Depletion of Superbanana Trapped 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 ∇B 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 accomodate access ports.[1,2] Such ions do not circulate around the torus and do not undergo a rotational transform, but rapidly ∇B 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

$$\frac{\partial f_T}{\partial t} = 0 = - \frac{f_T}{\tau_L} + \frac{f_o(v)}{\tau_{IN}} - \nabla \cdot (f_T \vec{v}_o) \qquad (1)$$

where τ_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 $v_o = v_\perp^2/(2\omega_{ci}R)$ is the ∇B drift velocity. The loss cone in velocity space which contains the ripple trapped ions is defined by $|v_{||}/v| \leqslant \sqrt{\Delta B/B}$, where ΔB 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 $f_T = f_o 4\pi\delta^{\frac{1}{2}}$, where $\delta = \Delta B/B$, then $\tau_{IN} = \delta^{\frac{1}{2}}\tau_D/(2\pi)$, where τ_D is the 90° scattering time.[3] Letting the vertical drift be in the y direction, we obtain

$$\frac{\partial f_T}{\partial y} + \frac{f_T}{d} = \frac{4\pi\delta^{\frac{1}{2}} f_o}{d} \tag{2}$$

where $d = 2\delta\tau_D v_o$ 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

$$f_T(v) = e^{-y/d} \int_{-a}^{y} \frac{4\pi\delta^{\frac{1}{2}} f_o(\xi,v)}{d} e^{\xi/d} d\xi \quad . \tag{3}$$

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

$$f_T(v) \approx 4\pi\delta^{\frac{1}{2}} f_o(v) \tag{4}$$

whereas for $d >> a/2$

$$f_T(v) \sim 4\pi\delta^{\frac{1}{2}} f_o(v) \frac{a}{2d} \tag{5}$$

where f_T is being estimated at $y = 0$ and the source $f_o(y,v)$ 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

$$E_c = \left[\frac{8\pi}{2^{7/2}} \frac{ne^4 \ell n\Lambda m_d^{1/2} aR\omega_{ci}}{\delta} \right]^{2/5} \tag{6}$$

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

Figure (1) shows a fast neutral spectrum obtained from charge exchange measurements of ions with velocities perpendicular to $\vec{B}_T$ within the magnetic well of the gap in the toroidal field magnets. Between $E_i = 2$ keV and $E_i = 5$ keV the flux exhibits a Maxwellian velocity distribution with $T_i \simeq 700$ eV. However, at $E_i > 5$ keV the flux rapidly decreases and for $E_i \geq 7$ 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 ∇B 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 ∇B 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 $\tau_{loss} \sim 4(v_{||}/v)^2 \tau_D$, where $v_{||}/v \sim \sqrt{T_i/E_i}$ 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 ∇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 $n_e = 7 \times 10^{14} \mathrm{cm}^{-3}$, $B_T = 60$ kG, and deuterium, $E_c \simeq 24$ 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 θ is the poloidal angle. The effective ripple would then be

$$\delta_{eff} = \left.\frac{\Delta B}{B}\right|_{eff} = \delta_o\left[\sqrt{1 - (\alpha^2/\delta_o^2)} - \frac{\alpha}{\delta_o}\left(\frac{\pi}{2} - \sin^{-1}\frac{\alpha}{\delta}\right)\right] \qquad (7)$$

where δ_o is $\Delta B/B$ in the absence of a rotational transform, $\theta = \pi/2$ and we approximate $B \simeq B_o(1 - r/R\cos\theta - \delta/2\cos N\phi)$. When $\alpha > \delta_o$, the effective ripple disappears altogether. Figure (3) graphs δ_{eff} vs. r/a for Alcator C and shows the resulting decrease in δ 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 $\bar{n}_e = 1 \times 10^{14}\,cm^{-3}$ 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 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

1. T. E. Stringer, Nucl. Fusion 12, 689 (1972).
2. D. L. Jassby, H. H. Towner, and D. J. Goldston, Nucl. Fusion 18, 825 (1978).
3. Lyman Spitzer, Jr., Physics of Fully Ionized Gases (John Wiley & Sons, Inc., New York) 1962.
4. J. J. Schuss, et al., Phys. Rev. Lett., 43, 274 (1979).

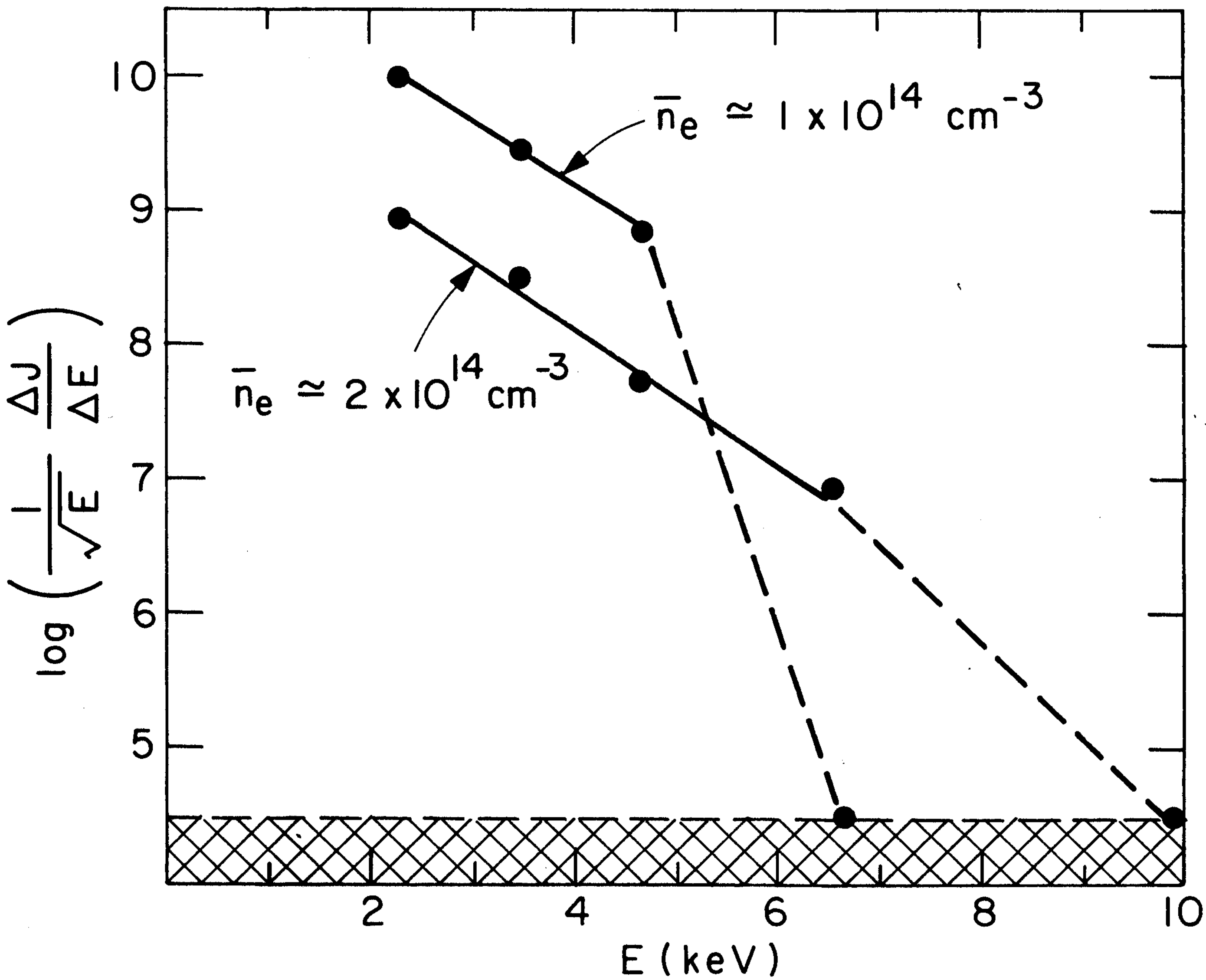
Figure Captions

Fig. 1 Charge exchange flux is plotted vs energy for two values of plasma density; $\bar{n}_e = 1 \times 10^{14} cm^{-3}$ 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.

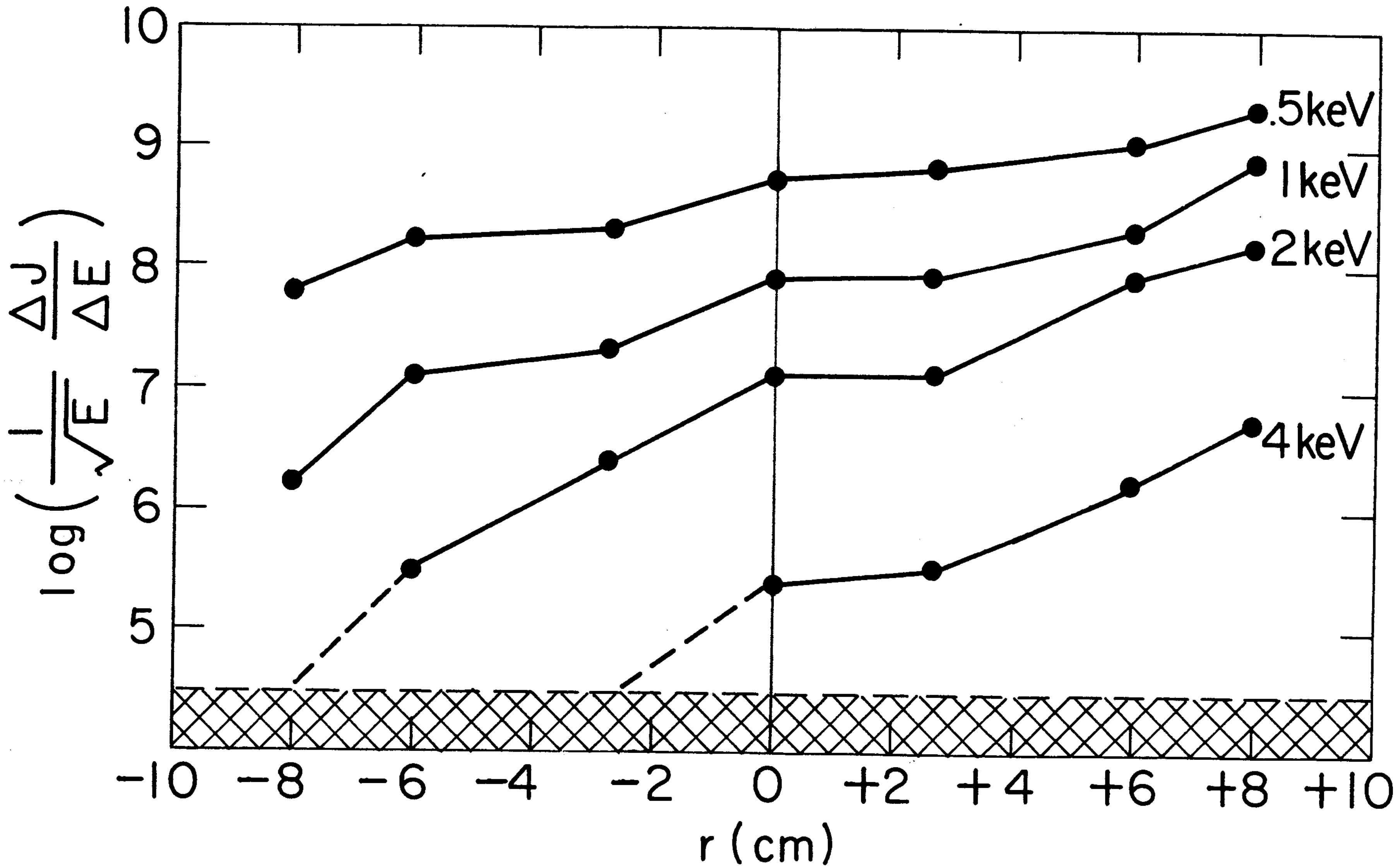
Fig. 2 Results of up-down scans with a neutral atom analyzer are shown at four different energies. Log of charge exchange flux (cm^{-2} str^{-1} ev^{-1} sec^{-1}) divided by $\sqrt{E(eV)}$ is plotted against minor radius. The shaded area represents flux levels below the sensitivity of the instrument. 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 $\bar{n}_e \simeq 3 \times 10^{14} cm^{-3}$ in deuterium.

Fig. 3 (a) ripple δ, α, and effective ripple δ_{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. $E_c(\delta_{eff})$ is obtained by using δ_{eff} in Eq. (6) but still requiring $\Delta r > a/2$ for ripple depletion. Here we consider deuterium ions, B_T = 100kG, and n_e = $7 \times 10^{14} cm^{-3}$.

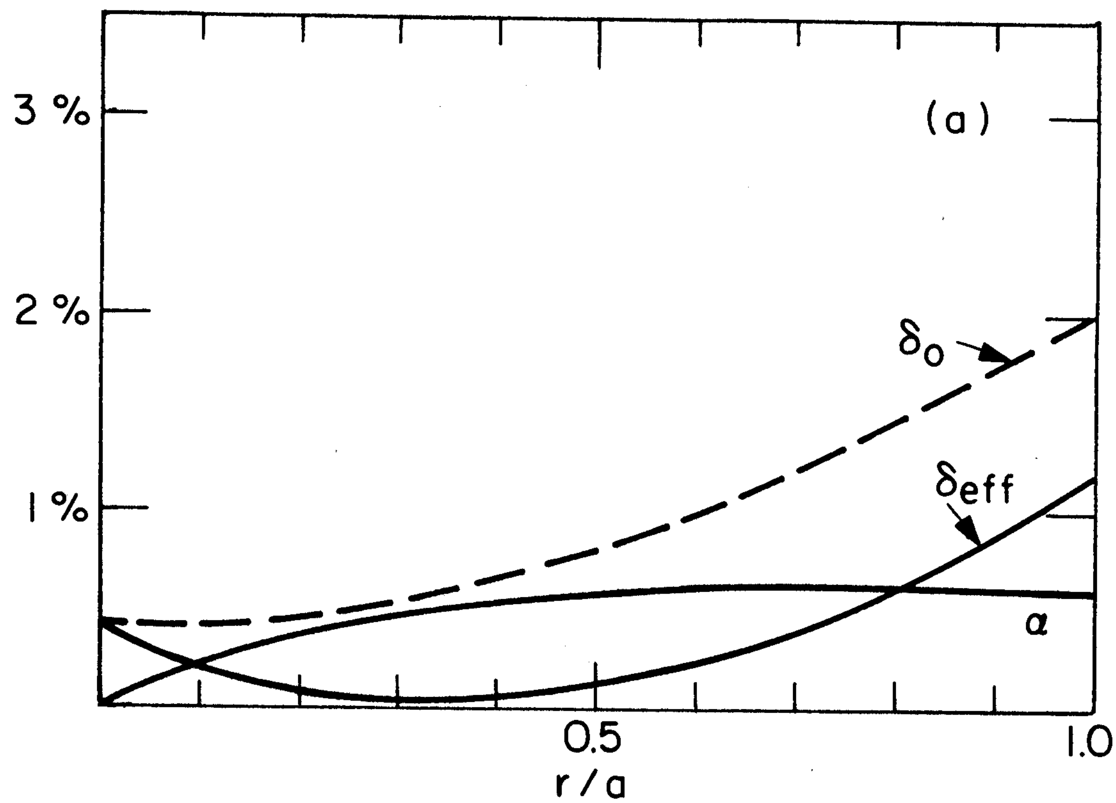
Fig. 4 Charge exchange flux from hydrogen discharges in Alcator C is plotted vs energy. No depletion of energetic ions is seen at energies up to 13 keV. At this energy, flux levels fall below the sensitivity of the instrument (shaded region). The data is taken from 16 separate discharges where the macroscopic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



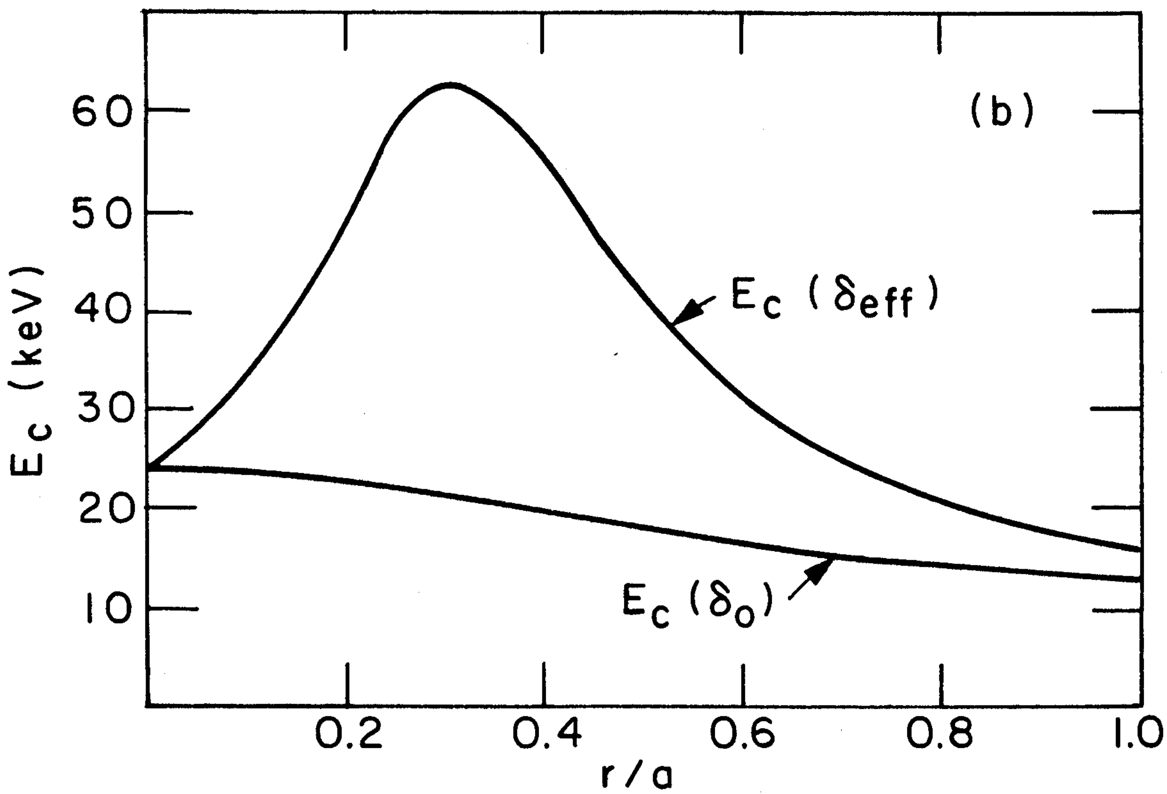
$\bar{n}_e \simeq 1 \times 10^{14}\ cm^{-3}$
$\bar{n}_e \simeq 2 \times 10^{14} cm^{-3}$
$\log\left(\frac{1}{\sqrt{E}}\ \frac{\Delta J}{\Delta E}\right)$
10
9
8
7
6
5
2
4
6
8
10
E (keV)



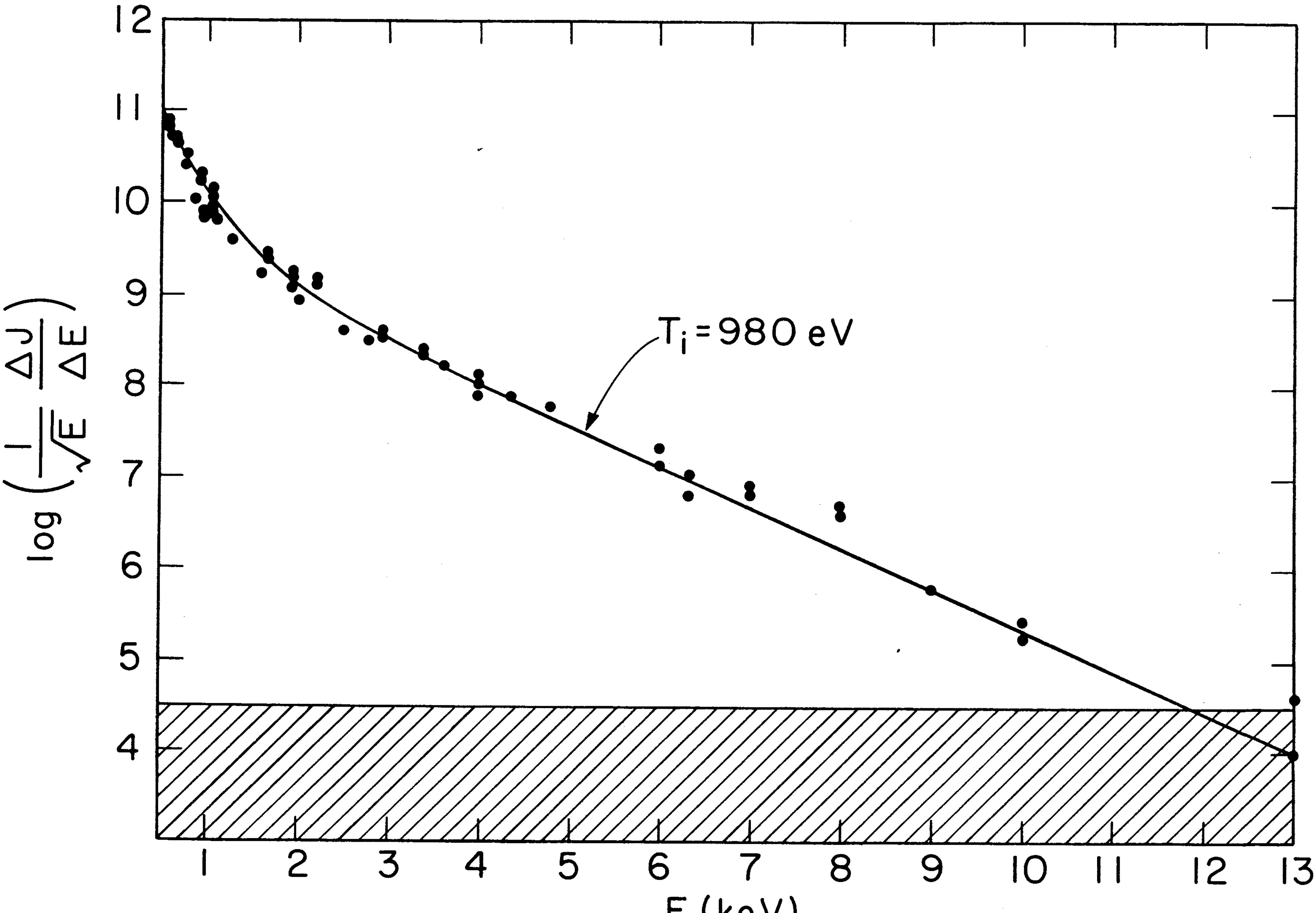
.5keV
1keV
2keV
4keV
10
9
8
7
6
5
$\log\left(\frac{1}{\sqrt{E}}\frac{\Delta J}{\Delta E}\right)$
−10 −8 −6 −4 −2 0 +2 +4 +6 +8 +10
r (cm)



3 %
2 %
1 %
(a)
δo
δeff
α
0.5
1.0
r / a



(b)
E_c (δ_{eff})
E_c (δ_o)
E_c (keV)
60
50
40
30
20
10
0.2
0.4
0.6
0.8
1.0
r/a



$\log\left(\frac{1}{\sqrt{E}}\frac{\Delta J}{\Delta E}\right)$
12
11
10
9
8
7
6
5
4
$T_i = 980$ eV
1
2
3
4
5
6
7
8
9
10
11
12
13
E (keV)