Energetic Particle Transport and Alfvén Instabilities in Compact Stellarators

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Stellarator design tools have evolved in recent years to allow the development of a number of new compact stellarator configurations (QPS, NCSX) that maintain good plasma neoclassical confinement while improving on various shortfalls of the tokamak (e.g., absence of disruptions, stability to neoclassical tearing instabilities, lowered poloidal flow damping). These improvements have resulted from the development of rapidly evaluated optimization targets for thermal plasma stability and transport. In the case of energetic particle confinement and stability, efficiently evaluated target functions remain to be developed and, as a result, energetic particle physics issues must be evaluated a posteriori. Significant issues include: classical confinement of energetic ions during slowing-down, Alfvén gap modes, interaction of fast ions with plasma MHD modes, and impact of energetic ions on core transport properties (i.e., parallel viscosity, bootstrap current). We have developed tools to address a number of these issues. These include a parallel/vectorized fast particle Monte Carlo code (DELTA5D) and an Alfvén gap stability code (STELLGAP). These codes have been applied both to compact stellarators (QPS, NCSX) and to a variety of existing experiments (CHS, LHD, W7-AS, TJ-II, HSX). This analysis can lead to the development of optimization target functions that can be useful in flexibility studies and in the design of future devices. A moments method analysis has also been developed for analyzing both the E x B shearing rates driven by ambient flows (diamagnetic and E x B) and modifications due to beam momentum sources.

I. Introduction

Low aspect ratio stellarators potentially offer a lower cost development path to fusion, as well as near-term experimental concepts that provide large confined plasma volumes at moderate cost. These devices have been designed in recent years using optimization methods that target a variety of physics and engineering targets. A central theme of these efforts has been the improvement of confinement since traditional (un-optimized) stellarators have unattractively high levels of thermal and energetic particle loss. Confinement improvement has been achieved through measures such as the targeting of lowered effective ripple, alignment of collisionless drift surfaces with magnetic flux surfaces and lowered collisional transport coefficients. This has lead to configurations that are nearly quasi-symmetric; exact quasi-symmetry would provide a conserved canonical momentum invariant in the symmetry direction and zero bounce-averaged deviation of drift surfaces from flux surfaces. Two forms of quasi-symmetry have so far been found to be compatible with low aspect ratio: quasi-poloidal symmetry and quasi-toroidal symmetry. This has resulted in the QPS[1] and NCSX[2] designs, respectively. Configurations have not been found in either case (and may not be possible) that provide exact quasi-symmetry. The more realistic goal has been to lower neoclassical transport to a level where it is negligible in comparison to expected levels of anomalous transport. This can be achieved, but leaves open the question of confinement of the energetic, more collisionless particle populations used for heating. Energetic particle confinement has been analyzed using particle following calculations for these devices and is adequate for the purposes of the proposed experiments. Also, alpha particle confinement in reactor extrapolations of the QPS and NCSX configurations is adequate for power balance and ignition (based on thermal plasma confinement enhancement factors in the range 2 - 3), but may require further optimization to avoid unacceptably high heat loads on the first wall.

In this paper two specific issues related to the confinement of energetic particle and their effects in compact stellarator systems will be analyzed. These are the confinement of fast ions in the presence of instabilities and the impact of fast ion momentum sources on the ambipolar electric field and associated E x B velocity shearing rates.

II. Energetic particle confinement studies

The classical slowing-down and confinement of energetic particle populations in compact stellarator systems has been simulated both for versions of QPS and NCSX scaled to reactor size (R_0 = 10m, B = 5T), as well as for versions scaled to the size of the proposed experimental devices. Here only results for alpha particle slowing-down in a reactor scale QPS device will be discussed. As with thermal plasma transport, the actual levels of confinement will be influenced by fluctuation and turbulence that may be present in the plasma. Energetic particle confinement can especially be degraded by instabilities such as fishbones and Alfvén modes that involve resonant wave-particle interactions.

In order to analyze such effects, we have developed a Monte Carlo code (DELTA5D) that solves the following guiding center equations, which include a perturbed field component[3]:

$$\frac{d\theta}{dt} = \left[\left(\mu + \frac{mv_{\parallel}^2}{B}\right)\frac{\partial B}{\partial \psi} + e\frac{\partial \Phi}{\partial \psi}\right]\frac{\partial \psi}{\partial P_\theta} + eBv_{\parallel}\frac{\partial \rho_{\parallel}}{\partial P_\theta} + ev_{\parallel}B\frac{\partial \alpha}{\partial \psi}\frac{\partial \psi}{\partial P_\theta}$$

$$\frac{d\psi}{dt} = \frac{\dot{P}_\theta g - \dot{P}_\zeta I}{D}$$

$$\frac{d\zeta}{dt} = \left[\left(\mu + \frac{mv_{\parallel}^2}{B}\right)\frac{\partial B}{\partial \psi} + e\frac{\partial \Phi}{\partial \psi}\right]\frac{\partial \psi}{\partial P_\zeta} + eBv_{\parallel}\frac{\partial \rho_{\parallel}}{\partial P_\zeta} + ev_{\parallel}B\frac{\partial \alpha}{\partial \psi}\frac{\partial \psi}{\partial P_\zeta}$$

$$\frac{d\rho_{\parallel}}{dt} = \frac{\iota\!\!\!- - \left(\rho_{\parallel} + \alpha\right)g'}{D}\dot{P}_\theta + \frac{\left(\rho_{\parallel} + \alpha\right)I'}{D}\dot{P}_\zeta + \frac{d\alpha}{dt}$$

These are solved in the presence of collisions, modeled using a Langevin[4] stochastic collision term. This is based on a collision operator that includes pitch angle and energy scattering, using the velocity-dependent potential coefficients. For the current calculations, Boozer magnetic coordinates (ψ, θ, ζ) are used.[5] The following form for the perturbed field function, α, is used:

$$\delta\vec{B} = \vec{\nabla} \times \left(\alpha \vec{B}\right) \qquad \alpha = \sum \alpha_{0mn}\left(n - im\right)\, e^{-(\psi-\psi_{mn})^2/\Delta_{mn}^2} e^{-i\left(\omega_r t + n\zeta - m\theta\right)}$$

A study has been made of the effect of several different forms of perturbed field. These include: (1) a collection of single mode number pairs with tearing parity displacement functions localized about their associated rational surfaces (referred to here as resonant MHD – characteristic of resistive tearing or ballooning modes), and (2) a dominant mode pair with coupled sidebands in which toroidal (TAE), mirror (MAE), and helical (HAE) couplings have been considered. Results for losses of slowing-down alpha particles in a reactor-sized QPS device are shown in Figure 1(a). This is based on an equilibrium at $\langle\beta\rangle$ = 6%; the rotational transform profile had relatively weak shear, varying from 0.44 at the magnetic axis to 0.48 at the edge as shown in Figure 1(b).

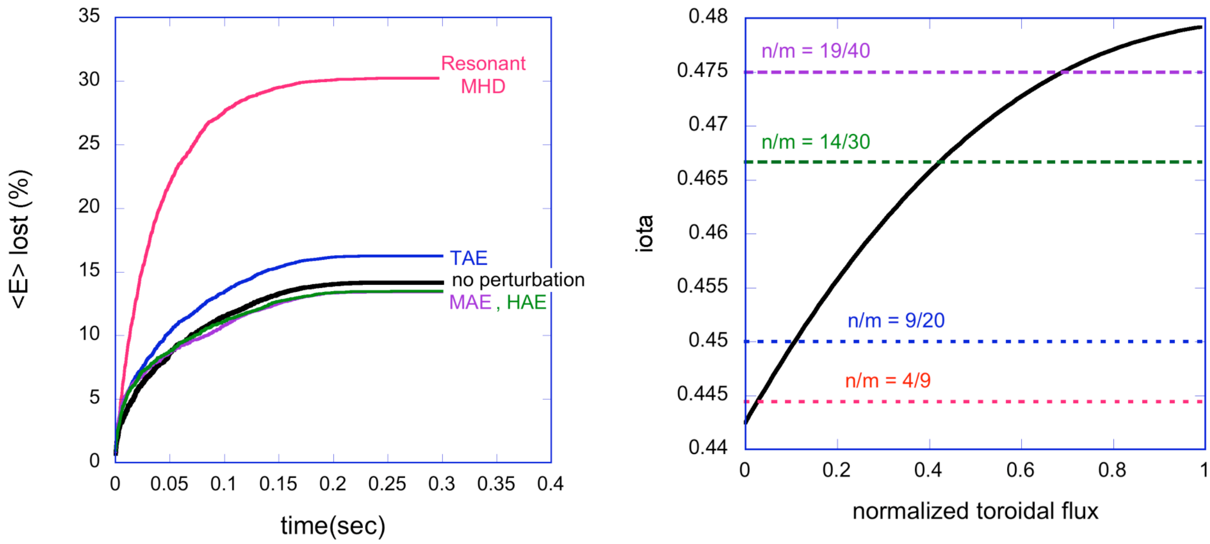

Figure 1 – (a) Alpha particle losses vs. time for various perturbed field models in a QPS configuration, (b) rotational transform profile with resonant surfaces indicated.

In this case, the resonant MHD perturbation included equal size terms for n/m = 9/20, 14/30, and 19/40. The TAE/MAE/HAE perturbations included a central n/m = 14/30 mode with coupled sidebands at n/m = 14/29, 14/31 (TAE), n/m = 15/30, 13/30 (MAE), and n/m = 15/31, 15/29 (HAE). For the AE cases, the sideband amplitudes were 0.4 times that of the central mode. In all cases a fixed frequency of $\omega_{real} = 10^6$ sec^{-1} was assumed. Fig. 1(b) indicates the location of the various rational surfaces in the rotational transform profile. As Fig. 1(a) shows, the resonant MHD perturbation model lead to the largest enhancement of losses. This is likely due to the fact that all three modes had the same amplitude and their resonant surfaces covered a range of radii in the plasma. The TAE perturbed field model resulted in increased losses while the MAE and HAE models actually decreased losses slightly. This effect of the MAE/HAE models is possibly due the instability causing an increased effective collisionality for the slowing-down alphas. Since the alphas are deeply in the $1/\nu$ transport regime, increased collisionality can improve their confinement. This effect has recently been proposed and analyzed for thermal stellarator plasmas[6] in the presence of electrostatic fluctuations.

III. Ambient and beam-driven E x B velocity shear

Plasma flow velocity characteristics are of importance in understanding and controlling the performance of toroidal plasmas for a number of reasons. First, there is much evidence both from simulations and experimental measurements that sheared flows can suppress turbulence and lead to enhanced confinement regimes. Next, it is expected that plasma flows can influence the formation and growth of magnetic islands.[7] Finally, plasma flow characteristics are closely coupled to understanding impurity transport in toroidal devices. Stellarators offer a range of different preferred plasma flow damping characteristics, depending on what form of quasi-symmetry they have.[8] Also, energetic particle populations, such as neutral beams and RF heating that act as momentum sources for the thermal plasma, will influence the ambipolar electric field and thus the plasma sheared flow properties.

In order to quantitatively analyze such effects in compact stellarators, a computational model has been developed,[9] based on a moments method analysis for stellarators.[10] This model calculates the plasma viscous stress tensor, and then uses the parallel momentum balance coupled with the ambipolar condition to solve for the self-consistent plasma flows and electric field. From this, flux surface average E x B velocity shearing rates can be calculated as shown in Figure 2.

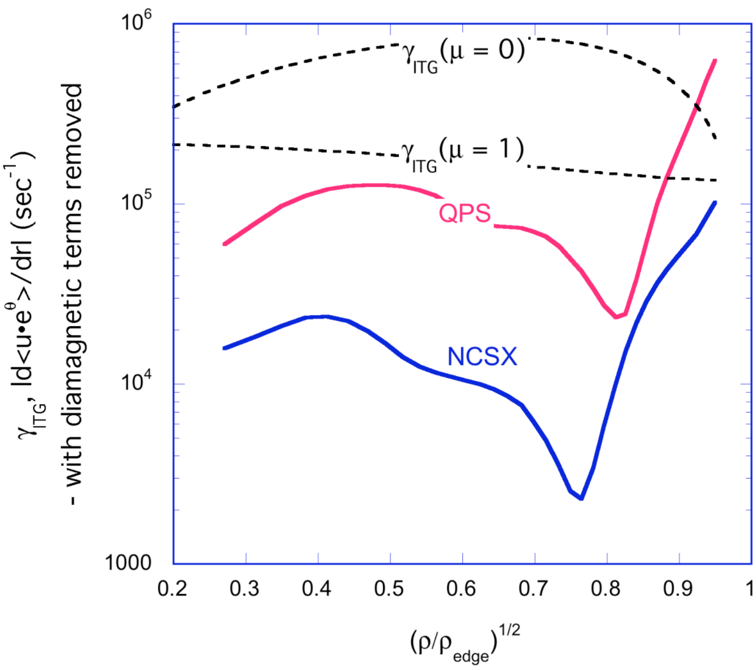

Figure 2 – Ambient E x B velocity shearing rates and ITG growth rate estimates vs. flux surface location.

These calculations are based on central temperatures and densities of $T_{ion}(0)$ = 0.3 keV, $T_{electron}(0)$ = 0.5 keV and n(0) = 8 x 10^{19} m^{-3}. As can be seen, QPS has the largest shearing rates due to its lowered level of poloidal viscosity and the stronger variation of its E x B velocity within flux surfaces (a consequence of its lower aspect ratio = 2.7). These shearing rates are compared with tokamak based estimates of ITG mode growth rates,[11] indicating that shearing rates can exceed growth rates near the plasma edge regions. More recent ITG/DTEM linear stability analysis,[12] based on fully 3D stellarator equlibria, for these two devices has indicated growth rates in the range of 0.2 to 1.6 x 10^5 sec^{-1}. The above shearing rates would easily exceed these growth rates for either device.

These shearing rates are based on the electric fields and flows that result from what are termed ambient conditions, i.e., only the diamagnetic drifts and electric fields resulting from neoclassical transport are taken into account. When momentum sources, such as neutral beams are included in the parallel force balance, these will perturb the ambipolar condition and can lead to either smaller or larger electric fields and E x B shearing rates. A beam induced momentum source has been introduced into this analysis, leading to the electric field variations shown in Figure 3(a) and 3(b).

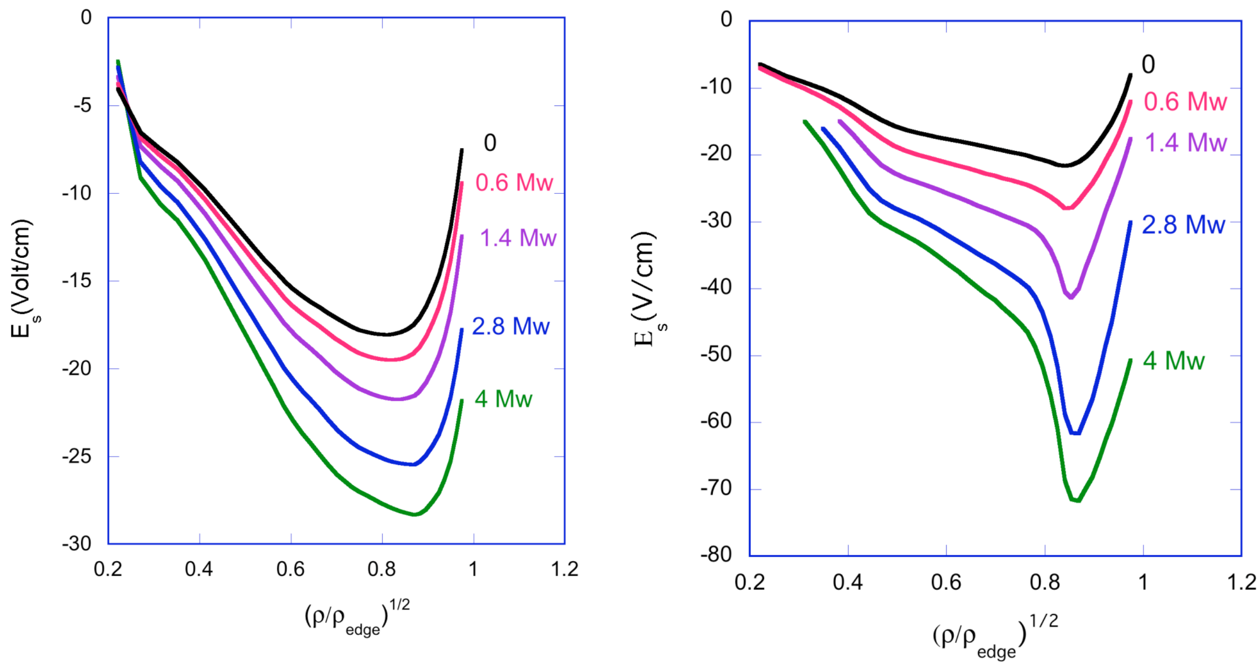

Figure 3 – Impact of a beam momentum source on the radial electric field levels in (a) QPS and (b) NCSX configurations.

In these calculations, various levels of momentum source were introduced into the ion and electron parallel force balance relations. The power levels indicated on Figure 3 are obtained by assuming that these momentum values come from a 40keV beam component injected parallel to field lines. As can be seen, the electric fields and thus E x B shearing rates in NCSX are more sensitive to the beam momentum source than for QPS. This is a consequence of the different magnetic symmetries. It would be expected that different beam injection angles than parallel may result in stronger sensitivities for the electric fields in QPS and devices with other forms of non-toroidal symmetry.

IV. Conclusions

Compact stellarators will provide a variety of energetic particle physics issues that differ from those of tokamaks. Two have been analyzed here: the effect of fluctuations on energetic particle confinement and the influence of beam momentum sources on electric field generation. In the case of particle confinement, a regime has been identified where fluctuations seem to slightly lower loss rates. In the case of beam induced changes in the electric field, the variation of this effect with different magnetic symmetries (quasi-poloidal and quasi-toroidal) has been studied. Besides these two areas, there are many other energetic particle issues such as Alfvén instabilities, fishbones, etc. that will need to be addressed in greater depth in the future for compact stellarator systems.

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