Improved Tandem Mirror Fusion Reactor

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It is shown that the introduction of barrier potentials between the plugs and solenoid of a tandem mirror substantially reduce ion energy and density required in end plugs. Several means for creating barriers and some of the important physics issues are discussed.

In tandem mirror (TM) confinement of fusion plasma, ions in a magnetized solenoid are confined axially (plugged) by electrostatic potentials of denser mirror-confined plasma.[1,2] For a uniform electron temperature T_e, an ion-confining potential φ_c requires a plug-to-central-cell density ratio[1]

$$n_p/n_c = \exp(\varphi_c/T_e). \tag{1}$$

φ_c varies only logarithmically in the density ratio, whereas the ratio of central-cell fusion power density to the injection power density required to maintain the plugs varies as n_c^2/n_p^2. Increasing T_e by auxiliary heating permits a decrease of n_p/n_c for fixed φ_c, improving the reactor picture. Even with this, however, a conceptual TM reactor has severe technological requirements.[3] To plug a central cell of density $\approx 10^{14}$ cm^{-3}, temperature ≈ 40 keV, and magnetic field ≈ 2 T requires plugs of density $\approx 10^{15}$ cm^{-3} having peak fields ≈ 17 T and neutral-beam injection energies of order 600 keV with, or of order 1–2 MeV without, auxiliary electron heating. In the following, we describe a means by which, for the same central-cell conditions, the density of the plugs might be reduced to a few 10^{13} cm^{-3} requiring peak fields $\lesssim 10$ T and beam injection energies as low as 200 keV.

The essential idea is to raise the plug-electron temperature T_{ep} above the central-cell electron temperature T_{ec} by auxiliary electron heating in the plugs alone. Consider the magnetic field, potential, and density profiles shown in Fig. 1. Electrons from the central cell pass through the plug and mix by weak collisions with those trapped in the higher potential. In TM reactors as previously conceived, the mixing is sufficient to allow only relatively small electron temperature differences between plug and central cell, even though considerable neutral-beam and auxiliary neutral-beam and auxiliary heating are applied to the plug. Introduction of a potential dip $\varphi_b \gtrsim T_{ec}$ markedly increases achievable temperature differences by having φ_b act as a thermal barrier between the plug and solenoid electrons. Because plug electrons are then confined by a potential $\varphi_b + \varphi_c$, the power per volume transferred between the plug and transiting central-cell electrons can be estimated[4] to be

$$P_{cp} \approx G_e(n_p^2/n\tau_{ee})(T_{ep} - T_{ec}) \times \exp[-(\varphi_b + \varphi_c)/T_{ep}], \tag{2}$$

where

$$n\tau_{ee} = (m^{1/2})4\pi e^4 \ln\Lambda)(2T_{ep})^{3/2} = (8.2\times 10^9/\ln\Lambda)T_{ep}^{3/2}\ \mathrm{cm^{-3}\ s},$$

where T_{ep} is expressed in keV and G_e of order unity is a weak function of potential and mirror ratio. (Accurate determination of this transfer rate is important for detailed reactor calculations and is being pursued by analytical and numerical means.) The power applied to the plug electrons transfers to the central-cell electrons and contributes to their total power balance.

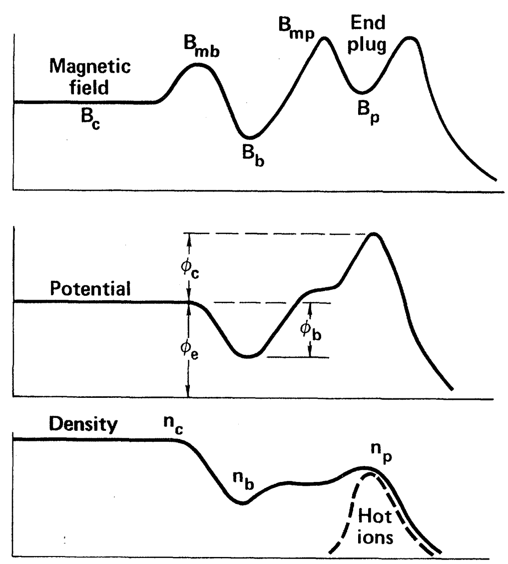

FIG. 1. Sample magnetic field, potential, and density profiles for a thermal barrier.

The barrier density n_b is related to n_c and n_p by

$$n_b = n_c \exp(-\varphi_b/T_{ec}) \tag{3a}$$

$$\simeq n_p \exp[-(\varphi_b + \varphi_c)/T_{ep}] \tag{3b}$$

or, replacing Eq. (1), there results

$$n_p/n_c \simeq \exp[-\varphi_b/T_{ec} + (\varphi_b + \varphi_c)/T_{ep}]. \tag{4}$$

[The approximate equality in Eqs. (3b) and (4) is used because the potential depth $\varphi_b + \varphi_c$ is to be determined by equality of the trapping and entrapping of electrons in the plugs, rather than by a strict Boltzmann relation.]

The depression in the barrier density required in Eq. (3a) is limited by the minimum density n_b(passing) of central-cell ions streaming through the locally negative potential. Assuming that this drop in potential is accompanied by a drop in the magnetic field by a factor $R_b + B_{mb}/B_b$ and that $\varphi_b > T_{ic}$, we obtain

$$n_b(\text{passing}) \approx (n_c/R_b)(T_{ic}/\pi\varphi_b)^{1/2}. \tag{5}$$

Added to this will be the density of ions trapped in φ_b, and it will be most important that their accumulation be prevented. If the total barrier-ion density n_b(passing plus trapped) is normalized to the density of passing ions, i.e., $n_b = g_b n_b$(passing), then from Eqs. (3a) and (5) we find

$$(T_{ic}/\varphi_b)^{1/2} \exp(\varphi_b/T_{ec}) = R_b \pi^{1/2}/g_b. \tag{6}$$

This result points up the importance of a large mirror ratio R_L, and a nearly complete pumpout of the trapped thermal ions from this region (for which $g_b \to 1$). In assessing reasonable estimates for g_b, two considerations are important: (i) the degree to which specific pumpout mechanisms can compete with collisional trapping, and (ii) the questions of microstability of the resulting distributions.

Several schemes for maintaining a thermal barrier have been considered. The first three described require strengthening the field at the end of the solenoid to generate a local mirror-field peak. The barrier region would then lie between this peak and the end plug [see Fig. 1(a)]. The field peak throttles flow toward the plug; without collisions the density and potential in the barrier would decrease with B giving Eq. (5).

As a first pumpout means, we propose transit-time pumping of locally trapped ions by means of a parallel force applied at the ion bounce frequency. Examples are a parallel electric field (difficult at high density) or small oscillation of the position, depth, or axial extent of the local magnetic well. The former was used to eject electrons from the Phoenix mirror machine,[5] creating a rise in the ambipolar potential. The absorbed power density for this heating, which ends up as heating to the whole central cell, is that which competes with the trapping rate for passing central-cell ions into the potential well:

$$P_{\text{pump}} \approx G_i \frac{n_b^2(\text{passing})(B_{mb}/B_b)}{(n\tau)_{ii}} T_{ic}, \tag{7}$$

where $(n\tau)_{ii} = 5\times10^{11} T_{ic}^{3/2}/\ln\Lambda$ cm^{-3} sec, and $G_i \approx 3$. Determination of the degree to which thermal ions can be pumped out by this means against collisional filling and the amplitude of the required fields depends upon details of the electrostatic and magnetic well shapes, resonance frequencies, their widths and overlap, the applied frequency spectrum, island formation in phase space, etc. Modeling of this process in both the diffusion, or Fokker-Planck, limit and by single particles with a Monte Carlo collision process is underway at Livermore.

In a second pumpout scheme, the minimum of the barrier region in Fig. 1(a) would periodically be raised to the peak mirror value, so that all trapped thermal ions would escape. When returned to its minimum value, the barrier regions would remain empty of trapped ions for a fraction of a collision time, at which time the cycle would be repeated. The potential barrier offered by such a barrier region would not be constant in time, so that this method might require a pair of such barriers, operating out of phase.

A third pumpout method would be the injection of a neutral beam of energy $< \varphi_b$ in to the barrier, at an angle $\theta < \arcsin(1 - \sqrt{R_b})$ with respect to the magnetic axis, so that ionization of beam atoms by charge-exchange, ion-impact, and electron-impact collisions would form passing ions. Charge-exchange collisions between beam atoms and trapped barrier ions would convert those trapped ions to neutrals, permitting their escape from the barrier. The beam atoms thereby converted to passing ions would then contribute to fueling the center-cell ion losses.

Microstability due to beam-type modes does not appear to pose a serious limit of the density in the barrier region. We have examined ion-ion two-stream, ion-acoustic, and ion-beam–cyclotron modes[6] and find that $g_b \gtrsim 2$ is sufficient for stability. Accordingly, we have taken $g_b = 2$ in reactor evaluations.

Potential magnetohydrodynamics (MHD) modes in the barrier region are the firehose, requiring for stability $\beta_\parallel - \beta_\perp \lesssim 2$, and the flute interchange, requiring for low-β stability that

$$\int \frac{ds(p_\perp + p_\parallel)K_\psi}{B^2} > 0, \tag{8}$$

where K_ψ is the component of the line curvature normal to the constant-pressure flux surface and the integration runs the entire TM length. We rely on higher-pressure, positive-curvature plugs to stabilize the negative-curvature regions joining the plugs with the uniform central cell, as in the conventional TM.[7] Of possible concern is the added destabilization of the barrier region. Using model fields and pressure profiles, we find that minimum-B plugs of mirror ratio 2 and ellipticity 30 can line-average stabilize a mirror-ratio-10 barrier region of $\beta_{\parallel b} \approx 2\beta_{\perp p}$. This curvature constraint is more stringent than the firehose, but is easily satisfied. Local ballooning ultimately sets a β limit,[7] and is currently being evaluated.

In the stream-stabilized mode of 2XIIB operation,[8] it frequently occurred that the density outside the mirror on the upstream side exceeded the hot-ion density between the mirrors by a factor of 3 or more and the density in the mirror throat by a factor of 10 to 20, with T_e inside twice that outside. (The potential profile was not measured.) We believe residual ion-cyclotron fluctuations precluded accumulation of ions at the magnetic maximum by $\vec{\mu} \cdot \nabla B$ forces induced by perpendicular ion heating. If this interpretation proves correct, it might be possible to extend this technique to reactor conditions, either by internally or externally generated rf, at either the plug or auxiliary mirror peak.

Although a complete TM reactor design employing thermal barriers awaits a more careful evaluation of the efficiency and stability of specific ion-pumping mechanisms, we can get a rough idea of the impact of thermal barriers by estimating the densities, fields, and powers for the plugs and the barriers for $g_b = 2$. Let us take a central-cell density $n_c = 10^{14}$ cm^{-3}, temperature $T_{ic} = T_{ec} = 40$ keV, field $B_c = 2.1$ T ($\beta_c = 0.7$), and radius $r_c = 100$ cm (giving $\simeq 20$ MW fusion power/m). At $\varphi_c \simeq 3T_{ic}$ and $\varphi_e \simeq 7T_{ec}$, fusion α particles will sustain central-cell energy losses at $n_c \tau_{\rm loss} \simeq 10^{15}$ cm^{-3} s obtainable by electrostatic confinement,[9] neglecting radial loss. For a maximum MHD-stable barrier mirror ratio $R_b = 10$, Eqs. (3) and (5) give $n_b = n_c/14 \simeq 7 \times 10^{12}$ cm^{-3} at $\varphi_b = 2.6T_{ec}$. Choosing the maximum $T_{ep} \simeq \varphi_b + \varphi_c \simeq 230$ keV consistent with our assumption of plug electrons being Maxwellian up to their confining potential, we have $n_p/n_b = 2.7$, or $n_p = 2 \times 10^{13}$ cm^{-3}, 5 times smaller than n_c. For plug ions to be mirror confined they must be injected above $(\varphi_e + \varphi_c)/(R_p - 1)$, which equals 150 keV for plug mirror ratios $R_p = B_{mp}/B_p(1-\beta_p)^{1/2} = 3.7$; so take $E_{\rm inj} = 200$ keV for adequate confinement. Ion scattering with small electron drag (high T_{ep}) leads to mean plug-ion energies $\overline{E}_p \simeq 2E_{\rm inj} \simeq 400$ keV, requiring plug fields $B_p \simeq 2.7$ T at $\beta_p \simeq 0.7$, mirror fields $B_{mp} \simeq 5.4$ T for $R_p = 3.7$, and maximum conductor fields $B_{\rm max} \simeq 8$ T. Flux conservation gives $r_p = r_c(2.1/2.7)^{1/2} \simeq 90$ cm; so with spherical plugs $V_p \simeq 3 \times 10^6$ cm^3, and using Eq. (2), we find an auxiliary electron heating power $P_{cp}V_p \simeq 9.4$ MW per plug. The required injected-neutral-beam power per unit volume is

$$P_{\rm NB} \simeq n_p{}^2 E_{\rm inj}/(n\tau)_p \tag{9}$$

with[10]

$$(n\tau)_p \simeq 6 \times 10^{10} E_{\rm inj}{}^{3/2} \log_{10}\left[\frac{R_p}{1 + (\varphi_e + \varphi_c)/E_{\rm inj}}\right] \simeq 1.5 \times 10^{13}\ {\rm cm^{-3}\ s} \tag{10}$$

being the particle confinement for hydrogen plug ions with the above parameters, giving a neutral-beam power $P_{\rm NB}V_p = 2.5$ MW per plug. For the barrier parameters we have a barrier field $B_b = 0.5$ T for an MHD-stability-limited $\beta_{\parallel b} \simeq 1.4$ with $\beta_{\perp b} \simeq 0.5$ ($T_{i\perp} \simeq T_{ic}/R_b$ in the barrier); so at $R_b = 10$, $B_b(1-\beta_b)^{1/2} \simeq 0.35$ T, and $B_{mb} = 3.5$ T. Flux conservation gives $r_b = 1.8\, r_c \simeq 180$ cm; approximating the barrier volume as a sphere of this radius and using Eq. (7), we have $P_{\rm pump}V_b = 0.6$ MW per barrier. Thus the total required plasma input power $2(P_{cp}V_p + P_{\rm NB}V_p + P_{\rm pump}V_b)$ would be in the range of 25 MW. Since the center cell produces 20 MW fusion power/m, the TM reactor Q (central-cell fusion power)/(plug + barrier input power) would be approximately $Q = 40$ for a central-cell length of 50 m, and would increase proportionately at higher powers and lengths.

An addition that might be necessary in some situations is the confinement of anisotropic, hot electrons in the barrier region. When added to the right side of Eq. (3a), the presence of such electrons would give a larger φ_b for a given n_b, further reducing the power transfer between the plug and central-cell electrons. However, the power necessary to sustain these hot electrons can be comparable to the bulk plug-electron heating estimated above.

Finally, we see a number of issues concerning conventional TM confinement to be little affected by the addition of a barrier cell. This would certainly be true for the drift-cyclotron-loss-cone mode[11] in the plugs. Various drift modes in the solenoid would be forced to fit parallel wavelengths between the barrier regions. Neoclassical and related transport[12] would be reduced, roughly by a factor $B_c(1-\beta_c)^{1/2}/B_{mb}$, due to that fraction of the solenoidal ions being confined by an axisymmetric field.

In summary, thermal barrier potentials can substantially reduce plug power in TM reactors. Of crucial importance are the questions of how the barrier is formed and how completely the accumulation of thermal ions can be prevented. Methods of forming thermal barriers may represent rather small changes in the conventional TM geometry. We seek to apply electron heating power selectivity in such a way as to improve confinement. The degree to which this can be done will take time to evaluate, and probably we have not yet found the best scheme for efficiently pumping thermal ions. The potential improvements to be gained from this approach are so great as to warrant a thorough theoretical and experimental study.

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Enhanced Drag by Radiation for Runaway Electrons

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Relativistic particle simulations of the beam-plasma interaction show that a dc electric field intensifies the interaction and amplifies radiation; radiation in turn clamps the runaway momentum. When the dc field exceeds a critical value, the runaways are detached from collective interactions. The effect of enhanced radiation and clamping may be of significance for devices such as traveling-wave tubes and free-electron lasers and for tokamak experiments.

An applied dc electric field causes a variety of phenomena in a plasma, in particular, intensification of the coupling between plasma waves and particles. Among these, anomalous drags or resistivities were reported in experiments[1] and simulations,[2] and runaways[3] were observed in toroidal devices.[4] An interest in the interaction of intense waves and electrons in the presence of a dc electric field has been stimulated by the recent observation[5] of a dramatic increase in radiation yield of traveling-wave tubes with the application of a dc field. Particle simulations