under consideration. The transport coefficients that multiply $G$ are to be evaluated by using the vacuum toroidal field, $R B_{\text{vac}} = \text{const}$. Gradients of plasma parameters must be expressed as $\partial n/\partial \psi$, $\partial T/\partial \psi$, etc. since $G$ has the dimensions of $|\nabla \psi|$. $\alpha^*$ in this geometry is now given by

$$\alpha^* = \frac{R | \mathbf{B} - \mathbf{B}_{\text{sym}} |}{N \delta B_T^2}$$

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**REFERENCES**

[1] DNESTROVSKIJ, Yu.N., KOSTOMAROV, D.P., LYSENKO, S.E., Nucl. Fusion 15 (1975) 1185.

[2] UCKAN, N.A., TSANG, K.T., CALLEN, J.D., Effects of the Poloidal Variation of the Magnetic Field Ripple on Enhanced Heat Transport in Tokamaks, ORNL/TM-5438 (1976).

[3] UCKAN, N.A., UCKAN, T., MOORE, J.R., Calculation of Magnetic Field Ripple Effects in Circular and non-Circular Tokamaks, ORNL/TM-5603 (1976).

[4] CONNOR, J.W., HASTIE, R.J., Nucl. Fusion 13 (1973) 221.

[5] STRINGER, T.E., Nucl. Fusion 12 (1972) 289.

[6] GOLDSTON, R.J., TOWNER, H.H., Effects of Toroidal Field Ripple on Supra-Thermal Ions in Tokamak Plasmas, PPPL-1637 (1980).

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time [3]. Letting the vertical drift be in the y-direction, we obtain

\[ \frac{\partial f_T}{\partial y} + \frac{f_T}{d} = \frac{4\pi \delta^{1/2} f_0}{d} \]  \hspace{1cm} (2)

where \( d = 25r_0v_0 \) and is the mean drift distance of a trapped ion in the well. For a plasma column of minor radius \( a \), the solution to Eq.(2) is

\[ f_T(v) = e^{-y/d} \int_{-a}^{y} \frac{4\pi \delta^{1/2} f_0(\xi, v)}{d} e^{t_1/\delta} d\xi \]  \hspace{1cm} (3)

If \( f_0(y,v) \) has a scale length of \( a/2 \), it is easy to see that for \( d < a/2 \)

\[ f_T(v) \approx 4\pi \delta^{1/2} f_0(v) \]  \hspace{1cm} (4)

whereas for \( d > a/2 \)

\[ f_T(v) \sim 4\pi \delta^{1/2} f_0(v) \frac{a}{2d} \]  \hspace{1cm} (5)

where \( f_T \) is being estimated at \( y = 0 \) and the source \( f_0(y,v) \) extends from \( y = -a/2 \) to \( y = a/2 \). \( d \) varies as \( E_1^{1/2} \), so that, above an energy \( E_c \) at which \( d = a/2 \), we expect \( f_T(v) \) to be depleted. \( d = a/2 \) is equivalent to

\[ E_c = \left[ \frac{8\pi n_e^2 \ln \Lambda \delta^{1/2} a R \omega_c}{\delta} \right]^{2/5} \]  \hspace{1cm} (6)

and for \( n_e = 2.4 \times 10^{14} \text{ cm}^{-3} \), deuterium, \( R = 54 \text{ cm} \), \( B_T = 60 \text{ kG} \) and \( \delta = 2\% \) (the plasma parameters during lower hybrid heating on Alcator A [4]), and \( E_c \approx 5 \text{ keV} \).

Figure 1 shows a fast-neutral spectrum obtained from charge-exchange measurements of ions with velocities perpendicular to the \( B_T \) within the magnetic well of the gap in the toroidal field magnets. Between \( E_i = 2 \) and 5 keV the flux exhibits a Maxwellian velocity distribution with \( T_i \approx 700 \text{ eV} \). At \( E_i > 5 \text{ keV} \), however, the flux rapidly decreases, and for \( E_i > 7 \text{ keV} \) it is below the sensitivity of the detector. Figure 2 illustrates the variation of neutral flux at fixed energy as a function of up-down position of the detector. The strong asymmetry in the direction of the VB drift is evident. (The slow rise in flux as \( r \) increases from +5 cm to +10 cm is due to the increasing neutral density.) This asymmetry is evidence of the strong effect of the VB drift on the trapped-particle distribution and their subsequent loss.

We have thus observed a depletion in the perpendicular energetic ion distribution within the magnetic well of the coil gap. While we have only measured the depletion of the trapped particles, this loss creates a hole in velocity space which would allow rapid pitch-angle scattering and escape of ions into this loss one. This is to a certain extent evidenced by the decrease in flux at \( E > E_c \), which is more rapid than the \( a/d \) dependence of Eq.(5) and could be caused by a decrease in the circulating particles due to the ripple effect.

**FIG. 1.** Charge-exchange flux is plotted versus energy for two values of plasma density: \( n_e = 1 \times 10^{14} \text{ cm}^{-3} \) and \( 2 \times 10^{14} \text{ cm}^{-3} \). The shaded area represents flux levels below the sensitivity of the instrument. Portions of the plots completed with dotted lines represent upper bounds on the charge-exchange flux. The data were taken with \( B_T = 60 \text{ kG} \) and \( I_p = 150 \text{ kA} \) in deuterium.

**FIG. 2.** Results of up-down scans with a neutral-atom analyser are shown at four different energies. Log of charge-exchange flux \( (\text{cm}^{-2} \text{ sr}^{-1} \text{ eV}^{-1} \text{ s}^{-1}) \) divided by \( \sqrt{E(\text{eV})} \) is plotted against minor radius. The shaded area represents flux levels below the sensitivity of the instrument. The portions of the plots completed with dotted lines represent upper bounds on charge-exchange flux at the positions and energies indicated. The data were taken for \( B_T = 60 \text{ kG} \); \( I_p = 150 \text{ kA} \) and \( n_e \approx 3 \times 10^{14} \text{ cm}^{-3} \) in deuterium.
FIG. 3. a) Ripple $\delta$, $\alpha$, and effective ripple $\delta_{\text{eff}}$ in Alcator C. Here we assume $q(r) = 1 + 2r^2/a^2$, $a = 17$ cm, $R = 64$ cm, $N = 30$ and approximate $\delta_0(r) = 0.4 + 1.6r^2/a^2$ (%).
b) $E_e$ versus $r/a$. $E_e(\delta_{\text{eff}})$ is obtained by using $\delta_{\text{eff}}$ in Eq. (6) but still requiring $\Delta \delta > a/2$ for ripple depletion. Here we consider deuterium ions, $B_T = 100$ kG, and $n_e = 7 \times 10^{14}$ cm$^{-3}$.

FIG. 4. Charge-exchange flux from hydrogen discharges in Alcator C is plotted versus energy. No depletion of energetic ions is seen at energies up to 13 keV. At this energy, flux levels fall below the sensitivity of the instrument (shaded region). The data are taken from 16 separate discharges, where the macroscopic parameters were held constant: $B_T = 60$ kG, $I_p = 320$ kA, $n_e = 1 \times 10^{14}$ cm$^{-3}$.

loss. This mechanism would be extremely important for RF heating, where the loss time would be $\tau_{\text{loss}} \sim 4v_f v^2 T_D$, where $v_f/v \sim \sqrt{T_i/E_i}$ for RF heated ions. If this loss time is less than or comparable to the slowing-down time, a substantial fraction of the heating power will exit the plasma, because of the $\nabla B$ drift.

In Alcator C it is expected that this ripple loss will be less important. Here $\delta \sim 0.4\%$ on axis, $R = 64$ cm, $a = 17.0$ cm, and for $n_e = 7 \times 10^{14}$ cm$^{-3}$, $B_T = 60$ kG, and deuterium, $E_c \approx 24$ keV from Eq. (6). Furthermore, the rotational transform will further reduce the effective ripple [1] when $\alpha \sim \delta$, where $\alpha = 2 \sin \theta/[N R q(r)]$ and $\theta$ is the poloidal angle. The effective ripple would then be

$$\delta_{\text{eff}} = \frac{\Delta B}{B_{\text{eff}}} = \frac{\Delta B}{B_0} \left(\frac{1 - (\alpha^2/\delta_0^2)}{\delta_0} - \frac{\alpha}{\delta_0} \left(\frac{\pi}{2} - \sin^{-1} \frac{\alpha}{\delta_0}\right)\right)$$

(7)

where $\delta_0$ is $\Delta B/B$ in the absence of a rotational transform, $\theta = \pi/2$ and we approximate $B = B_0 (1-r/R \cos \theta - 5/2 \cos N \phi)$. When $\alpha > \delta_0$, the effective ripple disappears altogether. Figure 3 represents $\delta_{\text{eff}}$ versus $r/a$ for Alcator C and shows the resulting decrease in $\delta$ and increase in $E_c$ due to the rotational transform. We would then expect the depletion of high-energy ions to occur at much higher energies in Alcator C than Alcator A, if it occurred at all.

Figure 4 shows a charge-exchange spectrum taken in hydrogen on Alcator C. The discharge parameters were $n_e = 1 \times 10^{14}$ cm$^{-3}$ and $B_T = 60$ kG. Where we calculate $E_c$ on axis to be $10-15$ keV, no depletion of flux is seen at energies up to 13 keV. At higher energies the flux falls below the sensitivity of the analyser. This lack of depletion on Alcator C implies better confinement of the high-energy ions excited in RF heating schemes. Further work on Alcator C under a variety of discharge conditions is planned.

REFERENCES

[1] STRINGER, T.E., Nucl. Fusion 12 (1972) 689.
[2] JASSBY, D.L., TOWNER, H.H., GOLDSTON, R.J., Nucl. Fusion 18 (1978) 825.
[3] SPITZER, L., Jr., Physics of Fully Ionized Gases, John Wiley & Sons, New York (1962).
[4] SCHUSS, J.J., FAIRFAX, S., KUSSE, B., PARKER, R.R., PORKOLAB, M., et al., Phys. Rev. Lett. 43 (1979) 274.

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