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Particles in the Alcator Tokamaks

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ABSTRACT

The presence of a toroidal field ripple greater than 2% in the Alcator A tokamak allows for the trapping and rapid VB drift loss of ions in the port gap of the toroidal field magnet. The resulting depletion of high energy ions is observed by perpendicular charge exchange measurements and may point to a significant energetic ion loss mechanism in Alcator A. Smaller ripple, larger minor radius and toroidal field lead to greatly reduced losses in Alcator C.
The confinement of energetic ions is crucially important to the success of rf or neutral beam heating schemes in tokamak plasmas. One possible loss mechanism is the trapping of ions in the magnetic wells formed by the gaps in the toroidal field magnets to accommodate access ports.\textsuperscript{1,2} Such ions do not circulate around the torus and do not undergo a rotational transform, but rapidly VB drift out of the plasma. For sufficiently high energies, particles trapped in the magnetic ripple can be completely depleted by this loss mechanism. This depletion would allow the rapid loss of untrapped particles as they pitch angle scatter into the resulting hole in velocity space. In this letter we will show that the Alcator A tokamak satisfies the criteria necessary for the depletion of ripple trapped particles and that in fact this depletion is observed at sufficiently high energies.

We can write the equation describing the trapped particle distribution function within the magnetic well in steady state as

\[
\frac{\partial f_T}{\partial t} = 0 = - \frac{f_T}{\tau_L} + \frac{f_O(v)}{\tau_{IN}} - \nabla \cdot (f_T v_O^+) \tag{1}
\]

where $\tau_L$ is the time in which a trapped particle scatters out of the loss cone, $f_O(v)/\tau_{IN}$ is the rate at which ions scatter into the loss cone, $f_O(v)$ is the distribution function of the untrapped particles, and $v_O = v_{||}/(2\omega ci R)$ is the VB drift velocity. The loss cone in velocity space which contains the ripple trapped ions is defined by $|v_{\parallel}/v| < \sqrt{\Delta B/B}$, where $\Delta B$ is the total variation.
of the toroidal magnetic field in the ripple well. \( f_T \) is the integral of the distribution function of trapped particles.

Since in the absence of any drift losses \( f_T = f_0 \cdot 4\pi \delta^{\frac{1}{2}} \), where \( \delta = \Delta B/B \), then \( \tau_{IN} = \delta^{\frac{1}{2}} \tau_D/(2\pi) \), where \( \tau_D \) is the 90° scattering time. Letting the vertical drift be in the \( y \) direction, we obtain

\[
\frac{\partial f_T}{\partial y} + \frac{f_T}{d} = \frac{4\pi \delta^{\frac{1}{2}} f_0}{d} \tag{2}
\]

where \( d = 2\delta \tau_D v_0 \) 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

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

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

\[
f_T(v) \approx 4\pi \delta^{\frac{1}{2}} f_0(v) \tag{4}
\]

whereas for \( d >> a/2 \)

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

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 \( E_i^{5/2} \), 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

\[
E_c = \left[ \frac{8\pi n_e^4 \ln \Lambda_m \frac{a}{2} \sqrt{R} \omega_{ci}}{2^{7/2} \delta} \right]^{2/5}
\]

(6)

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

Figure (1) shows a fast neutral spectrum obtained from charge exchange measurements of ions with velocities perpendicular to \( \tilde{B}_T \) within the magnetic well of the gap in the toroidal field magnets. Between \( E_i = 2 \text{ keV} \) and \( E_i = 5 \text{ keV} \) the flux exhibits a Maxwellian velocity distribution with \( T_i \approx 700 \text{ eV} \). However, at \( E_i > 5 \text{ keV} \) 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 cone. 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 loss. This mechanism would be extremely important for rf heating, where the loss time would be $\tau_{\text{loss}} \sim 4\frac{v_{\parallel}/v}{v_{\parallel}/v} \tau_D$, where $v_{\parallel}/v \sim \sqrt{T_i/E_i}$ 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 due to the VB 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 when $\alpha \sim \delta$, where $\alpha = 2r\sin\theta/[NRq(r)]$ and $\theta$ is the poloidal angle. The effective ripple would then be

$$\delta_{\text{eff}} = \left. \frac{\Delta B}{B} \right|_{\text{eff}} = \delta_0 \left[ \sqrt{1 - \left( \frac{\alpha^2}{\delta_0^2} \right)} - \frac{\alpha}{\delta_0} \left( \frac{\pi}{2} - \sin^{-1} \frac{\alpha}{\delta_0} \right) \right]$$

(7)

where $\delta_0$ is $\Delta B/B$ in the absence of a rotational transform, $\theta = \pi/2$ and we approximate $B = B_\theta \left( 1 - r/R \cos\theta - \delta/2 \cos\phi \right)$. When $\alpha > \delta_0$, the effective ripple disappears altogether. Figure (3) graphs $\delta_{\text{eff}}$ vs. $r/a$ 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 $n_e = 1 \times 10^{14} \text{ cm}^{-3}$ and $B_T = 60 \text{ kG}$. Where we calculate $E_c$ on axis to be $10 - 15 \text{ keV}$, no depletion of flux is seen at energies up to $13 \text{ keV}$. At higher energies the flux falls below the sensitivity of the analyzer. 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

Figure Captions

Fig. 1 Charge exchange flux is plotted vs energy for two values of plasma density; $n_e = 1 \times 10^{14}$ cm$^{-3}$ and $2 \times 10^{14}$ 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 was taken with $B_T = 60$ kG and $I_p = 150$ kA in deuterium.

Fig. 2 Results of up-down scans with a neutral atom analyzer are shown at four different energies. Log of charge exchange flux (cm$^{-2}$ str$^{-1}$ ev$^{-1}$ sec$^{-1}$) divided by $\sqrt{E(eV)}$ 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 was taken for $B_T = 60$ kG; $I_p = 150$ kA and $n_e \approx 3 \times 10^{14}$ 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 $\delta_o(r) = 0.4 + 1.6r^2/a^2$ ($\%$). (b) $E_c$ vs $r/a$. $E_c(\delta_{\text{eff}})$ is obtained by using $\delta_{\text{eff}}$ in Eq. (6) but still requiring $\Delta r > a/2$ 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 vs 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 is taken from 16 separate discharges where the macroscopic parameters were held constant; $B_T = 60 \text{ kG}, \bar{I}_p = 320 \text{ kA}, \bar{n}_e = 1 \times 10^{14} \text{ cm}^{-3}$. 
\[ \log \left( \frac{\Delta J}{\sqrt{E}} \right) \]

- \( \bar{n}_e \approx 1 \times 10^{14} \text{ cm}^{-3} \)
- \( \bar{n}_e \approx 2 \times 10^{14} \text{ cm}^{-3} \)

\( E \) (keV)
\[ \log \left( \frac{1}{\sqrt{E}} \frac{\Delta J}{\Delta E} \right) \]