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Current Drive and Profile Control in Low Aspect Ratio Tokamaks

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Introduction

The key to the theoretically predicted high performance of a low aspect ratio tokamak (LAT) is its ability to operate at very large plasma current I_p. The plasma current at low aspect ratios follows the approximate formula: $I_p \sim (5a^2B_t/Rq_\psi)\ [(1+\kappa^2)/2]\ [A/(A-1)]$ where $A \equiv R/a$ which was derived from equilibrium studies [1]. For constant q_ψ and B_t, I_p can increase by an order of magnitude over the case of tokamaks with $A \gtrsim 2.5$. The large current results in a significantly enhanced β_t ($\equiv \beta_N I_p/aB_t$) possibly of order unity. It also compensates for the reduction in A to maintain the same confinement performance assuming the confinement time τ follows the generic form $\sim HI_pP^{-1/2}R^{3/2}\kappa^{1/2}$. The initiation and maintenance of such a large current is therefore a key issue for LATs.

Current Profile Requirements for LATs

To be economically competitive, a large fraction of I_p has to come from bootstrap current, which requires operating at high β_p since $I_{BS}/I_p \sim A^{-1/2}\beta_p$. At the same time, some current profile control is necessary to maintain MHD stability to ballooning and kink modes at high β_t, *i.e.*, high Troyon coefficient. Therefore some fraction of I_p has to be provided by non-inductive current drive for steady-state operation. Stability studies suggest that Troyon scaling should still hold at low aspect ratio, hence tradeoffs exist between maximizing β_t and bootstrap fraction. Specifically, the quantities β_t and β_p are related by $\beta_t\,\beta_p = 25\,\kappa(\beta_N/100)^2$. If $\beta_N \sim 10$ can be achieved, a LAT can operate with both high β_p and high β_t.

Table 1 shows two LAT equilibria illustrating the tradeoffs between β_t and bootstrap fraction. Both equilibria have high β_N values and are stable to ballooning modes. The total current profiles and bootstrap profiles are depicted in Fig. 1 which clearly displays the different external current drive requirements for the two cases. For Case A with a higher β_t, the bootstrap current is not well-aligned with the total current except at the plasma edge. Significant external current drive of up to 30% mostly at the outer half of the plasma is required. Case B has lower β_t, but the bootstrap current is for the most part well-aligned, requiring external current drive of 10% at the plasma interior.

RF Wave Penetration and Current Drive

Since space is of a premium for LATs, neutral beam injection is not an attractive option. However, LATs possess some unique characteristics which make it very challenging to

Table 1

[$A = 1.2$, elongation = 2.2, triangularity = 0.7]

	Case A		Case B	
β_N	8		7.57	
β_t	0.329		0.224	
β_p	1.36		1.79	
I_p (MA)	8.226		5.913	
I_{dia}	1.054	71.1%	0.692	88.6%
$I_{p\text{-}s}$	−0.552		−0.367	
I_{bs}	5.347		4.915	

use rf waves for heating and current drive. The very large β_t causes the total B-field $|B|$ to be non-monotonic in R (Fig. 2). Also the ohmic loss constraint on the centerpost limits on-axis B_t to relatively low values (~ 1.2 T for Cases A and B). The tight inboard space eliminates launching rf on that side. For electron cyclotron ordinary waves (O–mode), the low B_t limits the maximum density to $n_e < 9.74 \times 10^{12} (B_T)^2\ \mathrm{cm}^{-3}$. Because of the non-monotonic $|B|$, one can use the extraordinary wave (X–mode) launched from the outside but the density is still limited to $n_e < 1.95 \times 10^{13}\ (B_T)^2\ \mathrm{cm}^{-3}$ where B_T is normalized to 1 T. For lower hybrid waves, the accessibility condition is $n_\parallel^2 \equiv (ck_\parallel/\omega)^2 > 1 + \omega_{pe}^2/\Omega_{ce}^2$. To avoid strong Landau damping at the edge and for efficient current drive, $\omega/k_\parallel$ has to be much larger than the thermal velocity. Typically $n_\parallel \sim 1.5$ which limits the density to $n_e < 1.2 \times 10^{13} (B_T)^2\ \mathrm{cm}^{-3}$.

At the ion cyclotron frequency range, the challenge is to find a frequency window which avoids cyclotron resonances at the plasma edge because of the non-monotonic $|B|$. For the equilibria in consideration, we have found only one frequency range near $f \sim 8.5$ MHz which has a single fundamental tritium resonance at the inboard side [Fig. 3(a)] for a 50–50 D–T plasma. We have not found a scenario with a cyclotron resonance or two-ion hybrid resonance on-axis with no edge cyclotron resonance. However, with the high β_t and a relatively flat $|B|$ well, electron Landau damping and cyclotron damping are strong enough for the rf energy to be damped in the core before reaching the resonance [Fig. 3(b)]. Because $|B|$ increases toward the outer edge, a hybrid resonance exists in the outer half of the plasma similar to high field launch in standard tokamaks. Near the resonance layer, the magnetosonic wave is described by the coupled equations

$$\begin{pmatrix} \epsilon_{11} - n_\parallel^2 & \epsilon_{12} \\ -\epsilon_{12} & \epsilon_{22} - n_\parallel^2 + \dfrac{\partial^2}{\partial x^2} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = 0 \quad , \tag{1}$$

where x replaces the major radius R in a quasi-slab approximation, ϵ_{ij} are the dielectric tensor elements including warm plasma effects. If we identify the warm plasma part of the tensor elements separately as k_{ij} following Ref. 2, Eq. (1) becomes

$$\left(S - n_{\parallel}^2\right) \frac{\partial^2 E_y}{\partial x^2} + \Big[\left(\epsilon_{11} - n_{\perp}^2\right)^2 - k_{12}^2 + \left(k_{22} - n_{\perp \mathrm{F}}^2\right)\left(\epsilon_{11} - S\right) + k_{22}\left(S - n_{\parallel}^2\right)\Big] E_y = 0 \quad . \tag{2}$$

where we assume $n_{\perp \mathrm{F}}^2 = (R - n_{\parallel}^2)(L - n_{\parallel}^2)/(S - n_{\parallel}^2)$ and R, L, and S are the usual cold plasma dielectric elements. The coefficients in Eq. (2) are expanded about the hybrid resonance, assuming the gradient of R to be small, to give the standard Budden equation from which we obtain the tunneling parameter η. The transmission coefficient is $T = e^{-2\eta}$ and the mode conversion coefficient is $M = 1 - e^{-2\eta}$. Taking $n_{\parallel} = 3$ at the edge, assuming $\sim 1/R$ variation, $n_e = 1 \times 10^{14}$ cm^{-3} and $T_e = 20$ keV $= T_i$ which corresponds to $\langle \beta_t \rangle = 22\%$, the transmission efficiency is computed to be only 33%. Hence, a large fraction of the rf power is mode converted and absorbed at the hybrid resonance. This suggests that wave penetration at the ion cyclotron frequency range is also very difficult.

If the frequency is lowered to sub-cyclotron range, the hybrid resonance becomes the Alfvén resonance and moves closer to the edge. We estimated the fraction of power absorbed at the resonance following Karney *et al.* [3] for a cold plasma to be small, hence coupling to the plasma interior is possible. The Alfvén wave is damped in the plasma core in a single pass because of the high β_t [Fig. 3(c)].

We have identified two schemes for current profile control in LATs. Mode conversion current drive at the tritium ion cyclotron frequency can be used for off-axis profile control and sub-cyclotron Alfvén waves for on-axis current drive. Because of the low $|B|$ and high β_t, a novel effect first discussed in the context of wave helicity injection [4] becomes non-negligible and can enhance the current drive efficiency by a factor $\sim 1 + \beta_e |\zeta_e Z(\zeta_e)|$ with $\zeta_e \equiv \omega / k_{\parallel} v_{te}$ and Z is the plasma dispersion function. We estimated that with Alfvén wave current drive for case B, 250 kA/MW is possible.

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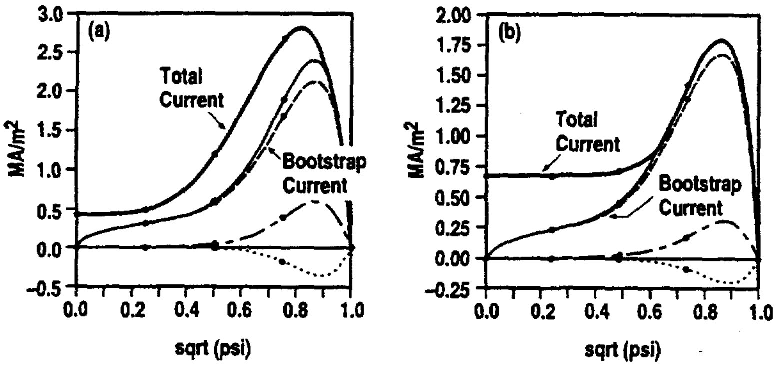

Case A

Case B

Fig. 1: Current profile for high β equilibria.

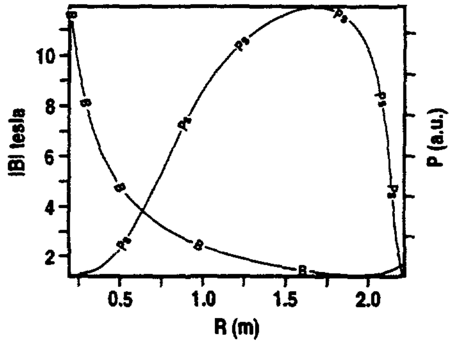

Fig. 2: $|B|$ and pressure profile versus major radius for case B.

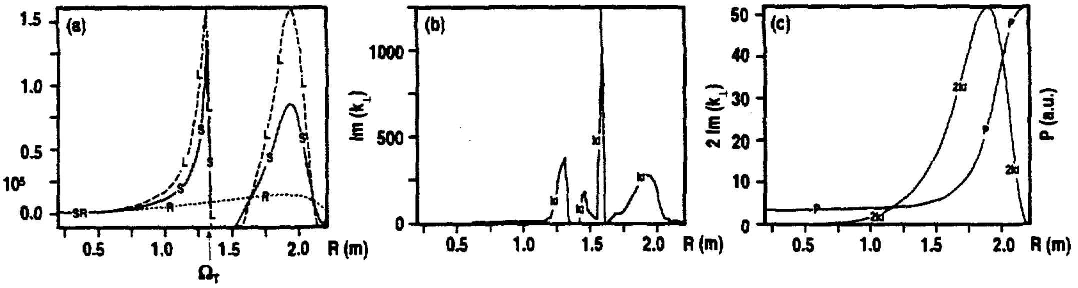

Fig. 3: (a) Cutoffs ($R = n_{\|}^2$, $L = n_{\|}^2$) and resonances ($S = n_{\|}^2$) for $f = 8.4$ MHz. (b) Combined electron Landau and ion cyclotron damping decrement assuming $n_{\|} \propto 1/R$ for $f = 8.5$ MHz (no mode conversion damping). (c) Electron Landau damping rate [$2\, Im(k_{\perp})$] and rf power profile for $f = 5$ MHz (sub-cyclotron).