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IMPLEMENTATION OF VERTICALLY
ASYMMETRIC TOROIDAL-FIELD RIPPLE
FOR BEAM HEATING OF TOKAMAK
REACTOR PLASMAS

BY

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The neutral-beam energy required for adequate penetration of tokamak plasmas of high opacity can be reduced by a large factor if the beam is injected vertically into a region of large TF (toroidal-field) ripple. Energetic ions are trapped in local magnetic wells and drift vertically toward the midplane ($z = 0$). If the ripple is made very small on the opposite side of the midplane, drifting ions are detrapped and thermalized in the central plasma region. This paper discusses design considerations for establishing the required vertically asymmetric ripple. Examples are given of special TF-coil configurations, and of the use of auxiliary coil windings to create the prescribed ripple profiles.

INTRODUCTION

A recently proposed technique for heating large, dense tokamak plasmas employs ∇B drift to effectively increase the penetration length of injected neutral-atom beams.⁽¹⁾ A ripple with significant top-bottom asymmetry is created in the toroidal magnetic field, as shown schematically in Fig. 1. When neutral beams are injected vertically from the side of stronger ripple ($z < 0$), energetic ions formed from the beams are trapped in the ripple magnetic well, and drift upward with the ∇B -drift velocity to the central plasma region, where the ripple becomes small and the ions are detrapped. Penetration to the center by ions of a given energy can always be ensured by adjusting the ripple well depth. For a given plasma opacity $n_e a_p Z_{eff}$, the required injection energy⁽¹⁾ is $W_b = (n_e a_p Z_{eff} / \delta_0)^{2/5}$, where δ_0 is the peak-to-peak ripple on the magnetic axis. Figure 2 shows that for very

large, dense plasmas, W_b can be an order of magnitude smaller than that required by the conventional method. The feasibility of the ripple-assisted penetration technique

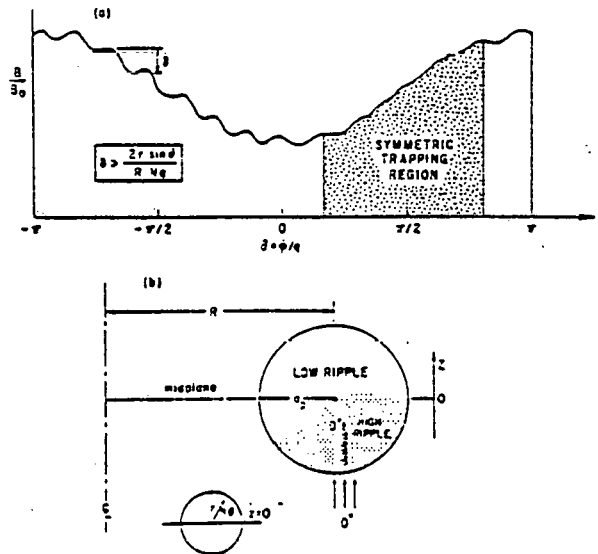


FIGURE 1. (a) Variation of magnetic field B following a flux line in a tokamak plasma. (b) Vertical injection of energetic deuterium atoms. PPPL 763880.

is supported by particle orbit calculations with a Monte Carlo guiding-center code.^(1,2)

In the "symmetric-trapping" region of Fig. 1(a), there are no local magnetic wells; ions with small $v_{||}/v$ must follow banana orbits, and have no time-averaged vertical drifts.⁽³⁾ Because of the diffusive nature of the pitch-angle scattering process, the symmetric trapping region is an essential element in the capture of all injected ions that drift to the center; it also prevents further upward drift of these ions during their thermalization process. Implementation of this type of ripple configuration generally requires some modification of the conventional TF (toroidal-field) coil layout. The present paper describes new designs for the TF coils, as well as for auxiliary windings for creating prescribed ripple contours. The illustrative examples

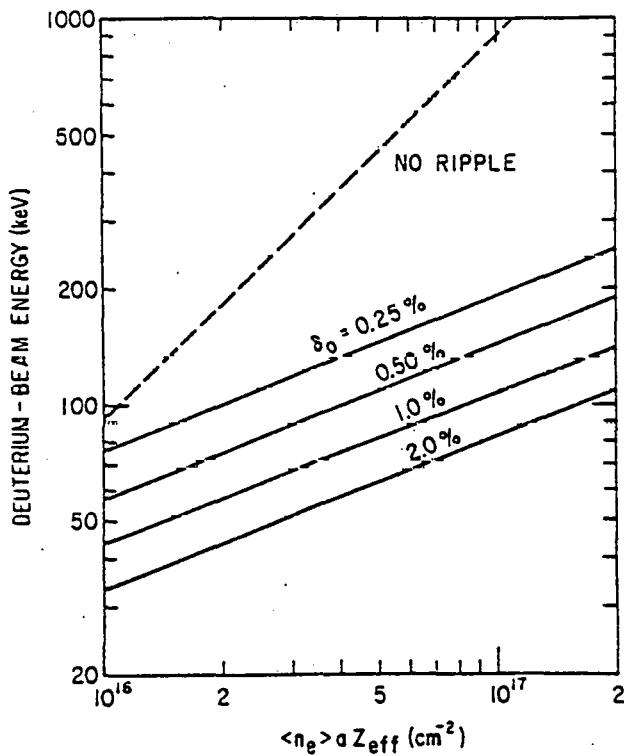


FIGURE 2. Required injection energy⁽¹⁾ to enable deuterons to drift from the bottom of the torus to the midplane ($z = 0$). $\delta_0 =$ peak-to-peak ripple on magnetic axis. $R_0 = 6.0$ m, $B_+ = 5.0$ T. PPPL 763879.

generally make use of parameters appropriate to the TFTR facility⁽⁴⁾ now under construction. But the injection methods described here can utilize 120-keV (TFTR-type) injectors to heat to ignition very dense tokamak plasmas that make use of either high magnetic fields, or $\beta \geq 0.1$.

GENERAL DESIGN CONSIDERATIONS

Ripple Strength

The local magnetic well depth along a field line is defined

$$\Delta(r, \theta) = 200 \frac{B_{\max}(r, \theta) - B_{\min}(r, \theta)}{B_{\max}(r, \theta) + B_{\min}(r, \theta)} (\%) \quad (1)$$

Figure 3 shows illustrative "vacuum" ripple contours $\delta(r, \theta)$, where δ is the ripple produced by the magnetic coil configuration alone. In the presence of rotational transform $2\pi/q$ caused by a plasma current, Δ is reduced significantly below δ ⁽⁵⁾ [See Fig. 1(a).] For $q_0 = q(r = 0) = 1.0$ and $q_a = q(r = a_p) = 3.0$, the local magnetic wells in the shaded region of Fig. 3 are "washed out." (For a periodically varying ripple, the boundary of this symmetric-trapping region is given by^(3,5)

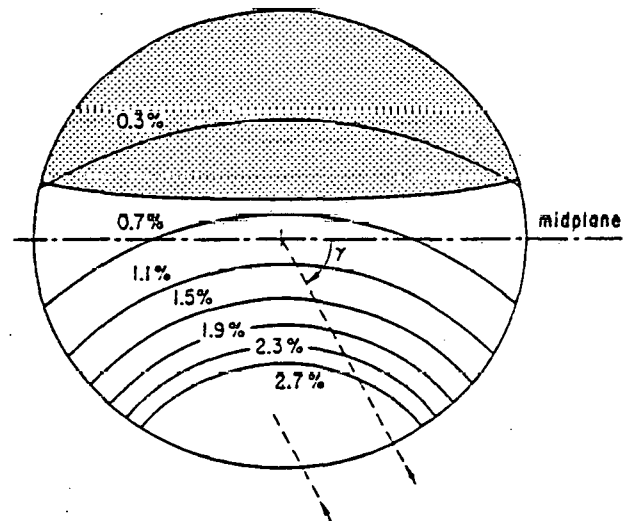


FIGURE 3. Illustrative ripple contours, labeled by peak-to-peak ripple.⁽²⁾ Symmetric-trapping region for $q_0 = 1$, $q_a = 3$ is shaded. Dashed lines show boundary of injected beam. PPPL 763882.

$\delta = 2r|\sin\theta|/RNq$, where N is the number of TF coils.) At $\theta = -\pi/2$ on the $\delta = 2.7\%$ contour, Δ is only 0.9%, and similar reductions are found elsewhere in this region. To avoid a symmetric-trapping region in the lower half-plane, the "vacuum" ripple must be made to increase sufficiently rapidly toward the injection position. It turns out that this variation is inherent in most methods of applying ripple.

If $n_e a_p Z_{\text{eff}} = 10^{17} \text{ cm}^{-2}$, which is a typical value for a power reactor, then the ripple contours of Fig. 3 permit penetration to the plasma center by deuterons injected at 110 keV (see Fig. 2). There is some incentive to impose even larger ripple, so that W_b can be reduced further. For a number of practical reasons, however, it seems best to restrict W_b to at least 100 keV in reactor-sized plasmas: (a) Charge-exchange loss of slowly drifting beam ions in the outer plasma region can be significant at small W_b . (b) For a given power input, the required injection current — and beam access area — is inversely proportional to W_b . (c) The beam-target fusion reaction rate for D→T is maximized at $W_b = 120\text{-}180$ keV. (d) The required W_b varies only as $\delta_0^{-2/5}$, so that extremely large ripple is required to reduce W_b significantly below 100 keV. The use of large ripple can also aggravate a number of adverse effects, which are summarized in the following.

In the presence of large ripple, the banana orbits of ions tend not to close. With vertically symmetric ripple, unclosed bananas give rise to a stochastic wandering of banana orbits, even in the absence of collisions.⁽⁶⁾ In the presence of vertically asymmetric ripple, the stochastic motion is replaced by a steady outward drift.^(1,2) This outward drift velocity is actually required by Liouville's Theorem as a mechanism

for collisionless orbits to escape the magnetic trap. Coulomb drag does, however, allow ions injected in a limited energy range, near the value given by Fig. 2, to penetrate to the central region and to thermalize in the plasma.⁽²⁾ The extent of outward drift during the thermalization process is reduced by installing TF ripple in only those locations that are absolutely needed for injection. For example, calculations with the Monte Carlo guiding-center code show that if the ripple pattern of Fig. 3 is established between 18 TF-coil pairs for a plasma with $n_e a_p Z_{\text{eff}} = 10^{17} \text{ cm}^{-2}$, then on the average 85% of the energy of injected 120-keV deuterons is deposited in the plasma, but only 20% of the energy of injected 180-keV deuterons is retained. If the number of ripple locations is reduced to 9, then 99% of the energy of 120-keV deuterons and 50% of the energy of 180-keV deuterons is captured.

The outward drift is most important for charged fusion-reaction products, such as 3.5-MeV D-T alpha particles, whose asymmetric unclosed bananas readily "walk out" of the plasma. Even for an exceedingly large ripple, however, only alphas that are born in or near the banana-trapped region of velocity space could be lost in this way. (One can take advantage of this phenomenon for thermal feedback-stabilization of an ignited plasma, by applying ripple to control the fraction of ejected alphas.⁽⁷⁾)

Another ripple-induced effect is enhanced particle and heat diffusion of the bulk plasma.^(5,6) In the presence of vertically asymmetric ripple the character of this diffusion is altered slightly, since the diffusion consists both of vertically drifting orbits in one-half the plasma, and radially drifting bananas. Heuristic arguments show that the diffusion rate in the asymmetric

ripple is comparable with that in symmetric ripple of the same magnitude, and can be important when T_i is very large.

The minimum value of δ is determined by the need to avoid a symmetric trapping region in one half-plane of the plasma, and also to accommodate finite beam divergence: For the case of Fig. 3, $v_{||}/v$ at injection must be no greater than ± 60 mrad ($\pm 3.4^\circ$), in order that injected ions not be detrapped prematurely.⁽¹⁾ When all considerations are made, the most useful ripple strength is calculated to be 0.6-1.0% on the magnetic axis, and increasing to about 4 times this value at the injection position. For reactor-sized plasmas, the corresponding W_b are 110-150 keV.

Injection Angle

Strictly vertical injection is often inconvenient, because of the limited access between the TF coils at small major radius. In order to determine the effect of injecting at a somewhat oblique angle — but still in the vertical plane — we have followed the orbits of a large number of particles injected at 120 keV along various beam paths into the ripple configuration of Fig. 3. We find that fast-ion penetration and thermalization are adequate ($\geq 90\%$ energy retained) when the angle γ in Fig. 3 is at least 60° ; the beam width can be as large as $0.4 a_p$. If the neutral-beam intensity is 0.020 A-equiv/cm², a single injection port of dimensions $0.5 \text{ m} \times 1.0 \text{ m}$ can pass 15 MW at $W_b = 150$ keV. Typical injection powers for beam-driven TCT reactors, or for beam-heating to ignition, are in the range 60 to 300 MW, requiring 4 to 20 injection ports. The use of a poloidal magnetic divertor would have to be restricted to a single null and collection chamber in the upper half-plane.

Design Approaches

There are three general methods of implementing vertically asymmetric TF ripple: (a) Asymmetric positioning of the plasma column in a vertically symmetric ripple. (b) Special design of the TF coils. (c) Activation of auxiliary coils with adjustable current. Examples of these techniques are discussed in the following sections. In each case the magnetic design is carried out to approximate the ripple contours prescribed for adequate ion penetration and trapping, as determined by the particle guiding-center code. Particular attention is paid to the location of the symmetric-trapping region. The examples herein do not represent working designs: The position of the symmetric trapping region is not optimized, while the ampere-turns and dissipated power in the ripple coils (when used) are not minimized. Nevertheless, these examples do illustrate the various techniques that are available for generating the desired ripple configuration.

ASYMMETRIC PLASMA POSITIONING

Figure 4 shows the (vertically symmetric) ripple contours of the TF coils of the TFTR device.⁽⁴⁾ By suitable positioning of the

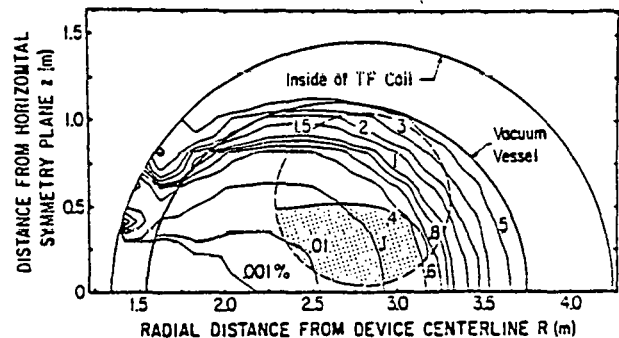


FIGURE 4. Cross-section of upper half of TFTR device,⁽⁴⁾ showing ripple contours (% peak-to-peak). Dashed circle shows offset plasma location. Symmetric-trapping region for $q_0 = 1$, $q_a = 3$ is shaded. PPPL 763883.

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 circle in Fig. 4. (In the configuration shown, the beams must be injected from the top, but similar plasma positioning below the mid-plane is possible.) The ripple strength in the plasma decreases rapidly with distance from the injection port, and the boundary of the symmetric-trapping region is suitably located for detrapping fast ions. If $\langle n_e \rangle = 10^{14} \text{ cm}^{-3}$ and $Z_{\text{eff}} = 3$, the injection energy must be 70 keV for adequate penetration.

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. Most reactor designs employ D-shaped TF coils, with some margin in the vertical position of the plasma. Thus if near-vertical perpendicular injection is used, one has the option of moving the plasma into the region of higher ripple, if neutral-beam penetration is degraded by an increasing Z_{eff} , for example.

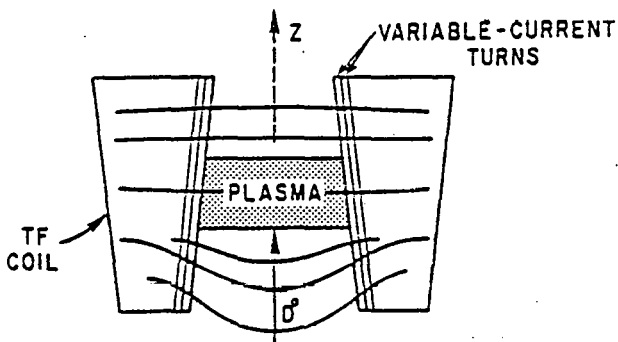


FIGURE 5. Schematic design of TF coils that provide decreasing ripple with increasing z. PPPL 763881.

SPECIAL TF-COIL DESIGN

Figure 5 shows a coil embodiment that represents the least departure from conventional coil design. The tapered structure is also convenient for injecting large beam power from the bottom. If necessary for structural strength, however, only the coil windings would have the vertical cross section shown, with the coil casing having uniform width. Some control over the amount of ripple can be realized by varying the current in the windings adjacent to the injection port. (3)

A more radical approach to providing a decreasing $\delta(z)$ is the shunt-segment coil design illustrated in Fig. 6. The effect of the "counter-current" segment is to strengthen the field under the coil and to weaken the field in the gap between TF coils. (An analogous method was proposed in Ref. (8) to reduce ripple.)

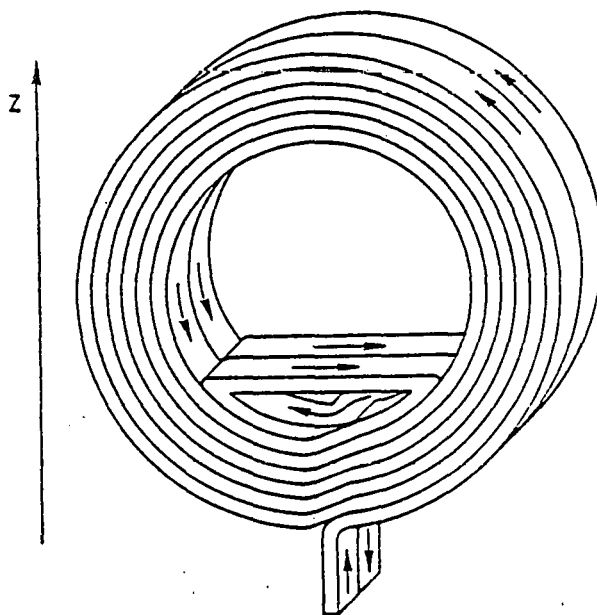


FIGURE 6. Coil-winding configuration that provides decreasing ripple with increasing z. PPPL 763884.

Bifurcated Coils

A large local ripple coupled with generous access for vertical beam injection can be obtained with the bifurcated-coil design illustrated in Fig. 7(a). In this method, each branch of the bifurcated coil C-1 in the angular sector α is bent out in the direction of the adjacent conventional coil C-2. The amount of field ripple created increases with the angle α , and also with the extent to which the legs of C-1 are diverted.

Figure 7(b) shows a simplified bottom view of this design, using dimensions appropriate to the TFTR device.⁽⁴⁾ Here $\alpha = 50^\circ$; the separated legs of C-1 are bent out at nearly right angles, and taken up to the adjacent coil. (The actual geometry is, of course, wedge-shaped.) Figure 7(c) shows the associated ripple contours for the TFTR plasma with $I_p = 2.5$ MA, giving $q_0 = 1$ and $q_a = 3$. The field minima lie in the vertical plane at the center of C-1. Evidently, the ripple is too small to prevent the appearance of a significant symmetric-trapping region in the lower half-plane. But this region disappears when $I_p \leq 1.8$ MA. The difficulty at $I_p = 2.5$ MA could be remedied by increasing α , or by rotating the divided sector about the x-axis. There is insufficient room in the present TFTR design for the latter modification, however.

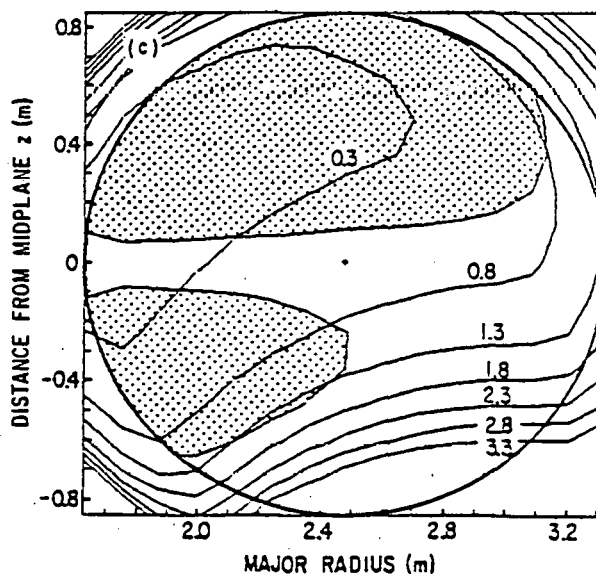
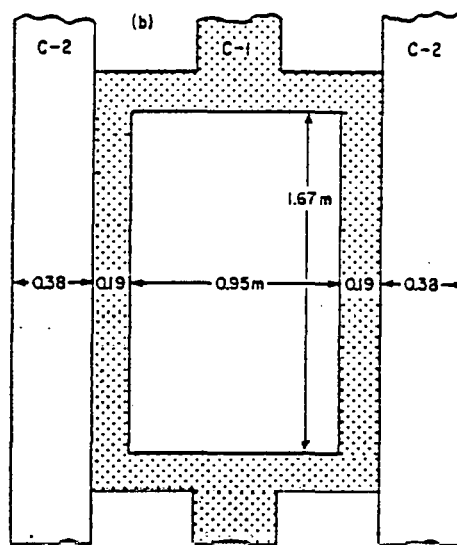
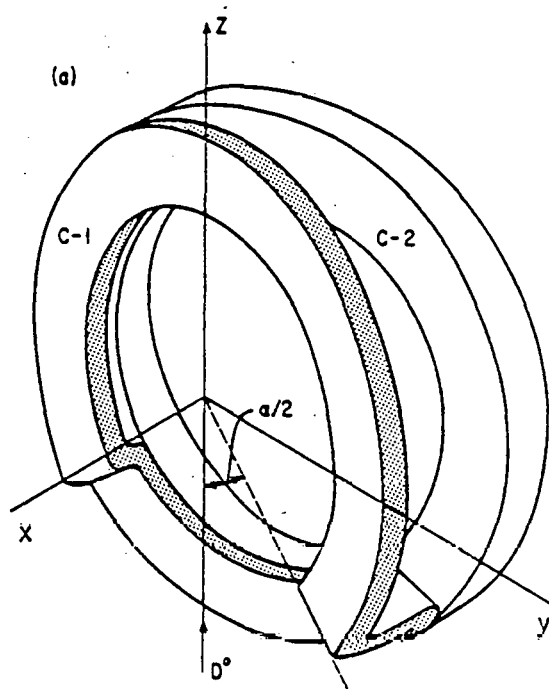


FIGURE 7. (a) Coil C-1 is bifurcated with one branch shown here. In angular sector α , each branch of C-1 is diverted to the adjacent coil C-2. (b) Simplified bottom view of illustrative TFTR 3-coil module with bifurcated coil C-1 and $\alpha = 50^\circ$. Actual geometry is wedge-shaped. Dimensions shown apply only to $R = 2.7$ m. (c) Cross-section of the TFTR plasma, showing ripple contours (% peak-to-peak) for configuration (b). Symmetric trapping regions for $q_0 = 1$, $q_a = 3$ are shaded. PPPL 763893.

A principal attraction of the bifurcated-coil design is the large access area for vertical beam injection. In the present case, the area useful for injection into the plasma is about 1.0 m^2 , which is sufficient to pass 24 MW at $W_b = 120 \text{ keV}$. The forces on the TF coils are generally comparable with those in a conventional 3-coil module. Excessive local forces at the diverted legs of C-1 can be counteracted by steel reinforcement in the large bottom region, still leaving ample room for injection.

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 (rather than field ripple) must be varied for optimal penetration. In some cases, however, a change in vertical position of the plasma could offer sufficient flexibility. Another disadvantage is the permanent adverse effect on the orbits of fusion alpha particles. However, a large ripple is easily tolerated in heavily beam-driven TCT-type devices, where τ_E can be small, and the confinement of alpha particles is not necessary.

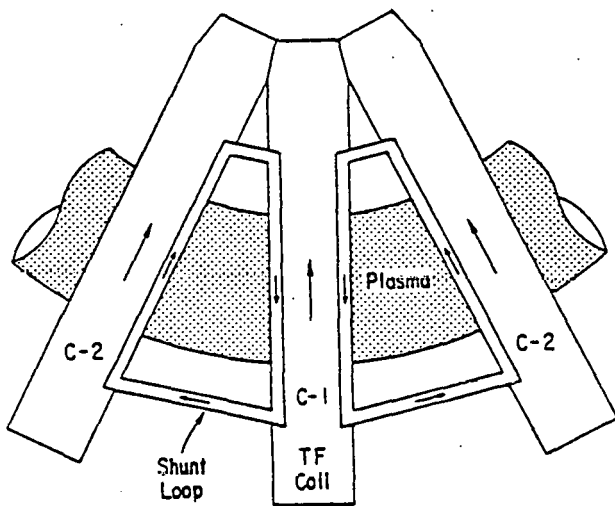


FIGURE 8. Projection of bottom view of torus sector with shunt loops. Neutral beams are injected through the loops. PPPL 763895.

AUXILIARY COILS

For an ignited tokamak reactor in particular, the most attractive method of introducing asymmetric ripple is by means of a set of auxiliary copper windings with adjustable current. The windings would be activated only during the heating stage, thereby avoiding the ripple-induced loss of banana-trapped fusion alphas during the thermonuclear burn. (One or two coils might still be activated for thermal feedback stabilization.⁽⁷⁾) The coil power dissipation per injection port would be in the range 3 to 10 MW. Note that a perturbation $\delta \ll 1$ in the toroidal magnetic field can be applied extremely fast — a time of order R/v_{Alfven} . The principal factor determining the "turn-on" time is the reactive power required by the coil.

External Shunt Coils

Figure 8 shows schematically one of the two approaches we have used. Here shunt loops are placed around three adjacent TF coils, with the shunt currents directed so that in effect current is removed from coil C-1 and added to coils C-2. The resulting ripple configuration in the region between the C-2 coils resembles that in the bifurcated-coil module of Fig. 7. If a short injection period is satisfactory, the shunt currents can be provided by capacitor banks. In principle, the shunt coils can be placed either outside or inside the TF-coil set. While placement outside demands more driving power, the magnetic forces on the shunt coils are reduced greatly. The largest forces are experienced by the shunt legs on coil C-1.

In the TFTR device,⁽⁴⁾ the limited space inside the TF coils dictates that the shunt loops be placed outside. Figure 9(a) shows schematically the locations of the TF coils and shunt coils, here represented by

filaments. Figure 9(b) shows the ripple contours for a shunt-coil current of 0.7 MA. This current is slightly below the level at which the symmetric trapping region in the lower half-plane completely disappears. The ripple strength is sufficient to allow adequate penetration by injected 100-keV ions

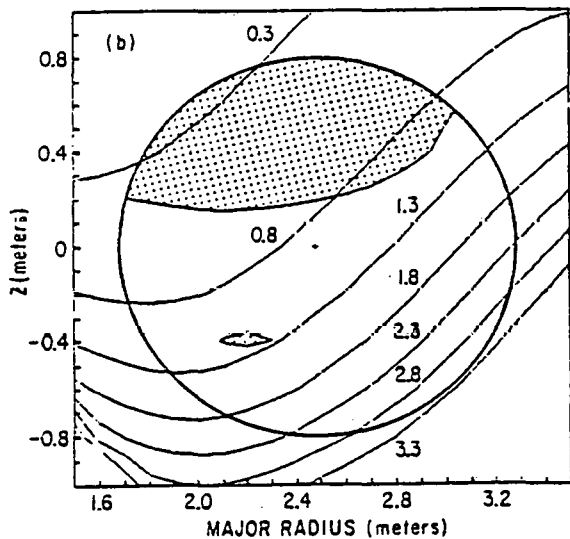
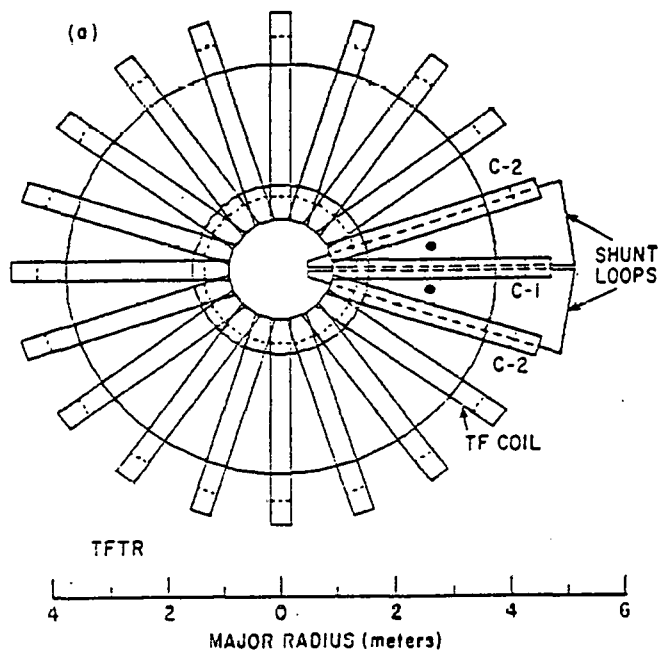


FIGURE 9. Application of shunt loops to the TFTR coil assembly. (See also Fig. 8.) Large dots indicate centers of injection ports. (b) Cross-section of 1.6-m diameter TFTR plasma showing ripple contours (% peak-to-peak) produced by shunt loops carrying 0.7-MA current. Symmetric trapping regions for $q_n = 1$, $q_n = 3$ are shaded. PPPL 763894.

when $\langle n_e \rangle = 3 \times 10^{14} \text{ cm}^{-3}$ and $Z_{\text{eff}} = 3$ [cf. Fig. 2].

The shunt coils are fabricated of water-cooled copper, and have the following characteristics:

Coil current = 0.70 MA.

Coil diameter = 30 cm.

Resistive power loss = 4.8 MW.

Reactive power = 8.1 MW for 0.5-s risetime.

Internal Auxiliary Coils

In a large tokamak device with D-shaped TF coils, it is possible to locate auxiliary ripple-producing coils in the blanket region, as shown schematically in Fig. 10(a). One auxiliary coil is positioned on each side of the injection port located between adjacent TF coils, so that the field minima lie in the injection region. In the case of a superconducting TF-coil set, an "active shield" coil⁽⁹⁾ would have to be placed between the blanket and the high-field region of the TF coils to minimize dissipation induced by the time-varying ripple field.

Figure 10(b) shows the ripple contours in the 4-m diameter plasma when the auxiliary-coil current is 3.0 MA and $B_t = 5.0 \text{ T}$ on the magnetic axis. As in the previous example, the coil current is slightly below the level at which the symmetric trapping region in the lower half-plane completely disappears. The ripple strength is sufficient to allow adequate penetration by injected 150-keV ions when $\langle n_e \rangle = 2.5 \times 10^{14} \text{ cm}^{-3}$ and $Z_{\text{eff}} = 3$ (cf. Fig. 2). If the auxiliary coils are fabricated of water-cooled copper, the total resistive power loss for two coils of diameter 50 cm is 11 MW.

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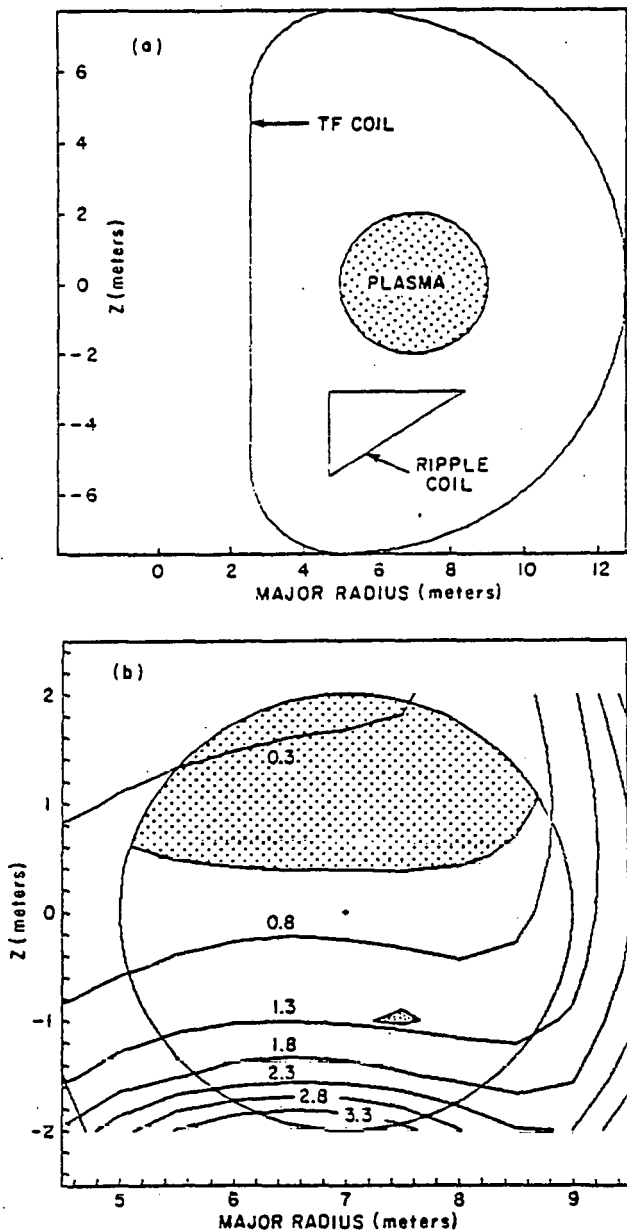


FIGURE 10. (a) Positions of current filaments to represent TF coil and ripple coil in tokamak of power-reactor size ($a_p = 2$ m). (b) Ripple configuration (% peak-to-peak) when TF coils provide 5.0 T on magnetic axis, and current in ripple coils = 3.0 MA. Symmetric trapping regions for $q_0 = 1$, $q_a = 3$ are shaded. PPPL 763892.