CONFINEMENT PHYSICS OF QUASI-POLOIDAL STELLARATORS

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1. Introduction

Very low aspect ratio ($R_0/\langle a \rangle = 2.7$) 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 plasma performance predictions. The neoclassical fluxes are modeled using an integral[1] formulation for the electric field dependence and the NEO[2] $\epsilon_{eff}^{3/2}$ 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. 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 [$n(0) = 1.3 \times 10^{19}$ m^{-3}, $T_i(0) = T_e(0) = 0.5$ keV] using Monte Carlo methods with $E_r = 0$ for our reference configuration (QPS CDR), several previous QPS 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.

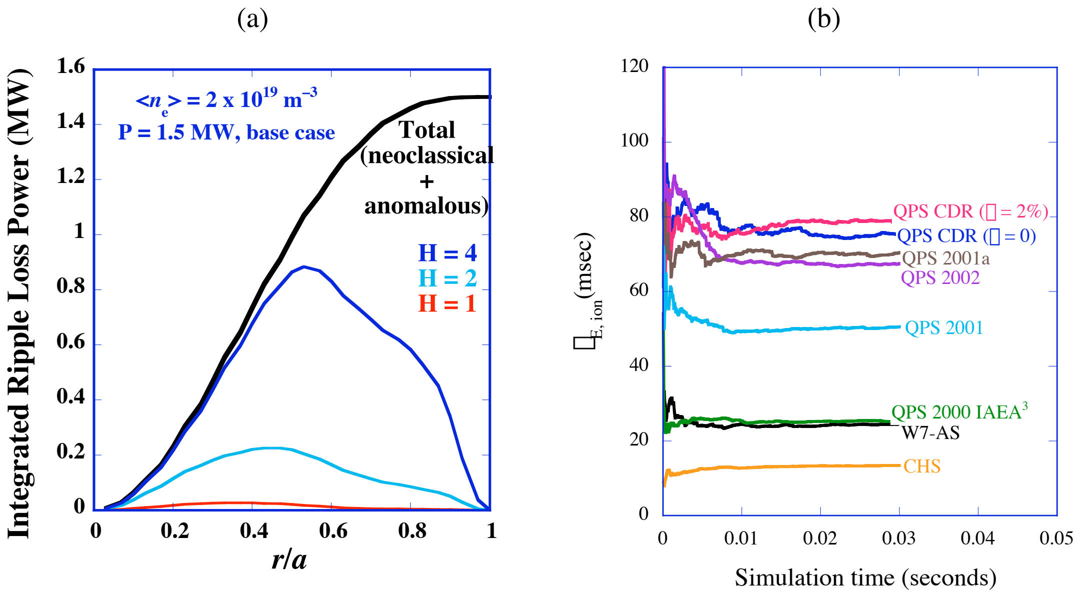

Figure 1 – (a) Integrated power flows vs. radius for 1.5 Mw ECH case, and (b) Monte Carlo ion energy lifetimes of different configurations for the ICH case.

3. Neoclassical Viscosities, Flow Damping

Recent methods developed by Sugama[4] have allowed the calculation of the neoclassical viscosity tensor using the three transport coefficients obtained from the DKES[5] code. 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: □/v ~ 0.01 (relevant to ion flows) to negate the $(B_t/B_p)^2$ enhancement factor. 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). 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.

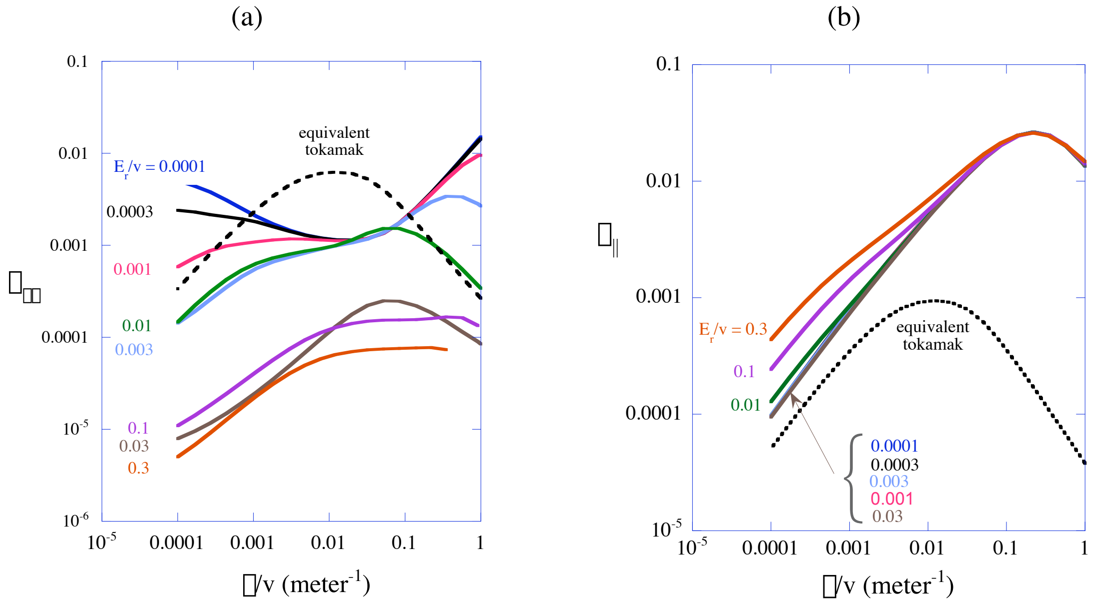

Figure 2 – Monoenergetic (a) poloidal and (b) parallel neoclassical viscosities vs. collisionality and ambipolar electric field for the QPS configuration.

4. QPS Transport Flexibility Studies

Our QPS design includes three magnetic coil systems [modular, vertical, toroidal – see Figure 3(a)] that will have separate power supplies, allowing independent control over coil

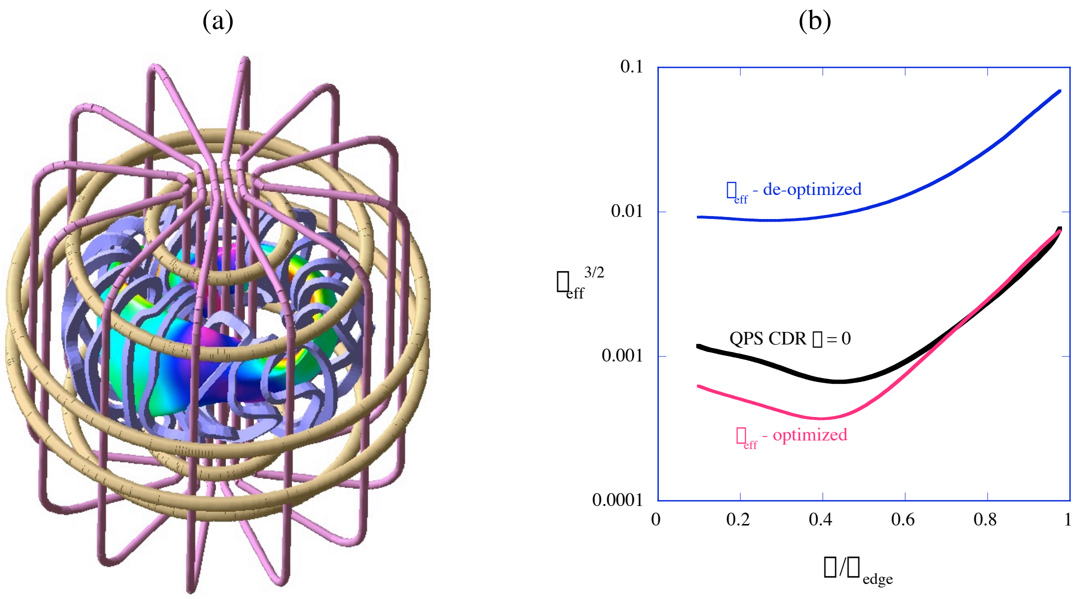

Figure 3 – (a) QPS modular (light blue), vertical (light brown) and toroidal (pink) coil systems, and (b) range of flexibility for the effective ripple[2] coefficient $\epsilon_{eff}^{3/2}$.

current levels. Within the modular coil system, the maximum number of coil currents (five) are varied consistent with the maintenance of stellarator symmetry. This flexibility is expected to offer significant control over the transport and stability properties of the QPS configuration. The control of these coil currents has been analyzed by use of the same STELLOPT optimization algorithm as was used to design QPS. An example of the flexibility available in low collisionality transport is shown in Figure 3(b), indicating that up to a factor of 25 variation is possible in the effective ripple coefficient.[2] Further studies have indicated that factors of 10 variation are possible in the degree of QP-symmetry and in the poloidal viscosity. We have also used coil current control coupled with Ohmically driven plasma currents to both raise iota and lower its shear so as to avoid rational surfaces and the associated magnetic islands.

5. Conclusion

Optimized compact configurations ($R/\langle a \rangle = 2.7$) 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.

Acknowledgement

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