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Bernstein mode current drive in spherical tokamaks

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Electron Bernstein wave heating and current drive in spherical tokamaks is being explored because the high density, low magnetic field configuration of these machines makes the plasma inaccessible to the O and X modes used in standard tokamaks, a problem that Bernstein modes, capable of propagating at arbitrarily high densities, do not suffer from. It has been shown previously that Bernstein modes are very strongly absorbed in the vicinity of cyclotron resonances, the wave generally being almost completely absorbed on the wings of the cyclotron resonance [1,2].

In our earlier work we have presented some estimates of current drive efficiency of electron Bernstein waves, based on the relativistic formalism of Fisch [3,4]. These suggest that current drive efficiency in a spherical tokamak might be somewhat greater than the values typical of electron cyclotron current drives by O or X modes in a standard tokamak. This is because strong absorption near the edge of the resonant region means that waves are absorbed on particles with high velocity which are more effective for current drive.

This type of simple estimate does not take account of particle trapping which, of course, can have a strong effect on current drive efficiency in a toroidal machine. We have suggested previously that trapping effects might not be so important for Bernstein mode current drive as for O and X mode current drive because absorption near the edge of the resonance takes place on particles with high parallel velocity. The Bernstein modes typically possess high perpendicular wave numbers which may also reduce trapping. This comes about because the quasilinear diffusion coefficient contains Bessel functions, coming from the gyro-orbit in the same way as in the wave dispersion relation, and in the small Larmor radius limit we use the approximation $J_n\left(\frac{k_\perp v_\perp}{\omega_c}\right) \approx \frac{1}{n!}\left(\frac{k_\perp v_\perp}{2\omega_c}\right)^n$. If, however, the argument of the Bessel functions is not small, because of the high $k_\perp$ typical of Bernstein modes, the diffusion coefficient increases less rapidly with $v_\perp$ than in the small Larmor radius approximation and there is proportionately less emphasis on the high $v_\perp$ particles, which are more affected by trapping.

Nevertheless, trapping is still likely to be important and in this paper we look at current drive efficiency with toroidal plasma effects taken into account, employing both an analytic formulation and numerical solutions of the Fokker-Planck equation using the BANDIT code which has been developed at Culham.[5]

For the analytic formulation we adapt the theory of Lin-Liu et al [6] who use a Green's function technique to calculate electron cyclotron current drive efficiency in general tokamak geometry in the low collisionality regime. A more general diffusion operator is used than in Lin-Liu et al's paper, which was concerned with O and X modes, putting in the full expression without the small Larmor radius expansion of the Bessel functions. We have written a computer code to evaluate the Lin-Liu et al current drive efficiency with the full Kennel-Engelmann quasilinear diffusion operator [7]. The Lin-Liu et al formalism involves flux surface averages and for the moment we have simply used a simple model circular equilibrium to obtain preliminary results. However, the eventual aim is to apply the method to realistic equilibria of machines such as MAST, where the minor cross section is very far from circular. For this purpose we are developing a numerical scheme to take data on equilibrium magnetic fields, specified on a grid, and from these reconstruct the flux surfaces and calculate flux surface averages.

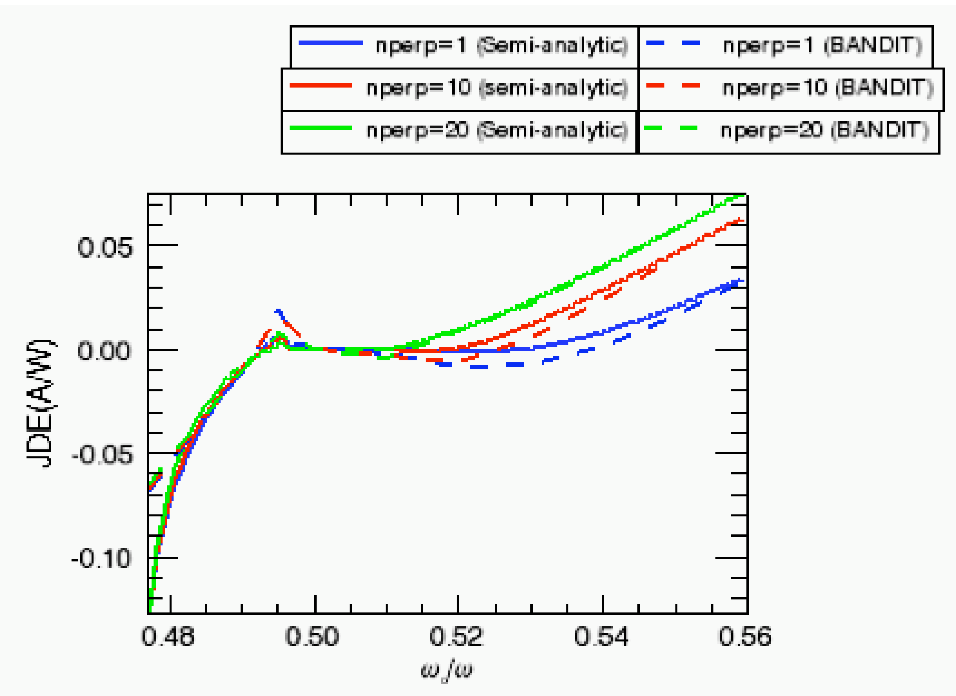

Fig. 1: Comparison of BANDIT and analytic results

In Fig. 1 we show the value of the total current driven per unit power absorbed as a function of ω_c / ω in the vicinity of the second harmonic. Following Lin-liu at al we take a simple circular model equilibrium with inverse aspect ratio 0.2, electron density $n_e = 2 \times 10^{19}$ m^{-3}, electron temperature T_e =2keV, major radius R=1.76 m and effective charge Z_{eff} =1.6. We drive the current at a poloidal angle of 90^O and take refractive indices $n_{\parallel}$ =0.3 and $n_{\perp}$=1,10,20. The corresponding graph given in Lin-Liu et al is restricted to a much smaller range near the harmonic, but in the region of overlap our analytic results for $n_{\perp}$=1 agree with their small Larmor radius results. In the same plot we show results from the BANDIT Fokker-Planck code for the same parameters.

The effect of increasing $n_{\perp}$ on the low field side of the resonance is negligible, but current drive efficiency on the high field side is enhanced. Resonant particles on the high field side have a greater probability of possessing high perpendicular momentum, because of the nature of the relativistic resonance condition, so the effect mentioned above seems a possible cause for the difference. However, we have yet to investigate this in detail.

Comparing the semi-analytic results with BANDIT, it can be seen that the results diverge in two regions. The first is far from the resonance on the low field side. This is a region in which the resonant particles are at very high velocity and there are few of them. Although the current to power ratio becomes high here, there is very little absorption and the current and power are individually very small. For this reason it is not surprising that there are discrepancies and in practical terms the results in this region are of no importance. The other region where the results diverge is close to the resonance. This is a regime in which the resonant particles are mostly at low velocities and a substantial fraction of them are either trapped or close to the trapping boundary. Why the analytical and numerical results do not agree well in this region is something which we intend to investigate further. However, this is a region in which current drive is relatively ineffective and any part of the wave energy absorbed in this region will not contribute very significantly to the total current. This leaves us with a region in which there is satisfactory agreement between the analytical and numerical results. Since this region is the one in which there is both significant energy absorption and effective current drive, we may conclude that when power absorption and current drive are integrated over the wave absorption profile there will be satisfactory agreement between the analytic and numerical results.

To summarise, our intention is to apply the method of Lin-Liu et al to the problem of Bernstein wave current drive. The motivation of such an approach is, of course, that the computation involved is much less than that needed to solve the Fokker-Planck equation, so this type of calculation is ideal for coupling to ray-tracing and absorption codes. The main requirement is to include a quasilinear diffusion coefficient which is not the lowest order expansion in the ratio of Larmor radius to perpendicular wavelength. Small perpendicular wavelengths are typical of Bernstein modes, so the full form of the quasilinear term must be used. Also, numerical flux surface averaging in a non-circular cross section is needed for application to MAST and other spherical tokamaks. This is also under development.

Here we have presented some preliminary results, to verify that our code agrees with that of Lin-Liu et al in the small Larmor radius regime. We have also compared the results in this regime with Fokker-Planck solutions. While there are some discrepancies, which we will investigate further, the analytic and numerical results appear to be in reasonable agreement in those parts of the absorption profile in which there is both significant energy absorption and largest current. It seems, therefore, that this approach could be a useful tool in the analysis of Bernstein wave current drive, giving a computationally simple and reasonably accurate prediction of current drive efficiency.

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