)/\mathrm{mv_T}K^{3/2}$ where $K = (v/v_T)^2$ and $v_T = (2kT/m)^{1/2}$; M_{aPP} and M^* are defined in equations (B5) and (54) of ref. 4. These characteristics of QP systems lead us to conclude that it should be possible to control the electric field level and shear with less required momentum input than for a similar axisymmetric system.

4. QPS Flexibility Studies

The current reference design for QPS is based on a set of 20 modular field coils (with 5 unique coil shapes), six vertical field coils, and 12 toroidal field coils. In Figure 3 the full set of coils are shown along with the plasma outer flux surface.

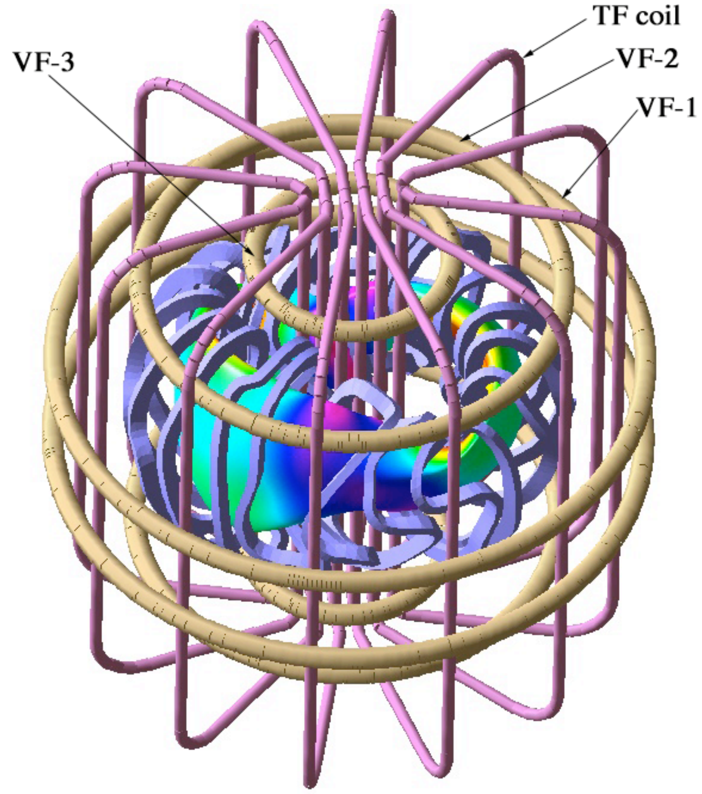

Figure 3 – QPS Coil-sets and plasma. Modular coils are shown in light blue, toroidal field coils are pink, vertical field coils are in tan. Color contours (blue = low field, red = high field) show the magnetic field strength on the outer plasma magnetic flux surface.

A high degree of flexibility can be achieved through variation of the currents in modular coils, vertical field coils and the toroidal field coils. Stellarator symmetry is maintained by keeping the currents in each unique modular coil group equal. Engineering constraints will limit the range over which these currents can be varied; the current constraints that we assume are listed in table 1. It should also be noted that in an experimental device some component of the vertical field coil currents are required for plasma positioning and compensation of stray fields from the Ohmic transformer. We will not directly assess the latter current requirements in this paper, but will check that the plasma-coil separation does not become too small.

Table 1 - Minimum, maximum and reference current levels for our flexibility study.

Coil	Mod 2	Mod 3	Mod 4	Mod 5	VF 1	VF 2	VF 3	TF
Minimum current (kAmps)	0	0	0	0	-60	-180	-130	-75
Maximum current (kAmps)	380	380	380	380	+60	+180	+130	+75
Reference design current (kAmps)	300	300	300	300	0	-75.5	-129	-24.9

As a first example of coil current optimization, we will find current distributions that can either improve or degrade the neoclassical transport properties of QPS. A number of transport measures are available for this purpose, including: the effective ripple from the NEO[2] code; collisional transport coefficients from the DKES[5] code; quasi-poloidal symmetry; and centering of J* (longitudinal adiabatic invariant)[6], B_{min}, and B_{max} contours. The primary target we will focus on in this article is the effective ripple provided by the NEO[2] code. Work is underway on some of the other targets, but this is not yet complete. Control over the effective ripple has so far had the most direct correlation with other measures of transport such as DKES[5] and global Monte Carlo lifetime estimates. We have also been able to improve quasi-poloidal symmetry by a factor of 4–5 over the reference design, but this has proven to be anti-correlated with other transport measures. This characteristic is possibly related to the path that the optimizer chooses for QP–symmetry improvement; this involves increasing the currents in the corner section modular coils (Mod-4,5) and weakening currents in the side modular coils (Mod-2,3).

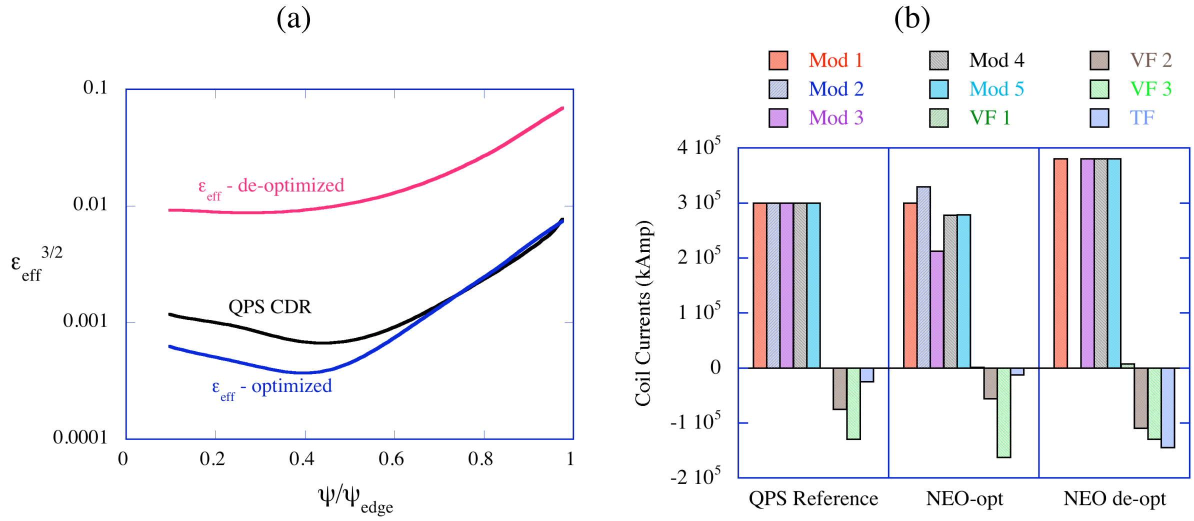

Figure 4 – (a) Effective ripple coefficient[2] as a function of normalized toroidal flux for the reference configuration (QPS CDR) and for improved (red) and degraded (blue) configurations, (b) Coil current distributions for transport optimized and de-optimized cases.

This increases the overall ripple level (i.e., symmetric + effective) and the fraction of trapped particles; over this range of parameters these effects seem to have a more negative impact than the positive effect from the symmetry improvement.

In Figure 4(a) the range of effective ripple coefficients that has been obtained by targeting either improved or degraded transport is plotted as a function of flux surface. Figure 4(b) shows the distribution of coil currents that was used to achieve these transport levels. As may be seen, about a factor of 30 variation in effective ripple can be produced. Coil-plasma separations have not been significantly changed by these optimizations; for the reference configuration, the minimum coil-plasma separation is 13.2 cm - it becomes 11.9 cm for the NEO[2] optimized case and 13.9 cm for the NEO[2] de–optimized case.

In addition to variations in the coil currents for confinement optimization, we have also carried out similar optimizations in order to control the shape of the rotational transform profile. The goal here has been to use combinations of Ohmically driven plasma current and modifications in the coil current distributions in order to keep the iota profile bounded in between windows determined by the adjacent low order rational surfaces (which occur for QPS at iota = 2/8, 2/7, 2/6, 2/5, etc.). Once such configurations are found, they are checked by use of the PIES[7] code. If good surfaces are found then the search ends; if large islands are present, further optimizations are performed to avoid whatever resonance has entered into the plasma. As there is generally some deviation between the rotational transform predicted by VMEC[8] and that given by PIES[7], several iterations of this process may be required to find a satisfactory configuration.

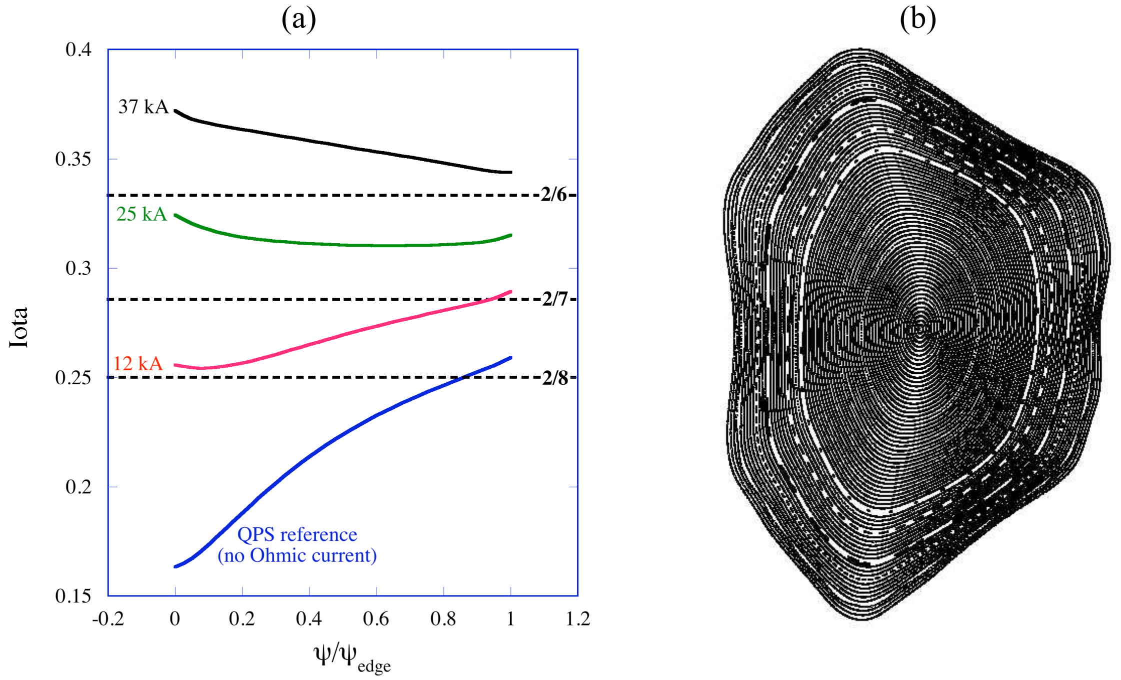

Figure 5 – (a) A selection of QPS rotational transform profiles that have been attained through combinations of Ohmic plasma current and coil current optimization; (b) PIES[7] magnetic surfaces for the coil current optimized case with 25 kA. The transform profile is constrained to remain between the 2/6 and 2/7 resonances.

We have optimized vacuum configurations with most of the weight placed on the target of attaining a specific rotational transform profile. For the results presented here, the transport properties have then been checked a posteriori, indicating that, in addition to decreased island sizes, the new configurations generally lead to improved confinement. The coil current optimizations have been carried out with varying levels of Ohmic current present; the Ohmic current profile has been modeled as centrally peaked. By combining the coil current optimization with finite plasma current levels, we have been able to both raise the rotational transform profile and flatten it at the same time. Figure 5(a) shows some of the VMEC[8] rotational transform profiles that we have obtained by this procedure. Of these profiles, only the 25 kA has so far resulted in good surfaces. The 37 kA profile generated 4/11 islands that destroyed the outer part of the plasma while the 12 kA case generated 2/7 islands. With further iterations between the optimizer and PIES[7], it should also be possible to avoid major islands in the 12 and 37 kA cases. The □ = 0 flux surface as calculated by PIES[7] for the 25 kA case is shown in Figure 5(b). The 25 kA optimized case had a minimum coil-plasma separation of 14.6 cm as compared to 13.2 cm in the reference case.

5. Conclusion

Optimized compact configurations (R/<a> = 2.7) with near quasi-poloidal symmetry (QPS) have been developed that offer significant reductions in neoclassical transport from anomalous levels. This feature, coupled with lower levels of poloidal viscosity than in similar tokamak systems, should offer good access to enhanced confinement regimes and measurable changes in transport properties. A high degree of flexibility can be achieved through independent control over modular, vertical and toroidal coil currents. Substantial control is possible over confinement through such flexibility, allowing the potential of continuous variation from regimes dominated by micro-turbulent transport to those dominated by neoclassical transport.

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