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VARIATIONAL FULL WAVE CALCULATION OF FAST WAVE CURRENT DRIVE IN DIII-D USING THE ALCYON CODE

by
A. BECOULET and D. MOREAU

Prepared under
Contract No. DE-AC03-89ER51114
for the U.S. Department of Energy

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GENERAL ATOMICS

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ABSTRACT

Initial fast wave current drive simulations performed with the ALCYON* code for the 60 MHz DIII-D experiment are presented. Two typical shots of the 1991 summer campaign were selected with magnetic field intensities of 1 and 2 teslas respectively. The results for the wave electromagnetic fields in the plasma chamber are displayed. They exhibit a strong enrichment of the poloidal mode number m -spectrum which leads to the upshift of the parallel wavenumber, $k_{\parallel}$, and to the wave absorption. The m -spectrum is bounded when the local poloidal wavenumber reaches the Alfvén wavenumber and the $k_{\parallel}$ upshifts do not destroy the wave directionality. Linear estimations of the driven current are made. The current density profiles are found to be peaked and we find that about 88 kA can be driven in the 1 tesla/1.7 keV case with 1.7 MW coupled to the electrons. In the 2 tesla/3.4 keV case, 47 kA are driven with a total power of 1.5 MW, 44% of which are absorbed on the hydrogen minority, through the second harmonic ion cyclotron resonance. The global efficiency is then $0.18 \times 10^{19} \text{ A m}^{-2} \text{ W}^{-1}$ if one considers only the effective power going to the electrons.

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1. INTRODUCTION

In this report, we describe the main features of the ALCYON 2D-Full Wave code, and its application to the modeling of the first fast wave current drive experiments in DIII-D.

ALCYON contains the basic physics for the propagation and absorption of the fast magnetosonic wave in a toroidal axisymmetric geometry, starting from a consistent magnetohydrodynamic (MHD) tokamak equilibrium. The wave fields are Fourier analyzed along the toroidal and poloidal directions, the axisymmetry allowing a separate treatment for each toroidal harmonic number. The code is based on a variational formulation of the Maxwell-Vlasov equations, and on a full Hamiltonian description of the wave-particle interactions [1,2]. The functional form contains the physics related to the first and second harmonic ion cyclotron effects and the electron Landau and damping (ELD) and transit time magnetic pumping (TTMP).

Satellite programs have been developed, which post-process the rf fields computed by ALCYON. They allow :

1. To display the various components of the rf field.
2. To compute the complete local quasilinear diffusion operator in velocity space, on each flux surface. This operator can then be used in a Fokker-Planck code to evaluate the perturbed distribution function. A comparison of the diffusion coefficient with the collisional drag validates the linear approximation (small perturbation of the Maxwellian distribution function), at least in the phase space domain where the electron-wave interaction is governed by ELD ($v_{\perp} \leq v_{the}$).
3. To estimate the wave driven current in this linear approximation, as well as the power deposition and current density profiles, and to derive a global current drive efficiency.

The work which is reported here consists of a quantitative simulation of two DIII-D typical shots (#72715 & #73071), which essentially differ by their toroidal

magnetic field and temperature. For each of these cases, the computation of the required MHD equilibrium has been made using data from the DIII-D/EFIT code output. Then ALCYON has been run for all relevant toroidal mode numbers, giving on each flux surface the Fourier amplitudes of each field component (parallel magnetic field, perpendicular vector potential and scalar potential). Finally these data have been processed through the above-mentioned programs in order to evaluate the current drive effect in DIII-D.

In the following section we shall detail the plasma equilibria used in our study. Then, in Section 3, the ALCYON results concerning the wave propagation/absorption and the field structure will be described and discussed with respect to the single pass absorption parameter. Section 4 deals with the wavenumber spectrum of the absorbed power on a given flux surface and shows the modification of the launched spectrum and of its directivity as the wave propagates into the plasma. Section 5 is devoted to the estimation of the driven current and of the fast wave current drive (FWCD) efficiency and it is followed by a short conclusion.

2. MHD EQUILIBRIUM

Before running ALCYON one must compute the MHD plasma equilibrium. Up to now, this is done by a separate code (SCED), which solves the Grad-Shafranov equation inside a boundary flux surface described by the following parameters:

1. Inner ($R_{\min}$) and outer ($R_{\max}$) major radii;
2. Elongation $\kappa = (Z_{\max} - Z_0)/a$
3. Triangularity $\gamma = \text{Arcsin}[R_0 - R(Z_{\max})]/a$, where $R_0 = (R_{\min} + R_{\max})/2$, and $a = (R_{\max} - R_{\min})/2$.

This boundary flux surface is assumed to be symmetric with respect to its equatorial plane $Z = Z_0$, and is supposed to be a closed magnetic surface.

The plasma boundary is given by the major radius of a limiter in the equatorial plane, on the low field side (R_{dph}). The vacuum toroidal magnetic field B_{toro} must be provided at a given major radius R_{zero} . The total plasma current I_p is also required.

The flux functions, p' and ff' , in the Grad-Shafranov equation, are assumed to be proportional to $(1 - \bar{\Psi}^\alpha)^\eta$, where $\bar{\Psi} = (\Psi - \Psi_{\text{axis}})/(\Psi_{\text{edge}} - \Psi_{\text{axis}})$ is the normalized flux. The poloidal beta is also requested.

2.1. THE 1 TESLA CASE (#72715)

The following parameters have been chosen after running the DIII-D/EFIT code, at the time 3.550 s:

$$R_{\min} = 1.045 \text{ m}$$

$$R_{\max} = 2.36 \text{ m}$$

$$\kappa = 1.93$$

$$\gamma = 0.988$$

$$Z_0 = 0$$

$$R_{\text{dph}} = 2.347 \text{ m}$$

$$B_t = -1.012 \text{ T}$$

$$R_{\text{zero}} = 1.6955 \text{ m}$$

$$I_p = 500 \text{ kA}$$

$$\alpha = 0.94$$

$$q = 1.45$$

$$\beta_p = 0.38$$

giving the following values:

$$\langle \beta_t \rangle = 0.57\%$$

$$\ell_i = 1.21$$

$$R_{\text{axis}} = 1.76 \text{ m}$$

$$q(0) = 0.94$$

$$p(0) = 13 \text{ kPa}$$

$$j(0) = 970 \text{ kA/m}^2.$$

The q -profile is shown in Fig. 1. The plasma shape and mesh are displayed in Fig. 2.

The other plasma parameters and profiles have been chosen from fitting the experimental data obtained from the DIII-D/ENERGY code and using the approximation $r/a \approx \sqrt{\bar{\Psi}}$. They are the following:

$$n_e = [(2.33 \times 10^{19}) - (5.8 \times 10^{18})] \times (1 - \bar{\Psi}^1)^{2.2} + 5.8 \times 10^{18} \text{ m}^{-3}$$

$$T_e = 1.677 \times (1 - \bar{\Psi}^1)^{4.6} \text{ keV}$$

$$n_H = 0.025 n_e$$

$$n_D = 0.975 n_e$$

$$T_H = T_D = 0.73 \times (1 - \bar{\Psi}^{0.5})^1 \text{ keV}$$

Fig. 1. Profile of safety factor q for the $B_t = 1$ tesla case.

Fig. 2. Plasma shape and mesh for $B_t = 1$ tesla case.

2.2. THE 2 TESLA CASE (#73071)

The following parameters have been chosen after running the DIII-D/EFIT code, at the time 2.700 s:

$$R_{\min} = 1.06 \text{ m}$$

$$R_{\max} = 2.36 \text{ m}$$

$$\kappa = 1.90$$

$$\gamma = 0.563$$

$$Z_0 = 0$$

$$R_{\text{dph}} = 2.345 \text{ m}$$

$$B_t = 2.03 \text{ T}$$

$$R_{\text{zero}} = 1.6955 \text{ m}$$

$$I_p = 796 \text{ kA}$$

$$\alpha = 0.96$$

$$q = 1.71$$

$$\beta_p = 0.3965$$

giving the following values:

$$\langle \beta_t \rangle = 0.37\%$$

$$\ell_i = 1.33$$

$$R_{\text{axis}} = 1.78 \text{ m}$$

$$q(0) = 1.0$$

$$p(0) = 39 \text{ kPa}$$

$$j(0) = 1800 \text{ kA/m}^2.$$

The q -profile is shown in Fig. 3. The plasma shape and mesh are displayed in Fig. 4.

Fig. 3. Profile of safety factor q for the $B_t = 2$ tesla case.

Fig. 4. Plasma shape and mesh for $B_t = 2$ tesla case.

The other plasma parameters and profiles have been chosen from fitting the experimental data obtained from the DIII-D/ENERGY code and using the approximation $r/a \approx \sqrt{\bar{\Psi}}$. They are the following:

$$n_e = [(3.5 \times 10^{19}) - (6.0 \times 10^{18})] \times (1 - \bar{\Psi}^{0.9})^{1.5} + 6.0 \times 10^{18} \text{ m}^{-3}$$

$$T_e = 3.4 \times (1 - \bar{\Psi}^{0.8})^{2.2} \text{ keV}$$

$$n_H = 0.025 n_e$$

$$n_D = 0.975 n_e$$

$$T_H = T_D = 1.0 \times (1 - \bar{\Psi}^{0.5})^1 \text{ keV}$$

3. FAST WAVE FIELD COMPUTATION AND RESULTS FOR DIII-D

The 60 MHz wave is launched from an antenna situated at $R = R_{\text{ant}}$, in the vacuum region between the plasma boundary (R_{dph}) and the last (perfectly conducting) flux surface used in the calculation (R_{max}). We have taken $R_{\text{ant}} = (R_{\text{dph}} + R_{\text{max}})/2$ and the antenna poloidal extension is ± 0.35 radian. The antenna is fed in a poloidal monopole mode and the toroidal mode number spectrum of the antenna current is created by four equal currents in the four current straps (Fig. 5).

Fig. 5. Spectrum of $n_{||}$ obtained for equal currents in all antenna straps, with $\pi/2$ phasing between straps.

Each ALCYON run is performed for a single toroidal mode number N and we have varied $|N|$ between 3 and 35. The corresponding parallel wavenumbers at the antenna vary from $n_{\parallel} = 1$ ($k_{\parallel} = 1.25 \text{ m}^{-1}$) to $n_{\parallel} = 12$ ($k_{\parallel} = 15 \text{ m}^{-1}$). In all these runs the antenna current is taken to be the same (1000 A). The deposited toroidal power spectrum is then the convolution between the absorbed power resulting from these runs and the real current spectrum in the antenna [Fig. 6(a) for the 1 T case and Fig. 6(b) for the 2 T case]. Eighty-one poloidal mode numbers m between -40 and $+40$ are used for the description of the fields. Thus, on each of the 75 flux surfaces, the field is described by more than 5000 Fourier components each giving rise to a wave-particle resonance.

3.1. THE 1 TESLA/1.7 keV CASE (#72715)

Figures 7 (2-D contours) and 8 (equatorial section) display the modulus of the wave magnetic field in a poloidal cross-section for $N = 17$. Because of the very weak electron damping the wave tends to build up cavity modes through multiple passes, while developing large poloidal m components. As a result, the wave pattern is rather complicated and does not exhibit any ray structure.

The Fourier m -spectrum ($N = 17$) of the wave magnetic field modulus is shown in Fig. 9 for a central flux surface. In Fig. 10, level curves in the $(r/a \approx \sqrt{\Psi}, m)$ space show the extension of this spectrum as a function of plasma radius. Quite interestingly, the extension of the m -spectrum decreases towards the plasma center, in agreement with an upper bound obtained where the equivalent poloidal wavenumber (m/r) is of the order of the Alfvén wavenumber, ω/c_A .

Wave structures which have a wavelength much shorter than the Alfvén wavelength are due either to some hot plasma wave (in which case they cannot be resolved on the ALCYON mesh size) or simply to the finite mesh itself. In any case the power going into these short wavelength modes is generally small (except if there is a mode conversion layer in the plasma) and they can be filtered out *a posteriori*, or damped *a*

Fig. 6. Power absorbed in the plasma as a function of toroidal mode number, for the (a) $B_t = 1$ tesla case and (b) $B_t = 2$ tesla case, and 1 kA in each antenna strap.

Fig. 7. Contours of $|B_{rf}|$ for the 1 tesla case.

Fig. 8. $|B_{rf}|$ versus major radius for $B_T = 1$ tesla case.

Fig. 9. $|B_{rf}|$ versus poloidal mode number for toroidal mode $N = 17$, for the $B_t = 1$ tesla case.

Fig. 10. Contours of amplitude of power in poloidal mode numbers between 40 and -40, as a function of minor radius, for $N = 17$ and $B_t = 1$ tesla.

priori through an artificial damping term in the variational form. Figures 11 and 12 are the same as Figs. 7 and 10 after filtering out the small wavelength components.

A simple slab calculation based on a single pass through the plasma at constant $n_{\parallel}$, and using the damping decrement given in Ref. [4], yields a power absorption coefficient of the order of 0.07% for $N = 11$, and it reaches only 4.6% for $N = 20$. Even though the damping length scales as the cubic power of the inverse toroidal field, the temperature is too small and therefore the fast wave experiences poor damping, and thus strong poloidal enrichment.

3.2. THE 2 TESLA/3.4 keV CASE (#73071)

In this case, the single pass electron absorption coefficient just mentioned varies between 0.7% ($N = 11$) and 32% ($N = 20$).

However, the second harmonic cyclotron resonance of the hydrogen lies in the center of the plasma. Consistently with the experiments, we have assumed a 2.5% minority hydrogen population in a deuterium plasma. As a result, the electron absorption is dominant for large N , about equal to the hydrogen absorption for $N = 18$ where most of the power is launched, and then smaller than the hydrogen absorption for $N < 18$ (Fig. 13).

The wave field for this case is displayed in Fig. 14 ($N = 20$) and the power deposition profile in Fig. 15. The multi-pass character of the propagation is still clear on Fig. 14.

3.3. SINGLE-PASS DAMPING

In order to simulate the propagation in a single pass absorption situation, we have run the 2 tesla case while artificially increasing the absorption. This is done either by choosing the central electron temperature and density to be 5 keV and $5 \times 10^{19} \text{ m}^{-3}$ respectively (Fig. 16), or simply by adding an artificial damping term

Fig. 11. Contours of $|B_{rf}|$ for the 1 tesla case with the components with short wavelength removed.

Fig. 12. Contours of amplitude of power in poloidal mode numbers between 40 and -40, as a function of minor radius, for $N = 17$ and $B_t = 1$ tesla, with the components with short wavelength removed.

Fig. 13. For the $B_t = 2$ tesla case, the power absorbed by electrons through ELD and TTMP (solid line) and the power absorbed by the hydrogen minority ions (dashed line) as a function of toroidal mode number.

Fig. 14. Contours of $|B_{rf}|$ in a poloidal cross section for the 2 tesla case.

Fig. 15. Power deposition as a function of minor radius for the 2 tesla case.

Fig. 16. Contours of $|B_{rf}|$ for the 2 tesla case, but with $\bar{n}_e = 5 \times 10^{19} \text{ m}^{-3}$ and $T_e = 5 \text{ keV}$ to enhance the damping.

(anti-hermitian) to the ALCYON variational form (Fig. 17). The ray character of the wave pattern is then clearly apparent and one can easily recognize the ray trajectory.

Fig. 17. Contours for the 2 tesla case, but with the damping arbitrarily increased, of (a) $|\mathcal{B}_{rf}|$ and (b) absorbed power.

4. WAVENUMBER SPECTRUM OF THE ABSORBED POWER

In order to display the $n_{\parallel}$ -spectrum modifications due to both the N/R dependence and the poloidal component of the wave, we show on Figs. 18 and 19 the absorbed power spectrum (electron channel) on a given flux surface corresponding to $r/a = 0.06$ and $r/a = 0.59$ respectively, for the 2 tesla case. The upper curves represent the launched spectrum, and the lower curves the absorbed spectrum. Near the center of the plasma where the broadening due to the m-spectrum is not too large, one clearly sees the global upshift of the spectrum due to the N/R dependence.

The current drive efficiency depends strongly upon the local absorbed power spectrum and it is interesting to study how it varies when the launched spectrum is shifted by changing the antenna phasing. This can help select the best compromise between high efficiency (low $n_{\parallel}$) and good antenna coupling (high $n_{\parallel}$). As an example we see by comparing Figs. 20 and 21 with Figs. 18 and 19 that there is not much interest in launching a lower $n_{\parallel}$ spectrum (45 degree phasing) for this plasma temperature, since the power is still absorbed in the same $n_{\parallel}$ range, *i.e.* by electrons in the same velocity range.

The coupling problem will be addressed in a future work by matching the plasma surface impedance obtained from ALCYON to an antenna code [5] which contains the exact geometry of the antenna and which shall yield a current spectrum consistent with the full wave calculation. This consistent spectrum could then be used, rather than the assumed one, for a better estimation of the power deposition and wave driven current profiles.

Fig. 18. Launched spectrum and absorbed spectrum of $n_{||}$ for the 2 tesla case at a minor radius $r = 0.06$ A.

Fig. 19. Launched spectrum and absorbed spectrum of $n_{||}$ for the 2 tesla case, at a minor radius $r = 0.59$ A.

Fig. 20. Launched spectrum and absorbed spectrum of $n_{||}$ for the 2 tesla case at a minor radius $r = 0.06$ A, but the spectrum of launched power is shifted to lower $n_{||}$.

Fig. 21. Launched spectrum and absorbed spectrum of $n_{||}$ for the 2 tesla case, at a minor radius $r = 0.59$ A, but the spectrum of launched power is shifted to lower $n_{||}$.

5. WAVE DRIVEN CURRENT AND CURRENT DRIVE EFFICIENCY

The quasi-linear wave driven current can be calculated on each magnetic flux surface using a Fokker-Planck code [6] and this will be done in a future work.

However, a comparison of the quasi-linear diffusion coefficient (obtained from the ALCYON results) with the collisional drag operator shows that a strong deformation of the electron distribution function can occur only for perpendicular velocities much higher than the thermal velocity (TTMP). When electron Landau damping is dominant, as in DIII-D, one can assume in the first approximation that the wave-particle interaction is linear. In this work, the driven current will then be estimated by linearizing the Fokker-Planck equation and solving it by the adjoint method. An analytical solution can be obtained for velocities larger than the thermal velocity, by retaining only the collisional drag and the pitch angle scattering terms in the collisional operator. Corrections due to trapping effects and other collisional terms have opposite signs and will be neglected here. Therefore, for each (N, m) resonance, the driven current is obtained as an integral over perpendicular velocities, taking into account the dependence of the quasi-linear diffusion operator, *i.e.* its vanishing at a critical perpendicular velocity when ELD and TTMP cancel each other. The critical velocity is taken to be $v_{\text{crit}} = (1 + 1/\alpha)^{1/2} v_{\text{thermal}}$ where $\alpha = (\omega_{\text{pi}}^2/\omega^2) (T_e/m_e c^2)$ [7].

This approximate way of calculating the driven current provides useful estimates without running a Fokker-Planck code and could be refined to include thermal effects and trapping corrections [8].

The results are shown in Fig. 22 for the 2 tesla case. The upper figures show the radial profile of the power density going to the electrons and the radial profile

of the driven current density. The lower ones show the radial dependence of the normalized efficiency in each plasma layer, $n_e R \Delta I_{rf} / \Delta P_e$, and the integrated driven current which amounts to 47 kA for 0.85 MW absorbed by the electrons. The global efficiency, $\eta = \bar{n}_e R I_{rf} / P_e$, is $0.18 \times 10^{19} \text{ Am}^{-2} \text{ W}^{-1}$. The same calculation for the 1 tesla case (assuming the same antenna phasing) (Fig. 23) leads to 88 kA for 1.7 MW coupled to the electrons, and a global efficiency $\eta \approx 0.1 \times 10^{19} \text{ Am}^{-2} \text{ W}^{-1}$.

Fig. 22. Radial profiles of power density, current density, local efficiency of current drive, and integrated current, for the 2 tesla case.

Fig. 23. Radial profiles of power density, current density, local efficiency of current drive, and integrated current, for the 1 tesla case.

6. CONCLUSION

Because of the weak electron damping inherent to the fast magnetosonic wave, full wave codes are very useful for modeling fast wave current drive experiments.

For the two cases we have considered, we have shown that the field structure in the plasma is indeed very different from a single pass structure, and in particular the build up of high poloidal mode numbers leads to strong modifications in the absorbed spectrum. The global directivity is not affected by this process but the current drive efficiency depends on it. In particular we have shown that the local extension of the poloidal mode number spectrum increases with minor radius and therefore the local j/p decreases slightly, from the plasma center to the edge, despite the density decrease. Since the electron temperature plays a major role in the absorption, the power deposition profiles are already peaked, and therefore the rf current profiles are also very peaked.

Quantitatively, we find that about 88 kA can be driven in the 1 tesla/1.7 keV case with 1.7 MW coupled to the electrons, *i.e.* with a global efficiency $\eta \approx 0.1 \times 10^{19} \text{ Am}^{-2} \text{ W}^{-1}$. In the 2 tesla/3.4 keV case, 47 kA can be driven with a total power of 1.5 MW, 44% of which are absorbed on the hydrogen minority, through the second harmonic ion cyclotron resonance. The global efficiency is then $0.18 \times 10^{19} \text{ Am}^{-2} \text{ W}^{-1}$ if one considers only the effective power going to the electrons. Further experiments at a higher electron temperature and with no second harmonic layer in the plasma are needed and should produce larger driven currents with a better efficiency.

Our efficiency estimates have been obtained in the linear approximation, using the high velocity limit of the collision operator (under-estimation) and neglecting

trapping effects (over-estimation). A more accurate Fokker-Planck calculation will be performed using the diffusion operator deduced from the same ALCYON results.

Another direction in which the calculation can be improved concerns the antenna current spectrum. In this report, we approximated this spectrum by assuming four equal currents in the four current straps, with a perfect 90 degree phase shift. Later on, the plasma surface impedance calculated from the ALCYON output will be inserted into an antenna code which will compute the antenna current spectrum consistently.

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