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APPLICATIONS OF FAST WAVE IN SPHERICAL TOKAMAKS

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Applications of Fast Wave in Spherical Tokamaks

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Abstract. In spherical tokamaks (ST), the magnetic field strength varies over a wide range across the plasma, and at high betas it deviates significantly from the $1/R$ dependence of conventional tokamaks. This, together with the high density expected in ST, poses challenging problems for RF heating and current drive. In this paper, we investigate the various possible applications of fast waves (FW) in ST. The adjoint technique of calculating current drive is implemented in the raytracing code CURRAY. The applicability of high harmonic and subharmonic FW to steady state ST is considered. We find that high harmonic FW tends to be totally absorbed before reaching the core and may be considered a candidate for off axis current drive while the subharmonic FW tends to be absorbed mainly in the core region and may be considered for central current drive. A difficult problem is the maintenance of current at the startup stage. In the bootstrap ramp-up scenario, the current ramp-up is mainly provided by the bootstrap current. Under this condition, the role of rf becomes mainly the sustainment of plasma through electron heating. Using a slab full-wave code SEMAL, we find that the ion-ion-hybrid mode conversion scheme is a promising candidate. The effect of possible existence of edge Alfvén resonance and high harmonic cyclotron resonance is investigated and regimes of minimization of edge heating identified.

Spherical tokamaks (ST) have been of great interest recently because of their potential for high β, the ratio of the plasma pressure to magnetic pressure, and high current I_p [1,2]. This is beneficial because both the confinement and the beta limit increase with plasma current. An important issue is the maintenance of the required current. In this respect, STs pose rather challenging problems. Briefly, the mod-B surfaces deviate significantly from the $1/R$ dependence, and can become non-monotonic in R. This, together with the high β usual in STs, causes occurrence of multiple cyclotron resonances and cutoffs which pose restrictions to the accessibility of rf waves at various frequencies. In this paper, we investigate the possibility of applying fast waves (FW) in ST. Specifically, we study the applicability of high harmonic and low frequency FW power for current drive (CD), and the ion-

ion hybrid mode-conversion for low temperature electron heating during startup for an ST similar in parameters to that of Ref. 2. In another paper by Mau *et al.*, studies in reactor parameters are made [3].

The application of high frequency FW and low frequency FW for CD in ST were proposed by Ono [4] and Chan *et al.* [5]. Here we investigate the feasibility of these schemes from the physics point of view. For this purpose, we have implemented the adjoint function code ADJ [6] into the raytracing code CURRAY. It should be noted that in ST, the use of the usual large aspect ratio approximation and related empirical formulae can significantly underestimate the CD efficiency, especially off-axis as illustrated in Fig. 1. Hence, we use ADJ to evaluate the exact integral in a numerically determined ST equilibrium. The details of the implemented formulae are presented in a more complete form of the present paper [7].

We use an equilibrium of a high beta plasma reminescent of a steady-state ST discharge with $\beta = 20\%$,. The bootstrap current is 7.0 MA out of total current 7.5 MA, so that the RF driven current needed is rather small. For D–T plasmas, the fusion produced alphas are computed by the reaction rate and the absorption of FW power is modeled by unmagnetized absorption. Figure 2(a) and (b) show the absorption profile and partition of absorbed power among the plasma species for toroidal indices of refraction of $n_\phi = 6$ and $n_\phi = 3$ at 240 MHz. At low n_ϕ the electron damping is relatively weak, but the power is absorbed by ions at half the plasma minor radius (we neglect alpha absorption here). At high n_ϕ, the electron damping dominates, but the absorption profile is shifted towards the outer part of the plasma. We have also studied plasmas of medium β (12%) and low β (3%) and at a lower frequency of 120 MHz; and we conclude that at medium and high β the waves fail to penetrate to the core. Only at low β was the wave able to reach the center. The CD efficiency is moderately low, about 0.14 (10^{20} A/M^{2}W).

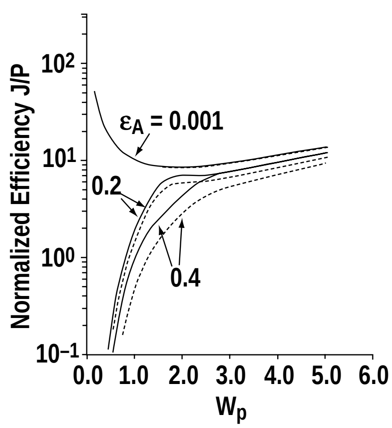

FIGURE 1. Normalized current drive efficiency versus resonant momentum normalized to thermal momentum on the outboard midplane (poloidal angle = 0) for ε_A = 0.001, 0.2, 0.4. Solid lines are for exact equilibrium, dashed lines are for circular approximation. The frequency is 240 MHz. Plasma parameters are $n_{e0} = 1\times10^4/\mathrm{cm}^3$, $\beta = 20\%$, $T_0 = 9$ keV, $B_0 = 2$ T, $R_0 = 14$ m, $I_p = 7.51$ MA, 50–50 D–T.

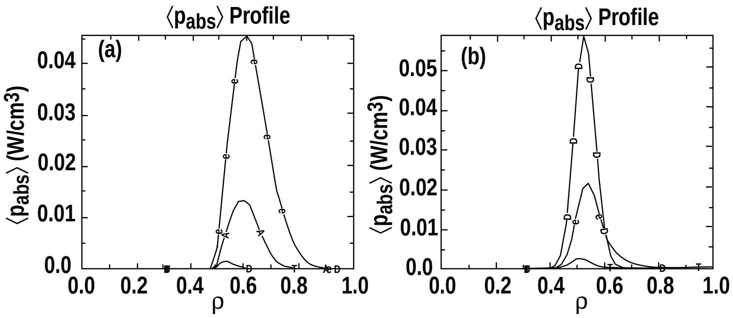

FIGURE 2. Absorption profiles for 240 MHz FW; plasma parameters are the same as in Fig. 1; (a) $n_\phi = 6$, (b) $n_\phi = 3$

For the low frequencies scheme, we choose a frequency of 4 MHz and a β of 20%. Wave penetration to the core is found to be quite adequate at n_ϕ as high as 15. There is however an Alfvén resonance at the edge. A slab model estimation of the absorption in this resonance region indicates that the layer is thin and the power-loss is very small. The current drive efficiency at 4 MHz for various values of n_ϕ and densities is shown in Fig. 3. The efficiencies are not high but adequate for the small amount of central current drive.

Startup is a critical issue. In order to ramp up to full current in a reasonable time, the most attractive method conceptually appears to be bootstrap ramp-up. In this scenario, the ramp-up of current is provided by the bootstrap current. However, auxiliary electron heating is needed to sustain the plasma.

We considered electron heating through minority energetic tail, direct electron heating, and electron heating by mode converted IBW in ion-ion hybrid heating at high minority concentration. The third mechanism is attractive in the present situation because ion-ion hybrid resonance is a cold resonance. In a D–T plasma, presence of tritium complicates the resonance structures. However, in a D plasma with added H impurities, such as DST [2], the structure is relatively simple.

We take a sequence of plasma parameters shown in the first four columns of Table 1 corresponding to increasing times in the ramp-up stage. The slab full-wave code SEMAL [8] developed by Sauter is used. The parallel refractive index in this case is 14. As shown in the last column of the table, electron power absorption

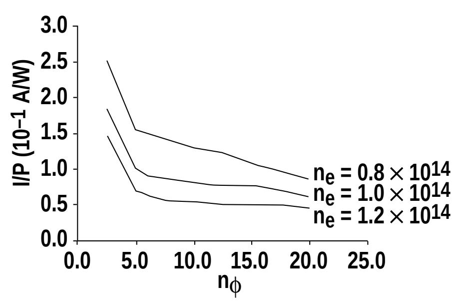

FIGURE 3. Current drive efficiencies versus n_ϕ, for n_{e0} = 0.8e14, 1.0e14, 1.2e14. Frequency is 4 MHz and $\beta = 20\%$.

TABLE 1. Partition of power for 30 MHz, $n_z = 14$, $B_0 = 2$ T, 70–30 D–H

a (m)	$n_e(0)$ (1.e14)	$T_e(0)$ (keV)	$T_i(0)$	P_e/P
0.4	0.29	1.29	0.57	0.95
0.5	0.32	1.72	0.70	0.92
0.6	0.36	1.76	0.88	0.74
0.7	0.41	1.57	1.03	0.89

is the dominant mechanism over this range. The fraction of power absorbed by electrons is still the dominant mechanism over a wide range of parallel wave-numbers. When the minor radius exceeds 0.7 m, an Alfvén resonance can occur at the high field edge. By going to parallel wavenumbers above 12, edge electron heating can be kept at a low level.

In summary, we find that the high frequency FWCD scheme fails to penetrate to the plasma center at β values above about 10% because the absorption mechanisms are too strong. It can only be used for off-axis current drive in steady state operations. The low frequency scheme penetrates adequately for a wide range of toroidal wave numbers and can be considered for central current drive. For electron heating in the bootstrap current ramp-up scenario, we find that the ion-ion hybrid mode-conversion provides a possible method at the low temperatures typical of startup plasmas.

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