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CALCULATED NEUTRAL BEAM
DEPOSITION AND VELOCITY SPACE
LOSS REGIONS FOR THE
PRINCETON LARGE TORUS

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Calculated Neutral Beam Deposition and Velocity Space
Loss Regions for the Princeton Large Torus

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ABSTRACT

The radial profiles of hot ion birth rates for injection of H^0 and D^0 with energies of 20, 40, and 60 keV have been calculated for PLT. For tangential injection a centrally peaked hot ion birth profile requires a beam at least as penetrating as 40 keV H^0 . Somewhat more peaked deposition is possible with nearly perpendicular injection. The velocity space boundaries separating confined drift orbits and lost drift orbits are shown. H^+ ions launched near the magnetic axis with an energy of approximately 0.5 MeV are confined, and the best confinement is at major radii somewhat smaller than the magnetic axis. Significant confinement of α particles from D-T reactions or T particles from D-D reactions is predicted.

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INTRODUCTION

In preparation for neutral beam injection into the Princeton Large Torus Tokamak, the methods developed at the Oak Ridge National Laboratory have been used to investigate tangential injection of H^0 and D^0 at several energies and fixed injection geometry. The method will be briefly described before showing the tangential injection results. With further approximations we will then discuss the injection of a 40 keV H^0 beam nearly perpendicular to the toroidal field. Finally, we will describe the calculation of the velocity space boundaries between the group of ions born at a particular point which remain within the plasma boundary and the group which hits a circular limiter. These calculations show that perpendicular injection will not be seriously affected by the loss regions.

HOT ION BIRTH RATE

The hot ion birth rate in units of ions $\text{cm}^{-3} \text{sec}^{-1}$ per equivalent ampere of injected neutral beam has been calculated as a function of distance from a line representing the center of the hot ions' drift orbits approximated for parallel injection, the so-called stagnation line. This function is then re-averaged to yield the birth rate averaged over a flux surface. The present method is a modest extension of the method in Ref. 1. Within the approximations of concentric circular contours of density and temperature and of concentric circular drift surfaces, arbitrary electron density profiles and arbitrary constant area beam profiles

can be specified. With the current density profile specified as $J(r) \propto [1 - (r/a)^N]^M$, where N and M are integers, and assuming $T_e(r) \propto [J(r)]^{2/3}$, the orbit shift X_s is approximately calculated. The fraction of the input beam which is retained in the plasma is computed both by integrating the birth rate and by calculating the attenuation through the contained orbit region of several pencil beams comprising the injected beam. These numbers are consistent to 1%.

First consider the contribution of one pencil beam to the birth rate at distance ρ from the stagnation line and major radius R . The pencil beam is defined by its height above the midplane z_B and its tangent radius R_B , which is the distance between the machine centerline and the point where the pencil beam is tangent to the toroidal field. Defining $\dot{n}(\rho)$ as the ions per second per amp deposited along the path increment dS over the volume element $dv = 2\pi(R_O + X_s)2\pi\rho d\rho$, it is shown in Ref. 1 that

$$\dot{n}(\rho) = \frac{I_B}{e} \frac{1}{\lambda(r)} \exp\left[-\int_{-S_{\max}}^S \frac{dS}{\lambda(S)}\right] \times$$

$$\times \frac{1}{4\pi^2 (R_O + X_s)} \frac{R}{\rho (R^2 - R_B^2)^{1/2}} \frac{\rho}{(\rho^2 - z_B^2)^{1/2}}$$

where $r = [(R - R_O)^2 + z_B^2]^{1/2}$, R_O is the location of the magnetic axis, $S = 0$ at the tangent point, $S_{\max} = (R_{\max}^2 - R_B^2)^{1/2}$; R_p is the plasma minor radius; $|dS| = R dR (R^2 - R_B^2)^{-1/2}$; and λ is the neutral beam mean free path for the combined processes of ion impact ionization, electron impact ionization, and charge exchange.

In this expression, there are integrable singularities which are "subtracted out" during computation. The singularity at $\rho = 0$ for $Z_B = 0$ produces a peaked hot ion profile if enough of the beam reaches the vicinity of the stagnation axis, as shown in Ref. 1.

The above formula is incomplete, because for each pencil beam there could be two values of R which might contribute to a given ρ , and each of these two values of R could be reached on both the inward and outward segments of a given pencil beam. Refer to Fig. 1, which explains the relation between R_1 and R_2 , the inner and outer major radii corresponding to a given ρ , and R_{B1} and R_{B2} , the inner and outer major radii of the distribution of pencil beams at height Z_B comprising the actual injected beam, which is taken to be circular as an example in Fig. 1. If R_B is between R_1 and R_2 , then that pencil beam can only contribute twice to that shell of a given ρ at one value of R on the inward and outward half of its path.

The actual injected beam is distributed over some cross section such that the total beam current $I_B = \iint dR_B dZ_B J(R_B, Z_B)$. The hot ion birth rate is normalized to the birth rate which would occur if the injected ions were all contained and were uniformly distributed throughout the plasma volume. For a beam symmetric with respect to the midplane, the integral over dZ_B runs from zero to the minimum of ρ or Z_{Bmax} and is then doubled by symmetry. The present program can also use beams which are not symmetric about $Z = 0$. For each pencil beam considered in the numerical integration, the quantity $-\int dS/\lambda$ is evaluated on the inward path

as I_1 and on the outward path as $I_2 + I_3$, where

$$I_1 = - \int_R^{R_{\max}} \frac{R dR}{(R^2 - R_B^2)^{1/2}} n_e(r) \sigma_T(r)$$

$$I_2 = - \int_{R_B}^{R_{\max}} \frac{R dR}{(R^2 - R_B^2)^{1/2}} n_e(r) \sigma_T(r)$$

$$I_3 = - \int_{R_B}^R \frac{R dR}{(R^2 - R_B^2)^{1/2}} n_e(r) \sigma_T(r)$$

The explicit formula for the birth rate is

$$H(\rho) = \frac{R_O R_p^2}{2I_B(R_O + X_S)} \left\{ \int_{Z_{CB}}^{\min(Z_{Bmax}, \rho)} \frac{dZ_B}{(\rho^2 - Z_B^2)^{1/2}} + \int_{\min(Z_{Bmin}, \rho)}^{Z_{CB}} \frac{dZ_B}{(\rho^2 - Z_B^2)^{1/2}} \left[\int_{R_{B1}}^{\min(R_1, R_{B2})} \frac{R_1 dR_B}{(R_1^2 - R_B^2)^{1/2}} \frac{1}{\lambda(R_1, Z_B)} J(R_B, Z_B) \right. \right.$$

$$\left. \left\{ \exp [I_1(R_1, Z_B, R_B)] + \exp (I_2 + I_3) \right\} U(R_1 - R_{B1}) + \right.$$

$$\left. \int_{R_{B1}}^{\min(R_2, R_{B2})} \frac{R_2 dR_B}{(R_2^2 - R_B^2)^{1/2}} \frac{1}{\lambda_2} J \times [\exp(I_1) + \exp(I_2 + I_3)] U(R_2 - R_{B1}) \right\}$$

where some of the arguments have been omitted, and U is the Heaviside step function. The center of the beam is assumed to be above

the midplane, i.e., $Z_{CB} \geq 0$. Once the contours of $H(\rho)$ have been obtained, the flux surface averages $\langle H(r, \theta) \rangle = H_{avg}(r)$ are found by averaging $H(\rho)$ over circles centered on the magnetic axis.

$$H_{avg}(r) = (1/2\pi) \int_0^{2\pi} d\theta H(\rho = [r^2 + x_s^2 - 2rx_s \cos\theta]^{1/2}).$$

The mean free path is computed once as a function of r and stored in a table. The rate coefficient for electron impact ionization is fitted by four point Lagrangian interpolation in $\log T_e$. This provides an adequate fit from $T_e = 0.1$ to 1.0 keV for the case where the beam velocity is ignored relative to the electron thermal velocity. For practical cases, the most important processes are charge exchange and ion impact ionization. These are evaluated by the formulas in Ref. 2, which states

$$\log_{10} \sigma_i = -0.8712 K^2 + 8.156 K - 34.833$$

$$\sigma_{cx} = (0.6937 \times 10^{-14}) (1 - 0.155 K)^2 / [1 + 0.1112 \times 10^{-14} (E/m/m_p)^{3.3}]$$

where $K = \log_{10}(E/m/m_p)$, and E is the beam energy in electron volts.

TOROIDAL SHIFT OF MAGNETIC AXIS

A further approximation inherent in the assumption of circular flux surfaces is the assumed centering of the magnetic

axis within the circular limiter defining the plasma. In fact, the magnetic axis is shifted outside of the discharge centerline. This shift can be estimated using Eq. (18) of Ref. 3 with $\gamma = 0$ to represent the motion of electrons. This equation assumes a uniform current density and neglects toroidal effects in the computation of A_ϕ . Defining S_1, S_2 as the distances in the mid-plane, normalized to the magnetic axis radius, from the magnetic axis (M.A.) to the outside and inside of the plasma in the mid-plane, β as the quantity [(centerline radius/plasma minor radius) - 1], and R_{CL} as the distance from the centerline to the center of the circular limiter, one can solve the three equations

$$\frac{(1 + S_1) + (1 - S_2)}{2} R_{MA} = R_{CL}$$

$$\frac{S_1 + S_2}{2} R_{MA} = R_P$$

$$(1 + S_1)S_1^2 = (1 - S_2)S_2^2$$

to obtain

$$S_1 = \frac{-\beta^2 + [\beta^4 + 2\beta(3\beta^2 + 6\beta + 4)]^{1/2}}{3\beta^2 + 6\beta + 4}$$

$$S_2 = (2 - \beta S_1)/(\beta + 2)$$

$$R_{MA} = R_{CL} \cdot 2/(S_1 + S_2)$$

Substituting the numbers appropriate for PLT where $R_P = 45$ and $R_{CL} = 130$, one obtains $R_{MA} = 138$ cm. For the present calcula-

tions this effect is ignored and the flux surfaces are assumed to be circular with the magnetic axis at the center of the discharge chamber.

STAGNATION POINT

The stagnation point is that point where an ion launched with the appropriate angle with respect to the toroidal plasma current will have infinitesimal drift orbit. This point is calculated in Ref. 3 for a uniform current density. The location of the stagnation point can be estimated for ions launched with $v_{\perp} = 0$ in a nonuniform current distribution by balancing the curvature drift against the azimuthal speed which an ion would need to follow a field line.

Then if R_p is the plasma minor radius, the orbit shift will be $x \times R_p$, where x satisfies

$$\frac{\int_0^x J(x') x' dx'}{\int_0^1 J(x') x' dx'} = 1445 \cdot \frac{x}{2} \frac{R_p}{R_o} \frac{1}{I_{amp}} (W \text{ eV } m/m_p)^{1/2} = \frac{x}{2} \frac{R_o}{R_p} \gamma$$

where γ is defined in Ref. 3, p. 376.

TANGENTIAL INJECTION INTO PLT

Several cases of tangential injection into PLT are shown in Figs. 2 through 6. The plasma parameters are as follows:

$$R_o = 130 \text{ cm}$$

$$R_p = 45 \text{ cm}$$

$$I_p = 1000 \text{ kA}$$

$$n_e = n_e(0) \cdot \{0.8[1 - (r/a)^3] + 0.2\}$$

$$J(r) = J(0) [1 - (r/a)^2]$$

$$T_e(r) = 2500 [J(r)/J(0)]^{2/3}$$

$$\text{plasma volume/e} = 1.67 \times 10^{12}$$

$$\text{beam radius} = 10 \text{ cm, uniform profile.}$$

Several energies of H⁺ and D⁺ from 20 to 60 keV, several beam tangency points from 100 to 140 cm, and several peak densities from 6 to 12 x 10¹³ cm⁻³ are considered in Figs. 2 - 6. The plotted quantities are the hot ion creation rates normalized to the value that would result from complete containment of the injected beam and uniform distribution of the fast ions throughout the plasma. It is clear that 20 keV injection results in much higher power densities at the edge of the plasma than at the center, and the situation is especially bad for D⁺ injection. This is contrary to the goal of achieving the highest central temperature and may result in an inverted temperature profile. Lowering the central density can be helpful, as can aiming the beam at a steeper angle.

In order to obtain higher power densities in the center, nearly perpendicular injection was considered. For this calculation, the same program was used but the orbit shift was set equal to zero. Thus the resultant information is the rate density of ionization on a circular flux surface and ignores the deviation of the ion motion from the flux surfaces. This does not result in an error due to the loss of particles by large banana orbits, because the loss region in velocity space begins at about

1/2 MeV for the center of PLT. However, ions launched nearly perpendicularly will not spread uniformly around a flux surface, which is known to lead to the possibility of poloidal electric fields.

In Fig. 7 we see the results for direct perpendicular injection of a 40 keV H^0 beam of radius 10 cm and a peak electron density of 5, 10, and $15 \times 10^{13} \text{ cm}^{-3}$. For these cases, the fractions ionized are 80%, 96%, and 99%, respectively. The total fraction trapped is somewhat less because the outside edges of the beam in the midplane are injected slightly co and counter and are lost if ionized at large minor radii, but this will not affect the central values of the ionization profiles. Peaked deposition profiles are obtained even at quite high electron density.

VELOCITY SPACE LOSS REGIONS

In order to support the statement that the central region of PLT will contain 0.5 MeV H^+ ions, we will briefly discuss a method of rapidly characterizing all possible ion orbits in tokamaks. This approach has been given considerable attention at the Oak Ridge National Laboratory by Rome and his collaborators, who will describe it in more detail elsewhere.⁴

Neglecting scattering or acceleration by the toroidal E field, an ion will follow a path such that

$$R_O \frac{Ze}{c} A_\phi + mV_\phi R = \text{constant}.$$

on its drift orbit, where circular flux surfaces have been assumed. This can be re-written as

$$F(r/R_p) \mp \alpha R/R_o (1 - \sin^2 \theta_1 R_1/R)^{1/2} = \text{constant}$$

where

$$F(x) = 2 \left[\int_0^{xR_p} (dr'/r') \int_0^{r'} J(r'') r'' dr'' \right] / \int_0^{R_p} r' J(r') dr'$$

and

$$\alpha = 1.444 \cdot (W \text{ eV } m/m_{\text{proton}})^{1/2} / Z I_p (\text{amps})$$

The - sign is for ions circulating (co-) parallel to the plasma current, and the + sign is for the antiparallel or counter streaming ions. For a given ionization point in the midplane at the major radius R_1 and a given initial pitch angle θ_1 , we wish to find the values of α separating the contained and lost orbits. If S is the path length along the orbit, $\partial/\partial S(R_o A_\phi) = 0$ implies that the ion is at the midplane for the present choice of circular flux surfaces. Thus $R_o A_\phi$ which measures the distance from the magnetic axis, reaches its maximum and minimum values for the orbit in the midplane.⁵ There are several possible ways for an ion orbit to go outside the limiter: (a) it may begin as either a co or counter orbit and strike at $Z = 0$, $R \geq R_o + R_p$ on the co orbit branch; (b) it may begin as a counter orbit and strike at $R \leq R_o - R_p$; (c) it may begin as a counter orbit, reach a mirror point, and be lost on the co-orbit branch. It is necessary to reject spurious solutions of the orbit equation which do not connect with the injection point. In case (c) the velocity space

boundary at a given angle is determined by the existence of a "pinch point" where the orbit is tangent to the midplane and which corresponds to the "World's Fattest Banana³," except for those angles for which a trajectory pinches but does not reach $R_0 + R_p$. For those angles the energy is found from the assumption that the orbit will strike $R_0 + R_p$ on the co branch. Under the present assumption of circular flux surfaces it is straightforward to solve for the initial pitch angle which will result in a pinch point at a given major radius smaller than the initial one, and then from this angle the corresponding value of α may be determined. However, there may not be a pinch point possible at every major radius between $R_0 - R_p$ and R_1 .

The equations for the normalized velocity for cases (a) and (b) above are:

$$\alpha_{\pm} = \frac{F(R_p) - F(R_1)}{(R_1/R_0 \cos\theta) \pm (1 \pm R_p/R_0) \{1 - [R_1 \sin^2\theta / (R_0 \pm R_p)]\}^{1/2}}$$

where + refers to case (a) and - to case (b). Case (c) is somewhat more involved.

If one is given the initial ionization point R_1 and the initial pitch angle θ , then if a pinch occurs at R we have

$$\alpha_{\text{pinch}} = \frac{[d/dr F(r)]_{R_0} (1 - R_1 \sin^2\theta/R)^{1/2}}{1 - R_1 \sin^2\theta/2R}$$

It is more useful to be given the location of a pinch point, solve for the required initial pitch angle, and then find the required value of α . If $x = \sin^2\theta$, the equation for x is

$$\frac{F(r_1) - F(r)}{R_0 \frac{d}{dr} F(r)} \left(1 - \frac{1}{2} \frac{R_1 x}{R}\right) - \frac{R}{R_0} + \frac{R_1 x}{R_0} = \frac{R_1 (1 - x)^{1/2}}{R_0} \left(1 - \frac{R_1 x}{R}\right)^{1/2}.$$

Then if we define

$$G = [F(r) - F(r_1)]/[R(d/dr) F(r)]$$

$$A = \left(1 + \frac{1}{2} G\right)^2 - \frac{R_1}{R}$$

$$B = \left(1 + R_1/R\right) - R/R_1 (G + 1)(G + 2)$$

$$C = [R/R_1 (G + 1)]^2 - 1$$

we obtain

$$x = \sin^2 \theta = [-B + (B^2 - 4AC)^{1/2}]/2A$$

There may be no solution, in which case there is no pinch at the assumed value of R .

The procedure for producing the accompanying graphs is as follows: (1) test for the existence of a pinch point at $R_0 - R_p$ with corresponding initial pitch angle θ_{pinch} ; (2) if there is such a pinch, for $\pi \geq \theta_1 \geq \theta_{\text{pinch}}$ solve for α under assumption (b) above; (3) starting at $R_0 - R_p$, find the pinch angles and values of α assuming pinches at successively larger values of the major radius R until the pinched orbits do not reach $R_0 + R_p$; (4) for smaller angles down to zero, solve for α under assumption (c) or (a) above. If there is no pinch possible at $R_0 - R_p$, try larger values of R until such an orbit is found, then proceed as before.

Figures 8 - 12 show the boundaries between lost and contained particles for H^+ ions in PLT under the assumptions that $R_0 = 130$ cm, $R_p = 45$ cm, and $I = 1$ MA. The initial ionization points in the midplane are identified in Figs. 8 - 11 by their distance outside (+) or inside (-) the magnetic axis normalized to the minor radius, and the current is assumed to be parabolic in r . The velocities are normalized to the value shown on the graph. A comparison of Figs. 8 - 10 shows that the loss region for a given initial minor radius is worse on the outside than on the inside of the magnetic axis. Figure 11 investigates several ionization points inside of the magnetic axis. As the initial major radius is varied from R_0 to $R_0 - 0.4 \times R_p$ in steps of $0.1 \times R_p$, the lowest energy on the loss boundary takes the values 716, 789, 847, 841, and 747 keV for the parabolic current profile of Fig. 11. Figure 12 shows the effect of increasing the peaking of the current profile, assumed to be of the form $[1 - (r/R_p)^N]^M$, from flat to $[1 - (r/R_p)^2]^3$. The lowest lost energy increases as the peaking increases, as one would expect. If one considers α particles launched in the center at 3.5 meV under the conditions of Fig. 12, the loss regions are $51.0^\circ - 139.7^\circ$, $81.4^\circ - 124.0^\circ$, $89.8^\circ - 119.2^\circ$, and $94.7^\circ - 116.1^\circ$ for the four increasingly peaked current profiles. Thus one could estimate that the fraction of alphas contained immediately upon creation at the magnetic axis would be 30%, 65%, 76%, and 84%.

One can estimate the radial variation of the initially contained fractions of alpha particles by using the results for initial ionization in the midplane for R greater than R_0 . For the choice of parabolic current profile; the angular regions of

lost alpha particle orbits for $rb/R_p = 0, 0.2, 0.4, 0.6,$ and 0.8 are $81.4^\circ - 124.0^\circ, 85.0^\circ - 131.2^\circ, 85.1 - 180^\circ, 83.1 - 180^\circ,$ and $79.8 - 180^\circ$. The corresponding fractions of initially contained alpha particles are 65%, 63%, 46%, 44%, and 41%. A sizeable fraction of the initially contained ions will diffuse into the loss region before slowing down, but this will not be calculated here. Because the orbits scale as the square root of (energy x mass) divided by (ion charge x plasma current), the 1.01 MeV tritons produced by D-D reactions will be somewhat better confined than the alpha particles considered above. A sufficient number of tritons might be produced and retained during the injection of an energetic deuterium beam into a deuterium plasma so that D-T reactions between the background ions or the injected ions with tritons could occur at a detectable rate. Comparing the count rate for 2.45 MeV neutrons from D-D reactions with the count rate for 14.1 MeV neutrons might prove a usable diagnostic for such quantities as the triton confinement time.⁶

CONCLUSIONS

Detailed calculations have been made of the radial hot ion birth profiles for the specific case of neutral beam injection into the Princeton Large Torus. In order to achieve the maximum heating near the magnetic axis, a tangentially injected beam must be at least as penetrating as 40 keV H^0 . The radial birth profile is much worse for D^0 than for H^0 at the same energy. A peaked profile for the ionization of the injected beam is much

easier to obtain with nearly perpendicular injection than with tangential injection. Perpendicular injection may suffer from an initially nonuniform poloidal distribution of fast ions, but the losses of hot ions born near the magnetic axis due to large banana orbits will not be a problem in PLT. In fact, there will be fair confinement of 3.5 MeV alpha particles from D-T reactions and of 1.01 MeV tritons from reactions of plasma D ions with either a thermal D ion or an energetic injected D ion. This confinement of tritons may provide new diagnostic possibilities.

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⁴To be published.

⁵R. Goldston, private communication.

⁶F. H. Tenney, K. K. Tang, and D. L. Jassby. These authors followed the detailed trajectories of orbits launched at many angles from specified points in the plasma.

746107

Fig. 1. The relationship between the tangent radius and height, R_B and Z_B , which characterize a particular pencil beam and a particular drift surface at radius, ρ from the stagnation line.

753170

Fig. 2. Normalized hot ion birth rates for H° injected parallel to the plasma current for the energies of 60, 40, and 20 keV.

746109

Fig. 3. Normalized hot ion birth rate for H° injected antiparallel to the plasma current for the energies of 60, 40, and 20 keV.

746104

Fig. 4. Normalized hot ion birth rates for D° injected both parallel and antiparallel to the plasma current at energies of 20 or 40 keV.

746129

Fig. 5. Normalized hot ion birth rates for 40 keV H° injected parallel to the plasma current for peak electron densities of 6, 8, 10, and $12 \times 10^{13} \text{ cm}^{-3}$. The injected beam is aimed at 130 cm for this and preceding figures.

746106

Fig. 6. Normalized hot ion birth rates for 40 keV H° injected parallel to the plasma current for beam aiming points of 100, 120, 130, and 140 cm from the machine centerline.

746103

Fig. 7. Normalized ionization rates neglecting orbit shift for 40 keV H^+ injected nearly perpendicular to the toroidal field for peak electron densities of 5, 10, and $15 \times 10^{13} \text{ cm}^{-3}$.

746100

Fig. 8. Velocity space boundary between confined and lost ions for R_B greater than R_O . $R_O = 130 \text{ cm}$, $R_B = 45 \text{ cm}$, $I = 1 \text{ MA}$. Both parallel and antiparallel velocities are shown. The minimum energies for $R_B = 139, 148, 157, \text{ and } 166 \text{ cm}$ are 515, 297, 123, and 27 keV, respectively.

746101

Fig. 9. Velocity space boundary between confined and lost ions for R_B less than R_0 . Plasma parameters the same as Fig. 8. The minimum energies for $R_B = 121, 112, 103, \text{ and } 98 \text{ cm}$ are 847, 747, 396, and 97 keV, respectively.

753116

Fig. 10. Velocity space boundary between confined and lost ions for birth points above the midplane at $R = R_0$. The minimum energies for $Z_B = 0, 9, 18, 27, \text{ and } 36 \text{ cm}$ are 716, 611, 387, 175, and 40 keV, respectively.

746108

Fig. 11. Best confinement is for r/R_p between 0.2 and 0.3 for R_B less than R_0 . The minimum energies for $R_B = 130, 125.5, 121, 116.5$, and 112 cm 716, 789, 847, 841, and 747 keV, respectively.

746099

Fig. 12. Velocity space boundary between confined and lost ions for different current profiles for ions born on the magnetic axis. The plasma current is assumed to have a radial profile proportional to $[1 - (r/R_p)^N]^M$. The lowest curve is for a uniform current with $N = 1$, $M = 0$. As the current profile becomes more peaked, the minimum energies are 291, 716, 1121, and 1526 keV.

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