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Confinement Physics, Equilibrium Robustness, and Flexibility Studies of the Quasi-Poloidal Stellarator (QPS)

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1. Introduction

Quasi-poloidal (QP) symmetry is a stellarator optimization strategy that is compatible with the design of very low-aspect-ratio ($R_0/\langle a \rangle = 2.7$), low-field-period ($N_{fp} = 2$) configurations, such as the QPS device. Approximate poloidal symmetry in magnetic coordinates is achieved by the use of a racetrack-shaped magnetic axis and vertically elongated crescent-shaped cross-sections in the regions of high toroidal curvature. A sufficient degree of symmetry and low effective ripple can be attained so as to make neoclassical losses negligible in comparison to anomalous transport. Quasi-poloidal symmetry leads to plasma flows that are predominantly poloidal with suppressed toroidal components; this characteristic is expected to allow more efficient access to enhanced confinement regimes. The QPS device has also been designed with a high degree of flexibility to enable exploration of a range of physics issues, including neoclassical transport, island suppression, reduced poloidal viscosity, and generation of sheared flows.

2. Neoclassical Viscosities, Flow Damping in Quasi-Poloidal Configurations

Plasma flow generation and damping in stellarators is of significance to enhanced confinement regime access, impurity transport and magnetic island growth. Unlike the tokamak, where there is a strongly preferred direction (toroidal) for plasma flows, stellarators generally possess finite flow components in both toroidal and poloidal directions. The drive mechanisms for stellarator flows also differ from those of tokamaks since an ambipolar electric field is inherently present and will drive flows even in the absence of external momentum sources. We have developed a fluid moments approach based upon a recently developed theory for 3D systems [1]; this provides a self-consistent method to evaluate both parallel and perpendicular neoclassical transport for stellarators of arbitrary magnetic field structure. Typical results of this model for flows in the QPS device are shown in Figs. 1 and 2.

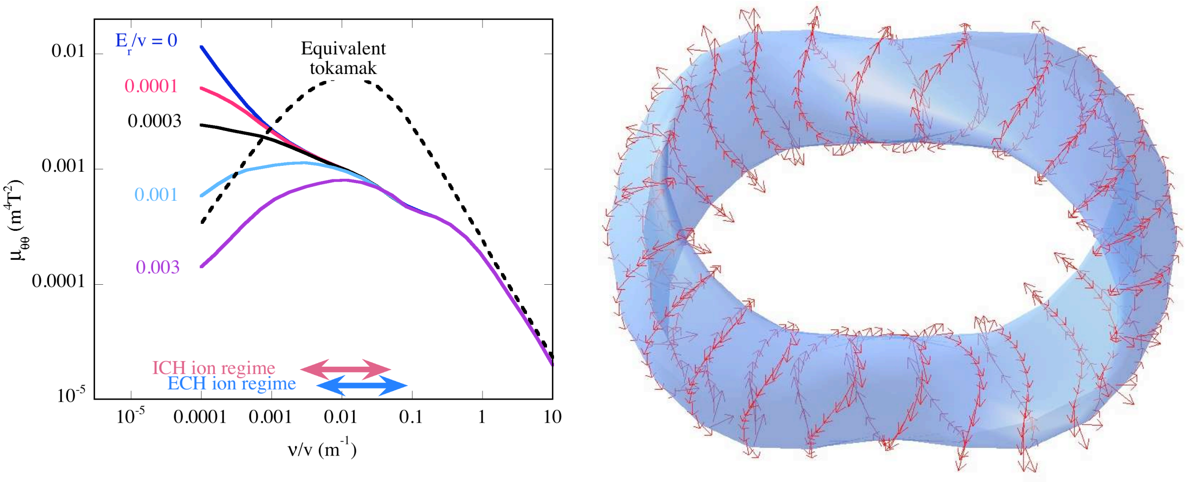

Figure 1 – (a) Poloidal viscosity coefficient at $(\psi/\psi_{edge})^{1/2} = 0.5$ for quasi-poloidal configuration and equivalent tokamak; (b) Flow velocity vectors and magnetic flux surface at $\psi/\psi_{edge} = 0.8$ for QPS ICRF regime parameters.

As indicated in Fig. 1(a), the mono-energetic poloidal viscosity is reduced by a factor of 10 below that of the equivalent tokamak in the experimentally relevant plateau regime [the quantity plotted here is related to the M_{PP} viscosity tensor component of ref. 1 by: $\mu_{\theta\theta} = M_{PP}/(mv_{th}K^{3/2})$, where m = mass, v_{th} = thermal velocity, and $K = (v/v_{th})^2$]. Fig. 1(b) indicates the flow velocity vectors on an internal flux surface based on the results of Figs. 2(a) and 2(b).

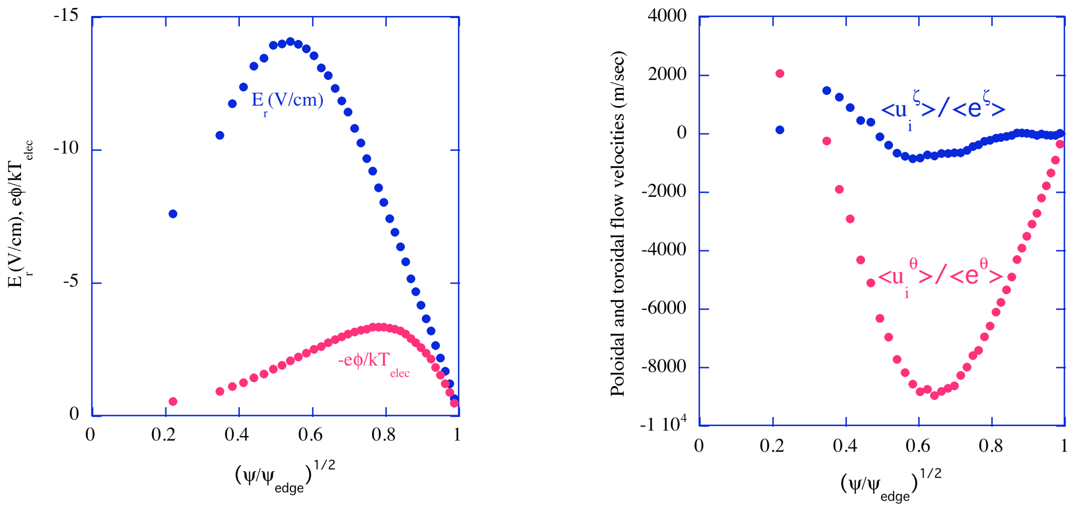

Figure 2 – (a) Ambipolar electric field and potential profiles and (b) poloidal and toroidal flow velocity profiles for QPS ICRF regime parameters.

In Fig. 2 the moments method has been applied to QPS ICRF regime parameters: $n(0) = 8.3 \times 10^{19} m^{-3}$, $T_{ion}(0) = 0.38$ keV, $T_{elec}(0) = 0.53$ keV. In Fig. 2(a) the self-consistent ambipolar electric field and potential profiles are given while in Fig. 2(b) the flux surface averaged contra-variant flow velocity profiles normalized to the associated flux surface averaged contra-variant basis vectors are displayed. This flow velocity partitioning has been obtained by solving the two-species parallel force balance relation. The sheared, poloidally dominated flows plotted in Fig. 2(b) should provide an effective environment for the break-up of turbulent eddies, which are expected to be elongated in the toroidal direction.

3. Flexibility Studies in QPS

The QPS device will have the capability to vary current levels not only in the vertical and toroidal magnet coils, but also in the plasma and each unique modular coil group. In order to search for extremes in the physics properties accessible through the control of these currents, we have used the merged coil-plasma optimizer code STELLOPT. Large changes in low collisionality transport coefficients (factor of ~20), quasi-poloidal symmetry (factor of 10), and poloidal viscosity (factor of 10) have been obtained [2].

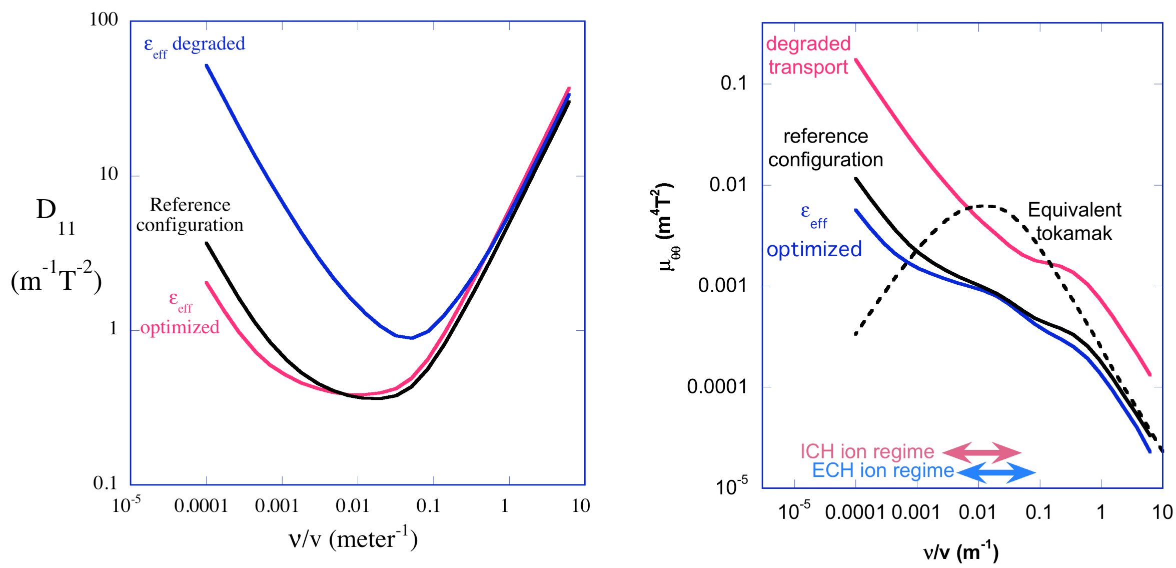

Figure 3 – (a) Monoenergetic transport coefficients vs. collisionality for the reference and transport extremized configurations; (b) Poloidal viscosity coefficient for the reference and transport extremized configurations vs. collisionality. Both plots are for $\psi = 0.25\ \psi_{edge}$.

Figure 3(a) shows the large dynamic range over which the monoenergetic transport coefficient (evaluated for $E_r = 0$) obtained from the DKES code [3] can be varied. Figure 3(b) shows how these same variations in effective ripple influence the viscosity coefficient of Fig. 1(a) for the $E_r = 0$ case. In addition, ballooning stability β thresholds can be lowered into ranges that should be accessible by the experiment. This degree of flexibility should lead to improved exploration of new confinement regimes and exploration of the stability boundaries that may limit performance.

4. Magnetic Island Suppression

Vacuum islands in the QPS device have been minimized by varying the modular coil currents so as to minimize the residues of the dominant island chains [4]. In addition, we have minimized island widths both at vacuum and <β> = 2% by using the more conventional technique of targeting ɨ profiles that avoid nearby low order resonances. This is achieved through varying both the coil currents and the plasma current. An example of island suppression in vacuum is illustrated in Fig. 4 for a case with the ɨ profile remaining between 2/7 and 2/6. Island suppression has been achieved at <β> = 2% by keeping ɨ within either the 2/7 to 2/6 window or the 2/6 to 2/5 window. These techniques should provide adequate vacuum island suppression methods and viable startup-up scenarios for access to finite <β> regimes in the QPS device.

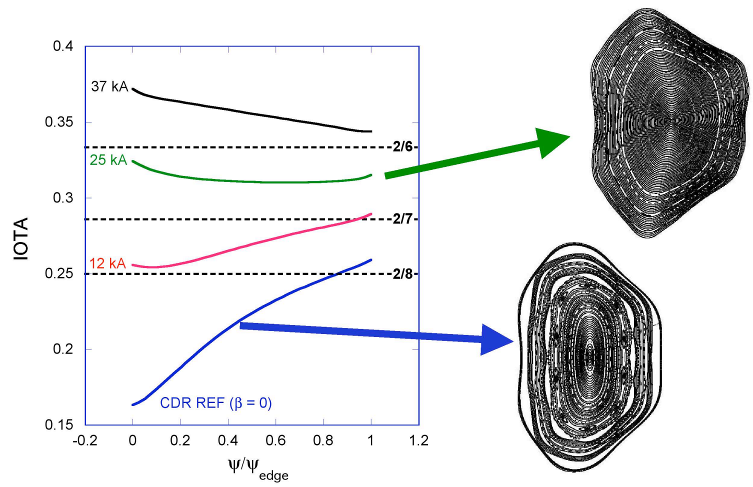

Figure 4 – A range of vacuum ɨ profiles produced by variations in coil and plasma currents (labeled to left of the profiles), illustrating good island suppression at 25 kAmps of plasma current.

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