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ENHANCED PENETRATION OF NEUTRAL-BEAM-INJECTED IONS BY VERTICALLY ASYMMETRIC TOROIDAL-FIELD RIPPLE

BY

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ENHANCED PENETRATION OF NEUTRAL-BEAM-INJECTED IONS BY VERTICALLY ASYMMETRIC TOROIDAL-FIELD RIPPLE

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ABSTRACT

The penetration length of energetic neutral-atom beams injected into a tokamak plasma can be effectively increased by a large factor, if the beams are injected vertically and the toroidal magnetic field has significant ripple below the midplane. The energetic ions resulting from ionization of the fast neutrals are ripple-trapped and drift upward to the midplane region. The ripple must decrease substantially in the region above the midplane, so that the ions can be captured and retained in the central plasma region during their entire slowing-down period. Orbit calculations with a Monte Carlo guiding-center code demonstrate the feasibility of this trapping process. 110 to 150-keV deuterons can be deposited near the center of plasmas with $\langle n_e \rangle a\, Z_{eff} \sim 10^{17}\ \mathrm{cm}^{-2}$, when the ripple near the magnetic axis and in the region below is of order 1%.

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1. INTRODUCTION

The neutral-beam energy, W_o, required for satisfactory penetration of large tokamak plasmas varies roughly as $\langle n_e \rangle a Z_{eff}$, where $\langle n_e \rangle$ is the spatially-averaged electron density, a is the plasma radius, and Z_{eff} is the effective ionic charge. For $\langle n_e \rangle a Z_{eff} \gtrsim 2 \times 10^{16}$ cm^{-2}, W_o for deuterium atoms must be at least several hundred kilovolts [1]. The production efficiency of D^o beams formed from positive ions decreases rapidly for $W_o > 60$ keV, unless direct recovery methods can be developed, and even this technique permits good overall efficiency only for $W_o \lesssim 200$ keV [2]. For larger energies, high efficiency is attainable, in principle, with the use of negative ion beams, but the practical production of high-current D^- beams has not been demonstrated.

In this paper, we describe a technique for achieving adequate penetration, by energetic ions formed from neutral-atom beams of relatively moderate energy, into tokamak plasmas of nearly arbitrarily large $\langle n_e \rangle a Z_{eff}$. The proposed technique takes advantage of the azimuthal toroidal-field (TF) ripple, and relies on vertical injection of the neutral beams, as shown schematically in Fig. 1. In usual tokamak operation, the TF ripple is symmetric about the horizontal midplane. Energetic ions trapped in the mirror field between TF coils drift vertically in the $\vec{B} \times \vec{\nabla} B$ direction, and consequently can escape the plasma, unless they are first detrapped by collisional scattering [3]. The essential feature of the present scheme is that the TF ripple is large in the region below the midplane, at least in the shaded region of Fig. 1, but is very small in a substantial region above the midplane. Thus energetic ions formed from vertically injected

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Line 12 should read as follows:

$\ldots\gamma = (\Delta B/B)^{1/2} = 0.12\ldots\ldots$

neutral beams are mirror-trapped and drift upward to the midplane region, but no further; thereupon, they take up a variety of banana-type orbits. The ripple requirement for adequate penetration is calculated in Sect. 2 of this paper. Illustrative deuteron trajectories calculated with a Monte Carlo guiding-center code are presented in Sect. 3.

The vertically asymmetric ripple can be provided by specially designed TF coils, or by auxiliary coils that provide variable ripple. The latter option is more useful if Z_{eff} varies with time during the injection or if the enhanced ripple is to be terminated during a thermonuclear burn. Practical embodiments are summarized in Sect. 4.

The ripple-assisted injection technique may be most appropriate for beam-driven systems of relatively small Γ = fast-ion pressure/bulk-plasma pressure, so that the purely perpendicular injection does not give rise to velocity-space instability that would pitch-angle scatter the incoming energetic ions, and destroy their mirror trapping [4]. Potential practical applications of the ripple-injection technique are discussed in Sect. 5.

2. RIPPLE REQUIREMENT

2.1 THE TRAPPING PROCESS

Consider an energetic deuterium atom injected vertically between TF coils into a tokamak plasma with geometry shown in Fig. 1. The atom is ionized, mirror-trapped, and drifts upward with velocity

$$v_z = 1.0 \times 10^{11} \frac{W}{RB_t} \qquad (1)$$

where W is the ion energy (in keV), R is in cm, and B_t is the toroidal-field strength (in G). (Reversing the direction of the toroidal field causes the ion to drift downward.) We assume that the magnitude of the TF ripple has a strong z-dependence, and define

$$\varepsilon(r,\theta) = \frac{2(B_{max} - B_{min})}{B_{max} + B_{min}} \qquad (2)$$

In order to escape the mirror, an ion must be scattered through an angle $\delta\gamma \sim (\varepsilon)^{\frac{1}{2}}$. An ion will reach the midplane provided that during its journey, $\varepsilon(z<0) > \varepsilon(0) = \varepsilon_o$, and that $\delta\gamma(z<0) < (\varepsilon_o)^{\frac{1}{2}}$. We also require that ε decrease rapidly for z>0, in order to insure detrapping, and elimination of drift in the region above the midplane. In regions where the ripple is sufficiently small, all ions — no matter how small $v_{||}/v$ —follow banana orbits [3]. In such "symmetric trapping" regions, trapped ions have no time-averaged vertical drifts. At $\theta = -\pi/2$, the condition for symmetric trapping is that $\varepsilon < 2r/NqR$, where N is the number of TF coils [3]. By suitable choice of the spatial dependence of ripple, we can localize the symmetric trapping region to $z > 0$. Figure 2 shows illustrative ripple contours, and the boundary of the symmetric trapping region when $q_o = 1.0$ and $q_a = 3.0$. Sufficiently energetic ions injected vertically from the bottom drift upward to this boundary, and then take up banana orbits. (These contours were formed by displacing to positive z and smaller R, a symmetric ε(r) of the form e^{r/r_o}. The ripple contours in present tokamak designs (e.g., PLT, TFTR) can be approximated by a symmetric ε(r) shifted to smaller R.)

An ion born near the bottom of the torus drifts to the horizontal midplane without scattering into a banana orbit at $z < 0$, if

$$\frac{a}{v_z} \lesssim \varepsilon_o \tau_{sc} \tag{3}$$

where τ_{sc}, the scattering time for a magnetized particle with $v_{||}/v = 0$, is [5]

$$\tau_{sc} = 3.4 \times 10^{11} \frac{A^{1/2}\, W^{3/2}}{\ln \Lambda\, n_e\, Z_{eff}} \tag{4}$$

Here A is the atomic mass of the injected ions, $Z_{eff} = \Sigma n_i Z_i^2 / n_e$, and $\ln \Lambda$ is the Coulomb logarithm. Combining (1), (3), and (4), we obtain

$$\varepsilon_o \gtrsim 2.9 \times 10^{-23} \frac{n_e\, a\, Z_{eff}}{W^{5/2}} RB_t \frac{\ln \Lambda}{A^{1/2}} \tag{5}$$

(The maximum ripple, near the bottom of the torus, may be significantly larger than ε_o, but the precise nature of $\varepsilon(z)$ is of secondary importance.)

As an illustrative example, we take parameters typical of "EPR" designs [6]: $R = 600$ cm, $B_t = 50$ kG, $\ln \Lambda = 20$, $A = 2$. Then

$$\varepsilon_o \gtrsim 1.24 \times 10^{-14} \frac{n_e\, a\, Z_{eff}}{W^{5/2}} \tag{6}$$

with W in keV. Figure 3 shows the variation in ε_o calculated using an equality sign in Eq. (6). The trapping length, λ_t, of neutral beams of energy W_o is, approximately, $\lambda_t \propto W_o/(n_e Z_{eff})$. In the conventional injection method, barely acceptable penetration is possible for $\lambda_t/a = \frac{1}{4}$ [7], which is indicated by the contour $\lambda_t/a = (1/4)$ in Fig. 3. Evidently, ripple-assisted injection allows the heating of large, dense plasmas by neutral beams with energy many times smaller than those required in the conventional method. With $\varepsilon_o \sim 0.01$, beam energies in the range 120-150 keV are apparently adequate even for the largest, most dense plasmas with high impurity content.

2.2 ADVERSE EFFECTS OF LARGE RIPPLE

A minimum ripple is required at $z < 0$ in order that magnetic wells persist when q is small. There is some incentive to increase ε well above this minimum, so that W_o can be reduced. However, the required W_o varies only as $\varepsilon_o^{-2/5}$ [cf. Eq. (5)], and for most applications involving D-T plasmas, it is best to use $W_o \gtrsim 100$ keV, in order to maximize the beam-target fusion reaction rate.

One adverse effect of a large ripple, whether or not it is vertically symmetric, is that the banana orbits of ions tend not to close. In the presence of a magnetic well, an ion may spend larger or smaller amounts of time at the tips of its banana, depending on its phase with respect to the ripple; this lingering period determines the extent of its radial drift at the banana tips. This effect is most important for very energetic ions, such as D-T alpha particles (3.5 MeV), whose asymmetric unclosed bananas may "walk out" of the plasma. Even for an exceedingly large ripple, only alphas that are banana-trapped at birth could be lost in this way. (Note that fusion alphas do not scatter significantly before losing 80% of their energy.)

Another unfavorable effect is ripple-induced particle and heat diffusion of the bulk plasma [8]. However, such diffusive losses tend to scale inversely with $n_e Z_{eff}$, and may be unimportant for applications requiring ripple-assisted injection. In particular, ripple-induced diffusive losses are insignificant when $\varepsilon \sim 0.01$ and $\langle n_e \rangle a\, Z_{eff} \gtrsim 2 \times 10^{16}\ \mathrm{cm}^{-2}$ [8,9].

3. ORBIT CALCULATIONS

3.1 CALCULATIONAL MODEL

Ion trajectories have been calculated by numerical integration of the standard guiding-center equations of motion for a torus with rotational transform [10]. The TF ripple is included in the expression for the toroidal field:

$$B_t(r,\theta,\phi) = \frac{B_o R_o}{R} \left[1 + \frac{1}{2}\varepsilon(r,\theta) \cos(N\phi)\right]. \qquad (7)$$

Here, B_o is the toroidal field on the magnetic axis $(R = R_o)$. The particle drifts in the gradient and curvature of the ripple and poloidal fields are not included in the guiding-center motion. At each r, the rotational transform is specified in order to generate concentric flux surfaces containing the field lines that define the "parallel" motion of particles.
In these calculations, we use a current-density profile $J = J_o(1 - r^2/a^2)^2$, so that $q(r = a) = 3.0$ when $q(r = 0) = 1.0$.

The injected energetic ions undergo Coulomb collisions with the bulk ions (including impurities) and with electrons. The effects of these collisions are calculated at each time-step, Δt, along the ion orbit, using the local Fokker-Planck equation averaged over the cyclotron motion [5]. The fast ions are slowed on bulk ions and on electrons, and their pitch-angle scattering is simulated using a random-number generator weighted with the short-time propagator of the angular scattering operator:

$$P(\zeta) \propto \exp\left\{-\frac{(\zeta-\zeta_o)^2\tau_{sc}}{2(1-\zeta_o^2)\Delta t}\right\}, \quad \zeta = \frac{v_{\parallel}}{v} \tag{8}$$

The orbit calculations employ the plasma parameters listed in Table 1. These parameters are typical of "EPR" designs [6], with the temperature appropriate for the heating stage. The temperature profile is $T_e(r) = T_{ec}\exp[-2.0(r/a)^2]$, while the density profile is $n_e(r) = n_{ec}[1-(r/a)^2]$. There are 18 toroidal-field coils.

3.2 ENERGY DEPENDENCE OF PENETRATION

In this section, we present the guiding-center trajectories of ions formed from neutral beams of energy W_o injected vertically at $\theta = -\pi/2$, and ionized at $r = 160$ cm $(r/a = 0.80)$. The ripple contours are displayed in Fig. 2. Figure 4 shows the initial trajectories of ions at various W_o. Evidently, ions with $W_o \lesssim 100$ keV are pitch-angle scattered from the ripple-trapped regime before they can reach the boundary of the symmetric trapping region. Ions with $W_o \gtrsim 110$ keV do reach this boundary, and take up banana orbits.

(The orbits of various ions of the same W_o differ, of course, because of the random nature of the scattering process. For the conditions of Table 1, most ions with $W_o \geq 110$ keV reach the central plasma region, while most ions with $W_o < 100$ keV do not.)

Table 1.

PLASMA PARAMETERS USED IN THE ORBIT CALCULATIONS

R_o = 6.0 m

a = 2.0 m

B_t = 5.0 T on axis

I_p = 5.5 MA

q_o = 1.0

q_a = 3.0

T_{ec} = 5.0 keV

n_{ec} = $2 \times 10^{14} \text{cm}^{-3}$

Z_{eff} = 1 to 10

In the present example, $\langle n_e \rangle a\, Z_{eff} = 1.1 \times 10^{17}$ cm^{-2}, where $\langle n_e \rangle$ is the radially averaged electron density, and $\varepsilon_o \approx 0.010$. According to the approximate analysis of Sect. 2, which is represented by Fig. 3, the minimum W_o for complete penetration should be 110 to 115 keV, which is in good agreement with the results of the guiding-center code. The strong energy-dependence of penetration for $W_o < 110$ keV, as predicted by Eq. (5), is quite evident from the results displayed in Fig. 4.

Figure 5 shows various stages in the lifetime of an ion injected at 120 keV. After the ion is first trapped in the central region, its banana orbit gradually increases its angular extent (in θ), because of pitch-angle scattering. Finally, this ion becomes a passing particle at relatively small minor radius, and remains in the central region until it is thermalized. (We often observe that on the lower part of one of its banana orbits, an ion may find itself ripple-trapped for a short time, so that it again drifts upward, and takes up a banana orbit at smaller r.)

Figure 6 shows the orbits over the slowing-down periods of energetic ions formed from neutral beams of various energies. If W_o is very much larger than the minimum value required for trapping near $r = 0$ (say, $W_o > 150$ keV), the energetic ions are often lost before completely thermalizing [Fig. 6(g),(i)]. This loss occurs partly by the same process (discussed in Sect. 2.2) that damages alpha-particle confinement, and partly because the symmetric trapping region in the present example does not extend to sufficiently small θ, so that ions at $z > 0$

can still drift significantly upward [Fig. 6(g)]. In practice, this loss could be minimized by establishing field ripple in as few regions around the torus as absolutely necessary. A favorable phenomenon, illustrated in Fig. 6(b), is that ions with initial energies slightly smaller than 110 keV can be ripple-trapped several times, and eventually these ions work their way toward the center. We find that for a given set of plasma conditions, ions with energy in the range given by Eq. (5) with an equality sign are always confined until they thermalize.

We emphasize that it is essential to maintain a symmetric trapping region in the upper part of the plasma cross section. If the ripple were symmetric about the horizontal midplane, a certain fraction of the injected ions would always drift to the top, because of the random nature of pitch-angle scattering. Furthermore, an ion just scattered out of the ripple-trapping band may diffuse back to this band and again drift upward; this process can be repeated several times. Finally, after the ion becomes a passing particle, if $Z_{eff}>>1$ it can again be trapped in a ripple well while still having appreciable energy, and the symmetric trapping region is once more essential to prevent significant upward drift.

3.3 INJECTION ANGLE

Practical injector systems have finite beam divergence. We now examine the penetration of ions injected at small angles $\gamma = v_{||}/v_o$ with respect to the vertical plane. Here $v_{||}$

is the velocity parallel to the toroidal field lines, and $v_o = (2W_o/M)^{1/2}$. Figure 7 shows the initial trajectories of 120-keV ions injected at various γ. Evidently, penetration is achieved for $\gamma \lesssim 0.06$, which corresponds to a total beam divergence $2\gamma \lesssim 120$ mrad (± 3.4°). Smaller beam divergence is easily achieved by practical injectors [11].

Except at $\theta = 0$ or π, the magnetic well depth is always reduced below the "vacuum" value by the slow 1/R variation in B along a field line. An expression for the actual well depth, $\Delta B/B$, is given by Eq. (3) of Ref. [8]. This expression predicts that the largest possible γ for ripple trapping at $\theta = -\pi/2$ and $q = 3.0$ is $\gamma = (\Delta B/B)^{1/2} = 0.012$. This value is in rather good agreement with our code results (Fig. 7), that indicate $\gamma \simeq 0.10$ for ions that are barely ripple-trapped at $r/a = 0.8$. The slight discrepancy is due to the fact that because of the 1/R variation in toroidal field, the minimum $|B|$ is not located directly between the field coils, while in the code, particle orbits are initiated directly between the coils.

4. IMPLEMENTATION OF ASYMMETRIC RIPPLE

There are three general methods of applying asymmetric TF ripple to a tokamak plasma:

(1) asymmetric positioning of the plasma column in a vertically symmetric ripple;

(2) special design of the TF coils;

(3) employing auxiliary coils with variable current.

These techniques are discussed briefly in the following.

4.1 ASYMMETRIC PLASMA POSITIONING

Figure 8 shows the (vertically symmetric) ripple contours of the TF coils of the proposed TFTR device [12]. By suitable positioning of the initial break-down plasma, and appropriate programming of the equilibrium-field coils, it is possible to form a plasma whose boundary is indicated by the dashed line in Fig. 8. (In the configuration shown in this figure, the beams must be injected from the top, but similar plasma positioning below the midplane is possible.) The ripple contours in the plasma are qualitatively similar to those of Fig. 2, and the symmetric trapping region has approximately the same relative position. If $\langle n_e \rangle = 10^{14}$ cm^{-3} and $Z_{eff} = 3$, the injection energy must be 60 keV.

The plasma position shown in Fig. 8 is not appropriate for quasi-stationary operation, but in a very large device, this method could be used to heat a D-T plasma to extremely high temperature, employing relatively low energy beams. Following this heating, the plasma would be moved rapidly to a more central position, and allowed to expand so that both its temperature and energy confinement time would be sufficiently large for ignition.

4.2 TF COIL DESIGN

The TF ripple will decrease monotonically with increasing z, if the coil thickness increases gradually with z. A coil design of the type shown conceptually in Fig. 9(a) is also convenient for injecting large neutral-beam power from the bottom.

The principal disadvantage of introducing asymmetric ripple by means of specially shaped TF coils is the lack of flexibility. If plasma conditions change drastically, the beam energy must be varied for optimal penetration. Another disadvantage is the permanent adverse effect on the orbits of alpha particles.

4.3 AUXILIARY COILS

Perhaps the most desirable method of introducing asymmetric ripple is by means of a set of auxiliary coil windings, whose current can be varied. The design approach described in Ref. [13] makes use of windings nestled inside the main TF coils, or wound about them. For the present purpose, an auxiliary coil would be located between the plasma and the bottom of each TF coil, as shown in Fig. 9(b). The ripple field tends to fall off very rapidly with vertical distance from the auxiliary coil. For example, when the ripple is a few tens of per cent at a position 1 m below the plasma (between two TF coils), the ripple drops from about 5% at the plasma edge to about 1% at the horizontal midplane, and to less than 0.2% at the upper edge of the plasma [13]. The auxiliary coils must be made of copper, in order that they can be placed as close as possible to the plasma, but the power dissipation would still be relatively small. Even in a reactor, the use of such coils is probably economically acceptable, especially if they are used with only a few TF-coil pairs, or employed only during initial heating.

5. APPLICATIONS

This section summarizes the potential reactor applications of the ripple-assisted injection technique.

5.1 INTENSELY BEAM-DRIVEN REACTORS

The power densities and wall loadings attainable in TCT-type operation in smaller-size plasmas ($\langle n_e \rangle a \sim 10^{16}\ \mathrm{cm}^{-2}$) with $\Gamma \sim 1$ are sufficiently large so that the conventional injection method is always adequate, provided that $Z_{eff} \lesssim 2$ [14,15]. The chief deleterious effect of moderate-to-high Z impurity ions in such reactors is reduced penetration of neutral beams. The ripple-assisted technique allows adequate penetration by 100-200 keV beams for $Z_{eff} >> 1$. Two caveats are (1) the possibility of exciting loss-cone instabilities by intense perpendicular injection [4], and (2) the limited access available in a small machine for vertical injection of several hundred megawatts. On the other hand, a large ripple is easily tolerated in TCT-type devices, where the plasma energy confinement time can be small, and the confinement of fusion alpha particles is not important [14].

5.2 BEAM-DRIVEN THERMONUCLEAR REACTORS

Sub-ignition thermonuclear plasmas providing $Q \gtrsim 5$ can be viable fusion reactors [14,16] provided that a method is found to assist the fusion alphas in maintaining the plasma temperature. These plasmas may be incapable of ignition because of radiation loss by an impurity population with $Z_{eff} >> 1$ [16]; typically, $\langle n_e \rangle a\, Z_{eff} \gtrsim 5 \times 10^{16} \mathrm{cm}^{-3}$. Ripple-assisted injection is ideally suited for providing the auxiliary heating with beams of moderate energy. A relatively small amount of beam power is required (compared with TCT devices), so that access should be quite feasible. But the ripple contours must be carefully chosen in order to minimize alpha-particle diffusion.

5.3 HEATING LARGE PLASMAS TO IGNITION

According to present speculation, the size of a tokamak plasma capable of reaching ignition is $\langle n_e \rangle a \gtrsim 2 \times 10^{16}$ cm^{-2} [6], so that conventional injection with 200-keV beams might just be adequate, if $Z_{eff} \approx 1$. With larger Z_{eff}, or if it is desirable to use beams of smaller W_o (and presumably higher efficiency), the ripple-assisted technique can be effective. This method also provides a means of heating to ignition the very dense reactor plasmas proposed in Ref. [17], where $\langle n_e \rangle a = 5$ to $10 \times 10^{16} \mathrm{cm}^{-2}$ in the examples given therein. For this application, asymmetric ripple produced by auxiliary coils would be most desirable, since the coils could be turned off during the thermonuclear burn, thereby eliminating the ripple enhancement of the diffusion of alpha particles born on banana orbits [cf. Sect. 2.2].

For pulsed ignition reactors using the injection-compression technique followed by a propagating thermonuclear burn [18], a permanent asymmetric ripple on the large-R side of the torus might be acceptable.

5.4 FUELING

The present technique provides a means of fueling a large thermonuclear plasma by neutral-beam-injected ions of moderate energy. However, this fueling method may be energetically unfavorable, even though while slowing down the fast ions reproduce a substantial fraction of their energy by target-plasma reactions [15]. For example, if the injection energy for both D and T is 100 keV, the plasma temperature is 10 keV, the injector efficiency is 70%, and the blanket conversion efficiency is 40%, a burn-up of 2% would be required just to recover the injector energy.

5.5 DIRECT ION INJECTION

If a means can be found of bringing energetic ions to the edge of the torus, the asymmetric ripple technique permits the direct injection of these ions to the central plasma region. Perhaps some type of poloidal divertor can be designed for this purpose. (Upon reaching the separatrix, the ion must, of course, be travelling perpendicular to the magnetic field.) Elimination of the neutralization process would result in beam injector efficiencies substantially greater than 50%.

It should be remarked that the injection and trapping process described in this paper does not violate Liouville's theorem, because the Coulomb slowing-down and angular scattering of the energetic ions removes them from the region of phase space that is occupied by the injected beam, and prevents them from returning to the point of ionization.

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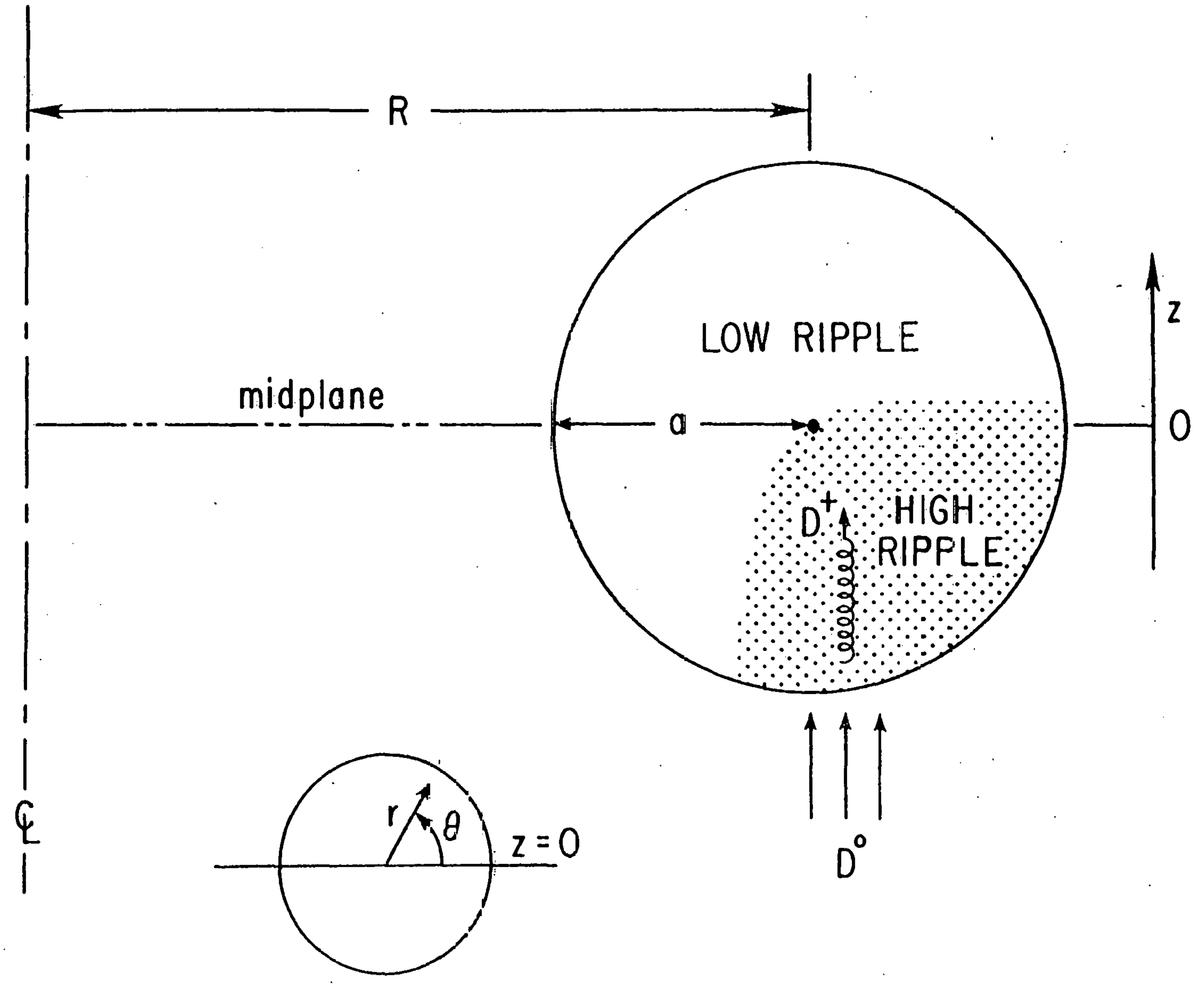

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Fig. 1. Vertical injection of energetic deuterium atoms into a tokamak plasma with large TF ripple in the region below the midplane.

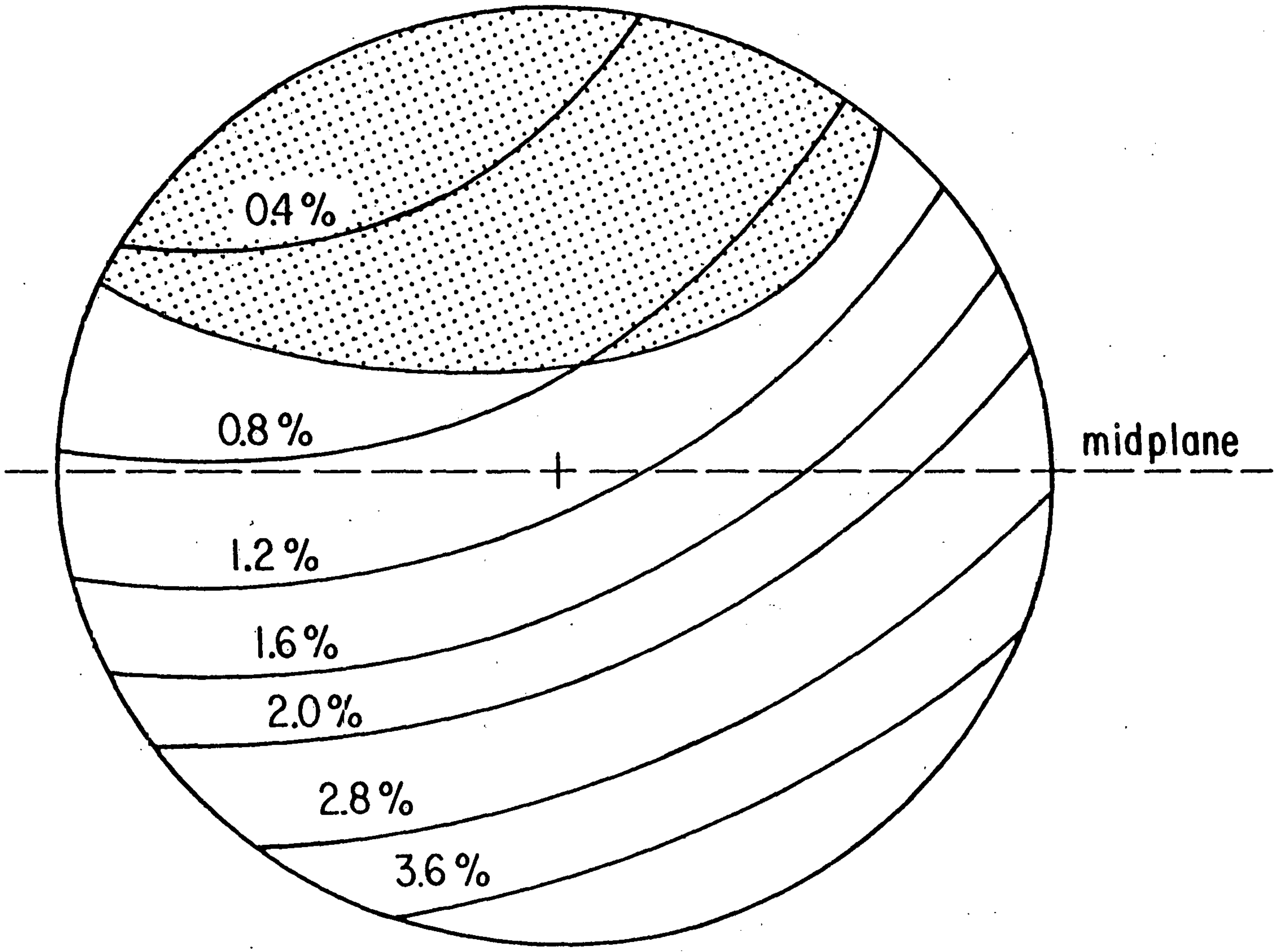

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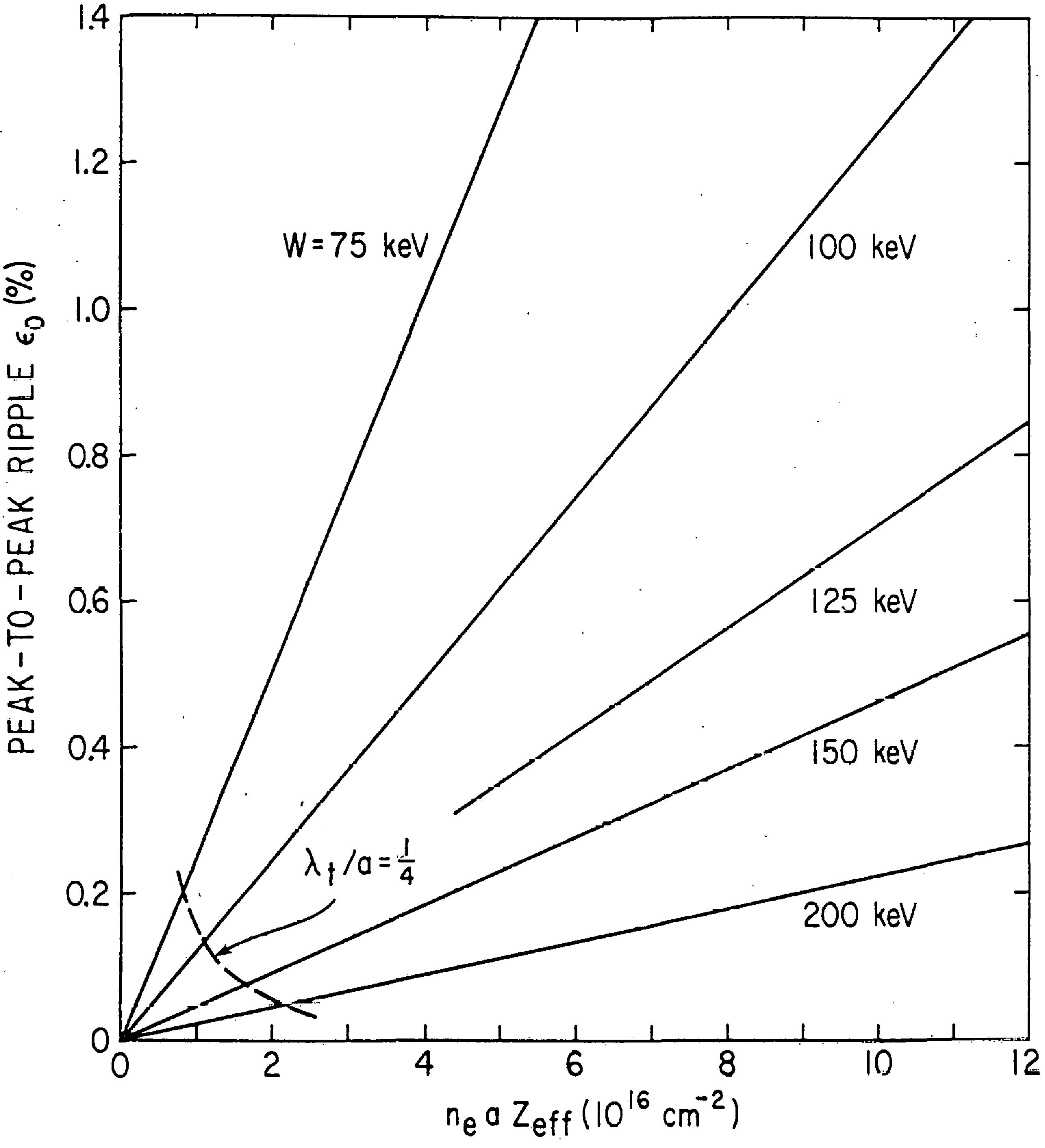
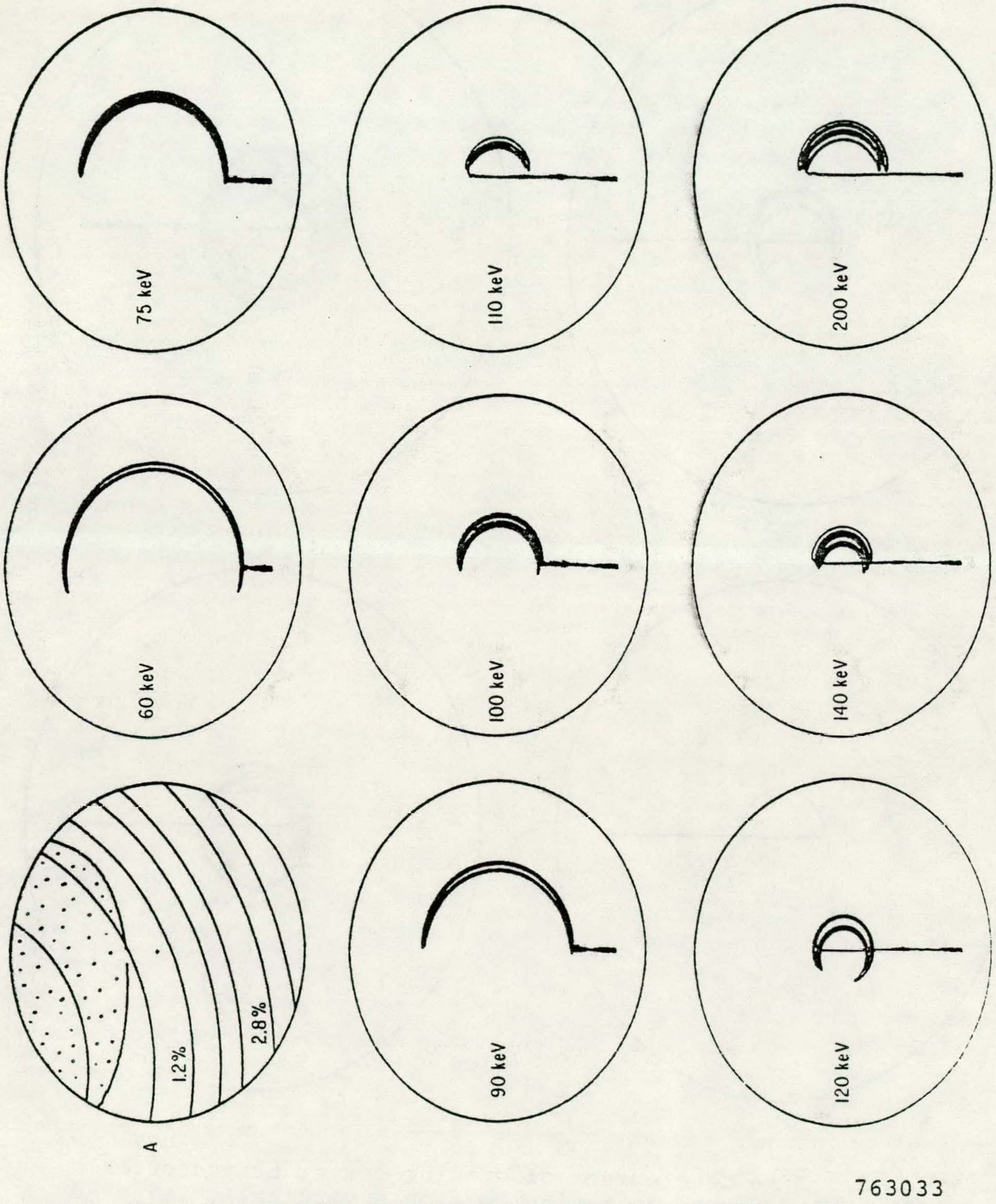
Fig. 2. Cross section of the plasma showing illustrative ripple contours labeled by peak-to-peak ripple. The symmetric trapping region is shaded. $q_o = 1.0$, $q_a = 3.0$.



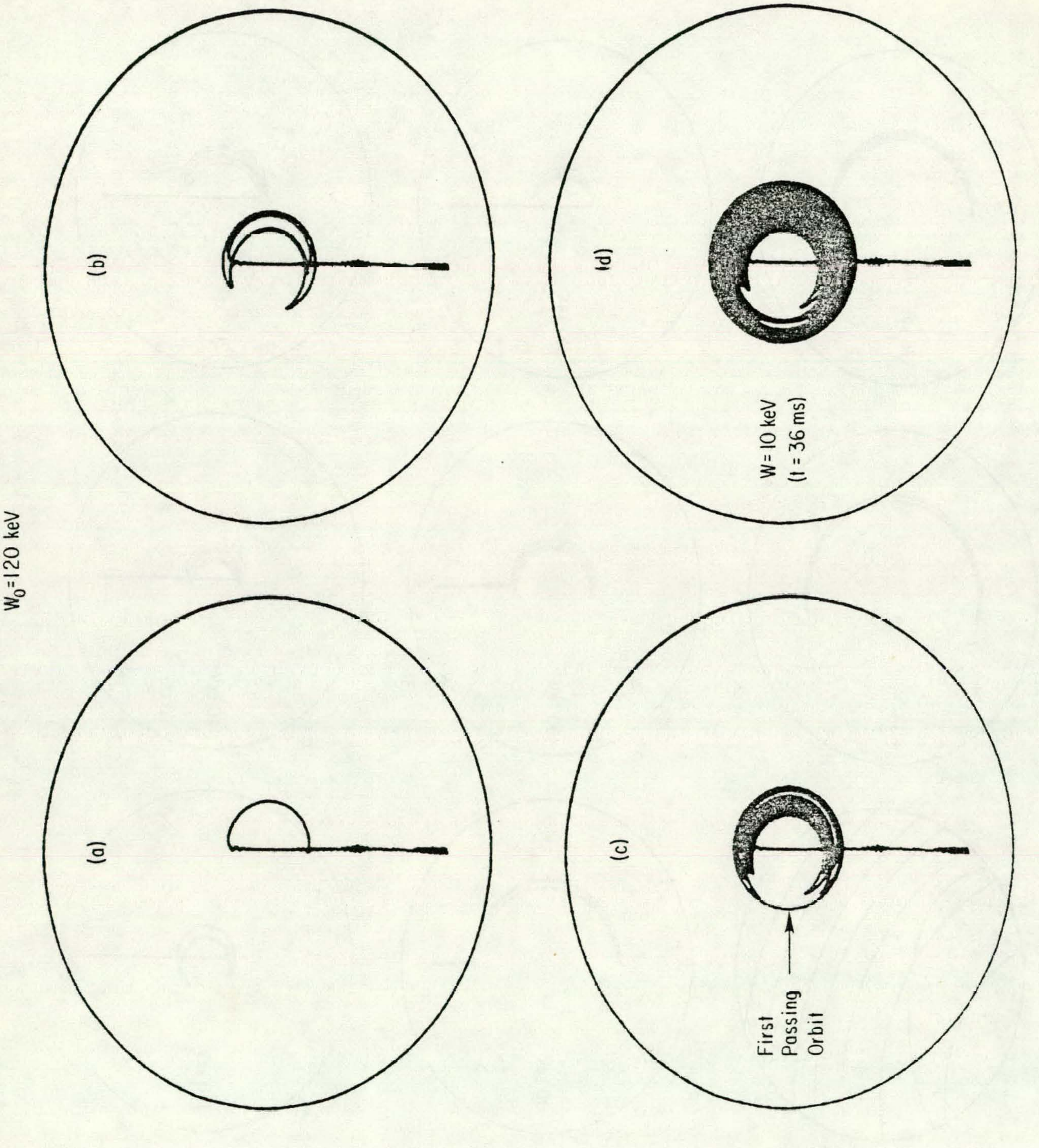
763068

Fig. 3. Required ripple in the midplane region to insure that deuterons of energy W drift from the bottom of the torus to the midplane. Below the midplane, $\varepsilon > \varepsilon_o$; above the midplane, $\varepsilon \ll \varepsilon_o$. $R = 6.0$ m, $B_t = 50$ kG.



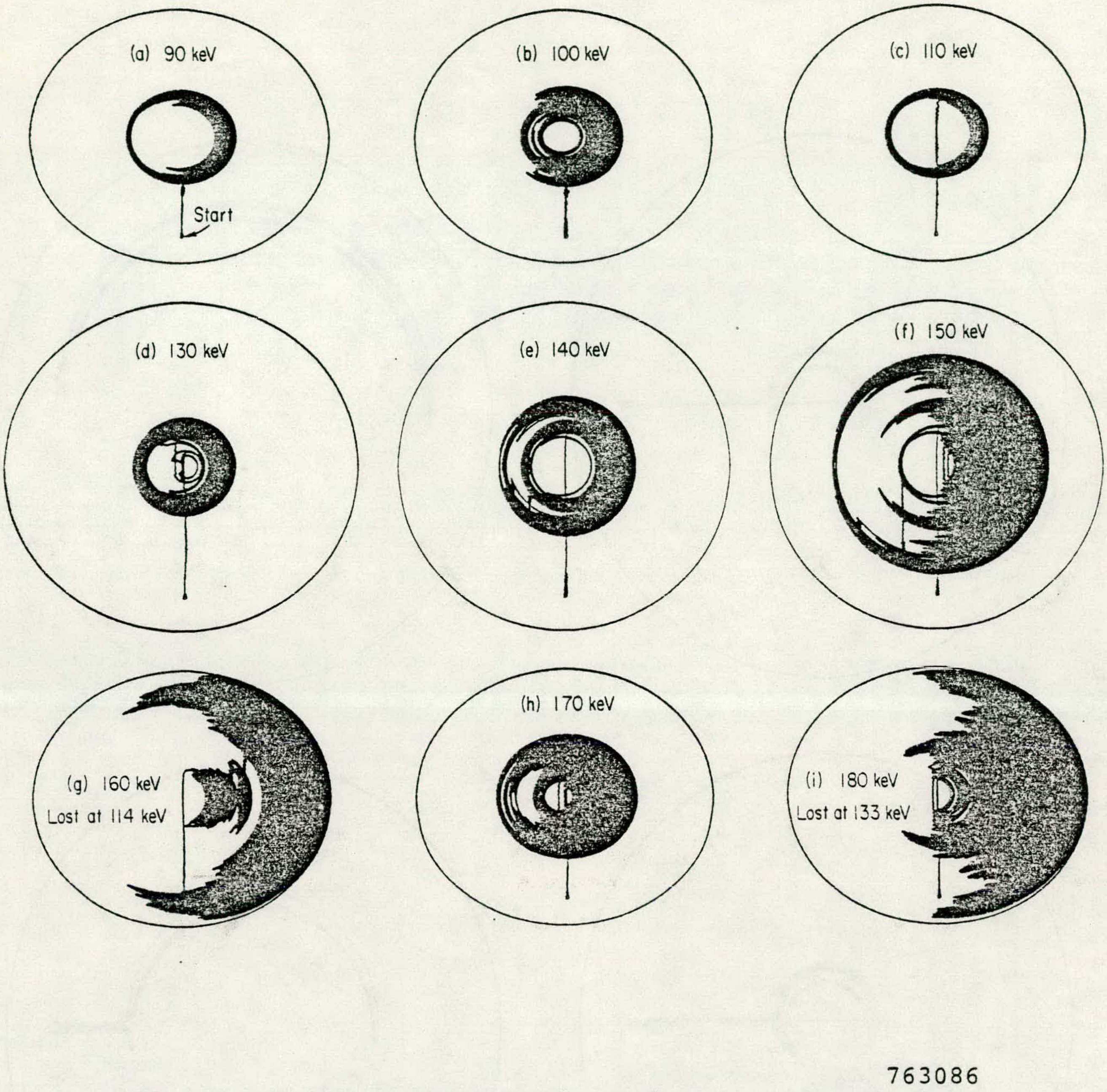
763033

Fig. 4. Guiding-center trajectories for the first five orbits of ions formed at r = 160 cm from vertically injected neutral beams of energy W. Ripple contours are shown in A. (See also Fig. 2.) The symmetric trapping region is shaded. Plasma parameters as in Table 1, with $Z_{eff} = 4$.



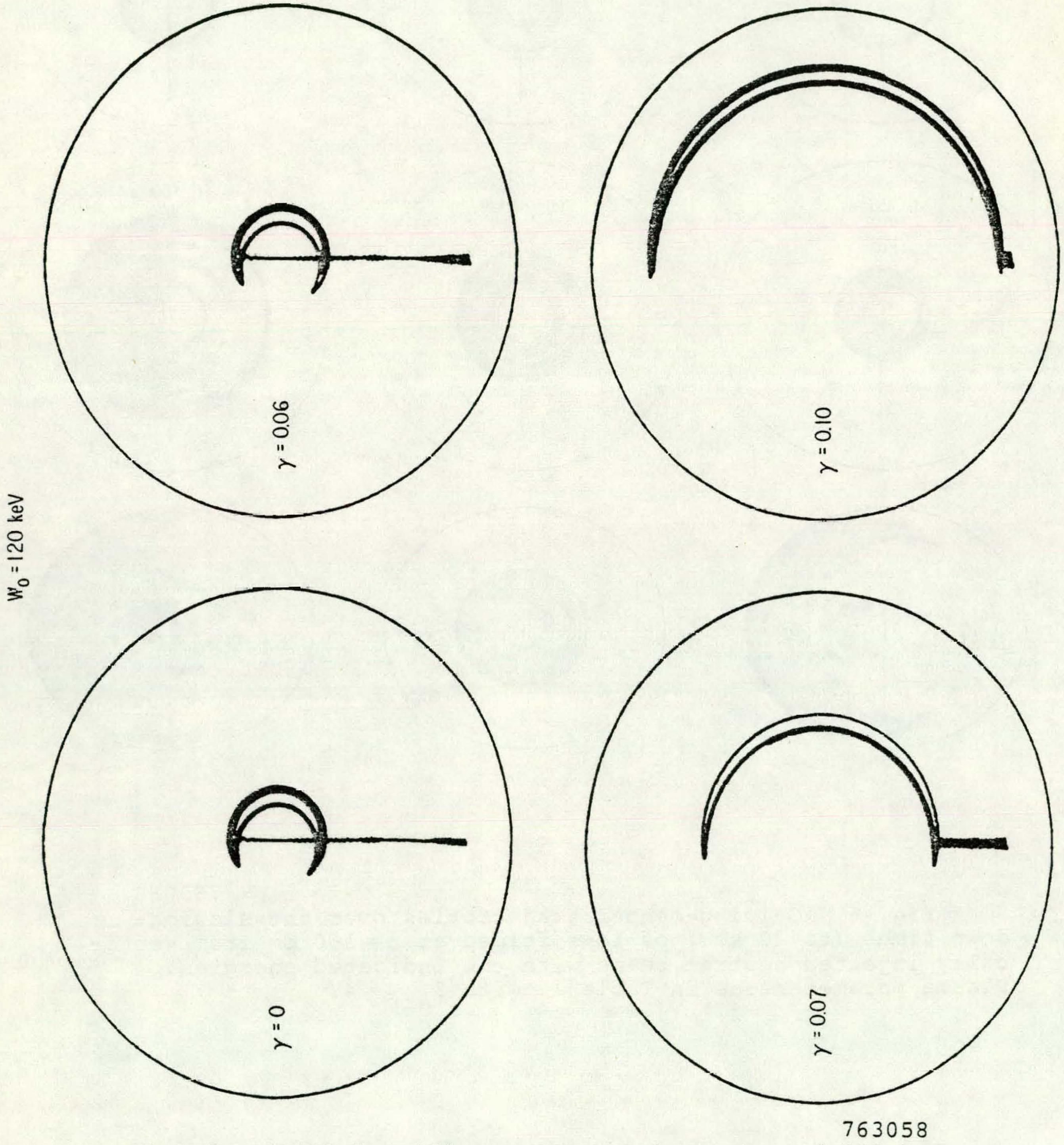
763059

Fig. 5. Time development of guiding-center trajectories of a 120-keV ion formed at r = 160 cm from a vertically injected neutral beam. Ripple contours are shown in Fig. 2. Plasma parameters as in Table 1, with $Z_{eff} = 4$. In (d), the ion has decelerated to 10 keV.



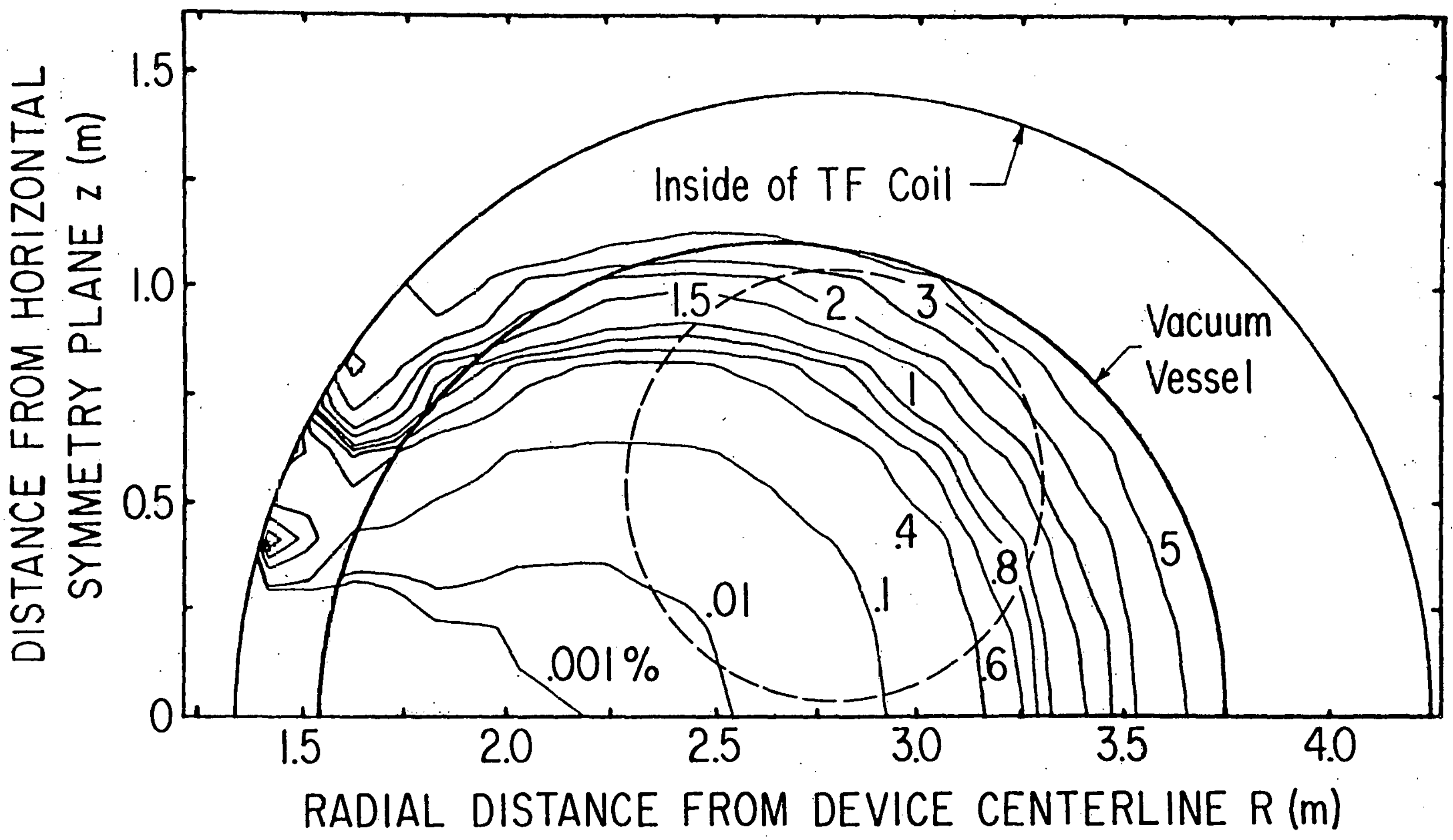
763086

Fig. 6. Guiding-center trajectories over the slowing-down times (to 20 keV) of ions formed at $r = 160$ cm from vertically injected neutral beams with the indicated energies. Plasma parameters as in Table 1, with $Z_{eff} = 4$.



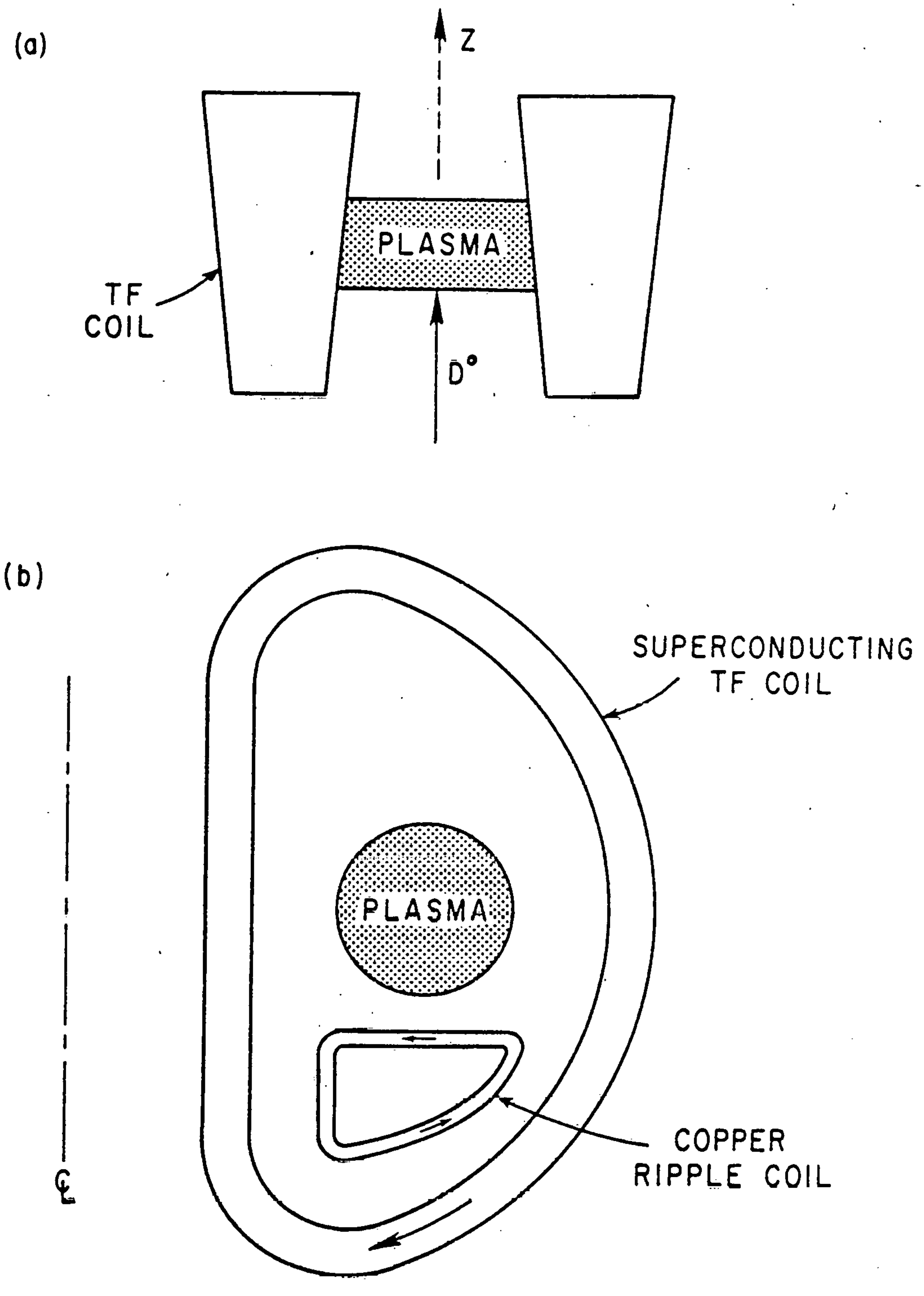
763058

Fig. 7. Initial guiding-center trajectories of 120-keV ions formed at $r = 160$ cm from neutral beams injected at various angles γ from the vertical plane. Ripple contours are shown in Fig. 2. Plasma parameters as in Table 1, with $Z_{eff} = 3$.



763085

Fig. 8. Cross section of the upper half of the proposed TFTR device, showing ripple contours labeled by peak-to-peak per cent ripple. The dashed line is the boundary of a plasma to be heated by low-energy beams injected from the top.



763087

Fig. 9(a). Schematic design of TF coils that provide decreasing ripple with increasing z. (b) Showing position of auxiliary coil for enhancing ripple. Arrows show direction of current.