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QPS Transport and Energetic Particle Physics

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Abstract. Quasi-poloidal symmetry is a new approach to stellarator confinement optimization that we have used to design very low plasma aspect ratio configurations (<R>/<a> ~ 2.7, 1/2–1/4 that of existing stellarators). An experiment, the Quasi-Poloidal Stellarator (QPS), is being developed to test the main features of this approach. QPS has <R> = 0.9 m, <a> = 0.33 m, $\langle B_0 \rangle$ = 1 T for a 1-s pulse, and $P_{heating}$ = 1-3 MW. An important criterion for our optimization has been to achieve sufficiently low levels of neoclassical transport so that the dominant losses are from anomalous transport. A number of recently developed/improved tools have been used to evaluate both perpendicular and parallel transport properties in this device. These include: the DKES transport coefficient code, the DELTA5D Monte Carlo model, and several 0-D and 1-D models. We apply these models to the QPS configuration and discuss the neoclassical properties of the various transport regimes it can access.

I. Introduction

In this paper we analyze the transport properties of low aspect ratio devices with quasi-poloidal symmetry. For this form of symmetry, the dominant components of the magnetic field have the poloidal mode number *m* equal to zero. In the limit of exact poloidal symmetry, the canonical poloidal angular momentum P_θ would be conserved and the orbit excursions away from a flux surface would be limited by the gyroradius in the toroidal magnetic field ρ_{tor} rather than the gyroradius in the poloidal magnetic field ρ_{pol} (banana width) as is the case for axisymmetric devices. Since $\rho_{tor} << \rho_{pol}$, this can lead to substantial reductions in neoclassical transport. Another way of viewing this is to consider that of the three possible forms of stellarator symmetry, poloidal symmetry most nearly aligns the direction of $\vec{B}$ and $\vec{\nabla}|B|$, thus minimizing cross field drifts. Further properties of devices with exact poloidal symmetry would be minimal flow damping in the poloidal direction and reduction of the bootstrap current by a factor of ι/N_{fp} where ι is the rotational transform (=1/q) and N_{fp} is the number of field periods. Exact poloidal symmetry can not be achieved in realizable devices and, for this reason, transport analysis of these configurations (taking into account multi-helicity effects) is an important issue.

Our design goal has been to reduce neoclassical transport to levels sufficiently below the expected anomalous transport[1] so that a noticeable transport reduction would be observed if enhanced confinement regimes are accessible.

II. Local Transport Coefficient Evaluations

We have evaluated and compared the neoclassical confinement properties of QPS devices using several theoretical models based on local diffusive transport assumptions. The tools used have been the low collisionality NEO[2] code and the DKES model.[3] In Figure 1 we plot the low collisionality effective ripple coefficient $\varepsilon_{eff}^{3/2}$ obtained from the NEO code and the DKES monoenergetic transport coefficient L_{11} for various QPS and torsatron configurations.

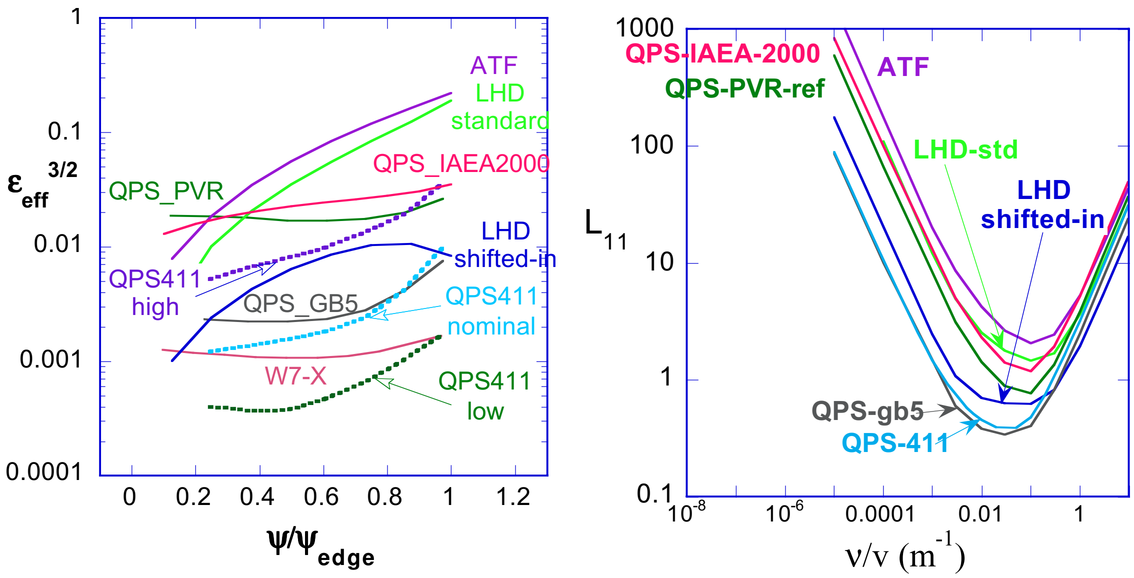

Fig. 1. (a) Low collisionality effective ripple coefficient $\varepsilon_{eff}^{3/2}$ from the NEO[2] code and (b) DKES monoenergetic L_{11} density/temperature diffusion coefficient.

As can be seen, reductions in both $\varepsilon_{eff}^{3/2}$ and L_{11} have been achieved for our recent QPS configuration (QPS411) as compared to some of the earlier devices. Also, the QPS device incorporates a high degree of flexibility by allowing variable current levels in the different coil sets; there are four sets of modular coils that can have different current levels, one set of toroidal field coils, and four sets of vertical field coils that can be independently controlled. We have made further optimizations (both to improve as well as degrade neoclassical transport) keeping a fixed coil geometry and using these 8 coil currents as our independent parameters. The results are indicated in Fig. 1(a) by the

QPS411 high (degraded confinement), QPS411 nominal (design currents), and QPS411 low (improved confinement) curves. As may be seen, this allows a factor of 10 - 25 variation in the low collisionality neoclassical transport in this device.

In Fig. 2(a) we have used both the collisional DKES model and an asymptotic collisionless calculation[4] to obtain bootstrap current levels in the QPS411 device. As might be expected, collisional effects lead to reductions in the predicted levels of bootstrap current.

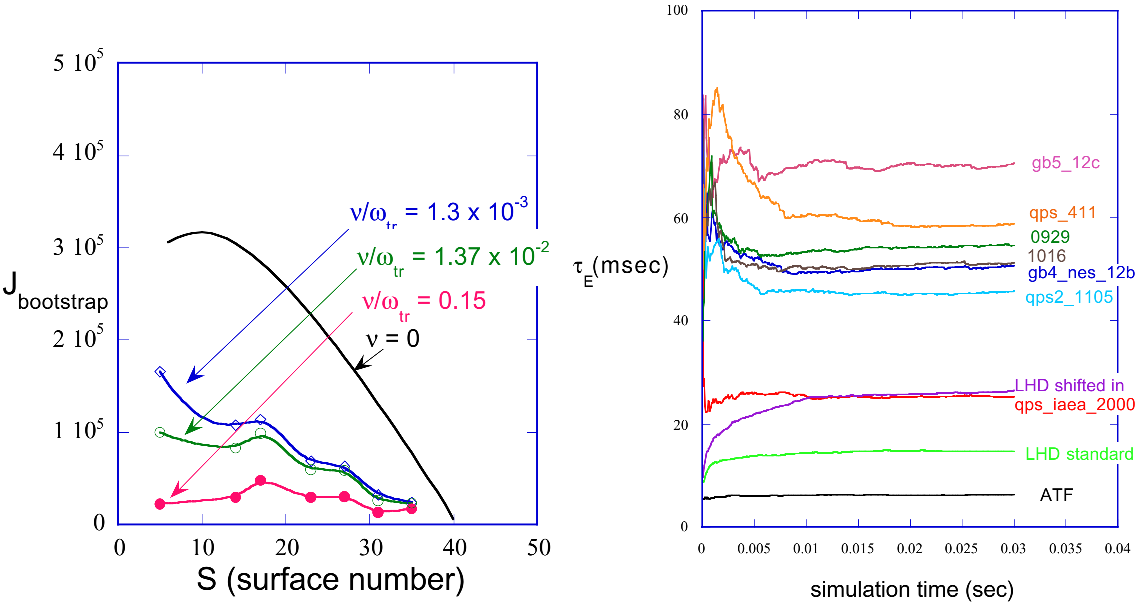

Fig. 2. (a) Energy integrated DKES bootstrap currents (collisional) and collisionless bootstrap levels (s = 40 is the edge), (b) Monte Carlo global ion energy confinement times for ions in ICH heated plasmas.

III. Monte Carlo simulations of QPS devices

Global Monte Carlo calculations based on the DELTA5D code[5] have also been used to compare various QPS configurations. Typically, full-f calculations are carried out and the complete guiding center orbits are followed; thus, both diffusive and direct orbit losses are included. An initial loading of particles is made over the cross-section of the device with the particle distributions determined by the density and temperature profiles. This ensemble of particles is then followed for a sufficient period of time so that the loss rate of particles through the outer surface reaches an approximate equilibrium. As particles leave the outer flux surface, they are re-seeded back into the plasma at random energies and locations consistent with the assumed profiles. In Fig. 2(b) Monte Carlo ion energy confinement times are displayed for a range of configurations based on ICH heated parameters [the ICH regime is $n(0) = 8.3 \times 10^{19}$ m^{-3}, $T_e(0) = 0.5$ keV, and $T_i(0) = 0.5$

keV]; here we have taken the ambipolar electric field to be 0 to more directly compare the effects of the magnetic structure of the different devices. Taking into account both ion and electron losses at expected values of the ambipolar electric field, we have found that neoclassical energy confinement times in the range of 2 – 7 times the ISS95 empirical scalings[1] are possible for QPS devices.

IV. Energetic Particle Physics

We have developed a high resolution code (STELLGAP) that can calculate both the continuum gap structure and discrete Alfvén eigenmodes in compact stellarators. These devices typically have a more fine scale gap structure than large aspect ratio devices and are more dominated by the helical and mirror coupled gaps than by toroidal gaps.

V. Conclusions

Quasi-poloidal symmetry is a new approach to stellarator confinement optimization that has been used to design very low plasma aspect ratio configurations ($\langle R\rangle/\langle a\rangle \sim 2.7$, 1/2–1/4 that of existing stellarators). This form of symmetry offers reduced flow damping of poloidal flows, reduced bootstrap current from the equivalent tokamak, and good neoclassical confinement. We have verified the degree of neoclassical confinement using a variety of analysis tools, including direct measures of the degree of symmetry, the DKES transport coefficient code, the NEO effective ripple code, and Monte Carlo global confinement time calculations. Besides verifying that basic configurations can be designed with adequate confinement, we have also found that they possess flexibility through variations of the vertical and toroidal field coil currents for testing a range of confinement issues.

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[1] U. Stroth, et al., Nuclear Fusion **36**, 1063 (1996).
[2] Nemov, V. V., et al., Phys. Plasmas **6**, 4622 (1999).
[3] W. I. Van Rij, S. P. Hirshman, Phys. Fluids B, **1** (March, 1989).
[4] K.C. Shaing, E.C. Crume, Jr., et al, Phys. Fluids B **1**, 148 (1989).
[5] see Chapter 6, section 6.2.3 of "QPS: A Low-Aspect Ratio Quasi-Poloidal Concept Exploration Experment," issued by Oak Ridge National Laboratory in June, 2001 at http://qps.fed.ornl.gov/pvr/docment.htm.