STUDIES OF A STRAIGHT FIELD LINE MIRROR WITH EMPHASIS ON FUSION-FISSION HYBRIDS

O. ÅGREN,[a]* V. E. MOISEENKO,[b] K. NOACK,[a] and A. HAGNESTÅL[a]

[a]*Uppsala University, Ångström Laboratory, Division of Electricity, Box 534, SE-751 21 Uppsala, Sweden*
[b]*Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology," Akademichna st. 1, 61108 Kharkiv, Ukraine*

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The straight field line mirror (SFLM) field with magnetic expanders beyond the confinement region is proposed as a compact device for transmutation of nuclear waste and power production. A design with reactor safety and a large fission-to-fusion energy multiplication is analyzed. Power production is predicted with a fusion Q = 0.15 and an electron temperature of ~500 eV. A fusion power of 10 MW may be amplified to 1.5 GW of fission power in a compact hybrid mirror machine. In the SFLM proposal, quadrupolar coils provide stabilization of the interchange mode, radio-frequency heating is aimed to produce a hot sloshing ion plasma, and magnetic coils are computed with an emphasis on minimizing holes in the fission blanket through which fusion neutrons could escape. Neutron calculations for the fission mantle show that nearly all fusion neutrons penetrate into the fission mantle. A scenario to increase the electron temperature with a strong ambipolar potential suggests that an electron temperature exceeding 1 keV could be reached with a modest density depletion by two orders in the expander. Such a density depletion is consistent with stabilization of the drift cyclotron loss cone mode.

KEYWORDS: *hybrid reactor, fusion-fission reactor, mirror machine*

I. INTRODUCTION

The linear geometry of magnetic mirrors possesses several advantages.[1] A continuous mode of operation (for years) is possible without the need for an inductive current drive, and a mirror fusion source could rapidly be turned off, which could be beneficial for reactor safety. Violent large-scale plasma instabilities are avoided in stabilized magnetic mirrors.[1] Large magnetic expanders beyond the confinement region drastically reduce the power load on divertor plates.[1,2] Radio-frequency (rf) antennas for plasma heating could be placed outside the fusion neutron region,[3,4] and holes for rf power feed and diagnostic windows and mirrors could be located outside the fusion region. Loads on such sensitive equipment are then minimized. Superconducting coils can be computed that allow for a fission mantle with no holes apart from a narrow region at the ends of the confinement region.[5,6] Such a geometry would be optimal for capturing fusion neutrons at the fission mantle, and thereby for achieving a large energy multiplication M of the neutrons by the activated fission reactions. The neutron energy multiplication M is the ratio of the fission power to the power of the injected neutrons from the external source. As will be shown, computations for the straight field line mirror (SFLM) with reactor safety margins yield the possibility that the neutron energy multiplication M exceeds

$$M = \frac{P_{fission}}{P_{fusion\ neutrons}} > 125 \ , \tag{1}$$

where the 14.1-MeV neutron energy represents ~80% of the energy produced in each deuterium-tritium reaction (the remaining is the 3.5-MeV energy of the alpha particles). With M values in this range, more than nine fission reactions in the mantle are activated per incident fusion neutron. A high M would relax demands on plasma confinement[6,7] for energy production. The most serious drawback of the open geometry of magnetic mirrors is the

*E-mail: Olov.Agren@angstrom.uu.se

semipoor axial electron energy confinement, which leads to comparatively low electron temperatures and could result in too strong of a power drain. Power loss in modest-size mirror machines is typically dominated by electron drag from the hotter ions to the electrons (possibly with the exception of tandem mirrors with a strong ambipolar potential and reduced electron drag, where ion longitudinal power loss and radial losses may become an essential fraction of the power loss; compare Ref. 8). With a power loss dominated by electron drag, the demands on the electron temperature could be relaxed drastically for a mirror fusion-fission device with a large M. An estimate of the lower bound on electron temperature for power production (with a ratio of electric power output to input power exceeding 5) in a fusion-fission mirror reactor with $M > 125$ is (see Sec. VI)

$$T_e^{(crit)}\,[\mathrm{keV}] \approx \frac{12}{M^{2/3}} < 0.5\ \mathrm{keV} \quad . \tag{2}$$

Electron temperature measurements (by soft X-rays) in the Gamma 10 tandem mirror indicate that electron temperatures in this range have been achieved.[8] The gas dynamic trap (GDT) device has recently demonstrated an increase of the electron temperature to 250 eV (measured with Thompson scattering) with improved confinement by sheared E × B rotation (or vortex confinement) created by potential plates at the magnetic expander,[9] and there is hope to increase the GDT electron temperature further with increased neutral beam power. Plasma β rising to 60% at the sloshing ion peaks has been achieved in GDT (Ref. 9). Plasma flow into the expander, required for stabilization of the interchange mode of axisymmetric devices, is a potential threat for increase of T_e. In the SFLM scenario, the situation is different since there is no need for an expander plasma to provide interchange stability, and this opens the possibility of creating a strong electric potential (that increases electron confinement) by density depletion in the expander[10] and thereby a higher electron temperature.[2,5] A model with a balance of electron drag and losses carried out by loss cone electrons indicates that an electron temperature exceeding 1 keV could be possible with a modest density depletion by two orders in the expander region.[5]

Fast reactors, with a fast neutron energy spectrum, could burn plutonium and certain minor actinides and fission products more efficiently than standard light water reactors. Most fast fission reactor proposals are critical reactors without an external neutron source. In critical reactors, the actions of delayed neutrons are crucial to avoid hazardous events with an exponential power increase associated with a neutron multiplicity exceeding unity. In standard light water reactors, which are capable of using only a minor part of the nuclear fuel energy content for power production, Doppler broadening, the void of the coolant, and the fraction of delayed neutrons are important for reactor safety. All these stabilizing effects are seriously reduced in fast reactors, but a subcritical fast reactor design (with an external neutron source) could enhance reactor safety. Power production in a driven subcritical system is controlled by the external neutron source, and the power production is terminated by turning off the external neutron source. Alternatives for the external neutron source are accelerator-driven systems (ADSs) with a spallation source or, as in the framework in this paper, a fusion device. In particular, industrial incineration of minor actinides, with its low fraction of delayed neutrons, would require a driven system. In addition, a driven fast reactor could offer enhanced reactor safety for plutonium burning, aiming at long-term global-scale power production with efficient use of the nuclear fuel resources.

Analytical results for the SFLM field will be briefly reviewed. Results on the rf heating, magnetic coil, and neutron computations will be presented, as well as calculations for the neutron energy multiplication M and the electron temperature. Detailed computations for a compact 25-m-long confined plasma with a 40-cm plasma radius[5] support the possibility to make a neutron source and a fission blanket with a high value of M, with a corresponding 1.5-GW thermal power production.

II. THE SFLM FIELD

A yardstick to obtain magnetohydrodynamic (MHD) stable mirror confined plasma equilibrium is to construct an average minimum B field by quadrupolar coils. A drawback of the quadrupolar field is the tendency for strong ellipticity of the flux tube near the mirrors.[1,11] The optimal choice that combines MHD stability with the smallest possible ellipticity ought for this reason to be a marginal minimum B field. In the paraxial approximation, the unique solution for this magnetic field reads[11,12]

$$\frac{\mathbf{B}}{B_0} = \frac{\nabla s}{1 - s^2/c^2} = \nabla x_0 \times \nabla y_0 \ , \tag{3a}$$

where

s = arc length of the magnetic field lines

x_0, y_0 = Clebsch coordinates

c, B_0 = constants.

To leading orders in a/c, where a is the midplane radius of the flux tube, the arc length is

$$\bar{s}(x,y,z) = \bar{z} + \frac{1}{2}\left(\frac{\bar{x}^2}{1+\bar{z}} - \frac{\bar{y}^2}{1-\bar{z}}\right) \ , \tag{3b}$$

where $\bar{s} = s/c$ and $\bar{z} = z/c$ and the Clebsch coordinates are $x_0 = x/(1+\bar{z})$ and $y_0 = y/(1-\bar{z})$, which describes straight nonparallel field lines with focal lines at $z = \pm c$; see Fig. 1. As the field lines are straight, there is zero

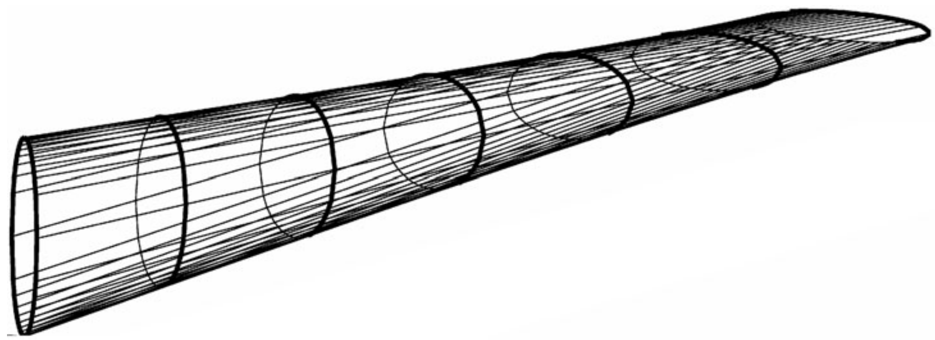

Fig. 1. The straight nonparallel magnetic field lines in the marginal minimum B field. Each gyro center bounces back and forth on a single field line in this particular field.

field line curvature, which is consistent with a marginal minimum B field. The flux tube boundary is determined by

$$a^2 = \left(\frac{x}{1+\bar{z}}\right)^2 + \left(\frac{y}{1-\bar{z}}\right)^2 \tag{3c}$$

with the corresponding ellipticity $\varepsilon_{ell} = (\sqrt{R_m} + \sqrt{R_m - 1})^2$, where $R_m = B_{\max}/B_0$ is the mirror ratio for the confinement region. For a mirror ratio of 4, $\varepsilon_{ell} = 13.9$, which seems acceptable for a mirror reactor.

A check shows that to leading orders, $|\nabla s| = 1$, and thus, $B = B(s)$ is a marginal minimum B field. From this follows that the guiding center magnetic drift is zero since

$$\mathbf{v}_\perp \sim \mathbf{B} \times \nabla B(s) = 0 \ . \tag{4}$$

This implies that each ion moves back and forth on a single magnetic field line, whereby the guiding center values of the Clebsch coordinates are constant[12]:

$$x_{0,c} = x_0 + (1 - \bar{s})^2 \dot{y}_0/\Omega_0 \tag{5}$$

and

$$y_{0,c} = y_0 - (1 + \bar{s})^2 \dot{x}_0/\Omega_0 \ . \tag{6}$$

The energy ε and the magnetic moment μ are also constants of motion, and Vlasov equilibria to first order in the plasma β can be described with distribution functions of the form $F(\varepsilon, \mu, x_0^{(c)}, y_0^{(c)})$. The resulting finite β magnetic field (in the paraxial approximation) can be written[12]

$$\mathbf{B} = \left(1 - \frac{\beta}{2}\right) \frac{B_0 \nabla s}{1 - s^2/c^2} \ , \tag{7}$$

where $\beta = 2\mu_0 P_\perp / B_v^2(s)$. This leads to $j_\parallel = 0$, which is a sufficient criterion to obtain omnigenous equilibria; i.e., the gyro center moves on a magnetic flux surface even to first order in β (a poloidal drift on the magnetic surface is added by the finite β, but the radial drift is zero). There is therefore no neoclassical enhancement of the radial transport, and this is achieved without axisymmetrization of the confining field.[12] Near omnigenuity is expected up to reasonably high β, say, $\beta \leq 30\%$ at the midplane. Although it is possible to create average minimum B fields at even higher β, near omnigenuity could not be expected if the β value is too high when quadrupolar fields are present.

Omnigenous equilibria, where the guiding center drift surfaces traverse a finite portion of a magnetic surface (not just a single magnetic field line as would be the case in the SFLM vacuum field), can also arise with an electric potential $\phi(s, r_0)$ (independent of the azimuthal angle), which is consistent quasi-neutrality and distribution functions of the form $F(\varepsilon, \mu, r_{0,c})$ for both ions and electrons, where $r_{0,c} = \sqrt{x_{0,c}^2 + y_{0,c}^2}$ is the radial guiding center Clebsch coordinate. The corresponding E $\times$ B rotation has no radial component, and the azimuthal rotation can be controlled with potential control plates in the expander region.

The influence on the ellipticity of a finite β has been examined,[13] as well as more recently the effect of magnetic expanders beyond the mirrors.[5] Suitable superconducting coils for a field with expanders have been determined for a representative case with a 25-m-long confinement region between field maxima and expanders outside. To satisfy the interchange stability criterion together with the plateau in magnetic field strength associated with the addition of expander regions, the ellipticity has to be increased somewhat from the ideal SFLM case. With a mirror ratio of 4, an ellipticity around 17 is sufficient to simultaneously satisfy the interchange stability requirement.

III. RADIO-FREQUENCY HEATING

Ion cyclotron resonance heating in the SFLM field has been studied numerically.[3,4] With a 40% minority deuterium concentration and 60% tritium majority concentration, the deuterons can be heated at the fundamental cyclotron frequency, while the triton ions can be heated at the second harmonic of the cyclotron frequency. The frequencies of the waves are selected to match the resonance absorption of waves at about half the maximum strength of B, which correspond to sloshing ion peak locations. The sloshing ions give the major contribution to the neutron production. Sloshing ions are favorable for plasma stability; enhanced stability margins against the Alfvén ion cyclotron mode arise as a result of the reduced overall velocity anisotropy in the mirror confined ion distribution, and a warm plasma can trap between the sloshing ion density peaks, which is useful for stabilizing electrostatic modes; see p. 1694 in Ref. 1.

Good coupling between the plasma and the launched rf waves can be achieved with the antennas located in the low-density region near the field maxima, where the neutron radiation is limited,[3,4] and electric breakdown in the antennas can be avoided with the rf voltage decrease in internally parallelized antennas.[3,4] Studies for a fusion reactor parameter case have predicted efficient heating with strong absorption of the rf fields near the resonance zones (>80% of the power), where sloshing ion peaks are formed by the heating.[3,4] Similar behavior is expected for a more compact fusion-fission hybrid scenario for the SFLM. Neutral beams, as in the GDT experiments, are an alternative means to heat the fuel ions and to produce sloshing ions. With a midplane neutral injection, a fission blanket would split into two parts (separated by the neutral beam openings), while it is possible to maintain a singly connected fission blanket within the rf heating scenario.

IV. NEUTRON TRANSPORT MONTE CARLO SIMULATIONS

A primary task is to determine the neutron energy multiplication M, and thereby the ratio $P_{fis}/P_{fus} \approx 0.8\,M$ of the ratio of produced fission and fusion power. The fusion power from the neutron source is $P_{fus} = E_{fus}S$, where $E_{fus} = 17.6$ MeV is the energy produced in a single deuterium-tritium fusion reaction and the source intensity S is the number of neutrons produced per second. The fission power is

$$P_{fis} = E_{fis} N_{fis} S \ , \tag{8a}$$

where

E_{fis} = average energy released per fission reaction

N_{fis} = average number of fission reactions initiated per source neutron.

In case of spent nuclear fuel, a representative value is $E_{fis} = \sim 190$ MeV. In addition, it is useful to relate N_{fis} to another quantity M_S:

$$M_S = \bar{\nu} \cdot N_{fis} \tag{8b}$$

with $\bar{\nu}$ as the average number of secondary neutrons that are released per fission reaction. Then, M_S is the average number of secondary neutrons that are released in fission reactions per source neutron. This quantity is a measure of the ability of the fission blanket to multiply a source neutron and depends primarily on the fuel composition and on the neutron spectrum within the fission blanket. A representative value with spent nuclear fuel is $\bar{\nu} \approx 2.96$, which is the number obtained in the GDT minor actinide burner simulations.[14] In the frame of the static reactor equation, which is an eigenvalue equation with the eigenvalue k_{eff} (Ref. 15) (where the neutron multiplicity k_{eff} has the particular value 1 for a critical nuclear reactor), the quantity

$$M_{eff} = \frac{k_{eff}}{1 - k_{eff}} \tag{8c}$$

expresses the ability of the fission system to multiply a fission neutron (in difference to it, M_S refers to a source neutron). However, in both cases the main part of the neutron multiplication is realized in cascades of fission reactions in the blanket, and this suggests that M_S has almost the same dependency on k_{eff} as M_{eff}, where notably both M_S and M_{eff} become singular as $1 - k_{eff}$ approaches zero. On this background the ADS community—see for instance Ref. 16—has introduced the quantity

$$\varphi^* \equiv \frac{M_S}{M_{eff}} \tag{8d}$$

from which the k_{eff} dependency should be (approximately) eliminated. The φ^* parameter reflects the quality of the coupling between the neutron driver and the fission blanket rather than the neutron multiplicative ability of the fission core itself. Several experiments and calculations of different driven subcritical systems have demonstrated this fact. For illustration, $\varphi^* \to 0$, if the source is removed outside of the blanket or neutron absorbers are introduced between the source and the blanket. On the other hand, it is possible to achieve $\varphi^* > 1$, provided that the source is located just in the very center of the fission blanket and additional multiplication of the fusion source neutrons, i.e., by $(n, 2n)$ reactions, can be arranged. In the study of the GDT-driven system, even the value $\varphi^* = 1.94$ was achieved.[14] For the SFLM with a 25-m-long fission blanket and an axially dependent source with representative sloshing ion peaks, it is merely $\varphi^* = 1.24$.

Inserting all quantities, one obtains finally

$$M \equiv \frac{P_{fission}}{P_{fusion\ neutrons}} = \varphi^* \frac{1}{\bar{\nu}} \frac{E_{fis}}{E_{fus}^{(n)}} \cdot \frac{k_{eff}}{1 - k_{eff}} \ , \tag{9a}$$

where $E_{fus}^{(n)} = 14.1$ MeV is the energy of the fusion neutrons. Equation (9a) describes the general structure of the power amplification factor of a fusion-driven subcritical system (FDS). Deriving the M values for a given system with φ^* and k_{eff} calculated either by precise neutron transport methods (e.g., Monte Carlo methods) or by the diffusion approximation can give substantially different results (the mean free paths for fusion neutrons are too long for a diffusion approximation). Preliminary Monte Carlo simulations for the SFLM (the neutronics calculations are still in progress, and detailed results will be published separately) give the formula (compare also Refs. 14 and 17)

$$M \equiv \frac{P_{fission}}{P_{fusion\ neutrons}} = \frac{1.24}{2.96} \cdot \frac{190}{14.1} \cdot \frac{k_{eff}}{1 - k_{eff}}$$
$$= 5.65 \cdot \frac{k_{eff}}{1 - k_{eff}} \leq 183 \ . \tag{9b}$$

The upper limit on M is restricted by reactor safety requirements, and we assume the range $k_{eff} \leq 0.97$ provides reactor safety margins for the driven system. A high M is achieved by minimizing holes in the fission blanket through which neutrons can escape, and the locations of the neutron reflectors, coolant, and tritium reproduction zone are important as well as the choice of coolant material (liquid lead-bismuth eutectic). For the SFLM with magnetic expanders, nearly all fusion neutrons give rise to fission reactions, and the formula

$$N_{fis} = \frac{E_{fus}^{(n)}}{E_{fis}} M = 0.0742M \leq 13.5 \tag{9c}$$

shows that in the range $125 < M < 183$, the average number of fission reactions activated per fusion neutron is within the range $9.2 < N_{fis} < 13.5$.

The neutron computations demonstrate the possibility of reproducing tritium and an acceptable neutron load on the first wall, and the requirements for sufficient shielding of the superconducting coils from the neutron flow can be checked. Less than 200 displacements per atom is predicted for the first wall within a 20-yr time of operation.[5] Neutrons produced in the fission mantle contribute substantially to the embrittlement of the first wall. The geometry in the neutron computations, i.e., a 25-m-long and 90-cm-wide vacuum tube for the confinement region and a 1.1-m-wide annular fission blanket between the vacuum chamber and the magnetic coils, is consistent with magnetic coil computations.[5] Computations are carried out with expected source distributions of fusion neutrons with intensity peaks at the sloshing ion density peaks. The fission blanket contains fission fuel, neutron reflectors, liquid lead-bismuth coolant, tritium reproduction zones, and a free space available for boron rods or added fuel. Simulations show good reactor safety margins concerning sudden loss-of-coolant accidents (LOCAs). The choice of coolant location and coolant material (lead-bismuth) add to stability; in a LOCA k_{eff} is not increased, primarily because the coolant acts like a neutron reflector. Preliminary Monte Carlo results (with $k_{eff} = 0.97$ and $\bar{\nu} \approx 3$) predict that almost all of the produced fusion neutrons contribute to fission reactions (the holes in the fission mantle are minimized in this mirror concept) and have resulted in $M \approx 183$.

A thermal fission power of 1.5 GW could be achieved with a fission blanket providing a high M and a neutron source intensity in the range $3.6 \times 10^{18} < S < 10^{19}$ n/s. The 1.5-GW fission power and the neutron source intensity range correspond to the range $183 > M > 66$ and, as follows from Eqs. (9b) and (9c) for the SFLM computations, $0.97 > k_{eff} > 0.92$ and $13.5 > N_{fis} > 4.9$, i.e., a lower bound on 4.9 activated fission reactions per incident fusion neutron. The higher neutron source intensity would allow broad margins for a drop in k_{eff} during the operation cycle. Alternatively, slow changes in the content of fuel and neutron absorbing materials in the mantle can be compensated by control rods to keep k_{eff} at a fixed value, with $1 - k_{eff} \approx 3\%$ not too small to maintain reactor safety without the need of the actions of delayed neutrons. The source intensity $S = 3.6 \times 10^{18}$ n/s (relevant for $k_{eff} = 0.97$ and a 1.5-GW thermal power in the SFLM) corresponds to a fusion power of 10 MW.

V. SUPERCONDUCTING COILS

The magnetic field could be produced from a combination of circular coils and baseball coils proving the stabilizing quadrupolar field[5]; see Fig. 2. Important tasks are to create an average minimum B field in the confinement region, link expanders to it, avoid too strong of flux tube ellipticity, assure current densities below thresholds for superconductivity, and arrange neutron shielding for the superconducting coils. It turns out that a complex set of axisymmetric and baseball coils is required for this strongly constrained problem, in particular, to reproduce strong gradients near the magnetic field maxima, and to obtain a minimal flux tube ellipticity with the plasma average minimum B stability satisfied.[5] For a plasma radius of 40 cm at the midplane and a 25-m-long confinement region with a mirror ratio of 4, the best ellipticity found was 17.1, which is somewhat larger than the ideal SFLM result.[5] The alpha-particle gyroradius exceeds the smallest gradient scale lengths of the magnetic field (even at the elliptic flux tube regions near the field maxima). Space is available for a fission blanket and coolant tubes, and the expanders have a nearly circular cross section near the limiting walls, which simplifies accessibility to the confinement region. Potential plates can be introduced in the expander regions to enhance plasma confinement by sheared rotational E × B flow.

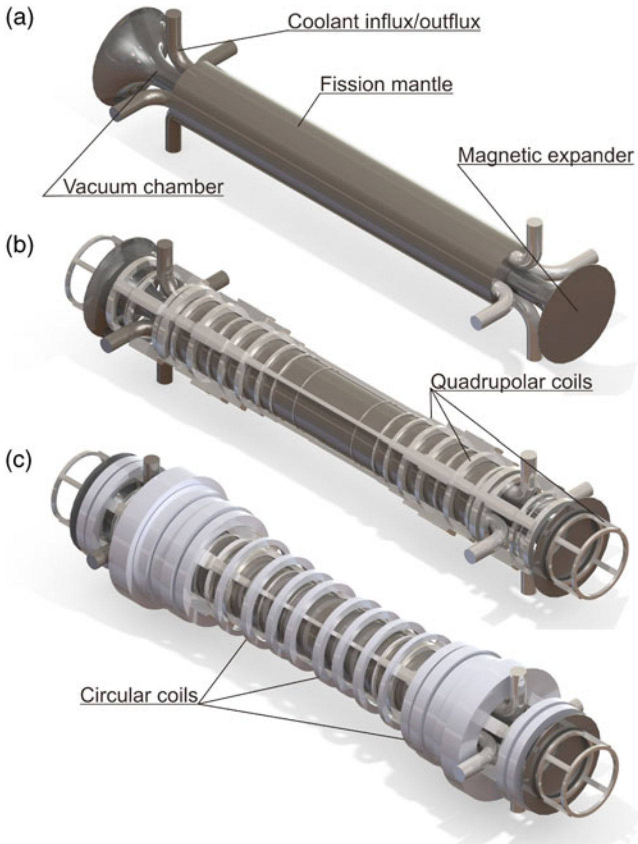

Fig. 2. Coils for an SFLM mirror hybrid machine: (a) the chamber stripped from coils, (b) the quadrupolar coils, and (c) the entire coil set with the exterior axisymmetric coils.

Pumping in the expander could be a means to achieve strong density depletion in the expander.

VI. SCENARIO FOR INCREASED ELECTRON TEMPERATURE

Single cell mirrors can operate with a high M and substantially relaxed (compared to a fusion reactor) demands on the electron temperature, but it is still desirable to identify a scenario for increased electron temperature in mirror machines to reduce the power required to sustain the plasma ion kinetic energy. A scheme is outlined here to achieve this by density depletion in the expander region of a mirror with a confined plasma stabilized by quadrupolar fields.

In mirror experiments with not too low electron temperature and a "thermal separation" of the confinement region from an outer region, the longitudinal loss is orders of magnitude smaller than predicted by simple thermal conduction; see p. 1595 in Ref. 1. This is due to the ambipolar potential and its spatial distribution; most electrons are confined to the region between the mirrors, where a Boltzmann relation for the potential and density is representative if there is no external heating directly on the electrons. Most of the few electrons that escape through the region between the mirrors do not have sufficient energy to overcome the ambipolar potential, and those electrons continue to bounce back and forth through the mirror confining region with bounce points primarily determined by the electric potential distribution and the energy of the particle. Only a tail of the escaping particles has sufficient energy to reach the wall and overcome the wall potential sheath (where the Boltzmann relation does not apply).

The electron temperature results from a balance of the energy sources (electron-ion drag) and losses (primarily associated with loss cone electrons escaping through the mirrors),[10]

$$\frac{dW_e}{dt} \approx P_{drag} - P_{el,loss} \ , \tag{10a}$$

where the ion-electron drag is $P_{drag} \approx (1/\tau_d) n_0 k_B T_i$ and

$$\tau_d\,[\mathrm{s}] \approx \frac{1.1 \times 10^{18}}{n_e\,[\mathrm{m}^{-3}]} T_e^{3/2}\,[\mathrm{keV}] \tag{10b}$$

is the drag time. Pastukhov[18] modeled the longitudinal loss term in a long-mean-free-path parameter range by electrons escaping through the wall sheath potentials in a square well magnetic model, and the parameter region is extended in Ref. 19 to include also short mean free paths; see also Ref. 20. We here use a simplified approach and model the longitudinal loss by the following formula, with the intention to obtain simple scaling formulas for the density depletion and ambipolar potential and how this could lead to an increased electron temperature:

$$P_{el,loss} \approx \eta_{loss} \frac{n_{lc}}{\tau_{tr}} k_B T_e \ , \tag{10c}$$

where

n_{lc} = loss cone density in the region outside the confinement region where the important sinks for the electron energy appear

$\tau_{tr} \approx L_{conf}/v_{th,e}$ = transit time of the electrons; L_{conf} is length between the bounce points

$1/\eta_{loss}$ = parameter estimating how many longitudinal bounces an average loss cone electron could make before its energy is lost in the "sink region" (where impurity radiation, ionization of neutral gas, secondary emission, etc., appear).

Most loss cone electrons bounce back to the confinement region by a potential sheath near the wall, and thus, $\eta_{loss} \ll 1$ in representative situations. Secondary emission (which has the effect that the charged ion and electron outflow need not be identical) tends to go to zero as the expander mirror ratio increases (the ratio of the field maximum to the lowest field in the expander), which is an additional beneficial feature of expanders. Impurity and gas reduction in the expander tend to increase $1/\eta_{loss}$. Equation (10) implies that the electron energy and temperature would increase by depleting the electron loss cone density n_{lc} sufficiently much. A Boltzmann relation between the density variation and the electric potential along a magnetic surface is realistic in this case for the region between the wall sheath potential and the magnetic field maximum (the scenario involves no external heating directly on the electrons):

$$\frac{e(\phi - \phi_0)}{k_B T_e} = \ln \frac{n}{n_0} \ , \tag{11}$$

where n_0 and ϕ_0 are the plasma density and the electric potential at the midplane. An electron temperature increase is predicted from Eq. (10) if

$$\frac{n_{lc}}{n_0} = e^{-\phi*} \le \frac{1}{\eta_{loss}} \frac{T_i}{T_e} \frac{\tau_{tr}}{\tau_d} \approx 0.5 \times 10^{-25} \frac{n_0\,[\mathrm{m}^{-3}]\,L_{conf}\,[\mathrm{m}]}{\eta_{loss}} \frac{T_i\,[\mathrm{keV}]}{T_e^3\,[\mathrm{keV}]} \ , \tag{12}$$

where $\phi^* \equiv -e\Delta\phi/k_B T_e = \ln(n_0/n_{lc})$ is a dimensionless ambipolar potential produced by the density depletion. Representative figures for the mirror FDS are $T_i \approx 50$ keV; $L_{conf} \approx 25$ m (the expander length is much shorter than the confining region); and $n_0 = 10^{20}$ m^{-3}, which corresponds to a predicted electron temperature increase in Eq. (10) provided

$$\frac{n_{lc}}{n_0} \le \frac{6 \times 10^{-3}}{\eta_{loss} T_e^3\,[\mathrm{keV}]} \ . \tag{13}$$

This condition does not seem to be very restrictive for a mirror FDS, as a few numerical examples illustrate. With $n_{lc}/n_0 = 10^{-2}$ and $T_e \approx 1$ keV, it would be enough if it takes two bounces ($1/\eta_{loss} > 2$) before the loss cone electrons lose their energy, and this low value of $1/\eta_{loss}$ suggests that the electron temperature could increase even further. If there are adequate pumping capabilities to achieve a density depletion of $n_{lc}/n_0 = 10^{-2}$, Eq. (13) predicts that the electron temperature reaches

$$T_e \approx \left(\frac{0.6}{\eta_{loss}}\right)^{1/3} \mathrm{keV} > 2 \ \mathrm{keV} \ , \tag{14}$$

where we have used the rough estimate $1/\eta_{loss} \approx 20$. This indicates that a density depletion by two orders could be an adequate measure to reach an electron temperature above 1 keV [a possible upper bound in Eq. (14) may be ~4 keV, dependent on the value of $1/\eta_{loss}$]. For a power device, $T_e \approx 1$ keV would have broad operational margins since an energy multiplication $M \approx 40$ is predicted to be sufficient for a net power production by Eq. (2). The value $M \approx 40$ corresponds in Eq. (9b) to $k_{eff} \approx 0.876$. Thus, if the electron temperature could be increased to 1 keV or more [as predicted by Eq. (14)], such a low value of the neutron multiplicity would account for any realistic swing in k_{eff} for a power-producing device. The power output, which is proportional to the fusion power, can be kept nearly constant by adjusting the plasma β and plasma heating to a slow evolution of k_{eff}. As already mentioned, slow changes in the content of fuel and neutron absorbing materials in the mantle can be compensated by control rods to keep k_{eff} at a fixed operational value, say, $k_{eff} \approx 0.97$, thereby reducing the need for broad operational margins on the fusion neutron source to control the power production. As high an electron temperature as possible is in any case desirable to lower the demands on plasma heating power.

A finite plasma flow through the mirror ends can stabilize the drift cyclotron loss cone (DCLC) mode.[21] Pumping in the expanders could maintain the density within the margins given by Eq. (13), even with the DCLC mode stabilized in the confinement region, to reach an electron temperature above 1 keV.

In situations when electron drag dominates the power loss, the input power would have to balance this loss, i.e., $P_{in} \approx P_{drag}$. In a representative fusion device, it could be expected that the electron temperature needs to be ~10 keV to assure a tolerable power loss. With additional power produced in a fission mantle surrounding the fusion device, the demands on the electron temperature can be reduced. With $P_{fis}/P_{fus} \approx 0.8\,M$ and assuming that the drag time increases as $T_e^{3/2}$ from Eq. (10b), the critical electron temperature for power production when electron drag dominates the power losses is given by the scaling in Eq. (2).

VII. RECYCLING POWER AND THERMAL FUSION *Q* FACTOR

Efficient power production requires $Q_{el} \ge 5$, where Q_{el} is the electric power gain factor for the whole system. This corresponds to a thermal fusion $Q = P_{fus}/P_{in}$ factor of ~15 with the estimate of one-third efficiency for the overall conversion from thermal to electric power. For a fusion-fission hybrid reactor, the thermal fusion Q factor can be substantially lower if there is a high M, i.e., a high fission-to-fusion energy multiplication. With $M = 125$ (or even higher values), which still would be within reactor safety margins for the neutron multiplicity, Q may be as low as 0.15 for a power-producing device with a tolerable limit on overall recycling power, and a Q factor reaching 0.2 would provide broad margins for power production, which follows from the high fission power, $P_{fission} = 0.8MP_{fus} > 100P_{fus}$ if $M > 125$. This range for Q seems achievable for the mirror hybrid reactor scheme studied here if the electron temperature reaches 500 eV. The density depletion scenario in the expander suggests the possibility to achieve electron temperatures exceeding 1 keV [even substantially higher electron temperatures are indicated by Eq. (13) if a density depletion below two orders is achieved].

The overall recycling power is tolerable as long as $Q_{el} \geq 5$. There may for any specific design be additional limits associated with local constraints, such as load on antennas, first wall, divertor plates, superconductors, and diagnostic windows and equipment. In the studies of the SFLM with expanders, we have found no sign of criticality connected with such constraints, and the studies require neither alpha-particle heating of the plasma nor recovery of the power associated with escaping particles. The studies predict that $Q = 0.15$, and $T_e \approx 500$ eV would be sufficient for power production.

VIII. COMMENTS ON TOROIDAL AND OPEN SYSTEMS

A reactor producing power in the gigawatt range ought preferentially to be capable of a continuous operational cycle in the range of a year, to avoid cyclic thermal stresses and costly demands on the power grid. This is a major obstacle for axisymmetric tori, where the toroidal plasma current (driven by inductive current drive) is used to produce a rotational transform of the magnetic field lines to achieve plasma confinement. The inductive current drive limits the pulse length of a tokamak.

A stellarator, where the rotational transform is produced by the vacuum field, does not require inductive current drive, and compared to a mirror machine, the toroidal geometry is beneficial for plasma confinement. Mirror machines and stellarators share the qualities of continuous operation and absence of major disruptions. If proper (nested) magnetic field surfaces could be achieved, it may be beneficial to combine the favorable properties of a stellarator (electron confinement in particular) and the possibility to have local neutron production of hot sloshing ions in the mirror part, where the ends of the mirror part are connected with a stellarator tube with a rotational transform. A brief theoretical study of such a stellarator-mirror device is carried out in Ref. 22, which indicates the potential for power production for a reasonably compact device. One concern is the complexity introduced by a toroidal machine, and another is the lowered plasma β limits in the toroidal sections compared to the β limits of mirror machines. A mirror device is considerably simpler than a toroidal device, and if the electron confinement issue is solved, an open geometry seems adequate for a fusion-fission reactor.

Compared to axisymmetric tori, a hybrid reactor based on a mirror machine can use a higher-energy multiplication in a fission mantle. One reason is that holes in the fission mantle cannot be avoided in axisymmetric tori and a substantial part of the fusion neutrons would not activate fission reactions [a simulation of the subcritical advanced burner reactor (SABR) tokamak predicted that only 39% of the fusion neutrons are active[23]]. Another reason is that scaling laws predict that a tokamak even with $Q = 0.1$ needs to have a considerably higher neutron output than would be necessary for a hybrid. For instance, the SABR simulations have given the high lower bound $S > 5 \times 10^{19}$ fusion neutrons per second for a total thermal fission power or 3 GW or more[23] (corresponding neutron intensities in a mirror could be lower). To avoid too large a total power (which would have implications on cooling, the power grid, and power production diversity), it would be necessary to limit the energy multiplication factor of a tokamak hybrid reactor. Mirror hybrid machines can be designed more compact to take advantage of a substantially higher-energy multiplication factor M.

IX. CONCLUSIONS

The geometry of the SFLM with magnetic expanders has several beneficial features for a fusion-fission hybrid reactor. Continuous operation for long time is possible since there is no need for inductive heating and current drive. The fusion plasma can be contained within a tube, a fission mantle can be placed outside the vacuum tube, and the magnetic field can be produced by superconductors with sufficiently large coil radii to fit in the fission mantle and the vacuum tube inside the coils. Holes in the fission mantle are minimized by locating diagnostics, power feeding, and refueling and pumping devices outside a strong neutron flux region. The geometry and reactor safety margins provide the possibility for a fission-to-fusion neutron energy multiplication exceeding 125 (this number is substantially larger than the corresponding number for axisymmetric toroidal devices, which are limited by holes in the fission mantle and a stiffer lower bound on fusion power), with correspondingly relaxed demands on plasma confinement and the electron temperature of a mirror confined plasma. Power production is predicted with a fusion $Q = 0.15$ and an electron temperature of $\sim$500 eV. A scenario to reach this electron temperature by magnetic expander and plasma depletion in the expander is suggested. Results of computations for a compact reactor case with a 25-m-long plasma confinement region, capable of producing a thermal power of 1.5 GW, are summarized.

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REFERENCES

1. R. F. POST, *Nucl. Fusion*, **27**, 1578 (1987).

2. O. ÅGREN, V. E. MOISEENKO, and A. HAGNESTÅL, "The Straight Field Line Mirror Concept and Applications," *Problems At. Sci. Technol. Ser. Plasma Phys.*, **6**, 8 (2008).

3. V. E. MOISEENKO and O. ÅGREN, *Phys. Plasmas*, **12**, 102504 (2005).

4. V. E. MOISEENKO and O. ÅGREN, *Phys. Plasmas*, **14**, 022503 (2007).

5. A. HAGNESTÅL, O. ÅGREN, V. E. MOISEENKO, and K. NOACK, "A Study on Theoretical Field and Coil Design for a Single Cell Minimum-B Mirror-Based Fusion-Fission Reactor," *Fusion Eng. Des.* (submitted for publication).

6. A. S. TACZANOWSKI, G. DOMANSKA, and J. CETNAR, *Fusion Eng. Des.*, **41**, 455 (1998).

7. W. C. WOLKENHAUER and B. R. LEONARD, Jr., "The Nuclear Data Requirements for Fusion-Fission (Hybrid) Reactors," IAEA/SM-170/56 (1972); available from U.S. Department of Energy Office of Science and Technology Information at www.osti.gov.

8. T. CHO et al., *Phys. Rev. Lett.*, **97**, 055001 (2006).

9. A. BEKLEMISHEV, P. BAGRYANSKY, M. CHASCHIN, and E. SOLDATKINA, "Vortex Confinement of Plasmas in Axially Symmetric Mirrors," presented at American Physical Society Mini-Conference Innovative Magnetic Mirror Concepts and Applications, Atlanta, Georgia, November 2–6, 2009.

10. O. ÅGREN and N. SAVENKO, *Phys. Plasmas*, **12**, 022506 (2005).

11. O. ÅGREN and N. SAVENKO, *Phys. Plasmas*, **11**, 5041 (2004).

12. O. ÅGREN, V. MOISEENKO, and N. SAVENKO, *Phys. Rev. E*, **72**, 026408 (2005).

13. N. SAVENKO and O. ÅGREN, *Phys. Plasmas*, **12**, 122504 (2006).

14. K. NOACK, A. ROGOV, A. V. ANIKEEV, A. A. IVANOV, E. P. KRUGLYAKOV, and Yu. A. TSIDULKO, *Ann. Nucl. Energy*, **35**, 1216 (2008).

15. G. I. BELL and S. GLASSTONE, *Nuclear Reactor Theory*, Van Nostrand Reinhold Company (1970).

16. G. ALIBERTI, G. PALMIOTTI, M. SALVATORES, and C. G. STENBERG, "Impact of Nuclear Data Uncertainties on Transmutation of Actinides in Accelerator-Driven Systems," *Nucl. Sci. Eng.*, **146**, 13 (2004).

17. K. NOACK, A. ROGOV, A. A. IVANOV, and E. P. KRUGLYAKOV, "The GDT as Neutron Source in a Sub-Critical System for Transmutation," *Fusion Sci. Technol.*, **51**, 65 (2007).

18. V. P. PASTUKHOV, *Nucl. Fusion*, **14**, 3 (1974).

19. T. D. ROGNLIEN and T. A. CUTLER, *Nucl. Fusion*, **20**, 1003 (1980).

20. V. P. PASTUKHOV, "Classical Longitudinal Plasma Losses from Open Adiabatic Traps," *Rev. Plasma Phys.*, **13**, 203 (1987).

21. D. E. BALDWIN, H. L. BERK, and L. D. PEARLSTEIN, *Phys. Rev. Lett.*, **36**, 1051 (1976).

22. V. E. MOISEENKO, K. NOACK, and O. ÅGREN, "Stellarator-Mirror Based Fusion Driven Fission Reactor," *J. Fusion Energy*, DOI 10.1007/s10894-009-9233-y (2009).

23. W. M. STACEY et al., "A TRU-Zr Metal-Fuel Sodium-Cooled Fast Subcritical Advanced Burner Reactor," *Nucl. Technol.*, **162**, 53 (2008).